MILESTONE REPORT

Status Report on Time-dependent Modeling for Current Profile Feedback Control

T.A. Casper, J. Crotinger, S. Haney, J.M. Moller, L.D. Pearlstein, B.W. Rice, and
B.W. Stallard

September 29, 1995

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Introduction

During the past year, LLNL efforts in the DIII-D experimental program have expanded to include time-dependent modeling of advanced tokamak (AT) operating modes. Consistent with our involvement in experimental operations, we have directed our initial efforts at modeling the negative central shear (NCS) configuration, an important and attractive mode of operation for reducing the size and cost of future tokamak experiments without sacrificing performance. In this endeavor, we have brought into use the Corsica[1] modeling code as a tool for investigating the time-dependent evolution and control of various operating modes. In our current efforts, we are contributing to the analysis of the NCS experimental data using analysis tools such as the EFIT equilibrium code and the ONETWO and TRANSP transport codes. Results of these analyses are being used for comparisons with the Corsica modeling. Future directions include the modeling of startup and sustaining of NCS (and other AT) configurations, the understanding of current drive effects, the development of current drive scenarios and control algorithms, and the design of experiments and prediction of experimental results. We are currently in the early stages of applying this powerful modeling tool to the DIII-D experimental program.

Synopsis of the Corsica Modeling Code

At the start of this modeling effort, we reviewed the various codes available for their flexibility in providing time-dependent calculations useful to design experiments and control algorithms. The design of the Corsica code incorporated the required inherently time dependent calculations on time scales appropriate for plasma evolution studies with flexibility and an interface (BASIS) ideally suited to testing ideas using various plasma parameterizations and analytic models. It's short-coming was in it's maturity; it had a limited set of installed models and lacked benchmarking with experimental data. However, the free boundary equilibrium portion, TEQ, was in use for designing both TPX and ITER and Corsica itself was being used for development of operations scenarios for these devices. These results have been presented at various ITER and TPX control and PF meetings.

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Corsica is a time-dependent equilibrium and transport code, that was formulated and is being developed mostly under internal funding at LLNL. It couples 1-D slow-timescale core transport to 2-D free-boundary MHD equilibrium including the external coil currents. Development is also in progress to couple the core calculations to the edge physics modeling via the UEDGE[2] code. The EQ package can be run either for free or fixed boundary calculations and includes both the active poloidal field coil components and the passive wall structures. In addition, it provides the ability to calculate ballooning and vertical stability during the modeled plasma evolution. The transport calculation can then evolve the flux (i.e. current profile and therefore q , poloidal field, etc.), the electron and ion temperatures (2 fluid model), and the ion and impurity densities with the electron density determined from quasi-neutrality. Various models can easily be incorporated for testing transport (presently a simple geometric, Rebut-Lallia-Watkins, and neoclassical Chang-Hinton models are installed). In addition, particle fueling (wall recycling and gas puffing) and ad-hoc heating models are available. The transport is evolved consistent with the flux evolution to maintain a pressure-weighted equilibrium.

Development of this code has been done as part of a major effort in the LLNL theory group using mostly laboratory internal development (LDRD) funding and not funded by the DIII-D experimental effort. There has been considerable effort by the theory group for consultation in the operations of the code. ITER funding has supported applications of the Corsica code to the development of equilibria and operating scenarios. The effort to validate code operations with DIII-D specific experiments typically is funded through the collaboration between LLNL and GA. One area of development that has been pursued under the DIII-D collaboration is the addition of the NFREYA neutral beam heating and current drive package. This is critical to our understanding of the NCS experiments in that a combination of core electron heating, off-axis current drive from bootstrap current and neutral beam heating and ohmic current diffusion due to plasma current ramping are instrumental in establishing the NCS configuration on DIII-D. We have installed the NFREYA package (version consistent with ONETWO code at GA) into Corsica/BASIS and we are presently in the code validation stage.

Benchmarking with Experimental Measurements

We have run Corsica in a mode that can be used for simulation of experimental operation. As a reference case, we selected an NCS shot, 83729, since it exhibits a strongly inverted q -profile, enhanced thermal confinement, and a high performance phase. To date, the Corsica code has been run in a hybrid modeling/analysis mode for this NCS experiment chosen for benchmark calculations. Measurements of the profiles of electron density and electron and ion temperatures were made and supplied as Corsica inputs to avoid the need, at least initially, to model the particle and energy transport which requires a NCS transport model. A simple linear (in flux coordinates) model for the Z_{eff} is used for carbon impurities with the deuterium and carbon densities determined subject to quasi-

neutrality. Since we are still in the process of implementing the NFREYA neutral beam package, we use the ONETWO calculation of the neutral beam current drive as an additional input. One of the significant advantages of the BASIS code interface used for Corsica is the ability to easily enter either experimental measurements or modify the models in use at any point in time during the calculation.

With the density and temperature profiles fixed from experimental measurements and the neutral beam current drive treated as an external source, we can evolve the flux to determine the temporal evolution of the current distribution, that is, of the q-profile. As a first step, we benchmarked the equilibrium calculation with respect to the EFIT calculation typically done for experimental data analysis. We use the fit parameters obtained from an acceptable, converged EFIT equilibrium as inputs to Corsica's equilibrium solver along with the E- and F- coil currents. A procedure was developed (by Dick Bulmer, LLNL) to force the equilibrium solver to converge to these coil currents. The calculated equilibrium should be the same as that determined from EFIT. In the table below, we list a comparison of several parameters calculated for shot 83729, our reference case, and observe that the agreement is quite respectable.

Parameter	Corsica	EFIT
betap	..468	.47
li	.811	.82
elongation	1.852	1.83
q95	11.054	11.11
betan	.441	.41
q0	6.011	6.2
betat (betaphi)	.213	.22
Volume	21.758	22.4
Area	2.149	2.225
a	.61	.61
R0	1.677	1.674

In addition, we show the equilibrium flux contours calculated in the two codes in Figure 1. Our conclusion is that EFIT and TEQ have reasonable agreement in their reconstruction of the DIII-D equilibrium.

Application to Negative Central Shear Experiments

1. Flux evolution using full estimates of the neutral beam current drive from ONETWO

Corsica has been run in time dependent mode for comparison with the evolution of parameters observed on the experiment. This was done in fixed boundary mode so as to keep the flux surface shape consistent with the EFIT result. To run "in free boundary mode", we would have to "program" the coil current excitation in a manner similar to that done during DIII-D experiments. While we

have completed much of the work to make this possible, i.e. we have the coil geometry and coil current excitation mapping, we have not tested it and running in this mode is premature relative to our progress in code validation. Thus, with the equilibrium boundary fixed (the internal flux distribution is still free to evolve) and with experimentally measured pressure profiles, we let the code step the calculation in time.

In Figure 2. we show a comparison between q_0 , the on-axis value of q , as determined by Corsica and experimental measurements obtained from EFIT using Motional Stark Effect (MSE) and pressure profile constraints. It is obvious from this data that there is a significant discrepancy between this first code result and the experimental measurements. Before 0.4 seconds, neutral beam injection has not yet started and, therefore, no MSE measurements of the q -profile are available. We use the equilibrium obtained from EFIT at this time to fix the plasma shape rather than attempting to model the full coil excitation. The large discrepancy observed before 0.4 seconds is due to a mismatch between the Corsica startup and the conditions present in this DIII-D discharge. The more rapid fall of Corsica's q -profile after 0.4 seconds is indicative of an error in the modeling of the non-inductive current drive source, a combination of bootstrap and neutral beam current drive. Due to the relatively small volume of flux surface near the magnetic axis, the value of q_0 is very sensitive to small errors in the current flow in this region. This effect has been observed experimentally in the sensitivity to current profile reconstruction using the MSE diagnostic. This is also an added incentive for us to complete the self-consistent calculation of the neutral beam current drive which is now our highest priority for Corsica modeling as applied to DIII-D.

2. Demonstration of current drive sensitivity and control using scaled ONETWO current drive

Using the above reference case, we can easily demonstrate the sensitivity of q_0 to the current profile present while demonstrating active control over the current profile and the ability to better match the experimentally observed variations in q . In the code experiment performed, we held the neutral beam current profile fixed and varied the peak current to attempt to better match the evolution of q_0 . This not only demonstrates how Corsica can be used to develop current profile control scenarios but also how we can determine the required current drive profile to achieve a q -profile that matches the temporal evolution of experimental parameters. The results we now present were obtained by interactive control over the peak current via the BASIS interface which allows access to most (all) parameters and display of results during the evolution.

One difficulty in matching the modeled results with the experiment is the code startup issue and the possibility of unmatched transients. This is compounded by the lack of experimental q -profile measurements early in time since the MSE diagnostic requires neutral beam injection which typically is not turned on at the beginning of current rampup. We must then provide a prescription for matching the code evolution to the first available measurements. This was accomplished with the addition of a multiplication factor for scaling the entire current drive

profile and varying this parameter as a function of time during the evolution. Using this technique, we are, in effect, actively controlling the q-profile by adjusting the external current drive but not that due to bootstrap current.

The neutral beam current drive prescription that provides a better fit to the experimental evolution of q_0 is shown in Figure 3 along with the spatial and temporal evolution of the q-profile. In Figure 4, we show the now good agreement between modeling and experiment for both q_0 and q_{95} where q_{95} is determined by the flux boundary, i.e. we have the shape correct in Corsica. The large discrepancy early in time is eliminated by slowly increasing the peak current drive which presumably provides a better match to the experiment. The subsequent decay of q_0 with time is slowed by increasing the available current drive which peaks just inside the radial location of q_{min} . Using feedback control of the total current, as is done in the DIII-D experiments, the Ohmic current profile adjusts and the rate of decay of q_0 is reduced to match the experimental evolution as shown in Figure 4. In Figure 5., however, we show a comparison of the internal inductance, l_i , and the radial q-profile at 0.4 seconds. This indicates that we must also alter the current drive profile slightly to better match the shape of the current density which determines l_i . Finally, we show in Figure 6 the resulting spatial and temporal profiles of the various current density components as determined in this Corsica run.

3. Flux evolution using model current distribution

In an effort to begin to understand the role of the current density distribution and our ability to control the q-profile, we are employing a model current distribution to simulate any non-inductive current drive mechanism, i.e. neutral beam current drive, fast waves, ECH, etc. We have chosen a simple model with enough structure to model a wide variety of shapes for peaked (on or off axis) or hollow profiles. The model in use is shown in Figure 7 where the values for p_i determine the shape in flux coordinates and the values for f_j determine the relative amplitudes. The integrated total current is set by one additional multiplicative factor. This profile is smoothed in ρ -space to avoid the effects of the non-physical discontinuities at the break points that arise when the flux is evolved consistent with this current drive. With the density and temperature again set from experimental measurements, we "feedback control" the current drive and evolve the current distribution in a fully nonlinear, self-consistent fashion to determine the ohmic current distribution and the q-profile with the plasma current ramped or held constant in a manner similar to DIII-D operation.

To demonstrate our capability to control the q-profile, we varied the model current distribution in time for the parameters of our reference shot to alter the temporal evolution of the minimum of the q-profile. In so doing, we are exploring a very preliminary look at modeling the current profile control requirements while investigating the discrepancy observed in matching the experimental evolution using the scaled neutral beam current drive calculation. In Figure 8 we show the time history of the minimum of the q-profile, q_{min} , obtained with the model current drive and value of q_{min} inferred from experimental measurements along

with the resulting q-profile. Again, for times less than 400ms, there are no data for comparison with the experiment (times before the MSE neutral beam is turned on). In Figure 9 we show the model calculations of the current profile consistent with this evolution of q. We are just beginning to investigate the non-inductive current drive effects, both bootstrap and external sources, and our ability to modify the q in some prescribed manner.

Future Directions

We currently have an active role in both the MSE diagnostic (provided by LLNL) and in the planning, execution and analysis of the advanced tokamak experiments with the NCS operation currently of highest priority. We are continuing to support the analysis of the NCS experiments with analysis of the temporal variation of current profiles and transport. We will be adding these models for current drive and transport to the Corsica environment so as to enhance our understanding of how to control and sustain this configuration.

1. Transport coefficients

A necessary step for predictive modeling of the current profile evolution will be to use models of energy and particle transport, instead of profiles input to the code, to determine self consistent temperature and density profiles. The response of the plasma current profile to a current source will depend on plasma resistivity, Z , and the resistivity, in turn, depends upon electron temperature and plasma impurities, e.g. using a model for neo classical resistivity with $\sigma \sim (T_e^{3/2}/Z)f(\epsilon)$, where $f(\epsilon)$ is a function of the inverse aspect ratio $\epsilon=a/R$ that includes the trapped electron effects. Using the appropriate models is essential because of the strong parameter dependence of the resistivity.

For NCS plasmas, transport parameters vary by large factors during and after current rampup, and during periods of enhanced confinement. This is illustrated by the electron and ion thermal diffusivities shown in Figures 10 and 11 calculated for a typical DIII-D NCS discharge, shot 84736, before the high power beam phase. Transport parameters for an experimental shot were inferred from the transport analysis code ONETWO using measured kinetic profiles and models for neutral beam heating, electron-ion heat exchange, etc. The plots show electron and ion thermal diffusivities at three times: during the current rampup, at flat top time, and after flat top. These show large time dependent and spatial changes for both electrons and ions and large reductions in diffusivity within the negative shear region.

For both CORSICA and ONETWO, various empirical and theoretical transport models can be used to calculate profile evolution. These models will be bench-marked against experimental data to determine the appropriate models to use for current profile control.

2. Additional Corsica models

In terms of current drive models, two are of immediate interest to the DIII-D applications, NFREYA[3] for neutral beam current drive and the fast wave current drive model by Kupfer[4]. We have completed the programming work to install the NFREYA code consistent with that in use in the ONETWO code and are in the process of validating this model. Once this is complete, we will install the fast wave current drive code. These current drive sources, along with the model current distribution to simulate off-axis current drive associated with either ECH or mode converted ICH, provide the basic tools necessary to investigate feedback control of current profiles in DIII-D.

We are also involved in an effort to identify reasonable transport models to describe the NCS experiments on DIII-D. Based on the results of this investigation, we anticipate the installation of a few of the more promising models in Corsica. These will be used to model the formation and ability to sustain this NCS configuration. In addition, these models will be useful for developing algorithms for feedback control of the current profile in DIII-D.

Summary

The Corsica code is now in use for modeling advanced tokamak modes of operation in DIII-D. We have compared the equilibria generated from Corsica with that typically produce from the EFIT code and found them to be in reasonable agreement provided consistent pressure profiles are used. We have begun to benchmark the simulated evolution of plasma parameters with DIII-D experiments using a recent negative central shear shot, 83729. Corsica has been run in a hybrid modeling/analysis mode to evolve the current profile using experimentally measured profiles of density and temperature as inputs in place of a transport model. We have obtained preliminary results simulating modification of the q-profile using either an input reference current drive profile or a model current distribution to simulate off-axis current drive sources. We have recently added the NFREYA neutral beam current drive model and are currently validating the code. We are investigating transport models applicable to the NCS operation which will also be added to the existing models in Corsica. In addition to a continued effort to compare the simulation results with experimental data, we will begin to include transport models in the simulation and investigate the effects of current drive on profile evolution and control.

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(a) Corsica

(b) EFIT

Figure 1. Equilibrium flux contours calculated for DIII-D shot #83729 from Corsica (a) and EFIT (b) at 0.4 seconds.

Figure 2. Comparison of q evolution from Corsica (+) and from MSE-constrained EFIT. The large early discrepancy results from too much current drive before experimental measurements are available.

(a) modified neutral beam current drive profile

(b) q-profile resulting

Figure 3. Spatial and temporal variations of the scaled neutral beam current drive (a) and q profile (b) yielding the better comparisons of q_0 and q_{95} .

Figure 4. Comparison of q_0 and q_{95} as determined from Corsica (+) and EFIT calculations along with the current rampup. Neutral beam injection and, therefore, MSE data start at 0.4 seconds where the equilibrium conditions are set.

(a) q -profile

(b) l_i

Figure 5. (a) Comparison of the profile of q at time = .4 seconds for Corsica (+) and EFIT analysis indicating that there is a mismatch in the current drive profiles which can explain the discrepancy in l_i (b).

(a) Total Current

(b) Ohmic current

(c) Bootstrap current

(d) neutral beam current

Figure 6. Spatial and temporal evolution of current densities as calculated in Corsica for shot 83729.

(a) Definition of piecewise linear parameters

(b) Corsica case for $\rho(i)=0.1, 0.2, 0.4$, and 0.6 with $f_0=1$, $f_f=.5$, and $f_t=.15$ with a total current of 0.5MA .

Figure 7. Simulation of generic current drive source

(a) q-profiles

(b) $q_{\min}$ comparison

Figure 8. (a) q -profile resulting from model current drive calculation and (b) a comparison of $q_{\min}$ to the EFIT calculation

(a)

(c)

(b)

(d)

Figure 9. Current profiles resulting from simulation with the model current distribution shown in (d).

Figure 10. Time and spatial dependence of electron thermal diffusivity for NCS discharge 84736

Figure 11. Time and spatial dependence of ion thermal diffusivity for NCS discharge 84736

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