NSTX-U

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

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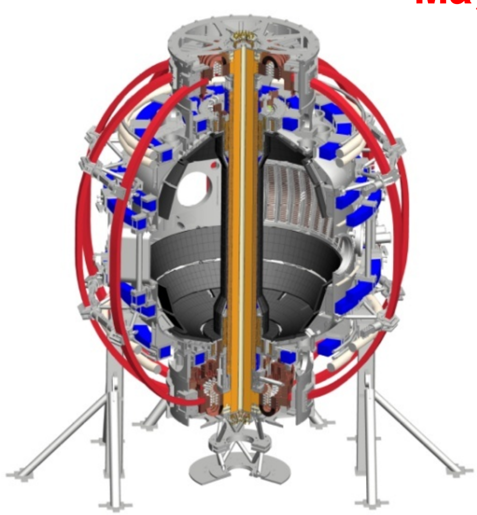

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Outline

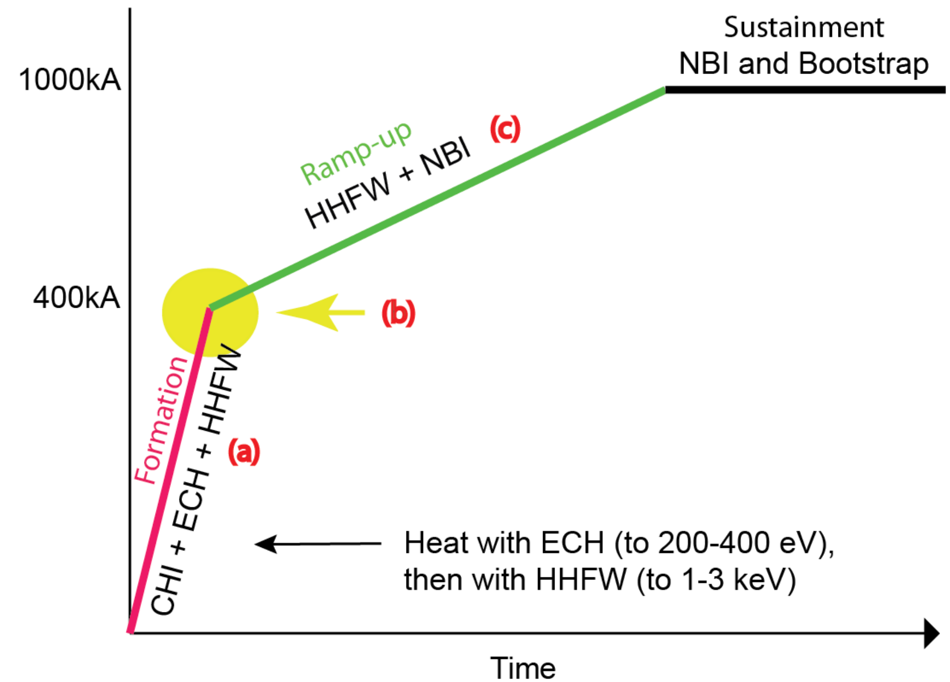
- Motivation & Goals
- Transient CHI Plasma Start-up
- Point Source Helicity Injection Plasma Start-up
- Supporting modeling work
- Research Thrusts
- Plans for Current Ramp-up studies
- Summary

Goal: Develop & 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:
  1) Establish and extend solenoid-free plasma start-up and test NBI ramp-up
  2) 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 & ramp-up is front end of that objective

Ramp-up scenario development will initially rely on inductively generated plasmas with varying plasma parameters

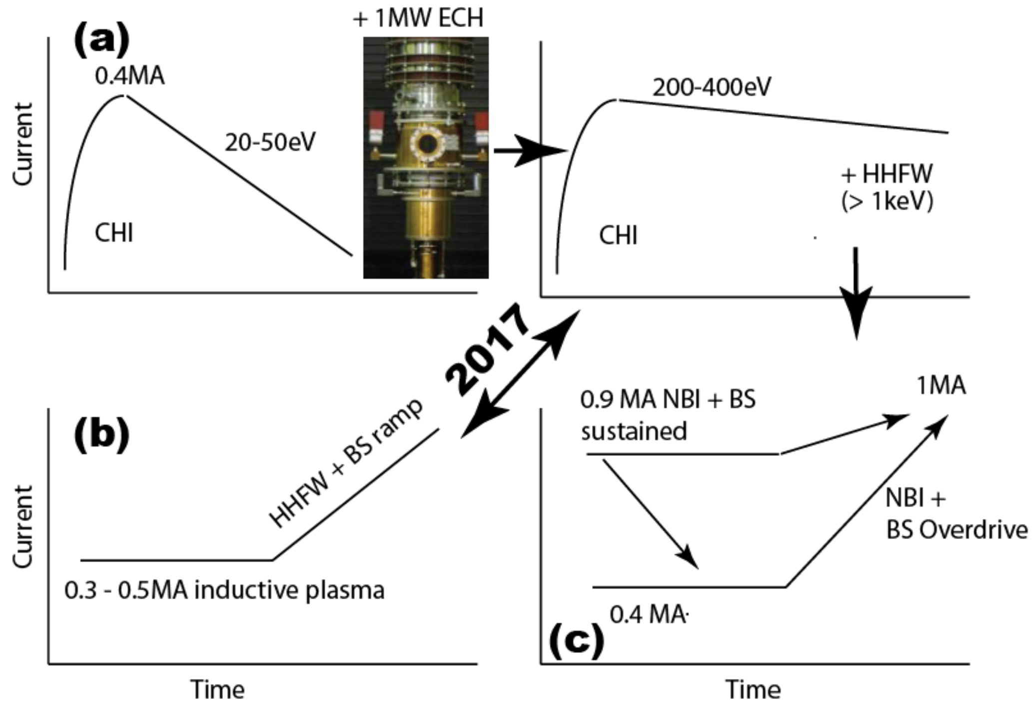
Start-up and Ramp-up Research Involves Three Parallel Paths that Will be Linked as Technical Capabilities Permit

(a) Generate and increase current produced by CHI

- Heat with ECH (to 200-400eV)
- Then heat with HHFW (to > 1keV)
- Then ramp-up current using NBI and BS current overdrive

(b) Current ramp-up of intermediate I_p plasmas (Wave particle TSG)

- Progressively increase initial current (from 0.3 to 0.5MA) and ramp-up using HHFW and BS current overdrive
- Assist extension of NBI CD to lower I_p



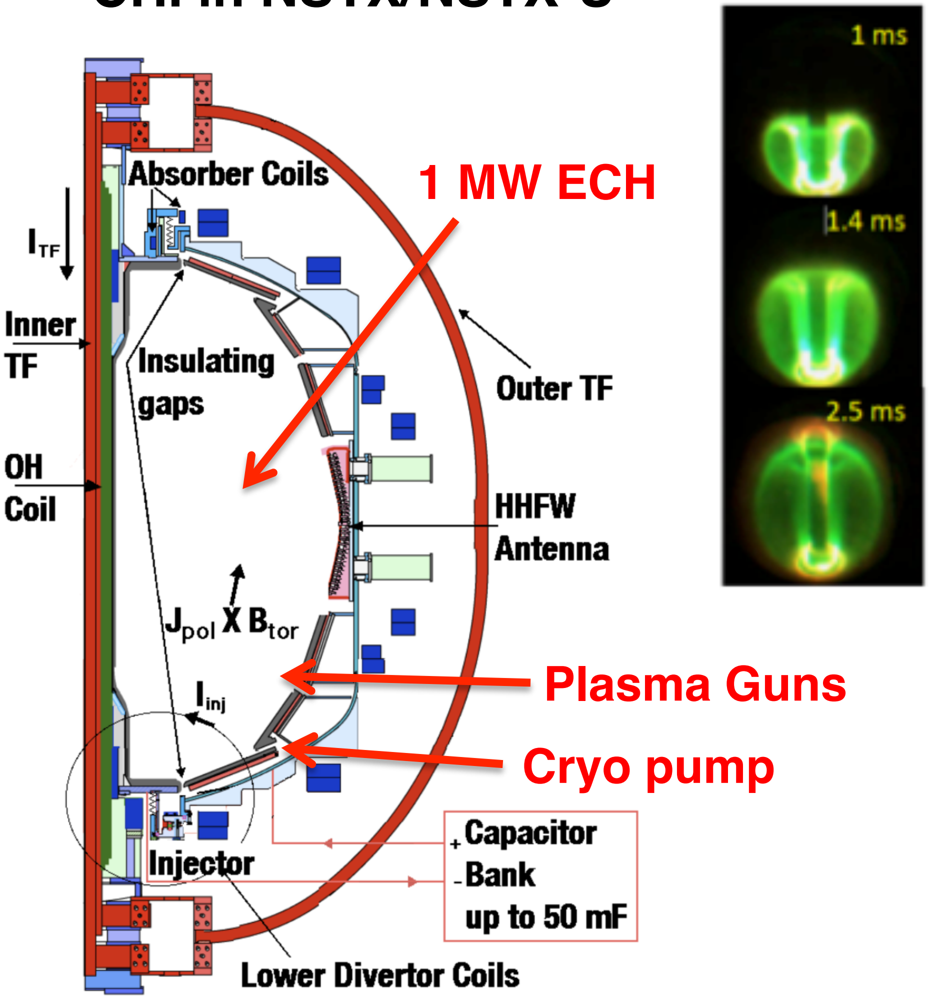
(c) Current ramp-up at near full I_p with NBI and bootstrap current overdrive

- Progressively reduce initial current from 0.9 to 0.4MA and non-inductively ramp-up current to 1MA using NBI and BS current overdrive

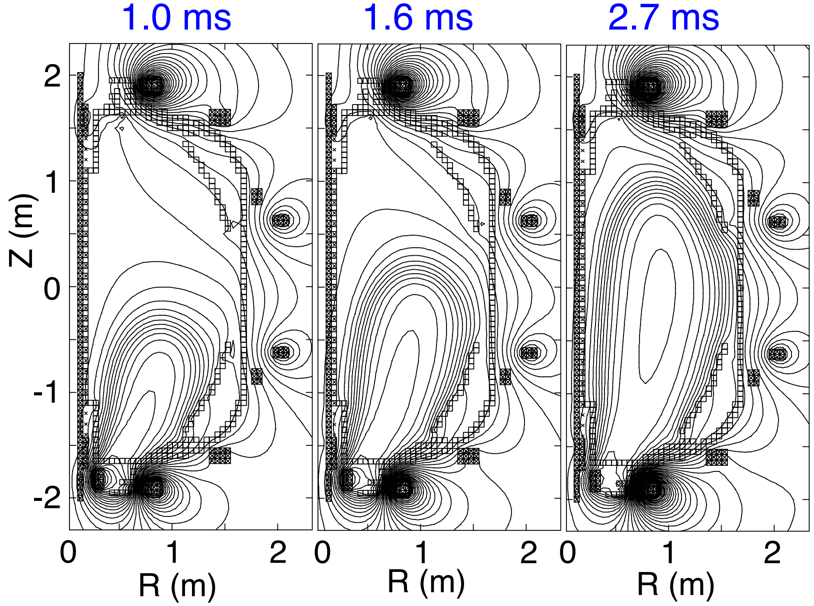
CHI and Plasma Gun Start-up

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

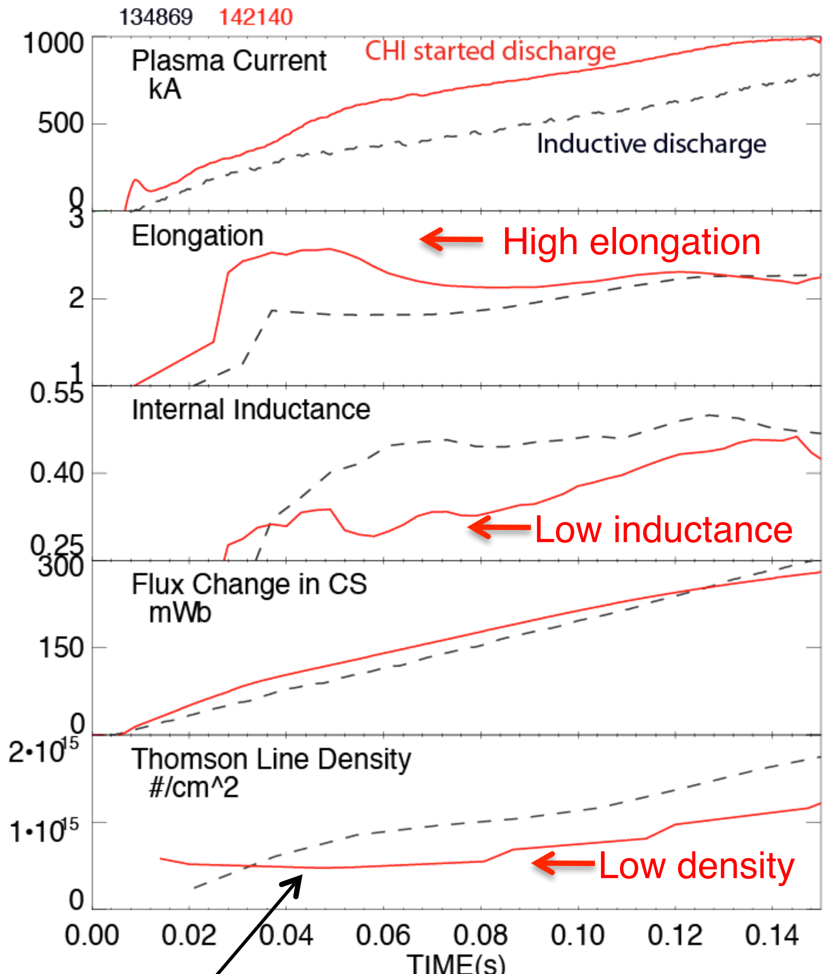


New Tools for CHI on NSTX-U

- > 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)

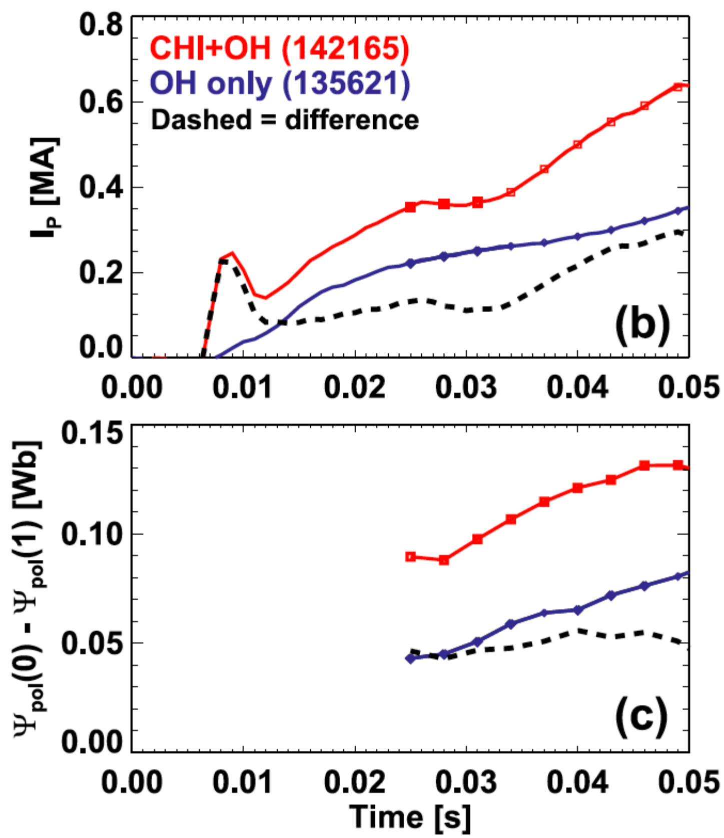
Plasma Discharge Ramping to 1MA Required 35% Less Inductive Flux when Coaxial Helicity Injection (CHI) is Used

CHI assisted startup in NSTX



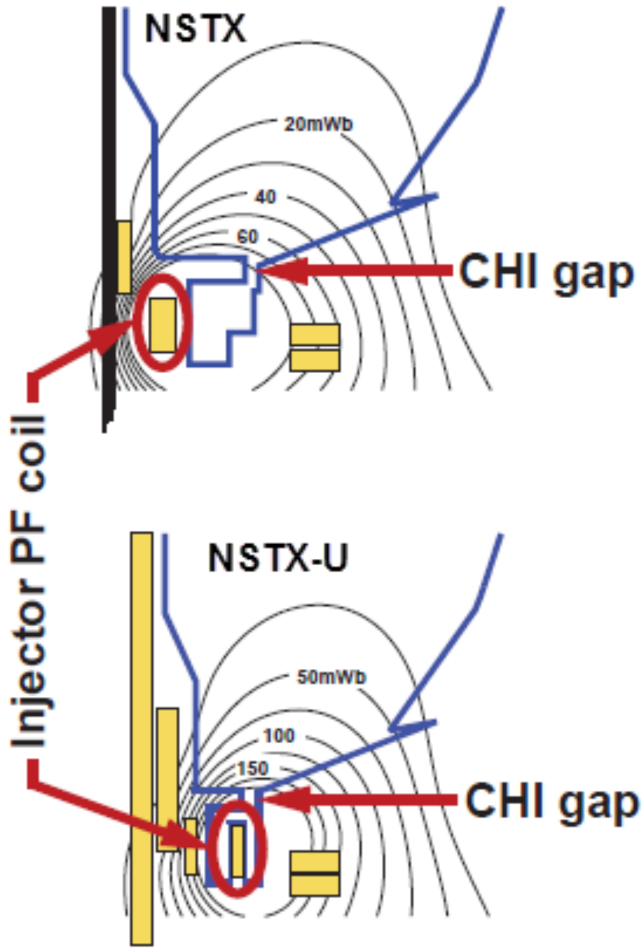
CHI generates plasmas with low n_e below ECH cut-off

CHI produces closed flux change of ~ 50 mWb



CHI produced plasma is clean (Transitions to H-mode after coupling to induction)

CHI Start-up to ~0.4MA is Projected for NSTX-U, and Projects to ~20% Start-up Current in Next-step STs



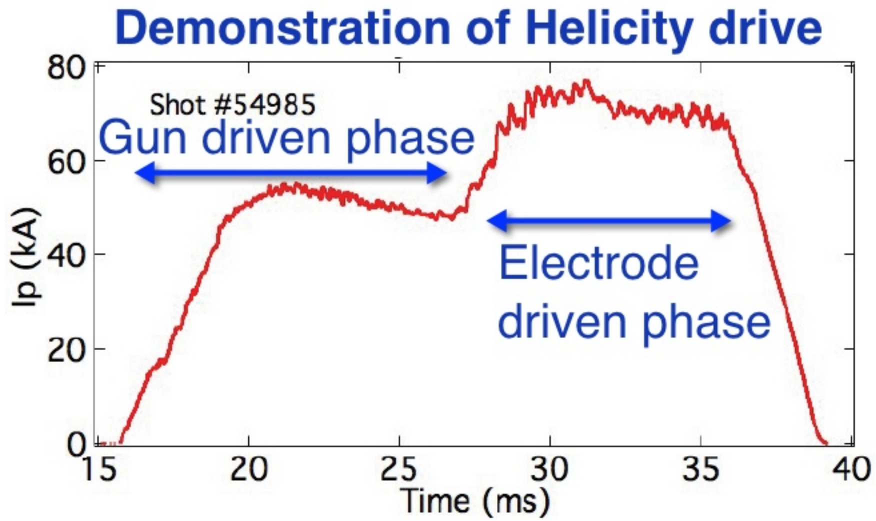
Parameters	NSTX	NSTX-U	ST-FNSF
Major Radius [m]	0.86	0.93	1.2
Minor Radius [m]	0.66	0.62	0.80
B_T [T]	0.55	1.0	2.2
Toroidal Flux [Wb]	2.5	3.9	15.8
Plasma current [MA]	1	2	10
Projected Start-up Current (MA)	0.2	0.4	2.0
Poloidal Flux (Wb)	0.04	0.08	0.53
Injector Flux [Wb]	0.047	0.1	0.66

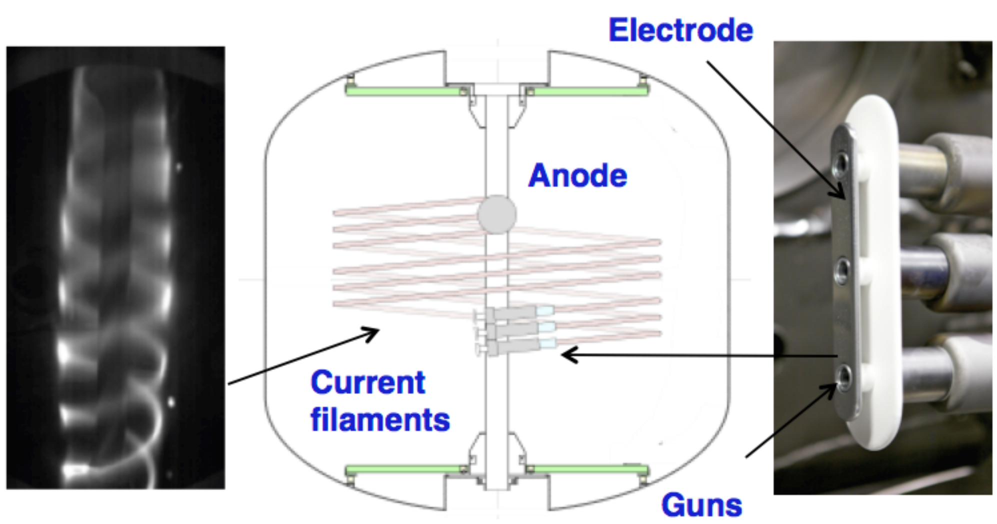
Injector flux in NSTX-U is ~ 2.5 times higher than in NSTX → supports increased CHI current

FY15 Research Milestone (Incremental):
1) Establish CHI start-up and 2) 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$)^{0.5}$



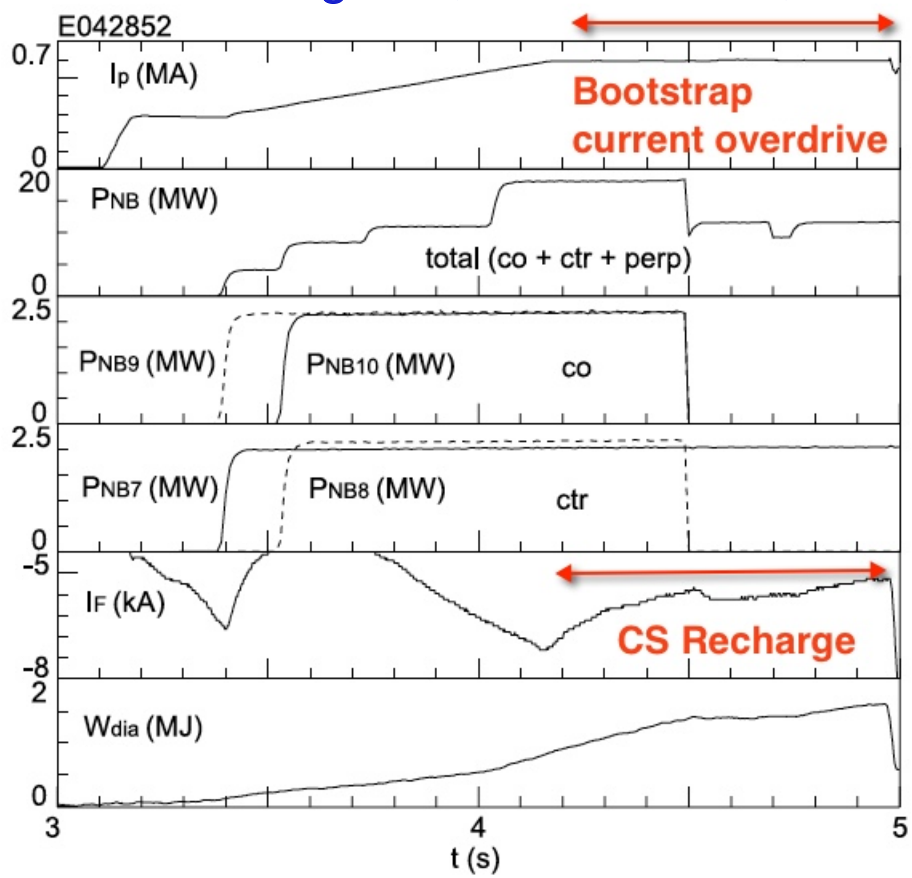


- Issues being addressed by Pegasus to achieve high I_p
  - Large-area electrode with uniform current density
  - Characterization of plasma confinement/dissipation and injector impedance
  - Pegasus wants to deliver MA-class (I_p > 0.5 MA) to NSTX-U by end of 5YR plan

Non-inductive Current Ramp-up

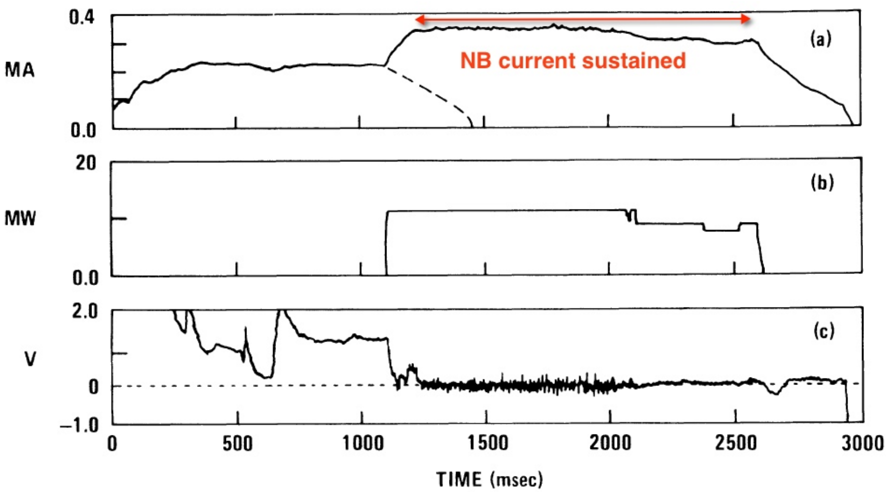
Results on JT-60U and DIII-D Suggest I_p Ramp-up is Possible with Combination of Bootstrap Current Overdrive and NBI CD

JT-60U [NF 46 (2006)]
Ref: Ushigome, Takase et al.,



Plasma current should have ramped-up if solenoid current had been held constant

DIII-D [PRL 61(1998)]
Ref: Simonen, et al.,

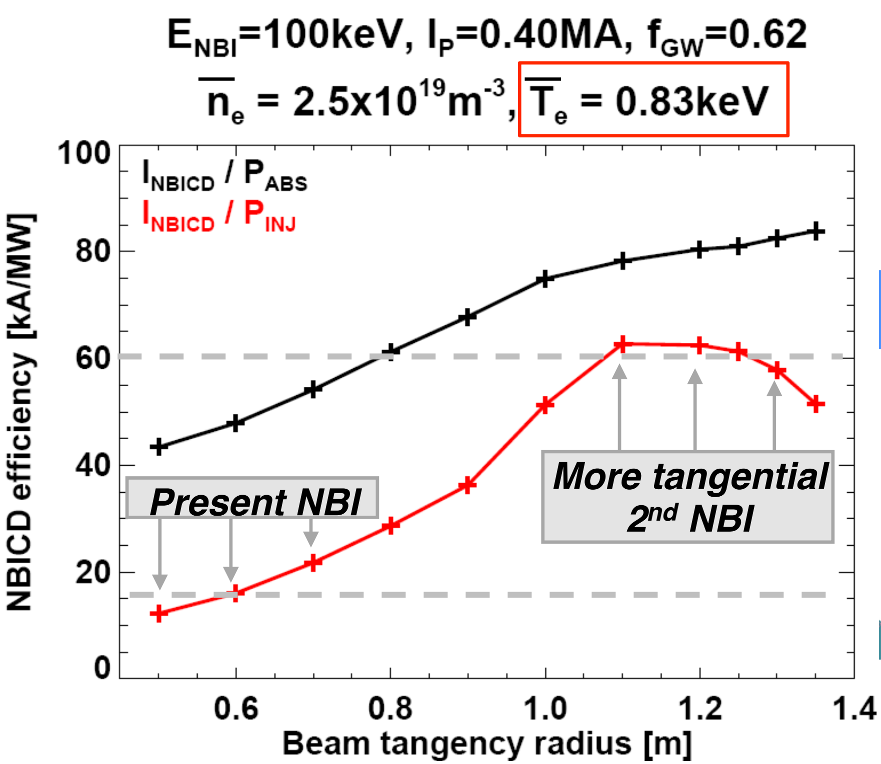


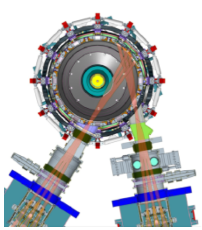
350 kA plasma sustained mostly by neutral beams and without MHD

NSTX-U research will extend previous experimental work to demonstrate full non-inductive start-up, ramp-up, and sustainment

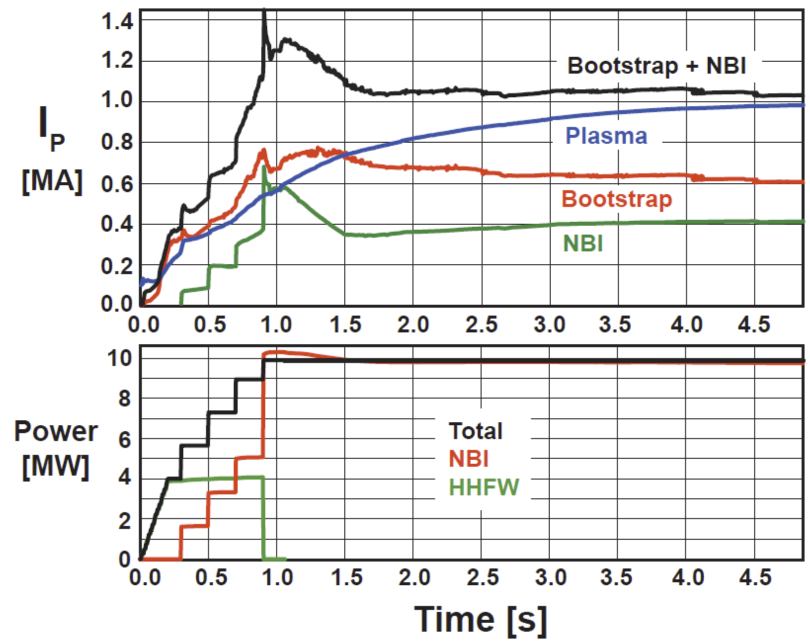
Non-inductive Ramp-up from ~0.4MA to ~1MA Projected to be Possible with More Tangential 2nd NBI

- **More tangential NBI provides 3-4x higher CD at low I_P:**
  - 1.5-2x higher current drive efficiency, plus
  - 2x higher absorption (40→80%) at low I_P = 0.4MA



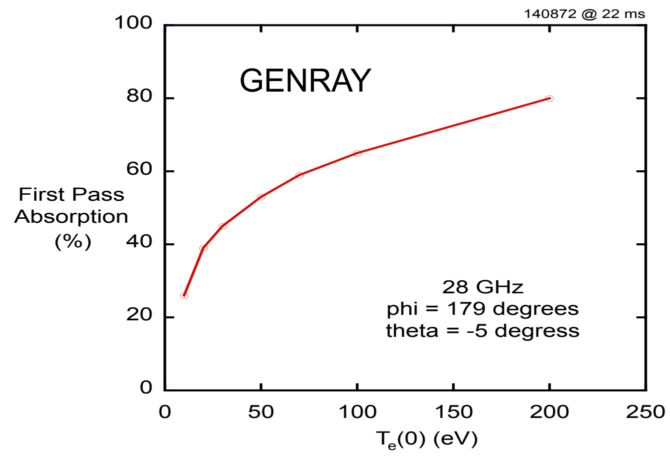


- **TSC simulation of non-inductive ramp-up from initial 400kA target**
  - Simulations now being improved to use TRANSP/NUBEAM loop within TSC
  - Experimental challenges:
    - Maximum NBI power in low inductance CHI plasma

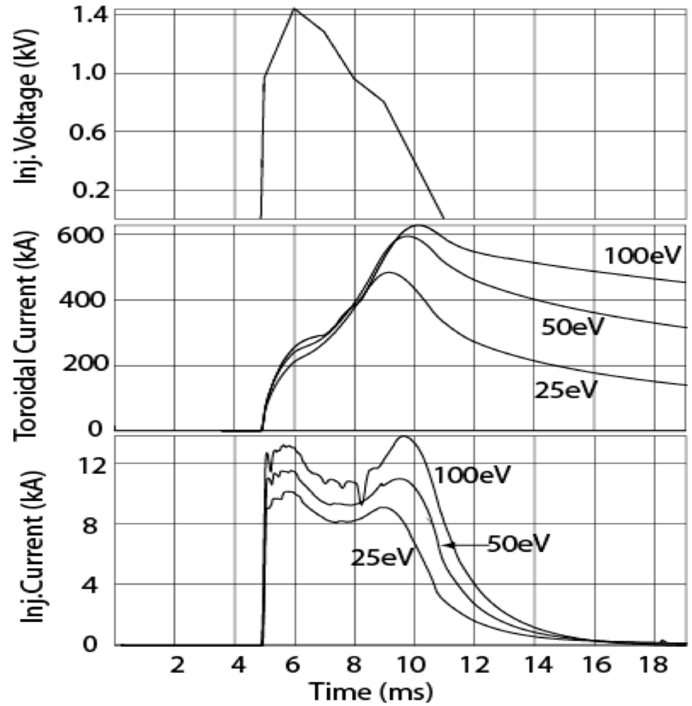


Ramp-up Strategy Significantly Benefits from 1-2 MW ECH to Heat CHI Plasma

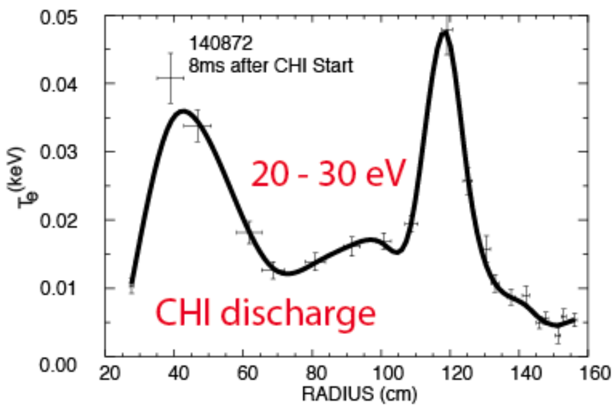
- TSC simulations indicate 0.6MW of absorbed ECH power could increase T_e to ~400eV in 20ms (with 50% ITER L-mode scaling)
  - CHI discharge densities at T_e = 70 eV would allow 60% first-pass absorption by 28 GHz ECH in NSTX-U



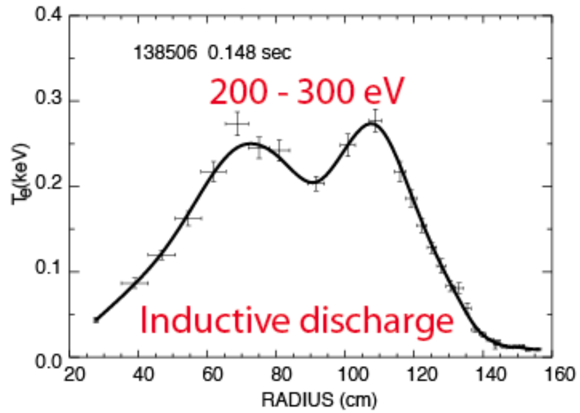
- Increased T_e predicted to significantly reduce current decay rate due to resistive dissipation
  - ECH heated plasma can be further heated with HHFW
  - Maximum HHFW power < 4MW, higher B_T in NSTX-U would improve coupling
  - HHFW has demonstrated heating a 300 kA / 300 eV plasma to > 1 keV in 20ms



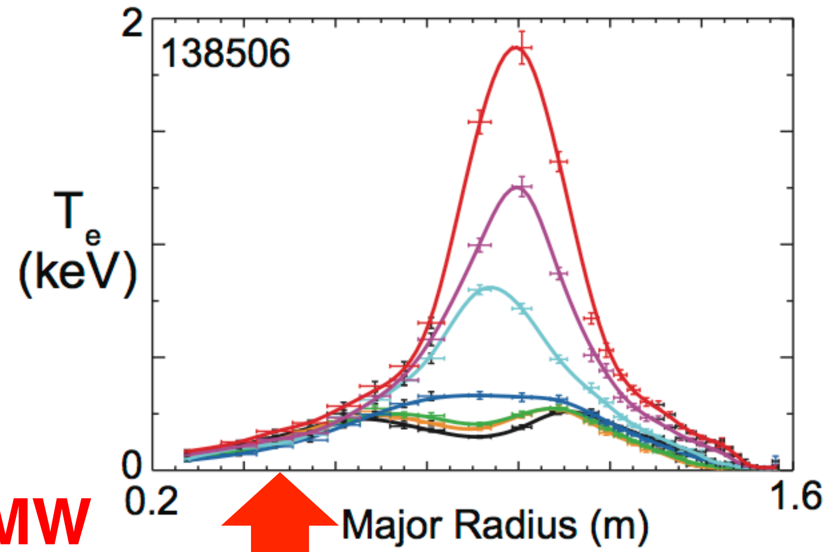
Bridge Electron Temperature Gap Between CHI Start-up and Current Ramp-up Requirements with ECH Heating

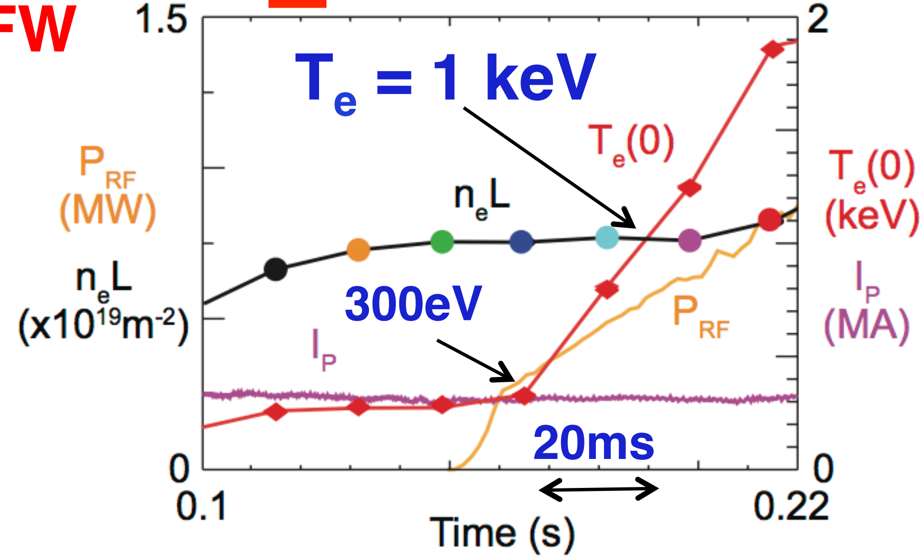


1MW ECH



1-2 MW HHFW





Research Plan

Thrust PSR-1a: Establish and Extend Solenoid-free Plasma Start-up

- FY15: Re-establish transient CHI discharges utilizing
  - Graphite lower divertor tiles, increased toroidal field capability
  - Full Li coating of lower divertor tiles + Li conditioning of upper divertor
  - Develop CHI targets using TSC and model ECH absorption in TSC generated equilibria (FY13-14)
  - Improve NIMROD simulations to obtain good agreement with NSTX transient CHI discharges (FY13-14) [See backup slide 27 for more detail]

- FY15-16: Determine maximum toroidal currents generated by CHI
  - Vary and increase the amount of injector flux, the size of the capacitor bank, and the CHI voltage (up to 2 kV).
  - Study coupling of the CHI generated plasma to inductive drive
  - Use experimental results to Improve TSC models for CHI start-up

Thrust PSR-1b: Test NBI Current Ramp-up

- FY15-16: Assess NBI coupling + current drive efficiency in 300-800kA flat-top current inductive plasmas, compare to TSC/ TRANSP
  - Vary the plasma density and T_e
  - Inject new more tangential beams into CHI + induction targets and assess current-drive and compare to TSC/TRANSP simulation

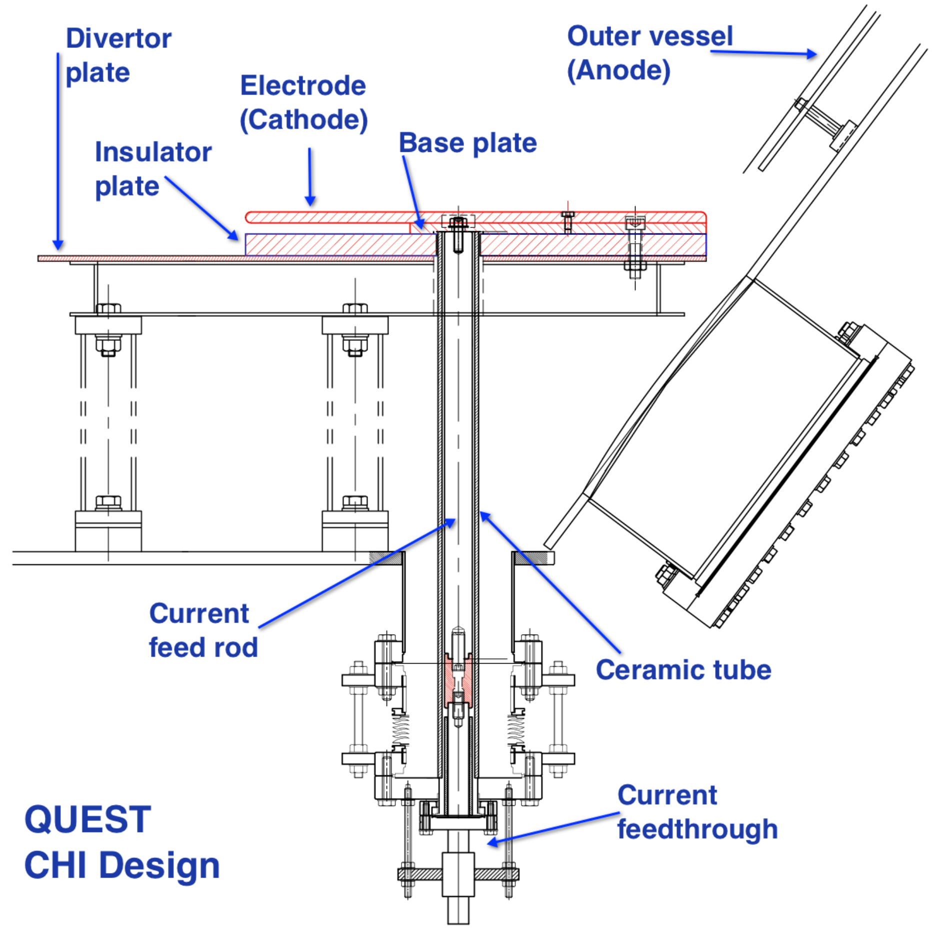
- FY16-17: Use combinations of NBI and HHFW to attempt non-inductive ramp-up of I_P = 0.5-0.6MA (inductive target) to 0.8-9MA
  - Use TSC/TRANSP in predictive mode to support experiments

Thrust PSR-2: Ramp-up CHI Plasma Discharges Using ECH, HHFW and NBI and Test Plasma Gun Start-up

- Maximize the levels of CHI-produced plasma currents using:
  - 1 MW 28GHz ECH (FY17) [CHI goal 0.3-0.5MA]
  - Metallic divertor plates (as available) to reduce low-Z impurity radiation
  - 2.5-3 kV CHI capability (FY18) [CHI goal 0.4-0.6MA]
  - Validate CHI started discharge modeled using NIMROD
- FY17: Extend duration of high-current CHI target using ECH/HHFW and test effectiveness of NBI coupling to CHI-target
  - Validate ECH heated CHI discharge models using GENRAY
- FY17-18: Ramp-up of CHI target + ECH/HHFW → HHFW+NBI
  - Validate simulations of current ramp up using TSC/TRANSP
  - Develop TSC/TRANSP/GENRAY & NIMROD models for establishing start-up/ramp-up requirements in ST FNSF
- FY17-18: If guns ready, commission and test on NSTX-U

CHI Design for QUEST Supports NSTX-U and FNSF Research (Collaboration with Japan)

- QUEST ST aims to develop technologies for SS operation
  - Use CHI in biasing mode to vary edge density gradient for EBW experiments
  - High CHI current provides new target for SS CD studies on QUEST
  - Interested in potential of steady-state CHI for edge current drive (aided by all metal nature of QUEST + ECH)
- Benefits to NSTX-U
  - Test metal electrodes to reduce low-Z impurities
  - Test ECH heating of CHI target at 0.5MW level
  - Test new electrode configuration to enhance compatibility with FNSF



QUEST CHI Design

Electrodes mounted on top of existing divertor plate

NSTX-U is Well Poised to Demonstrate Full Non-inductive Start-up and Ramp-up in Support of Next Step Devices

- CHI start-up aided achievement of record-low flux consumption on NSTX to ramp 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

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)
  - Use TSC generated inductive equilibria (with varying parameters) to calculate NBI absorption efficiency and current drive
  - Assess requirements for electron heating by HHFW (with ECH heating)
  - Requirements for NBI ramp-up to1MA of CHI target with ECH + HHFW

  - Improve NIMROD simulations to 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 FY15-16 Ops.
  - Couple TSC directly to TRANSP/NUBEAM/GENRAY codes to self-consistently calculate NBI and RF power 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 TSC/NIMROD models & extend to FNSF
  - Use in predictive mode to support experiments
  - Incorporate CHI model in free-boundary predictive TRANSP
  - Understand plasma current 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 [FY13 - 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 [FY13 - 14] – Baseline capability
  - Voltage increased to ~2 kV & improve voltage snubbing systems
  - NSTX-U coil insulation is designed to support 4kV operations
  - Capacitor bank power supply [YR16-18] – Upgraded capability
  - Voltage increased to ~2.5-3 kV
  - Additional modules for improved voltage control

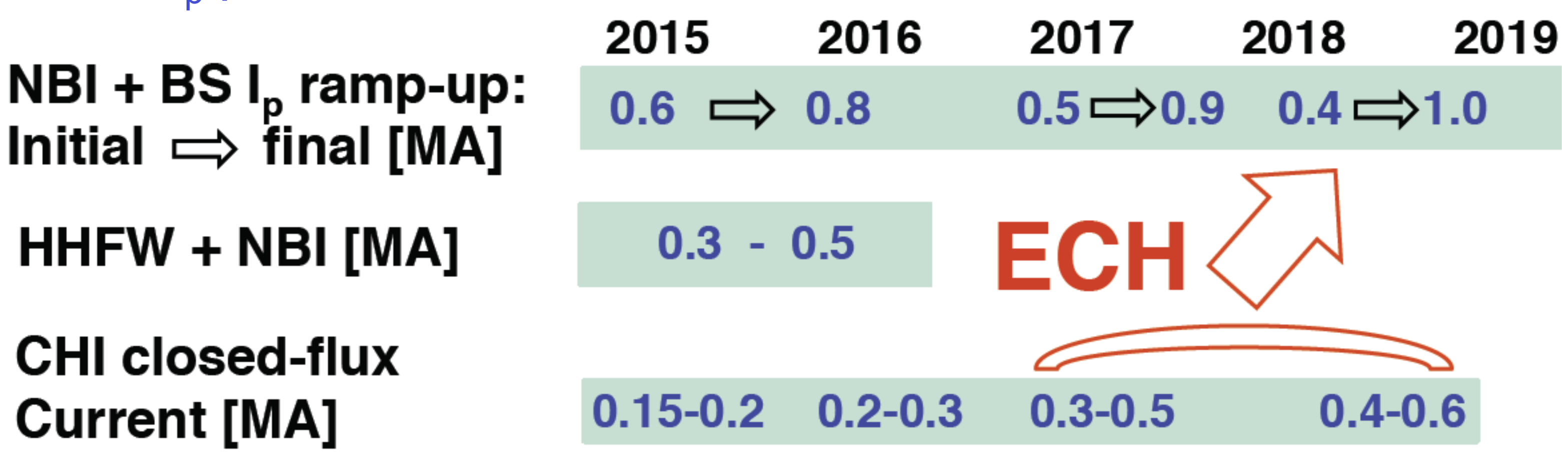
Plans for External Collaboration & Design Studies

- FY13-15
  - Finalize CHI design for QUEST
  - CHI system design for FNSF
  - Participation with HIST device for CHI studies (device size scaling)
  - Participation with PEGASUS on plasma gun start-up
    - Assessment of hardware requirements for NSTX-U
  - Possible installation of CHI capability on QUEST
    - Establish Transient CHI discharges on QUEST

- FY16-18
  - Assessment of benefits of metal electrodes on QUEST
  - Test of edge current drive & steady-state CHI on QUEST

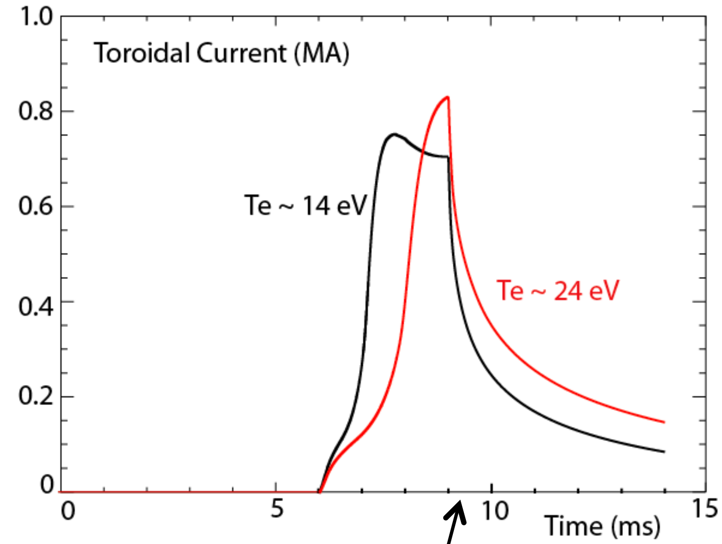
NSTX-U Current Start-up and Ramp-up Plan Involves Three Parallel Paths

- CHI initiated current progressively increased in current magnitude to exceed minimum I_p parameters established by inductive plasmas (ECH needed to increase T_e)
- HHFW + Bootstrap current overdrive developed on 0.3-0.5 MA plasmas to understand HHFW coupling to ECH heated CHI plasmas and to provide more flexibility in lower current levels at which to start NBI current ramp
- The magnitude of the initial inductive I_p target will be progressively decreased below the 100% NBI + BS sustained value (~1 MA) to find the minimum I_p parameters for overdrive

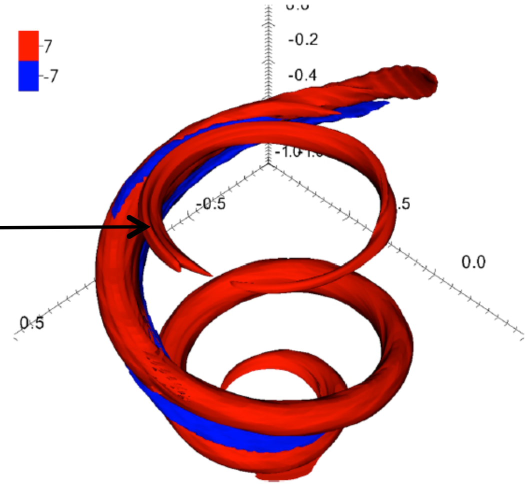


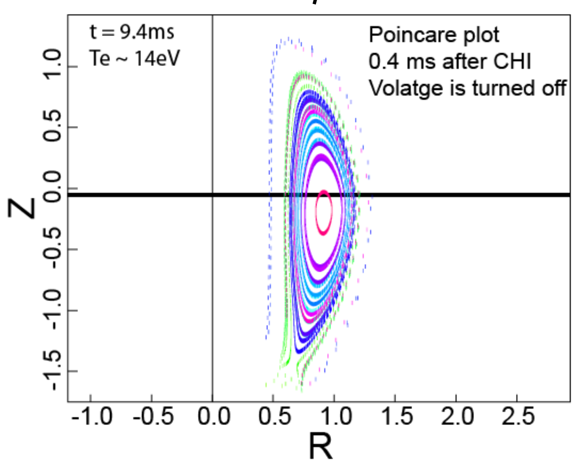
Nimrod will Study T_e Evolution, Transport and Ohmic Heating During CHI Evolution Phase

- Will 3D physics in NIMROD alter our present expectations for scaling to next-step devices?
  - MHD stability limits on CHI current density and/or current profile minimum
- Ongoing simulations show promising results
  - Now starting to show flux closure on experimental time scales



Point source (local) helicity injection simulations show release of a current ring following reconnection





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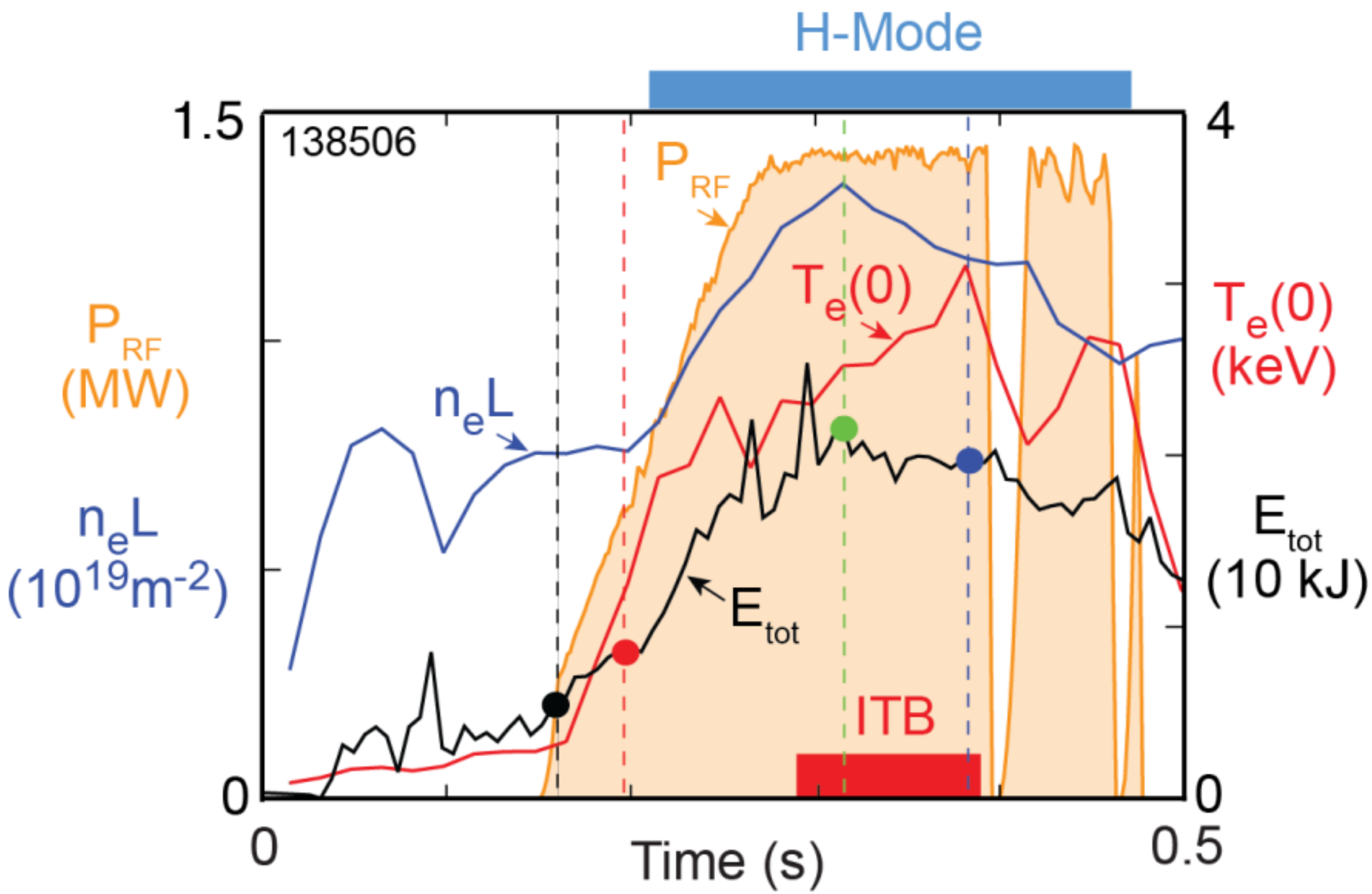
C. Sovinec (Univ. of Wisconsin)

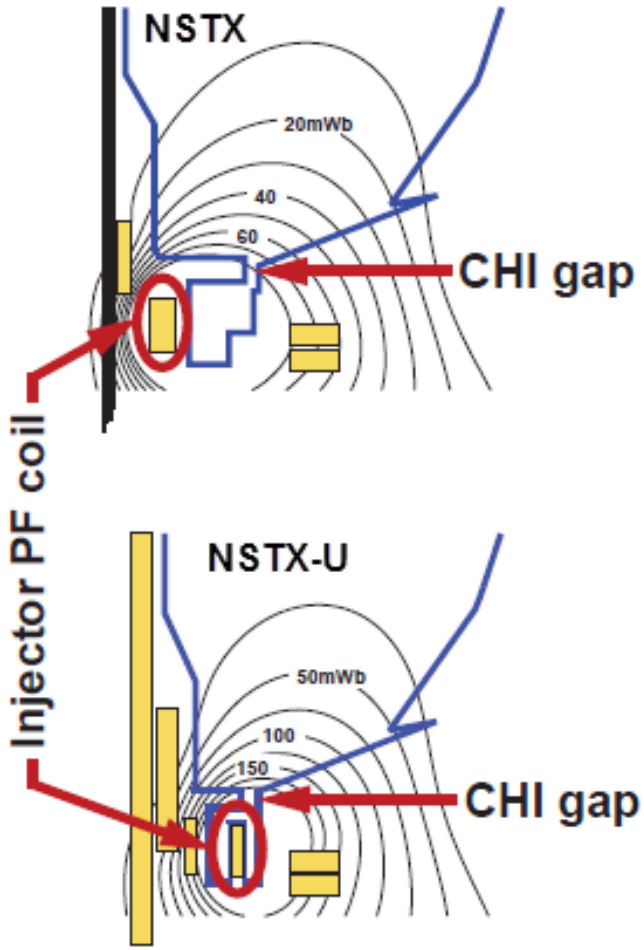
~500 kW of HHFW Increases $T_e(0)$ to Over 1 keV in ~30 ms

300 kA Inductive Plasma



TRANSPARENT analysis indicates significant levels of non-inductive current drive fraction (discussed in Talk by Taylor)

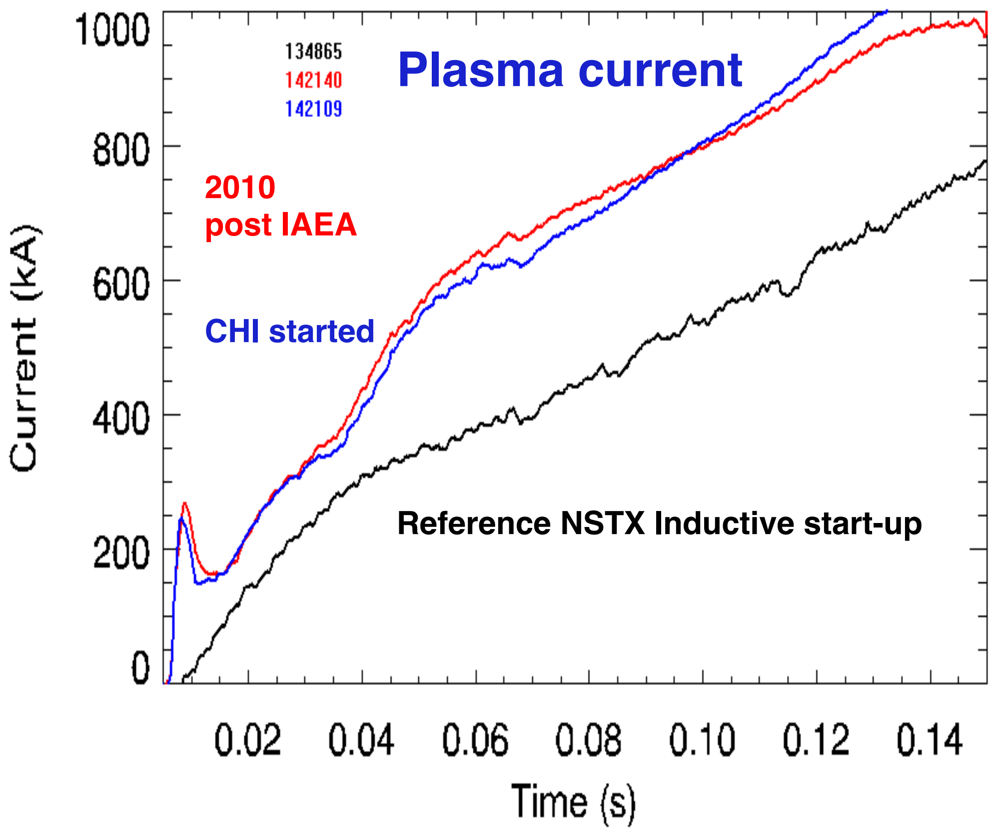
CHI Start-up to ~0.4MA is Projected for NSTX-U, and is Projected to Scale Favorably to Next-step STs

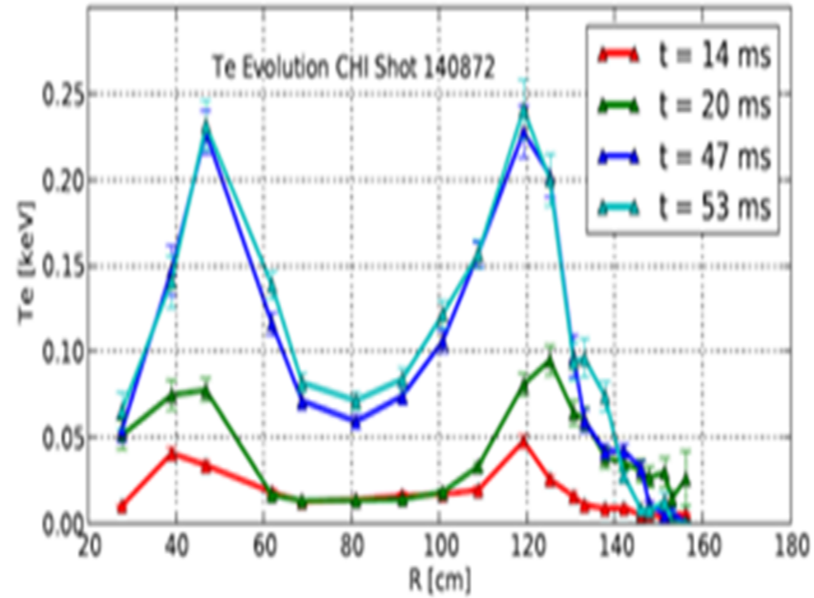


Injector flux in NSTX-U is ~ 2.5 times higher than in NSTX → supports increased CHI current

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

Standard L-mode NSTX Discharge Ramps to 1MA Requiring 50% More Inductive Flux than a CHI Started Discharge





Hollow electron temperature profile maintained during current ramp

- Important beneficial aspect of using CHI startup

- **Reference Inductive discharge**
  - **Uses 396mWb to get to 1MA**
- **CHI started discharge**
  - **Uses 258 mWb to get to 1MA (138 mWb less flux to get to 1MA)**