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NSTX-U

Generation of Non-Inductive H-Mode Plasmas with 30 MHz Fast Wave Heating in NSTX-U*

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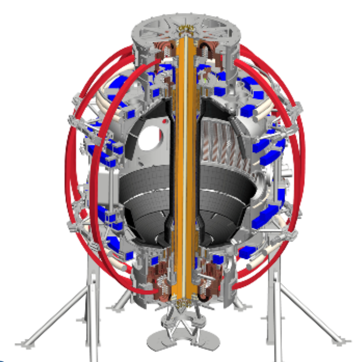

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Introduction

Developing fully non-inductive (NI) plasmas is a NSTX-U 10-year research goal

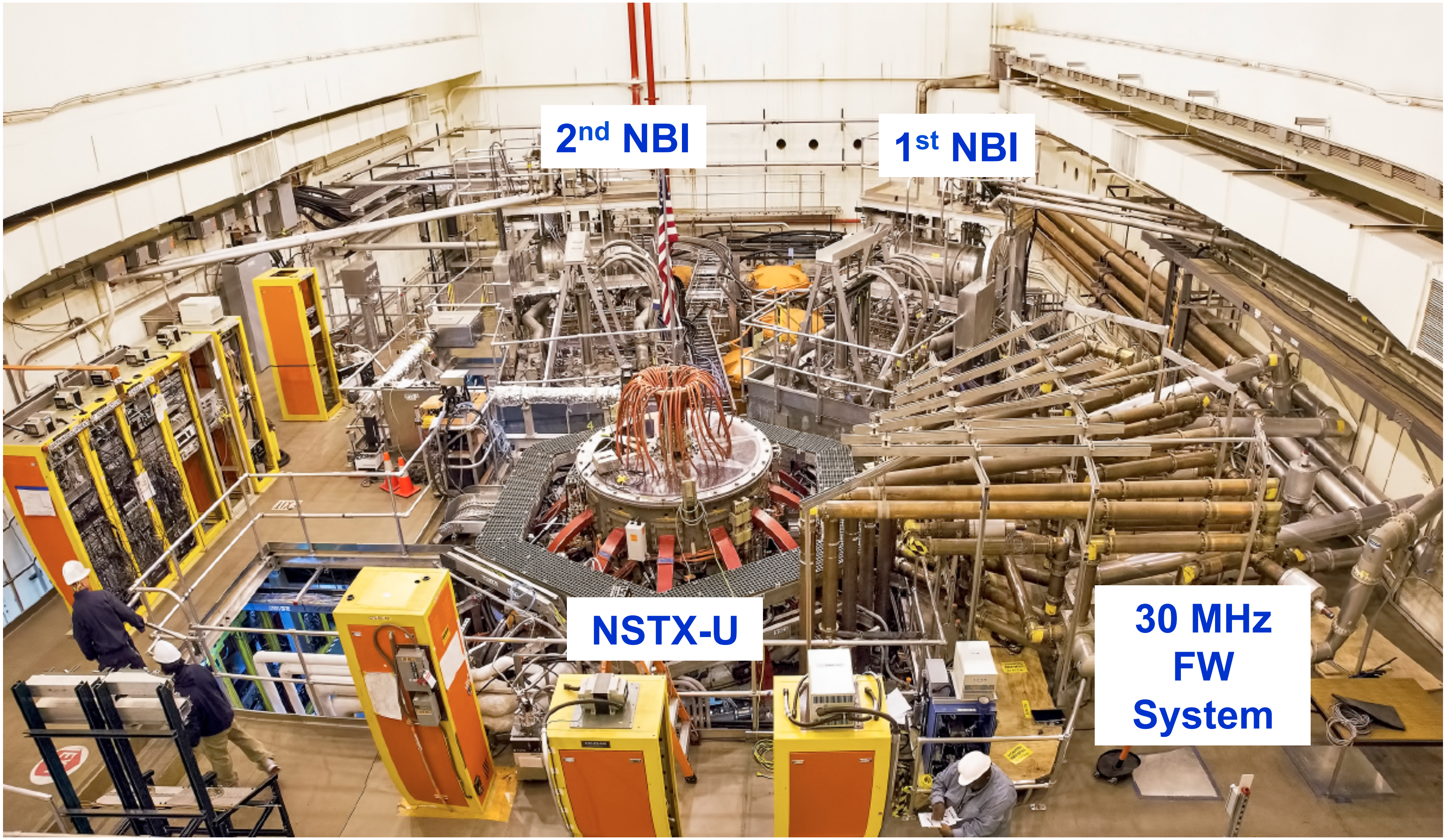
- In a Fusion Nuclear Science Facility based on a spherical tokamak the plasma current (I_p) needs to be initiated, ramped-up and sustained with little or no central solenoid field

- 30 MHz fast wave (FW) heating can play a critical role in NSTX-U supporting non-inductive (NI) I_p ramp-up to 300 kA:
  - FW heating effectively heats low density plasmas with $I_p \leq 300$ kA, whereas neutral beam injection (NBI) requires $I_p \geq 300$ kA to ensure fast ion confinement and to maintain shine through below 50%

- Experiments on NSTX-U aim to couple ~ 3 MW of FW power into I_p ~ 300 kA plasmas, achieving NI current fraction, $f_{NI} \geq$ I

- This poster presents the first results from time-dependent transport simulations of these FW-heated I_p ~ 300 kA plasmas

NSTX-U facility includes a 6 MW, 30 MHz FW heating system previously used on NSTX



NSTX-U performance will far exceed NSTX with regard to maximum I_p, B_T and I^2t*

Parameter	NSTX (Max.)	FY2016 NSTX-U Operations Achieved	FY2017 NSTX-U Repair PF	FY2018 NSTX-U Operations	NSTX-U Ultimate Goal
I_P (MA)	1.2	~1.1	-	2.0	2.0
B_T (T)	0.55	~ 0.65	-	1.0	1.0
Allowed TF I^2t (MA^2s)	7.3	80	-	160	160

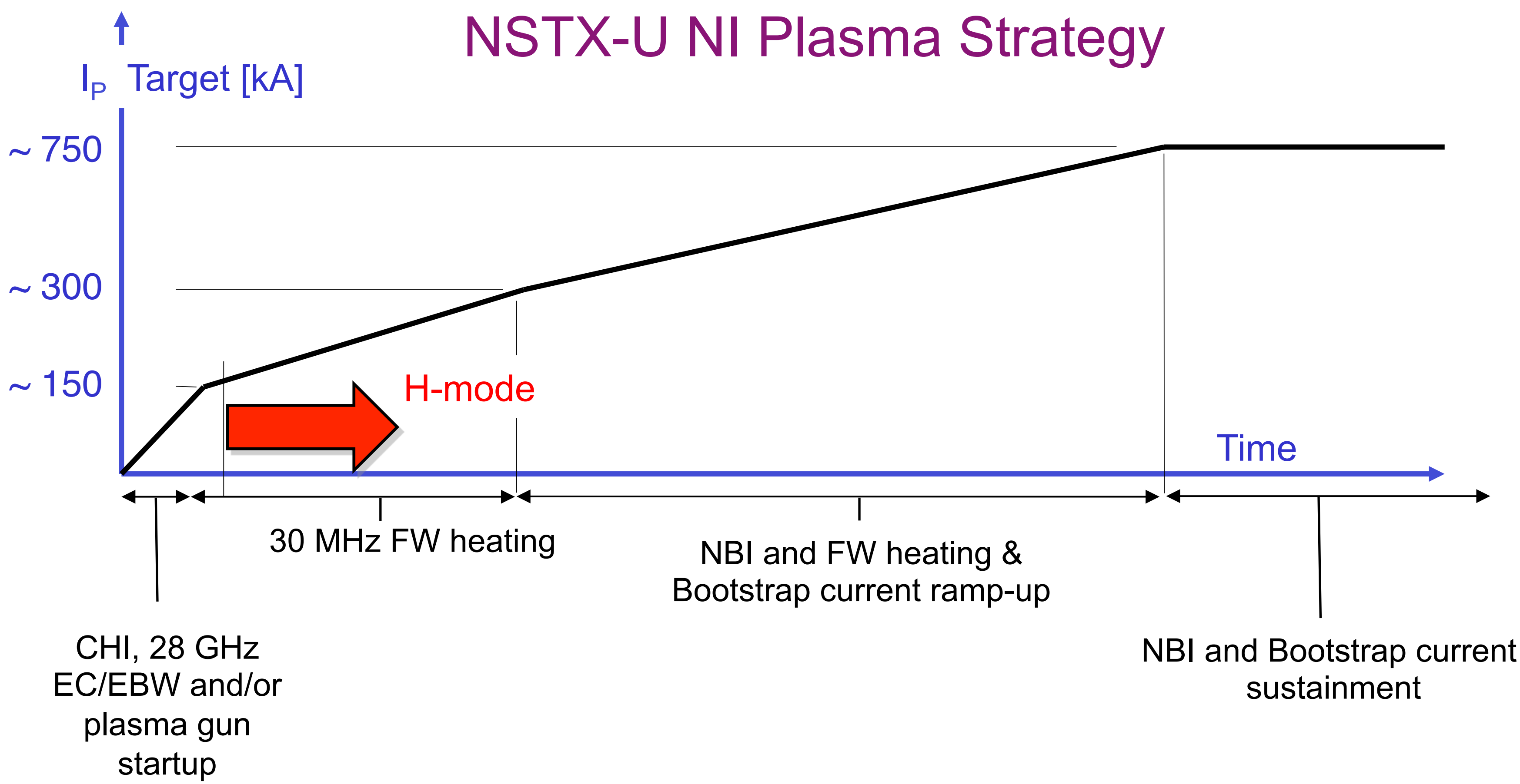
- NSTX 30 MHz FW heating was operated in the high harmonic FW (HHFW) regime, with RF damping on up to $11w_{ci}$ at $B_T(0)$ = 0.55 T

- NSTX-U 30 MHz FW heating will operate in the Medium Harmonic FW (MHFW) regime, with RF damping on up to $5w_{ci}$ at $B_T(0)$ = 1 T

* J. E. Menard *et al.*, Nucl. Fusion **52** (2012) 083015

Development of NI Plasmas Heated by 30 MHz FW Power

Experiments in NSTX-U will develop NI start-up, ramp-up and plasma sustainment separately



Time-dependent modeling of NSTX-U NI I_p ramp-up predict that NBI is not suitable for $I_p \leq 300$ kA

- TRANSP modeling of NI plasma started with NBI predicts very high shine-through during the first 100 ms when $I_p \leq 300$ kA
- Simulations suggest that an additional source of current is needed in the first 200 ms of a NI plasma*
- FW power can effectively heat plasma at low density
- FW heating can be through both the electron and ion channels, depending on the antenna phasing**
- Plan to use ~3 MW of 30 MHz FW power to ramp I_p to 300 kA

* F. M. Poli *et al*., Nuclear Fusion **55** (2015) 123011

** N. Bertelli *et al*., AIP Conf. Proc. **1580** (2014) 310

To support development of FW-heated I_p ramp-up in NSTX-U first demonstrate fully NI I_p ~ 300 kA discharges

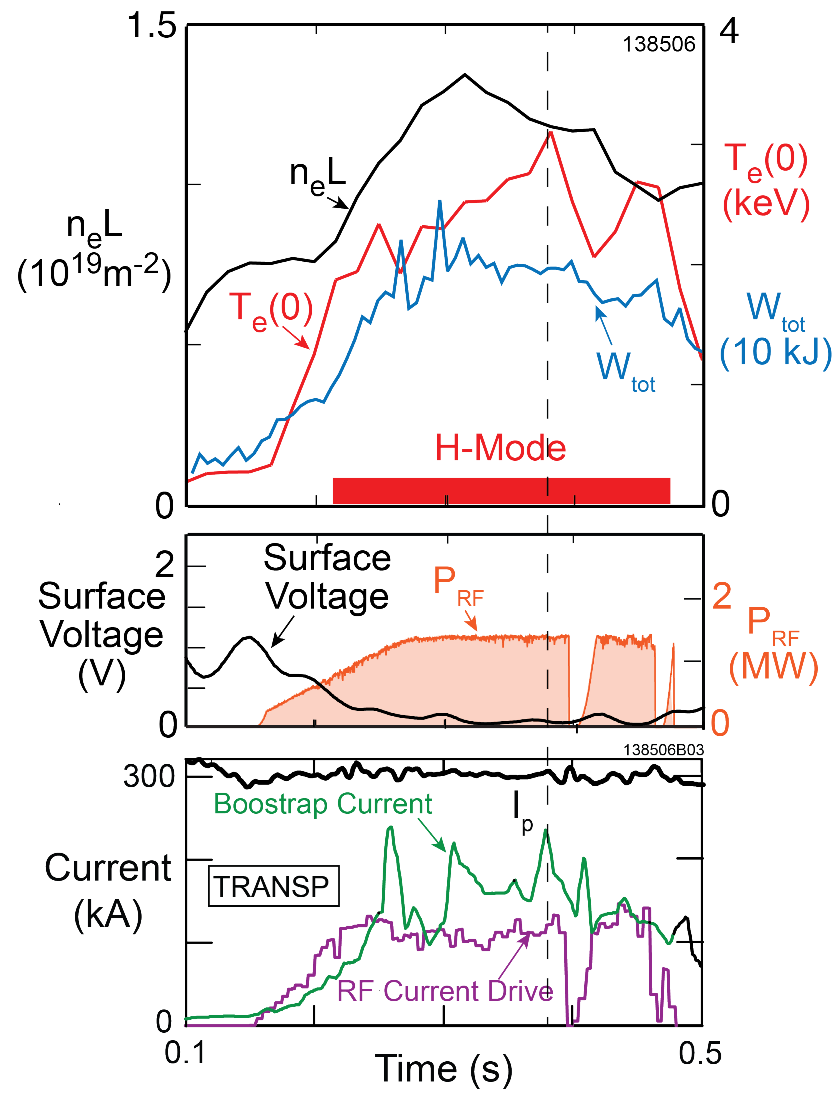
- Couple 30 MHz FW heating as early as possible into the I_p flattop
- Ramp FW power as fast as possible to maximum FW power, preferably in < 50 ms to generate early H-mode transition
- Use $k_{//} = -8\ m^{-1}$ current drive phasing
- NI current drive via both direct FW current drive and bootstrap current generated through FW heating
- First experiment was run in NSTX during 2010 campaign:
  - Achieved $f_{NI} \sim 0.7$ in an I_p = 300 kA H-mode plasma sustained for several 100 ms using only $P_{rf} \sim 1.4$ MW (next slide)
- Extend scenario to higher P_{rf} at higher $B_T(0)$ in NSTX-U to achieve sustained I_p = 300 kA H-mode plasma with $f_{NI} \geq 1$

FW heating of an I_p = 300 kA plasma in NSTX resulted in rapid increase of $T_e(0)$ and f_{NI} > 70% H-mode*

- 1.4 MW of 30 MHz, $k_{//} = 8\ m^{-1}$ HHFW power rapidly increased $T_e(0)$ from 250 eV to 2 keV and triggered an H-mode transition (NSTX shot 138506)

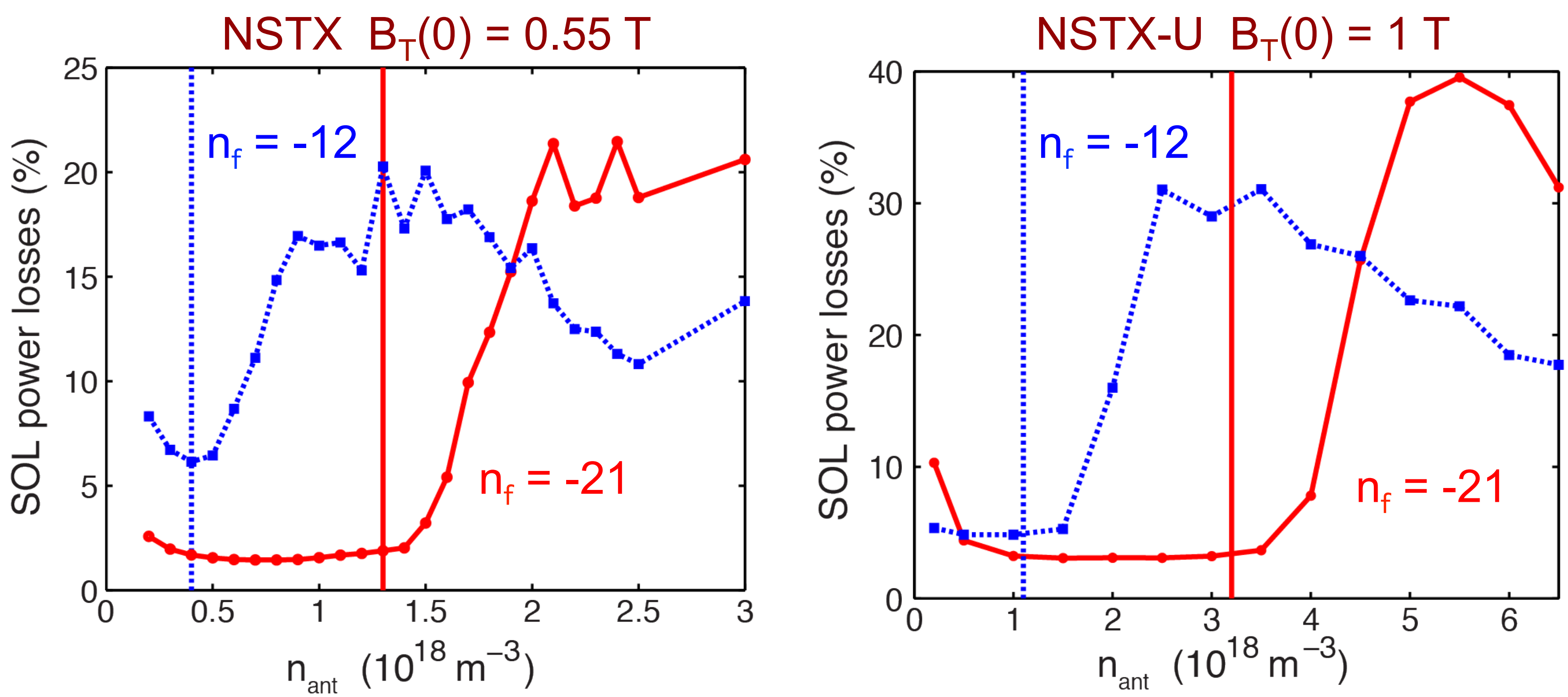
- Notably the Bootstrap current contribution was greater than that from direct RF current drive

- 50% fluctuations in bootstrap current during H-mode phase due to fluctuations in pressure profile



* G. Taylor *et al*., Phys. Plasmas **19** (2012) 042501

Modeling predicts low 30 MHz power losses over a wider range of SOL densities at higher $B_T(0)$ in NSTX-U



SOL power losses versus SOL density in front of antenna. Vertical lines represent values of density for which the FW cutoff starts to "open" in front of the antenna

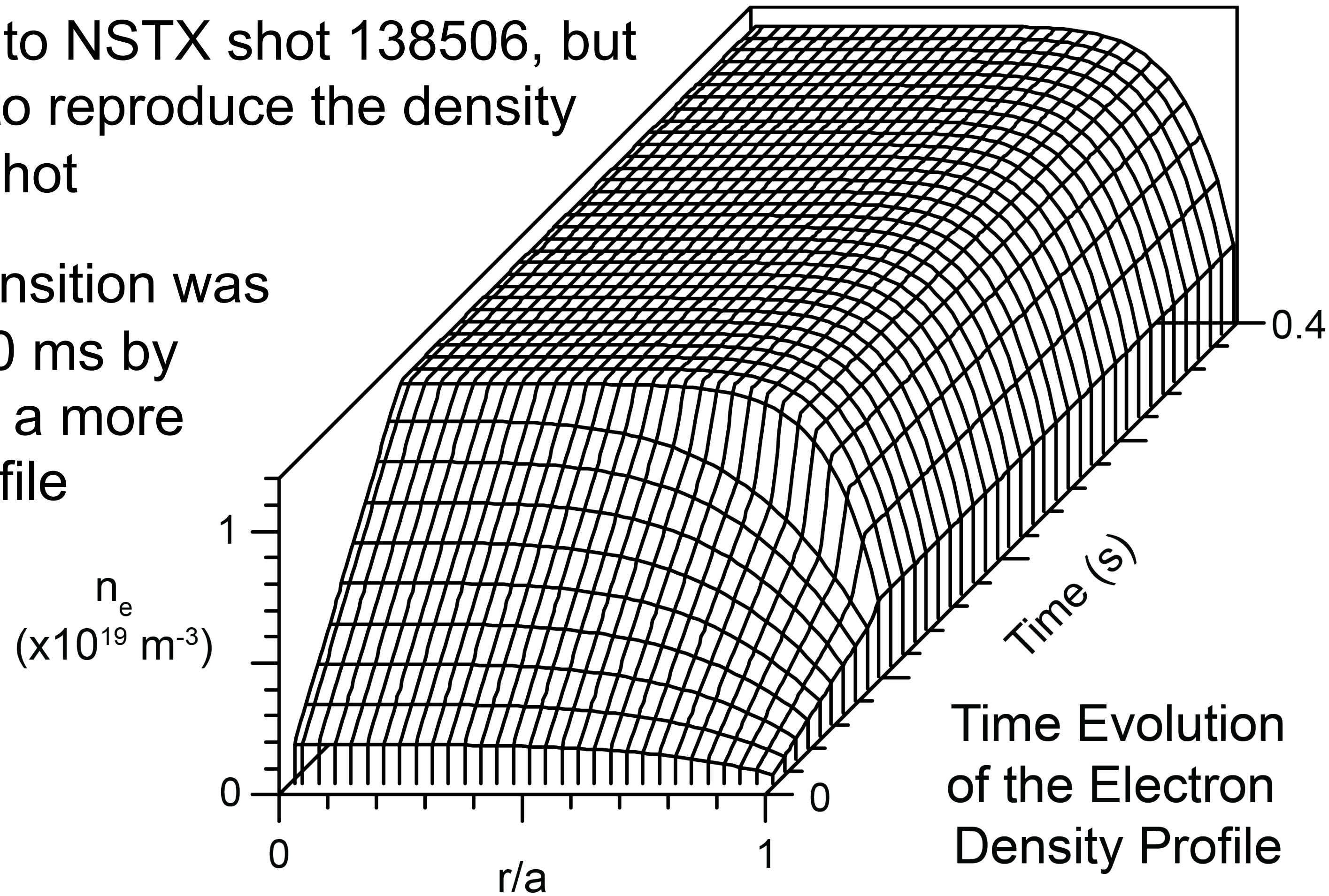
- AORSA modeling predicts RF power losses to SOL increase substantially above the FW cutoff density, consistent with experimental trends*

* N. Bertelli *et al*., Nuclear Fusion **54** (2014) 083004

TRANSP Modeling of I_p = 300 kA Plasmas Heated by 30 MHz FW Power

TRANSP time-dependent transport simulation being used to model FW heated NI NSTX-U plasmas

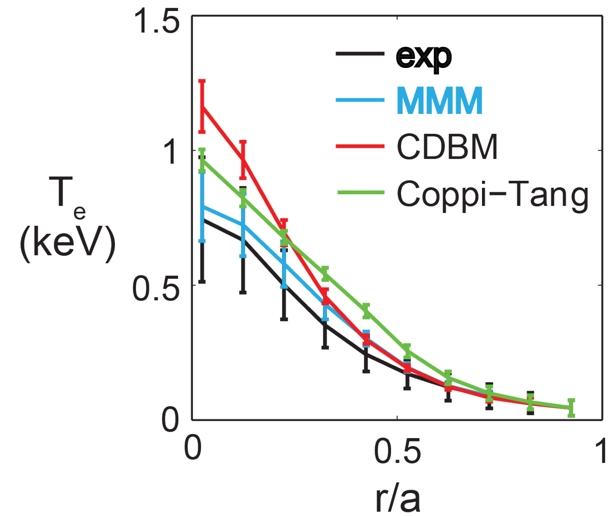
- Simulations ramped $n_e(0)$ to 1.15×10^{13} m^{-3}, between 0 and 100 ms
- $n_e(0)$ is similar to NSTX shot 138506, but didn't attempt to reproduce the density profile of that shot
- An H-mode transition was imposed at 100 ms by transitioning to a more flat density profile



Time Evolution of the Electron Density Profile

TRANSP simulated FW heating of an I_p = 300 kA plasma with $B_T(0)$ between 0.5 and 1 T and P_{rf} up to 4 MW

- MultiMode MMM7.1* transport model used for ions and electrons:
  - MMM7.1 gave the best fit to experimental electron temperature profile for NBI-heated I_p = 300 kA NSTX plasmas, compared to Coppi-Tang or current diffusive ballooning mode model (CDBM)**
- I_p flat top started at 100 ms, FW power turned on at 100 ms and ramped to full power in 40 ms
- FW heating and current drive calculated with TORIC full wave spectral code+
- Used $k_{//}$ = 8 m^{-1} current drive antenna phasing
- Simulations for $B_T(0)$ = 0.5, 0.75 and 1.0 T and P_{rf} = 2, 3 and 4 MW



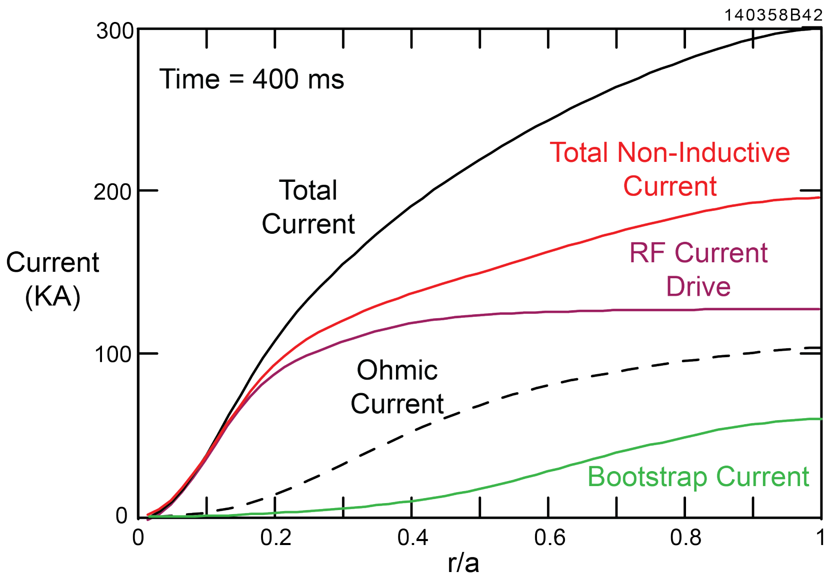
I_p = 300 kA NBI-heated NSTX plasma

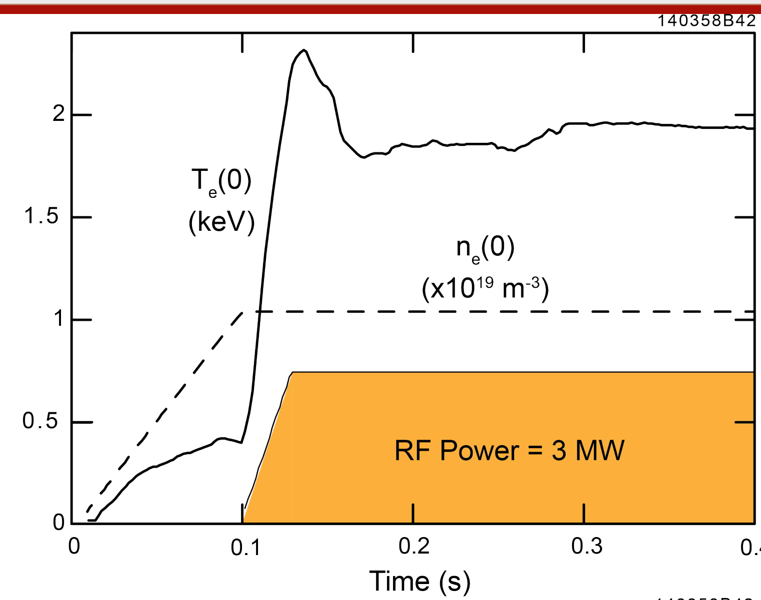
* T. Rafiq *et al*., Phys. Plasmas **20** (2013) 032506 + M. Brambilla, Plasma Phys. Control. Fusion **44** (2002) 2423
** F. M. Poli *et al*., Nucl. Fus. **55** (2015) 123011

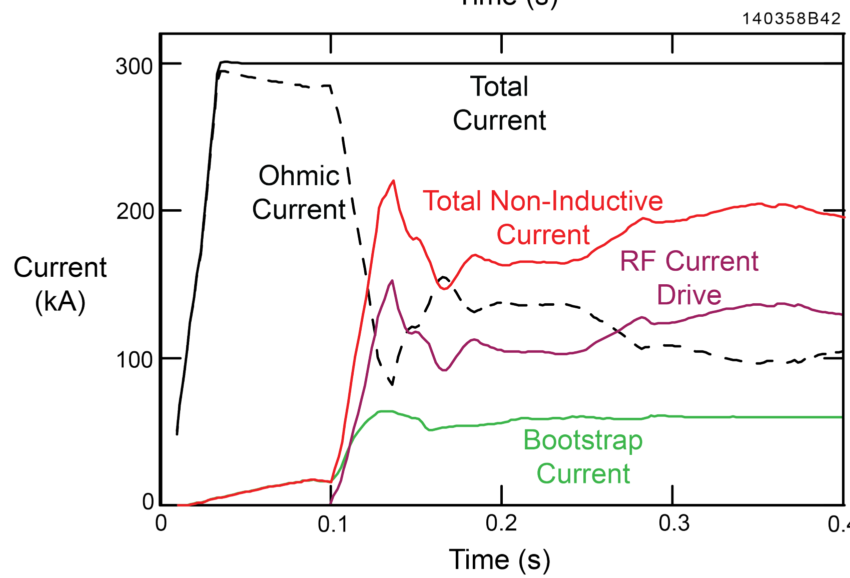
Simulation for $B_T(0)$ = 0.5 T NSTX-U plasma predicts $f_{NI} \geq 1$ is only achievable with P_{rf} ~ 4 MW

At 400 ms:

- RF current drive = 130 kA
- Bootstrap current = 60 kA
- Increasing P_{rf} to 4 MW yields a NI current of 280 kA



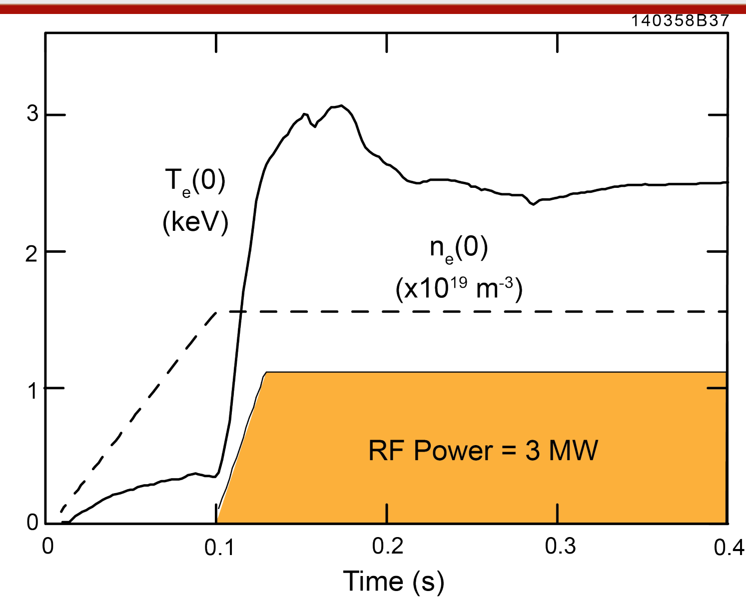


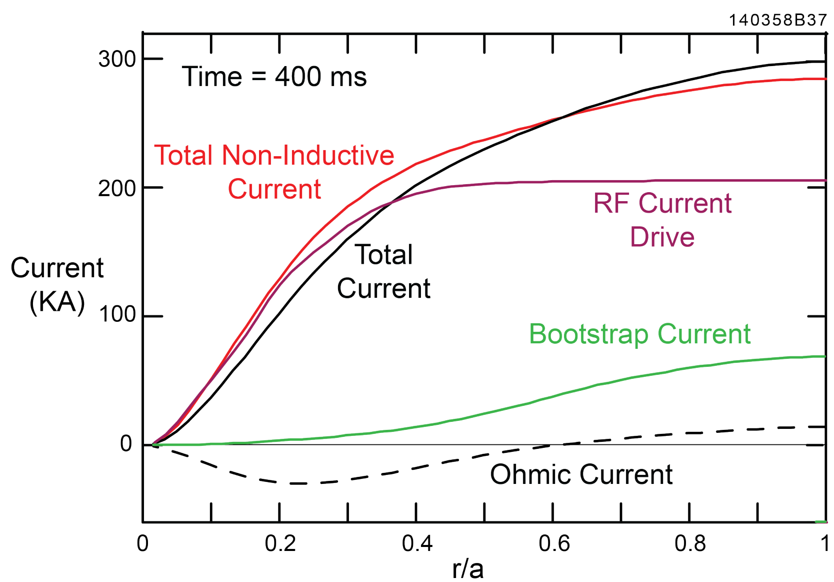


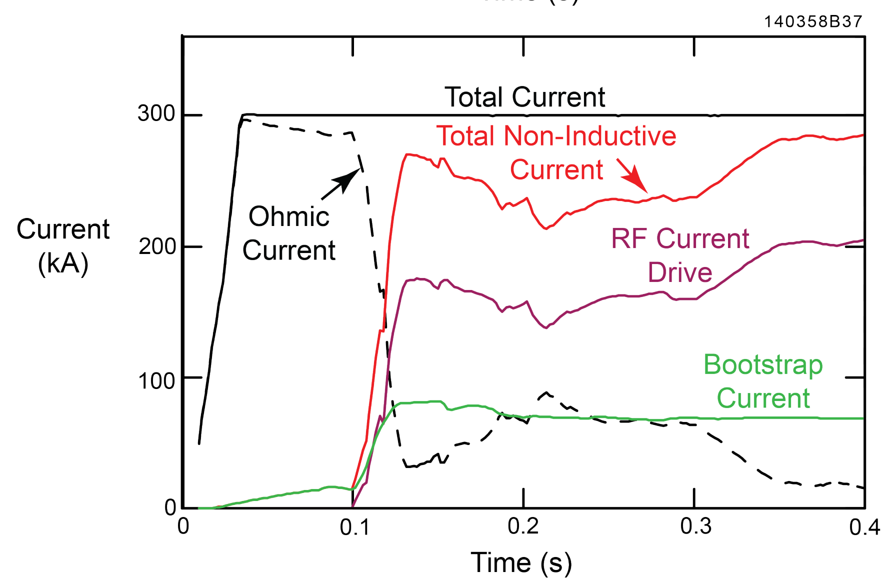
Simulation for $B_T(0)$ = 0.75 T NSTX-U plasma predicts $f_{NI} \geq 1$ probably achievable with P_{rf} ~ 3 MW

At 400 ms:

- RF current drive = 205 kA
- Bootstrap current = 70 kA
- Increasing P_{rf} to 4 MW yields a NI current of 400 kA



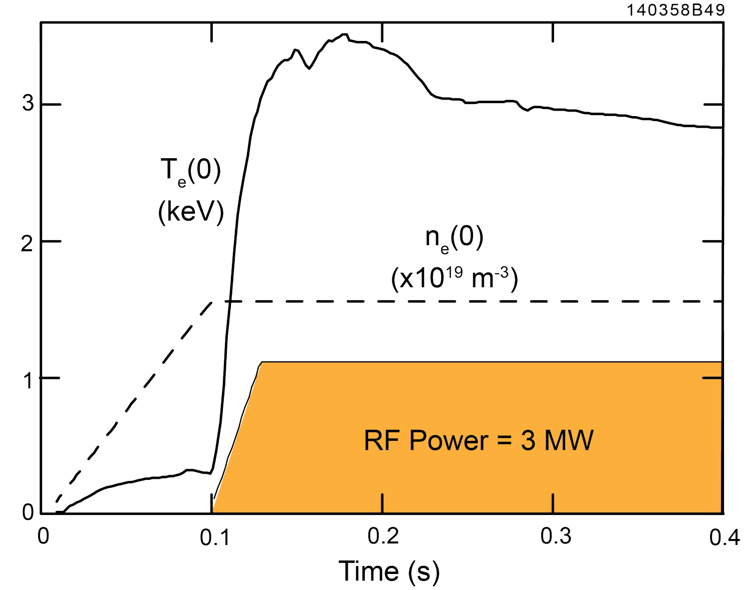


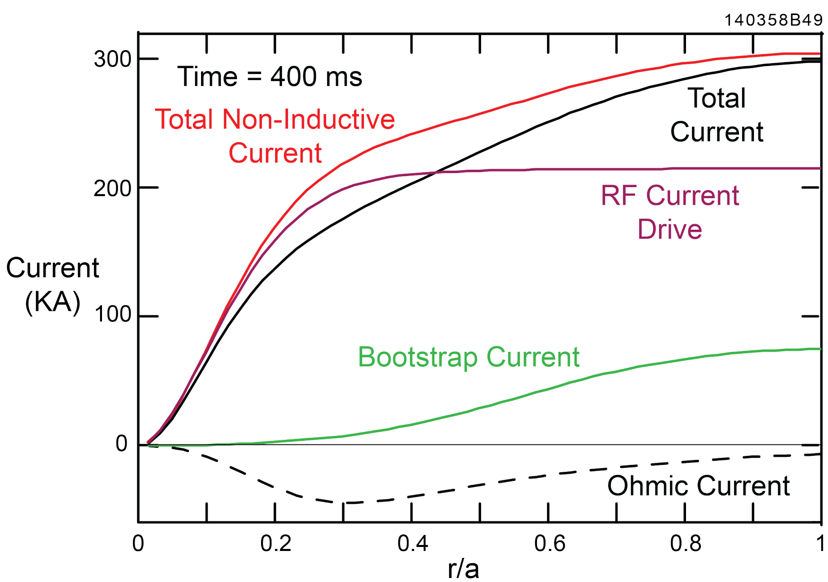


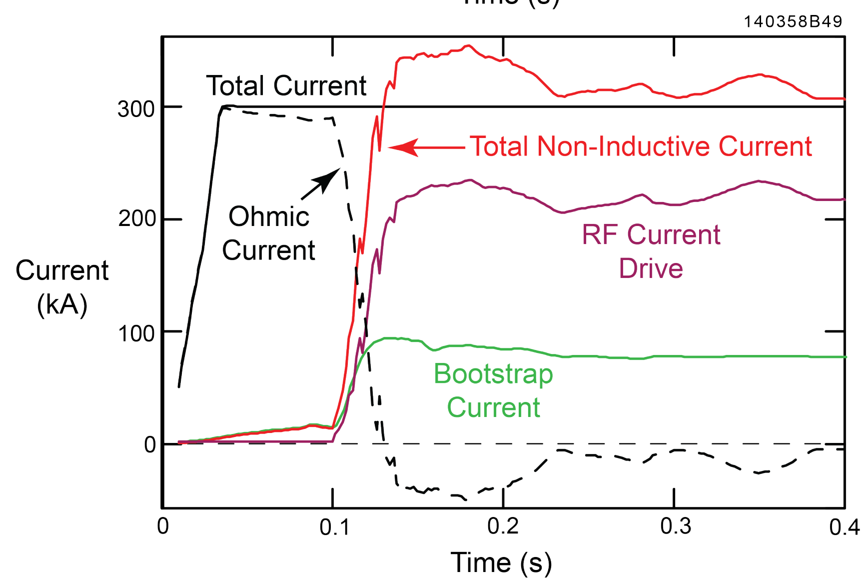
Simulation for $B_T(0)$ = 1.0 T NSTX-U plasma predicts $f_{NI} \geq 1$ is achievable with P_{rf} ~ 3 MW

At 400 ms:

- RF current drive = 220 kA
- Bootstrap current = 80 kA
- Increasing P_{rf} to 4 MW yields a NI current of 410 kA

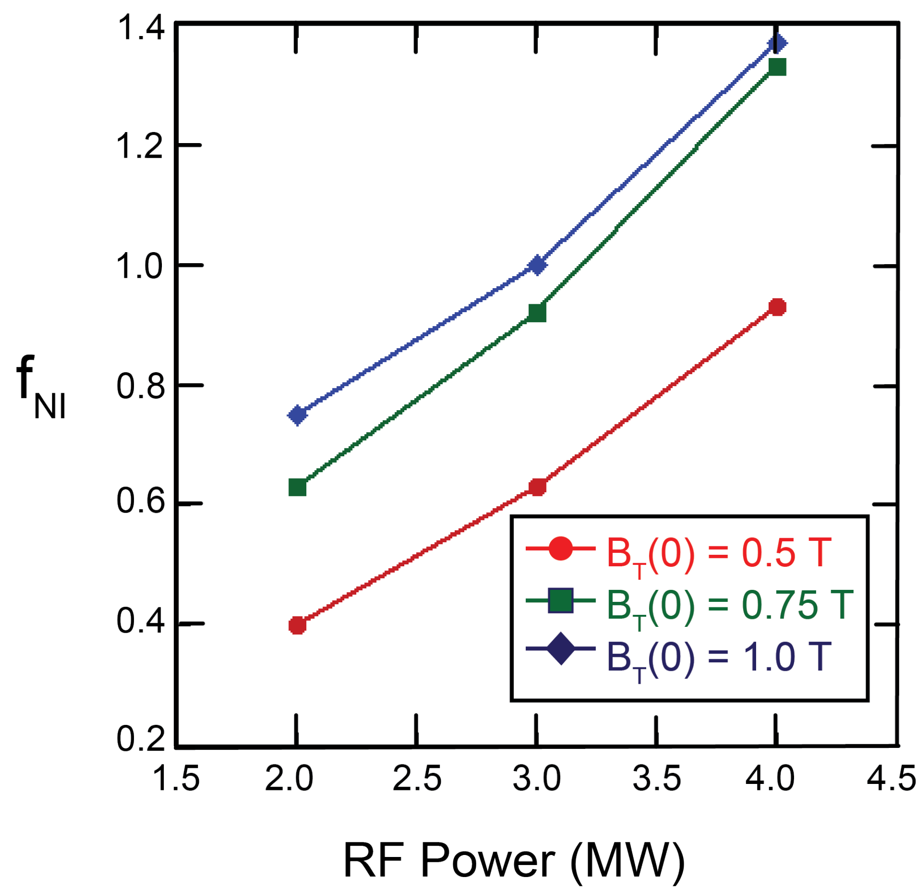




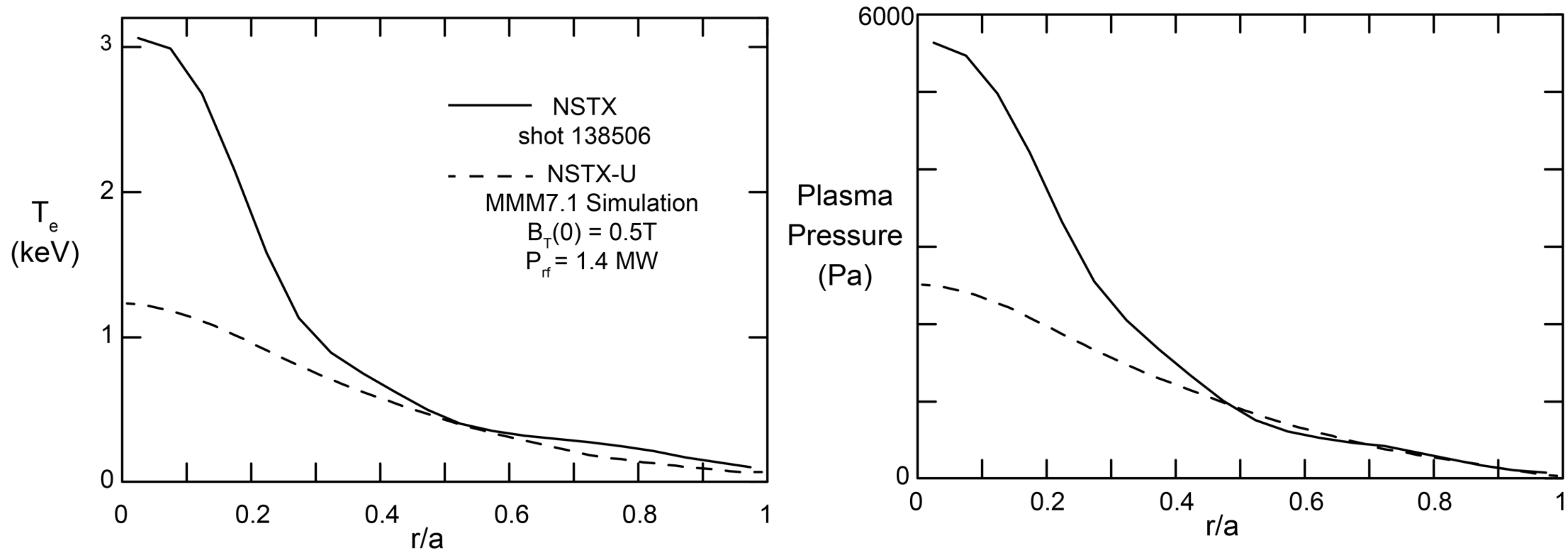


For the same P_{rf}, f_{NI} improved significantly when $B_T(0)$ was increased from 0.5 to 0.75 T

- Much smaller improvement in f_{NI} when $B_T(0)$ was increased from 0.75 T to 1 T, compared to f_{NI} increase when $B_T(0)$ was increased froim 0.5 to 0.75T
- When P_{rf} was increased from 2 to 4 MW, the relative improvement in f_{NI} became smaller when $B_T(0)$ was increased from 0.75 T to 1 T



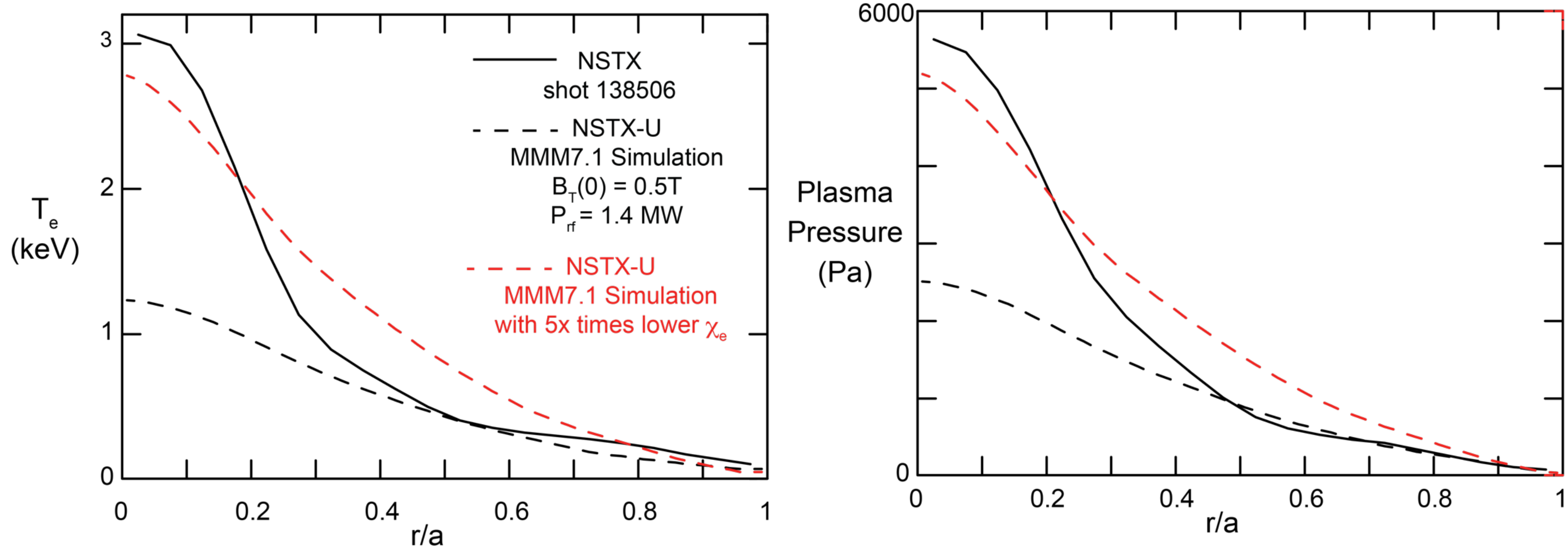
Simulations using MMM7.1 transport model show significant disagreement with NSTX shot 138506



- Simulation of an I_p = 300 kA plasma using MMM7.1 transport model with similar $B_T(0)$ and P_{rf} to NSTX shot 138506 predicts much lower $T_e(0)$ and central plasma pressure than was obtained in experiment

- Simulation using MMM7.1 transport model also predicts much lower FW current drive and bootstrap current than attained in shot 138506

Simulation with 5 times lower electron diffusivity gives better match to $T_e(0)$ in NSTX shot 138506

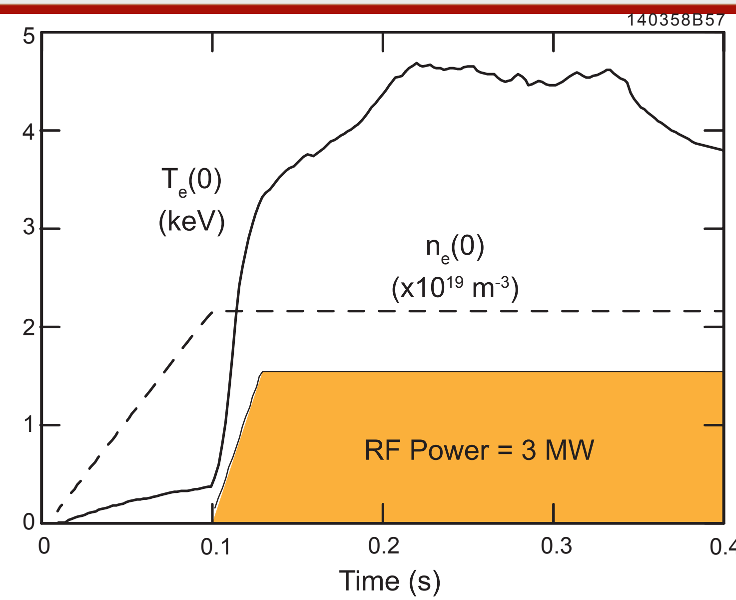


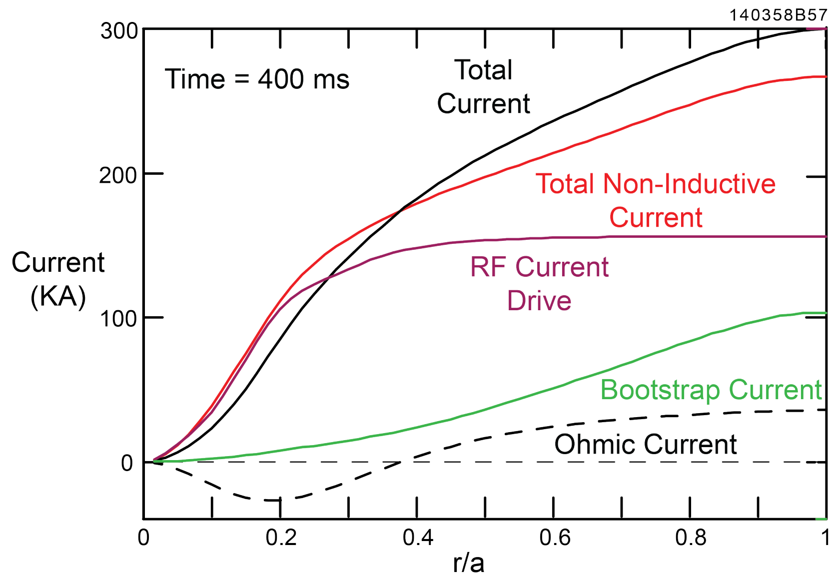
- Simulation with 5 times lower electron diffusivity better matches $T_e(0)$ and central pressure on NSTX shot 138506, but poorer match at r/a ~ 0.5
- Appears core transport in the FW-heated I_p = 300 kA discharge is much lower than in the NBI-heated I_p = 300 kA discharge

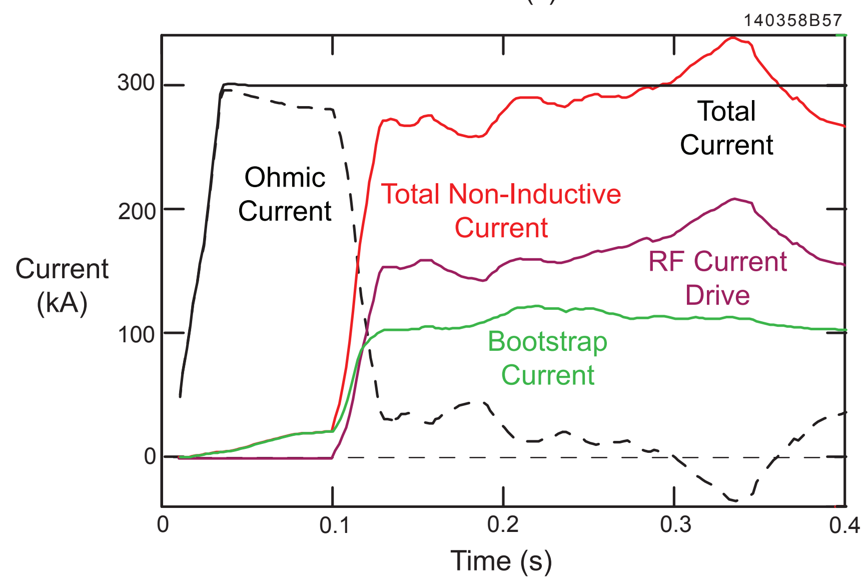
Simulation with $B_T(0)$ = 0.5 T, P_{rf} = 3 MW and 5 times lower electron diffusivity predicts f_{NI} ~ 1

At 400 ms:

- RF current drive = 160 kA
- Bootstrap current = 105 kA







Summary

- TRANSP simulations, using MMM7.1 transport model, were run for FW-heated I_p = 300 kA NSTX-U plasmas with $B_T(0)$ = 0.5, 0.75 and 1.0 T and P_{rf} = 2, 3 and 4 MW
- For the same P_{rf}, f_{NI} improved significantly when $B_T(0)$ was increased from 0.5 to 0.75 T
- f_{NI}=1 should be achievable with P_{rf} ~ 3 MW in $B_T(0)$ =1 plasma and possibly in $B_T(0)$ = 0.75 T plasma
- Simulation using the MMM7.1 model under conditions similar to FW-heated NSTX shot 138506 predicts much lower $T_e(0)$ than was achieved experimentally:
  - Suggests core transport lower in FW-heated plasma than in NBI-heated plasma, where MMM7.1 model predictions agree better with experiment
  - Decreasing c_e by 5x gave better agreement between predicted and measured $T_e(0)$ in 138506 → possible that f_{NI} ~ 1 is achievable in a $B_T(0)$ = 0.5 T NSTX-U plasma with P_{rf} ~ 3 MW

Future Work

- Need transport model that gives better agreement to $T_e(R)$ profile obtained in NSTX shot 138506 in order to project performance of FW heating and current drive in NSTX-U

- Simulations will be run with a density profile that better matches NSTX shot 138506

- Study the effect of the timing and ramp rate of P_{rf} on f_{NI}