CONF-9704102--4

Radio Frequency Current Drive for Small Aspect Ratio Tori

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Abstract. Non-inductive current drive (CD) is required during plasma initiation and for current sustainment in NSTX[1]. The physics of high harmonic fast waves (HHFW) and the design of an antenna system for NSTX are studied. It is found that the theoretical current drive efficiency for HHFW can be high, and a general survey of parameters gives a good target for the antenna design. The primary issue for HHFW during plasma initiation is loading since the CD efficiency is very high for low density plasmas. For high beta operation at full current, launching in the usual manner from the equatorial plane may lead to marginal CD performance. However, advanced antenna designs exploiting the theoretical results show some promise for high beta operation. Two methods to optimize the CD efficiency have been explored. The first, non-zero poloidal mode excitation, provides enhanced efficiency because of improved penetration and a reduction of detrimental trapped particle effects. A second, placement of the antenna away from the equatorial plane, can also be used to reduce trapped particle effects. These methods can be used separately or together, yielding potential improvements of more than a factor of 2 in CD efficiency for NSTX.

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INTRODUCTION

Radio frequency (RF) power in the ion cyclotron range of frequencies is a useful tool for plasma heating and current drive that has not yet been extensively tested in a small aspect ratio torus (ST). Non-inductive current drive (CD) is required during plasma initiation and for current sustainment in NSTX[1]. In this paper, we use the RANT3D[2], GLOSI[3] and PICES[4] computer models to suggest two methods for optimizing current drive efficiency in a ST using RF power in the high harmonic fast wave (HHFW) regime. One method uses poloidal antenna phasing with launch from the equatorial plane, while the other launches waves from a location significantly above or below the equatorial plane. These methods enhance the current drive efficiency for scenarios with strong damping by enhancing wave penetration and reducing the power absorbed by trapped electrons.

The PICES and GLOSI plasma models both rely upon a warm plasma approximation where $k_\perp\rho$ is assumed to be small, and only second order terms are retained. This assumption becomes suspect for the proposed initial NSTX parameter regime because $k_\perp\rho \approx (\omega v_{ti})/(\Omega_i v_A) \propto \omega(n_iT_i)^{1/2}/B^2 \sim \omega\beta_i^{1/2}/B$ can be large. Thus, we have checked the validity of the warm ion approximation for "NSTX-like" parameters by comparing the dispersion relation obtained from a full hot plasma dielectric, retaining 40 Bessel functions, with that obtained from the warm ion approximation. The results of this study for various β_i conditions at 41 MHz with "NSTX-l

ike"parameters show that the PICES and GLOSI models give errors of less than 10% for NSTX cases with frequencies below 41 MHz and $n_i T_i < 6\times10^{19}$ KeVm^{-3}.

CURRENT DRIVE EFFICIENCY AND ACCESSIBILITY

The theoretical limit for CD efficiency is obtained by exciting one toroidal and poloidal mode at a time on the plasma surface in PICES. The efficiency for 30 MHz with peak plasma parameters of $n_0=3\times10^{19}\mathrm{m}^{-3}$, T_{i0}=1KeV, and T_{e0}=2KeV is shown in Fig. 1. A Solov'ev equilibrium was used with the current drive efficiency determined by the Ehst, Karney empirical fit. The maximum possible CD efficiency for these parameters is 0.05 A/W/m^2 for HHFWs, corresponding to roughly 1.0 MA for 6 MW of delivered power for these parameters. The CD efficiency for more accurate EQDSK equilibria can be somewhat higher.

One reason for the improved current drive efficiency with non-zero poloidal mode numbers is because of the combination of very strong absorption and the large angle of the static magnetic field at the antenna. Modes with long wavelengths parallel to the magnetic field are not as strongly absorbed as those with shorter parallel wavelengths. Thus, power absorption in the edge can be reduced by launching in a direction that is somewhat perpendicular to ***B*** near the antenna as shown in Fig. 1. As the power penetrates through the edge region, the magnetic geometry changes to shorten the parallel wavelength and strongly damp the power.

Unfortunately, accessibility to these high efficiencies is restricted by the antenna coupling. Results from both the PICES and RANT3D/GLOSI codes show that power coupling is dramatically reduced when the launch angle exceeds roughly 20° relative to the toroidal direction for "co" CD phasing. This study suggests that

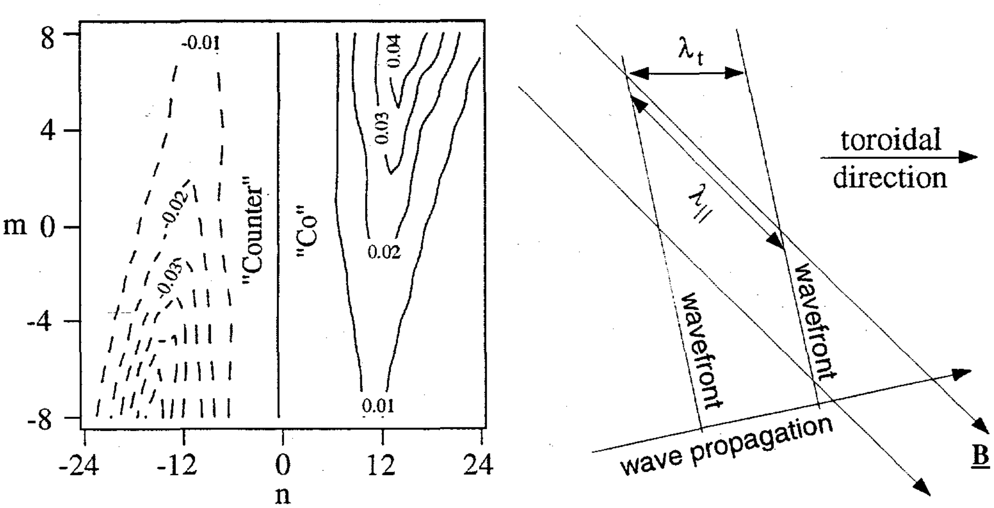


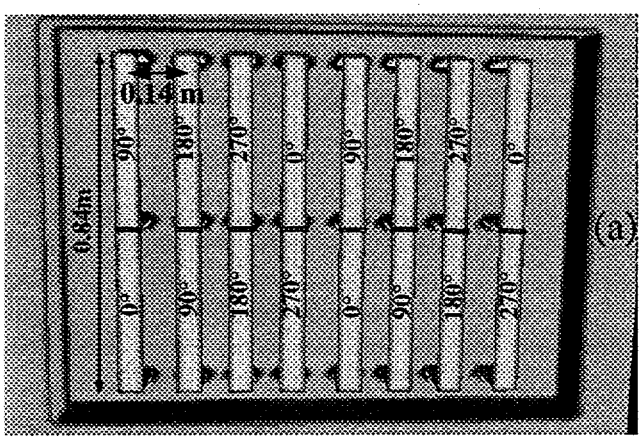
Figure 1. *The maximum current drive efficiency occurs for non-zero poloidal mode numbers because the waves have a relatively long wavelength near the antenna, and are not strongly damped until they penetrate through the edge.*

launching at a fixed angle may be preferable to launching with a fixed poloidal mode number, and that poloidal mode numbers (m), greater that ~4 or 5 will not couple for the appropriate range of toroidal mode numbers (n).

ANTENNA PERFORMANCE FOR NSTX

Initial RF operation in NSTX will likely require launch from the equatorial plane because of the placement of large conducting plates for MHD stabilization. Therefore, we concentrate on the effects of poloidal phasing and geometry for CD optimization in NSTX. The models for the antennas considered are shown in Fig. 2. They were constructed by using the RANT3D and GLOSI codes to calculate the antenna fields at the opening of the antenna. The resulting electric fields parallel and perpendicular to the magnetic field are then mapped onto the first wall location in the PICES code and Fourier analyzed in flux coordinates. Specific results for 6 MW operation for the type "a" and type "b" designs are given in Table I.

In general, the results can be summarized as follows: 1) The theoretical current drive efficiency for HHFW can be very high, and Fig. 1 provides a good target for the actual antenna design. Non-zero poloidal mode excitation provides the best efficiency because of improved penetration to regions where trapped particle effects are reduced. However, practical limitations on antenna



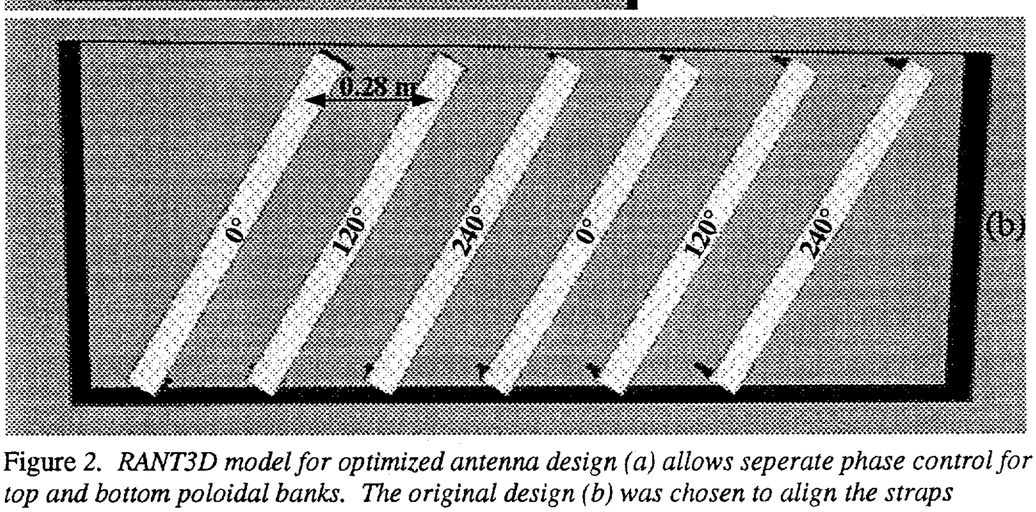


Figure 2. *RANT3D model for optimized antenna design (a) allows seperate phase control for top and bottom poloidal banks. The original design (b) was chosen to align the straps perpendicular to the magnetic field in an average sense over the course of a shot. The numbers on the strap segments indicate the relative phase for maximum poloidal directivity.*

placement and phase control can substantially reduce the efficiency. 2) During plasma initiation, the primary issue for HHFW is loading since the CD capability is good. 3) Standard launch from the equatorial plane with the type "b" design leads to poor CD performance at moderate density and full current for both the Solov'ev and EQDSK equilibria in these models. The problem is that the desired "co" CD wave is too fast for type "b" even with 120° toroidal phasing, and an undesirable "counter" CD wave is launched with good CD efficiency that partially cancels the total "co" driven current. The type "a" designs exploit the theoretical results, and show significantly enhanced CD efficiency. Poloidal phasing can add roughly 30% to the CD efficiency for the type "a" design for the Solov'ev equlibrium. The type "a" design may also be able to self-consistently achieve 1 MA of driven current with 6 MW of delivered power using the 5.7% β equilibrium from EQDSK. 4) Placement of the antenna away from the equatorial plane near the top or bottom of the tokamak (studied but not shown) can also improve efficiency by about 100% provided that access through the stabilizing shell is possible.

Ant.	freq.	Δt	Δp	Equilibrium	KA	Ω/m
(b)	30 MHz	120°	NA	Solov'ev	50	12.
(b)	30 MHz	120°	NA	EQDSK(5.7%β)	70	18.
(a)	30 MHz	90°	0°	Solov'ev	190	17.
(a)	30 MHz	90°	90°	Solov'ev	310	10.
(a)	41 MHz	90°	0°	Solov'ev	280	19.
(a)	41 MHz	90°	90°	Solov'ev	360	11.
(a)	41 MHz	90°	90°	EQDSK(5.7%β)	1000	10.

Table I. *Driven current in KA for 6 MW of delivered HHFW power shows substantial advantages for the type (a) design. The type (a) design can also be modified to have a strap-to-strap separation of 0.2 m and remain optimal by changing the toroidal phasing (Δt) to 135°. Poloidal phasing (Δp) can add 30% to the efficiency.*

The most important issues yet to be studied are edge phenomena that may limit the power handling capability of the antenna. HHFW produces, and in fact requires substantial electric field components parallel to $\boldsymbol{B}$. These parallel fields may cause heating of the lateral protection for the antenna through edge Landau damping, sheath rectification and nonlinear heating. Large parallel fields may also lead to substantial ponderomotive effects because of the relatively low B.

ACKNOWLEDGMENTS

This work is sponsored by Oak Ridge National Laboratory, managed by Lockheed Martin Energy Research Corp. for the U.S. Department of Energy under contract number DE-AC05-96OR22464.

REFERENCES

1. Ono, M., Phys. Plasmas **2** (1995) 4075
2. E.F. Jaeger, D.B. Batchelor, D.C. Stallings, Nuclear Fusion **33** (1993) 179.
3. M.D. Carter et.al., Nucl. Fusion **36** (1996) 209.
4. D.A. Ehst and C.F.F. Karney, Nucl. Fusion **31** (1991) 1933.