PREDICTIONS OF ELECTRON CYCLOTRON CURRENT DRIVE AND HEATING IN ITER

R.V. Budny*, C.E. Kessel, and K. Indireshkumar

Princeton Plasma Physics Laboratory, Princeton University, Princeton, NJ 08543, USA

**E-mail: budny@princeton.edu*

The TORAY module in PTRANSP is used to generate self-consistent, time-evolving predictions of electron cyclotron current drive and heating in H-mode and Hybrid ITER plasmas. Various scenarios for steering midplane and upper launching antenna are considered. Electron cyclotron current drive (ECCD) is deposition beyond $r/a \simeq 0.3$ can delay the decrease of the central safety factor in Hybrid plasmas below unity, maintaining $q(0)$ above unity for long durations.

Keywords: ITER, PTRANSP, TORAY, ECCD, ECH, H-mode, Hybrid

1. Introduction

Electron cyclotron current drive (ECCD) and Electron cyclotron heating (ECH) offer several services for improving the performance of ITER plasmas. These include adding auxiliary heating and plasma current as well as controlling MHD and the q profile. One of the challenges for ITER will be achieving enhanced confinement such as the H-mode and Hybrid mode. The H-mode is achieved in present plasmas when the heating is above a threshold power $P_{L\to H}$. Scaling results for $P_{L\to H}$ indicate that it will depend linearly with electron density and inversely with the isotopic mass of the bulk ions. The magnitude of $P_{L\to H}$ is expected to be high, especially during the hydrogen-only operation, so causing the transition early as the density is ramped up may be necessary, but at low density the power in the negative ion neutral beam injection (NNBI) may need to remain below the maximum available ($\simeq$ 33MW) to prevent excessive power shine through the plasma to the armor protecting the vacuum vessel. ECH might help achieve the needed $P_{L\to H}$ without adding to the shine through.

Driving sufficient plasma current for good confinement for long durations is another issue for ITER and more advanced Tokamaks such as DEMO. ECCD is an attractive method for driving current since it appears to be less costly and more reactor compatible than some other schemes such as NNBI. Also ECCD can alter the current profile locally. This could be very useful for controlling MHD and the q profile. One interesting application of q control might be maintaining the central q near or above unity. This appears advantageous for creating and maintaining the Hybrid mode in ITER with higher confinement and/or β_n than accessible with the standard H-mode.

2. Predictions of ITER plasmas

The PTRANSP code is a new version of the TRANSP code, being developed to improve the the predictive capabilities by PPPL, Lehigh University, LLNL, Tech-X, and GA. It is being used for generating time-dependent integrated modeling predictions for ITER (see Ref. 1). This paper extends this work to include effects of ECCD and ECH. The procedure is to first use the TSC code (see Ref. 2) to form and to feedback control the plasmas consistent with the planned ITER coils and circuit equations. The ramp-up, steady-state, and ramp-down are modeled. The boundary from TSC is input into PTRANSP for more detailed treatment of the heating, fueling, current drive and plasma equilibrium. The GLF23 (See Ref. 3) module in PTRANSP is used to predict plasma temperatures. The fixed boundary TEQ module (See Ref. 4) computes the shaped equilibrium. Achieving an accurate solution of the Grad-Shafranov equation can be challenging, especially in cases where the q profile is contorted. The NUBEAM Monte Carlo package (Ref. 5) computes negative-ion-neutral-beam injection (typically 1MeV deuterium at 17 or 33 MW), deposition, heating, torquing, current-drive, fueling, and shine-through, and alpha heating and slowing down. The TORIC (See Ref. 6) module in PTRANSP predicts ICRH heating (20-40 MW He^3 minority around 53 MHz). The TORAY-GA code (see 7) in PTRANSP is used to predict the ECCD and ECH. TORAY predictions for ITER have been benchmarked with other codes (see Ref. 8).

Effects of sawtooth mixing and ash accumulation are included in the predictions. Examples of PTRANSP predictions for a base line H-mode (from Ref. 1) are given in Figs. 1 - 2. The ITER plasmas are assumed to have the full toroidal field of 5.3 T with standard shaping. The H-mode plasmas are assumed to have I_p = 15MA and the Hybrid plasmas to have 12 MA.

3. TORAY predictions ECH and ECCD

Three midplane launchers and two upper launchers are assumed. Locations and assumed angles for one of the H-mode cases are shown in Table 3.1. The divergence of the rays is assumed to be 1.2 deg. The frequency is assumed to be 170 GHz, launched in O-mode. TORAY launched 20 rays from each antenna at each time step, and used 251 radial zones. Examples of an elevation view of the rays are shown in Fig. 3-a). Plan views are shown in Fig. 3-b). Profiles of $n_{||}$ are shown in Fig. 4. The time evolution of the ECCD profile from one of the upper antenna is shown in Fig. 5. The efficiency for current drive in the H-mode increased from 7.3 to 11.5, then 16.7 kA/MW as the plasma ramped up to steady state.

Predictions for Hybrid plasmas were also performed. One of the issues for these plasmas is maintaining the central q values near or above unity. Below-axis NNBI has been predicted to main q(0) above unity for long durations (see Ref. 9). Figure 6-a) shows examples of two predictions where the ECCD maintained the central above unity for more than 100 s beyond the prediction without ECCD. The q profiles at one time is shown in Fig. 6-b), and the ECCD profile at this time is shown in Fig. 7.

3.1. *Tables*

Launcher	Midplane 1	Midplane 2	Midplane 3	Upper 1	Upper 2
Major Radius [m]	8.50	8.50	8.50	6.48	6.45
Height [m]	0.01	0.61	1.21	4.11	4.20
Poloidal angle [deg]	90.0	90.0	90.0	146.0	150.0
Toroidal angle [deg]	40.0	38.0	32.0	42.0	25.0

Acknowledgments

Work supported in part by the US DoE Contracts No. DE-AC02-76CH03073

References

1. R. V. Budny, R. Andre, G. Bateman, F. Halpern, C. E. Kessel, A. Kritz and D. McCune, *Submitted to NF* **?**, p. ? (2008).
2. C. E. Kessel, G. Giruzzi, A. C. C. Sips, R. V. Budny, J. F. Artaud, V. Basiuk, F. Imbeaux, E. Joffrin, M. Schneider, M. Murakami, T. Luce, H. S. John, T. Oikawa, N. Hayashi, T. Takizuka, T. Ozeki, Y.-S. Na, J. M. Park, J. Garcia and A. A. Tucillo, *Nucl. Fusion* **47**, p. 1274 (2007).

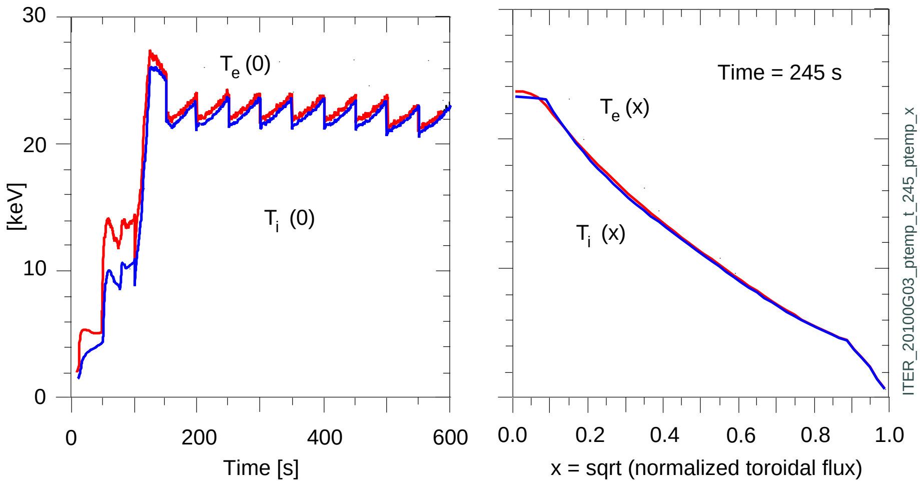

Fig. 1. Example of PTRANSP predictions of the plasma temperatures in an ITER H-mode plasma. The GLF23 model is used from x=0 to 0.9 where boundary values for T_i and T_e are assumed.. Sawtooth breaks were assumed with period 50 s.

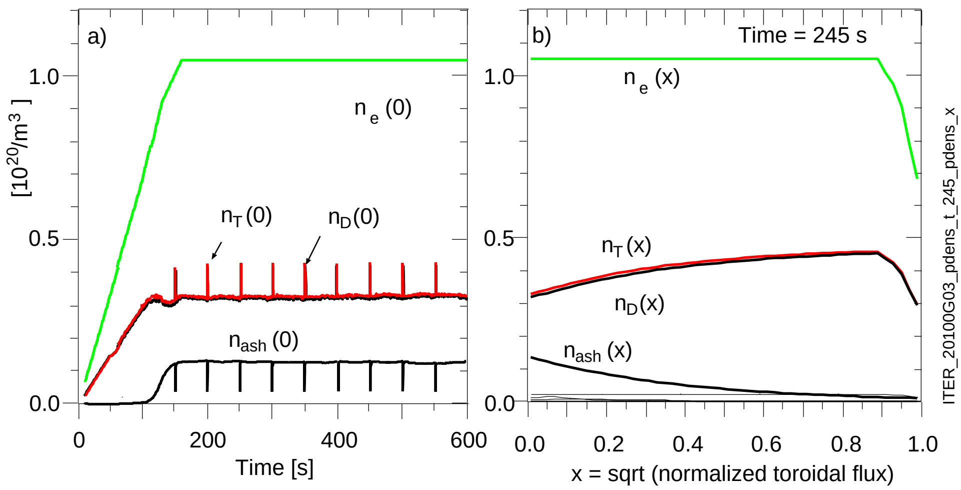

Fig. 2. Example of PTRANSP predictions of the plasma densities in an ITER H-mode plasma. The electron density is assumed.

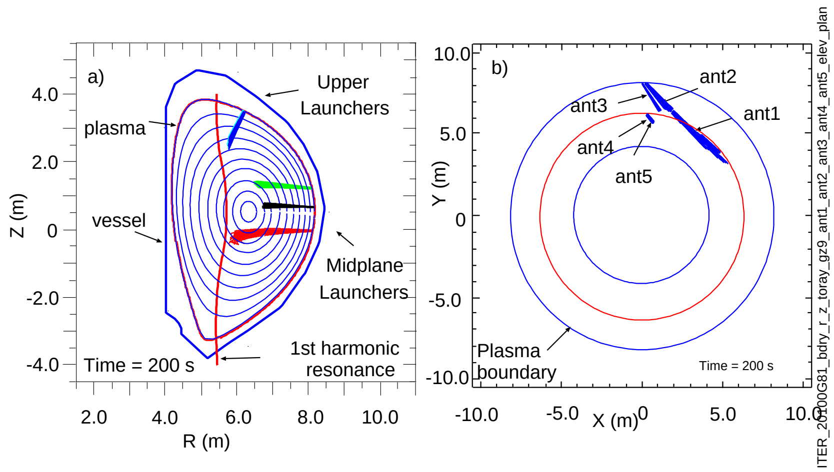

Fig. 3. Elevation view of the TORAY rays the upper and midplane antennas. The vertical curve shows the location of the fundamental resonance layer.

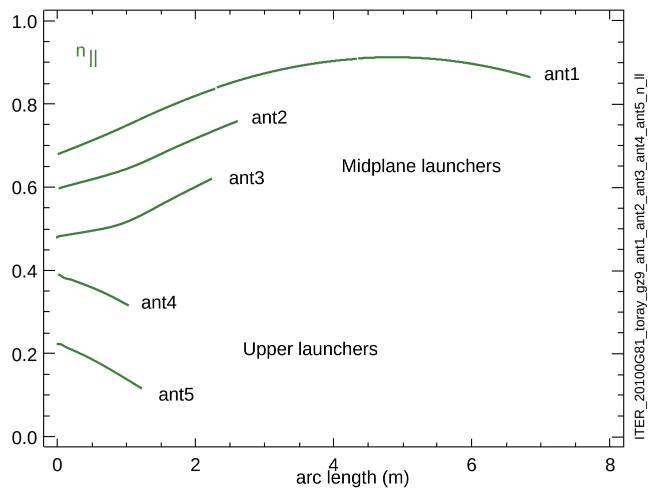

Fig. 4. Profiles of $n_{||}$ from the antenna.

3. R. E. Waltz, G. M. Staebler, W. Dorland, G. Hammett, M. Kotschenreuther and J. Konings, *Phys. Plasmas* **4**, p. 2482 (1997).
4. L. Dectyarev and V. Drozdov, *Computer Physics Reports 2* **7**, p. 341 (1985).
5. A. Pankin, G. Bateman, R. Budny, A. Kritz, D. McCune, A. Polevoic and I. Voitsekhovitch, *Comput. Phys. Commun.* **164**, p. 421 (2004).

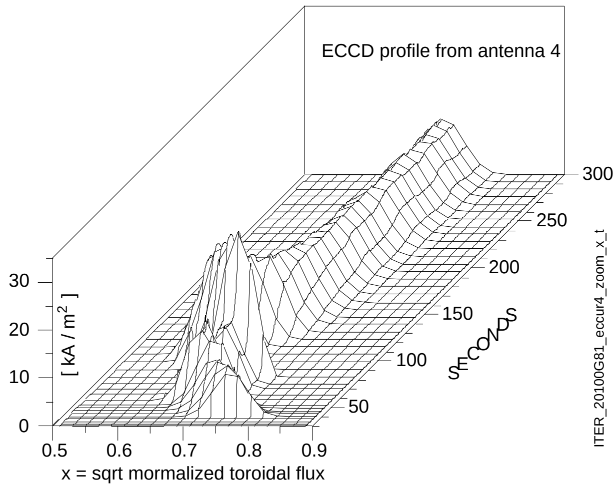

Fig. 5. Profile of ECCD from antenna 4 launching 4 MW into an ITER H-mode. The peak total current is 50 kA and the steady state value is 29 kA. The q = 3/2 surface is at x = 0.6 and 0.68 at 50 and 200 s. The q = 2/1 surface is at x = 0.7 and 0.79 at 50 and 200 s.

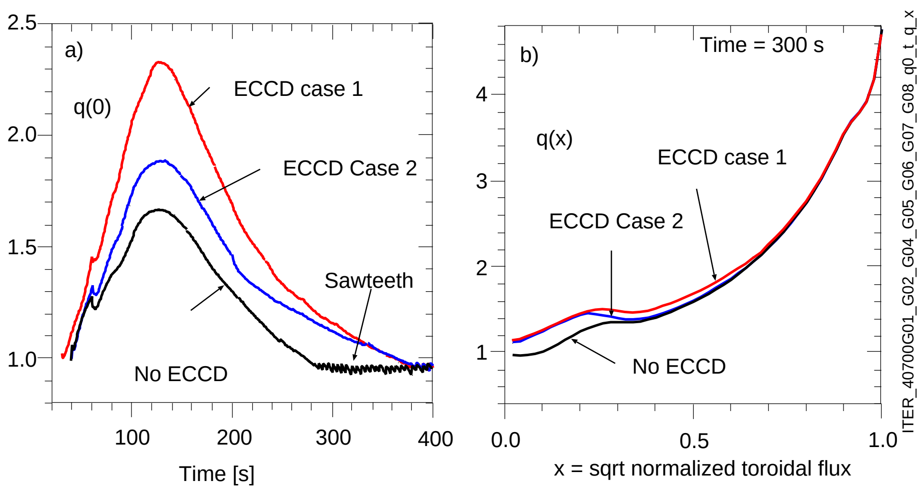

Fig. 6. Evolution in Hybrid plasmas of a) central q; b) q profile with and without ECCD.

6. M. Brambilla, *Plasma Phys. Controlled Fusion* **44**, p. 2423 (2002).
7. A. H. Kritz, H. Hsuan, R. C. Goldfinger and D. B. Batchelor, in *1982 Conf.*

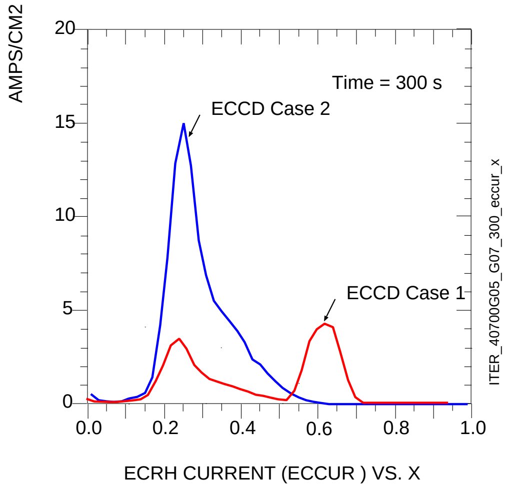

Fig. 7. q profiles in Hybrid plasmas with and without ECCD.

Proc. 3rd Int. Symp. on Heating in Toroidal Plasmas, (ECE Brussels, Belgium, 1982).

8. R. Prater, D. Farina, Y. Gribov, R. W. Harvey, A. K. Ram, Y.-R. Lin-Liu, E. Poli, A. P. Smirnov, F. Volpe, E. Westerhof, A. Zvonkov and the ITPA Steady State Operation Topical Group, *Nucl. Fusion* **48**, p. 035006 (2008).
9. R. V. Budny, C. E. Kessel, J. E. Kinsey, F. Imbeaux, I. Voitsekhovich, J. Candy, R. E. Waltz, T. Fujita, C. M. Greenfield, M. Murakami, A. C. C. Sips, W. A. Houlberg and E. J. Doyle, *Fusion Energy 2006 (Proc. 21st Int. Conf. Chengdu, 2006) (Vienna: IAEA) CD-ROM file TH/P1-5 and http://www-naweb.iaea.org/napc/physics/FBC/FEC2006/html/inded.htm* .