NSTX

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

Non-inductive Plasma Start-up in NSTX Using Transient CHI

College W&M
Colorado Sch Mines
Columbia U
Comp-X
General Atomics
INL
Johns Hopkins U
LANL
LLNL
Lodestar
MIT
Nova Photonics
New York U
Old Dominion U
ORNL
PPPL
PSI
Princeton U
Purdue U
SNL
Think Tank, Inc.
UC Davis
UC Irvine
UCLA
UCSD
U Colorado
U Maryland
U Rochester
U Washington
U Wisconsin

R. Raman[1], D. Mueller[2], S.C. Jardin[2], T.R. Jarboe[1], B.A. Nelson[1], M.G. Bell[2], S.P. Gerhardt[2], E.B. Hooper[3], S.M. Kaye[2], C.E. Kessel[2], J.E. Menard[2], M. Ono[2], V.A. Soukhanovskii[3]

[1]University of Washington
[2]Princeton Plasma Physics Laboratory
[3]Lawrence Livermore National Laboratory
and the NSTX Research Team

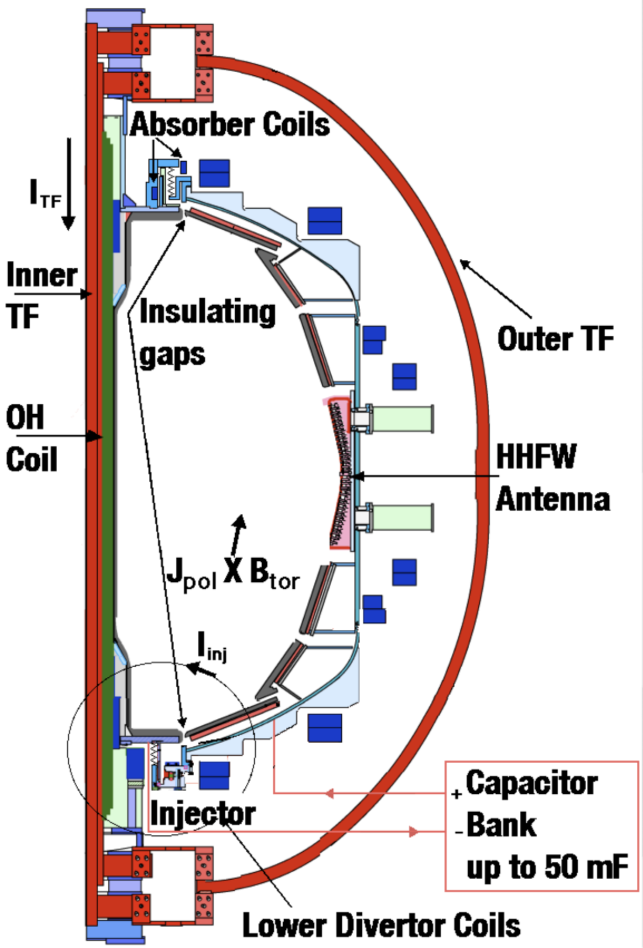
This work is supported by US DOE contract numbers FG03-96ER5436, DE-FG02-99ER54519, DE-SC0006757, and DE-AC02-09CH11466

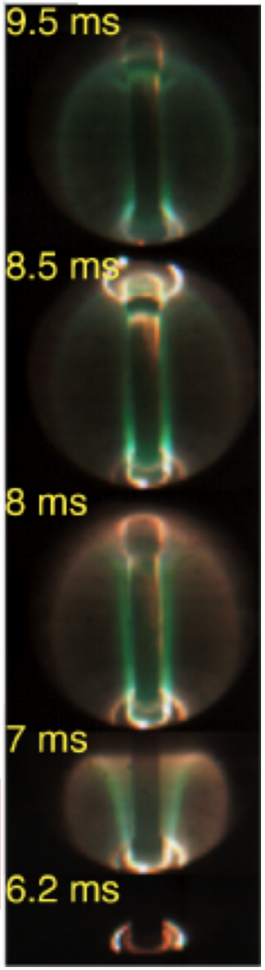
24th IAEA FEC Conference
San Diego, CA (October 8-13, 2012)
Presentation: EX-P2-10 (Tuesday October 9, 2012)

Culham Sci Ctr
U St. Andrews
York U
Chubu U
Fukui U
Hiroshima U
Hyogo U
Kyoto U
Kyushu U
Kyushu Tokai U
NIFS
Niigata U
U Tokyo
JAEA
Hebrew U
Ioffe Inst
RRC Kurchatov Inst
TRINITI
KBSI
KAIST
POSTECH
ASIPP
ENEA, Frascati
CEA, Cadarache
IPP, Jülich
IPP, Garching
ASCR, Czech Rep
U Quebec

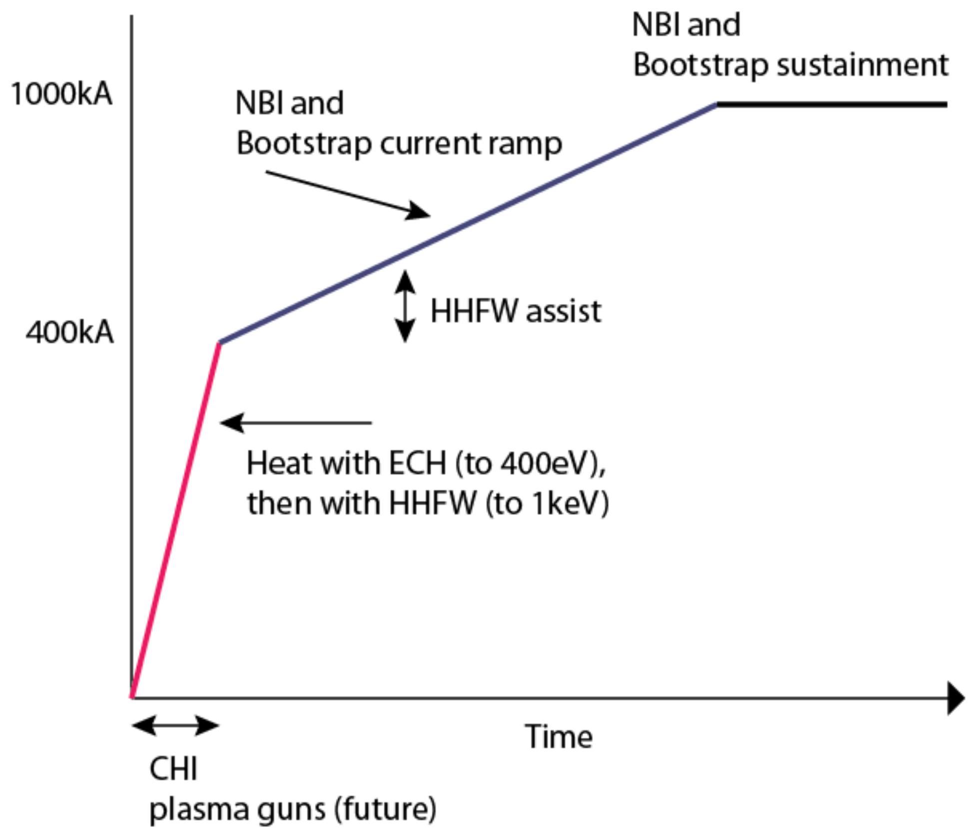
CHI is Planned to be Used as Initial Current Seed for Subsequent Non-inductive Current Ramp-up in NSTX-U

CHI in NSTX/NSTX-U



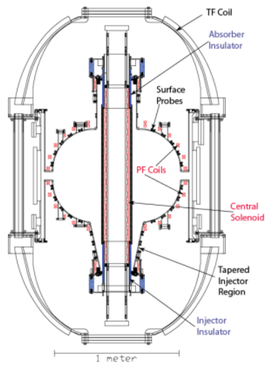


NSTX-U Start-up and Ramp-up strategy



NSTX-U goal is to demonstrate and understand solenoid-free current start-up and ramp-up

NSTX CHI Research Follows Concept Developed in HIT-II

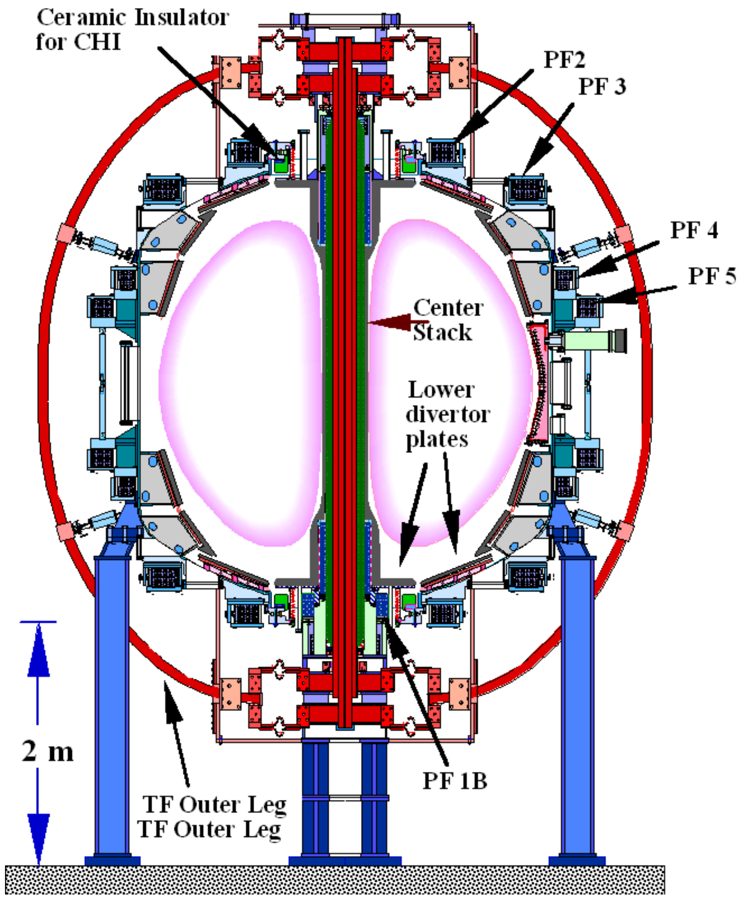


Approximately To scale

ICC 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

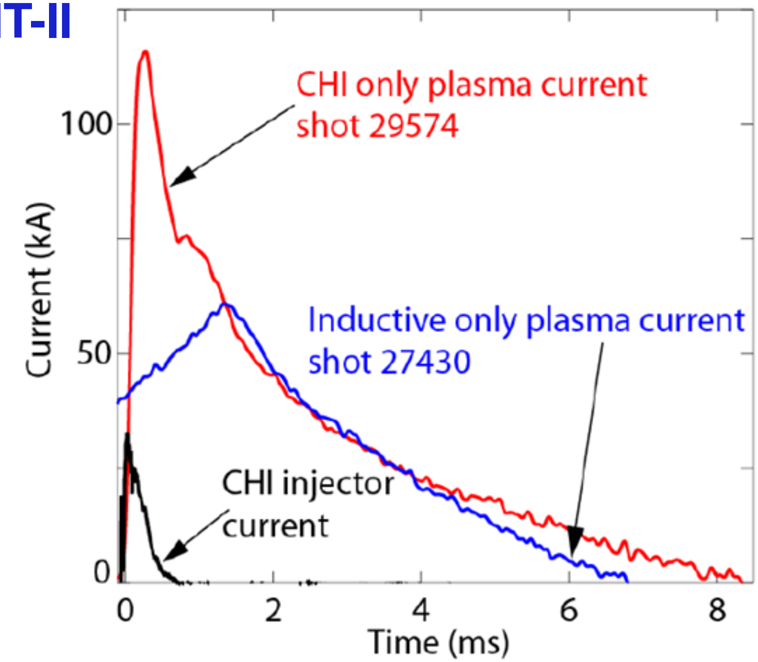


Proof-of-Principle NSTX device

- 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

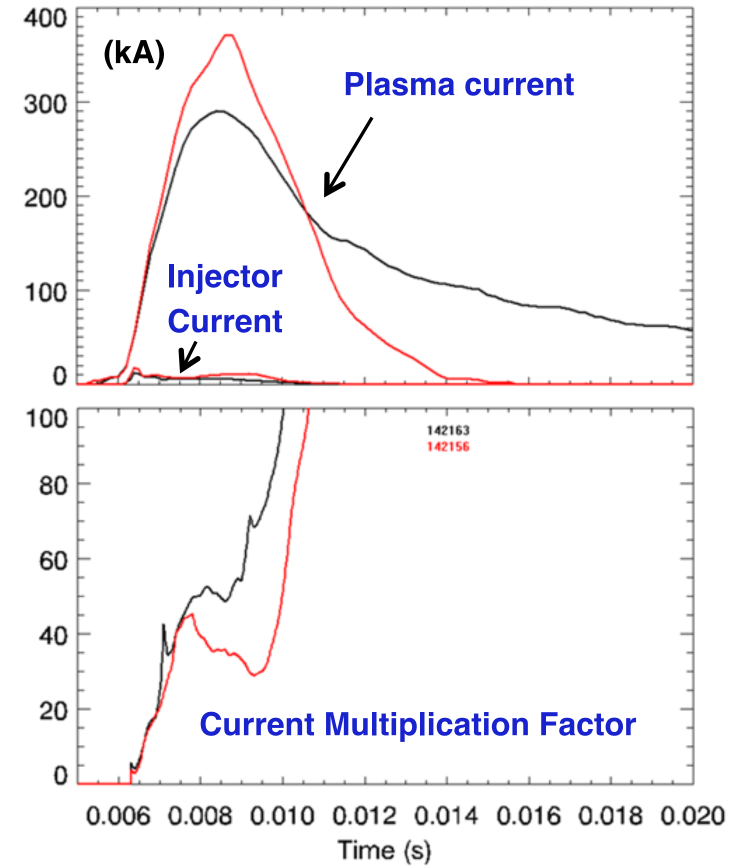
HIT-II



- -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

R. Raman et al, Nuclear Fusion 45, L15-L19 (2005)

NSTX



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

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

Externally Produced Toroidal Field makes CHI much more Efficient in a Lower Aspect Ratio Tokamak

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

  ψ_{inj} = injector flux

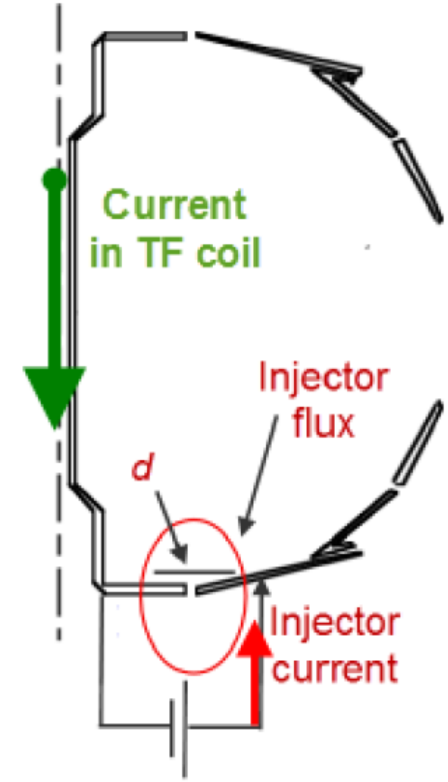
  d = flux foot print width

  I_{TF} = current in TF coil

Injector current **Toroidal flux**

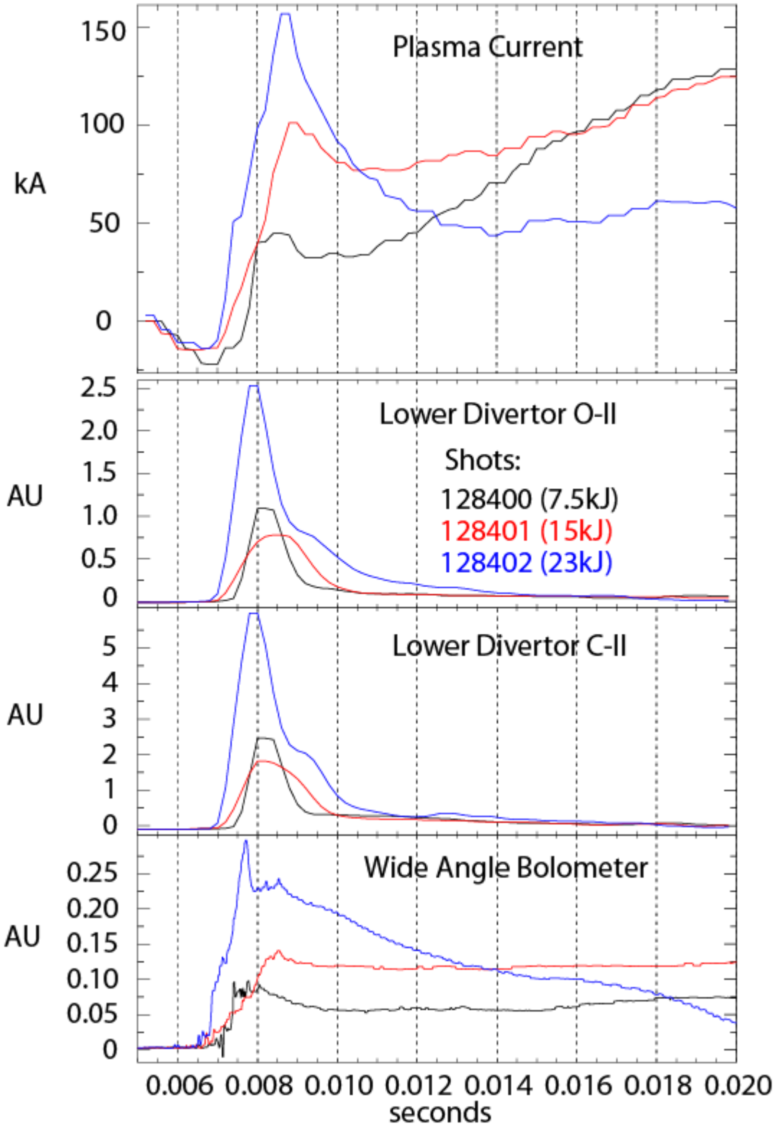
$$I_P = I_{inj}(\psi_T / \psi_{inj})$$

- 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)

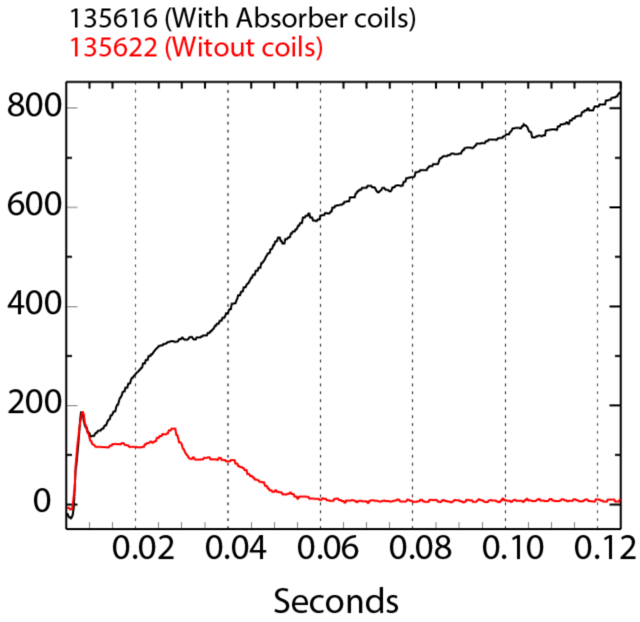
Low-Z Impurity Radiation Needs to be Reduced for Inductive Coupling

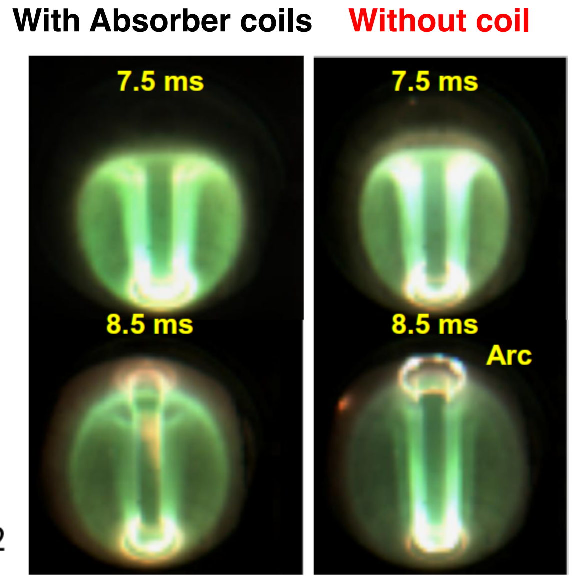


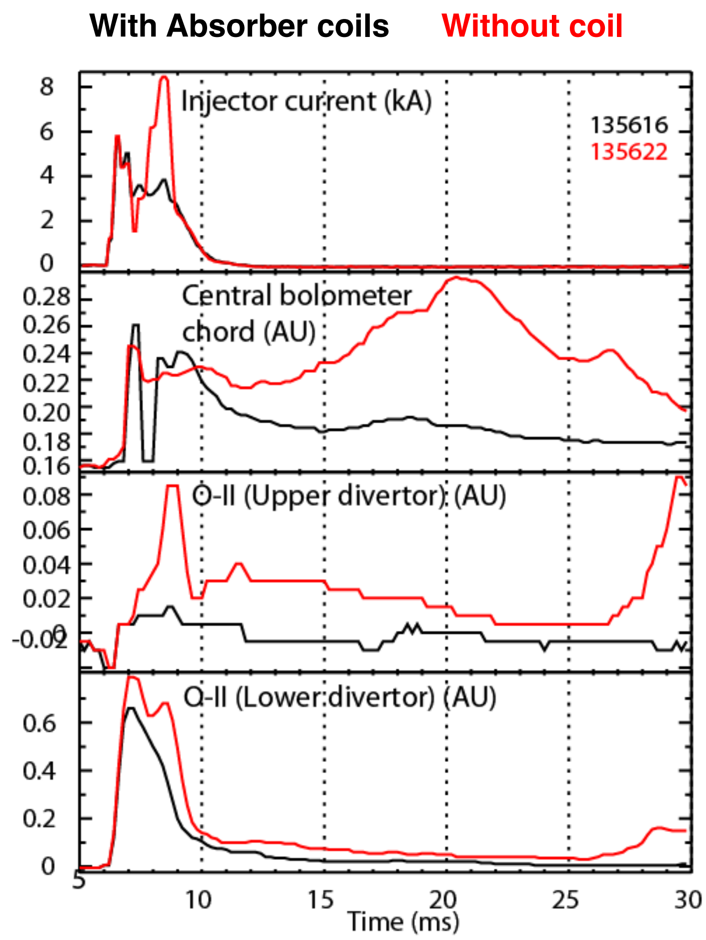
- Low-Z impurity radiation increases with more capacitors
- Possible improvements
  - Metal divertor plates should reduce low-Z impurities
    - High Te in spheromaks (500eV) obtained with metal electrodes
  - Discharge clean divertor with high current DC power supply
  - Use auxiliary heating during the first 20ms

Filter scopes: V. Soukhanovskii (LLNL)

Absorber Coils Suppressed Arcs in Upper Divertor and Reduced Influx of Oxygen Impurities





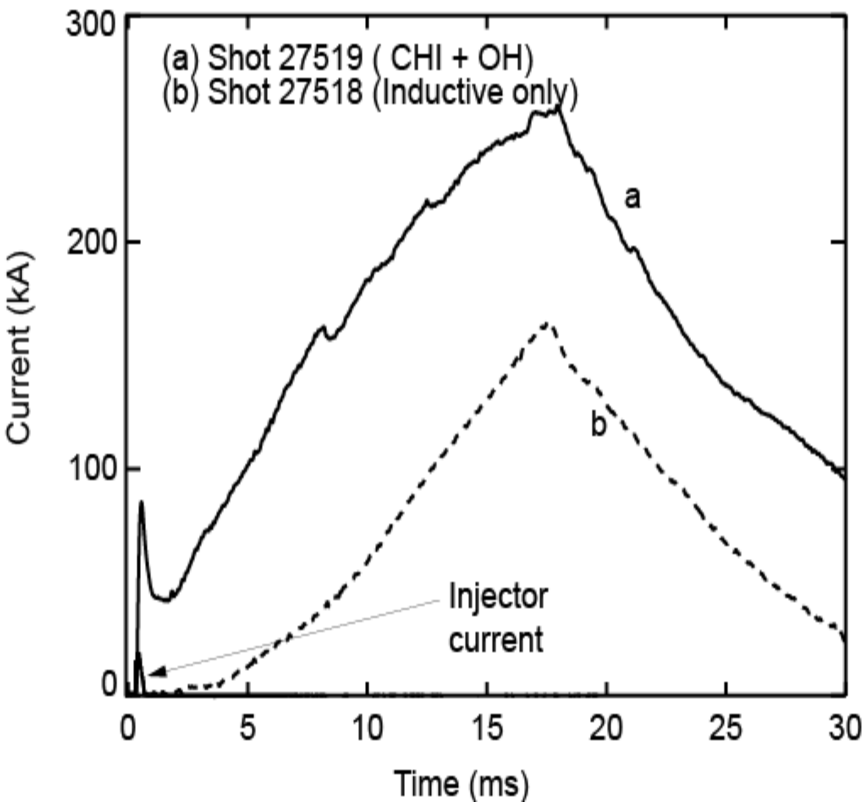


- Divertor cleaning and lithium used to produce reference discharge
- Buffer field from PF absorber coils prevented contact of plasma with upper divertor

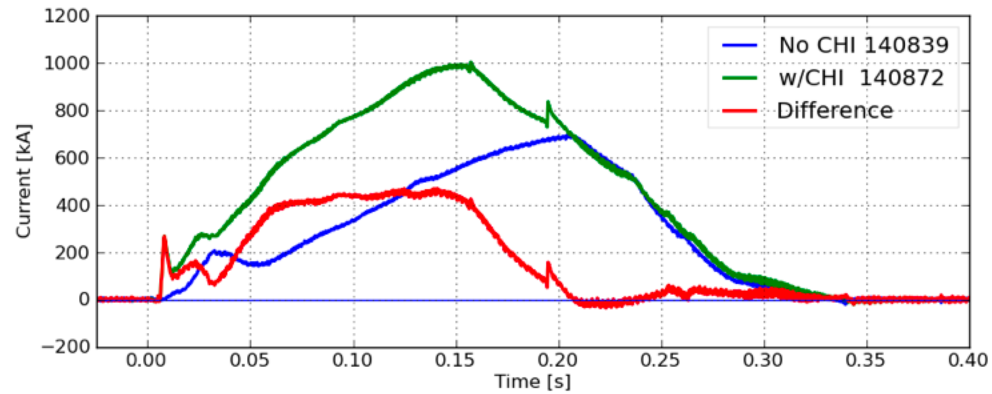
R. Raman, D. Mueller, B.A. Nelson, T.R. Jarboe, et al., PRL 104, (2010) 095003

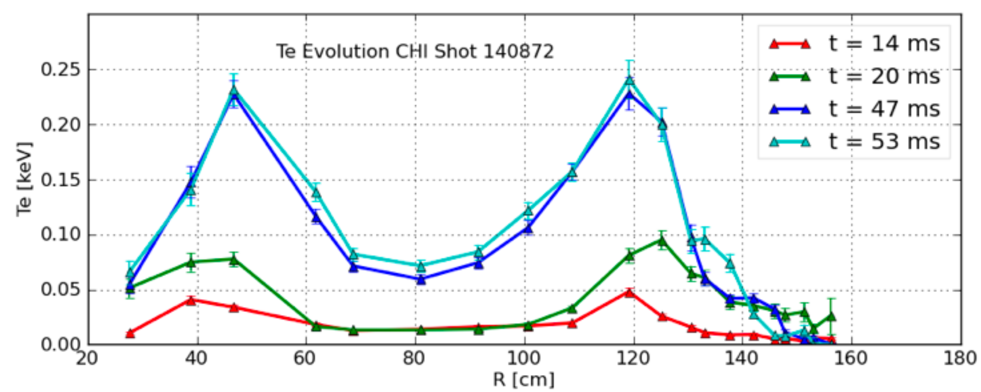
In NSTX Using Only 27kJ of Capacitor Bank Energy CHI Started a 300kA Discharge that Coupled to Induction

HIT-II



NSTX

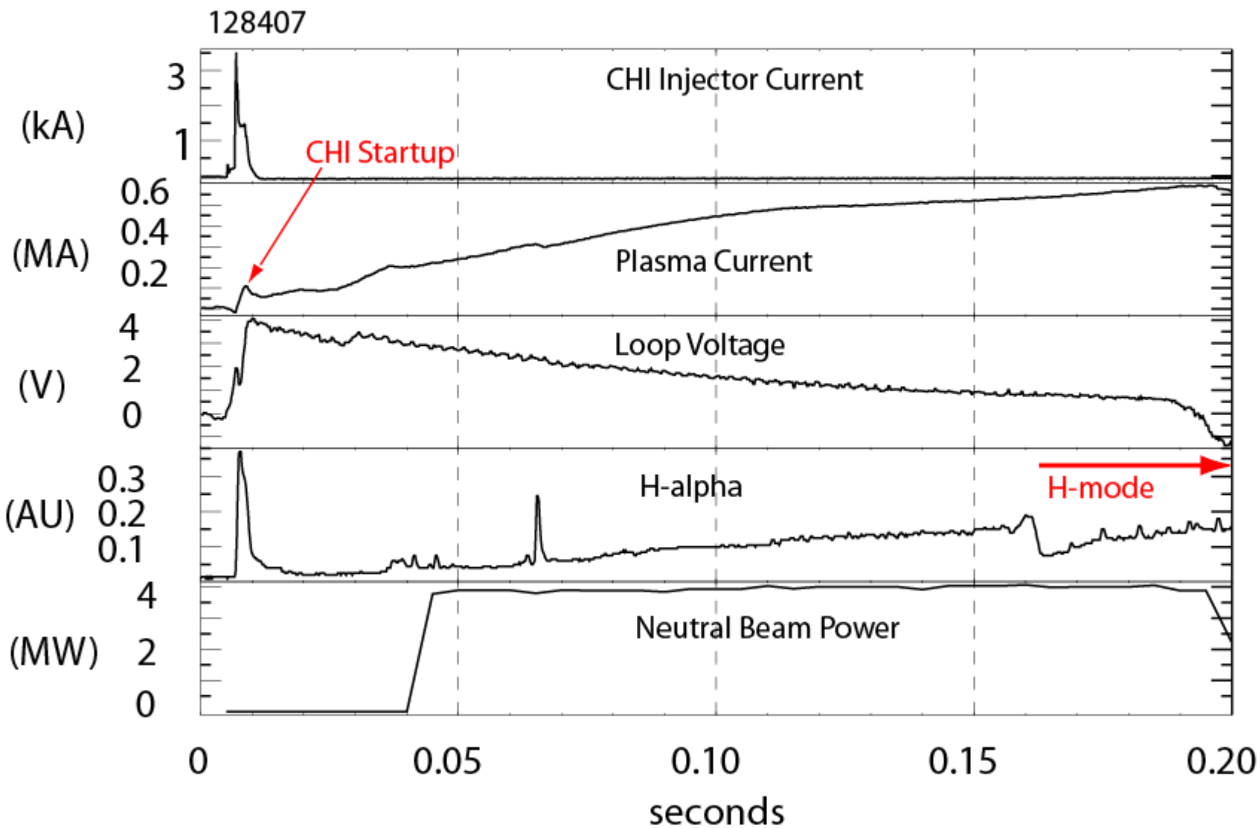




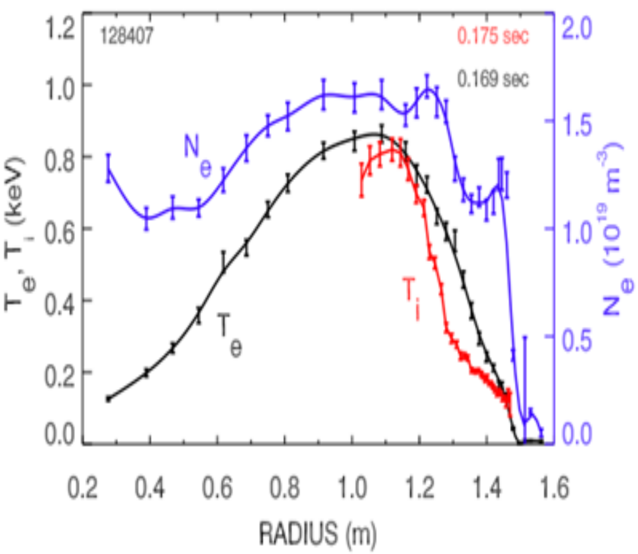
R. Raman, T.R. Jarboe, B.A. Nelson et al, Phys. Plasmas 14, 022504 (2007)

Thomson: B. LeBlanc (PPPL)

CHI Started Discharge Couples to Induction and Transitions to an H-mode Demonstrating Compatibility with High-performance Plasma Operation



T_e & N_e from Thomson
T_i from CHERS



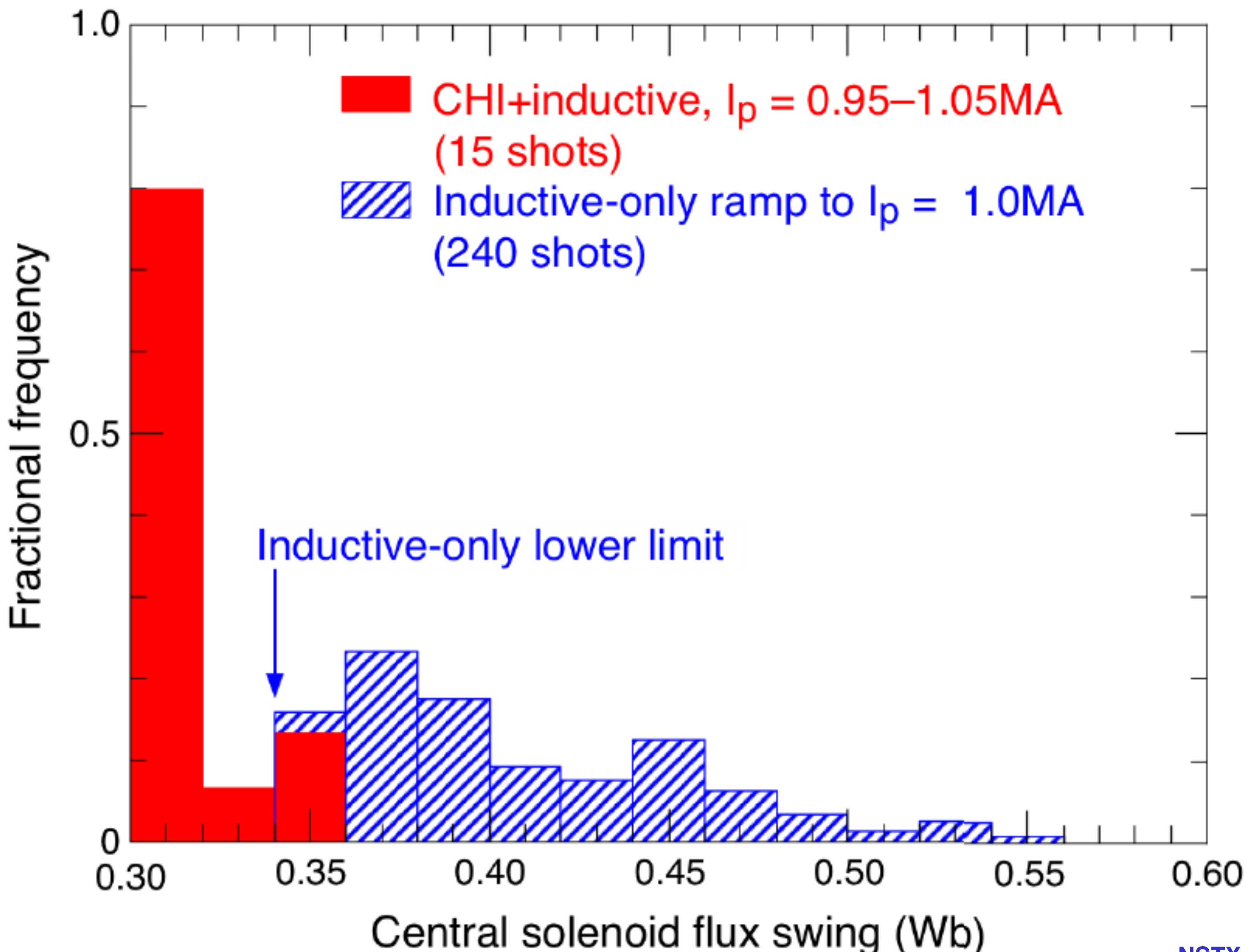
CHERS : R. Bell
Thomson: B. LeBlanc

Discharge is under full plasma equilibrium position control

– Loop voltage is preprogrammed

CHI Started Discharges Require Less Inductive Flux than Discharges in NSTX Data Base

Comparison of CHI Startup to H-modes using more than 1 NBI source

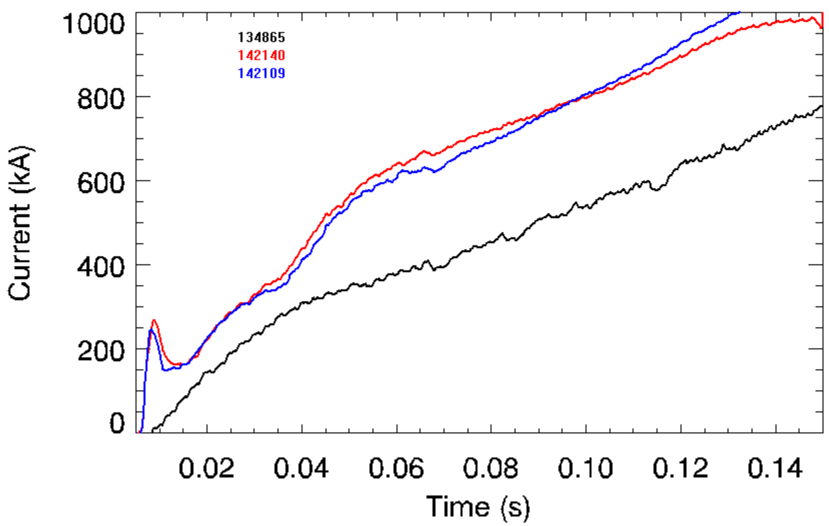


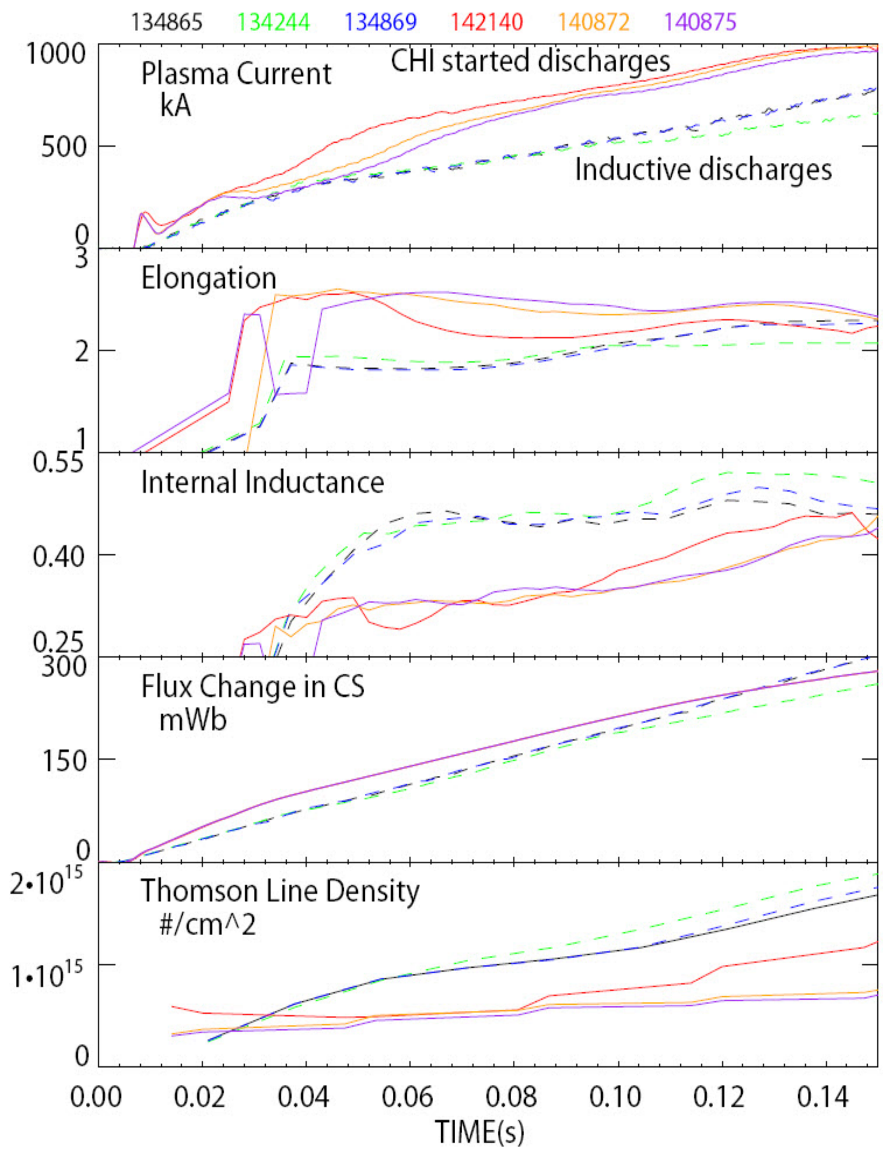
FY11 discharges require 258 mWb of flux

(less flux than shown here)

NSTX Data Base Analysis: M. Bell

NSTX has made Considerable Progress in Developing CHI as a Method to Start-up an ST

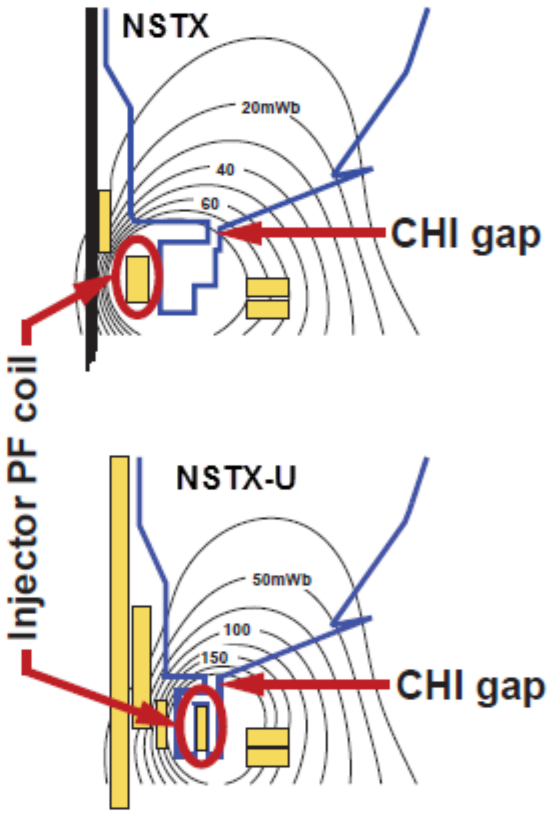




- Best inductive plasma (from 10 YR NSTX data base) uses 340 mWb of solenoid flux to get to 1MA
- Un-optimized CHI started discharges require 258 mWb
- Full non-inductive start-up and ramp-up will be developed on NSTX-U

R. Raman, et al., Phys Plasmas, 18, 092504 (2011)

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

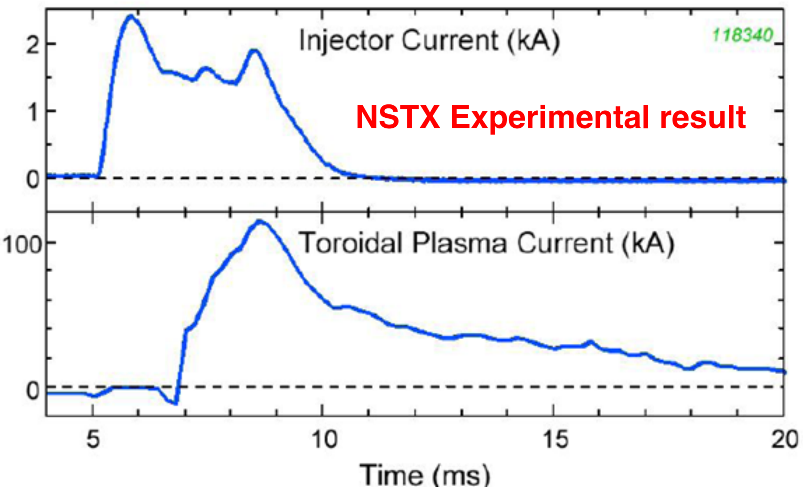


Injector flux in NSTX-U is ~ 2.5 times higher than in NSTX → supports increased CHI current

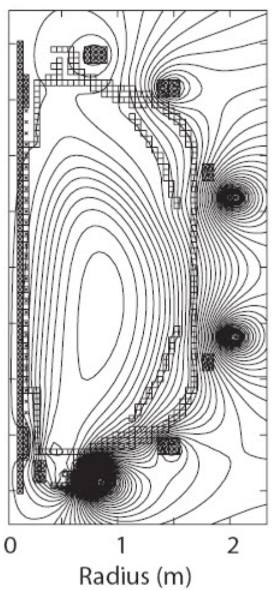
J.E. Menard, et al., Nuclear Fusion (accepted)

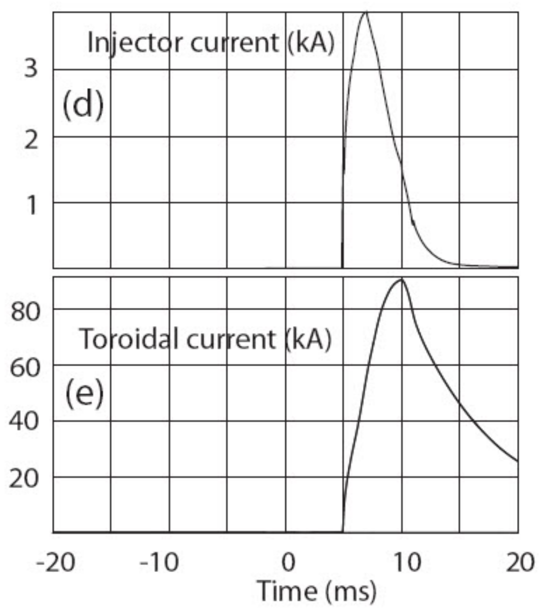
Parameters	NSTX	NSTX-U	ST-FNSF	ST Pilot Plant
Aspect ratio: A	1.30	1.50	1.50	1.70
Elongation: κ	2.6	2.8	3.1	3.3
Major radius: R_0 [m]	0.86	0.93	1.2	2.2
Minor radius: a [m]	0.66	0.62	0.80	1.29
Toroidal field at R_0: B_T [T]	0.55	1	2.2	2.4
TF rod current: I_{TF} [MA]	2.4	4.7	13.2	26.4
Toroidal flux: Φ_T [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

TSC Simulations are being used to Understand CHI-Scaling with Machine Size



TSC simulation

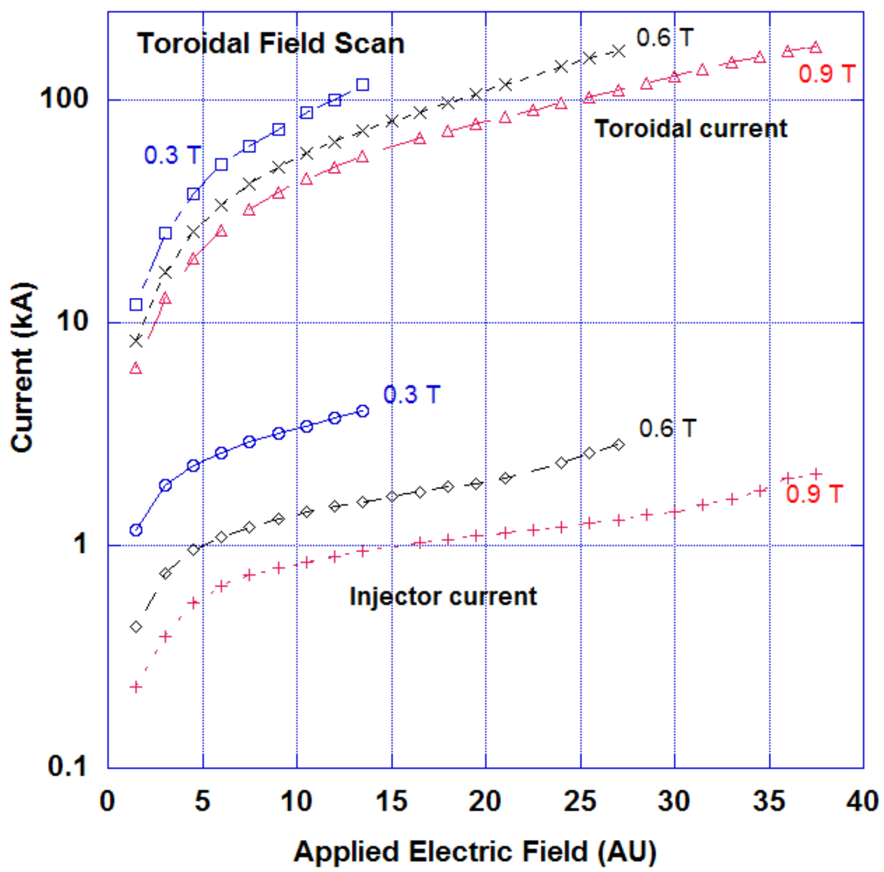


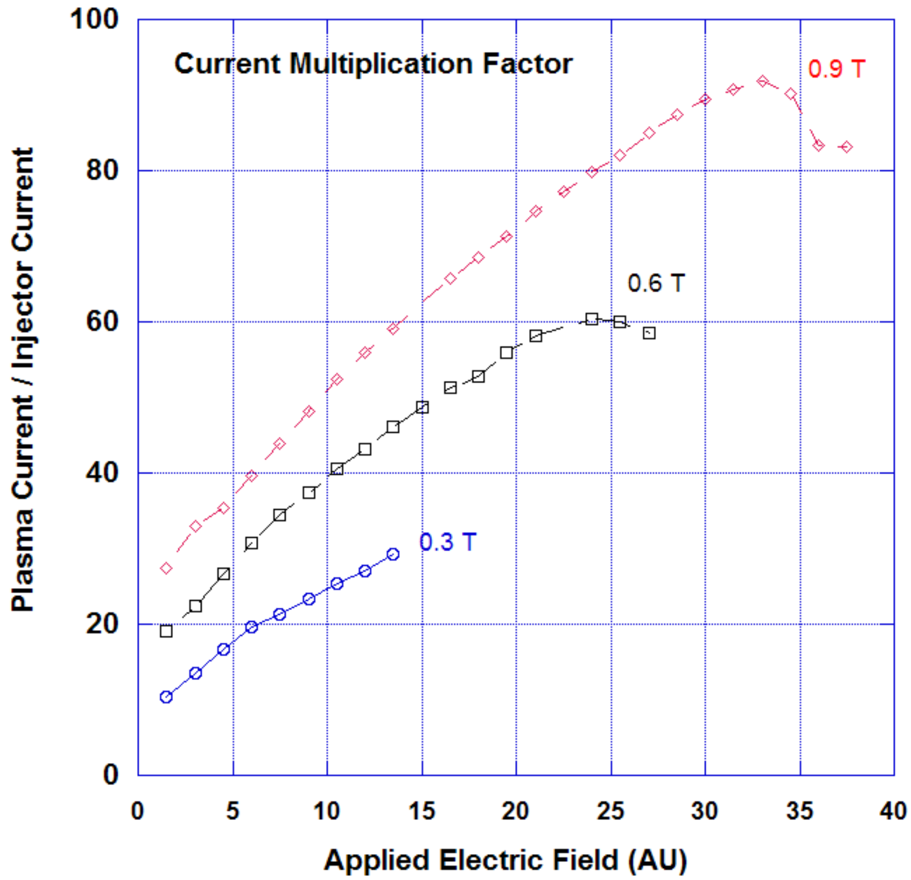


- Time-dependent, free-boundary, predictive equilibrium and transport
- Solves MHD/Maxwell's equations coupled to transport and Ohm's law
- Requires as input:
  - Device hardware geometry
  - Coil electrical characteristics
  - Assumptions concerning discharge characteristics
- Models evolutions of free-boundary axisymmetric toroidal plasma on the resistive and energy confinement time scales.
- NSTX vacuum vessel modeled as a metallic structure with poloidal breaks
  - An electric potential is applied across the break to generate the desired injector current

TSC: Developed by S.C. Jardin (PPPL)

TSC Simulations Show Increasing Current Multiplication as TF is Increased (NSTX geometry)



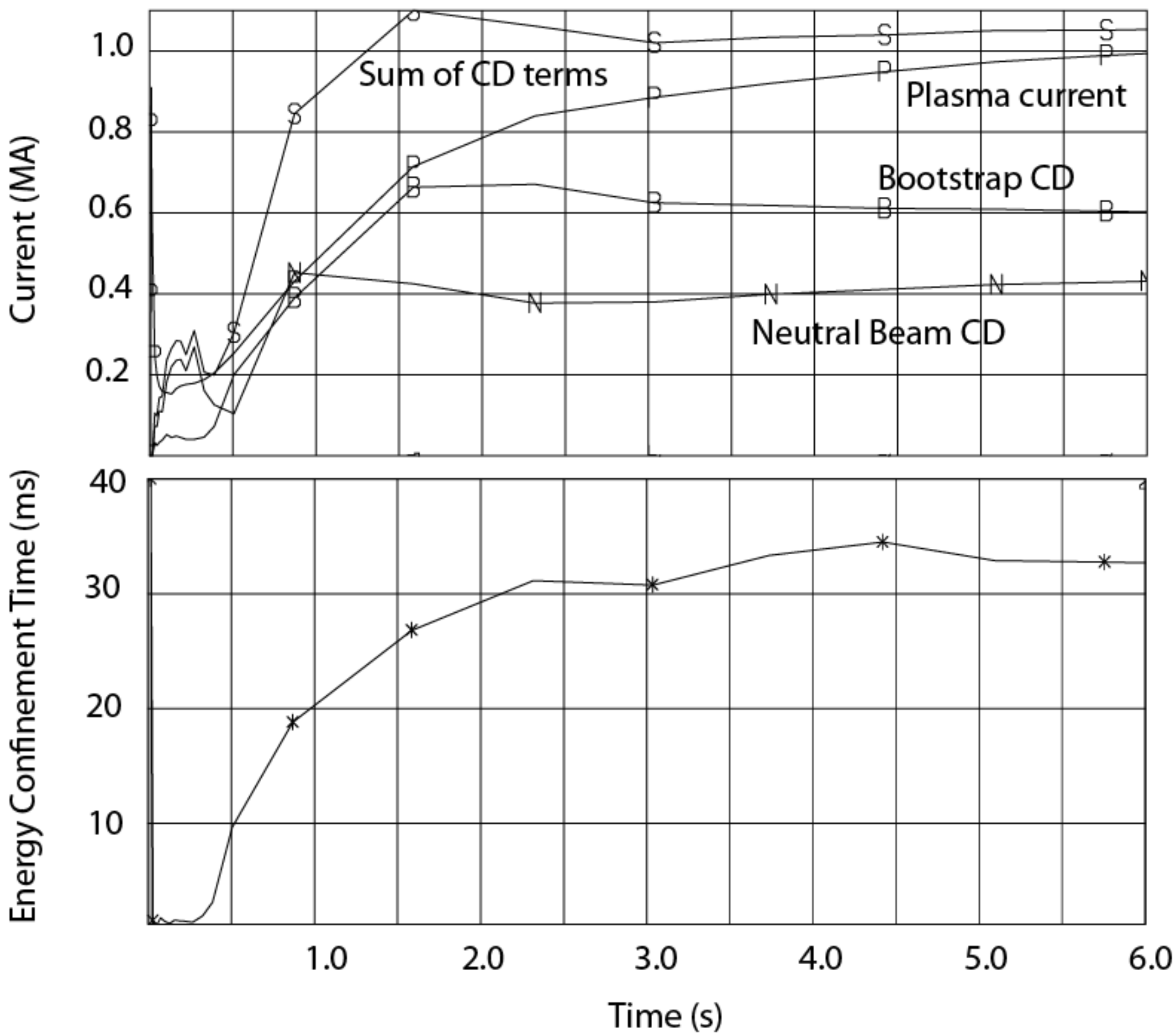


- Observed current multiplication factors similar to observations in NSTX
  - Higher toroidal field important as it reduces injector current requirement

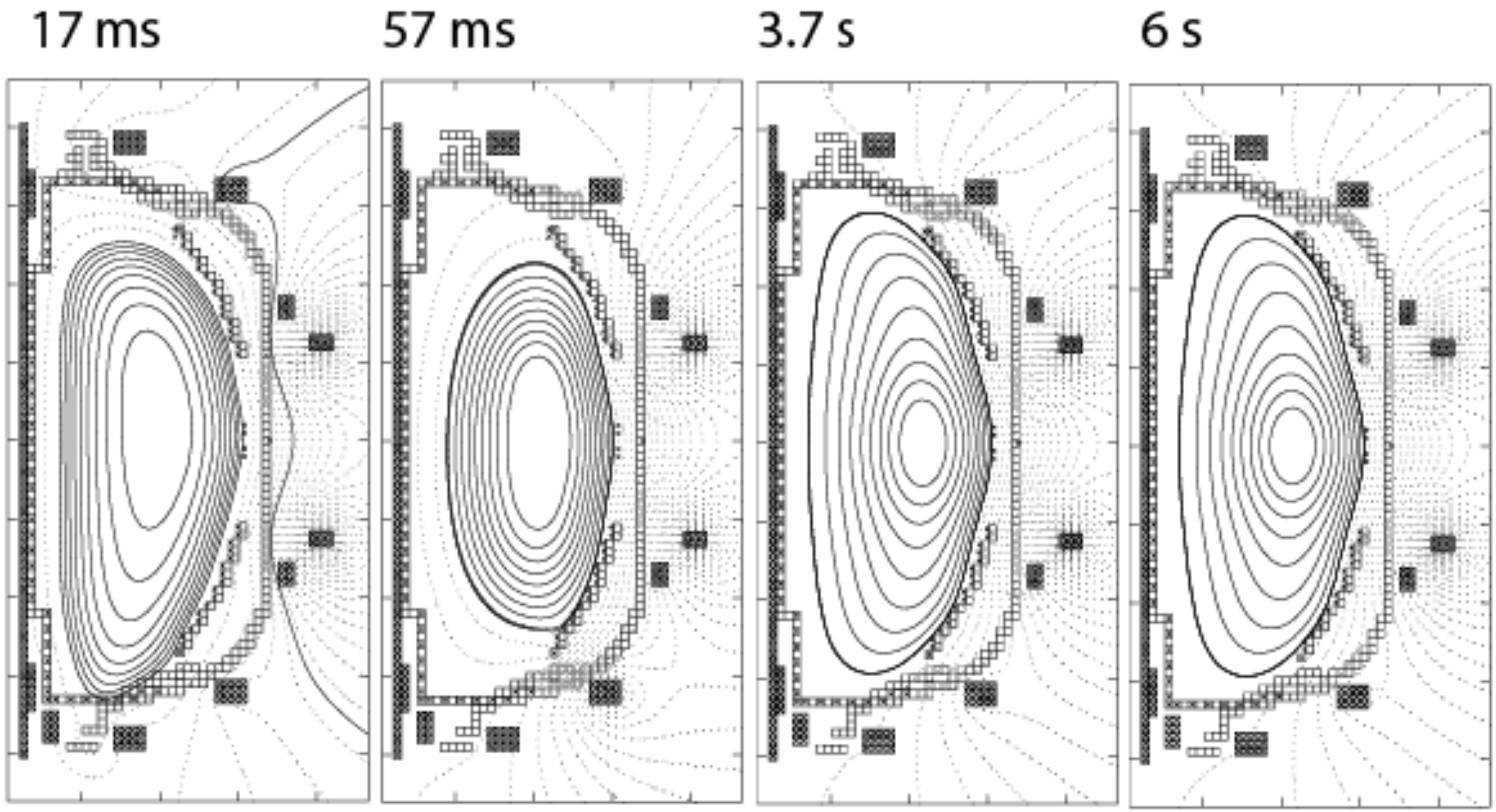
R. Raman, S.C. Jardin, J. Menard, T.R. Jarboe et al., Nuclear Fusion 51, 113018 (2011)

Preliminary Scenario for Ramping to 1MA in NSTX-U

- Initial 400 kA CHI target is generated by TSC
  - H-mode initiated at 500ms
  - NBI power programmed to increase with I_p
  - 0.5MW ECH + 2MW HHFW heats plasma to 1s
  - τ_E maintained at about 30ms, consistent with NSTX experimental results
  - Bootstrap current overdrive and NB current increases I_p to 1 MA at 6s



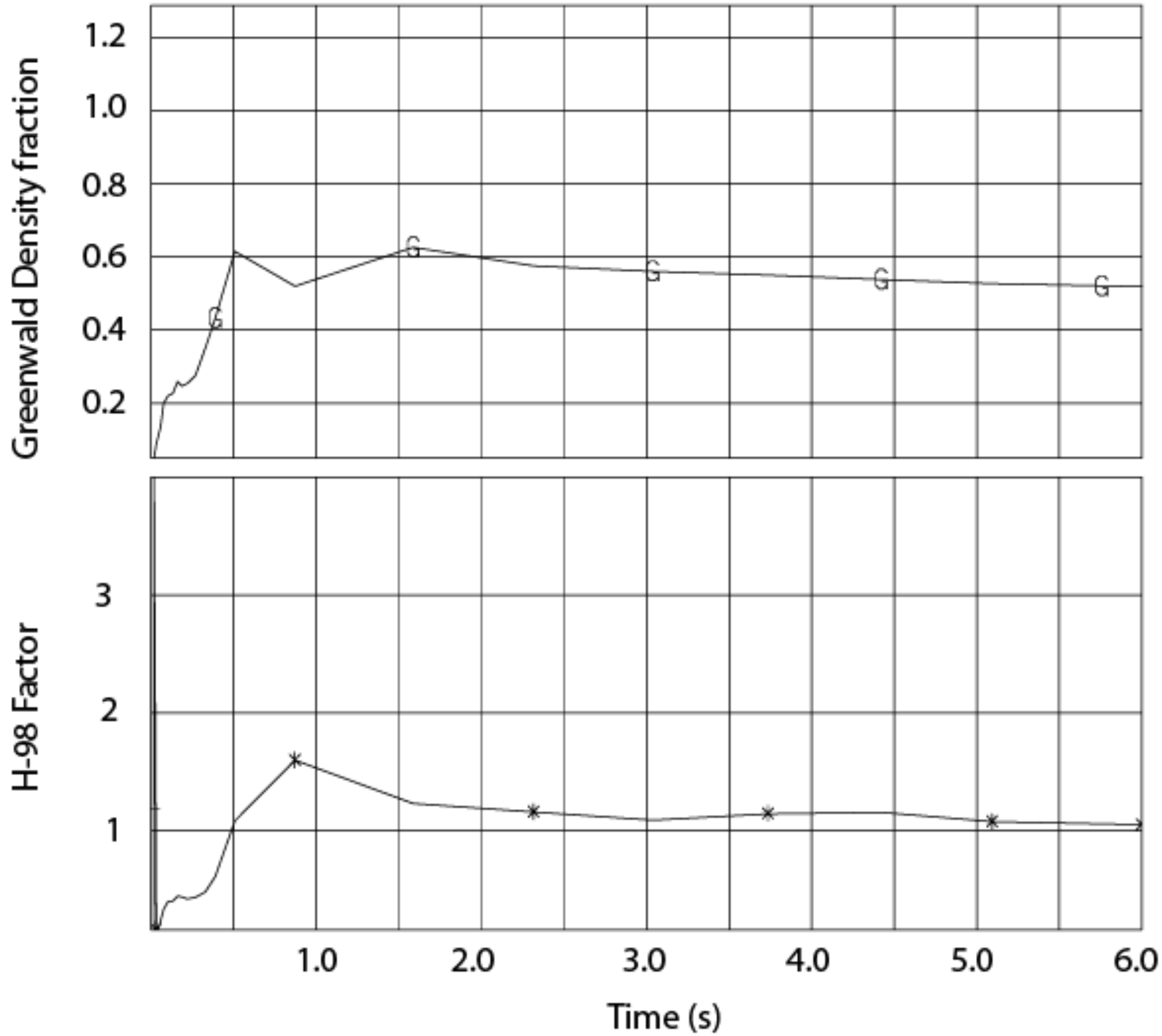
CHI-started Discharge is Position Feedback Controlled During Coupling Phase to NBI



Horizontal position control started at 20ms
Vertical position control started at 30ms

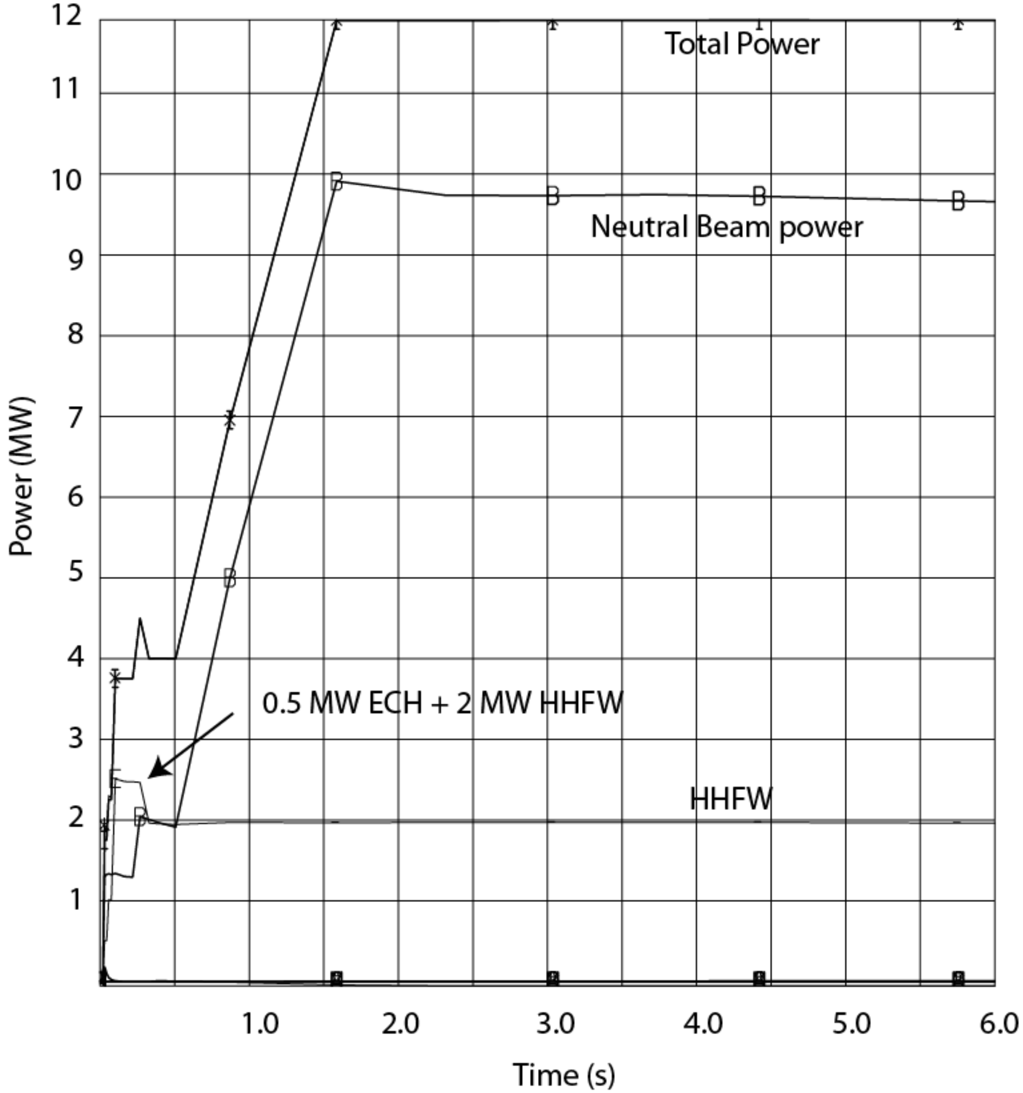
Greenwald Density Fraction and H-98 Factor Maintained constant during Current Ramp

- Greenwald density fraction of 0.6 maintained during current ramp
- H-98 factor of 1.2 is adequate for current ramp-up
  - consistent with NSTX experimental results



NSTX-U Heating and Current Drive Actuators are Adequate for Current Ramp-up to 1 MA

- NBI power programmed to increase with I_p and density
- Power ramp-up adjusted to avoid generation of very hollow current profiles
- 0.5MW (absorbed) ECH retained from 0.02 to 0.5s
- 2 MW (absorbed) HHFW retained from 0.02 to 6s
- T_e of 1.7 keV is maintained until 5s



NSTX Results Demonstrate Viability of CHI as a Solenoid-free Plasma Startup Method for NSTX-U and the Tokamak/ST

- 0.3MA 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 & transition to an H-mode demonstrates compatibility with high-performance plasma operation
- CHI start-up has produced the type of plasmas required for non-inductive ramp-up and sustainment (low internal inductance, low density)
- Favorable scaling with increasing machine size (from two machines of vastly different size, HIT-II and NSTX and in TSC simulations)
- Results and TSC simulations suggest high current start-up capability in NSTX-U
- Initial full discharge simulations (CHI start-up + NBI CD) using TSC provides viable scenarios for current ramp-up to 1MA