R(20-3): Integrated Disruption Modeling for NSTX-U

Description

Disruptions represent a major challenge for the tokamak path to magnetic fusion energy due to the significant electromechanical stresses, heat loads, and energetic electron beams they can create. Models for understanding and characterizing disruptions are critical for engendering confidence in the design and operation of reactor-scale tokamaks. In order to better understand electromechanical stresses, thermal loads during disruptions, nonlinear simulations of both the thermal quench and current quench phases of disruptions and vertical displacement events (VDE) will be carried out for NSTX and NSTX-U discharges. These 3D MHD simulations will be performed using an integrated physics model that includes models for impurity radiation and transport, halo, and eddy currents. Non-axisymmetric instabilities and magnetic stochasticity will also be included. The effects of mitigation using injected impurities will be considered. Where practical, simulations will be validated by comparing results with experimental measurements of vertical displacement, magnetic probes, shunt tile currents, and the change in stored thermal energy.

Accomplishments

Fully nonlinear, three-dimensional simulations initialized with vertically unstable equilibria in NSTX and NSTX-U, both with and without impurities, have been carried out using M3D-C1. These simulations used realistic resistivity in both the plasma and in the conducting wall, with the result that the modelled vertical displacement proceeded on a timescale comparable to that measured experimentally (~1 m / 10 ms in NSTX). The simulations self-consistently span the full evolution of the disruption, including both the thermal quench and current quench phases.

In cases with a large quantity of impurities present, a rapid reduction in the stored energy thermal energy is observed, as well as the onset of non-axisymmetric magnetohydrodynamic instabilities that lead to stochastization of the magnetic field. Cases with impurities exhibit faster current quenches, but are also found to displace vertically more quickly than those without impurities, with the result that a significant fraction of the plasma current remains when the plasma contacts the wall. Correspondingly, forces on the vessel from all sources (both halo and eddy currents) are found to be comparable in the cases with and without impurities. In the NSTX simulation without impurities, halo currents are found to be in rough quantitative agreement with those measured experimentally, peaking at around 50 kA/m^2, although additional analysis will be required to compare the simulated halo current density with the empirical shunt-tile measurements. When sufficient impurities are included, the halo currents are found to be reduced, although the maximum forces are not found to be strongly affected.

Future work will consider cases with even greater quantities of impurities, in order to quantify how short the current quench time must be in order to avoid having significant plasma current present when the plasma contacts the wall.

The results of these simulations are described in more detail below.

NSTX 139536

NSTX discharge 139536 was a 600 kA discharge that terminated in a vertical displacement event [Gerhardt 2012]. Nonlinear, 3D simulations of this discharge were conducted, in part for comparison with experimental data, with both M3D [Breslau 2015] and M3D-C1 [Pfefferlé 2018]. In that study, the roles of thermal conductivity and wall resistivity on the evolution of the VDE were explored, but impurities were not considered. Here we have performed additional nonlinear 3D simulations in order to gauge the effect of a large quantity of impurities (such as might be present after pellet injection or massive gas injection, for example) on the evolution.

Three such simulations are presented here: a fiducial case in which no impurities as present; and two cases in which there was an initial uniform density of argon n_{Ar}, one with $n_{\mathrm{Ar}} = 10^{18}$ m^{-3}, and the other with $n_{\mathrm{Ar}} = 2\times10^{18}$ m^{-3}. The total toroidal current, the Z-coordinate of the magnetic axis, the total electron thermal energy, and the net force on the vessel in these simulations are shown in Figure 1.

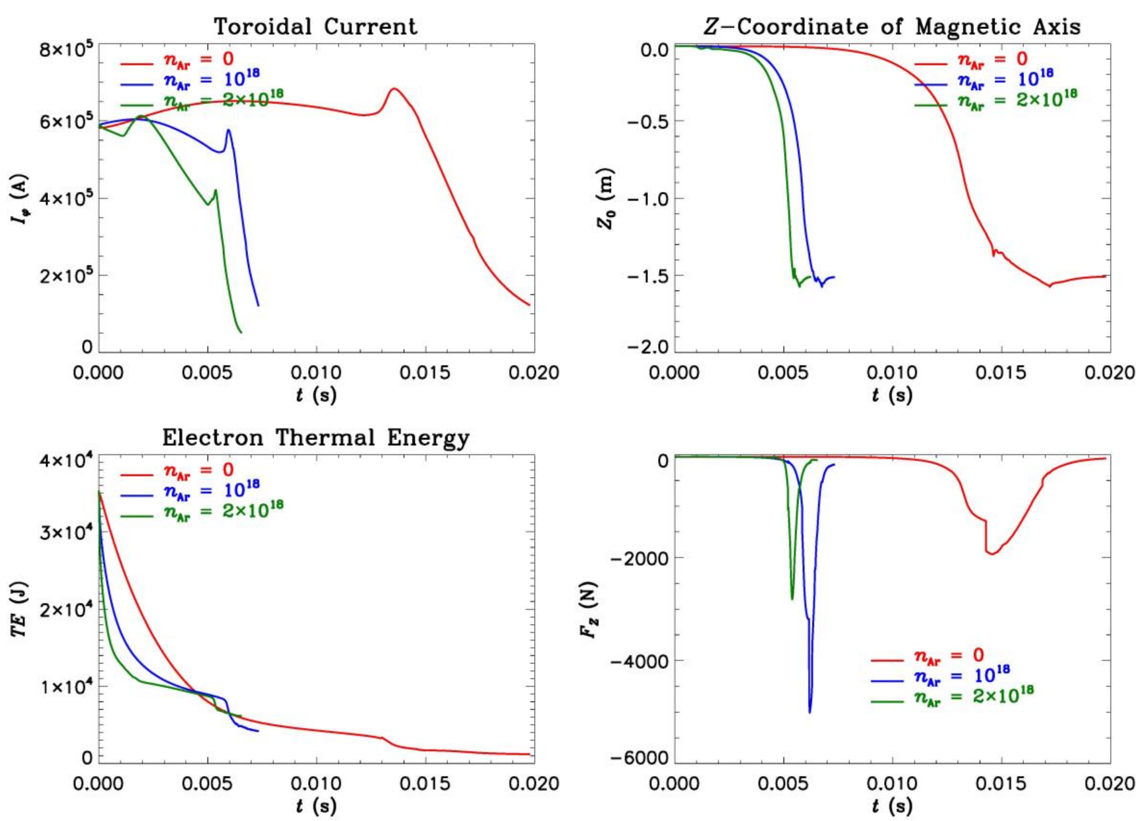

Figure 1 - The toroidal current, z-coordinate of the magnetic axis, electron thermal energy, and net vertical force on the vessel in simulations of NSTX 139536 with various initial quantities of neutral argon.

In the case without impurities, it is found that the vertical displacement proceeds on a timescale of ~10 ms, consistent with the findings of [Pfefferlé (2018)]. Note that even in this case, the thermal energy decays more rapidly (~1 ms) than the VDE proceeds because no sources are present in these simulations (ohmic heating is present, but no loop voltage is included). In the cases with impurities, both the thermal quench and the plasma displacement proceed more quickly than in the case without.

There are at least two potential explanations for why the vertical displacement is faster than the in the cases with impurities than in the case without impurities. The first is that the impurities cool the plasma in the scrape-off layer, which is known from previous studies [Ferraro 2016, Pfefferlé 2018, Krebs 2020] to have a considerable effect on the rate of displacement during a VDE. The second possibility is that the cooling of the core plasma leads to a faster current quench, which then induces co-IP eddy currents which pull the plasma toward the wall. This scenario has been described by [Kiramov 2018], for example.

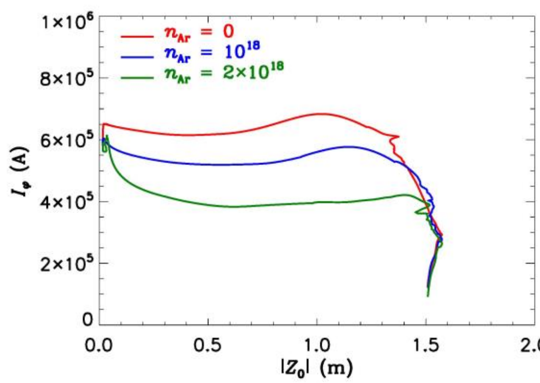

Figure 2 - The toroidal current versus the magnitude of the plasma displacement in simulations of NSTX 139536.

The toroidal current versus the magnitude of the plasma displacement is shown in Figure 2. From this figure it can be seen that the impurities have the effect of quenching a significant fraction of the current before the plasma moves. Despite this, the axisymmetric forces on the wall are comparable in all cases, which might be due to the enhanced rate of displacement in the cases with impurities. Presumably, with enough impurities present, the full current would quench before the plasma reaches the wall, thereby minimizing the wall forces. This will be explored in future work.

In all three of these simulations, a current spike is observed. The timing of this spike in all cases is coincident with the plasma becoming limited by the lower divertor, consistent with earlier results from axisymmetric simulations of VDEs in DIII-D with M3D-C1 [Ferraro 2016]. It can be seen that the axisymmetric wall force is also maximum at this time. Counterintuitively, the maximum axisymmetric wall force actually seems to increase somewhat when impurities are included.

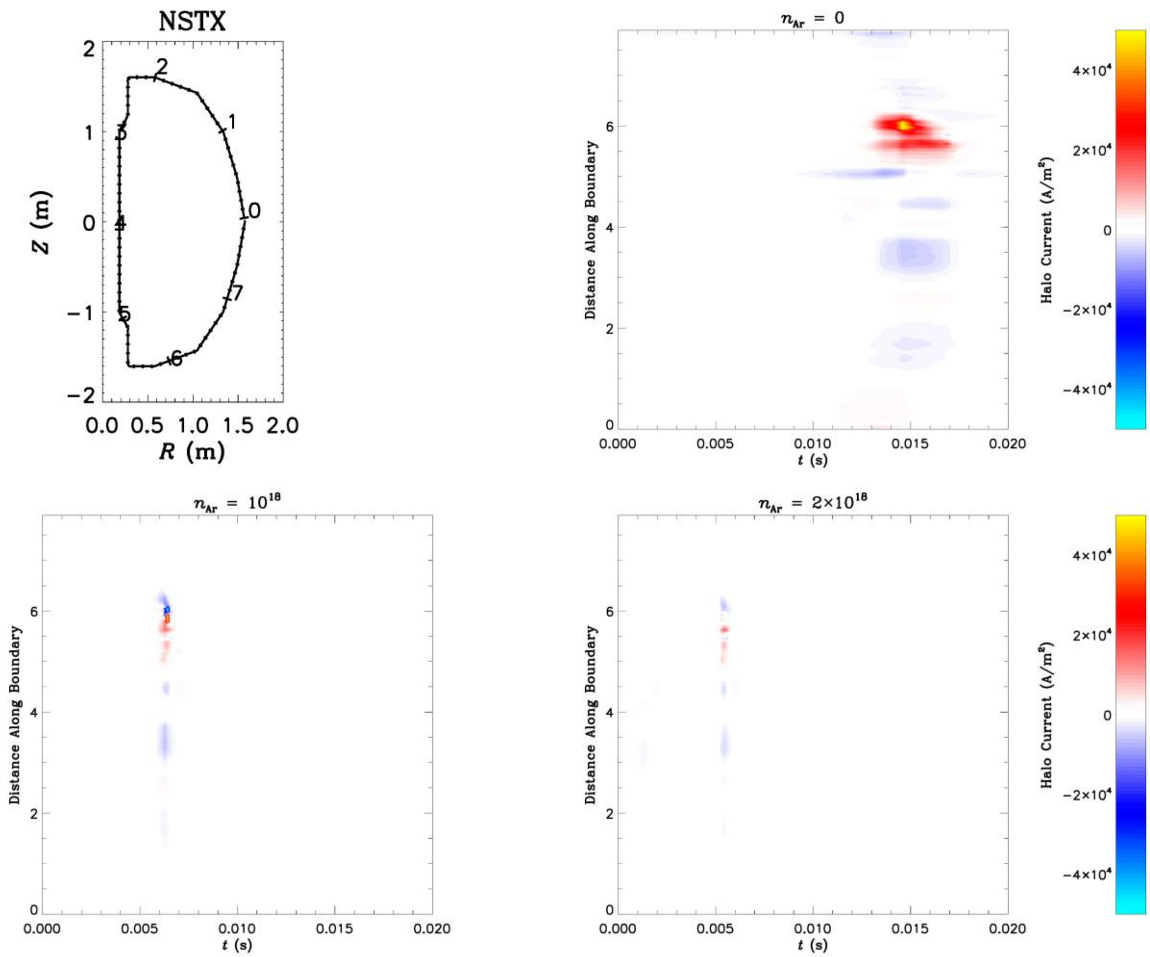

Figure 3 - *Top left*: the distance (ℓ) along the NSTX inner wall boundary from the outboard mid-plane in the counterclockwise direction. *Clockwise from top right*: the halo current density as a function of time and ℓ for the NSTX simulations with various initial values of neutral argon n_{Ar}.

The halo currents in the simulations are shown as a function of time and wall position in Figure 3. In the unmitigated case, the halo currents are found to peak at around 50 kA/m^2, in rough quantitative agreement with experimental measurements [Gerhardt 2012], although the electrical path through the shunt tile is not modeled in the simulation (the inner wall / vessel is modeled as an axisymmetric region of uniform resistivity). The halo currents also persist for longer in the unmitigated case.

NSTX-U 116313

This model discharge, based on NSTX discharge 116313, is intended to be representative of high-power, 2MA discharges in NSTX-U. Three simulations of this model discharge are presented here with varying amounts of an initial, uniform density of neutral argon: n_{Ar} = 0, n_{Ar} =

10^{19} m^{-3}, and the other with $n_{Ar} = 2{\times}10^{19}$ m^{-3}. Note that the argon densities here are ten times the densities in the NSTX simulations. This is roughly commensurate with the difference in the core thermal energy in the two cases, which peaks at 12 kJ/m^3 in the NSTX case and 136 kJ/m^3 in the NSTX-U case. The peak main ion density varies by a factor of five between the NSTX and NSTX-U cases (peaking at $n_D = 3.7{\times}10^{19}$ m^{-3} and $n_D = 2.0{\times}10^{20}$ m^{-3}, respectively). An animation of the toroidal current density in the simulation with $n_{Ar} = 2{\times}10^{19}$ m^{-3} can be found here.

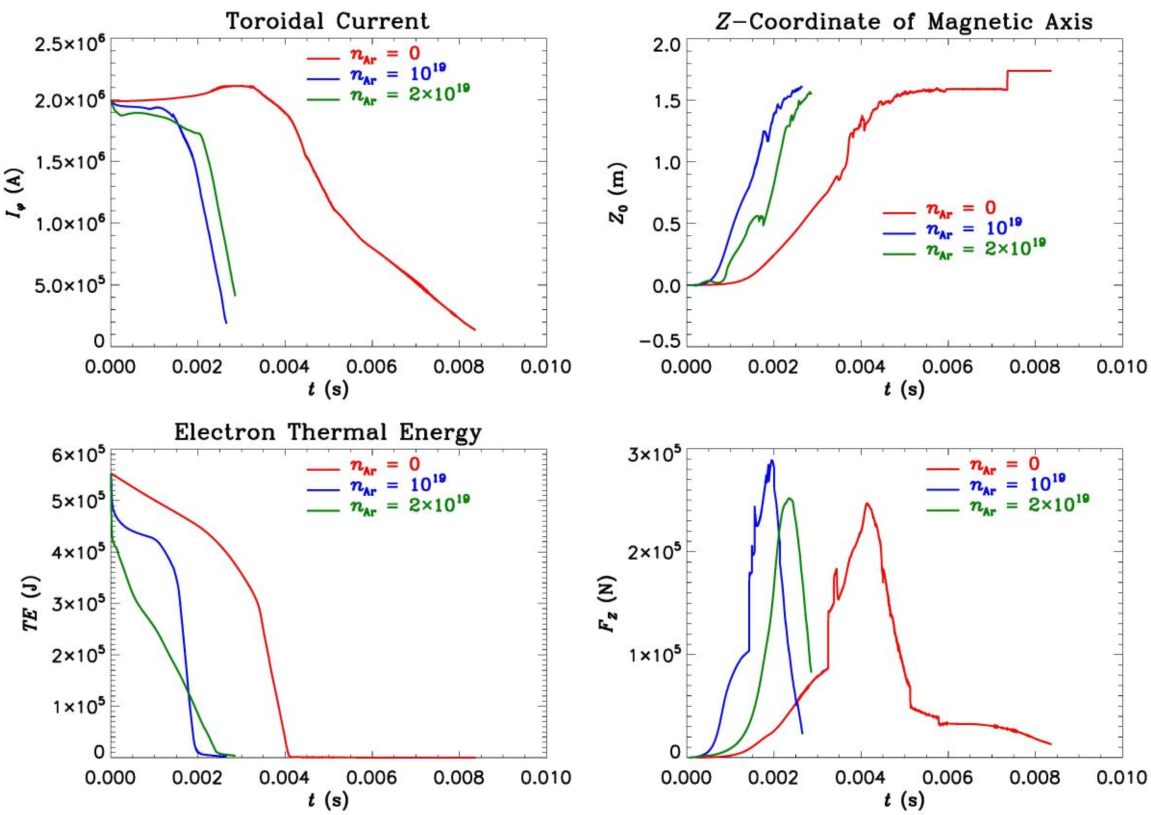

Figure 4 - The toroidal current, *Z*-coordinate of the magnetic axis, electron thermal energy, and net vertical force on the vessel in simulations of NSTX-U 116313.

The toroidal current, *Z*-coordinate of the magnetic axis, electron thermal energy, and net vertical force on the vessel in these simulations are shown in Figure 4. As with the NSTX simulations, it can be seen that the introduction of impurities hastens the displacement, the thermal quench, and the current quench, although it is not observed to significantly affect the maximum net vertical force on the vessel.

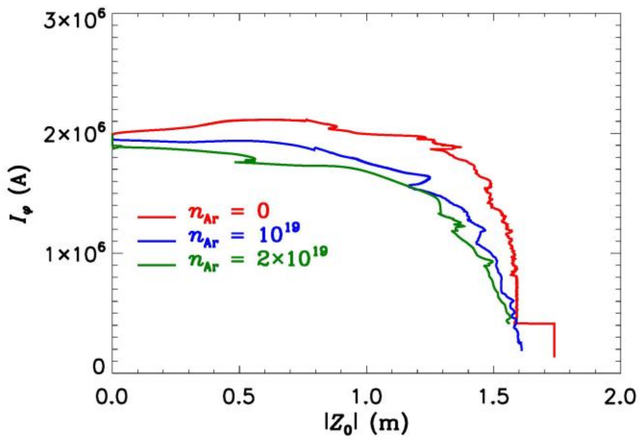

Figure 5 - The toroidal current as a function of the *Z*-coordinate of the magnetic axis in simulations of NSTX-U 116313.

Again, the observation that the impurities do not strongly affect the forces appears to be because the increased rate of displacement largely offsets the increased rate of current quench. The toroidal current as a function of the *Z*-coordinate of the magnetic axis is shown in Figure 5. Similarly to the NSTX simulations, the current decays somewhat more rapidly relative to the vertical displacement when more impurities are present. However, the effect is not as significant in these simulations as in the NSTX simulations. One possible explanation for the difference between the two sets of simulations is that the lower SOL temperature in the NSTX-U simulations (even without impurities) results in relatively less SOL cooling when impurities are introduced. This will require more investigation, and additional simulations with larger quantities of impurities should be carried out to determine whether the current quench can be completed before significant displacement occurs.

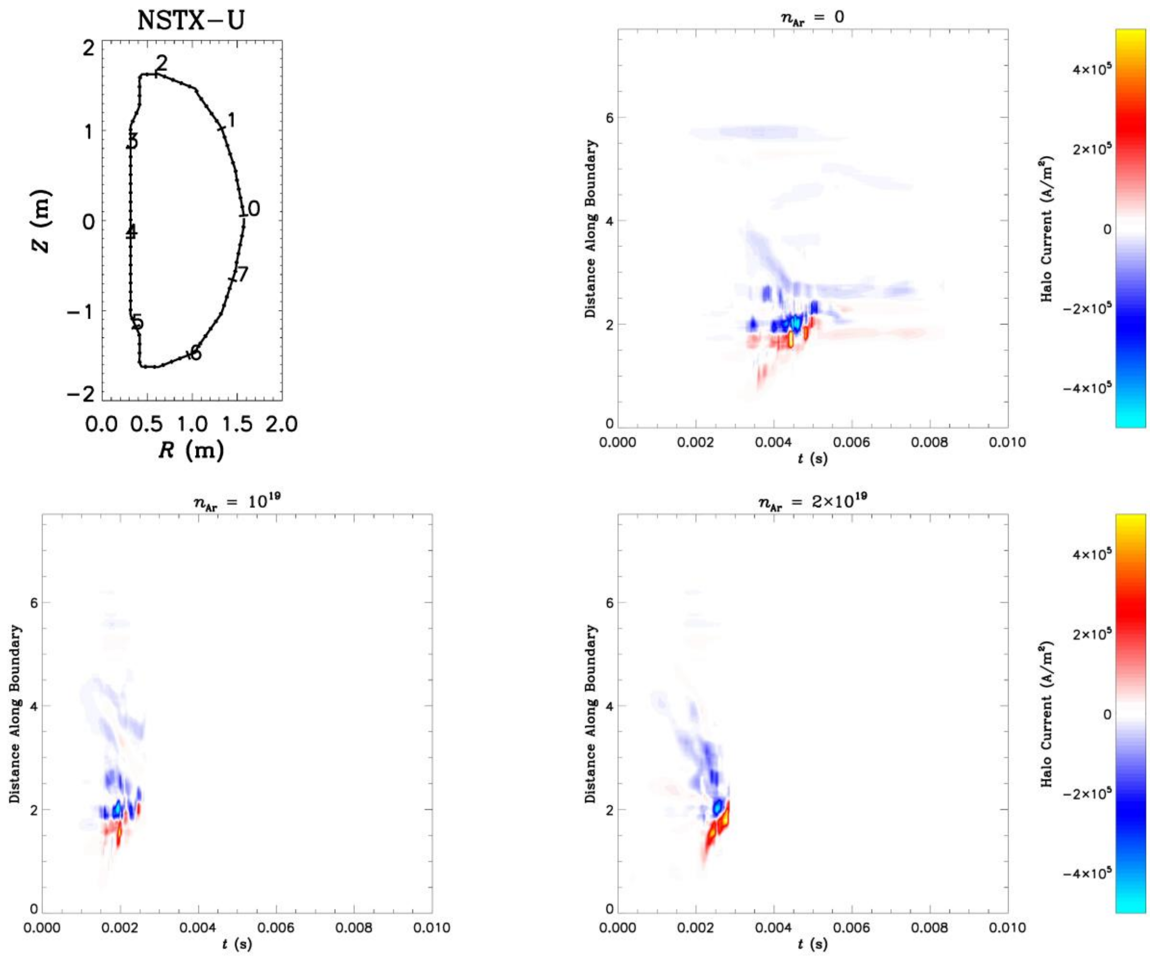

Figure 6 - *Top left*: the distance (ℓ) along the NSTX-U inner wall boundary from the outboard mid-plane in the counterclockwise direction. *Clockwise from top right*: the halo current density as a function of time and ℓ for the NSTX-U simulations with various initial values of neutral argon n_{Ar}.

The halo current density in each NSTX-U simulation is plotted as a function of time and wall position in Figure 6. The halo currents observed in each of these simulations peak at around 500 kA/m^2, nearly ten times higher than in the NSTX simulations. The maximum amplitude of the halo currents does not strongly depend on the presence of impurities (and hence, the current quench time) in these cases, but the halo currents persist for significantly longer in the unmitigated case.

References

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