Princeton Plasma Physics Laboratory

PPPL- 5024

PPPL- 5024

A Megawatt-level 28z GHz Heating System For The National Spherical Torus Experiment Upgrade

Gary Taylor, et. al.

APRIL, 2014

PRINCETON PLASMA PHYSICS LABORATORY

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

A megawatt-level 28 GHz heating system for the National Spherical Torus Experiment Upgrade

G. Taylor[1a] , R.A. Ellis[1], E. Fredd[1], S. P. Gerhardt[1], N. Greenough[1], R. W. Harvey[2], J. C. Hosea[1], R. Parker[3], F. Poli[1], R. Raman[4], S. Shiraiwa[3], A. P. Smirnov[5], D. Terry[3], G. Wallace[3], S. Wukitch[3]

[1]Princeton Plasma Physics Laboratory, Princeton, NJ 08543, USA
[2]CompX, Del Mar, CA 92014, USA
[3]Plasma Science and Fusion Center, MIT, Cambridge, MA 02139, USA
[4]University of Washington, Seattle, WA 98195, USA
[5]M.V. Lomonosov Moscow State University, Moscow, Russia

Abstract. The National Spherical Torus Experiment Upgrade (NSTX-U) will operate at axial toroidal fields of ≤ 1 T and plasma currents, $I_p \leq 2$ MA. The development of non-inductive (NI) plasmas is a major long-term research goal for NSTX-U. Time dependent numerical simulations of 28 GHz electron cyclotron (EC) heating of low density NI start-up plasmas generated by Coaxial Helicity Injection (CHI) in NSTX-U predict a significant and rapid increase of the central electron temperature ($T_e(0)$) before the plasma becomes overdense. 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. A megawatt-level, 28 GHz electron heating system is planned for heating NI start-up plasmas in NSTX-U. In addition to EC heating of CHI start-up discharges, this system will be used for electron Bernstein wave (EBW) plasma start-up, and eventually for EBW heating and current drive during the I_p flattop.

1 Introduction

Construction of the National Spherical Torus Experiment Upgrade (NSTX-U) [1] is currently being completed and the first experimental campaign is expected in early 2015. NSTX-U will operate at axial toroidal fields, $B_T(0) \leq 1$ T and plasma currents, $I_p \leq 2$ MA. For a Spherical Tokamak (ST) to be an attractive candidate for a Fusion Nuclear Science Facility [2] the physics basis for non-inductive (NI) start-up needs to be well established in an ST. Demonstrating fully NI I_p start-up, ramp-up and sustainment is a major goal of the NSTX-U research program. Coaxial Helicity Injection (CHI) [3] has been used successfully on NSTX for NI plasma start-up, but the T_e profile of CHI plasmas is extremely hollow. $T_e(0)$ ~ 10 eV and consequently I_p decays rapidly. Increasing $T_e(0)$ reduces the I_p decay rate of the CHI start-up plasma (Fig. 1). The electron density of CHI discharges is low enough to use electron cyclotron (EC) heating to increase $T_e(0)$. TRANSP [4] simulations of a NSTX-U $B_T(0) = 1$ T start-up plasma predict that 28 GHz EC heating can rapidly heat the core plasma, although the EC absorption is initially very weak. A megawatt-level 28 GHz heating system is currently planned for operation on NSTX-U in 2017-18, however at this time the system design is pre-conceptual. The 28 GHz heating system will

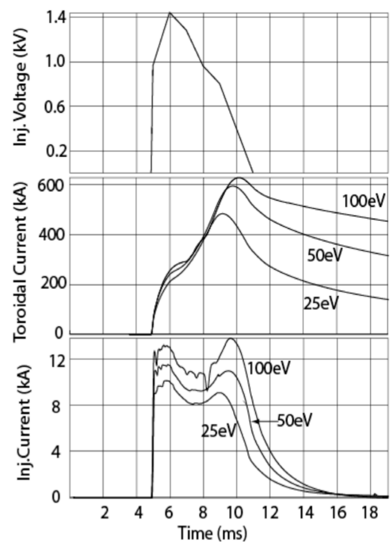


Figure 1. Simulations of three CHI startup discharges predict a significant reduction in I_p decay rate with increasing T_e. (a) CHI injection voltage, (b) plasma current, and (c) CHI injection current.

[a] Corresponding author: gtaylor@pppl.gov

initially be used for both EC heating during plasma start-up, and electron Bernstein wave (EBW) plasma start-up using a technique developed on MAST [5]. The heating system may be eventually upgraded to higher power O-X-B [6] heating system for localized heating and current drive during the I_p flattop.

2 TRANSP modeling results for EC heating of CHI start-up

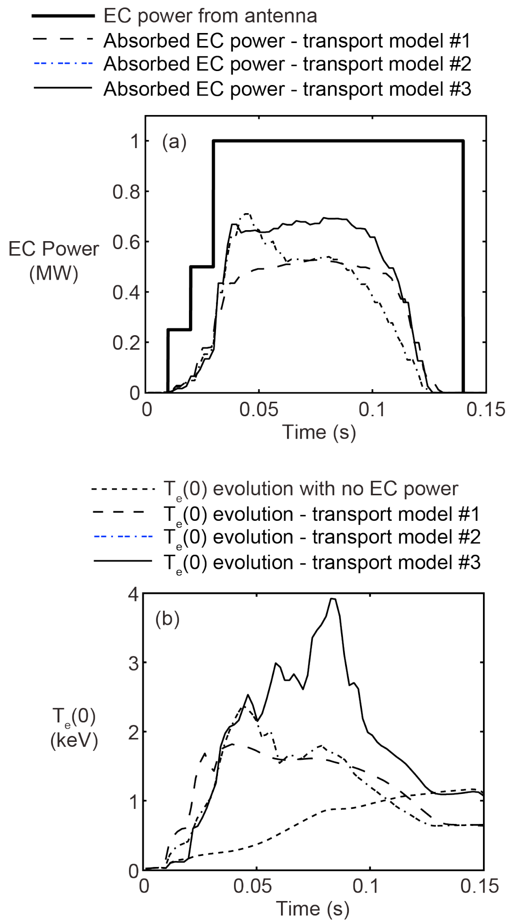


Figure 2. TRANSP simulation results for O-mode, fundamental 28 GHz EC heating of a CHI plasma. Time evolution of (a) the power leaving the antenna and the EC power absorbed in the plasma and (b) resulting time evolution of $T_e(0)$. Results are shown for three predictive transport model assumptions discussed in the text.

TRANSP simulations of 28 GHz O-mode EC heating of a NSTX-U $B_T(0)$ = 1 T start-up plasma [7] show that there is rapid core electron heating, even though the EC absorption is initially very weak [Fig. 2]. There are variations in time evolution of the EC absorption and $T_e(0)$ that are dependent on assumptions regarding electron density and I_p evolution. Model #1 in Fig. 2 uses analytic density profiles that reproduce NSTX L-mode profiles. Model #2 uses density profiles from an actual NSTX CHI discharge (shot #142140). Model #1 and #2 use an analytic I_p waveform that starts at 100 kA and ramps up to 300 kA in 50 ms. Model #3 uses the actual density profiles and I_p evolution from shot #142140, where I_p rises to 500 kA in ~ 50 ms and then to ~ 1 MA in ~150 ms. In all cases EC absorption reaches ~ 50% and $T_e(0)$ increases rapidly within 30 ms.

3 Pre-conceptual design of the 28 GHz heating system

A 28 GHz gyrotron capable of generating 1 MW for > 1 s has been developed by the University of Tsukuba [8] (Fig. 3). By changing the electron gun design and using a depressed collector the gyrotron should be capable of generating up to 2 MW pulses for several seconds. The plasma start-up EC/EBW heating system will use an in-vacuum, corrugated horn antenna, with some limited steering capability (Fig. 4). Microwave power will be transmitted to NSTX-U via a 50 mm diameter, low-loss HE_{11} corrugated circular waveguide. Either an existing modular insulated-gate bipolar transistor power supply will be used as the main power supply for the gyrotron or a new similar power supply will be purchased. The supply will be capable of serving as the main supply for two gyrotrons.

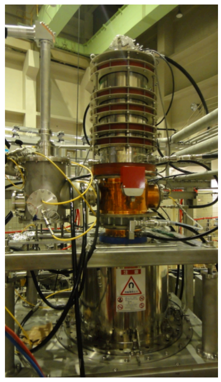


Figure 3. 1 MW, 28 GHz gyrotron used for EC heating on OUEST.

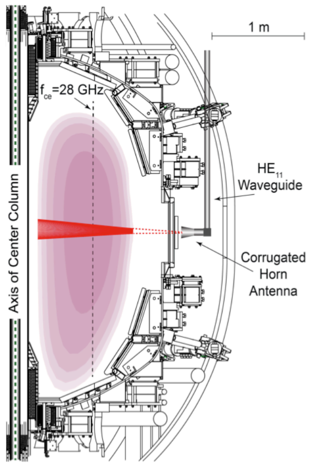


Figure 4. Cross section of the NSTX-U vacuum vessel showing a typical CHI plasma equilibrium and the location of the 28 GHz resonance for a $B_T(0)$ = 1 T

4 Simulation results for 28 GHz heating of a CHI start-up discharge

O-mode fundamental EC heating has been simulated with GENRAY [9] for a NSTX-U $B_T(0)$ = 1 T CHI discharge and second harmonic X-mode EC heating was simulated for a NSTX $B_T(0)$ = 0.5 T CHI discharge (NSTX shot 140872 @22 ms). T_e and n_e profiles used for both cases were taken from NSTX shot 140872 @22 ms (Fig. 5(a)). Both cases were under-dense at 28 GHz allowing access for EC heating (Figs. 5(b) and 5(c)), although the fundamental O-mode case is well into the underdense regime, whereas the second harmonic X-mode case is only marginally underdense. The antenna orientation was scanned to find the maximum first pass absorption.

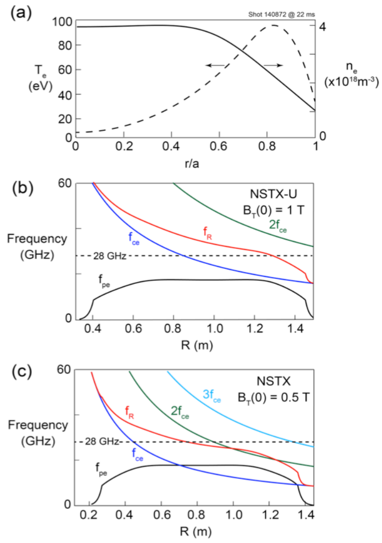
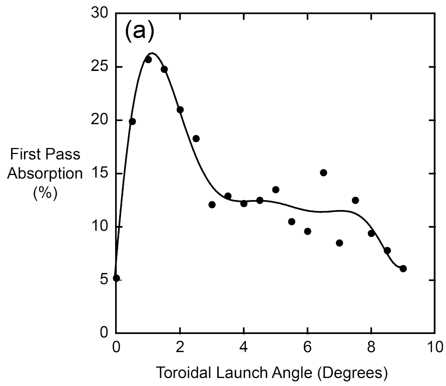


Figure 5. (a) n_e and T_e profiles used for modeling the CHI plasmas. Resonances and cutoffs for (b) the NSTX-U $B_T(0) = 1$ T CHI plasma and (c) the NSTX $B_T(0) = 0.5$ T CHI plasma.

The peak first pass absorption for second harmonic X-mode EC heating in the NSTX $B_T(0) = 0.5$ T CHI plasma was 25% (Fig. 6(a)), but more typically only 5%,



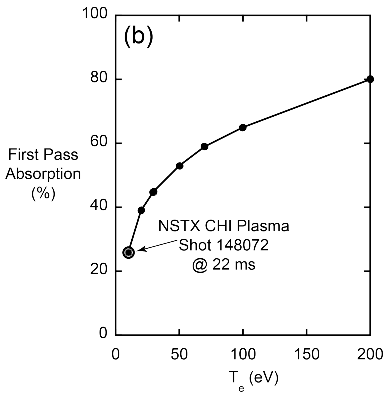
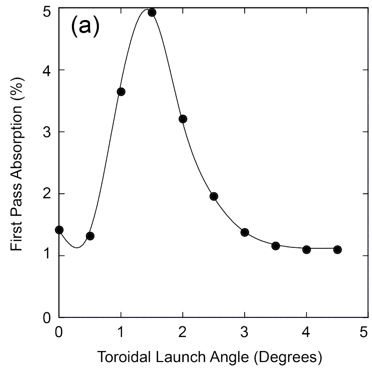


Figure 6. Second harmonic X-mode EC heating results for the $B_T(0) = 0.5$ T NSTX CHI discharge 148072 @ 22 ms. (a) Absorption versus toroidal angle between antenna axis

rising to 80% when $T_e(0)$ was increased to 200 eV (Fig. 6(b)). The peak first pass absorption for fundamental O-mode EC heating in the NSTX-U $B_T(0) = 1$ T CHI plasma is 5% (Fig. 7(a)), but more typically only 1%, rising to 20% when $T_e(0)$ was increased to 200 eV (Fig. 7(b)).



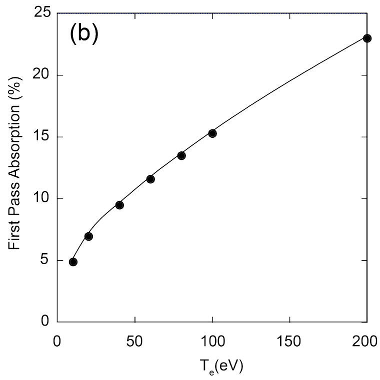


Figure 7. Fundamental O-mode EC heating results for the $B_T(0) = 1$ NSTX-U CHI discharge. (a) Absorption versus the toroidal angle between the antenna axis and the normal to the plasma surface with the antenna pointing 1.5 degrees up to for maximum absorption. (b) Dependence of first pass absorption on $T_e(0)$.

5 Simulation results for 28 GHz EBW current drive in NSTX-U neutral beam injection (NBI) H-mode discharges

GENRAY-ADJ [10] numerical simulations were run for two $I_p = 1.2$ MA, $B_T(0) = 1$ T, 100% NI NSTX-U NBI H-mode cases, one with broad n_e and T_e profiles and the other with narrow profiles [11] [Fig. 8]. The location of the antenna was scanned in poloidal angle from the midplane to 70 degrees above the midplane and the antenna was oriented to launch $n_{//} = 0.7$. For cases where the antenna was within 40 degrees of the midplane the EBW-driven current density profile was narrow, with peak CD densities

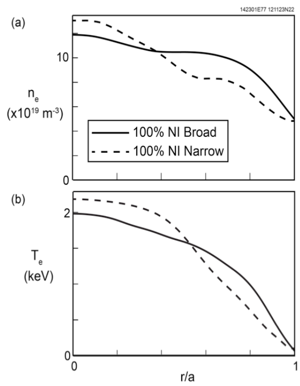


Figure 8. (a) n_e profiles and (b) T_e profiles used for modeling EBWCD in NSTX-U 100% NI H-mode plasmas.

of 0.8 MA/m^2/MW near r/a = 0.2 [Fig. 9]. When the antenna was greater than 40 degrees above the midplane the location of the peak density shifted further off-axis to r/a = 0.3 – 0.6 and the CD density fell to 0.05 – 0.1 MA/m^2/MW [Fig. 10].

The EBWCD efficiency reached 40 kA/MW when the CD was located near the axis but fell to 10 - 15 kA/MW when current was driven out at r/a = 0.6 - 0.7

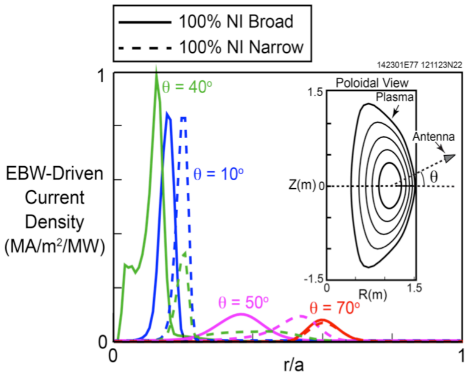


Figure 9. EBW driven current density versus normalized minor radius (r/a) for two $B_T(0) = 1$ T, $I_p = 1.2$ MA NSTX-U 100% NI H-mode plasmas for the antenna oriented to launch $n_{//} = 0.7$.

[Fig. 10(a)]. The CD efficiency was similar for the broad and narrow profile cases but for a given antenna poloidal location the EBW-driven current density peaked further off axis for the case with narrower n_e and T_e profiles [Fig. 10(b)].

A Synthetic Aperture Microwave Imaging diagnostic (SAMI) [12] will be installed on NSTX-U in 2014-15. The SAMI diagnostic will measure the B-X-O mode conversion efficiency and determine under what conditions the B-X-O 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, will provide valuable data for the design an EBW heating and CD system for NSTX-U in the future.

Acknowledgement

This work was supported under United States Department of Energy contract number DE-AC02-09CH11466.

References

1. J. E. Menard, et al., Nucl. Fusion **52**, 083015 (2012).
2. Y.-K.M. Peng, et al., Fusion Sci. Technol. **56**, 957 (2009).
3. R. Raman, et al, Nucl. Fusion **53**, 073017 (2013).
4. R. J. Hawryluk, in “Physics of plasmas close to thermonuclear conditions,” in Proc. Int. School of

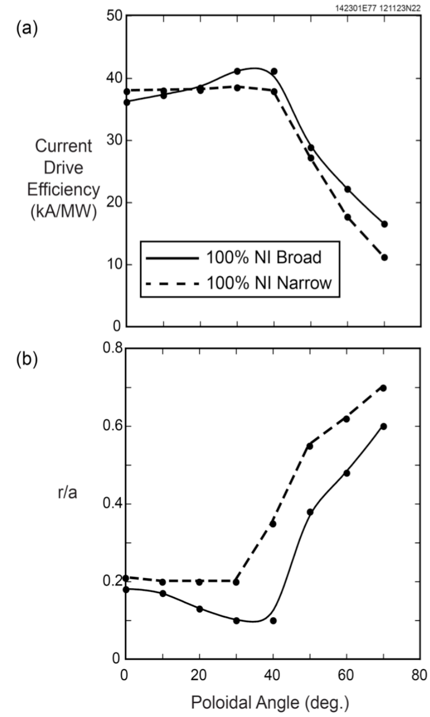


Figure 10. EBW driven current density versus normalized minor radius (r/a) for two $B_T(0) = 1$ T, $I_p = 1.2$ MA NSTX-U 100% NI H-mode plasmas for the antenna oriented to launch $n_{//} = 0.7$.

Plasma Physics (Pergamon, Varenna, Italy, 1981) Vol. 1, p. 19.
5. V. F. Shevchenko et al., Nucl. Fusion **50**, 022004 (2010).
6. J. Preinhaelter and V. Kopécky, J. Plasma Phys. **10** (1973) 1
7. F. M. Poli, et al. ”Modeling of fully non-inductive ramp-up towards development of advanced scenarios in NSTX-U”, submitted to the IAEA 25th Fusion Energy Conf., St. Petersburg, Russia, October 2014.
8. R. Minami, et al, Nucl. Fusion **53**, 063003 (2013).
9. A. P. Smirnov and R.W. Harvey, Bull. Am. Phys. Soc. **40** (1995) 1837.
10. A. P. Smirnov, et al., Proc. 15th Workshop on ECE and ECRH, World Scientific (2009), pp. 301-306
11. S.P. Gerhardt, et al, Nuclear Fusion **52**, 083020 (2012) ; NSTX-U cases with TRANSP ID 142301E77 and 121123N22 @ 11.9 s
12. S. Freethy, et al., Proc. 38th EPS Conf. 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