Runaway electrons in stellarators

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Runaway electrons (REs) pose a major challenge for development of tokamak fusion reactors [1]. The generation is exponentially sensitive to the initial plasma current [2], and in tokamaks with plasma currents of several MAs, RE currents of similar magnitude can be generated during disruptions, posing a risk for plasma facing components. Due to the lack of an externally driven plasma current, generation of REs is not anticipated to be a concern in stellarators. However, there can be significant bootstrap currents, driven by radial pressure gradients, possibly on the order of MAs, e.g. in quasi-axisymmetric devices [3]. The bootstrap current would disappear should there be a sudden loss of thermal confinement, for instance due to impurities entering the plasma. However, as the total plasma current cannot change instantaneously due to the self-inductance, an electric field will be induced to maintain the current that could be sufficiently large for RE generation. We have therefore studied REs in stellarators during temperature collapses.

Numerical model To study REs in stellarators, a fluid plasma model applicable for stellarator configurations has been implemented in the simulation code DREAM [4]. In DREAM, the electric field, plasma current and poloidal flux are evolved in time according to Faraday's and Ampère's laws. In DREAM, Faraday's law is formulated as

$$\frac{\partial \psi_\mathrm{p}}{\partial t} = \frac{2\pi \langle \boldsymbol{E}\cdot\boldsymbol{B}\rangle}{\langle \boldsymbol{B}\cdot\nabla\varphi\rangle}, \tag{1}$$

where $\langle \boldsymbol{E}\cdot\boldsymbol{B}\rangle$ is the flux surface averaged scalar product of the electric field $\boldsymbol{E}$ and the magnetic field $\boldsymbol{B}$, and ψ_p is the poloidal flux. The expression is valid for stellarators under the assumption that the toroidal flux is constant in time, which can be motivated by the toroidal flux being maintained by the magnetic field coils. Furthermore, for Ampère's law to be valid for toroidal plasmas in general, it has been extended to

$$2\pi\mu_0 \langle \boldsymbol{B}\cdot\nabla\varphi\rangle \frac{j_\parallel}{B} = \frac{1}{V'}\frac{\partial}{\partial\rho}\left[V'\left\langle\frac{g_{\theta\theta}}{g}\right\rangle\frac{\partial\psi_\mathrm{p}}{\partial\rho} + V'\left\langle\frac{g_{\theta\varphi}(1+\lambda_\theta) - g_{\theta\theta}\lambda_\varphi}{g}\right\rangle\frac{\partial\psi_\mathrm{t}}{\partial\rho}\right], \tag{2}$$

where $g_{\theta\theta}$ and $g_{\theta\varphi}$ are metric tensor components, g is the spatial Jacobian squared, V' is the radial derivative of the plasma volume, and λ_θ and λ_φ are derivatives of the stream function [5]. The expression is derived using the approximation that $j_\parallel/B$ is constant on a flux surface.

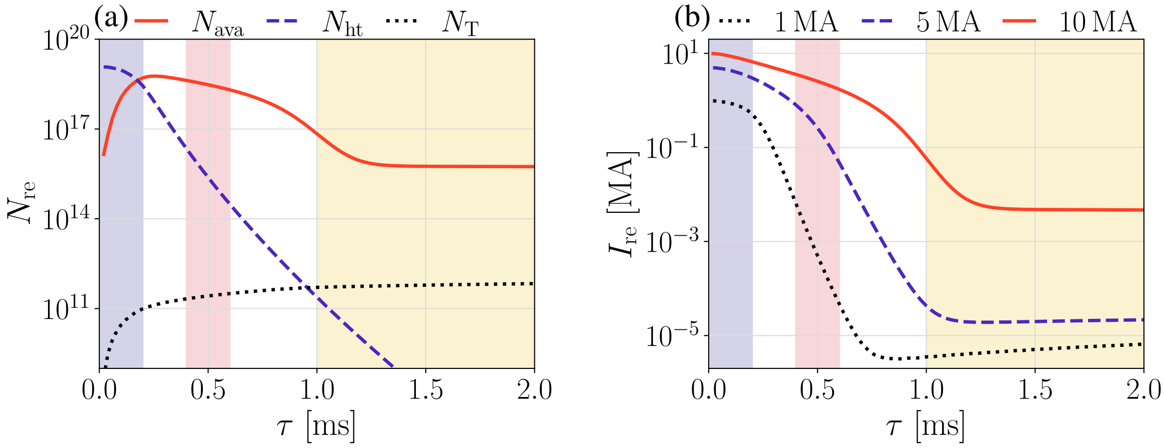

Figure 1: (a) Number of REs generated by the most significant mechanisms as a function of temperature decay time scale for $I_p = 10\,\mathrm{MA}$ and $T_{\mathrm{final}} = 1\,\mathrm{eV}$. The generation mechanisms are avalanche (solid red), hot-tail (dashed purple) and tritium beta decay (dotted black). (b) Maximum RE current as a function of decay time scale for the $I_p = 1\,\mathrm{MA}$ (dotted black), $I_p = 5\,\mathrm{MA}$ (dashed purple) and $I_p = 10\,\mathrm{MA}$. The three TQ scenarios considered are highlighted, with fast TQ highlighted with purple, intermediate TQ with red and slow TQ with yellow.

To cover a varied set of thermal quench (TQ) scenarios, we explore how the decay time scale, post-TQ temperature, and initial plasma current influence the generated RE current in a quasi-axisymmetric deuterium-tritium plasma. The temperature collapse is prescribed according to $T(r,t) = (T_{\mathrm{initial}}(r) - T_{\mathrm{final}})\exp(-t/\tau) + T_{\mathrm{final}}$, where the decay time scale $\tau \in [0.02,\ 2]\,\mathrm{ms}$ and the post-TQ equilibrium temperature $T_{\mathrm{final}} \in [1,\ 100]\,\mathrm{eV}$. The plasma currents considered are $I_p \in \{1,\ 5,\ 10\}\,\mathrm{MA}$, but the magnetic configuration has been kept fixed for all simulations, meaning it is not consistent with the plasma currents considered. This is deemed not to be a concern, since the configuration is mainly maintained by the magnetic field coils. We have used a magnetic configuration with major radius $R_0 = 8.8\,\mathrm{m}$ and minor radius of $a = 1.7\,\mathrm{m}$[1].

Since we are studying a deuterium-tritium plasma, all RE generation mechanisms relevant for a fusion plasma can be facilitated. The generation mechanisms considered are Dreicer, hot-tail and avalanche generation, as well as generation from tritium beta decay and Compton scattering, induced by gamma photons emitted from the activated walls. We have assumed that the photon flux spectrum is the same as for that of ITER. The RE population can also be influenced by transport, but we have chosen to neglect this to be conservative in our predictions.

Results The RE dynamics during the TQ are sensitive to the temperature decay time scale. In figure 1, the RE generation mechanisms and maximum RE current generated are plotted as functions of the temperature decay time scale for $T_{\mathrm{final}} = 1\,\mathrm{eV}$. The RE generation decreases significantly with increasing decay time scale, resulting in almost full conversion of the initial plasma currents for small τ, and $I_{re} < 10\,\mathrm{kA}$ for large τ. The RE dynamics can be grouped

[1]The magnetic equilibrium can be found at https://sb0095.mycpanel.princeton.edu/QA/notes.html

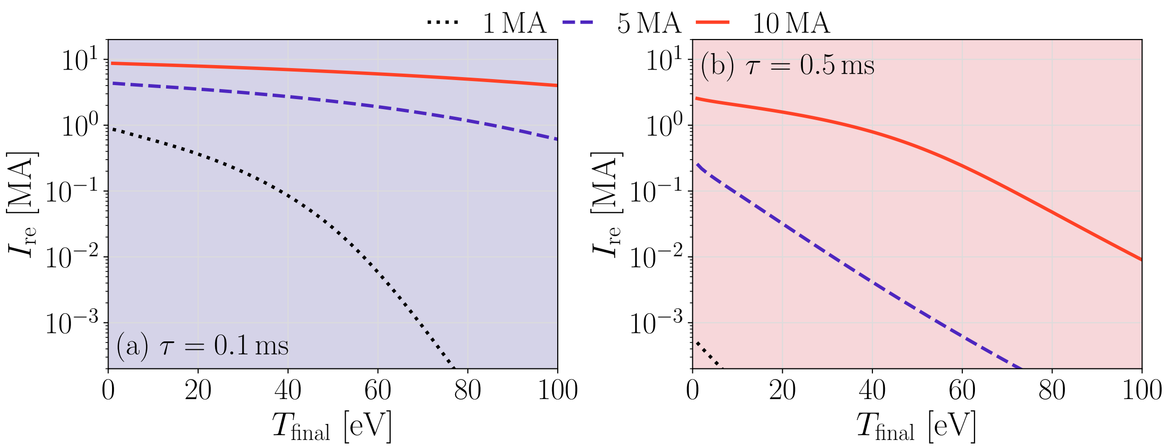

Figure 2: Maximum RE current as a function of post-TQ temperature for the 1 MA (dotted black), 5 MA (dashed purple) and 10 MA stellarator plasma scenario for a temperature decay time scale of (a) 0.1 ms and (b) 0.5 ms.

into three categories based on if the TQ is fast ($\tau \sim 0.1$ ms), intermediate ($\tau \sim 0.5$ ms) or slow ($\tau \gtrsim 1$ ms). During fast TQs, the hot-tail generation is very strong – even stronger than avalanche for $\tau < 0.2$ ms – but it is very sensitive to τ, as would be expected. The hot-tail generation is still the dominating primary mechanism during intermediate TQs. During slow TQs, the hot-tail generation becomes weaker than the generation from tritium beta decay. The tritium generation is largely unaffected by τ, meaning that the generated RE population stabilizes for $\tau \gtrsim 1$ ms.

For fast and intermediate TQs, significant RE currents can be generated, but it is dependent on the post-TQ temperature and the initial plasma current. In figure 2, the generated RE current for fast and intermediate TQs as functions of T_{final} are illustrated in panes (a) and (b), respectively. For the fast TQ, the RE current is only sensitive to T_{final} for $I_p = 1$ MA. For $I_p \gtrsim 5$ MA, there is strong RE generation ($I_{re} \gtrsim 1$ MA), regardless of T_{final}. On the other hand, for intermediate TQs, the generation is sensitive to T_{final} regardless of I_p. More specifically, $I_{re} > 100$ kA for low T_{final} and $I_p \gtrsim 5$ MA, while $I_{re} < 10$ kA for high T_{final} even for $I_p = 10$ MA. This suggests that there can be significant RE generation if two of the following conditions are met: (1) large I_p ($I_p \gtrsim 5$ MA), (2) low T_{final} ($T_{final} \lesssim 20$ eV), and (3) short τ ($\tau \lesssim 0.30$ ms). If the TQ is slow ($\tau \gtrsim 1$ ms), a very high plasma current would be needed for significant RE generation, as for $I_p = 10$ MA and $T_{final} = 1$ eV the generated RE current is less than 10 kA.

The low RE currents generated for the slow TQs, even for plasma currents of magnitudes similar to tokamak reactors ($I_p = 10$ MA), illustrates that the avalanche generation is relatively weak in the stellarator plasma we have considered. Stellarator plasmas are in general more elongated than tokamak plasmas, as the twisted magnetic field lines are partly caused by the stretching of the flux surface cross sections. It has been demonstrated that the elongation of tokamak plas-

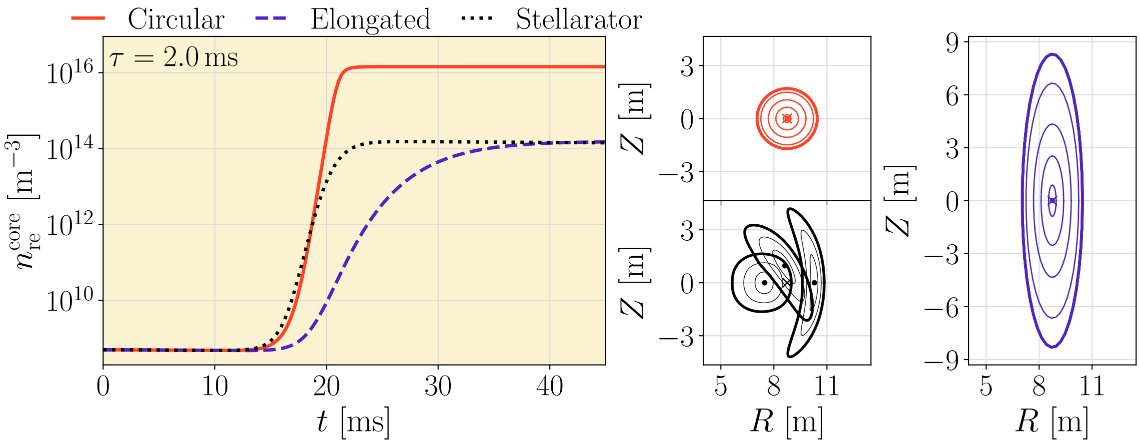

Figure 3: RE density in the core ($r = 0$) as a function of time for a circular (solid red) and elongated (dashed purple) tokamak plasma, as well as the stellarator plasma used in this work (dotted black) for a plasma current of $10\,\mathrm{MA}$, decay time scale of $2\,\mathrm{ms}$ and post-TQ temperature of $1\,\mathrm{eV}$. The flux surfaces of the different configurations are plotted to the right, in the same color scheme.

mas, quantified by κ, reduces the avalanche multiplication by a factor of $2/(\kappa+\kappa^{-1})$ [6]. The elongation of stellarator plasmas is not as easily parameterizable as that of tokamak plasmas, but the underlying effect on the avalanche should be similar. To investigate the effect of elongation on the avalanche, we have compared the avalanche generation for our stellarator plasma to that of a circular plasma and to an elongated plasma, all with an initial plasma current of $10\,\mathrm{MA}$ and equal major and minor radii. The elongation of the tokamak plasma was chosen so that the $V'\langle g_{\theta\theta}/g\rangle$ coefficient is equal to the corresponding coefficient of the stellarator plasma. To isolate the effect of the avalanche generation, all three scenarios were initialized with a seed electron density of $n_{\mathrm{re}} = 5\times10^{8}\,\mathrm{m}^{-3}$. The time evolution of the electron densities at the core for the three differently shaped plasmas are illustrated in figure 3, together with the three cross sections of the flux surfaces. As predicted, the stellarator and elongated plasma have practically the same RE density at the core, while in the circular plasma it is larger by a factor of 100.

Conclusions There can be significant RE generation in stellarators, but it should pose less of a concern compared with tokamaks. We found that there can be significant RE generation if two of the following conditions are met: (1) large initial plasma current, (2) low post-TQ temperature, and (3) fast TQ. The avalanche multiplication in a stellarator is, however, predicted to be weaker than in a tokamak due to the stronger elongation and lower plasma current.

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