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Discussing RE Mitigation in the Context of Developing SPI for ITER

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Abstract—*Nuclear fusion reactors are considered a futuristic cure to society's energy crunch, with the tokamak fusion reactor design being most prominent. Runaway electrons are a phenomenon of electrons in the tokamak fusion reactor escaping the plasma and damaging reactor walls as well as diminishing plasma performance, therein proving itself to be a major roadblock in the development of commercial nuclear fusion reactors. This paper reviews the phenomenon of runaway electrons (REs): what causes them, how they are brought about physically, and how they harm a tokamak fusion reactor. It also briefly reviews Tokamak reactors and specifically the International Thermonuclear Experimental Reactor (ITER) currently being prepped and prepared. After reviewing contemporary mitigation methods, the paper focuses on Shattered Pellet Injection (SPI), why it is chosen over other mitigation methods, and various facets of its functioning that will most effectively mitigate REs. This includes focusing on deuterium, argon and neon as the pellet materials. After reviewing the currently proposed Disruption Mitigation System (DMS) design for ITER, the paper analyses the current challenge of space distribution and speculates the alterations necessitated for SPI in the new environment of ITER along with effects that the new environment will have on SPI data which has been experimentally derived from smaller reactors in the past. The paper assists in the development of DMS for ITER evaluating the best mitigation method, its specifics in application and solving logistical issues in this DMS like space congestion.*

1.1: Introduction

Currently, a lot of research has been taking place in the field of Tokamak fusion reactors, with the latest being on the commission of the International Thermonuclear Experimental Reactor (ITER) [2]. Runaway electrons (REs) are electrons that have gained enough kinetic energy to escape the plasma of the reactor through various perpetual cycles of acceleration. These REs may significantly damage the inner walls containing the plasma's components and also disrupt plasma functioning, significantly lowering plasma performance. Several mitigation methods for this are currently being experimented upon, with Shattered Pellet Injection (SPI) having a significant success and positive feedback for simulations of the unprecedentedly large ITER environment. This paper aims to review the production, threat, and mitigation of REs along with arriving at solutions for the limitations presented in current literature.

1.2: Background of Tokamak Reactors

In a magnetic confinement nuclear fusion facility, the central element is the Tokamak, the Russian acronym for a Magnetic Toroidal Chamber. It is a donut shaped enclosure which is initially evacuated. Several groups of coils surround the Tokamak, called the Toroidal field coils. Their superconducting windings must carry a huge current in the toroidal direction. The toroidal coils generate an extremely intense magnetic field inside the chamber. Under such conditions, when a Deuterium and Tritium plasma is injected into the chamber, all the particles are forced to follow helical trajectories, twisted along the field lines. This prevents the plasma from getting close to the chamber walls.

The plasma must be heated up to the order of 100 million degrees kelvin. Part of the work is done by a second set of coils, called the central solenoid. The same principle governs the interaction between the plasma and the central solenoid. When an intense variable current flows through it, all the particles, the deuterium ions, tritium ions, and electrons are vigorously accelerated; the positive ions in one direction, and electrons in the opposite direction. The collisions between particles increase the energy of the plasma, that is its temperature which can read 10s of millions of degrees. The desired temperature is reached using additional heating methods such as radiating the plasma with electromagnetic waves of suitable frequencies as in a huge microwave oven and bombarding the plasma with jets of high energy neutral deuterium atoms.

Now deuterium and tritium atoms will have enough kinetic energy to overcome their mutual electrostatic repulsion and come into close contact and fusion reactions will occur, giving out energy much higher than that invested in heating the plasmas.

1.3: Understanding Runaway Electrons

Dreicer mechanism:

Runaway electrons (REs) are generated in tokamaks when the energy loss of electron collisions with plasma does not compensate for the externally induced electrical force of the coils winding, As these accelerated electrons continue to gain energy, they enter a runaway phase wherein their energies are in a significantly increased state, up to several million electron volts (MeV). The runaway electrons can then escape from the magnetic confinement of the Tokamak, due to their high state of energy and resulting momentum, these electrons can cause serious structural damage to the reactor. This is known as the Dreicer mechanism.

Avalanche mechanism:

The avalanche process in Tokamak fusion reactors is another mechanism in charge of producing runaway electrons. This technique causes the plasma's electrons to accelerate quickly through a self-reinforcing process.

The high-energy electrons' interaction with the background plasma must be conceptualised to comprehend the avalanche mechanism. Electron collisions take place regularly in plasma. These collisions can occasionally give an electron enough energy to move it into a higher energy state. If the plasma already contains a few high-energy electrons, these electrons can now act as a source of further energy for other electrons. An electron with higher energy can provide some of its energy to an electron with lower energy when they collide, giving the latter electron more energy and moving it towards a higher energy state.

A chain reaction comparable to an avalanche is started by this technique. When newly energised electrons collide with lower-energy electrons, they receive additional energy since they are now at a higher energy level. As a result, an increasing number of electrons acquire energy and accelerate. With a rise in high-energy electrons, the avalanche mechanism accelerates. This is due to the increased likelihood of collisions and energy transfer. The number of runaway electrons increases quickly as the process goes on, and their energies can reach several MeV.

As a result of a few high-energy electrons colliding with lower-energy electrons, the avalanche mechanism of runaway electron creation results in a chain reaction of energy transfer. In the Tokamak plasma, this causes a rapid acceleration and a rise in the number of runaway electrons, which create the threat of damaging the inner walls of the reactor along with disrupting plasma performance.

Hot-tail mechanism:

A third mechanism contributing to the production of runaway electrons is the 'hot-tail' mechanism. This mechanism depends on the existence of a population of extremely energetic electrons with a certain energy distribution known as the "hot tail."

A collection of high-energy electrons that are much more energetic than the plasma's average electron energy is referred to as the hot tail. The tail end of the electron energy distribution is often where these high-energy electrons can be found.

Now, these high-energy electrons in the hot tail can encounter a distinctive interaction in the presence of a powerful electric field, such as the toroidal electric field in a Tokamak. The electrons are pushed in a specific direction by the electric field, which applies a force to them.

These hot tail electrons may more easily withstand the frictional forces brought on by electron collisions because of their high energy. They are therefore able to absorb more energy from the electric field, accelerating even further.

A positive feedback loop drives the hot tail mechanism. The population of high-energy hot tail electrons grows as they gain energy and accelerate. As a result, the high-energy electrons and electric field interact more strongly, accelerating the acceleration process.

Because of this, some of these runaway electrons have the potential to reach a very high energy level, in the range of several MeV. Due to their ability to escape magnetic confinement and damage the Tokamak vessel, these runaway electrons present considerable concerns.

1.4. Exploring damage caused to the reactor due to Runaway Electrons

Runaway Electrons pose a major threat to damage the reactor, causing physical damage, disruptions in plasma stability, and contributing to adverse effects on plasma performance.

Upon escaping the plasma in a Tokamak fusion reactor, Runaway Electrons can collide with the walls of the reactor, leading to the transfer of energy and heat. This transfer of energy can cause damage to the Tokamak reactor, particularly to the materials comprising the reactor walls.

Upon collision, the high energy of the Runaway Electrons is rapidly transferred to the wall material through various processes. One primary mechanism is based on the electronic stopping power [5] of the reactor's walls. In this, the high-energy electrons interact with the atomic electrons of the wall material, transferring their energy to these electrons. This energy transfer results in the excitation and ionisation of the wall materials, leading to several damaging effects. These primary damaging effect is material erosion - where the intense energy flux causes the surface of the wall to erode, resulting in a loss of material and compromising the structural integrity of the reactor's walls over time, surface melting - wherein energy deposition from runaway electrons can cause the surface temperature to rise significantly, surpassing the melting point of the material, again causing the wall material to erode or ablate, and creating the possibility of the formation of a molten layer over the wall material.

The depth of the melting depends on factors such as the energy of the runaway electrons, the duration of the energy deposition, and the thermal properties of the specific material. When considering mainstream metals used in Tokamaks, such as beryllium and tungsten, the depth of melting can vary. Beryllium has a relatively low melting point of about 1,287 degrees Celsius (2,349 degrees Fahrenheit), therein its melting depth due to the energy deposition from runaway electrons is of the order of a few micrometres. However, the order of melting depth of Tungsten is only a fraction of a micrometre, this is due to its melting point being much higher at about 3,422 degrees Celsius (6,191 degrees Fahrenheit).

The repeated impact of high-energy runaway electrons can also cause structural damage beyond just the melting of materials lining the walls. This includes the formation of cracks and surface roughness. These effects can further compromise the integrity of the reactor walls and necessitate maintenance or repair to ensure the safe and efficient operation of the Tokamak fusion reactor.

These issues show why mitigating the damage caused by runaway electrons is a vital aspect of Tokamak design and operation. Mitigating methods, such as using materials with high melting points and exploring advanced wall coatings, are being investigated to enhance the resistance of reactor walls to the energy deposition from runaway electrons. Additionally, optimising the magnetic field configurations and employing control techniques to suppress runaway electron formation can help minimise the impact of runaway electrons on the reactor walls. These methods will be explored in a subsequent section of this paper.

In summary, when runaway electrons collide with the walls of a Tokamak fusion reactor, the transfer of energy and heat occurs. This can result in material erosion, surface melting, and structural damage to the reactor walls. The depth of melting depends on factors such as the energy of the runaway electrons and the thermal properties of the specific material.

2.1: Contemporary Disruption Mitigation Methods

In order to minimise the impact of runaway electrons in Tokamak fusion reactors, several strategies are being investigated [6, 8, 12]. Shattered Pellet Injection (SPI) and externally applied perturbation fields that allow for time consuming methods like Reversed Loop Voltage and Collisional Dissipation at lower impurity levels and Runaway Beam Control are three noteworthy methods.

Shattered Pellet Injection (SPI):

As mentioned in the previous section, one of the primary causes of runaway electrons is the Drecier mechanism wherein electrons accelerate enough to escape the plasma due to inadequate collisions resulting in inadequate friction to compensate for the acceleration generated by the externally generated electrical force in the reactor.

To combat this, small solid pellets, such as neon or argon, are injected into the plasma. The technique is labelled ‘Shattered Pellet Injection’ (SPI). As these pellets interact with the plasma, they rapidly vaporise, creating a dense cloud of impurities. This causes the electrons in the plasma to undergo frequent collisions with the cloud of impurities, resulting in the dissipation of energy to the impurity particles. Therein increasing the collisional friction experienced by the electrons, the generation of runaway electrons is mitigated.

SPI is the successor of the Massive Gas Injection (MGI) technology which involved the usage of high-speed gas jets instead of injection shattered pellets that functioned by increasing the volume of the plasma, decreasing the plasma density and temperature and thereby disrupting thermal energy deposition.

The success of SPI as a mitigation strategy has been demonstrated in various fusion reactor experiments, including some studies conducted at the Joint European Torus (JET)[4]. At JET it was confirmed that SPI leads to increased collision frequencies between runaway electrons and the impurity cloud, resulting in significant energy dissipation of runaway electrons, resulting in reducing the overall impact of runaway electrons on the plasma and improving the stability of the fusion reactor. The ITER research program recognizes the importance of controlling runaway electrons and has included SPI as a potential approach for mitigating their effects.

It is worth noting that the specific choice of material for the pellets in SPI depends on several factors, including the plasma conditions and the desired impurity cloud characteristics. Different materials have different ionisation and vaporisation properties, which can influence the collisional drag experienced by runaway electrons. Careful optimization of the pellet size, injection rate, and pellet trajectory is necessary to achieve the desired mitigation effects.

In summary, Shattered Pellet Injection (SPI) is a mitigation strategy that involves injecting small pellets of solid or frozen material into the plasma to generate an impurity cloud. The impurity cloud increases collision frequencies between runaway electrons and impurity particles, leading to energy dissipation and reduction in the population of runaway electrons.

Externally Applied Perturbation Fields:

Perturbation fields are disturbances applied to a system, applied perturbation fields in the context of Tokamak fusion reactors mean externally induced changes to the magnetic field. These fields, such as resonant magnetic fields or magnetic perturbations[9], are externally generated and applied to the plasma.

One form of perturbation fields is resonant magnetic fields. These fields, created by introducing specific magnetic configurations matching the natural oscillation frequency of the runaway electrons change the trajectory of runaway electrons, causing them to experience enhanced pitch angle scattering (changes the electrons’ trajectory relative to the magnetic field lines). This scattering prevents runaway electrons from gaining excessive energy by causing them to lose energy through collisions with other particles in the plasma. Thus reducing the impact of REs on plasma facing components like the walls lining the plasma.

Magnetic perturbations involve the intentional modulation of the magnetic field of the reactor. The diversion of the trajectory of runaway electrons is produced by controlled variations in the magnetic field's strength and direction through externally applied coils. It is this modulation of the magnetic field that can increase the collisionality and pitch angle scattering experienced by runaway electrons, leading to the above mentioned energy dissipation and mitigation of their impact.

Externally applied perturbation fields have been studied extensively in various fusion devices, including experiments conducted on the DIII-D tokamak[9]. In these experiments, testing the effects of resonant magnetic fields and magnetic perturbations on runaway electron behaviour, it has been observed that these fields altered the trajectories of runaway electrons, enhancing their scattering and reducing their energy content. Therefore, it contributes to improved plasma stability and reduced damage to the reactor walls.

In the context of ITER, the ITER research program acknowledges the importance of externally applied perturbation fields as a potential strategy for runaway electron mitigation.

It is important to note that the application of externally applied perturbation fields requires careful optimization to balance the desired mitigation effects with the overall stability of the plasma. The amplitude, frequency, and spatial distribution of these fields must be controlled to ensure effective runaway electron suppression without compromising the performance of the fusion reactor.

Reversed Loop Voltage:

The reversed loop voltage strategy mitigates the effect of runaway electrons by counteracting their acceleration and energy growth due to reversing the direction of the electric field within the plasma.

In a Tokamak fusion reactor, the electric field is aligned in the direction that accelerates the electrons which leads to the growth of runaway electron populations and the subsequent increase in their energy. Under the reversed loop voltage technique, the polarity of the electric field is switched, causing the runaway electrons to experience a decelerating force instead of acceleration.

This limits the energy content of electrons thereby reducing the population size of runaway electrons consequently preventing the perpetual cycle of acceleration of the electrons labelled the 'Avalanche Mechanism'. This therefore results in reducing the impact on the plasma and the walls containing the plasma.

One example of the successful application of reversed loop voltage in mitigating the effects of runaway electrons can be found in experimental studies conducted in fusion reactors such as the Joint European Torus (JET) and the DIII-D tokamak[9]. For instance, in JET experiments, researchers implemented reversed loop voltage to prevent runaway electrons from gaining excessive energy. They demonstrated that by changing the electric field polarity, the runaway electron energy growth could be effectively suppressed.

It is important to note that the application of reversed loop voltage requires careful control and optimization to ensure the desired effects on runaway electrons without compromising the overall plasma stability.

In summary, reversed loop voltage is a mitigation strategy that aims to control runaway electrons in Tokamak fusion reactors. By reversing the direction of the electric field, it counteracts the acceleration forces acting on runaway electrons, limiting their energy growth and population. The successful application of reversed loop voltage has been demonstrated in other fusion reactor experiments[9], showcasing its potential as an effective mitigation strategy.

2.2: High Z vs Deuterium SPI

As mentioned above, different materials have different ionisation and vaporisation properties, which can influence the collisional drag experienced by runaway electrons. In this regard two prominent material profiles have emerged: the High-Z SPI and the Deuterium SPI (or the D2 injection).

High-Z SPI uses high atomic number (Z) pellets (typically argon and neon) [8: section 3.1]. High-Z SPI mitigates RE beams by providing a scattering mechanism for runaway electrons during their formation phase. Heavy impurities like Argon and Neon effectively scatter and absorb runaway electrons, preventing them from gaining large amounts of kinetic energy which upon forming RE beams would transfer to the walls of the reactor causing physical damage to the lining and also contribute to plasma disruption.

However, High-Z SPI involving argon or neon are highly unsuccessful in mitigating fully developed RE beams. The injected High-Z impurities introduce significant amounts of thermal energy into the plasma, leading to transfer of thermal energy at levels similar or even higher than unmitigated RE beams [8]. Along with this, the presence of high argon content in the plasma due to the injection is likely to cause regeneration of runaway electrons upon decay.

Therefore, Deuterium SPI is considered a better alternative for mitigating fully grown RE beams. This is because it reduces the deposition of thermal energy on the reactor walls and also minimises the regeneration of runaway electrons upon decay.

Deuterium SPI involves injecting D2 (Deuterium) pellets instead of High-Z pellets.

Upon injection, deuterium particles interact with runaway electrons through Coulomb collisions. During Coulomb collisions, the particles involved exchange energy and momentum, which affects their state and trajectory. For high-energy particles such as runaway electrons, Coulomb collisions can significantly impact their scattering and energy dissipation due to their propensity to significantly alter trajectories and energy levels.

As mentioned above, DSPI (Deuterium Shattered Pellet Injection) is relatively highly effective in mitigating the effects of full grown RE breams. When a full-grown RE beam is present, the injection of deuterium pellets results in increased collision frequencies between the runaway electrons and the deuterium particles. This enhanced collisional interaction facilitates energy dissipation of the runaway electrons, significantly reducing their impact on the plasma and reactor components.

However, the reason DSPI is not a successful mitigation method for preventing the formation of RE beams is because of the lightweight nature of D2 particles relative to High-Z materials

like argon and neon, they are less effective in scattering runaway electrons during their initial formation. This is because Deuterium is 12 times lighter than argon, which means upon collision it does not absorb nearly as much kinetic energy from electrons as argon, causing the cascading build up - of kinetic energy to not be hindered to the point of prevention.

However, if used for mitigating a full-grown RE Beam, it will not only result in heat deposits similar to an unmitigated beam but will also cause the regeneration of runaway electrons upon decay due to the high High-Z material (like Argon) content in the plasma as a result of their injection.

Therefore, D2 injections are a much more effective mitigating method for full-grown RE beams: Not only do they purge the plasma of Argon or other High-Z materials, avoiding regeneration of runaway electrons during current decay, but also that they effectively dissipate the energy of the RE beam, nullifying the damage to the reactor and disruption to the plasma by transfer of kinetic energy and thermal deposition.

2.3 Specifics of Pellet Design in the context of ITER

Pellet Size:

It is not possible to establish the exact anticipated dimensions for pellet injection in ITER, as the dimensions depend on factors including the specific injection system employed (Gas Guns, Centrifugal Guns, Pneumatic Systems, Electro-Magnetic Launchers are the conventional injection systems for SPI in runaway electron mitigation [1]) and target plasma parameters. Plasma parameters are parameters for the properties of a plasma. It is crucial to understand and estimate these parameters because they directly influence the interaction between the injected pellets and the electrons in the plasma. Key plasma parameters relevant to SPI are: Electron Temperature, Plasma Density, Magnetic Field Strength and Plasma Impurities [1].

Currently at Oak Ridge National Laboratory, USA, a modified variant of a pipe gun injector that forms a large cryogenic pellet in the barrel is utilised to accelerate the pellets to speeds of 300 m/s [1], this speed is deemed to be an ideal balance between the pellets not having adequate kinetic energy to dissipate RE energy or the pellets having excess kinetic energy which cannot be ablated by the collisions in the plasma and causes damage to the inner walls of the reactor upon impact. For this pellet speed, the size chosen to use for experiments by the laboratory is a 16 mm pellet.

Cooling Time:

Cooling time is the duration of time required by the pellets to reach a temperature cool enough for injection into the plasma. This varies significantly upon the material used in the pellet. Metallic pellets, for instance, have a shorter cooling time compared to more complex composite materials. Cooling times generally vary from several minutes to tens of minutes.

Selection of materials: In this paper we are only considering High-Z materials like Argon and Neon and the low atomic number material: Deuterium. These are the most commonly used pellet materials for DMS [15]. This is for several reasons.

Argon and Neon pellets are highly conventional materials for SPI because:

1. The inert nature of the two elements causes them to not readily react with the plasma, their inertness also allows the pellets to maintain their integrity and survive longer in the hot plasma environment.
2. Neon also provides effective cooling of the plasma, assisting in dissipation of the thermal quench.

Deuterium is commonly used for several reasons as well:

1. Their functionality is diverse, they fuel the plasma by introducing deuterium atoms into the plasma core as Deuterium can readily ionise to be used as a fuel.
2. Deuterium pellets can effectively modify the density profile of the plasma, local injection of Deuterium can increase the density of specific regions as well. This allows researchers to optimise plasma parameters and improve the overall fusion performance.
3. It of course is very effective in RE beam dissipation and thermal quench dissipation and therefore is crucial for maintaining stable plasma operations.

2.4: DMS Design and Integration in the context of ITER

The ITER Organization (IO) is currently designing a Disruption Mitigation System (DMS) with the perspective of setting up SPI systems distributed among various tokamak ports [1].

The ITER fusion power production goals are Quality Factor (Q)[20] = 10 inductive operation for 300 - 500 s and Q >= 5 for 1000 s and in steady-state up to 3000 s. The envisioned DMS equipped to enable reaching these production goals is to be described below.

As stated in a recent progress report on the ITER DMS design and integration[1]: There will be a “total of 27 injectors distributed toroidally and poloidally in six ports.” “In the three larger equatorial ports, a total of 24 injectors (6 to 12 injectors per port) will be installed to provide thermal quench mitigation, RE generation avoidance, and RE energy dissipation.”

And the “three upper ports (120 degrees toroidally apart) will house one SPI injector each and will provide current quench mitigation.” The paper envisions this as a “second layer of defence” in case the DMS has not been triggered before the thermal quench. The key for all this is to have the ability to inject impurities into the plasma at all temperatures of thermal decay. The three ports at the top, for instance, are there to provide smaller fragments or gaseous material to ensure “sufficient assimilation in the colder post-thermal quench plasma.” [1]

The pellet design planned is this report envisions the use of hydrogen pellets with 3-5% Ne for thermal quench mitigation, pure hydrogen pellets for RE energy dissipation and pure Neon pellets for RE generation avoidance (These conclusions made at Oak Ridge National Laboratory [1] fall in line with the above stated perspective of effective DMS as the paragraphs above too have stated that High-Z materials like Argon and Neon are effective in preemptively avoiding RE generation and that Deuterium and its isotopes are an effective DMS for dissipating the energy of full grown RE beams).

The currently envisioned DMS design for ITER proposed by MIT[1]:

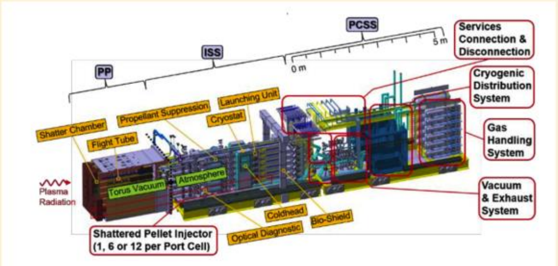

Figure 1: DMS in equatorial port and the three distinct areas of the ITER port cells: Port Plug (PP), Interspace Support Structure (ISS), Port Cell Support Structure (PCSS). source: [1]

2.5: DMS Design Limitations

There are two key design limitations in the envisioned plan as stated by U. Kruezi [1]:

Space congestion, all components that provide key functions (this includes all ports and systems related to production, containment and functioning of the plasma) have to be integrated into the ITER port cells. This is a constrained space with high temperatures and radiation. As shown in the diagram above, on the right of the Bio-Shield, inside PCSS (Port Cell Support Structure) most commercially available radiation and magnetic field compatible equipment can be utilised. And the area around the ISS (Interspace Support Structure) requires the use of only select qualified components and materials. Inside the PP (port plug) area however, the equipment has to withstand very high vacuum, high temperatures, and the exposure to electromagnetic radiation from the plasma.

A large limitation of the congested space is that it disallows the placement of a propellant recovery system which is a conventional facet of current experiments at JET and other reactors. Therein instead of having actively pumped volume, we must rely solely on a suppressor tasked to slow down the propellant gas outflow.

A solution to this currently being explored [1] is that the placement of baffles inside the volume can lead to a significant suppression by utilising the diverter regions:

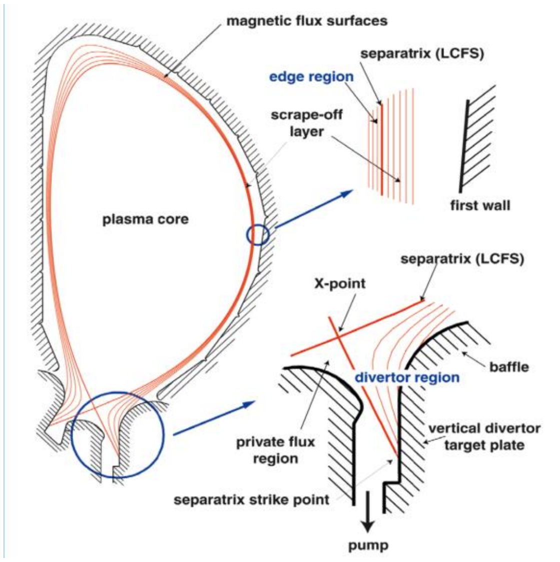

Figure 2: A structural perspective of baffles for suppression by utilising the diverter regions source: [22]

As far as SPI is concerned, the fast cryogenic pellets enter the shatter chamber in the PP and disperse into fragments with the envisioned size, velocity, and scatter angle.

The second primary design concern is the radiation exposure of servicemen in this space. The movement of servicemen will be in the PC, currently the precautions taken to protect their health is that a majority of service connections and disconnections have been placed in the PCSS in a manner that it is behind the Bio-Shield, which is placed above and below the designated human space. However, there is still a high liability of radiation leak or plasma disruption and overheating posing a health hazard to servicemen. The design is yet to be incorporated for this.

2.6: Proposed DMS Design Alterations

Through experiments over the decades, scientists have observed that RE generation during plasma disruption is largely preceded by the following sequence of events [2]: Thermal Quench (TQ), then Current Quench (CQ), finally followed by a runaway plateau.

What leads to this sequence beginning at a TQ varies between Tokamaks, however there are two common factors: Impurity influx (or injecting impurities) (which we have mentioned above as a drawback of using High-Z material injection to attempt to mitigate fully grown RE beams) which results in strong radiative losses and “Magnetohydrodynamic (MHD) events that enhance heat transport via stochastization of the magnetic field lines”[2].

ITER’s unprecedented size, surprisingly provides several advantages in this regard. The larger volume of the plasma in ITER (twice as large as JET with a plasma volume of 840 m^3 and a magnetic field strength of 13 Tesla (T)[21]) allows for a greater dilution of impurities, reducing their concentration and limiting their impact on plasma performance.

But it is due to this that experimented High-Z and D2 ratios for SPI will have to be significantly altered upon real experimentation in ITER. This is because the D2 injection volume will have to be increased inordinately to reach the dilution of plasma density required to provide a high probability of electron-impurity collisions for kinetic and thermal energy dissipation. On the contrary, due to the above-mentioned quality of ITER’s large plasma, there is an innate low proportion of high-Z impurity in the plasma. Therefore, injecting a small ratio of High-Z impurities along with D2 injections to mitigate the effects of fully grown RE beams will save the infrastructural hazard of injecting a very large volume of D2 pellets in a very short time (in the order of tens of milliseconds). The volume and mass of High-Z impurities will also significantly increase the injection’s effect on energy dissipation. However, the catastrophic effect of injecting high-Z impurities to mitigate fully grown RE beams observed in reactors like JET, resulted not only in poorer energy dissipation than unmitigated beams but also significantly increased the likelihood or RE regeneration during plasma decay. This effect will not be so in ITER due to the initial low proportion of high-Z impurities in the ITER plasma, allowing this to be more effective, and therefore be a part of future ITER DMS Systems.

3: CONCLUSIONS AND DISCUSSION

To conclude, as we understand the damage that runaway electrons can afflict on surrounding plasma-containing materials and the disruption in plasma performance it can cause, we aim to understand what is needed to effectively mitigate their effects in the ITER currently being built. The most efficient DMS for avoiding REs as well as mitigating full grown RE beams has been evaluated to be SPI, the predecessor of Massive MGI. This is not only due to the efficiency of impurities in dissipating RE energy but also due to SPI being significantly more energy efficient than other conventional methods like Externally Applied Perturbation Fields and Reversed Loop Voltage as these techniques require a constant input of energy as they attempt to actively mitigate the disruption[13]. In SPI the effects of high-Z vs low high-Z impurity injections are compared, based on experimentation and established physics we understand that high-Z materials give rise to RE regeneration. We also understand that the former is efficient in avoiding RE generation whilst the latter is efficient in mitigating fully grown RE beams.

Evaluating the logistical implementation of an SPI DMS in ITER, it is seen that the unprecedented plasma volume of ITER will require a mix of high-Z and low high-Z impurities to balance out the probability of collisions (increasing it by adding high-Z particles so that REs are likely to collide and dissipate their energy) against that of RE regeneration (unlike previous Tokamaks which were smaller, the ITER plasma will reduce the impact of high-Z materials and therein increase the threshold of high-Z material that may cause RE regeneration) during plasma decay.

This insight will allow the DMS in ITER to be logistically smaller (due to the requirement of lesser D2 injectors which took up a majority of the space in DMS (six or twelve injectors per port [1]), you can view the number of ports and their positioning in figure 1.) which will solve a major concern of congestion in the ITER DMS [1].

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