GA–A26677

RUNAWAY ELECTRON MODELING FOR RAPID SHUTDOWN SCENARIOS IN DIII-D, ALCATOR C-MOD, AND ITER

by

V.A. IZZO, A.N. JAMES, J.H. YU, D.A. HUMPHREYS, L.L. LAO,
R.W. HARVEY, E.M. HOLLMANN, J.G. WESLEY, D.G. WHYTE,
R.S. GRANETZ, P.B. PARKS, and V.S. CHAN

FEBRUARY 2011

GENERAL ATOMICS

DISCLAIMER

GA–A26677

RUNAWAY ELECTRON MODELING FOR RAPID SHUTDOWN SCENARIOS IN DIII-D, ALCATOR C-MOD, AND ITER

by
V.A. IZZO*, A.N. JAMES*, J.H. YU*, D.A. HUMPHREYS, L.L. LAO,
R.W. HARVEY†, E.M. HOLLMANN*, J.G. WESLEY, D.G. WHYTE‡,
R.S. GRANETZ‡, P.B. PARKS, and V.S. CHAN

This is a preprint of a paper to be presented at the 23rd IAEA Fusion Energy Conference, October 11–16, 2010 in Daejon, Republic of Korea and to be published in Proceedings.

*University of California-San Diego, La Jolla, California
†CompX, Del Mar, California
‡MIT Plasmas Science and Fusion Center, Cambridge, Massachusetts

Work supported in part by
the U.S. Department of Energy
under DE-FG02-95ER54309, DE-FC02-04ER54698,
and DE-FG03-99ER54541

GENERAL ATOMICS ATOMICS PROJECT 03726
FEBRUARY 2011

GENERAL ATOMICS

The 3D MHD code NIMROD has recently been extended to include a single-particle model for trace runaway electrons (RE), whose (guiding center drift) orbits are followed as the background MHD fields evolve during the disruption simulation. The model, which includes E-field acceleration and collisional and radiation drag, predicts the confinement time for REs (τ_{RE}) on stochastic magnetic fields, as well as the strike points of escaping REs on the first wall (Fig. 1). ITER disruptions are likely to generate runaway electrons in much larger numbers than present tokamaks since the runaway avalanche gain is proportional to the exponential of the plasma current: $G_{\mathrm{RE}} \approx \exp[2.5\ I_{\mathrm{p}}\ (\mathrm{MA})]$. The limited applicability of devices with just a few avalanche e-foldings to ITER, with several tens of e-foldings, demands the strategic use of modeling to bridge the gap in parameter space. The NIMROD RE confinement model does not predict RE generation, but can be iterated with the 1D Fokker-Plank code CQL3D [1] to obtain a complete picture of the RE growth and loss rates during the disruption evolution. Three key questions are considered: 1) Is rapid-shutdown-induced MHD sufficient to suppress a runaway avalanche by reduction of τ_{RE}; 2) Can τ_{RE} be further reduced through the application of $n>0$ perturbing fields; and 3) does ITER differ qualitatively from smaller tokamaks with regard to 1 and 2?

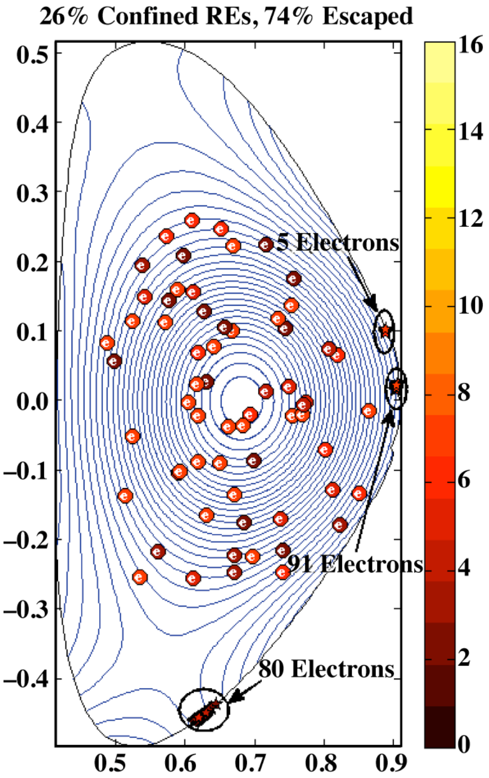

Fig. 1. An Alcator C-Mod simulation with over 200 electron orbits tracked. Circles represent [R,Z] locations of confined electrons while stars represent the accumulated strike points of escaped electrons. Colors are electron energy in MeV. Electrons follow field lines to the outer divertor, or hit the outer midplane due to curvature drift.

On DIII-D, experiments with Ar pellet injection most reliably generate runaways, and have aimed both to characterize REs with a variety of new diagnostics and also to alter τ_{RE} with the application of $n>0$ perturbing magnetic fields. In NIMROD, a simplified Ar delivery model produces a rapid radiative thermal quench (TQ) and quickly enters the current quench (CQ) phase in which RE generation is of primary concern. Significantly, since the temperature quickly drops below ~30 eV everywhere, typical of the CQ, these simulations are conducted with no artificial enhancement of resistivity. Hence all time scales (current diffusion, MHD growth, radiation, RE transport) maintain the correct relationship. These simulations find a prompt loss of many (lower energy) REs to the outer divertor at the time of the disruption induced MHD crash, and a subsequent loss of high energy REs to the outer midplane due to large curvature drift and a shrinking equilibrium. Both of these features have been observed in DIII-D RE experiments. Simulations including n=3 magnetic perturbations find that the applied fields interact with and qualitatively alter the disruption-induced MHD, but have no direct effect on the centrally confined REs in the later phase of the current quench. A more gradual but continuous loss process is found with applied n=1 fields. Simulations with larger electron numbers have enabled the electron data to be mapped to continuum quantities (Fig. 2) for comparison to machine diagnostics, such as measured synchrotron radiation brightness, which is a key RE diagnostic on DIII-D. Even without direct calculation of the avalanche generation of secondary REs in NIMROD, from the orbit model we calculate the loss rate $[1/N_{RE}\,(\partial N_{RE}/\partial t)]$ versus time in the presence of perturbing fields to compare directly to the theoretical avalanche growth rate.

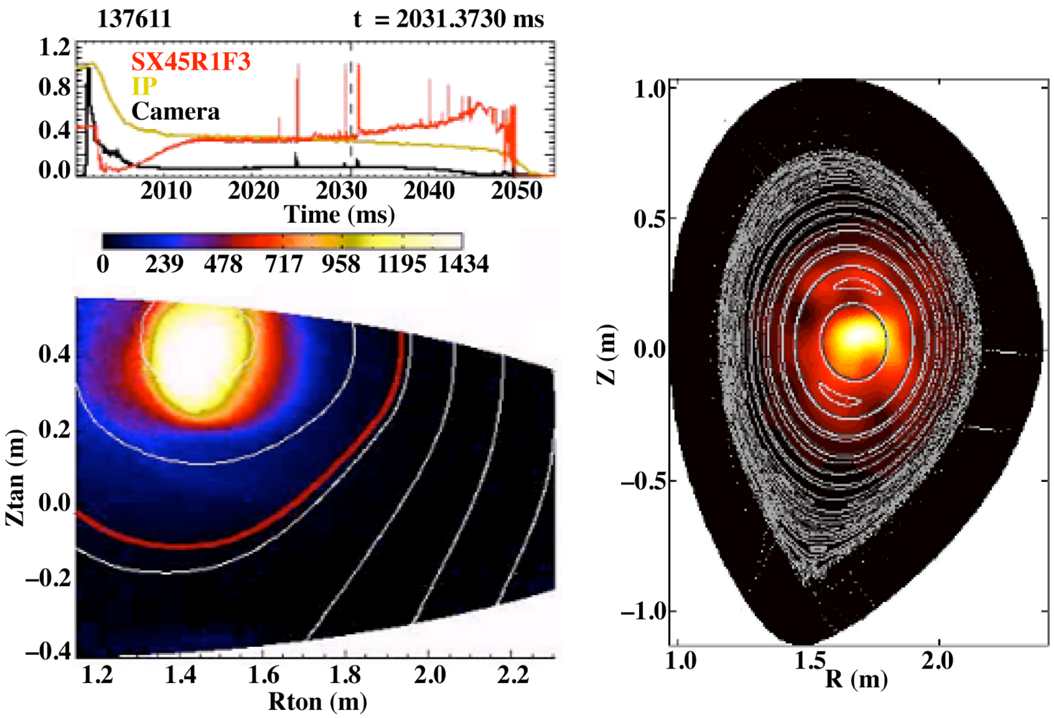

Fig. 2. (Left) Fast camera measurement of synchrotron radiation from a runaway beam in DIII-D. (Right) Synchrotron radiation brightness from a simulation with nearly 2000 electron orbits. Field lines are superimposed.

Alcator C-Mod RE experiments have focused on the de-confining effects of disruption induced MHD during massive gas injection (MGI). The experiments employ the lower-hybrid current drive (LHCD) system to generate a substantial seed capable of producing a large runaway current fraction after just a few e-foldings. Nonetheless, MGI experiments show a total loss of the REs during the TQ-induced MHD and no residual avalanche growth during the CQ. MGI in Alcator C-Mod has been simulated with NIMROD [2] and the orbit following model has been used to examine confinement during the MHD phase. The NIMROD results are consistent with a total loss of pre-TQ RE seed due to MGI induced MHD, and show other similarities to C-Mod diagnostics.

Simulations of the CQ phase of an ITER disruption have previously been carried out with NIMROD at realistic CQ plasma parameters [3]. Here we perform CQ simulations similar to the C-Mod and DIII-D cases, including cooling by Ar deposition, to examine the effects of larger machine size, and higher temperature and plasma current on the resulting RE confinement. In C-Mod and DIII-D the maximum achievable RE energies (~20 MeV and ~55 MeV respectively) are set by confinement, and are demonstrated numerically to scale as BR^2, as expected theoretically. In ITER, REs with energies as high as 1000 MeV would be well confined by this scaling, and the energy is instead limited by synchrotron radiation drag.

This work was supported by the US Department of Energy under DE-FG02-95ER54309, DE-FC02-04ER54698, and DE-FG03-99ER54541.

[1] R.W. Harvey, *et al.*, Phys. Plasmas **7**, 4590 (2000).

[2] V.A. Izzo, *et al.*, Phys. Plasmas **15**, 056109 (2008).

[3] V.A. Izzo, *et al.*, in Plasma Phys. Control. Fusion **51**, 105004 (2009).