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Exploring Runaway Electron mitigation systems in the STEP Tokamak

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Contents

1. Nomenclature

A list of key words and their relevant definitions pertaining to tokamaks, plasmas and my research. If not cited otherwise, the following definitions were obtained from the official Nucleus website for UKAEA.[1]

Tokamak	The most successful device yet found for magnetic confinement of plasma. Its magnetic field consists of helical lines lying on toroidal surfaces, and is generated both by external field coils and by the current in the plasma
Spherical Tokamak (ST)	A spherical tokamak works in the same way as conventional tokamaks, but it holds the plasma in a more compact magnetic field, shaping it more like a cored apple than a donut
Spherical Tokamak for Energy Production (STEP)	A nuclear fusion project, run by the UK Government, aiming to produce an operational Spherical Tokamak Fusion reactor by 2040
Joint European Torus (JET)	Joint European Torus, sited at Culham. The world's leading tokamak, capable of mimicking the geometry of ITER, and having associated facilities such as power supplies and tritium plant
International Thermonuclear Experimental Reactor (ITER)	ITER is the world's largest and most advanced fusion experiment. It will be the first magnetic confinement fusion device to produce a net surplus of thermal fusion energy. ITER is currently being built in southern France within an international collaboration between China, Europe, India, Japan, Korea, Russia and the USA
Mega Ampere Spherical Tokamak Upgrade (MAST-U)	The upgraded Mega Amp Spherical Tokamak (MAST-Upgrade) facility at Culham Centre for Fusion Energy is one of the medium-sized tokamaks that contributes to EUROfusion experiments. It's the first tokamak to trial the innovative Super-X divertor - an exhaust system that handles higher power from particles leaving the plasma
Disruption Runaway Electron Analysis Model (DREAM)	"A fluid-kinetic framework for tokamak disruption runaway electron simulations"[2]
Runaway Electron (RE)	In a plasma, the collisional friction force experienced by an electron is inversely proportional to it's velocity squared. 'Since collisional friction is often the dominant braking force felt by most electrons, a constant accelerating force of sufficient strength would increase the energy of the electrons indefinitely and cause them to "run away" '.[3]
Magnetohydrodynamics (MHD)	A mathematical description of the plasma and magnetic field, which treats the plasma as an electrically conducting fluid. Often used to describe the bulk, relatively large-scale, properties of a plasma.
Disruption	A complex phenomenon involving MHD instability which results in rapid heat loss and termination of a discharge. Plasma control may be lost, triggering a vertical displacement event in which the apparatus may be damaged, particularly in large machines. This phenomenon places a limit on the maximum density, pressure and current in a tokamak.
Thermal Quench (TQ)	Rapid loss of plasma thermal energy following a disruption event due to increased MHD activity.[3]
Current Quench (CQ)	A period of decay of the current in a plasma following a thermal quench, due to the reduction in the plasma conductivity. [3]
Disruption mitigation System (DMS)	A system designed to ideally prevent, but at a minimum mitigate, the effect of a disruption event in a tokamak i.e. suppress runaway electron generation
Idealized Impurity Injection (III)	Injection of large quantities of gases into a plasma uniformly as a disruption mitigation system
Shattered Pellet Injection (SPI)	Injection of shattered frozen pellets into a plasma as a disruption mitigation system
Runaway Electron Mitigation Coil (REMC)	A magnetic coil which deconfines REs in a tokamak to suppress their generation.[4]

2. Technical Overview

The United Kingdom Atomic Energy Authority (UKAEA) is a Government research body focusing on developments in the field of plasma physics and nuclear fusion. It is based south of Oxford at the Culham Centre for Fusion Energy (CCFE) and has been since its creation in 1965. The principal achievement of UKAEA has been the JET device, the world's first Deuterium-Tritium fusion demonstration and largest magnetic confinement device, operated since 1983. Over JETs 40 year lifespan, it has conducted more than 103 000 pulses (up to 10s each), and broken numerous records. More recently, UKAEA built the MAST-U experiment to explore the fusion capabilities of spherical tokamaks, knowledge which is invaluable to the development of STEP.

My placement was undertaken from the 22/08/2022 until 21/08/2023 and I was to investigate the avoidance or mitigation of Runaway Electrons (RE) in STEP. My university placement supervisor was Prof. Zsolt Podolyak, with my workplace supervisors being Dr. Alexandre Fil and Dr. Sarah Newton. To facilitate my research I used the DREAM code, a relatively novel but advanced code that was purpose built to investigate REs during plasma disruption events. Utilizing preliminary work and input files from my supervisor, I began simulating Idealized Impurity Injection (III) as a possible Disruption Mitigation System (DMS) in a STEP scenario. Throughout my placement I would extensively modify the input files to model Shattered Pellet Injection (SPI) and a Runaway Electron Mitigation Coil (REMC) as possible DMS's. I enhanced the scripts used to read and display the simulation data, further creating functions to generate an animation of the movement of the SPI shards through the plasma for example.

I produced an academic poster and have started writing an academic paper in conjunction with Dr. Fil for the International Atomic Energy Agency (IAEA) fusion energy conference. The poster was based on all the research prior to the SPI modelling, and was presented at the IOP 49^{th} Plasma Physics conference in Oxford at the end of March 2023 (Appendix A). Following my SPI simulations, we began a paper detailing all of the research I had conducted. The paper is due to be completed and submitted for peer-review to the Nuclear Fusion journal, early 2024. Additionally, I attended the Oxford University Collisional Plasma Physics course, the Princeton Plasma Physics Laboratory (PPPL) online Introduction to Plasma Physics and the CCFE Plasma Physics summer schools in April, June and July 2023 respectively.

Plasma physics and tokamak science is an advanced field of research and I had to conduct a significant amount of background reading into the theory. I will limit to introducing integral topics and explain them at a general level in order for any reader of this report to attain a brief but sufficient understanding.

3. Investigating the use of SPI as a possible DMS for STEP

3.1. Aims & Objectives

- Assess the viability of SPI as a DMS for STEP
- Evaluate DREAM simulations as a tool to influence STEP design decisions
- Increase my personal proficiency in coding for physics based purposes using Python, C++ and high performance computing facilities
- Elevate my understanding of the workflow required for professional and applied physics simulation and research

3.2. Supporting Theory

$$^2H + {}^3H \rightarrow {}^4He + n \tag{1}$$

An alternative energy source to fossil fuels is the nuclear fusion of two isotopes of Hydrogen, Deuterium & Tritium. To overcome the electrostatic repulsion between the nuclei, they need to be at temperatures in the order of kilo-electron-volts (keV), far exceeding their ionization energies. At these temperatures atoms are fully ionized into a collection of positive nuclei and negative electrons known as a plasma. A tokamak utilizes the charged nature of plasma constituents and a combination of magnetic fields to confine a plasma. A toroidal field generated from the toroidal field coils (seen in blue, Figure 1), directs the plasma around the tokamak in the toroidal direction. A central solenoid induces a voltage sufficient to drive Mega-Amperes (MA) of current in the highly conducting plasma, subsequently generating a poloidal magnetic field (seen in green, Figure 1). The combination of the toroidal and poloidal fields create a helical magnetic field confining the plasma. The magnetic field lines can be shown to circulate in the plasma following nested toroidal-like surfaces called flux surfaces (example surface seen in pink, Figure 1). Flux surfaces are characterized by a constant poloidal magnetic flux across a surface[5]. A set of outer coils (seen in grey, Figure 1) are there for further plasma control and shaping.

Plasmas in a tokamak can become unstable due to MHD instabilities culminating in disruption events. Disruptions, if not avoided or mitigated, can lead to the reactor being terminally damaged. Disruptions follow a standard series of events. MHD instabilities lead to a loss of magnetic confinement and the plasma loses most of its thermal energy. This 'Thermal Quench' (TQ) sees the plasma temperature drop from keV's to eV's in a matter of miliseconds. The conductivity of a plasma is a function of its temperature and with the rapid temperature drop in the TQ, a subsequent decrease in the conductivity occurs. The ohmic current being driven through the plasma will begin to decay in the presence of this conductivity decrease. This 'Current Quench' (CQ) is opposed by an induced large electric field which will begin to accelerate electrons in the plasma. For MA current tokamaks, the induced electric field will far exceed a critical

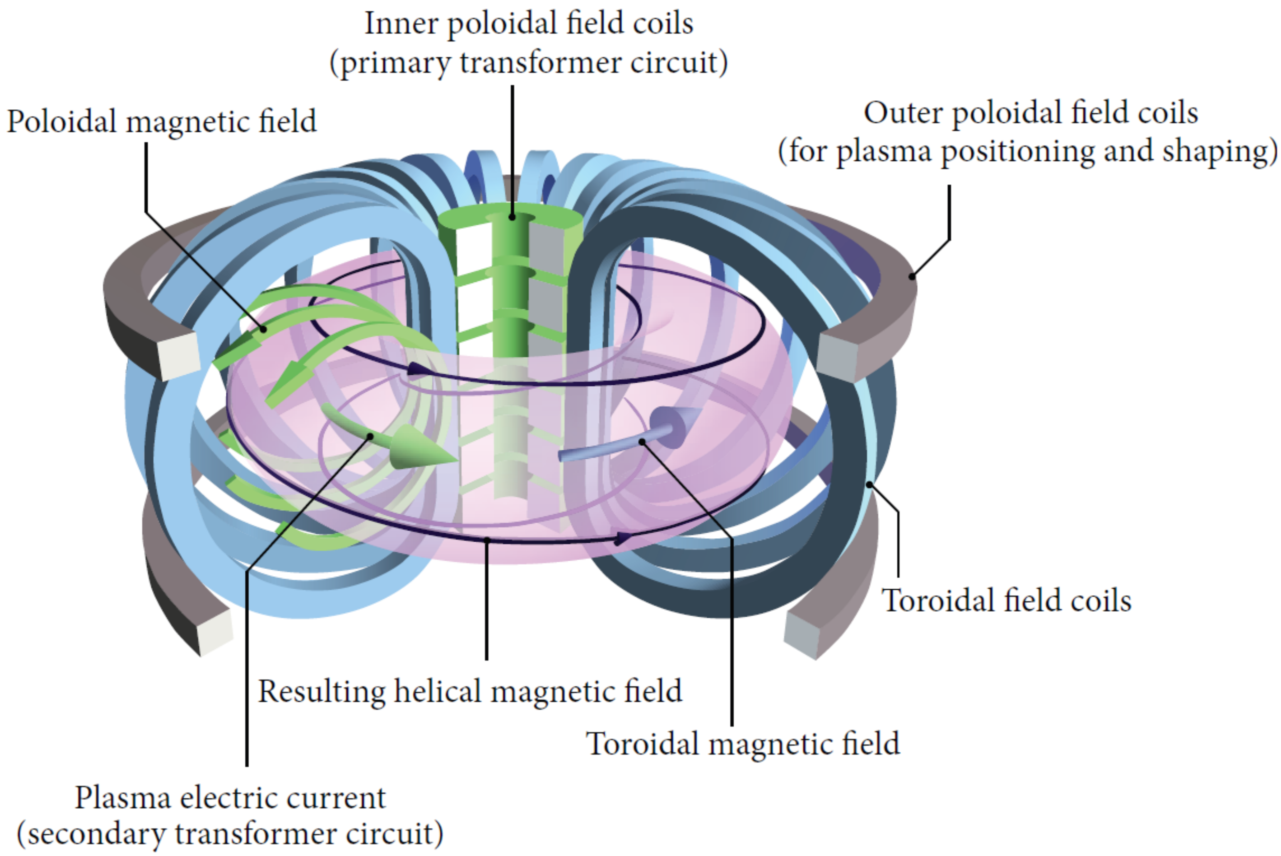

Figure 1. Standard magnetic confinement tokamak layout. [6]

magnitude, generating so many REs at significant fractions of the speed of light that they will carry most of the pre-disruption ohmic current. Once the ohmic current fully decays, a RE beam will form and remain in the tokamak in the final 'Runaway Plateau' phase section of a disruption event (see Figure 2).

Disruptions give rise to the following physical mechanisms and forces:

- Large thermal loads during the TQ which can melt the plasma facing components
- Halo & eddy currents + magnetic forces in conducting structures which can exceed structural limits
- Possible RE beam impact on plasma facing components (see Figure 3)

To mitigate these effects of a disruption, an adequate DMS is required. Current design choices focus on the injection of Deuterium and Noble gas to reduce the loads and suppress RE generation. The Massive Gas Injection (MGI) system sees the impurity material injected into the plasma in gaseous form. Drawbacks such as rapid material assimilation at the plasma edge, sees MGI being ineffective for larger fusion plasmas. Alternatively, frozen pellets of the same material can be shattered and fired into the plasma from a number of injectors at various locations around the tokamak. This SPI

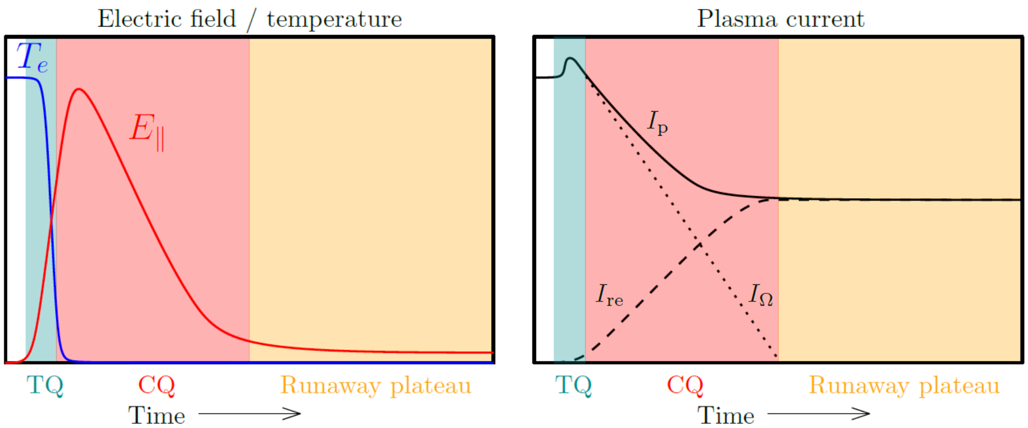

Figure 2. Typical electric field, electron temperature and plasma current evolution during a disruption. Division into 3 phases: Thermal Quench, Current Quench, Runaway Plateau.[3]

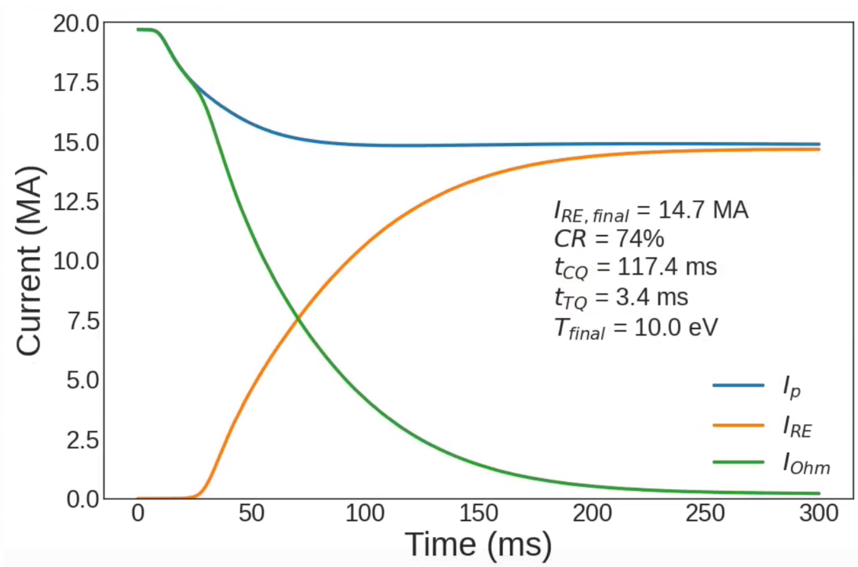

Figure 3. Current evolution during an unmitigated disruption scenario in DREAM. Majority of pre-disruption plasma current is carried by REs post disruption exceeding RE current maximum limits.[7]

sees a better core penetration of the impurities where it can provide the most efficient RE generation suppression. An SPI system is the design choice for STEP (see Figure 4) and the primary subject of my investigation and placement project. The aim was to find an injected material sequence that would keep the disrupting system within the operational limits of component power loading and structural forces.

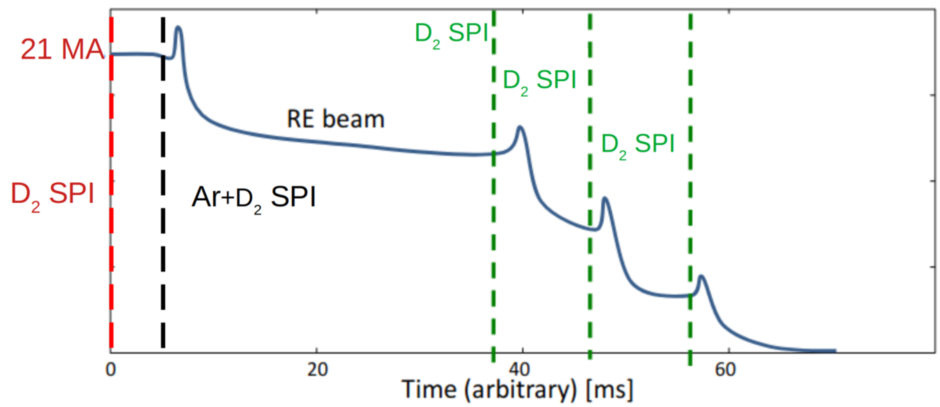

Figure 4. STEPs current SPI strategy. Ideally an incoming disruption will be detected early enough by the plasma control system, which will trigger up to 12 SPI injectors containing pure Deuterium. During/before the TQ, a second stage of up to 15 SPI injectors will be fired containing a mixture of Argon and Deuterium (molar fraction of 20%). Finally multiple subsequent Deuterium SPIs will be fired in an attempt to reduce the RE beam. Note: Only the first and second SPI's are modelled in DREAM.[8]

In typical fluid dynamics, the friction force experienced by a particle will typically increase linearly, or quadratically, with the particle velocity, giving rise to a terminal velocity. However, in plasmas, the friction force experienced by an accelerating electron initially increases linearly with the particle velocity. Once a critical velocity is surpassed, the collisional friction force decreases with increasing velocity. An electron exceeding the critical velocity will experience a diminishing drag force as it accelerates and hence 'run away' to relativistic speeds. An electron population in a steady-state fusion plasma can be characterized by a Maxwellian distribution. The critical velocity denotes the minimum velocity at the start of the 'runaway region', where an electron will undergo runaway phenomenon when accelerating. The minimum electric field required to start accelerating electrons at, or above the critical velocity, is known as the critical electric field. During a disruption, a large electric field is induced due to the decaying current which will likely exceed the critical value leading to RE generation (see Figure 5). There are 4 primary mechanisms for RE generation during a disruption in the presence of an electric field greater than the critical value:

1. **Dreicer** - Electrons in the runaway region of the electron distribution function accelerate to higher energies and become REs. Lower energy electrons will diffusively leak into the high momentum runaway region to re-equilibriate the distribution to a Maxwellian, further becoming REs themselves.
2. **Tritium Decay** - Tritium undergoes beta decay, generating electrons with a continuous energy spectrum. These electrons could have sufficient energy to be in the runaway region and become REs.
3. **Compton Scattering** - By-product nuclear fusion neutrons will excite atoms in the first wall structures. De-excitation of these atoms release gamma rays which

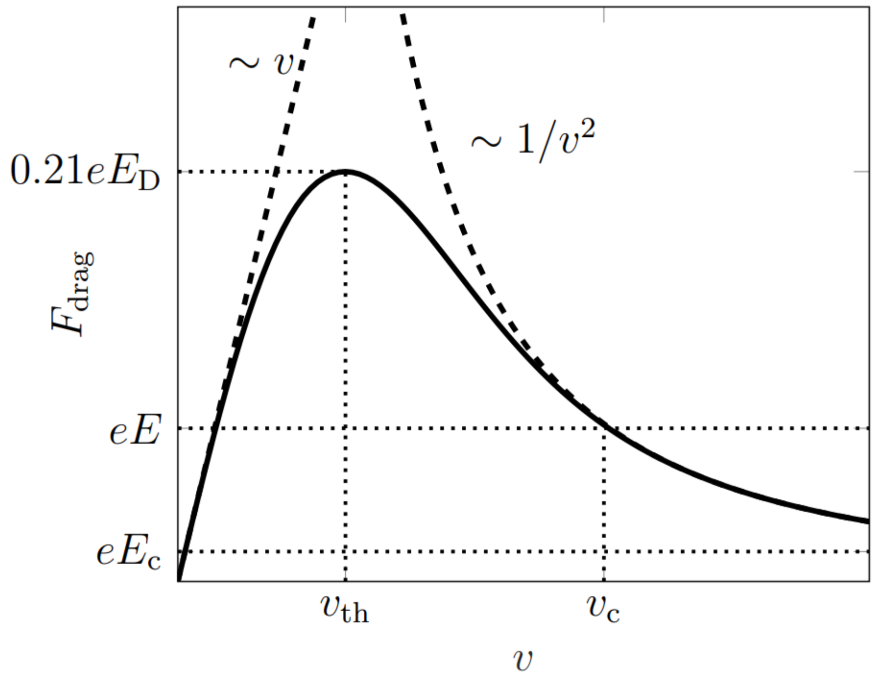

Figure 5. "Illustration of the drag force felt by an electron moving through a plasma as a function of velocity. The presence of an accelerating electric field [E] creates a runaway region at velocities larger than [v_c], where the drag force becomes weaker than the accelerating electric force. The Dreicer field [E_D] and the critical electric field [E_c] are also marked."[5]

can compton scatter with electrons in the plasma, pushing them into the runaway region.

4. **Hot-Tail** - During the TQ, hot, high energy electrons might not be able to thermalize due to their collision timescale being longer than that of the TQ time. Electrons with such a high energy will find themselves in the runaway region once the electric field increases during the CQ.

Once a small RE seed population is generated, a secondary mechanism occurs. Electrons that have been accelerated into REs via primary mechanisms will likely collide with lower energy electrons, additionally accelerating them into the runaway region. This will lead to an exponential growth, or 'Avalanche' of the RE population, which contributes the most to overall RE generation.

3.3. Simulation Setup

The SPI simulations were run using the DREAM[2] code on the Cambridge Service for Data-Driven Discovery (CSD3) high performance computing cluster. Four input files were used:

1. **DREAM_run**: Bash script to run the simulation on the CSD3 cluster using the 3 following files

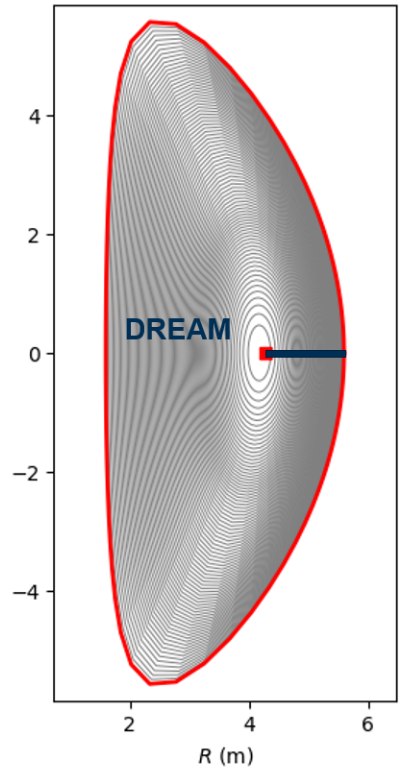

Figure 6. STEP equilibrium with flux surfaces generated from FIESTA simulations. DREAM models one spatial dimension from plasma center to plasma edge via flux surface averaging.[7]

2. **SPR045.h5**: SPR-045 Free-boundary equilibrium data and plasma profiles from external simulation codes FIESTA and JETTO
3. **SPR045.py**: Python file containing a list of key variables and parameters of STEP, and simulation setup
4. **driver.py**: Python file specifically setting up the plasma scenario and DREAM simulation environment

The specifics of designing a plasma scenario and exact STEP plasma parameters are both outside the scope of this report and confidential information. In brief, to run a simulation, DREAM is supplied with information about the planned STEP plasma parameters, generated by other codes, via the input files. Using the input parameters DREAM constructs a virtual plasma with a single spatial dimension (Figure 6) simulating the plasma center to the outboard plasma edge. Typical parameters for an operational scenario are a plasma current of 19.7MA, core electron temperature of 2x10^5 eV and toroidal magnetic field strength of 3.2 Tesla.

3.4. Methodology

A full DREAM simulation of an SPI scenario contains multiple restarts. The simulation is restarted to either change settings e.g., enable radial electron transport, or to set SPI shards into motion. Restarting the simulation is a product of the DREAM code architecture, where the settings cannot be set in advance. The order of a full simulation is as follows:

1. Initialization restart
   i. Constructs plasma scenario and spatial grid
   ii. Length = $1\text{x}10^{-11}$ seconds
2. Init restart
   i. Sets up final DREAM settings and initializes SPI shards outside of plasma
   ii. STEP plasma self consistently evolves in time
   iii. Reflects the downtime between detecting an incoming disruption and triggering the first SPI
   iv. Length = $3\text{x}10^{-3}$ seconds
3. First SPI, Deuterium pellets restart
   i. First SPI shards set in motion
   ii. DREAM models shard motion, assimilation and subsequent self-consistent plasma evolution
   iii. Length = $4\text{x}10^{-3}$ seconds
4. Second SPI, Argon & Deuterium pellets restart
   i. Second SPI shards set in motion
   ii. DREAM models shard motion, assimilation and subsequent self-consistent plasma evolution
   iii. Length = $2\text{x}10^{-2}$ Seconds
5. CQ and runaway plateau
   i. DREAM models self-consistent plasma evolution following multiple SPIs
   ii. Length = $1.5\text{x}10^{-1}$ Seconds

Simulations were judged against a list of criteria based on limits that are needed in order to prevent damage to the tokamak (Table 1). For example, the planned wall of STEP, made of Tungsten, can withstand up to 60 $MJ.m^{-2}.s^{-0.5}$[9] before melting and as such, a successful DMS should limit the peak Heat Impact Factor (HIF) below this maximum. STEP's current DMS envisions up to 12 Deuterium injectors and 15 Argon + Deuterium (20% molar fraction) injectors. Combinations of injectors that could be used characterized the discretized parameter space I was to scan over (Table 2) to assess its performance regarding the avoidance of REs. Excluding scenarios where the second SPIs fail, 12x15 multi-injection + 15 single injection simulations were conducted, for a total of 195 simulations.

Table 1. STEP DMS criteria

Parameter	**Criteria**
Runaway Electron Current	$I_{re} \leq 0.5MA$
Thermal Quench time	$1 \leq t_{TQ} \leq 10ms$
Current Quench time	$20 \leq t_{CQ} \leq 120ms$
Peak Heat Impact Factor	$HIF_{peak} \leq 60MJ.m^{-2}.s^{-0.5}$
Radiation Fraction	$Rad_{Fraction} \geq 0.9$

Table 2. SPI impurity densities

SPI Material	**Atoms**
1^{st} SPI: Deuterium	$5\text{x}10^{23} \leq NinjD \leq 6\text{x}10^{24}$
2^{nd} SPI: Argon	$1.57\text{x}10^{22} \leq NinjAr \leq 2.36\text{x}10^{23}$
2^{nd} SPI: Deuterium	$7.7\text{x}10^{22} \leq NinjAr_D \leq 1.15\text{x}10^{24}$

3.5. Results

The output data of an example simulation is seen in Figure 7. A sharp electron temperature decrease during the TQ is seen due to first Deuterium SPI (velocity prescribed to $400ms^{-1}$ at $t = 3ms$) diluting and rapidly cooling plasma. The second SPI, of Argon + Deuterium, is prescribed with a velocity of $200ms^{-1}$ at $t = 7ms$. The fastest shards of the second SPI cross the q=3 flux surface at $11ms$, where $\delta B/B$ is prescribed as 1.8×10^{-3} for $1ms$. The RE current, density & generations rates, electric field and radiation, all increase following the second SPI. A background $\delta B/B$ of 4×10^{-4} remains during the CQ and runaway plateau, for heat transport. Analyzing all 195 simulations, no operating window was found that satisfied all of the DMS criteria (see Figure 8). All the simulations satisfied the $Rad_{Fraction}$ and t_{TQ} constraints. 12 simulations satisfied the t_{CQ} constraint. However, all simulations failed to satisfy the I_{re} and HIF_{peak} constraints.

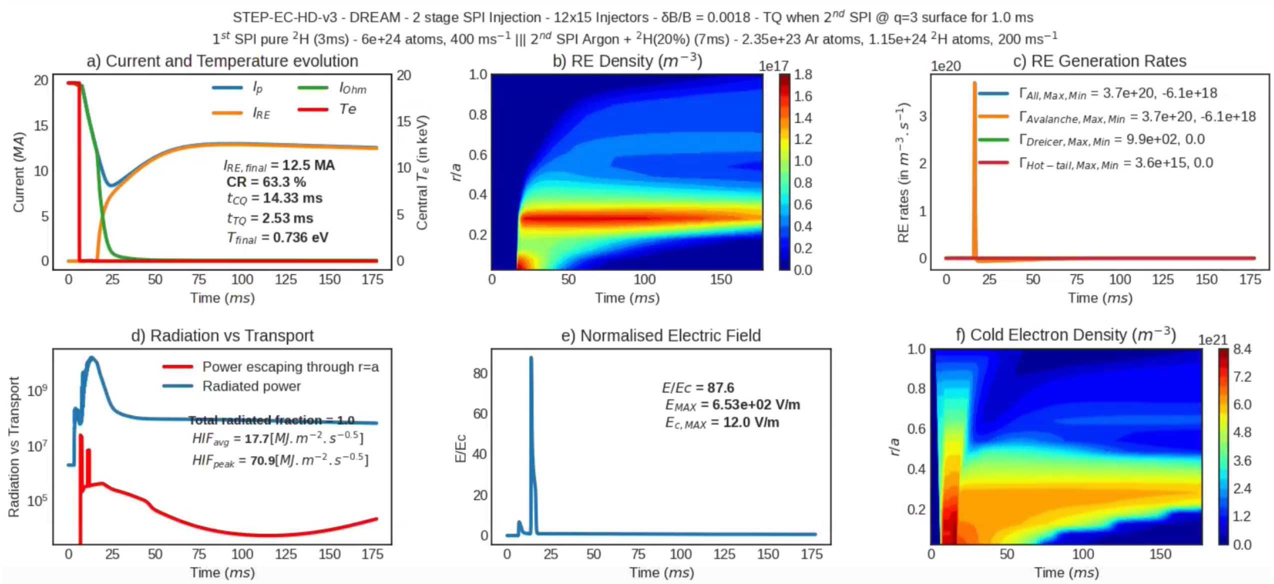

Figure 7. Typical DREAM SPI simulation data. Simulation setup and settings displayed in the title e.g., specific plasma profile, $\delta B/B$ settings and SPI parameters. All DMS criteria data is displayed including various other parameters e.g., electron densities, normalised electric field evolution and RE generation rates during the simulation. Data, in plots b) & f), are graphed in time and a single spatial dimension, noted r, usually normalised by the radius of the plasma (a = 1.45m here, see Figure 6) . Data, in plots a) & e), is taken at the innermost radial grid point, or the plasma core. Data, in plots c) & d), are quantities integrated over the radius, or taken at r=a.

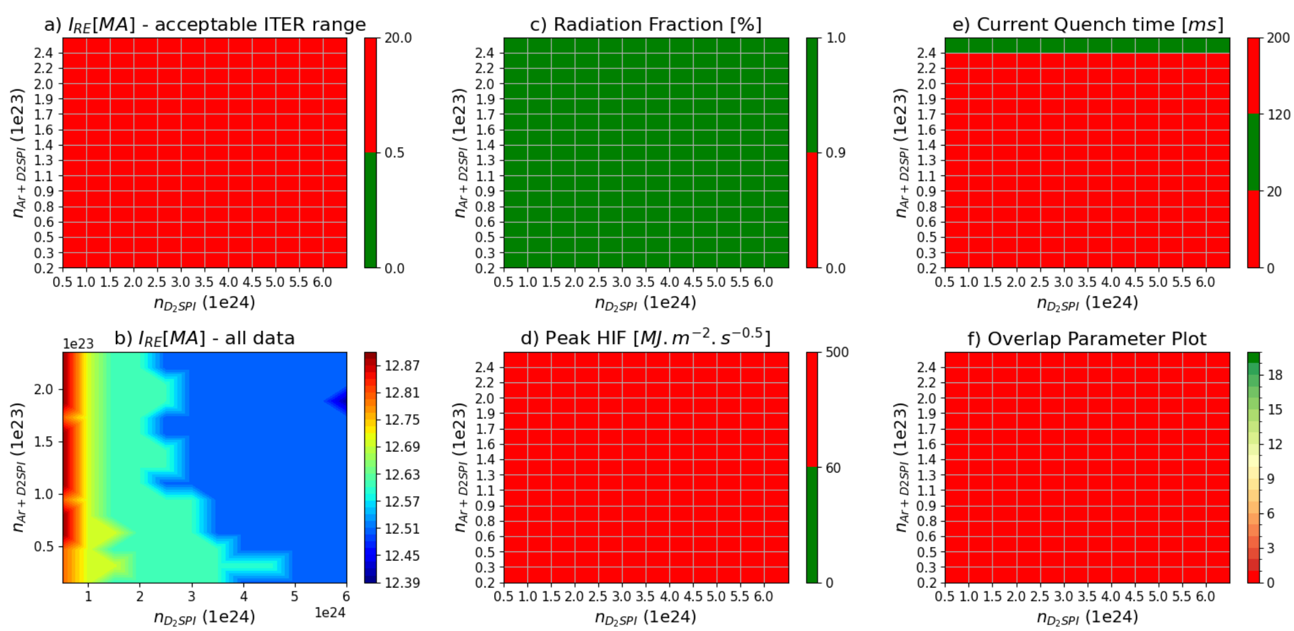

Figure 8. SPI 12x15 injectors scan data. Simulations are graded with green indicating a DMS target being met. b) Final RE current data is displayed via a contour plot, over the parameter space, with all values lying within $12.6 \pm 0.3MA$. f) All criteria data overlapped and plotted for cross simulation and parameter analysis.

3.6. Discussion

There is a significant lack of distribution of the output data considering the wide range of injected material used. Such variation can be seen in the previous III simulations[10] (see Appendix A), with impurity densities approximately $10^1 - 10^3$ less than that of the SPI injections. This is indicative of over saturation and motivates further simulations with reduced injected densities to verify this.

Numerous free parameters had to be prescribed based on experimental scalings or modelling which includes MHD processes. The data, simulations, and theory to support choices of free parameters was at many times uncertain/unknown and the values that were chosen constitute the best guesses at the time of research. An example is the radial electron transport coefficients due to magnetic perturbations (which depend on $\delta B/B$) and its related settings. In these DREAM simulations, the magnitude of $\delta B/B$ is prescribed as constant, for a fixed period of time (1ms), when the fastest SPI shards reach a flux surface with a specific magnetic field pitch, denoted q=3. We know that $\delta B/B$ evolves in time due to MHD activity following material injection in a tokamak[11][12][13]. It was also seen in a prior III study that the $\delta B/B$ settings have a significant impact on I_{re}[10]. However, to properly simulate the evolution of $\delta B/B$ a code such as JOREK must be utilized, as MHD modelling is outside the capabilities of DREAM. Such modelling has been done for the SPARC reactor and contrasts the simplified setup we used for $\delta B/B$[11]. Simulations for JET[13] and ITER[14] show that the TQ begins (and hence when to activate $\delta B/B$ due to flux surface breaking) when the fastest second SPI shards reach the q=2 flux surface, however STEP doesn't have a q=2 surface. SPI research, including the aforementioned for ITER, is currently focused on ITER's strategy of a base Neon pellet. The research into Argon based pellets (STEP strategy) is minimal, and as such, Neon SPI data was used to construct our statistical fragmentation model. While these simulations and data cannot be used to inform accurate choices for the DREAM simulations, their influence improves the estimations we had to make for the research.

Table 3 contains other DREAM free parameters and parameters that require optimization. With so many free and optimizable parameters, which have a supportive but not a strong theoretical and/or experimental backing, the accuracy of the simulations are undoubtedly affected. To what extent is difficult to yet quantify. It can be said qualitatively, that they were choices informed by the best available research and theory and likely didn't degrade the efficacy of the research to a great extent. Consequently, it would be imperative to conduct follow up research into the parameters to better support future SPI simulations of STEP.

Table 3. DREAM SPI optimization and free parameters

Optimization parameters	Free parameters
Mean shard speed	Background $\delta B/B$
Divergence angle (SPI tube)	$\delta B/B$ activation time
Width of the uniform shard speed distribution	$\delta B/B$ activation duration
2^{nd} SPI doped with Deuterium (20% molar fraction)	$\delta B/B$ magnitude
Time delay between 1^{st} & 2^{nd} SPIs	
Use of DREAM SPI 'Parks NGS ablation model'[15]	
Use of DREAM SPI 'Local deposition model'	
Statistical fragmentation model[13][16][17][18][19]	

Simulations were run in fluid mode, the weakest mode in DREAM in terms of physics integrity but with a considerably lower computation time. Recently, fluid DREAM simulations have been shown to overestimate the dreicer, and significantly overestimate the hot-tail RE generation rates, compared to simulating in the most comprehensive, fully kinetic mode in DREAM. Additionally, a lack of kinetic ionization modelling yields a reduced number of free electrons leading to an increase in REs. Furthermore, fluid modelling overestimates the heat transport as it only simulates a single electron population[20]. Lastly, the tritium and compton scattering mechanisms were neglected due to the lack of the required supporting data to ensure appropriate simulation e.g., unknown Tritium ion density and total γ photon flux for STEP. Recently, an improved hot-tail model for a low-Z plasma has been introduced in DREAM. This should be explored in subsequent research as it is a more appropriate regime for a STEP plasma. Research also shows shaping effects can reduce the electric field and restrict the electron motion[21][22]. The SPI simulations were conducted in a cylindrical plasma geometry due computational constraints, neglecting the shaping (see Figure 6) effect of the STEP plasma, which likely increased the RE generation.

3.7. Conclusions

Current DREAM simulations for a two stage SPI system will not prevent the formation of a RE beam in a STEP-like plasma. It sets a requirement for the subsequent RE beam mitigation SPI to terminate a RE beam of 12-13MA. The planned DMS design succeeds in yielding a high radiation fraction, but vitally fails to successfully bring the I_{re}, t_{TQ}, t_{CQ} and HIF_{peak} within acceptable ranges. Consequently, the current SPI DMS approach must be improved or alternate DMS's should be explored such as the use of a REMC as is planned on SPARC[11]. Drawbacks within the DREAM code and the simulation setup (the free parameters notably), negatively impact the accuracy of the simulations but not severely. Of greatest importance is the apparent over saturation of injected impurity material in the simulations producing an unexpectedly uniform data distribution. As a result, follow up sensitivity studies should focus on exploring the injected material quantities and free parameters. STEP would benefit from additional studies with codes such as JOREK into plasma and MHD behavior during a SPI, due to the significant aforementioned simulation outcomes. The use of codes such as JOREK could be extended to investigate MHD mechanisms which have been seen to suppress runaway formation on the DIII-D tokamak e.g., resistive kink instabilities[23]. Such studies could prove beneficial as they could ease the steep RE suppression requirements for the current STEP DMS, or be coupled with DMS simulations to yield a favorable, mitigated disruption scenario.

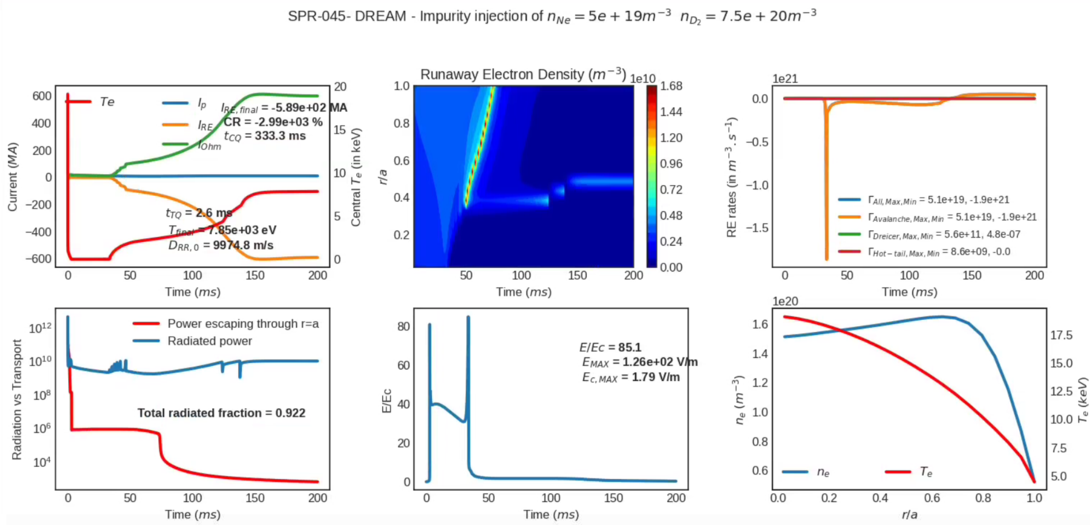

Figure 9. A DREAM simulation of III where non-physical current evolution can be seen (compared to Figure 3). Hence the simulation is deemed to "blow up".

4. Reflective Section

4.1. Personal & Professional growth

Prior to my placement, I had experience coding in python, with an emphasis on physics-orientated computation from my first two years at university. My skill set developed significantly over the course of my placement with coding, simulations and linux based operations forming the core of my work at UKAEA. Almost immediately, an error presented itself while setting up the coding environment. Learning about Linux systems and the DREAM code on the go, I independently investigated, determined the cause of the error, and implemented a non-trivial fix. The crux of the issue was the builder files of DREAM incorrectly reading the current python version as 3.1 instead of 3.10. While the issue itself may be novel, immediately attempting to diagnose a problem in the first week regarding an unfamiliar system was difficult, but very rewarding when my resilience paid off.

Further into my placement, while conducting research into a STEP DMS, simulations presented themselves with non-physical values (Figure 9). Standard analysis of the output data couldn't explain this phenomenon, so I explored parameters which are typically ignored. After various failed approaches, I explored the conductivity in the simulation, where an unrealistic evolution was present (Figure 10). DREAM employs an analytical formula for the conductivity[24], which contains the square roots of two variables. Plotting both, I found that the collisionality of the electrons becomes negative (see Figure 11), in turn, yielding an imaginary variable in the conductivity calculation and blowing up the simulation. Such error and data analysis is very important for DREAM as it is in active development, where bugs can be forwarded to the devel-

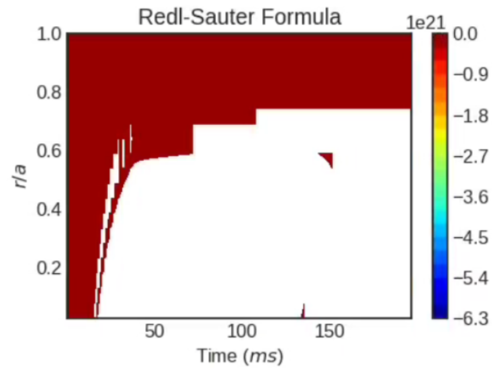

Figure 10. Plotting the Redl-Sauter analytical formula as a function of time and radius for the blow up case seen in Figure 9

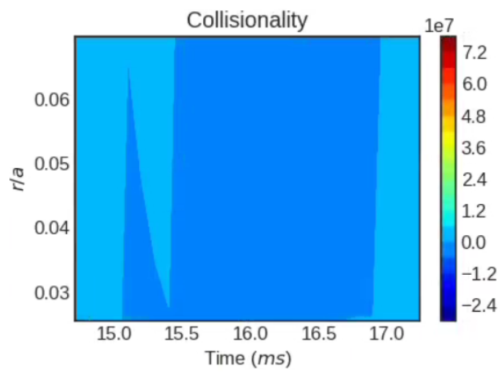

Figure 11. The collisionality of the electrons plotted as a function of time and radius for the blow up case seen in Figure 9.

opers to improve the code. For simulation data handling I employed various familiar and unfamiliar Python modules. I learned to use new modules such as pandas[25] and h5py[26] with tabulated data, while also increasing my experience with modules such as matplotlib[27] creating animations of SPI in the simulations. This development culminated in scripts which are multi-functional and enable easy data analysis and simulation assessment, essential for analyzing the hundreds of simulations required in the scans.

Research that is conducted needs to be documented and reported, particularly for proper STEP workflow. My supervisors highly endorsed my learning of LaTeX typesetting for document creation, software I was completely unfamiliar with. Subsequently, I began documenting the work I carried out weekly in a LaTeX document. This allowed me to track all the tasks I carried out over my placement in parallel to learning how to use LaTeX. Importantly, after conducting the SPI simulations, myself and my supervisor are co-authoring a paper mostly detailing my research into DMS simulations for STEP. The learning of LaTeX document creation, combined with the paper writing, has given me invaluable insight into the workflow required for proper scientific research and publications. This was compounded by STEP work reporting requirements where I worked jointly with my supervisors to summarize and record the work we conducted into 'Programme Increment Reports'. This provided me with additional insight into the design workflow at an organizational level.

4.2. Personal Development plan

A personal achievement has been acquriring an understanding of REs and their mitigation research. This knowledge exceeds that of a superficial layer and has greatly facilitated my project of exploring RE mitigation for STEP in DREAM. To further this strength, I plan to conduct further reading into RE research in existing devices such as JET, TCV and DIII-D, as most of my current knowledge is applied to theoretical plasmas e.g., STEP modelled in DREAM. While my RE knowledge has proven to be very valuable, the tight focus of the topic alone would not give broad exposure to the field of plasma physics and tokamak science. I proactively combatted this by attending the 49th IOP Plasma Physics conference, and presented a poster on my research. Furthermore, I attended the MMathPhys 'Collisional Plasma Physics' course at Oxford University run by my supervisor, Dr. Newton. The course explored plasma behavior from a mathematical standpoint, an area I had little exposure to during my placement. Finally, I attended both the PPPL (remotely) and CCFE (in person) summer schools for plasma physics in June and July respectively. They covered plasmas & magnetic confinement fusion in depth while also teaching other areas of plasma physics e.g. low temperature plasmas, space physics, particle acceleration.

Another key strength has been my enhanced coding proficiency, specialized in using the DREAM code. Such proficiency has not only facilitated my placement project, but it has allowed my supervisor to delegate a significant quantity of work to me. Being able to carry out these tasks autonomously has eased workloads on my supervisor. However, a weakness that arises is my fine tuning of my coding skill set to specific python modules, a specific coding language and a very specific code, DREAM. DREAM itself is a very novel and relatively unknown code and my usage/understanding is still regarded as limited. DREAM is constructed with a python interface for researchers, and a C++ mathematical and simulation backbone suitable for code developers. In this respect, my enhanced knowledge of python and its modules is very useful for aiding my work relating to data handling and analysis, where the language is very widely used in scientific work and is an excellent transferable skill to future projects. However, an extensive amount of the DREAM code was inaccessible to me due to my novice understanding of C++. It would be very prudent for me to begin learning other coding languages such as C++, which would improve my general coding practices as well as developing a coding skill set which is multi-lingual.

4.3. Future Progression

Prior to my placement, my knowledge and aspirations for plasma physics were minimal to non-existent. I was attracted to this placement as the project aimed to contribute to the goal of achieving commercial fusion energy, a clean energy source which holds significance for me personally. However, my personal reading into the field, my simulation work, my attendance to the aforementioned university and summer school courses, and the general exposure to the field of fusion research, has shifted my perspective and future prospects. I have come to find that I have a significant amount of personal interest in the field of plasmas and an enjoyment of coding which I was unaware of prior to the placement. As a result, I have solidified my decision to carry out postgraduate training - I am currently exploring multiple Masters/PhD courses, and postgraduate employment schemes all with a relation or focus on plasma physics.

Additionally, my perspective on the use of physics in the workplace has been dramatically shifted. I used to be quite uncertain about how physics-focused my future career would be. I presumed my physics knowledge wouldn't be directly applied in most jobs, where business practices would take precedence instead. While working at UKAEA, this uncertainty has dissipated. I have experienced a work culture seeing physics beings utilized and applied daily. Some employees focused heavily on research while others hold more corporate responsibilities but nonetheless physics oriented. Furthermore, seeing and experiencing the width of the expanding fusion industry gives me confidence in the wide variety of career opportunities available to explore for a plasma physicist prospective like myself. For example, while I worked more in a research role, I attended a talk by Sachin Desai (Helion Energy)[28] where he presented a talk on the regulatory framework for fusion energy and the significant work going into law and economy aspects of fusion and fusion energy devices. It was incredibly interesting learning about the work done in this little known, but vitally important area of physics, and how regulators and lawyers for fusion companies need to have specialist knowledge of the physics to carry out their roles.

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Exploration of mitigation systems for disruption generated Runaway Electrons in a STEP concept

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Introduction

- A significant threat is posed by the formation of relativistic Runaway Electrons (**RE**) during disruptions in the Spherical Tokamak for Energy Production (**STEP**)[1]
- Disruption induced RE beams have been observed to cause critical damage to the Plasma Facing Components structures (**PFC's**) on low megampere devices such as JET[2]
- Disruptions have been simulated using the advanced DREAM code[3] in a STEP preferred concept with a predicted operating current of > 20 MA
- Unmitigated scenarios see the generation of a no less than 10 MA RE beam. An impact of this beam would exceed the predicted first wall structural integrity limits and cause terminal damage to the PFC's which will need replacing[4]

DREAM

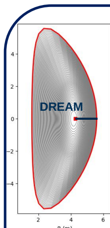


Fig. 1: STEP equilibrium modelled in DREAM, shaping effects included

- **D**isruption & **R**unaway **E**lectron **A**nalysis **M**odel
- State of the art flux-surface averaged 1-D code
- Advanced RE generation rates: Dreicer, Hot-tail, Tritium decay, Compton Scattering & Avalanche mechanisms

DREAM STEP inputs:

1. **FIESTA** Free-boundary equilibrium
2. **JETTO** Plasma profiles
3. **STEP** DMS specifications

STEP

STEP Key Parameters[1]

- I_p = 21 MA
- B_T = 3.2 T
- $T_{e,0}$ = 20 keV
- R_{geo} = 3.6 m
- A = 1.8 m
- κ ~ 3
- P_{aux} ~ 150 MW
- P_{fus} = 1.8 GW
- $n_{e,0}$ ~ 1.4x10^{20} m^{-3}
- W_{th} = 520 MJ

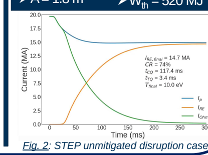


Fig. 2: STEP unmitigated disruption case

Idealized Impurity Injection

- Runaway Electron avoidance was tested using an Idealized (radially flat) Impurity Injection model with a Ne/Ar and D_2 mixture
- Radial electron transport due to field line disruption is imposed with D ∝ $(\delta B/B)^2$
- Transport is activated during a prescribed Thermal Quench time with a self consistent Temperature & Electric field evolution
- Hot-Tail RE generation dominates the primary mechanisms with a very high Avalanche factor for the secondary generation mechanism

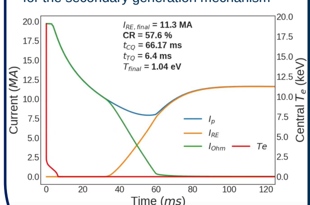


Fig. 3: Typical STEP idealized impurity injection DMS simulation: n_{Ar} = 1x10^{19} m^{-3}, n_{D2} = 1x10^{21} m^{-3}, and a magnetic perturbation of δB/B = 2x10^{-3}

Impurity Injection Scan

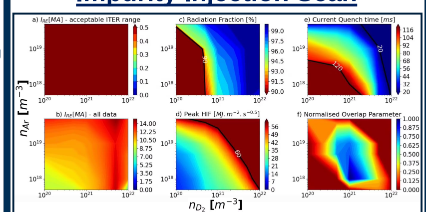


*Fig.4: Idealized impurity injection of Ar+D_2 with a magnetic perturbation δB/B = 2x10^{-3} scan. Key DMS constraints are graphed against the varying injected impurity densities. Plot **f)** combines the constraints displaying a possible operating window for the DMS (excluding RE current)*

Scans over multiple parameters:

1. Impurities: Ne + D_2 or Ar + D_2
2. Transport coefficients: *δB/B* = 2&6 x10^{-3}
3. Impurity Densities: 10^{17} ≤ n_{imp} ≤ 10^{22} m^{-3}

DMS constraints

- I_{RE} < 0.5 MA
- f_{rad} > 90%
- 20 ≤ t_{CQ} ≤ 120 ms
- HIF_{peak} < 60 MJ.m^{-2}.s$^{0.5}$

- **NO** scenario found with a I_{RE} < 7 MA
- Possible operating windows which satisfy other DMS constraints
- Neon marginally outperforms Argon in final RE current reduction
- Assumed transport coefficients are generous and uniform spatially + temporally for ideal case modelling (unrealistic)
- Overall, Idealized Impurity Injection is insufficient for runaway electron avoidance in STEP

Runaway Electron Mitigation Coil

- Effects of a Runaway Electron Mitigation Coil (**REMC**) were explored with DREAM
- REMC's, like that planned for SPARC[5], disrupt the fluxes surfaces within the plasma via external magnetic perturbations, increasing RE transport
- Within DREAM, this is modelled by imposing extra radial electron transport during the decay of the ohmic current
- Significant RE generation suppression was seen in the REMC simulations
- However, amplitude of δB/B is unknown and will vary radially (lower in the core). As such, this is an optimistic scenario

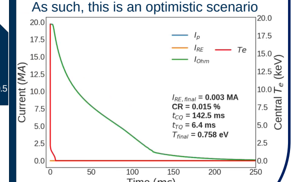


Fig. 5: Fig 3 simulation, altered with extra δB/B = 1x10^{-3} at 20ms, throughout the current quench

Shattered Pellet Injection

Multi-stage, synchronised, SPIs for loads mitigation:

1. **RE Avoidance Inj.** – Pure D_2 from HFS, 12 Injectors
2. **TQ/CQ inj.** – Argon + D_2, LFS at 4 toroidal locations (15 inj.)
3. **RE Mitigation inj.** – Pure D_2 in RE beam, 30 Injectors

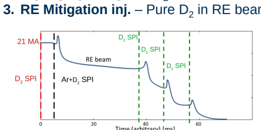
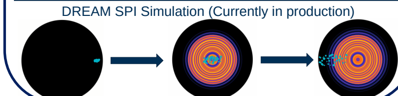


Fig. 6: Multiple staged SPI, using Ar and D_2 is STEP current disruption mitigation strategy

DREAM SPI Simulation (Currently in production)



Conclusions

- Utilizing the sophisticated DREAM code, detailed simulations can be explored for future devices such as STEP and ITER.
- Current research, conducted for STEP's latest concept, shows total runaway electron avoidance can't be achieved in a high current, reactor-grade fusion plasma.
- Novel REMC simulations provide a potential complementary DMS for STEP, offering more promising RE mitigation. With this alternate DMS, many technical, scientific and engineering challenges would have to be overcome before the system could be deemed a viable solution.
- At present, STEP is planned to have ~ 30 D_2 SPI systems for RE beam mitigation. While the capabilities of SPI systems have been verified on other fusion devices e.g. JET[6], it is paramount research is conducted on DREAM and more comprehensive codes e.g. JOREK, to validate the proficiency of an SPI system for RE mitigation in a fusion device such as STEP.

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Appendix A.

Exploration of mitigation systems for disruption generated Runaway Electrons in a STEP concept

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STEP, the Spherical Tokamak for Energy Production, is a project currently under development by UKAEA. During operation, plasma disruption events can lead to a significant generation of Runaway Electrons (RE) which have the potential to critically damage PFCs and the reactor. STEP planned operating plasma current of > 20MA increases the potential danger posed by a high Mega-Ampere Runaway beam and yields a necessity for an extensive and reliable Disruption Mitigation System (DMS). This has been corroborated using the advanced DREAM code [1], which model RE generation and evolution in addition to several other key plasma parameters, and where STEP unmitigated disruptions produce a Runaway Beam of current greater than 10MA which far exceeds acceptable limits [2]. For mitigated disruptions, idealized impurity injections have been extensively scanned over varying densities of Argon and D_2 & Neon and D_2. No scenario has been found where a RE beam of current less than 8MA can be created, while also satisfying other DMS targets such as keeping the radiation fraction above 90%, current quench times greater than 20 ms but less than 120 ms, and a Heat Impact Factor lower than 60 $MJ.m^{-2}.s^{-0.5}$ to avoid W melting during the radiation flash. It was also found that Neon provided a marginally lower RE formation and a wider operational window compared to Argon. Subsequently, additional systems must be investigated, in particular higher-fidelity modelling of pure D_2 RE mitigation Shattered Pellet Injection (SPI) [3] which is currently the primary RE mitigation strategy for both ITER and STEP. Another alternative is the use of a passive Runaway Electron Mitigation Coil (REMC) which is planned for DIII-D and is the primary RE DMS in the under construction SPARC tokamak [4]. Initial simulations with simplified magnetic stochasticity assumptions have seen outstanding success in reducing the runaway generation, however, a more detailed study is needed to assess the viability of a REMC in STEP.

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Appendix B.