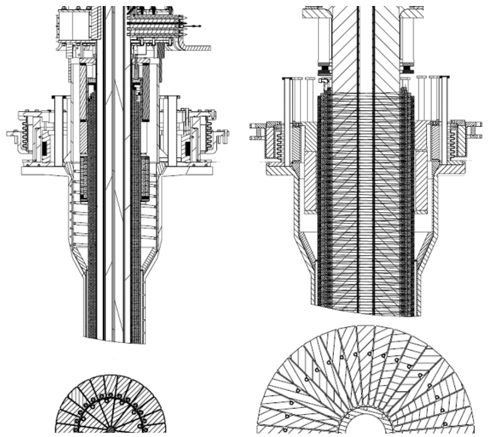
ABSTRACT

The National Spherical Torus eXperiment Upgrade (NSTX-U) will operate at maximum axial toroidal field of 1T, maximum plasma current (I_p) of 2MA, and pulse length up to 5 seconds. Three additional neutral beam injection (NBI) sources, with tangency radii of 110-130cm, will provide significant off-axis current drive. Time-dependent free-boundary TRANSP/ISOLVER simulations have self-consistently modeled fully non-inductive (NI) I_p ramp-up. Non-solenoidal startup with Coaxial Helicity Injection (CHI), simulated with TSC, provides the initial plasma condition for the simulations. RF waves are injected to prepare target plasmas where NBI can be used with minimal power/particle losses. 1MW of Electron Cyclotron (EC) power can rapidly heat CHI plasmas up to 1keV, and 4MW of High Harmonics Fast Wave power can drive I_p~350kA. With 10MW of NBI, NI I_p ramp up to ~900kA is possible in 2.5s. In this paper we discuss how the time of the NBI sources and the NBI source energy affect the profile evolution and access to advanced target scenarios in NSTX-U. These simulations provide a reference operational space for NI ramp-up experiments during the first two years of operation of NSTX-U, as well as guidance for the EC accessibility and use for optimization in later non-solenoidal startup experiments.

This work is supported by the US Department of Energy under DE-AC02-CH0911466

NSTX-U will increase the operational space by adding two new capabilities

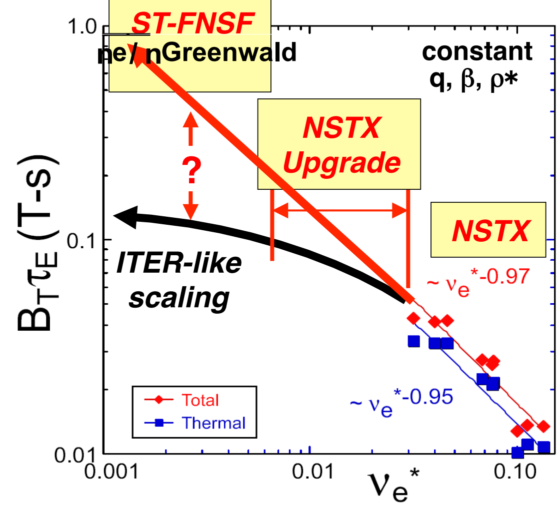
Previous center-stack | **New center-stack**



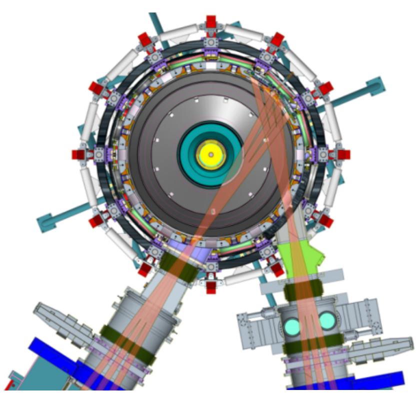
TF OD = 20cm | **TF OD = 40cm**

- **Reduces ν^* → ST-FNSF values to understand ST confinement**
  - Expect 2x higher T by doubling B_T, I_P, and NBI heating power
- **5x longer pulse-length**
  - q(r,t) profile equilibration
  - Test non-inductive ramp-up

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

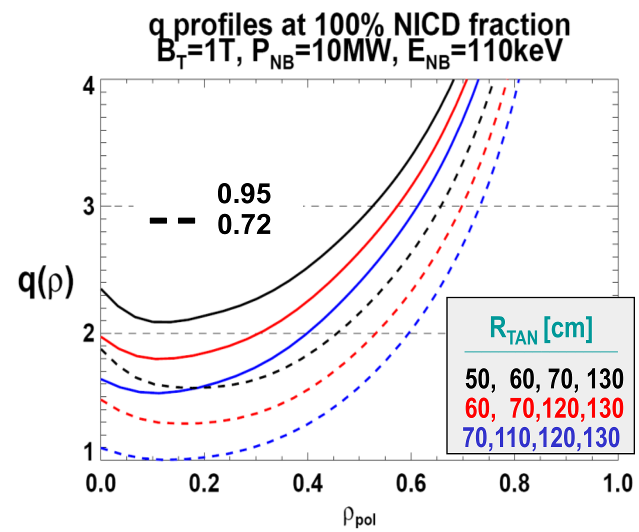


Normalized e-collisionality $\nu_e^* \propto n_e / T_e^2$



Present NBI | **New 2nd NBI**

- **2x higher CD efficiency from larger tangency radius R_{TAN}**
- **100% non-inductive CD with core q(r) profile controllable by:**
  - NBI tangency radius
  - Plasma density, position (not shown)



NSTX-U experiments will guide development of ST-FNSF strategies for non-inductive ramp-up and sustainment

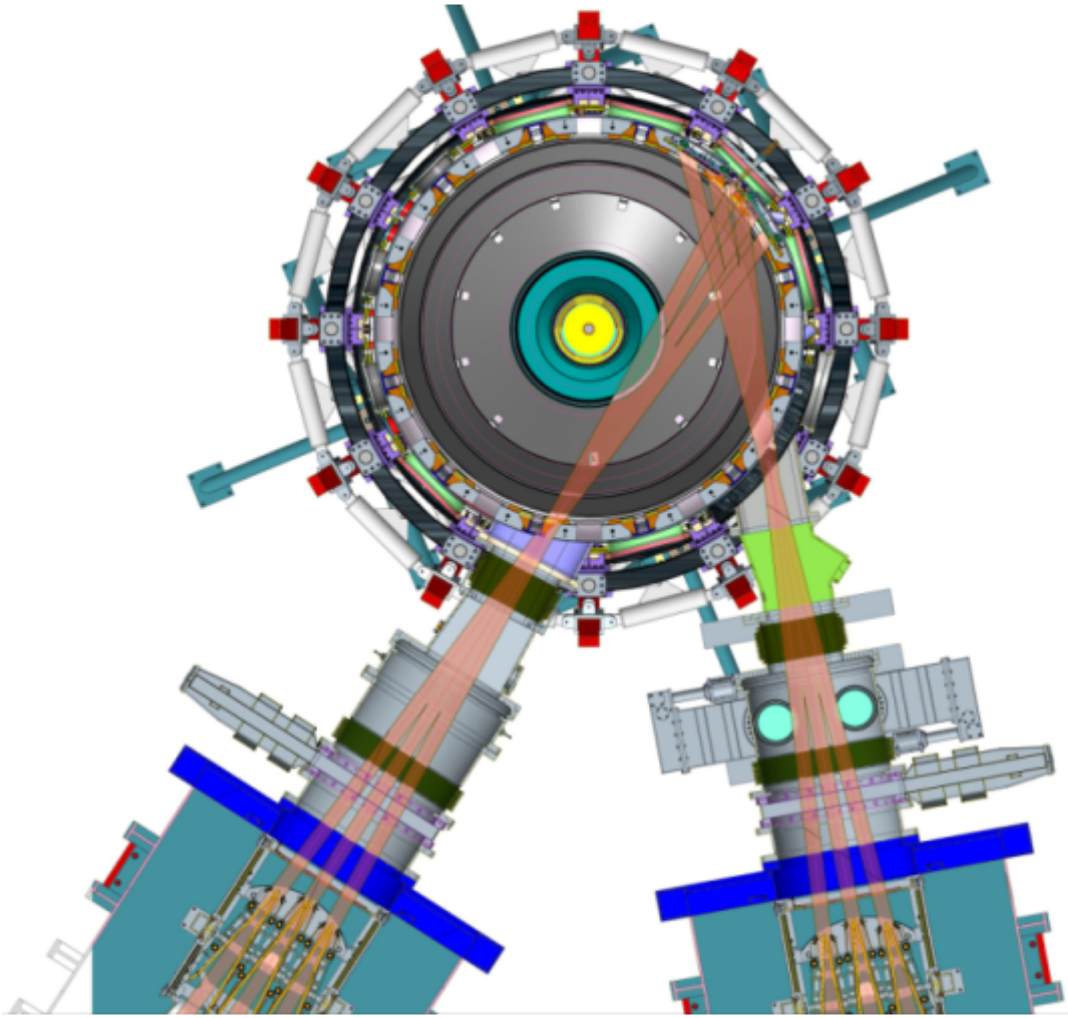
1. Develop and understand non-inductive start-up and ramp-up (overdrive) to project to ST-FNSF with small/no solenoid
   – Contributes to the finalization of the EC system design
   – Contributes to optimized use and synergy of RF and NBI in ramp-up
2. Demonstrate 100% non-inductive sustainment at performance that extrapolates to ≥ 1MW/m^2 neutron wall loading in FNSF
   – Contributes to the optimization of profile evolution and control in the ramp-up to access advanced operation

"the gap in demonstrating non-inductive startup and ramp-up is larger than the gap in demonstrating 100% non-inductive sustainment in the ST" [PAC33]

(Also emphasized in FESAC TAP 2008, RENEW 2009)

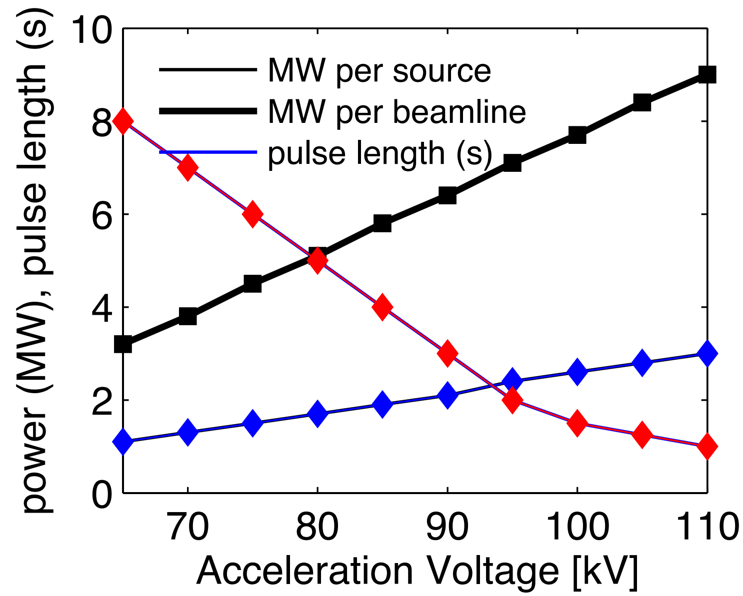
Second beamline at larger tangency radius will allow fully non-inductive operation up to 1MA

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

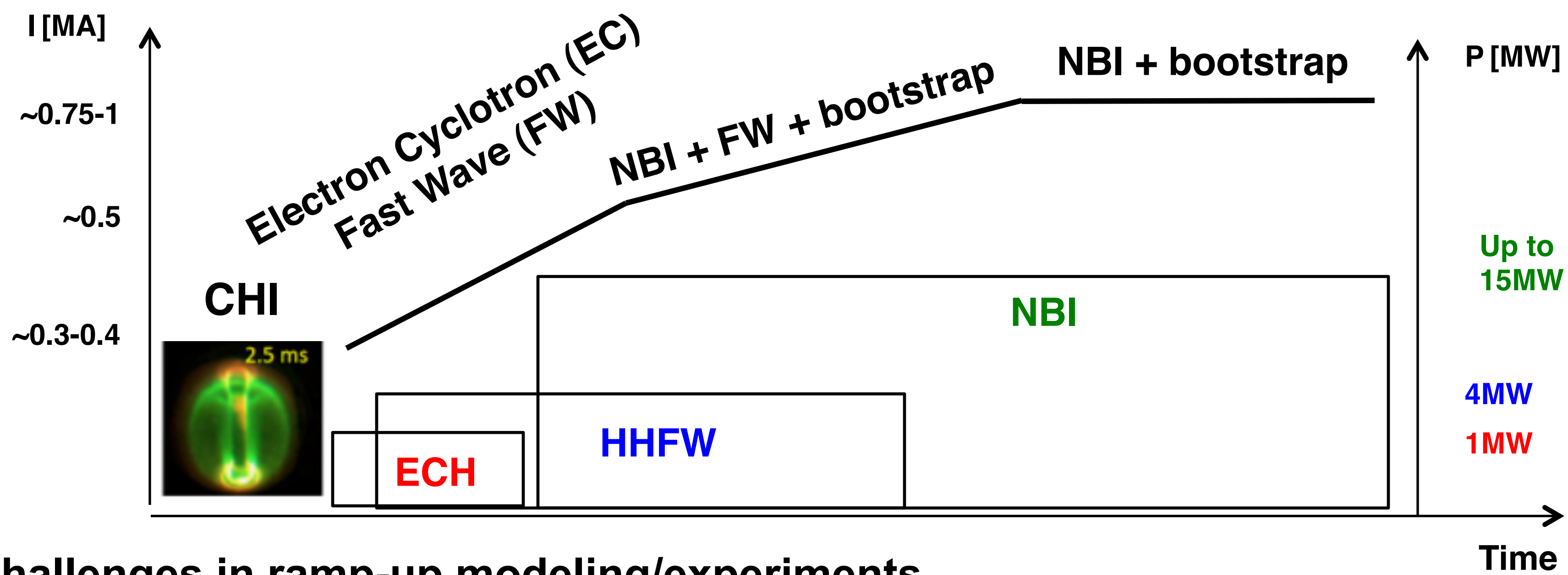


Present NBI

New 2nd NBI



Non-inductive startup, ramp-up and sustainment needs to combine RF, NBI and non-solenoidal startup



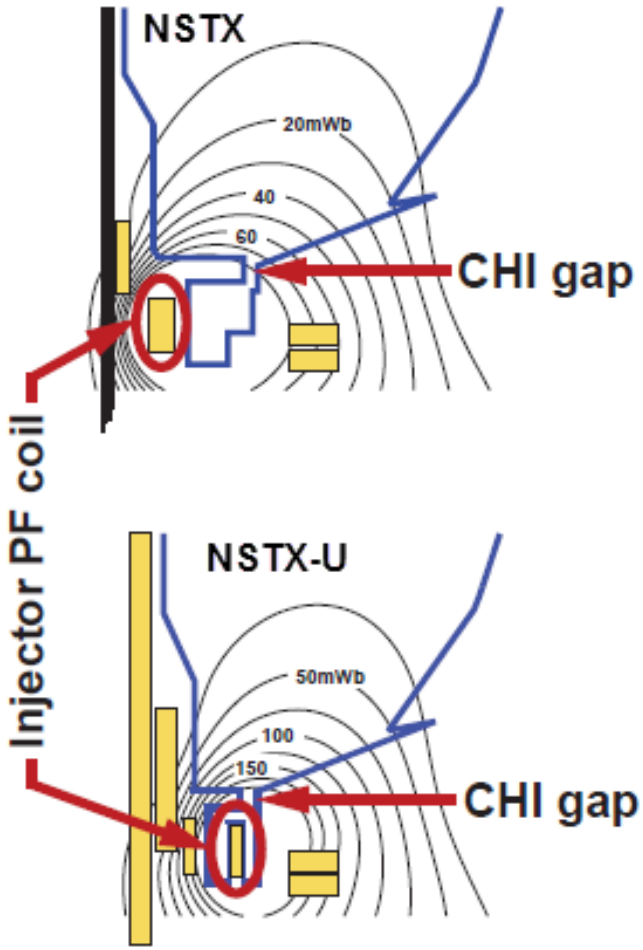
Challenges in ramp-up modeling/experiments

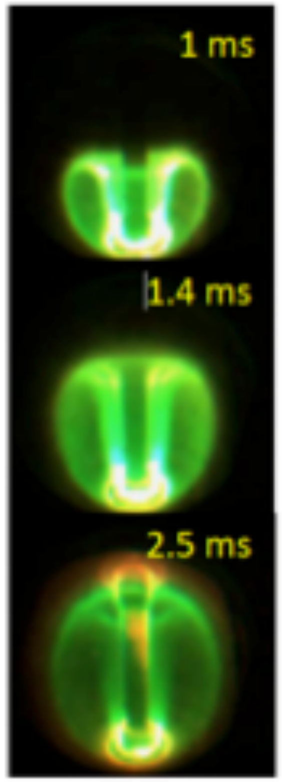
1. Heat CHI target plasma to maximize efficiency of external H/CD sources
2. Combine RF and NBI, aim at best synergy of sources
3. Minimize beam losses at low current => density control, heat start-up plasma
4. Optimize NBI source combination for profile control

Tailor kinetic and current profiles to access target flattop plasmas

(and do this while maintaining the discharge in the MHD stable operational space)

Non inductive startup successfully demonstrated on NSTX, it is projected to induce up to 450kA startup in NSTX-U





Injector flux in NSTX-U is ~ 2.5 times higher than in NSTX → supports increased CHI current

CHI: Coaxial Helicity Induction

Simulations of startup performed with:

- TSC

  Raman (U. Washington), S. Jardin (PPPL)

  IEEE Trans. Plasma Sci. 42 (2014) 2154

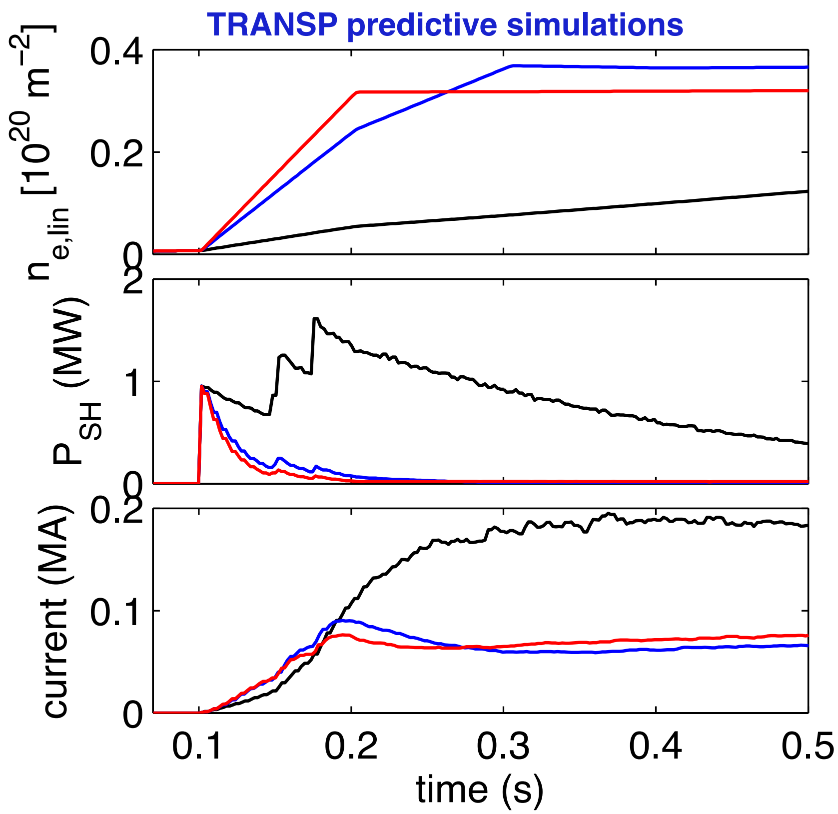
- NIMROD

  B. Hooper (LLNL)
  C. Sovinec (U-Wisconsin)
  F. Ebrahimi (Princeton University)

Hoover et al, Phys. Plasmas 20 092510 (2013)
F. Ebrahimi, et al., PoP 20 090702 (2013)

Challenges with using beams on CHI plasma target

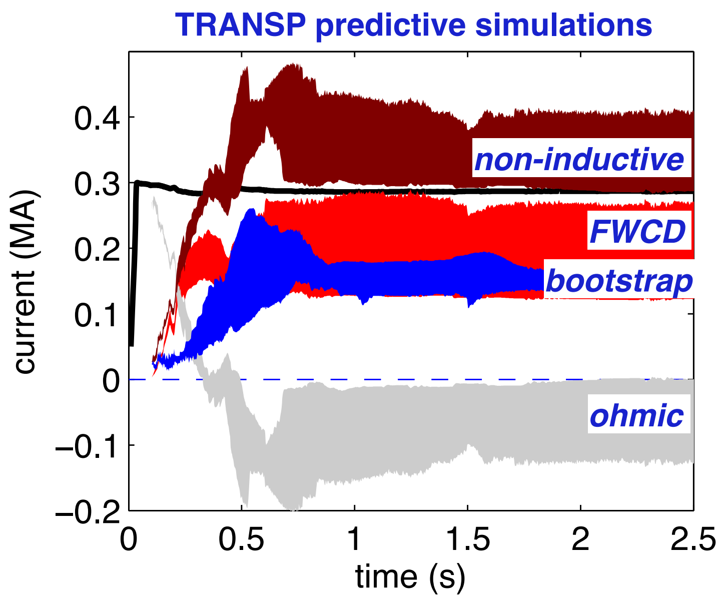
- Larger magnetic field in NSTX-U improves beam confinement. However:
  - Startup current of at least 300kA required
  - low beam absorption at low temperature
  - Large beam shine-thru at low density

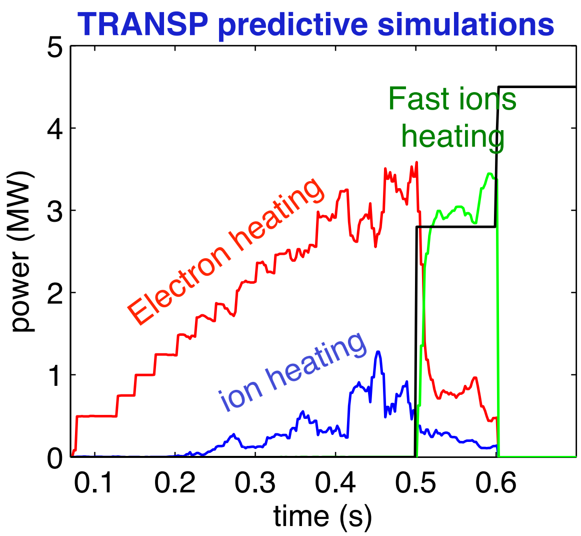


- Electron Cyclotron heating can effectively raise temperature
- Shine-thru could be reduced by controlling density at low current
- Might be an issue for EC accessibility
- Driven beam current still low

=> need to optimize startup phase to optimize beam absorption and confinement

Optimal range of 350-400kA for non-inductive current from HHFW predicted in start-up plasma conditions

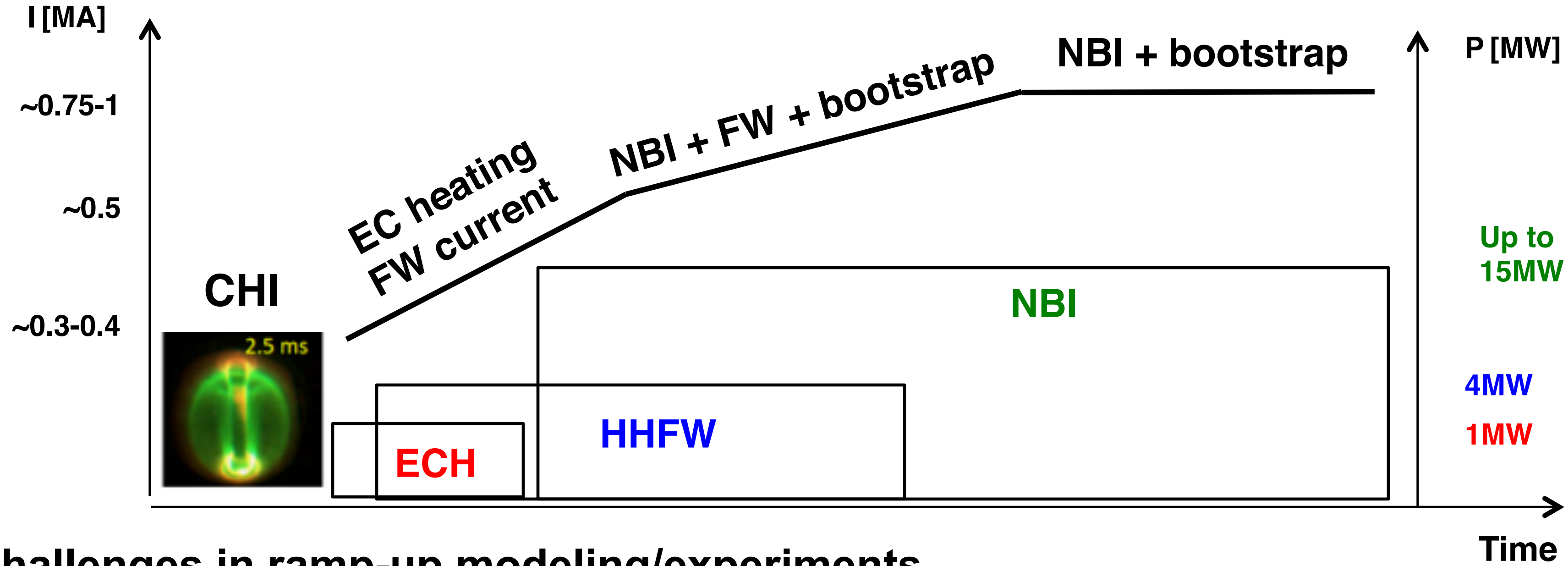




- NSTX experiments demonstrated sustainment of 300kA with 1.4MW of HHFW, bootstrap 75% of non-inductive [*G. Taylor et al, Phys. Plasmas, **19**, 042501 (2012)*]
- However, we aim at using HHFW at startup where
  - Density is low
  - Coupling might be an issue
- Absorption of FW to fast ions is another issue

  => avoid to superpose FW and NBI in simulations

Non-inductive startup, ramp-up and sustainment needs to combine RF, NBI and non-solenoidal startup



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(and do this while maintaining the discharge in the MHD stable operational space)

The discharge is evolved with free-boundary TRANSP/Isolver

Procedure

1. Select discharge from NSTX high aspect ratio exp. [*Gerhardt et al, NF 51 (2011) 073031*]
2. Use free-boundary equilibrium Isolver to generate equilibria in NSTX-U geometry
3. Use new boundary to build-up discharge in TRANSP with self-consistent evolution of pressure (temperature) profiles and H&CD profiles
    - EC model is GENRAY with corrections for electron momentum
    - FW model is reduced full wave TORIC-5 (*GENRAY+CQL3D work in progress*)
4. Electron energy transport model chosen for RF phase is MMM (Multi-Mode)
5. Ion energy transport model chosen is Neoclassical (NCLASS)
6. Density profiles are prescribed in shape, based on NSTX experiments
    - Amplitude scan between 60% and Greenwald density in H-mode

Isolver is a free boundary equilibrium solver available in TRANSP both in interpretive and predictive runs

R. Andre, DPP-APS 2012

• **Free boundary**: magnetic field representation outside plasma useful for RF codes and fast ion orbit

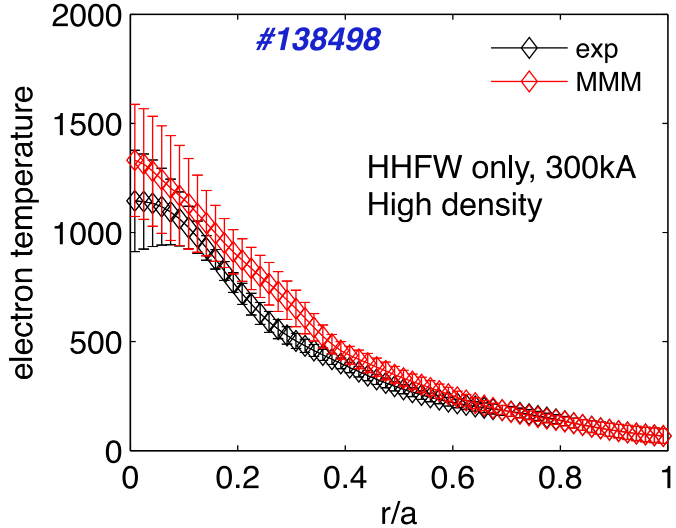
• **Coil currents**
Least squares mode – coil currents selected to match boundary
(default operation, not self-consistent)

Measured coil currents mode – feedback applied to center the plasma at the prescribed boundary (analysis and predictive mode)

• **Passive structures** – induced currents in vacuum vessel
Affects plasma evolution and shape particularly during current ramp-up

• **Coupled flux diffusion** – time evolution of q profile coupled to equilibrium solution
Self-consistent solution of coupled plasma and coil circuit equations for predictive modeling

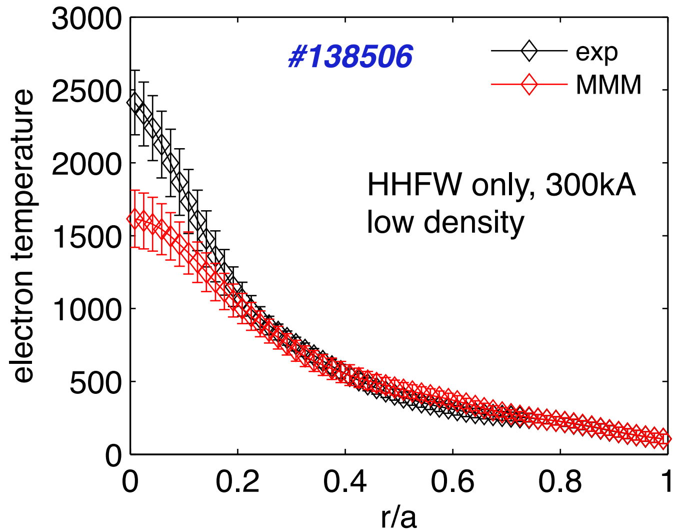
MMM95 reproduces (on average) amplitude and peaking of electron temperature profiles during the HHFW phase

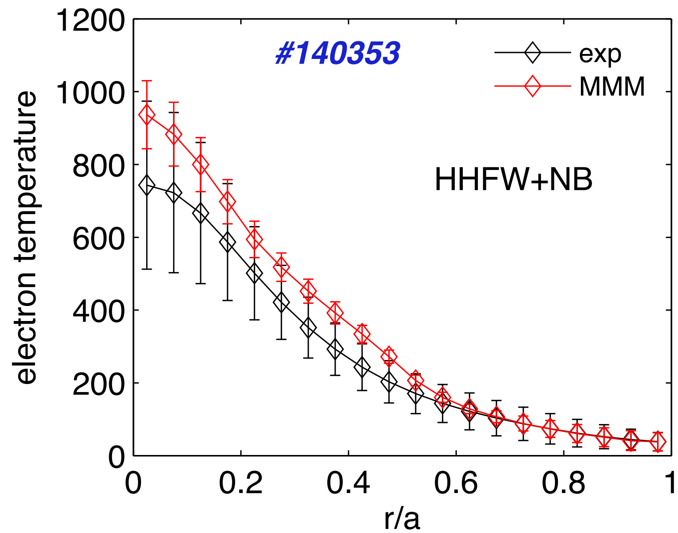


Profiles averaged over the heating phase

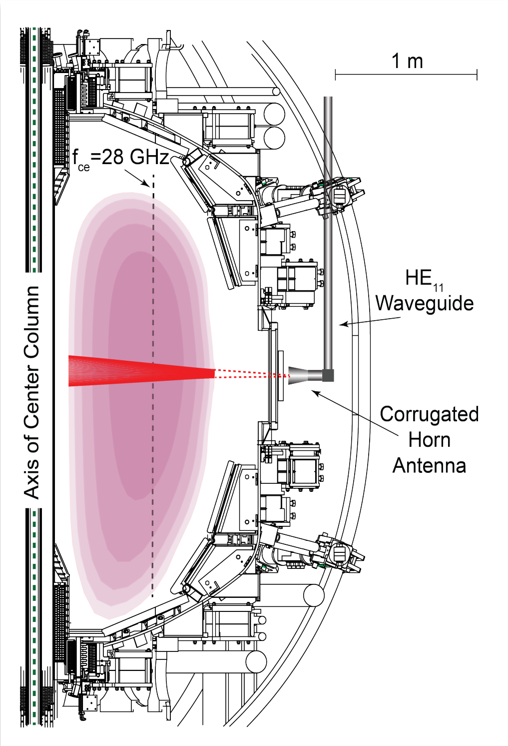
- MMM95 reproduces within 20% the average amplitude and peaking in HHFW discharges and in discharges with HHFW+NBI.
- Ion temperature overestimated in NBI discharges

  (no data available in RF heated discharges)





28 GHz EC heating bridges the $T_e(0)$ gap between CHI start-up and RF/NB heating during the I_p ramp-up



NSTX-U vacuum vessel showing a $B_T(0)$ = 1 T CHI plasma and location of 28 GHz resonance

G. Taylor et al., AIP Conf. Proc. vol. 1580, p. 534 (2014).
G. Taylor et al., Proc. 18th Joint Workshop on ECH, Japan (2014).

1.5 MW, 28 GHz (O-mode) or 1.0 MW, 35 GHz (X-mode)

(Tsukuba university, used on QUEST for EC heating)

The tube will have depressed collector, improved electron gun design.

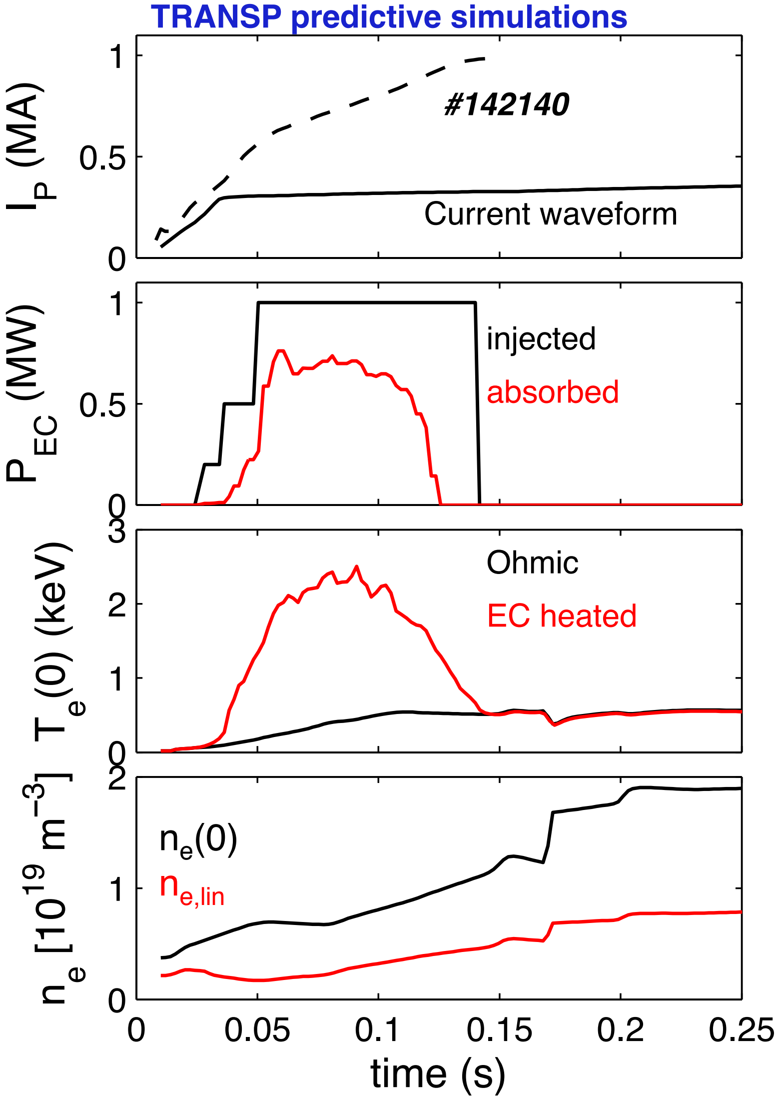
Use 2nd X-mode ECH for start-up at Bt(0)~0.7 T on NSTX-U.

The role of EC is to heat CHI plasma to a level where FW and/or NBI can be efficiently absorbed

⇒ Without electron heating, CHI current would decay within 5-10ms

⇒ expect it to be difficult to couple FW directly to CHI-only target

Planned ECH system needed to heat CHI targets from 10eV to above 500eV in 30ms

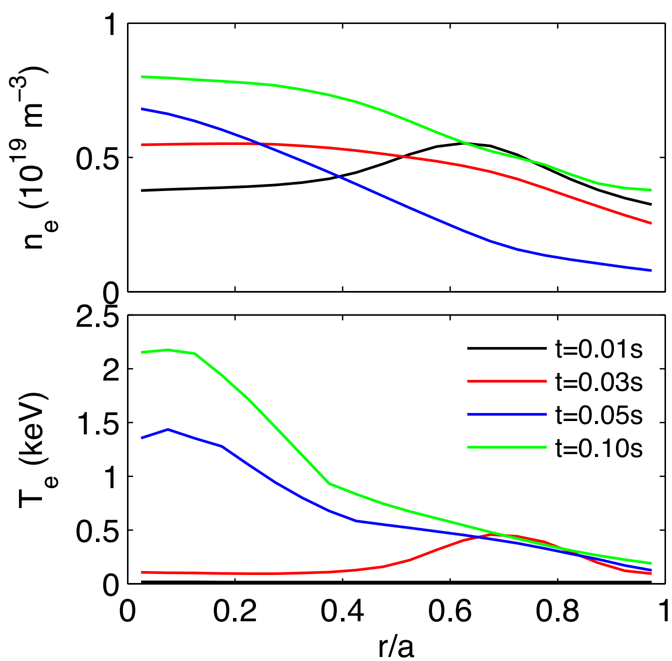


Use NSTX CHI→OH+NBI H-mode discharge

As a reference for CHI-startup density and temperature profiles

(*Raman, Nucl. Fusion,* ***53*** *073017 (2013)*)

- Prescribe current waveform



Need additional heating and current drive

Challenges in heating CHI target plasma

☺ First-pass absorption in low density startup plasma

☹ Plasma becomes overdense to EC at t~130ms => $n_e(0)\sim 10^{19}\ m^{-3}$

$n_{e,lin} \sim 0.5\times10^{19}\ m^{-2}$

☹ low absorption at startup

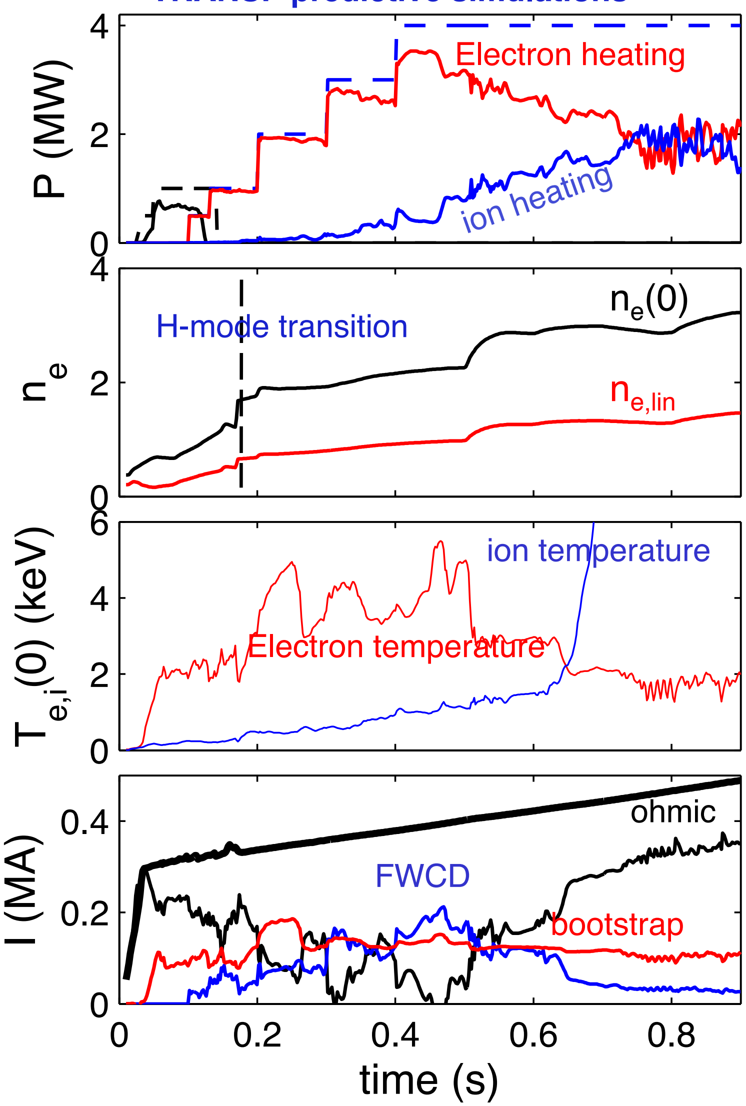
☹ Time window for EC heating is short

Would need CHI to drive at least 300 kA to delay current decay and use RF/NB

(projections indicate 450 kA available on NSTX-U with new design)

HHFW mostly effective at sustaining current during the first 500ms of ramp-up

TRANSP predictive simulations



Electron heating decreases with increasing density
=> Reduces FWCD

HHFW trigger L-H transition
(prescribed in this simulation, thru the density profile)

Decreased electron heating causes decrease in electron temperature

~3MW absorbed needed to ramp current to ~450kA
=> Pessimistic compared to NSTX experiments

Likely need to rely on Neutral Beam Injection to ramp-up current from 450kA to 1MA

Putting the pieces together …

Select target scenario (*Menard et al, NF 2012, Table I, Gerhardt NF 2012*)
100% NICD (1T/1MA) with 10MW of NBI @0.5-1.0n_G, bootstrap fraction 0.61-0.85

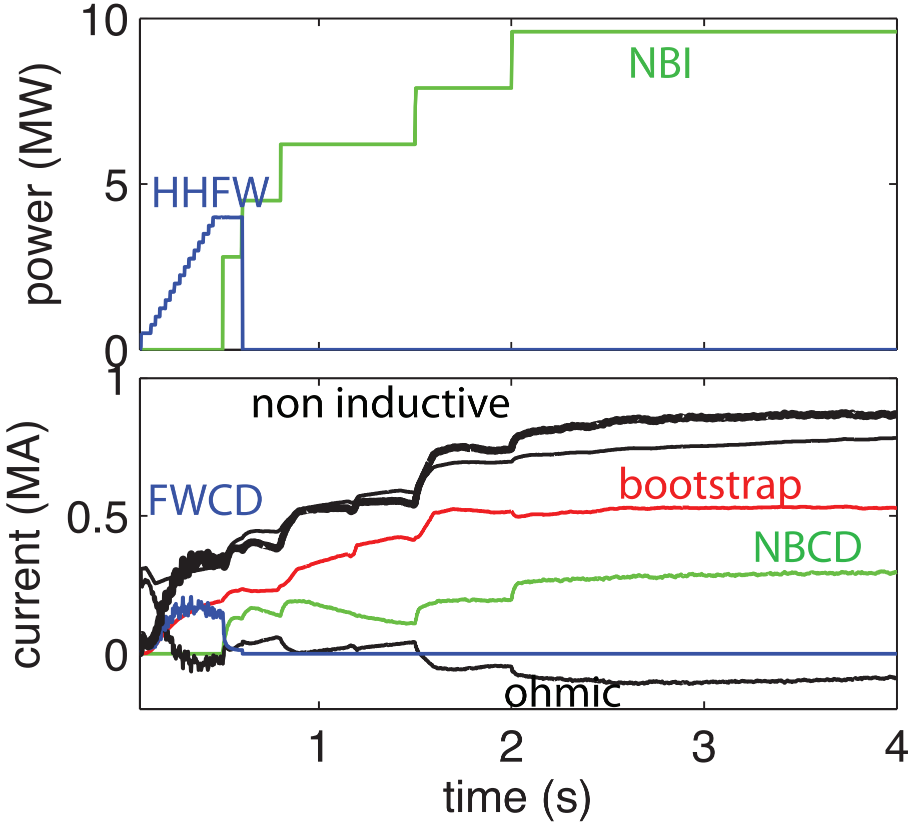
- Use reference discharge #142305, κ~2.55, li(1)~0.5, A~1.55 (*Gerhardt, NF 2011*)
- Assume initial target of 300kA
- CHI plasma heated by EC (needed for HHFW absorption)
- Use 4MW of HHFW and 10MW of NBI at 80keV
- HHFW drives L-H transition and current at low density where NBI shine-thru large
- NBI second beam-line ramps current to the target plasma

H/CD sources are evolved self-consistently in TRANSP with free-boundary equilibrium solver (Isolver)

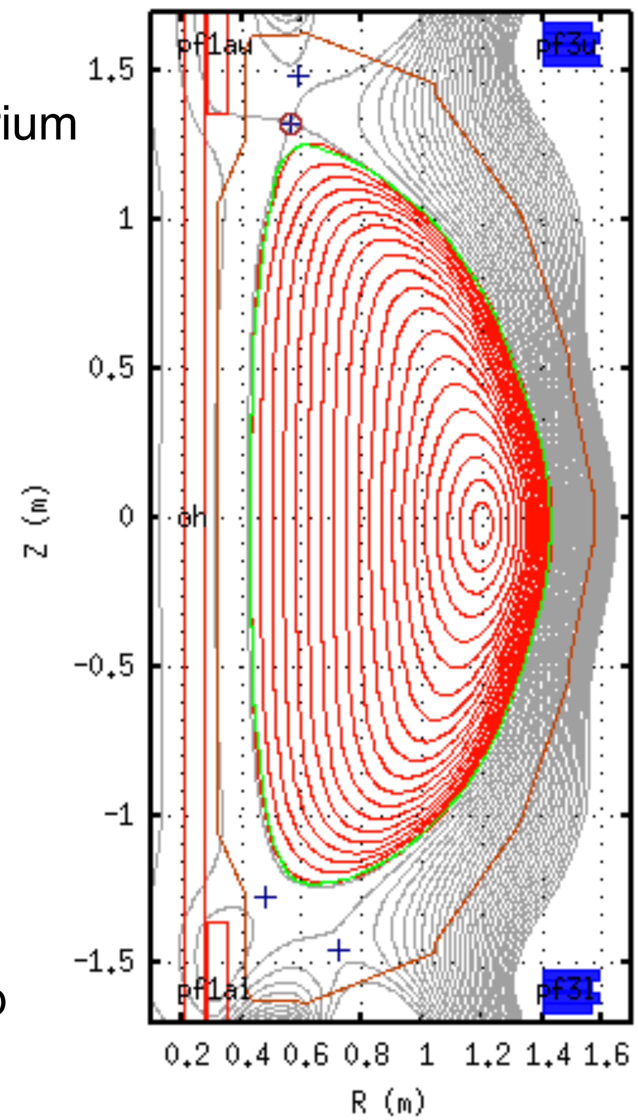
- Use NSTX discharges to build-up discharge in NSTX-U geometry
- Addressing challenges along the way:
  - Self-consistent evolution of equilibrium and pressure evolution during startup with external H/CD
  - Confinement level typically $H_{98,y2}$~1.0-1.2
  - Thermal transport => either predictive or scale analytic temperature profiles (use MMM95 in RF phase, analytic T_e and $\chi_i = \chi_e$ in NBI phase)
  - Particle transport => density profiles are prescribed (0.5-1.0 n_{Gw})

- ECRH: ray tracing codes (TORAY-GA, GENRAY)
- HHFW: full wave code TORIC with Fokker-Planck treatment for resonant species
- NBI: Monte-Carlo orbit NUBEAM

2^{nd} NB line can ramp-up current from HHFW-heated plasma and sustain stationary 900kA



Isolver equilbrium
t = 3.5s
κ~2.50
δ~0.75

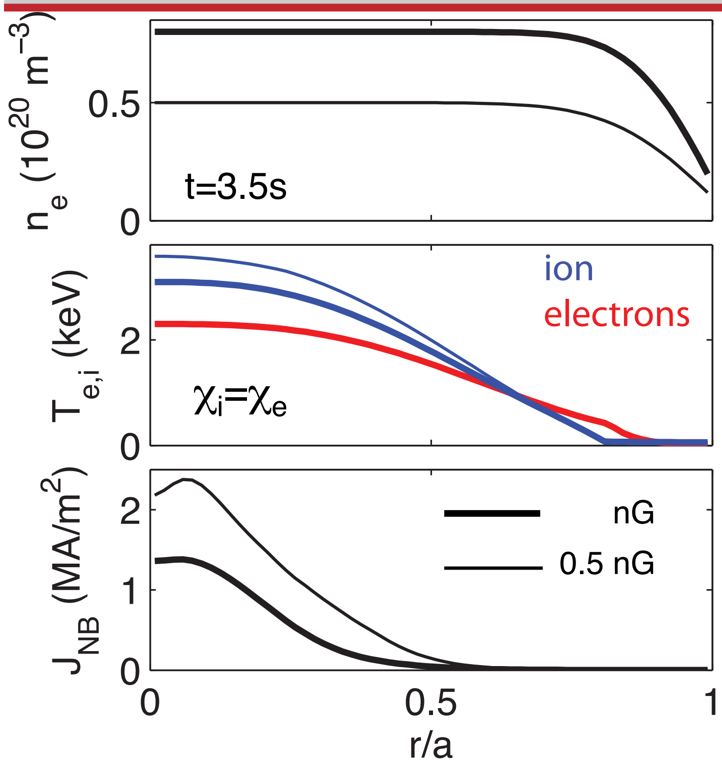


HHFW used @ t<0.5 to ramp to ~400kA

$n_{e,lin}$ = 8x10^{19} m^{-2} -> ~900kA non-inductive, ~60% bootstrap

β_T~7%, β_P~6%, β_{FAST}/β_{TOT}~0.25-0.35, H_{98}~1.2 (τ_{98}~70ms)

Results sensitive to Greenwald fraction, which affects the beam pressure and shape control



- Second beam line has high efficiency
- Peaked deposition profiles at low density (~50%n_G)

=> elongation decreases, l_i increases

=> q(0) drops below 1 in the flattop

=> q(0) drops below 1 during the HHFW phase

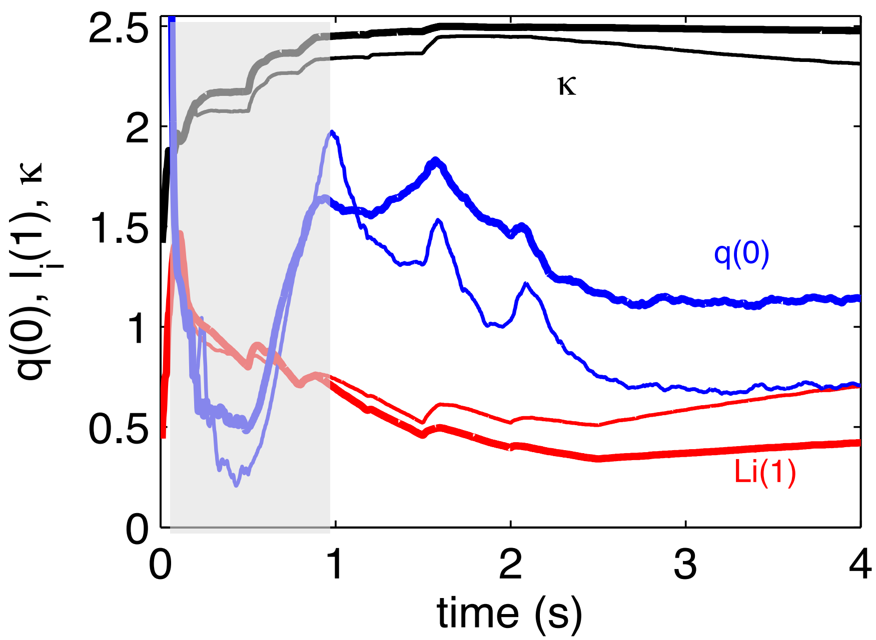
NBI phase needs optimization: broad deposition

⇒ Optimize outer gap

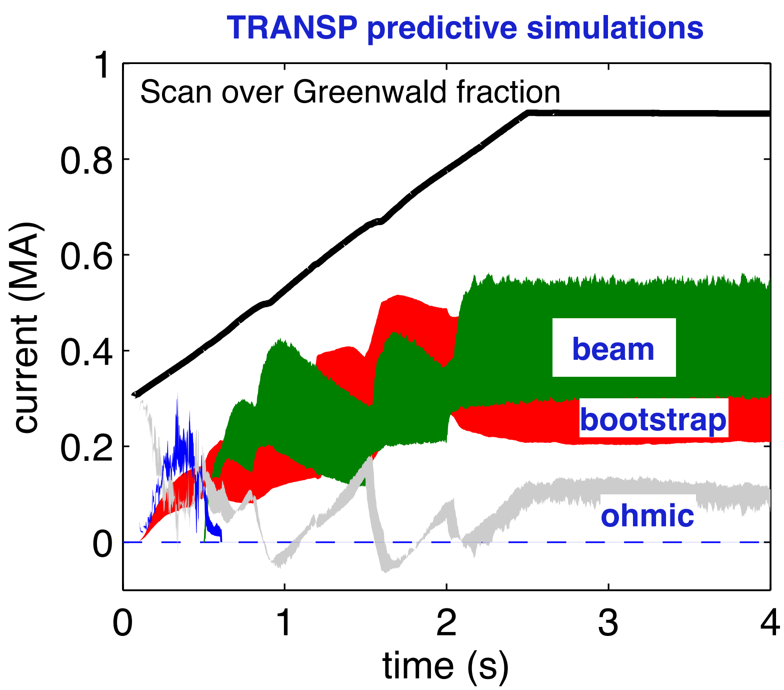
⇒ Beam modulation

Early phase needs optimization: elevate q(0)

⇒ Use beams early in the discharge (with RF)

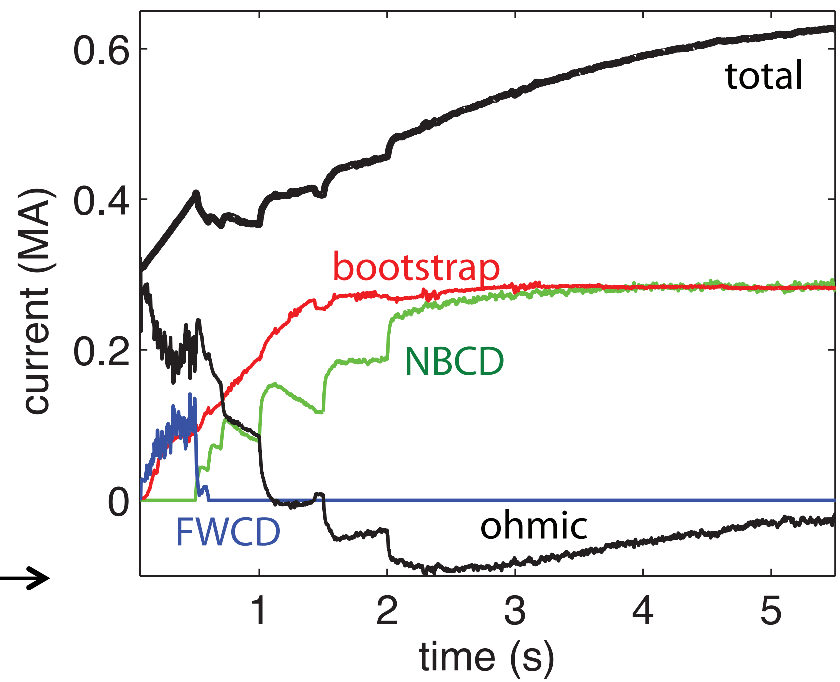


Procedure for non-inductive ramp-up experiments



Clamp ohmic at progressively earlier times

- Start with a fully inductive discharge
- Optimize non-inductive fraction (density is critical)
- Clamp ohmic at progressively earlier times



Used on DIII-D, including national campaign, to demonstrate non-inductive ramp-up and sustainment with electron cyclotron heating and neutral beam injection

Goals: validate simulations for non-inductive startup and ramp-up

Modeling:

- ECRH: TSC CHI startup simulations as initial conditions to improve time-dependent predictions using ECRH
- Simulate EC+NBI and EC+FW combinations for CHI target
- HHFW: Explore effect of FW phasing on scenarios
- NBI: scan density and temperature and source energy to optimize deposition

Experiments:

- NBI: assess NBI injection and CD profiles in targets with 0.5-1.0MA, 0.75T with density of 0.5-1.0 Greenwald
- Learn from H-mode characteristic and pedestal to improve predictions of H-mode ramp-up plasmas with NBI.

=> experiments, including National Campaign on DIII-D to constrain simulations of NSTX-U overdrive ramp-up discharges at 1T with inductive seeding to guide experiments in FY16.

Summary

- Substantial progress in ramp-up modeling using TRANSP
  - Compute RF NBI absorption and CD self-consistently for the first time
  - Use experimental discharges from NSTX for projection
  - Simulations of the startup phase present computational challenges
  - Density control is crucial to the scenario solution and to the evolution in the ramp-up and flattop sustainment.
- Future work:
  - more physical constraint on surface voltage, use coil currents to drive the simulation and control the discharge (shape, gaps, aspect ratio)
  - Specification of Greenwald fraction vs time in TRANSP simulations
  - control of beta in simulations through NB power
  - Sensitivity studies on choice of thermal transport models