Real-Time Parallel DCON for Feedback Control of ITER Profile Evolution

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Topic A: Disruption prevention, avoidance, and mitigation
Oral Presentation Requested

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 the DCON ideal MHD code.

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.

We are developing real-time parallel computing architecture for stability calculations with ideal DCON (Direct Criterion of Newcomb).[1] DCON is widely used for fast, accurate determination of ideal MHD stability of axisymmetric toroidal plasmas. It computes determines stability to ideal and resistive interchange modes, ballooning modes with large toroidal mode number n, and low-n fixed and free boundary modes.[2] 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 parallelize DCON on a shared-memory computer with ~64 cores to achieve a speedup of 50, allowing it to perform these cases in 80 and 200 ms, respectively. This should be fast enough to control profile evolution on ITER.

An understanding of DCON operation reveals essential features which can be parallelized and how it is to be used for feedback control. DCON reads a file specifying a Grad-Shafranov equilibrium solution. It fits the data to 2D cubic splines and maps them to an internal inverse representation using straight-fieldline coordinates. It computes the Mercier, resistive interchange, and high-n ideal ballooning criteria on each flux surface and computes matrices coupling different poloidal Fourier harmonics. Using these matrices and an adaptive ODE solver, it integrates the 2D Newcomb equation, the Euler-Lagrange equation for minimizing δW, from the magnetic axis to the plasma-vacuum interface, to obtain complex $2M$-vectors $\Xi(\psi)$ of Fourier components of the perturbed normal displacement. For M coupled Fourier harmonics, each Ξ vector is initialized to one of the M regular solutions at the axis. At every step of the adaptive integrator, it uses the solutions to compute *crit,* the real determinant of an MxM Hermitian matrix, the 2D generalization of the Newcomb crossing criterion. A change of the sign of *crit* indicates the presence of a fixed-boundary instability, and the location of the change of sign indicates the proximity to the stability boundary. At each singular surface where $m=nq(\psi)$, boundary conditions are used to exclude the large resonant solution and relaunch a new small resonant solution. At the plasma-vacuum interface, the matrix of solutions is used to construct a plasma response matrix $\mathbf{W}_P$. The VACUUM code is called to return a vacuum response matrix $\mathbf{W}_{V,}$ using a collacation method on a grid along the boundary of the vacuum region. These matrices are added to form the total response matrix $\mathbf{W}_T = \mathbf{W}_P + \mathbf{W}_V$, whose eigenvalues are computed with an LAPACK routine. DCON uses this to determine the plasma, vacuum, and total energies of the most unstable mode. If the total energy of this mode is negative, it indicates the presence of free-boundary instability. The relative magnitudes of the plasma, vacuum, and total energies provide a measure of the proximity to the stability boundary.

For parallelization, processing of the equilibrium data, evaluation of local stability criteria, and computation of the Euler-Lagrange matrices are easily parallelized by domain decomposition, assignment a portion of the domain to each core. Integration of the Newcomb equation can be parallelized by assigning each independent solution vector $\boldsymbol{\Xi}$ to its own core. Computation of the *crit* determinant can be parallelized by distributed LU factorization with SuperLU. Computation of the boundary grid in VACUUM is easily parallelizable by domain decomposition. Solution of the collocation matrix can be done with SuperLU.

Parallel DCON will be used as a component of a feedback loop to control the relatively slow evolution of current and pressure profiles in ITER. At regular time intervals during a discharge, multiple diagnostics (magnetic loops, laser Thomson scattering, FIR interferometry, charge exchange recombination spectroscopy, and MSE data) are used to compute a fast, automated, parallel kinetic EFIT equilibrium. The resulting Grad-Shafranov solution is passed to DCON to deterimine ideal MHD stability to multiple modes. The total energy of the most unstable mode, as well as other indicators, are fit to polynomial representations and extrapolated to the near future. If this indicates the approach to a stability boundary, it is used to trigger actuators controlling the plasma profiles, e.*g.* neutral beam injection power. The exact choice of sensors, stability parameters, and actuators remains to be determined as part of the research.

We have acquired a shared-memory computer, an Intel Xeon Phi server with 61 cores,[3] which is better-suited to this application than distributed-memory clusters or GPUs. The server is now connected to the DIII-D tokamak to enable this computationally intensive analysis. We propose to convert parts of the code that are out of date (Fortran 77 and earlier) to Fortran 95, which will facilitate parallelization. Then, the coordinate transfers and the integration of the ODEs in DCON will be parallelized. This work will be done in the first two years of the project.

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* This white paper is being submitted to both the Transient and Integrated Simulation Workshops, after discussion with the organizers, because it is relevant to both.

[1] A. H. Glasser and M. S. Chance, "Determination of Free Boundary Ideal MHD Stability with DCON and VACUUM," Bull. Am. Phys. Soc. 42, 10, 1848 (1997).

[2] https://fusion.gat.com/THEORY/dcon/, accessed on November 18th 2014

[3] http://www.intel.com/content/www/us/en/processors/xeon/xeon-phi-detail.html