# Physics Basis, Optimization, and Control for Integrated 3D Edge Long-pulse Tokamak Scenarios

As a part of a collaborative project proposal

in response to DoE Program Funding Opportunity Announcement Numbers:

**DE-FOA-0002076 and LAB 19-2076**

In the area of **1. Long Pulse Control**

May 9, 2019

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Fusion Energy Sciences Program Office

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# Supplemental for Collaborative Proposal

**J.-K. Park (Lead PI)** will be the point of contact and coordinator for the combined research activity of this proposal.

**Collaborating Institutions:**
Princeton Plasma Physics Laboratory (PPPL) - J.-K. Park (PI), N. C. Logan, Q. Hu, C. Zhu
General Atomics (GA) - C. Paz-Soldan (PI), T. E. Evans, Y. Q. Liu, D. Weisberg
University of Wisconsin Madison (UW) - H. Frerichs (PI), O. Schmitz
University of California Irvine (UCI) - Z. Lin (PI)
Princeton University (PU) - E. Kolemen (PI)

**Leadership structure:** Dr. J.-K. Park is the lead PI, and Dr. C. Paz-Soldan is acting as the co-lead PI. Both Drs. Park and Paz-Soldan will oversee and integrate the research progress for each task in the breakdown. Each task is led by either an institutional PI or a key contributor, and all institutional participants including PPPL sub-contractors (UCSD and UNIST) will work in coordination towards completion of each year's milestones.

**Resources:** Experimental data, analysis, and proposal opportunities in AUG, EAST, KSTAR, and COMPASS-U will be available to each institutional PI and contributors from PPPL, GA, UW, UCI, PU throughout this project as indicated by attached letters of collaboration.

**Summary of Budget Request:**

| **Institution** | **PI** | **Average Effort by Task (FTE)** | | | | | | **Total Effort** | **Funding by Year (k)** | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 | | Year 1 | Year 2 | Year 3 |
| PPPL | Park | 0.50 | 0.54 | 0.72 | 0.27 | 0.02 | 0.47 | 2.52 | 636 | 658 | 643 |
| GA | Paz-Soldan | 0.50 | 0.58 | 0.13 | 0.27 | 0.0 | 0.0 | 1.48 | 404 | 390 | 405 |
| UW-Madison | Frerichs | 0 | 0 | 0 | 0.96 | 0 | 0 | 0.96 | 182 | 199 | 193 |
| UC-Irvine | Lin | 0 | 0 | 1.08 | 0 | 0 | 0 | 1.08 | 150 | 150 | 150 |
| PU | Kolemen | 0 | 0 | 0 | 0 | 1.08 | 0 | 1.08 | 250 | 258 | 268 |
| | **Totals** | **1.00** | **1.12** | **1.93** | **1.50** | **1.10** | **0.47** | **7.12** | **1622** | **1655** | **1659** |

# 1. Executive Summary

This project aims to leverage the unique research capabilities of international tokamak facilities to develop a unified physics basis and predictive capability for the control of edge-localized modes (ELMs) with optimized non-axisymmetric (3D) fields. This project complements work being done on US domestic facilities by enabling access to unique plasma regimes and long-pulse operation, thus expanding the viability and applicability of this US-pioneered control technique towards the ITER era. Furthermore, the project team consists of the leading US experts in this area and conducting this research will position the US research team to continue its leading role internationally and form the core of the international team to develop 3D field control for ITER and beyond.

The proposed tasks address high-priority research questions and necessary operational demonstrations sequentially, with the ultimate goal of a predictive capability for optimized 3D coil and plasma scenario design, culminating in demonstrated long-pulse stationary ELM suppressed discharges on KSTAR. The proposal is structured into six cross-cutting tasks, as illustrated by Fig. 1.1. Task 1 focuses on targeted experiments to resolve open issues in ELM suppression access criteria leveraging the key capabilities of international facilities. Task 2 uses this information to develop extrapolatable empirical and first-principles scaling laws. Task 3 enhances the predictive understanding of the transport changes implicit in the earlier tasks and validates key scaling trends. Task 4 applies earlier results to the prediction and optimization of divertor heat flux profiles in ELM suppressed scenarios. Task 5 develops real-time control of key actuators to enable routine long-pulse ELM suppressed operation. Finally, the scaling laws are further applied in Task 6 to the development of innovative 3D coils to isolate the spectral components of interest for more reactor relevant 3D field control.

KSTAR will be the focus device to test the 3D optimization to control ELMs in long pulse, while scaling laws will be developed using additional data from the AUG and EAST facilities, as well as DIII-D. Innovative 3D coil designs will be targeted to COMPASS-U and KSTAR where timely opportunities are presented, and to reactor relevant ex-vessel coils. The participating US institutions are the Princeton Plasma Physics Laboratory (PPPL, lead institution), General Atomics (GA), Princeton University (PU), the University of Wisconsin-Madison (UW), and the University of California-Irvine (UCI). This proposal also includes subcontracts for the University of California-San Diego (UCSD) and Ulsan National Institute of Science and Technology (UNIST, Korea) for small but necessary tasks.

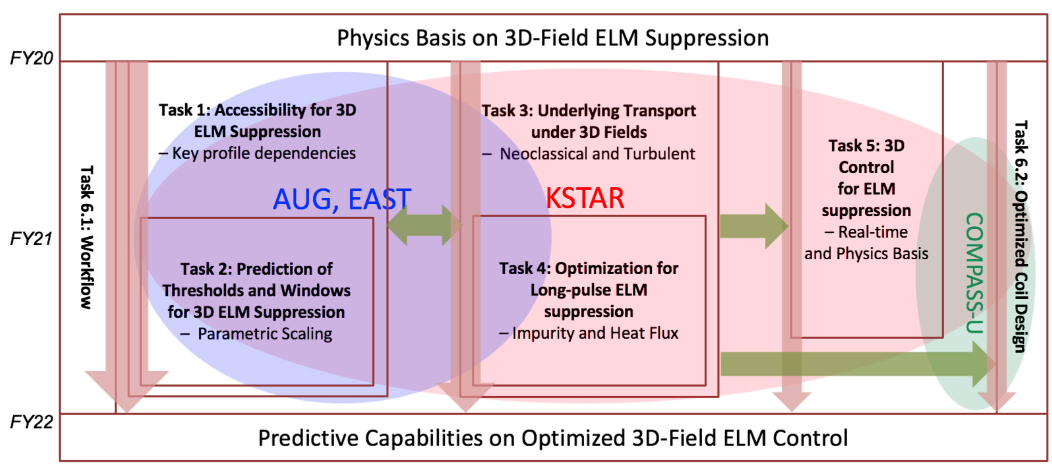


Figure 1.1. Schematic overview of task breakdowns and timelines, from the development of physics basis towards optimization, control, and design of 3D tokamaks. The cross-cutting nature of each task is also indicated (green arrows), with the collaborative facilities.

# 2. Introduction and Background

Small non-axisymmetric (3D) magnetic fields can greatly alter tokamak performance and provide unique and stable ways to control transport and instabilities when judiciously used [Evans15]. A key example of this is the demonstration of complete edge-localized mode (ELM) suppression using resonant magnetic perturbation (RMP) [Evans06, Suttrop11, Jeon12, Sun16]. In reactor-scale tokamaks like ITER, extremely stringent ELM mitigation factors are necessary [Hawryluk09, Loarte14], leading to the proposal of 3D fields as a candidate ELM control technique after its pioneering discovery by US scientists at DIII-D [Evans04]. Since its early discovery, US researchers have played a central role in exporting this control technique to the international tokamak research program. Taking the experience of AUG as an example, careful shape-matching identity experiments with DIII-D [Nazikian16IAEA] paved the way for ELM suppression access in that device after increasing the plasma triangularity. Another example is the first complete ELM suppression using the lowest toroidal mode (n=1) in KSTAR [Jeon12] and the successful prediction of ELM suppression operating windows in the full 3D phase space, also led by US scientists [Park18]. These discoveries put the field of 3D ELM control in a unique position to benefit from international collaboration. Though similar at a high level, data from the international program are regularly revealing seemingly inconsistencies, opening new methods to clearly identify the truly common physics basis that unifies observations made across the world program. This proposal seeks to leverage US scientists, active already in the US program, to benefit from these observations made abroad and lead the development of the physics basis and subsequently enabled predictive optimizations.

A central complexity in this field arises from the many degrees of freedom in generating 3D fields and plasma responses. Machine-machine variations in coil row position and coil density (Fig. 2.1) can easily confuse studies without a clear physics basis. Recent progress in KSTAR is potentially providing a resolution, by demonstrating that the variable effects due to 3D field spectrum can be predicted by linear response to 3D fields and can be well separable as an outer-layer response distinct from inner-layer field penetrations to islands in slower time scales. The diagram shown in Fig. 2.2 indicates three major consequences of n=1 3D fields in KSTAR, disruptive MHD driven by core resonant 3D fields in red, ELM suppression driven by edge resonant 3D fields in blue, and no major MHD events other than transport degradation by non-resonant 3D fields, as a function of the coil configuration in a special sub-space using the unique 3 rows of in-vessel coils. The operating space was predicted before the experiment, and the explored trajectories (a-e) including the dynamic path (e) to reach to the isolated ELM suppression window which is otherwise inaccessible, were deployed and successfully validated [Park18]. The degrees of 3D variability in KSTAR is high enough for us to claim that its prediction should be valid in entire 3D-field space in the studied target plasmas.

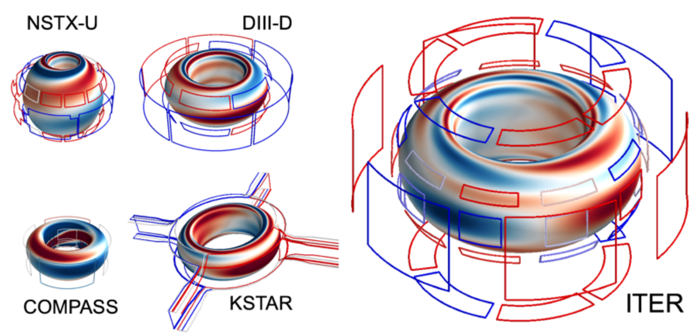

Figure 2.1. 3D field coils on existing world tokamaks and ITER. The color contours on each plasma surface show the various structures of the plasma response driven by each coil.

While demonstrating important progress, the above example also illustrates open areas in the field. There is still no ability to predict the core and edge field penetration thresholds, which were obtained empirically in the above case, thus limiting present-day spectral optimization to already well-documented plasma conditions. Furthermore, the additional transport and heat flux to plasma facing components driven by the 3D fields can also not yet be verifiably predicted, preventing the inclusion of these important effects in the 3D optimization framework. This is in particular of great importance to demonstrate 3D ELM control in

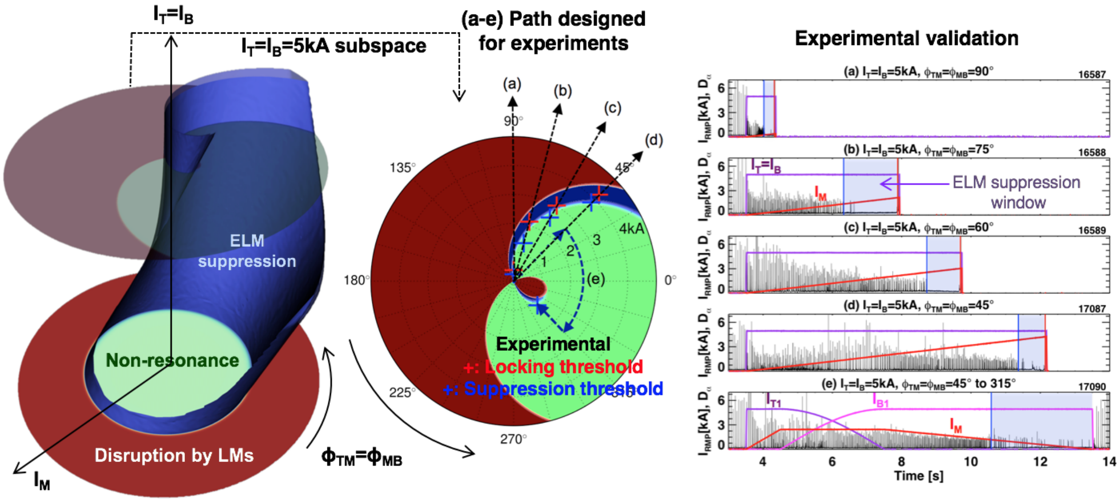


Figure 2.2. The predicted n=1 RMP ELM suppression windows on a KSTAR coil phase space; on two coil amplitudes and one phase on the left, and one coil amplitude and one phase in the middle. The ELM suppression experiments are designed based on this phase diagram and validated as shown on the right. Taken from [Park18].

long pulse, as has been already challenged in KSTAR as illustrated in Fig. 2.3 [In18] and will be targeted throughout this project. This collaborative proposal is motivated by these open questions together with other recent important progress made by project participants, as each background and proposed work will be described in detail by the task breakdowns, in Sec. 4.

The proposed international collaborations are critical to strengthening the US domestic research program in this research area. We target for studying questions that cannot be well addressed using US tokamaks and highlight the complementarity of these studies to work being done in the DIII-D national program by project participants. Seemingly disparate results obtained in the worldwide program should be unified by a common physics basis, which this proposal seeks to further develop. Our goal for an extended predictability and controllability of 3D ELM suppression can be achieved only by integrating observations across the international program, and further US leadership in this area can be best assured by supporting US scientists to take leadership roles in the international program. Enabling US experts to participate strongly in the international program is further posited to be the most effective path to effectively exploit the physics of ITER in this research area. ITER exploitation will necessarily be carried out in an international framework with many parallels to the collaborative framework proposed here.

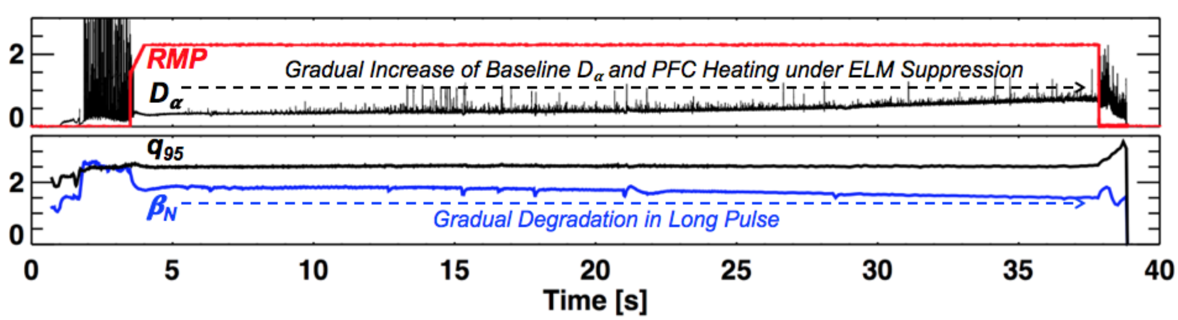


Figure 2.3. 3D ELM suppression for ~34s in KSTAR, ended by control sequence against PFC overheating. Gradual changes and degradations present a challenge in long pulse for 3D ELM suppression.

# 3. Project Objectives

The aim of this proposed project is to develop a unified physics basis and predictive capability for the control of edge-localized modes (ELMs) with optimized non-axisymmetric (3D) fields, by leveraging the unique research capabilities of international tokamak facilities. The proposed tasks first address high-priority research and physics questions and then move on to operational demonstrations. The project focuses on 3D ELM suppressed regimes as the most relevant for future reactor operation, as opposed to studying ELM mitigation physics. The ultimate goal is a capability to optimize 3D coils and plasma scenarios for ELM control in ITER and next-step devices, culminating in demonstrated long-pulse stationary ELM suppressed discharges on KSTAR.

The proposal is organized into six cross-cutting tasks, as already introduced in Fig 1.1. First several open questions regarding macro-scale parameter compatibility with edge field penetration and ELM suppression will be addressed via cross-machine study. Work focuses on the critical parameters of plasma axisymmetric shape, flow, and edge $q$-profiles, which are known to fundamentally determine the accessibility of 3D ELM suppression (Task 1). This task will use targeted experiments on several tokamaks to progressively establish the access boundaries and viable operating space, enabling the development of empirical and predictive scaling laws for 3D ELM suppression. Additional key parameters (such as density and toroidal field) that strongly affect the edge field penetration threshold will also be incorporated into penetration scaling laws. Other effects that limit the stable ELM suppressed operating window, such as core field penetration, H-L back-transition, and confinement degradation, will also be parametrized into scaling laws to enable robust operating space prediction (Task 2). These two tasks will provide datasets to study underlying transport mechanisms, which will be elucidated by leveraging the unique diagnostics of international facilities and simulating the observed effects with both neoclassical and turbulent transport models (Task 3). Next the implications on divertor heat flux of variations within the stable operating windows will be addressed, with a central aim being long-pulse ELM stable operation enabled via reduced divertor heat flux (Task 4). In addition to open-loop prediction and control, closed-loop feedback control will be developed to allow the plasma to automatically remain in the stable parameter ranges and configurations developed in earlier tasks (Task 5). Finally, fundamental understanding and predictive scaling laws gained in the previous sections are applied to the development of next-generation more distant coil sets for reactor-relevant long-pulse 3D tokamak operation.

KSTAR is chosen to be a focus device for the project as a whole, featuring prominently in all six tasks. The common physics basis (Tasks 1-3) however will be developed by exploiting the unique capabilities of AUG and EAST as well as KSTAR, and will be further levered by existing datasets and experience from US facilities such as DIII-D. The design on 3D coils (Task 6) will be mainly performed on COMPASS-U as well as KSTAR, motivated by plans by these facilities to invest in advanced coil sets for future, but also will be explored on ex-vessel options feasible in reactor scale.

# 4. Proposed Research and Methods

## 4.1. Common physics basis for accessibility conditions for 3D ELM suppression (Task 1)

This task is to resolve outstanding issues and to develop the common physics basis for 3D ELM suppression by exploiting the unique capabilities of AUG, EAST, and KSTAR facilities. The research focus here is in particular to understand the modifications of the profiles with the most critical macro-parameters; shape, flow, and $q_{95}$, as 3D ELM suppression is almost forbidden if these quantities are not properly adjusted. A testable hypothesis is the steep matching conditions among the strong peeling response by shape, the location of the resonant surface near the top of the pedestal related to $q_{95}$, and the stationary point of flows in the frame of $E \times B$, electrons or ions (i.e. $\omega_{E\times B}$, $\omega_{\perp e}$, $\omega_{\perp i}$, respectively) required for a bifurcation of islands or underlying transport. The work proposed under this task will remain largely empirical to define the boundaries of searching space of target plasmas, but will feed data and understanding for predictive scaling of ELM suppression in Task 2 and for transport studies in Task 3, targeting for integrated development of comprehensive physics basis. A path dependency to enter or exit ELM suppression in hysteresis will also be considered in experiments by forward and backward parameter scans if possible, as it can provide important dataset for Task 4 and 5. The numerical element defined under this task is the linear or quasi-linear 3D MHD only, for consistent interpretation of 3D fields and responses.

### 4.1.1. Physics basis for access dependencies on shape and divertor configurations

This sub-task focuses on providing the foundational understanding to explain targeted experiments on AUG and KSTAR that have found strong dependencies of accessing the 3D ELM suppressed states on the plasma shape [Nazikian16IAEA, Jeon16IAEA].

***Background:*** Recent AUG experiments discovered that increasing the upper triangularity $\delta_{up}$ is essential to access full ELM suppression on that device [Nazikian16IAEA]. This discovery was enabled by dedicated joint AUG-DIII-D experiments matching the plasma shape, as shown in Fig 4.1. Similarly, recent dedicated experiments on DIII-D have found strong dependencies of the plasma response on $\delta_{up}$, as shown in Fig 4.2, which are presently under active study. KSTAR experiments have also shown the criticality of 3D ELM suppression on plasma shaping [JeonIAEA16, JeonIAEA18]. It has been best characterized by the radial position of the lower X-point, as an example is shown in Fig. 4.3, where if the position is sub-optimal, ELM suppression is lost or limited due to the excitation of core locked modes (LMs). Linear plasma response modeling predicts that a small change of $\delta_{down}$ may be responsible, especially since these results are obtained with low toroidal mode n=1 to which the resonant response becomes very sensitive. Alternatively however, these results may also be affected by the variation in pedestal-foot profiles due to the change in divertor geometry and recycling, which can occur even irreversibly across these scans as implied in Fig. 4.3. These questions are essential to predict the application of

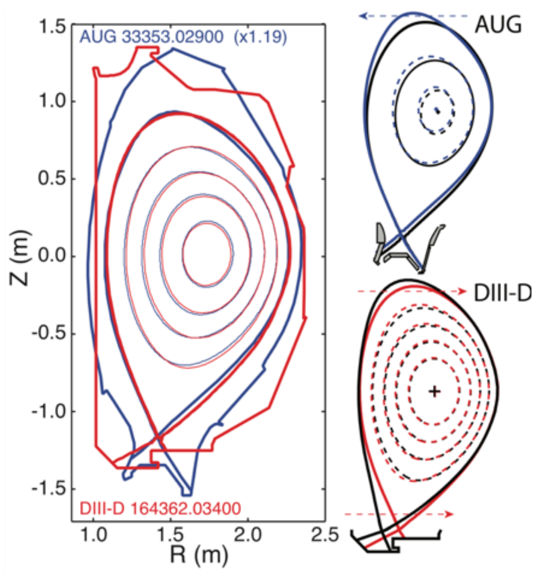


Figure 4.1. Access to 3-D ELM suppression in AUG was enabled by a shape-matching experiment with DIII-D, revealing crucial dependencies on the upper triangularity.

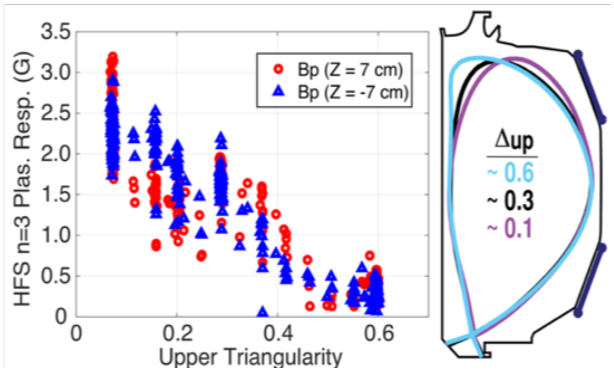


Figure 4.2. DIII-D results indicate a dramatic impact of plasma shape on the measured magnetic response, motivating cross-machine study.

3D ELM control scenarios to future tokamak designs, where the plasma shape is a clear design parameter of interest, and to understand the applicability of present experiments to ITER.

***Proposed Work:*** This task will aim to study and resolve these important open questions related to shaping, clarifying the role of 3D equilibrium and outer-layer response consistent across devices. In the case of AUG, we propose to deploy the IPEC & GPEC codes [Park07, Park17] (**Each code and capabilities relevant to this project is summarized in the Appendix 4.3*) to improve the understanding of shape effects and their modification of the ideal MHD drive for islands [PazSoldan16IAEA], utilizing existing data and participating in planned dedicated experiments. This modeling activity will complement existing modeling with other codes (MARS-F [Liu10], VMEC [Hirshman83]) by AUG team members, and add significant value to the similarity experiments being executed at DIII-D. The shape or X-point dependencies in KSTAR will also be thoroughly investigated by improved modeling of existing data as well as collaborating on new experiments. The shape dependencies of ELM suppression thresholds found across 2016 and 2017 campaigns will be studied by revisiting and kinetically reconstructing the equilibrium profiles using OMFIT-workflow in the collaborations with NFRI and SNU (See Task 6). The possible role of divertor effects will be resolved by varying $\delta_{up}$ vs. $\delta_{down}$ separately in new experiments, while maintaining constant divertor conditions. For both devices, GPEC modeling will continue to be a key tool to resolve the response effects of plasma shape. By leveraging DIII-D data, and combining observations from KSTAR and AUG, we aim to significantly advance the common physics understanding of the role of plasma shape or divertor configurations on ELM suppression.

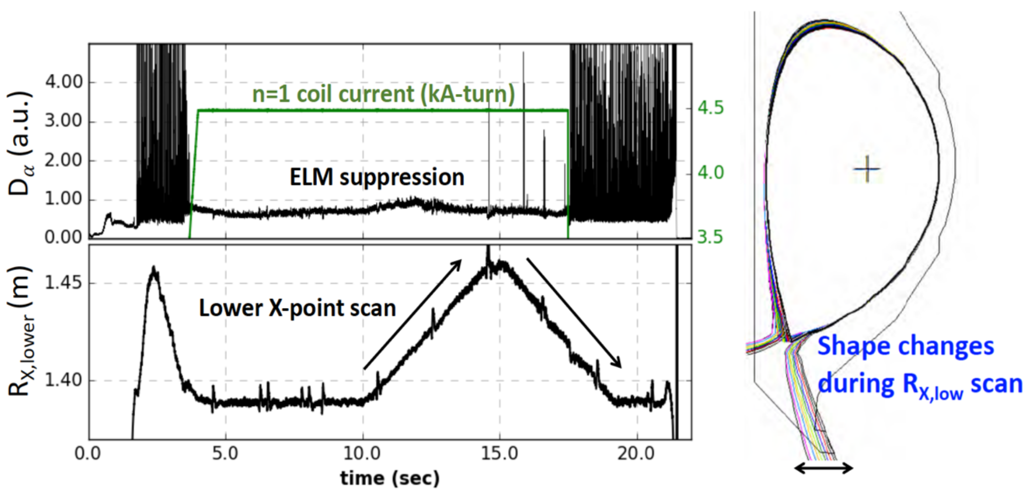


Figure 4.3. KSTAR experiments in 2017 campaign showing the loss of 3D ELM suppression during the X-point scan, with a hysteresis. Although the ELM suppression window in terms of $R_{X,lower}$ was extended in 2017 from (1.42m<$R_{X,lower}$<1.46m) seen in 2016 [Jeon18IAEA], but still sensitive to any variation in $R_{X,lower}$ as illustrated here.

### 4.1.2. Physics basis for access dependencies on flow and heating mix

This sub-task focuses on resolving the role of plasma flow to accessing the 3D ELM suppressed state and utilizing this understanding to improve ELM control access in RF-dominated regimes. This task will consist of linear and quasi-linear analysis of results from planned and existing dedicated experiments on EAST and AUG exploring the role of plasma flow under different heating mixes (input torques) and 3D spectra. Study of RF dominated regimes is enabled by focusing on experiments where the available RF power substantially exceeds that of domestic US facilities (See A4.1). Furthermore, high-*n* 3D fields are targeted in this sub-task, providing advance data to leverage planned 3D coil upgrades on US domestic facilities. The flow dependencies explored in this task will support later scaling studies of edge resonant field penetration in Task 2.

***Background:*** Recent work on both DIII-D and AUG have aimed to resolve the common physics of the rotation threshold for 3D ELM suppression. As shown in Fig 4.4, no rotation threshold has yet been observed on AUG [Suttrop18] while a clear threshold is found on DIII-D [PazSoldan19], indicating either novel physics or too large an input torque on AUG. Whether or not a rotation threshold is observed is of direct importance to whether 3D ELM suppression can be sustained without input torque, as would be expected in RF-dominated regimes. Exploration of RF-dominated regimes (with low input torque) are thus a very high priority for both the AUG and EAST research programs, as is understanding how to optimize 3D ELM control in these conditions.

The importance of this topic is several-fold. First, operation at low input torque on existing devices is thought to be more representative of expected ITER operating modes due to its large moment of inertia as compared to its input torque. As such, predictive understanding of the rotation threshold is important to understand 3D ELM suppression application to ITER. Second, long-pulse operation is necessarily RF-dominated, and thus understanding and optimizing RF-dominated regimes is on the critical path to long-pulse 3D ELM suppression. Finally, concerning the *n*-number spectrum effect, these studies will

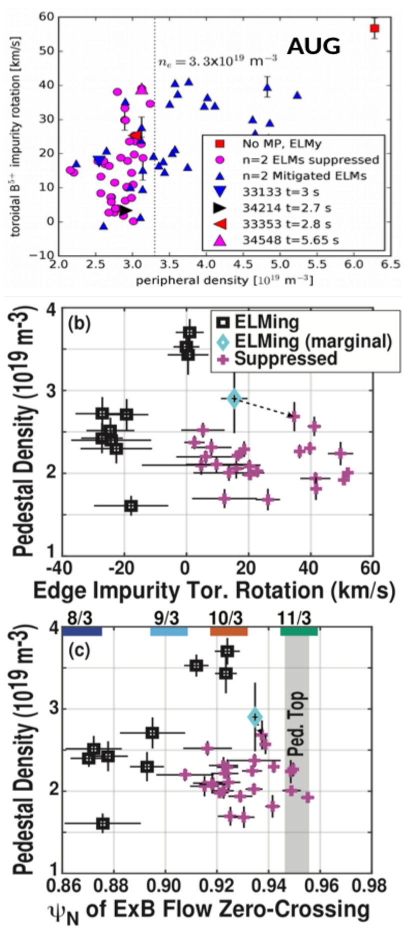


Figure 4.4. AUG thus far has found no critical rotation for ELM suppression [Suttrop2018], though on DIII-D a critical rotation is found that translates to a critical radius for the $\omega_{E\times B}$ zero crossing. [PazSoldan2019].

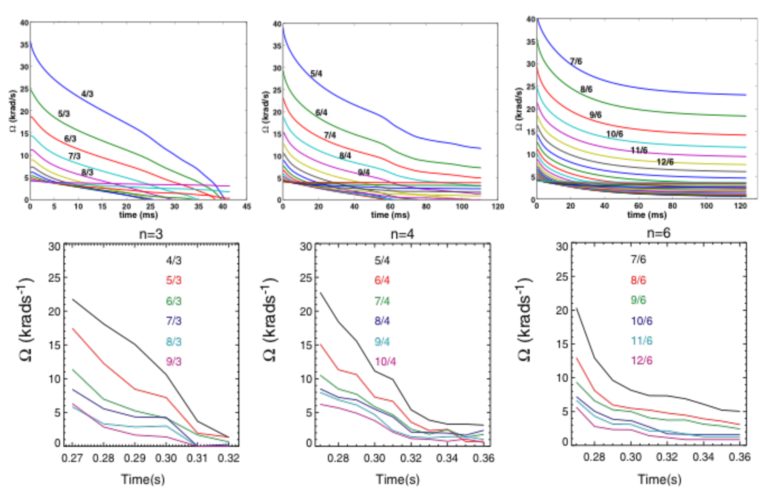


Figure 4.5. MARS-Q time-dependent flow damping modeling of MAST plasmas (upper panels) of n=3,4,6 3D fields and comparison with experiments (lower panels) [Liu12].

directly inform and leverage planned DIII-D investments in spectral flexibility offered through the new M-coil concept [D3D5YP].

***Proposed work:*** We propose to join the local teams in these studies and specialize in the plasma response and quasilinear flow predictions essential to understand and optimize the experiment. First, the linear plasma response will be computed with the GPEC and MARS-F [Liu12], enabling accurate treatment of plasma flow effects in the linear response. Here, the *n*-number of the 3D field will be highlighted in the optimization of RF-dominated regimes since the flow damping varies strongly with the *n*-number. Second, the flow profile expected from a given torque profile and RMP spectrum will be computed using MARS-Q [Liu13], a quasi-linear extension of the MARS-F. In MARS-Q, flow damping is computed from underlying NTV, $J\times B$, and Reynolds' stress torques, the flow profile is adjusted based on these torques, and the process repeated iteratively to evolve the flow. To focus on the input torque, we propose to modify the MARS-Q to explicitly include a user-defined momentum source. These tools will be utilized to aim to recover the experimentally observed changes in the plasma flow profiles upon change of the torque balance via heating mix as well as 3D spectrum, and demonstrate a path forward for demonstrating 3D ELM suppression in low input torque / RF dominated conditions.

### 4.1.3. Physics basis for access dependencies on edge safety factor ($q_{95}$)

This sub-task is to investigate the accessibility of 3D ELM suppression with respect to $q_{95}$, as is well known as "*q-window*" for resonance between 3D fields and edge plasmas, to develop its common physics basis across tokamak devices.

***Background:*** The q-window for 3D ELM suppression has been observed in all relevant devices. The observations indicate $q_{95}$~3.4-3.7 in DIII-D with n=3, $q_{95}$~3.5, $q_{95}$~4.0 in KSTAR and DIII-D with n=2 while $q_{95}$~3.6 in AUG, and $q_{95}$~4.0, 5.0, 6.0 in KSTAR with n=1 (Fig. 4.6). Generally, only narrow windows are observed ($\Delta q_{95}$ ~0.1). ELM suppression is almost forbidden outside these q-windows, whereas the modification of the pedestal in prior to ELM suppression seems to change continuously across the windows. It is important to understand its physics mechanism and find a resolution to overcome the accessibility limited by $q_{95}$, as otherwise 3D ELM suppression is not viable to many of baseline or advanced scenarios in ITER. An interesting observation recently made in DIII-D is the alleviated accessibility in hybrid high-$\beta_P$ scenarios [Nazikian18], possibly due to its wide pedestals, which are needed to be tested in other devices for its general applicability.

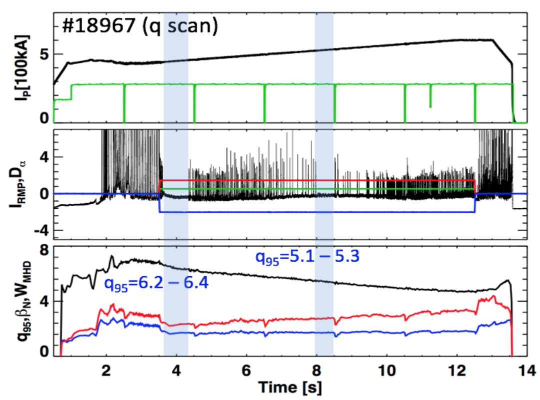


Figure 4.6. KSTAR $I_P$-ramp (Top) experiments showing q-windows (Bottom) of n=1 ELM suppression (Middle), with NBI power (MW, green), stored energy (100kJ, red) and $\beta_N$ (blue).

***Proposed Work:*** The $q_{95}$ is generally the first parameter scanned for 3D ELM suppression. As such a number of existing datasets from international tokamaks are already available, first the existing profile data from these devices (and DIII-D) will be investigated. Its outer-layer resonant drive will be analyzed with GPEC under this task, with layer studies in Tasks 2-3. New $q_{95}$ scan experiments will be designed and performed to investigate the upward and downward accessibility in terms of $I_P$ and also $B_T$, as well as hysteresis. Exploration of new $q_{95}$ windows will be pursued in KSTAR, particularly $q_{95}$<3.5 with n=2 and $q_{95}$>6.5 with n=1. Finally, 3D ELM suppression will be tested on high-$\beta_P$ poloidal scenarios in KSTAR using the upgraded NBI and RF heating powers in later years (See A.3), in particular with a focus to reproduce broader $q_{95}$ windows observed in DIII-D with n=3, but instead using KSTAR's low-n spectra.

## 4.2. Parametric threshold scaling and windows for 3D ELM suppression (Task 2)

This task is to assemble multi-machine datasets of both ELM suppression threshold conditions and confinement quality to allow the development of semi-empirical scaling laws. These scaling laws will then be deployed for near-term projection from existing tokamaks to ITER and beyond. Building on the successful framework of the original empirical scaling of core error field penetration [Buttery99, Buttery00], and its subsequent updating as part of the ITPA joint experiment MDC-19 [Park17ITER], data from all participating experiments (EAST, KSTAR, AUG, and DIII-D) will be assembled and regression techniques used to enable projection. The physics basis developed under Task 1 will be used to reduce the highly dimensional 3D spectrum into a tractable parameter space. GPEC will be used to characterize response for edge resonant drive as a metric and a non-linear analytic model [Fitzpatrick12, Fitzpatrick18] or reduced modeling, TM1 [Yu09], will be used to inform and interpret the developed scalings. This task will then be focused to the identification of operating window boundaries for stable 3D ELM suppression while avoiding core locked modes and/or H-L back-transitions. We note that this activity is strongly synergistic with the currently active early career research project (ECRP) by N. M. Ferraro, "*Integrated Predictive Modeling of ELM Suppression and Mitigation*" whereby we aim to assist assembling of the relevant datasets (See the letter of collaboration from N. M. Ferraro, in A7.5). This ECRP will then aim to use M3D-C1 to develop a numerically predictive model, while this activity will remain more empirically and semi-empirically focused. Several sub-tasks are now described, each consisting of their own scaling activity. While each scaling is presented separately, all scalings will be conducted from the same underlying datasets.

### 4.2.1. Parametric threshold scaling for 3D ELM suppression

This sub-task is planned to follow the successful framework of 3D error field studies, by investigating the correlation between edge resonant field as a metric for outer-layer response and key inner layer parameters, such as $n_e$, $B_T$, and flow, for ELM suppression.

***Background:*** 3D ELM suppression is often explained hypothetically, by a field penetration to an island bifurcation at the resonant layer on the top of the pedestal [Fitzpatrick18]. Although its later dynamics is more complicated due to transport across the steep profiles in the edge, its onset mechanism is similar to the field penetration of error field to locked modes (LMs) in the core region [Fitzpatrick12]. As will be illustrated in the next section, the core field penetration against LMs in various devices has been successfully predicted by an empirical scaling $\delta B_{mn} \sim n_e^a B_T^b \omega^c$. These key parameter dependencies have been successfully modeled by TM1 code simulations (See also Sec. 4.3.3), and also found in the edge field penetration relevant for ELM suppression [Hu19a], as an example shown in Fig. 4.7. Similarly to LMs, it is important to measure $\delta B_{mn}$ correctly under 3D equilibria, where ideal MHD is shown to be sufficient even for the edge resonant drive as strongly implied by work in DIII-D [Paz-Soldan15] and KSTAR [Park18].

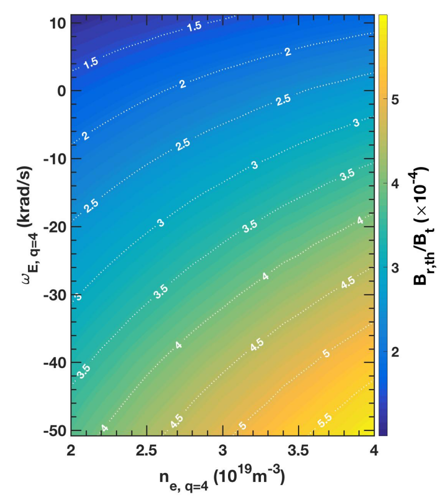


Figure 4.7. Predicted density and rotation scaling of edge field penetration thresholds (at q=8/2 for n=2) in DIII-D from TM1 modeling [Hu19b].

***Proposed work:*** This sub-task will utilize a similar framework to the next sub-task (Sec. 4.2.2) but the threshold for ELM suppression will be documented instead of the threshold for core field penetration. While each device may have only a limited number of threshold conditions for ELM suppression, by combining the experience of AUG, KSTAR, EAST with the more extensive DIII-D datasets, it is expected that several dozen ELM suppression threshold conditions will be tabulated as a function of their pedestal parameters as well as their 3D spectrum. New experiments in Task 1 will also be used to obtain the threshold data, by ramping up or down 3D coil currents, which will also provide data for the next subtask. A dedicated set of experiments to this task can be designed to validate the dependencies on $n_e$, $B_T$, and flow ($\omega_{E\times B}$ vs. $\omega_{\perp e}$ or $\omega_{\perp i}$) as needed basis, in particular in KSTAR when high NBI & RF power (See A.3) ensures highly advanced regimes. To facilitate comparison, the 3D spectrum will be parametrized semi-empirically in terms of its edge resonant field or overlap [Park11] using GPEC. This ensemble will then be utilized to both catalog the accessible operating space with ELM suppression and scaled in a regression framework to identify any underlying dependencies for comparison with TM1 modeling described below, as well as M3D-C1 modeling being carried out through the aforementioned ECRP proposal by Ferraro.

## 4.2.2. Scaling against core LMs or H-L back-transitions for 3D compatibility

This sub-task is to incorporate and expand the existing empirical scaling of core LM onset (Fig. 4.8) into the scaling law for edge field penetration based on its physics similarity. It is also an extension of the existing ITPA MDC-19 joint experiment on ITER error field correction, as the LM data are largely populated in low-density Ohmic plasmas and are yet sufficient to cover high-performance regimes. An important addition in high $\beta$ regime is to separately develop empirical scaling of H-L back-transition, as it often occurs below the thresholds of LMs.

$$\delta_{pen} = \frac{\delta B_{ov1}}{nB_{T0}} \leq 0.93\times10^{-4}\left(n_e[10^{19}m^{-3}]\right)^{1.32\pm0.08}\left(B_{T0}[T]\right)^{-1.95\pm0.11}\left(R_0[m]\right)^{0.35\pm0.09}\left(\frac{\beta_N}{l_i}\right)^{-0.50\pm0.11}$$

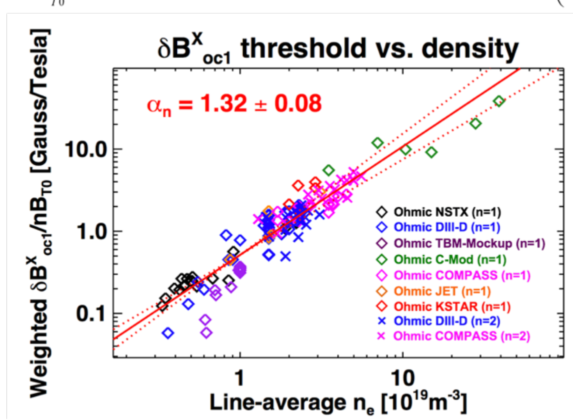


Figure 4.8. Empirical density scaling developed of the core RMP threshold ($\delta_{pen}$, estimated by overlap field $\delta B_{ov1}$) for LMs in Ohmic regimes [Park17ITER].

***Background:*** Combining scaling laws for core and edge field penetration provides an attractive near-term extrapolation methodology that avoids the many complications of a fully first-principles predictive model. The core field penetration threshold against LMs is essential to identify the valid 3D field operating boundaries for ELM suppression with the low n=1 or n=2 fields, where low-*n* 3D fields provide a distinct advantage in a nuclear environment beyond ITER (See Task 6.2) due to their less stringent proximity requirements. With higher *n*'s, the 3D operating windows can be eventually limited by H-L back-transition, which will also be examined to catalog the effect in a scaling law framework. In particular, the threshold dependencies on $\beta$ and flow are important in the presence of the auxiliary heating and momentum injection, and should be represented by more appropriate functional forms than the simple power scaling. For example, dependence on $\beta$ should represent the step-like dependence expected from the field amplification mechanism across the no-wall pressure limit [Wang14].

***Proposed Work:*** There are large LM database in KSTAR 3D experiments in 2015-2018, which will be first utilized and analyzed with GPEC response modeling and reconstructed profiles. The non-linear analytic and modeling predictions will be tested on the core LM thresholds, which will be important cross-benchmarking for similar activities planned on the edge field thresholds. The initial TM1 predictions on the DIII-D discharge conditions used for n=1 and n=2 LM thresholds were successful in reproducing the qualitative scaling trends [Hu19b]. This numerical scaling was however performed with theoretically isolated variables and will be revisited with operationally co-dependent variables on the dedicated samples from the database or newly designed experiments when needed. The targeted experiments for high $\beta$ or low rotation will be conducted where data is lacking in the existing scaling database. Also, the unique lower hybrid RF actuator available on EAST will be used to increase the minimum safety factor and remove core resonances (2/1, 3/2) from the plasma to isolate the effect of the edge vs core resonance on error field penetration. This study will also enable measurement of the plasma response in the broad current profile conditions typical of these discharges and also candidate steady-state reactor scenarios. Any experiments undertaken by the local international teams will also be available for addition to the database, enabling robust scaling for this classic 3D physics phenomenon.

### 4.2.3. Confinement scaling under 3D ELM control

This modest sub-task will utilize a similar framework to the previous tasks to develop a scaling law for the global confinement quality in plasmas with 3D ELM suppression. This activity follows in the spirit of the well-known development of the $H_{89}$ and $H_{98y2}$ confinement quality factor, but in this task we propose to isolate only discharges with 3D ELM suppression and re-derive a scaling law in these conditions.

***Background:*** The $H_{89}$ and $H_{98y2}$ confinement quality factors are extensively used to compare confinement across devices and conditions. However, the generally data arises from type-I ELMy discharges. No similar scaling exists for plasmas without ELMs, where conditions are different from the aforementioned regime, and no dependency on 3D coil current is included.

***Proposed work:*** By leveraging the ability of EAST, KSTAR, AUG, and DIII-D to access 3D ELM suppression, a more extensive operating range will now be covered, enabling the first development of a confinement quality factor derived exclusively from plasmas with 3D ELM suppression. Developing a scaling law for plasma conditions with 3D fields but without ELM suppression is also planned to assess whether ELM suppression itself is statistically significant to the confinement quality. Finally, where sufficiently accurate pedestal-top measurements are available, a similar exercise is planned but scaling against the pedestal pressure as opposed to the global confinement.

### 4.2.4. Predict and validate stable 3D operational windows in KSTAR

The predictive scalings of edge field penetration for ELM suppression and core field penetration against LMs and H-L in the previous tasks will provide opportunities to identify the stable 3D operating windows across key parameters and regimes, as proposed in this sub-task. The predicted windows will then offer critical guidance for target plasmas and 3D fields to be used in the Tasks 3-6.

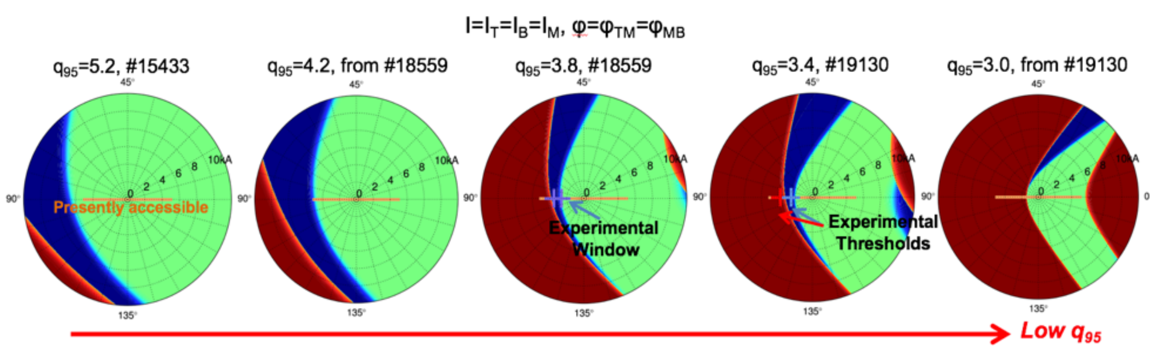


Figure 4.9. Modification of the stable 3D ELM suppression window (Blue), as opposed to LMs (Red) and non-resonant response (Green) in terms of n=2 coil amplitudes and phases in KSTAR as $q_{95}$ is changed [Park18].

***Background:*** Recent studies in KSTAR have shown the possibility to identify the stable 3D ELM suppression windows in the complex 3D phase space accessible with the full coil sets, when plasma response is properly included to estimate the critical component of 3D fields as well illustrated in Fig. 2.2. [Park18]. This work validates a key assumption behind our research plans; a separation of outer-layer 3D response in the fast-MHD scale that determines a local resonant drive, from the inner-layer dynamics reacting to the resonant drive on a single pivotal resonant surface. Either 3D ELM suppression or LM/H-L back-transitions is assumed as a consequence of the local field penetration or subsequent bifurcation in transport as will be studied in Task 3, when the critical component of 3D fields exceeds a threshold. The same logic is behind the idea of empirical scaling between the 3D response metrics and parameters involved in the field penetration at the resonant layers.

***Proposed work:*** The predictions for the edge and core resonant field threshold in earlier tasks will be accordingly integrated under this task for the successful window predictions through the extended space in the key 2D parameters combined with the 3D field space. Fig. 4.9 shows an example, a variation of the stable RMP windows due to $q_{95}$ in KSTAR n=2, which was however developed by assuming the same core and edge RMP thresholds despite $q_{95}$ variations. As a result, it was only partially successful in predicting the overall $q_{95}$ windows due to the 3D response, but not the fine-scale multiple $q_{95}$ windows often observed in KSTAR as well as other devices [Evans08]. The goal of this task is to predict the stable RMP windows in different shapes, $q_{95}$, flow, and also collisionality across devices, after each major step of the development of the parametric scaling planned in earlier tasks, starting from the second year. The predicted windows will be improved and tested against the database in KSTAR/AUG/EAST as well as the domestic devices, and will be used to limit the searching space of resonant 3D optimization in Tasks 4-5, and finally to design the 3D coils in KSTAR and COMPASS-U in Task 6.

## 4.3. Underlying transport mechanisms during 3D ELM suppression (Task 3)

The research proposed in this task is aimed at acquiring data needed to develop and test predictive models of the turbulence response that affects the global particle, energy and momentum transport due to magnetic islands and stochasticity in KSTAR. In addition to leveraging results from the parametric and scaling in Tasks 1-2, this research will involve targeted turbulence experiments in KSTAR and gyrokinetic turbulent transport simulations using the GTC code. In addition to the turbulence studies, we will examine neoclassical toroidal viscosity (NTV) particle transport using the MARS-Q code, and also more classical Braginskii transport physics using nonlinear TM1 code, in order to shed light on the fundamental transport channels during the optimized ELM suppression. Ultimately, the goal is to use the combined experimental and simulation result to develop models that can be used to extend the duration of 3D ELM suppression in KSTAR and also apply these models to the optimization of the ITER PFPO-1&2 phases as well as the $Q_{DT}$ = 10 phase [IO18].

### 4.3.1. Experimental studies of turbulent transport during 3D ELM suppression

***Experimental background:*** A central issue facing long-pulse ELM suppression hinges on controlling the interaction of heat and particle fluxes with plasma facing surfaces while simultaneously minimizing the influx of impurities into the core plasma. This requires controlling interactions with the divertor components, the main chamber walls, RF antennas and other 3D objects in the machine. More generally, it is essential to maintain optimal plasma performance with the best possible particle, energy and momentum confinement during the application of 3D fields for ELM suppression. Results from L-mode experiments have shown that, while it is possible to control the heat and particle transport with 3D fields, the physics mechanisms involved are complex and not well understood. For example, in TEXT it was shown that increasing the 3D coil current ($I_h$) between +1 and +4 kA caused a maximum reduction of 20% in the particle confinement time ($\tau_p$), shown in Fig. 4.10, [McCool90]. Continuing the increase in $I_h$ beyond 4 kA resulted in a recovery and the onset of an increase in confinement. Alternatively, when L-mode plasmas were limited on the high-field side plasma facing surfaces in Tore Supra [Evans92] and DIII-D [Evans15], $\tau_p$ increases by more than 25%. Improved particle confinement (IPC) was also observed in TEXTOR L-modes with high-field side 3D coils [Finken07]. These results are indicative of the global particle and heat transport that exists when remnant magnetic islands are embedded in a partially stochastic versus a strongly stochastic region. In TEXTOR the transition to a strongly stochastic regime resulted in a reversal of the turbulent flux from outward to inward [Xu06]. These changes in the particle transport will be studied using the 2 toroidal angle 2D ECEI data, such as that shown in Fig. 4.11 [Choi17], and the 2D MIR [Lee18] systems.

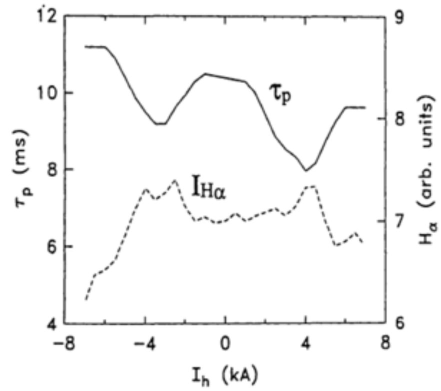


Figure 4.10. Scaling of the thermal electron confinement in TEXT with RMP coil current.

***Proposed experimental work:*** One of the goals of the research proposed in this task is to understand the differences between turbulent transport driven by isolated magnetic islands versus that of islands imbedded in stochastic layers. Based on this, we will carry out targeted experiments needed to separate these effects followed by gyrokinetic simulations. Our year 1 targeted experiment in this task will benefit from previous KSTAR 3D physics results, using a variety of boundary shapes and parameters that displayed changes in turbulence and transport and by a detailed survey of the available turbulence data from these discharges. The goal is to identify existing data sets that can be used to quantify trends in the 3D-field turbulence and transport data and to evaluate the quality of the existing turbulence data from each diagnostic. This information will be used to assemble candidate data sets for comparing with GTC simulations during the first year. This will also facilitate our planning of several targeted experiments that will be proposed and carried out in years 1 and 2. Here, we will work closely with each of the turbulence diagnostics teams on: CTS measurements of high-k turbulence, ECEI measurement of 2D magnetic island and stochastic layer $T_e$ turbulence [Lee15, Choi17] and MIR measurements of 2D $n_e$ turbulence [Lee18], through a subcontract, to better understand the full extent of the existing turbulence and transport data. While extensive ECEI island turbulence measurement have been carried out in KSTAR, there is still a plethora of physics insight to be gained, when combined with gyrokinetic turbulence modeling [Taimourzadeh19a, Kwon18], especially during the transition from isolated islands to mixed island-stochastic regimes. We will augment the previous work done by the KSTAR team on turbulence and transport by carrying out perturbative particle and energy transport studies in year 1 using modulated Supersonic Molecular Beam Injection (SMBI) [Xiao17] and modulated ECH (MECH) [Evans14IAEA, Ida15]. These studies have been very successful in previous KSTAR and DIII-D magnetic island turbulence and transport experiments.

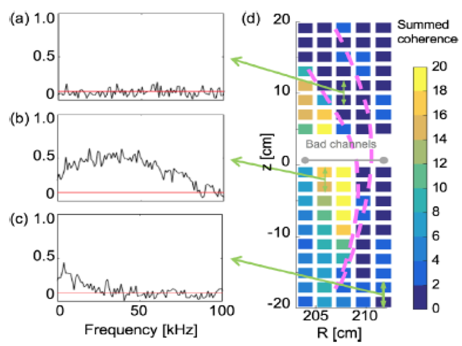


Figure 4.11. Turbulent cross-coherence inside (a) and on the HFS (b) and LFS © of the island shown in (d) from [Choi17].

Our proposed year 2 experiment will benefit from experiments done in year 1 of Tasks 1-3 discussed above and will include a study of changes in the magnetic island turbulence evolution during long-pulse ELM suppression discharges. In the record long-pulse discharge shown in Fig. 2.3, $\beta_N$ slowly drops from ~1.9 to ~1.6 while the line average density increases from 2.5 to 3.2×$10^{19}$ $m^{-3}$ indicating a significant and continuous change in the plasma confinement and incomplete control over the particle and energy transport.

Although a 90 sec. NBI-dominated H-mode discharge length was achieved in low $I_P \sim 0.4$-0.45 MAKSTAR discharges during the 2018 campaign, it was found that more generally a performance degradation is observed after 20-30 seconds. Resolving this issue is a high-priority KSTAR research topic during the 2019 operations phase. One of the goals of the research discussed in this task is to provide input to the KSTAR team on changes in the island turbulence and transport that may be responsible for the increase in density along with the increase in recycling and possible increases in the impurity influx. Following the completion of our year 1 experiment, we will carry out an extensive analysis of the data provided by the turbulence diagnostics listed above along with the plasma parameters corresponding to each of these data sets. Once this analysis has been completed, we will identify key data sets to be simulated with the GTC code.

### 4.3.2. Gyro-kinetic turbulent transport simulations during 3D ELM suppression

***Background***: DIII-D RMP experiments [McKee13, Evans15, Nazikian15, Paz-Soldan16, Moyer17] often suggest that enhanced top of pedestal turbulent fluctuations may play some role in the suppression of ELMs, consistent with an earlier hypothesis that enhanced top of pedestal transport is required to suppress ELMs with 3D fields [Snyder12].

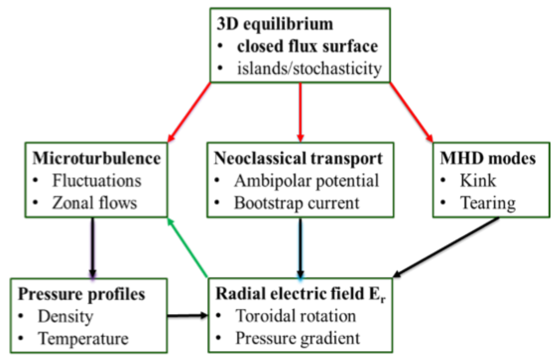


Figure 4.12. Effects of 3D magnetic fields on transport in tokamak edge plasmas.

As illustrated in Fig. 4.12, the 3D magnetic fields could affect turbulent transport directly through modifications of fluctuation amplitudes of drift wave instabilities or zonal flows, or indirectly through modifications of radial electric fields due to neoclassical transport, MHD modes, and plasma profiles. In the proposed project, we will use GTC [Lin98] to study the direct effects of the resonant components of the 3D magnetic fields (including both magnetic islands and stochastic magnetic field lines) on microturbulence on the pedestal top and steep gradient region of the pedestal. We will also use GTC to study the mechanisms of the changes in radial electric fields through neoclassical ambipolar potential. We will not use GTC to simulate the ELM cycle in the proposed project period. Rather we will focus on the effects of 3D equilibrium on turbulent and neoclassical transport that leads to ELM suppression, and to extrapolate the optimal ELM control parameters from KSTAR to ITER with proper validation of GTC simulations using KSTAR ECEI data.

We will also extend our gyrokinetic simulation to study possible 3D magnetic field effects on microturbulence and neoclassical transport that could lead to fluctuation increases, particle pump-out, and changes in toroidal rotation. The proposed research has partially been initiated by using global gyrokinetic toroidal code (GTC) for studying effects of 3D equilibrium with closed flux surfaces on turbulent transport in the pedestal top in DIII-D experiments. The current proposal will focus on new effects of magnetic islands and stochastic region on microturbulence in collaboration with other researchers of this proposed project and with KSTAR researchers. The proposed project will also leverage the physics expertise and computational resources of the DOE SciDAC ISEP project (2017-2022) led by the UCI institutional PI (Z. Lin) of this proposal.

*Direct Effects of 3D magnetic fields with closed flux-surfaces on turbulent transport:* GTC was first used to study the effects of non-resonant part of 3D magnetic fields on electrostatic drift wave turbulence. We have shown that the ideal MHD response to 3D fields is insufficient to affect fluctuation induced transport and thus we are drawn to the conclusion that other physics must come into play for affecting profile and fluctuation changes in the pedestal and pedestal top [Holod16]. Since ideal MHD effects are insufficient to change the linear growth rates of the drift-Alfvénic instabilities or of zonal flows, then other physics must account for the observed transport change. This additional physics may be related to non-ideal MHD effects such as tearing modes that generate magnetic islands or to the neoclassical responses to 3D fields that change the radial electric field ($E_r$) and its shear.

*Indirect Effects of 3D magnetic fields on turbulent transport: changes in $E_r$:* Regarding changes in $E_r$ due to 3D fields, GTC simulations on DIII-D find that the weaker $E\times B$ shearing rate in the ELM suppressed state allows ITG-like turbulence in plasma outer edge to nonlinearly spread to the pedestal top. This spreading leads to a broader region of microturbulence and larger calculated turbulent transport at the pedestal top. The increase in driftwave turbulence is not present in two corresponding ELMing cases, and ELMing case with insufficient 3D fields and an ELMing case without 3D fields. Our result demonstrates a plausible mechanism for the observed increase in pedestal top turbulence and transport, enhanced by RMP through reduced $E\times B$ shear [Taimourzadeh19a].

However, we cannot claim that the reduction of $E\times B$ shear is the cause of the turbulence increase in all cases of 3D ELM suppression. A recent study of ELM suppression with n = 3 RMP reveals no significant increase in the top of pedestal ion scale fluctuations, nor a significant decrease in the $E\times B$ shear in the transition to ELM suppression [Moyer17]. Another study using modulated n = 3 RMPs in an ELM suppressed state indicated that an increase in ion-scale turbulence with increasing RMP level before an observable change in the $E\times B$ shear [McKee13]. We also note that an increase in fluctuations at intermediate scales ($k\text{-}s > 2$) is seen during n = 2 and n = 3 ELM suppression [Paz-Soldan16, Moyer17]. These various studies performed under different plasma conditions and with different 3D fields yield a somewhat confusing array of results. These results indicate that a comprehensive assessment of the conditions in ELM suppression over a wide range of conditions is needed.

***Proposed Work:*** In the proposed project, we will use GTC simulation to study the direct effects of magnetic islands and/or stochastic region due to the resonant part of the 3D magnetic fields. Magnetic islands are believed to play important roles in the ELM suppression by 3D fields in DIII-D [Wade15]. Even if islands do not overlap, particle orbits could be stochastic within certain radial domain due to nonlinear effects or finite orbit width. Electron response to zonal flows in the presence of magnetic islands and/or stochastic region can be adiabatic due to the radial components of the 3D magnetic fields. Zonal flow dielectric constant can increase significantly for long wavelength fluctuations such as TEM and ITG turbulence. Zonal flow generation is then drastically reduced and the turbulence can be enhanced greatly, which could drive a higher level of particle transport. We will use GTC simulation to study the possible roles of magnetic islands and/or stochastic region that lead to the fluctuation increase and particle pump-out.

To incorporate the magnetic islands in GTC simulation, the 3D equilibrium will be solved by two-fluid M3D-C1 and provided to GTC. The equilibrium 3D magnetic fields are separated into two parts: a non-resonant part with closed flux surface and a resonant part that induces magnetic island and/or stochastic region. We will simulate the turbulence with or without the resonant perturbations to elucidate the effects of magnetic island and stochasticity in zonal generation. We can vary the degree of the stochasticity by scanning the amplitude of the resonant part. Given the experimental uncertainty of the magnetic island size or the existence of the stochasticity, it will be of great interest to find out from GTC simulations what island size and/or degree of stochasticity will inhibit zonal flow generation. We will compare simulation results with KSTAR ECEI measurements of magnetic islands. The GTC capabilities of simulating magnetic islands [Fang19] and comparing with ECEI through synthetic diagnostics [Taimourzadeh19b] have recently been demonstrated.

### 4.3.3. Kinetic neoclassical transport simulations during 3D ELM suppression

This subtask is to investigate another channel of transport that may also be attributed to the so-called density pump-out by 3D fields. Via the MARS-Q full toroidal geometry-based modelling, we have shown that the radial particle flux, associated with NTV due to magnetic field symmetry breaking, can play a key role in producing large density pump-out in RMP experiments [Liu18]. More specifically, the kinetic resonance enhanced NTV particle flux, due to processional drifts of bulk thermal particles near the pedestal top of the H-mode plasma, can substantially increase the outward radial particle flow.

***Background:*** Close examination of MARS-Q simulations for DIII-D discharges shows that the NTV can provide a significant contribution to the particle flux near the pedestal top. In fact, the radial distribution of the NTV flux strongly peaks near the $q$=11/3 rational surface in that example. This large peak of NTV flux in turn is caused by the processional drift resonance of trapped thermal ions, which occurs when the toroidal precession of trapped particles matches $\omega_{E\times B}$. The latter is typically much larger than the processional drift frequency in high-torque DIII-D discharges, except near the $q$=11/3 surface, where the $E\times B$ frequency crosses zero during ELM suppression. It is this frequency match near the $q$=11/3 surface, and hence the drift kinetic resonance, that substantially enhances the NTV particle flux.

***Proposed work:*** MARS-Q will be extensively used to simulate flow dependencies and changes during 3D ELM suppression in AUG and EAST in parallel with Task 1, as already described in Sec. 4.1.2. On the other hand, since density pump-out is a relatively ubiquitous phenomenon observed in 3D experiments, it is natural to apply the MARS-Q code to various other experimental data obtained in Tasks 1-2, to try to gain the common ground behind neoclassical particle transport by 3D fields. MARS-Q has so far identified the significant role of the NTV particle flux in density pump-out observed in DIII-D. The question is whether the NTV flux plays the role in density pump-out in other devices and to what degree. A multi-machine based, conclusive understanding may help to provide quantitative prediction of the density pump-out (and hence the resulting reduction of plasma confinement) fraction for ITER. More importantly, the study may also provide a way to avoid or at least minimize the density pump-out in ITER, without compromising the ELM suppression capability, e.g. by tuning the plasma conditions and/or the applied 3D field spectrum.

### 4.3.4. Two-fluid MHD transport simulations during 3D ELM suppression

This small sub-task is to utilize TM1 code to investigate transport in more classical viewpoints due to Braginskiis, as an additive or alternative mechanism for 3D ELM suppression.

***Background:*** TM1 is a relatively new for 3D field applications but has been largely successful in simulating 3D field penetration and bifurcation to islands, reproducing the penetration thresholds shown in experiments. TM1 is a resistive nonlinear two-fluids MHD code with cylindrical geometry and circular cross-section with the momentum transport based on the torque balance between the electromagnetic (EM) torque due to the 3D fields and the plasma viscosity, which governs the bifurcation from screening to penetration. The energy and particle transport caused by 3D fields or magnetic islands are also included and determined by classical transport in the parallel direction and anomalous transport in the perpendicular direction. Previously, TM1 has been used for modelling NTM stabilization by ECCD [Yu08a], core LM penetration [Yu08b], momentum [Yu09] and particle [Yu11, Hu14] transport on AUG, TEXTOR and J-TEXT. Recently, TM1 has been modified to perform multi-resonant field simulations in the DIII-D edge region, and reproduced core heat transport by locked modes [Hu19b] and edge density pump-out in ELM control on DIII-D [Hu19a]. The simulations find that field penetration at the foot of pedestal excites magnetic island, which flattens density profiles around the island region, decreases density at the top of pedestal and is the dominant contributor to density pump-out in prior to ELM suppression.

***Proposed work:*** The primary application area of TM1 in our project is the MHD simulation for the core/edge field penetration thresholds as already described in Task 2, but the particle transport data numerically obtained through its applications will also be utilized for comparison with experiments throughout Task 1-3 activities, as it has been largely successful in explaining particle transport on DIII-D n=2 ELM suppression experiments [Nazikian15]. The outer-layer 3D response calculated by GPEC/MARS will be used as the initial and boundary conditions for TM1, and turbulent and anomalous transport coefficients will also be incorporated into the coefficients if motivated by the previous two sub-tasks.

## 4.4. Heat flux prediction and optimization for long pulse (Task 4)

The control of ELMs with resonant 3D fields induces a 3D plasma boundary which has a visual and measurable impact on the divertor heat and particle fluxes and the overall divertor regime. Assessing the alteration of the divertor regime during 3D ELM suppression and exploring counter measures to maintain dissipative and detached divertor regimes as required for ITER and beyond demands a fundamental understanding of the relation between the applied 3D field, the plasma response which yields suppression of the ELMs and the eventual heat and particle fluxes. This task addresses the quest to establish this fundamental understanding. This needs to be addressed with high spectral fidelity to optimize the 3D setup on targets, and also at long pulse, to address equilibration time scales from current relaxation in the plasma to wall outgassing during a different power deposition pattern when suppression is achieved. This task will be dedicated to KSTAR only, due to its unique capabilities with respect to these two goals.

### 4.4.1. Physics basis and optimization of heat flux

***Background:*** The control of ELMs by 3D fields has a prominent impact on the divertor heat and particle fluxes. The magnetic separatrix is decomposed into a set of non-linear magnetic field trajectories, which transform the toroidally symmetric heat flux into a pattern with the shapes of helical lobes [Evans02, Evans05, Schmitz08]. Heat and particles can be deposited well outside of the small heat and particle flux deposition width on the target and areas can be reached which are not designed to handle such fluxes. This was seen experimentally and the consequences for ITER were assessed numerically using the EMC3-EIRENE plasma edge fluid and kinetic transport code [Frerichs10, Schmitz16]. Also, the resulting erosion and deposition balance might be perturbed, which impacts design criteria for the wall lifetime and the overall integrity of the wall. For instance, modeling with the ERO plasma surface interaction model in toroidally axisymmetric (2D) patterns demonstrate the necessity of alignment between the erosion zone, the migration path of eroded particles and the deposition location, as such the eroded particles can be deposited in places of other eroded particles to have a local erosion and deposition balance that reduces to a small amount of net-erosion [Kirschner00, Kirschner07]. If now due to the 3D helical lobes the erosion and deposition positions are decoupled, the amount of net-erosion might grow and the life time of the plasma facing components is reduced when compared to the 2D assumptions.

The ITER divertor is designed with high fidelity in a partially detached, dissipative regime, and the assessment of the actual working point is already quite challenging in 2D situation [Pitts16, Loarte14]. If 3D ELM control is used, the assumption of 2D divertor fluxes might not be justified anymore. This points

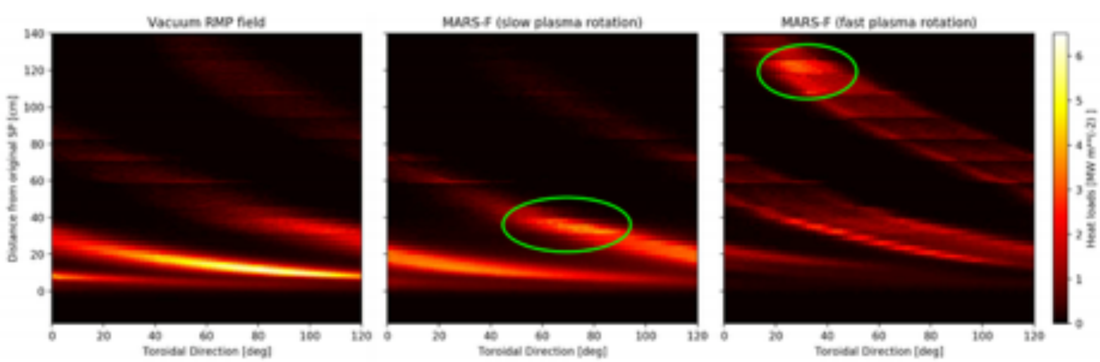


Figure 4.13. EMC3-EIRENE simulated divertor heat load for an ITER plasma, using the 3D RMP fields computed by MARS-F with different assumptions of the plasma toroidal flow speed. Compared is also the heat flux pattern with the vacuum RMP field. Results from Ref. [Frerichs18APS].

out that aside of the generic understanding of 3D ELM control and the optimization of the 3D fields for stable and robust access to the 3D ELM controlled H-mode regime, we also need to address the integration issue on how the specific 3D scenario for ELM control can be made compatible with the ITER divertor solution. This is the central question of this task, i.e. to combine optimized non-axisymmetric heat fluxes with the most robust 3D ELM suppression scenario and then to assess the impact the optimized divertor regime with 3D fields has on the erosion and deposition processes. As this direction of research is still in the state of infancy, we will focus in this proposal in particular on attached divertor scenarios to investigate the link between a specific 3D setup for optimal access to ELM suppression with minimized impact on plasma core performance (as described in Task 1-2) and the actual heat and particle fluxes. At the end of this activity we will address the collisionality scaling of this optimized regime to prepare exploitation of the fundamental knowledge gained in the detached divertor regime.

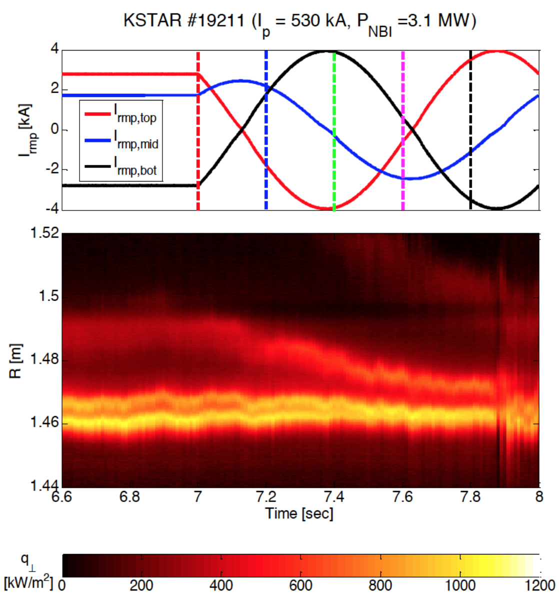


Figure 4.14. Heat flux measurements at the outer leg of the KSTAR divertor (lower panel) showing the change in the strike line splitting extension with changing phasing between the RMP currents in the top, middle and lower row of coils [LeeHH18].

This optimization approach has two aspects to it. First, the plasma response which is found for optimized access to ELM suppression will define the radial magnetic field amplitude at the separatrix and by this the shape and extension of the separatrix deformation and hence the helical lobes on the divertor surface. This was for instance seen at DIII-D, when a screening plasma response vanished and RMP field penetration occurred linked to strike line splitting [Schmitz2014]. Considering (i) flow screening of local resonant field component and (ii) kink amplification of the non-resonant portion of the spectrum, there can be quite drastic changes to the divertor heat load distribution. A recent study for ITER using MARS-F response and EMC3-EIRENE for the divertor heat flux [Frerichs18] shown in Fig. 4.13 reveals a clear difference in the heat flux pattern along the ITER divertor, between the vacuum field approximation (left figure) and that including the plasma response (two figures on the right). Note that this is an extreme example of the dramatic difference in the divertor heat flux, with or without including the plasma response, since the coil phasing is carefully tuned to maximize plasma amplification. It is also certainly possible to trigger a comparable level of plasma response, but provide a mitigated impact on the divertor flux distribution, for instance a reduced width of the spreading or smaller heat flux peaking in the outer lobes. Recent results from a dedicated experiment at KSTAR support this idea. In figure 4.14, heat flux measurements (lower panel) are shown during a sweep of the relative coil current phasing between the upper, middle and lower row of 3D coils (upper panel) at KSTAR, while full 3D ELM suppression was maintained. The heat flux clearly is compressed with increasing lag of the phase of the middle coil with respect to the two other ones with the top and bottom coil being power with opposite polarity. Optimizing the heat flux in such variability within 3D ELM suppression window can be indeed important in long pulse (>50s) and high power (>10MW) KSTAR operation as expected in coming years.

These experimental results demonstrate on one hand the superior flexibility of the 3D coil setup at KSTAR which is an asset for such experiments. On the other hand, the result itself provides first time insight into the strong dependence of the divertor flux pattern on the actual 3D coil current distribution. Mating the optimisation of this current distribution with respect to robust access to 3D ELM suppression (Task 1) and mitigated overall impact on confinement and H-mode thresholds (Task 2), with optimized heat fluxes compatible with the divertor design and operation requirements in long pulse is a critical integration question of 3D ELM control. This 3D plasma edge and surface interaction aspect will be addressed in this proposal by dedicated experiments and state of the art 3D modeling with the EMC3-EIRENE code. The sequence of activities is described in the following.

***Proposed Work:*** This task (4.1) is dedicated to modeling of the divertor heat loads, and ultimately finding an optimal 3D coil phasing for minimal heat load peaking that is still compatible with 3D ELM suppression. As we will be concentrating on conduction limited divertor regimes in this work, a key element is to improve the description of the classical heat conductivity presently applied in EMC3-EIRENE for transport along field lines. The first part (year 1) of this task therefore addresses a correction (i.e. heat flux limit). Such a correction was already implemented in an earlier development version and applied for TEXTOR-DED [Harting08], but was not included in the master version of the code due to its sensitivity on noisy profiles intrinsic to Monte Carlo method. We propose to re-activate this implementation with a benchmark of noise reduction / smoothing filters. Furthermore, we propose a different implementation based on an iterative approximation of the heat flux correction factor, and an implicit (two-step) method [Feng14] for the Monte Carlo jump steps that avoid explicit calculation of temperature gradients.

For the second part (year 2) of this task, we propose to analyze the sensitivities of the EMC3-EIRENE heat load calculation on the plasma response included with dedicated parameter scans. This is a high priority due to the fact that the internal plasma response fields and the externally applied 3D fields interfere at the separatrix and shape a complex dependency between external field setup and the internal plasma response. Guided by the optimization and verification effort for the most robust 3D scenario with respect to ELM suppression and reduced impact on plasma confinement, the according plasma response solutions will be used here and assessed with respect to their impact on the heat and particle loads.

Ultimately, we aim at optimizing the divertor heat flux while maintaining ELM suppression in long pulse on KSTAR. This last part (year 3) of this task is based on results from tasks 1-3 in which the ELM suppression window with respect to 3D coil phasing is determined. We propose a series of dedicated EMC3-EIRENE runs over this ELM suppression window (and marginally beyond) to determine the optimal coil phasing for divertor operation which may be different than the optimal operation point for ELM suppression. These simulations will be based on the GPEC or MARS to EMC3-EIRENE coupling using the FLARE grid generator. Simulations will be performed for multiple present day machines with extrapolations to ITER, with a primary focus on KSTAR and secondary focus on ITER. This offers a potential path to the compromise between (best) ELM suppression and (less intensive) divertor heat load in long pulse. This substantial effort can already start in parallel to the first work packages, which will ultimately narrow down the uncertainties in the model (i.e. corrections to the classical heat flux, impact of resistivity and toroidal flow on plasma response).

### 4.4.2. Impurity effects on 3D ELM suppressed scenarios

This sub-task focuses on the pedestal physics of operating 3D ELM suppressed discharges towards more dissipative divertor conditions. Dedicated experiments on KSTAR will be conducted to measure the limits of 3D ELM suppression with dissipation provided by impurity radiators, and compare results to penetration threshold modeling in Task 2. These studies will be foundational for later long-pulse extensions compatible to ITER in Tasks 4 and 5. Impurity injection studies further leverage previous US investments in this area [Nagy18].

***Background:*** Coupling dissipative divertors with 3D ELM suppression is fundamentally challenging due to the necessity of staying below pedestal-top density thresholds for ELM control [Suttrop18, NazikianIAEA14], yet requiring high downstream density to enable dissipative divertor operation. While these constraints are predicted to be relieved in high $T_{e,ped}$ reactor conditions (capable of high density and low collisionality simultaneously), present experiments (at relatively lower $T_{e,ped}$) are not offered the same flexibility [Petrie11]. Recent DIII-D work has demonstrated a path to improved compatibility of an 3D-ELM suppressed pedestal with high-Z impurity seeding, in excess of that expected by collisionality arguments alone [Orlov18IAEA]. Examination of the heat flux profile reveals a factor of two reduction is possible while maintaining a low pedestal density and 3D-ELM suppressed state, shown in Fig. 4.15. These important observations offer a path to developing improved dissipative divertor scenarios with a 3D-ELM controlled edge without relying on improvements to the divertor configuration (ie, closure), laying the foundation for high power and long pulse ELM-controlled operation.

***Proposed Work**:* The US team will join the research group on KSTAR investigating compatibility of 3D ELM control with impurity seeding, a topic given high priority at KSTAR. Noble gas radiators will be injected by gas valves while solid impurities will utilize the US-supplied solid impurity injectors [Nagy18]. Plasma response modeling will be performed by GPEC or MARS, and employing the improved kinetic equilibrium reconstructions developed in Task 6, and benefitting from the control improvements of Task 5. Kinetic equilibria will be further constrained by X-ray tomography, bolometry, and impurity charge exchange measurements. Observed thresholds for 3D ELM suppression here will be combined with scaling studies in Task 2 and be studied with non-linear TM1 modeling.

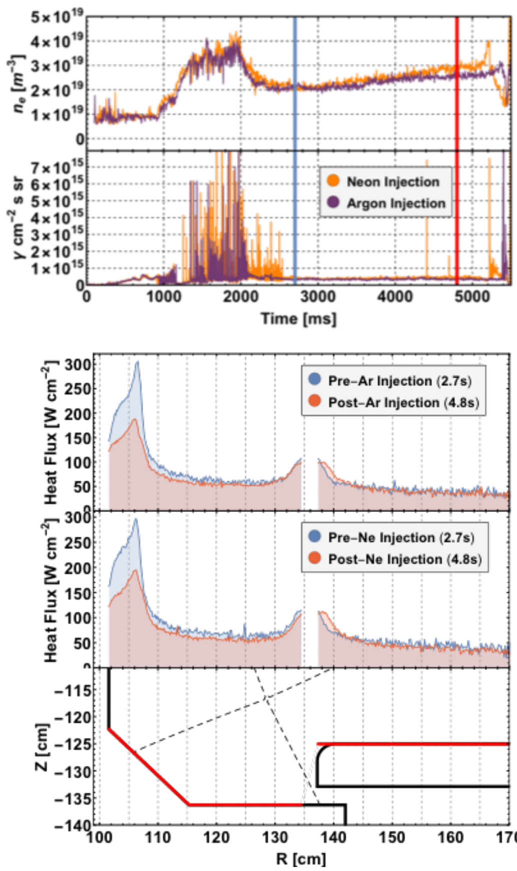


Figure 4.15 Operating impurity seeded conditions allows reduction of the observed heat-flux profile while maintaining a 3-D ELM suppressed pedestal in DIII-D.

To assess the divertor state, the upstream to downstream condition will be connected with EMC3-EIRENE utilizing again the same established framework to include the plasma response inferred before, and then studying the impurity transport and the impact on the optimized heat flux pattern. This activity includes utilization of the trace impurity model for EMC3-EIRENE. These efforts will develop the fundamental physics understanding necessary to exploit the impurity seeded path to divertor heat load control in the subsequent tasks of this proposal.

Eventually, the impurity household will be defined by the level and distribution of the erosion source. While KSTAR is operating presently with graphite surfaces, a change of the wall material to tungsten (W) is envisaged at the end of the funding period of this solicitation. Within this proposal we aim on using the knowledge and experience gained with the detailed analysis of the 3D boundary in attached and conduction limited conditions as discussed in task 4.1, to provide a well vetted plasma background for such 3D surface modeling efforts. This will be on the level of an initial assessment to provide insight into the relevance of the 3D boundary perturbation for the design and implementation efforts of a metallic divertor at KSTAR. The recently updated state of the art ERO2 [Romazanov17] plasma surface interaction model will be used to address this question in comparison to the Monte Carlo Impurity (MCI) code [Evans1998] through a subcontract. MCI will be coupled to EMC3-EIRENE for a 3D plasma background, and results from MCI will be benchmarked against ERO2 before the long-pulse evolution of impurity transport will be investigated via several time-slice simulations in the discharge.

## 4.5. Active control of 3D ELM suppression in long pulse (Task 5)

This task aims to develop a comprehensive closed-loop, real-time (RT) active feedback control of 3D fields and pedestals to allow routine access to long-pulse ELM suppression. Active control will be combined with predictive open-loop control capability from Tasks 1-4, with the prediction essentially forming the feedforward initial guess or target waveform. The RT 3D field control space will be narrowed down to several key variables based on the accessibility from Task 1 and valid 3D operating windows from Task 2. The path dependencies and hysteresis expected during RT 3D field and gas control will provide important dynamics and data for underlying transport studies in Task 3. RT impurity and radiation control is also planned to reduce heat loads under ELM suppression utilizing data and knowledge obtained with Task 4. The 3D coil current, gas, and impurity RT control developed in this task will be tested in KSTAR to maintain ELM suppression towards longer pulse and higher confinement operation than achieved so far, and to thus build the operational basis for long pulse 3D ELM suppression control for the next step devices.

### 4.5.1. Active ELM suppression maintenance: Real-time 3D field and gas control

This sub-task focuses on building and deploying an adaptive RT control system using 3D coil current and gas puffing to improve plasma performance while maintaining 3D ELM suppression. This is achieved by exploiting key properties of pedestal physics and utilizing multiple diagnostic inputs.

***Background:*** As introduced in Sec. 2, KSTAR has shown large changes in the pedestal structure as the plasma naturally evolves in long-pulse discharges, leading to the loss of ELM suppression even though the 3D field currents are kept constant. This motivates the development of an active ELM control strategy at KSTAR to facilitate long pulse operation, with the additional benefit of identifying the most appropriate strategies for ITER ELM suppression control. Recent ELM control experiments at DIII-D show a clear hysteresis of the plasma confinement when transitioning to/from ELM suppression [Ege19, PazSoldan16IAEA]. Specifically, higher confinement can be achieved by exploiting hysteresis effects to reduce the final 3D coil current after first accessing ELM suppression at higher current. With respect to ITER, the achieved results emphasize the need for a control system to keep the 3D amplitude close to (but below) the ELM suppression threshold at all times. Implementation and testing of these ITER-relevant control schemes in long pulse tokamas such as KSTAR is here proposed.

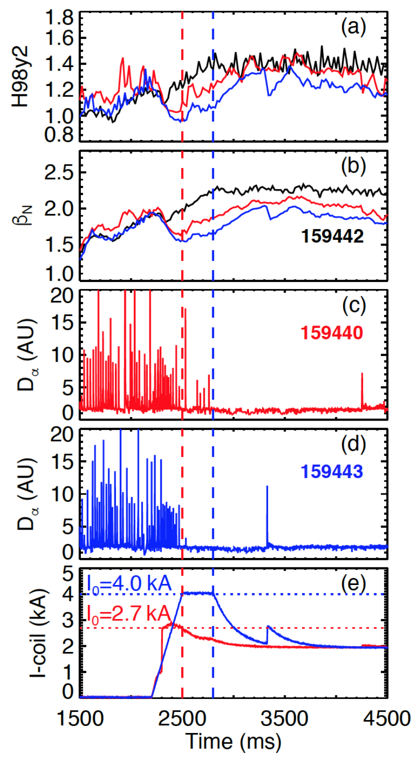


Figure 4.16. Adaptive 3D control enables ELM suppression with minimal confinement reduction: (a) confinement enhancement factor, (b) normalized ratio of thermal to magnetic pressure, (c,d) divertor Dα emission (ELM monitor) and (e) 3D coil current for the ELMy reference (black), high initial 3D coil current (blue, 4 kA) and reduced initial 3D coil current (red, 2.7 kA).

*3D field control:* Fig. 4.16 shows such an example of the RT ELM control in DIII-D. In both of the ELM-suppressed cases, the controller was able to substantially reduce the amplitude of the 3D coil currents (bottom), while maintaining ELM suppression. The reduction of the applied 3D fields lead to a partial recovery of the $H_{98(y,2)}$ and $\beta_N$. Even though the final 3D coil currents of

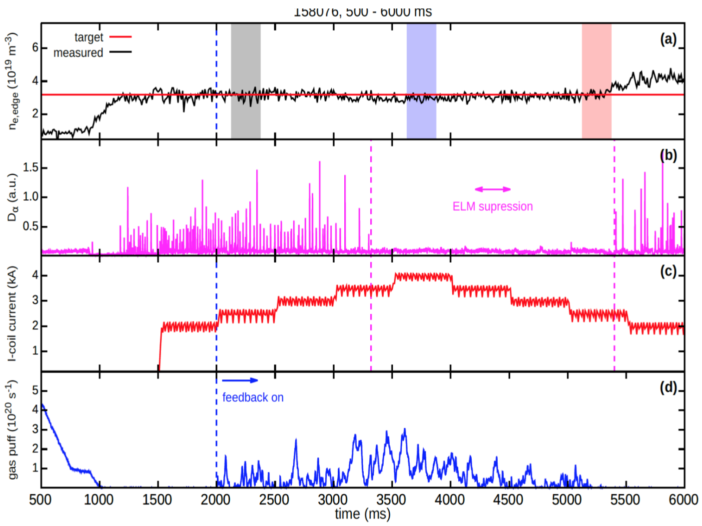


Figure 4.17. Hysteresis in accessing and exiting ELM suppression at controlled edge electron density ($n_e$): (a) edge ne, (b) D$\alpha$, (c) 3D coil current and (d) gas puff.

both ELM suppressed states are the same, the $H_{98(y,2)}$ and $\beta_N$ recovery exhibits a path dependence. High initial 3D coil currents lead to lower recovery of confinement and performance later on in the discharge. This irreversible performance degradation effect comes with the excitation of core MHD modes, which do not cure after reducing the initial 3D field amplitude. The profile analysis also shows the evolutions in detail that can be studied with simulations in Task 3. Immediately after the transition to ELM suppression, $\beta_N$ is at its minimum and the $p$ pedestal is relatively low though high $\omega_{\perp,e}$ exhibits strong rotation shear in the region of the depth of the radial electric field well. As the 3D field amplitude is reduced, first the pedestal top $\omega_{\perp,e}$ is enhanced (red), while the pedestal pressure and $\beta_N$ recovers slowly. As the 3D field amplitude is reduced further, $\omega_{\perp,e}$ at the pedestal top continues to spin up and the pressure increases stringer until an ELM crash reappears.

*Integrated 3D field and gas control:* The DIII-D ELM control system also demonstrated that the concept of RT pedestal profile control is feasible with line-integrated density measurement and $D_\alpha$ diagnostics, gas and MP coil feedback regulation as illustrated in Fig. 4.17. Here an interesting limit-cycle behavior of 3D field amplitude and edge toroidal rotation $v_{tor}$ at the pedestal top was seen, as shown in Fig. 4.18. The color bar indicates the $f_{\mathrm{ELM}}$ and $f_{\mathrm{ELM}}= 0$ prescribes ELM suppressed conditions. This hysteresis behavior for ELM suppression can be outlined as follows: Initially the 3D fields need to penetrate, which requires a higher 3D coil current. When transitioning in ELM suppression $v_{tor}$ goes up (phase (a)), while $\omega_{\perp,e}$ is reduced in the pedestal region. The modification of the edge flows likely allows better coupling of the 3D field [Hu19a]. Once in ELM suppression, the 3D field amplitude can be reduced though remaining high $v_{tor}$ (phase (b)). As the pedestal $n_{C6+}$ and $T_{C6+}$ increase, the pedestal pressure increases. This pushes the pedestal structure towards P-B unstable state, which leads to ELMs, slow down of $V_{\mathrm{tor}}$ and loss of ELM suppression (phase (c)). There is also the risk of locking in reduced performance for the remainder of the discharge.

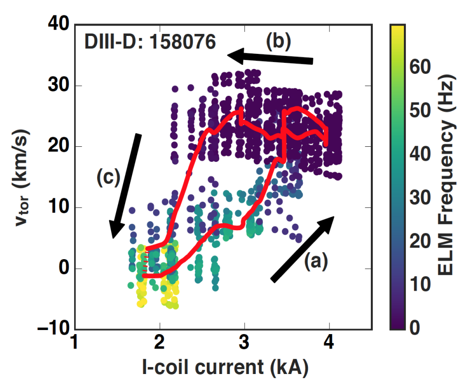


Figure 4.18. Limit cycle behaviour of MP coil current and edge toroidal rotation ($V_{\mathrm{tor}}$): The red path indicates the discharge evolution.

***Proposed work:*** This adaptive 3D control proposal at KSTAR will be to bring the knowledge and control developed at DIII-D to long pulse operations and improve upon this control. We will first optimize the 3D coil configuration for ELM suppression based on off-line plasma response calculations, starting from the predictive optimizations based on Task 2. The amplitude of the 3D coil will be further regulated by detecting ELMs based on $D_\alpha$ line radiation measurements from the divertor region and adjusting the coil current to avoid them if necessary [Eldon17]. The eddy currents induced during RT control can also be important in KSTAR [ParkYS17], and will be estimated by VALEN3D [Bialek01] and included if necessary as a time-response correction to GPEC (See the letter of collaboration by Y.-S. Park in Columbia University as an unfunded collaborator, in A7.6).

Additionally in KSTAR, it is important to avoid locked modes or H-L back transition while using n=1 for ELM suppression. In the beginning, we will use the predicted LM/H-L thresholds (Task 2) as allowable upper bound of the field amplitude. Alternatively, active MHD spectroscopy based on pick-up coils will also be tested and compared to off-line correlation analysis with LM/H-L limits. We will run KSTAR 3D coils in feedback with response that is obtained from the pick-up coils, and check multiple points on the Nyquist plot in one feedback cycle (very fast) to obtain stability margin directly. Analysis of the response then gives the "gain margin", which is a measure of the closeness to the instability.

For pedestal control, the plasma control system (PCS) will acquire RT density diagnostic data and use off-line profile fits to extract the pedestal width and height for electron density ($n_e$). Based on those, the PCS is capable to regulate the pedestal $n_e$ by adjusting either the gas puff to increase $n_e$ or use the 3D induced density "pump-out" to reduce it. These developments have been successful in DIII-D as described earlier, and thus we will adapt the DIII-D ELM control system and PCS to KSTAR PCS.

## 4.5.2. Active heat load mitigation: Radiated Power and Impurity Inventory Control

In long-pulse high performance plasmas, the temperature of plasma-facing components dramatically increases and start introducing more impurities and fuel into the plasma - often leading to degraded performance and termination of the ELM suppressed phase. This is indeed the present hypothesis for the gradual degradation of performance and loss of ELM suppression in the long-pulse ELM suppressed KSTAR discharge shown in Fig. 2.3. As such, the heat load to the divertor needs to be minimized while keeping core properties stable. As described in Section 4.4.2, this can be most effectively achieved through the introduction of an impurity radiator that does not excessively increase the pedestal density (thus maintaining ELM suppression compatibility). Due to long-time scale recycling changes, the impurity inventory needs to be adjusted throughout the discharge and can not be simply fed-forward. This sub-task focuses on developing and testing the control of the divertor radiated power, leveraging physics understanding from and feeding important data to Task 4.

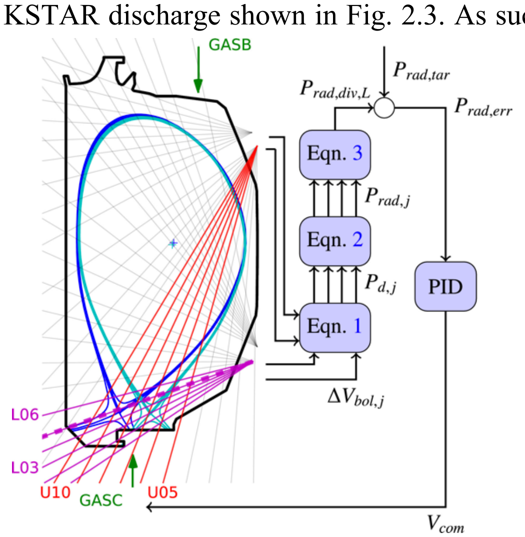


Figure 4.19 DIII-D cross section and impurity and $P_{rad}$ control schematic.

***Background:*** Recently, a feedback control system of radiated power from the lower divertor ($P_{rad;div;L}$) has been successfully implemented in the DIII-D Plasma Control System (PCS) (Schematics shown in Fig. 4.19). A realtime sensor for $P_{rad;div;L}$ has been constructed from 12 foil bolometer channels which agrees with standard post-shot analysis to within 20% [Eldon19]. Using impurity (N2) seeding under feedback control, $P_{rad;div;L}$ has been increased by up to 150% compared to unseeded levels (Fig. 4.20), and a radiated power fraction ($f_{rad}$) ~ 80% has been demonstrated compared to $f_{rad}$ ~ 55%. When operating at high $f_{rad}$, a challenge was the fluctuations in pedestal $T_e$ due to ELMs and the subsequent perturbations to $P_{rad}$, which were destabilizing to the feedback controller. Such sensitivity of the radiation controller due to a disturbed pedestal can also be problematic when combined with the feedback control of 3D ELM suppression.

***Proposed work:*** In this sub-task we will develop feedforward and feedback control systems to adjust impurity seeding levels to minimize the core degradation and heat loads during 3D ELM suppression. As KSTAR's real-time radiation measurements become available (in later project years) we will test the integrated feedback control of both radiation and 3D fields, by exporting the radiation control that we developed for DIII-D PCS to the KSTAR PCS. Prior to the availability of RT impurity signals, initial control schemes will feed-forward the impurity seeding level using the predictive optimization results (Tasks 1-3) with closed-loop control of 3D fields (Sec. 4.5.1) for the best 3D ELM suppressed scenarios in long pulse. Knowledge of impurity transport time scales from EMC3-EIRENE or MCI in Task 4 (or alternatively STRAHL code [Beringer07]) will inform the initial feed-forward applications. During the project period either real-time Charge Exchange Recombination (RT-CER) or RT radiation diagnostics are planned to become available in KSTAR. This will provide measurements to implement active control of the impurity seeding level, actuating either the 3D field amplitude or the impurity gas valve (analogously to Sec 4.5.1). Finally, this control, integrating predictive feed-forward guesses from earlier Tasks with the discussed active feed-back control, will be used to extend the duration of 3D field ELM suppression in KSTAR to discharge durations longer than 50 s and with higher input power (> 5MW).

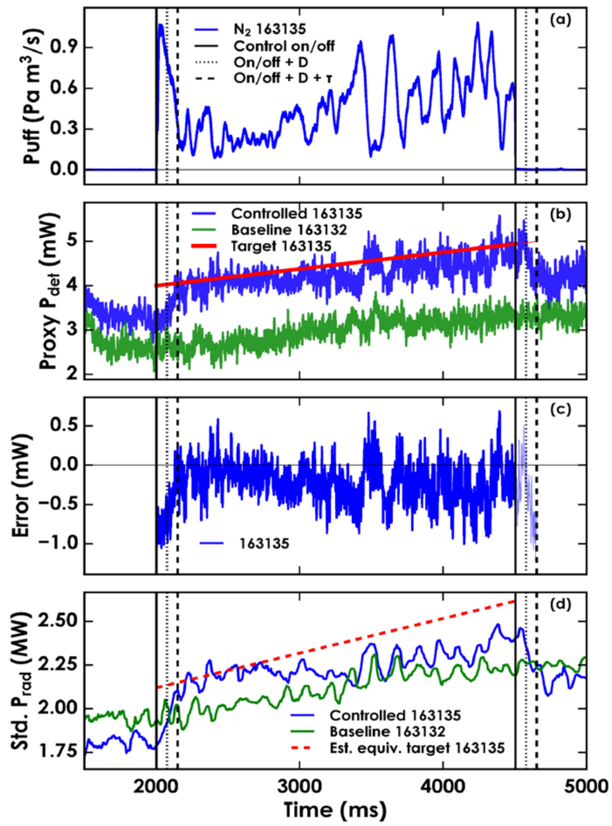


Figure 4.20. Control of $P_{rad;div;L}$ by local N2 seeding (GASC port; see Fig. 4. 19). (a) N2 gas flow rate control between the solid vertical lines, delay in dashed and dot lines. (b) Local $P_{rad}$ from the controlled (blue) and reference (green) shots. (c) Error between the local proxy measurement and its target. (d) $P_{rad;div;L}$ obtained by standard automatic analysis of all relevant bolometer channels.

# 4.6. Integrated analysis tools and innovative 3D coils (Task 6)

This task builds a streamlined interface between experimental data and simulation capability for the KSTAR program, concentrating on aspects needed for accurate MHD model input and validation. The 2015 U.S. Department of Energy (DOE) community workshop report on integrated simulations of fusion plasmas called for the community to prioritize streamlining the interface between experimental tokamak data and simulations for the purpose of verification and validation of whole device modeling (WDM) [Bonoli15]. This is especially true for 3D MHD modeling, which requires accurate initial 2D equilibrium information to properly predict the stability and response to 3D fields. The work proposed here will build a framework for analysis starting from the raw data, coupling transport modeling with axisymmetric equilibrium solvers, and forming consistent inputs for reliable 3D response model predictions. This workflow will then be extended further by feeding the resulting 3D models to 3D coil design optimization codes - building coils custom optimized for KSTAR as well as COMPASS-U plasmas.

### 4.6.1. Profile fitting and kinetic EFITs

In this task we will develop a workflow for accurate spatio-temporal profile evolution and kinetic equilibrium reconstruction of KSTAR plasmas. This will require interfacing raw data with the TRANSP code at PPPL in order to calculate the neoclassical bootstrap current in a manner consistent with the pressure pedestal. The influence of the pedestal gradients on the edge MHD stability motivates physics-based processing of the data such as causal filtering, filtering fast-timescale edge-localized mode (ELM) dynamics from the slower equilibrium evolution, and profile edge alignment. The modern One Modeling Framework for Integrated Tasks (OMFIT, [Meneghini15]) profile fitting tools [Logan18] has been developed for this purpose on US machines such as DIII-D and NSTX-U. We propose to apply these sophisticated fitting tools to KSTAR plasmas. In parallel, we will also collaborate with Seoul National University (SNU) and NFRI to adopt their kinetic EFIT processing schemes, for benchmarking purposes as well as contingencies especially when a profile data is missing.

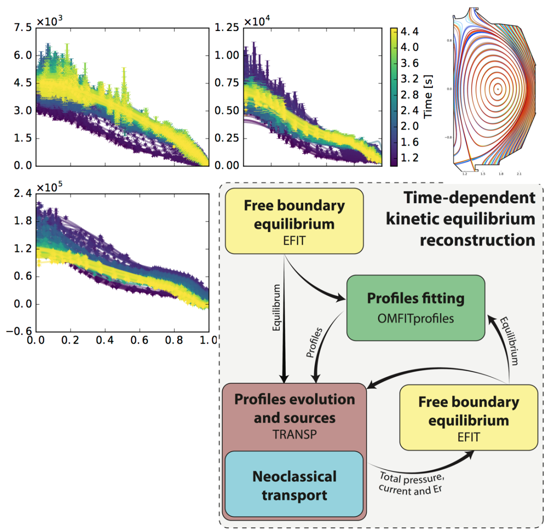


Figure 4.21: Kinetic profiles fit in flux space and time are combined with TRANSP to form constraints for a kinetic equilibrium.

***Background:*** The OMFIT profiles workflow offers an alternate paradigm to the existing "snapshot" analysis, integrating the many diverse diagnostics on any tokamak device into a regular data structure and consistently applying spatial and temporal treatments to each channel of data. OMFITprofiles provides flexible, physics-based data processing through a workflow that emphasizes transparency and visualization at each step to ensure the implication of each decision is understood by diagnosticians and modelers whether they work in the KSTAR control room every day or are collaborating from laboratories in the US. Using the same framework already available on DIII-D, NSTX-U, C-MOD, and many European machines will leverage institutional knowledge of best practices for which official citations in the literature are rare. An example of the very successful DIII-D kinetic equilibrium reconstruction workflow, for example, is shown in Fig. 4.21. Including KSTAR will, in turn, inspire new functionalities and institutional knowledge from that machine that will improve the accuracy and robustness of analysis on US machines. Using the same toolbox, with increased transparency through the use of open source software and documentation, we aim to remove the bottleneck of fundamental profile fitting and the associated kinetic equilibrium construction from KSTAR physics analysis. This will clearly benefit the project participants, local users, and all KSTAR collaborators.

These profiles and improved equilibrium reconstructions will provide a critical connection between experimental observations and 3D MHD modeling through the kinetic profiles and EFITs in Tasks 1-4. In addition to the direct and necessary benefits of this effort for the current proposal, the tools and modeling workflows developed here will have a broad impact on the KSTAR collaboration as a whole. The streamlined connection to TRANSP will enable a surge in fundamental transport modeling. The fast and robust profile analysis will enable experimental physicists to visualize profile dynamics for decision making during experiments. Interaction with the dynamic profiles and visualization of their consequences in terms of common derived quantities will enable informed decision making when planning and running experiments. Here again, consistency between KSTAR and the US facilities will enable smooth collaboration between Korean and US physicists participating in experiments on either side of the ocean.

***Proposed work:*** First we will develop a kinetic EFIT workflow in OMFIT. This includes tackling KSTAR-specific profile fitting challenges such as producing robust, physically meaningful fitting of the high-scatter Thomson scattering data in the pedestal. This may require integration between fitting and pedestal height prediction models. It also requires the regular preparation and sending of KSTAR data to PPPL for TRANSP modeling as well as fetching and archiving of TRANSP results at KSTAR, which will also be orchestrated within the OMFIT framework. We will also collaborate with SNU (Fusion and Plasma Application Laboratory, http://fusma.snu.ac.kr, led by Prof. Y.S. Na) and NFRI (H.-S. Kim) to adopt their processing schemes and obtain kinetic EFITs as needed basis. Their schemes will be used to reconstruct a q-profile based on ASTRA or CRONOS modeling particularly for the cases where MSE data are missing (which is especially true for 2016-2018 KSTAR data) and also to include fast-ion pressure based on NUBEAM calculations. Finally, we will develop a consistent and automatic profile analysis and kinetic EFIT workflow in OMFIT. The deliverable is a robust workflow requiring the user to enter only shots and times and producing consistent profiles and equilibria. This will enable the large database studies in Tasks 1 through 4.

### 4.6.2. 3D field coil design

As a practical application of the lessons learned in this study, the data and the models developed in Tasks 1-5 will be integrated into physics design studies of innovative 3D coils. Physics illuminated in the previous tasks (EFC and ELM suppression thresholds, transport and footprint scaling, etc.) will become additional inputs into cost functions to be minimized in coil design optimizations. Note that this proposed task is also a complementary extension of the existing activity by Park "3D field and coil optimization in KSTAR" planned until FY20, including improved physics basis and predictive capability for ELM suppression. That is, the design of coils will utilize the edge resonant field threshold scaling for ELM suppression, while simultaneously minimizing the danger of reaching a core LM or H-L threshold as well as minimizing heat flux and confinement degradation. This sort of cost function analysis will be performed by flagship US stellarator optimization tools such as STELLOPT [Spong01], FOCUS [Zhu18], and REGCOIL [Landreman17] integrated - using OMFIT - with the data and the 3D MHD modeling used in the previous tasks. Another important and new element is to design 3D EF correction and ELM suppression coils on COMPASS-U and to exercise conceptual ex-vessel 3D coils across different sizes ultimately for ITER/DEMO.

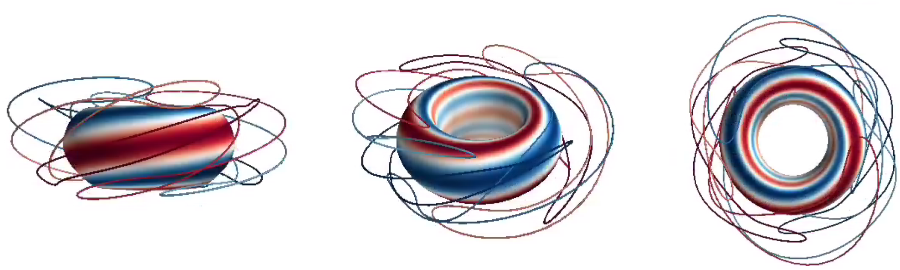

Figure 4.22: 3D coil shapes and currents optimized to produce the dominant resonant coupling spectrum for a DIII-D ITER baseline scenario plasma discharge.

***Background:*** Initial integration of the FOCUS coil optimization code with GPEC EFC targets was performed in [Logan17APS], which informed the DIII-D M-coil design [Weisberg16APS] while also showing that there is under-utilized potential in shaped ex-vessel coils (examples shown in Fig. 4.22). These ex-vessel coils are thought to be of particular importance for reactor designs beyond ITER, where neutron rates are expected to make in-vessel conducting coils prohibitively difficult to deploy. In today's machines, similar shape optimizations can be combined with the close coupling of in-vessel coils to deliver highly efficient 3D perturbations. The KSTAR team has indicated an openness to the possibility of substantial investment in optimized coil shapes in or ex-vessel, which would be an ultimate practical application of the cumulative knowledge developed throughout this proposal. In addition, the COMPASS-U project [Urban18] has also indicated an interest in building such optimized 3D coils for ELM control as well as error field correction. COMPASS-U is relatively small in size but aims at high performance with higher toroidal field ($B_T$=5T), density ($10^{20}m^{-3}$), and also with advanced divertors such as snowflake [Urban18]. The application of this work on these two devices therefore provides an important opportunity to study the influence of size, regimes and divertor configurations, on the optimal coil shapes.

***Proposed work:*** The GPEC code will first be used to calculate 3D fields that maximize edge resonance and minimize core resonance [Park18] in selected experimental/numerical target scenarios in KSTAR and COMPASS-U. The FOCUS code will be used to optimize the 3D shape and current of distant (ex-vessel) coils with minimum engineering constraints, providing "best case" scenarios and basic intuition as to what geometric shapes are most efficient. We will then also add more rigorous engineering constraints to coil design optimizations, by coupling GPEC targets to an integrated STELLOPT/FOCUS/REGCOIL workflow that enables coil designs constrained to winding surfaces to investigate the trade-offs between in and ex-vessel optima. Returning to the physics of interest from Tasks 1-3, we will utilize these newly developed coil optimization workflows to design coils simultaneously meeting accessibility and threshold conditions for ELM suppression (Tasks 1&2) while optimizing for nonlinear transport such as divertor heat loads within these hard threshold limits (Tasks 3-5). The influence of the relative weights in this multiple-object optimization will be investigated and top designs selected for flexibility and efficiency. As the best geometries are being honed in on, the optimizations will be integrated more and more with the fundamental engineering constraints of the KSTAR and COMPASS-U such as forbidden spatial regions, coil winding limits, and coil current limits. While rigorous engineering design reviews will be left to the host institution, the final product of this work will be buildable coil designs optimized to meet the multiple physics objectives of ELM suppression in addition to error field correction (EFC).

# 5. Project Management Plan

The project performance will be assessed by main coordinators for each major task while actively exchanging data and progress to build up predictive capabilities of 3D ELM suppression. The main coordinator will also oversee the research progress and plan of participating institutional PIs, contributors, and subcontractors, on collaborating facilities, as summarized by Table in Sec. 5.1, and also on milestones for each major task as described in Sec. 5.2. Regular bi-weekly video-conference meetings will take place to ensure active communication among the project team.

## 5.1. Coordination and Responsibilities

*PD: Post-doctoral fellow, TBD and affiliated by PPPL (PD-L), GA (PD-G), UCI (PD-I), PU (PD-P)
*SC: Sub-contractor, Dmitry Orlov in UCSD (SC1) and a post-doctoral fellow in UNIST (SC2)
*GS-W: Graduate (Ph.D) student in UW

| Task | Coordinator | Sub | Contributors | Codes | Facilities | Link |
|---|---|---|---|---|---|---|
| T1 | Paz-Soldan (GA) | 1.1 | Paz-Soldan, PD-G, Park, PD-L | GPEC | AUG, EAST, KSTAR | T2-5 |
| | | 1.2 | Paz-Soldan, Weisberg, Liu, PD-G | MARS | AUG, EAST | T2&3 |
| | | 1.3 | Park, PD-L | GPEC | AUG, KSTAR | T2&3 |
| T2 | Park (PPPL) | 2.1 | Logan, Hu, PD-L Paz-Soldan, PD-G | GPEC, TM1 | AUG, EAST, KSTAR | T3&4 |
| | | 2.2 | Park, Hu, PD-L Paz-Soldan, PD-G | GPEC, TM1 | AUG, EAST, KSTAR | T3&4 |
| | | 2.3 | Paz-Soldan, PD-G | GPEC | AUG, EAST, KSTAR | T3&4 |
| | | 2.4 | Park, PD-L | GPEC | AUG, EAST, KSTAR | T1&3-6 |
| T3 | Evans (GA) & Lin (UCI) | 3.1 | Evans, Lin, PD-I, SC2 | M3D-C1, GTC | KSTAR | T1-3 |
| | | 3.2 | Liu | MARS | AUG, EAST, KSTAR | T1&2 |
| | | 3.3 | Hu, SC2 | TM1 | AUG, EAST, KSTAR | T1&2 |
| T4 | Frerichs (UW) | 4.1 | Frerichs, Schmitz, GS-W Liu, Weisberg | MARS, M3D-C1 | KSTAR | T1&2&5 |
| | | 4.2 | Frerichs, Schmitz, GS-W, SC1 | M3D-C1, EMC3, ERO2, MCI | KSTAR | T1&2&5 |
| T5 | Egemen (PU) | 5.1 | Egemen, PD-U | GPEC, VALEN3D | KSTAR | T1&2 |
| | | 5.2 | Egemen, PD-U | PCS | KSTAR | T1&2&4 |
| T6 | Logan (PPPL) | 6.1 | Logan | OMFIT | KSTAR | T1-5 |
| | | 6.2 | Zhu, Logan | FOCUS | KSTAR, COMPASS-U | T1-5 |

## 5.2. Milestones and Timetables

### 5.2.1. Common physics basis for accessibility conditions for 3D ELM suppression (Task 1)

| | |
|---|---|
| Y1 | ● Deploy GPEC to IPP, and model shape impact on core/edge coupling in AUG. Analyze lower X-point impact on core/edge coupling in KSTAR using GPEC (Paz-Soldan, PD-G)<br>● Measure experimental ELM control behavior from NBI to RF heated plasmas in EAST, AUG. Perform quasilinear MARS-Q modeling of flow and 3D spectrum (Paz-Soldan, PD-G)<br>● Investigate profile dependencies across $q_{95}$ windows in the past AUG and KSTAR discharges, in comparison with DIII-D (Park, PD-L) |
| Y2 | ● Compare Upper/Lower shape dependence in dedicated experiments with GPEC in KSTAR (Park, PD-L)<br>● Perform MARS-Q modeling of 3D spectrum effect and NBI/RF input torque (Liu)<br>● Design and perform new experiments possibly for new $q_{95}$ windows in AUG and KSTAR with a combination of ($I_P$, $B_T$) variations to understand hysteresis and dynamics (Park, PD-L) |
| Y3 | ● Combine KSTAR, EAST, AUG data (w/DIII-D) observations on shape, flow, $q_{95}$ to propose physics basis for accessibility conditions for 3D ELM suppression (Paz-Soldan, Park)<br>● Integrate experimental analysis with scaling (Task 2) and transport modeling (Task 3) in the unified report (Paz-Soldan, Park, Evans, Lin) |

### 5.2.2. Parametric threshold scaling and windows for 3D ELM suppression (Task 2)

| | |
|---|---|
| Y1 | ● Apply GPEC to measure ELM suppression thresholds in $\delta B_{edge}$ in the past AUG and KSTAR discharges. Plan a single dedicated shot for 3D ramp-up in all new targets under this proposal to obtain the threshold data (Logan, Paz-Soldan, PD-G)<br>● Apply GPEC to measure LM or H-L thresholds in $\delta B_{core}$ in the past and current AUG and KSTAR discharges and combine them into the existing LM scaling in MDC-19 (Park, PD-L)<br>● Measure $H_{89}$ or $H_{98y2}$ for available 3D ELM suppressed discharges (Paz-Soldan, Weisberg, PD-G) |
| Y2 | ● Develop empirical ELM suppression threshold scaling for n=1 and n=2. Continue to deploy a dedicated 3D ramp-up shot to obtain the threshold data (Logan, PD-L)<br>● Take the finalized LM scaling across L to H-modes in MDC-19 and separate H-L back-transition scaling if necessary (Park, PD-L)<br>● Develop confinement scaling for 3D ELM suppressed discharges (Paz-Soldan, Weisberg)<br>● Produce phase-space diagram for ELM suppression windows in KSTAR (Park, PD-L) |
| Y3 | ● Improve empirical ELM suppression threshold scaling for n=1 and n=2 with TM1 guidance (Park, Hu)<br>● Predict ELM suppression windows in phase space of 3D fields and key parameters including density, within the accessibility conditions, in KSTAR and DIII-D (Park, PD-L)<br>● Propose confinement scaling to optimize 3D ELM suppression in windows (Paz-Soldan, Weisberg, PD-G) |

### 5.2.3. Underlying transport mechanisms for 3D ELM suppression (Task 3)

| | |
|---|---|
| Y1 | ● Survey existing KSTAR magnetic island turbulence data, propose and carry out a targeted island turbulence experiment followed by GTC simulations (Evans, Lin, PD-I, SC2)<br>● Run TM1 codes for a selected set of LM threshold experiments to understand two-fluid MHD effects and numerically verify empirical scaling (Hu) |
| Y2 | ● Use Y1 experimental and simulation results to propose and carry out additional targeted island turbulence experiments including perturbative heat and particle island transport studies (Evans, Lin, PD-I, SC2)<br>● Perform MARS-Q modeling of particle transport in AUG/EAST plasmas focusing on spectrum effect (Liu)<br>● Run TM1 codes for a selected set of ELM suppression threshold experiments to understand two-fluid MHD |

| | |
|---|---|
| | effects in the pedestal and numerically verify empirical scaling (Hu, SC2) |
| Y3 | ● Carry out detailed experimental analysis and GTC simulations of Y2 experiment. Prepare detailed report of Y1 and Y2 experimental and simulations results (Evans, Lin, PD-I)<br>● Perform MARS-Q modeling of particle transport in KSTAR plasmas in long-pulse scenario (Liu)<br>● Combine physics understanding on turbulent, neoclassical, and two-fluids effects in a unified report (Evans, Lin, Liu, Hu) |

### 5.2.4. Heat flux prediction and optimization for long pulse (Task 4)

| | |
|---|---|
| Y1 | ● Re-activate heat flux limit in EMC3, and add alternative implementation based on iterative approximation of the correction factor (Frerichs, GS-W)<br>● Perform dedicated experiments varying radiator species (Schmitz, GS-W)<br>● Integrate MCI (Monte Carlo Impurity) code with EMC3-EIRENE (SC1) |
| Y2 | ● Analyze sensitivities in the MARS-F to EMC3-EIRENE coupling (level of toroidal plasma rotation, poloidal inhomogeneities, etc), in particular with respect to the radial connection of field lines from the divertor plates (Frerichs, GS-W)<br>● Create constrained equilibria including radiator profile, model heat flux reduction with EMC3-EIRENE (Frerichs, Schmitz, GS-W)<br>● Benchmark MCI and ERO2 impurity transport codes (SC1) |
| Y3 | ● Based on plasma response and transport modeling from Task 3, evaluate divertor heat loads at KSTAR with EMC3-EIRENE for different RMP coil phasings and mode numbers within (and moderately beyond) the ELM control suppression (Frerichs, GS-W, Evans, Park)<br>● Conduct initial assessment of surface erosion and deposition dynamics with ERO2 and MCI to better constrain intrinsic impurity source (Schmitz, GS-W, SC1) |

### 5.2.5. Active control for 3D ELM suppression in long pulse (Task 5)

| | |
|---|---|
| Y1 | ● Implement Real-Time 3D field amplitude control (Kolemen, PD-P) |
| Y2 | ● Implement integrated Real-Time 3D field amplitude and gas control (Kolemen, PD-P)<br>● Implement integrated radiated power and 3D control if RT measurement available (Kolemen, PD-P) |
| Y3 | ● Compile results into a report and peer-reviewed output (Kolemen, PD-P) |

### 5.2.6. Integrated analysis tools and innovative 3D coils (Task 6)

| | |
|---|---|
| Y1 | ● Develop robust, manual kinetic equilibrium workflow (Logan)<br>● Begin study of ex-vessel coil designs using relatively unconstrained FOCUS shape optimizations and single fundamental targets from GPEC for COMPASS-U (Zhu) |
| Y2 | ● Develop a consistent, automated profile analysis and kinetic equilibrium workflow (Logan, PD-U)<br>● Improve ex-vessel coil designs using the accessibility conditions and threshold scaling in Task 1-2 for COMPASS-U (Zhu, Park) |
| Y3 | ● Leverage the extended predictive capability of 3D ELM suppression from Task 1-5 to coil designs and propose ex-vessel coils to COMPASS-U and KSTAR with and without engineering constraints (Zhu, Park) |

# Appendix

## Appendix 1. Biographical Sketch

Jong-Kyu Park (Lead PI, PPPL)

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**Education and Training:**

- Ph.D. - Physics, Department of Astrophysical Sciences, Princeton University, USA (2009)
- M.S. - Engineering, Department of Nuclear Engineering, Seoul National University, Korea (2002)
- B.S. - Engineering, Department of Nuclear Engineering, Seoul National University, Korea (2000)

**Research and Professional Experience:**

- Principal Research Physicist - Princeton Plasma Physics Laboratory, USA (2016 - )
- Lecturer - Department of Astrophysical Science, Princeton University, USA (2013 - )
- Research Physicist - Princeton Plasma Physics Laboratory, USA (2012 - )
- Staff Physicist - Princeton Plasma Physics Laboratory, USA (2009 - )

**Selected Publications:**

- J.-K. Park, Y. M. Jeon, Y. In, J.-W. Ahn, G. Y. Park, J. H. Kim, H. H. Lee, W. Ko, H. Kim, E. Feibush, Z. R. Wang, N. C. Logan, R. Nazikian and M. Zanstroff, "Predictive Use of 3D Magnetic Field in a Tokamak for Edge Instability Control", Nature Physics **14**, (2018) 1223
- J.-K. Park and N. C. Logan, "Self-consistent Perturbed Equilibrium with Neoclassical Toroidal Torque in Tokamaks", Physics of Plasmas **24** (2017) 032505
- Y. In, J.-K. Park, Y. M. Jeon, J. Kim, G. Y. Park, J.-W. Ahn, A. Loarte, W. H. Ko, H. H. Lee, J. W. Yoo, J. W. Juhn, S. W. Yoon, H. Park, and 3D Physics Task Force in KSTAR, "Enhanced Understanding of Non-axisymmetric intrinsic and controlled field impacts in Tokamaks", Nuclear Fusion **57**, 116054 (2017)
- M. J. Lanctot, J.-K. Park, P. Piovesan, Y. Sun, R. J. Buttery, L. Frassinetti, B. Grierson, J. Hanson, S. Haskey, Y. In, Y. M. Jeon, R. J. La Haye, N. C. Logan, L. Marrelli, D. M. Orlov, C. Paz-Soldan, H. Wang, E. Strait, and JET Contributors, "Impact of Toroidal and Poloidal Mode Spectra on the Control Of Non-Axisymmetric Fields in Tokamaks", Physics of Plasmas **24**, 056117 (2017)
- N. C. Logan, J.-K. Park, C. Paz-Soldan, M. J. Lanctot, S. P. Smith, and K. H. Burrell, "Dependence of Neoclassical Toroidal Viscosity on the Poloidal Spectrum of Applied Nonaxisymmetric Fields", Nuclear Fusion **56**, 036008 (2016)
- Y. In, J.-K. Park, Y. M. Jeon, J. Kim, M. Okabayashi, "Extremely Low Intrinsic Non-axiymmetric Field in KSTAR and its Implication", Nuclear Fusion **55**, 043004 (2015)
- Z. R. Wang, M. J. Lanctot, Y. Liu, J.-K. Park, J. E. Menard,, "Three-Dimensional Drift Kinetic Response of High-beta Plasmas in the DIII-D Tokamak", Physical Review Letters **114**, 145005 (2015)
- J.-K. Park, Y. M. Jeon, J. E. Menard, W. H. Ko, S. G. Lee, Y. S. Bae, M. Joung, K.-I. You, K.-D. Lee, N. Logan, K. Kim, J. S. Ko, S. W. Yoon, S. H. Hahn, J. H. Kim, W. C. Kim, Y.-K. Oh, and J.-G. Kwak, "Rotational Resonance of Non-axisymmetric Magnetic Braking in the KSTAR Tokamak", Physical Review Letters **111**, 095002 (2013)
- Y. M. Jeon, J.-K. Park, S. W. Yoon, W. H. Ko, S. G. Lee, K. D. Lee, G. S. Yun, Y. U. Nam, W. C. Kim, J.-G. Park, G. S. Lee, H. K. Kim, H. L. Yang, and the KSTAR Research Team, "Suppression of Edge Localized Modes in High-confinement KSTAR Plasmas by Non-axisymmetric Magnetic Perturbations", Physical Review Letters **109**, 035004 (2012)
- J.-K. Park, M. J. Schaffer, J. E. Menard, and A. H. Boozer, "Control of Asymmetric Magnetic Perturbations in Tokamaks", Physical Review Letters **99**, 195003 (2007)

**Selected Synergistic Activities:**

- ITPA US member for MHD and Leader of ITPA MDC-19 on 3D error fields (2016-)
  - J.-K. Park, N. Logan et al., "*Assessment of Error Field Correction Criteria for ITER*", Project Report to ITER Organization, IDM #ITER_D_UMLSUW (2017)
  - J. E. Menard, J.-K. Park et al., "*Task on the Study of Error Fields using Ideal Perturbed Equilibrium Code (IPEC)*", Project Report to ITER Organization, IDM #ITER_D_3VUEES (2010)
- Deputy Leader of 3D Task Force in KSTAR (2016 - 2017)
- Co-Leader of Joint Research Target (JRT)
  - E. Strait, J.-K. Park, E. Marmar et al., "*Quantify Plasma Response to Non-axisymmetric (3D) Magnetic Fields in Tokamaks*", Project Report to FES in USA (2014)
- Leader or Deputy of Macro Stability Topical Science Group in NSTX (2011 - )
  - Leader of Non-axisymmetric Control Coil (NCC) physics analysis in NSTX-U (2013 - 2015)
- US committee member for the MHD Mode Control Workshop (2010 - )
  - J.-K. Park, "*Special Issue on the 20th Workshop on MHD Stability Control*", Preface (2016)

**Collaborators and Co-editors:**
A. H. Boozer (CU), J. W. Berkery (CU), R. J. Buttery (GA), N. M. Ferraro (PPPL), A. H. Glasser (Private), Y. Gribov (IO), B. Grierson (PPPL), S. Haskey (PPPL), Q. Hu (PPPL), Y. In (UNIST), Y. M. Jeon (NFRI), G. Kramer (PPPL), H.-S. Kim (NFRI), J. Kim (NFRI), W. H. Ko (NFRI), M. Lanctot (FES), H. H. Lee (NFRI), Y. Liu (GA), A. Loarte (IO), N. C. Logan (PPPL), M. Marascheck (IPP-Germany), T. Markovic (IPP-CAS), J. E. Menard (PPPL), O. Meneghini (GA), C. Myers (SNL), Y. Na (SNU), R. Nazikian (PPPL), M. Okabayashi (PPPL), D. Orlov (UCSD), C. Paz-Soldan (GA), G. Park (NFRI), P. Piovesan (RFX), L. Piron (CCFE), E. Strait (GA), B. Tobias (LLAL), H. Wang (IPP-China), Z. Wang (PPPL), S. W. Yoon (NFRI).

**Graduate and Post-doctoral Advisors:**
A. H. Boozer (CU), Y. S. Hwang (SNU), J. E. Menard (PPPL)

**Graduate and Post-doctoral Advisees:**
K. Kim (NFRI), N. C. Logan (PPPL), S. M. Yang (PPPL), Z. Wang (PPPL)

# Carlos Paz-Soldan (Co-Lead PI, GA)

DIII-D Program, General Atomics
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**Education and Training:**

- B.Sc.E, Engineering Physics, Queen's University at Kingston, 2007
- M.Sc.E, Nuclear Engineering and Engineering Physics, University of Wisconsin-Madison, 2009
- Ph.D., Physics, University of Wisconsin-Madison, 2012

**Research and Professional Experience:**

Dr. C. Paz-Soldan is a Scientist with the DIII-D Program at General Atomics. He has made significant contributions to research in the areas of 3D fields and ELM control, and has published over 75 peer-reviewed journal articles. He is the 2013 recipient of the Marshall Rosenbluth Outstanding Doctoral Thesis Prize. He presently leads the ELM Control Research Area for the DIII-D Program.

| | | |
|---|---|---|
| 2014-present | Scientist VI | General Atomics |
| 2012-2014 | Post-Doctoral fellow | Oak Ridge Associated Universities |

**Synergistic Activities:**

- ELM Control Research Thrust / Area Leader, DIII-D Program (2016-present)
- Expert, ITPA MHD, Disruptions, and Control Group (2014-present)
- Expert, ITPA Pedestal and Edge Physics Group (2017-present)
- Principal Investigator, GA Internal R&D Project on Advanced Coilsets for DIII-D (2016-2017)
- Topical Area Leader, MHD & Macroscopic Plasma Physics, US Burning Plasma Org (2017-present)

**Selected Publications:**

Dr. Paz-Soldan has authored/co-authored over 75 peer-reviewed journal papers, below is a selection:


- C. Paz-Soldan, R. Nazikian, L. Cui, B. C. Lyons, D. Orlov, A, Kirk, N. Logan, T. Osborne, W. Suttrop and D. Weisberg, "The Effect of Plasma Shape and Neutral Beam Mix on the Rotation Threshold for RMP-ELM Suppression", *Nucl. Fusion* **59**, 056012 (2019)
- C. Paz-Soldan, C.M. Cooper, P. Aleynikov, D.C. Pace, N.W. Eidietis, D.P. Brennan, R.S. Granetz, E.M. Hollmann, C. Liu, A. Lvovskiy, R.A. Moyer, and D. Shiraki, "Spatiotemporal Evolution of Runaway Electron Momentum Distributions in Tokamaks", *Phys. Rev. Lett.* **118**, 255002 (2017)
- C. Paz-Soldan, N.C. Logan, S.R. Haskey, R. Nazikian, E.J. Strait, X. Chen, N.M. Ferraro, J.D. King, B.C. Lyons and J.-K. Park, "Equilibrium drives of the low and high field side n = 2 plasma response and impact on global confinement", *Nucl. Fusion* **56**, 056001 (2016)
- N.C. Logan, C. Paz-Soldan, J.-K. Park, R. Nazikian, Identification of multi-modal plasma responses using the plasma reluctance, *Phys. Plasmas* **23,** 056110 (2016)
- C. Paz-Soldan, N.C. Logan, M.J. Lanctot, J.M. Hanson, J.D. King, R.J. La Haye, R. Nazikian, J-K. Park, E.J. Strait, "Decoupled recovery of energy and momentum with correction of n=2 error fields", *Nucl. Fusion* **54**, 083012 (2015)
- C. Paz-Soldan, R. Nazikian, S.R. Haskey, N.C. Logan, E.J. Strait, N. Ferraro, J.M. Hanson, J.D. King, M.J. Lanctot, R. Moyer, M. Okabayashi, J-K. Park, M. Shafer, and B.J. Tobias, "Observation of a Multimode Plasma Response and its Relationship to Density Pumpout and Edge-Localized Mode Suppression", *Phys. Rev. Lett.***114**, 105001 (2015)

- R. Nazikian, C. Paz-Soldan, J. D. Callen, J. S. DeGrassie, D. Eldon, T. E. Evans, N. M. Ferraro, B. A. Grierson, R. J. Groebner, S. R. Haskey, C. C. Hegna, J. D. King, N. C. Logan, G. R. Mckee, R. A. Moyer, M. Okabayashi, D. M. Orlov, T. H. Osborne, J.-K. Park, T. L. Rhodes, M. W. Shafer, P. B. Snyder, W. M. Solomon, E. J. Strait, and M. R., "Pedestal Bifurcation and Resonant Field Penetration at the Threshold of Edge-Localized Mode Suppression in the DIII-D Tokamak", *Phys. Rev. Lett.* **114**, 105002 (2015)
- C. Paz-Soldan, R. J. Buttery, A. M. Garofalo, J. M. Hanson, R. J. La Haye, M. J. Lanctot, J-K. Park, W. Solomon, and E. J. Strait, "The spectral basis of optimal error field correction on DIII-D", *Nucl. Fusion* **54**, 073013 (2014)
- C. Paz-Soldan, M.I. Brookhart, A.T. Eckhart, D.A. Hannum, C.C. Hegna, J.S. Sarff, C.B. Forest, "Stabilization of the Resistive Wall Mode by a Rotating Conducting Wall", *Phys. Rev. Lett.* **107**, 245001 (2011)

**Collaborators and Co-editors:**
P. Aleynikov (IPP-Greifswald), M.E. Austin (UT-Ausin), J.E. Boom (CCFE), A. Boozer (Columbia), D.P. Brennan (Princeton U), R.J. Buttery (GA), I.T. Chapman (CCFE), X. Chen (GA), C.M. Cooper (LLNL), N.A Crocker (UCLA), D. del-Castillo Negrete (ORNL), X. Du (GA), N. Eidietis (GA), N.M. Ferraro (PPPL), C. Forest (UW-Madison), T. Fulop (Chalmers), A.M. Garofalo (GA), R. Granetz (MIT), J. Hanson (Columbia), S.R. Haskey (PPPL), C. Hegna (UW-Madison), B. Heidbrink (UCI), E.M. Hollmann (UCSD), V. Izzo (Fiat Lux), A. Kirk (CCFE), R.J. La Haye (GA), Y.Q. Liu (GA), C. Liu (PPPL), N.C. Logan (PPPL), B. Lyons (GA), R. Moyer (UCSD), S. Munaretto (GA), R. Nazikian (PPPL), M. Okabayashi (PPPL), D. Orlov (UCSD), J.-K. Park (PPPL), M.W. Shafer (ORNL), D. Shiraki (ORNL), W.M. Solomon (GA), D. Spong (ORNL), E. Strait (GA), Y. Sun (ASIPP), W. Suttrop (IPP-Garching), B. Tobias (LANL), F. Turco (Columbia), M. Van Zeeland (GA), B. Wilcox (ORNL), A. Wingen (ORNL), Y. Zhu (UCSD)

**Graduate and Postdoctoral Advisees:**
Chris Cooper – 2014-2015, Andrey Lvovskiy – 2016-present, Luke Stagner – 2018-present
David Weisberg – 2016-2017

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**Education and Training:**

- PhD - Physics, RWTH-Aachen University, Germany (2010)
- Diplom (Msc) - Physics, RWTH-Aachen University, Germany (2006)

**Research and Professional Experience:**

- Associate Scientist, University of Wisconsin - Madison (2017 - today)
- Assistant Scientist, University of Wisconsin - Madison (2014 - 2017)
- Post doctorate studies at Forschungzentrum Juelich, Germany (2010 - 2014)

**Selected Publications:**

- H. Frerichs, X. Bonnin, Y. Feng, A. Loarte, R.A. Pitts, D. Reiter and O. Schmitz, "Stabilization of EMC3-EIRENE for detachment conditions and comparison to SOLPS-ITER", Nuclear Materials and Energy, **18** (2019) 62–66
- H. Frerichs, O. Schmitz, B. Covele, Y. Feng, H.Y. Guo and D. Hill, "Numerical exploration of non-axisymmetric divertor closure in the small angle slot (SAS) divertor at DIII-D", Nucl. Fusion **58** (2018) 051001
- H. Frerichs, O. Schmitz, I. Waters, G. P. Canal, T. E. Evans, Y. Feng and V. A. Soukhanovskii, "Exploration of magnetic perturbation effects on advanced divertor configurations in NSTX-U", Phys. Plasmas **23**, 062517 (2016)
- H. Frerichs, O. Schmitz, T. Evans, Y. Feng, and D. Reiter, "The pattern of parallel edge plasma flows due to pressure gradients, recycling, and resonant magnetic perturbations in DIII-D", Phys. Plasmas **22**, 072508 (2015)
- H. Frerichs and D. Reiter, "Stability and control of iterated non-linear transport solvers for fusion edge plasmas", Comp. Phys. Commun. **188** (2015) 82-87
- H. Frerichs, O. Schmitz, D. Reiter, T. E. Evans, and Y. Feng, "Striation pattern of target particle and heat fluxes in three dimensional simulations for DIII-D", Phys. Plasmas **21**, 020702 (2014)
- H. Frerichs, D. Reiter, O. Schmitz, P. Cahyna, T. E. Evans, Y. Feng, and E. Nardon, "Impact of screening of resonant magnetic perturbations in three dimensional edge plasma transport simulations for DIII-D", Phys. Plasmas **19**, 052507 (2012)
- H. Frerichs, D. Reiter, O. Schmitz, D. Harting, T.E. Evans and Y. Feng, "On gas flow effects in 3D edge transport simulations for DIII-D plasmas with resonant magnetic perturbations", Nucl. Fusion **52** (2012) 054008
- H. Frerichs, D. Reiter, O. Schmitz, T.E. Evans and Y. Feng, "Three-dimensional edge transport
- simulations for DIII-D plasmas with resonant magnetic perturbations", Nucl. Fusion **50** (2010) 034004
- H. Frerichs, D. Reiter, Y. Feng, D. Harting, "Block-structured grids in Lagrangian 3D edge plasma transport simulations", Comp. Phys. Commun. **181** (2010) 61-70

**Synergistic Activities:**

- Extensive modeling for RMP scenarios at DIII-D, NSTX-U, ITER and TEXTOR-DED with EMC3-EIRENE
- Development of versatile grid-generator (FLARE) for different field configurations and unifyed coupling to different plasma response models
- Extended numerical development and application expertise with Monte Carlo procedures on high performance computing architectures

**Collaborators and Co-Editors:**

A. Bader (UW), C. Biedermann (MPG, Germany), P. Boerner (FZJ, Germany), X. Bonnin (IO, France), A. Briesemeister (GA), G.P. Canal (GA), B. Covele (GA), F. Effenberg (UW), T.E. Evans (GA), Y. Feng (MPG, Germany), D. Gates (PPPL), D. Gradic (MPG, Germany), H.Y. Guo (GA), D. Hill (GA), E. Hinson (UW), M. Jakubowski (MPG, Germany), M. Kobayashi (NIFS, Japan), R. Koening (MPG, Germany), M. Krychowiak (MPG, Germany), S. Lazerson (PPPL), A. Loarte (IO, France), J. D. Lore (ORNL), J. E. Menard (PPPL), H. Niemann (MPG, Germany), T.S. Pedersen (MPG, Germany), R.A. Pitts (IO, France), M. Rack (FZJ, Germany), D. Reiter (FZJ, Germany), V. A. Soukhanovskii (LLNL), J. Schmitt (Auburn University), O. Schmitz (UW), L. Stephey (UW), I. Waters (UW), R. Wolf (MPG, Germany), G.A. Wurden (LLNL)

**Graduate and post-doctoral Advisor:**

D. Reiter (FZJ, Germany)

# Zhihong Lin (PI, UCI)

Physics and Astronomy, University of California - Irvine
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**Education and Training:**

- Ph.D. - Department of Astrophysical Sciences, Princeton University, USA (1996)
- B.S. - Department of Physics, Peking University (1989)

**Research and Professional Experience:**

- Professor, Physics & Astronomy, University of California, Irvine. (2008 - Present)
- Associate Professor, Physics & Astronomy, University of California, Irvine. (2005 - 2008)
- Assistant Professor, Physics & Astronomy, University of California, Irvine. (2002 - 2005)
- Research Physicist, Princeton Plasma Physics Laboratory. (2001 - 2002)
- Staff Research Physicist, Princeton Plasma Physics Laboratory. (1997 - 2001)
- Post-doctoral Fellow, Princeton University. (1995-1997)

**Selected Publications:**

- Taimourzadeh, S., L. Shi, Z. Lin, R. Nazikian, I. Holod, D. Spong. "Effects of RMP-Induced Changes of Radial Electric Fields on Microturbulence in DIII-D Pedestal Top", Nuclear Fusion **59**, 046005 (2019).
- Taimourzadeh, S. et al. "Verification and validation of integrated simulation of energetic particles in fusion plasmas", Nuclear Fusion **59**, 066006 (2019).
- Fang, K. S. and Z. Lin, "Global gyrokinetic simulation of microturbulence with kinetic electrons in the presence of magnetic island in tokamak", Phys. Plasmas **26**, in press (2019).
- Dong, G., J. Bao, A. Bhattacharjee, and Z. Lin. "Nonlinear Saturation of Kinetic Ballooning Modes by Zonal Fields in Toroidal Plasmas", Phys. Plasmas **26**, 010701 (2019).
- Aslanyan, V. et al. "Gyrokinetic simulations of Toroidal Alfven Eigenmodes excited by energetic ions and external antennas on the Joint European Torus", Nuclear Fusion **59**, 026008 (2019).
- Holod, I., Z. Lin, S. Taimourzadeh, R. Nazikian, D. Spong, and A. Wingen. "Effects of Resonant Magnetic Perturbations on Microturbulence in DIII-D Pedestal", Nuclear Fusion **57**, 016005 (2017).
- Dong, G. and Z. Lin. "Effects of Magnetic Islands on Bootstrap Current in Toroidal Plasmas", Nuclear Fusion **57**, 036009 (2017).
- Rizvi, H., C. M. Ryu, and Z. Lin. "Multiple toroidal Alfven eigenmodes with a single toroidal mode number in KSTAR plasmas", Nuclear Fusion **56**, 112016 (2016).
- Jiang, P., Z. Lin, I. Holod, and C. Xiao. "Effects of magnetic islands on drift wave instability", Phys. Plasmas **21**, 122513 (2014).
- Lin, Z., T. S. Hahm, W. W. Lee, W. M. Tang, and R. B. White. "Turbulent Transport Reduction by Zonal Flows: Massively Parallel Simulations", Science, **281**, 1835 (1998). (1037 citations)

**Synergistic Activities:**

- Director and PI, DOE Scientific Discovery through Advanced Computing (SciDAC), Integrated Simulation of Energetic Particle in Burning Plasmas (GSEP/ISEP) Center, 2008-present. (consortium of UCI, PPPL, GA, ORNL, LLNL, LBNL, PU, UCSD)
- PI, DOE Innovative and Novel Computational Impact on Theory and Experiment (INCITE) project, 2010-2011, 2019-2022; GTC project; DOE ASCR Oak Ridge Leadership Computing Facility (OLCF) Center for Accelerated Application Readiness (*CAAR*) program, 2015-2018; DOE ASCR Leadership Computing Challenge (*ALCC*) project, 2012-2014, 2017-2018.

- Associate Editor, *Communications of Computational Physics* (CiCP), 2006-present. Editorial Board, *Reviews of Modern Plasma Physics*, 2016-present; *Plasma Science and Technology*, 2016-present.
- Founding Director and Visiting Chair Professor, Fusion Simulation Center (FSC), Peking University, Beijing, China, 2009-present. Visiting Chair Professor, Xiamen University, 2012-present.
- Report Section Lead, DOE Exascale Requirements Review, lead of energetic particle and MHD, 2016-2017.

**Collaborators and Co-editors:**

V. Aslanyan, A. Bhattacharjee, M. W. Binderbauer, C. S. Chang, L. Chen, J. Y. Cheng, X. Cheng, S. A. Colgate, B. H. Deng, S. A. Dettrick, G. Dong, S. Ethier, H. Y. Feng, N. J. Fisch, X. R. Fu, H. D. He, H. Gota, R. J. Groebner, W. W. Heidbrink, P. Jiang, B. Li, H. Li, S. H. Ku, P. Lauber, J. C. Li, X. Liao, J. B. Lin, D. J. Liu, Y. Q. Liu, X. F. Meng, M. Porkolab, M. Tuszewski, R. Nazikian, H. Rizvi, E. Ruskov, C. M. Ryu, L. Schmitz, S. E. Sharapov, D. A. Spong, L.C. Steinhauer, G. Y. Sun, T. Tajima, B. Tobias, M. Van Zeeland, E. D. Wang, P. Wang, W. X. Wang, F. Wessel, A. Wingen, C. J. Xiao, H. S. Xie, B. Zhang, C. X. Zhang, H. S. Zhang, Y. Zhao

**Graduate and Postdoctoral Advisors:**

W. M. Tang, W. W. Lee

**Graduate and Postgraduate Advisees:**

Jian Bao, Andreas Bierwage, Xi Chen, Xi Cheng, Cami Collins, Wenjun Deng, Daniel Fulton, Ihor Holod, Animesh Kuley, Calvin Lau, Pengfei Liu, Onnie Luk, Joseph McClenaghan, Javier Nicolau, Yasutaro Nishimura, David Pace, Peter Porazik, Hongpeng Qu, Lei Shi, Sam Taimourzadeh, Wenhao Wang, Zhixuan Wang, Xishuo Wei, Yong Xiao, Wenlu Zhang

**Honors and Awards:**

Visiting Chang Jiang Scholars, Peking University, 2009-2015
American Physical Society, Fellow, 2006
NSF CAREER Award, 2004
DOE Plasma Physics Junior Faculty Development Award, 2003
Presidential Early Career Awards for Scientists and Engineers (PECASE), 2000
DOE Early Career Awards in Science and Engineering, 2000
Kaul Foundation Prize for Excellence in Plasma Physics and Technology Development, 1999

# Egemen Kolemen (PI, PU)

Mechanical and Aerospace Engineering, Princeton University
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**Education and Training:**

| | |
|---|---|
| Postdoctoral Research Fellow<br>*Princeton University, Princeton, NJ* | Sep 2008 – Oct 2009 |
| Ph.D. Mechanical & Aerospace Engineering<br>*Princeton University, Princeton, NJ* | Sep 2002 – Aug 2008 |
| B.S. Mechanical Engineering<br>*Bogazici University, Istanbul, Turkey* | Sep 1998 – Jun 2002 |

**Research and Professional Experience:**

| | |
|---|---|
| Assistant Professor, *Princeton University* | Sep 2014 – present |
| Collaborating Research Scientist, *DIII-D, General Atomics, San Diego, CA* | Jun 2011 – present |
| Leader of the Operations and Control Group | Jun 2013 – present |
| Deputy Leader of the Operations and Control Group | Jun 2011 – Jun 2013 |
| Research Collaborator<br>*The Korean Superconducting Tokamak Reactor (KSTAR), Korea*<br>*Developed the PCS shape control algorithm that enabled the first 10 second H-mode plasma.* | Dec 2011 – present |
| Research Collaborator<br>*Experimental Advanced Superconducting Tokamak (EAST), China* | Apr 2012 – present |
| Research Scientist, *PPPL* | Oct 2011 – Sep 2014 |
| Associate Research Scientist, NSTX, *PPPL* | Oct 2009 – Oct 2011 |
| Postdoctoral Research Fellow, *Princeton University* | Sep 2008 – Oct 2009 |

**Selected Publications:**

- A. S. Glasser (grad student) and E. Kolemen, "A robust solution for the resistive MHD toroidal $\Delta'$ matrix in near real-time", Physics of Plasmas, **25**, 082502 (2018)
- A. S. Glasser (grad student), E. Kolemen, and A. H. Glasser, "A Riccati solution for the ideal MHD plasma response with applications to real-time stability control", Physics of Plasmas **25**, 032507 (2018)
- A Fil (postdoc), E Kolemen, N Ferraro, S Jardin, PB Parks, R Lunsford, R Maingi, "Modeling of lithium granule injection in NSTX using M3D-C1", Nuclear Fusion **57** (5), 056040
- D. Eldon, R. L. Boivin, R. J. Groebner, T. H. Osborne, P. B. Snyder, A. D. Turnbull, G. R. Tynan, J. A. Boedo, K. H. Burrell, E. Kolemen, L. Schmitz and H. R. Wilson, "Investigation of peeling-ballooning stability prior to transient outbursts accompanying transitions out of H-mode in DIII-D" Phys. Plasmas **22**, 052109, 2015
- E. Kolemen, S.L. Allen, B.D. Bray, M.E. Fenstermacher, D.A. Humphreys, A.W. Hyatt, C.J. Lasnier, A.W. Leonard, M.A. Makowski, A.G. McLean, R. Maingi, R. Nazikian, T.W. Petrie, V.A. Soukhanovskii, E.A. Unterberg, "Heat flux management via advanced magnetic divertor configurations and divertor detachment", Journal of Nuclear Materials, Volume **463**, Pages 1186–1190, 2015
- R. Nazikian, D. Eldon, T.E. Evans, N.M. Ferraro, B.A. Grierson, R. Groebner, J. King, E. Kolemen, N. Logan, G.R. McKee, O. Meneghini, R.A. Moyer, D.M. Orlov, T. Osborne, C. Paz-Soldan, T. Rhodes, W.M. Solomon, O. Schmitz, M.W. Shafer, S. Smith, P.B. Snyder, E.J. Strait, M.R. Wade, "Advances in the Understanding of ELM Suppression by Resonant Magnetic Perturbations (RMPs) in DIII-D and Implications for ITER", Proceedings of IAEA 2014, EX1-1

- R.J. Hawryluk, N.W. Eidietis, B.A. Grierson, A.W. Hyatt, E. Kolemen, N. Logan, R. Nazikian, C. Paz-Soldan, W.M. Solomon and S. Wolfe, "Control of Plasma Stored Energy for Burn Control Using DIII-D In-Vessel Coils", Nuclear Fusion **55** 053001, 2015
- E. Kolemen, A.S. Welander, R.J. La Haye, N.W. Eidietis, D.A. Humphreys, J. Lohr, V. Noraky, B.G. Penaflor, R. Prater and F. Turco, "State-of-the-art Neoclassical Tearing Mode Control in DIII-D Using Real-Time Steerable Electron Cyclotron Current Drive Launchers", Nuclear Fusion **54** 073020, 2014
- E. Kolemen, R. Ellis, R.J. La Haye, D.A. Humphreys, J. Lohr, S. Noraky, B.G. Penaflor, A.S. Welander, "Real-time mirror steering for improved closed loop neoclassical tearing mode suppression by electron cyclotron current drive in DIII-D", Fusion Engineering and Design, Vol. **88**, pp. 2757-2760, 2013

**Synergistic Activities:**
- ITER Fellow in control area
- Leader of the Machine Learning Control Panel for the DOE Workshop on Machine Learning Applications for Fusion
- Leader of the Topical Group on Operations and Control of the USBPO
- Application of machine learning to fusion control at DIII-D

**Collaborators and Co-editors:**
A.W. Hyatt, GA, R. La Haye, GA, M.J. Lanctot, GA, A.W. Leonard, GA, J. Lohr, GA, M.A. Makowski, LLNL, A.G. McLean, LLNL, R. Nazikian, PPPL, V. Noraky, GA, M. Okabayashi, PPPL, K.E.J. Olofsson, GA, C. Paz-Soldan, GA, B.G. Penaflor, GA, T.W. Petrie, GA, R. Prater, GA, E. Schuster, Lehigh University, V.A. Soukhanovskii, LLNL, W. Solomon, PPPL, E.J. Strait, GA , F. Turco, Columbia University, E.A. Unterberg, ORNL, F.A. Volpe, Columbia University, Anders S. Welander, GA

**Graduate and Postdoctoral Advisors and Advisees:**
Alexander Glasser, Patrick Vail, Adam Fisher, Alexander Fil, Michael Hvasta, Mikhail Modestov, Florian Flagger, Olivier Izacard (PU), David Eldon, (GA)
David A. Gates, Stellarator Physics Leader, Princeton Plasma Physics Laboratory
Clarence W. Rowley, Professor at Princeton University
N. Jeremy Kasdin, Professor at Princeton University

Nikolas C. Logan (PPPL)

Princeton Plasma Physics Laboratory
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**Education and Training:**

PRINCETON UNIVERSITY,
*Princeton, New Jersey — Ph.D. Astrophysical Sciences - Plasma Physics, 2015*
Thesis: *"Electromagnetic Torque in Tokamaks with Toroidal Asymmetries"*
Advisors: *Jong-Kyu Park, Jonathan E. Menard, Edward J. Strait*

PRINCETON UNIVERSITY,
*Princeton, New Jersey — M.A. Astrophysical Sciences - Plasma Physics, 2011*

BROWN UNIVERSITY,
*Providence, Rhode Island — B.Sc.. Physics, Magna Cum Laude, Honors, 2009*
Thesis: *"Measurement of the Electromagnetic Torque on Rotating DIII-D Plasmas"*
Advisors: *Ian Dell'Antonio*

**Professional and Research Experiences:**

STAFF Research Physicist *2016-Present*
*ITER and Tokamaks Division, R. Nazikian* *Princeton Plasma Physics Laboratory, NJ*
Development and public release of the Generalized Perturbed Equilibrium Code (GPEC), written in FORTRAN. Development of a OMFIT GPEC module and continued development of the TRANSP and OMFITprofiles modules. Application of integrated modeling tools to study temporal evolution of kinetic-MHD stability, neoclassical nonambipolar transport and NTV torque. Optimization of NTV profiles for control of rotation and stability using new GPEC torque matrices.

Associate Research Physicist *2015-2016*
*ITER and Tokamaks Division, R. Nazikian* *Princeton Plasma Physics Laboratory, NJ*
Identification of nonaxisymmetric plasma response observed in the DIII-D tokamak using the Ideal Perturbed Equilibrium Code (IPEC). IPEC and Generalized Perturbed Equilibrium Code (GPEC) development in FORTRAN. Momentum transport modeling using the TRANSP code, and development of the OMFIT TRANSP module in Python (now publicly available, see *http://gafusion.github.io/OMFIT-source* and *docs* therein). Development of OMFIT profiles module optimizing time dependent experimental profile analysis.

**Selected Publications:**

- N. C. Logan, L. Cui, H. Wang, Y. Sun, S. Gu, G. Li, R. Nazikian, and C. Paz-Soldan, "Magnetic polarization measurements of the multi-modal plasma response to 3D fields in the EAST tokamak," Nuclear Fusion, vol. **58**, no. 7, p. 076016, May 2018.
- N. C. Logan, B. A. Grierson, S. R. Haskey, S. P. Smith, O. Meneghini, and D. Eldon, "OMFIT Tokamak Profile Data Fitting and Physics Analysis," Fusion Science and Technology, vol. **74**, no. 1–2, pp. 125–134, Jan. 2018.
- N. C. Logan, J.-K. Park, C. Paz-Soldan, M. J. Lanctot, S. P. Smith, and K. H. Burrell, "Dependence of neoclassical toroidal viscosity on the poloidal spectrum of applied nonaxisymmetric fields," Nuclear Fusion, vol. **56**, no. 3, p. 036008, Mar. 2016.
- N. C. Logan, C. Paz-Soldan, J.-K. Park, and R. Nazikian, "Identification of multi-modal plasma responses to applied magnetic perturbations using the plasma reluctance," Physics of Plasmas, vol. **23**, no. 5, p. 056110, May 2016.

- N. C. Logan, J.-K. Park, K. Kim, Z. Wang, and J. W. Berkery, “Neoclassical toroidal viscosity in perturbed equilibria with general tokamak geometry,” Physics of Plasmas, vol. **20**, no. 12, p. 122507, Dec. 2013.
- N. C. Logan, E. J. Strait, and H. Reimerdes, “Measurement of the electromagnetic torque in rotating DIII-D plasmas,” Plasma Physics and Controlled Fusion, vol. **52**, no. 4, p. 045013, Apr. 2010.
- C. Paz-Soldan, R. Nazikian, L. Cui, B. C. Lyons, D. M. Orlov, A. Kirk, N. C. Logan, T. H. Osborne, W. Suttrop, and D. B. Weisberg, “The effect of plasma shape and neutral beam mix on the rotation threshold for RMP-ELM suppression,” Nuclear Fusion, vol. **59**, no. 5, p. 056012, May 2019.
- J.-K. Park, Y. Jeon, Y. In, J.-W. Ahn, R. Nazikian, G. Park, J. Kim, H. Lee, W. Ko, H.-S. Kim, N. C. Logan, Z. Wang, E. A. Feibush, J. E. Menard, and M. C. Zarnstoff, “3D field phase-space control in tokamak plasmas,” Nature Physics **12**, 1223 (2018)
- J.-K. Park and N. C. Logan, “Self-consistent perturbed equilibrium with neoclassical toroidal torque in tokamaks,” Physics of Plasmas, vol. **24**, no. 3, p. 032505, Mar. 2017.
- Q. M. Hu, R. Nazikian, B. A. Grierson, N. C. Logan, J.-K. Park, C. Paz-Soldan, and Q. Yu, “The Role of Resonant Fields in Edge-Localized-Mode Suppression and Pump- out in the DIII-D Tokamak,” Nature Physics (in Review), 2019.

**Synergistic Activities:**

- Chairman of Workshop on MHD Stability Control - a joint US-Japan workshop in 2018 and national workshop in 2019.
- Deputy leader of MDC-19 ITPA Joint Experiment on Error Field Control at Low Plasma Rotation 2018-present.
- 3D & Stability Physics Group Leader at the DIII-D National Fusion Facility 2018-present.
- Software Development Manager for GPEC package and OMFIT framework.

**Collaborators and Co-editors:**

T. Abrams (GA), E.A. Belli (GA),J. Buchanan (CCFE), R. V. Budny (PPPL), I. Bykov (UCSD), L. Cui (PPPL), D. Eldon (GA), T. Evans (GA), M. Fitzgerald (CCFE),A. Garofalo (GA), M. Gorelenkova (PPPL), B. A. Grierson (PPPL), X. Gong (IPP, CAS), S. Gu (IPP, CAS), W. Guo (IPP, CAS), S.-H. Hahn (NFRI), J.M. Hanson (Columbia University), S.R. Haskey (PPPL), Q. Hu (PPPL), M. Jia (IPP, CAS), Z.H. Jiang (Huazhong University), J. Kang (NFRI), S. Kaye (PPPL), H.-S. Kim (NFRI), A. Kirk (CCFE), W.-H. Ko (NFRI), E. Kolemen (Princeton University), C. Lasnier (LLNL), M. Lee (NFRI), Y.Q. Liu (GA), B.C. Lyons (GA),M. Makowski (LLNL), J.E. Menard (PPPL), O. Meneghini (GA), S. Munaretto (GA), R. Nazikian (PPPL), D. Orlov (GA), T. Osborne (GA),T. Shi (IPP, CAS), S.P. Smith (GA), G.M. Staebler (GA), E.J. Strait (GA), P.B. Snyder (GA), Y. Sun (IPP, CAS), W. Suttrop (Max Planck IPP), J.-K. Park (PPPL), C. Paz-Soldan (GA), F. M. Poli (PPPL), H.H. Wang (IPP, CAS), Z.R. Wang (PPPL), D. Weisberg (GA), X. Yuan (PPPL)

**Post-Doc Advisors**:
J. Menard (PPPL), J.-K. Park (PPPL), E.J. Strait (GA)

**Post-Doc Advisees**:
Q. Hu (PPPL), S. Yang (PPPL)

# Qiming Hu (PPPL)

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**Education and Training:**

- Ph.D. - Physics, College of Electric and Electronic Engineering, Huazhong University of Science and Technology, China (2014)
- B.S. - Engineering, College of Electric and Electronic Engineering, Huazhong University of Science and Technology, China (2009)

**Research and Professional Experience:**

- Associated Research Physicist - Princeton Plasma Physics Laboratory, USA (2017- )
- Lecturer - College of Electric and Electronic Engineering, Huazhong University of Science and Technology, China (2014-2017)

**Selected Publications:**

- Q. M. Hu, R. Nazikian, B. A. Grierson, N. C. Logan, J.-K. Park, C. Paz-Soldan, and Q. Yu, "The Role of Resonant Fields in Edge-Localized-Mode Suppression and Pump- out in the DIII-D Tokamak," reprint, 2019.
- Q.M. Hu, X.D. Du, Q. Yu, N.C. Logan, E. Kolemen, R. Nazikian, Z.H. Jiang, "Fast and pervasive heat transport induced by multiple locked modes in DIII-D", Nuclear Fusion **59** (2019) 016005
- X.D. Du, M.W. Shafer, Q.M. Hu, T.E. Evans, E.J. Strait, S. Ohdachi, Y. Suzuki, "Direct measurements of internal structures of born-locked modes and the key role in triggering tokamak disruptions", Physics of Plasmas **26** (2019) 042505
- Q.M. Hu, Q.Yu, "Suppressing magnetic island and accelerating its rotation by modulated resonant magnetic perturbation", Nuclear Fusion **56** (2016) 034001
- Q.M. Hu, N.C. Wang, Q.Yu, Y.H. Ding, B. Rao, Z.P. Chen, H. Jin, "Research on the effect of resonant magnetic perturbations on disruption limit in J-TEXT tokamak", Plasma Physics and Controlled Fusion **58** (2016) 025001
- Q.M. Hu, J.C. Li, N.C. Wang, Q.Yu, J. Chen, Z.F. Cheng, Z.P. Chen, Y.H. Ding, H. Jin, D. Li, M. Li, Y. Liu, B. Rao, L.Z. Zhu, G. Zhuang and J-TEXT Team, "Plasma response to m / n = 3/1 resonant magnetic perturbation at J-TEXT Tokamak", Nuclear Fusion **56** (2016) 092009
- Q.M. Hu, Q.Yu, N.C. Wang, P. Shi, B. Yi, Y.H. Ding, B. Rao, Z.P. Chen, L. Gao, X.W. Hu, H. Jin, M. Li, J.C. Li, K.X. Yu, G. Zhuang and J-TEXT Team, "Influence of rotating resonant magnetic perturbations on particle confinement", Nuclear Fusion **54** (2014) 122006
- Q.M. Hu, G. Zhuang, Q.Yu, B. Rao, L. Gao, N.C. Wang, W. Jin, B. Yi, W.B. Zeng, W. Chen, Y.H. Ding, Z.P. Chen, X.W. Hu and J-TEXT Team, "Enhanced particle transport caused by resonant magnetic perturbations in the J-TEXT tokamak", Nuclear Fusion **54** (2014) 064013
- Q.M. Hu, B. Rao, Q.Yu, Y.H. Ding, G. Zhuang, W. Jin, X.W. Hu, "Understanding the effect of resonant magnetic perturbations on tearing mode dynamics", Physics of Plasmas **20** (2013) 092502
- Q.M. Hu, Q. Yu, B. Rao, Y.H. Ding, X.W. Hu, G. Zhuang and J-TEXT Team, "Effect of externally applied resonant magnetic perturbations on resistive tearing modes", Nuclear Fusion **52** (2012) 083011

**Selected Synergistic Activities:**

- **MHD Physics Task Force Leader** at the J-TEXT device 2014-2017.

**Collaborators and Co-editors:**
Z.F. Cheng (HUST), Z.P. Chen (HUST), Z.Y. Chen (HUST), W. Chen (HUST), Y. H. Ding (HUST), X.D. Du (GA), L. Gao (HUST), B. A. Grierson (PPPL), D. J. Guo (HUST), J.Y. He (HUST), X.W. Hu (HUST), H. Jin (HUST), W. Jin (HUST), X.K. Ji (HUST), M. Jiang (SWIP), Z.H. Jiang (HUST), E. Kolemen (PPPL), D. Li (HUST), J.C. Li (HUST), M. Li (HUST), N.C. Logan (PPPL), J.K. Park (PPPL), C. Paz-Soldan (GA), B. Rao (HUST), P. Shi (HUST), K.X. Yu (HUST), Q. Yu (IPP), G. Zhuang (USTC)

**Graduate and Post-doctoral Advisors:**
Q. Yu (IPP), X.W. Hu (HUST), R. Nazikian (PPPL)

**Graduate and Post-doctoral Advisees:**
D.J. Guo (HUST), C.S. Shen (HUST)

# Caoxiang Zhu (PPPL)

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**Education and Training:**

- Eng.D. - Nuclear Science and Technology, University of Science and Technology of China (2018)
- B.E. - Nuclear Engineering and Technology, University of Science and Technology of China (2012)
-

**Research and Professional Experience:**

- Associate Research Physicist, Princeton Plasma Physics Laboratory, USA (2018 - )
  - Develop tools for directly identifying dangerous error fields caused by coil perturbations;
  - Explore novel designs for new stellarator configurations, including searching the optimal aspect ratio quasi-axisymmetric stellarators, stellarator designs using permanent magnets.
  - Optimize non-axisymmetric coils for Tokamaks using FOCUS and REGCOIL.
- Visiting Research Scholar, Princeton Plasma Physics Laboratory, USA (2015 - 2017)
  - Developed a new stellarator coil design code FOCUS using fully 3D representations and applying fast, robust optimization algorithms ;
  - Demonstrated coil optimizations for existing stellarators and investigated coil solutions for the next generation stellarators designs, including LHD-like, HSX-like and CNT-like machines;
  - Introduced a new approach to analyze the coil sensitivities on error fields using the eigenvalues and eigenvector of the Hessian matrix;
  - Modified FOCUS compatible to explore a unique method designing resonant magnetic perturbation (RMP) coils in DIII-D.
  -

**Publications:**


- C. Zhu, D. A. Gates, S. R. Hudson, H. Liu, Y. Xu, A. Shimizu, and S. Okamura, "Identification of dangerous error fields in stellarators using Hessian matrix method", arXiv: 1904.04147. (2019).
- S. R. Hudson, C. Zhu, D. Pfefferlé, and L. Gunderson, "Differentiating the shape of stellarator coils with respect to the plasma boundary", Phys. Lett. A. **382**, 2732 (2018).
- C. Zhu, S. R. Hudson, S. A. Lazerson, Y. Song, and Y. Wan, "Hessian matrix approach for determining error field sensitivity to coil deviations", Plasma Phys. Control. Fusion **60**, 054016 (2018).
- C. Zhu, S. R. Hudson, Y. Song, and Y. Wan, "Designing stellarator coils by a modified Newton method using FOCUS", Plasma Phys. Control. Fusion **60**, 065008 (2018).
- C. Zhu, S. R. Hudson, Y. Song, and Y. Wan, "New method to design stellarator coils without the winding surface", Nucl. Fusion **58**, 016008 (2018).
- C. Zhu, J. Zheng, X. Liu, L. Wang, and R. Kang, "Electromagnetic and mechanical analysis of CFETR toroidal field coils", Fusion Eng. Des. **101**, 9 (2015).
- L. Wang, J. Zheng, J. Hao, F. Jiang, and C. Zhu, "Evaluations of CFETR ripple and optimization analyses of ferromagnetic inserts", Fusion Eng. Des. **100**, 513 (2015).
- J. X. Zheng, Y. T. Song, X. F. Liu, J. G. Li, Y. X. Wan, B. N. Wan, M. Z. Lei, C. X. Zhu, R. Kang, and S. U. Khan, "Conceptual design of the CFETR toroidal field superconducting coils", IEEE Trans. Appl. Supercond. **25,** 1 (2015).

**Collaborators and Co-editors:**
S. R. Hudson (PPPL), Y. Wan (USTC), Y. Song (ASIPP), D. A. Gates (PPPL), J. Zheng (ASIPP), L. Wang (USTC), S. A. Lazerson (PPPL), H. Liu (SWJTU), Y. Xu (SWJTU), A. Shimizu (NIFS), S. Okamura (NIFS).

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**Education and Training:**

- University of Texas at Austin, Doctor of Philosophy in Physics, 1984
- University of Texas at Dallas, Master of Science in Physics, 1979
- Wright State University, Bachelor of Science in Physics *(with honors)*, 1978
- Wright State University, Bachelor of Science in Engineering, 1978

**Research and Professional Experiences:**

- Senior Technical Advisor, Scientist IX, GA, October 2015 – present: International Collaborations leader on 3D physics, resistive MHD simulation studies and experimental research in tokamaks, stellarators and heliotorns.
- Senior Technical Advisor, Scientist VIII, GA, September 2011 – October 2015. Leader of the General Atomics International Collaborations Activities on the 3D Physics, ELM Control and Stochastic Boundary physics in tokamaks, stellarators and heliotorns.
- Senior Staff Scientist VII, GA, September 2006 – September 2011. Project leader for joint experiments on RMP ELM suppression with off-axis non-axisymmertic perturbation coils within the ITPA Pedestal Topical Group.
- Principal Scientist VI, GA, August 2002 – September 2006// Staff Scientist V, GA, August 1990 – August 2002// Associate Staff Scientist, GA, April 1988 – August 1990. Served as the Tore Supra Ergodic Divertor Program leader// Senior Scientist, GA, February 1985 – April 1988.
- Concurrently Held Research Position: Invited Visiting Senior Scientist - KFA Forschungszentrum, Institut für Plasmaphysik, TEXTOR, Jülich GmbH, Germany, January-March 1996.
- Post Doctoral Research Experience: Research Fellow, Fusion Research Center, University of Texas at Austin, 1984 – 1985.
- Teaching Experience: Invited Distinguished Visiting Professor, Heinrich-Heine-Universität, Düsseldorf, Germany, January-March 1996

**Selected Publications:**

- T. E. Evans and the DIII-D Team, “Suppression and mitigation of edge localized modes in the DIII-D tokamak with 3D magnetic perturbations” Plasma and Fusion Research **7** (2012) 2402046.
- T. E. Evans, A. Wingen and K. H. Spatschek, “A conceptual model for the nonlinear dynamics of edge localized modes in tokamak plasmas”, in Nonlinear Dynamics, Ed. T. E. Evans, ISBN: 978-953-7619-61-9, In-Tech Press, Vienna (2010).
- T. E. Evans “Implications of topological complexity and Hamiltonian chaos in the edge magnetic field of toroidal fusion plasmas”, in Chaos, Complexity and Transport: Theory and Applications, Ed.Cristel Chandre, Xavier Leoncini and George Zaslavsky, World Scientific Press, May 2008, pp 147-176.
- T. E. Evans, M. E. Fenstermacher, R. A. Moyer, T. H. Osborne, J. G. Watkins, P. Gohil, I. Joseph, M. J. Schaffer, L. R. Baylor, M. Bécoulet, et al., “RMP ELM suppression in DIII-D plasmas with ITER similar shapes and collisionalities”, Nucl. Fusion **48** (2008) 024002.
- T. E. Evans, R. A. Moyer, K. H. Burrell, M. E. Fenstermacher, I. Joseph, A. W. Leonard, T. H. Osborne, G. D. Porter, M. J. Schaffer, P. B. Snyder, et al., “Edge stability and transport control with resonant magnetic perturbations in collisionless tokamak plasmas”, Nature Physics **2** (2006) 419-23 (doi: 10.1038/nphys312), cover article.

- T. E. Evans, K. H. Burrell, M. E. Fenstermacher, R. A. Moyer, T. H. Osborne, M. J. Schaffer, W. P. West, L. W. Yan, J. A. Boedo, E. J. Doyle, et al., “The physics of edge resonant magnetic perturbations in hot tokamak plasmas”, Phys. of Plasmas **13** (2006) 056121.
- T. E. Evans, R. A. Moyer, J. G. Watkins, T. H. Osborne, P. R. Thomas, M. Becoulet, J. A. Boedo, M. E. Fenstermacher, K. H. Finken, R. J. Groebner, et al, “Suppression of large edge localized modes with edge resonant magnetic fields in high confinement DIII-D plasmas”, Nucl. Fusion **45** (2005) 595.
- T. E. Evans, R. K. W. Roeder et al.,“Experimental signatures of homoclinic tangles in poloidally diverted tokamaks”, J. Phys.: Conf. Ser. **7** (2005) 174.
- T. E. Evans, R. A. Moyer, P. R. Thomas, J. G. Watkins, T. H. Osborne, J. A. Boedo, E. J. Doyle, M. E. Fenstermacher, K. H. Finken et al., “Suppression of large edge-localized modes in high-confinement DIII-D plasmas with a stochastic magnetic boundary”, Phys. Rev. Lett. **92** (2004) 235003-1.
- T. E. Evans, R. K. W. Roeder, J. A. Carter and B. I. Rapoport, “Homoclinic tangles, bifurcations and stochasticity in poloidally diverted tokamaks”, Contrib. Plasma Phys. **44** (2004) 235.

**Synergistic Activities:**
Stochasticity in Fusion Plasmas Program Committee (1999 to 2009), TTF Executive Committee (2010 to date) and ADAS - atomic data Steering Committee (1999 to date), IAEA Nuclear Fusion Prize (2008), APS Fellow (2009) and John Dawson Award for Excellence in Plasma Physics (2018), The New York Academy of Sciences (elected in 1985).

**Collaborators and Co-editors:**
Abrams T (GA), Ahn JW (ORNL), Austin ME (U. Texas), Barr J (GA), Baylor LR (ORNL), Becoulet M (CEA Cadarache), Belli E (GA), Bortolon A (PPPL), Burrell KH (GA), Buttery R (GA), Bykov I (UCSD), Campbell DJ (ITER), Caldas I (U. Sao Paulo), Canal G (U. Sao Paulo), Canik J (ORNL), Chen X (GA), Chrystal C. (GA), Ciro D (Federal U. Parana), Cui L (PPPL), Davis E (MIT), Du X (GA), Eidietis N (GA), Eldon D (GA), Fenstermacher M (LLNL(, Ferraro N (PPPL), Frerichs H (U. Wisconsin), Garofalo A (GA), Gohil P (GA), Goldston RJ (PPPL), Gofinopoulos T (MIT), Gong X (IPP Hefei), Greenfield CM (GA), Grierson B (PPPL), Groebner RJ (GA), Gu S (IPP Hefei), Guo W (IPP Hefei), Haskey S (PPPL), Hirshman S (ORNL), Hollmann E (UCSD), Hu Q (PPPL), Hubbard A (MIT), Hughes J (MIT), Humphreys D (GA), Ida K. (NIFS), Jai M (IPP Hefei), Jeon Y (NFRI), Kaye S (PPPL), Kobayashi T (NIFS), Knolker M (Ludwig Maximilians U), Ko W (NFRI), Koleman E (PPPL), Kriete M (U Wisconsin), LaBombard B (MIT), Laggner F (PPPL), La Haye RJ, (GA) Lao LL (GA), Lasnier CJ (LLNL), Lee J (UCLA), Leonard AW (GA), Liu Y (GA), Loarte A (ITER), Logan N (PPPL), Lore J (ORNL), Luce TC (GA), Lyons, B. (GA), McKee G (U. Wisconsin), Maingi R (PPPL), Makowski MA (LLNL), Manard JE (PPPL), Mansfield D (PPPL), Marinoni A (MIT), Meneghini O (GA), Mordijck S (W&M), Moyer RA (UCSD), Munarreto S. (GA), Nam Y (NFRI), Nazikian RM (PPPL), Oh Y (NFRI), Ohdachi S (NIFS), Ono M (NIQ&RS&T Naka), Orlov DM (UCSD), Osborne TH (GA), Park YS (Columbia U.), Parks PB (GA), Paz-Soldan C (GA), Sun Y (IPP Hefei), Petrie TW (GA), Petty C (GA), Pinsker R (GA), Rhodes T (UCSD), Sabbagh SA (Columbia U.), Schmitz L (UCLA), Schmitz O (U. Wisconsin), Scott S (PPPL), Shafer MW (ORNL), Shi T (IPP Hefei), Shiraki D (ORNL), Sieglin (MPI Garching), Snyder PB (GA), Solomon WM (PPPL), Stacey WM (Georgia Tech.), Strait EJ (GA), Suzuki Y (NIFS), Taylor TS (GA), Teklu A (Oregon State U.), Trevisan G (ORAU), Turco F (Columbia U), Tynan GR (UCSD), Unterberg EA (ORNL), Van Zeeland M (GA), Viana R (Federal U. Parana), Wade MR (GA), Wali N (Zhejiang U ), Wang C (Zhejiang U ), Wang H (GA), Wang HH (IPP Hefei), Wang HQ (ORAU), Watkins J (Sandia N L), Weisberg D (GA), Wilcox R (ORNL), Wilson H (U York), Wingen A (ORNL), Wu W (GA), Yoon SW (NFRI), Xiao W (Zhejiang U), Zeng L (UCLA), Zhu Y (UCI), Zohm H (MPI Garching).

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**Education and Training:**

- B.S., Mathematics, Moscow State University, 1994
- M.Sc., Applied Mathematics and Informatics, Moscow State University, 1996
- Ph.D., Physics and Mathematics, Moscow State University, 1999

**Research and Professional Experiences:**

- 2017-present Scientist VII General Atomics
- 2015-2017 Senior Plasma Physicist VI* CCFE
- 2008-2015 Senior Fusion Theorist VI CCFE
- 2008-2017 Adjunct Professor Chalmers University of Technology
- 2003-2008 Associate Professor Chalmers University of Technology
- 2000-2003 Assistant Professor Chalmers University of Technology
- 1999-2000 Postdoctoral Fellow Chalmers University of Technology

**Selected Publications:**


- Yueqiang Liu, A. Kirk, Li Li, Y. In, R. Nazikian, Youwen Sun, W. Suttrop, B. Lyons, D. Ryan, Shuo Wang, Xu Yang, Lina Zhou, and the EUROfusion MST1 team, “Comparative investigation of ELM control based on toroidal modelling of plasma response to RMP fields”, Phys. Plasmas **24**, 056111 (2017)
- Yueqiang Liu, C.J. Ham, A. Kirk1, Li Li, A. Loarte, D.A. Ryan, Youwen Sun, W. Suttrop, Xu Yang, Lina Zhou, “ELM control with RMP: plasma response models and the role of edge peeling response”, Plasma Phys. Control. Fusion **58**, 114005 (2016)
- Yueqiang Liu, R. Akers, I.T. Chapman, Y. Gribov, G.Z. Hao, G.T.A. Huijsmans, A.Kirk, A. Loarte, S.D. Pinches, M. Reinke, D. Ryan, Y. Sun, Z.R. Wang, “Modelling toroidal rotation damping in ITER due to external 3D fields”, Nucl. Fusion **55**, 063027 (2015)
- Yueqiang Liu, A. Kirk, Y. Sun, P. Cahyna, I.T. Chapman, P. Denner, G. Fishpool, A.M. Garofalo, J.R. Harrison, E. Nardon, and the MAST team, “Toroidal modelling of plasma response and RMP field penetration”, Plasma Phys. Control. Fusion **54**, 124013 (2012)
- Yueqiang Liu, Y. Gribov, M.P. Gryaznevich, T.C. Hender, A. Kirk, E. Nardon, “Modelling of plasma response to RMP fields in MAST and ITER”, Nucl. Fusion **51**, 083002 (2011)
- Yueqiang Liu, A. Kirk, and E. Nardon, “Full toroidal plasma response to externally applied non-axisymmetric magnetic fields”, Phys. Plasmas **17**, 122502 (2010)
- Yueqiang Liu, M.S. Chu, I.T. Chapman and T.C. Hender, “Toroidal self-consistent modelling of drift kinetic effects on the resistive wall mode”, Phys. Plasmas **15**, 112503 (2008)
- Yueqiang Liu, A. Bondeson, Y. Gribov, A. Polevoi, "Stabilization of resistive wall modes in ITER by active feedback and toroidal rotation", Nucl. Fusion **44**, 232 (2004)
- Y.Q. Liu, A. Bondeson, C. M. Fransson, B. Lennartson, and C. Breitholtz, "Feedback stabilization of non-axisymmetric resistive wall modes in tokamaks. Part 1: electromagnetic model", Phys. Plasmas **7**, 3681 (2000)
- Y.Q. Liuand A. Bondeson, "Active feedback stabilization of toroidal external modes in tokamaks", Phys. Rev. Lett. **84**, 907 (2000)

**Synergistic Activities:**

- 2015-present Coordinator of ITPA TC 24 on 3D plasma response
- 2014-present Deputy leader of IPTA MHD MDC-21 on Global mode stabilization physics and control
- 2011-2014 Leader of ITPA MHD Working Group W7 on RWM control in ITER
- 2000 Invited visitor to Princeton Plasma Physics Laboratory

**Collaborators and Co-editors:**

Z.R. Wang, J. Menard, J.K. Park, R. Nazikia, M. Okabayashi (PPPL), R. La Haye, E. Strait, L. Lao (GA), A. Kirk, R. Akers, J. Connor, J. Hastie, T.C. Hender, C. Ham, L. Piron, S. Sareelma, I.T. Chapman, D. Ryan (CCFE), S. Sabbagh, J. Berkery (CU), W. Suttrup, V. Igochine (IPP), Y. Sun, Y. Liang, H. H. Wang (AS-IPP), H. D. He, S. Wang, N. Zhang, X. Bai, G. Q. Dong (SWIP), L. LI, F. C. Zhong (Donghua U.), Y. In (NFRI), G. Z. Hao (UCI), P. Piovesan, M. Gobbin, T. Bozenella (RFX), A. Loarte, A. Polevoi, Y. Gribov, S. Pinches (IO)

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**Education and Training:**

- University of Wisconsin-Madison, Physics, PhD, 2016
- University of Wisconsin-Madison, Physics, Masters, 2012
- Duke University, Physics, BS, 2009

**Research and Professional Experiences:**

- Scientist IV, General Atomics, 2017-present
- Postdoctoral researcher, Oak Ridge Associated Universities, 2016-2017
- Research assistant, University of Wisconsin-Madison Dept. of Physics, 2010-2016
- Teaching assistant, University of Wisconsin-Madison Dept. of Physics, 2009-2010
- Research assistant, Duke University Dept. of Physics, 2008-2009
- Research assistant, University of Pittsburgh Dept. of Microbiology & Molecular Genetics, 2005-2006

**Selected Publications:**

- **DB Weisberg**, C Paz-Soldan, Y Liu, N Logan, "Optimizing multi-modal, non-axisymmetric plasma response metrics with additional coil rows on DIII-D" Nuclear Fusion (pre-print, 2019)
- **DB Weisberg**, E Peterson, J Milhone, D Endrizzi, C Cooper, V Desangles, I Khalzov, R Siller, CB Forest, "Driving large magnetic Reynolds number flows in highly ionized, unmagnetized plasmas" Physics of Plasmas **24**, 056502 (2017)
- CM Cooper, **DB Weisberg**, I Khalzov, J Milhone, K Flanagan, E Peterson, C Wahl, CB Forest, "Direct measurement of the plasma loss width in an optimized, high ionization fraction, magnetic multi-dipole ring cusp" Physics of Plasmas **23**, 102505 (2016)
- CB Forest, K Flanagan, M Brookhart, M Clark, CM Cooper, V Desangles, J Egedal, D Endrizzi, IV Khalzov, H Li, M Miesch, J Milhone, M Nornberg, J Olson, E Peterson, F Roesler, A Schekochihin, O Schmitz, R Siller, A Spitzkovsky, A Stemo, **DB Weisberg**, E Zweibel, "The Wisconsin plasma astrophysics laboratory" Journal of Plasma Physics **81** 5 (2015)
- CM Cooper, J Wallace, M Brookhart, M Clark, C Collins, WX Ding, K Flanagan, I Khalzov, Y Li, J Milhone, M Nornberg, P Nonn, **DB Weisberg**, DG Whyte, E Zweibel, CB Forest, "The Madison plasma dynamo experiment: A facility for studying laboratory plasma astrophysics" Physics of Plasmas **21**, 013505 (2014)
- IV Khalzov, BP Brown, CM Cooper, **DB Weisberg**, CB Forest, "Optimized boundary driven flows for dynamos in a sphere" Physics of Plasmas **19**, 112106 (2012)

**Synergistic Activities:**

- Participant in US Burning Plasma Organization (USBPO) Outreach planning (2018-present)
- Participant in Early Career Fusion Scientists (ECFS) forum, providing input to NAS committee on a Strategic Plan for US Burning Plasma Research (2017-present)
- Participant in US Magnetic Fusion Research (MFR) Strategic Directions workshops (2017)

**Collaborators and Co-editors:**

R.J. Buttery, A.M. Garofalo, E. Strait, Y.Q. Liu, B. Lyons, S. Munaretto, M. VanZeeland, A. Turnbull (General Atomics), J.-K. Park, N.C. Logan, R. Nazikian, J.-M. Park (PPPL), D. Shiraki, M.W. Shafer, B.

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**Education and Training:**

- Physics (PhD), University Düsseldorf, Germany, 2006
- Plasma Physics (Post Doctoral Researcher), Research Center Juelich, Germany, 2006-2008
- Plasma Physics (Habilitation), University Düsseldorf, Germany, 2013

**Research and Professional Experience:**

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| since 06/2018 | Professor University of Wisconsin - Madison, USA<br>Research on 3D edge physics, plasma surface interaction, helicon physics for AWAKE project at CERN, active spectroscopy |
| 06/2017 - 06/2018 | Associate Professor University of Wisconsin - Madison, USA<br>Research on 3D edge physics, plasma surface interaction, helicon physics, active spectroscopy |
| 03/2014 - 06/2017 | Assistant Professor University of Wisconsin - Madison, USA<br>Research on 3D edge physics, helicon physics, active spectroscopy |
| 01/2013 - 03/2014 | Privatdozent University Duesseldorf, Germany<br>Lectures on plasma edge transport and plasma wall interaction |
| 02/2012 - 03/2014 | Group Leader Research Center Juelich, Germany<br>Responsible for collaboration with W7-X stellarator |
| 02/2010 - 01/2012 | Senior Staff Scientist Research Center Juelich, Germany<br>3D edge transport, impurity and neutral transport |
| 09/2008 - 01/2010 | Staff Scientist Research Center Juelich, Germany<br>Research on 3D plasma wall interaction, spectroscopy |
| 06/2006 - 08/2008 | Post Doctoral Research Research Center Juelich, Germany<br>Post-doctoral work on 3D plasma edge transport |

**Selected Publications:**

- J. Green, O. Schmitz, G. Severn, N.Hershkowitz, “Exploiting Zeeman effect symmetries to measure ion flows in magnetized plasmas”, Measurement Science and Technology (2019), at press.
- M. Griener, J.M. Muñoz Burgos, M. Cavedon, G. Birkenmeier, R. Dux, B. Kurzan, O. Schmitz, B. Sieglin, U. Stroth, E. Viezzer, E. Wolfrum, and the ASDEX Upgrade Team, “Qualification and implementation of line ratio spectroscopy on helium as plasma edge diagnostic at ASDEX Upgrade”, Plasma Physics and Controlled Fusion, **60**(2):025008, 2018.
- I. Waters, H. Frerichs, S. Silburn, Y. Feng, J. Harrison, A. Kirk, and O. Schmitz, “Field aligned flows driven by neutral puffing at MAST”, Nuclear Fusion, 58(6):066002, 2018.
- T. Barbui, M. Krychowiak, R. König, O. Schmitz, J. M. Muñoz Burgos, B. Schweer, and A. Terra. “Feasibility of line-ratio spectroscopy on helium and neon as edge diagnostic tool for Wendelstein 7-X”, Review of Scientific Instruments, **87**(11):11E554, 2016.
- K. Flesch, T. Kremeyer, O. Schmitz, V. Soukhanovskii, and U. Wenzel. “Development of miniaturized, spectroscopically assisted Penning gauges for fractional helium and hydrogen neutral pressure measurements”, Review of Scientific Instruments, **87**(11):11E529, 2016.
- O Schmitz, I L Beigman, L A Vainshtein, B Schweer, M Kantor, A Pospieszczyk, Y Xu, M Krychowiak, M Lehnen, U Samm, B Unterberg, and the TEXTOR team. “Status of electron

temperature and density measurement with beam emission spectroscopy on thermal helium at TEXTOR". Plasma Physics and Controlled Fusion, **50**(11):115004, 2008.

- O. Schmitz, M. Becoulet, P. Cahyna, T.E. Evans, Y. Feng, H. Frerichs, A. Loarte, R.A. Pitts, D. Reiser, M.E. Fenstermacher, D. Harting, A. Kirschner, A. Kukushkin, T. Lunt, G. Saibene, D. Reiter, U. Samm, and S. Wiesen. "Three-dimensional modeling of plasma edge transport and divertor fluxes during application of resonant magnetic perturbations on ITER". Nuclear Fusion, **56**(6):066008, 2016
- O. Schmitz, K. Ida, M. Kobayashi, A. Bader, S. Brezinsek, T.E. Evans, H. Funaba, M. Goto, O. Mitarai, T. Morisaki, G. Motojima, Y. Narushima, D. Nicolai, H. Tanaka, M. Yoshinuma, Y. Xu, the TEXTOR, and LHD experiment teams. "Enhancement of helium exhaust by resonant magnetic perturbations at TEXTOR and LHD". Nuclear Fusion, **56**(10):106011, 2016
- H. Frerichs, O. Schmitz, I. Waters, G. Canal, T.E. Evans, Y. Feng, and V.I. Soukhanovskii. "Exploration of magnetic perturbation effects on advanced divertor configurations at NSTX-U", Physics of Plasmas, **23**(062517), 2016
- O. Schmitz, T.E. Evans, M.E. Fenstermacher, M. Lehnen, H. Stoschus, E.A. Unterberg, J.W. Coenen, H. Frerichs, M.W. Jakubowski, R. Laengner, C.L. Lasnier, S. Mordijck, R.A. Moyer, T.H. Osborne, H. Reimerdes, D. Reiter, U. Samm, B. Unterberg, and the DIII-D and TEXTOR teams. "Resonant features of energy and particle transport during application of resonant magnetic perturbation fields at TEXTOR and DIII-D". Nuclear Fusion, **52**(4):043005, 2012.

**Selected synergistic activities:**
• Associate member of AWAKE project at CERN, Geneva, Switzerland
• Science Fellow of the ITER Organisation, Cadarache, France
• Plasma Science outreach activity for high-school students and teachers (NSF-CAREER grant)
• U.S. member of the International Tokamak Physics Activity (ITPA), Plasma Edge and Divertor (DSOL)
• Member of American Physics Society (APS) and of the German Physics Society (DPG)

**Collaborators and co-editors:**
E. Gschwendter, A. Caldwell, P. Muggli (AWAKE), B. Buntenschoen, Y. Feng, O. Grulke, M. Jakubowski (IPP, Germany), T.E.Evans, M. Lanctot, P. Snyder. M. Wade (GA), D.T. Anderson, C. Hegna, A. Bader, R. Fonck, C. Forest, J. Sarff (UW), E.A. Unterberg, C.C.Klepper (ORNL), A. Loarte, R. Pitts (IO, France), M. Becoulet (CEA, France), M.E.Fenstermacher, H. A. McLean, C. Lasnier, I. Joseph (LLNL) H. Reimerdes (EPFL, Switzerland), R. Nazikian, J. Munoz-Burgos (PPPL), R. Moyer, D. Orlov, J. Boedo (UCSD), S. Mordijk (CW&M), S. Brezinsek, D. Reiter (FZJ, Germany), J.G. Watkins (Sandia NL)

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**Education and Training:**

- Ph.D. Aerospace and Mechanical Engineering, University of Notre Dame, Notre Dame, Indiana, 2007
- M.S.A.E. Aerospace and Mechanical Engineering, University of Notre Dame, Notre Dame, Indiana, 2005
- M.S. Applied Physics and Mathematics, Moscow Institute of Physics and Technology, Zhukovsky, Russia, 1998 (w/honors)
- B.S. Applied Physics and Mathematics, Moscow Institute of Physics and Technology, Zhukovsky, Russia, 1998 (w/honors)

**Research and Professional Experience:**

- 2017–pres. Associate Project Scientist, Center for Energy Research, UC San Diego
- 2011–2017 Assistant Project Scientist, Center for Energy Research, UC San Diego
- 2008–2011 Post-doctoral Researcher, Center for Energy Research, UCSD
- 2006–2008 Research Associate, Department of Physics, US Air Force Academy
- 2000–2006 Graduate Research Assistant, Aerospace and Mechanical Engineering, University of Notre Dame

**Selected Publications:**

- Orlov D.M., Moyer R.A., Bykov I.O., Evans T.E., Teklu A.M., Lee J., Loarte A., Fenstermacher M.E., Lasnier C.S., Watkins J.G., Wang H., Leonard A., "Favorable Impact of RMP ELM Suppression On Divertor Heat Fluxes at ITER-like Conditions", 27th IAEA Fusion Energy Conference, Ahmedabad, India, 22-27 October 2018
- Orlov D.M., Evans T.E., Moyer R.A., Lyons B.C., Ferraro N.M., and Park G.-Y., "Perturbation coil geometry effects on spectral sideband generation and MHD response in DIII-D and KSTAR", Plasma Physics and Controlled Fusion, **58** (2016) 075009
- Orlov D.M., Moyer R.A., Evans T.E., Paz-Soldan C., Ferraro N.M., Nazikian R., deGrassie J.S., Grierson B.A., Eldon D., Fenstermacher M.E., King J.D., Logan N.C., Lanctot M.J., Maingi R., Snyder P.B., Strait E.J., and Wingen A., "Suppression of Type-I ELMs with reduced RMP coil set on DIII-D", Nuclear Fusion, **56**, 2016, 036020
- Nazikian R., Paz-Soldan C., deGrassie J.S., Eldon D., Evans T.E., Ferraro N.M., Grierson B.A., Groebner R.J., Haskey S.R., Hegna C., King J.D., Logan N.C., McKee G.R., Moyer R.A., Okabayashi M., Orlov D.M., Osborne T.H., Park J.-K., Rhodes T.L., Shafer M.W., Snyder P.B., Solomon W.M., Strait E.J., Wade M.R., "Pedestal Bifurcation and Resonant Field Penetration at the Threshold of ELM Suppression in the DIII-D Tokamak", Physical Review Letters **114** 105002, 2015
- Meneghini O., Smith S.P., Lao L.L., Izacard O., Ren Q., Park J.-M., Candy J., Wang Z., Luna C., Grierson B.A., Snyder P.B., Holland C., Penna J., Lu G., Raum P., McCubbin A., Orlov D.M., Belli E.A., Ferraro N.M., Prater R., Osborne T.H., Turnbull A.D., Staebler G.M., and the ATOM team, "Integrated Modeling of Tokamak Experiments with OMFIT", Nuclear Fusion, **55**, 2015, 083008
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**Synergistic Activities:**

- UCSD Center for Energy Research Outreach Committee, Member, 2015 – present
- UCSD Center for Energy Research Diversity Committee, Member, 2016 – present
- ITER ITPA Pedestal and Edge Physics Topical Group, Expert, 2014 – present
- U.S. Transport Task Force, Executive Committee member, 2018 – present
- U.S. Transport Task Force, 3D Fields Working Group leader/chair, 2017 – present

**Collaborators and Co-editors:**

Becoulet M (CEA Cadarache), Boedo JA (UCSD), Brooks, JN (Purdue), Buttery RJ (GA), Bykov IO (UCSD), Candy J (GA), Chang C.S. (PPPL), Chapman IT (CCFE), Corke TC (Notre Dame), Dorf M. (LLNL), Elder D. (U. Toronto), Evans TE (GA), Fenstermacher ME (LLNL), Ferraro NM (PPPL), Font GI (Lockheed Martin), Grierson BA (PPPL), Groebner RJ (GA), Holland C (UCSD), Hollmann EM (UCSD), Jardin S. (PPPL), Kalling RC (Kalling Software), Lao LL (GA), Lasnier CJ (LLNL), Leonard AW (GA), Loarte A (ITER), Lyons BC (ORNL), Maingi R (PPPL), Meneghini O (GA), Mordijck S (William and Mary), Nazikian RM (PPPL), Nogami S (WVU), Osborne TH (GA), Paz-Soldan C (GA), Rhodes TL (UCLA), Ronglien T. (LLNL), Rudakov DL (UCSD), Shafer M (ORNL), Smith SP (GA), Snyder PB (GA), Stangeby P. (U. Toronto), Stotler D. (PPPL), Sun Y. (ASIPP), Sugiyama L (MIT), Umansky M. (LLNL), Wade MR (GA), Watkins JG (SNL), Wingen A (ORNL), Wu W (GA)

**Graduate and Post-doctoral advisors and advisees:**

Corke TC (Notre Dame), Bashkin VA (MIPT), Egorov IV (MIPT), Moyer RA (UCSD), McHarg MG (USAFA)

Appendix 2. Current and Pending Support

# Jong-Kyu Park (Lead PI, PPPL)

**Current Support:**

**Sponsor:** Department of Energy, Office of Fusion Energy Sciences (OFES)
**Project**: National Spherical Torus Experiment Upgrade (NSTX-U) – Research
**Award Number:** FWP #1100
**Award Amount:** $9,000,000 for FY19
**Period of Performance**: Funded annually
**Annual Level of Effort:** 5.5 Months
**Research Description:** NSTX-U is a major U.S. facility designed to study the physics of fusion plasmas magnetically confined in a very low aspect-ratio Spherical Torus (ST) configuration. This unique NSTX-U characteristic allows the achievement of a high plasma pressure relative to that of the applied magnetic field and complements the tokamak in addressing the overarching issues in magnetic fusion energy science, encompassing macroscopic MHD stability, turbulence and transport, wave-particle interactions, solenoid-free current generation and sustainment of magnetic flux, and the plasma interface with its surrounding environment. The unique operating regimes of NSTX-U provide high leverage to address several important issues in the physics of burning plasmas to optimize the performance of ITER. The NSTX-U program further aims to determine the attractiveness of the compact ST for addressing key research needs on the path toward a fusion demonstration power plant (DEMO).

**Sponsor:** Department of Energy, Office of Fusion Energy Sciences (OFES)
**Project:** PPPL Participation in the National DIII-D Research Program
**Award Number:** FWP #1050
**Award Amount**: $4,342,000 Received in FY2019
**Period of Performance:** Funded Annually
**Annual Level of Effort:** 3.6 Months
**Research Description:** PPPL contributes to the DIII-D research program in three key research areas central to the strategic mission of the DIII-D program which include the following: 3D fields and MHD stability, scenario development and control, and core-edge integration.

**Sponsor:** Department of Energy, Office of Fusion Energy Sciences (OFES)
**Project:** 3D Field and Coil Optimization in KSTAR
**Award Number:** FWP #1017
**Award Amount:** $375,000
**Period of Performance:** August 15, 2018 – August 14, 2020
**Annual Level of Effort:** 1.2 Months
**Research Description:** The aim of the research is to apply the advanced 3D simulation tools developed in the US, such as GPEC at PPPL, on the superconducting - KSTAR tokamak to optimize low-n 3D perturbations for robust and stable long pulse operation.

**Princeton University** supports approximately 1.7 months of Dr. Park's time to teach one semester course each academic year.

## Pending Support:

**Sponsor:** Department of Energy, Office of Fusion Energy Sciences (OFES)
**Project:** Physics Basis, Optimization, and Control for Integrated 3D Edge Long-pulse Tokamak Scenarios
**Award Amount:** $1,937,200
**Period of Performance:** September 1, 2019 – August 31, 2022
**Annual Level of Effort:** 2.2 Months
**Research Description:** This collaborative project aims to leverage the unique research capabilities of international tokamak facilities, AUG, EAST, and KSTAR, to develop the unified physics basis and predictive capabilities for the control of edge localized modes (ELMs) with optimized non-axisymmetric 3D fields.

**Sponsor:** Department of Energy, Office of Fusion Energy Sciences (OFES)
**Project:** Spherical Tokamak Physics Research on ST40
**Award Amount:** $2,539,100
**Period of Performance:** July 1, 2019 – June 30, 2022
**Annual Level of Effort:** 1.6 Months
Research Description: The goal of this project is to collaborate with the high-field ST40 spherical tokamak in the United Kingdom on different physics aspects, such as transport and confinement, pedestal and boundary physics, energetic particles physics, and RF physics. Studies in ST40 of plasma and energetic particle stability and confinement in both the core and edge regions of the plasma, as well as the studies of plasma exhaust properties, complement existing or planned DOE-funded programs on NSTX-U, MAST-U and other STs.

# Carlos Paz-Soldan (Co-Lead PI, GA)

## Current Support:

**Activity/Award Sponsor or Source of Funding:** DOE
**Activity/Award Number**: DE-FC02-04ER54698
**Sponsored Activity/Award Title:** DIII-D / Capital / Collaboration / AFT
**Total Activity/Award Cost/Value:** $906,354,246
**Award Period:** 01 November 2003 – 30 June 2019
**Person-Months Per Year Dedicated to the Activity/Award**: 5.8
**Description of Research:** Fusion research on the DIII-D tokamak.

**Activity/Award Sponsor or Source of Funding:** DOE
**Activity/Award Number:** DE-SC18992
**Sponsored Activity/Award Title:** 3D Response & Control on MAST-U Tokamak
**Total Activity/Award Cost/Value:** $1,923,366
**Award Period:** 01 July 2018 – 30 June 2021
**Person-Months Per Year Dedicated to the Activity/Award:** 2.0
**Description of Research:** Investigate plasma response and control in the presence of 3D magnetic field perturbations in the spherical tokamak MAST-U (Mega Amp Spherical Tokamak, upgraded).

**Activity/Award Sponsor or Source of Funding:** DOE
**Activity/Award Number:** DE-SC0016452
**Sponsored Activity/Award Title:** SciDAC Simulation Center for Runaway Electron Avoidance and Mitigation 2 (SCREAM 2)
**Total Activity/Award Cost/Value:** $1,376,000
**Award Period:** 15 July 2016 – 14 July 2022
**Person-Months Per Year Dedicated to the Activity/Award:** 0.6
**Description of Research:** Research in runaway electron avoidance and mitigation.

## Pending Support:

**Activity/Award Sponsor or Source of Funding:** DOE Office of Science, Office of Fusion Energy Sciences
**Activity/Award Number:** N/A
**Sponsored Activity/Award Title:** Physics Basis, Optimization, and Control for Integrated 3D Edge Long-pulse Tokamak Scenarios (20013314)
**Total Activity/Award Cost/Value:** TBD *(proposed: $1,200,354-GA budget)*
**Award Period:** 15 August 2019 – 14 August 2022 *(anticipated)*
**Person-Months Per Year Dedicated to the Activity/Award:** TBD *(estimated: 2.4)*
**Description of Research:** the proposed project will exploit the unique capabilities of international tokamaks to develop a common physical basis, predictive capability, and long-pulse demonstration for 3D-field integrated ELM-suppressed scenarios.

Activity/Award Sponsor or Source of Funding: DOE

Activity/Award Number: N/A

Sponsored Activity/Award Title: Disruption Mitigation Solutions For Long-Pulse Tokamaks (20012828)

Total Activity/Award Cost/Value: TBD *(proposed: $957,000-GA budget)*

Award Period: 15 August 2019 – 14 August 2022 *(anticipated)*

Person-Months Per Year Dedicated to the Activity/Award: TBD *(estimated: 0.5)*

Description of Research: the proposed project will provide an integrated package of modeling, diagnostic enhancement, and experimental benchmarking of SPI disruption mitigation experiments in the large Joint European Torus (JET) and superconducting long-pulse Korea Superconducting Tokamak Advanced Research (KSTAR), in order to further extend the physics understanding required to develop and deploy an effective disruption mitigation system on ITER and beyond. This project will exploit SPI systems recently installed or planned on those devices provided by USITER.

## Heinke Frerichs (PI, UW)

**Current Support:**

**Title:** Three dimensional equilibrium stability and its impact on edge transport and divertor performance in Wendelstein 7-X
**Agency:** U.S. Dept. of Energy, Office of Fusion Energy Sciences
**Grant number:** renewal for grant DE-SC0014210
**Award Period:** Aug. 17, 2018 – Aug. 16, 2021
**Total Award:** $1,198,827
**Annual Level of Effort:** 2 months
**Proposed Research:** Plasma edge physics in the W7-X stellarator, He beam and WISP gauges installed as well, synergistic expertise and analysis methods

**Title:** Three dimensional equilibrium stability and its impact on edge transport and divertor performance in Wendelstein 7-X
**Agency:** U.S. Dept. of Energy, Office of Fusion Energy Sciences
**Grant number:** DE-SC0014210 - Supplement 3
**Award Period:** Aug. 17, 2018 – Aug. 16, 2019
**Total Award:** $236,000
**Annual Level of Effort:** additional 2 months in FY19
**Proposed Research:** Plasma edge physics in the W7-X stellarator, He beam and WISP gauges installed as well, synergistic expertise and analysis methods

**Title:** Control of Neutral Fueling and Helium Exhaust to NSTX-U Plasmas by Means of Three-Dimensional Magnetic Control Fields.
**Agency:** U.S. Dept. of Energy, Office of Fusion Energy Sciences
**Grant number:** DE-SC0012315
**Award Period:** Aug. 15, 2014 – Aug. 14, 2018
**No cost extension:** Aug. 15, 2018 – Aug. 14, 2019 *(see supplement below)*
**Total Award:** $1,134,450
**Annual Level of Effort:** 3 months, **ended 08/2018**
**Proposed Research:** neutral exhaust studies at NSTX-U, grant not renewed

**Title:** Control of Neutral Fueling and Helium Exhaust to NSTX-U Plasmas by Means of Three-Dimensional Magnetic Control Fields.
**Agency:** U.S. Dept. of Energy, Office of Fusion Energy Sciences
**Grant number:** DE-SC0012315 - Supplement
**Award Period:** Aug. 15, 2014 – Aug. 14, 2018
**No cost extension:** Aug. 15, 2018 – Aug. 14, 2019
**Total Award:** $279,368
**Annual Level of Effort:** 5 months in FY19
**Proposed Research:** neutral exhaust studies at NSTX-U, grant not renewed

**<u>Pending support:</u>**

**Title:** Physics Basis, Optimization, and Control for Integrated 3D Edge Long-pulse Tokamak Scenarios
**Agency:** U.S. Dept. of Energy, Office of Fusion Energy Science, DE-FOA-00002076
**Grant number:** *this proposal*
**Award Period**: August 1, 2019 – July 31, 2022
**Total Award:** $573,361 for UW Madison contribution
**Annual Level of Effort:** 5 months

**Title:** Detachment Physics at High Power and Long Pulse
**Agency:** U.S. Dept. of Energy, Office of Fusion Energy Science, DE-FOA-00002076
**Grant number:** to be submitted
**Award Period:** August 1, 2019 – July 31, 2022
**Total Award:** $671,989 for UW Madison contribution
**Annual Level of Effort:** 5 months

**Title:** Enhanced plasma edge characterization for investigation of helicon wave coupling and neutral compression with the SAS divertor at the DIII-D U.S. National Fusion Facility
**Agency:** U.S. Dept. of Energy, Office of Fusion Energy Science, DE-FOA-0001974
**Grant number:** submitted
**Award Period:** August. 15, 2019 – August. 14, 2022
**Total Award:** $1,315,503
**Annual Level of Effort:** 4 months
**Proposed Research:** Installation of thermal helium beam and WISP gauge at DIII-D and divertor and 3D edge physics studies

# Zihong Lin (PI, UCI)

**Current Support:**

DOE, DE-SC0018270, $2,680,000, 9/1/2017-8/31/2022,
*SciDAC ISEP Center: Integrated Simulation of Energetic Particle in Burning Plasmas.*
PI committed 4 months of effort per year.

DOE, DE-FG02-07ER54916, $1,114,000, 1/1/2007-6/30/2019,
*Gyrokinetic Particle Simulations of Core Turbulence in Fusion Plasmas.*
PI committed 2 months of effort per year.

DOE, DE-SC0013804, $285,000, 7/1/2015-6/30/2019,
*Energetic Particle Transport in 3D Equilibrium.*
PI committed 2 months of effort per year.

TAE Technologies, TAE-50726, TAE-52989, TAE-101419, TAE-200441, $964,765, 1/1/2011-6/30/2019,
*Particle Simulation of turbulent transport in FRC.*
PI committed 2 months of effort per year.

**Pending Support:**

DOE, $671,403, 7/1/2019-6/30/2022,
Renewal of DE-FG02-07ER54916: *Gyrokinetic Particle Simulation of Plasma Transport in 3D Equilibrium.*
PI commits 3 months of effort per year.

DOE, $450,000, 9/1/2019-8/31/2022
*Physics Basis, Optimization, and Control for Integrated 3D Edge Long-pulse Tokamak Scenarios*
PI commits 1 month of effort per year.

## Egemen Kolemen (PI, PU)

**Current support:**

**Title:** Physics-Based Real-time Analysis and Control to Achieve Transient-Free Operations for the ITER Era
**Sponsor:** DOE
**Sponsor Award Number:** DE-SC0015878
**Period:** 7/15/2016 - 7/14/2021
**Amount:** $848,599
**Location:** Princeton University
**Person-months per Year:** 0.5 Summer Months

**Title:** Controlled Plasma-Catalytic Reactor for Conversion of Methane and CO2 to Methanol Using Vibrational Excitation
**Sponsor:** ExxonMobil Research and Engineering Co.
**Sponsor Award Number:** EM09125.A1.TO2
**Period:** 9/01/2016 - 8/31/2019
**Amount:** $361,000
**Location:** Princeton University
**Person-months per Year:** 0.0 Summer Months

**Title:** Real-time Electron Temperature and Density Profile Measurements for NSTX-U
**Sponsor:** DOE
**Sponsor Award Number:** DE-SC0015480
**Period:** 5/15/2016 - 5/14/2019
**Amount:** $648,052
**Location:** Princeton University
**Person-months per Year:** 0.75 Summer Months

**Pending Support:**

**Title:** Control of Plasma-Material Interface for Long-Pulse Optimization in Tokamaks
**Sponsor:** DOE
**Period:** 9/1/19 – 8/31/22
**Amount:** $330,000
**Location:** Princeton University
**Person-months per Year:** 0.5 Summer Months

**Title:** Optimization of Steady-State and ITER-Inductive Long-Pulse Scenarios in KSTAR
**Sponsor:** DOE
**Period:** 9/1/19 – 8/31/22

**Amount:** $750,000
**Location:** Princeton University
**Person-months per Year:** 1.0 Summer Months

**Title:** Physics Basis, Optimization, and Control for Integrated 3D Edge Long-Pulse Tokamak Scenarios
**Sponsor:** DOE
**Period:** 9/1/19 – 8/31/22
**Amount:** $776,554
**Location:** Princeton University
**Person-months per Year:** 1.0 Summer Months

**Title:** AI-Deep Learning for Plasma Behavior Prediction and Manipulation at KSTAR
**Sponsor:** DOE
**Period:** 9/1/19 – 8/31/22
**Amount:** $2,138,729
**Location:** Princeton University
**Person-months per Year:** 1.0 Summer Months

# Nikolas C. Logan (PPPL)

## Current Support:

**Sponsor:** Department of Energy, Office of Fusion Energy Sciences (OFES)
**Project:** PPPL Participation in the National DIII-D Research Program
**Award Number:** FWP #1050
**Award Amount:** $4,342,000 Received in FY2019
**Period of Performance**: Funded Annually
**Annual Level of Effort:** 10 Months
**Research Description:** PPPL contributes to the DIII-D research program in three key research areas central to the strategic mission of the DIII-D program which include the following: 3D fields and MHD stability, scenario development and control, and core-edge integration.

**Sponsor:** Department of Energy, Office of Fusion Energy Sciences (OFES)
**Project:** 3D Field and Coil Optimization in KSTAR
**Award Number:** FWP #1017
**Award Amount:** $375,000
**Period of Performance:** August 15, 2018 – August 14, 2020
**Annual Level of Effort:** 2 Months
**Research Description:** The aim of the research is to apply the advanced 3D simulation tools developed in the US, such as GPEC at PPPL, on the superconducting - KSTAR tokamak to optimize low-n 3D perturbations for robust and stable long pulse operation.

## Pending Support:

**Sponsor:** Department of Energy, Office of Fusion Energy Sciences (OFES)
**Project:** Physics Basis, Optimization, and Control for Integrated 3D Edge Long-pulse Tokamak Scenarios
**Award Amount:** $1,937,200
**Period of Performance:** September 1, 2019 – August 31, 2022
**Annual Level of Effort:** 1.8 Months
**Research Description:** This collaborative project aims to leverage the unique research capabilities of international tokamak facilities, AUG, EAST, and KSTAR, to develop the unified physics basis and predictive capabilities for the control of edge localized modes (ELMs) with optimized non-axisymmetric 3D fields.

# Todd E. Evans (GA)

## Current Support:

**Activity/Award Sponsor or Source of Funding:** DOE
**Activity/Award Number:** DE-FC02-04ER54698
**Sponsored Activity/Award Title:** DIII-D / Capital / Collaboration / AFT
**Total Activity/Award Cost/Value:** $906,354,246
**Award Period:** 01 November 2003 – 30 June 2019
**Person-Months Per Year Dedicated to the Activity/Award:** 8.2
**Description of Research:** Fusion research on the DIII-D tokamak.

**Activity/Award Sponsor or Source of Funding:** DOE
**Activity/Award Number:** DE-SC0019078
**Sponsored Activity/Award Title:** Laser Inverse Compton Scattering Design
**Total Activity/Award Cost/Value:** $139,971
**Award Period:** 01 September 2018 – 31 August 2020
**Person-Months Per Year Dedicated to the Activity/Award**: 1.8
**Description of Research:** Design laser inverse Compton Scattering system for diagnosing runaway electrons on DIII-D.

**Activity/Award Sponsor or Source of Funding:** DOE
**Activity/Award Number:** DE-SC0018030
**Sponsored Activity/Award Title:** Modeling Plasma Response to Namfp in Tokamaks
**Total Activity/Award Cost/Value:** $15,000
**Award Period:** 01 September 2017 – 30 August 2020
**Person-Months Per Year Dedicated to the Activity/Award:** 0.1
**Description of Research:** Carry out resistive Magnetohydrodynatic (MHD) simulations of the linear and nonlinear plasma response to 3D magnetic field perturbations using first principles MHD codes and engineering quality descriptions of the full, multi-mode, toroidal spectrum of applied, intrinsic error-field, and error field correction perturbations.

## Pending Support:

**Activity/Award Sponsor or Source of Funding:** DOE Office of Science, Office of Fusion Energy Sciences
**Activity/Award Number:** N/A
**Sponsored Activity/Award Title:** Physics Basis, Optimization, and Control for Integrated 3D Edge Long-pulse Tokamak Scenarios (20013314)
**Total Activity/Award Cost/Value:** TBD *(proposed: $1,200,354-GA budget)*
**Award Period:** 15 August 2019 – 14 August 2022 *(anticipated)*
**Person-Months Per Year Dedicated to the Activity/Award:** TBD *(estimated: 1.6)*
**Description of Research:** the proposed project will exploit the unique capabilities of international tokamaks to develop a common physical basis, predictive capability, and long-pulse demonstration for 3D-field integrated ELM-suppressed scenarios.

## Yueqiang Q. Liu (GA)

**Current Support:**

**Activity/Award Sponsor or Source of Funding:** DOE
**Activity/Award Number:** DE-FC02-04ER54698
**Sponsored Activity/Award Title:** DIII-D / Capital / Collaboration / AFT
**Total Activity/Award Cost/Value:** $906,354,246
**Award Period:** 01 November 2003 – 30 June 2019
**Person-Months Per Year Dedicated to the Activity/Award:** 2.6
**Description of Research:** Fusion research on the DIII-D tokamak.

**Activity/Award Sponsor or Source of Funding:** DOE
**Activity/Award Number:** DE-FG02-95ER54309
**Sponsored Activity/Award Title:** Theory & Simulation of Fusion Plasmas
**Total Activity/Award Cost/Value:** $50,911,828
**Award Period:** 15 February 1995 – 14 January 2020
**Person-Months Per Year Dedicated to the Activity/Award**: 1.0
**Description of Research:** Research in plasma theory.

**Activity/Award Sponsor or Source of Funding:** DOE
**Activity/Award Number:** 1.4
**Sponsored Activity/Award Title:** 30462 SIM Center for Runaway Electron Avoidance & Mitigation
**Total Activity/Award Cost/Value:** $1,376,000
**Award Period:** 15 July 2016 – 14 July 2022
**Person-Months Per Year Dedicated to the Activity/Award:** 1.4
**Description of Research:** Research in runaway electron avoidance and mitigation.

**Activity/Award Sponsor or Source of Funding:** DOE
**Activity/Award Number:** DE-SC18992
**Sponsored Activity/Award Title:** 3D Response & Control on MAST-U Tokamak
**Total Activity/Award Cost/Value:** $1,923,366
**Award Period:** 01 July 2018 – 30 June 2021
**Person-Months Per Year Dedicated to the Activity/Award:** 5.1
**Description of Research:** Investigate plasma response and control in the presence of 3D magnetic field perturbations in the spherical tokamak MAST-U (Mega Amp Spherical Tokamak, upgraded).

**Pending Support:**

**Activity/Award Sponsor or Source of Funding:** DOE Office of Science, Office of Fusion Energy Sciences
**Activity/Award Number:** N/A
**Sponsored Activity/Award Title:** Physics Basis, Optimization, and Control for Integrated 3D Edge Long-pulse Tokamak Scenarios (20013314)
**Total Activity/Award Cost/Value:** TBD *(proposed: $1,200,354-GA budget)*
**Award Period:** 15 August 2019 – 14 August 2022 *(anticipated)*
**Person-Months Per Year Dedicated to the Activity/Award:** TBD *(estimated: 1.1)*
**Description of Research:** the proposed project will exploit the unique capabilities of international tokamaks to develop a common physical basis, predictive capability, and long-pulse demonstration for 3D-field integrated ELM-suppressed scenarios.

**Activity/Award Sponsor or Source of Funding:** DOE
**Activity/Award Number:** N/A
**Sponsored Activity/Award Title:** Disruption Mitigation Solutions For Long-Pulse Tokamaks (20012828)
**Total Activity/Award Cost/Value:** TBD *(proposed: $957,000-GA budget)*
**Award Period:** 15 August 2019 – 14 August 2022 *(anticipated)*
**Person-Months Per Year Dedicated to the Activity/Award:** TBD *(estimated: 0.25)*
**Description of Research:** the proposed project will provide an integrated package of modeling, diagnostic enhancement, and experimental benchmarking of SPI disruption mitigation experiments in the large Joint European Torus (JET) and superconducting long-pulse Korea Superconducting Tokamak Advanced Research (KSTAR), in order to further extend the physics understanding required to develop and deploy an effective disruption mitigation system on ITER and beyond. This project will exploit SPI systems recently installed or planned on those devices provided by USITER.

## Oliver Schmitz (UW)

**Current Support:**

**Title:** Three dimensional equilibrium stability and its impact on edge transport and divertor performance in Wendelstein 7-X
**Agency:** U.S. Dept. of Energy, Office of Fusion Energy Sciences
**Grant number:** renewal for grant DE-SC0014210
**Award Period:** Aug. 17, 2018 – Aug. 16, 2021
**Performance site:** University of Wisconsin - Madison and IPP Greifswald, Germany
**Total Award:** $1,198,827
**Annual Level of Effort:** 1 month

**Title:** Three dimensional equilibrium stability and its impact on edge transportand divertor performance in Wendelstein 7-X
**Agency:** U.S. Dept. of Energy, Office of Fusion Energy Sciences
**Grant number:** DE-SC0014210 - Supplement 3
**Award Period:** Aug. 17, 2018 – Aug. 16, 2019
**Performance site:** University of Wisconsin - Madison and IPP Greifswald, Germany
**Total Award:** $236,000
**Annual Level of Effort:** no salary support

**Title:** Control of Neutral Fueling and Helium Exhaust to NSTX-U Plasmas by Means of Three-Dimensional Magnetic Control Fields.
**Agency:** U.S. Dept. of Energy, Office of Fusion Energy Sciences
**Grant number:** DE-SC0012315
**Award Period:** Aug. 15, 2014 – Aug. 14, 2018
**No cost extension:** Aug. 15, 2018 – Aug. 14, 2019
**Performance site:** University of Wisconsin - Madison and CCFE Culham, UK
**Total Award:** $1,134,450
**Annual Level of Effort:** 2 months, ended 08/14/2018

**Title:** Control of Neutral Fueling and Helium Exhaust to NSTX-U Plasmas by Means of Three-Dimensional Magnetic Control Fields.
**Agency:** U.S. Dept. of Energy, Office of Fusion Energy Sciences
**Grant number:** DE-SC0012315 - Supplement
**Award Period:** Aug. 15, 2014 – Aug. 14, 2018
**No cost extension:** Aug. 15, 2018 – Aug. 14, 2019
**Performance site:** University of Wisconsin - Madison and CCFE Culham, UK
**Total Award:** $279,368
**Annual Level of Effort:** 1 month (for academic buyout in FY18)

**Title:** CAREER: Understanding of neutral particle physics to generate a helicon wave driven high density laboratory plasma
**Agency:** U.S. National Science Foundation
**Grant number:** PHY-1455210
**Award Period:** Mar. 1, 2015 – Feb. 31, 2020
**Performance site:** University of Wisconsin - Madison
**Total Award:** $545,000
**Annual Level of Effort:** 1 month (summer)

**Title:** CAREER: Understanding of neutral particle physics to generate a helicon wave driven high density laboratory plasma
**Agency:** U.S. National Science Foundation
**Grant number:** PHY-1455210 - Supplement
**Award Period:** Mar. 1, 2015 – Feb. 31, 2020
**Performance site:** University of Wisconsin - Madison
**Total Award:** $100,000
**Annual Level of Effort:** no salary support

**Title:** Plasma wall interaction with three-dimensional plasma boundaries (DoE Early Career Award)
**Agency:** U.S. Dept. of Energy, Office of Fusion Energy Sciences
**Grant number:** DE-SC0013911
**Award Period:** May. 1, 2015 – April 31, 2020
**Performance site:** University of Wisconsin - Madison and DIII-D National Fusion facility, San Diego, USA and IPP Greifswald, Germany
**Total Award:** $992,310
**Annual Level of Effort:** 0.5 months (summer) + 0.5 months for buyout during academic year

**Title:** Vilas Faculty Mid-Career Achievement Award
**Agency:** Vilas Foundation
**Award Period:** Jun. 1, 2017 – Jun. 31, 2019
**Performance site:** University of Wisconsin - Madison
**Total Award:** $50,000
**Annual Level of Effort:** no salary support

## <u>Pending Support:</u>

**Title:** Detachment Physics at High Power and Long Pulse
**Agency:** U.S. Dept. of Energy, Office of Fusion Energy Science, DE-FOA-00002076
**Grant number:** *To be submitted*
**Award Period:** August 1, 2019 – July 31, 2022
**Total Award:** $671,989 for UW Madison contribution
**Annual Level of Effort:** 0.5 months

**Title:** Physics Basis, Optimization, and Control for Integrated 3D Edge Long-pulse Tokamak Scenarios
**Agency:** U.S. Dept. of Energy, Office of Fusion Energy Science, DE-FOA-00002076
**Grant number:** This proposal
**Award Period**: August 1, 2019 – July 31, 2022
**Total Award:** $573,361 for UW Madison contribution
**Annual Level of Effort:** 0.5 months

**Title:** Enhanced plasma edge characterization for investigation of helicon wave coupling and neutral compression with the SAS divertor at the DIII-D U.S. National Fusion Facility
**Agency**: U.S. Dept. of Energy, Office of High Energy Physics
**Grant number:** submitted
**Award Period:** August. 15, 2019 – August. 14, 2022
**Performance site:** University of Wisconsin - Madison and DIII-D National Fusion facility, San Diego, USA
**Total Award:** $1,315,503
**Annual Level of Effort:** 1.5 months

**Title:** Development of a high density, helicon wave driven plasma column for plasma wake-field accelerator applications
**Agency:** U.S. Dept. of Energy, Office of High Energy Physics
**Grant number:** under review
**Award Period:** April. 1, 2019 – March. 31, 2022
**Performance site:** University of Wisconsin - Madison
**Total Award:** $1,083,131
**Annual Level of Effort:** 1.5 months

**Title:** Unraveling the link between radio-frequency wave propagation and high ionization efficiency of helicon plasmas
**Agency:** U.S. Dept. of Energy, Office of Fusion Energy Sciences & NSF, Basic Plasma Science partnership
**Grant number:** under review
**Award Period**: Jan. 1, 2019 – Dec. 31, 2022
**Performance site:** University of Wisconsin - Madison
**Total Award:** $728,298
**Annual Level of Effort:** 1 month

Dmitry M. Orlov (Sub-contractor, UCSD)

**Current Support:**

**Agency:** DOE –NRG5065 / DE-FG02-05ER54809
**Project Title:** Modeling Plasma Response to Non-Axisymmetric Magnetic Perturbations in Tokamak Boundaries
**PI:** R. Moyer
**Percent Effort:** 4.0 Person Months
**Total Award Amount:** $2,184,308
**Total Award Period Covered:** 4/15/05-8/31/20
**Location of Project:** General Atomics

**Agency:** DOE – NRG6729 / DE-SC0018287
**Project Title:** AToM: Advanced Tokamak Modeling Environment
**Percent Effort**: 8.0 pers mo
**PI:** C. Holland
**Total Award Amount:** $1,800,000
**Total Award Period Covered:** 9/1/17- 8/31/22
**Location of Project:** General Atomics

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# Appendix 4. Facilities and Other Resources

## A4.1. International Facilities

### A4.1.1. KSTAR

Korean Superconducting Tokamak Advanced Research (KSTAR) facility is a main experimental device for this project, from the development of physics basis to demonstration of optimization and control of 3D ELM suppression throughout all 6 tasks. KSTAR is located in Daejeon city, South Korea, managed by National Fusion Research Institute (NFRI) and supported by the Korean Ministry for Science and Technology. The access to the main control room, workstations, offices will be allowed to the members of this project via NFRI-visitor-form request to local hosts, such as 3D Task Force leaders and members (currently W. H. Ko, G. Park, or J. H. Lee and M. Choi who are responsible for ECEI). This permission is implied in the letter of collaboration by the current KSTAR program director, S. W. Yoon as attached in A7.1. KSTAR will provide unique opportunities and capabilities on the topical areas of this project, as can be summarized as follows.

- *Long pulse and High power:* KSTAR has already achieved ITER-relevant $\beta_N$>1.5, $\beta_P$>2.0, in long pulse > 70s, and with ELM suppression > 34s. Such a long pulse, which is not accessible in current US devices, is already presenting new challenges on instability and boundary control as explained in the proposal (e.g. Fig. 2.3). In the following three years, KSTAR will be equipped with the routine operations of the 2$^{nd}$ NBI system up to 12MW in total for NBI only, 6MW of new ECH (4 MW of 105/140 GHz and 2 MW of 170 GHz), with the potential additions for 2 MW from ICRH and also Helicon system. The operational regimes anticipated from the higher power are unprecedented, including $\beta_N$>3.0 and >100s H-mode operation, and will offer unique opportunities to test 3D optimization for ELM control as planned for Task 4&5.
- *Flexible low-n 3D fields and Upgrades:* KSTAR 3D coils are unique in having 3 rows of in-vessel coils similarly to ITER in-vessel RMP coils. Although its phasing flexibility is limited to n=1 due to only 4 toroidal arrays in each row, it allows a fine tuning of poloidal spectrum and enables the unique n=1 ELM suppression in KSTAR and data for physics basis planned in Task 1&2&4. KSTAR is also known as smaller intrinsic error fields than other devices and thus provides less uncertainties in interpreting data, validating 3D physics, (Task 1-3) and demonstrating the optimization and control (Task 4&5). The success with n=1 fields also implies a possibility of ELM suppression using deeply penetrating 3D fields from the outside of the vessel, which may be necessary under nuclear contamination in a reactor. KSTAR is willing to invest such reactor-relevant ex-vessel 3D coil design activities and also installations during the outage planned in 2022 if the design is attractable for physics and engineering, motivating our Task 6.2.
- *Advanced Diagnostics:* Electron Cyclotron Emission Imaging (ECEI) diagnostics in KSTAR has been unique in resolving and providing internal structure of perturbations and flows, by instabilities such as Sawtooth, Neoclassical Tearing Modes (NTMs) and ELMs, and by 3D fields. This ECEI ability, in addition to other fluctuation diagnostics including MIR and high-k in KSTAR, can offer critical evidence for validating underlying transport physics as planned in Task 3. The synthetic interpretations of data may have to utilize various profile diagnostics and equilibrium reconstruction, as planned in Task 6.1.

### A4.1.2. AUG

The Max Planck Institute for Plasma Physics (IPP), Operates the Axisymmetric Divertor Upgrade (AUG) tokamak in Garching, Germany. In addition the IPP operates the Wendelstein 7-X stellarator experiment in Greifswald, Germany, and also maintains a world-class theory group. The AUG plasma ring has a major radius of 1.60 meters and a volume of 13 cubic meters. The entire AUG first-wall is made of tungsten, a unique feature world-wide. The tokamak is heated by three different systems, 20 MW of NBI, in particular 6 MW of ICRF, and 4 MW of ECH which make AUG unique in 3D studies with RF-heated plasmas (Task 1). Typical pulse lengths are 5-7 seconds. Over 40 world-class diagnostics are available, enabling robust reconstruction of tokamak equilibria. The 3D coil system consists of two rows of 8 coils, placed above and below the device midplane inside of the vacuum vessel. This 3D coil set allows application of n=1-4 perturbations and allows poloidal spectrum control of n=1,2.

### A4.1.3. EAST

Academica Sinica Institute of Plasma Physics (ASIPP), located in Hefei, China, is the leading plasma physics and fusion laboratory of the Chinese Academy of Sciences. ASIPP operates the EAST superconducting tokamak. In addition to the EAST experimental facility and team, the institute includes an extensive theory group, and many technology and fabrication facilities. Several of the ITER technology packages are being produced by ASIPP, including the Error Field Correction Coils and many power supplies.

EAST (Experimental Advanced Superconducting Tokamak) is a highly shaped (vertically elongated, D-shaped plasma) advanced steady-state plasma tokamak. Its scientific mission is to realize stable operation and carry out experiments on heating and confinement improvement in long pulse. EAST will have long pulse (400-1000s) fully non-inductive current drive capability, a flexible PF system (superconducting ex-vessel PF coils and Cu in-vessel coils), and a wide variety of auxiliary heating and current drive systems (ICRF, LHCD, NBI, and ECH/ECCD), which also give advantages on 3D studies under RF heating (Task1). It will operate with hot metal walls and be able to accommodate divertor heat loads that make it an attractive test facility for the development of advanced tokamak operating modes. EAST shares the DIII-D Plasma Control System with seven other devices worldwide, including DIII-D and KSTAR. Similar to AUG, the EAST 3D coil system consists of two rows of 8 coils, placed above and below the device midplane inside of the vacuum vessel. This 3D coil set allows application of n=1-4 perturbations and allows poloidal spectrum control of n=1,2.

### A4.1.4. COMPASS-U

COMPASS-U is presently under design in Institute of Plasma Physics in the Czech Academy and Science (IPP-CAS), Prague, Czech Republic, with high density ($10^{20}m^{-3}$) and magnetic field ($B_T$=5.0T) and relevant plasma geometries that are missing in the European fusion programme (and worldwide after the shut-down of Alcator C-MOD). The purpose of the project is to enlarge the COMPASS operational space, improve its performance and address some of the key gaps in the Plasma Exhaust Physics (PEX). The upgrade will keep the advantage of mid-size devices with their flexibility for scalings towards ITER and DEMO. The start of operation is planned at the end of 2021.

## A4.2. Resources in Participating Institutions

### A4.2.1. Princeton Plasma Physics Laboratory (PPPL) and Princeton University (PU)

Princeton Plasma Physics Laboratory (PPPL), the lead US institution of this proposal, is operated by Princeton University (PU) and supported by the Department of Energy (DOE) with the missions dedicated to plasma physics including science of magnetic fusion confinement. Under the supervision of the department of ITER & Tokamak in PPPL, J.-K. Park (Lead PI in PPPL), E. Kolemen (PI in PU), N. C. Logan, Q. Hu, C. Zhu and new post-doctoral fellows will routinely perform various tasks on-site in PPPL and PU as well as and off-site in GA. This proposal will take advantage of the broad resources of PPPL and PU for R&D, in particular, computing resources and services. This includes PPPL and PU campus computer clusters for running simulation codes such as GPEC, M3D-C1, TM1, STELLOPT, FOCUS, REGCOIL and TRANSP, and extensive network connectivity to remote control rooms situated as well as the facilities at AUG, EAST, KSTAR and COMPASS-U.

### A.4.2.2 General Atomics (GA) and the DIII-D Facility

General Atomics (GA) and its affiliated companies comprise one of the world's leading resources for high technology systems development and nuclear technology. GA specializes in diversified research and development in energy, defense, and other advanced technologies. For over 40 years, GA has been qualified as a government contractor and facilities operator by the United States (U.S.). Government and other organizations, including the Department of Defense, Department of Energy (DOE), and the National Science Foundation. GA's history of good performance within budget on cost-reimbursement contracts is also well-established. GA performs multi-year research and development contracts in compliance with contractual requirements and in accordance concurrently with DOE-CHI financial plans.

In programs such as fission, fusion, advanced materials, and unmanned vehicles, GA is renowned for qualities that will lead to successful project execution. The GA fusion effort, which began 50 years ago, is comprised of the largest ($60M/year) magnetic fusion energy (MFE) program in private industry as well as the largest ($20M/year) inertial confinement fusion program in private industry. The MFE program centers on the DIII-D National Fusion Facility (DIII-D) in San Diego, California, operated for the DOE. The DIII-D experimental fusion machine, an extremely versatile device conceived, designed, constructed, and operated by GA, is a principal site for U.S. efforts to explore improvements in reactor-grade fusion plasmas through magnetic shaping. The DIII-D National Team consists of about 120 operating staff and on-site research scientists drawn from nine U.S. national laboratories, 19 foreign laboratories, 16 universities, and five industrial partnerships. Limited comparative experiments will be carried out on DIII-D within the present proposal.

The project participants, C. Paz-Soldan (Co-lead PI), T. E. Evans, Y. Liu, D. Weisberg and new post-doctoral fellow will employ local computer resources at GA to analyze various experimental data from international devices as well as DIII-D and to use OMFIT, MARS-F/Q and also M3D-C1. The computer system is managed by the Computer Systems and Science (CSS) Group within GA. The CSS Group is responsible for ensuring that the computing infrastructure remains capable of supporting the scientific missions of DIII-D, and GA's Theory and Inertial Fusion Technology Divisions. The CSS Group operates and maintains a diverse campus-wide computer facility for fusion research, including 1) LSF cluster (the main Linux computational cluster for DIII-D data analysis); 2) STAR cluster (the DIII- D between-pulse data analysis Linux-based cluster); 3) IRIS cluster (the computational cluster for integrated modeling and other highly parallel computations); 4) the DROP cluster (the Theory and Computational Science cluster used for transport, radio frequency, and magneto-hydrodynamic calculations: 216 cores in a dual-hex-core node format); 5) real-time systems for data acquisition; 6) the Plasma Control cluster (the specialized computer hardware and software system for performing real-time control of the DIII-D plasma); and 7) personal computers for user desktops.

### A4.2.3. University of Wisconsin - Madison (UW)

The project participants including H. Frerichs (PI) and O. Schmitz will perform the computational work for the plasma boundary modeling on the high-performance computing (HPC) cluster in the Center for High Throughput Computing (CHTC) at the University of Wisconsin - Madison. The HPC cluster has 3616 cores with a total of 20 Tb of RAM available for UW-Madison researchers. This system is already being used for EMC3-EIRENE simulations for DIII-D, NSTX-U and ITER.

### A4.2.4. University of California - Irvine (UCI)

The UCI team led by Z. Lin (PI) will benefit from collaborations with the GTC team and the SciDAC ISEP Center that the UCI PI (Z. Lin) directs, which currently receive an INCITE award with about 2% computer time allocation on the Summit computer at ORNL (the fastest supercomputers in the world), and 65,000,000 core-hours on the supercomputers at NERSC.

## A4.3. Summary of Simulation Codes

*PD: Post-doctoral fellow, TBD and affiliated by PPPL (PD-L), GA (PD-G), UCI (PD-I), PU (PD-P)
*SC: Sub-contractor, Dmitry Orlov in UCSD (SC1)
*GS-W: Graduate (Ph.D) student in UW

| Code | Description | User | Task |
|---|---|---|---|
| GPEC | Single-fluid 3D perturbed equilibrium code with ideal scalar pressure (IPEC) and kinetic tensor pressure consistent with neoclassical 3D transport | Park, Logan, PD-L | 1 & 2 & 3 |
| MARS | Single-fluid linear 3D MHD codes including resistive and flow (MARS-F) and kinetic MHD (MARS-K), and run quasi-linearly with flow evolving in time (MARS-Q) | Liu, PD-G, GS-W | 1 & 4 |
| M3D-C1 | Two-fluids linear & non-linear 3D MHD codes including magnetic islands | Hu, Evans, PD-G | 3 & 4 |
| TM1 | Two-fluids and non-linear 3D MHD codes in cylindrical geometry | Hu | 1 & 2 |
| GTC | Particle code for microturbulence and MHD modes in tokamak, stellarator, and FRC | Lin, PD-I | 3 |
| EMC3-EIRENE | 3D steady state plasma boundary fluid transport code including neutral gas and fluid impurities | Frerichs | 4 |
| ERO2 | Impurity sputtering and kinetic transport code | GS-W, Schmitz | 4 |
| MCI | The Monte Carlo Impurity (MCI) code with kinetic sputtering and transport code with complete set of chemical and physical sputtering models, and atomic data (ADAS) | SC1 | 4 & 5 |
| STELLOPT | Stellarator optimization suites to explore advanced MHD equilibrium with good stabilities, particle confinement and heat transport. | Logan, Zhu | 6 |
| FOCUS | Nonlinear optimization code to design 3D coils subjected to practical engineering constraints. | Zhu | 6 |
| REGCOIL | Coil design code using Green’s function method to find surface current solution on a pre-defined surface. | Zhu | 6 |

# Appendix 5. Equipment

Appendix 5, Equipment, is not applicable for this submittal.

# Appendix 6. Data Management Plan

## A6.1. Overview

This Data Management Plan (DMP) describes the sources of procedures for managing the digital data life cycle process involved in this proposed project, including capture, analysis, sharing, and preservation of experimental and modeling data, as well as the related digital files. The DMP will generally make use of the Data Management Plan for each participating institution (See A6.2, PPPL, GA, UW, UCI, PU) for data and code archiving, with certain key extensions, as detailed below. All data generated by project activities will be made available to all participants and preserved on PPPL and GA computer archiving systems, and archives in collaborating facility institutions (KSTAR, AUG, EAST, See A6.3) or home institution resources for each participating team member. Analysis codes and related digital files will be similarly shared and archived, and also preserved through common access to PPPL and GA computer systems. This data access policy will conform to all U.S. Department of Energy requirements for research funded by the United States Government.

All publications resulting from external collaborations, either domestic or international, will report a DOI number that links to the full text document. Where the Journal provides open access to the full, published text, the DOI will be associated with the Journal archive. Where the Journal does not provide open access to the full text, the DOI will be associated to a separate archive. In all cases where the open access is not provided by the Journal, the publication of the published article on a local server must comply with the Journal policy, which might require the layout of the archived document to be not the final, published one.

## A6.2. Compliance with institutional DMP

### A6.2.1. PPPL and PU DMP

Through Princeton University, we will facilitate the sharing of digital data by use of linking supplemental material to a local dataspace [http://dataspace.princeton.edu/jspui/] using Archival Resource Keys "ARKs". In sharing digital data resulting from experiments and simulations, this fulfills the PPPL requirement of making available at the time of publication all data displayed in charts, figures, and images included in published articles. This is accomplished by links to supplemental material appearing on the same web page as the article -- together with an ARK for easy access. Non-U.S. collaborators working on PPPL facilities and/or with theoretical and design R&D led by PPPL are subject to all of the same DMP rules as U.S. researchers with respect to, for example, sharing published data. They are not governed by their home institution guidelines if they are working on U.S. facilities and/or with theoretical and design R&D projects that are led by scientists within our country.

### A6.2.2. GA and DIII-D DMP

The D3DDMP provides methods, procedures, and resources for managing experimental data, codes, and digital files produced in the course of DIII-D operations and computational analysis. The resources and methods provided in the D3DDMP are generally sufficient to support the needs of the proposed project, with some extensions. The D3DDMP is described at https://fusion.gat.com/global/D3D_DMP/. Instructions for D3DDMP support and procedures are provided at https://diii-d.gat.com/diii-d/DMP/. Cyber access to the DIII-D resources required to make use of the D3DDMP is provided upon approval of a request made through https://diii-d.gat.com/ssl_form/cyberaccess/. The D3DDMP provides computational and archiving resources to all members of the DIII-D team, as well as all members of the present project team, upon request. The D3DDMP provides methods for making all data linked to publications open, machine-readable, and digitally-accessible.

### A6.2.3. UW DMP

All data included in future publications will be accessible through permanent storage on a University of Wisconsin - Madison hosted publication web-server. This service is presently under development, and as a temporary solution a specific web-server is being set up for the group of the PI to supply all published data. Acknowledgements will be included in all publications to reflect this and provide directions to access data.

### A6.2.4. UCI DMP

All raw simulation data are available upon request to the corresponding authors for five years after the publication dates. All data included in future publications will be accessible through permanent storage on a University of California - Irvine webpage: http://phoenix.ps.uci.edu/GTC/.

## A6.3. Management of Modeling Data

### A6.3.1. PPPL and PU

The GPEC code package that will be actively used for various tasks in this project will be shared and maintained at the GitHub repositories (https://github.com/PrincetonUniversity/GPEC/) in Princeton University. As needed basis, the most up-to-date GPEC version will be deployed through a User Agreement in local workstations of international facilities, as done in UKSTAR server and planned for AUG. Other data sharing will also be facilitated through web-based visualization tools accessible to public, common MDSPlus architecture/tools including shared analysis code, NTCC module library, FTP services, common login cluster (ability to access main computer cluster from on- or off- site), trusted data movement mechanisms among PPPL, GA and NERSC, common output file formats (e.g., Plasma State file from TRANSP runs, NETCDF files), 10 Gigabyte ESNET connection to all national Labs, GLOBUS on-line for transferring data over the internet. Data provenance is limited to maintaining histories of data calibrations, etc. through MDSPlus and keeping track of data smoothing, averaging, etc. in UFILES (for TRANSP runs).

### A6.3.2. GA

The GA suite of codes is maintained in various separate repositories at GitHub (https://github.com/) (or its equivalent), using the git version control system. For example, the MARS-F/K/Q codes suite is available at https://bitbucket.org/. For this online content to be visible and accessible, a user must have a GitHub account (free) and be granted project access. Access is granted upon signing a User Agreement. All modeling data included in future publications will be accessible via the D3DDMP that has been developed by the DIII-D Computer Systems and Science Group (https://fusion.gat.com/global/D3D_DMP/) as already described in A6.2.2. Acknowledgements will be included in publications to reflect this and provide directions to access data. This data will be accessible within one month of acceptance of publication. Generation of these files and directories is the responsibility of the publication's first author. Shared data will be stored in file systems at the National Energy Research Scientific Computing (NERSC) center.

A6.3.3. UW

The UW plasma boundary production toolkit (EMC3-EIRENE itself as well as FLARE for grid generation and PYMC3 for data visualization) is maintained under version control in separate repositories at GitLab (https://about.gitlab.com). Access to the individual packages requires a collaboration agreement between the interested user(s), the Max-Planck Institute for Plasma Physics in Germany (for EMC3), the Forschungszentrum Juelich in Germany (for EIRENE), and the University of Wisconsin - Madison. Access to numerical data from simulations will be made available to collaborators upon request through direct transfer.

A6.3.4. UCI

The UCI PI maintains a single production version of GTC, which is open-source and available for general public at the GTC homepage http://phoenix.ps.uci.edu/GTC/. The public release of the current production version (GTC version 4.0) is distributed under the 3-Clause BSD License.

The current "development" version of GTC (version 4.3) is shared among all GTC team members and collaborators (about 40 researchers in US, EU, China, India, and South Korea). The "development" version is available from the Bitbucket repository: https://bitbucket.org/uciplasmatheory/gtc. Any code modifications by the collaborators should be incorporated into the central version. No variation or extension to the code name could be made.

## A6.4. Access to Data in International Facilities

In addition to the procedures and resources provided by US DMP, data acquired from international facilities in the course of the project can be archived, shared, and preserved on KSTAR/NFRI computer systems (https://kstar.nfri.re.kr), EAST/ASIPP computer systems (http://d07.ipp.ac.cn/EAST), and AUG/IPP computer systems (https://www.mpcdf.mpg.de). All three groups provide data access interfaces, computer accounts, and other data archiving systems, accessible with approval and password authentication by all project participants. Support letters in the present proposal provide approval for team members' use of each respective device and associated computer facilities, and specific approval is granted to each participant with account creation and approval.

# Appendix 7. Other Attachment - Letters of Collaboration

The letters of collaboration from each facility and unfunded collaborator are attached in the following order.

A7.1. KSTAR

A7.2. AUG

A7.3. EAST

A7.4. COMPASS-U

A7.5. Nathaniel M. Ferraro (Princeton Plasma Physics Laboratory)

A7.6. Young-Seok Park (Columbia University)

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Dr. Matthew Lanctot, Program Manager
US-DOE/FES
19901 Germantown Rd.
Germantown, MD 20874
USA

03/May/2019

Dear Dr. Matthew Lanctot:

As the director of KSTAR Research Center, it is my pleasure to write a letter in strong support of the US Proposal titled *"Physics Basis, Optimization, and Control for Integrated 3D Edge Long-pulse Tokamak Scenarios"* led by Dr. Jong-Kyu Park and teamed up with top-class technical experts.

Ever since the KSTAR program became operational in 2008, the KSTAR has been closely collaborating with the US researchers not only for successful commissioning and control, but also for plasma stability and transport. While we have made significant progress in various capacities in recent years, the KSTAR is now proudly leading the 3D physics research topics, some of which are quite unique in the world directly relevant to ITER and future reactors. At the same time, we are also aware of a strong need about more refined physics basis that should be unified among all the available devices, without machine-specific dependences.

In this regard, the proposed set of 6 tasks is expected to be well incorporated into the high-priority research themes in the planned KSTAR program in 2019 – 2021. Specifically, Task 1 (common physics basis) and Task 2 (parametric threshold study) are aligned with the on-going 3D physics group efforts in KSTAR, as well as the community interest to establish the database of RMP-driven, ELM-crash-suppression. Task 3 (physics mechanism) and Task 4 (Heat flux optimization for long pulse) are indeed among the highest priority topics of KSTAR 3D physics and divertor research groups would emphasize respectively. Task 5

(Active control of 3D ELM suppression) and Task 6 (Integrated analysis tool) are the timely themes to make KSTAR more versatile for 3D physics, as well as for streamlined experimental result analysis.

In fact, I believe Dr. Park and his team, together with the KSTAR 3D Physics group, are in the better position in KSTAR to address any remaining uncertainties in 3D physics than elsewhere. At the same time, almost all the task leaders in this proposal have the prior experiences with the KSTAR experiments, which are expected to allow them to directly spearhead each issue seamlessly. Considering that we are in need of manpower and resources in KSTAR, the planned reinforcement of several full-time postdocs would be quite well-balanced. Unreservedly, I will do my best to accommodate their on-site needs to focus on the high-quality outcome in each planned task in KSTAR.

Finally, I believe, utilizing the expertise of US fusion researchers and advanced capability of KSTAR, the combined effort of the US & KSTAR team will provide the unprecedented depth of understanding on the mechanism of the edge stability and control which are one of the urgent issues to be resolved for safe operation of ITER and beyond. KSTAR will allocate the required run-time and other resources necessary to make this collaboration successful.

Should you have any questions, please feel free to contact me (swyoon@nfri.re.kr) without hesitation.

Sincerely,

Yoonw

Si-Woo Yoon
Director of KSTAR Research Center
National Fusion Research Institute

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Dr. Matthew Lanctot
Office of Science
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19901 Germantown Road
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Garching, 11 April 2019

Dear Dr. Lanctot,

As the host institution and operator of the ASDEX Upgrade tokamak, the Max Planck Institute of Plasma Physics (IPP), Garching is pleased to strongly support the US proposal for collaboration on "Physics Basis, Optimization, and Control for Integrated 3D Edge Long-pulse Tokamak Scenarios". The proposed work on ASDEX Upgrade will provide a novel benefit to our research program in this area, and as such improve the ability of both the US and ASDEX Upgrade teams to exploit ITER.

The first emphasis on dynamic plasma response modeling using a quasi-linear rotation evolution will provide a novel method of interpreting the important experimental results obtained on ASDEX Upgrade, with the ultimate goal of predictively improving the application of the different applied 3D spectra accessible on ASDEX Upgrade as well as understanding the role of the heating mix and plasma flow on the control of the 3D edge.

The second emphasis on application of the Ideal and General Perturbed Equilibrium Code (IPEC/GPEC) to ASDEX Upgrade discharges will also provide a novel computational tool to understand the basic plasma response phenomena observed in our device. This tool can supplement existing approaches and deliver new insights on the role of spectral optimization and plasma shaping to achieving an instability-free edge state on ASDEX Upgrade.

The proposed third emphasis involves completing the installing and commissioning of in-situ penning gauges to aid in the diagnosis of multiple impurity species existing in the exhaust manifolds of the ASDEX Upgrade device. The proposal to continue supporting these activities will ensure their timely completion and maximize their effectiveness in planned joint studies on the role of light impurities in accessing the instability-free edge state.

These proposed efforts build on the very successful existing collaborations between the US project team and local scientists. Over the last few years this collaboration has been very important in developing the stable edge regimes on ASDEX Upgrade that are now extensively being exploited by the local team for their application to ITER and beyond. Several recent publications with joint authorship stand as evidence to this already established and successful interaction[1-3].

In support of this project, IPP offers to provide office space and administrative support for the involved US project team travel to ASDEX Upgrade. We invite the US team to collaborate on-site for as many visits and for whatever duration your funding will support. The proposed collaboration strongly builds on existing data, and we will grant full access to the ASDEX Upgrade data to the collaborators involved. Furthermore, should further experimental ideas result from the collaboration, the collaborators will have the right to submit, through their IPP contacts, experimental proposals through the usual channels into the ASDEX Upgrade programme finding process.

We further generally welcome the participation of the US team in the ASDEX Upgrade experimental programme in this area, and look forward to a continued fruitful collaboration.

Sincerely yours,

(Prof. Hartmut Zohm)

[1] W Suttrop, A Kirk, R Nazikian, et al Plasma Phys. Control. Fusion 59 014049 (2017)
[2] W. Suttrop, A. Kirk, V. Bobkov, M. Cavedon, M. Dunne, R.M. McDermott, H. Meyer, R. Nazikian, C. Paz-Soldan, D.A. Ryan, E. Viezzer, M. Willensdorfer et al, Nucl. Fusion 58 096031 (2018)
[3] C. Paz-Soldan, R. Nazikian, L. Cui, B.C. Lyons, D.M. Orlov, A. Kirk, N.C. Logan, T.H. Osborne, W. Suttrop and D.B. Weisberg, Nucl. Fusion 59 056012 (2019).

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Dr. Matthew Lanctot
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Dear Dr. Lanctot

As the host institution and operator of the EAST long pulse superconducting tokamak, Institute of Plasma Physics, Chinese Academy of Sciences (ASIPP) is pleased to strongly support the US proposal for "Physics Basis, Optimization, and Control for Integrated 3D Edge Long-pulse Tokamak Scenarios". The proposed work on EAST will greatly accelerate progress in the area of 3D physics, to the benefit of EAST operation, US expertise, and ITER exploitation.

The proposed emphasis on understanding edge localized mode (ELM) control in RF-dominated regimes will assist in exploiting the unique capabilities of EAST to expand the boundaries of this technique towards long-pulse operation, again in support of both EAST and ITER. The second emphasis on understanding and controlling the heat flux challenge in 3D scenarios will further complement EAST emphasis on reactor-relevant first-wall materials and further support long-pulse operation.

The proposed effort builds on many existing collaborations between ASIPP and US scientists engaged in 3D research. These collaborations have been highly successful in the past, resulting in for example an invited talk at the prestigious 2018 IAEA Fusion Energy Conference reporting advances in 3D control combining EAST and DIII-D results. The existing collaborations between ASIPP and US scientists have also resulted in at least 4 joint peer-reviewed publications in the last year alone[1-4], and there has been significant integration of the research efforts between EAST and DIII-D in this area. As such, we anticipate continuing to support ASIPP personnel at DIII-D to participate in relevant experiments and further enhance the collaboration in this area, and look forward to continuing to receive collaborations from US scientists through this project.

In support of this project, ASIPP proposes to provide full support for housing of your participating personnel during their visits to EAST. When available, we offer the use of apartments near the institute at no charge to your project and daily living expense. Otherwise, we would fund your visitors' use of local hotel facilities. We invite the US team to collaborate on-site for as many visits and for whatever duration your funding will support. We welcome your experimental proposals and extensive participation in EAST experimental campaigns, and look forward to a fruitful collaboration in understanding the physics basis and optimization of 3D long pulse scenarios on EAST.

Sincerely yours,

B. N. Wan

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Fax:86-551-65591310

List of related joint publications:

[1] M. Jia, Y. Sun, C. Paz-Soldan, R. Nazikian, S. Gu, Y. Q. Liu, et al, Phys Plasmas 25, 056102 (2018)

[2] S. Gu, Y. Sun, C. Paz-Soldan, R. Nazikian, M. Jia1, H.H. Wang, W. Guo, Y.Q. Liu, et al, Nucl. Fusion 59 026012 (2019)

[3] N.C. Logan, L. Cui, H. Wang, Y. Sun, S. Gu, G. Li, R. Nazikian, and C. Paz-Soldan, Nucl. Fusion 58 076016 (2018)

[4] Z.R. Wang, N.C. Logan, S. Munaretto, Y.Q. Liu, Y. Sun, et al Nucl. Fusion 59 024001 (2019)

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**To whom it may concern**

## Letter of collaboration

The Institute of Plasma Physics of the Czech Academy of Sciences (IPP Prague) has designed a new tokamak – COMPASS-U, which is currently under construction. It will be a compact, medium-size (R = 0.89 m, a = 0.3 m), high-magnetic-field (5 T) device. COMPASS-U will be equipped by a flexible set of poloidal field coils and capable to operate with plasma current up to 2 MA and, therefore, high plasma density (~ $10^{20}$ $m^{-3}$). The device is designed to generate and test various DEMO relevant magnetic configurations, such as conventional single null, double null, single and double snow-flake, negative triangularity, etc. The plasma will be heated using 4 MW Neutral Beam Injection (NBI) heating system with future extension up to 10 MW Electron Cyclotron Resonant Heating (ECRH) system. The COMPASS-U tokamak will be located in the same experimental hall as present COMPASS tokamak.

COMPASS-U will be equipped with lower and upper closed, high neutral density divertors. Due to high PB/R ratio COMPASS-U will represent a device which will be able to perform ITER and DEMO relevant studies in as the plasma exhaust, development of new confinement regimes, etc. The divertors will use conventional materials in the first stage, however, in the later stage, the liquid metal technology, which represents a promising solution for the power exhaust in DEMO, will be installed into the lower COMPASS-U divertor. The metallic first wall will be operated at high temperature - approx. 300 °C (500 °C in later phase) during plasma discharge, which will enable to explore the edge plasma regimes relevant to DEMO operation. The first plasma is scheduled for 2022/2023.

Besides these goals, the COMPASS-U tokamak also aims at investigation of the reactor-relevant plasma regimes without the presence of ELMs. This includes the regimes where the ELMs are suppressed by the external 3D magnetic field perturbations. However, prediction of such regimes for devices under construction is difficult due to lack of predictive understanding of ELM suppression by 3D fields. Furthermore, poloidal field coils in COMPASS-U will be located inside the toroidal field coils and thus stronger error fields from the imperfections in their manufacture and alignment can appear, leading to a more likely occurrence of locked modes. The 3D field coil system for COMPASS-U will be, therefore, required to allow for both the correction of such error fields as well as to provide a capability to suppress the ELMs at ITER and DEMO relevant plasma parameters. Design of such coil configuration for a tokamak is a complex and demanding task. Therefore, IPP Prague strongly welcomes the proposal by very experienced US team and confirms to provide to the US collaborator the necessary information regarding:

- The plasma equilibria and the expected plasma parameters.
- Space ex- and in-vessel available for the installation of the 3D coils.
- Limits of available power supplies and feed cable port access.
- Any further engineering constraints that might be relevant.

The collaborating IPP Prague team will consist of the following experts (including indicative PPY, which may vary during years depending on the project phase):

- Tomas Markovic (0.2 ppy) - scientist, coordination of the collaboration with the US partner. GPEC simulations.
- Pavel Junek (0.2 ppy) – electrical engineer
- David Sestak (0.3 ppy) – mechanical engineer

After the coils are successfully designed, manufactured, installed and commissioned, the IPP Prague will provide the US collaborators the experimental time and access to COMPASS-U device to perform the experiments with the ELM control and error field correction to further exploit this novel 3D coil system.

Radomir Panek
director

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Princeton, New Jersey
08540

Dear Dr. Jong-Kyu Park,

If your proposal entitled, "Physics Basis, Optimization, and Control for Integrated 3D Edge Long-pulse Tokamak Scenarios", is selected for funding under the DOE National Laboratory Program (LAB 19-2076), it is my intent to collaborate in this research by offering advice to M3D-C1 code users, sharing progress of physics understanding of ELM suppression by 3D fields, and exchanging AUG and DIII-D data that can be mutually beneficial to both my Early Career Research Program (ECRP) project and your proposed project.

Thank you for the opportunity to participate.

Sincerely,

Nathaniel M. Ferraro

Research Physicist, Princeton Plasma Physics Laboratory
May 8th, 2019

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New York, NY 10027
609-243-3507
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May 7th, 2019

Jong-Kyu Park
Principal Research Physicist
Princeton Plasma Physics Laboratory
P.O. Box 451
Princeton, NJ 08543-0451

Dear Dr. Jong-Kyu Park:

If your proposal entitled, “Physics Basis, Optimization, and Control for Integrated 3D Edge Long-pulse Tokamak Scenarios” is selected for funding under the DOE National Laboratory Program (LAB 19-2076), it is my intent to collaborate in this research by running the VALEN3D code for ELM-suppressed KSTAR scenarios by 3D fields, and providing time-response characteristics due to eddy currents and possibly corrections necessary to the GPEC simulations. Thank you for the opportunity to participate.

Sincerely,

Young-Seok Park
Associate Research Scientist

Park Y S