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Case in Point: Quench Response of the SPARC Toroidal Field Model Coil

Brian LaBombard

[1]MIT Plasma Science and Fusion Center, Cambridge, Massachusetts, USA

E-mail: labombard@psfc.mit.edu

***Abstract*–"Are NI magnets really self-protecting?" A review of experimental findings from the CFS/MIT NI magnet development program, which culminated in the construction, operation and quench-testing of the SPARC Toroidal Field Model Coil (TFMC) [1], serves to inform this question.**

SPARC TF coils employ a unique no-insulation design in which HTS tape is inserted and soldered into grooves cut into Nitronic® radial plates [2]. This robust mechanical design facilitates 22T on conductor in large-bore D-shaped coils, needed to attain SPARC's fusion power mission [3]. Initial R&D of this grooved-plate topology involved quench-testing small 20 turn double-pancake coils (~10 cm dia. bore) operating with 10kA in conductor at 12K. With stored magnetic energy less than ~4kJ, these coils were self-protecting, providing an excellent platform to study NI quench dynamics. Next, 16 turn, D-shaped single pancakes (1.4m x 0.7 m bore) were constructed for the TFMC winding pack. These were electrically tested by pushing them into deep saturation with terminal currents of ~12 kA at 77K. Due to low turn-to-turn resistance, LN2 immersion and stored energies of only 50kJ, these pancake coils were also robustly self-protecting. However, the TFMC – constructed from 16 pancakes (256 turns) operating at 40kA and 20K with stored magnetic energy of 110MJ – decisively transitioned into the non-self-protecting category.

Quench simulations of the coil's response to an open circuit fault condition at 31kA clearly informed why. While heating from open-circuit radial current flow is uniform throughout the coil, it is very low, at the level of ~10 W/m along the winding with an L/R decay time of ~3 hrs. When a section of the winding passes through critical (as it ultimately must when the coil heats up), local heating from current flow through the normal zone greatly exceeds 10 W/m, leading to a local runaway hot spot and burn. Thus, if one operates an NI coil in this regime, it is not self-protecting.

Mitigation strategies include: (1) increase radial current flow heating and decrease L/R time by increasing turn-to-turn resistance, (2) "flatten the Tc map" along the conductor so that the windings tend to pass though Tc everywhere at the same time, (3) employ externally driven heaters to quench the coil quickly and uniformly in azimuth, (4) trigger a turn-by-turn inductive quench cascade that causes the coil to quench uniformly in azimuth. Informed by the quench response of the TMFC, such strategies have been implemented for quench protection of SPARC's TF magnet.

***Keywords (Index Terms)*–No-insulation, HTS, quench, large bore, magnetic fusion, self protecting, high stored energy, 20 tesla, SPARC, toroidal field model coil**

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