Magnetic-Confinement Fusion and Runaway Electrons

ID: 9097858
School of Physics and Astronomy, University of Manchester
(Dated: September 25, 2017)

In the last two decades, as magnetic field strengths in fusion devices have increased in order to improve confinement, the emergence of beams of highly relativistic *runaway electrons* (REs) from magnetic field instabilities inside the fusion plasma has been an issue of growing concern [1]. Counter-intuitively, these electrons experience a decreasing friction force with increasing speed, leading to rapid acceleration and energies ~ 30 MeV. Simulations show that next generation fusion reactors, such as the *The International Thermonuclear Experimental Reactor* (ITER) currently under construction in France, may produce REs with energies of up to 100 MeV [2]. At which point, impacts with the walls of the reactor vessel will likely cause significant damage to sensitive operation-critical instruments, leading to costly repairs and frequent periods of inactivity [3]. The understanding and mitigation of REs is of paramount importance if power production is to be achieved through controlled thermonuclear fusion. This essay aims to describe the mechanisms of RE generation in fusion devices and the efforts undertaken to mitigate their effect.

1. INTRODUCTION

With global energy demands rising, the development and implementation of sustainable energy sources is imperative if we are to reduce greenhouse gas emissions and slow down global warming. In this endeavour, controlled nuclear fusion is a promising technology which may provide long-term, near inexhaustible clean energy for an ever growing population. Current fusion research points towards deuterium-tritium (D-T) fusion as the most promising approach [4]. At sufficiently high energies, the nuclei of these hydrogen isotopes may overcome their mutual coulomb repulsion and fuse:

$$\mathrm{D} + \mathrm{T} \rightarrow {}^4\mathrm{He} + n + 17.6\ \mathrm{MeV}\ , \tag{1}$$

where the energy released comes from differences in nuclear binding energy. This however requires a D-T plasma at temperatures $\sim 10^8$ Kelvin, which no existing material is able to contain [4]. Therefore, magnetic fields are employed to confine the plasma in so-called magentic-confinement devices, the most common of which is the *tokamak*[1] design. In a tokamak the plasma is confined to the inside of a torus shaped vessel, kept away from the walls by a precise combination of magnetic fields. The reason for a torus shape is ultimately topological [6]. A famous theorem in algebraic topology, called the "Hairy ball theorem", states that any continuous vector field which is tangent to the surface of a sphere, must contain at least one singular point [7]. For a magnetic field on a sphere, or any shape that is topologically equivalent to a sphere [8], the theorem implies that there will always exist a point on the surface where the magnetic field vanishes, which is illustrated in figure 1. If the magnetic field was zero anywhere on the surface of the plasma the high pressures and temperatures required for fusion would rapidly force the plasma to escape at that point. The topology of a torus however allows for magnetic fields which are non-zero everywhere and is thus suitable for plasma confinement.

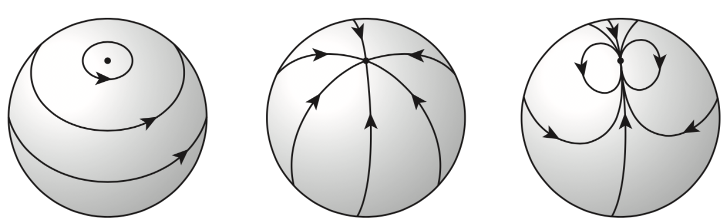

FIG. 1. Example of the hairy ball theorem for three different magnetic field configurations on a sphere [7]. Regardless of the configuration, as long the magnetic field is continuous, the theorem implies that there will always be a point where the magnetic field is zero. The theorem gets its name from the fact a hairy ball can not be combed flat without creating a tuft of hair sticking out [9]. Interestingly, the same theorem implies that since earth is spherical there must always be a point on earth with no wind.

[1] An acronym which rougly translates to "toroidal chamber with magnetic coils" [5] from its original Russian description **то**роидальная **ка**мера с **ма**гнитными **к**атушками

The magnetic field configuration in a tokamak will not be explored in great detail in this essay but some key features will be noted. Firstly, due to the Lorentz force law a charged particle in a magnetic field will gyrate in circular orbits perpendicular to the magnetic field lines [10]. The tokamak design, illustrated in figure 2, employs a primary magnetic field bent in the toroidal direction which causes particles to move around the torus whilst simultaneously gyrating around its field lines. This however introduces a varying centripetal force on the particles depending on whether they are closer or further away from the center of the torus. This will inevitably lead to particles drifting outwards, into the walls of the vessel, regardless of the magnetic field strength [11]. Therefore, a magnetic field perpendicular to the toroidal field, in the poloidal direction, is added to effectively twists the toridal magnetic field into a helix. It can be shown that this generates magnetic flux surfaces of constant pressure which are able counteract the particle drifts [12]. Poloidal fields are generated using seperatel poloidal field coils as well as by setting up a current inside the plasma. As we shall see later, this so-called poloidal current is key to the phenomena of REs.

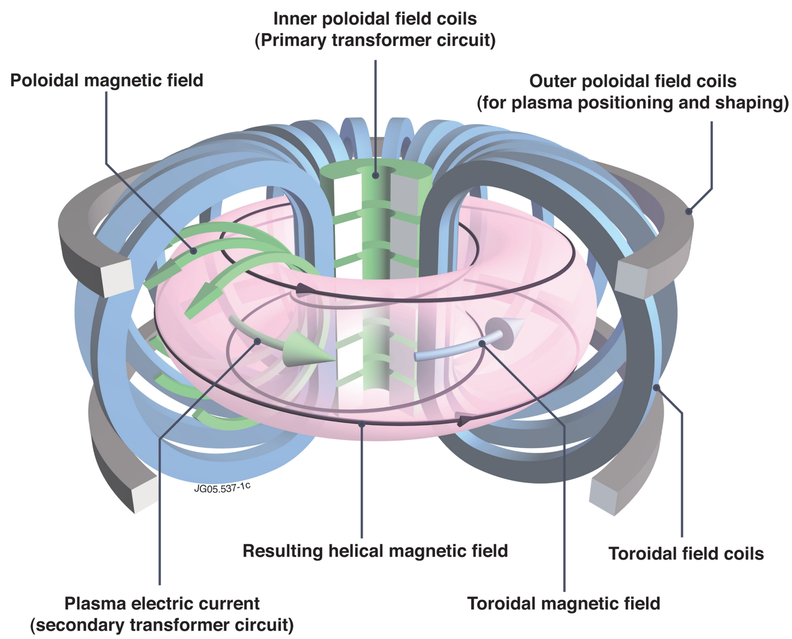

FIG. 2. Outline of the tokamak fusion design [13]. The toroidal field coils set up a magnetic field in the counter-clockwise direction as seen from above. The poloidal field coils, together with plasma current, act to twist the magnetic field into a helical configuration which is able to confine the D-T plasma.

The largest and most ambitious of the tokamak reactors, ITER, is scheduled for completion in 2025 [14]. Once operational, the research conducted at ITER will endavour to demonstrate that full-scale energy production is possible from magnetically confined plasmas. If successful, the knowledge gained from ITER will be implemented into the construction of its successor, the *DEMOnstration Power Station* (DEMO), the first fusion reactor capable of producing power to the electric grid. To achieve this goal several difficult problems need to be addressed, one of which is the runaway problem.

2. RUNAWAY ELECTRON GENERATION

2.1 Dreicer Generation

To describe the runaway phenomena we will consider the friction force experienced by an electron in a completely ionized plasma. The large mass difference between electrons and protons allows us to neglect the energy loss from electron-proton interactions since their collisions are highly elastic [15]. Consequently, to a first approximation the friction force is described by electron-electron interactions. It can be shown [15] that the drag force experienced by an electron due Coulomb interactions with electrons is given by,

$$F_{ee}\left(v\right) = \frac{m_e c^3}{v^2}\nu_{rel} \ , \tag{2}$$

where m_e is the electron mass and ν_{rel} is the collision frequency of a high-energy electron in a plasma. A detailed derivation of ν_{rel} is provided by Helander [16], whereby the momentum change in a collision is calculated by considering the associated energy exchange using the electron-electron scattering cross-section, which yields a friction force

$$F_{ee}\left(v\right) = \frac{1}{v^2}\frac{n_e e^4 \ln\Lambda}{4\pi\epsilon_0^2 m_e} \ , \tag{3}$$

where n_e is the electron number density, $\ln\Lambda$ is called the Coulomb logarithm and $\Lambda = \theta_{max}/\theta_{min}$ is the fraction of the maximum and minimum scattering angles. The implications of this frictional force can be seen in figure 3, where the magnitude of the force has been plotted as a function of electron speed. From the plot we may conclude that an accelerated electron in a fusion plasma will experience and initial increase in friction until a point where, counter-intuitively, the force starts to decrease. This occurs because at high speed the time spent in the proximity of particles during collisions is reduced, which consequently limits the possible exchange of energy [15]. Even though an electron has more interactions at high speed, thus increasing energy exchange, it can be shown [16] that this has a smaller overall effect compared to the reduced interaction times.

Since magnetic fields act to accelerate charged particles in a direction perpendicular to their velocity they do not lead to REs directly. As we shall see, however, magnetic fields act indirectly via the induction of electric fields. To this end, we introduce a force $\mathbf{F}_e = -e\mathbf{E}$ due to an electric field acting on the electrons and define the *critical field* $\mathbf{E}_c$ as the field required to balance the friction force in the limit as $v \to c$. By setting $eE_c = \lim_{v\to c} F_{ee}\left(v\right)$ we find,

$$E_c = \frac{n_e e^3 \ln\Lambda}{4\pi\epsilon_0^2 m_e c^2} \ . \tag{4}$$

Thus for all $E > E_c$ there exists a critical speed,

$$v_c = \sqrt{\frac{n_e e^3 \ln\Lambda}{4\pi\epsilon_0^2 m_e E}} \ , \tag{5}$$

above which the electric force acting on the electron is larger than the frictional drag, such that the electron gets accelerated. Furthermore, as the electron speed increases friction drops which results in an increasing acceleration and the so-called runaway reaction.

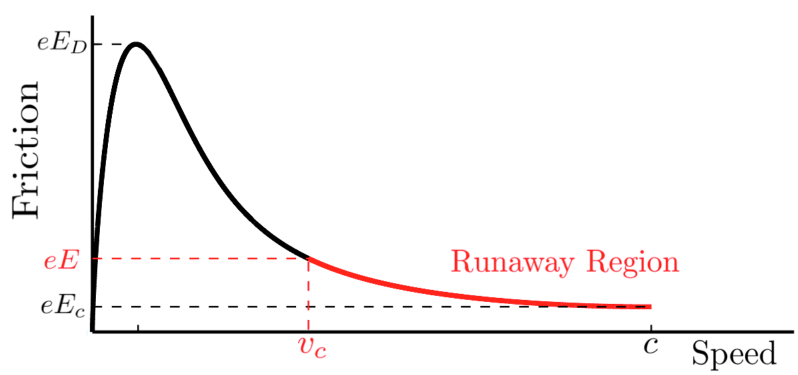

FIG. 3. Plot of the force of friction as a function of speed, as experienced by an electron in a completely ionized plasma. Figure modified from original by Nilsson [5]

We may also define the so-called *Dreicer field* $\mathbf{E}_D$ as the electric field corresponding to the maximum of equation (3), such that $E_D = \left(F_{ee}\right)_{max}/e$, which yields

$$E_D = \frac{n_e e^3 \ln\Lambda}{4\pi\epsilon_0^2 T_e} \ , \tag{6}$$

where we have defined $T_e = m_e v_{th}^2$ as the electron bulk temperature [5]. Consequently, if an electric field of this magnitude is generated within the plasma, electrons on the left side of the maximum will experience a decreasing acceleration as their speeds increase towards the maximum, at which point their acceleration increases rapidly as they enter the runaway region. As a result, for $E > E_c$ all electrons become REs.

Even though fusion reactors may operate at temperatures of up to 10^8 K, equivalent to a few keV's, the peak of equation (3) lies at approximately 100 keV for most standard fusion experiment [15]. Consequently, since the velocity distribution of electrons is approximately Maxwellian [16], only a small fraction of electrons have speeds high enough to reach the runaway region unaided. Therefore, to understand the generation of REs we need to investigate how electric fields may be generated within the plasma.

The most prominent event in reactors leading to RE generation is that of a magnetic field disruption [1]. The effects of large temperature and density gradients in fusion plasmas, together with strong magnetic fields, lead to turbulence and regions of unstable confinement. These instabilities are usually manageable. Disruptions, however, are characterized by rapidly growing instabilities resulting in loss of plasma confinement. This may result in the plasma coming into contact with the walls of the vessel, which sets up large temperature gradients at the points of contact. Heat conduction subsequently leads to a rapid drop in plasma temperature T_e, which implies a corresponding growth in plasma resistivity ρ. This occurs due to the fact that the plasma resistivity $\rho \sim T_e^{-3/2}$. From Ohm's law we know that the poloidal plasma current j_p is given by $j_p = E_\parallel/\rho$ where the electric field is parallel to the magnetic field lines in the toroidal direction. Thus from this argument alone it appears that j_p should decrease during a disruption. However, since the poloidal current is effectively a large loop, self inductance via the Faraday-Lenz law will act to oppose the decrease in current by inducing an increase in $E_\parallel$ such that j_p remains unchanged. Through disruptions we therefore find a possible mechanism for RE generation. This acceleration of electrons into REs through electric fields is called Dreicer generation after its discoverer.

2.2 Avalanche Generation

For an electric field $E_c < E < E_D$ Dreicer generation predicts that only those electrons with $v > v_c$ become REs. Early experiments [17], however, showed a larger than expected RE population based on the known electron velocity distribution. In response, Sokolov [18] suggested that the rate of RE generation might increase due to Coulomb collisions between pre-existing relativistic ($10-20$ MeV) REs (primary) and the remaining thermal electrons (secondary). Specifically, if the secondary electron gains enough momentum in the collision to reach the runaway region while the primary electron still remains an RE. In that case, even if the two REs have new speeds at the low end of the runaway region the continuously increasing acceleration implies that they will quickly gain enough momentum to cause further such collisions. This mechanism is known as avalanche generation due to its potential for exponentially increasing the RE population. More detailed investigations of avalanche generation have been performed by Putvinski et al.[19]. By considering the evolution of the RE population, using the relativistic Fokker-Planck equation to model multiple scattering processes, it was shown that under certain geometric constraints the RE population growth rate follows approximately,

$$\frac{\mathrm{d}n_r}{\mathrm{d}t} \approx n_r \nu_{rel} \left(\frac{\epsilon - 1}{c_z \ln \Lambda}\right) \left(1 - \epsilon^{-1} + \frac{4(Z_{eff}+1)^2}{c_z^2(\epsilon^2+3)}\right)^{-1/2} \tag{7}$$

where $\epsilon = E/E_c$, $c_z = \sqrt{3(Z_{eff}+5)/\pi}$ and ν_{rel} is the same as in equation (2). Z_{eff} is the effective ion charge which depends on the ions presents in the plasma and electron screening effects. The above expression is mathematically intricate, however we note that the population growth rate, $\mathrm{d}n_r/\mathrm{d}t$, is proportional to the population size, n_r, itself, thus showing that exponential growth does indeed occur. Through simulations of ITER it was further found that as reactors grow larger the avalanche effect becomes increasingly prominent. In fact, the simulations indicated that mega-ampere currents consisting of 100 MeV REs may very well be produced in ITER during disruptions. As is noted in paper [20], this would most likely make ITER inoperable, further emphasizing the need for effective RE mitigation.

3. SYNCHROTRON RADIATION

The model of continuously accelerating REs described so far is in clear violation of special relativity since it predicts superluminal electrons. In reality, several mechanisms act to restrict the velocity of REs. In this essay we will focus primarily on the emission of synchrotron radiation, however, X-rays and γ-rays from bremsstrahlung emission due to heavy-ion scattering is thought to be an important energy loss mechanism at relativistic energies as well [21]. There are also suggestions that Čerenkov radiation, due to electron speeds above the phase velocity of light in the plasma, may be important [22].

All charged particles emit radiation during accelerated motion. Due to the helical orbits of electrons around magnetic field lines, as well as the toroidal motion around the tokamak, the electrons in a fusion plasma will experience continuous centripetal acceleration. The emission emitted by non-relativistic and relativistic electrons is categorized as cyclotron and synchrotron radiation, respectively. To see the importance of RE synchrotron radiation let $\mathbf{r}_s(t)$ represent the position of a relativistic electron in purely circular motion. The accelerated motion generates electric and magnetic fields which are emitted isotropically in the rest frame of the electron. For a stationary observer at a position $\mathbf{r}$, however, the fields are described by the Liénard-Wiechert fields [11];

$$\mathbf{E}(\mathbf{r},t) = \frac{e}{4\pi\epsilon_0}\left[\frac{\mathbf{n}-\boldsymbol{\beta}}{\gamma^2(1-\mathbf{n}\cdot\boldsymbol{\beta})^3|\mathbf{r}-\mathbf{r}_s|^2} + \frac{\mathbf{n}\times\left((\mathbf{n}-\boldsymbol{\beta})\times\dot{\boldsymbol{\beta}}\right)}{c(1-\mathbf{n}\cdot\boldsymbol{\beta})^3|\mathbf{r}-\mathbf{r}_s|}\right] \tag{8}$$

and

$$\mathbf{B}(\mathbf{r},t) = \frac{1}{c}\left[\mathbf{n}\times\mathbf{E}(\mathbf{r},t)\right] \tag{9}$$

where $\mathbf{n} = (\mathbf{r}-\mathbf{r}_s)/|\mathbf{r}-\mathbf{r}_s|$ is the displacement unit vector from electron to observer and $\boldsymbol{\beta} = \mathbf{v}/c$.
Following an approach by Hoppe [6], we now use the Poynting vector $\mathbf{N} = (\mathbf{E}\times\mathbf{B})/\mu_0$ and note that the expression $\mathbf{N}\cdot\mathbf{n}$ gives the power received at the observer per unit area. If we then define a spherical coordinate system relative to the electron and substitute the Liénard-Wiechert fields we find the power emitted per unit solid angle, per unit time [6],

$$\frac{\mathrm{d}P}{\mathrm{d}\Omega} = \frac{e^2\dot{\beta}^2}{16\pi^2\epsilon_0 c}\left[\frac{1}{(1-\beta\cos\alpha)^3} - \frac{\sin^2\alpha\cos^2\phi}{\gamma^2(1-\beta\cos\alpha)^5}\right] \tag{10}$$

where we have defined α as the angle between the electrons velocity vector and the displacement vector, ϕ is the azimuthal angle in this coordinate system. The expression implies that at relativistic speeds the synchrotron radiation is emitted into a cone with an opening angle $\sim 1/\gamma$ radians in the direction of motion of the electron and that the power peaks in the forward direction, where $\alpha = 0$. This is illustrated in figure 4. Since each emitted synchrotron photon carries a momentum, $p = \hbar k$, there is momentum transfer in the forward direction, which due to conservation of momentum results in a damping force in the opposite direction. It is this so-called radiation-reaction force which ultimately stops the REs from reaching arbitrarily high energies. However, even with these factors taken into account, ITER could still yield REs at 100 MeV [2].

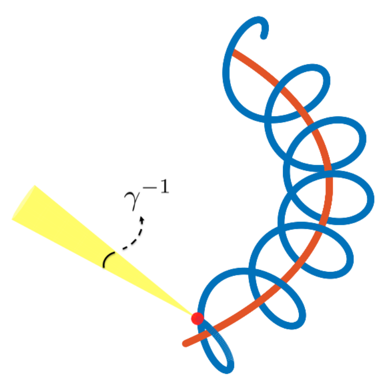

FIG. 4. Synchrotron emission (yellow) from a runaway electron as it gyrates around a magnetic field line (red) and traces out a helical path (blue) [6]. Due to relativistic beaming effects the emission is emitted into a cone of opening angle $\sim 1/\gamma$ in the forward direction, where $\gamma = (1-\beta^2)^{-1/2}$.

The importance of synchrotron radiation can further be seen by considering the power spectrum $\mathcal{P}(\lambda)$ of the emitted radiation as a function of wavelength, from equation (10) it can be shown that [12],

$$\mathcal{P}(\lambda) = \frac{1}{\sqrt{3}}\frac{ce^2}{\epsilon_0\lambda^3\gamma^2}\int_{\lambda_c/\lambda}^{\infty} K_{5/3}(\ell)\,\mathrm{d}\ell \tag{11}$$

where $K_{5/3}$ is the modified Bessel function of fractional order 5/3 and λ_c defines the wavelength at which the total radiated power from $\lambda < \lambda_c$ is equal to that from $\lambda > \lambda_c$ [23]. By calculating the power curve for different RE energies we find that the synchrotron radiation peaks in the infrared part of the spectrum but also emits extensively in the visual part of the spectrum [12]. If we compare this to the emitted black body radiation from a plasma at $10^7 - 10^8$

K using Wien's law we find that this peaks in the far ultra-violet range, making it effectively transparent in the visual range. This means that the REs' synchrotron radiation will be easily detectable using rather inexpensive visual-range cameras. An example of which is shown in figure 5, where a large synchrotron spot due to REs is clearly visible inside the plasma. Since the measured synchrotron radiation of REs depend on their acceleration, which in turn depends on electric fields caused by magnetic field disruptions, synchrotron diagnostics is being used to probe the plasma interior and as the primary tool to understand RE generation.

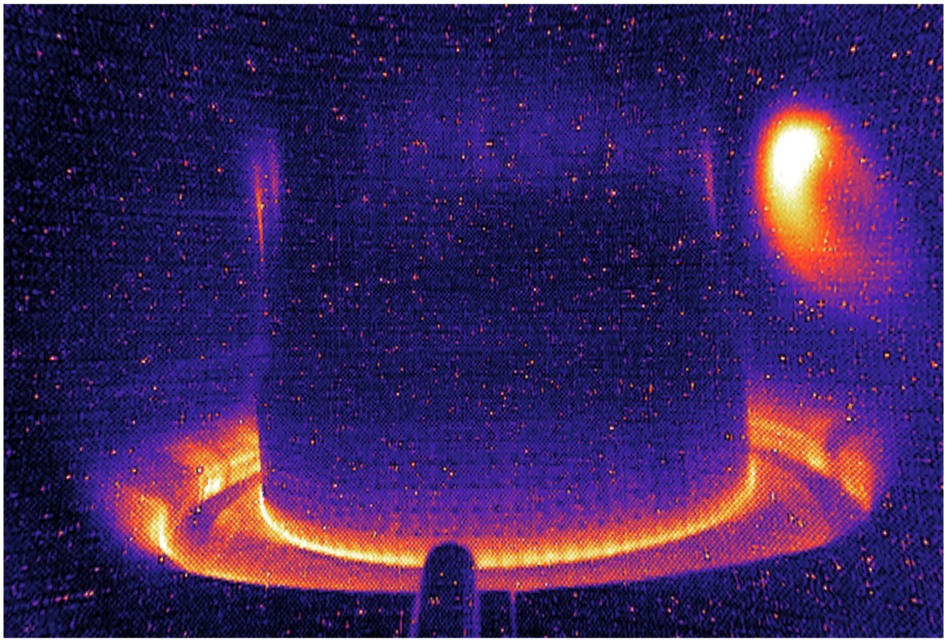

FIG. 5. Image from inside the tokamak reactor Alcator C-Mod at MIT from 2015 during operation. The large bright spot on the right side of the central pillar is due to RE synchrotron radiation, which is visible through the visually transparent hot plasma. At the bottom of the reactor the plasma is in contact with the vessel which cools it down enough to radiate in the visual range. The REs circulate towards the camera on the right side and away from it on the left. Since they radiate almost exclusively in their forward direction this explains why no spot is seen on the left side. A colour filter has been used on the original black and white image to highlight its features. Courtesy of Dr. R.A Tingely.

4. MITIGATION

Multiple studies [3][17][20] have emphasized the need for effective RE mitigation techniques if ITER is to avoid significant damage. This includes minimizing both the formation and growth of RE populations during disruptions. To this end, several mitigation techniques have been proposed, the most promising of which rely on either material injection or magnetic field perturbations. The idea behind material injection is to impede REs by rapidly increasing the plasma density via injection of a heavy noble gas such as Argon [24]. Equation (2) shows that a higher density leads to increased collisional frequency and force of friction. As a result, the critical field $\mathbf{E}_c$ and critical velocity v_c, equations (4) and (5), are increased. This raises the lower bound on the runaway region in figure 3, which subsequently reduces the population of REs and the probability of avalanching. This approach, however, has proven problematic since effective mitigation requires a local increase of plasma density by up to a factor 100 in timescales of $10 - 20$ ms [17].

Magnetic field perturbations, in turn, may be introduced early in the generation of a runaway population to inhibit further growth. By applying small periodic perturbations $\delta B(t)$, where $\delta B(t)/B \sim 10^{-3}$, at specific resonant frequencies the diffusion transport of REs towards the walls of the vessel may increase significantly [2]. If applied in the early stages of a disruption, when the population is small and at relatively low energy, this approached has been demonstrated to successfully suppress avalanche generation in controlled deliberate disruption events [25]. However, for ITER sized plasma volumes the REs need to travel larger distances to reach the walls which may reduce the effectiveness of this approach [2]. As discussed in paper [26] the method to be used in ITER will most likely a combination of these two approaches.

5. CONCLUSION

In this essay we have shown how REs may be generated from magnetic field disruptions in fusion plasmas, the methods by which these are studied and how they may be mitigated. The equations describing REs presented here are only valid for idealized cases, yet still provide valuable insight into the behaviour of REs in fusion experiments. To completely describe this phenomena, however, one needs to include advanced models from quantum mechanics, fluid mechanics, non-linear physics and many other branches of physics. In fact, most equations are too complex for an analytical approach and can only be solved numerically. As a result, much work is currently being put into developing all-inclusive codes to simulate the behaviour of charged particles in turbulent plasmas [1]. The challenges still remaining are highlighted by Boozer's note that more than 150 papers have been published on REs in ITER, yet to this date no "suitable scheme for the active suppression or mitigation of runaway electrons has been confirmed" [1].

References

[1] A. H. Boozer, "Runaway electrons and ITER," Nuclear Fusion **57** (2017).

[2] T. Fulop P. Helander G. Papp, M. Drevlak and G. I. Pokol, "Runaway electron losses caused by resonant magnetic perturbations in ITER," Plasma Physics and Controlled Fusion **53** (2011).

[3] T. Fulop D. A. Humphreys V. A. Izzo M. Lehnen V. E. Lukash G. Papp G. Pautasso F. Saint-Laurent E. M. Hollmann, P. B. Aleynikov and J. A. Snipes, "Status of research toward the ITER disruption mitigation system," Physics of Plasma **22** (2015).

[4] F. F. Chen, *An Indispensable Truth: How Fusion Power Can Save the Planet* (Springer, 2011).

[5] E. Nilsson, *Dynamics of runaway electrons in tokamak plasmas* (Physics, CEA, 2015).

[6] M. Hoppe, *Synthetic synchrotron diagnostics for runaways in tokamaks* (Department of Physics, Chalmers University of Technology, 2017).

[7] I. Leader T. Gowers, J. Barrow-Green, *The Princeton Companion to Mathematics* (Princeton University Press, 2008).

[8] J. Milnor, "Analytic proofs of the" hairy ball theorem" and the Brouwer fixed point theorem," The American Mathematical Monthly **85.7**, 521–524 (1978).

[9] S. Sen C. Nash, *Topology and Geometry for Physicists (Dover Books on Mathematics)* (Dover Publications Inc, 2011).

[10] I. S. Grant and W. R. Philips, *Electromagnetism 2nd edition* (John Wiley & Sons, Inc, 2011).

[11] J. D. Jackson, *Classical Electrodynamics. 3rd ed* (John Wiley & Sons, Inc, 1999).

[12] A. Stahl, *Momentum-space dynamics of runaway electrons in plasmas* (Department of Physics, Subatomic and Plasma Physics (Chalmers), Chalmers University of Technology, 2017).

[13] "Efda - european fusion development agreement," `https://www.euro-fusion.org/wpcms/wp-content/uploads/2011/11/energy_es.pdf`, accessed: 2017-09-23.

[14] ITER Organization, `https://www.iter.org`, accessed: 2017-09-22.

[15] R. J. Jaspers, *Relativistic Runaway Electrons in Tokamak Plasmas* (Technische Universiteit Eindhoven, 1968).

[16] P. Helander and D. J. Sigmar, *Collisional Transport in Magnetized Plasmas, Vol.4* (Cambridge: Cambridge Univ. Press, 2002).

[17] R. S. Granetz, B. Esposito, J. H. Kim, R. Koslowski, M. Lehnen, J. R. Martin-Solis, C. Paz-Soldan, T. Rhee, J. C. Wesley, and L. Zeng, "An ITPA joint experiment to study runaway electron generation and suppression," Physics of Plasma **21** (2014).

[18] Yu A Sokolov, "Multiplication of accelerated electrons in a tokamak," JETP journal **29**, 218 (1979).

[19] M.N. Rosenbluth and S.V. Putvinski, "Theory for avalanche of runaway electrons in tokamaks," JETP journal **37**, 1355–1362 (1997).

[20] P. Aleynikov D. Campbell P. Drewelow N. Eidietis Y. Gasparyan R. Granetz Y. Gribov N. Hartmann E. Hollmann V. Izzo S. Jachmich S.-H. Kim M. Kocan H. Koslowski D. Kovalenko U. Kruezi A. Loarte S. Maruyama G. Matthews P. Parks G. Pautasso R. Pitts C. Reux V. Riccardo R. Roccella J. Snipes A. Thornton M. Lehnen, K. Aleynikova and P. de Vries, "Disruptions in ITER and strategies for their control and mitigation," Journal of Nuclear Materials **39** (2015).

[21] A Stahl O Embrus and T Fulop, "Effect of bremsstrahlung radiation emission on fast electrons in plasmas," New Journal of Physics **18**, 093023 (2016).

[22] C. Liu, *Doctoral Dissertation: Runaway electrons in tokamaks* (Princeton, NJ : Princeton University, 2017).

[23] G.V. Marr, *Handbook on Synchrotron Radiation, Volume 2* (North Holland, 1987).

[24] Lehnen M et al., "Disruption mitigation by massive gas injection in JET," Nuclear Fusion **51** (2011).

[25] Lehnen M et al., "Runaway Generation During Disruptions in JET and TEXTOR," Journal of Nuclear **390** (2009).

[26] T. Fulop P. Helander G. Papp, M. Drevlak and G. I. Pokol, "Runaway electron drift orbits in magnetostatic perturbed fields," Nuclear Fusion **51** (2011).

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