Simulations of non-inductive current rampup and sustainment in NSTX-U

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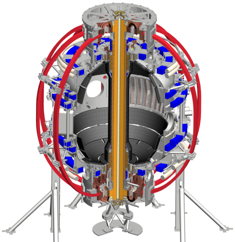
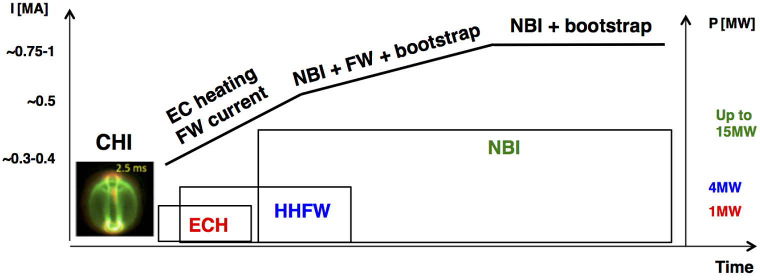


Challenges in modeling and experiments



- Heat CHI plasma to maximize efficiency of H/CD sources
- Minimize beam losses at low current
- Combine RF and NBI, aim at best synergy of sources
- Optimize NBI source combination for optimal performance.

Outline

- Ramping-up the current with the available hardware.
- 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 the golden goal.

Aim at identifying challenges and needs to non-inductive ramp-up.
Remember! These are simulations, keep an open mind and relax ...

What transport model should be used?

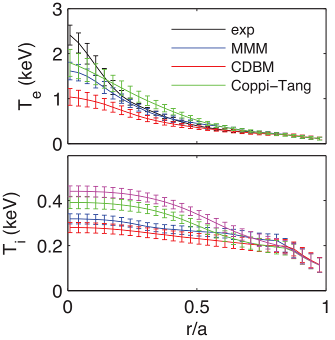
- Transport will be addressed during the next campaign
  - pedestal structure, confinement, rotation, turbulence ...
- Select NSTX discharges and choose the model that works better (on average).
  - RF at low current
  - NB at low current
  - NB in the ramp-up
  - NB at high current

CAVEAT: Startup/rampup not the same as relaxed, flattop plasma. Transport in this phase needs to be addressed.

MMM suitable for predictions with RF at 300kA

#138506 - high non-inductive fraction with HHFW

Predictive TRANSP, average profiles over RF phase.



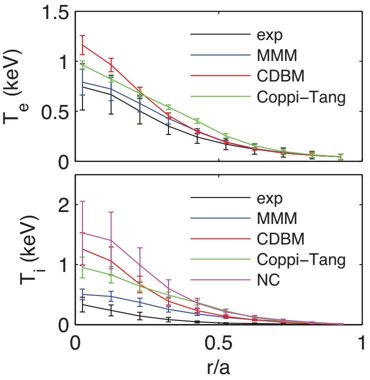
- no T_i measurements
  - agreement between models
  - Neoclassical higher
- MMM7.1: reproduces peaking
- Coppi-Tang: too broad profiles
- CDBM: too low temperature

Similar discharges give similar results.

MMM suitable for predictions with NBI at 300kA

#140353 - 2MW of NBI on 300kA plasma.

Discharge run for comparison with RF case. MHD activity.

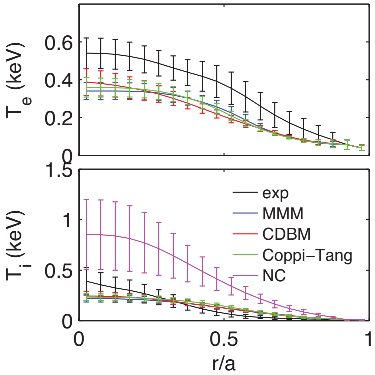


- Coppi-Tang: broad profiles
- CDBM: reproduces peaking of T_e
- MMM7.1: peaking and amplitude
- Neoclassical overpredicts T_i

All models agree in ramp-up of 300-900 kA

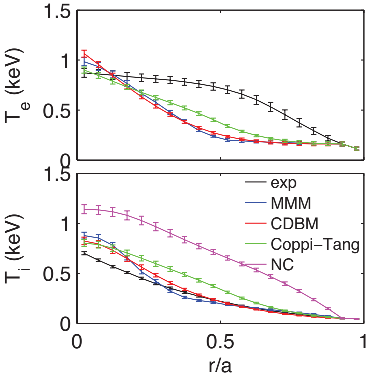
#142305 - 4-5MW of NBI at 900kA, 200ms rampup.

XP at higher aspect ratio [Gerhardt, NF2011].



- Neoclassical overpredicts T_i
- good agreement among models
- all reproduce T_e broadness
- all predict broader T_i

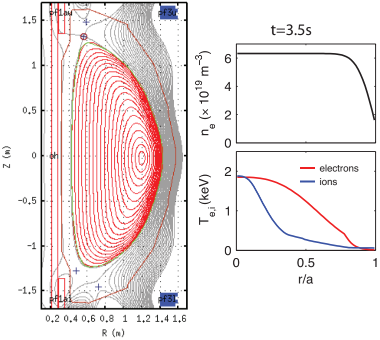
No model works for T_e at large current



- all models agree to each other
- all models predict $T_e(0)$
- None reproduces broad T_e profile
- Neoclassical overpredicts T_i

In the NB phase will use analytic profiles and central value from transport.

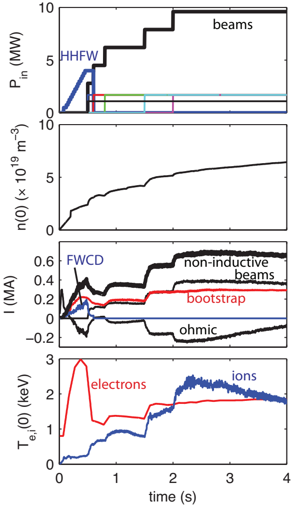
Build non-inductive ramp-up from #142305



- Generate equilibrium with Isolver
  - all discharge, from $t = 0$
- analytic n_e, T_e profiles
  - no rescale of pedestal
  - density probably too flat
  - n_e, T_e at startup emulate CHI
- use rotation profiles from exp.
  - no rescale
- use Zeff from experiments
  - no assumption on impurities
- target elongation k=2.55
  - lower than expected in NSTX-U

Time-dependent simulations with predictive, free-boundary TRANSP

10 MW of NBI ramp to 500-900kA ...

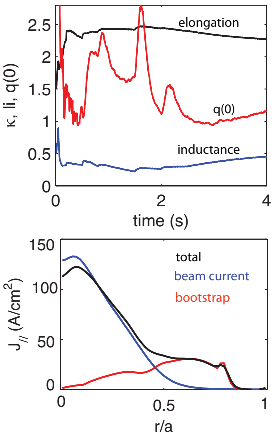


... depending on pressure and NB configuration.

- density of 75% of Greenwald
- two beamlines, 65kV at 130cm from 0.5s
- 900kA with 90%n_G and changing T_e
- MMM7.1 for thermal transport
  - T_e: during RF phase
  - T_e: during NB phase, analytic with on-axis predictions.
  - T_i always
- small differences in scenario between MMM and NC
  - NC T_i twice as large
  - non-inductive current <5% difference

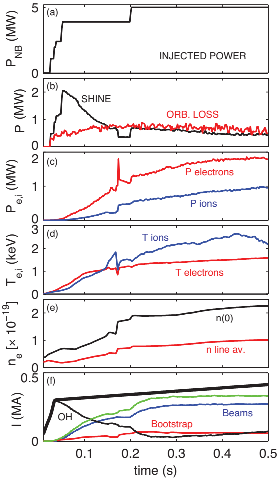
Issues needed to be addressed

Low-current evolution determines where the plasma lands.



- large beam pressure
  - unable to use 2nd beam before 1s
  - had problems keeping the shape
- keep $q > 1$ at high current
  - keep density $>0.70 n_G$
  - broad beam deposition
    - strongly depends on early ramp
- safety factor and li at startup
  - RF profiles too peaked, $q < 1$
  - had problems with vertical position
    - combine with NB to broaden
    - minimize RF to fast-ion
- maintain shape
  - beam configuration + control

Optimize use of NBI on low temperature target

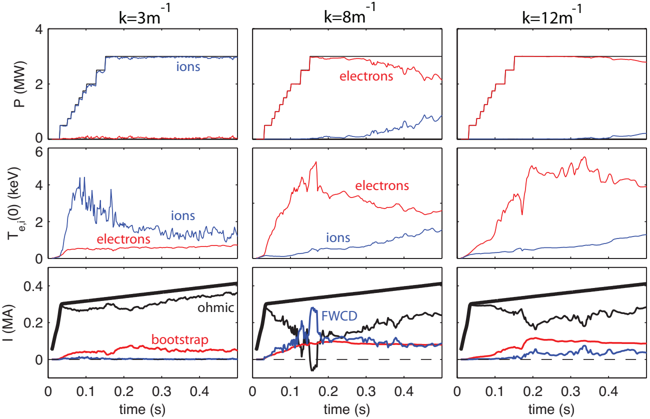


- Optimize beam configuration to:
  - minimize shine-thru
  - maximize non-inductive current
  - maximize confinement

Why?

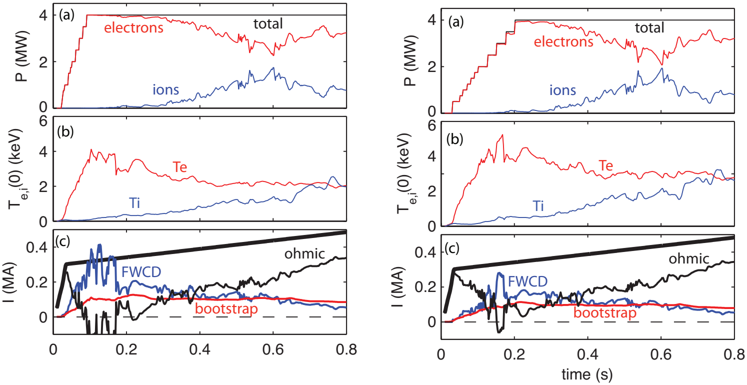
- always need a plan B ...
  - if CHI >400kA, might want to try NB
    - need current from NBI
  - NB might broaden RF profiles
    - need to reduce fast-ion absorption
  - if problems with RF, we are left with NBI

HHFW might provide the needed current at startup



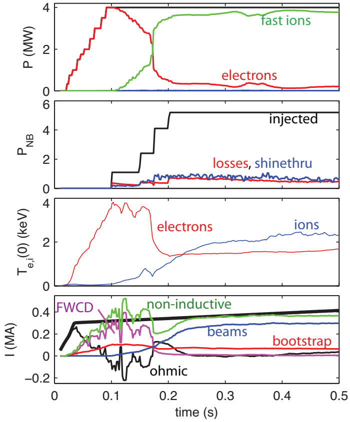
- Intermediate phasing most favorable for FWCD
- Both electron heating and current needed
- Experimental validation of FWCD at low current, low $T_{e,i}$

Good coupling critical for driving current at startup



- 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 control and MHD.

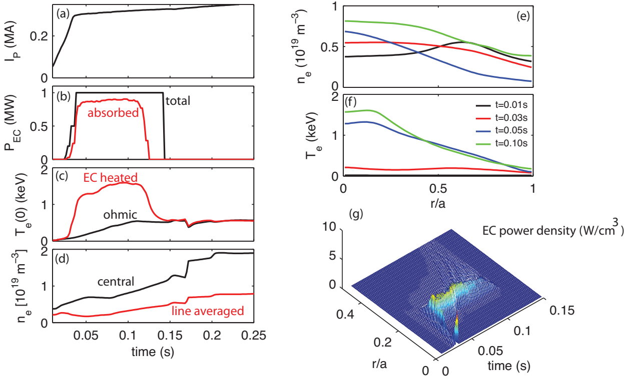
Combining HHFW and NBI at low current



- RF+NBI at low current might be better option than ramping to 450kA with RF
  - broader current and pressure profiles
    - good for MHD stability
    - good for plasma control
- need to reduce RF absorption on fast ions
  - more electron heating
  - more direct FW current
- Change phasing for smooth transition to NBI phase

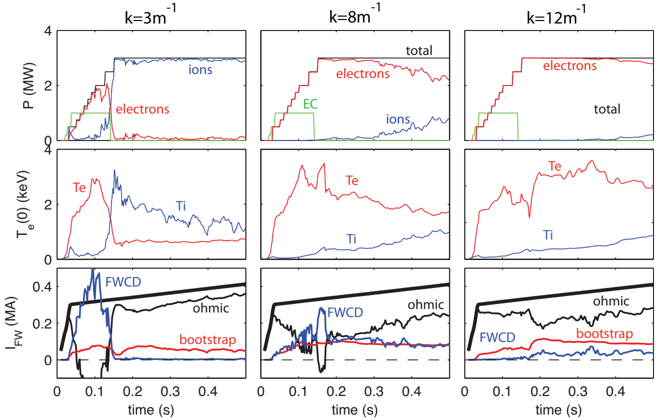
Experimental validation needed.

EC is a game changer for non-inductive ramp-up



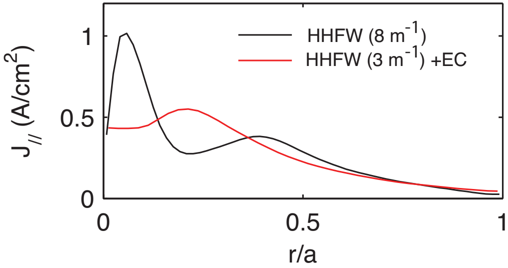
- it heats low temperature plasma to 1keV in 30ms
  - However, accessibility limited to low density.

ECH creates flattop temperature conditions



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

EC+HHFW sustain broad current profiles



- start with EC+HHFW at lowest phasing
- increase phasing and transition to NBI phase
  - lower HHFW power needed !

Conclusions

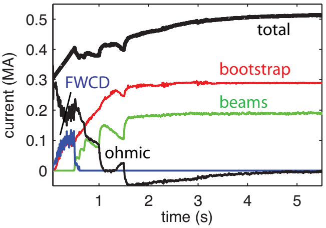
- Non-inductive scenarios achievable, with I_{NI}>500kA.
  - even with non-optimal NBI configurations, like those used here.
- The early rampup phase is particularly critical:
  - for control, for stability
  - current drive is as important as heating
- EC has strong impact on HHFW direct current drive
  - can reduce HHFW power requirements
  - helps sustaining broad profiles
  - antenna phasing important
- Now we need to connect the dots ...

What little steps can be taken now to guarantee success later?

Planning for improving modeling

- Transport predictions: benefit from all TSG X(M)Ps
  - pedestal structure, rotation, confinement, ...
  - ohmic and NBI ramp-up
  - low density ohmic ramp-up
  - particle transport, density predictions (medium term)
- RF modeling: benefit from RF and EP
  - RF-fast ion interactions
  - heating, current drive, coupling at low current
- NB modeling: benefit from NB XMPs, EP, ASC
  - beam configuration
  - high non-inductive fraction
- CHI-initiated discharges: benefit from SFSU
  - boundary conditions for non-inductive startup projections

Optimize the ramp-up converging from the sides



- Demonstrate sustainment of 0.5-0.6MA
- Minimize ohmic contribution at low current
  - optimize profile shaping and stability
- Clamp OH and demonstrate NBI overdrive
  - what is the earliest time for NBI?
- Combine HHFW+NBI at low current
  - current, stability, impurities

Modeling is critical: be prepared in the control room !!!
Validation, validation, validation ...

... AND WE START CONNECTING THE DOTS ...