NSTX-U

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NSTX-U 5 Year Plan for Plasma Start-up and Current Ramp-up

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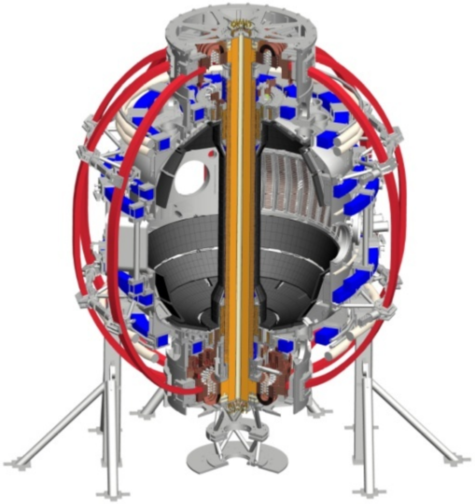
R. Raman
D. Mueller, S.C. Jardin
for the NSTX Research Team

NSTX-U PAC-33 Meeting
PPPL – B318
February 19-21, 2013



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Outline

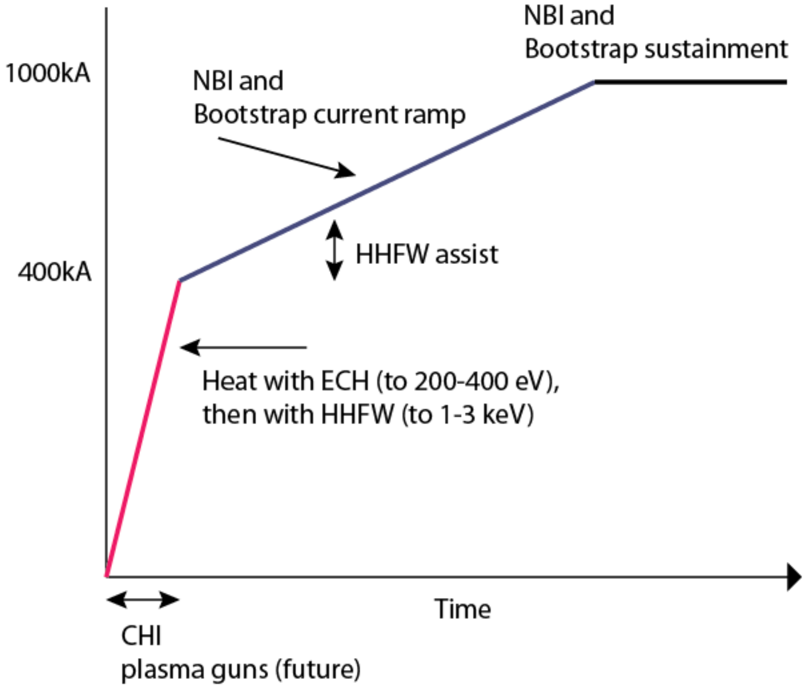
- Motivation & Goals
- Transient CHI Plasma Start-up
- Point Source Helicity Injection Plasma Start-up
- Supporting modeling work
- Research Thrusts
- Hardware preparation
- External collaboration activities
- Summary

Goal: Develop and understand non-inductive start-up/ramp-up to project to ST-FNSF operation with small or no solenoid

- Aligned with OFES program vision for FNSF requirements
  - Establish physics basis for ST-FNSF, and non-inductive start-up is essential in ST
  - Simplify the tokamak concept to reduce cost

- High level NSTX-U Thrusts:
  - Establish and extend solenoid-free plasma start-up and test NBI ramp-up
  - Ramp-up CHI plasma discharges using NBI and HHFW and test plasma gun start-up

NSTX-U Start-up and Ramp-up strategy

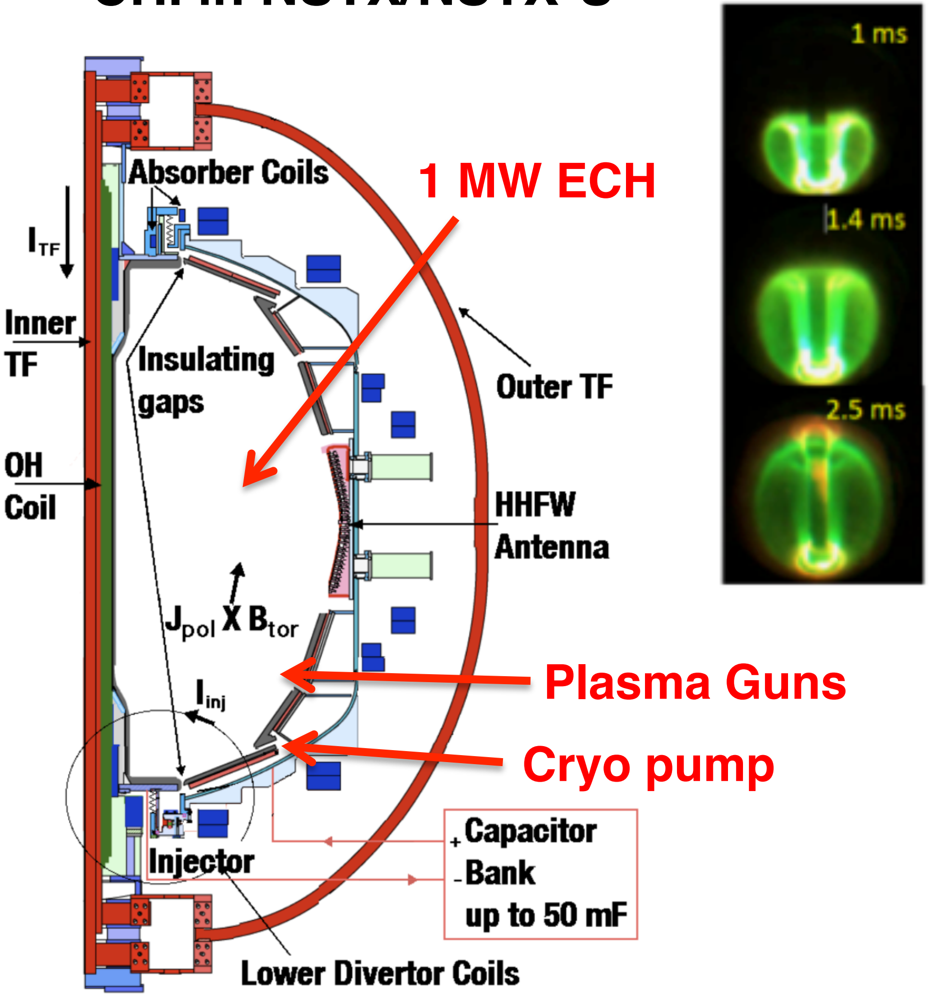


NSTX-U is striving for fully non-inductive operations

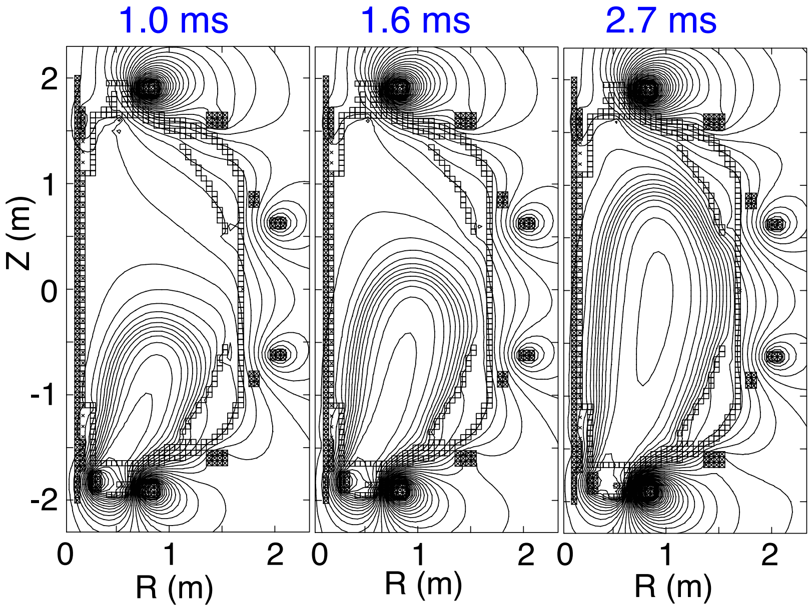
CHI start-up and ramp-up is the front end of that objective

CHI is planned to be used as initial current seed for subsequent non-inductive current ramp-up in NSTX-U

CHI in NSTX/NSTX-U



TSC (axisymmetric 2D) simulation of CHI startup

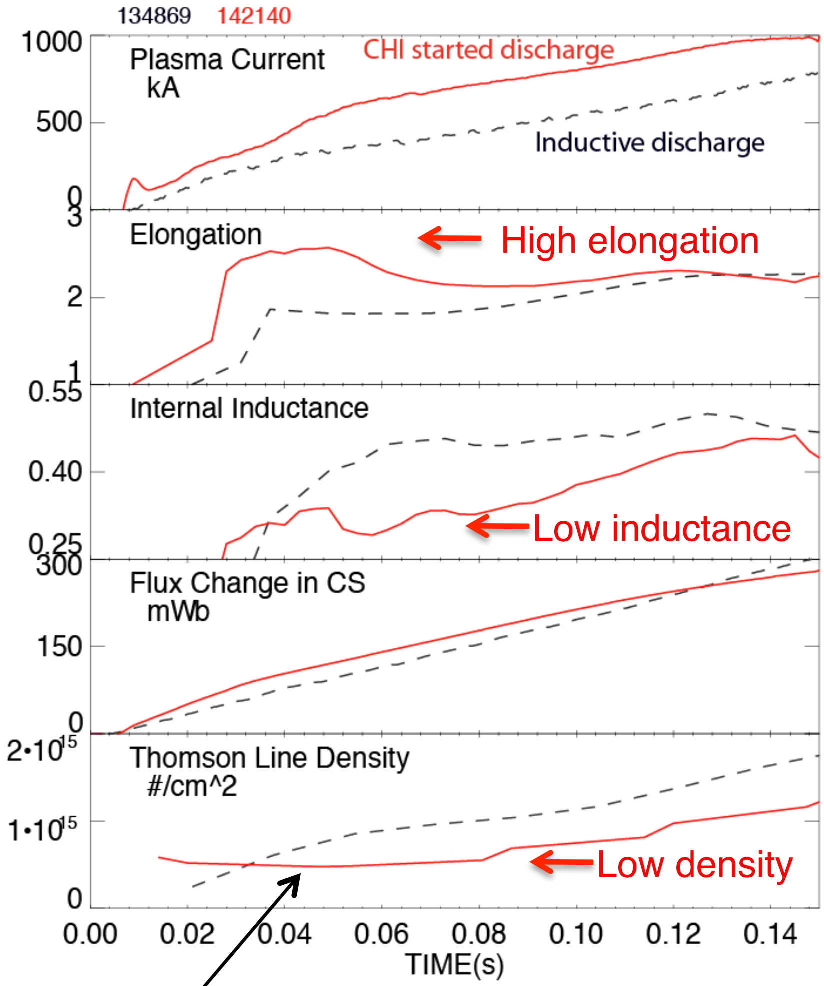


New Tools for CHI

- > 2.5 x Injector Flux (proportional to I_p)
- TF = 1 T (increases current multiplication)
- ECH (increases T_e)
- > 2kV CHI voltage (increases flux injection)
- Full Li coverage (reduces low-Z imp.)
- Metal divertor, Cryo pump (increases T_e)

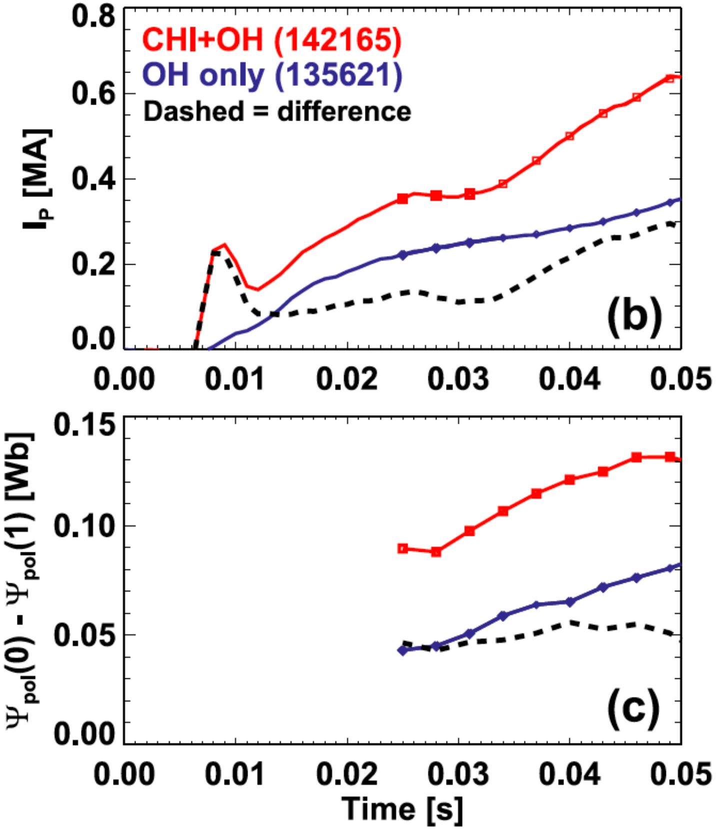
Plasma discharge ramping to 1MA requires 35% less inductive flux when coaxial helicity injection (CHI) is used

CHI assisted startup in NSTX

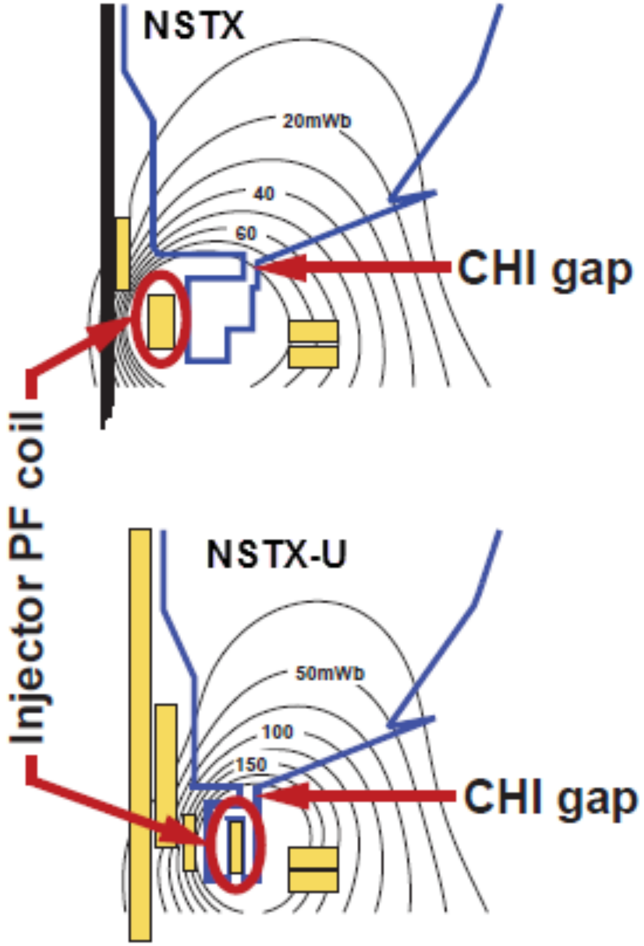


CHI generates plasmas with low n_e below ECH cut-off

CHI produces closed flux change of ~ 50 mWb



CHI start-up to ~0.4MA is projected for NSTX-U, and projects to ~20% start-up current in next-step STs



Parameters	NSTX	NSTX-U	ST-FNSF	ST Pilot Plant
Major radius [m]	0.86	0.93	1.2	2.2
Minor radius [m]	0.66	0.62	0.80	1.29
B_T [T]	0.55	1.0	2.2	2.4
Toroidal flux [Wb]	2.5	3.9	15.8	45.7
Sustained I_p [MA]	1	2	10	18
Injector flux (Wb)	0.047	0.1	0.66	2.18
Projected Start-up current (MA)	0.2	0.4	2.0	3.6

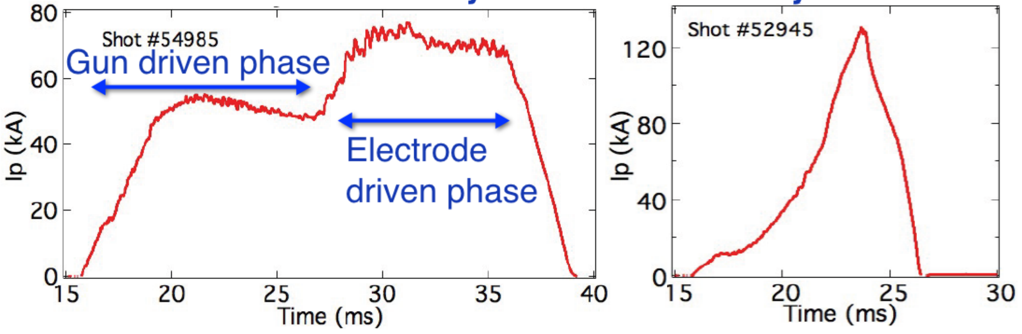
Injector flux in NSTX-U is ~ 2.5 times higher than in NSTX → supports increased CHI current

Incremental programmatic goal:

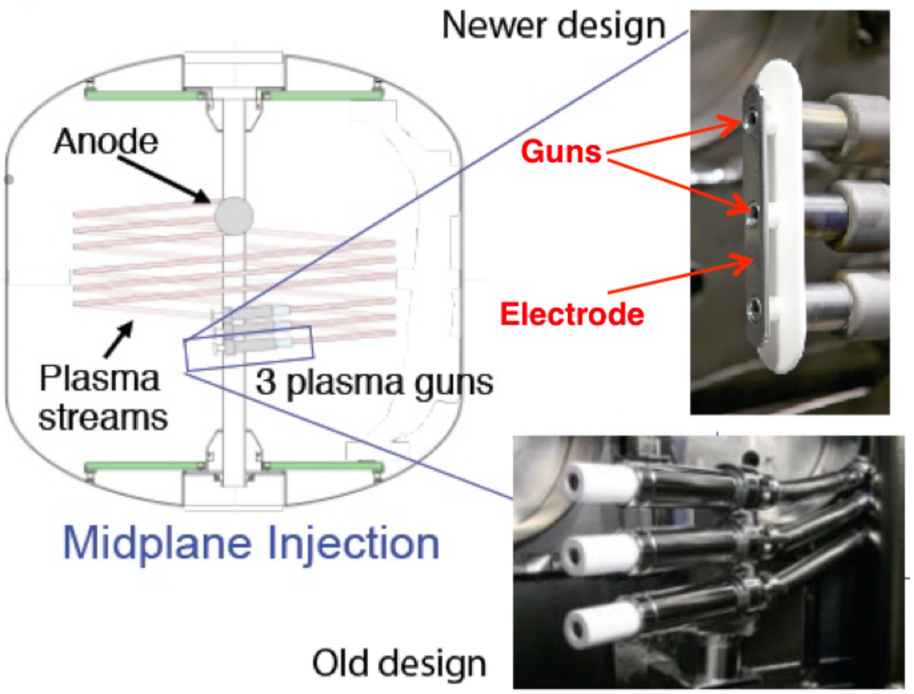
FY15: Establish CHI start-up and Ramp-up a 300-600kA inductively generated plasma using RF and NBI (with Wave Particle TSG)

Local helicity injection being developed by PEGASUS is an alternate method for plasma start-up in NSTX-U

- Retractability of guns potentially advantageous in FNSF/Demo nuclear environment
- Plasma guns(s) & electrodes biased relative to anode or vessel
  - Helicity injection rate $\dot{K}_{inj} = 2V_{inj}B_N A_{inj}$
  - $I_p \sim (I_{inj}\, I_{TF}$ / electrode width)^0.5:



Demonstration of Helicity drive and Helicity + Induction

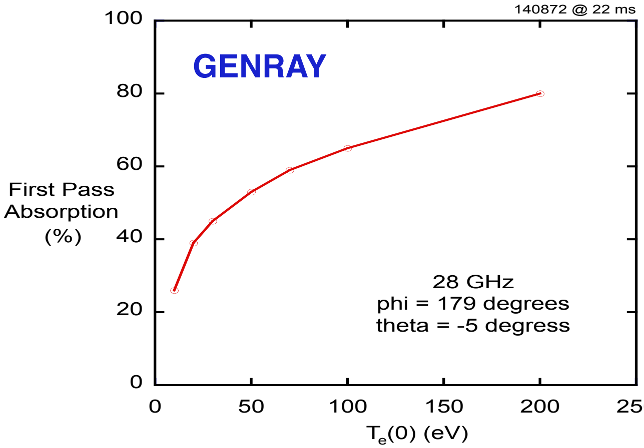


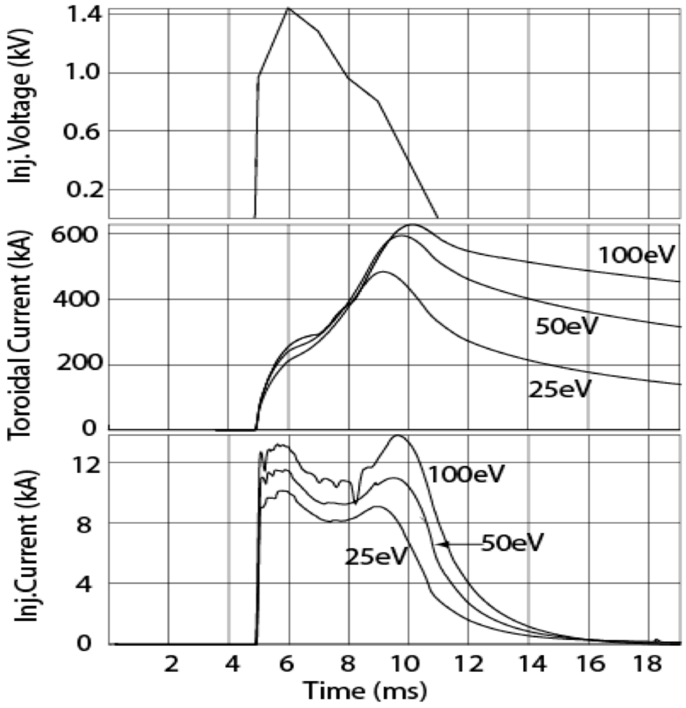
- Issues being addressed by Pegasus to achieve high I_p
  - Effective voltage scales with electrode area
  - Large-area electrode with uniform current density
  - Characterization of plasma confinement/dissipation and injector impedance
  - Pegasus wants to deliver MA-class (I_p > 0.5 MA) to NSTX-U

Ramp-up strategy significantly benefits from 1-2 MW ECH to heat CHI plasma

GENRAY

- In a 500kA decaying inductive discharge, TSC simulations indicate 0.6MW of absorbed ECH power could increase T_e to ~400eV in 20ms (with 50% ITER L-mode scaling)
  - ECH absorption and deposition profile being modeled using GENRAY
  - CHI discharge densities at T_e = 70 eV would allow 60% first-pass absorption by 28 GHz ECH in NSTX-U
- Increased T_e predicted to significantly reduce I_p decay rate
  - ECH heated plasma can be further heated with HHFW
  - Maximum HHFW power < 4MW, higher B_T in NSTX-U would improve coupling
  - HHFW has demonstrated heating a 300 kA / 300 eV plasma to > 1 keV in 40ms



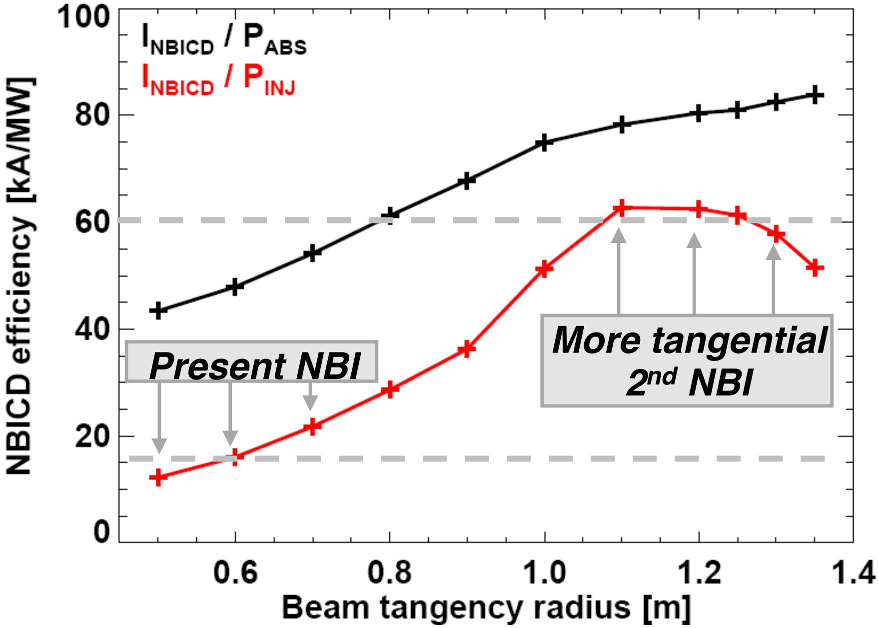


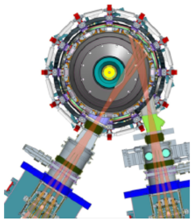
Non-inductive ramp-up from ~0.4MA to ~1MA projected to be possible with new CS + more tangential 2nd NBI

- **More tangential NBI provides 3-4x higher CD at low I_P:**
  - 2x higher absorption (40→80%) at low I_P = 0.4MA
    - Now modeling coupling to 0.2-0.3MA targets (TRANSP)
  - 1.5-2x higher current drive efficiency

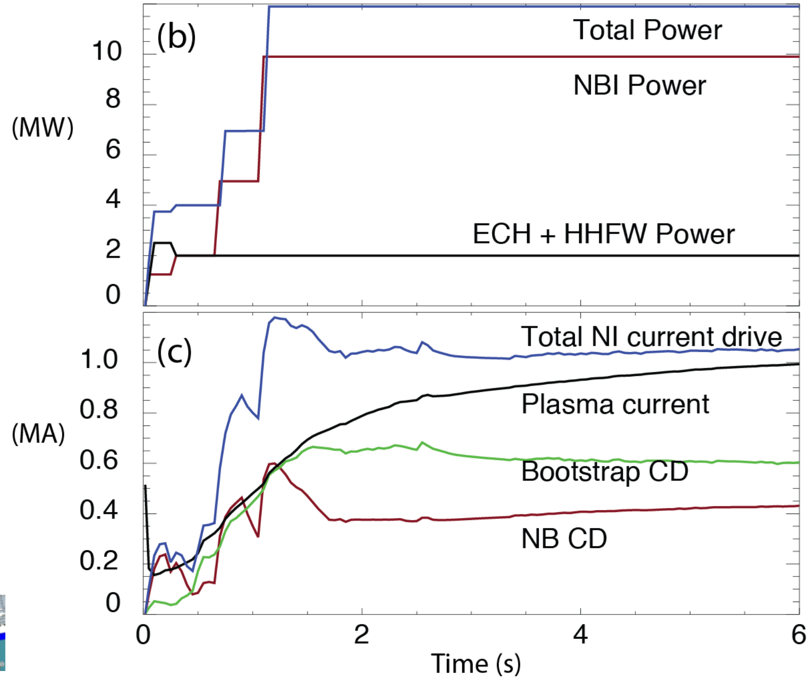
E_{NBI}=100keV, I_P=0.40MA, f_{GW}=0.62

$\overline{n}_e = 2.5\times10^{19}m^{-3}$, $\overline{T}_e$ = 0.83keV





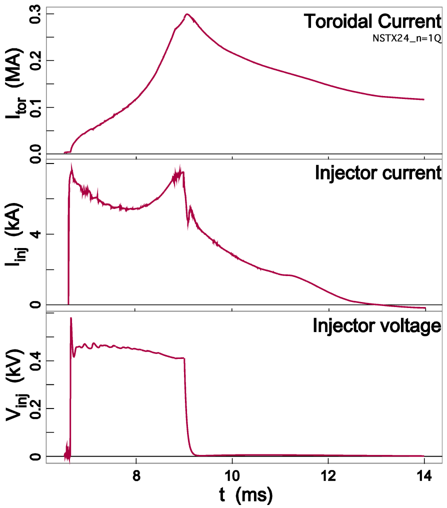
- **TSC simulation of non-inductive ramp-up from initial CHI target**
  - Simulations now being improved to use TRANSP/NUBEAM loop within TSC
  - Experimental challenges:
    - Maximum NBI power in low inductance CHI plasma



R. Raman, F. Poli, C.E. Kessel, S.C. Jardin

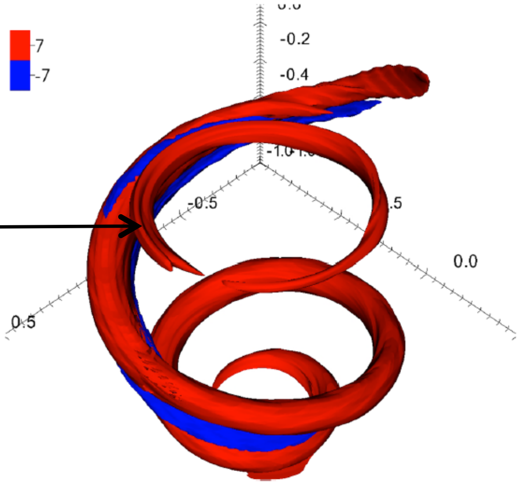
Simulations using Nimrod making good progress in modeling helicity injection start-up in NSTX

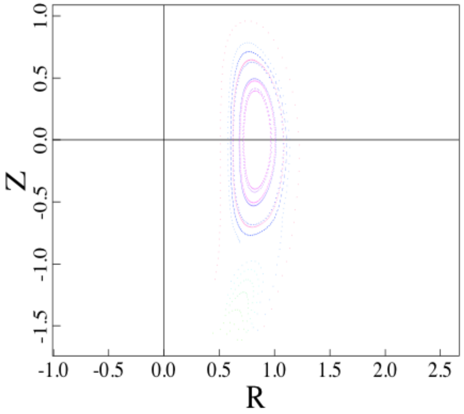
- Will 3D physics in NIMROD alter our present expectations for scaling to next-step devices?
    - Additional physics (T_e evolution, transport, ohmic heating)
- Ongoing simulations show promising results
    - Now starting to show flux closure on experimental time scales
    - Next step is to develop a realistic model for NSTX



Simulations of an NSTX CHI discharge (E.B. Hooper)

Point source (local) helicity injection simulations show release of a current ring following reconnection
(J.B. O' Bryan)





Flux closure 0.87 ms after voltage turn-off in a CHI simulation with constant coil currents (F. Ebrahimi)

E.B. Hooper (LLNL)
F. Ebrahimi (Princeton University)
J. B. O'Bryan (Univ. of Wisconsin)
C. Sovinec (Univ. of Wisconsin)

Thrust PSR-1: Establish and extend solenoid-free plasma start-up and test NBI ramp-up

- Re-establish transient CHI discharges utilizing: **YR1 NSTX-U Ops**
  - Graphite lower divertor tiles, increased toroidal field capability
  - Full Li coating of lower divertor tiles + Li conditioning of upper divertor
- Determine maximum toroidal currents generated with CHI: YR2
  - Vary and increase the amount of injector flux, the size of the capacitor bank, and the CHI voltage (up to 2 kV).
  - Use upper divertor buffer coils to suppress absorber arcs
  - Study coupling of the CHI generated plasma to inductive drive
- Assess NBI coupling + current drive efficiency in 300-400kA flat-top current inductive plasmas, compare to TSC/TRANSP (YR3)
  - Also inject new more tangential beams into CHI targets and assess current-drive and compare to simulation
- Use combinations of NBI and HHFW to attempt non-inductive ramp-up of I_P = 0.3-0.6MA (inductive target) to 0.8-1MA (YR2,3)

Thrust PSR-2: Ramp-up CHI Plasma discharges using NBI and HHFW and Test Plasma Gun Start-up

- Maximize the levels of CHI-produced plasma currents using:
  - 1 MW 28GHz ECH (YR3)
  - Metallic divertor plates (as available) to reduce low-Z impurity radiation
  - 2.5-3 kV CHI capability (YR4)
- Extend duration of high-current CHI target using ECH/HHFW and test effectiveness of NBI coupling to CHI-target (YR3)
- Ramp-up of CHI target + ECH/HHFW → HHFW+NBI (YR4+5)
- Perform detailed comparisons of CHI current drive results to 2D TSC/TRANSP and 3D NIMROD simulations (YR4)
  - Develop a TSC/NIMROD model of CHI for FNSF design studies.
- If guns ready, commission plasma guns on NSTX-U (YR4+5)
  - Compare point-helicity injection (plasma gun) current formation on NSTX-U to Pegasus results, assess implications for FNSF

Plans for start-up/ramp-up simulations (TSC-TRANSP/NUBEAM/GENRAY, NIMROD)

- FY13 Start-up and Ramp-up of CHI-started discharge
  - Use TRANSP analysis of NSTX CHI discharges with inductive ramp to obtain electron transport model
    - Use TSC generated CHI equilibrium to obtain ECH absorption and heat deposition profiles and extend to 1T (GENRAY)
    - Assess requirements for electron heating by HHFW (with ECH heating
    - Requirements for NBI ramp-up to1 MA of CHI target with ECH + HHFW

  - With NIMROD obtain good agreement with an NSTX transient CHI discharge
    - Requirements for voltage/injector current programming and injector flux footprint shaping

Plans for start-up/ramp-up simulations

- FY13-14 Extend to NSTX-U geometry
  - Develop start-up scenarios for YR1-2 Ops.
  - Couple TSC directly to TRANSP/NUBEAM/GENRAY codes to self-consistently calculate deposition profiles
  - Assess impact of including additional parameters (n_e and Z_{eff}) and impact of injector gap width in NIMROD simulations

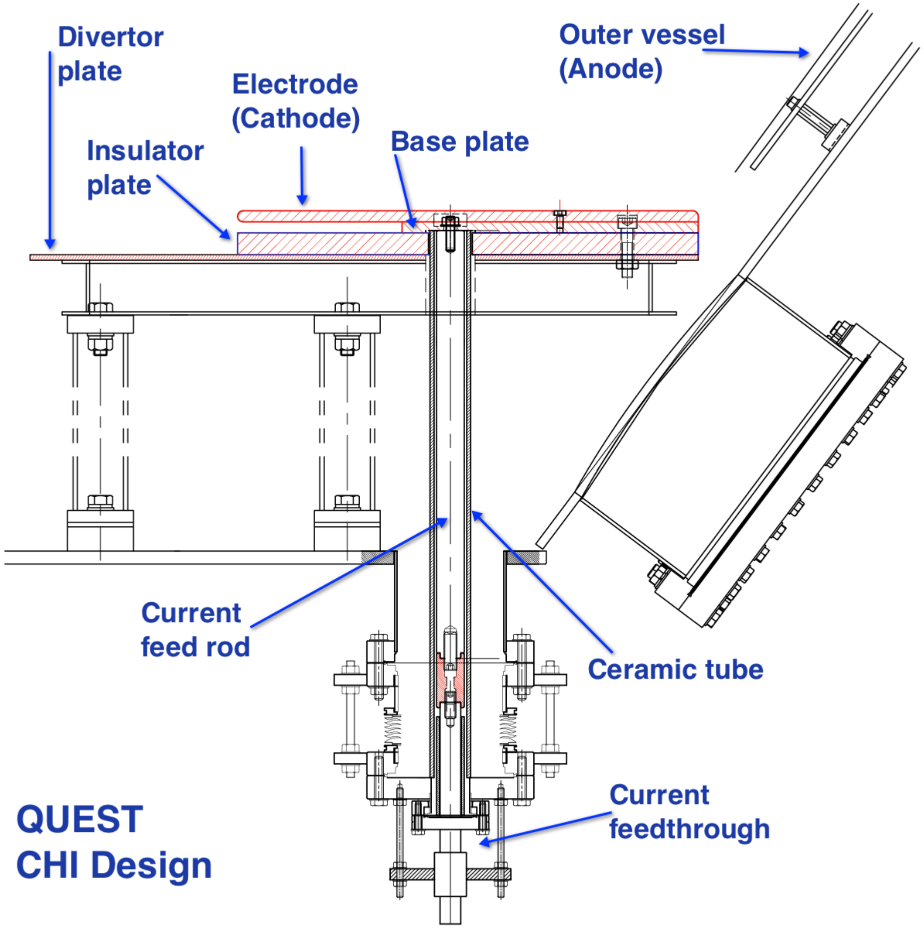
- FY15-18 Support NSTX-U Ops. & Extend to FNSF/ST Demo
  - Use experimental results to improve model & extend to FNSF
  - Use in predictive mode to support experiments
  - Incorporate CHI model in free-boundary predictive TRANSP
  - Understand plasma growth rate implications for electron heating
  - Understand 3D effects on fast flux closure as I_p is increased to MA levels
  - Requirements for establishing a start-up discharge in next step devices

Hardware preparations for NSTX-U Start-up

- Diagnostics [FY 13 - 14]
  - New additional fast voltage monitors for upper divertor
  - Additional dedicated current monitors near injector
  - Special set of EMI shielded inner vessel magnetics
  - Additional flux loops and Mirnov coils on lower and upper divertor
    - Langmuir probe array on lower divertor
  - Multipoint Thomson scattering, Filter scopes, multi chord bolometers and SXR arrays
- Capacitor bank power supply [FY 13 - 14] – Baseline capability
  - Voltage increased to ~2 kV & improve voltage snubbing systems
  - NSTX-U to support 4kV Ops. including transients
- Capacitor bank power supply [YR 16-18] – Upgraded capability
  - Voltage increased to ~2.5-3 kV
  - Additional modules for improved voltage control

CHI design for QUEST supports NSTX-U research (Collaboration with Japan)

- Preliminary design completed (January 2013)
  - Now working on finalizing design and pricing
- Electrode mounted on top of divertor plate
  - Insulators not part of vacuum structure
  - CHI operation at up to 3kV
  - Metallic electrodes (SS + Mo/W)
    - Provides data for NSTX-U metal electrodes



QUEST CHI Design

Plans for external collaboration & design studies

- FY 13-15
  - Finalize CHI design for QUEST
  - CHI system design for FNSF
  - Participation with HIST device for CHI (device size scaling)
  - Participation with PEGASUS on plasma gun start-up
    - Assessment of requirements for NSTX-U
  - Possible installation of CHI capability on QUEST
    - Establish Transient CHI discharges on QUEST

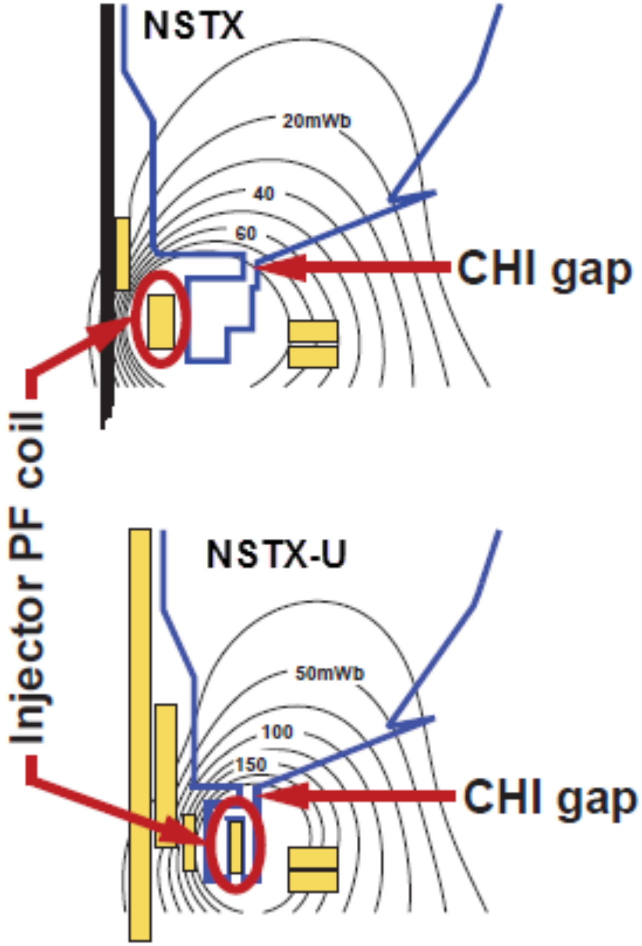
- Years 16-18
  - Assessment of benefits of metal electrodes on QUEST (for NSTX-U)
  - Test of edge current drive & steady-state CHI on QUEST

NSTX-U is well poised to demonstrate full non-inductive start-up and ramp-up in support of next steps devices

- CHI start-up achieves record-low flux consumption on NSTX to get to 1MA
  - Compatibility with H-mode operation demonstrated
  - Generates discharges with low internal inductance and density needed for ECH heating and non-inductive ramp-up with NBI on NSTX-U
  - Favorable scaling with machine size (HIT-II, NSTX)
- ~1MW 28 GHz ECH would greatly enhance start-up/ramp-up capabilities
  - Helicity injected plasmas require early heating to avoid rapid current decay
- MHD codes now starting to reproduce NSTX CHI discharges
  - TSC being used to develop initial start-up scenarios for NSTX-U
  - NIMROD (and possibly M3D-C1) to improve understanding of flux closure mechanisms and the early dynamic phase of CHI
- External collaboration aids NSTX-U, FNSF & ST Demo
  - Plan to test metal electrodes and new electrode design on QUEST
  - PEGASUS developing plasma gun start-up for implementation on NSTX-U

Back-up slides

CHI start-up to ~0.4MA is projected for NSTX-U, and is projected to scale favorably to next-step STs



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

Parameters	NSTX	NSTX-U	ST-FNSF	ST Pilot Plant
Aspect ratio: A	1.30	1.50	1.50	1.70
Elongation: κ	2.6	2.8	3.1	3.3
Major radius: R_0 [m]	0.86	0.93	1.2	2.2
Minor radius: a [m]	0.66	0.62	0.80	1.29
Toroidal field at R_0: B_T [T]	0.55	1	2.2	2.4
TF rod current: I_{TF} [MA]	2.4	4.7	13.2	26.4
Toroidal flux: Φ_T [Wb]	2.5	3.9	15.8	45.7
Reference maximum sustained plasma current: I_{PS} [MA]	1	2	10	18
Start-up plasma normalized internal inductance: l_i	0.35	0.35	0.35	0.35
Injector flux footprint: d [m]	0.6	0.56	0.73	1.17
Injector flux for projecting start-up current: ψ_{inj} [Wb]	0.047	0.10	0.66	2.18
Bubble-burst current: I_{bb} [kA]	3.3	9.0	79	165
Injector current: I_{inj} [kA]	4.0	10.8	95	198
Start-up plasma flux: ψ_p [Wb]	0.04	0.08	0.53	1.74
Start-up plasma current achieved or projected: I_P [MA]	0.20	0.40	2.00	3.60
Current multiplication: I_P / I_{inj}	50	37	21	18
Multiplication limit: Φ_T / ψ_{inj}	53	38	24	21
Injector current density [kA/m^2]	4.9	12	63	39

J. E. Menard et al., NF 52 (2012) 083015