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Toroidal field coil quench caused by runaway electrons on the WEST tokamak

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Runaway electrons (REs) are relativistic electrons produced during plasma breakdowns, ramp-ups and disruptions. They may reach several 10s of MeV and form multi-MA beams and pose a serious threat to the reliability and availability of future tokamak devices. During the initial commissioning phase of the WEST tokamak [Bucalossi 2014], a significant fraction of discharges contained runaway electrons created at breakdown. On discharge #52205, runaway electrons survived the current ramp-up and flat-top then hit the outboard limiter when the plasma disrupted. Shortly after the event, the quench of one of the toroidal field coil was observed. The large number of runaway electrons in the initial commissioning phase of WEST was attributed to the narrow operational window in which breakdown and burn-through was achievable. Too low prefill pressure led to non-sustained breakdowns, and surprisingly, too high prefill led first to runaway electrons (see figure 1). Machine conditions can explain this behavior, as most of the runaway discharges had higher radiated fractions in the first 25 ms after breakdown. In those situations, the ohmic current failed to rise quickly enough, and the available flux change from the central solenoid was preferentially taken by runaway electrons seeds. RE beam scenarios ranged from very early dissipation after breakdown to slide-away discharges in which REs were sustained during the entire pulse (see classification on figure 1). The latter usually led to the most severe impacts on the plasma facing components, especially when happening on the toroidally localized outboard Antenna Protection Limiter as in the event described below.

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Pulse #52205 was among the first X-point pulses attempts on WEST. Runaway electrons appeared during plasma current ramp-up then stayed during the whole current flat-top (350 kA). They were ultimately lost on the APL when the plasma disrupted 1.75 s after breakdown. The impact was visible during more than 1.5 s on the visible cameras, indicating strong in-depth heat deposition. A net voltage and a helium pressure rise appeared on Toroidal Field Coil #9 (TFC#9) 2 seconds after the runway loss event [Torre 2019]. Following the triggering of the safety discharge system, the current from TFC#9 was dumped in 20 s instead of the standard 120 s, indicating that the coil had quenched. The primary suspicion for the cause of the quench was the RE impact.
REs interacting with matter generate bremsstrahlung photons which produce photoneutrons by interaction with the nuclei of encountered atoms. Since REs are highly relativistic, their bremsstrahlung radiation is emitted in a forward-beamed cone. The emission cone of a runaway beam hitting tangentially the APL intersects TFC #9 and partially intersects TFC#10. The latter did not quench, but its temperature showed an anomalous increase after the RE event. This observation is a strong indication that REs were involved in the quench process. Furthermore, a similar quench event happened in 1989 [Duchateau 1991] after a disruption with REs. A retrospective analysis of the machine geometry at that time revealed that the relative location of the quenched coil and the outboard limiter was similar as in the event described in the present article.

Simulations of the RE impact on the APL have been made using the GEANT4 code [Agostinelli 2003]. GEANT4 is a Monte-Carlo code simulating the passage of particles through matter. Physics models include electromagnetic, hadronic, and optical processes over an energy range from 250 eV to several TeV. A library of materials is also provided. The code is used in a wide range of applications, including particle physics detectors design, space engineering and medical physics. The runaway impact was simulated in a 55° section of the torus (see figure 2a and 2b). It comprises the carbon limiter upon which the runaways were lost, the stainless steel first wall and vacuum vessel. Three TFCs (#8, #9 and #10) were included in the geometry. The vertical and horizontal impact angles were set to 10° and 1° respectively.. A mono-energetic beam of 108 electrons was simulated as a compromise between statistical noise and computational time. Total energy was re-normalized to the real number of electrons.

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The results confirm that most of the secondary particles (photons, electrons and neutrons) were emitted in a narrow forward beamed cone (see figure 2b). The energy deposited in various machine elements was computed for 15 MeV and 30 MeV electrons. Only their kinetic energy (300 kJ for 30 MeV) was considered. No conversion from magnetic to kinetic energy was assumed.
Simulation results show that half of the total energy was lost locally on the APL. The rest was spread over first wall, vacuum vessel and TFCs. The energy deposition map confirmed that TFC#9 was the most severely hit coil, with 6.8 kJ deposited in the casing, and 1.3 kJ in the winding pack. The deposition was peaked on the front side and corner of the winding pack (see figure 2c), with ~1500 cm3 receiving more than 100 kJ/m3. As a comparison, the winding pack of TFC#10 received only 0.6kJ. Due to the greater distance from the impact point, the heat deposition was also spread over a larger area on the side of the winding pack. This reinforces the hypothesis that REs are responsible for the quench of TFC#9 and the small temperature increase of TFC#10. Thermohydraulical simulations [Nicollet 2020] confirmed that the volume of high heat flux computed on TFC#9 was compatible with the temperature measurements on the coil casings as well as the dynamics of helium expulsion following the quench. An identical simulation with 15 MeV REs showed that the energy deposited in the TFC#9 winding pack was 6 times smaller, in worse agreement with thermo-hydraulical calculations. Finally, the nature of the radioisotopes detected on the impact point also confirmed that the maximum energy of the runaway beam was above 20 MeV. Measurements of material activation inside the torus showed that the highest count rate outside the direct impact point was observed on the path of the predicted gamma/neutron emission cone and in qualitative agreement with the map of heat deposition computed by the GEANT4.

The much larger amount of shielding material (several tens of cm) makes such a quench scenario less likely on ITER compared to WEST where the toroidal field coils are closer to the plasma (only a few cm steel thickness). However, it sheds light on the importance of limiting the number of runaway events due their potential to deposit heat in remote and unexpected areas.

[Bucalossi 2014] J. Bucalossi et al., Fusion Engineering and Design, 89, 907912 (2014)

[Torre 2019] A. Torre et al., IEEE Transactions on Applied Superconductivity, 29, 5, 4702805 (2019)

[Duchateau 1991] J.-L. Duchateau et al., IEEE Trans. Mag., vol. 27, no. 2, pp. 2053-2056, (1991)

[Agostinelli 2003] S. Agostinelli et al., Nuclear Instruments and Methods in Physics Research Section A 506, 3 (2003)

[Nicollet 2020] S. Nicollet et al., Cryogenics, 106 103042 (2020)

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