Outline

The goal: demonstrate fully non-inductive startup, rampup and sustainment up to 1MA

Available tools:
- CHI (Coaxial Helicity Induction) for startup
- HHFW (High Harmonics Fast Waves)
- Neutral Beam injection up to 10MW for 5s

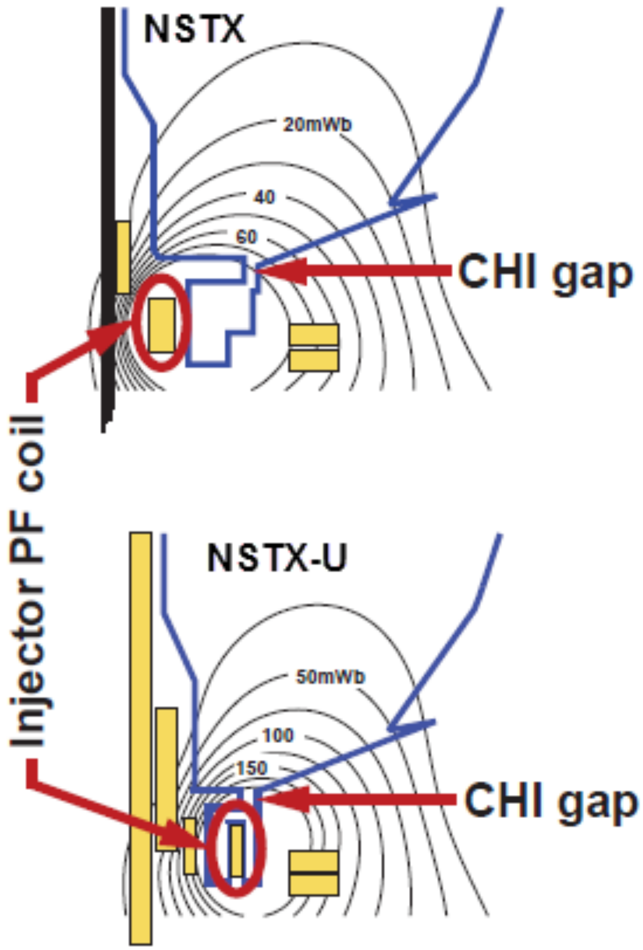
TRANSP (the golden standard for integrated modeling)

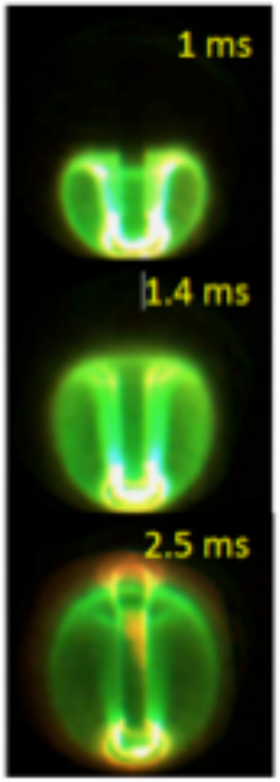
Planned upgrade: EC/EBW system

The integrated approach: combination of modeling and experiments
- for experiments preparation
- for validation
- for optimal use of resources

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

CHI projected 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

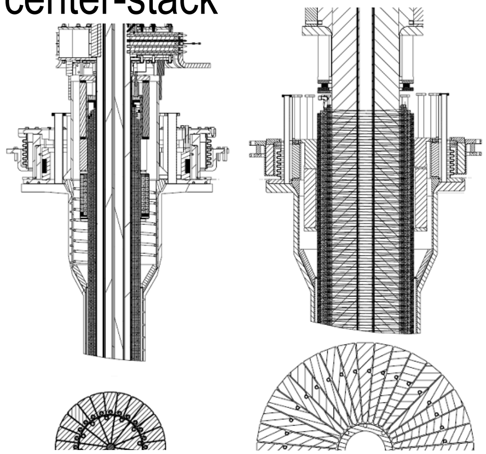
- NIMROD

  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)

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

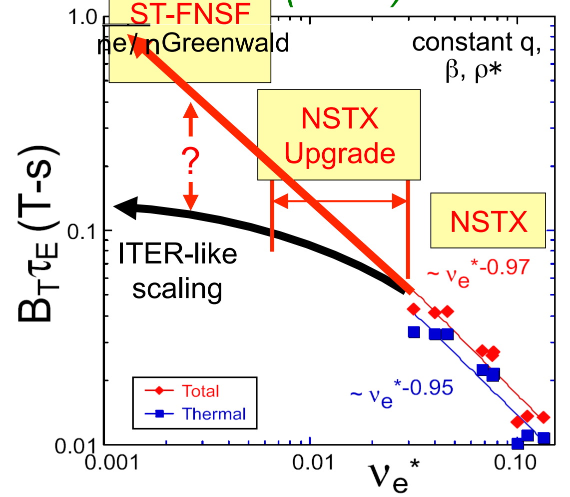
Previous center-stack | **New center-stack**



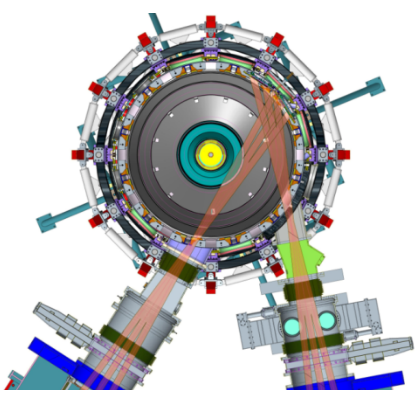
TF OD = 20cm | TF OD = 40cm

- 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*

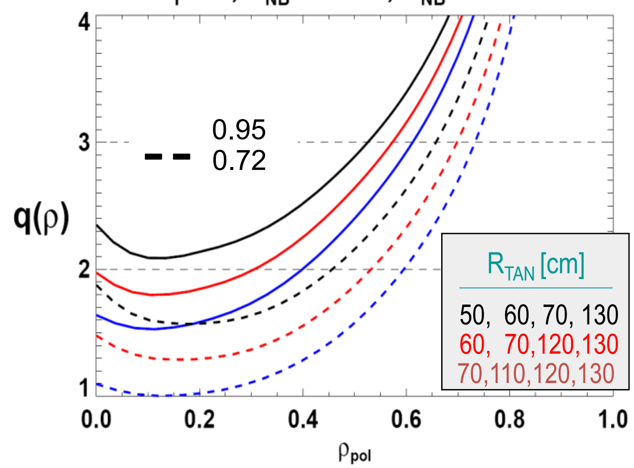


Normalized e-collisionality $\nu_e^* \propto n_e / T_e^2$



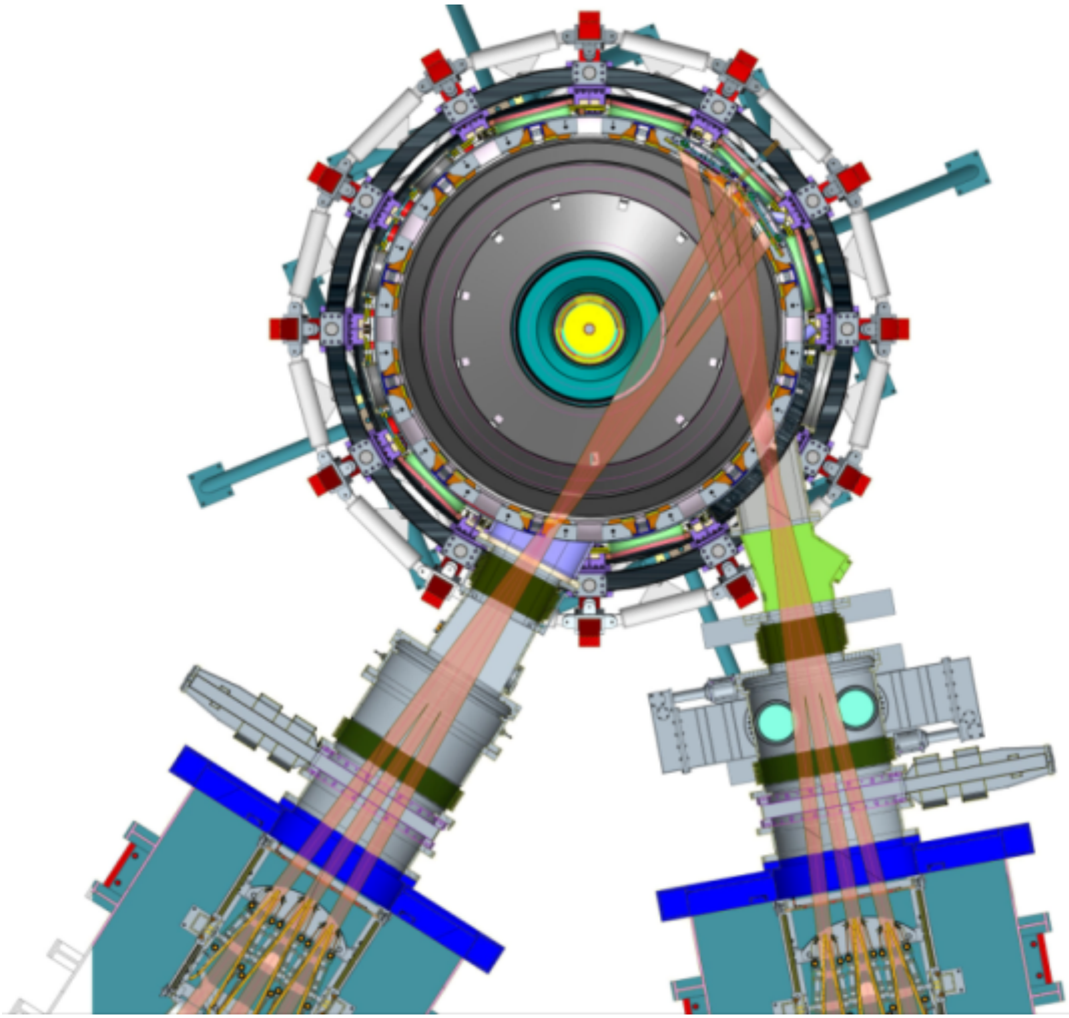
Present NBI | New 2nd NBI

- 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)



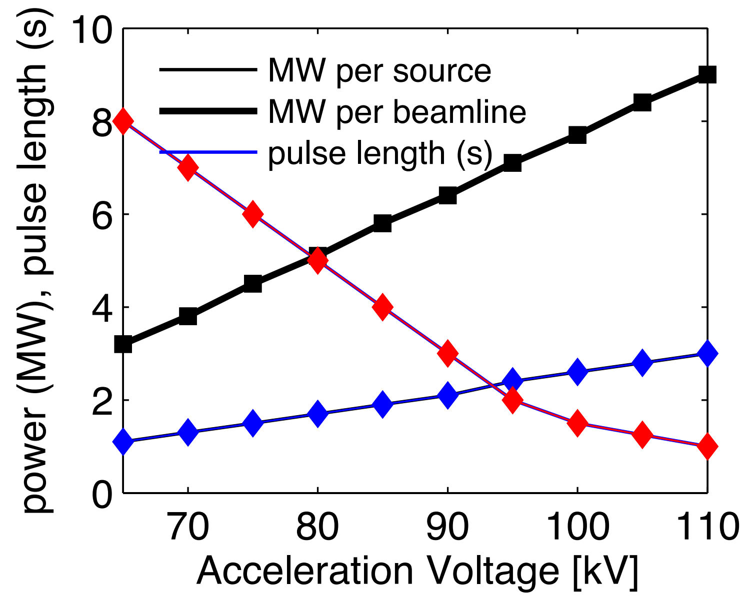
Second beamline at larger tangency radius will allow fully non-inductive operation up to 1MA

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

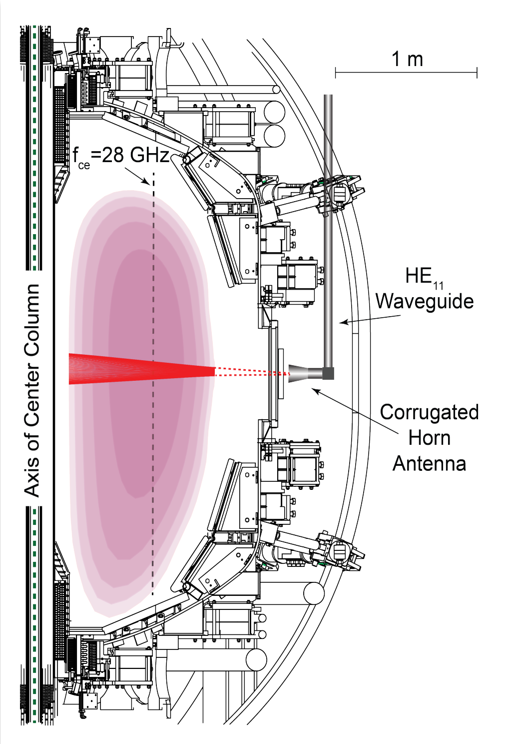


Present NBI

New 2nd NBI



EC bridges the gap between CHI startup and RF/ NB heating/current 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.

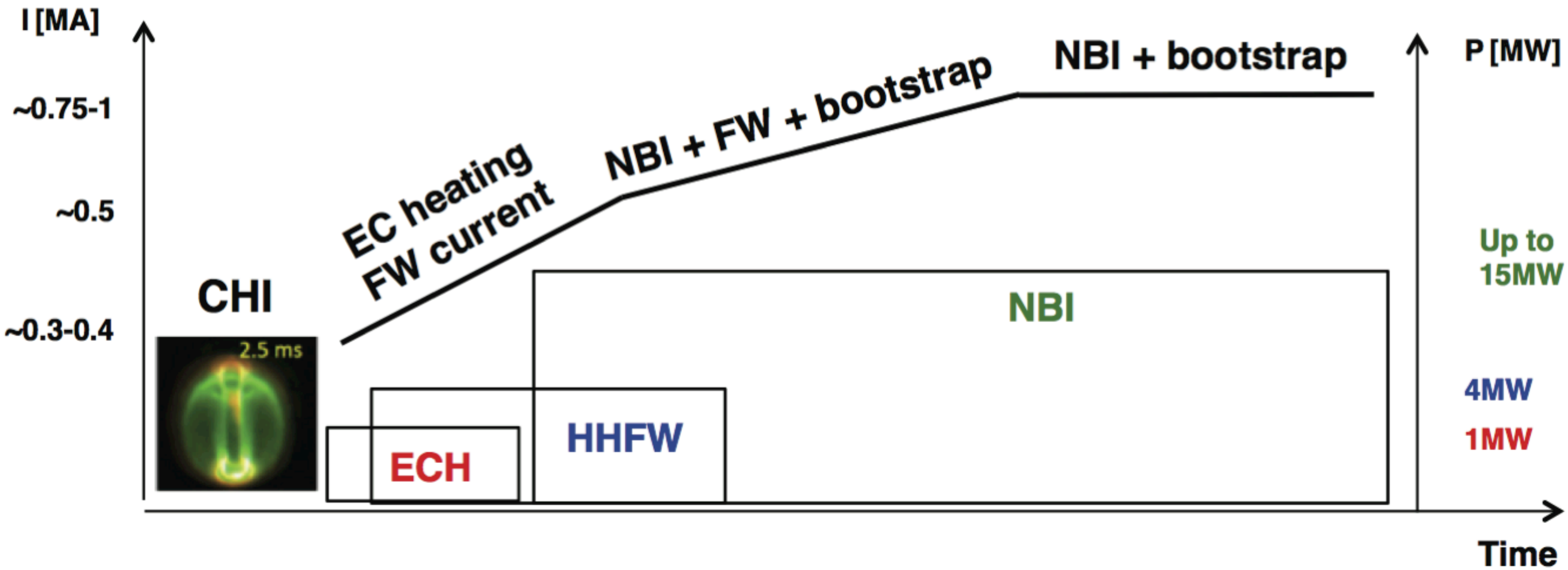
The role of EC is to heat CHI plasma to a level where

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

Our strategy: combine integrated modeling and experiments to address the issues



- Heat CHI plasma to maximize efficiency of H/CD sources
- Minimize beam losses at low current
- Combine RF and NBI for profile control
- Optimize NBI source combination for CD.
- Maintain control over position, current profile, MHD stability.

Identify challenges and needs towards non-inductive operation

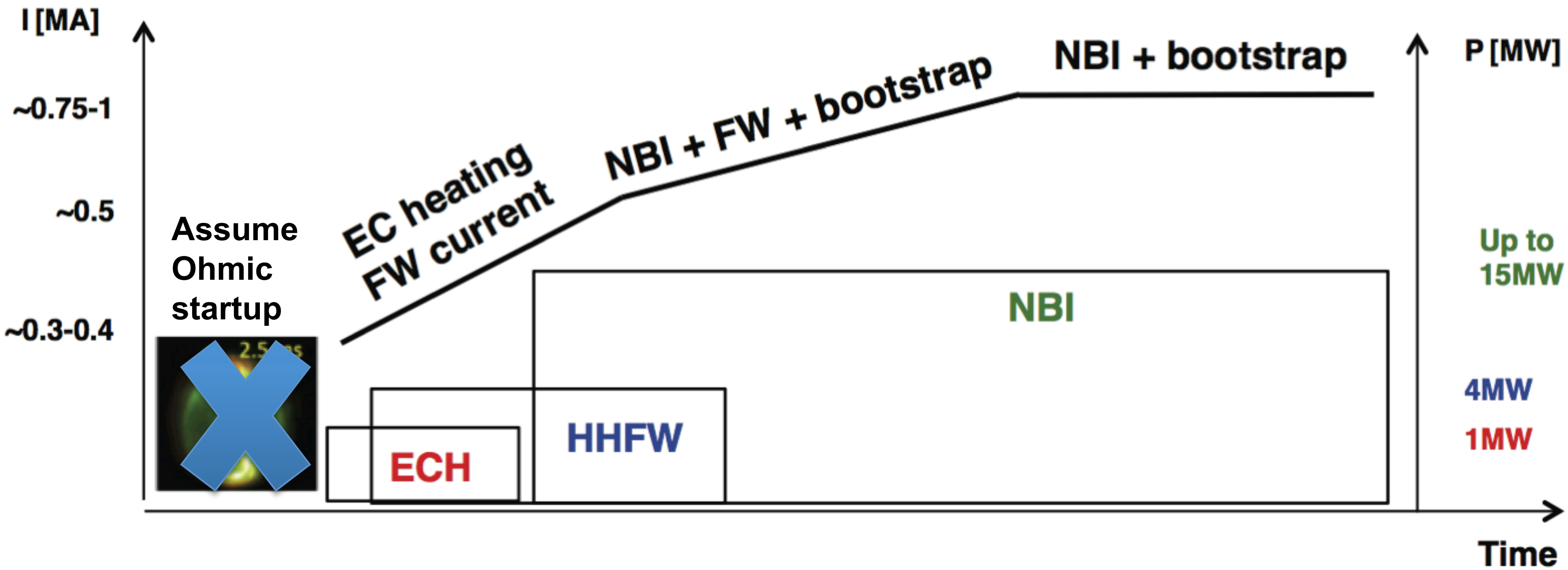
- Optimizing non-inductive current at startup with NBI.
- Optimizing non-inductive current at startup with HHFW.
- Prepare a target plasma with Electron Cyclotron Heating.
- Why is ECH a game changer for the startup?
- Experiments and modeling towards non-inductive operation.

*[F. Poli et al, Nucl. Fusion **55** (2015) 123011]*

Assumptions in the simulations

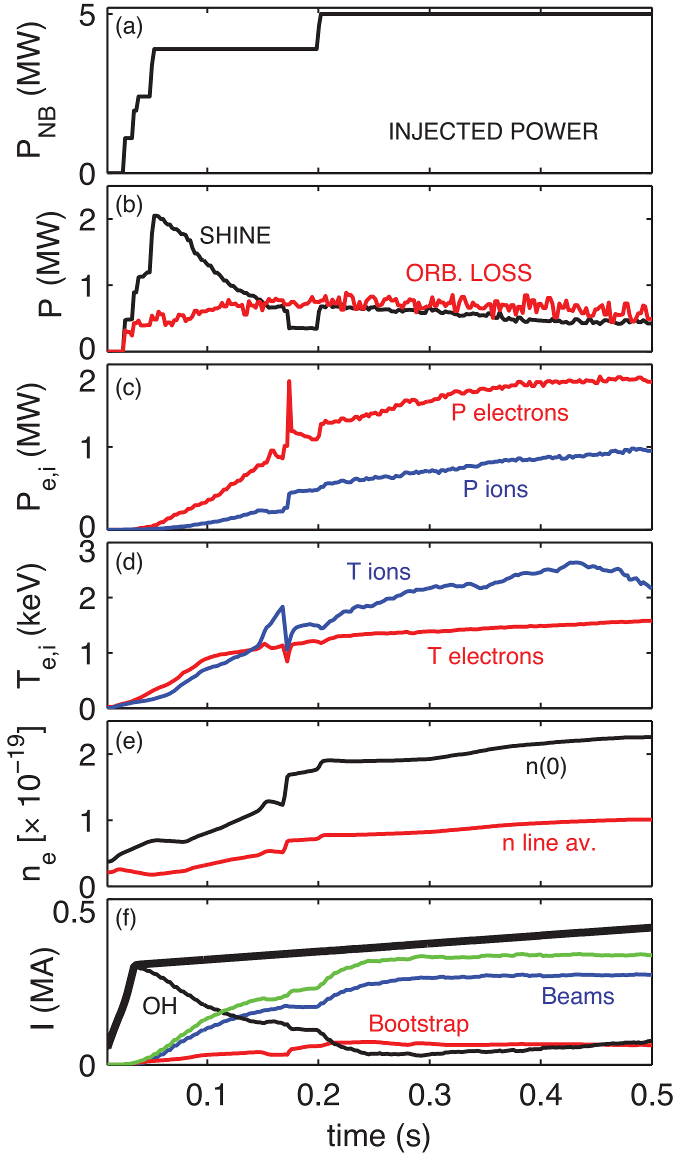
- Select NSTX discharges, compare transport models on:
  - RF and NB at low, constant current
  - NB in the ramp-up and at high current flattop
- CAVEAT: Startup/rampup not the same as relaxed, flattop plasma.
- Transport will be addressed during the next campaign
  - pedestal structure, confinement, rotation, turbulence ...
- All simulations run with free-boundary TRANSP
  - Isolver for equilibrium evolution and coil currents
  - TORIC for HHFW, NUBEAM for NBI, GENRAY for ECH
  - MMM for thermal transport
  - Prescribe I_P waveform and maximize non-inductive current drive

Assume ohmic startup in the simulations and optimize the use of RF sources



- Minimize beam losses at low current
- Combine RF and NBI for profile control
- Optimize NBI source combination for CD.
- Maintain control over position, current profile, MHD stability.

NBI alone likely unable to provide needed current on low temperature CHI target



- Optimize beam configuration to:
  - minimize shine-thru and losses
  - maximize non-inductive current

Why?

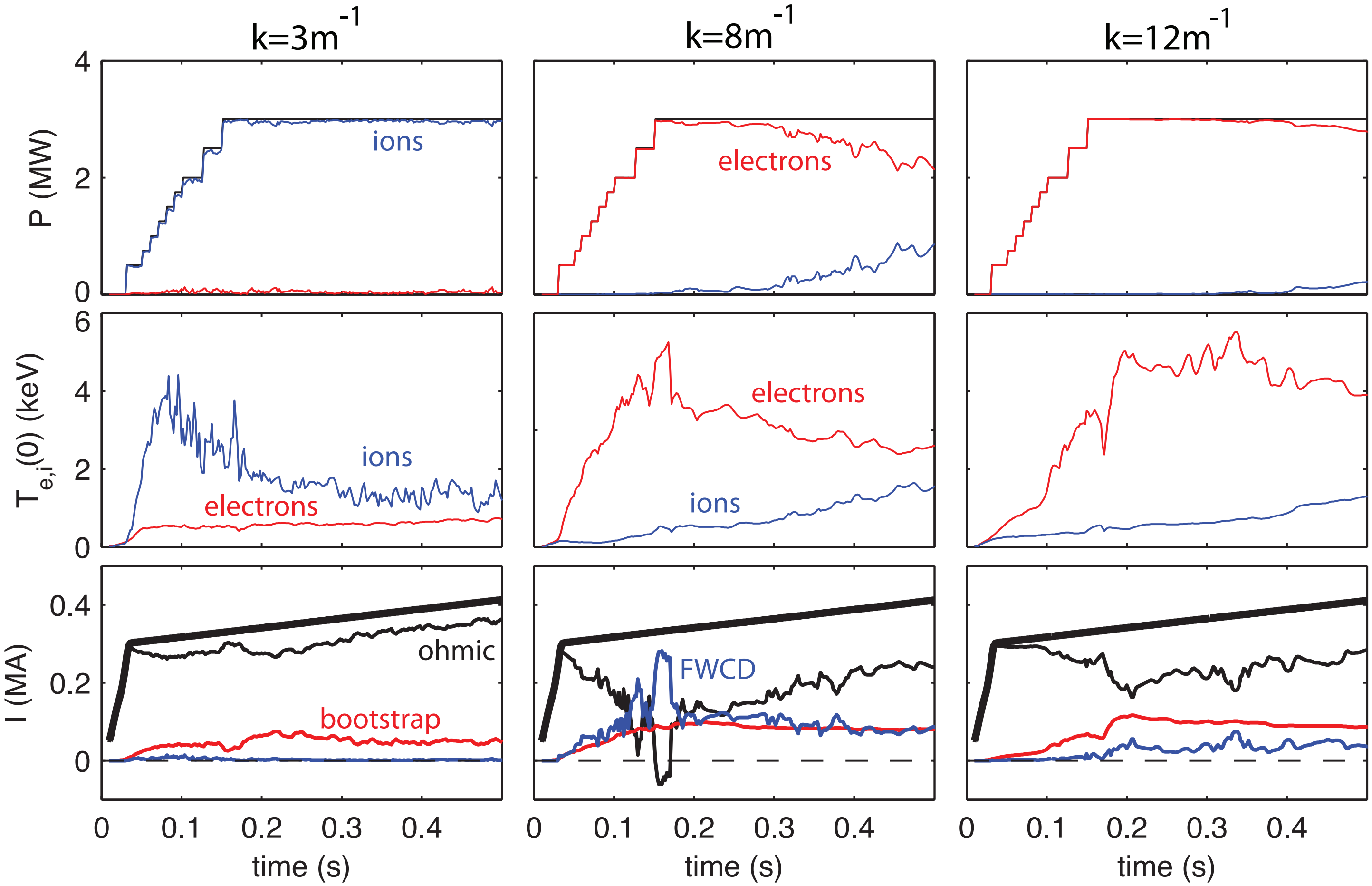
- NBI provides flexibility for current profile control

In progress: current and q profile control

[startup/rampup: W. Wehner, Lehigh university]

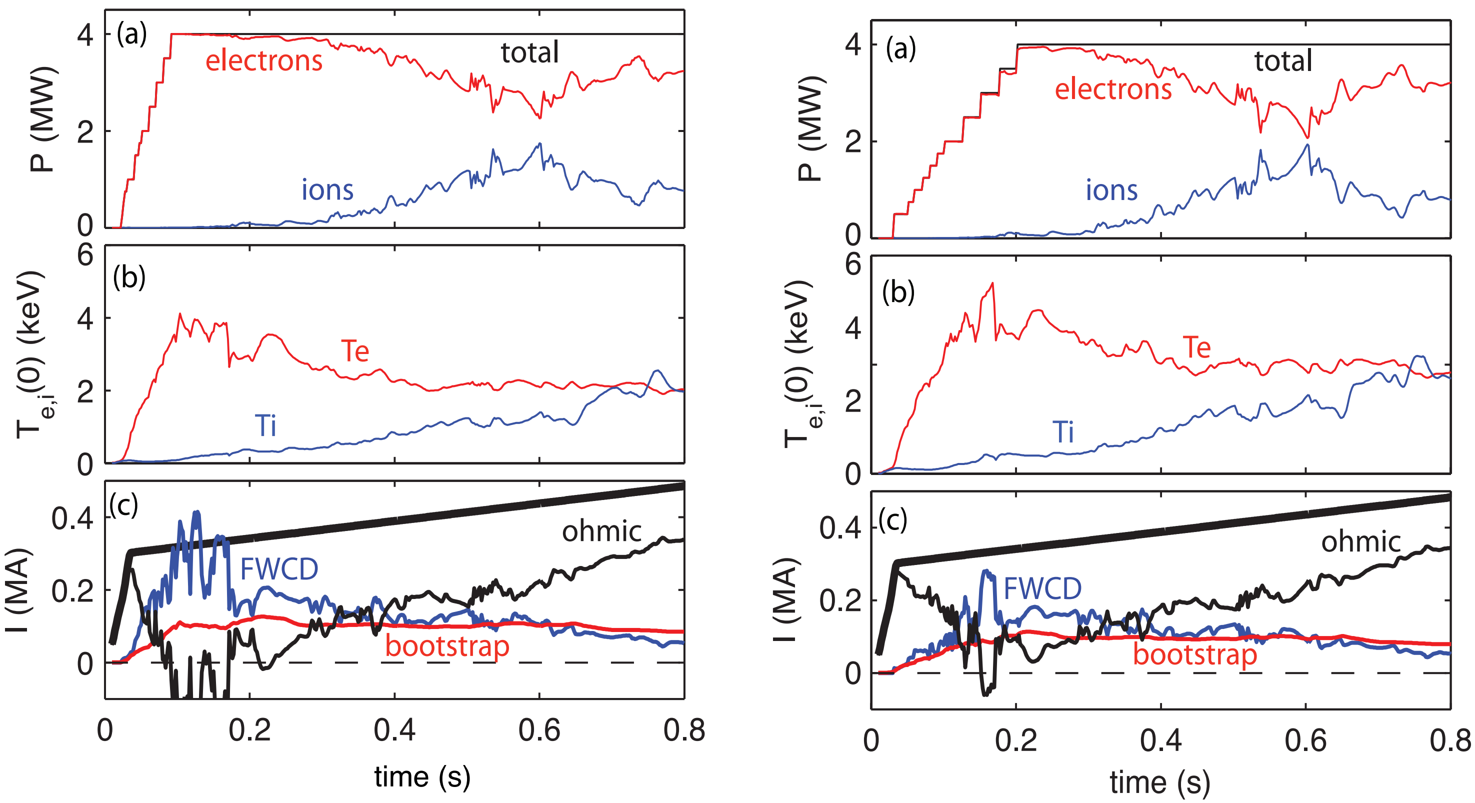
[flattop: D. Boyer, PPPL]

HHFW can provide needed current at startup



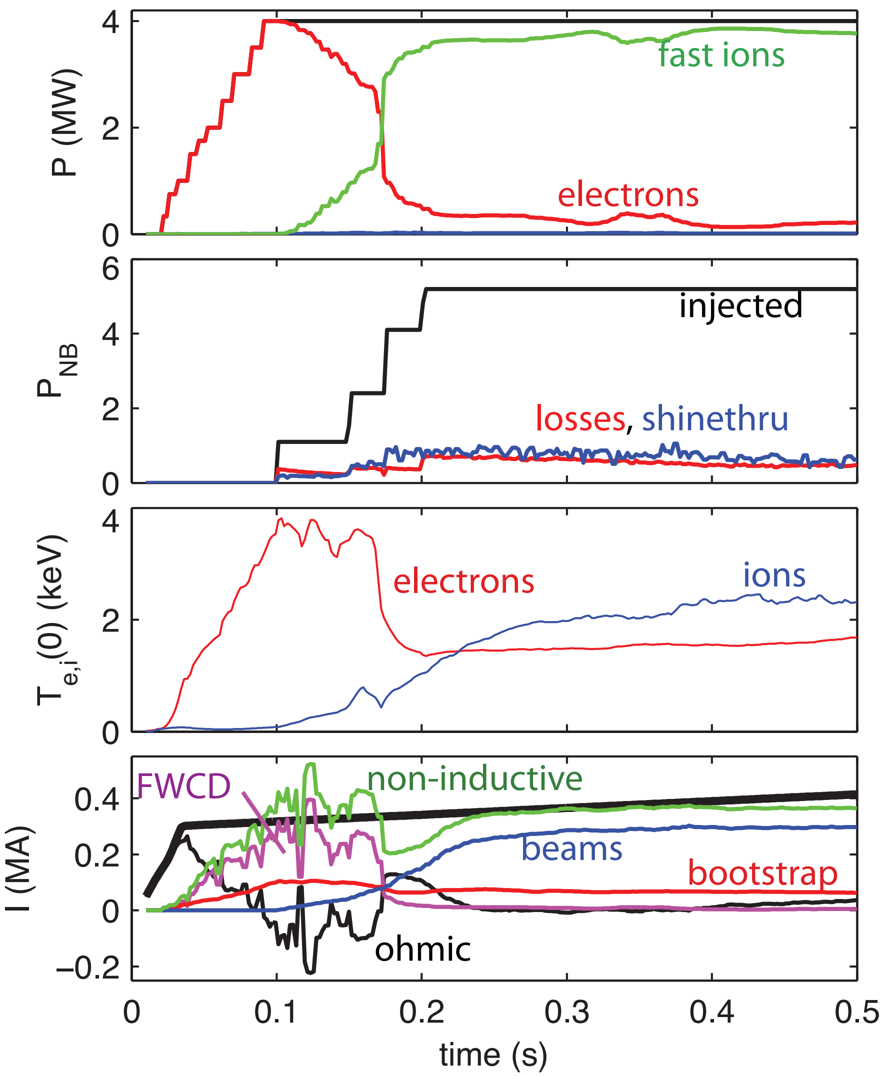
- Intermediate launched k most favorable for FWCD
- However, not large enough current drive

Good wave absorption is critical



- Need 4 MW for ~350kA current (to be verified in exp.)
- FWCD drops after L-H: higher n_e, lower electron absorption.
- Current profiles peaked => challenge for control and MHD.

Combine HHFW and NBI to drive current when HHFW becomes less efficient



Large absorption to fast ions
=> reduces efficiency

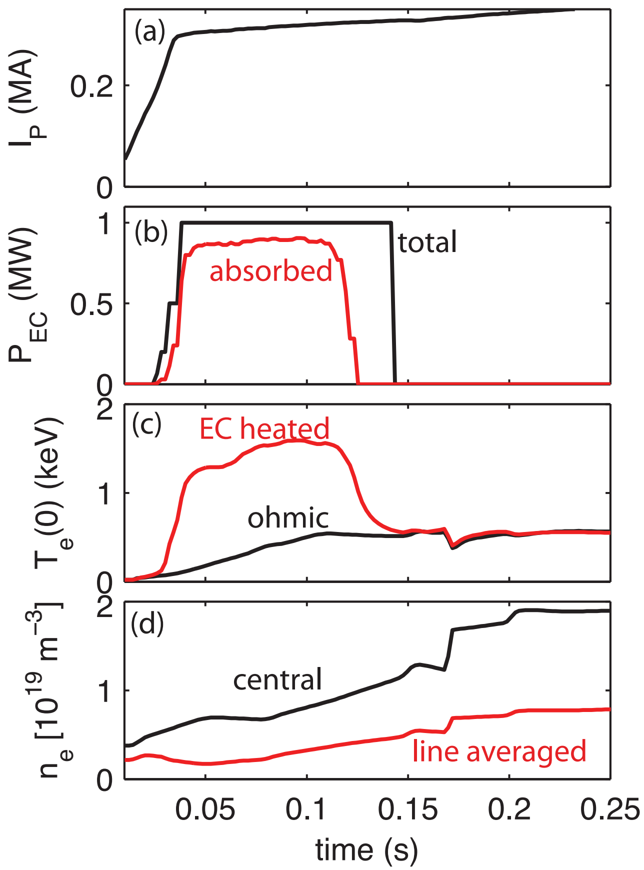
Delay NBI to minimize losses

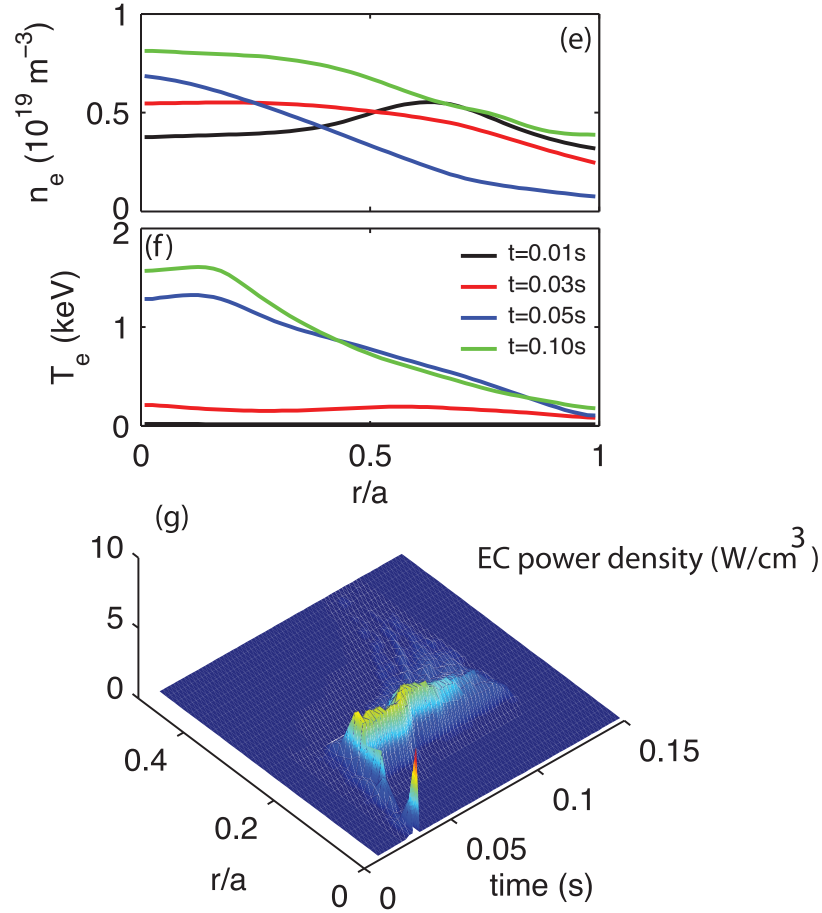
Lower electron absorption decreases T_e

Switch from HHFW to NBI after ~150 ms and ramp-up to full current

What about the startup phase ?

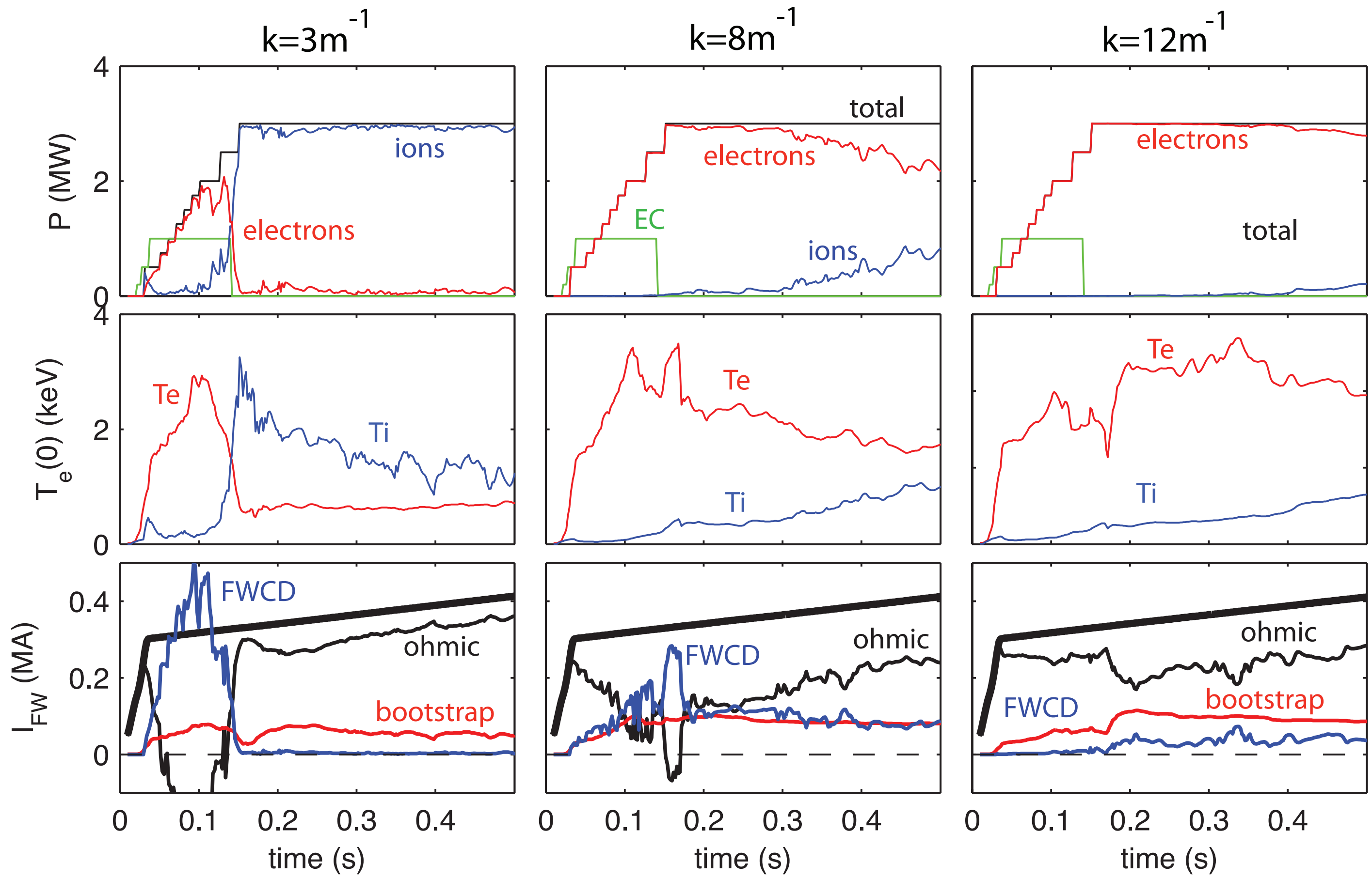
ECH is a game changer for non-inductive rampup





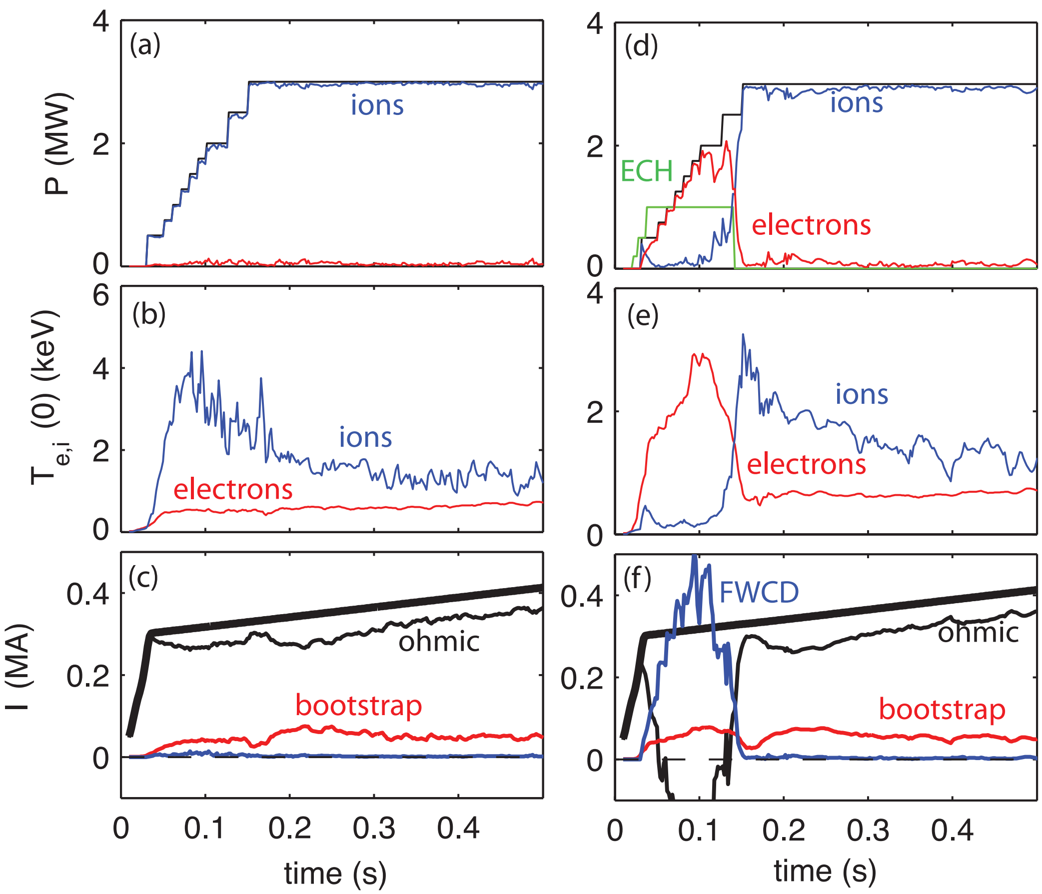
- it heats low temperature plasma to 1keV in 30ms
- However, accessibility limited to low density.

ECH creates flattop temperature conditions



- when combined with EC, lowest phasing most favorable
- half power needed to drive 400kA compared to w/o EC

Use ECH to improve HHFW efficiency

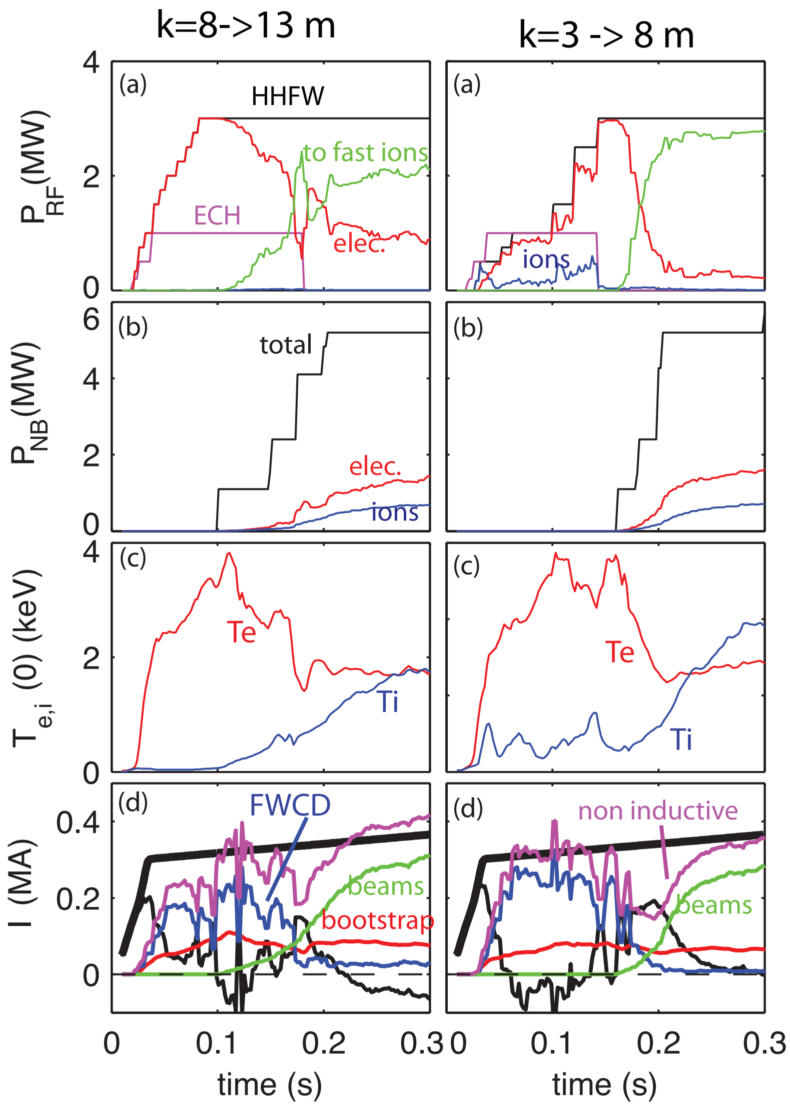


- HHFW with lowest k=3 m^{-1}
- ECH heats to 1-2 keV
- Up to 2 MW of (absorbed) HHFW to drive 400 kA
- 4 MW needed w/o ECH

=> Less HHFW power needs to be absorbed in the plasma to reach the same conditions.

Work in progress: optimize the use of EC at startup,
modeling of EC/EBW at startup [N. Lopez, Princeton University]

The best conditions obtained with dynamical change of HHFW antenna phasing



- Minimize HHFW power needs with lowest k=3 m^{-1}
- Minimize absorption to fast ion with largest k=13 m^{-1}
- Maximize non-inductive current

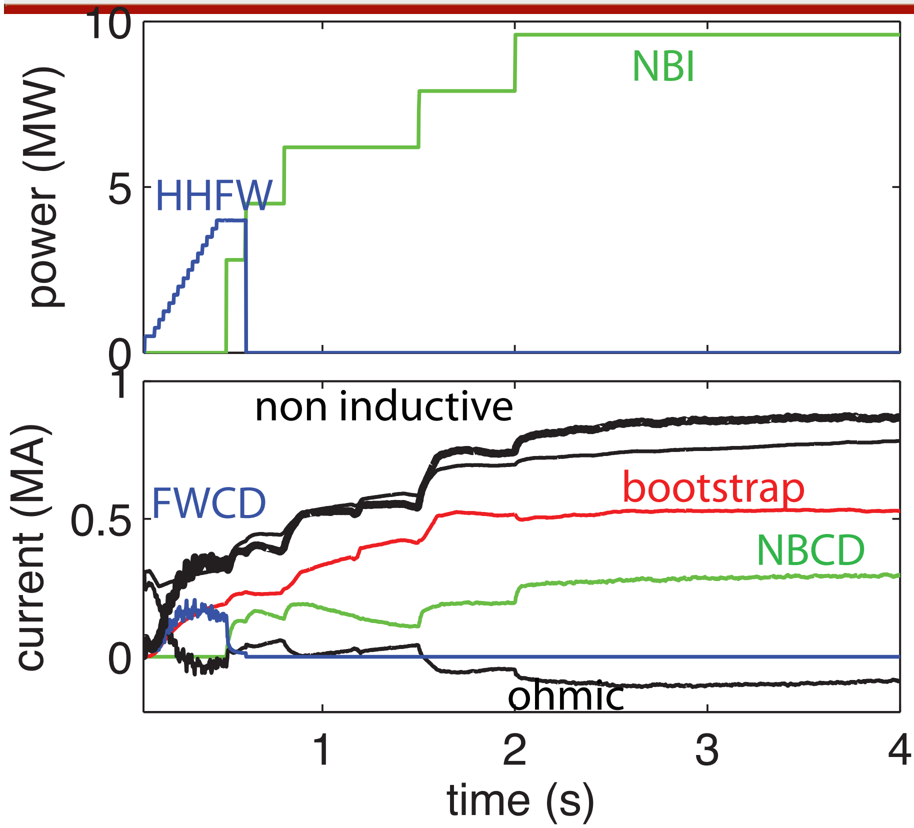
Everything works on paper …

The challenge now is to demonstrate in experiments

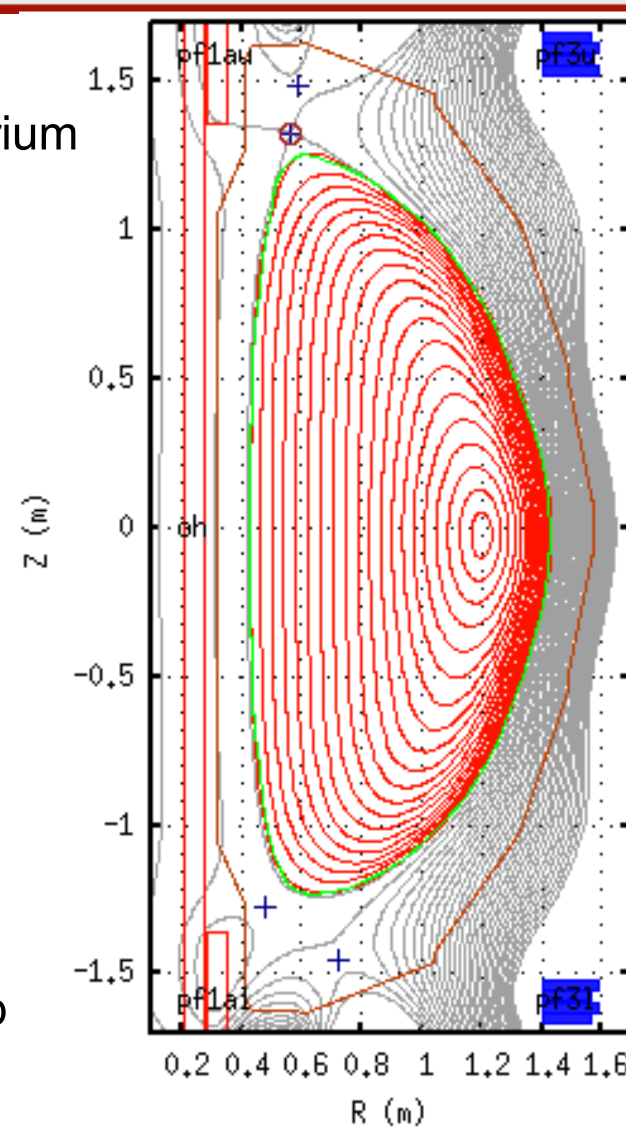
Summary: all sources needed for non-inductive ramp-up

- EC: to reduce HHFW power requirements
- HHFW: to drive current where NBI has high losses
- NBI: to ramp-up to full current
- Current and pressure profile control is critical
- ‘creative’ HHFW phasing can help to optimize scenario

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)