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Citation: Edlund, E. M., P. T. Bonoli, M. Porkolab, and S. J. Wukitch. "Modeling of EAST ICRF Antenna Performance Using the Full-Wave Code TORIC" AIP Conference Proceedings 1689, 060002 (2015)

As Published: http://dx.doi.org/10.1063/1.4936500

Publisher: American Institute of Physics (AIP)

Persistent URL: http://hdl.handle.net/1721.1/109214

Version: Author's final manuscript: final author's manuscript post peer review, without publisher's formatting or copy editing

PSFC/JA-15-26

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May 2015

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This work was supported by the U.S. Department of Energy, Grant No. DE-FC02-01ER54648. Reproduction, translation, publication, use and disposal, in whole or in part, by or for the United States government is permitted.

Modeling of EAST ICRF Antenna Performance Using the Full-wave Code TORIC

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Abstract. Access to advanced operating regimes in the EAST tokamak will require a combination of electron-cyclotron resonance heating (ECRH), neutral beam injection (NBI) and ion cyclotron range frequency heating (ICRF), with the addition of lower-hybrid current drive (LHCD) for current profile control. Prior experiments at the EAST tokamak facility have shown relatively weak response of the plasma temperature to application of ICRF heating, with typical coupled power about 2 MW out of 12 MW source. The launched spectrum, at n_φ=34 for 0-π -0-π phasing and 27 MHz, is largely inaccessible at line-averaged densities of approximately 2×10^{19} m^{-3}. However, with variable antenna phasing and frequency, this system has considerable latitude to explore different heating schemes. To develop an ICRF actuator control model, we have used the full-wave code TORIC to explore the physics of ICRF wave propagation in EAST. The results presented from this study use a spectrum analysis using a superposition of n_φ spanning -50 to +50. The low density regime typical of EAST plasmas results in a perpendicular wavelength comparable to the minor radius which results in global cavity resonance effects and eigenmode formation when the single-pass absorption is low. This behavior indicates that improved performance can be attained by lowering the peak of the $k_\parallel$ spectrum by using π/3 phasing of the 4-strap antenna. Based on prior studies conducted at Alcator C-Mod, this phasing is also expected to have the advantage of nearly divergence-free box currents, which should result in reduced levels of impurity production. Significant enhancements of the loading resistance may be achieved by using low $k_\parallel$ phasing and a combination of magnetic field and frequency to vary the location of the resonance and mode conversion regions. TORIC calculations indicate that the significant power may be channeled to the electrons and deuterium majority. We expect that implementation of these recommendations in EAST will yield substantial improvements in the net absorbed power that will greatly assist in the attempt to access advanced tokamak operating regimes.

INTRODUCTION

A core mission of the EAST experiments in the coming campaigns will be the development of operational regimes that are suitable as a foundation for exploration of Advanced Tokamak (AT) physics. The primary tools for providing auxiliary heating to the plasma are the ion-cyclotron resonance heating (ICRH) system with 12 MW of source power, the neutral beam injection (NBI) system with 10 MW of source power and the electron-cyclotron resonance heating (ECRH) system with 4 MW of source power. The NBI system will be pulsed due to thermal constraints, and the ECRH system alone is incapable of delivering the heating power necessary to reach the AT regime, thus the ICRH system stands prominently as one of the core utilities for delivering steady-state auxiliary heating. An additional 8 MW of source power will be available through the lower-hybrid (LH) system, though this is intended mainly as a source of current drive for advanced profile control.

Recent EAST experiments have shown that only about 2 MW of the 12 MW source power from the ICRH system is typically coupled to the plasma, enough to access H-mode, but with relatively little impact on the plasma temperature [1]. This is problematic from the standpoint of attaining the AT regime, and also raises operational issues due to the required cooling of the coaxial transmission lines. The goal of this work is to analyze the base operating conditions of EAST plasmas, in conjunction with variations of the ICRH antenna phasing and frequency, to search for conditions that offer substantial enhancements of the coupled power.

In the following sections we briefly introduce the TORIC code [2,3] that is used for these studies define the specific problem to be addressed. The analysis proceeds by way of examining the effect of the plasma density on the propagation of a single toroidal mode, as an illustrative example of some of the underlying physics issues. Prior studies of EAST ICRH have also used TORIC [4], though as we show here, consideration of a single mode is insufficient to give an accurate account of the coupled power and a full spectrum analysis is necessary. Following this we present the results of calculations that sum over a range of toroidal modes and examine the effects of density, antenna phasing and antenna frequency. Out of this we identify a set of testable conditions that, according to calculations, potentially offer an increase in the coupled power by many factors.

THE EAST ICRH ANTENNA SYSTEMS

The 12 MW of source ICRH power is divided over three antenna systems, two 2-strap systems and one 4-strap system that are largely based on the Alcator C-Mod design, though with a versatile source network that allows for both variable frequency and variable phasing between the straps [5]. In this analysis we consider the loading of the 4-strap antenna, characterized by the coupled power measured relative to the antenna current (measured in units of MW/kA^2), for four antenna phasings: 0-π-0-π (heating phasing), 0-π-π-0 (symmetric phasing), 0-π/2-π-3π/2 and 0-π/3-2π/3-π. The 2-strap antennas may be best suited for operation with heating phasing, and will have slightly broader spectral distributions than that for the 4-strap antenna.

The last phasing has the interesting property that the image currents in the antenna box should be nearly divergence-free, implying low rates of impurity generation. Together with a peak in the spectrum at comparably low values of n_φ, the π/3 phasing may be the most favorable case to examine in experiments. It also offers the potential to drive current due to the asymmetric nature of the launched spectrum, though that aspect is not explored in this analysis. As a reference point for the subsequent discussions, we present in Fig. 1 the calculated spectra of n_φ for these antenna phasings.

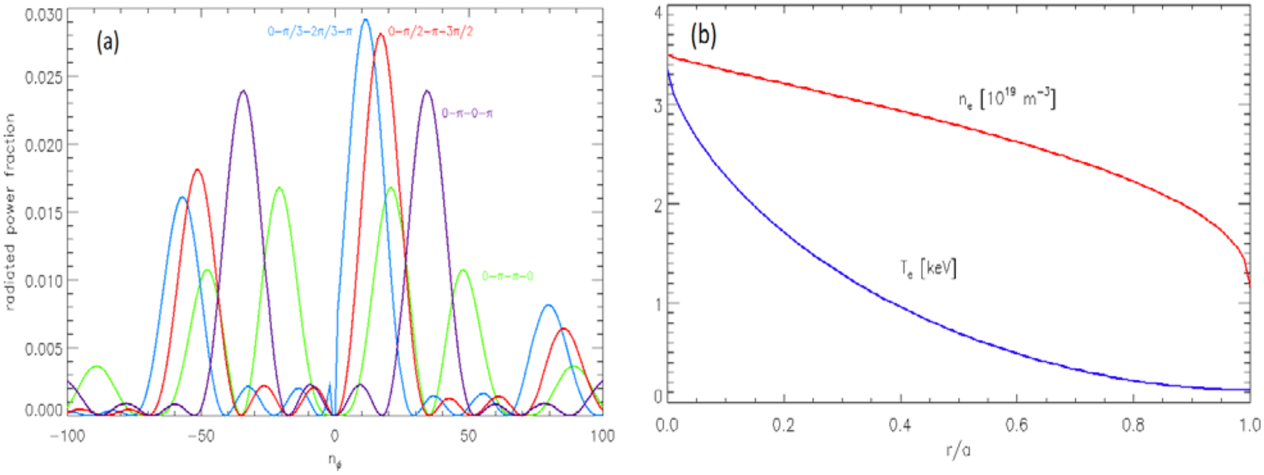

FIGURE 1. (a) Launched spectra (calculated) for the four phasings studied in this work. The peaks of the spectra occur for n_φ of ±34 (heating phasing), ±22 (symmetric phasing), +17 (π/2 phasing) and +11 (π/3 phasing). (b) Electron density and temperature profiles used in the TORIC modeling. The density profile is uniformly scaled to match the value of central density specified in the simulations, and the ion temperatures (for both D and H) are taken to be equal to 0.8 times the electron temperature.

TORIC MODELING OF ICRH WAVES

We explore the space of operational parameters for ICRH in EAST with the full-wave code TORIC. This code uses a linear spectral mode (n_φ) decomposition in the toroidal direction, coupled spectral representation in the poloidal coordinate and finite element in the radial coordinate. TORIC is parallelized, and for the simulations presented here has been run with 480 radial elements and up to 1024 poloidal components. In all cases examined here we use a magnetic geometry from EAST shot 048888 , with a magnetic field of approximately 2.2 T on axis, and a H/D ratio of 5% which should be favorable for minority heating.

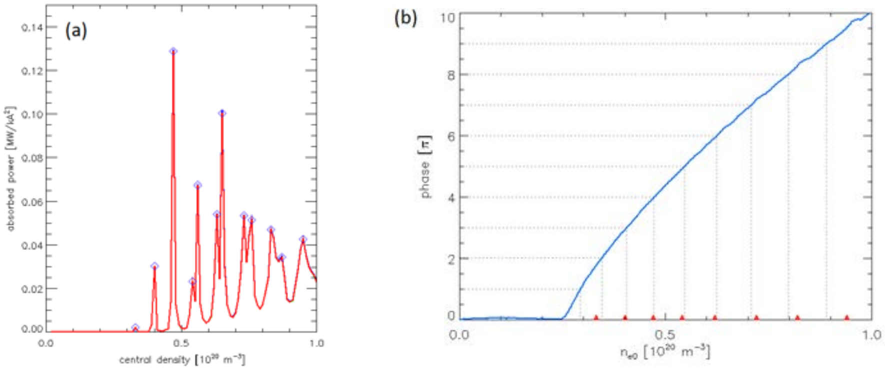

FIGURE 2. (a) TORIC calculations of the coupled power as a function of electron density for a toroidal mode number of 36. (b) Calculations of the perpendicular wave phase for this mode, integrated across the accessible plasma. The red triangles at the bottom indicate the densities corresponding to peaks in the TORIC calculations.

As a first case, we consider the effect of scaling of the density on a single toroidal mode number, presented in Fig. 2. A series of sharp peaks is observed as the density is scaled. TORIC calculations of the wave structure show that the perpendicular wavelength is comparable to the minor radius at low densities, indicating that cavity effects are important and strongly affect the wave structure. Similar effects were noted in an earlier numerical study [6], though the dependence on density was not examined in that work. As a means of insight into this problem, we calculated the perpendicular wave phase that results from integrating the fast-wave dispersion relation [7] across the accessible region of the plasma, as shown in panel (b) of Fig. 2. Here we note two important effects. First, the wave is entirely cutoff below densities of 0.25×10^{20} m^{-3}, and secondly, that the densities for which the wave phase is an integer multiple π very nearly coincide with the values of density for which the TORIC calculations exhibit spikes in the absorbed power. The range of central electron densities accessible to EAST experiments is in the range of 0.2×10^{20} m^{-3} to 0.4×10^{20} m^{-3}.

Each of the toroidal modes launched by the antennas will have slightly different propagation characteristics and the net effect will in part depend on the gap between the plasma and antenna, which for these studies we take to be 4.5 cm. While a single mode analysis may provide some insight into the general wave propagation characteristics, accurate calculations of the absorbed power and a fuller understanding of the physics requires that the full spectrum be considered. In the analysis of Fig. 3 we examine the response of the absorbed power for the four antenna phasings to variations in density and antenna frequency for a superposition of TORIC calculations spanning n_φ in the range of -50 to +50. These calculations indicate a trend of increasing absorbed power with density, and substantial increases in the absorbed power for the other phasings. The variation of antenna frequency is somewhat complicated in that this results in a variation of the minority resonance location and a change in the coupling of each mode through variation of $k_{||}$. The dominant effect is attributed to the variation of the resonance position since the variation in $k_{||}$ should amount to roughly a change of about 15%. This scan shows a very large increase in coupled power for high-field side absorption at a frequency of 39 MHz. Further analysis of the wave fields and the power deposition indicate strong mode conversion and damping on electrons and deuterium majority ions.

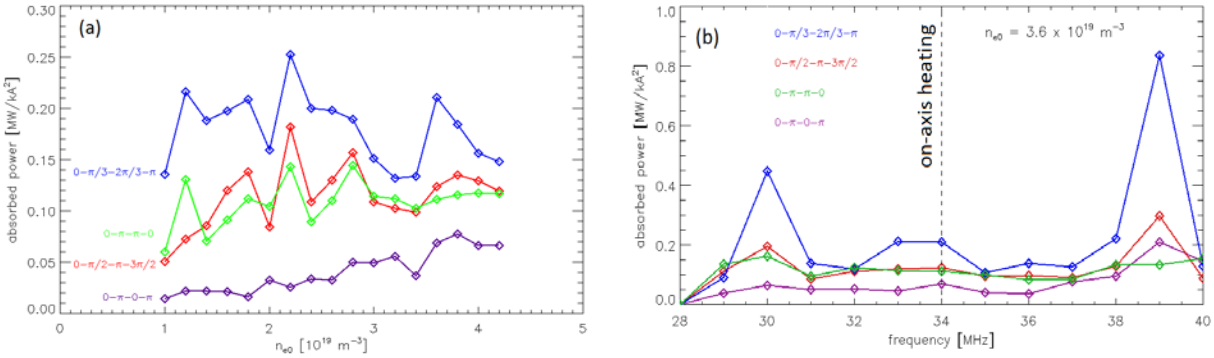

FIGURE 3. (a) Absorbed power calculations for the four antenna phasings using a superposition of n_φ over the range of -50 to +50. (b) Absorbed power as a function of antenna frequency, for a central density of 0.36×10^{20} m^{-3}.

SUMMARY

Theoretical analysis of the ICRF wave propagation under EAST conditions shows that the depolarization term [8] can be significant at temperatures of approximately 1-3 keV, but good polarization begins to be restored by raising the ion temperature to about 10 keV. This suggests that the initial heating of EAST plasmas may be especially difficult, but once the ion temperature is increased a substantial improvement in the coupling may be observed. The main findings of this work are that a single-mode analysis is an inadequate representation of the ICRH wave physics for EAST plasmas, primarily on account of the relatively low-density which results in cavity effects. Instead, a superposition of the full-spectrum of modes must be considered. When this is done, the TORIC calculations show substantial enhancements of the absorbed power for the alternate antenna phasings, compared to the standard 0-π-0-π heating phasing. Best performance is predicted for π/3 phasing, which we attribute mainly to much improved coupling of the launched spectrum that peaks at an n_φ of 11 (compared to 34 for heating phasing). The additional benefit of reduced impurity flux that is expected from this phasing should also have positive impacts on overall performance. Variation of the antenna frequency from 34 MHz, which places the H minority resonance on axis at 2.2 T, to 39 MHz, which places this resonance halfway to the high-field side, seems to offer large increases in the coupled power. Whether this scenario will in fact be useful is not yet clear, as the high-field side absorption occurs through mode-conversion and damping on electrons and the D majority. The deposition of a substantial fraction of the launched power at large minor radius may lead to poor ion confinement and large losses of power. A series of experiments have been proposed for the next EAST campaign in which we plan to explore these parameters to search for an optimal heating scenario.

ACKNOWLEDGMENTS

This work is funded by the US Department of Energy under contract DE-FC02-01ER54648.

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