Towards non-inductive operation in NSTX-U

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Our strategy: combine integrated modeling and experiments to address 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.

NOTE: focus here on startup and ramp-up, not sustainment.

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 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
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?
Use ECH to improve HHFW efficiency

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

\[ \Rightarrow \] 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 \[ \text{[N. Lopez, Princeton University]} \]
The best conditions obtained with dynamical change of HHFW antenna phasing

- Minimize HHFW power needs with lowest $k=3 \text{ m}^{-1}$
- Minimize absorption to fast ion with largest $k=13 \text{ m}^{-1}$
- 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
Backup slides
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