Princeton Plasma Physics Laboratory

PPPL- 4928

PPPL- 4928

Physics Design of a 28 GHz Electron Heating System For The National Spherical Torus Experiment Upgrade

Gary Taylor, et. al.

JULY, 2013

PRINCETON PLASMA PHYSICS LABORATORY

Prepared for the U.S. Department of Energy under Contract DE-AC02-09CH11466.

Physics Design of a 28 GHz Electron Heating System for the National Spherical Torus Experiment Upgrade

G. Taylor[1], N. Bertelli[1], R.A. Ellis[1], S.P. Gerhardt[1], R.W. Harvey[2], J.C. Hosea[1], F. Poli[1], R. Raman[3], A.P. Smirnov[4]

[1]*Princeton Plasma Physics Laboratory, Princeton University, Princeton, New Jersey 08543, USA*
[2]*CompX, Del Mar, California 92014, USA*
[3]*University of Washington, Seattle, Washington 98195, USA*
[4]*M.V. Lomonosov Moscow State University, Moscow, Russia*

Abstract. A megawatt-level, 28 GHz electron heating system is being designed to support non-inductive (NI) plasma current (I_p) start-up and local heating and current drive (CD) in H-mode discharges in the National Spherical Torus Experiment Upgrade (NSTX-U). The development of fully NI I_p start-up and ramp-up is an important goal of the NSTX-U research program. 28 GHz electron cyclotron (EC) heating is predicted to rapidly increase the central electron temperature ($T_e(0)$) of low density NI plasmas generated by Coaxial Helicity Injection (CHI). The increased $T_e(0)$ will significantly reduce the I_p decay rate of CHI plasmas, allowing the coupling of fast wave heating and neutral beam injection. Also 28 GHz electron Bernstein wave (EBW) heating and CD can be used during the I_p flat top in NSTX-U discharges when the plasma is overdense. Ray tracing and Fokker-Planck numerical simulation codes have been used to model EC and EBW heating and CD in NSTX-U. This paper presents a pre-conceptual design for the 28 GHz heating system and some of the results from the numerical simulations.

INTRODUCTION

The Spherical Tokamak (ST) has a compact size and modular design making it an attractive candidate for a Fusion Nuclear Science Facility (FNSF) [1]. A ST-FNSF device is expected to operate without a central solenoid, making non-inductive (NI) plasma start-up and ramp-up a key element of ST research. The National Spherical Torus Experiment Upgrade (NSTX-U) [2] is a device that will have an axial toroidal field, $B_T(0)$, up to 1 T, a plasma current, I_p, up to 2 MA, and a pulse length of 5-8 s. One of the major goals of the NSTX-U research program, which is currently scheduled to start operation in late 2014 or early 2015, is fully NI I_p start-up, ramp-up and sustainment. NI plasma start-up will be accomplished through a combination of coaxial helicity injection (CHI) [3], outer poloidal field start-up [4] and plasma guns [5]. CHI start-up discharges have a low enough electron density (n_e) to allow electron cyclotron (EC) heating. 0.6 MW of 28 GHz EC heating is predicted to increase the central electron temperature ($T_e(0)$) of a CHI discharge from 10 eV to 400 eV in about 20 ms, and this increase in $T_e(0)$ will significantly reduce the plasma current decay rate of CHI plasmas [6], allowing the coupling of fast wave heating and neutral beam injection. A megawatt-level 28 GHz heating system is planned for installation on NSTX-U in 2016-17. In this paper a pre-conceptual design for the 28 GHz EC heating system for NSTX-U is presented and ray tracing results for EC heating of CHI start-up discharges with $B_T(0)$ = 0.5 and 1 T are discussed. Eventually the 28 GHz heating system will be upgraded to allow electron Bernstein wave (EBW) heating, first for EBW-only plasma start-up using a technique being developed on MAST [7] and then for heating and current drive (CD) during the plasma current flat top via O-mode to slow X-mode to EBW (O-X-B) double mode conversion [8-10]. Results from ray tracing and Fokker-Planck simulations for EBWCD are presented for a typical H-mode scenario planned for NSTX-U.

DESIGN OF THE NSTX-U 28 GHZ HEATING SYSTEM

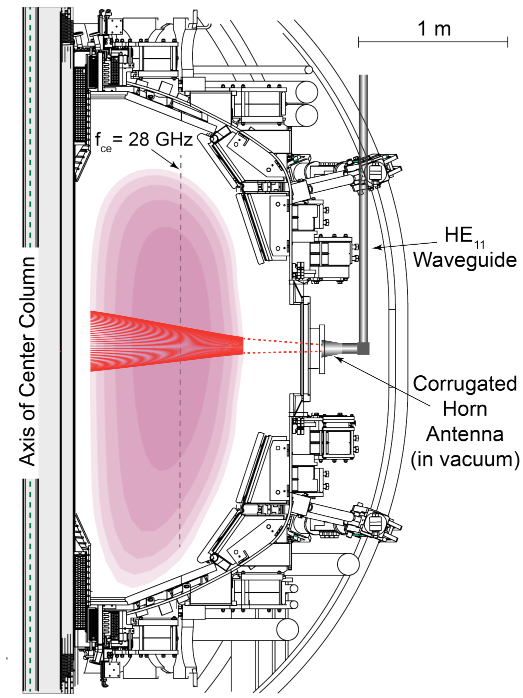

FIGURE 1. Cross section of the NSTX-U vacuum vessel showing the pre-conceptual layout of the 28 GHz waveguide and horn antenna. The axis of the NSTX-U center column is on the far left side of the figure. The plasma equilibrium shown in the vessel is for a $B_T(0)$ = 1 T CHI startup discharge used for ray tracing calculations. 100 rays calculated for 28 GHz EC heating are superimposed on the plasma equilibrium.

The long pulse, megawatt-level gyrotron design being considered for the NSTX-U 28 GHz electron heating system is being developed for EC heating on the GAMMA-10 tandem mirror [11]. The gyrotron uses a $TE_{8,3}$ cavity mode, will have an output power of at least 1 MW, and will be capable of pulse lengths of several seconds. The 28 GHz microwave power will be transmitted to NSTX-U via a low-loss, 50 mm diameter, corrugated $HE_{1,1}$ waveguide. Figure 1 shows a poloidal cross-section of the NSTX-U vacuum vessel and a $B_T(0)$ = 1 CHI plasma equilibrium 22 ms after plasma breakdown. For EC heating of CHI start-up discharges the low-loss waveguide will be connected to a corrugated horn antenna located in vacuum near the midplane of the vacuum vessel. The pulse duration used for heating the CHI start-up plasma will be typically ~ 50 ms. For EBW-only plasma start-up using the technique being developed on MAST [7], a grooved tile will be installed on the center column (shown on the far left side of Fig. 1). For O-X-B heating and CD experiments during the I_p flattop the gyrotron pulse length will be increased to several seconds, and a second megawatt-level gyrotron may be added. 28 GHz power will be launched either by a concave steerable mirror launcher or by a phased-array antenna [12].

MODELING RESULTS

28 GHz EC heating of a NSTX $B_T(0)$ = 0.5 T and NSTX-U $B_T(0)$ = 1 T CHI start-up discharges has been modeled with the GENRAY [13] ray tracing code, and 28 GHz EBW heating and CD in a NSTX-U $B_T(0)$ = 1 T H-mode plasmas has been modeled with GENRAY using the ADJ quasilinear package [14] and with the CQL3D Fokker-Planck code [15].

EC Heating Results for a CHI Start-Up Discharges

The T_e profile of a CHI discharge is extremely hollow (Fig. 2(a), dashed line) and the central electron density is only ~ 4 x 10^{18} m^{-3} (Fig. 2(a), solid line), low enough to allow EC heating near the plasma axis at both $B_T(0)$ = 0.5 T and 1.0 T. At $B_T(0)$ = 1.0 T the electron plasma frequency (f_{pe}) is well below the fundamental cyclotron resonance (f_{ce}) at a major radius, R = 0.9 m (Fig. 2(b)) where 28 GHz

O-mode power is absorbed. Although first pass damping for fundamental O-mode heating is expected to be weak in this case, wall reflections are expected to significantly enhance the fraction of power absorbed in the plasma. At $B_T(0)$ = 0.5 T first pass absorption is expected to be reasonably good for second harmonic X-mode heating, although the right hand cutoff (f_R) is only just below the $2f_{ce}$ resonance at a major radius, R = 0.9 m (Fig. 2(c)) where the 28 GHz X-mode power is absorbed.

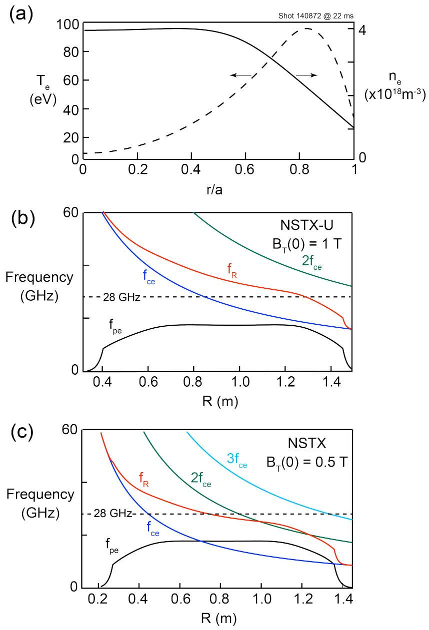

FIGURE 2. (a) Electron density (solid line) and temperature (dashed line) profiles used for GENRAY modeling of a CHI start-up discharge. Electron cyclotron resonances and cutoffs for (b) a NSTX-U $B_T(0)$ = 1 CHI start-up discharge and (c) an NSTX $B_T(0)$ = 0.5 CHI start-up discharge.

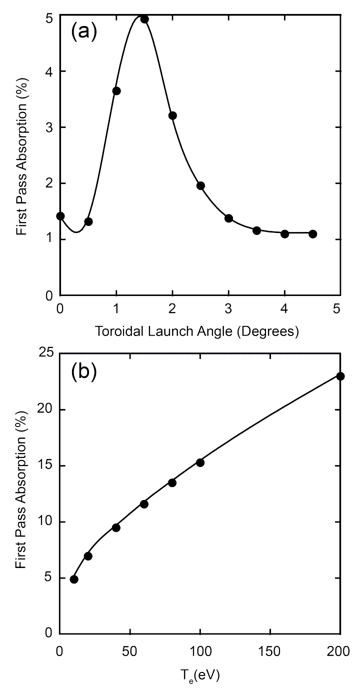

FIGURE 3. GENRAY results for the $B_T(0)$ = 1 CHI discharge. (a) First pass absorption fraction versus the toroidal angle between the antenna axis and the normal to the plasma surface when the antenna is pointing 1.5 degrees up from normal, and (b) the dependence of first pass absorption on T_e when the antenna is pointing 1.5 degrees toroidally and 1.5 degrees up poloidally.

The magnetic equilibrium and kinetic profiles used for simulating the NSTX-U $B_T(0)$ = 1 T case are shown in Fig. 1 and Fig. 2(a), respectively. 100 rays were used for the ray tracing simulations. The maximum first pass absorption of 5% was obtained with the antenna pointing 1.5 degrees up poloidally and 1.5 degrees toroidally from the normal to the plasma surface (Fig. 3(a)). TSC [16] simulations predict a temperature rise to ~ 100 eV in ~ 20 ms with 0.6 MW of EC heating power. GENRAY simulations predict a significant increase in first pass absorption, rising from 5% at $T_e(0)$ = 10 eV to 15% at $T_e(0)$ = 100eV (Fig. 3(b)). Earlier GENRAY simulations of EC heating of a $B_T(0)$ = 0.5 T NSTX CHI discharge predicted a first pass absorption of up to 25% at $T_e(0)$ = 10 eV and 65% at $T_e(0)$ = 100 eV [17].

EBW Heating and Current Drive Results for a NSTX-U H-Mode Discharge

GENRAY-ADJ and CQL3D simulations have been run for various H-mode scenarios being considered for NSTX-U [18]. Figure 4 summarizes EBWCD simulation results obtained for an I_p =1.1 MA, $B_T(0)$ = 1 T NSTX-U H-mode plasma. The density and temperature profiles used for this case are shown in Fig. 5(a) of [17]. The maximum O-X-B mode conversion efficiency was obtained at a parallel launch wavenumber, $n_{//}$ = ± 0.7. The EBW rays were launched at the last closed flux surface and the poloidal angle between the launcher axis and the midplane (θ) was scanned from θ = -30° and θ = 40° (see inset in Fig. 4). The maximum EBWCD efficiency was obtained between θ = 15 ° and 25° on either side of the midplane. For all the cases shown in Fig. 4 the EBW-driven current peaked near the axis (r/a ≤ 0.3) and there was good agreement between GENRAY-ADJ and CQL3D. By adjusting the toroidal magnetic field and/or frequency previous studies of EBWCD for NSTX [19, 20] have shown that EBW power can efficiently drive current out to r/a > 0.8.

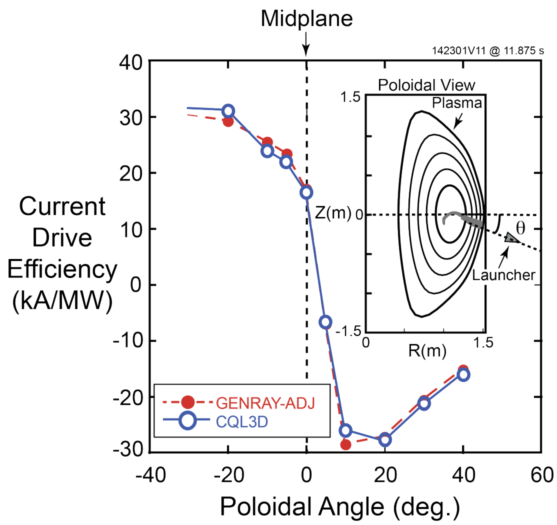

FIGURE 4. EBWCD efficiency versus the poloidal angle (θ) of the launcher location (launcher located at midplane corresponds to θ = 0) for an NSTX-U H-mode plasma. The launcher is oriented to launch $n_{//} = -0.7$ to provide efficient O-X-B coupling. Inset shows poloidal cross section with rays calculated by GENRAY when launcher is at θ = −20°.

Before implementing O-X-B heating experiments on NSTX-U, which will probably not occur until 2018 or later, the York Plasma Institute at the University of York in the United Kingdom has proposed a collaboration with NSTX-U that involves the installation of a Synthetic Aperture Microwave Imaging diagnostic (SAMI) [21] in 2014-15. Amongst other things, the SAMI diagnostic will measure the B-X-O mode conversion efficiency and determine where the conversion efficiency is a maximum, and also how stable the angular mode conversion window is with respect to fluctuations in the edge. These EBW mode conversion measurements, together with ray tracing and Fokker-Planck simulations, such as those presented here, will provide valuable data for designing an EBW heating and CD system for NSTX-U in the future.

ACKNOWLEDGMENTS

This work was supported by US Department of Energy contract DE-AC02-09CH11466.

REFERENCES

1. Y.-K.M. Peng, et al., *Fusion Sci. Technol.* **56**, 957 (2009).
2. J. E. Menard, et al., *Nucl. Fusion* **52**, 083015 (2012).
3. R. Raman, et al, *Nucl. Fusion* **53**, 073017 (2013).
4. W. Choe, et al., *Nucl. Fusion* **45**, 1463 (2005).
5. D. J. Battaglia, et al., J. Fusion Energy **28**, 140 (2009).
6. R. Raman, et al., *Nucl. Fusion* **51**, 113018 (2011).
7. V. F. Shevchenko et al., *Nucl. Fusion* **50**, 022004 (2010).
8. J. Preinhaelter and V. Kopécky, *J. Plasma Phys.* **10**, 1 (1973).
9. E. Mjolhus, *J. Plasma Phys*. **31**, 7 (1984).
10. F. R. Hansen, et al., *J. Plasma Phys*. **39**, 319 (1988).
11. R. Minami, et al, *Nucl. Fusion* **53**, 063003 (2013).
12. H. Idei, et al., *Proc. of the 16th Workshop on ECE and ECRH*, World Scientific (2011), p. 269.
13. A. P. Smirnov and R.W. Harvey, *Bull. Am. Phys. Soc.* **40**, 1837 (1995).
14. A. P. Smirnov, et al., *Proc. 15th Workshop on ECE and ECRH*, World Scientific (2009), p. 301.
15. R. W. Harvey et al., *Proc. 38th EPS Conf. on Plasma Phys.* (Strasbourg, France 2011) paper P4.017.
16. S.C. Jardin, et al., *J. Comput. Phys*. **66**, 481 (1986); also see http://w3.pppl.gov/topdac/tsc.htm
17. G. Taylor et al., *Proc. 17th Workshop on ECE and ECRH*, EPJ Web of Conferences **32**, 02014 (2012).
18. S.P. Gerhardt, et al, *Nuclear Fusion* **52**, 083020 (2012).
19. G. Taylor et al., *Phys. Plasmas* **11**, 4733 (2004).
20. J. Urban et. al., *Nucl. Fusion* **51**, 083050 (2011).
21. S. Freethy et al., *Proc. 38th EPS Conference on Plasma Physics* (Strasbourg, France, 2011) paper P2.050.

The Princeton Plasma Physics Laboratory is operated
by Princeton University under contract
with the U.S. Department of Energy.

Information Services
Princeton Plasma Physics Laboratory
P.O. Box 451
Princeton, NJ 08543

Phone: 609-243-2245
Fax: 609-243-2751
e-mail: pppl_info@pppl.gov
Internet Address: http://www.pppl.gov