3/30/05
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Report on completion of second quarter elm simulation milestone

2nd Q (end of March 05)
Do simulations using accurate experimental profiles, and extend models to include ion stress tensor effects.

During the previous (first) quarter, we reported linear and nonlinear simulations of edge localized modes (ELMs) in model equilibria using the NIMROD code. The linear growth rates of these modes were in good agreement with the results of ideal linear stability analysis carried out with the ELITE and GATO codes. The effects of finite resistivity and anisotropic thermal conduction on the linear stability were also studied. The nonlinear evolution of these modes showed the formation of "fingers" of plasma extending beyond the separatrix. These studies constituted the successful completion of the first quarter milestone.

Here we report the successful completion of the second quarter milestone, namely, *Do simulations using accurate experimental profiles, and extend models to include ion stress tensor effects.*

An equilibrium reconstruction from a high-β ELMing DIII-D discharge is used as a basis for the equilibria in this study. This equilibrium has a lower single null and has nondimensional geometric and profile properties that are similar to standard H-mode equilibria that characterize high performance tokamak operation, such as C-mod and ITER. In ELMing discharges, the pressure and current profiles near the edge are constantly changing as the gradients increase and decrease due to competition between heating and instability induced transport. It is therefore not possible to construct an equilibrium profile precisely before an ELM event. Thus, a parameterized pressure profile was created to match the characteristics of known experimental DIII-D profiles and allow for the specification of the edge profile within the range of variation typically observed in the experiment. This is shown in Figure 1. The q profile is above 1 everywhere, this avoids the internal ideal kink mode, allowing the study to focus on edge localized modes.

The ideal stability of the resulting equilibria were studied with the DCON and ELITE codes for various toroidal mode numbers. Edge localized modes with ballooning and peeling characteristics were found to be ideal unstable in the high gradient region of the edge pedestal. The ideal MHD eigenfunction computed with ELITE for the n=20 mode, of the equilibrium with the largest edge pressure in Figure 1, is shown in Figure 2. The growth rate of this ideal MHD mode is 2.5 X 10^5 sec^{-1}.

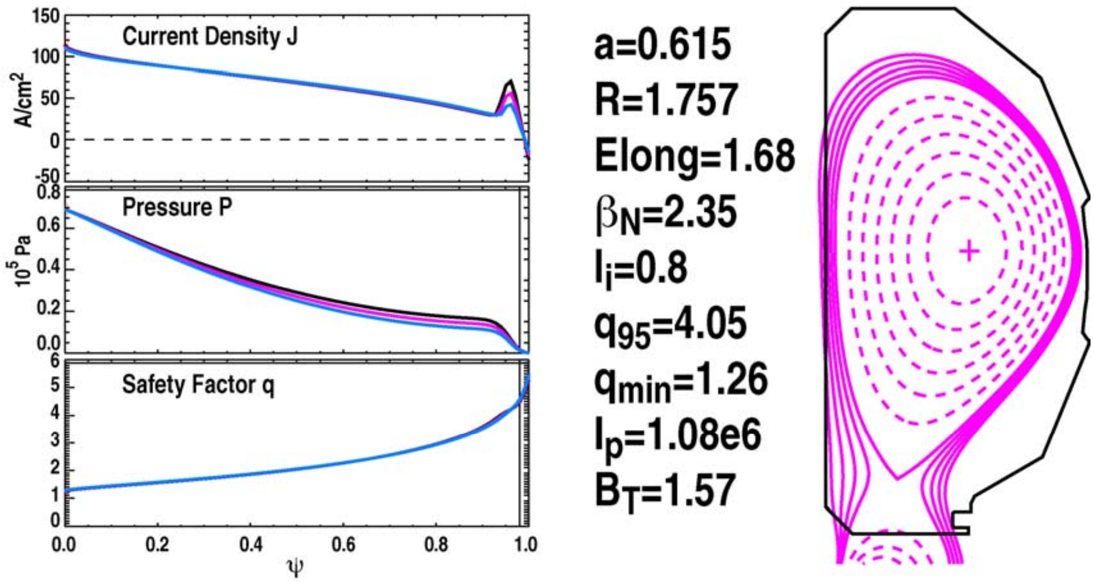

Figure 1. The profiles of current density, pressure and *q* for three equilibria used in this study, some common parameters for one of these equilibria, and the shape of one of these equilibria. The parameter values and shape do not change significantly between the three cases.

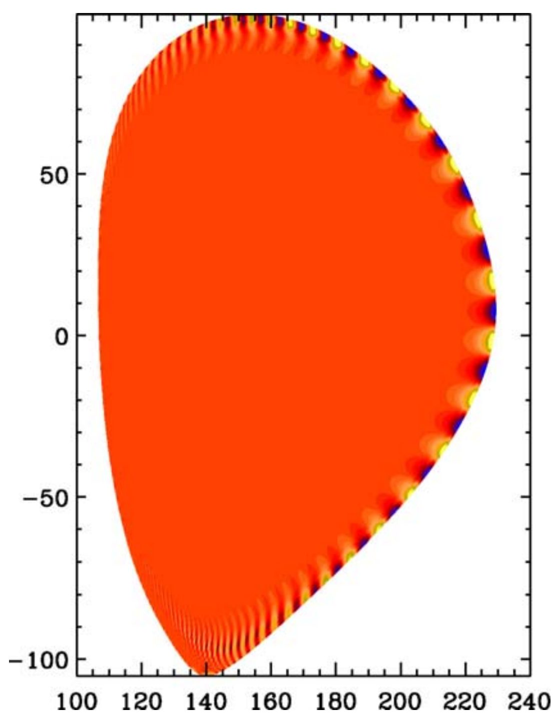

Figure 2. The eigenfunction for *n*=20 from ELITE of the edge localized mode found to be unstable in the equilibrium with the largest edge pressure in Figure 1.

The eigenfunction in Figure 2 is a typical, mostly ballooning ELM, with a noticeable peeling component. The equilibrium is unstable for all *n* in the range 5-30, and the growth rate peaks around *n*=10. (The value *n*=5 represents lower limit for the mathematical representation used in the ELITE code.) The three equilibria shown in Figure 1 are likely to bracket the linear stability boundary for at least some toroidal components of the edge mode.

These equilibria were then studied with the NIMROD code. For all cases, the Lundquist number was $S = 2 \times 10^7$. The linear growth rate spectrum with toroidal mode number is shown in Figure 3 for all three cases. (In Figure 3, the blue curve corresponds to the black curve in Figure 1, and the green curve corresponds to the blue curve in Figure 1.)

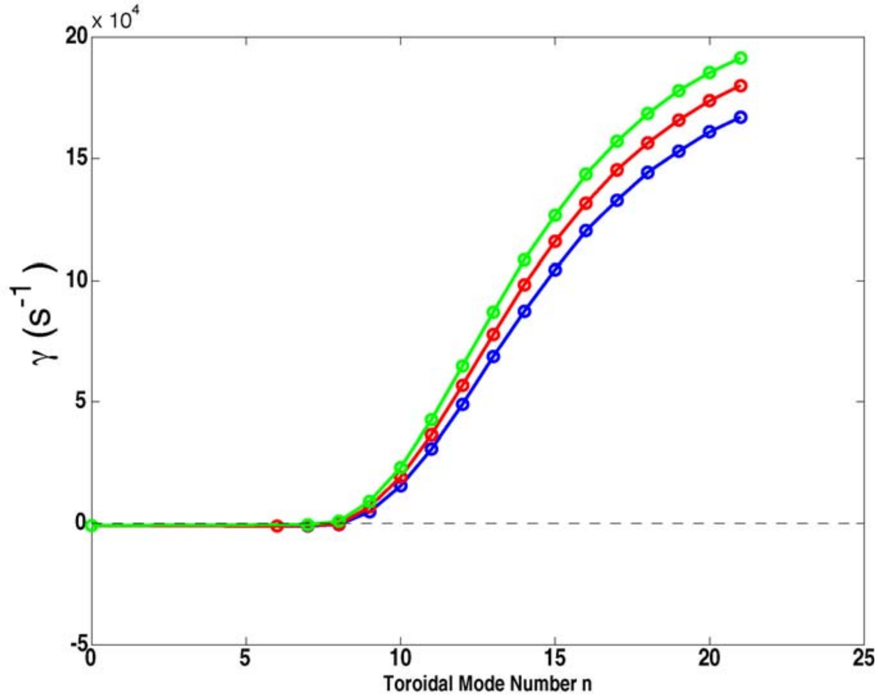

Figure 3. The linear growth rates as a function of n for each equilibrium as computed by NIMROD.

The mode numbers below *n*~7 are found to be stable, and the growth rates increase with *n*. An eigenfunction for the *n*=15 mode is shown in Figure 4.

Clearly, a significant difference in the mode structure is observed between the ELITE and NIMROD results. Although the growth rates are comparable between the ideal ELITE results and what is found with NIMROD, the eigenfunctions found by NIMROD are peaked inside the separatrix region, rather than localized at the edge. This is an interesting contrast from previous studies (see the Q1 report) with a strongly unstable model equilibria, where nearly identical eigenfunctions and growth rates were found in NIMROD, GATO and ELITE. This difference in mode structure, and its significance, is not understood at this time. We note that the NIMROD eigenfunction is very similar to that of a ballooning mode concentrated at the q = 3 surface. If this mode is a *resistive* ballooning mode, it would not be seen in either ELITE or DCON, which are ideal MHD codes. However, the measured growth rate from NIMROD is about 2×10^5 sec^{-1} (see

Figure 3), which is comparable to the growth rate of the ELM found by ELITE. Since our Q1 results showed good agreement between NIMROD and ELITE for both growth rates and eigenfunctions, one would therefore expect that at least some aspect of the ELM would be seen in the NIMROD eigenfunction. However, this is not the case. Perhaps the present case is more strongly affected by non-ideal effects such as resistivity and thermal conductivity than was indicated by our previous studies, but this has not yet been demonstrated. The differences between the ELITE and NIMROD results for this more "realistic" configuration remain unexplained at this time.

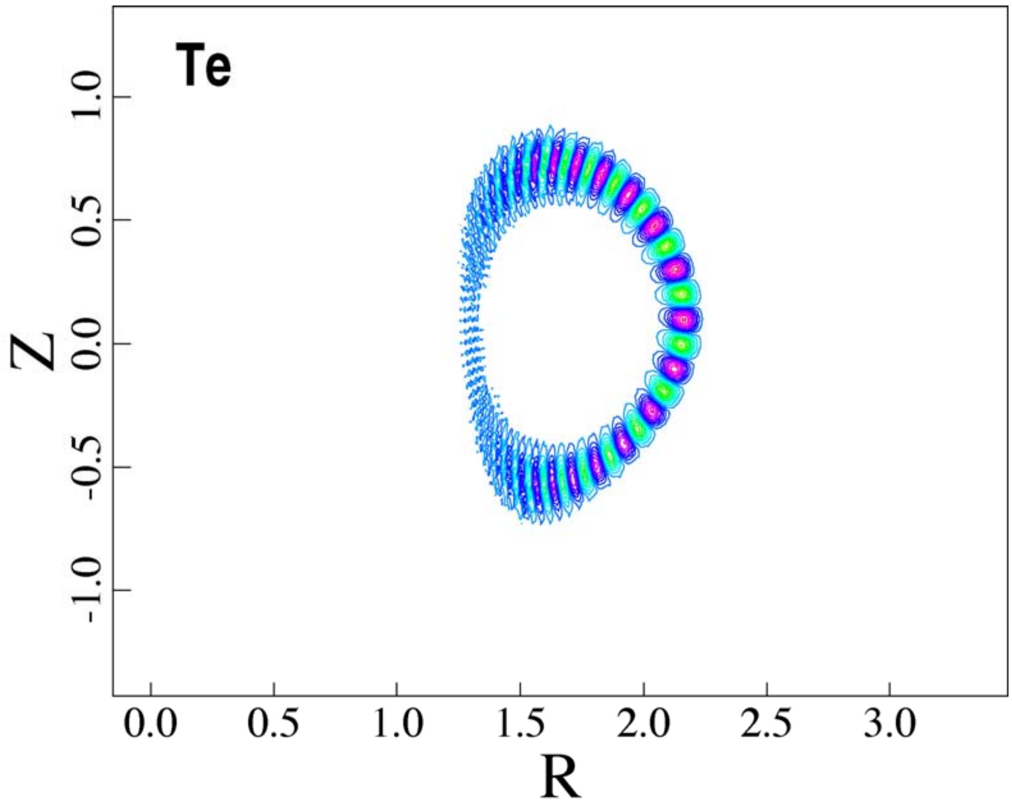

Figure 4. The eigenfunction for n=15, showing a mode peaked slightly inside of the separatrix.

The equilibrium was run with NIMROD into the nonlinear regime with modes n=0-21 present. The evolution of the magnetic and kinetic energy as a function of time can be seen in Figure 5. Note that the high-n modes (n> 10) are linearly unstable in the early phase, with higher n having larger growth rate. The low-n modes are nonlinearly driven as the high-n modes acquire finite amplitude. All modes eventually saturate nonlinearly, possibly due to quasi-linear modification of the background profiles, as indicated by the growth and eventual domination of the n=0 mode in Figure 5. Since the modes with highest n saturate with the largest amplitudes, the final spectrum is peaked at the shortest toroidal wavelength. This indicates that these runs have insufficient toroidal resolution.

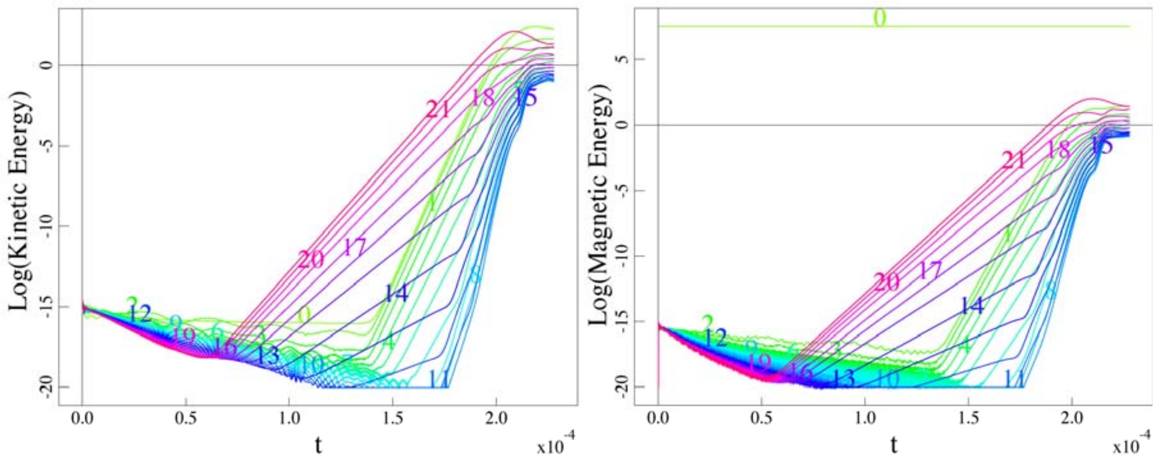

Figure 5. The Kinetic and Magnetic energy as a function of time for a nonlinear simulation of an edge localized mode in a DIII-D like simulation.

Contours of the electron temperature at two times near the peak of saturation are shown in Figure 6. The fingering of the temperature on the outboard side of the discharge is typical of the nonlinear evolution of ballooning modes. Note that there is no displacement of the separatrix, indicating a lack of true ELM character to the mode.

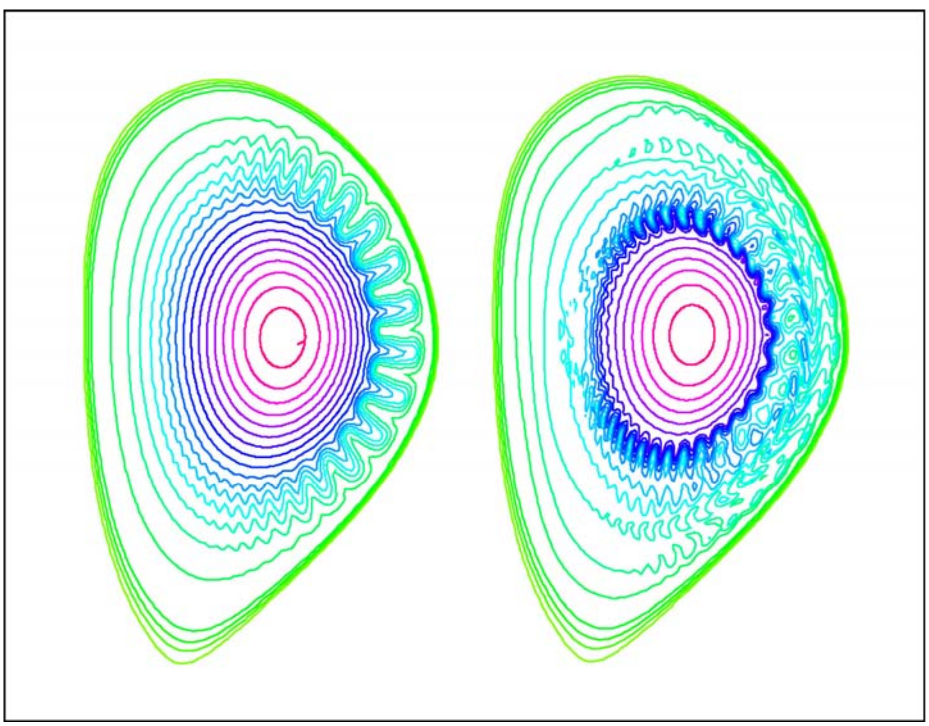

Figure 6. Two times late in the nonlinear simulation of the mode, showing the fingering structure of the temperature on the outboaard side of the discharge.

The effects of resistivity on the growth rates of the mode are moderate but important, and in previous studies the resistivity was held fixed throughout the simulations. The degree of thermal anisotropy was also shown to have little effect on the linear mode in the previous report. Here the effect of anisotropy on the mode is revisited with three dimensional resistivity which depends on the local temperature. Although we are discussing the linear growth rates of the mode, because the actual effect of the perturbation on the temperature distribution is a nonlinear process, the linear growth rates are taken from the early phase of nonlinear simulations, when the mode energies are small enough not to couple. In Figure 7 are shown the linear growth rates for large n modes with and without thermal anisotropy. In this case, and in contrast to the results reported in Q1, anisotropic heat flux has a significant stabilizing effect on the high-n modes.

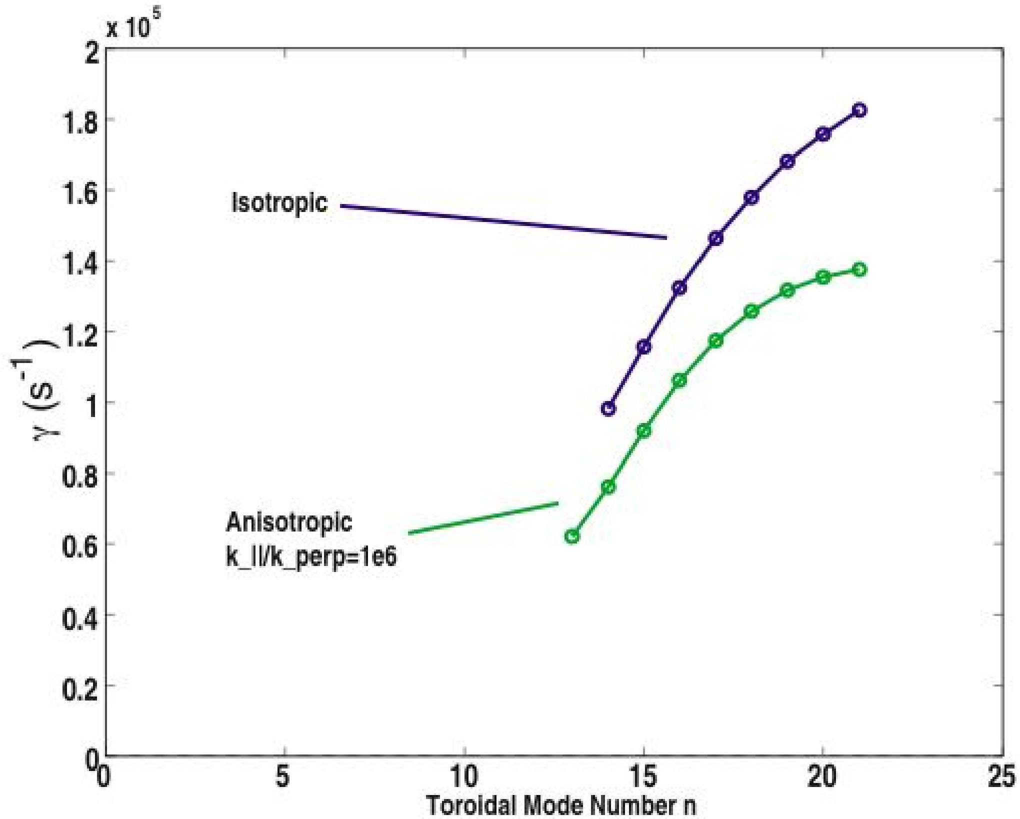

Figure 7. Illustrating the effect of anisotropic heat flux and temperature dependent resistivity on the growth rate of the modes in NIMROD.

A fluid model for gyroviscosity has been recently developed and included in the NIMROD code. The model is based on that of Braginskii, and therefore does not include any contribution from the heat flux rate of strain tensor. These new terms are non-dissipative, and are known to introduce new, dispersive ($w \sim k^2$) normal modes to the system. This is illustrated in Figure 8, where we plot the frequency of the perpendicularly propagating compressional mode as a function of the wave number k as obtained from the NIMROD code. For long wavelength thisis just the compressional Alfvén wave. It clearly becomes dispersive as k is increased.

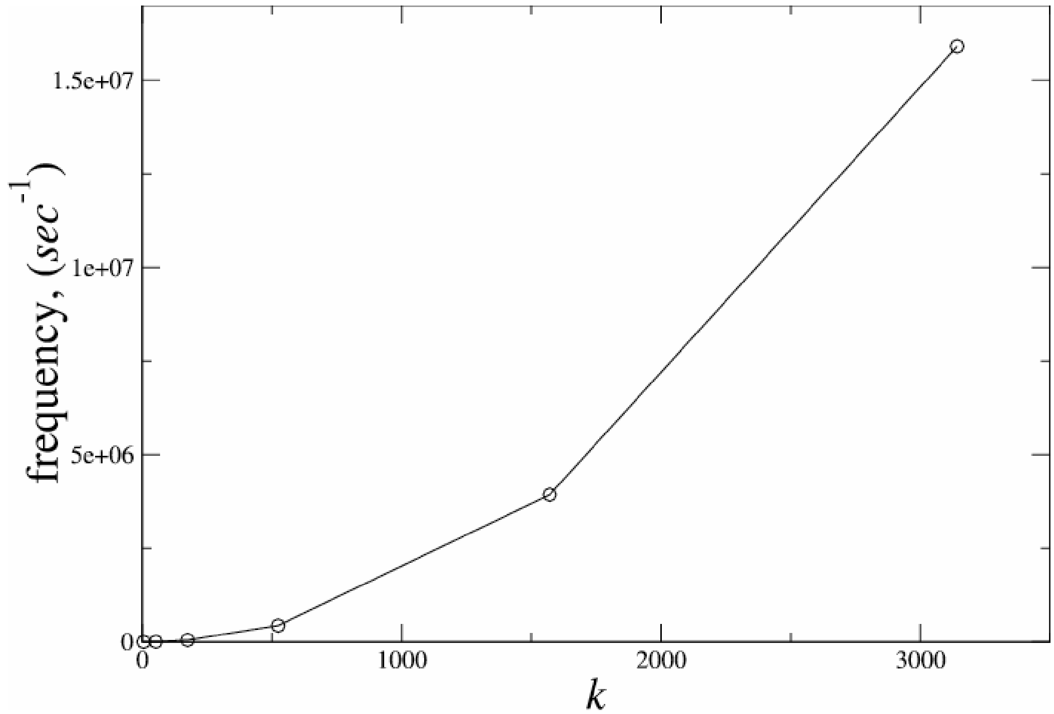

Figure 8. Frequency vs. wave number for the compressional Alfvén wave modified by gyro-viscosity, as computed with the NIMROD code.

We have applied this gyro-viscosity model to the linear stability properties of the modes described above. However, because of several uncertainties, we do not feel comfortable presenting these results at this time.

There are several caveats and cautions that should be kept in mind when examining the results presented above:

1. The equilibria used are not taken directly from specific experimental shots, but rather should be considered representative of "typical" ELMing operation in DIII-D. They were obtained by taking experimental profiles, without obvious internal modes (e.g. sawteeth), and enhancing the edge properties. Carrying out this procedure accurately proved to be quite time consuming because of the necessity to then include a consistent vacuum region solution. This was at the expense of effort needed to gain a proper understanding of the NIMROD results.

2. The equilibria have not been independently tested for resistive instability. There may be internal resistive modes that dominate the evolution of the discharge.

3. The NIMROD results are not in agreement with the ELITE results. This is not understood, although NIMROD and ELITE reported good agreement for a different set of equilibria in the Q1 report. There has not been sufficient time to resolve these issues.

4. The nonlinear results are not resolved toroidally. In principle, this requires more toroidal modes. However, we believe that it is important to understand first the present results before blindly committing to using more computer time.

5. This project requires significant expenditure of computational resources. (Approximately 450,000 cpu hours were used this quarter alone.) It also demands considerable human time for analysis. Until late in the quarter, there were severe limitations computational time available to the project. This resulted in a small amount of actual calendar time being available to analyze the computational results, and to respond to that analysis. In order to prevent this project from taking on the air of simply burning computer time, rather than studying and understanding a physics problem, more calendar and computational time are needed for a meaningful analysis. We hope and expect to continue to receive adequate resources in order to meet the future milestone challenge.