

# HIGH FREQUENCY FAST WAVE COUPLING AND HEATING STUDIES IN THE CDX-U SPHERICAL TORUS

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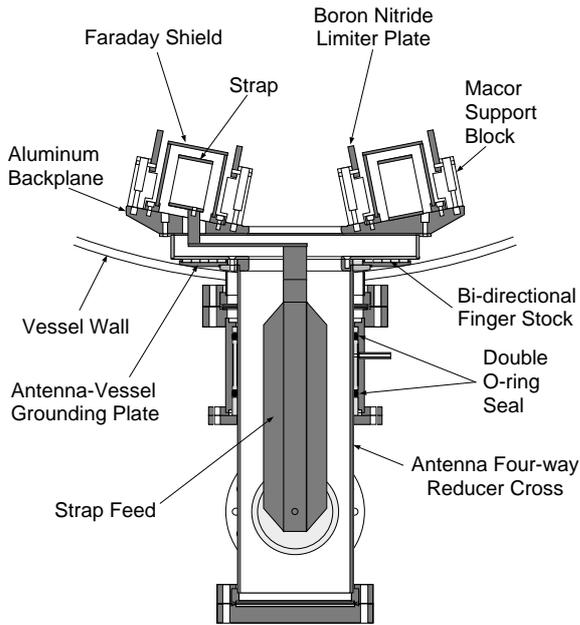
## 1. Introduction

High frequency fast waves appear promising [1] as a means of heating electrons and possibly driving off-axis current in upcoming low-aspect-ratio devices such as MAST [2] and NSTX [3]. However, the large and variable magnetic field-line pitch at the outboard mid-plane of such devices may make efficient coupling to the fast wave with poloidal loop antennas experimentally challenging. To address such coupling issues and attempt to observe electron heating using high frequency fast waves, a two strap antenna with arbitrary strap phasing was installed in the CDX-U spherical torus (ST). The novel feature of this antenna is that it is manually rotatable between plasma discharges. In this paper, we report on recent experimental and theoretical investigations of high frequency fast wave coupling and heating physics as a function of the angle between the antenna current straps and the edge magnetic field.

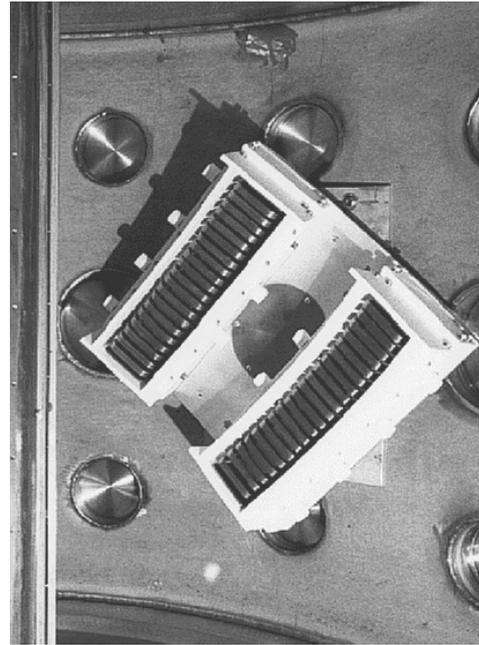
## 2. Experimental Apparatus

CDX-U is a low-aspect-ratio tokamak facility with  $R_0 \approx 35\text{cm}$ ,  $A \geq 1.5$ ,  $\kappa \approx 1.5$ ,  $B_{t0} \leq 1.2\text{kG}$ , and  $I_P = 50\text{-}80\text{kA}$ . The total discharge pulse-length is roughly 20 msec with a flat-top duration of approximately 5 msec. The peak central electron density is typically  $0.5\text{-}2 \times 10^{13} \text{ cm}^{-3}$ , the line-averaged density is  $2\text{-}4 \times 10^{12} \text{ cm}^{-3}$ , and  $T_e(0) \approx 100\text{eV}$ .

Top and front views of the CDX-U high ion-cyclotron-harmonic fast wave antenna are shown in Figure 1. The antenna is capable of coupling several hundred kilowatts to the plasma for typical loading values for pulse durations of  $\leq 10$  msec. The strap height, width, and center-to-center separation are approximately 27cm, 3.8cm, and 22cm, respectively. The strap separation was chosen to launch toroidal mode number  $n_\phi \approx 8$  with  $0\text{-}\pi$  phasing. Each strap is surrounded by four 0.635cm thick boron nitride insulating limiter plates to minimize radio-frequency sheath effects [4]. Taking advantage of the nearly spherical shape of the outboard plasma surface, the antenna backplane, straps, and limiter plates were shaped to keep the strap-



(a) Top view sectional drawing of antenna



(b) Photo of installed antenna

**Fig. 1:** The CDX-U rotatable high-harmonic fast wave antenna

plasma separation distance nearly independent of strap angle. With proper feed design, the total strap mutual inductance has been virtually eliminated by using the mutual inductance between the strap feeds to cancel the coupling between the current straps [4]. This allows arbitrary strap phasing with only minor changes in the external matching settings. For all data below, either hydrogen or deuterium plasmas were used and the antenna frequency was 12MHz corresponding to  $\omega/\Omega_H \approx 8$  and  $\omega/\Omega_D \approx 16$  at the antenna.

### 3. Plasma Loading

Early measurements of antenna loading resistance found that loading was largest at very low power levels and asymptotically approached a constant value above a few kW. Saturation in the loading resistance at sufficiently low power was also sometimes observed. Such behavior is consistent with an analytic model of sheath power dissipation in a plasma-filled parallel plate capacitor [5]. Ponderomotive effects should be negligible for these plasma and antenna parameters, so sheath-related power dissipation appears to be the most likely explanation of the power-dependent loading. Cold plasma slow waves are strongly evanescent for these plasma parameters and direct IBW excitation should be weak, so fast wave radiation should be the dominant source of loading if sheath dissipation is comparatively small at high power.

Figure 2 compares the measured plasma loading to that predicted by a cold-plasma coupling code written specifically for these spherical torus experiments. As seen in the figure, good agreement is obtained between experiment and theory so long as the tangential electromagnetic fields from the strap feeds are taken into account in the model and the straps are not too nearly

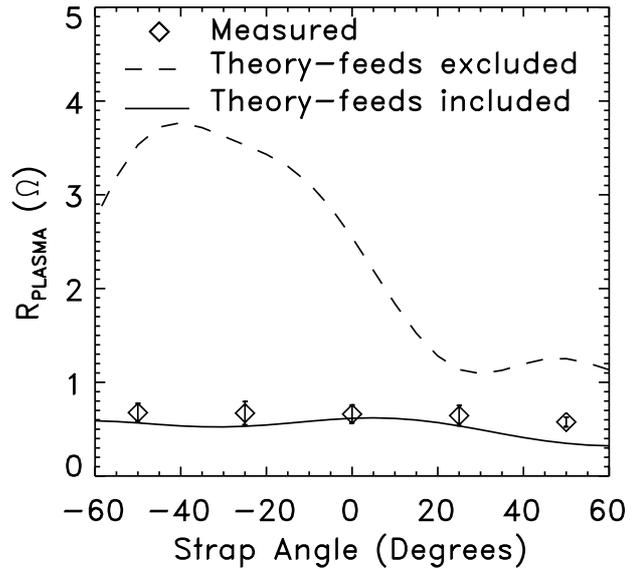
parallel to  $\vec{B}$ . Density and magnetic field profiles derived from equilibrium reconstructions were used in the coupling simulations, field-line pitch and shear effects were found to be important, and all relevant  $1/R$  effects are included in the equations for the fast wave fields in front of the antenna.

The antenna is modeled without a Faraday shield, as earlier coupling simulations with a shield included predicted unrealistically large loading values for strap angles other than orthogonal to  $\vec{B}$ .

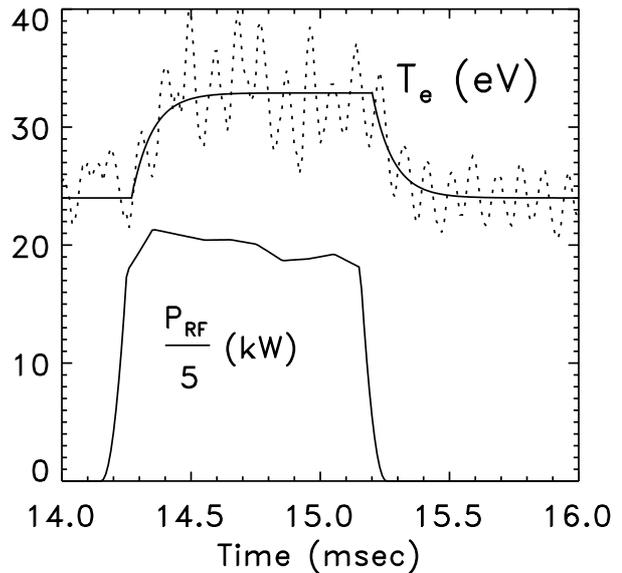
#### 4. Electron Heating

With antenna limiter bake-out and steady-state titanium sublimation gettering, increases in carbon and oxygen line radiation consume no more than 20% of the coupled RF input power ( $\leq 100\text{kW}$ ) even when the straps are parallel to the edge equilibrium  $\vec{B}$ . In such discharges, signs of ICRF electron heating have been observed in both hydrogen and deuterium plasmas using a triple Langmuir probe [6]. As seen in Figure 3, a relative electron temperature increase of 30-40% is measured using this probe which is located  $150^\circ$  away from the antenna toroidally at a normalized minor radius  $r/a \approx 0.7$  on the equatorial mid-plane.

The characteristic e-folding times of the rise and decay phases of the electron temperature increase during RF are consistent with the global energy confinement time ( $80\text{-}100\mu\text{sec}$ ) of these MHD-active plasmas [7]. Further, 50-80% of the coupled RF input power can be accounted for through increases in impurity line radiation and electron stored energy. However, the radial profile of electron heating observed during RF is significantly broader than the power deposition profile predicted by a fast wave ray tracing code (based on the hot-electron dispersion relation



**Fig. 2:** Plasma loading versus strap angle in hydrogen for  $0\text{-}\pi$  phasing and  $P_{\text{RF}}=50\text{-}70\text{kW}$ . Straps are orthogonal to  $\vec{B}$  at  $-30^\circ$ .



**Fig. 3:** Electron temperature increase in deuterium plasma during a  $100\text{kW}$  RF pulse. Strap phasing is  $0\text{-}\pi$ , strap angle is within  $10^\circ$  of being orthogonal to  $\vec{B}$ .

derived in [1]) written for these experiments. More systematic investigations of the electron heating efficiency as a function of strap angle, strap phasing, and plasma parameters will be performed in the upgraded CDX-U described below.

## 5. Conclusions

Detailed profile measurements and loading calculations indicate that most of the observed loading can be accounted for by fast wave excitation until the straps are within approximately  $30^\circ$  of being parallel to the edge magnetic field. Through the use of insulating antenna limiters and the recession of the Faraday shield sufficiently far behind these limiters, parasitic (power-dependent) loading and impurity generation are observed to be weak and nearly independent of strap angle and phasing. Lastly, signs of wave-induced electron heating have been observed at relative frequencies  $\omega/\Omega_D$  up to approximately 16. The NSTX ICRF system will use  $f=30\text{MHz}$  and have a similar wave to ion-cyclotron frequency ratio.

The CDX-U device is presently undergoing a significant upgrade in which the toroidal field and plasma current will be doubled and the flat-top duration increased by a factor of four. The RF system is also being improved to allow higher power fast wave heating studies along with the ability to pursue low frequency mode conversion and direct-launch ion-Bernstein wave heating scenarios. A multichannel Thomson scattering system currently being developed for CDX-U [8] should prove very useful in all of these studies.

## Acknowledgments

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