Integrated disruption mitigation planning on tokamak power reactors and its physics bases

Xianzhu Tang[1], J. Arnaud[3], O. Beznosov[1], A. H. Boozer[2], L. Chacon[1], J. Hamilton[1], M. Lively[1], C. McDevitt[3], D. Perez[1], P. Sharma[1], B. Uberuaga[1], Q. Zhang[1], Y. Zhang[1]

[1]*Los Alamos National Laboratory, Los Alamos, NM 87545, U.S.A.;* [2]*Columbia University, New York, NY 10027, U.S.A.;* [3]*University of Florida, Gainesville, FL 32611, U.S.A.*

The three leading fusion reactor prototypes under construction, the international ITER experiment at Cadarache, France, the Burning Plasma Experimental Tokamak (BEST) at Hefei, China, and the SPARC/ARC facility at Devens, Massachusetts, USA, are all tokamaks. So are the leading DEMO designs in the European Union, Japan, and China. On the ambitious path of bringing fusion to the power grid in two decades with the launch of the Milestone-Based Fusion Development program in the U.S., tokamaks, as being pursued by Commonwealth Fusion Systems (CFS) and Tokamak Energy Ltd. (TE), remain the most viable candidate for the fastest demonstration of fusion power. A key obstacle in tokamak fusion energy is effective disruption mitigation, without which there can be first wall and even subsurface component damages that lead to intolerably long downtime for power reactors [1].

The thermal quench (TQ) applies to both tokamaks and stellarators, usually associated with a sudden loss of plasma confining flux surfaces, and its mitigation targets the plasma thermal load management on the divertor plates and neighboring first wall surface. In contrast, the current quench (CQ) deals with magnetic energy dissipation and exclusively applies to tokamak reactors. Its mitigation primarily targets, besides electromagnetic force loading in reactor components, the avoidance/minimization and load management of runaway electrons at relativistic energies, which can be efficiently powered by poloidal magnetic dissipation in a post-TQ cold plasma. The primary challenge in disruption mitigation is the need for a comprehensive mitigation strategy integrated for both TQ and CQ in a tokamak reactor under all plausible scenarios. ITER's disruption mitigation system currently exclusively relies on shattered pellet injection of mixed hydrogen and neon pellets, while SPARC relies on massive gas injection and the first-of-its-kind runaway electron mitigation coils. Based on the research and capabilities developed in the Tokamak Disruption Simulation (TDS) and the Simulation Center for Runaway Electron Avoidance and Mitigation (SCREAM) SciDAC projects, we report here the development of a comprehensive mitigation recipe that accommodates both TQ and CQ in a variety of anticipated scenarios, with a particular emphasis on the physics bases underlying the various mitigation design, as well as known experimental evidences.

The integrated mitigation planning begins with the determination if sufficient lead time is available from the disruption prediction tools. If the answer is affirmative (Y for Yes), one can proceed with (Y.1) the normal high-Z impurity injection to mitigate the TQ load via core radiation, as planned for both ITER and SPARC. This will result in a robust Ohmic-to-runaway current conversion that produces a runaway current plateau, which can be mitigated by (Y.1.1) a 3D MHD flush or more likely multiple 3D MHD flushes to force runaway-to-Ohmic back-conversion [2], or (Y.1.2) alternatively via enhanced dissipation by additional high-Z impurity injection, or (Y.1.3) 3D field perturbation through inductively charged runaway coils [3], or (Y.1.4) external wave injection and deliberate internal wave excitation [4].

As a radically different alternative under the condition of enough lead time, one can aim for (Y.2) completely avoiding a fast TQ in the first place via massive low-Z (e.g. deuterium) injection, which has the ability to align the TQ with CQ at the same time duration. This removes the root cause of the inevitable Ohmic-to-runaway current conversion associated with the impurity radiative cooling (either by deliberate injection or wall impurity production via intensive PMI as a result of TQ), and opens the possibility of avoiding/minimizing runaways [5].

In the hopefully rare occasions that there is not (N for Not) enough lead time from the disruption prediction system to launch core-bound pellets, one would face a much more difficult TQ mitigation task by (N.1) a local massive gas/dust release in the divertor and its neighborhood region. The TQ wall damage is minimized if a significant burn-through of the dense and radiating edge/boundary does not materialize. The post-TQ runaway mitigation proceeds as in the previous Y.1.X scenarios. In both the Y and N scenarios, if all else fails, one would pursue runaway termination on sacrificial armor or tungsten dust shield, which is the last (L for Last) ditch defense against significant wall damage by runaways [6].

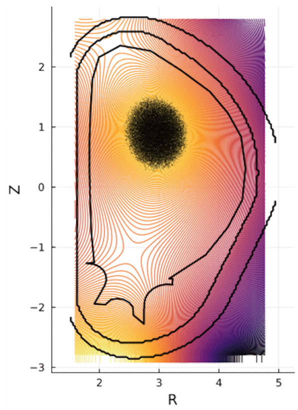

Figure 1: Ohmic-to-RE current conversion via avalanches plus VDE in an ITER plasma with hybrid kinetic REs/MHD model.

We arrive at this integrated mitigation design mostly through fundamental transport physics considerations, including the plasma particle and energy transport, radiative cooling, runaway electron dynamics, and runaway electron interaction with solid particles. The whole-device multiphysics simulations that account for the full geometry of a tokamak reactor like ITER, have been particularly informative on the mitigation design, for example, for the quantitative assessment of Y.1.1-3 and Y.2. Materials response simulations with MCNP have been informative in the mitigation design of L.

Among the most intriguing physics, we will show the first whole-device hybrid MHD-runaway simulation that tracks a vertical displacement event in its entirety, along with the initial Ohmic-runaway current conversion and the subsequent runaway loss by both radial transport and wall scrape-off, Fig.1. This yields important information on the runaway load distribution on the first wall, including both the pitch and energy distribution, as well as the spatial and temporal profiles, all quantities of critical importance in forming the wall damage metric for mitigation design. Another showcase is the whole-device extended MHD simulation that can track the entire process of TQ and CQ after an initial massive hydrogen injection. This is a rare case that a fusion plasma, upon dilutional cooling, falls into the collisional regime where Braginskii transport model is actually applicable. The interplay between collisional transport, field line stochaticization via self-consistently evolving magnetic fields, and radiation, is faithfully captured by high-resolution simulations, and yields critical physics that opens an alternative pathway for mitigating TQ and CQ simultaneously, Fig.2.

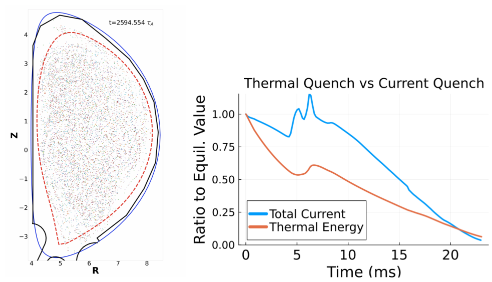

Figure 2: PIXIE3D simulation of a mitigated ITER disruption with massive deuterium injection (300 times increase in density). TQ slows down to CQ time scale even with a fully stochastic B field.

This work was supported by U.S. Department of Energy under the SciDAC program.

[1] Hender T.C. et al. Nucl. Fusion 47, S128 (2007).
[2] Reux C. et al. PRL 126, 175001 (2021); McDevitt & Tang, PRE 108, L043201 (2023).
[3] Boozer A.H. PPCF 53(8), 084002 (2011); Tinguely R.A. et al. NF 61, 124003 (2021).
[4] Guo Z. et al. Phys. Plasmas 25, 032504 (2018); Zhang Q. et al. arXiv:2409.15830 (2024).
[5] McDevitt & Tang, et al. NF 63, 024001 (2023).
[6] Lively M. et al. Nucl. Fusion 64, 056019 (2024).