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Modeling of Fast Wave Heating and Current Drive in DIII-D High Performance Plasmas

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The DIII-D tokamak is using Ion Cyclotron Range of Frequencies (ICRF) fast wave (FW) heating and current drive in high performance discharges. The ICRF system will supplement the existing neutral beam (NB) and electron cyclotron (EC) heating and current drive systems. This study addresses the application of FW heating and current drive to high beta discharges produced in 2005 [1], by reproducing a discharge (122976) in a transport simulation and adding the FW to observe the impact on the electron and ion temperatures, safety factor/current density profile evolution, and non-inductive current.

Fast Wave Heating and Current Drive

The ICRF system on DIII-D [2-4] is composed of 3 launchers, all 4 strap, one at 60 MHz and the other two at 83 MHz. The launched spectrum, in parallel index of refraction, is composed of a single broad lobe modeled as $n_{||} = (k_{||}c/\omega) = 1.85$, 3.05, 4.45, 5.85, and 7.05, with power fractions of 11%, 22%, 33%, 22%, and 11%, respectively, for the 83 MHz launchers. The values are $n_{||} = 2.45$, 3.50, 5.25, 7.00, and 8.06, with the same power fractions for the 60 MHz launcher. There are some additional lobes in the spectra but they are neglected here due to their small power fraction (< 5%). The powers delivered to the plasma, based on previous experiments[2], are 1.5 MW into L-mode plasmas and 0.7 MW into H-mode plasmas, for each of the 83 MHz launchers. The powers to the plasma are 1.2 MW into L-mode plasmas and 0.75 MW into H-mode plasmas for the 60 MHz launcher.

The calculations of the FW power deposition and current drive are done with CURRAY[5], assuming the fast ions from neutral beam injection (NBI) are Maxwellian at an effective temperature determined from the TRANSP[6] analysis, $T_{fast} = (2/3)\langle E_{fast}\rangle/n_{fast}$, where n_{fast} is the fast ion density and $\langle E_{fast}\rangle$ is the average fast ion energy density integrated over the slowing down distribution. Impurities assumed in the heating and CD calculations are 2% hydrogen, and 2% carbon in L-mode or 5% carbon in H-mode, the remainder being deuterium. In the transport simulations, the FW heating profiles are used from the CURRAY analysis, with the FW power deposited on fast ions redistributed 75% to electrons and 25% to thermal ions, based on the typical fast ion energy observed in previous FW experiments[2]. Efforts to better understand the power damping on fast particles and the subsequent slowing down on thermal particles is continuing[7]. Analysis shows that the low $n_{||}$ part of the spectra has the strongest absorption on fast ions, and the 60 MHz waves are absorbed more strongly on thermal ions than the 83 MHz. The few pass (1-2) absorption is strong for both FW frequencies at the high densities in this discharge. In fact, towards the end of the discharge at the highest densities, the absorption is all on the LFS with no access to the magnetic axis.

DIII-D High Beta Discharge 122976

The discharges 122976, 122004, and 121996, reported in ref.[1], are similar and represent the high beta plasma configuration of interest for this study. The plasma reaches β_N values of about 4.0 for 2 s, and possess internal transport barriers in the ion thermal, particle, and ion rotation channels, at a radius of approximately $\rho \approx 0.5$. The plasmas are produced by an I_p ramp up to 1.65 MA and a B_T rampdown, from 2.1 to 1.55 T, throughout the discharge. The line average density rises through the discharge from $1.5\text{-}7.5 \times 10^{19}$ /m^3 after the transition to H-mode, although the peak density reaches 1.0×10^{20} /m^3, giving a $n(0)/\langle n \rangle$ of about 1.6. In the high power phase the plasma κ is 1.85, $\langle \delta \rangle$ is 0.75, li(1) is 0.65, W_{MHD} is about 1.7 MJ, and the NB injected power is about 10 MW (which is feedback controlling β_N), with a broad centrally peaked deposition. The maximum NB driven current during the discharge is about 240 kA. The EC power in 122976 is injected for 3.1 s, beginning at 0.7 s, with power varying between 1.2 and 1.8 MW. Analysis with TORAY in TRANSP indicates that after 2.3 s of operation (or 3.1 s in the discharge), the high density in the plasma is cutting off the EC, and it no longer deposits power into the plasma. In addition, since the toroidal field is ramping down, the resonance location varies in major radius, resulting in a minor radial deposition that begins at a ρ of 0.45 and moves outward to 0.85 before being cutoff. The maximum EC driven current is about 50 kA, while the bootstrap current maximizes at about 1.1 MA.

Modification of High Beta Discharge 122976 with FW Heating

The discharge 122976 is reproduced in the Tokamak Simulation Code (TSC)[7] using the data from the TRANSP[6] analysis, including n, $\chi_{e,i}$, P_{NBe}, P_{NBi}, j_{NB}, P_{EC}, j_{EC}, the PF coil currents from the experiment, and several experimental parameters (R_o, a, Z_{mag}, li(1), W_{th}, V_{surf}, q_o, q_{min}) are matched as well as possible to those of the discharge. The thermal diffusivities are scaled by IPB98(y,2) in the H-mode phase to account for any changes to global parameters, particularly the addition of injected power from the FW. CURRAY calculations using time slices from the TSC simulation provides the P_{FWe}, P_{FWi}, and j_{FW} for the various phases of the discharge as described above. Although the B_T ramp causes the IC resonances to move across the plasma during the discharge this does not appear to affect the results significantly. FW current drive was found to be very small at the densities in these discharges, ranging from 5-10 kA/MW in the H-mode phase, and is neglected here.

Shown in Fig. 1 are the time histories of the plasma current and its contributions from NBI, EC, and bootstrap, for the reference case with NB and EC, and a case where the EC is replaced by 2.2 MW, from all 3 launchers, (4.2 MW injected) of FW. Cases where the FW was added to the EC were also done, but not shown. Also shown are the heating and parallel current density, at 1.5 s in the discharge simulation. Fig. 2 shows the central and minimum safety factor time histories, and profiles at 1.5 s. The heating profiles for the EC (electrons only) and FW (electrons and ions) are quite different in location and distribution. In spite of this, they both appear to have the same impact on the discharge, giving similar total non-inductive current, bootstrap current, and NB driven current. However, the EC clearly produces a very localized off-axis current deposition , while the FW heating yields slightly higher NB driven and bootstrap current density in the core. This results from higher temperatures produced in the core with FW heating. From the safety factor profiles it can be seen that the ECCD is producing a local safety factor minimum at a larger radius than the FW heating case, and this tendency persists until late in the discharge simulations.

Conclusions

It is found that the FW heating deposits its power near the plasma core ($\rho < 0.5$), the central T_e and T_i are increased by the FW heating, the FW heating leads to higher local NB and bootstrap current densities in the core, the FW power deposition persists at high density, and leads to similar total non-inductive current compared to EC. However, the ECCD produced a local q_{min} with larger radii than the FW heating. In addition, adding FW heating to the discharge with NB + EC did not result in a significant change in the q profile evolution. Future work will concentrate utilizing FW and EC heating and current drive at lower density (facilitated by the new lower pumped divertor geometry) and plasma current to sustain the high q_{min} and large $\rho(q_{min})$ characteristic of these discharges.

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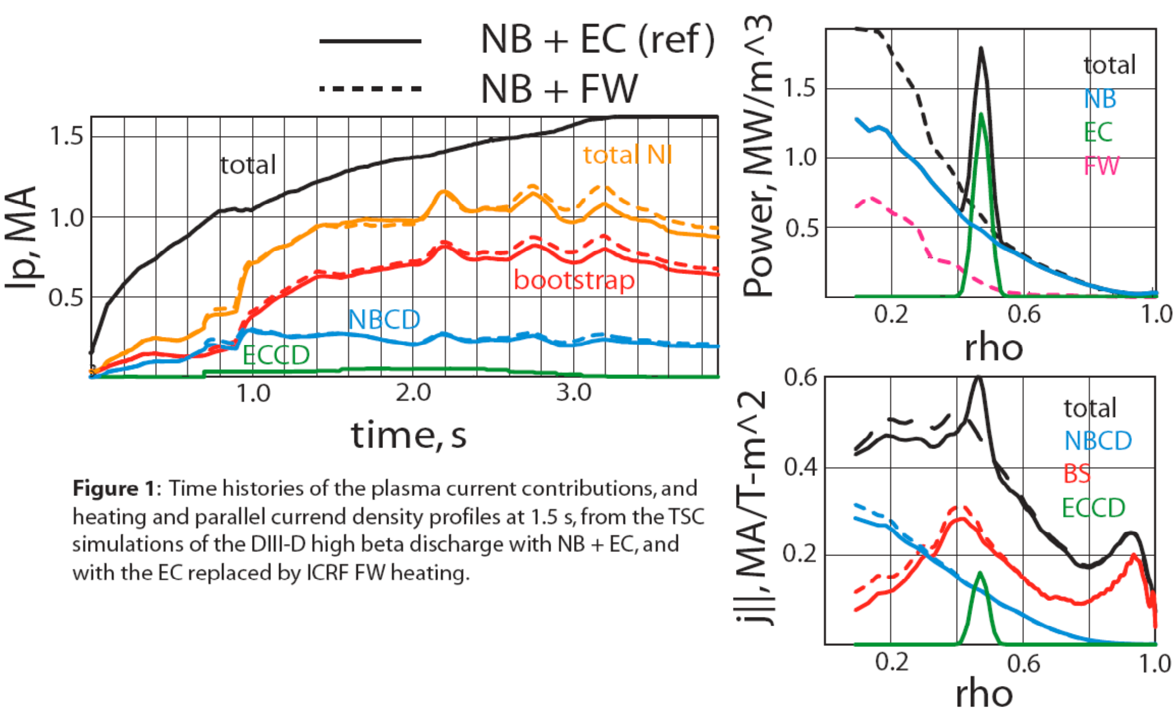

Figure 1: Time histories of the plasma current contributions, and heating and parallel currend density profiles at 1.5 s, from the TSC simulations of the DIII-D high beta discharge with NB + EC, and with the EC replaced by ICRF FW heating.

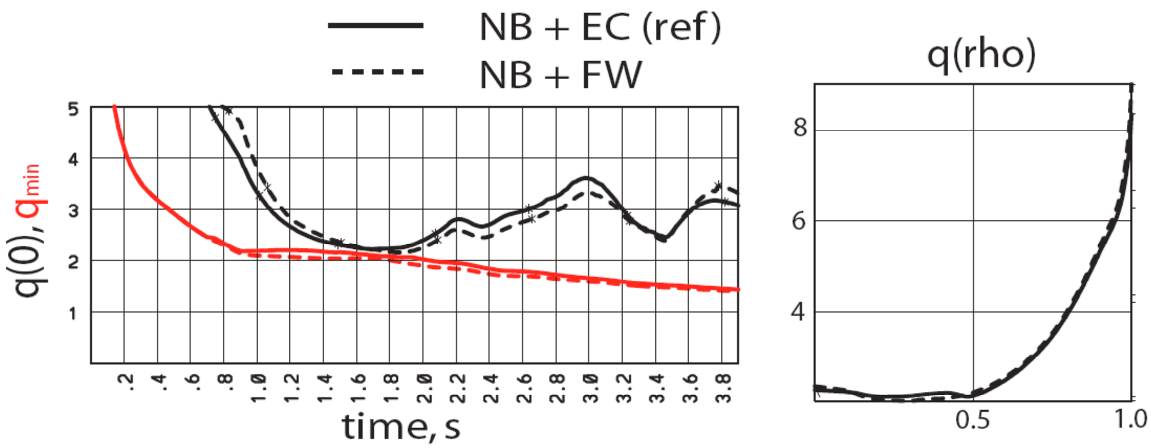

Figure 2: Time histories of the on-axis and minimum safety factor values, and the safety factor profiles at 1.5s, from the TSC simulations of the DIII-D high beta discharge with NB + EC and with the EC replaced by ICRF FW heating.

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