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

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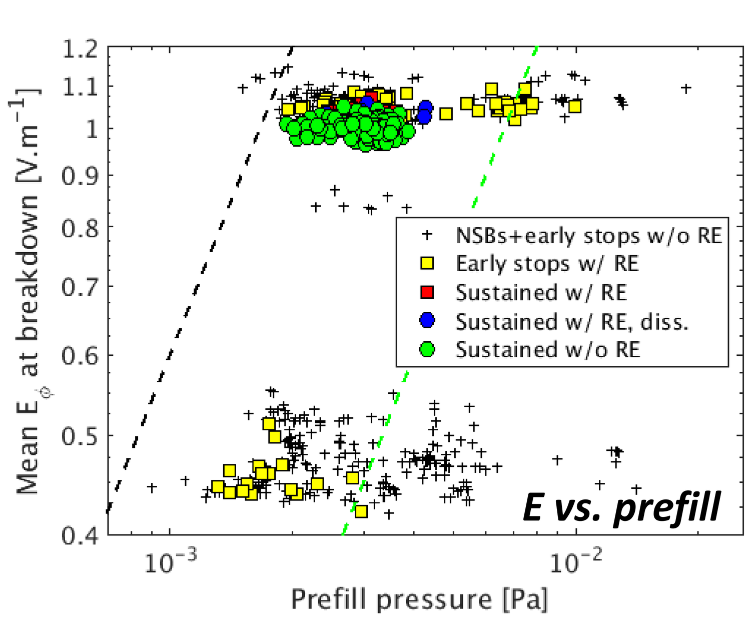
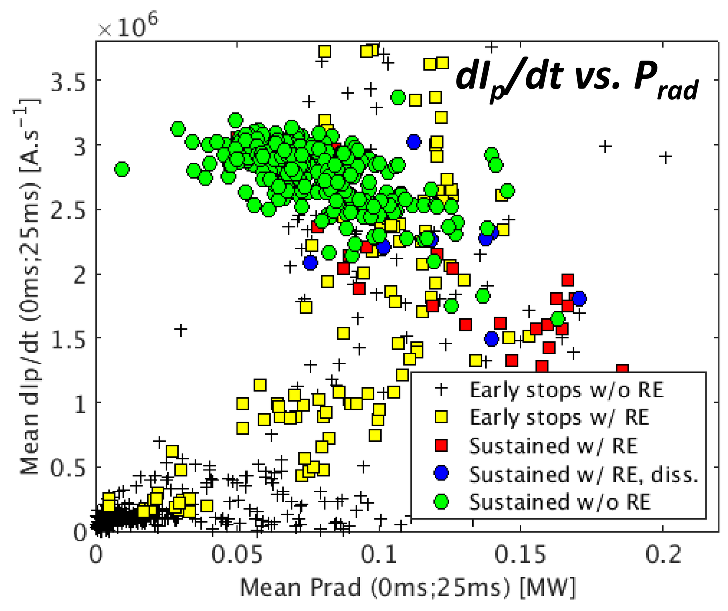
ABSTRACT

- WEST was faced with large amounts of runaway electrons generated at plasma breakdown due to poor wall conditioning during its first campaigns.
- One severe runaway impact event led to the quench of a superconductive toroidal field coil.
- GEANT4 Monte Carlo simulations showed that the quenched coil is on the path of the emission cone of secondary particles following the impact.
- Simulations showed that 1.3 kJ energy were deposited in the winding pack for a 30 MeV beam.
- Quantitative comparisons with thermohydraulic simulations confirmed a good agreement between the simulated figures and the pressure & temperature measurements.

RUNAWAY ELECTRONS AT STARTUP

- Runaway electrons were frequent during WEST first commissioning campaigns.
- The first stable plasmas were finally obtained by reducing the prefill pressure.
- This unusual behavior was attributed to the large amount of impurities preventing ohmic current from rising, and thus transferring the inductive flux to runaways.
- Only when the radiated power became low enough reliable plasmas could be obtained.

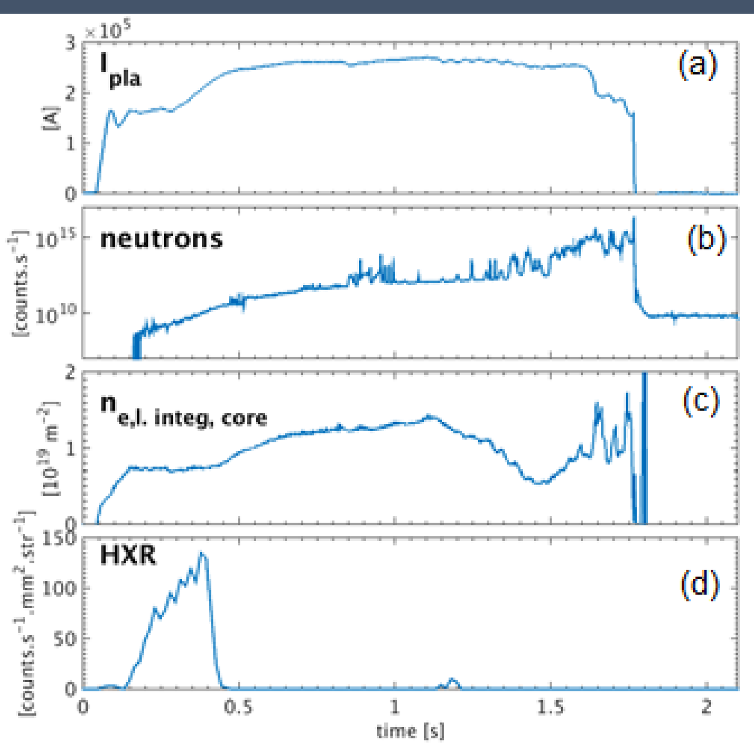




DESCRIPTION OF PULSE #52205

PLASMA

- Runaways were generated at breakdown and accelerated continuously during flat top at 250 kA.
- Low density (10^{19} m^{-2} core line-integrated).
- Neutron rate rising up to 10^{14} neutrons.s^{-1}: 10^3 to 10^4 more than an equivalent ohmic plasma.
- HXR up to 200 keV saturated.

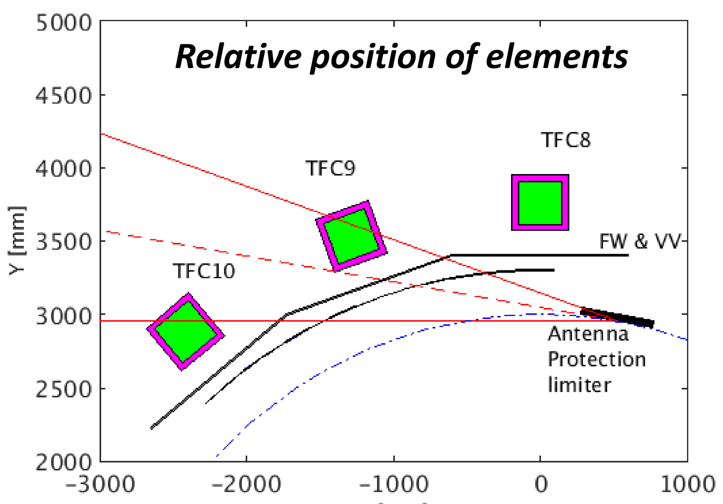


TERMINATION

- Major crash at 1.6s, but no runaway dissipation.
- Major disruption at 1.75s with 200 kA left.
  - WEST record neutron spike 10^{16} neutrons.s^{-1}.
- Impact on a singe point on the outer wall: Antenna Protection Limiter (APL).
- Hot spot observed during 1.5 s in visible light. Surprisingly, no sparks ejected from the limiter.

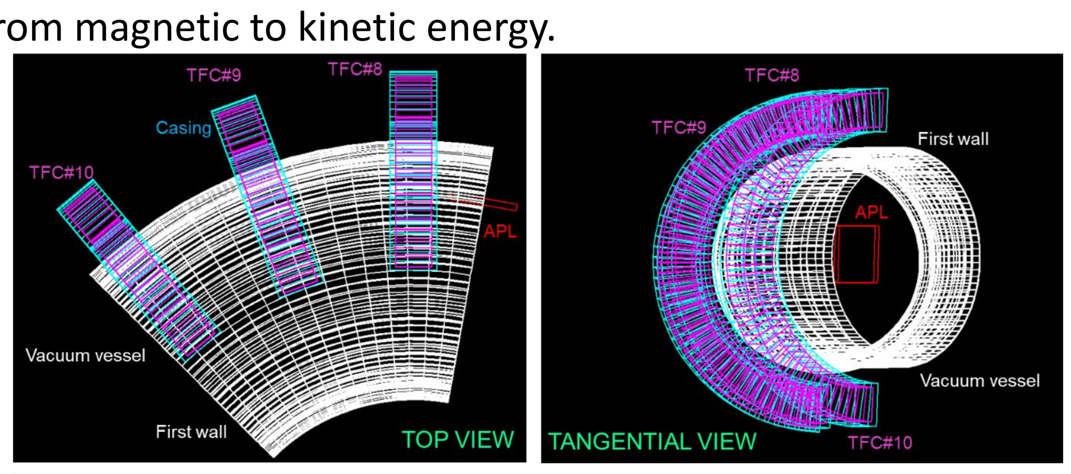
COIL QUENCH: RUNAWAY HYPOTHESIS

- Complete sequence of events described in Ref. [1].
- Toroidal field Coil No. 9 (TFC9): voltage and pressure. of the helium bath rise 2 seconds after the disruption.
- Fast safety discharge triggered 5.24s after the disruption.
- Elements in favor of the runaway responsibility in the quench:
  - Close time proximity between the two events.
  - Helium bath temperature rises following a similar less severe event earlier in the day, on the same coil.
  - Geometry: TFC9 is the most likely coil to be covered by a bremsstrahlung cone originating at the runaway impact point. TFC10 is also affected, and also saw a (more moderate) temperature increase.
  - Another quench in the history of Tore Supra (1989) happened in a similar situation: disruption with runaways, coil covered by the bremsstrahlung emission cone [2].



RUNAWAY IMPACT SIMULATIONS - GEOMETRY

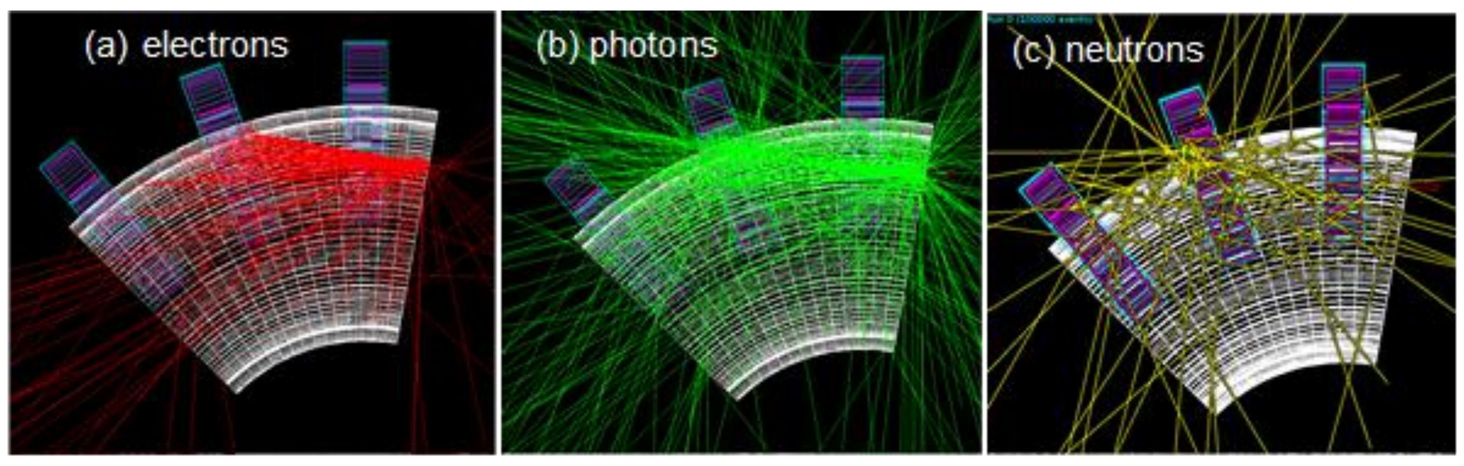
- GEANT4 Monte-Carlo code used [3].
  - Contains an extensive library of physics processes (hadronic and leptonic).
- 55° torus section simulated: 3 coils: TFC8, 9, 10 (copper + CuNi + NbTi), vacuum vessel (stainless steel), first wall (stainless steel) and impacted limiter (CFC).
- Only the low field side half of the coils are simulated with simplified geometries.
- Runaway beam: monoenergetic beam (15 MeV, 30 MeV) with no transverse dimension.
- Impact angles: 2 deg horizontally to force the impact on the limiter, 11 deg vertically.
- 10^8 electrons as a compromise between statistical noise and computation time.
- No conversion from magnetic to kinetic energy.



- Preliminary checks:
  - 295 kJ total kinetic energy in the beam (Etot = 2*π*R*Ip*ERE/(e*c)). 275 kJ (93%) are recovered in the simulation. The remaining 7% escape the simulation domain.
  - 1 neutron for 1000 runaways ➔ 6.15x10^{13} neutrons produced. Qualitatively consistent with the ~2x10^{13} neutrons produced during the 2 ms disruption.

SIMULATION RESULTS

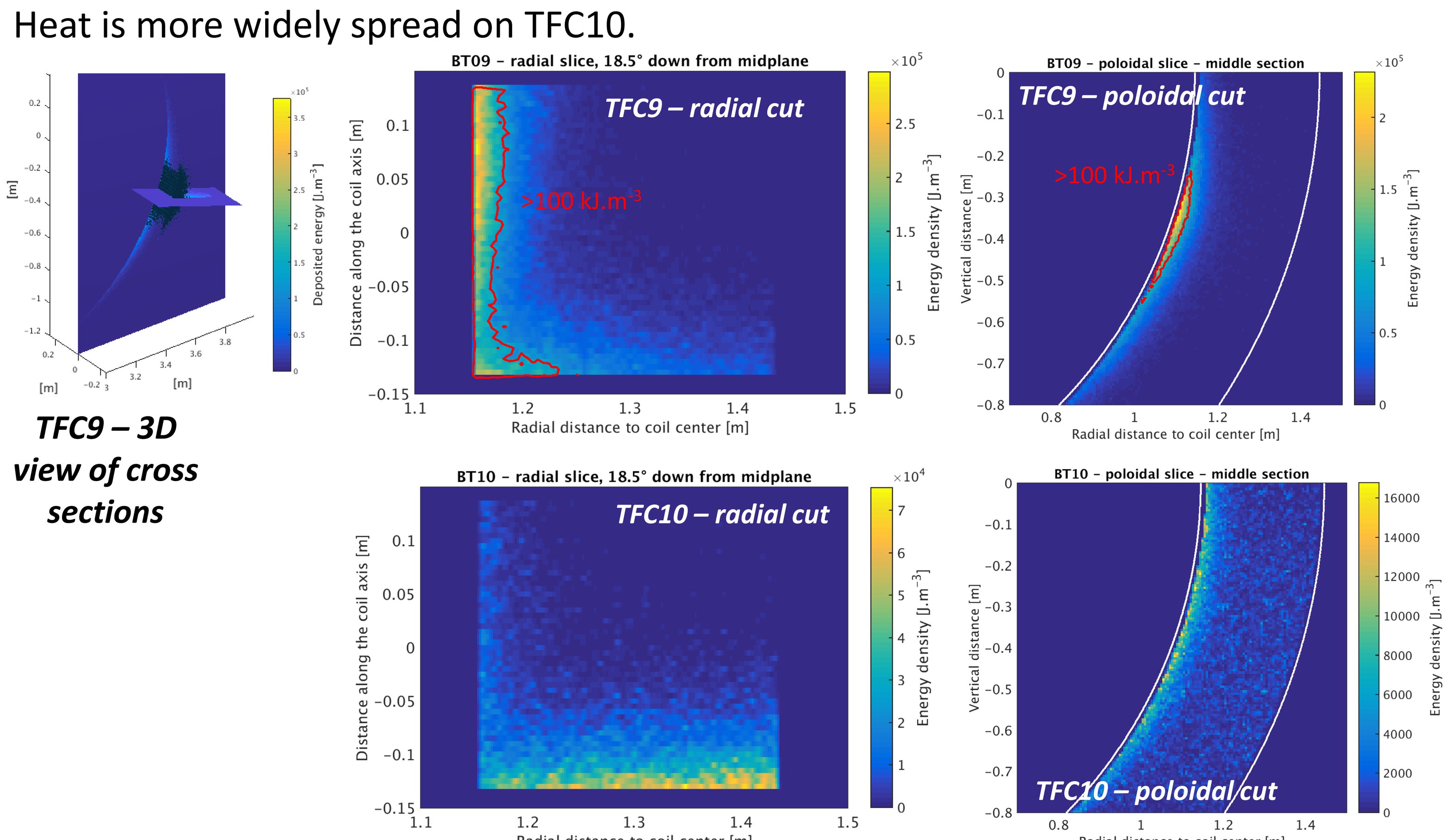
- Secondary particle trajectories confirm the forward-beamed emission cone.
- Mostly photons going through first wall and vacuum vessel. Neutrons produced locally.



- Total energy deposited in the various elements: TFC9 is the most affected.
- TFC10 takes less energy TFC9, reproducing qualitatively the small measured temperature increase. TFC8 takes almost nothing, in agreement with the absence of temperature rise.
- The steel casing of TFC9 absorbs 8 times more energy than the conductor.

Runaway energy (MeV)	TFC8	TFC9		TFC10
	Conductor (J)	Cond.+casing (J)	Conductor (J)	Conductor (J)
15	42	-	231	162
30	115	8140	**1312**	631

- Heat Deposition for TFC9 is concentrated in the volume facing the cone and the plasma.
- 1500 cm^3 of conductor take at least 100 kJ.m^{-3}. (~30 cm tall, 25 cm wide).
- Thermohydraulic simulations [4] confirmed that the volume and values of high heat flux computed by GEANT4 are compatible with the temperature measurements on the coil and the dynamics of the helium expulsion. They confirm a smooth quench scenario on a small length of conductor (0.4 m) propagating to the rest of the winding.
- The 15 MeV case shows worse agreement with the thermohydraulic simulations. Energies more than 20 MeV were also confirmed by activation measurements.
- Heat is more widely spread on TFC10.



TFC9 – 3D view of cross sections

CONCLUSIONS

- Simulations of runaway electron energy deposition in the tokamak components confirm that the quench of the WEST toroidal field coil #9 was caused by a runaway impact
- The situation is unlikely on ITER, but shows that runaways can deposit energy in unusual places

REFERENCES

- [1] A. Torre et al., *IEEE Trans. Appl. Supercond*. 2020 [2] J.-L. Duchateau et al., *IEEE Trans. Mag*. 1991. [3] S. Agostinelli et al. *Nuclear Instruments and Methods in Physics Research Section A* 2003. [4] S. Nicollet et al., *Cryogenics* 2020