NSTX-U Modeling Results for 28 GHz Heating and Current Drive in the National Spherical Torus Experiment Upgrade (NSTX-U)*

G. Taylor, N. Bertelli, R. A. Ellis, S. P. Gerhardt, J. C. Hosea, F. Poli (*PPPL*), R. W. Harvey (*CompX*), R. Raman (*Univ. of Washington*), A. P. Smirnov (*Lomosov Moscow State Univ.*)

*U.S. DoE contract DE-AC02-09CH11466

Introduction

- A Spherical Tokamak (ST) is an attractive candidate for a Fusion Nuclear Science Facility (FNSF), but the physics basis for a ST-FNSF and ST non-inductive (NI) start-up needs to be established.
- Demonstrating fully NI plasma current (I_p) start-up, ramp-up and sustainment is a major long-term NSTX-U research goal **[Fig. 1]** **[Raman, oral JO4.00002 on Tuesday afternoon]**
- A megawatt-level 28 GHz heating system is being planned for installation on NSTX-U in 2016-17:
  - *Initially it will be used for electron cyclotron (EC) heating of Coaxial Helicity Injection (CHI)[1] NI discharges and electron Bernstein wave (EBW) NI plasma start-up[2].*
  - *Eventually it will be upgraded for heating and current drive (CD) via O-mode to X-mode to EBW (O-X-B)[3] mode conversion during the I_p flat top of NSTX-U NBI H-mode discharges.*

[1] R. Raman, et al, Nucl. Fusion **53** (2013) 073017
[2] V. F. Shevchenko et al., Nucl. Fusion **50** (2010) 022004
[3] J. Preinhaelter and V. Kopécky, J. Plasma Phys. **10** (1973) 1

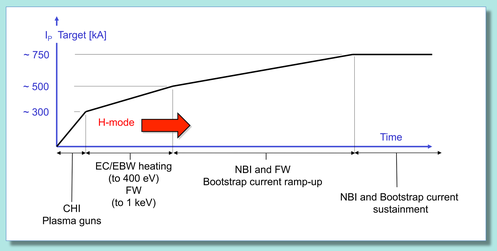

Fig. 1: NSTX-U NI plasma startup strategy. The plasma is started up with CHI and/or plasma guns, 28 GHz EC heating is applied to increase the core electron temperature ($T_e(0)$) from 10 eV to 400 eV. Fast wave (FW) heating and neutral beam injection (NBI) then further ramp the I_p.

- The electron density (n_e) of CHI discharges is low enough to allow electron cyclotron (EC) heating, but the T_e profile is very hollow with $T_e(0)$ ~ 10 eV.
- In a 500 kA decaying inductive discharge, TSC simulations predict that 0.6 MW of EC heating can increase $T_e(0)$ to ~ 400 eV in 20 ms **[Fig. 2]**:
  - *Increasing $T_e(0)$ reduces the I_p decay rate* **[Fig. 3]**.

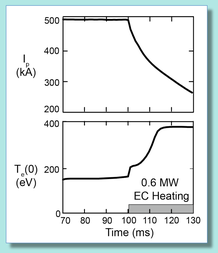

Fig. 2: TSC simulation predicts 0.6MW of 28 GHz EC heating will increase $T_e(0)$ to ~ 400 eV in 20 ms.

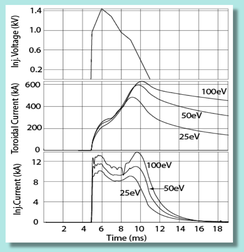

Fig. 3: Simulations of three CHI discharges with T_e = 25, 50 and 100 eV predict a significant reduction in I_p decay rate with increasing T_e.

- The GENRAY[4] ray tracing code has been used to simulate 28 GHz EC heating in NSTX and NSTX-U CHI start-up plasmas.
- The CQL3D[5] Fokker-Planck code and the ADJ[6] adjoint-based relativistic Coulomb Fokker-Planck package in GENRAY have been used to simulate 28 GHz EBW CD during the I_p flat top of $B_T(0)$ = 1 T NSTX-U NBI H-mode plasmas.

[4] A. P. Smirnov and R.W. Harvey, Bull. Am. Phys. Soc. **40** (1995) 1837
[6] R. W. Harvey et al., Proc. 38th EPS Conf. on Plasma Phys. (Strasbourg, France 2011) paper P4.017
[5] A. P. Smirnov, et al., Proc. 15th Workshop on ECE and ECRH, World Scientific (2009), pp. 301-306

GENRAY Ray Tracing Results for 28 GHz EC Heating of CHI Start-Up Discharges

- O-mode fundamental EC heating has been simulated for a NSTX-U $B_T(0)$ = 1 T CHI discharge **[Fig. 4]** and second harmonic X-mode EC heating was simulated for a NSTX $B_T(0)$ = 0.5 T CHI discharge **[Fig. 5]** (NSTX shot 140872 @22 ms).
- T_e and n_e profiles used for both cases were taken from NSTX shot 140872 @22 ms **[Fig. 6(a)]**.
- Both cases were under-dense at 28 GHz allowing access for EC heating **[Figs. 6(b) and 6(c)]**.
- The antenna orientation was scanned to find the maximum first pass absorption.
- 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. 7(a)]** rising to 80% when $T_e(0)$ was increased to 200 eV **[Fig. 7(b)]**.
- The peak first pass absorption for fundamental O-mode EC heating in the NSTX-U $B_T(0)$ = 1 T CHI plasma was 5% **[Fig. 8(a)]** rising to 20% when $T_e(0)$ was increased to 200 eV **[Fig. 8(b)]**.

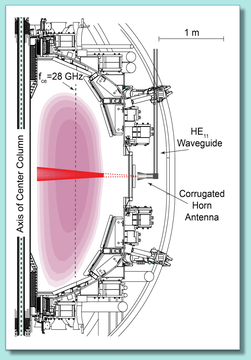

Fig. 4: Cross section of the NSTX-U vacuum vessel showing the plasma equilibrium used for the GENRAY ray tracing simulations of 28 GHz EC heating of a $B_T(0)$ = 1 T CHI startup discharge.

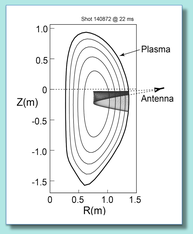

Fig. 5: Equilibrium for NSTX shot 140872 @22 ms used for GENRAY simulations of 28 GHz EC heating of a $B_T(0)$ = 0.5 T NSTX CHI discharge. Rays are shown for the case that yielded the highest first pass absorption for second harmonic X-mode EC heating. The rays reflect off of the right hand off (f_{rh} in **Fig. 6(c)**) after passing through the second harmonic EC resonance.

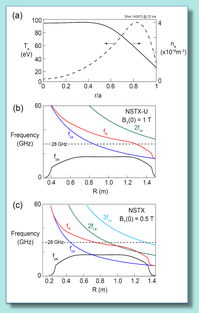

Fig. 6: (a) n_e and T_e profiles used for modeling the CHI plasmas. Resonances and cutoffs for (b) the NSTX-U $B_T(0)$ = 1 T CHI plasma and (c) the NSTX $B_T(0)$ = T 0.5 CHI plasma.

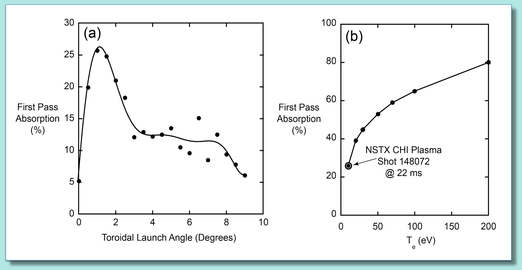

Fig. 7: Second harmonic X-mode EC heating results for the $B_T(0)$ = 0.5 T NSTX CHI discharge 148072 @ 22 ms. (a) Absorption versus toroidal angle between antenna axis and the normal to the plasma surface with the antenna pointing 5 degrees down for maximum absorption. (b) Dependence of the first pass absorption on $T_e(0)$.

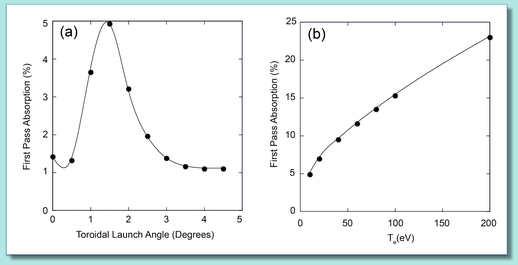

Fig. 8: Fundamental O-mode EC heating results for the $B_T(0)$ = 1 NSTX-U CHI discharge. (a) Absorption versus the toroidal angle between the antenna axis and the normal to the plasma surface with the antenna pointing 1.5 degrees up to for maximum absorption. (b) Dependence of first pass absorption on $T_e(0)$.

GENRAY-ADJ and CQL3D Numerical Simulation Results for 28 GHz EBWCD in NSTX-U NBI H-Mode Discharges

Good Agreement Between GENRAY-ADJ and CQL3D EBWCD Results

- GENRAY-ADJ and CQL3D 28 GHz EBWCD simulations were run for a $B_T(0)$ = 1 T, I_p = 1.1 MA advanced scenario NBI-heated H-mode plasma*, which had $T_e(0)$ = 1.4 keV and $n_e(0) = 9 \times 10^{19}$ m^{-3} **[Fig. 9(a)]**.
  - *The fundamental 28 GHz EBWs are resonant near the magnetic axis* **[Fig. 9(b)]**.
  - *The maximum O-X-B conversion efficiency was obtained with the antenna axis pointing with a poloidal angle of ± 10 degrees and a toroidal angle of ± 38 degrees, corresponding to $n_{//}$ = ± 0.7* **[Fig. 10]**.
- GENRAY-ADJ and CQL3D EBWCD results were in good agreement, both with regard to total CD efficiency **[Fig. 11(a)]** and location of the peak CD density **[Fig. 11(b)]**:
  - *Peak CD efficiency was ~ 30 kA/MW with a peak CD density ~ 1 MA/m^2/MW at r/a ~ 0.2* **[Fig. 12]**.

*NSTX-U case with TRANSP ID 142301V11 @ 11.875 s

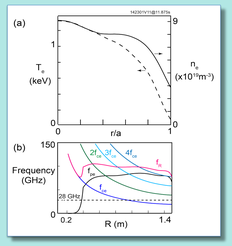

Fig. 9: (a) n_e and T_e profiles used for modeling EBWCD in a $B_T(0)$ = 1 T, I_p = 1.1 MA NSTX-U H-mode plasma. (b) Resonances and cutoffs.

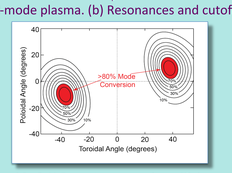

Fig. 10: O-X-B mode conversion efficiency versus poloidal and toroidal angle for NSTX-U $B_T(0)$ = 1 T, I_p = 1.1 MA NSTX-U H-mode plasma.

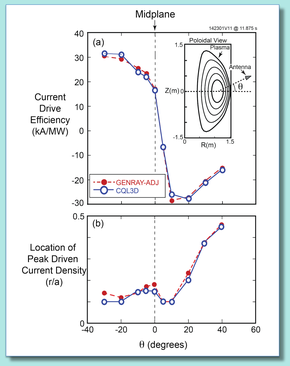

Fig. 11: (a) EBWCD efficiency calculated by GENRAY-ADJ and CQL3D versus the poloidal angle (θ) of the antenna location (antenna located at midplane corresponds to θ = 0) for the NSTX-U H-mode plasma. (b) Location of the peak driven current density. The launcher is oriented to launch $n_{//}$ = - 0.7 to provide the maximum O-X-B coupling. The EBW-driven current changes direction as the antenna location is scanned above and below the midplane.

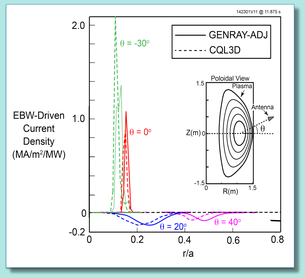

Fig. 12: Comparison of EBW driven current density versus normalized minor radius (r/a) calculated by GENRAY-ADJ and CQL3D for the $B_T(0)$ = 1 T, I_p = 1.1 MA NSTX-U H-mode plasma, for $n_{//}$ = -0.7.

EBWCD Efficiencies up to 40 kA/MW Obtained in 100% NI NSTX-U Plasmas

- GENRAY-ADJ 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[7] **[Fig 13]**.
- The location of the antenna was scanned in poloidal angle from the midplane to the 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 of 0.8 MA/m^2/MW near r/a = 0.2 **[Fig. 14]**.
- 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. 14]**.

[7] S.P. Gerhardt, et al., Nucl. Fus. 52 (2012) 083020; NSTX-U cases with TRANSP ID 142301E77 and 121123N22 @ 11.9 s

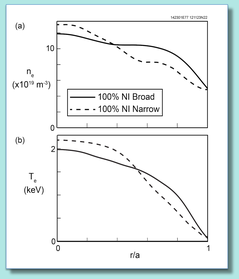

Fig. 13: (a) n_e profiles and (b) T_e profiles used for GENRAY-ADJ modeling of $B_T(0)$ = 1 T, I_p = 1.2 MA NBI NSTX-U 100% NI H-mode plasmas

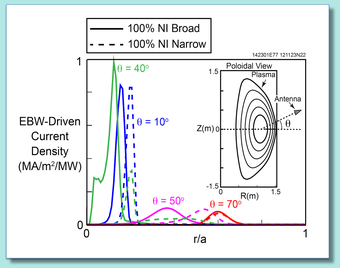

Fig. 14: EBW driven current density versus normalized minor radius (r/a) for two $B_T(0)$ = 1 T, I_p = 1.2 MA NSTX-U 100% NI H-mode plasmas for the antenna oriented to launch $n_{//}$ = 0.7

- 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 **[Fig. 15(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. 15(b)]**.

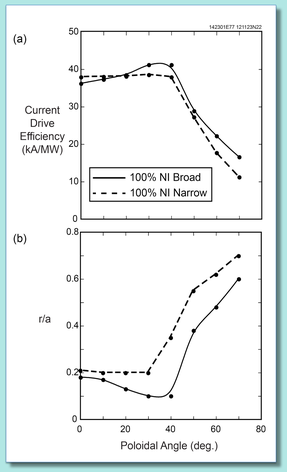

Fig. 15: (a) EBWCD efficiency calculated by GENRAY-ADJ versus the poloidal angle (θ) of the antenna location for the 100% NI two $B_T(0)$ = 1 T, I_p = 1.2 MA NSTX-U H-mode plasma. (b) Location of the peak driven current density. The antenna is oriented to launch $n_{//}$ = 0.7 to provide the maximum O-X-B coupling.

Summary

- A 28 GHz megawatt-level heating system is planned to support NI plasma startup and O-X-B heating and CD in NSTX-U.
- GENRAY ray tracing simulations for 28 GHz EC heating of CHI NI startup plasmas predict 25% first pass absorption for X-mode second harmonic EC heating of a $B_T(0)$ = 0.5 T plasma and 5% first pass absorption for O-mode fundamental EC heating of a $B_T(0)$ = 1 T plasma.
- 28 GHz EBWCD simulations for prospective NSTX-U NBI-heated H-mode discharges show good agreement between GENRAY-ADJ and CQL3D predictions of EBWCD efficiency and EBW-driven current profiles.
- 28 GHz EBWCD efficiencies of up to 40 kA/MW are predicted near the axis of 100% NI NSTX-U H-mode discharges.