*31st EPS Conference on Plasma Phys. London, 28 June - 2 July 2004 ECA Vol.**28G**, P-2.186 (2004)*

Simulation of DIII-D Flat q Discharges

C. E. Kessel[1], A. Garofalo[2], and T. Terpstra[3]

[1]*Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ, USA 08543*
[2]*Columbia University, New York, NY, USA 10027*
[3]*General Atomics, 3550 General Atomics Ct., San Diego, CA, USA 92121*

The Advanced Tokamak plasma configuration has significant potential for the economical production of fusion power. Research on various tokamak experiments are pursuing these plasmas to establish high β, high bootstrap current fraction, 100% non-inductive current, and good energy confinement, in a quasi-stationary state. One candidate is the flat q discharge produced in DIII-D[1], where the safety factor varies from 2.0 on axis, to slightly below 2.0 at the minimum, and then rises to about 3.5 at the 95% surface. This plasma is prototypical of those studied for power plants in the ARIES[2] tokamak studies. The plasma is produced by ramping up the plasma current and ramping down the toroidal field throughout the discharge. The plasma current reaches 1.65 MA, and the toroidal field goes from 2.25 to 1.6 T. The q_{min} remains high and at large radius, $\rho \approx 0.6$. The plasma establishes an ITB in the ion channel, and transitions to H-mode. The free-boundary Tokamak Simulation Code[3] (TSC) is being used to model the discharge and project the impact of changes in the plasma current, toroidal field, and injected power programming.

Simulation of Discharge #115400

The discharge #115400 ramped the plasma current and toroidal field throughout the discharge to obtain a flat safety factor profile. The flat q profile is projected to have high β limits[1]. The discharge suffered from a loss of density control and neutral beam source trips. However, in spite of this the β reached 6%, with the peak ion and electron temperatures at 6 and 3.75 keV, respectively, near the end of the discharge when the electron density was as high as 9×10^{19} /m^3. Shown in Fig. 1 are the time histories of the plasma current, toroidal field, stored energy, density, and safety factor values. In order to model the discharge, the electron (tangential and core Thomson) and ion (CER) temperature profile data, and density (tangential and core Thomson) profile data are fit to analytic functions, in order to make interpolation more robust. The functions are given by,

$$T_{e,i}(\phi) = T(0)\left[c_1(1-\hat{\phi}^{b_1})^{a_1} + c_2(1-\hat{\phi}^{b_2})^{a_2} + c_3 \tanh(\hat{\phi},\Delta\hat{\phi})\right]$$

$$n(\phi) = n(0)\left[(1-\hat{\phi}^{b_1})^{a_1} + c_2(1-\hat{\phi})^{b_2}\hat{\phi}^{a_2}\right] + n(\phi_b)$$

Here the argument is the local toroidal flux (ϕ) normalized to the toroidal flux enclosed by the plasma boundary (ϕ_b). The density profiles are not evolved in the simulations, but are prescribed as a function of time. The temperature profiles are evolved, but enforced in the simulation by using an approach where the thermal diffusivity profiles are made to reproduce the temperature profile shape. The steady state energy equations are used to relate the thermal diffusivity to the temperature profile locally,

$$|\nabla\phi|^2 \chi_{e,i} = -\frac{\int_0^{\phi} H_{e,i}(\phi')dV}{\frac{dV}{d\phi} n(\phi) \frac{dT_{e,i}(\phi)}{d\phi}},$$

where $H_{e,i}(\phi)$ is the heating profile minus the radiation, $n(\phi)$ is the density, V is local volume, and $T_{e,i}(\phi)$ is the temperature. The equipartition and any convective terms are neglected. Based on this the thermal diffusivities can be expressed as $\chi_{e,i}(\phi,t) = \chi_{e,i}^0(t)\times F_{e,i}(\phi,t)$, where $\chi_{e,i}^0(t)$ determines the magnitude of the temperatures and $F_{e,i}(\phi,t)$ determines the temperature profile shape. This shaping factor is given by a normalized expression,

$$F_{e,i}(\phi,t) = \frac{8\pi^2 P_{e,i}(\phi,t) n(0,t) R}{P_{e,i}(\phi_b,t) n(\phi,t) \frac{dV}{d\phi} \frac{1}{T(0,t)} \frac{dT_{e,i}(\phi,t)}{d\phi}}.$$

Here $P_{e,I}$ is the deposited power enclosed by the flux surface. The desired temperature profiles from fitting the experimental data are inserted in the above formula during the simulation, and scaling factors are used to adjust $\chi_{e,i}^0(t)$ to recover the peak temperature values. The results are thermal diffusivity profiles that can reproduce the experimental evolution to varying degrees of accuracy, and can be used with global energy confinement scalings to project to new experiments, say with different Ip, B_T, P_{INJ}, or density. It should be noted that the heating source deposition profiles are critical to obtaining a correct temperature evolution, and these profiles were generated by ONETWO analysis and reproduced in TSC. The entire simulation is still predictive, that is the forward time evolution of the energy equations is being solved.

In addition to this, since TSC is free-boundary, the poloidal field coil data is used to provide the entire discharge equilibrium evolution. The model includes the vacuum vessel, limiters, divertor strucutures, E-coils, and F-coils, and is shown in Fig. 2. Radial and vertical position feedback control is applied to keep the parameters close to the discharge. Isoflux shape control can be included as well to examine the impact of changing the plasma shape evolutions in future experiments, but has not been applied here.

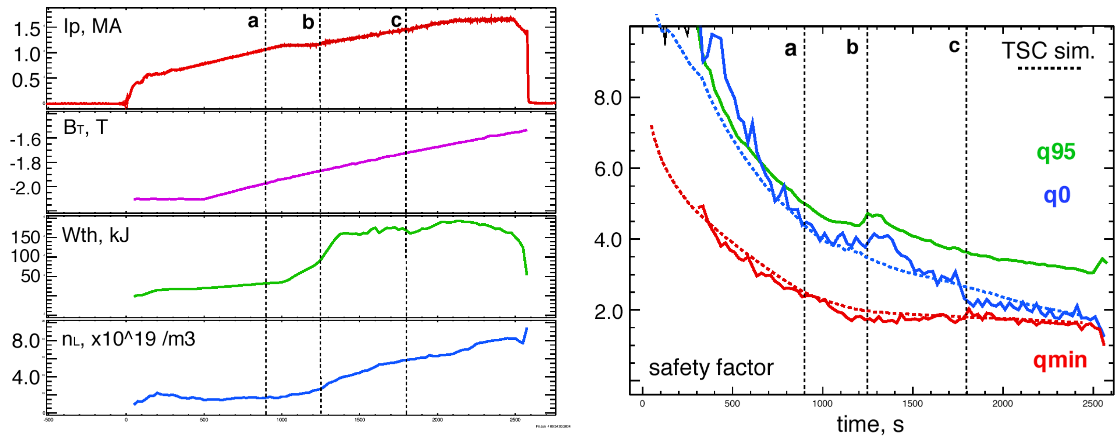

Figure 1. Time histories of the plasma current, toroidal field, stored energy and density for discharge #115400. The letters denote the ion ITB onset (a), the L to H transition (b), and the NB power trip from 15.5 to 11 MW (c). The TSC simulation safety factor values are also shown.

Also shown in Fig. 2 are the electron and ion peak temperatures from the experiment and from the simulation, showing reasonable agreement. The temperature profiles were also reproduced well. In Fig. 1 the safety factors at the axis and minimum from the TSC simulation are shown. From examination of several time histories; R, a, Z, li, κ, δ, β, W_{th}, and q_{95}, the discharge is being reproduced reasonably well. The plasma current is feedback controlled, while density and injected power are preprogrammed to match the experiment.

The thermal diffusivities from this simulation will be used as a basis for the projection simulations. They will be scaled by the global energy confinement scaling IPB98(y,2)[4] using

$$\chi_{e,i}(\phi,t) = \chi_{e,i}^{115400}(\phi,t)\frac{\tau_{E(y,2)}^{115400}(t)}{\tau_{E(y,2)}(t)}$$

Improvements to the match between TSC simulations and experiments can be obtained by, 1) utilizing more time slices for experimental temperature profile data, only 8 were used here, 2) using more time point input in the TSC code, 24 time points were used here, 3) including dynamic terms in the derivation of χ as a function of dT/dϕ, and 4) installing more self-consistent heating/CD source representations in TSC. Work continues to project the performance of this discharge.

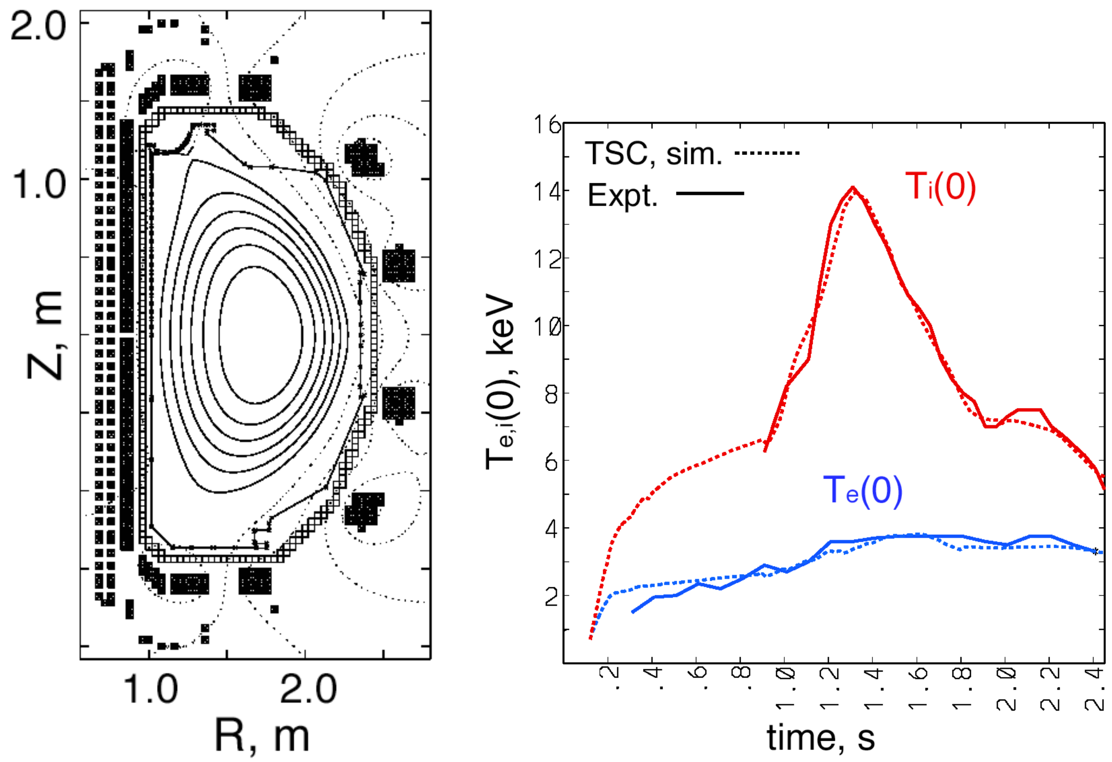

Figure 2. TSC simulation model showing the plasma at 910 ms in discharge #115400, vacuum vessel, limiters, divertors, E-coils and F-coils. Also shown is a comparison of the experimental and simulation peak ion and electron temperatures.

[1] R. J. Jayakumar, "Equilibrium and Stability Characteristics of DIII-D Discharges with Low Edge Safety Factor", Bull. Amer. Phys. Society, APS-DPP, Orlando, Florida, 2002.
[2] F. Najmabadi, 16th IAEA Int'l. Conf. Fusion Energy, IAEA Vienna, Montreal, 1996; 18th IAEA Int'l. Conf. Fusion Energy, IAEA Vienna, Sorrento, 1998.
[3] S.C. Jardin, N. Pomphrey, and J. DeLucia, J. Comp. Phys., vol. 66, pg. 481, 1986.
[4] ITER Physics Basis, Nuc. Fusion, vol. 39, pg 2175, 1999.