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EXPECTATIONS FOR THE NATIONAL SPHERICAL TORUS EXPERIMENT'S HIGH HARMONIC FAST WAVE SYSTEM

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ABSTRACT

High harmonic fast waves (HHFW) have been chosen as the primary method to drive steady state currents in the National Spherical Torus Experiment (NSTX). The somewhat limited experience with this frequency range in conventional tokamak plasma indicates that the coupling to electrons should be successful; however, there is no experimental data base for HHFWs in the unique and rapidly varying plasma regimes expected for NSTX. In this paper, we describe how the HHFW antenna was designed for NSTX using the computer codes to help make decisions that might affect the system's performance and operation. The antenna geometry has been optimized to maintain the power handling and phase control requirements within engineering constraints. The physics issues that lead to the choice of poloidal current strap orientation are discussed. Expectations for current profile control using the antenna's phase control system are also discussed.

I. INTRODUCTION

Non-inductive current drive is required during plasma initiation and for current sustainment in the National Spherical Torus Experiment (NSTX)[1]. Radio frequency (RF) waves launched from a phased antenna array have been chosen as the primary external method for driving these currents in the initial phases of operation. Waves in the high harmonic fast wave (HHFW) frequency range [2] are expected to allow the current carrying electrons to absorb most of the RF power, greatly reducing the power delivered to the ions. A specific frequency of 30 MHz has been chosen for NSTX because of practical considerations pertaining to the size of the device as well as the cost and availability of the 6 MW of RF power that will eventually be required. Early operation will not provide the full power at a single frequency, but may permit some mixed operation at 30 and ~41 MHz.

High values of β are expected in NSTX by driving a large toroidal current (1 MA) in a device with a relatively

low toroidal magnetic field (0.3 T). The full RF power is needed to both heat the plasma and efficiently drive current early in the discharge while the poloidal component of the magnetic field is negligible and β is low. The RF power and efficient current drive must also be maintained throughout the shot as the plasma β and current rise to their full values, at which time the toroidal and poloidal components of the magnetic field at the antenna location become comparable. Thus, the HHFW antenna system is required to deliver high power levels over a wide range of plasma geometries and parameters.

The somewhat limited experience with HHFWs in traditional tokamak experiments has shown that HHFWs can be used successfully. However, RF experience in the unique and rapidly varying plasma regimes expected for the NSTX is almost non-existent. Therefore, the physics of HHFWs and the design of the antenna system for NSTX have relied heavily on numerical models. Complete experimental testing is needed to verify the assumptions made in these models, to guide physics improvements for the codes, to give confidence to data analysis that will unravel RF physics from other effects, and to develop the knowledge base needed to effectively control parameters in NSTX.

From the RF physics perspective, the combination of low magnetic field and high electron density provides a medium with a very high dielectric constant. These parameters generally lead to good coupling between the antenna and the plasma. However, the strong coupling is partially mitigated by the large gap between antenna and separatrix (~0.05 m) as well as steep gradients at the separatrix. The density gradients and poloidal magnetic fields also give rise to substantial poloidal and toroidal asymmetries in the launched power. These coupling effects have been accounted for in the RF system design by assuming plasma parameters in the edge region. Although reasonable assumptions can be made, there is no good body of experimental data to verify these assumptions in the edge of a device like NSTX.

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Another implication of the high dielectric medium is a large perpendicular propagation number, $k_{\perp}$. The resulting short wavelength in conjunction with the low magnetic field tends to produce large values for $k_{\perp}\rho_i$ for ion temperatures above roughly 2 keV [3] where ρ_i is the ion gyroradius. The interaction of the waves with ions can become significant even at high ion harmonics as $k_{\perp}\rho_i$ becomes large. Thus, there is some concern over the partitioning of the HHFW power between electrons and ions as the ion temperature increases, or as a hot ion tail is introduced by neutral beams or RF heating. The confinement of hot ion tails is also not well understood for high β operation in a spherical torus. Hot ion orbits are expected to improve as high β closes |B| contours inside the device, but fluctuations, instabilities, and RF interactions may further alter these orbits. Continued modeling and experimental observations are required to fully grasp the salient physics of these processes.

Other RF effects that are more difficult to model include nonlinear RF/edge interactions. The antenna design employs boron nitride armor to help with operations in the NSTX environment; however, this solution may not be relevant for larger spherical tori. Large rectified voltages have been found using the RANT code [4]. However, a better understanding of the RF/edge interaction is needed for technology improvements, and the NSTX represents a useful place to do these edge experiments.

II. DESCRIPTION OF MODELS

The computer modeling in support of the NSTX antenna design was performed using the RANT [5], GLOSI [6], and PICES [7] codes. These tools were used to generate three-dimensional models for many alternative antenna geometries using several fixed plasma scenarios. Results from these models have directly influenced the final antenna design, and the planned modes for operation.

All of these codes solve Maxwell's equations with various approximations concerning the geometry and physics of the plasma response

$$-\nabla \times \nabla \times \mathbf{E} + \frac{\omega^2}{c^2} \left(\mathbf{E} + \frac{i}{\omega \epsilon_0} \mathbf{J}_p \right) = -i\omega \mu_0 \mathbf{J}_{ext}. \quad (1)$$

Periodic poloidal and toroidal mode expansions for the RF electric fields, $\mathbf{E}$, and currents, $\mathbf{J}$, are used in the plasma region when solving Eq. 1 as given by

$$\mathbf{E}(\rho, \vartheta, \zeta) = \sum_{n,m} \mathbf{E}_{m,n}(\rho) e^{i(m\vartheta + n\zeta)} \quad (2)$$

where m and n are the poloidal and toroidal mode numbers respectively, and ρ, ϑ, ζ , are the radial, poloidal and toroi-

dal coordinates. The plasma current $\mathbf{J}_p$ is related to the electric field through a plasma conductivity, $\underline{\sigma}$, tensor as

$$\mathbf{J}_p(\rho, \vartheta, \zeta) = \sum_{n,m} \underline{\sigma}(\rho, \vartheta, k_{\parallel}^{n,m}) \cdot \mathbf{E}_{n,m}(\rho) e^{i(m\vartheta + n\zeta)}. \quad (3)$$

The RANT code solves Eq. 1 in vacuum using Eq. 2 at the plasma boundary where continuity of the fields is enforced using a generalized impedance matrix for the plasma in Fourier space. A three-dimensional model of the antenna in vacuum is constructed in Cartesian coordinates, and perfectly conducting boundaries are imposed using waveguide basis functions in an arbitrary number of vacuum recesses in the conductor. The external antenna currents, $\mathbf{J}_{ext}$, are imposed within these recesses to provide the source term for the problem. The RANT model used for the final design review is shown in Fig. 1. For NSTX-like parameters, the impedance matrix for the plasma boundary in RANT is generated by the GLOSI code. GLOSI computes the impedance relationship for each toroidal and poloidal mode represented in Eqs. 1 and 2 for a sheared, plasma slab geometry using second order corrections in $k_{\perp}\rho_i$ for the conductivity tensor in Eq. 3, where the ϑ dependence of $\underline{\sigma}$ is ignored. The RANT and GLOSI codes are self-consistent and appropriate for power coupling and RF field calculation in the antenna region, the plasma edge and the outer-plasma core. The RANT code has been successfully benchmarked against data taken from RF experiments in TFTR [5].

The PICES code solves Eqs. 1-3 using a finite difference method in ρ that considers a general tokamak equilibrium. This description retains the coupling between m and n modes caused by the toroidal geometry, and is appropriate in the plasma core where magnetic flux surfaces are closed. Bernstein modes are eliminated in PICES using a reduced order method [8], however high harmonic cor-

Figure 1. The RANT model used for the final antenna design. The shape of the antenna and vacuum vessel cause a smaller spacing between the strap and backwall near the midplane of NSTX. The model includes this effect by placing extra metal behind the strap near midplane.

rections (40 Bessel functions for these studies) to the ion absorption terms are retained to provide a reasonable estimate for the RF power absorption by hot ion tails. The code has been used extensively to analyze RF interactions with hot ions in TFTR [9]. The equilibria considered so far for the PICES modeling of NSTX have been generated using prescribed pressure and current profiles. The HHFW current drive profiles are estimated by integrating the absorbed power weighted by the efficiency fits of Ehst and Karney [10] and retaining trapped electron effects. Rather than specifying J_{ext} in these studies, the antenna was modeled in PICES using the fields generated by the RANT code as a boundary condition.

III. RESULTS OF DESIGN STUDIES

The goal for the design was to maintain 6 MW of delivered RF power below the voltage limit of the RF system for strap-to-strap phasings ranging from 30° to 90° and plasma conditions ranging from start-up to 40%β with up to 1 MA of steady state current. The design was intended to minimize cost and complexity, and no modification of the existing vacuum chamber or stabilizing plate positions were allowed. A compromised configuration was chosen using 6 RF transmitters to drive 2 sets of 6 straps as shown in Fig. 1. This configuration provides ideal control of the spectrum for 30° and 90° phasings. The case of 60° phasing is not optimal, but it is still highly directional.

Launching HHFWs in NSTX suggests the use of compressional RF magnetic fields similar to conventional fast wave launchers. However, the large change in the magnetic field angle near the antenna during a shot complicates the choice for the antenna geometry. For high current, high β operation, the poloidal component of the static magnetic field may even exceed the toroidal component near the antenna. Traditional fast wave antennas have been oriented so that the RF current is carried in the poloidal direction, which is nearly perpendicular to the static magnetic field throughout the discharge. The angle of the current straps cannot be changed during a shot, so a single fixed position must be chosen for NSTX. Alternatives to provide reasonable performance over a broad range of plasma conditions in NSTX include active poloidal phase control and/or choosing an optimal angle for the current strap tilt; however, cost constraints do not initially allow for active poloidal phase control in NSTX. The maximum fixed tilt that a port will allow is 24° away from the poloidal direction.

The most obvious method to maintain the correct RF polarization in NSTX is to tilt the current straps at an in-

termediate angle that maintains reasonable polarization throughout the discharge. However, tilting the current straps of a phased array antenna has the added complication of modifying the Fourier spectrum in the poloidal direction. The peak in the poloidal spectrum for an infinite array of tilted current straps can be roughly estimated as

$$\frac{m}{n} \approx -\frac{a}{R} \cot(\theta) \quad (4)$$

where m and n are the poloidal and toroidal modes respectively, a is the average minor radius (the poloidal plasma circumference divided by 2π), R is the major radius at the antenna, and θ is the angle of the current straps relative to the toroidal direction. For conventional antennas, $\theta=90^\circ$ so that the Fourier spectrum of the antenna current is centered at $m=0$. Using NSTX-like parameters of $R=1.58\text{m}$, and $a=0.88\text{m}$, the Fourier spectrum for the RF current is centered near $m=n/4$ for $\theta=66^\circ$. The width of the excited spectrum, Δm , in poloidal Fourier space is estimated by considering that a half-wavelength in the poloidal direction is roughly the poloidal extent of the current straps. This dimension is constrained in the NSTX design to be ~1 meter, giving $\Delta m \approx 3$ for NSTX. Thus, several poloidal mode numbers must be considered to understand the effect of tilting on the plasma loading.

The global plasma response to the different polarization caused by tilting the current straps was investigated by exciting a very small current with a prescribed polarization in the RANT code. This small current generates a very broad source in Fourier space, and thus shows the modes preferred by the plasma. The results for the loading of the modes for various values of β are shown in Figure 2. These results indicate that a poloidal shift in the spectrum is not desirable for co-current drive operation at 5% β where operation at large $n \sim 12$ is desired, and the loading is low enough to approach the voltage limit on the antenna if the straps are tilted. The improvement in polarization does help the loading for the 40% β case for low n numbers, but the loading is sufficient to avoid voltage limits without tilting the straps for the 25% β and 40% β cases.

A reduction in loading caused by tilting the antenna at low β can be partly explained based on the illustration in Figure 3. The ability of the plasma to short out parallel electric fields allows waves with long parallel wavelength to penetrate further than waves with shorter parallel wavelength. As shown in Figure 3, tilting the current straps in order to improve the polarization of the fast wave can reduce the parallel wavelength of the wave in the plasma edge region. At high β and density, more plasma is moved toward the antenna because of the Shafranov shift, reducing the evanescent layer so that the improved polar-

ization eventually improves the loading.

The effect of the tilt was also studied for complete models of the antenna, and no benefits for plasma loading or current drive could be found except in the case of loading at $40\%\beta$. Thus, considering the added complexity of construction and the lack of benefits for low β operation, the current straps were chosen to have the usual poloidal orientation. However, added ports are engineered into the design so that new straps can be fabricated and tilted in the future if an unforeseen need to tilt the straps arises.

The results shown in Fig. 2 indicate that the only effective way to maintain an optimal match with the plasma would be to provide active control of the poloidal phase. However, such a system was rejected as too complex, costly, and unproven.

One of the most interesting findings from the preliminary models is that active current profile control may be possible for some scenarios with the final antenna design. This control could be a useful means for studying enhanced reversed shear operation and other physics in NSTX. These scenario studies are not yet complete, but the most promising regime for this type of operation appears to be in the range of $10\%-15\%\beta$ with roughly 0.5 MA of steady state current driven by the expected final antenna configuration (12 straps at 30 MHz). The ability to control the driven current profile for "standard" equilibria at 5% and $25\%\beta$ in 1 MA discharges is illustrated in Figure 4. The $25\%\beta$ scenario shows that the RF absorption to be too strong to achieve good control; however, the calculation at $5\%\beta$ indicates good penetration to the plasma center for all antenna phasings. Thus, we propose to computationally and experimentally explore scenarios with good prospects for control in the $10\%-15\%\beta$ range at ~ 0.5 MA of plasma current.

IV. CONCLUSIONS AND FUTURE DIRECTIONS

The computer models used to assist the NSTX antenna design indicate that reasonable performance can be obtained within the engineering constraints for the system. The models show that both the poloidal and toroidal mode structure of the launched power spectrum must be considered to optimize the design as shown in Figures 2 and 3. The models also indicate that tilting the current straps in the design might be detrimental to low β operation in addition to complicating the initial construction; therefore a poloidal orientation for the straps was chosen. Current profile control should be possible using phase control for

Figure 2. Evenly spaced contours of launched power (Poynting flux per mode) for uniform excitation in Fourier space using different strap tilt angles show the trade-off for loading between polarization and the launched m and n spectrum. Tilting the straps introduces a shift to $m \approx 3$ for the $n \approx 12$ spectrum desired for low β and startup operation. Maximum power is indicated in lower right corners.

Figure 3. Part of the variation in power launch with different strap angles can be attributed to the shorter parallel wavelengths that occur if the straps are tilted to improve the fast wave polarization at the plasma edge.

the antenna in plasmas with moderate β and current.

To consistently close these RF models, a transport and current evolution model should use the RF power and current deposition profiles to generate consistent pressure and current profiles. These profiles would then be used in an equilibrium code that could then feed the consistent equilibrium information back into the RF codes. Simplifications at each stage of such a model are needed to make this a tractable solution for NSTX scenario development and data analysis. Appropriate simplifications to a more consistent global model are the focus of our present work, and will continue into the phase 1 operation of NSTX.

Figure 4. Results from the PICES code indicate that current profile control should be possible using the phase control system for the antenna. Values of 15% β and 500 kA of driven current show the most promise for good control since penetration to the core occurs at 5% β for all phasings while some control is still possible at 25% β where strong absorption prevents penetration to the core.

NOMENCLATURE

β	ratio of plasma kinetic energy to static magnetic field energy
$\mathbf{B}$	static magnetic field vector

$k_{\perp}$	perpendicular (radial) wave propagation number
ρ_i	ion gyroradius
$\mathbf{E}$	RF electric field vector
$\mathbf{J}_p$	RF plasma current vector
$\mathbf{J}_{ext}$	Externally applied RF current vector
$\underline{\sigma}$	RF plasma conductivity tensor
m, n	poloidal, toroidal mode numbers
ρ, ϑ, ζ	radial, poloidal, and toroidal coordinates
θ	angle of straps measured from toroidal direction

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