HIGH FREQUENCY FAST WAVE RESULTS FROM THE CDX-U SPHERICAL TORUS*

R. KAITA, R. MAJESKI, J. MENARD, T. MUNSAT, H. KUGEL,
P. EFTHIMION, M. ONO, D. JENS, B. JONES
Plasma Physics Laboratory and Department of Physics,
Princeton University, Princeton, New Jersey, USA
D. STUTMAN, M. FINKENTHAL
Johns Hopkins University, Baltimore, Maryland, USA
T. INTRATOR, R. FONCK
University of Wisconsin, Madison, Wisconsin, USA
W.-H. CHOE, Y.-S. HWANG
Korea Advanced Institute of Science and Technology, Taejon, Korea
V. GUSEV, Y. PETROV
Ioffe Institute, St. Petersburg, Russia
T. SEKI
National Institute for Fusion Science, Nagoya, Japan
Y. TAKASE
Tokyo University, Tokyo, Japan

Abstract

The Current Drive Experiment-Upgrade (CDX-U) is the first spherical torus (ST) to investigate radio frequency (RF) heating and current drive. To address the concern that large magnetic field line pitch at the outboard midplane of ST's could inhibit successful coupling to the high harmonic fast wave (HHFW), a rotatable, two strap antenna was installed on CDX-U. Parasitic loading and impurity generation were discovered to be weak and nearly independent of antenna phasing and angle over a wide range, and fast wave electron heating has been observed. Plasma densities up to about 10^{12} cm^{-3} were obtained with noninductive startup solely with HHFW. New ST diagnostics under development on CDX-U include a multilayer mirror (MLM) detector to measure ultrasoft X-rays, a twelve spatial point Thomson scattering (TS) system, and an Electron Bernstein Wave (EBW) system for both electron heating and electron temperature measurements. Preliminary experiments with a boron low velocity edge micropellet injector have also been performed, and further studies of its effectiveness for impurity control will be conducted with a variety of spectroscopic and imaging diagnostics on CDX-U.

I. INTRODUCTION

The efficacy of high harmonic fast wave (HHFW) electron heating and off-axis current drive, and the development of non-inductive startup schemes, are two critical issues for very low aspect ratio ST devices. The HHFW can be used for current drive from startup through the high performance phase, since high frequency fast waves are effectively absorbed in plasmas with β from 5% up to about 50%.[1] Noninductive startup is a necessity for an ST-based reactor, since the OH transformer in the center stack would have to be eliminated to take full advantage of the compact ST geometry.

As the first fusion facility to investigate RF heating and current drive in an ST, CDX-U is exploring the physics of fast wave coupling, heating, and startup. A possible issue with HHFW heating is the large magnetic field line pitch at the outboard midplane of ST's, which could lead to undesirable slow wave excitation. To address this concern, a rotatable, two strap antenna was installed on CDX-U. Like the NSTX design, the antenna has an insulating limiter to minimize any RF-induced modifications to the scrape off layer, and is operable at arbitrary phasing.

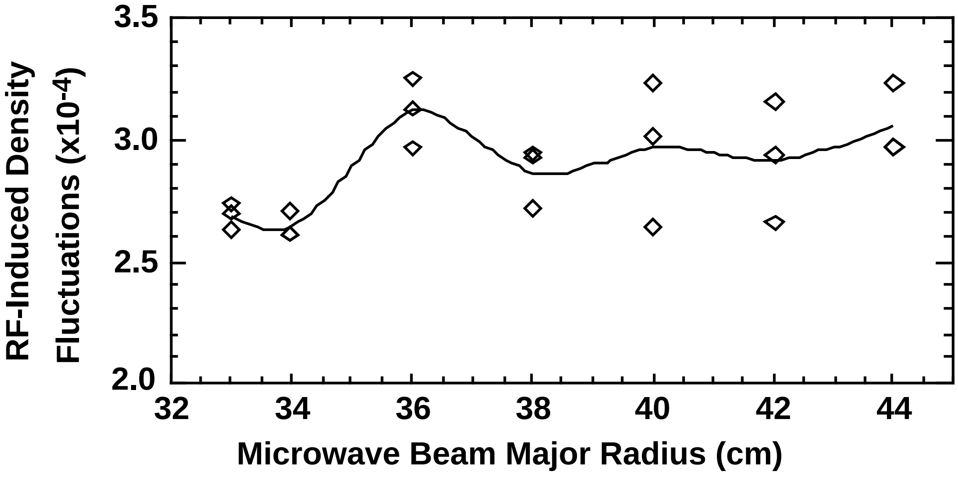

FIG. 1. Normalized RF-induced fluctuations in the line-integrated density.

II. RADIO FREQUENCY WAVE HEATING

One of the first detailed measurements of wave field profiles in a HHFW experiment was made with a vertical interferometer as the beam was scanned in major radius (Fig. 1). The RF-induced fluctuations in the line-integrated density were found to be proportional to the line-integrated background density. This implies that the line-averaged electric field amplitude profile is reasonably flat, and that wave fields are present in the plasma core. The observed loading can also be accounted for by fast wave excitation until the straps are within approximately 30° of being parallel to the edge magnetic field. Over the range of angles where the fast wave dominates, parasitic loading and impurity generation are weak and nearly independent of antenna phasing and angle. These results are encouraging for the application of the HHFW in future ST devices, since they relax the antenna requirements for optimized loading and coupling.

Fast wave electron heating has been observed in CDX-U with a Langmuir triple probe in both hydrogen and deuterium plasmas ($\omega/\Omega_H \approx 8$ and $\omega/\Omega_D \approx 16$, respectively). The temperature data shown in Fig. 2 are from a normalized minor radius of $r/a = 0.6$, or about two-thirds of the way out from the center of the plasma. An increase of up to about 50% in the local electron temperature is observed during RF heating, with 70% of the incident RF power coupled to the plasma based on the increase in stored energy and radiated power. The rate at which the electron temperature drops at the termination of the RF pulse is consistent with the estimated energy confinement time, and much slower than the characteristic decay time of the RF pulse. This indicates that the probe is responding to T_e rather than RF pickup.

Core electron heating with HHFW is also evident from the impurity radiation. The C V emission is very sensitive to changes in electron temperature relative to the O VI emission, and the intensity ratio of these lines peaks rapidly (within 0.5 ms) when RF power is applied. Using the MIST impurity transport code, we have demonstrated that the only self-consistent explanation for the observed time evolution of the C V and O VI lines is an RF-induced central electron temperature increase, which was as much as 50% (from 80 eV to 120 eV) in some cases. The line ratio technique was also validated on earlier, Ohmic discharges when the single-point Thomson scattering system was operable.

III. RADIO FREQUENCY PLASMA BREAKDOWN FOR STARTUP WITH HIGH HARMONIC FAST WAVES

Discharge initiation in CDX-U is usually effected with a separate RF system for electron cyclotron resonance heating (ECH). Recent experiments demonstrated plasma breakdown for noninductive startup solely with HHFW. The upper trace in Fig. 3 shows the time evolution of the plasma density, and the applied RF power is displayed below it.

Plasma densities up to ≈10^{12} cm^{-3} were obtained, although electron temperatures were only 5 - 10 eV. This is more than an order of magnitude higher density than the values obtained with ECH alone. These studies will be repeated in the future with additional RF sources operating near the ion cyclotron frequency. Numerical modeling of CDX-U performance indicates that noninductive startup of plasma currents up to 50 kA (q(a) ≈ 10) will be feasible in CDX-U using these systems for heating and current drive.

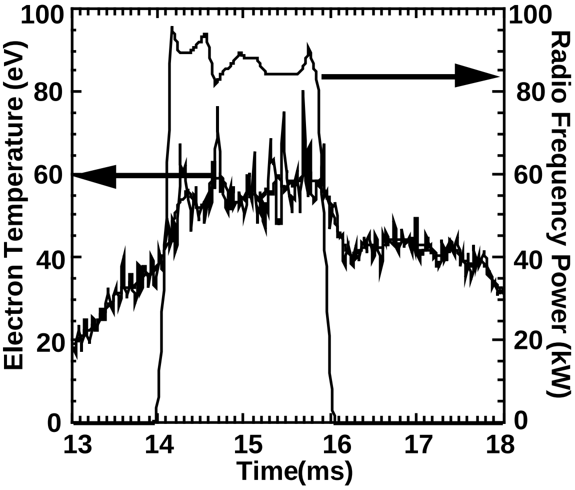

FIG. 2. Time evolution of electron temperature and RF power during HHFW heating.

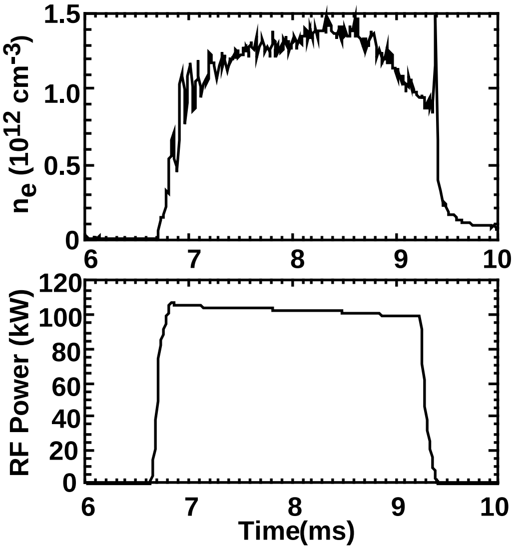

FIG. 3. Time evolution of electron density and RF power for plasma startup with HHFW alone.

IV. NEW TECHNIQUES FOR DIAGNOSTICS AND IMPURITY CONTROL

Sensitive imaging diagnostics are important for understanding plasma conditions during the relatively cool start-up phase of the discharge. Ultrasoft X-ray arrays[2] are planned for this purpose on the National Spherical Torus Experiment, a next-generation ST device at the Princeton Plasma Physics Laboratory. A prototype multilayer mirror (MLM) detector for this system was successfully tested on CDX-U,[3] using the C V emission at 40.5 Å. A scan of the mirror angle around the C V line showed a spectral resolution of 1.3 Å, and the time evolution of the signal matched the data from a photodiode detector with a 30-90 Å filter. Because the X-ray energies are determined from the angle of the Bragg scattering off the MLM, the detectors avoid a direct view of the discharge. This also makes them useful for edge fluctuation measurements, since unlike standard filtered photodiode detectors their signals are not dominated by the emission from the plasma core.

The low toroidal fields and high core plasma densities common to the ST preclude electron temperature measurements based on standard electron cyclotron emission techniques. Theory suggests, however, that the Electron Bernstein Wave (EBW) can propagate from the emission region to the plasma periphery, where it can be detected.[4] Studies of the EBW should then allow proof-of-principle tests of both electron heating and electron temperature measurements, and the latter diagnostic application would augment the twelve spatial point Thomson scattering (TS) system planned for CDX-U.[5]

The control of impurities is a critical issue for all magnetic confinement devices. For this purpose, titanium gettering has been used in CDX-U. In addition, preliminary experiments with a Boron Low Velocity Edge Micropellet Injector have been performed.[6] Further studies of its effectiveness will be conducted with diagnostics that include a filtered gated TV camera, bolometry, visible spectroscopy, and soft X-ray arrays.

V. SUMMARY AND FUTURE PLANS

The radio frequency heating and current drive experiments on CDX-U are the first of their kind in an ST. Results from the unique rotatable antenna on CDX-U demonstrated that with HHFW, parasitic loading and impurity generation were not significant, and little dependence on antenna phasing and angle was observed. There are also preliminary indications of fast wave electron heating. In noninductive startup studies, plasma densities that substantially exceeded the levels obtained with ECH were achieved with HHFW alone.

Several enhancements to the CDX-U facility are being made to improve plasma performance and permit more extensive RF experiments to be performed. With the modifications to the toroidal field supply, the field will increase to 2.3 kG, with a “flat-top” of 100 ms. The new power supplies for the vertical and shaping fields will allow a doubling of the Ohmic current, from 70 kA to 150 kA, with a discharge duration exceeding 25 ms. These changes will also greatly enhance the quality of the discharge “flat-top” for transport studies.

A new low frequency RF system is being added to CDX-U, to provide a total of 400 kW at 2 to 5 MHz for four antennas in a “rotating field” geometry. The primary heating technique will be mode conversion in a two ion species plasma, with the RF power being carried to the core of the discharge by a weakly damped, low frequency ($\Omega_{RF}/\Omega_i \approx 1$) fast magnetosonic wave. The efficient mode conversion at the ion-ion hybrid layer will generate a strongly damped electrostatic ion Bernstein wave, which deposits power near the mode conversion layer. This scenario will be used for electron heating and current drive near the plasma axis. Rotamak current drive will also be investigated.[7]

Among the diagnostics being developed on CDX-U is the MLM array for detecting ultrasoft X-rays. The successful test of an MLM detector on CDX-U makes the array a promising tool for edge fluctuation measurements for NSTX and other future ST devices. The ability of EBW to propagate from the emission region to the plasma periphery is being exploited for both electron heating and electron temperature measurements, and it complements the multipoint Thomson scattering (TS) system being installed on CDX-U. These diagnostics will also be used with boron micropellet injection for impurity control and transport studies.

ACKNOWLEDGMENTS

The authors wish to express their appreciation to P. Probert of the University of Wisconsin for his assistance with the EBW system and J. Taylor and the Princeton Plasma Physics Laboratory technical staff for their efforts on the CDX-U project.

REFERENCES

[1] ONO, M., Phys. Plasmas **2** (1995) 4075.
[2] STUTMAN, D., HWANG, Y. S., MENARD, J., CHOE, W., ONO, M. , FINKENTHAL, M., MAY, M. J., REGAN, S. P., SOUKHANOVSKII V., MOOS, H. W., Rev. Sci. Instrum. **68** (1997) 1055.
[3] STUTMAN, D., MENARD, J., HWANG, Y. S., CHOE, W., ONO, M. , FINKENTHAL, M., SOUKHANOVSKII V., MAY, M. J., REGAN, S. P., MOOS, H. W., Rev. Sci. Instrum. **68** (1997) 1059.
[4] HOSEA, J., ARUNASALAM, V., CANO, R., Phys. Rev. Lett. **39** (1977) 408.
[5] MUNSAT, T., LEBLANC, B., to be published in Rev. Sci. Instrum. (1999).
[6] KUGEL, H. W., GORMAN, J., KAITA, R., MUNSAT, T., to be published in Rev. Sci. Instrum. (1999).
[7] JONES, I. R., Proc. IAEA Technical Committee Meeting on Advances in Compact Torus Research, Sidney, Australia, 4-7 March 1985, IAEA-TECDOC-369 (1986) 117.

---

* This work supported by USDoE contract No. DE-AC02-76-CH0-3073.