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Abstract. Off-axis electron Bernstein wave current drive (EBWCD) may be critical for sustaining non-inductive high β NSTX plasmas. Numerical modeling results predict that the ~ 100 kA of off-axis current needed to stabilize a solenoid-free high β NSTX plasma could be generated via Ohkawa CD with 3 MW of 28 GHz EBW power. In addition, synergy between EBWCD and bootstrap current may result in a 10% enhancement in CD efficiency with 4 MW of EBW power. Recent dual-polarization EBW radiometry measurements on NSTX confirm that efficient coupling to EBWs can be readily accomplished by launching elliptically polarized electromagnetic waves oblique to the confining magnetic field, in agreement with numerical modeling. Plans are being developed for implementing a 1 MW, 28 GHz *proof-of-principle* EBWCD system on NSTX to test the EBW coupling, heating and CD physics at high rf power densities.

Keywords: Spherical tokamaks, electron Bernstein waves
PACS: 52.55.Fa, 52.35.Hr

INTRODUCTION

Off-axis, radially localized, rf-driven current may be critical for non-inductively sustaining high β plasmas in the National Spherical Torus Experiment (NSTX) [1,2]. However local rf current drive techniques established on conventional high aspect ratio tokamaks and stellarators are not readily applicable to spherical torus plasmas. Electron cyclotron current drive (ECCD) cannot be employed on high β NSTX plasmas, since these plasmas are overdense ($\omega_{pe} >> \omega_{ce}$) and therefore not accessible to low harmonic electron cyclotron waves. Furthermore, high harmonic fast wave current drive has proved incompatible with neutral-beam-injection due to fast ion absorption [3] and limits on wave accessibility would limit the efficiency of a lower hybrid current drive scheme [4]. In contrast, the electrostatic electron Bernstein wave (EBW) offers the potential for local current drive (EBWCD) in NSTX since the wave propagates in overdense plasma and is strongly absorbed at electron cyclotron resonances [5,6].

One goal of NSTX EBW research is to model the propagation, damping and CD efficiency of EBWs for various NSTX plasma scenarios. Numerical modeling results for a β ~ 40% NSTX plasma predict efficient off-axis EBWCD can be achieved [7] via the Ohkawa [8] CD process and that positive synergies may exist with the bootstrap current at multi-megawatt rf power levels [9]. Another goal of NSTX EBW research is to establish a viable and resilient technique for efficiently coupling rf power to EBWs in the plasma. Recent radiometric thermal EBW emission data acquired on NSTX [10] support efficient

EBW coupling via O-mode launch oblique to the confining magnetic field [11]. These thermal EBW coupling experiments and the associated numerical EBW modeling research support the design and implementation of a *proof-of-principle*, 1 MW, 28 GHz EBW heating and CD system planned for NSTX. This *proof-of-principle* system will test the EBW coupling, heating and CD physics at high rf power densities and the rf technologies needed for a future 4 MW EBWCD system.

EBWCD MODELING RESULTS

The GENRAY ray tracing computer code [6,12] and the CQL3D relativistic, bounce-averaged, Fokker-Planck code [13] have been used to model propagation and damping of EBWs and the EBW-driven current density profile for high β NSTX plasma equilibria. Figure 1 summarizes CQL3D modeling results for 3 MW of 28 GHz EBW power coupled into a β = 41% NSTX plasma. The EBW launcher couples rf power below the plasma midplane to generate 135 kA of EBWCD near a normalized radius, ρ = 0.7 (Fig. 1(a)). The driven-current density (33 kA/cm^2) exceeds the local bootstrap current density and therefore may be sufficient to suppress neoclassical tearing modes (NTMs) that can strongly degrade plasma confinement in spherical tokamaks [14,15]. Figure 1(b) shows that the rf quasilinear velocity space diffusion coefficient peaks near the trapped–passing boundary, efficiently driving current via the Ohkawa current drive process [7,8].

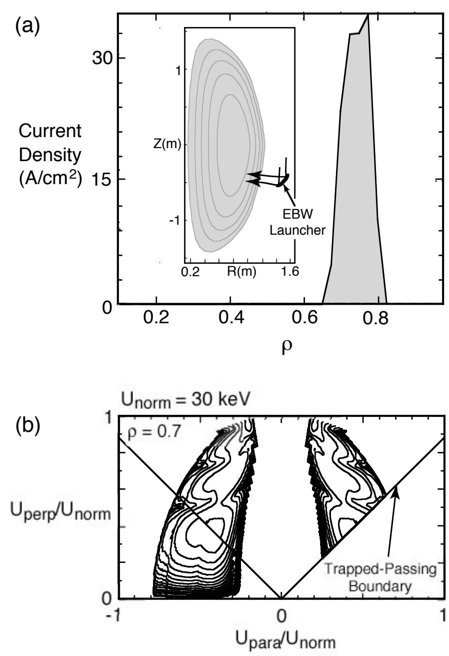

FIGURE 1: CQL3D modeling results for 3 MW of 28 GHz EBW power coupled into a β = 41% NSTX plasma with I_p = 1 MA and $B_t(0)$ = 0.35 T; (a) EBW-driven current density versus normalized minor radius (ρ) and (b) contours of the quasilinear rf velocity space diffusion operator plotted at ρ = 0.7.

The synergy between EBWCD and the current driven by the electron bootstrap effect have also been calculated with CQL3D [9]. A simple bootstrap model in CQL3D is used in these studies: the transiting electron distributions are connected in velocity-space at the trapped-passing boundary to trapped-electron distributions that are displaced radially outwards/inwards by a half-banana width for the co-/counter-passing regions. This model agrees well with standard bootstrap current calculations, over the outer 60% of the plasma radius [16]. At 4 MW of applied EBW power, there is a ~ 10% synergistic increase in the bootstrap current due to enhanced rf pitch angle scattering of the electrons. Locally, bootstrap current density increases in proportion to increased plasma pressure, and this effect can significantly affect the radial profile of the rf-driven current density.

EBW COUPLING CALCULATIONS AND MEASUREMENTS

A critical issue for implementing EBWCD on NSTX is to establish a resilient technique to efficiently couple rf power to EBWs in the plasma. Recently, the AORSA-1D

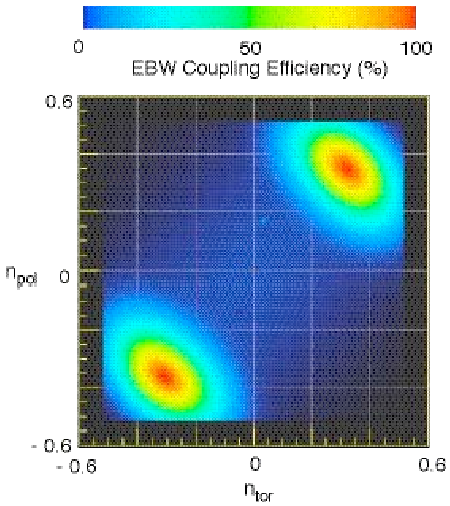

FIGURE 2: Contours of maximum EBW coupling efficiency calculated by AORSA-1D for 28 GHz rf power coupled into a β = 41% NSTX plasma. Coupling efficiency is plotted versus the n_{pol} and n_{tor} of the launched electromagnetic wave. The launch polarization was adjusted to determine the maximum EBW coupling efficiency at each value of n_{pol} and n_{tor}.

numerical computer code [17], an all orders, full wave rf code that imposes no limit on the number of cyclotron harmonics, has been modified to solve the EBW mode coupling in a 1-D slab geometry. The results of a mode-conversion study using this modified AORSA-1D code for a launch frequency of 28 GHz into a β = 41 % NSTX plasma with I_p = 1 MA and $B_t(0)$ = 0.35 T are summarized in Fig. 2. The launch polarization was adjusted to obtain the maximum EBW coupling efficiency as a function of the poloidal and toroidal wavenumber of the incident microwave power [n_{pol} and n_{tor}, respectively]. Efficient coupling of near-circularly polarized microwave radiation was found for a launched electromagnetic wave with $n_{pol} = \pm 0.35$ and $n_{tor} = \pm 0.3$.

Since the mode conversion process is reciprocal [18], studying mode-converted thermal EBW emission with absolutely calibrated radiometers allows experimental benchmarking of the numerical modeling predictions of EBW coupling efficiency for specific values of n_{pol} and n_{tor}. Recently, obliquely-viewing, dual polarization radiometry has been employed on NSTX to evaluate the coupling efficiency of 16-18 GHz thermal EBW emission [10]. An EBW coupling efficiency 80±20% was achieved in good agreement with ~ 65% coupling efficiency predicted by a numerical model that included a 1-D full wave calculation of the EBW mode conversion layer, radiometer antenna pattern modeling and 3-D EBW ray tracing and deposition modeling [19]. Thermal EBW emission at 16.5 GHz was consistent with the near-circular polarization predicted by the numerical modeling. Thermal EBW radiometric studies on NSTX will be extended to 20-40 GHz in 2005 [20] and will test EBW coupling efficiency predictions from AORSA-1D at 28 GHz.

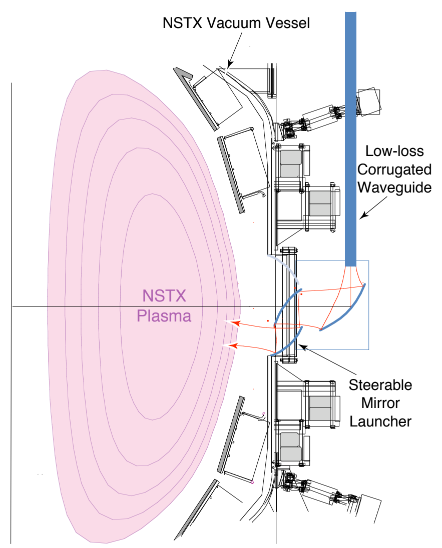

FIGURE 3: Conceptual design for a steerable EBW mirror launcher on NSTX. Second mirror may be switched to launch power above the midplane allowing EBWCD in the opposite toroidal direction.

PLANS FOR EBWCD ON NSTX

EBWCD numerical modeling predicts current drive efficiencies that are typically ~ 40-50 kA/MW at 28 GHz in β = 20 - 40% NSTX plasma equilibria [7]. Assuming that the EBWCD system needs to generate ~ 100 kA of plasma current [2], that the microwave coupling efficiency to EBWs is ~ 90% [10] and that the waveguide transmission loss is 10-15%, 4 MW of microwave source power would be needed in order to deliver the necessary 3 MW of EBW power into the plasma. Four EBW steerable mirror launchers will couple microwave power into the plasma. A sketch showing one possible conceptual design for an NSTX EBW launcher is shown in Fig. 3. This design would allow the second mirror to switch between steerable launchers above and below the midplane, to drive current in either toroidal direction [6]. A simpler single steerable mirror launcher, requiring less midplane port access, could be used if only one direction of current drive were needed.

The radiometric thermal EBW coupling experiments cannot test the importance of parametric decay to lower hybrid waves [21] and ponderomotive effects that can become important at high rf power densities. Furthermore, there is a negative particle pinch [22] that has not been included in our EBWCD modeling so far that can reduce the bootstrap current offsetting the Ohkawa current, thus reducing CD efficiency. In order to test these effects we propose to intall a ~ 1 MW, 28 GHz *proof-of-principle* EBWCD system on NSTX using one EBW launcher and transmission line.

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