FY2013 Theory Milestone
Second Quarterly Report
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I. Introduction and Background

The second quarter milestone for the FY2013 Theory Target on Disruption Physics (as described in the Appendix) has been completed and the results are described below. The second quarter milestone calls for investigation of the impurity source term effects on runaway electron confinement in the simulation of mitigated disruptions. The simulations are carried out with NIMROD including drift-orbit calculations for runaway electron (RE) test particles as the MHD fields evolve [1]. A brief description of prior simulations follows for the purpose of comparison with the new simulation having a modified impurity source.

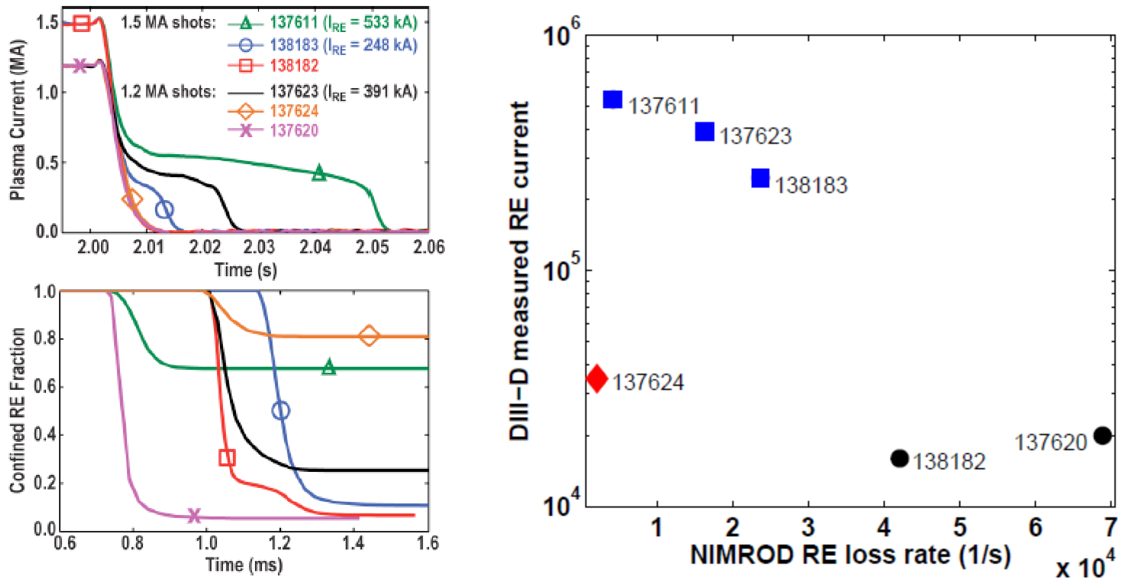

Figure 1. (Upper left). DIII-D measured current for six shots terminated by Ar pellets. (Lower left). Confined RE fraction vs. time for NIMROD simulations of the same six shots. (Right) DIII-D measured RE current vs. NIMROD calculated RE loss rate

Previously, NIMROD RE confinement modeling was done for the case of DIII-D rapid shutdown experiments using Ar pellet injection [1,2]. The Ar pellet experiments were performed on DIII-D expressly for the purpose of generating REs, not as a candidate method for disruption mitigation in ITER. Massive gas injection (MGI) rarely produces REs in DIII-D [3], and two major factors differentiate MGI rapid shutdowns from Ar pellet injection: first, Ar pellets penetrate deeply into the plasma, while MGI does not; and second, the Ar pellets contain considerably less material than a typical MGI pulse. Because of its deep penetration, the Ar pellet injection was approximated in NIMROD by a volumetric deposition of the total pellet material over the entire plasma, which was poloidally and toroidally symmetric and radially broad (though slightly peaked in the core). This triggered a rapid radiative thermal quench of the entire plasma followed by contraction of the current profile and the growth of MHD instabilities producing significant RE losses. In [2] a set of six DIII-D diverted discharges terminated by Ar pellet injection were simulated, and the experimental variation in measured RE current corresponded well with the simulated rate of RE losses—faster RE losses were predicted when RE current was lower in DIII-D—except in one case. Those results are summarized in Fig. 1. These results support the hypothesis that variation in observed RE currents in DIII-D on a shot-to-shot basis is related to variation in the RE losses produced by MHD.

II. MGI-like simulation with modified impurity source model

The fact that MGI does not typically produce runaway current plateaus in DIII-D could be attributable to a wide variety of factors—certainly not only a difference in MHD deconfinement effects. Still, since MGI is a strong candidate technology for the ITER DMS, the question of whether an impurity source localized to the edge will trigger substantially different MHD and have different RE loss characteristics than deeply penetrating pellet is important. So we carry out a simulation with an edge-localized MGI-like impurity source that can be compared directly to one of the six simulations shown in Figure 1. The equilibrium from shot 137623 is reused as the starting point for this simulation. That was one of the three Ar pellet shots in Fig. 1 that had an observable RE plateau.

The MGI-like simulation uses Ne as its impurity species, and has a source profile which is radially very localized to the region outside the separatrix and poloidally peaked on the low-field side (see Fig 2). The source is toroidally symmetric. The impurities cross the separatrix primarily due to diffusion. Cooling of the edge contracts the current profile and triggers MHD instabilities, and only after the onset of large MHD modes does mixing become more rapid due to convection. A very significant difference between the MGI-like and pellet-like cases is that, in the MGI-like case, the core T_e barely changes before the onset of the MHD-induce thermal quench (TQ) which occurs around 1.5 ms. In standard flat-top operation, a DIII-D plasma has $E<E_{crit}$ (the critical electric field for runaways), which means there can be *no* runaways—that is, even highly relativistic electrons will experience a net slowing force due to collisions and eventually thermalize. In these simulations, all test electrons are initiated with suprathermal energies of 150keV. Whereas in the Ar pellet simulations, the whole plasma rapidly enters the $E> E_{crit}$ regime—thereby converting these electrons to runaways—the core plasma in the MGI simulation remains hot until 1.5 ms, and many of the seed electrons in the core re-thermalize before that time. So, two curves for the confined RE fraction during MGI are plotted in Fig 2. The dashed curve is the total population of test electrons remaining confined in the volume, and the solid curve are only those that remain suprathermal, meaning that they have the potential to run away in a post-TQ plasma. The difference represents the thermalized population.

The primary result that we wish to compare between these two simulations is the rate of RE losses associated with the major MHD event at the time of the TQ. As we saw in the set of Ar pellet simulations, this rate could vary by an order of magnitude depending on the starting equilibrium. First, we compare the n=1 mode behavior (as seen in Fig. 2), which is the largest mode in each case. Although comparable in amplitude, we note very different time scales for the mode evolution in the two cases. With the Ar pellet model, the core plasma becomes very cold and resistive early on, and we see the n=1 mode both growing rapidly and decaying rapidly as a result. With a hot, less-resistive core , the n=1 mode in the MGI simulation grows more slowly, and also persists much longer, since even immediately after the TQ the plasma remains less resistive that the post-TQ plasma with Ar pellet injection. For the MGI simulation, the maximum rate of RE losses is $2.3x10^4$/s. Comparing with shot 137623 on the right side of Fig. 1, we see that this rate is slightly higher than for Ar pellet injection with the same starting equilibrium. But, this value is still in the range of those discharges that had substantial RE plateaus, and well below the maximum loss rate seen with Ar pellet injection over all shots.

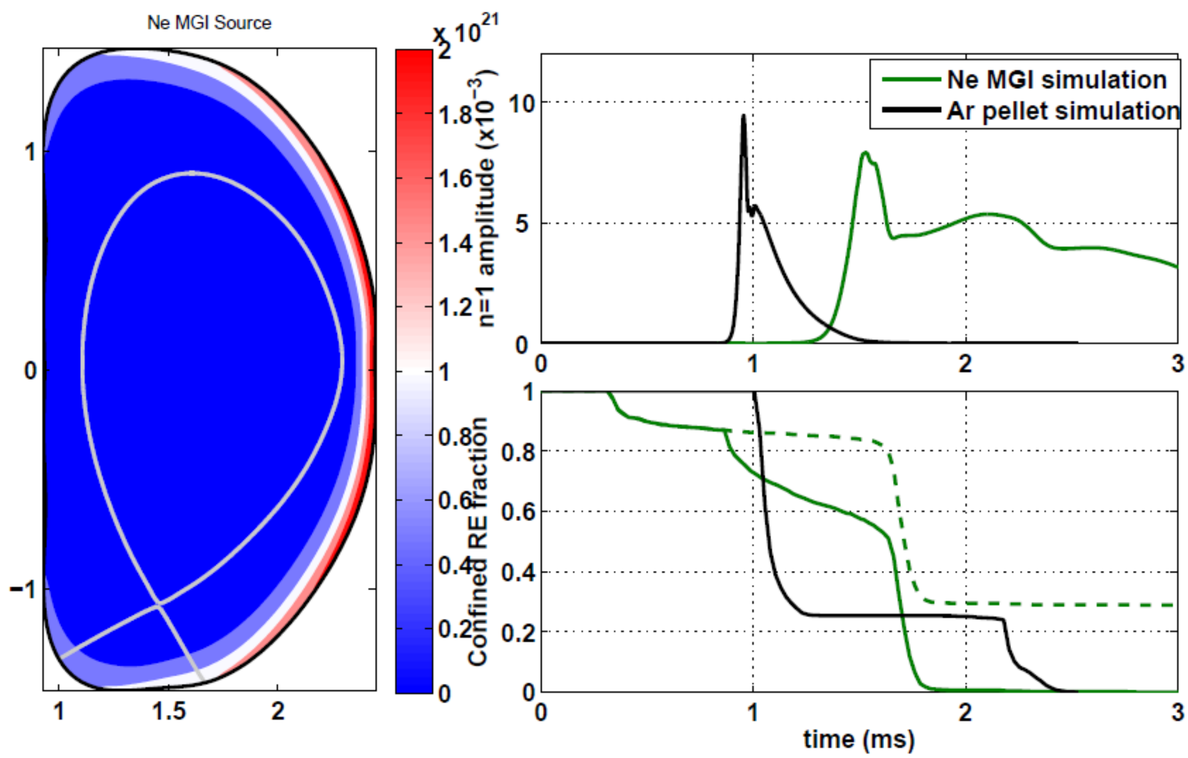

Figure 2. (Left) Ne density profile for the impurity source term in the Ne MGI simulation. (Upper right). Amplitude of the n=1 mode in the Ne MGI and Ar pellet simulations in units of $\delta B/B$ (calculated as the square root of the n=1 magnetic energy over the n=0 magnetic energy). (Lower right) Confined RE fraction vs. time for both simulations. In the Ne MGI simulation, the dashed line represents all tracked electrons, and the solid line represents only suprathermal (or runaway) electrons.

III. Summary and conclusions

In fulfillment of the second quarter milestone goal, a simulation of Ne MGI in DIII-D has been carried out to compare the effects of an edge-localized impurity source on RE confinement with the radially broad source used previously for Ar pellet simulations. The comparison yields three major observations:

First, with the MGI-like source, suprathermal electrons seeded at t=0 tend to thermalize before the onset of the MHD induced TQ. This does not preclude the possibility that in a real scenario, new seeds will be generated during the TQ itself, even as they are being lost along stochastic field lines, but it does suggest a possible difference in sequence when the radiative cooling of the core precedes the MHD onset vs. when it follows. If the initial rapid core cooling due to an Ar pellet produced seed REs in the core, these might have some time to accelerate to higher energies before the onset of stochasticity. The highly relativistic REs are less sensitive to magnetic fluctuations and thus better confined [4]. Seed REs generated only as the fields become stochastic in the MGI case might be more thoroughly deconfined.

Second, the rate of RE losses for the MGI-like source was found to be about 40% higher than the Ar pellet simulation with the same equilibrium. But, this value is not dramatically higher in light of the range of values found over the set of six Ar pellet simulations. In particular, it remains essentially on the low-loss-rate side of the right-hand plot in Fig. 1.

Third, the growth time and (most importantly) the duration of the n=1 mode were longer for the MGI case due to the lower core resistivity both pre- and post-TQ. While all the Ar pellet simulations had comparable mode decay times, the persistence of the n=1 mode in the MGI case could be far more significant than the RE loss rate itself, allowing nearly all seed REs to escape long before the flux surfaces are able to reheal.

Each of these three observations points to a lower likelihood of producing a runaway plateau with MGI compared with Ar pellet injection, which is consistent with operational experience on DIII-D. Separating the importance of these effects could be further explored both with the addition of a realistic runaway generation model in NIMROD, as well as modeling of other tokamaks that do routinely see RE plateaus after MGI.

[1] V.A Izzo, et al*, Nucl. Fusion.* **51** (2011) 063032

[2] V.A. Izzo, D.A. Humphreys, and M. Kornbluth, *Plasma Phys. Control. Fusion.* **54** (2012) 095002

[3] E. M. Hollmann, N. Commaux, , N. W. Eidietis, T. E. Evans , D. A. Humphreys, A. N. James, et al *Physics of Plasmas*, **17** (2010) 056117

[4] H. Mynick & J. Strachan, *Phys Fluids* **24** (1981) 695

Appendix: FY 2013 Theory Target on Disruption Physics:

Carry out advanced simulations to address two of the most problematic consequences of major disruptions in tokamaks: the generation and subsequent loss of high-energy electrons (runaway electrons), which can damage the first wall, and the generation of large electromagnetic loads induced by disruptions, and assess the severity of these effects on ITER

Quarterly Milestones:

Q1. Perform a 3D MHD simulation of a vertical displacement event (VDE) disruption at twice the resolution and wall time constant of previous studies to determine the scaling of the 3D forces on the axisymmetric conducting structures, and how these forces differ from those obtained in 2D calculations.

Q2. Perform a 3D MHD simulation of a DIII-D mitigated disruption experiment with symmetric impurity source terms to determine the effects of the source terms and MHD activity on test-particle runaway electron confinement.

Q3. Extend the 3D MHD simulations of VDEs to higher resolution by again doubling the grid resolution and increasing the simulation time period from that used in Q1. This will allow an increase in the Lundquist number to $S=10^6$ and a further doubling of the wall time-constant.

Q4. Extend the simulations of the DIII-D mitigated disruptions to model the effect of spatially non-symmetric source terms on runaway electron confinement.