Runaway electron dynamics in the Tokamak à Configuration Variable

M. Hoppe[1,2], J. Decker[2], U. Sheikh[2], T. Wijkamp[3,4], J. Cazabonne[2], B. P. Duval[2], G. Papp[5], A. Perek[2], Y. Peysson[6], L. Simons[2], A. Tema-Biwole[2], B. Vincent[2], L. Votta[2] and the TCV team[2,†]

[1]*KTH Royal Institute of Technology, Stockholm, Sweden,* [2]*Ecole Polytechnique Fédérale de Lausanne (EPFL), Swiss Plasma Center (SPC), Lausanne, Switzerland,* [3]*Eindhoven University of Technology, Netherlands,* [4]*DIFFER, Eindhoven, Netherlands,* [5]*Max Planck Institute for Plasma Physics, Garching, Germany,* [6]*CEA, IRFM, St-Paul-Lez-Durance, France,* [†]*See author list of "H. Reimerdes et al 2022 Nucl. Fusion* **62** *042018"*

Future reactor-scale tokamaks, such as ITER, must avoid the severe risk of localized damage to plasma-facing components caused by runaway electrons (REs) generated by disruptions. The Tokamak à Configuration Variable (TCV) has supported an ambitious research program into disruptions and REs for many years and has well-established scenarios for studying both. A recent overview of RE experimental studies at TCV was presented in ref. [1], and in this paper we extend the analysis using simulations from the fluid-kinetic disruption simulation framework DREAM [2].

Experimental setup TCV is a medium-sized tokamak hosted at EPFL, Switzerland. It has a rectangular cross-section ($1.54 \times 0.56\,\mathrm{m}^2$) with major radius $R_0 = 89\,\mathrm{cm}$ and plasma minor radius $a = 25\,\mathrm{cm}$. In this paper we examine the ohmic discharge #52717, featuring a plasma current of $I_\mathrm{p} = 200\,\mathrm{kA}$ and an on-axis $B_0 = 1.45\,\mathrm{T}$ toroidal field. Figure 1 shows the evolution of the main plasma parameters in the discharge. The plasma current is ramped up with a high loop voltage and low electron density, giving rise to a substantial fast electron population, monitored in figure 1c. The fast electrons enhance the effective plasma conductivity, causing V_loop to decrease together with the ohmic heating power. At $t = 0.47\,\mathrm{s}$, a massive neon-gas injection is triggered, causing a rapid cooling of the plasma leading to a disruption. During the disruption, the plasma current is fully converted into an RE current that is allowed to decay freely.

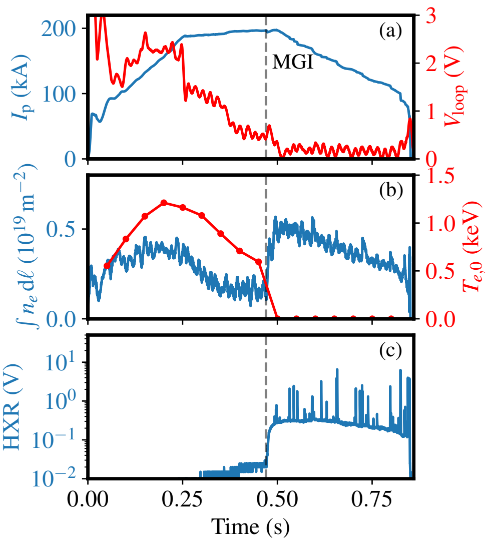

Figure 1: Plasma evolution in #52717. (a) Plasma current and loop voltage. (b) Line-integrated electron density and electron temperature. (c) Hard x-ray (HXR) intensity. The vertical dashed line indicates the time of massive gas injection (MGI).

Model We use DREAM [2] to simulate both the pre-disruption flat-top phase, and the disruption of #52717. Simulations use electron temperature and density profiles from the Thomson scattering measurements, and the loop voltage taken at the inside of the TCV vacuum chamber. The radial and temporal evolution of the electric field $E_{\|}(t,r)$ and current density $j_{\rm tot} = j_{\Omega} + j_{\rm re}$ is calculated by solving Ampère's and Faraday's laws, with the ohmic current given by Ohm's law $j_{\Omega} = \sigma E_{\|}$, where σ is the conductivity. The runaway current is given by $j_{\rm re} = ecn_{\rm re}$ with the flux surface averaged runaway density

$$\frac{\partial n_{\rm re}}{\partial t} = \gamma_{\rm Dreicer} + n_{\rm re}\Gamma_{\rm ava} - \frac{1}{V'}\frac{\partial}{\partial r}\left(V' D_{rr}\frac{\partial n_{\rm re}}{\partial r}\right), \tag{1}$$

where $\gamma_{\rm Dreicer}$ is the rate of RE production due to the Dreicer mechanism [3], $\Gamma_{\rm ava}$ is the avalanche growth rate [4], and V' is the jacobian. The radial diffusion coefficient D_{rr}—taken to be spatially uniform—is adjusted at each time step such that the simulated plasma current $I_{\rm p}$ is smaller than, or equal to, the experimental current. For $r > a$, $n_{\rm re} = 0$ is assumed.

In the disruption simulations, measurements are only used for the initial conditions. At the start of the simulation, neutral neon is taken to be distributed uniformly across the plasma triggering a rapid cooling through radiation. The electron temperature is evolved using an energy-balance equation, and the ion charge state distribution is calculated using ADAS ionization and recombination rates, both described in detail in ref. [2]. Convective heat losses are neglected for simplicity, but a sensitivity scan has showed that such losses do not impact the conclusions drawn herein. The electric field and current densities are evolved as in the flat-top simulation, and $n_{\rm re}$ evolves according to eq. (1), with the rate term $\gamma_{\rm hot}$ added to the RHS, representing RE generation via the hot-tail mechanism [5], and with D_{rr} prescribed to a constant value.

Flat-top simulation Simulations of the pre-disruption flat-top in #52717 were conducted at effective plasma charge values $Z_{\rm eff} \in [1,4]$. In all cases, throughout most of the discharge, $E_{\|}$ and $j_{\rm tot}$ are found to remain far from steady state, with an ohmic current far smaller than that expected in the time-asymptotic limit. For the last $\sim 50\,$ms before the disruption, as the temperature and density slowly decrease, the $E_{\|}$ and $j_{\rm tot}$ profiles approach their steady state values. Just before disruption onset, the flat-top simulations suggest that $\sim$ 70-90% of $I_{\rm p}$ is carried by superthermal electrons, depending upon the value of $Z_{\rm eff}$.

Matching $I_{\rm p}$ with experimental measurements suggests that D_{rr} drops to zero around $t = 0.37\,$s, at which time a significant drop is also observed in $V_{\rm loop}$ (c.f. fig. 1a). When the same process is conducted for #52742, which is similar to #52717 but with a higher pre-disruption electron density and no post-disruption RE plateau, $I_{\rm re}$ is found close to zero prior to the disruption and D_{rr} retains values $\sim$ 10-100$\,{\rm m}^2/{\rm s}$, depending on the assumed $Z_{\rm eff}$. Thus the simulations

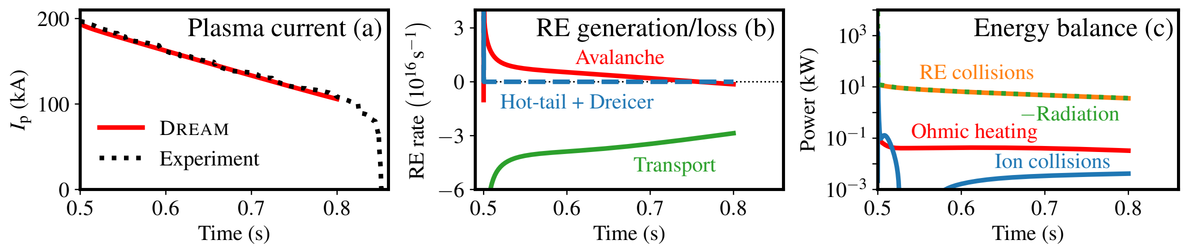

Figure 2: DREAM simulation results for #52717.

suggest that in #52717, a high RE confinement regime is entered, that is not achieved at the higher pre-disruption density of #52742.

Disruption simulation To simulate the disruption in #52717, initially neutral neon of density $n_{\mathrm{Ne}} = 10^{19}\,\mathrm{m}^{-3}$ was added to the plasma in the last time-step of the pre-disruption simulation. Figure 2a shows simulated plasma current evolution, where a radial diffusion coefficient for the REs $D_{rr} = 0.02\,\mathrm{m}^2/\mathrm{s}$ was applied in order for the current-decay rate to match the experiment. As in the experiment, almost all of the pre-disruption plasma current is replaced by fast electrons in the disruption, entirely explained by strong hot-tail generation, i.e. the plasma cooling is so rapid that a large number of fast electrons in the tail of the pre-disruption Maxwellian distribution undergo acceleration before they can thermalize to the new, much lower, temperature. Kinetic simulations further corroborate this and suggest that the electron energies after the current quench are relatively low, reaching only 1-2 MeV. The avalanche term in equation (1) is negligible during this conversion of ohmic to RE current, but is crucial in the subsequent RE current decay.

In addition to the current dynamics, DREAM also calculates the post-disruption electron temperature by balancing radiation losses, ohmic heating, and the collisional transfer of energy from REs $\partial W_{\mathrm{re}}/\partial t = ecE_{\mathrm{c}}n_{\mathrm{re}}$, where $E_{\mathrm{c}} = 4\pi n_e r_0^2 c^2 \log\Lambda/e$ is the critical electric field [6]. The electron temperature settles between $\sim$ 2-3 eV after the thermal quench, which is consistent with the experimental upper limit of 20 eV noted in Ref. [1]. As illustrated in figure 2c, this final temperature is the result of a competition between radiation losses and collisional heating of the bulk plasma by REs. We note that kinetic simulations support this result, suggesting even stronger heating from the REs when the higher collisionality of lower-energy REs is accounted for, resulting in final temperatures of $\sim$ 4-5 eV.

A long-standing question at TCV is whether the hard X-rays (HXR) measured, for instance, by the HXR diagnostic—a scintillator/photomultiplier assembly—originate from bremsstrahlung (BR) in RE interaction with the background plasma or with the wall. Two of the key unknowns in these processes are the confined RE density and the rate at which the REs are lost. DREAM gives a number for the former, and by matching the RE radial diffusion coefficient such that the current decay rate in the simulated disruption matches experiment, we can estimate the RE loss rate. One can show [7] that the HXR flux is $\phi_{\mathrm{HXR}} \propto Z_s^2 n_s N_{\mathrm{re}}$, where Z_s and n_s are the charge and density of the ion species that the RE collides with, and N_{re} is the number of RE inside the plasma/wall at a given moment. The number of RE in the wall at a particular time can be estimated from $N_{\mathrm{re,wall}} = \delta r \phi_{\mathrm{loss}}/c$, where $\delta r = 1\,\mathrm{cm}$ is the effective wall thickness and $\phi_{\mathrm{loss}} = 4\times 10^{16}\,\mathrm{s}^{-1}$ is the RE loss rate. The number of confined RE, according to DREAM, is $N_{\mathrm{re,plasma}} \approx 2\times 10^{16}$. The ratio of BR from the plasma to BR from the wall in the post-disruption plasma considered here is thus $\phi_{\mathrm{plasma}}/\phi_{\mathrm{wall}} \approx 3.7$, suggesting that slightly more HXRs originate from RE-plasma interactions. It is worth noting that the situation would be reversed in e.g. the pre-disruption plasma, for a negligible high-Z impurity content. These observations are compatible with the experience of how the HXR flux varies with the material parameters and externally induced transport.

Conclusions We have studied REs in the deliberately disrupted TCV discharge #52717. We find that REs comprise 70-90% of the total current prior to the disruption, and that the remainder of the thermal current is converted into RE via the hot-tail mechanism in the disruption. A significant improvement in RE confinement before the disruption, coincident with a drop in the measured loop voltage, is found in the cases resulting in post-disruption RE beams. The post-disruption bulk electron temperature (2-3 eV according to the simulation), results from the competition between radiation losses and collisional heating by RE. To match the simulated current decay to the experimental decay rate, a uniform radial diffusion of the RE with $D_{rr} = 0.02\,\mathrm{m}^2/\mathrm{s}$ was required. This provided a RE loss rate which was used to estimate the HXR flux, suggesting that bremsstrahlung from RE-plasma and RE-wall interactions are approximately equal after the disruption.

References

[1] J. Decker *et al*, Nucl. Fusion **62** 076038 (2022)
[2] M. Hoppe *et al*, Comp. Phys. Comm. **268** 108098 (2021)
[3] L. Hesslow *et al*, J. Plasma Phys. **85** 475850601 (2019)
[4] L. Hesslow *et al*, Nucl. Fusion **59** 084004 (2019)
[5] H. Smith and E. Verwichte, Phys. Plasmas **15** 072502 (2008)
[6] J. W. Connor and R. J. Hastie, Nucl. Fusion **15** 415 (1975)
[7] H. W. Koch and J. W. Motz, Rev. Mod. Phys. **31** 920 (1959)

This work has been carried out within the framework of the EUROfusion Consortium, partially funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 – EUROfusion). The Swiss contribution to this work has been funded by the Swiss State Secretariat for Education, Research and Innovation (SERI). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union, the European Commission or SERI. Neither the European Union nor the European Commission nor SERI can be held responsible for them. This work was supported in part by the Swiss National Science Foundation.