Time-Dependent Simulations of Fast-Wave Heated High-Non-Inductive-Fraction H-Mode Plasmas in the National Spherical Torus Experiment Upgrade

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Abstract. 30 MHz fast-wave heating may be an effective tool for non-inductively ramping low-current plasmas to a level suitable for initiating up to 12 MW of neutral beam injection on the National Spherical Tokamak Experiment Upgrade (NSTX-U). Previously on NSTX 30 MHz fast wave heating was shown to efficiently and rapidly heat electrons; at the NSTX maximum axial toroidal magnetic field ($B_T(0)$) of 0.55 T, 1.4 MW of 30 MHz heating increased the central electron temperature from 0.2 to 2 keV in 30 ms and generated an H-mode plasma with a non-inductive fraction (f_{NI}) ~ 0.7 at a plasma current (I_p) of 300 kA. NSTX-U will operate at $B_T(0)$ up to 1 T, with up to 4 MW of 30 MHz power (P_{rf}). Predictive TRANSP free boundary transport simulations, using the TORIC full wave spectral code to calculate the fast-wave heating and current drive, have been run for NSTX-U I_p = 300 kA H-mode plasmas. Favorable scaling of f_{NI} with 30 MHz heating power is predicted, with $f_{NI} \geq 1$ for $P_{rf} \geq 2$ MW.

1 Introduction

A Fusion Nuclear Science Facility based on the spherical tokamak concept needs to operate with little or no inductive drive from a central solenoid [1]. A long-term research goal of the National Spherical Tokamak Experiment Upgrade (NSTX-U) [2] is to develop fully non-inductive plasmas, and the NSTX-U fast-wave heating system may be an effective tool for non-inductively ramping low-current plasmas to a level suitable for initiating up to 12 MW of neutral beam injection [3]. On NSTX, 30 MHz fast-wave heating efficiently and rapidly heated electrons; at the NSTX maximum axial toroidal field ($B_T(0)$) of 0.55 T, 1.4 MW of fast-wave heating increased the central electron temperature ($T_e(0)$) from 0.2 to 2 keV in 30 ms and generated an H-mode plasma (NSTX shot #138506) with a non-inductive fraction (f_{NI}) ~ 0.7 at a plasma current (I_p) = 300 kA [4]. The NSTX-U fast-wave heating system will couple up to 4 MW of RF power (P_{rf}) and will operate again at 30 MHz, which is the 4th harmonic of deuterium at the maximum NSTX-U $B_T(0)$ of 1 T. Predictive TRANSP free boundary transport simulations [5] have been run for NSTX-U I_p = 300 kA H-mode plasmas in order to study the dependence of f_{NI} on $B_T(0)$ and P_{rf}. The TRANSP simulations used the TORIC full wave spectral code [6] to calculate the fast-wave heating and current drive. The transport in the simulations was benchmarked to the experimental results obtained on NSTX. This paper presents the results of these simulations and the implications for using 30 MHz power on NSTX-U to ramp I_p non-inductively.

2 Predictive modelling assumptions

The thermal transport model used in the predictive TRANSP simulations was the Multimode MMM7.1 model [7]. This model gave reasonably good agreement to plasma parameters (eg. f_{NI}, $T_e(0)$ and plasma pressure) obtained experimentally during NSTX shot #138506 for a NSTX-U simulation with similar $B_T(0)$ and P_{rf}. Effective charge, impurity, rotation and other profiles were taken largely from NSTX plasma shot #142305, a plasma that was part of an experimental campaign to support NSTX-U and next-step Spherical Tokamak devices [8].

All the simulations used a $k_{//}$ = 8 m^{-1} antenna phasing, the current drive antenna phasing used for shot #138506. The RF pulse was ramped up to the flat top level in 30 ms, starting at 100 ms. This RF power ramp rate was typical for experiments on NSTX.

In the simulations the electron density profile and central density ($n_e(0)$) were initially chosen to be similar to shot #138506, which had $n_e(0)$ = 1.15x10^{19} m^{-3}. The density in the simulation was ramped to this level in 100 ms, at that time a H-mode transition was imposed by flattening the density profile, as shown in figure 1. However when $B_T(0)$ > 0.75 T it was found that when using this relatively low density the plasma became unstable and the simulations terminated prematurely,

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typically only ~100 ms after the start of the RF pulse. Increasing $n_e(0)$ to 1.43×10^{19} m^{-3} resulted in stable plasma simulations up to $P_{rf} = 4$ MW and $B_T(0) = 1$ T. Simulations were run for $P_{rf} = 1.4, 2, 3$ and 4 MW, and for plasmas having $B_T(0) = 0.5, 0.65, 0.75, 0.89$ and 1 T.
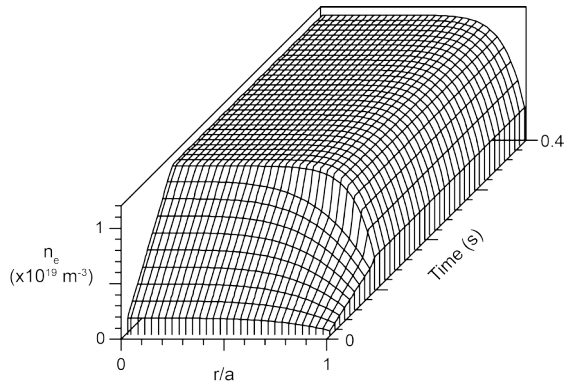

Fig. 1. Time evolution of the density profile used in the $n_e(0) = 1.15 \times 10^{19}$ m^{-3} TRANSP simulation.

3 Results

Figure 2 summarizes the predictive TRANSP simulation results for a NSTX-U plasma with the same
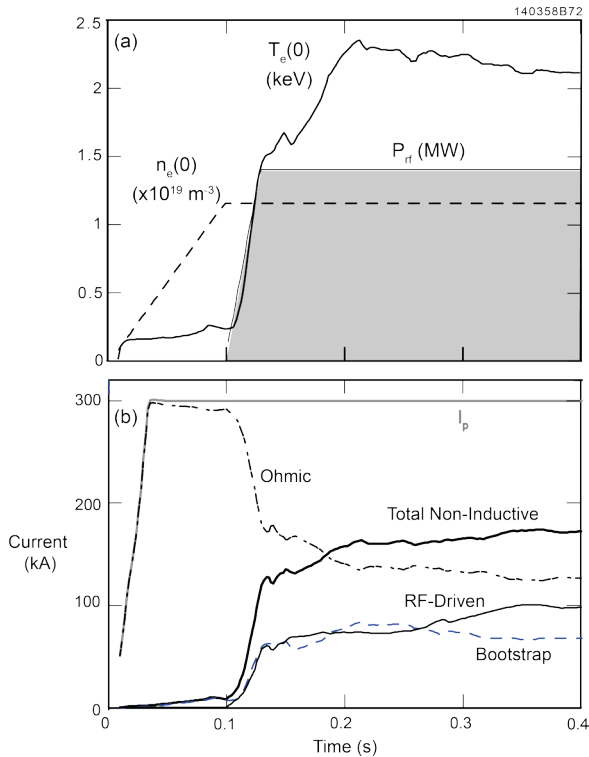

Fig. 2. Predictive TRANSP results for an $I_p = 300$ kA, $B_T(0) = 0.5$ T NSTX-U plasma with $P_{rf} = 1.4$ MW. (a) Time evolution of $n_e(0)$, $T_e(0)$ and P_{rf}. (b) Time evolution of various currents predicted by TRANSP. The predicted $T_e(0)$ and f_{NI} are similar to NSTX shot #138506.

P_{rf}, I_p and $n_e(0)$ as NSTX shot #138506, and $B_T(0) = 0.5$ T, compared to $B_T(0) = 0.55$ T for shot #138506. As shown in figure 2(a), $T_e(0)$ during the simulation was 2.2-2.4 keV, compared to 2.5-3 keV during shot# 138506. f_{NI} during the simulated NSTX-U plasma reached 0.6, compared to a fluctuating $f_{NI} = 0.7\pm0.2$ during shot #138506. One notable difference was that the bootstrap current was larger than the current driven directly by RF power in shot #138506. The fluctuation in f_{NI} during shot #138506 is due entirely to large fluctuations in the plasma pressure gradient resulting in fairly rapid changes in bootstrap current. In contrast, in the NSTX-U plasma simulation shown in figure 2(b) the bootstrap current is comparable to the RF-driven current and neither non-inductive currents have significant fluctuations.

The best value of f_{NI} reached during the lower density, $n_e(0) = 1.15 \times 10^{19}$ m^{-3} simulations was 1.7. This high value of f_{NI} was achieved for a simulation with
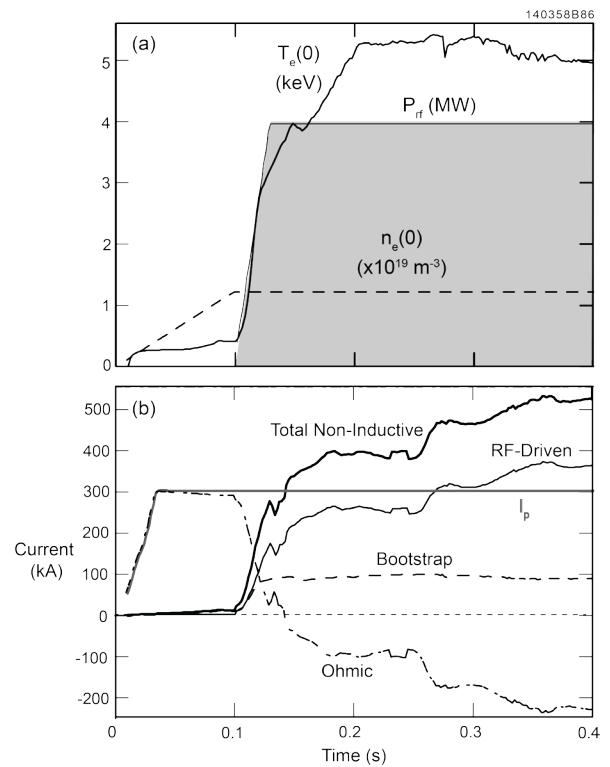

Fig. 3. Predictive TRANSP results for an $I_p = 300$ kA, $B_T(0) = 0.65$ T NSTX-U plasma with $P_{rf} = 4$ MW. (a) Time evolution of $n_e(0)$, $T_e(0)$ and P_{rf}. (b) Time evolution of various currents predicted by TRANSP.

$B_T(0) = 0.65$ T and $P_{rf} = 4$ MW. The results from this simulation are summarized in figures 3 and 4. Figure 3(a) shows the time evolution of $T_e(0)$ reaches 5 keV. As shown in figure 3(b), the bootstrap current remains constant around 100 kA and the RF-driven current reaches 370 kA at 0.4 s. Figure 4(a) shows T_e at the start of the RF pulse (dashed line) and at 0.4 s (solid line) for the case shown in figure 3. The T_e profile becomes very peaked during the RF pulse (figure 4(a)). Figure 4(b)

shows the area integrated current densities at 0.4 s. 90% of the RF-driven current is within $r/a = 0.2$, while 90% of the bootstrap current is generated within $r/a = 0.5$. Because the RF heating was strongly peaked near the axis this results in the development of a highly peaked $T_e(R)$ profile (figure 4(a)) which further increases the RF-driven current near the magnetic axis. This peaking
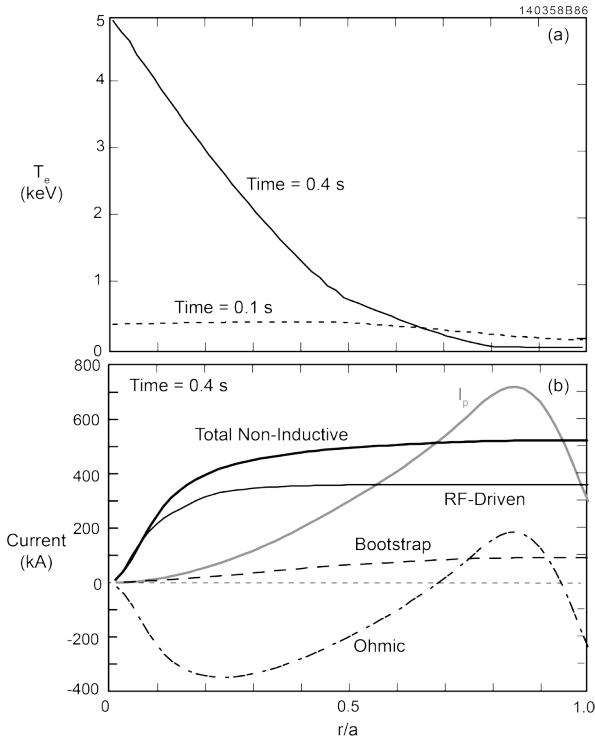

Fig. 4. (a) Electron temperature profile at 0.1 s, the start of the RF pulse (dashed line) and at 0.4 s (solid line). (b) Area integrated currents versus normalized minor radius for the case shown in figure 3 at 0.4 s. 90% of the RF-driven current is located inside $r/a = 0.3$.

of $T_e(0)$ and the RF-driven current at higher P_{rf}, particularly at higher $B_T(0)$, caused the plasma simulation to become unstable in the first 100 ms of the RF pulse, prematurely terminating the simulation, as mentioned earlier. This behaviour was also seen in NSTX shot #138506. Although it didn't cause the plasma to disrupt it did result in a magneto-hydrodynamic reconnection in the plasma core that rapidly reduced the stored energy resulting in the plasma moving radially and briefly tripping the RF heating pulse.

All the lower density, $n_e(0) = 1.15 \times 10^{19}$ m^{-3} simulations that didn't terminate by ~ 0.2 s reached a quasi-steady state condition by 0.4 s. Figure 5 shows the dependence of f_{NI} at 0.4 s on P_{rf} for the $n_e(0) = 1.15 \times 10^{19}$ m^{-3} simulations. Also plotted in this figure is the f_{NI} achieved during NSTX shot #138506. At $P_{rf} = 1.4$ MW all the simulations have an $f_{NI} \sim 0.6$, independent of $B_T(0)$, and in fairly good agreement with the $f_{NI} = 0.7\pm0.2$ achieved experimentally during NSTX shot #138506. Increasing P_{rf} from 1.4 to 4 MW for the $B_T(0) = 0.5$ T simulation approximately doubled f_{NI}. For the $B_T(0) = 0.65$ T and 0.75 T simulations f_{NI} increased

by 2.8 and 2.4, respectively. The $B_T(0) = 0.89$ T simulation became unstable at ~ 0.2 s when P_{rf} was
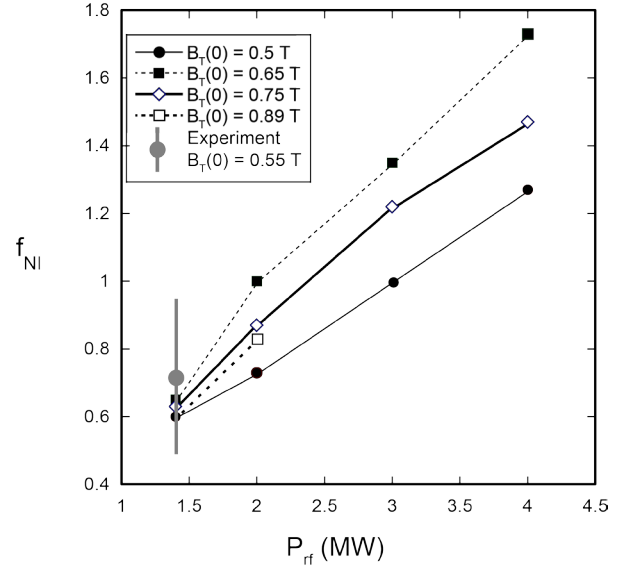

Fig. 5. f_{NI} at 0.4 s versus P_{rf} for plasma simulations with $n_e(0) = 1.15 \times 10^{19}$ m^{-3}. Also plotted in this figure is the f_{NI} achieved during NSTX shot #138506 (grey filled circle with range during the shot indicated by the vertical bar).

increased above 2 MW and the $B_T(0) = 1$ T simulations were all unstable early in the RF pulse.

Figure 6 shows the dependence of f_{NI} at 0.4 s on $B_T(0)$ for the $n_e(0) = 1.15 \times 10^{19}$ m^{-3} simulations. Increasing $B_T(0)$ from 0.5 to 0.65 T is predicted to significantly increase f_{NI}, particularly at the higher P_{rf}. However, f_{NI}
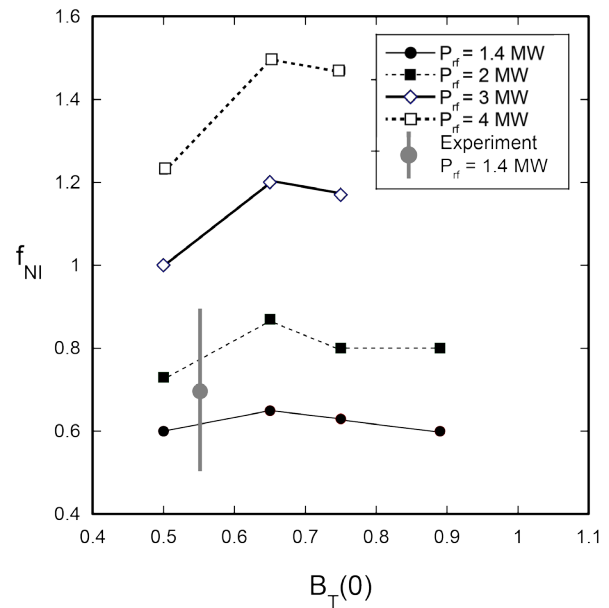

Fig. 6. f_{NI} versus $B_T(0)$ for the $n_e(0) = 1.15 \times 10^{19}$ m^{-3} plasma simulations. Also plotted in this figure is the f_{NI} achieved during NSTX shot# 138506 (grey filled circle with range during the shot indicated by the vertical bar).

decreases above $B_T(0) = 0.65$ T at all values of P_{rf}.

For the $n_e(0) = 1.15 \times 10^{19}$ m^{-3} simulations fully non-inductive operation is predicted with as little as 2 MW of RF power for a $B_T(0) = 0.65$ T plasma,
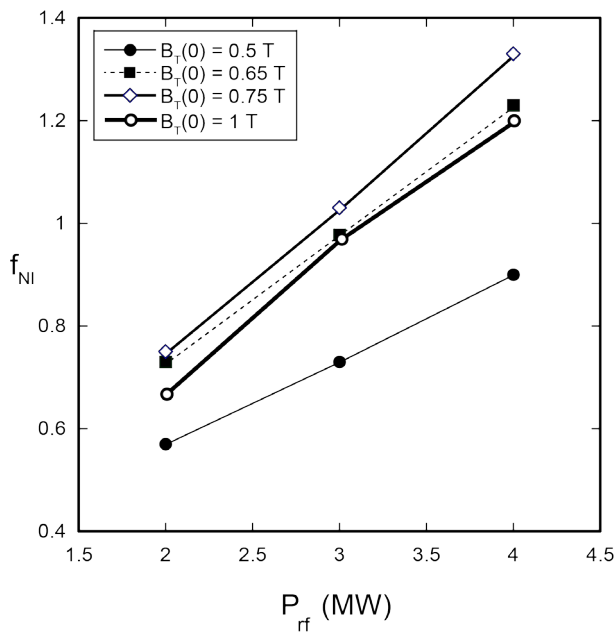

Fig. 7. f_{NI} versus P_{rf} for the plasma simulations with $n_e(0) = 1.43 \times 10^{19}$ m^{-3}.

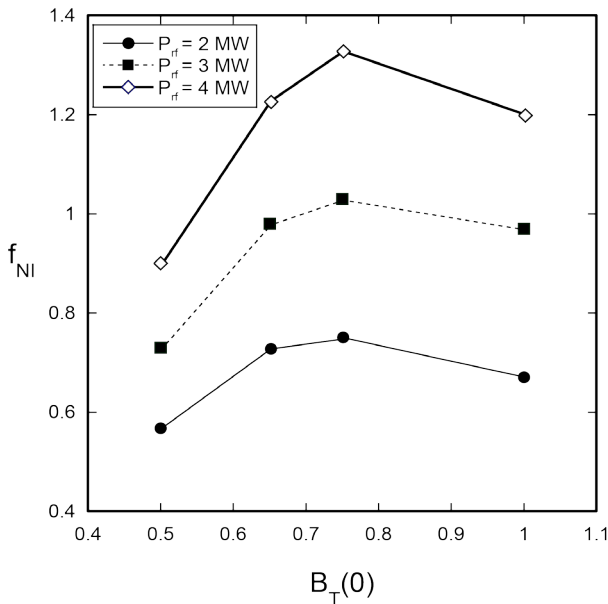**Fig. 8.** f_{NI} versus $B_T(0)$ for the plasma simulations with $n_e(0) = 1.43 \times 10^{19}$ m^{-3}.

As mentioned earlier, increasing $n_e(0)$ to 1.43×10^{19} m^{-3} provided stable plasma simulations up to $P_{rf} = 4$ MW at $B_T(0) = 1$ T. Figure 7 plots f_{NI} at 0.4 s versus P_{rf} for this slightly higher density case. $f_{NI} \geq 1$ is predicted for $P_{rf} \geq 3$ MW for the plasma simulations with $B_T(0) = 0.75$ T. At $P_{rf} = 4$ MW all the plasma simulations with $B_T(0) \geq 0.65$ predict fully non-inductive operation. Increasing P_{rf} from 2 to 4 MW increased f_{NI} by 1.6, 1.7, 1.8 and 1.4 for the 0.5 T, 0.65 T, 0.75 T and 1 T simulations, respectively. As expected, the somewhat

higher density reduced the f_{NI} achieved at a given P_{rf} and $B_T(0)$ compared to the lower density simulations.

Figure 8 plots f_{NI} at 0.4 s versus $B_T(0)$ for the $n_e(0) = 1.43 \times 10^{19}$ m^{-3} simulations. While f_{NI} increases significantly when $B_T(0)$ is raised from 0.5 T to 0.65 T, f_{NI} decreases when $B_T(0)$ increases from 0.75 to 1 T, as predicted for the $n_e(0) = 1.15 \times 10^{19}$ m^{-3} simulations.

4 Conclusions

The TRANSP simulation results presented here strongly support the possibility of achieving stable $f_{NI} \geq 1$ plasmas with $P_{rf} = 2$-3 MW in an $I_p = 300$ kA NSTX-U plasma. However while increasing P_{rf} to higher levels than were achieved on NSTX shot #138506 is predicted to increase f_{NI} the simulations also predict that the plasma may become unstable as P_{rf} is increased, particularly at the highest $B_T(0)$ values achievable on NSTX-U. The simulations predict that increasing $B_T(0)$ to 0.65 T from 0.55 T, the value used in NSTX experiment, may significantly increase the achievable f_{NI}. One caveat is that operationally it was difficult to control $I_p = 300$ kA NSTX plasmas when fast wave power was coupled into the I_p flattop, even at $P_{rf} = 1.4$ MW. Coupling fast wave power at even higher levels will no doubt be challenging. But even more challenging will be coupling fast wave power immediately after start up in order to ramp I_p up to 300-400 kA. These TRANSP simulation predictions must now await experimental validation in NSTX-U.

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