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MODELING RESULTS FOR PROPOSED NSTX 28 GHZ ECH/EBWH SYSTEM

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A 28 GHz electron cyclotron heating (ECH) and electron Bernstein wave heating (EBWH) system has been proposed for installation on the National Spherical Torus Experiment (NSTX). A 350 kW gyrotron connected to a fixed horn antenna is proposed for ECH-assisted solenoid-free plasma startup. Modeling predicts strong first pass on-axis EC absorption, even for low electron temperature, $T_e \sim 20$ eV, Coaxial Helicity Injection (CHI) startup plasmas. ECH will heat the CHI plasma to $T_e \sim 300$ eV, providing a suitable target plasma for 30 MHz high-harmonic fast wave heating. A second gyrotron and steered O-X-B mirror launcher is proposed for EBWH experiments. Radiometric measurements of thermal EBW emission detected via B-X-O coupling on NSTX support implementation of the proposed system. 80% B-X-O coupling efficiency was measured in L-mode plasmas and 60% B-X-O coupling efficiency was recently measured in H-mode plasmas conditioned with evaporated lithium. Modeling predicts local on-axis EBW heating and current drive using 28 GHz power in $\beta \sim 20\%$ NSTX plasmas should be possible, with current drive efficiencies ~ 40 kA/MW.

1. Introduction

The spherical tokamak (ST) can be a viable prototype for a high β nuclear fusion reactor or component test facility (ST-CTF) [1] if the plasma is initiated and sustained without using a central solenoid. Solenoid-free ST plasma startup can be produced by several techniques in the National Spherical Torus Experiment (NSTX) [2], including using only the outer poloidal field coils [3] or by employing coaxial helicity injection (CHI) [4]. A 350 kW, 28 GHz electron cyclotron heating (ECH) system (Fig. 1), operating at moderate RF power levels of a few hundred kilowatts [5], has been proposed that would heat these solenoid free startup discharges sufficiently to allow coupling of 30 MHz high harmonic fast wave (HHFW) [6] power. HHFW heating would then be used to ramp the plasma current from 250 kA to 500 kA through a combination of bootstrap current overdrive and HHFW current drive [7, 8]. Once the plasma current reaches ~ 500 kA, neutral-beam injection can be used to ramp and then sustain the plasma current.

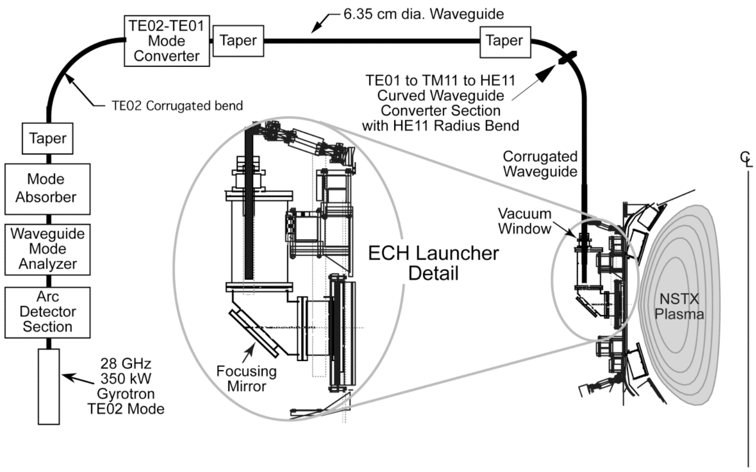

Figure 1: Schematic layout of the NSTX 28 GHz heating system.

Modeling has shown that efficient off-axis EBW current drive (EBWCD) can be generated in an ST [9] and that driving 1 MA of off-axis EBWCD in the ST-CTF plasma significantly increases plasma stability [1]. EBWCD in future STs may be used for current profile control to increase global stability, allowing access to higher β [10]. A moderate power EBWH system, with an RF power of about 700 kW and an oblique O-X-B mirror launcher [11], has been proposed to test the viability of EBWH on NSTX during the plasma current flattop.

In this paper we present GENRAY ray tracing [12] and CQL3D Fokker-Planck [13] code modeling results for 28 GHz ECH in an NSTX CHI startup plasma, and for 28 GHz on- and off-axis EBWH and ECCD during a β = 20% NSTX plasma.

2. 28 GHz ECH-Assisted Plasma Startup

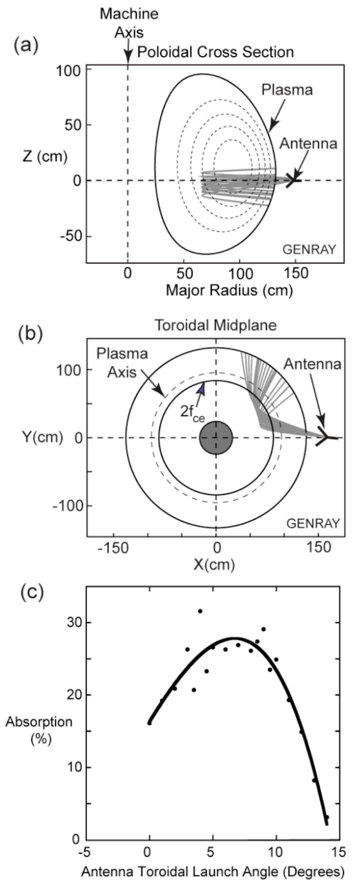

Figure 2: 28 GHz ray tracing in a CHI plasma in (a) poloidal and (b) toroidal midplane cross section. (c) Absorbed power versus toroidal antenna launch angle.

Fig. 2(a) shows the poloidal cross section of an NSTX CHI plasma magnetic equilibrium reconstructed from NSTX shot 120874 at 12 ms. Superimposed on the equilibrium are 28 GHz ray trajectories calculated by GENRAY [12]. $n_e(R)$ and $T_e(R)$ were assumed to be flat in the modeling, with $n_e = 3.5\times10^{18}$ m^{-3} and $T_e = 25$ eV. CHI startup plasma profiles have similar values but are generally somewhat hollow. A cone of 30 rays with a half angle of 3 degrees was launched in the model to simulate the divergence of a diffraction limited 28 GHz antenna pattern. The vertex of the cone of rays was located on the midplane at a major radius of 200 cm, the planned location of the 28 GHz ECH antenna. ECH was modeled for range of toroidal antenna pointing angles relative to the plasma surface normal. Ray trajectories in the horizontal midplane are shown in Fig. 2(b) for a case when the launch antenna axis is pointed toroidally 6 degrees from normal to the plasma surface. 28 GHz X-mode power reflects off the right hand cutoff, located just inboard of the plasma axis, at a major radius, R = 84 cm, so the RF power is absorbed twice during its first pass through the plasma. Optimum first pass EC absorption of 25-30% is predicted by CQL3D when the antenna was pointing toroidally 6-7 degrees from normal to the plasma surface, as shown in Fig. 2(c). Wall reflectivity can be expected to substantially increase the total absorbed RF power. As the electron temperature increases with the application of ECH the first pass absorption will increase, reaching > 75% when $T_e(0)$ is

~ 200 eV. At that temperature peak deposition will reach 4 W/cm^3 for 200 kW of coupled RF power.

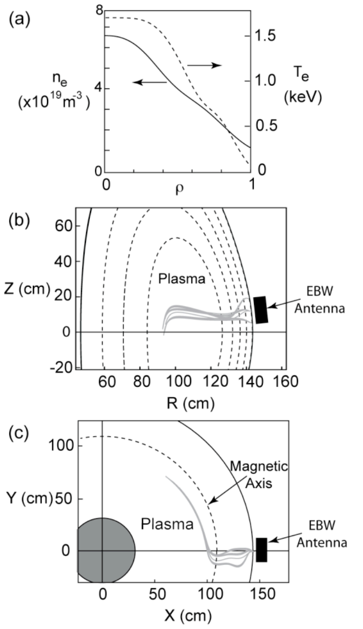

Figure 3: GENRAY 28 GHz on-axis EBW heating results. (a) T_e and n_e profiles. Ray tracing in (b) poloidal and (c) toroidal midplane cross section.

3. 28 GHz EBWH and EBWCD

Proposed NSTX O-X-B EBWH and EBWCD experiments require an obliquely directed RF antenna, probably consisting of a steered mirror launcher, located near the outboard midplane. Thermal EBW emission (EBE) measured on NSTX with two remotely steered B-X-O antennas near the midplane have measured the EBW coupling efficiency for a wide range of plasma conditions [14]. EBE measurements have yielded B-X-O EBW coupling efficiencies greater than 90% in L-mode and up to 60% in H-mode, with the assistance of evaporated lithium conditioning [15]. These results are in generally good agreement with EBE simulations of NSTX plasmas that use measured kinetic profiles and magnetic equilibria [16].

Figures 3(a) shows $n_e(R)$ and $T_e(R)$ profiles for a β = 20% NSTX discharge used for modeling 28 GHz on-axis EBWH and EBWCD. Figure 3(b) and 3(c) show the behavior of 28 GHz rays predicted by GENRAY when the EBW antenna is located slightly offset from the plasma midplane to provide a toroidally unidirectional wave spectrum near the second harmonic EC resonance, and hence generate net rf-driven current [17].

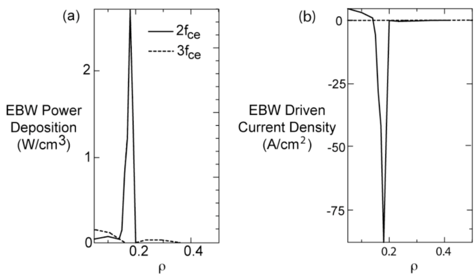

Figure 4: (a) EBW power density and (b) EBW current density obtained with 700 kW of 28 GHz EBW power and for the case shown in Fig. 3.

Figure 4(a) shows the EBW power deposition profile calculated by CQL3D for 750 kW of coupled RF power. 85% of the EBW electron heating occurs near a normalized minor radius, ρ = 0.2, through wave damping at the second EC harmonic. 15% of the heating results from EBW damping at the downshifted third EC harmonic, located within ρ = 0.35. Figure 4(b) shows the rf-driven current density profile. The rf-driven current is predominantly Fisch-Boozer [18] current in the counter-plasma current direction, near ρ = 0.2, with a small amount driven in the co-plasma current direction near the axis. 29 kA of rf-driven current is generated with 700 kW of RF power, or about 39 kA/MW.

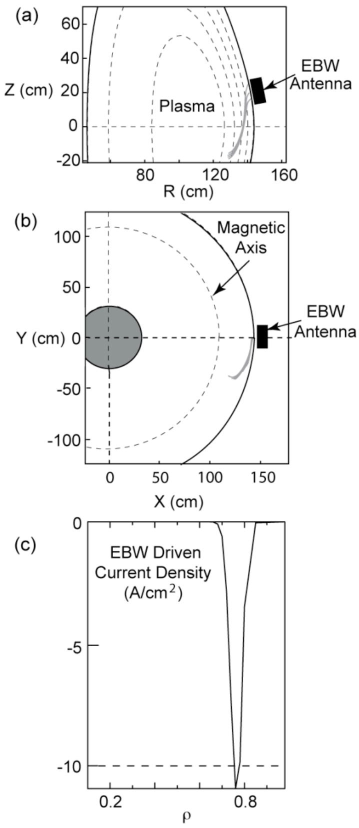

Figure 5: GENRAY 28 GHz off-axis EBW heating results. Ray tracing in (a) poloidal and (b) toroidal midplane cross section. (c) EBW current density obtained with 700 kW of 28 GHz EBW power.

Most future applications for EBWCD in STs, such as current profile control to increase global stability, require EBWCD far off-axis, typically at ρ > 0.6. This can be achieved on NSTX at 28 GHz with the same plasma as modeled in Figs 3 and 4 by moving the EBW launcher further off the midplane than for the case shown in Fig. 3(b). This increases the parallel wavenumber of the EBW after it is launched and consequently moves the region where the EBW is absorbed towards the outboard side of the plasma. Figures 5(a) and 5(b) show the trajectory of 28 GHz rays predicted by GENRAY in the plasma poloidal cross section and the toroidal cross section at the plasma midplane, respectively, for an off-axis EBWCD case. EBW power is deposited between ρ = 0.7 and 0.85. Using an EBW power of 700 kW and the same $n_e(R)$ and $T_e(R)$ shown in Fig. 3(a), but with $n_e(R)$ decreased by 33% and $T_e(R)$ increased by 50% to get the same electron pressure profile, resulted in CQL3D predicting the EBW driven current density profile shown in Fig. 5(c). 25 kA of net rf-driven current is generated in the co-plasma current direction via Ohkawa [19] current drive for 700 kW of RF power.

Acknowledgements

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