NSTX-U

Supported by U.S. DEPARTMENT OF ENERGY Office of Science

Progress and Plans for Solenoid-free Plasma Start-up and Ramp-up

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NSTX-U PAC-35 Meeting
PPPL – B318
June 11-13, 2014

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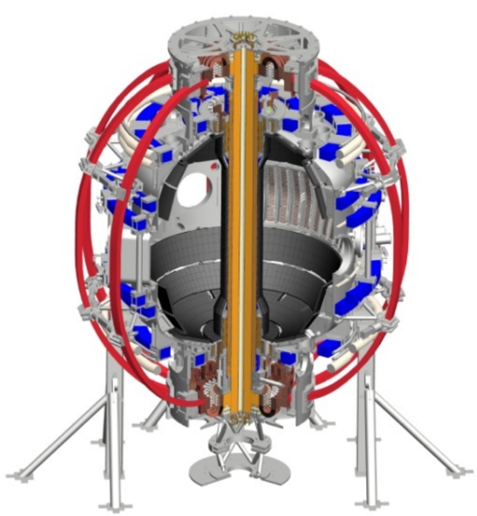

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Outline

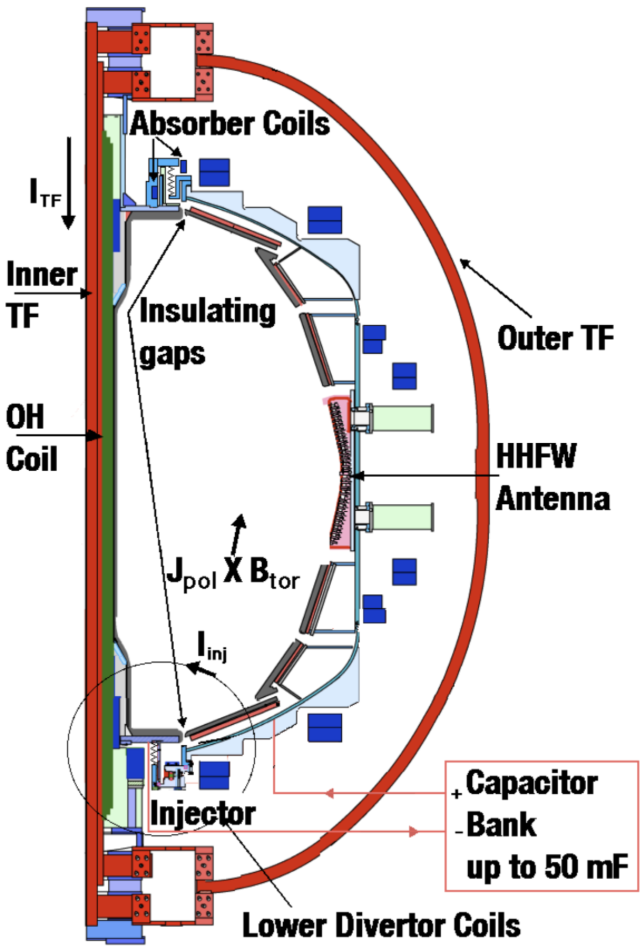
- Introduction
- Progress in the last year – in preparation for upcoming run
  - NIMROD & TSC Simulations
  - Progress with CHI on QUEST
- Solenoid-free Start-up & Ramp-up (SFSU) research goals and plans for FY15 & 16
- Key results expected by the end of the FY16 run
  - Impact on further NSTX-U operation and future devices

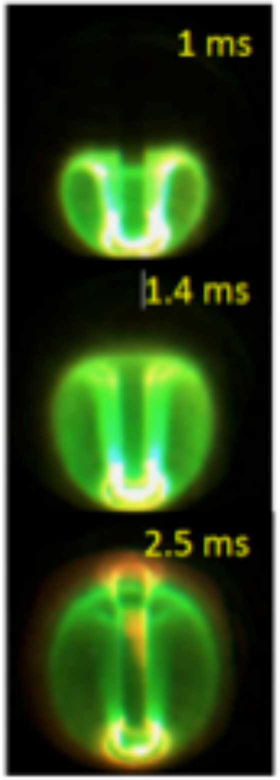
Goal: Develop and understand non-inductive start-up/ramp-up to project to ST-FNSF operation with small or no solenoid

- Aligned with FES program vision for FNSF requirements
  - Enabling access to low aspect ratio for nuclear applications
  - Simplify the tokamak concept to reduce cost
- High level NSTX-U goals:
  - Demonstrate and understand solenoid-free current start-up
  - Ramp-up the solenoid-less seed current non-inductively using RF and NBI
- Solenoid-free Start-up & Ramp-up 5YR objectives:
  - FY15-16: Establish high current CHI target that is suitable for non-inductive current ramp-up
  - FY15-16: Test Ramp-up of a 300-600kA inductively generated plasma using RF and NBI
  - FY17-18: Integrate non-inductive start-up to ramp-up. Test Ramp-up of ECH-heated CHI generated plasma with RF and NBI

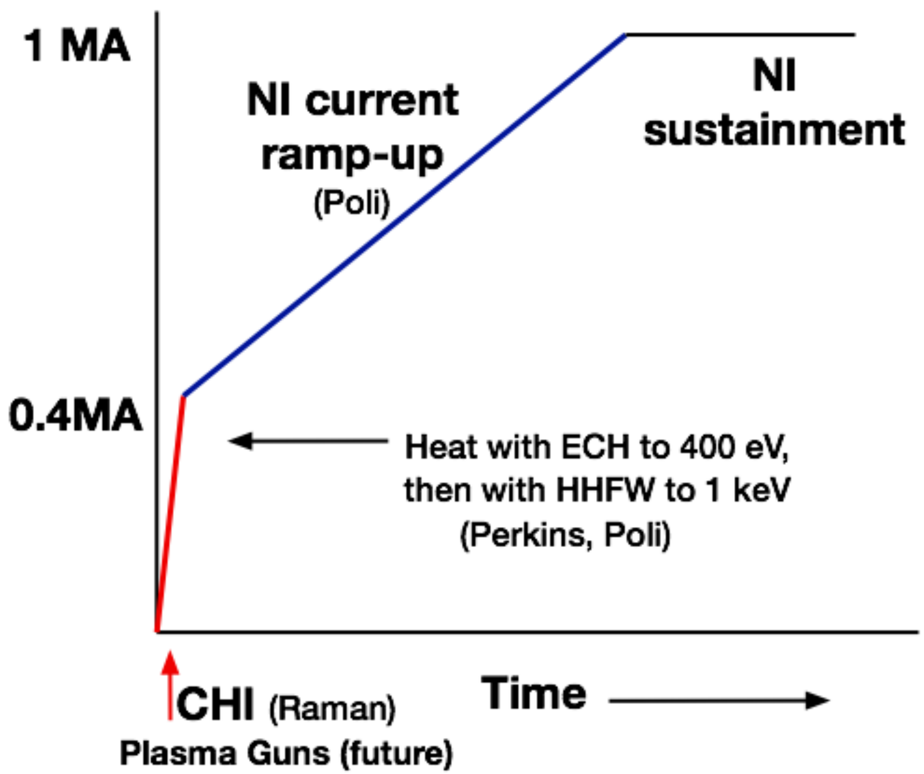
CHI is planned to be used as initial current seed for subsequent non-inductive current ramp-up in NSTX-U

CHI in NSTX/NSTX-U



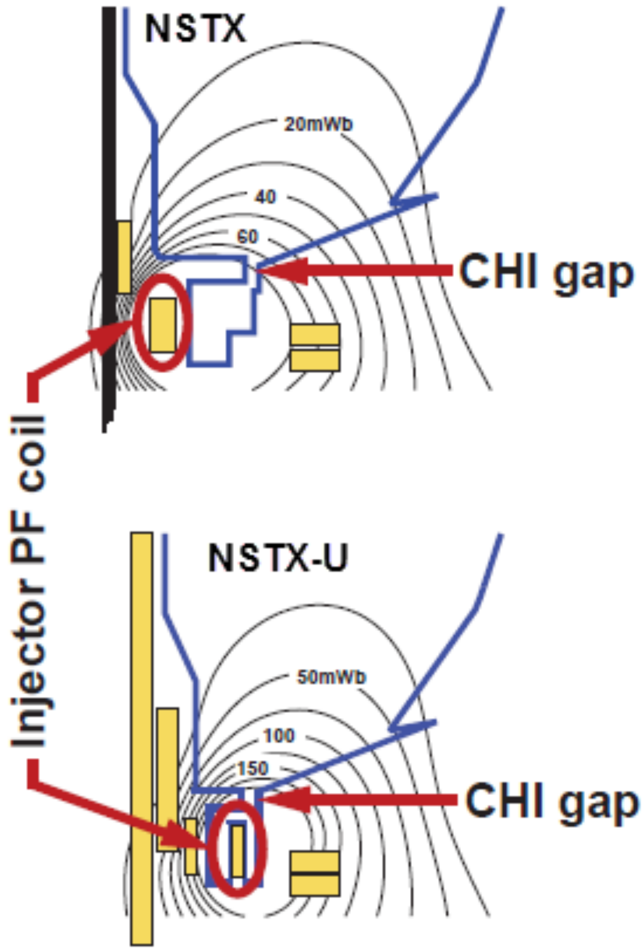


NSTX-U Start-up and Ramp-up strategy



Off-axis non-inductive current drive to be studied on DIII-D as part of DIII-D 2014 National Campaign (Mueller, Menard, Holcomb, et al.,)

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



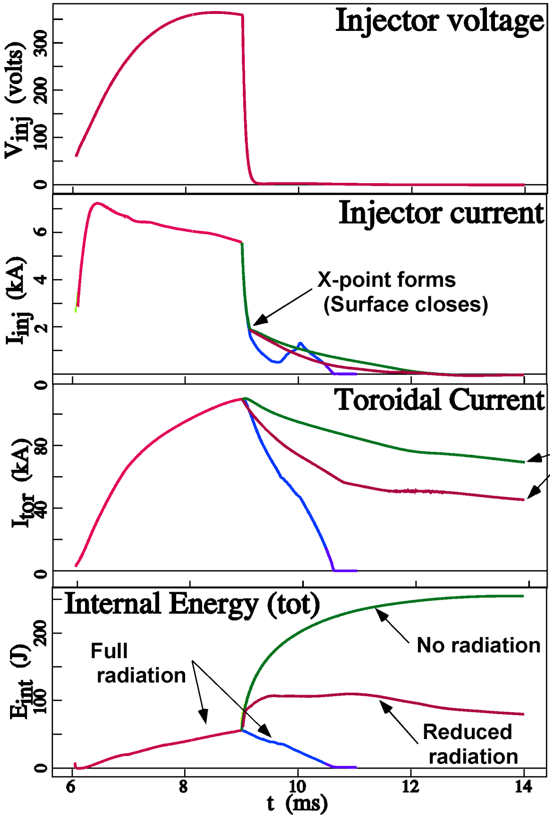
Injector flux in NSTX-U is ~ 2.5 times higher than in NSTX → supports increased CHI current

Parameters	NSTX	NSTX-U	ST-FNSF
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
Sustained I_p [MA]	1	2	10
Injector flux (Wb)	0.047	0.1	0.66
Projected Start-up I_p (MA)	0.2	0.4	2.0

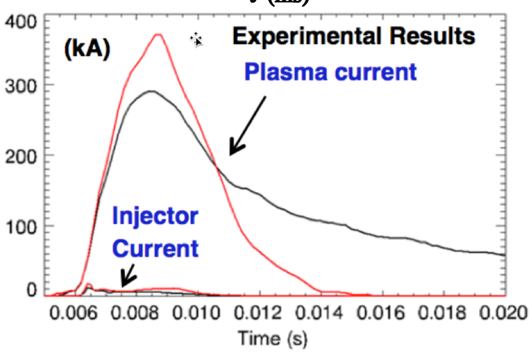
New Tools for CHI

- > 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)

Pursuing direct simulation of experiment and basic physics understanding of CHI trends using NIMROD (3 Publications)



Toroidal current is all within closed surfaces by 12.5 ms



Recent Modeling – Plasma injection with Impurity radiation

Helicity and plasma injection at the bottom slot into a low-density background generates flux bubble

An X-point forms near the bottom of NSTX as the injection voltage drops → forming closed magnetic surfaces

Impurity radiation — required to match experimental temperatures → fast current decay after injection ends

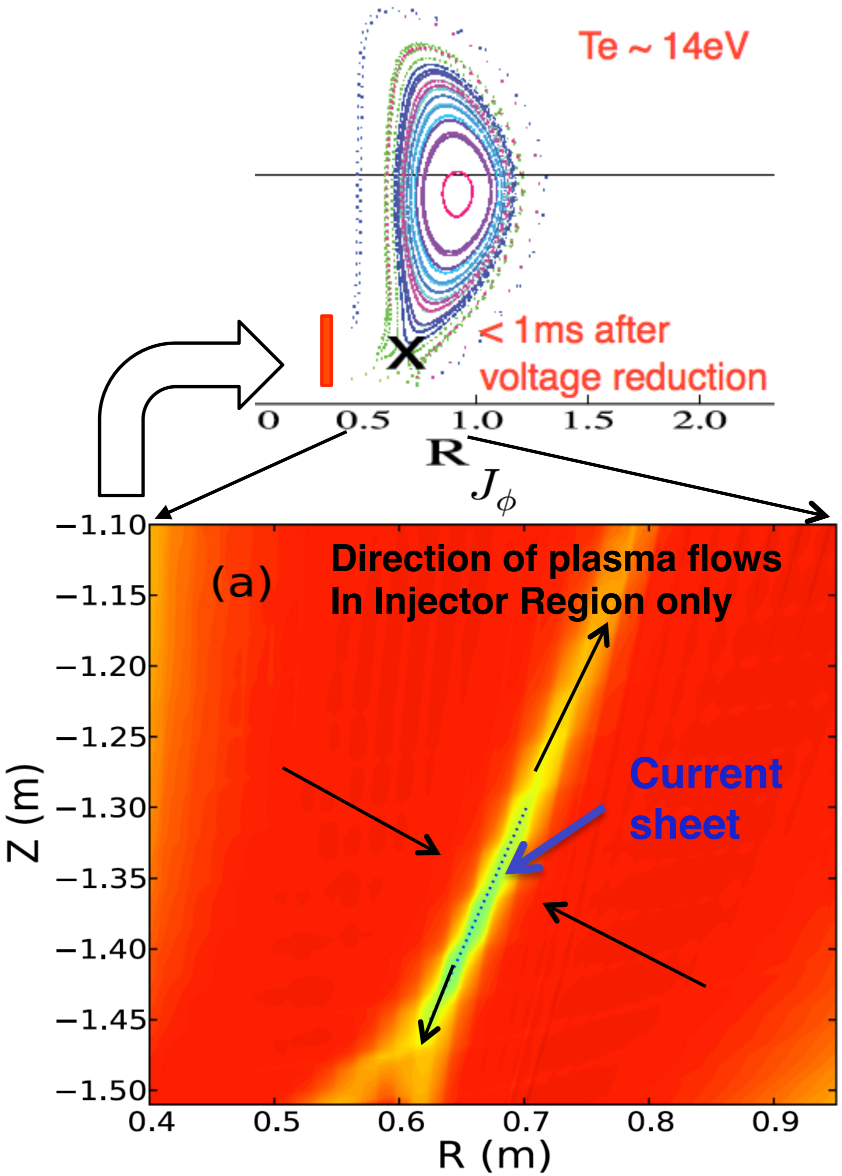
— Rapid removal of impurities following injection improves target-plasma quality and duration.

— Note plasma heating in “No radiation” and “Reduced radiation” models

Simulations by B. Hooper (LLNL) with support from C. Sovinec (U-Wisconsin)

E.B. Hooper et al., PoP (2013)

NIMROD simulations suggest Transient CHI has resemblance to 2D Sweet Parker-type reconnection

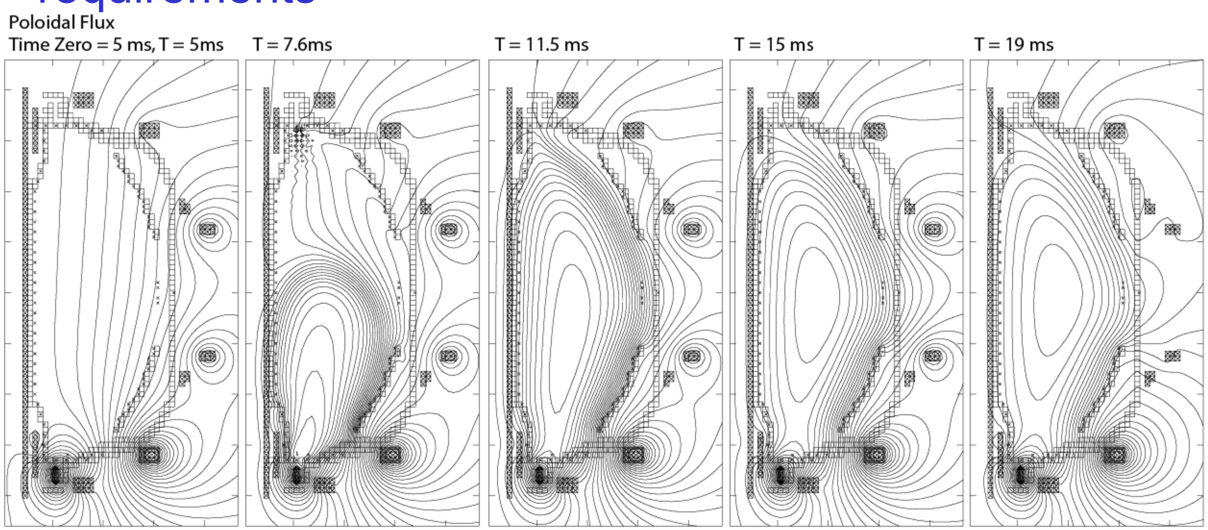


- With reduction of injector voltage & current a toroidal E-field is generated in the injector region
  - $E_{toroidal}$ X $B_{poloidal}$ drift brings oppositely directed field lines closer and cause reconnection generating closed flux
- Elongated Sweet-Parker-type current sheet forms in injector region
- Higher-n modes/MHD not impacting 2D reconnection

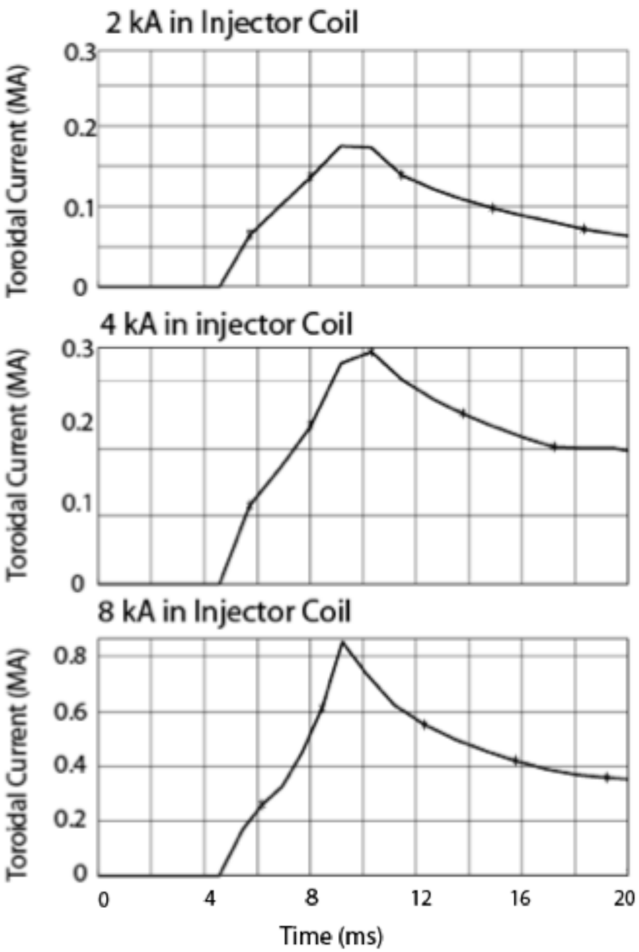
F. Ebrahimi, et al., PoP (2013)
F. Ebrahimi, et al., PoP (2014)

TSC simulations being used to guide choice of NSTX-U coil currents for initial CHI operation

- Initial Transient CHI discharges will start with increasing levels of current in the PF1C injector coil
- CHI discharge will be grown into magnetic well that is suitable for the final equilibrium
- PF1CU (absorber coil) coil current will be pre-programmed to provide a buffer flux
- PF1AL and PF2L, PF3L coil currents may be adjusted in time, as needed, to reduce injector current requirements

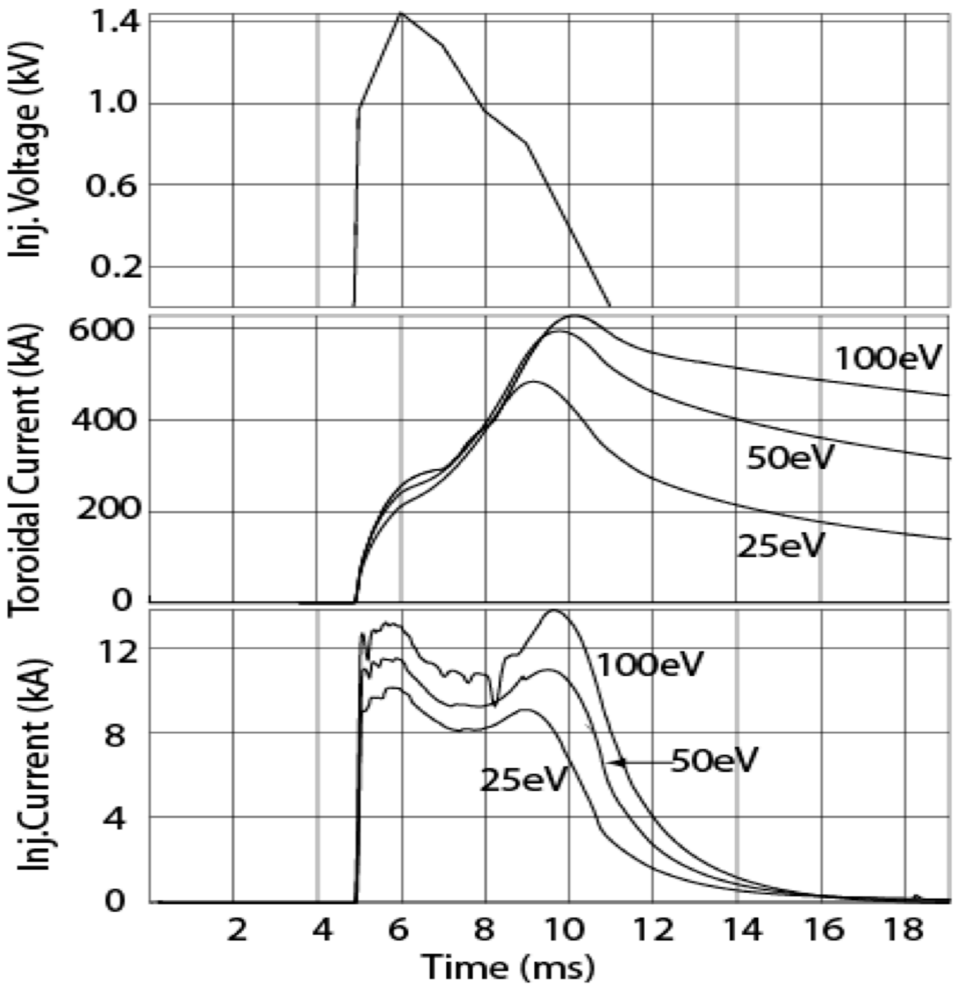


NSTX-U Vessel Geometry, 100 eV



CHI generated toroidal current increases approximately linearly with injector flux as expected

Helicity injected plasmas (CHI & Gun Start-up) can significantly benefit from ECH heating

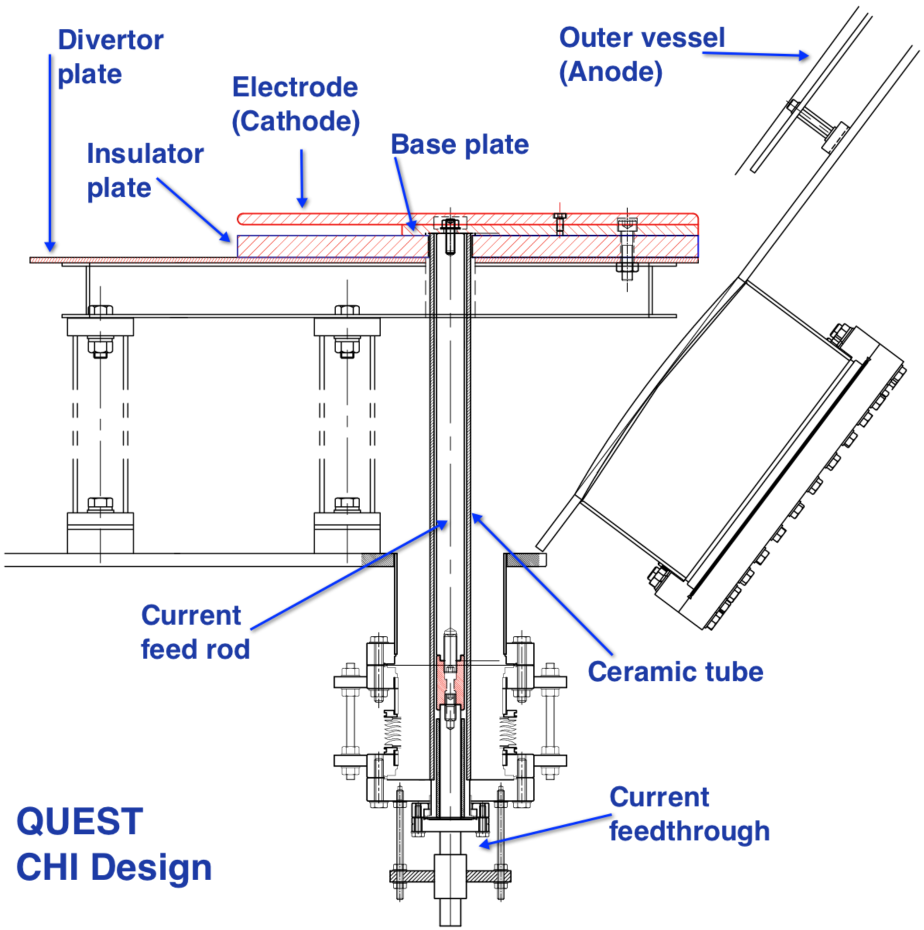


TSC simulations

- 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

New CHI Electrode Design to be Tested on QUEST (Collaboration with Japan)

- Provides early test of ECH heating of CHI plasma for NSTX-U/FNSF
- CHI design completed (March 2014)
  - CHI installation later during 2014
- Electrode mounted on top of divertor plate
- Electrode-based CHI may be applicable to FNSF
- US Contribution to project
  - Primary insulators
  - Capacitor bank power supplies
  - Gas injection systems



QUEST CHI Design

SFSU Research Plans for FY2015

- Transient CHI Start-up
  - Using PF1C as the primary coil, establish current targets approaching 200kA and compare scaling with NSTX results
  - Study improvements to CHI plasma T_e in discharges with higher poloidal flux with more complete Li coatings

- Assess inductive flux savings and compare to NSTX results

- Assess NBI coupling + current drive efficiency in 300-400kA flat-top current inductive plasmas (supports TRANSP validation activities – Poli)

SFSU Research Plans for FY2016

- Transient CHI Start-up
  - Study improvements to CHI plasma T_e in discharges with higher poloidal flux with Li coating of the upper divertor
  - Develop targets approaching 400kA for FY17 and FY18 ramp-up experiments (will need ECH + higher CHI voltage during FY17)
- Generate discharges with partial solenoid pre-charge
  - Ramp-up CHI discharge while reducing solenoid current to zero
- Test NB coupling to CHI targets with small inductive drive
  - Understand importance of current profile on NB coupling
- Obtain full non-inductive current drive in flat-top phase with ohmic seeding, then clamp OH coil current to constant value progressively earlier in time (in support of TRANSP validation)

SFSU expected results by end of FY2016 run

- Understand Transient CHI current generation potential in NSTX-U
  - T_e dependence on injected poloidal flux
  - Effect of more complete Li coatings on radiation and achievable T_e
  - CHI Voltage limits and requirements in preparation for FY17 and FY18
  - Improved modeling with 3D NIMROD and 2D TSC of NSTX-U CHI discharges
  - Understand performance of CHI in new configuration on QUEST in support of ST-FNSF

- Understand coupling of NBI to low current inductively generated targets
  - In plasmas with varying parameters (T_e and n_e and profiles)
  - Determine NI current ramp-up rates that do not lead to MHD
  - Lowest plasma current below which NB CD & Bootstrap current overdrive is not possible (may not cover all possibilities due to Run Time limitations)

Summary: FY15-16 Start-up & Ramp-up Research will Develop Capabilities for Eventual Full NI Ops. On NSTX-U

- Transient Coaxial Helicity Injection will develop capabilities for solenoid-free plasma start-up for the ST
  - Initial goal is to develop targets approaching 400kA targets in support of FY17-18 goals
  - Numerical simulations will/are supporting experiments
  - New CHI electrode design in support of ST-FNSF to be tested on QUEST
  - Localized Helicity Injection to be tested on NSTX-U, when technically ready (FY17 or later)

- NB Coupling in low current inductively generated discharges will be studied to apply this capability to CHI targets during FY17-18

Back-up Slides

CHI Research plans in preparation for NSTX-U operations in FY2015

- Initial NSTX-U Hardware Configuration for Transient CHI Start-up identified
  - Developed initial start-up scenarios for NSTX-U for FY15 Expts.
- MOV rating will be increased from 1.65kV to 2kV
  - NSTX-U Engineering will implement this capability in the near future
- Starting work on energizing CHI cap bank for tests into dummy load
  - FY2015 and 2016 experiments will use existing capacitor bank

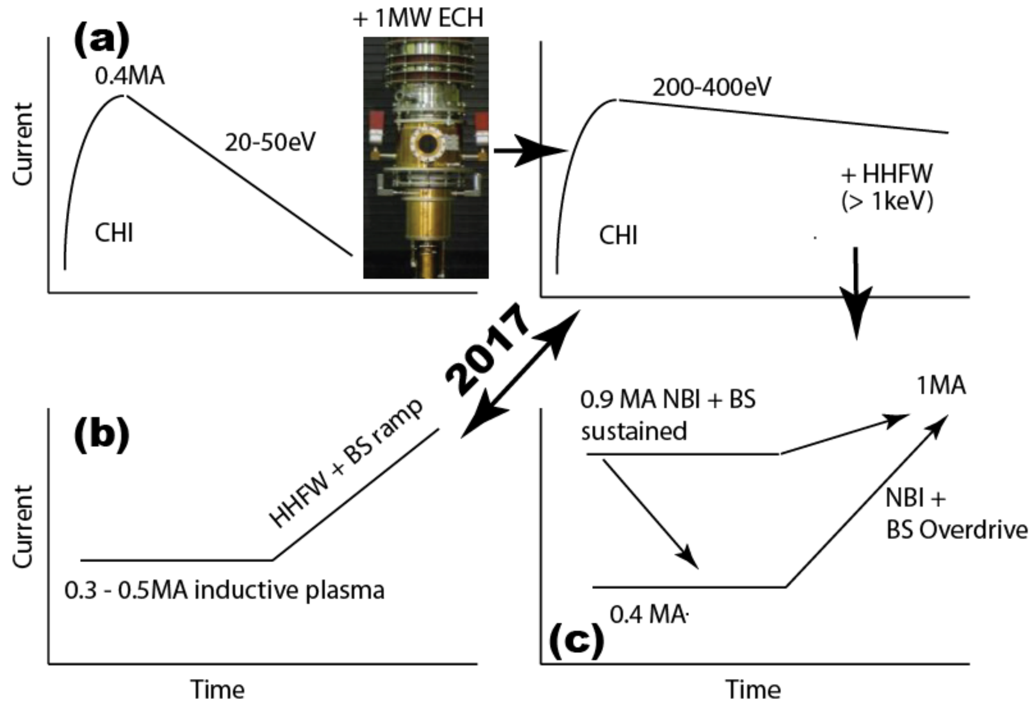
Start-up and Ramp-up Research Involves Three Parallel Paths that Will be Linked as Technical Capabilities Permit

(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)

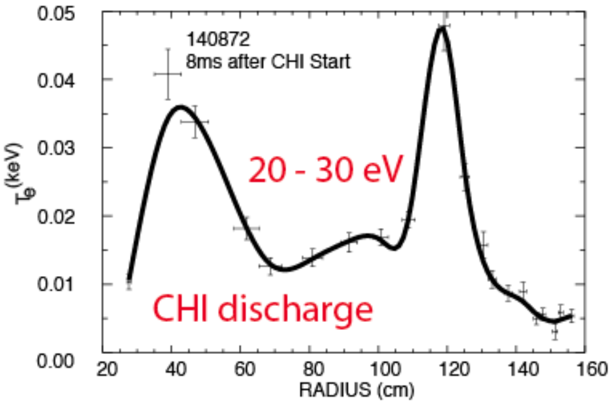
- Progressively increase initial current (from 0.3 to 0.5MA) and ramp-up using HHFW and BS current overdrive
- Assist extension of NBI CD to lower I_p



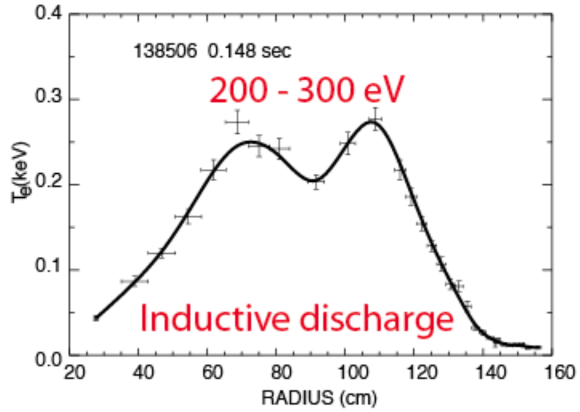
(c) Current ramp-up at near full I_p with NBI and bootstrap current overdrive

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

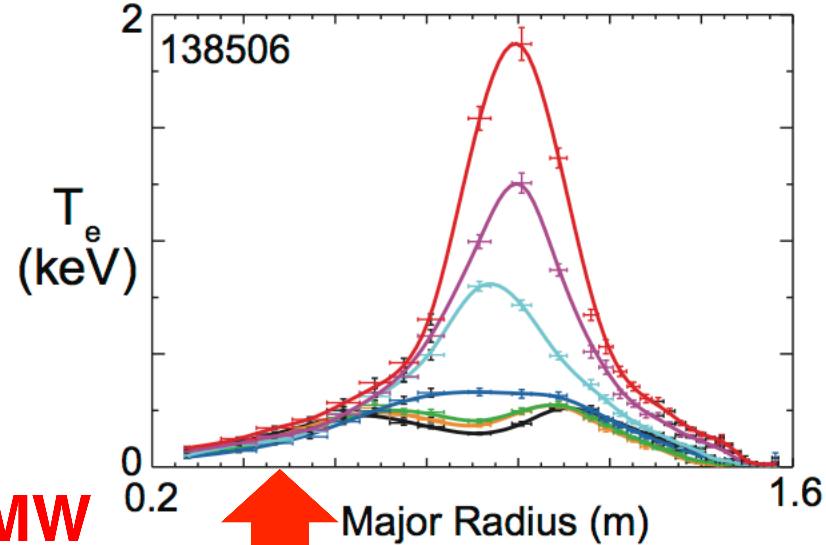
Bridge Electron Temperature Gap Between CHI Start-up and Current Ramp-up Requirements with ECH Heating

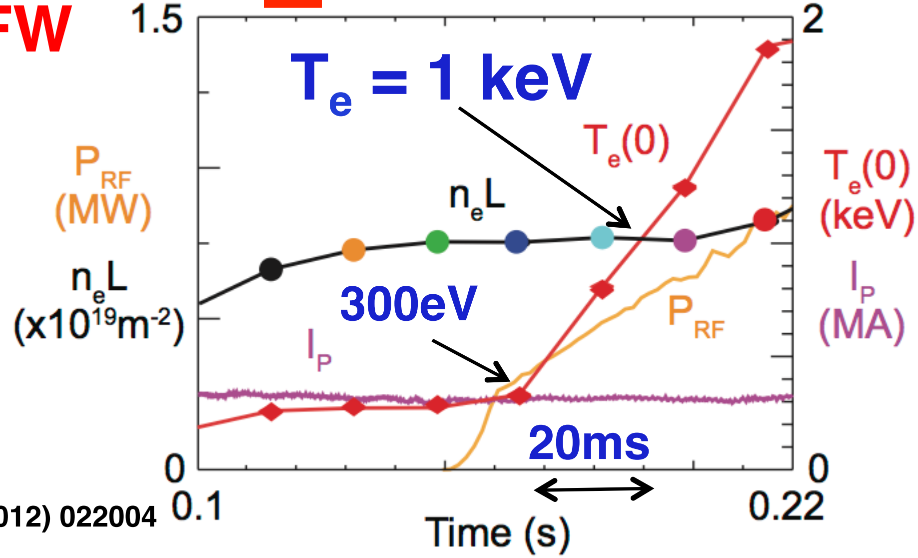


1MW ECH



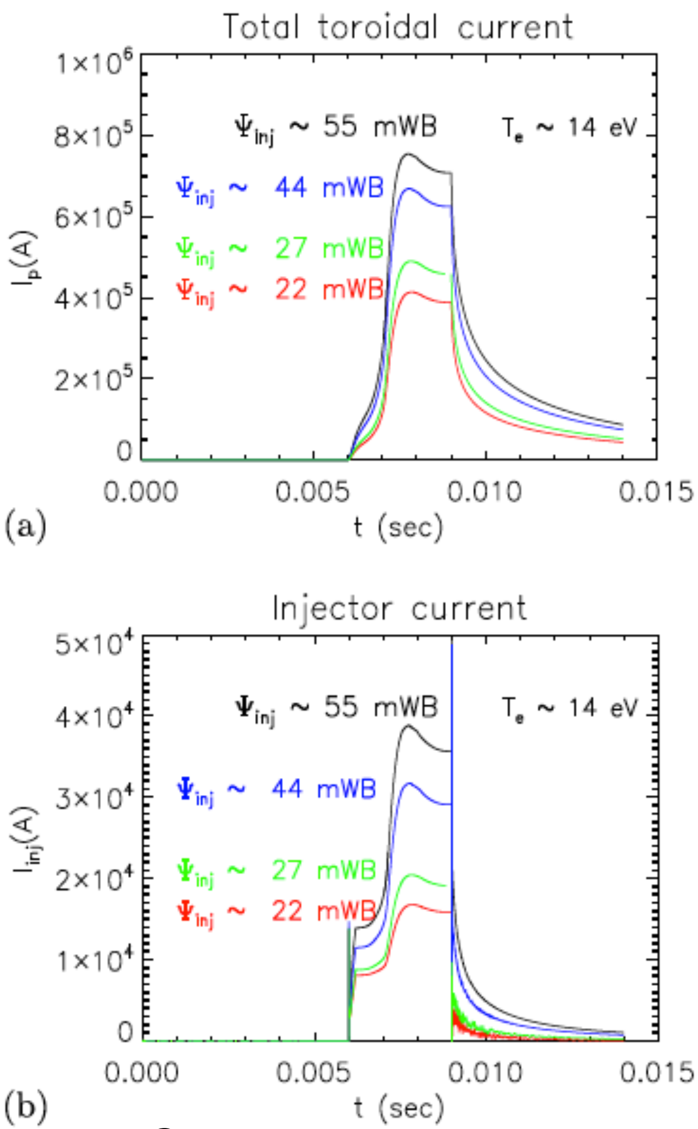
1-2 MW HHFW





G. Taylor, et al., Phys. Plasmas 19 (2012) 022004

NIMROD simulations show approximate consistency with scaling relations used for CHI design on NSTX and NSTX-U



NSTX vessel geometry

1. CHI produced current increases with Injector Flux
2. Injector current increases with injector flux
3. Closed flux fraction increases with narrowness of flux foot print width
4. Closed flux fraction increase with faster reduction of injector current to zero
5. Lower limit on Te below which closed flux does not for

   - Closed flux fraction increases with Te