The Feasibility of an Imaging Motional Stark Effect Diagnostic for MAST-U

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Proposal Objective

This proposal provides details on a research collaboration undertaken as part of the Fusion Center for Doctoral Training (CDT). The project is proposed between Miss Sam Gibson of the Center for Advanced Instrumentation (CFAI) at Durham University and Prof. John Howard and Dr Clive Michael of the Plasma Research Laboratory (PRL) at Australia National University (ANU) in Canberra, Australia.

Background and Motivation

A main objective of the Mega Amp Spherical Tokamak Upgrade (MAST-U) program is to "add to the knowledge base of the international fusion experiment ITER". ITER is the next step on the road map to a demonstration fusion power plant (DEMO). Research in the core scope of the next MAST-U campaign include pedestal physics, current drive and performance limiting MHD instabilities; an understanding of these physics aspects can be achieved through fusion diagnostics and significantly improve performance of these future fusion devices [1]. Motional Stark Effect (MSE) polarimetry measurements are particularly important for facilitating q profile tailoring, which optimizes stability and fusion performance. The collaboration proposes a feasibility study for an imaging motional Stark effect (IMSE) diagnostic for MAST-U. An IMSE system can provide 2 dimensional measurements of edge current pedestal profiles [2], q profiles and aligns directly with core research themes for MAST-U.

The primary focus for this collaboration is to use the IMSE hardware currently at ANU, which was previously used to acquire 2D edge current measurements on the K-STAR tokamak. Collaboration will provide an opportunity to understand the calibration processes required to optimize the diagnostic for measurements on a spherical tokamak and the opportunity to scope out the feasibility of such a diagnostic on MAST-U. This will hopefully lead to further collaboration with the ANU group on building a full polarimeter system for MAST-U. Building a diagnostic requires some modeling of particular features that will be captured. In this case, this entails modeling of the Stark spectra similar to that observed by the MSE diagnostic on MAST-U, whilst including realistic plasma equilibrium and neutral beam geometries. This model can be compared and integrated with models created by the ANU group on assessing non-ideal Stark-Zeeman coupling effects on MSE measurements. Modeling provides the groundwork for instrument design and an assessment of its capabilities. As previously stated, the primary focus is to use the specialist hardware available at ANU. Most of this modeling work can be done before and after the ANU visit, but comparisons to the unique models at ANU would be beneficial.

The Motional Stark Effect diagnostic is used routinely in fusion devices to infer the internal magnetic field, as well as the evolution of current and q profiles. These parameters play an important role in determining plasma stability and provides constraints for plasma equilibrium. As a form of non-inductive current drive, high energy neutral deuterium or hydrogen atoms are injected across the magnetized plasma, which induces a strong electric field $\mathbf{E} = \mathbf{V} \times \mathbf{B}$ in the rest frame of the beam atoms. Collisions between the background plasma and neutral beam atoms gives rise to orthogonally polarized and stark split light emission; when viewed perpendicular to the $\mathbf{E}$ field, the Δm=0 transition (π emission) is linearly polarized parallel to the electric field and the Δm=$\pm$1 transition (σ emission) is linearly polarized perpendicular to the $\mathbf{E}$ field. The MSE diagnostic measures the orientation of this polarized emission and thereby provides a spatial measurement of the local magnetic pitch angle [3].

In a conventional MSE optical setup, a pair of photoelastic modulators (PEM) and polarizer encodes polarization information as an amplitude modulation. A collection lens focuses light into a series of optical fibers, each having a radial viewing position across the plasma. The light passes through a filterscope, which is a collection of lenses and a narrowband interference filter and images light onto an avalanche photodiode (APD). The conventional MSE system is shown for MAST in Fig.1, with 36 filterscope channels and a spatial resolution of 2.5cm [4]. However, conventional systems has some limitations:

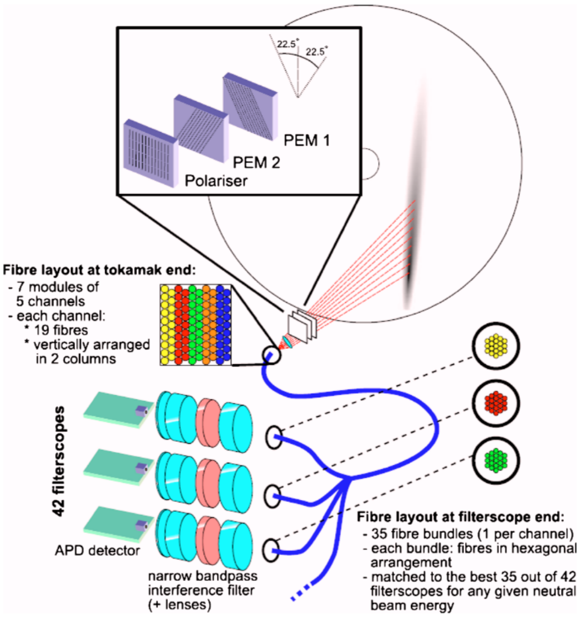

Figure 1: The MAST-U conventional MSE system [4].

- Spherical tokamaks such as MAST have a smaller magnetic field than conventional machines. Stark splitting is heavily dependent on field strength, so characteristic π and σ spectral features tend to overlap on MAST. Discerning polarization fractions can be difficult, but is required to fully resolve Stokes vector components and hence the polarization angle. Narrowband pass interference filters are required for each radial channel to isolate either the π or σ polarized emission, depending on their relative strengths, which can be expensive and inflexible. This limits the resolution of conventional systems to 20-40 spatial measurements.

- Doppler shift varies with neutral beam voltage and with the viewing angle between the line of sight and neutral beam. Fiber bundles need to be re-patched to alternative filterscopes to provide optimal wavelength matching with the narrowband filters. The change in Doppler shift is also more prevalent on the inboard side where the angle between the line of sight and beam axis is small. Large variations in neutral beam voltage over the course of a pulse inhibits measurements [5].

- Routine measurement of polarization angle is conceivable though inferring the magnetic field B and current j_ϕ profiles require a priori knowledge of equilibrium plasma parameters. These are obtained by constraining plasma equilibrium solvers such as EFIT++ with MSE measurements. B_z and j_ϕ measurements independent of an equilibrium solver is desirable and has been achieved with IMSE systems on other fusion devices.

Imaging MSE Diagnostic

An imaging MSE (IMSE) diagnostic uses a CCD camera to capture a 2D snapshot of the neutral beam, containing spectral and polarization information. The setup is shown in Fig.2. The concept is based off a simple interferometer system, where the information on the polarization orientation of the incoming light is encoded within the fringe contrast and phase of an interferogram. A pair of birefringent plates are joined together (Savart plate) with their optical axes rotated by 90° with respect to one another. The Savart plate introduces a phase shift, dependent on the incident angle, between the ordinary and extraordinary components. The two components are recombined by a polarizer, producing an interference pattern in the image plane. The two orthogonal components are π and σ emission, which incur a phase difference of 180° and have equal intensities, and so destructively interfere. A secondary fixed delay plate is added before the Savart plate to introduce a large phase delay τ between the two components. The plate is chosen such that τ is optimized for constructive combination of π and σ emission [7].

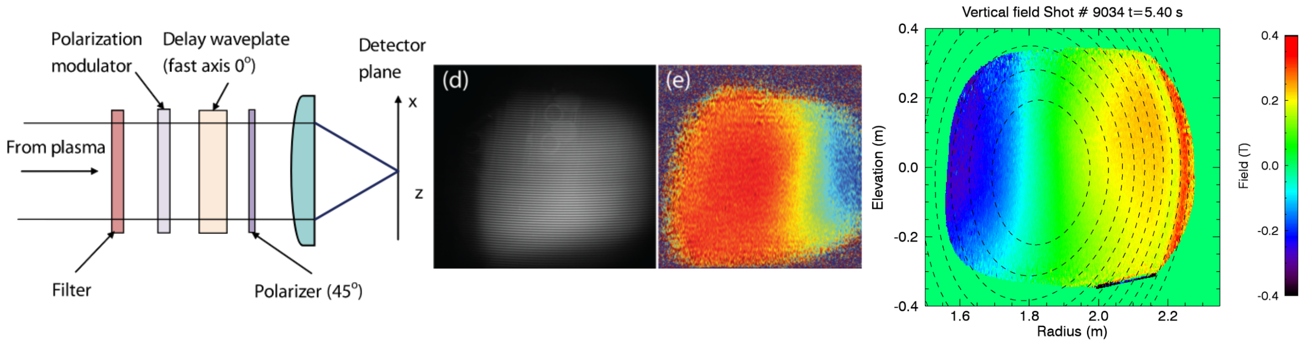

Figure 2: **Left:** Optical setup for an imaging MSE system. **Center:** Filtered neutral beam image taken on KSTAR and extracted phase image. **Right:** Reconstructed 2D $\mathbf{B}_z$ before a type I ELM on KSTAR. The dashed lines are overlays of magnetic field surfaces generated from EFIT [2].

The main advantages to this diagnostic are: Narrow-band filters are unnecessary as all of the MSE multiplet is used for measurement, an insensitivity to broadband polarized background light and non-statistical population of the Stark states (which effects beam into gas calibration of conventional MSE systems [9]. IMSE also has the potential to supply measurements such as: 2D current density profiles, synchronous imaging of sawteeth oscillations, MHD effects, ELMS (dependent on temporal resolution) and q profile evolution. Robust measurements of these parameters with a good understanding of their uncertainties are crucial for constraining plasma equilibrium and mitigation of plasma instabilities [10] [2] [12].

Project Outline

1. *Simulation of Stark Spectrum*

To successfully model the IMSE diagnostic for MAST-U, a simulation of the stark spectrum is required. This simulation needs relevant port geometries and neutral beam parameters (geometry, beam divergence, power fluctuations and voltage). The MAST-U MSE simulation code can be used and compared with models produced by ANU researchers which contain further atomic physics models currently not considered.

2. *Instrument design and optical component optimization*

Creation of a model of the IMSE system is required to optimize design and fully characterize instrument uncertainties. Faraday rotation can cause a systematic drift of polarization angle, induced by a change in magnetic field. Usually the diagnostic is situated between toroidal field coils, causing an inhomogeneity of the magnetic field across the collection optics. By optimizing the Verdet constant of the glass used in the port window, this affect can be minimized. This would also be beneficial to characterize for the conventional MSE system. The optical transmission of the system will need to be optimized with respect to the camera specifications (such as the magnification and positioning.) The specifications of a CCD camera that would be used with the system are required to optimize instrument design. Specifications equivalent to those of the MAST-U Doppler imaging diagnostic would suffice. It is also worth noting any access limitations to narrow down port availability which could hinder measurement capability. This modeling work will assist the experimental lab work in that we will understand how the optical setup needs to be modified for use on a medium sized spherical tokamak and specifically

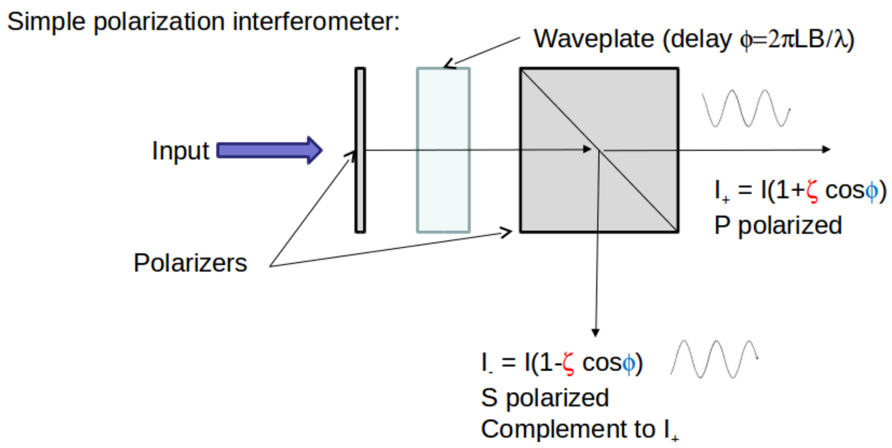

Figure 3: Optical arrangement to produce an approximate MSE spectrum as an input to the IMSE diagnostic. Input light passes through a waveplate to introduce a phase shift between orthogonal π and σ polarized components, then combine with a polarizer to produce a simplified version of the MSE spectrum. This may require extra optical components to match the line width and small peak separation of the spectrum as seen on MAST [6].

for MAST-U. There will be a much lower light intensity than in larger tokamaks and an overlapping spectra which can be difficult to discern - how do these issues affect the experimental design?

3. *Instrument building, testing and measurements*

The main benefit of this collaboration with ANU is the use of their IMSE hardware which was previously used at the K-STAR tokamak. This work will take up the majority of the time at ANU. A simplified version of the MSE spectrum can be built using a basic polarization interferometer (filters and a polarizer as shown in Fig.3). This is where the modeling of the stark spectra is put into context. It provides a basis for comparison to the lab generated simplified MSE spectrum. Then, instrument response is tested against against known polarized light sources in the lab. It is also necessary to determine the spatial and temporal resolutions of the system. Test the temperature sensitivity, as the refractive indices of the wave plates are dependent on temperature. The diagnostic must be calibrated using a known wavelength light source similar to that of the MSE emission, usually using a neon lamp.

Project Timeline

The Gantt chart in Fig.4 gives a breakdown of the project timeline. Some work is to be prepared beforehand at CCFE. At the end of the trip, feedback and presentation of work is important to both the ANU group, CCFE and at the CDT Sandpit to show the positive research outcomes as a result of the joint funding.

Risk Mitigation

It is necessary to consider any risks involved with undertaking a research collaboration and actions to mitigate the severity of the impact. An overview of the risks involved with the project are contained in Table 1. The risk has been evaluated in accordance with the impact-likelihood risk matrix [13]. Given that IMSE has not been implemented for a spherical tokamak before, there is a risk that measurement difficulties could arise due to overlapping of the π and σ spectral lines. However at ANU the PRL group developed the theory for this technique and have successfully implemented several IMSE systems at KSTAR in South Korea, D-IIID in the US and assisted with IMSE at ASDEX Upgrade in Germany. These systems have focused on physics aspects such as 2D edge current measurements on KSTAR [2] and

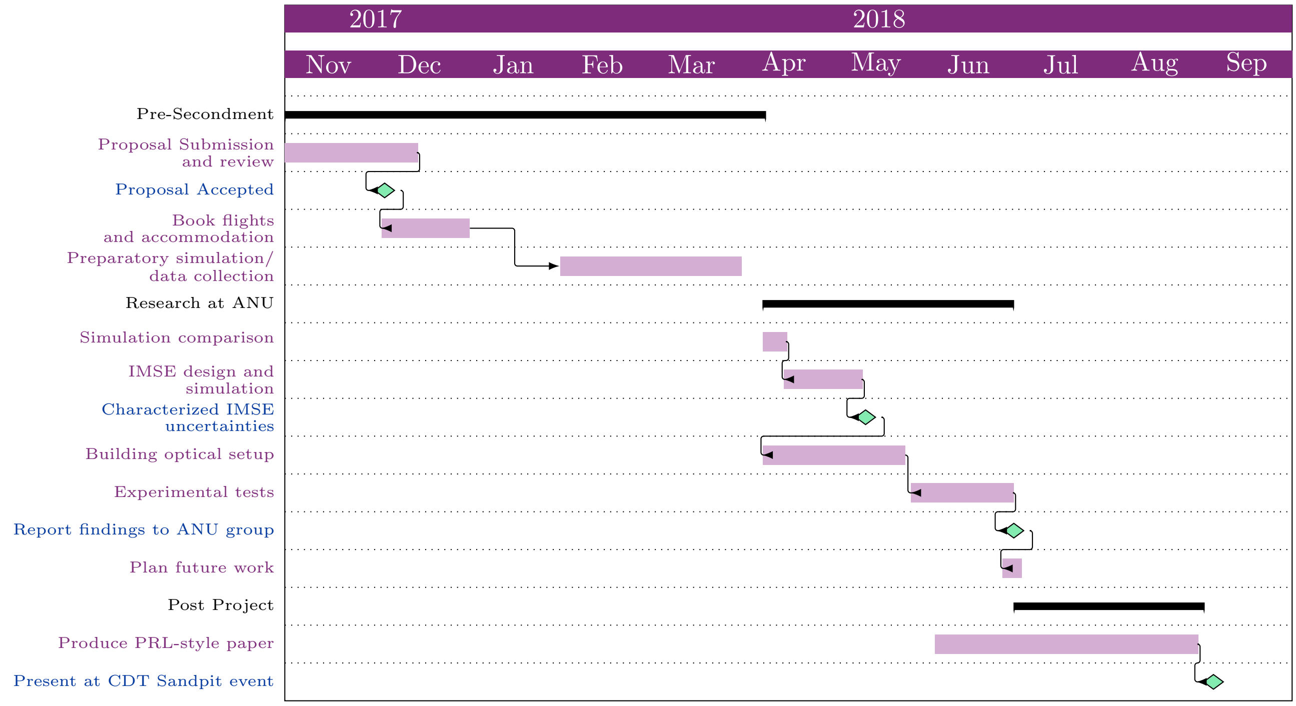

Figure 4: A Gantt chart denoting breakdown of proposed work and milestones to achieve.

core measurements at ASDEX for resolution of current redistribution during sawteeth [7], therefore the proof of concept for the diagnostic itself is sound. We may however need to make modifications to the design, though our fellow collaborators believe these will not make IMSE an implausibility for MAST-U.

Ferro-liquid crystal (FLC) waveplates are used for the Savart plate and switch the sign of the polarization angle on the order of 1μs, which could introduce a systematic uncertainty in the polarization angle measurement between successive images [8]. They might not have the tolerances specified by the manufacturers, so testing these components to accurately determine the actual switch in phase shift is required. Most of the optical setup is made from off the shelf optics, which should already be in good condition. Another risk is the MSE spectrum is tricky to replicate in the lab, however it is possible to test instrument response again similar known polarized light sources. Finally, considerations need to be taken to ensure that data is successfully backed up to cloud or external sources such as Github daily. It would be prudent to upload all necessary data and codes to Github and an external hard drive device. This mitigates the risk of being unable to get remote access to CCFE, which is likely given the distance between the research institutions. There are no intellectual property (IP) disputes, as the instrument theory and set up have been widely published prior to collaboration and the possibility of patenting or selling the technology is low.

Project Impact

A collaboration with ANU presents an opportunity to demonstrate a proof of concept prototype IMSE system for MAST-U, which provides an order of magnitude more data than a conventional MSE diagnostic, with improved signal to noise. This will be the first opportunity to deploy an imaging MSE system on a tight aspect ratio tokamak. As aforementioned, edge and pedestal physics is within the core scope of the MAST-U research plan and any improvement to edge current measurements would complement my research on similar measurements made with the conventional MSE system.

The major focus for the collaboration would be for experimental purposes: Building an IMSE optical setup, understanding the alignment and calibration processes, uncertainties and the post processing de-

Risk	Impact	Likelihood	Category	Mitigation
Equipment fault	5	1	Low	ANU check equipment is ready for use.
Difficultly in optical assembly	3	1	Low	Researchers have prior experience in designing/building IMSE.
Remote access issues	5	3	High	Bring relevant codes and data to ANU so that remote access is not essential.
Transport delays	1	2	Low	Extended time at ANU to 12 weeks.
Data corruption/loss	5	1	Low	Backup daily using Github repository

Table 1: Risks associated with research project and efforts to minimize impact of these risks.

modulation techniques. Working with Prof. John Howard who theorized and has implemented multiple IMSE diagnostics means I will be able to gain the necessary technical experience in order to further the work myself back at CCFE. It would not be possible to gain this experience anywhere else, as Prof. Howard and Dr Michael at ANU are the world leaders in this technology. IMSE is a relatively new diagnostic and so there are only a smaller number of researchers in the area.

The use of the comprehensive atomic physics model of the MSE spectra developed by PhD student Alex Thorman at ANU will be invaluable to understanding polarization angle measurement uncertainty of both the IMSE and conventional systems, leading to suggestions for future improvements to both systems for MAST-U. The idea that the Stark states are not equally statistically populated below certain plasma densities has not been taken into consideration for the MAST-U MSE system and though the effect is thought to be small, it would be very useful to gain this insight from Alex and the team at ANU whilst visiting. Again, the majority of the necessary modeling work will be completed before going to ANU. Remote computer access to Australia would be difficult and it would be much more beneficial to discuss and use the codes in person with the developer. This could be achieved through videoconferencing, however the time difference means meetings are sporadic and inconvenient. This collaboration provides good groundwork and proof of concept for further grant proposals to build a full polarimeter system for later in the MAST-U campaign. As the specifics into an IMSE system for a spherical tokamak have not yet been addressed, the possibility of publishing results is high.

Personal Development

This collaboration will foster positive working relationships between ANU and the MAST-U team, as well as allowing me to work with other experts in the field that I would not otherwise be able to. The project also provides the opportunity to undertake research at another world leading institution with the researchers who invented the system. The development of this diagnostic will form a significant portion of my thesis work, and opens up avenues for different directions my thesis could take. This is particularly beneficial due to the delay in the MAST-U timeline, as this work can be undertaken outside of a tokamak physics campaign. This work will hopefully continue collaboration between CCFE and ANU via future applications to research grants to take this work further. One other IMSE system is currently on ASDEX Upgrade in Germany, however they use a different optical setup and demodulation method for data analysis. By using the collaboratory funds to visit further afield to ANU and gain experience with researchers who advised and assisted ASDEX-U with their set up, I am then in the position to collaborate with ASDEX-U in the future through the Eurofusion MST framework, which would further improve the impact of my work.

Expense	**Type**	**Cost (GBP)**	**Comments**
Flights	*Travel*	£880	Newcastle ->Canberra ->Newcastle
Transfer	*Travel*	£50	Required transport to reach accommodation
Accommodation: ANU student accommodation	*Living*	£1920	£160 /week includes utilities
Accommodation Fees	*Living*	£377	Deposit
Living Costs	*Living*	£1000	∼£80/week for food/all other living necessities
Visa	*Visa*	£0	Free e-Visa subclass 651
Unforeseen Costs	*Living*	£250	Allowance for underestimated living costs or emergencies
Total (without ANU stipend)		**£4477**	
ANU stipend		**-£2400**	(paid directly to accommodation)
Total (minus ANU stipend)		**£2077**	

Table 2: Table showing a breakdown of living and travel costs for the collaboratory. The total cost is given in red, and the requested CDT contribution is shown in green, after the ANU stipend is taken into consideration.

Funding Requirements and Budget

Funding Sources

The PRL group at ANU have generously proposed that they will provide up to $350 (AUS) a week, which will cover the majority of the accommodation costs and allows for a 12 week project. This is slightly longer than the usual collaboratory project, though it is directly related to current research and has the approval of primary supervisors. An overview of all expenditure can be found in Table 2 using the current exchange rate between GBP to AUS dollars (£1:$1.71) and has remained relatively stable for the past year.

Travel Expenditure and Accommodation

The current cost of a flight between UK airports and Canberra are currently £850 depending on provider (Emirates, Qantas Airways and Singapore Airlines are all around this price) priced by Skyscanner and Expedia. The flights will be taken in off peak season which reduces the cost. Travel to and from UK airports is £40 fuel and Canberra airport to ANU accommodation is around $90(AUS) in taxi fares. The applicable visa is an eVisitor (subclass 651), which are free and allows the holder to "enter Australia for up to three months during each visit during the 12 months from the date the eVisitor is granted" provided they have a United Kingdom British Citizen passport [14]. Accommodation is sought from the university. The price quoted is that for standard self catered accommodation including all utilities (gas/electric/water/internet) [15]. Booking and pricing of accommodation is currently being discussed with ANU administration staff. This option is cheaper than those listed on AirBnB (£1500 per month) and hotels (£2100 per month), and is safer than hostels/sublets making it easier to fulfill any requirements to be covered via university insurance.

Summary

Imaging MSE systems have shown that they can robustly provide a 2D measurement of polarization angle in conventional tokamaks. Through collaboration with the pioneers of the underpinning theory and experimental IMSE systems at ANU, the proposed project provides an opportunity to expand the diagnostic capabilities of MAST-U which would be invaluable to many tokamak plasma research areas.

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