NSTX

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

Transient CHI Plasma Start-up and Non-inductive Current Ramp-up Simulations for NSTX-U

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[1]R. Raman, [1]T.R. Jarboe, [2]S.C. Jardin, [2]C.E. Kessel, [2]D. Mueller, [1]B.A. Nelson, [2]F. Poli, [2]G. Taylor, [2]S.P. Gerhardt, [2]S.M. Kaye, [2]J.E. Menard, [2]M. Ono, and the NSTX-U Research Team

[1]University of Washington
[2]Princeton Plasma Physics Laboratory

This work is supported by US DOE contract numbers FG03-96ER5436, DE-FG02-99ER54519 and DE-AC02-09CH11466

55th Meeting of the Division of Plasma Physics
APS 2013 Conference
Denver, Colorado, November 11-15, 2013

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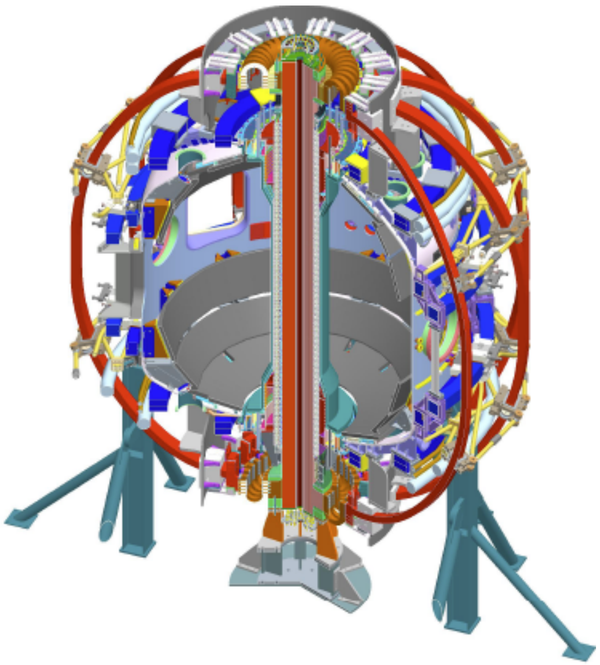
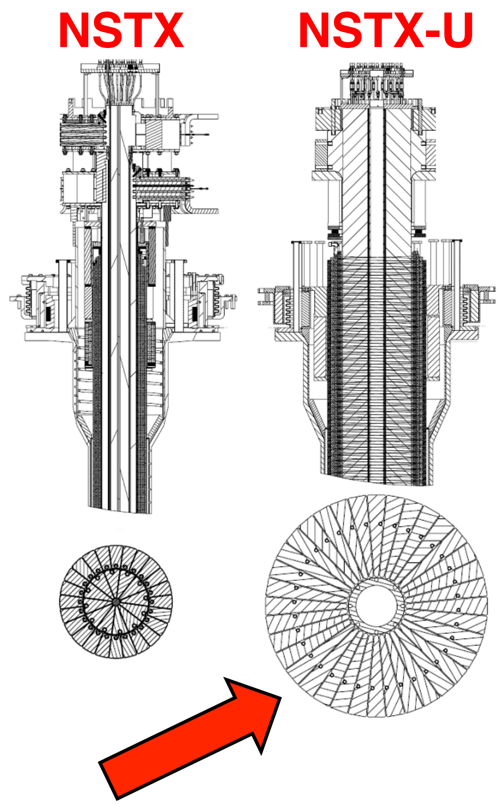
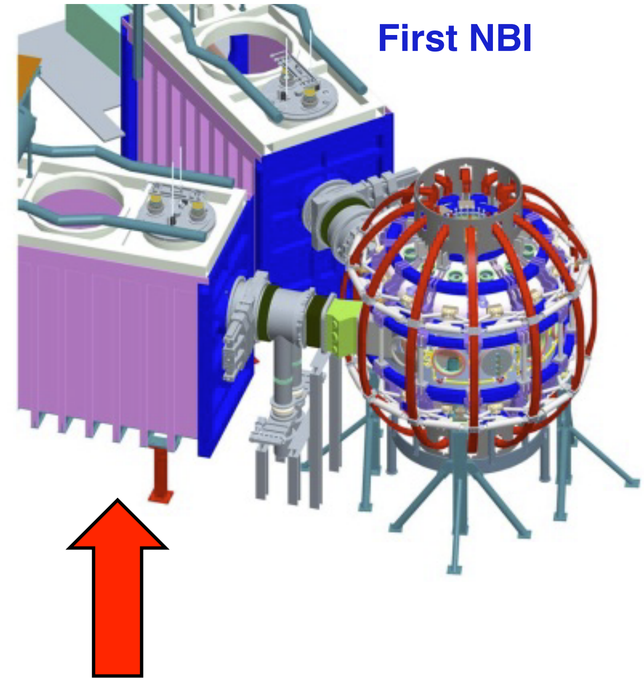
NSTX-U Research will Advance the ST as a Candidate for a Fusion Nuclear Science Facility (FNSF)







New large center stack in NSTX-U enables

- B_T: Increases from 0.55 to 1 T
- Plasma current: 1 to 2 MA
- Discharge pulse duration: 1s to 5 s

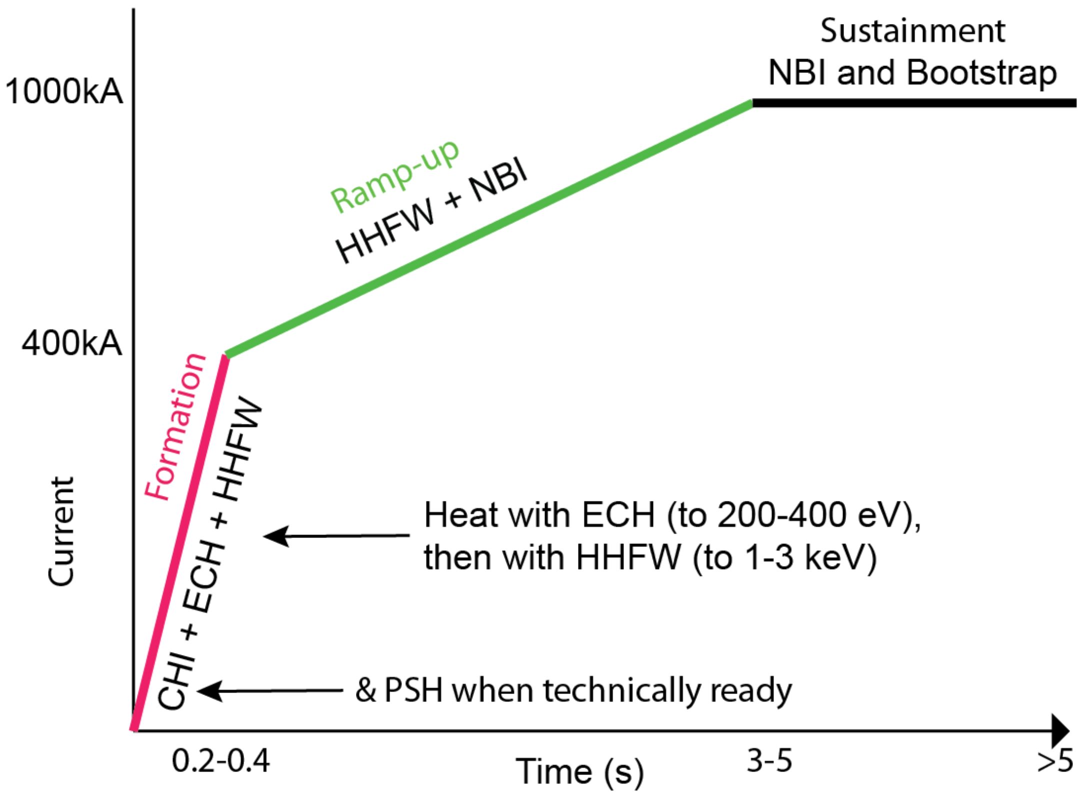
Second tangential Neutral Beam in NSTX-U enables

- Higher current drive at low plasma current

NSTX-U Aims to Develop and understand non-inductive start-up/ramp-up to project to ST-FNSF operation

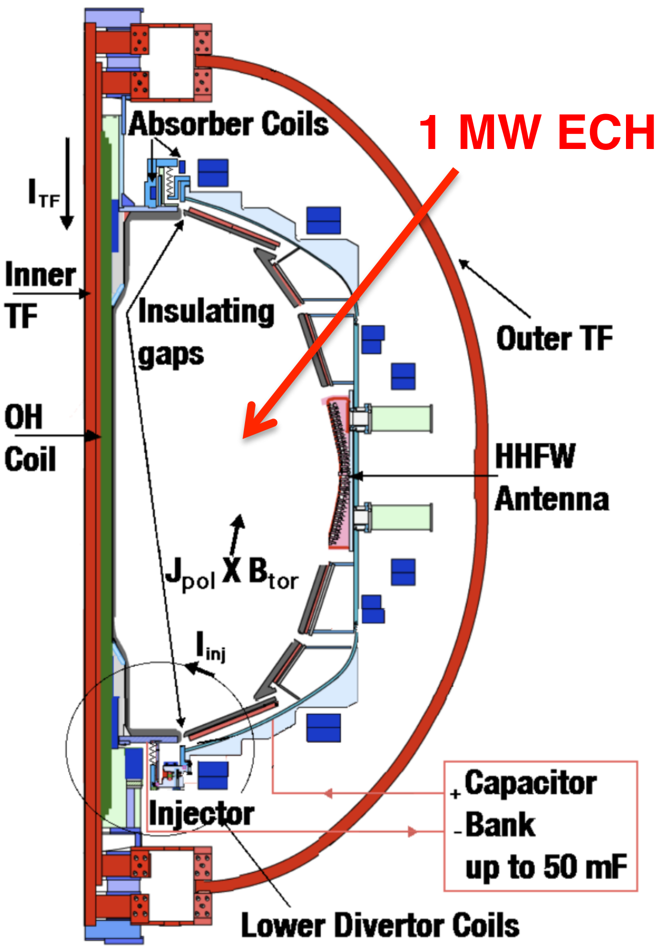
- Establish physics basis for ST-FNSF, and non-inductive start-up is essential in ST
  - Simplify the tokamak concept to reduce cost and allow Aspect ratio optimization
- NSTX-U is striving for fully non-inductive operations
  - Transient Coaxial Helicity Injection (CHI) start-up is the front end of that objective
  - Plasma guns and EBW will be tested after those systems are technically ready

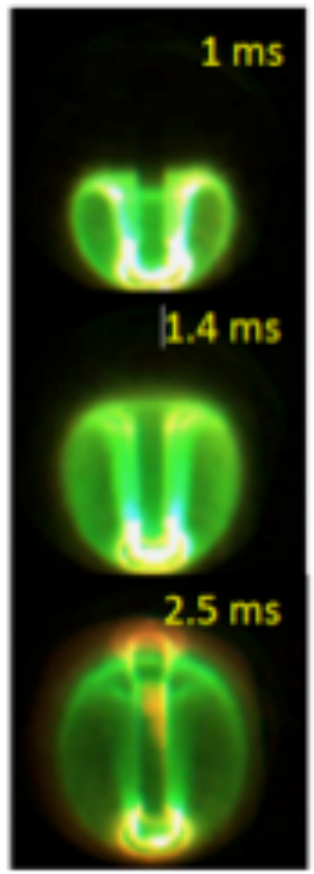
NSTX-U Start-up and Ramp-up strategy



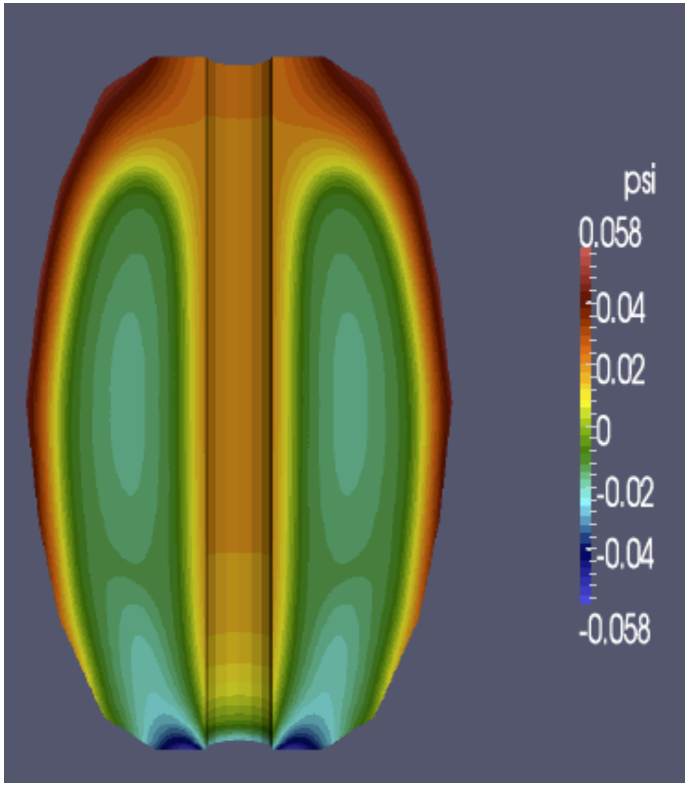
CHI is planned to be used as initial current seed for subsequent non-inductive current ramp-up in NSTX-U

CHI in NSTX/NSTX-U





NIMROD Simulation



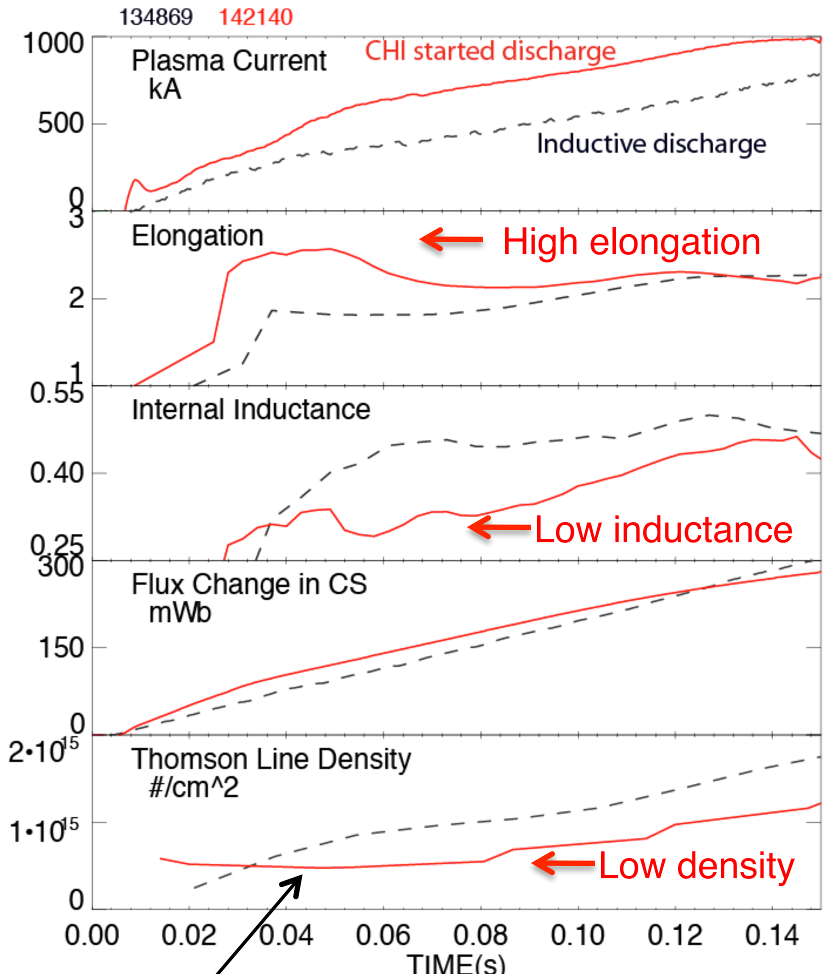
F. Ebrahimi (Invited Talk) PI2.00002 2:30-3:00PM Wednesday, PoP (2013)

E.B. Hooper, NP8.00023 Wednesday AM, PoP (2013)

R. Raman, et al. PRL (2006)

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

CHI assisted startup in NSTX



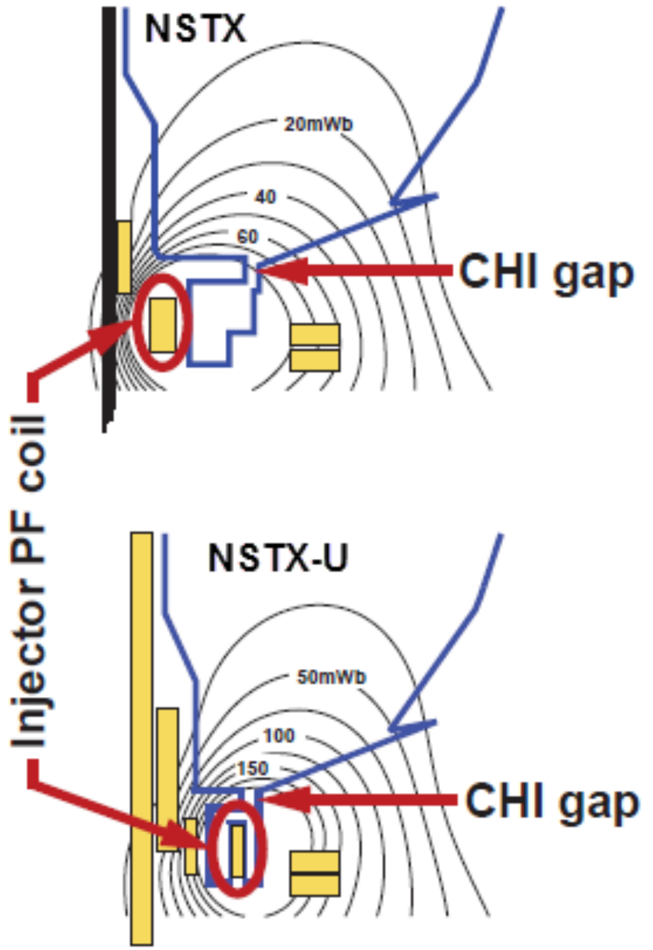
CHI generates plasmas with low n_e so that ECH could be used to heat these plasmas

27 kJ of stored capacitor bank energy used for CHI plasma start-up

CHI produced plasma is clean (Discharges have transitioned to H-mode after coupling to induction)

28 GHz Cut-off density at 1T ~1e13 cm^{-3} (>2 x CHI plasma density)

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
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 current (MA)	0.2	0.4	2.0

*Theoretical Maximum in NSTX-U > 0.3 Wb

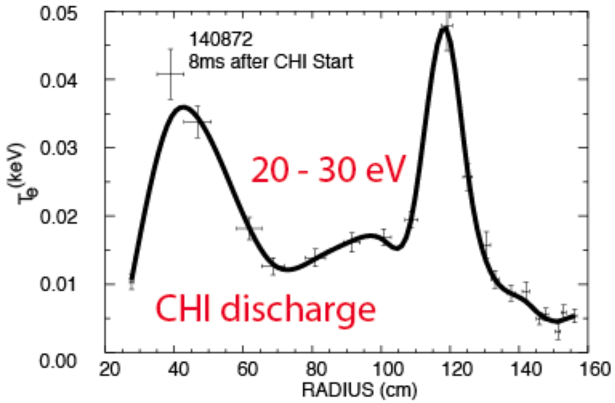
Injector flux in NSTX-U is ~ 2.5 times higher than in NSTX → supports increased CHI current

Projection based on:

- **Injector flux scales with device size**
- **Toroidal flux in device**
- **Injector flux footprint width scaled proportional to minor radius**

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

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

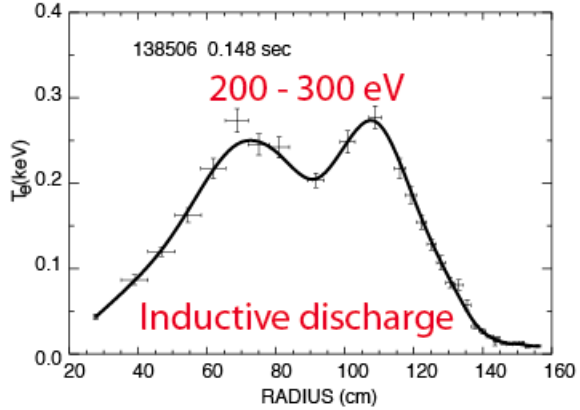


TSC simulations suggest that 0.6MW of ECH should increase T_e by ~200 eV in 20 ms

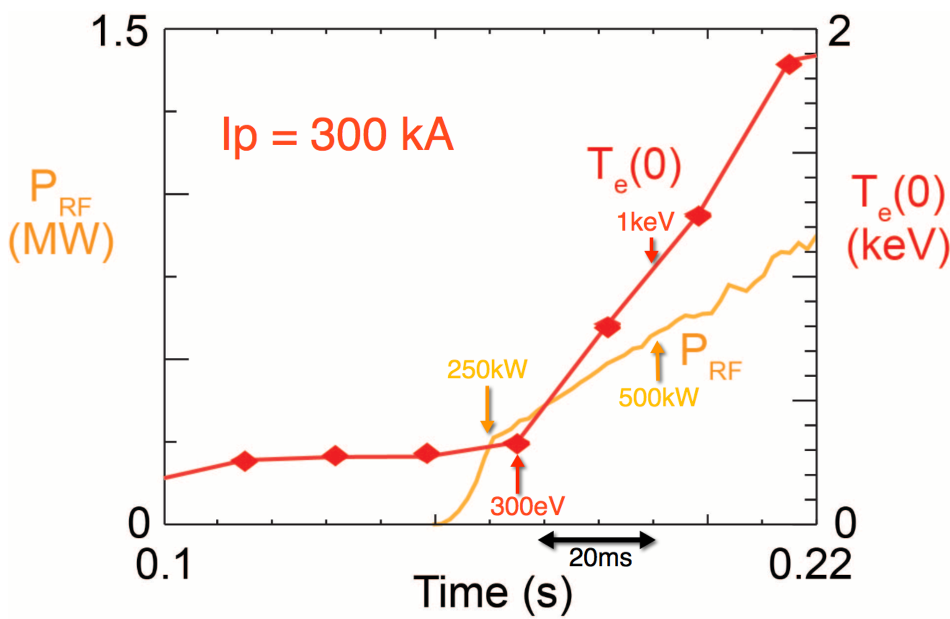
G. Taylor, NP8-26

Wednesday AM

1MW ECH



1-2 MW HHFW



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

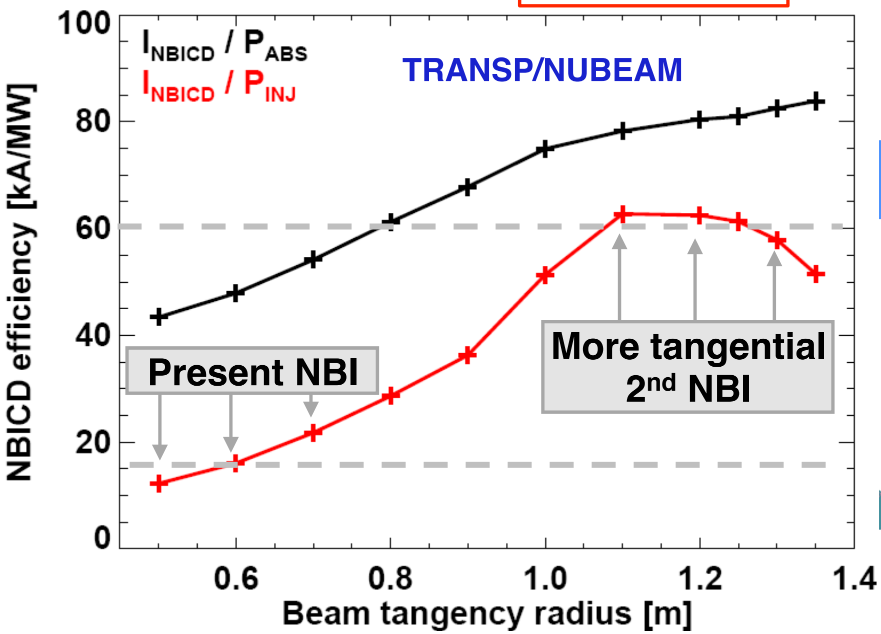
Non-inductive Ramp-up from ~0.4MA to ~1MA Projected to be Possible with Tangential NBI

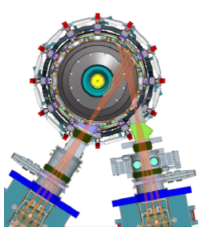
- **Compared to First NBI, the Second Tangential NBI provides 3-4x higher CD at low I_P :**
  - 1.5-2x higher current drive efficiency, plus
  - 2x higher absorption (40→80%) at low I_P = 0.4MA

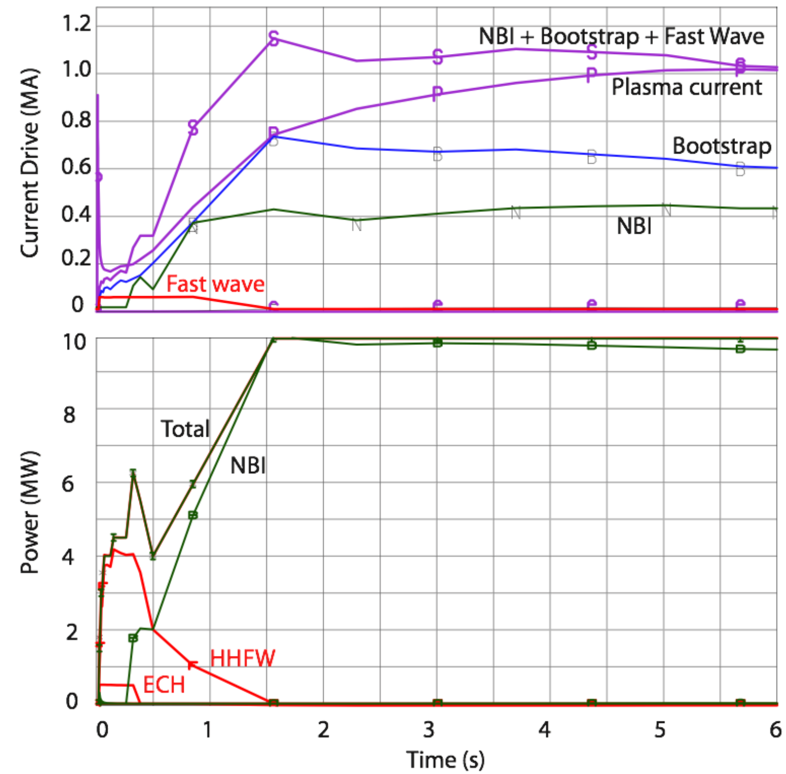
- **TSC simulation of non-inductive ramp-up from initial CHI target**
  - Simulations being improved to use TRANSP/NUBEAM loop within TSC

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

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





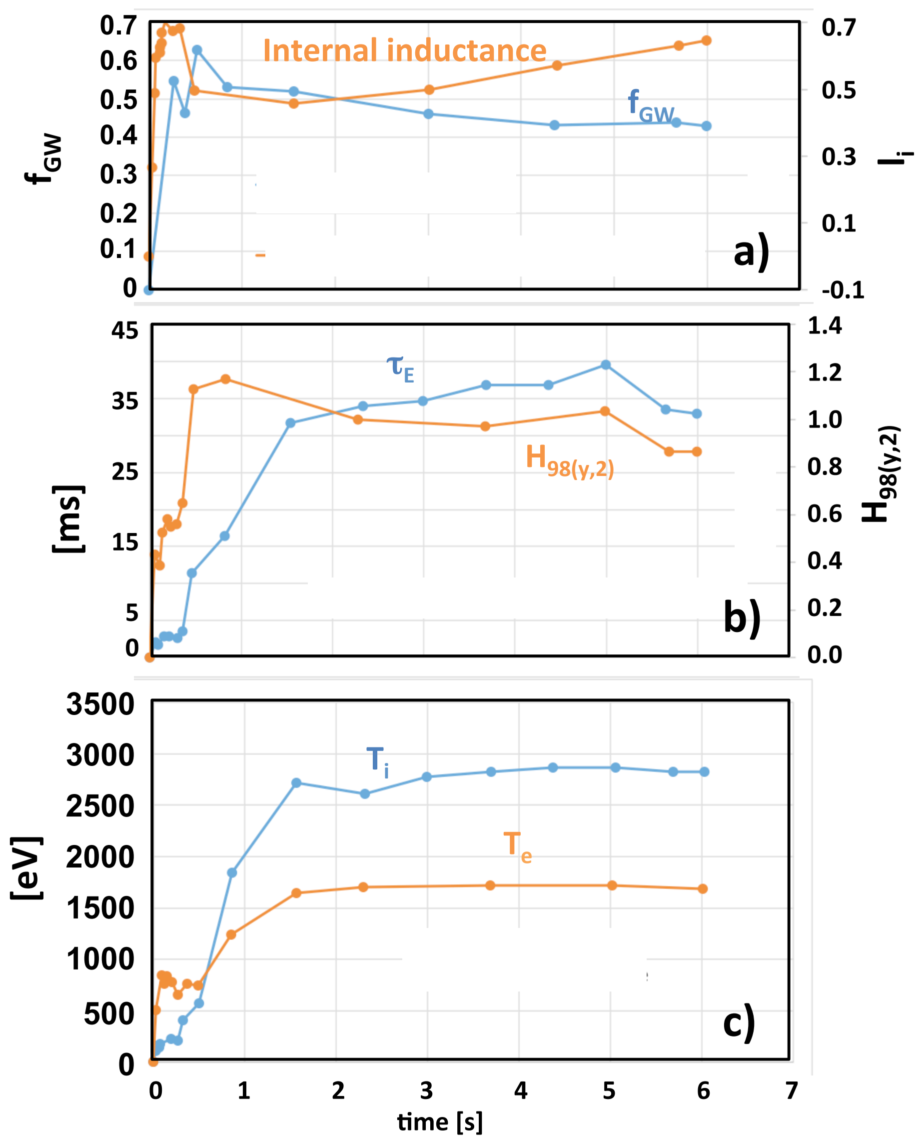


NSTX-U Aims to Develop Full Non-inductive Start-up and Current Ramp-up in support of FNSF and next step Tokamaks

- 0.2MA closed flux current generation in NSTX validates capability of CHI for high current generation in a ST
- Successful coupling of CHI started discharges to inductive ramp-up & transitioning to an H-mode demonstrates compatibility with high-performance plasma operation
- Favorable scaling with increasing machine size (from two machines of vastly different size, HIT-II and NSTX and in TSC simulations)
- NSTX-U is well equipped with new capabilities to study full non-inductive start-up and current ramp-up
  - 2x Higher TF, 1MW ECH, Second Tangential NBI for CD, 2x higher CHI voltage, >2.5x more injector flux

Back-up Slides

Back-up Slides



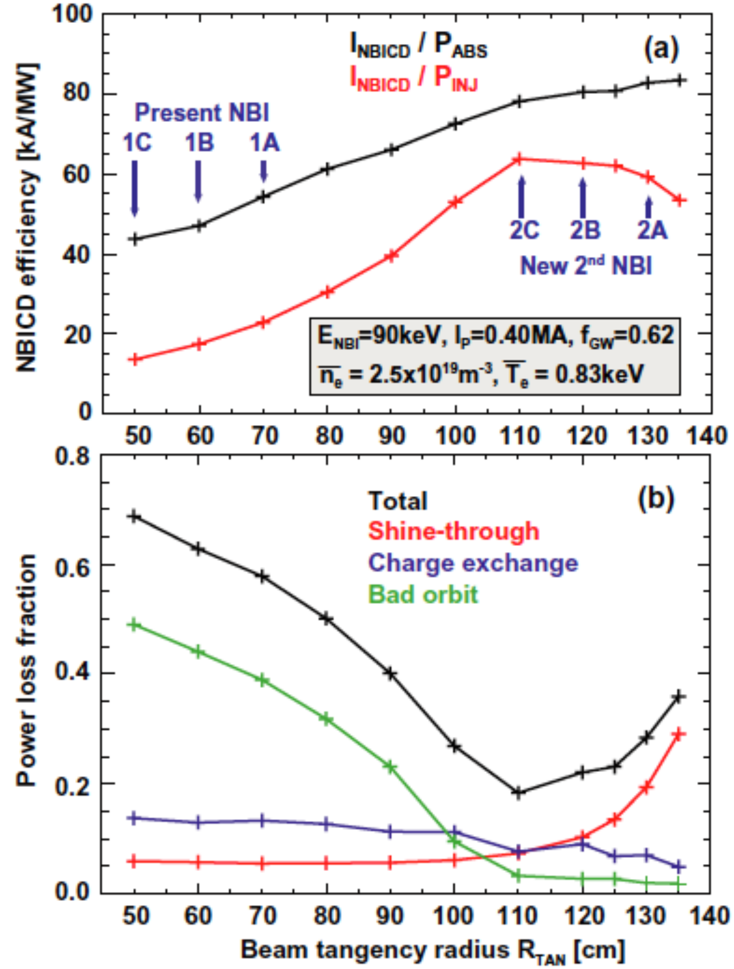


Figure 31. (*a*) NBICD efficiency (kA MW^{-1}) and (*b*) power loss fractions (total, shine-through, charge exchange, and bad orbit) as a function of beam tangency radius R_{TAN} for an $A = 1.65$, $I_P = 0.40$ MA, $B_T = 0.9$ T NSTX Upgrade target plasma with a 7.4 cm outer gap.

Requirements for the CHI Insulator are Less Demanding than the Insulation Requirements for a Mineral Insulated Solenoid

- Insulator Resistance > 1 Ohm
- Resistance to be maintained only during the plasma start-up phase (<30 ms in duration)
- The actual high-voltage phase < plasma start-up phase
- During the plasma start-up phase, there is no pre-existing plasma that can short out the insulator (and CHI current path is controlled by pre-programmed vacuum field line pattern)
- After the high-voltage phase, insulator could be shorted-out, if necessary

Because the Required Insulator Resistance is very low (few times the plasma impedance) other possibilities exist

- Layers of thin resistive metal coated with insulating layers
- Powdered, weakly bonded, insulator sandwiched between two metal plates
- The HIT-Si device used an insulator spray to achieve insulation *in a plasma environment* in an more complicated vessel geometry
- …. Other possibilities (including conventional insulator technology currently planned for next step machines to insulate PF coils and other components)
- Insulator could be hidden behind metallic structure as on NSTX-U

Assumptions for HIT-II / NSTX / FNSF / ST Pilot Plant

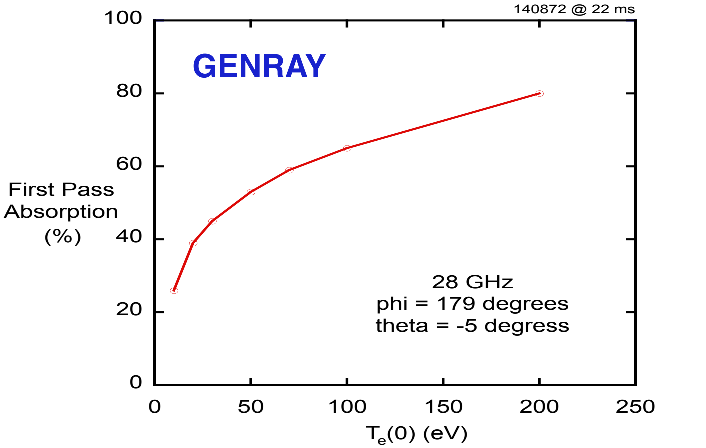
- Normalized internal inductance = 0.35
- The gap ‘d’ is assumed to scale as the minor radius d = 0.9 * a
- The injector flux scales as R*Ip
- Injector current = 1.2 or 1.3 times the bubble burst current
- Plasma poloidal flux = 80% of Injector flux
- The current multiplication factor Ip/Iinj is held below the limiting value of M = Toroidal flux / Injector flux
- Injector area = 2.pi.R*d/4

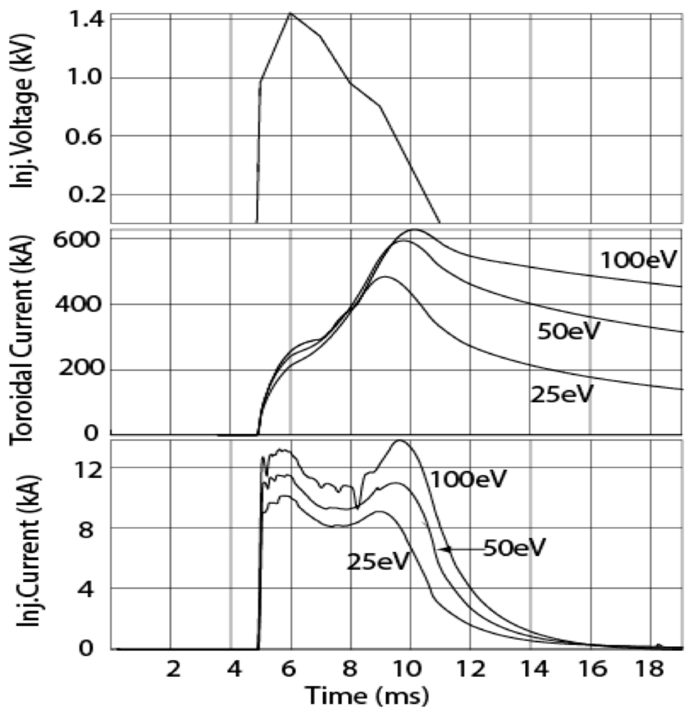
Modeling shows that the ramp-up strategy significantly benefits from 1-2 MW ECH to heat CHI plasma

•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

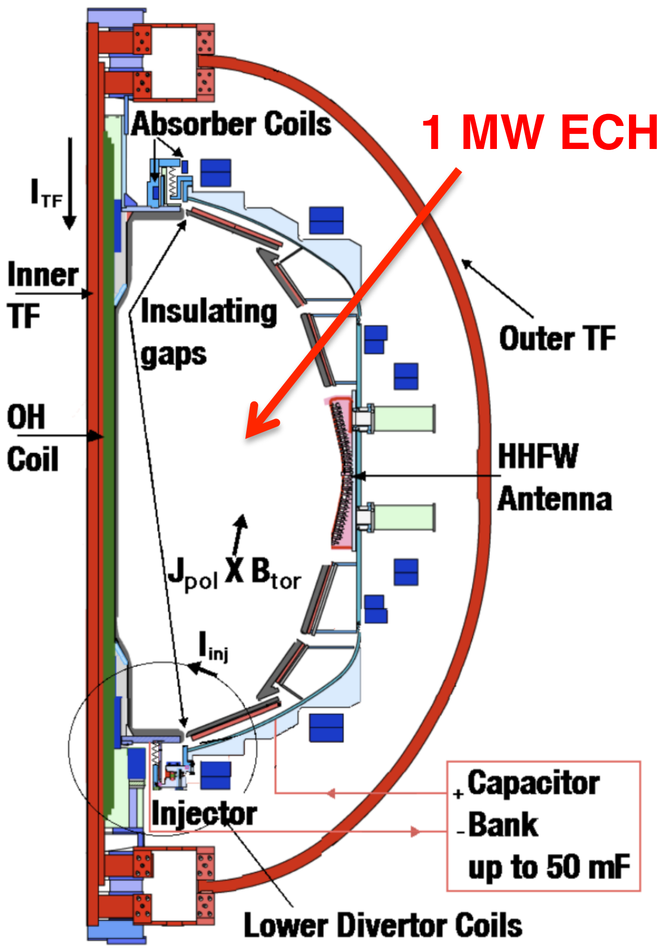
- Increased T_e predicted to significantly reduce I_p decay rate
  – ECH heated plasma can be further heated with HHFW
  – Maximum HHFW power < 4MW, higher B_T in NSTX-U would improve coupling
  – HHFW has demonstrated heating a 300 kA / 300 eV plasma to > 1 keV in 40ms

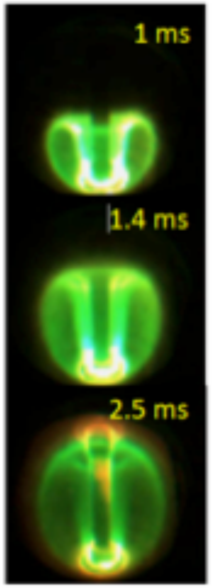




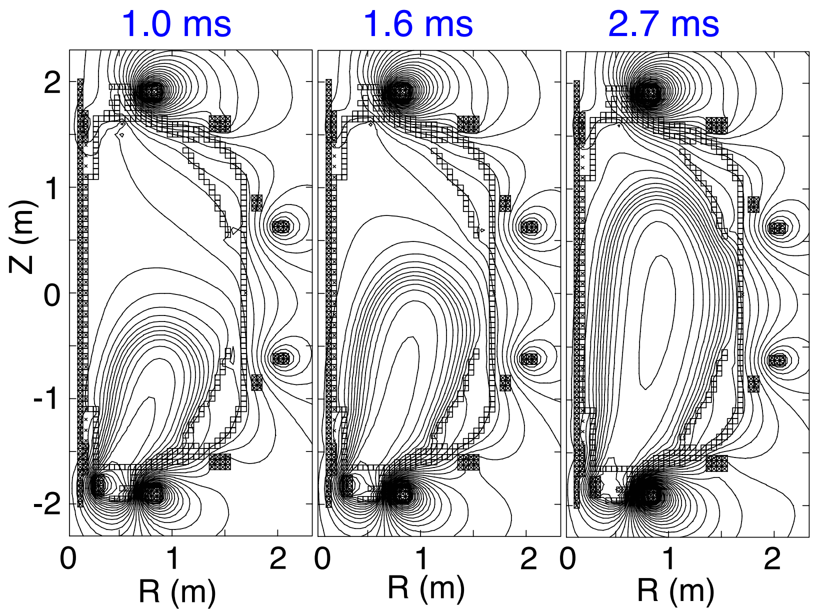
CHI is planned to be used as initial current seed for subsequent non-inductive current ramp-up in NSTX-U

CHI in NSTX/NSTX-U





TSC (axisymmetric 2D) simulation of CHI startup



New Tools for CHI

- > 2.5 x Injector Flux (Ip proportional to flux)
- 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)

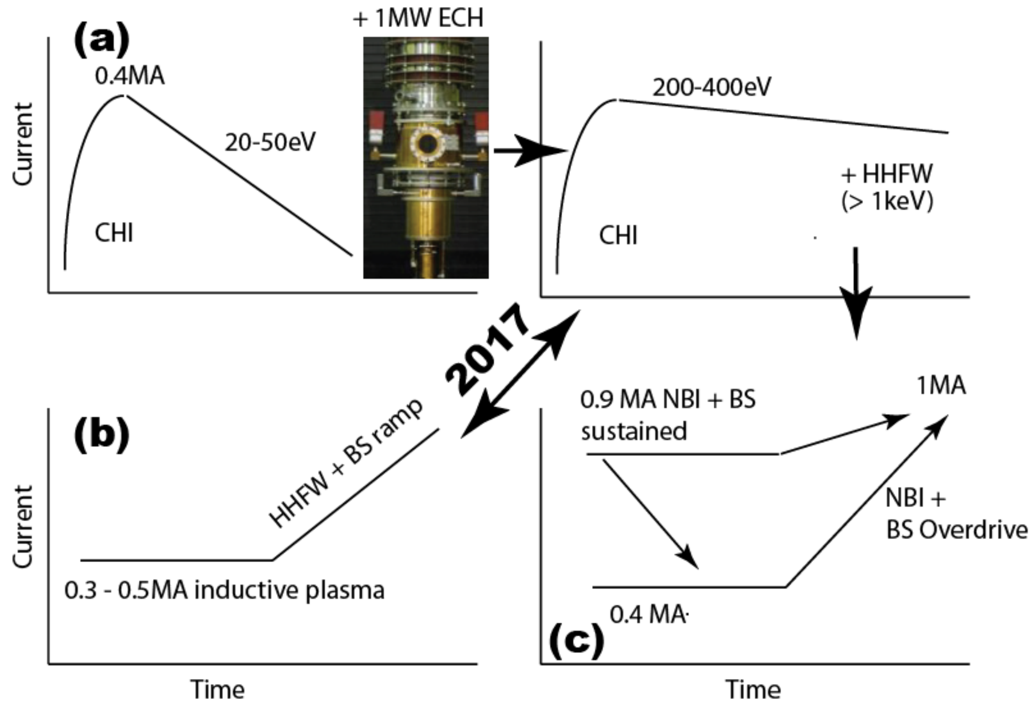
Start-up and Ramp-up Research Involves Three Parallel Paths that Will be Linked as Technical Capabilities Permit

(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

Externally Produced Toroidal Field makes CHI much more Efficient

- Bubble burst current*: $I_{inj} = 2\psi_{inj}^2/(\mu_o^2 d^2 I_{TF})$

  ψ_{inj} = injector flux

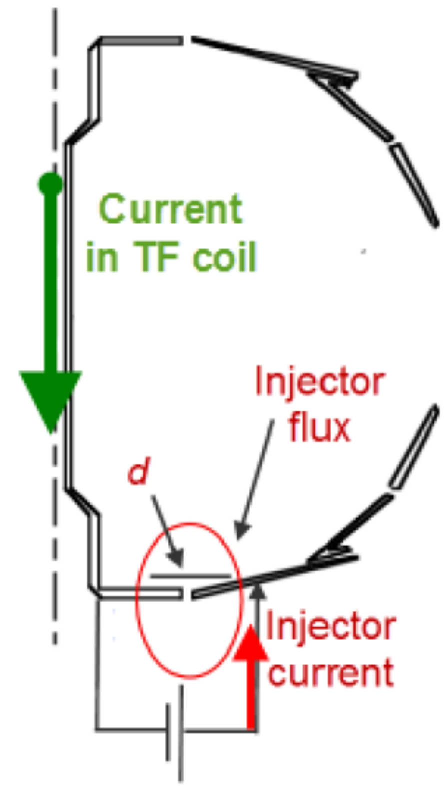
  d = flux foot print width

  I_{TF} = current in TF coil

$$\underbrace{I_{inj}}_{\text{Injector current}}\;\ \underbrace{\psi_T}_{\text{Toroidal flux}}$$

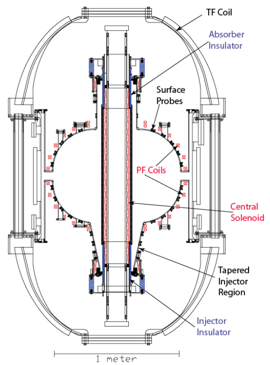
$$I_P = I_{inj}(\psi_T/\psi_{inj})$$

- Current multiplication increases with toroidal field
  - Favorable scaling with machine size
  - Increases efficiency (10 Amps/Joule in NSTX)
  - Smaller injector current to minimize electrode interaction



* T.R. Jarboe, Fusion Tech. 15, 7 (1989)

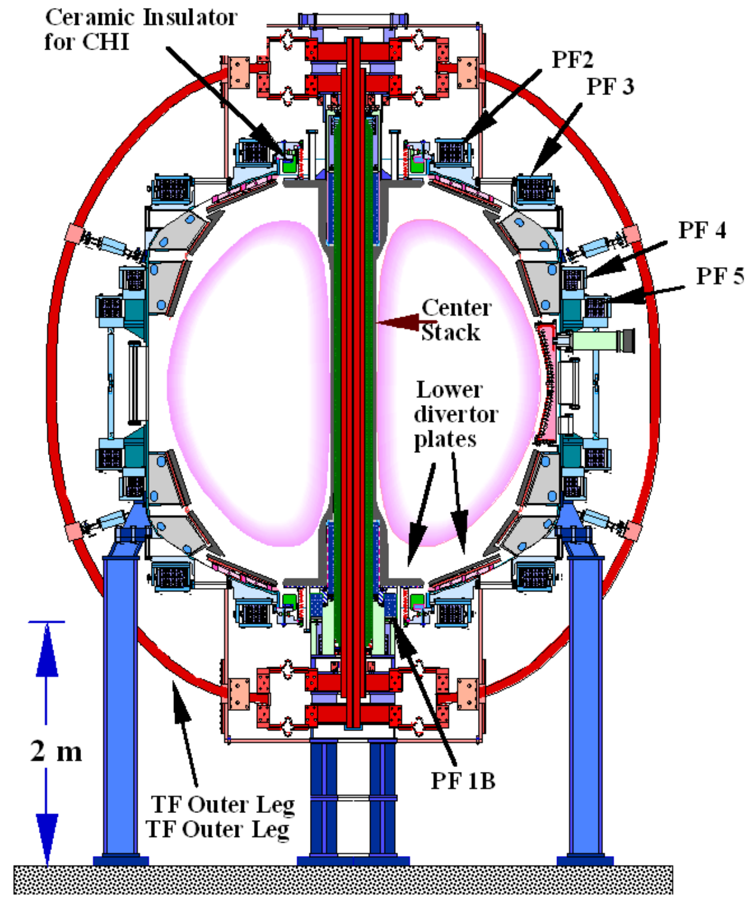
NSTX CHI Research Follows Concept Developed in HIT-II



Concept exploration device HIT-II

- Built for developing CHI
- Many close fitting fast acting PF coils
- 4kV CHI capacitor bank

NSTX plasma is ~30 x plasma volume of HIT-II

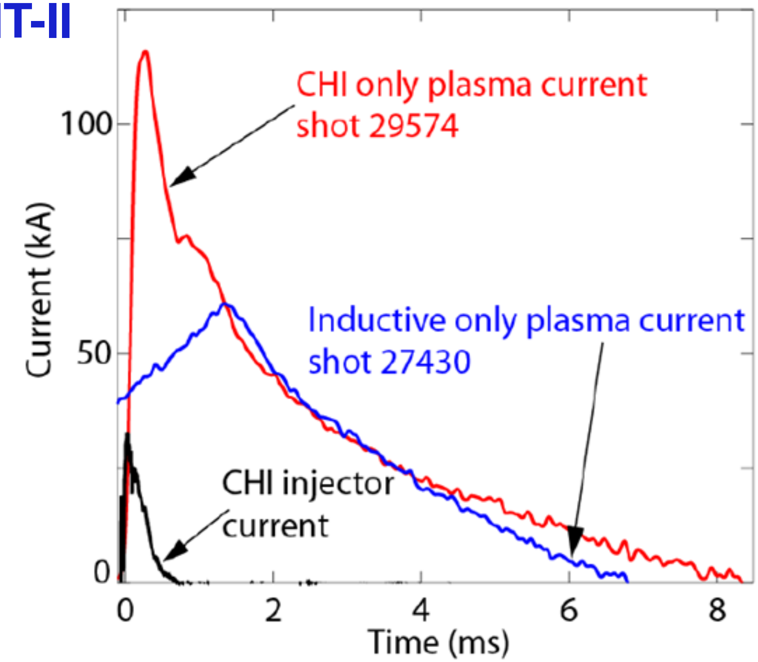


Proof-of-Principle NSTX device

- Built with conventional tokamak components
- Few PF coils
- 1.7kV CHI capacitor bank

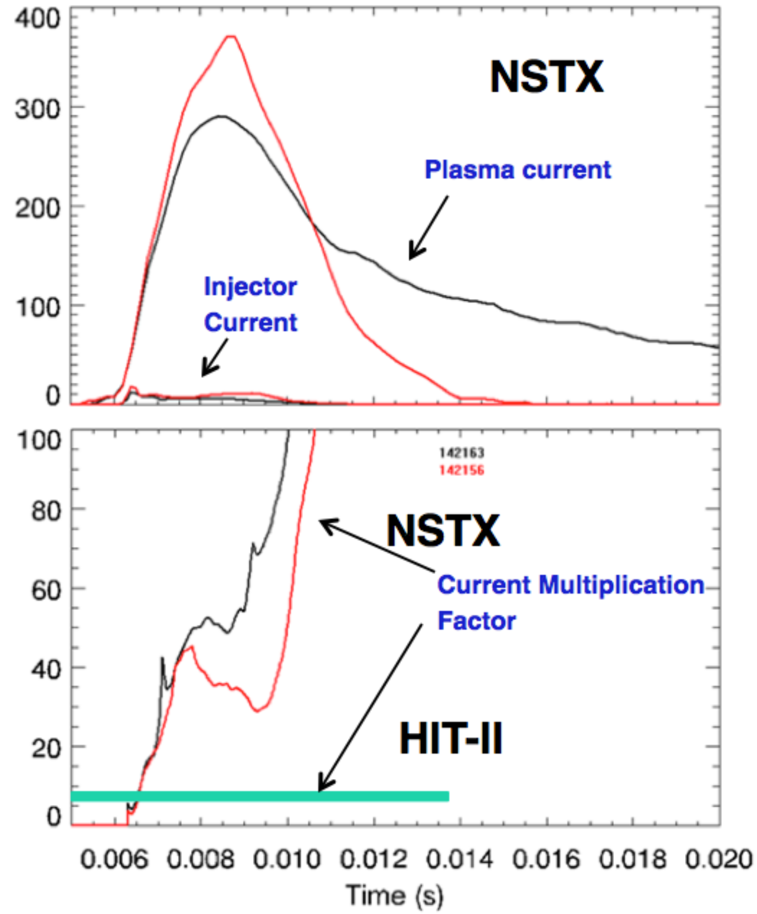
Very High Current Multiplication (Over 70 in NSTX) Aided by Higher Toroidal Flux

HIT-II



- -30kA of injector current generates 120kA of plasma current
- -Best current multiplication factor is 6-7
- -Current multiplication factor in NSTX is 10 times greater than that in HIT-II

NSTX



- Over 200kA of current persists after CHI is turned off

R. Raman, B.A. Nelson, D. Mueller, et al., PRL 97, (2006) 17002

Simulations Using TSC, coupled to TRANSP/NUBEAM and GENRAY being used for Current Ramp-up Simulations

CHI Research on NSTX-U Benefits from numerous hardware upgrades

- > 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)

CHI produces closed flux change of ~ 50 mWb