Real-Time Stability Analysis to Achieve Transient Free Operations with Feedback Control

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1. Technology to be assessed:

For cost-effective commercial fusion power plants to be feasible, they must operate at plasma parameters close to achievable stability limits. At the same time, disruption avoidance is essential in ITER and future power reactors, to avoid damage to plasma-facing components and structures. These competing goals can be met with real-time stability analysis and feedback control using first ideal MHD calculations then extension to resistive MHD calculations.

It is our belief that machine learning or big data based approaches are useful (any my group is working on these areas), physics based stability analysis will be necessary complement to operate expensive machines with high stored energy such as ITER. While the plasma physics analysis is machine independent, it is hard to scale the machine learning solutions obtained from one machine to a new machine or a new operation regime. This will be most obvious when unexpected behavior of the plasma leads to a ramp down request. From experience, ramp down is the most disruption prone phase of plasma operations. In addition, now the plasma is a state that was never seen in the database before thus previous operations points used in a machine learning would not be useful. In contrast, a physics based stability boundary calculation would allow finding a stable ramp path. It should be noted that ITER makes a distinction between machine safety and investment protection. A 10s ms lead time Massive Gas Injection (MGI) will be used to make sure the safety from tritium etc. However, protection multi-billion dollar machine will be left to Plasma Control System (PCS) and yet there is no detail on how this system should accomplish this goal.

The most violent and dangerous plasma instabilities are those due to ideal MHD. Determination of ideal MHD stability is a well-understood calculation. Various codes give the same results for the same inputs. These calculations allow us to understand and avoid a large class of instabilities. Finally, more complicated stability codes use ideal MHD stability calculation as subroutines, thus making ideal stability the correct place to start.

My group is developing real-time fast computing architecture for stability calculations. There are four parts to achieving this goal.

- Real-time data acquisition and analysis
- Automated consistent kinetic equilibrium formation
- Fast high accuracy Grad-Shafranov solver
- Fast stability analysis

Real-time data acquisition is mostly a mature technology. Though there are missing parts in the real-time analysis part, this is not a major issue at this point.

Fast gpu based Grad-Shafranov solvers are currently being tested (see Y. Huang and L. Lao [1.2]). This part of the problem is becoming mature and is currently in use at EAST tokamak's Plasma Control System (PCS).

This proposal focuses on the automated consistent kinetic equilibrium formation and fast stability analysis.

A main component of stability analysis is to obtain accurate kinetic equilibrium reconstruction. Consistent Automated Kinetic Equilibrium (CAKE) reconstruction is a platform that we developed to test the automated magnetics only equilibria, human made kinetic equilibria and automated kinetic equilibria. Presently, DIII-D real-time equilibrium reconstruction code, rt-EFIT [3], in which the Grad-Shafranov equations are solved, uses magnetic loops and MSE data. Reconstructions based on magnetics are good enough for boundary shape control but to be able to make intelligible stability calculations better internal kinetic profiles are necessary. To this aim, we are working on expanding the DIII-D rt-EFIT with laser Thomson scattering, FIR interferometry, charge exchange recombination spectroscopy. First the full pressure constraints are calculated from electron, ion and fast ion pressures. This is achieved by using Thomson and CER diagnostics. MSE measurements and numerical bootstrap calculations are used to constrain the current profile. Then all the constraints are used in a consistent way to solve for the equilibrium. This process of achieving accurate "kinetic EFITs" is currently done offline with human interface taking days of work, we are working on automating this process using CAKE and run it in real-time. This real-time automated kinetic EFIT will enable better constrains on the current and pressure profiles.

The resulting Grad-Shafranov solution will be used to determine linear ideal and resistive MHD stability to multiple modes. Stability of different paths the plasma can take will be calculated and the change in the stability in choosing these paths is compared. Based on this calculation the plasma will be steered to stay within stability boundaries. If the analysis indicates the approach to a stability boundary, it is used to trigger actuators controlling the plasma profiles, e.g. neutral beam injection power or gyrotrons. The exact choice of sensors, stability parameters, and actuators remains to be determined as part of the research.

In order to achieve stability analysis we are building a fast algorithm based on ideal DCON (Direct Criterion of Newcomb) (Glasser [4]). DCON is widely used for fast, accurate determination of ideal MHD stability of axisymmetric toroidal plasmas, including ideal and resistive interchange modes, ballooning modes with large toroidal mode number n, and low-n fixed and free boundary modes [5]. It is thoroughly verified against other stability codes and validated against experimental observations. Running on one core of a modern workstation, for a single-null NSTX case with $\beta_N = 5.6$, $q_a = 11.8$, and aspect ratio 1.5 runs in about 4 seconds for toroidal mode number $n = 1$ and 10 seconds for $n = 2$. Our goal is to use a server with ~64 cores to achieve high level of speedup to achieve ~250 ms ($\sim\tau_E$ for DIII-D) calculations. This should be enable control profile evolution at DIII-D and get ready for ITER and beyond. We also started work on the linear resistive stability analysis (such as deltaprime calculations) based on this algorithm. Initial tests show that the resistive calculation times will be similar to the ideal case.

2. Application of the technology (note – while the application presented may be useful for a variety of different machines, it must be applicable to a tokamak or stellarator concept).

The test and first application would be on DIII-D due to the availability of world-class diagnostics. Later on this system would be moved to other tokamaks. Finally, after tests and improvement this would be implemented at ITER.

3. Critical variable(s) – variable that determines or controls the output of the technology

The most critical variable is the quality of the diagnostic measurements. Without high quality measurements, the analysis that follows would be useless. The error bars needed to achieve the stability analysis that gives enough insight into plasma state will be determined as part of this investigation.

The second important variable is the correspondence between the Grad-Shafranov solution and the real plasma state. The idealized 2-D equilibrium with many assumptions may not represent the plasma behavior. We do not know the range at this point. This will be part of the database analysis study.

The third important variable is how good of an indicator the linear stability to the full nonlinear plasma stability. This is known issue but as far as the author knows there is no quantitative answer of the overlap between the linear and nonlinear stability for the general tokamak discharge database.

4. Design variables – parameters that can be controlled in order to optimize the critical variable. These could be qualitative.

We can currently achieve <500 ms calculation times for stability analysis. We are working optimization of the algorithm for speed. Also, we are looking into different computation hardware architectures to reduce the calculation time Our goal is to achieve ~250 ms ($\sim\tau_E$ for DIII-D) calculations. This should be enable the transformation. Then, we can control profile evolution at DIII-D and get ready for ITER and beyond. We also started work on the linear resistive stability analysis based on this algorithm. Initial tests show that the calculation times will be similar to the ideal case.

5. Risks and uncertainties

It is possible that the full stability analysis system put together will not be predictive enough to be used in stability control feedback. This may be due to inherent issues due to simplified plasma models that we work with or the lack of high accuracy diagnostic capability.

6. Maturity

I would estimate the current state of this technology to be TRL3. Real-time EFIT has been a big improvement for the fusion community in the last two decades. Real-time MSE EFIT became functional with the last decade. Stability analysis is becoming an important tool in plasma database analysis. These are mature parts of this technological development.

Consistent automated kinetic equilibrium has seen some improvements in incorporating some of the mentioned inputs. There was Thomson was offline automated equilibrium reconstruction at NSTX. There is offline code development at DIII-D that calculates the kinetic measurement constraints. However, this is not good enough for stability analysis. Researchers always make their own kinetic equilibria for analysis.

7. Technology development for fusion applications

As far as the author knows, there is no other institution that is developing a similar technology. US may lead in this area if enough emphasis is given. Most likely a decade of work is needed to get this system to a usable in a ITER like machine. In addition to DIII-D, NSTX-U is interested in this capability. We hope to include a similar system at Princeton after proof of concept in San Diego. EAST tokamak would be a good place to test these methods and technologies after the diagnostics systems are enhanced.

References:

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