NSTX

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Non-inductive Plasma Start-up and Current Ramp-up in NSTX-U

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and the NSTX Research Team

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54th Meeting of the Division of Plasma Physics
APS 2012 Conference
Providence, Rhode Island, October 29-November 2, 2012

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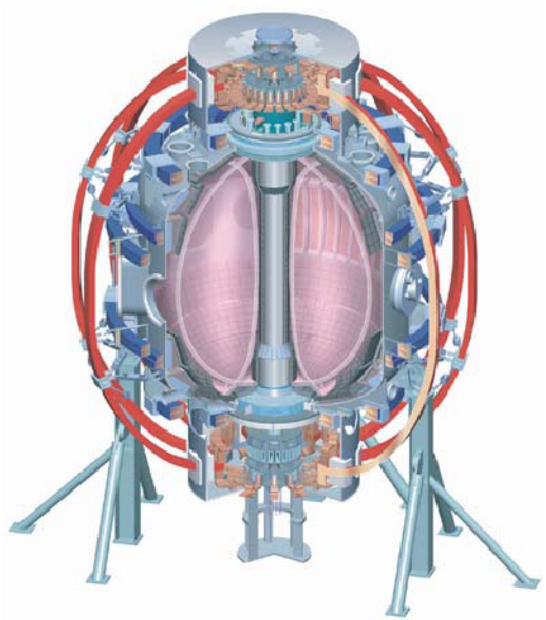
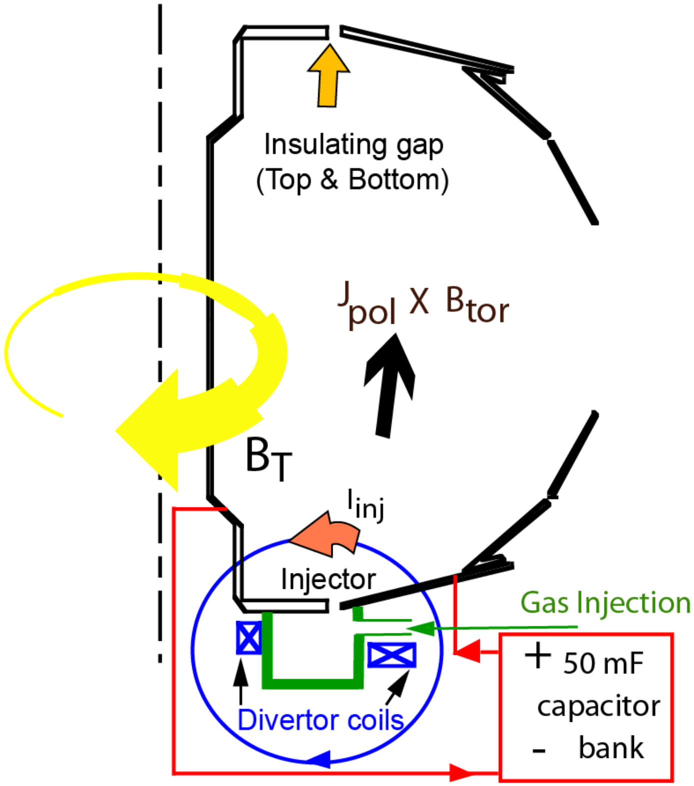
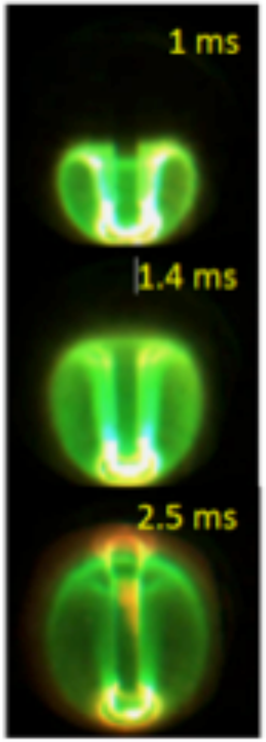
NSTX-U Will Use Transient CHI For Solenoid-free Plasma Start-up With Subsequent Current Ramp-up Using NBI







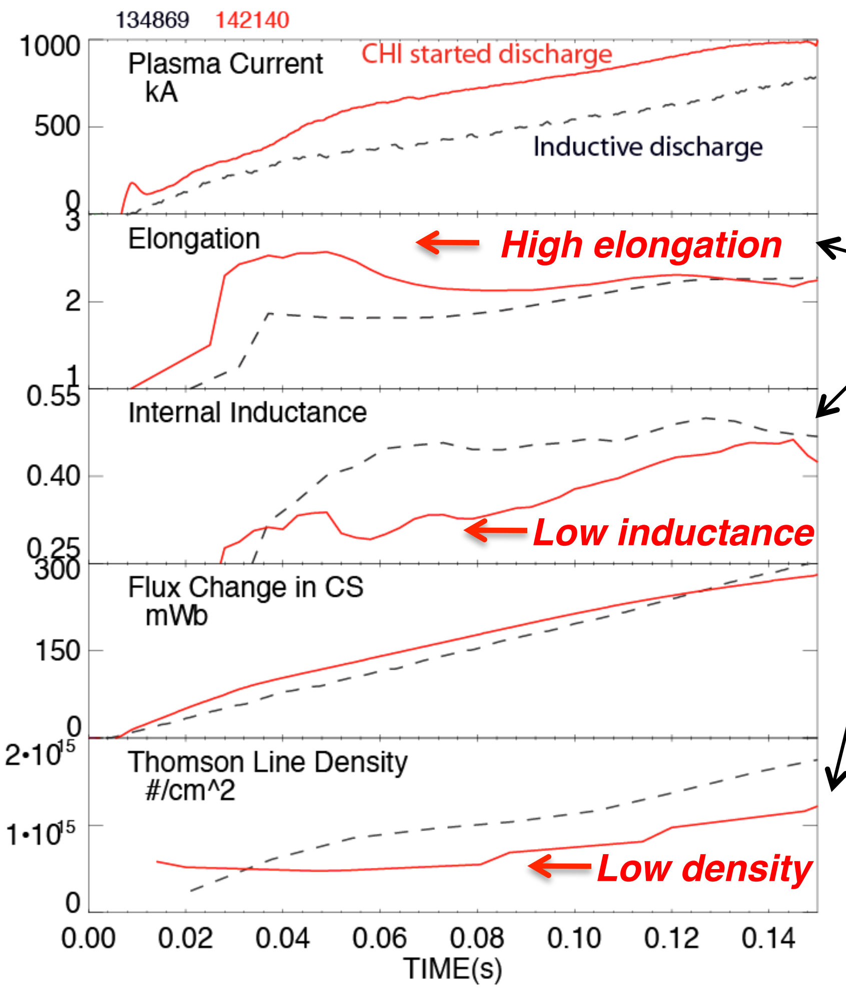
- Parameters to consider
  - Current multiplication factor
  - Effect of toroidal field
  - Magnitude of generated plasma current
  - New desirable features?

Fast camera: F. Scotti, L. Roquemore, R. Maqueda

CHI for an ST: T.R. Jarboe, Fusion Technology, 15 (1989) 7
Transient CHI: R. Raman, T.R. Jarboe, B.A. Nelson, et al., PRL 90, (2003) 075005-1

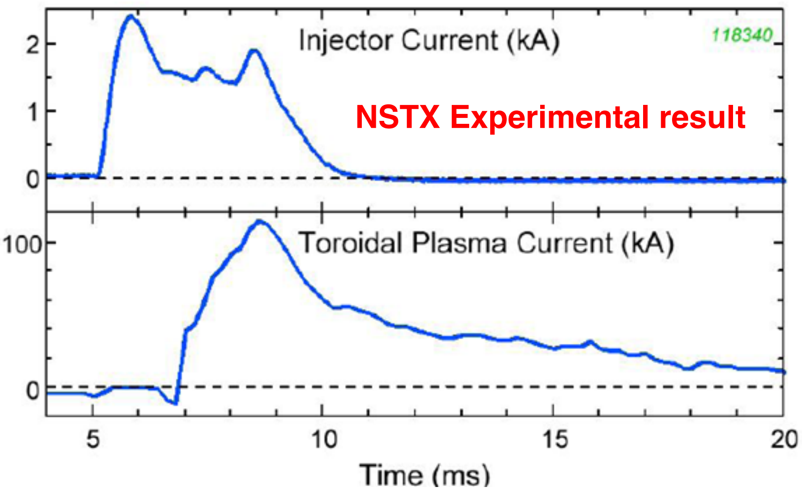
Plasma discharge ramping to 1MA requires 35% less inductive flux when coaxial helicity injection (CHI) is used

CHI assisted startup in NSTX

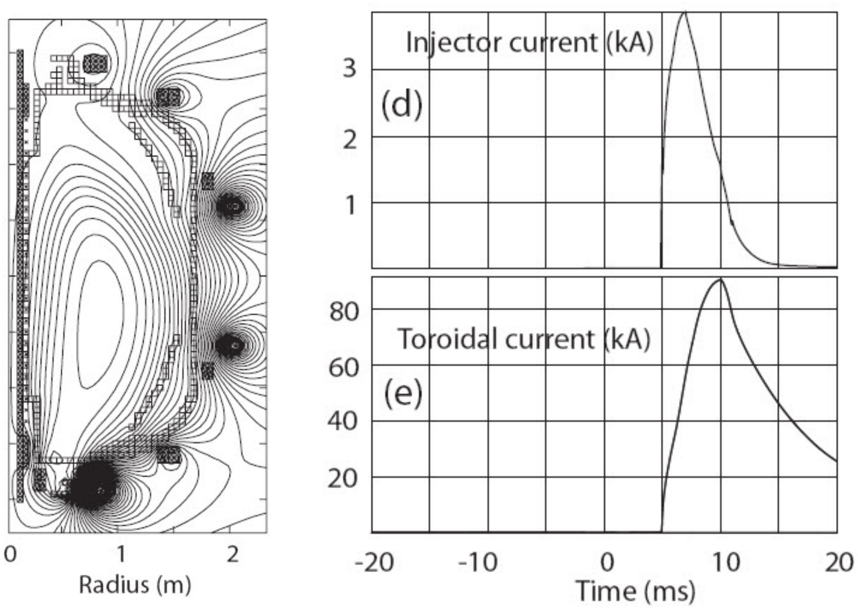


- CHI generates plasmas with high elongation, low l_i and n_e
- Results imply a doubling of closed flux current > 400kA in NSTX-U

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



TSC simulation

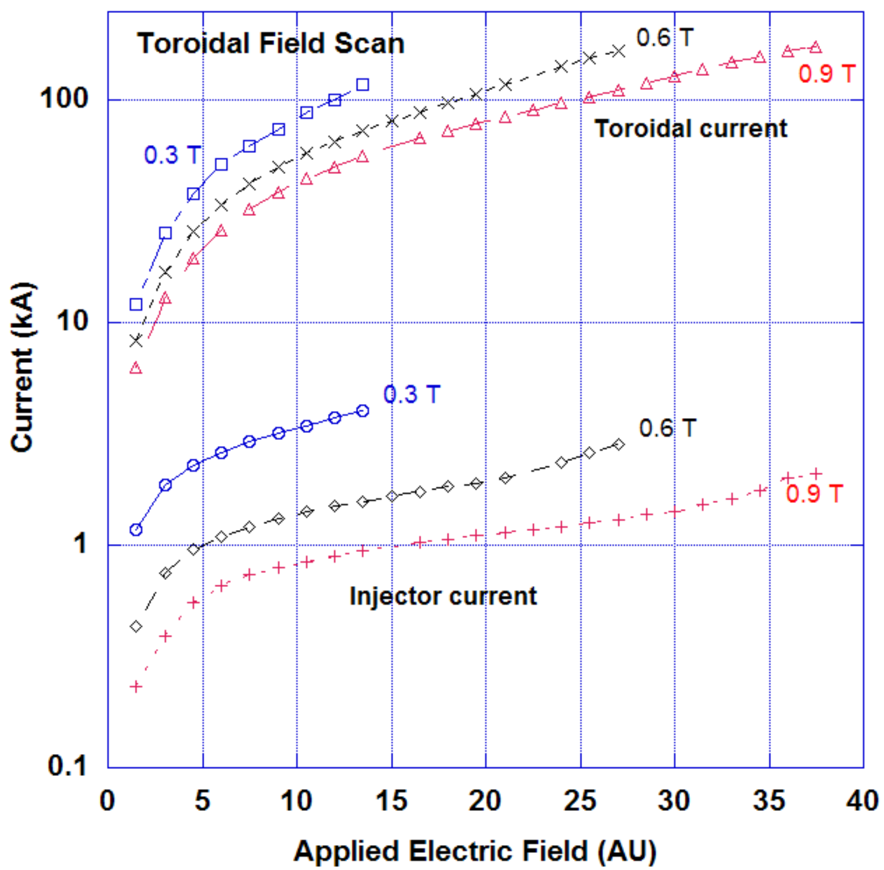


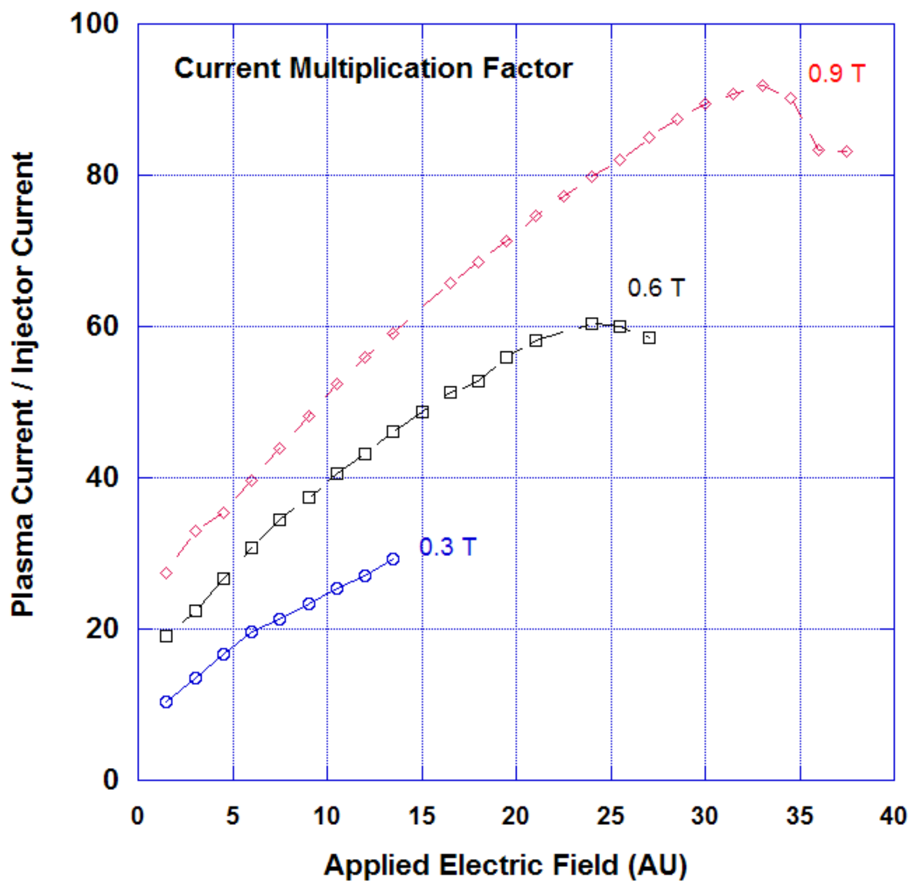
- Time-dependent, free-boundary, predictive equilibrium and transport
- Solves MHD/Maxwell's equations coupled to transport and Ohm's law
- Requires as input:
  - Device hardware geometry
  - Coil electrical characteristics
  - Assumptions concerning discharge characteristics
- Models evolutions of free-boundary 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

Early phase of CHI start-up now being studied using NIMROD simulations

(E. B. Hooper, poster Thursday PP8.00025)

TSC Simulations Show Increasing Current Multiplication as TF is Increased





- 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)

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

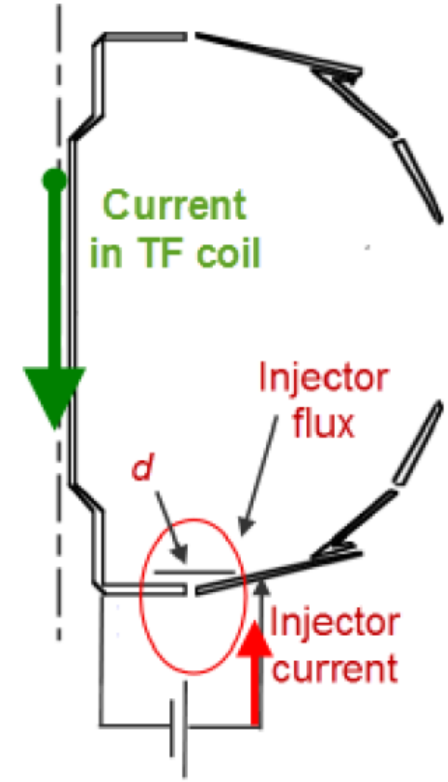
  d = flux foot print width

  I_{TF} = current in TF coil

Injector current **Toroidal flux**

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

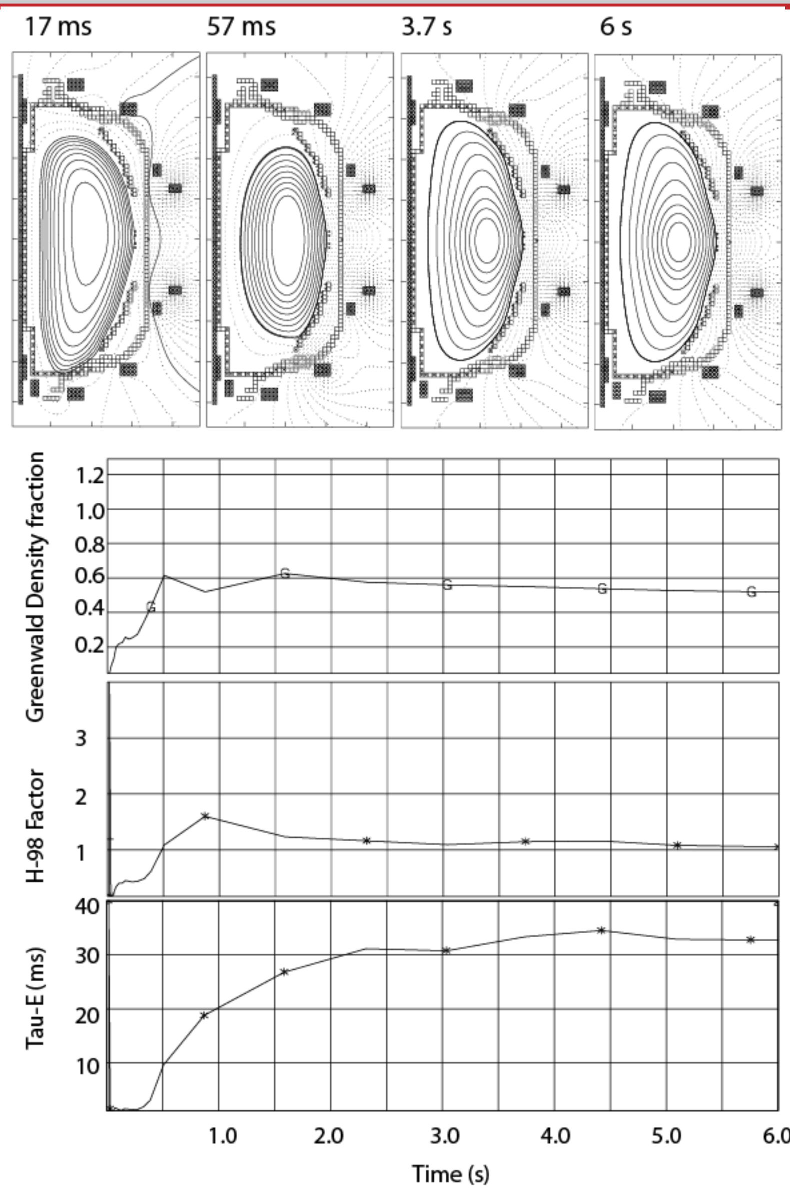
- Current multiplication increases with toroidal field
  - Favorable scaling with machine size
  - Increases efficiency (10 Amps/Joule in NSTX)
  - Smaller injector current to minimize electrode interaction



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

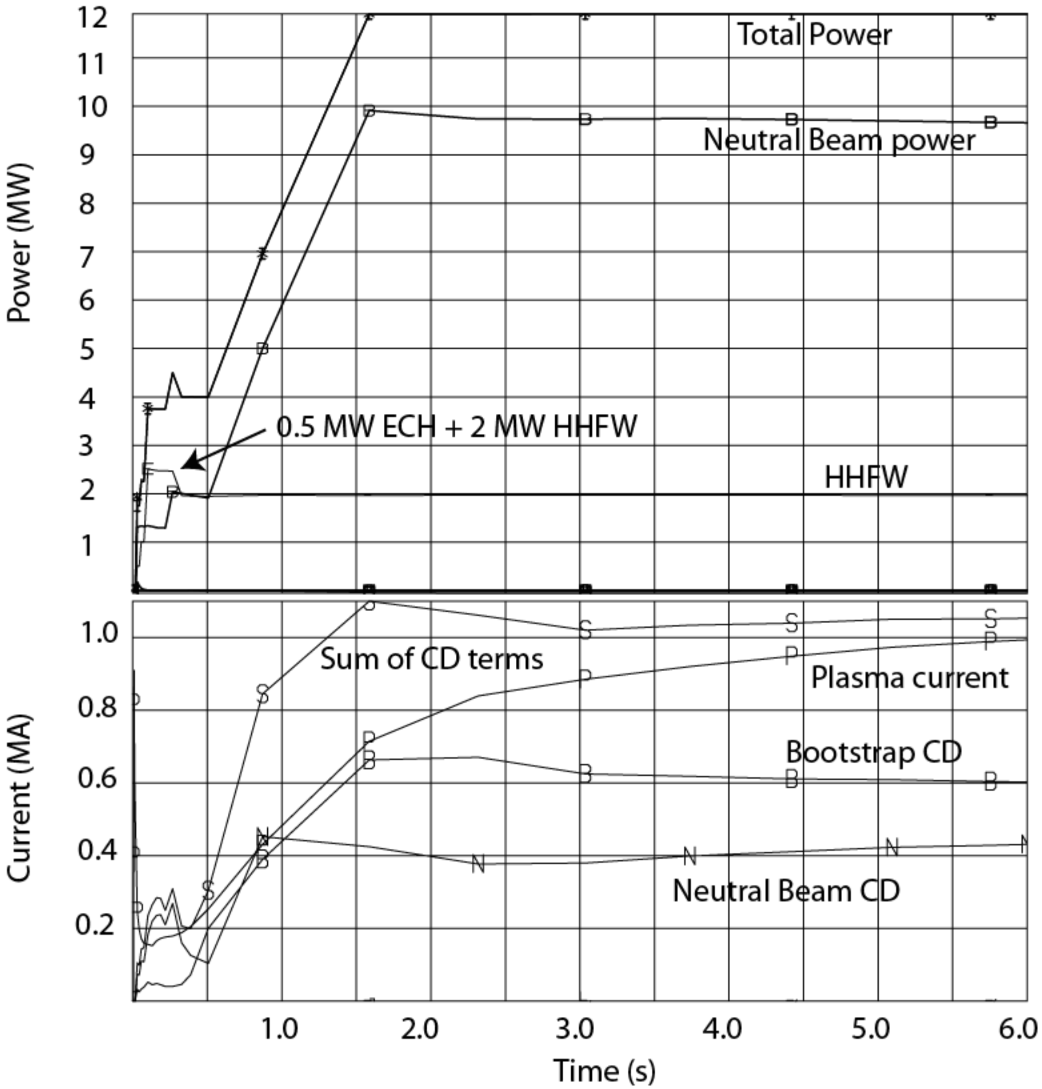
Preliminary Scenario for Ramping to 1MA in NSTX-U

- Initial 400 kA CHI target is generated by TSC
  - CHI phase ends at 17ms
  - Horizontal and vertical position control of CHI-started discharge initiated at 20 and 30ms
  - Density of 0.6 n_{GW} maintained during current ramp-up
  - H98 factor maintained near 1
  - τ_E maintained at about 30ms, consistent with NSTX experimental results
  - Normalized internal inductance (not shown)maintained below 0.6 during current ramp



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

- 0.5 MW ECH (absorbed power) maintained until 0.3s to heat CHI plasma
- 2 MW HHFW retained until 6s
- NBI power programmed to increase with I_p and density
- Power ramp-up adjusted to avoid generation of very hollow current profiles
- H-mode initiated at 500ms
- T_e of 1.7 keV is maintained until 6s
- Bootstrap & NBI current overdrive increases I_p to 1 MA at 6s



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

- 0.3MA current generation in NSTX validates capability of CHI for high current generation in a ST (>400 kA projected for NSTX-U)
- 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)
- Initial full discharge simulations (CHI start-up + NBI CD) using TSC provides viable scenarios for current ramp-up to 1MA
- 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, Improved upper divertor coils

Back-up Slides

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

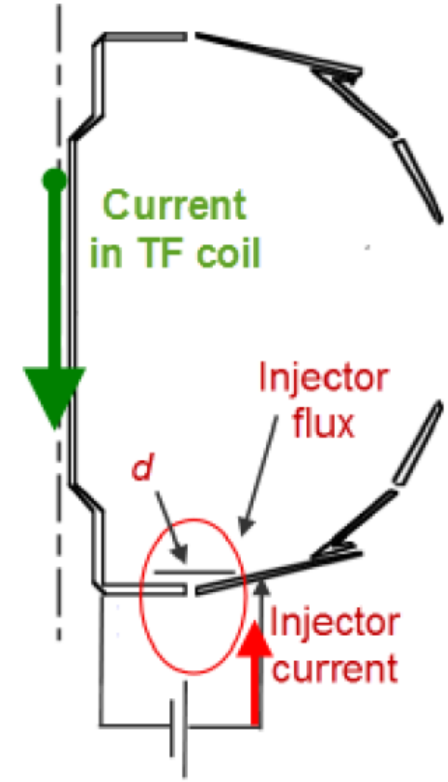
  d = flux foot print width

  I_{TF} = current in TF coil

Injector current → I_{inj}; **Toroidal flux** → ψ_T

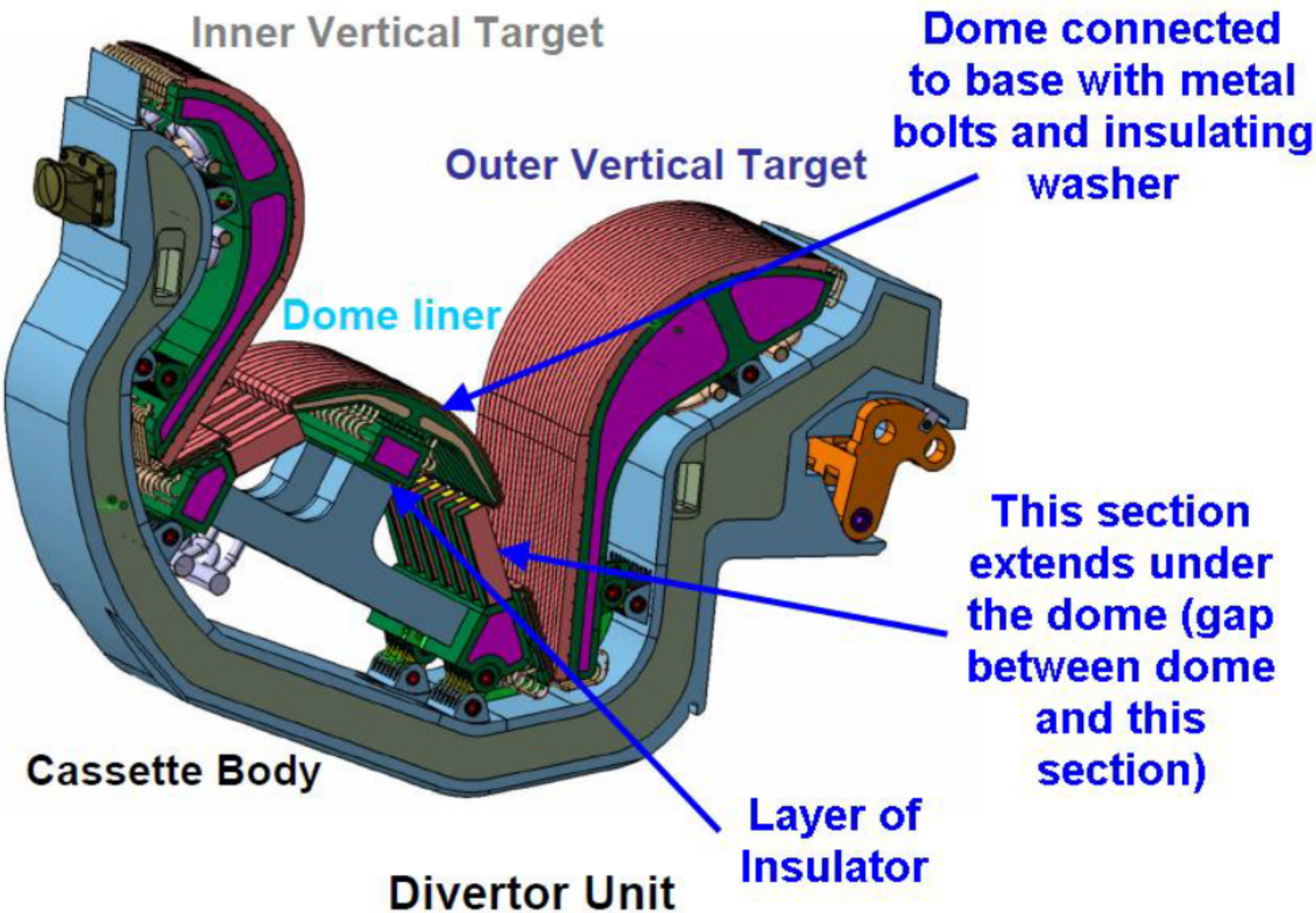
$$I_P = I_{inj}(\psi_T / \psi_{inj})$$

- 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)

Example of CHI Insulator Installation in a Reactor
(In ITER, the Dome Region would be Insulated from the Vessel)



Insulator is under compression and shielded from neutron

(Concept is similar to the biased ring electrode on DIII-D, but because of the short pulse length, and because of the lack of a pre-existing plasma, the requirements on the insulator are considerably less demanding than on DIII-D)

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

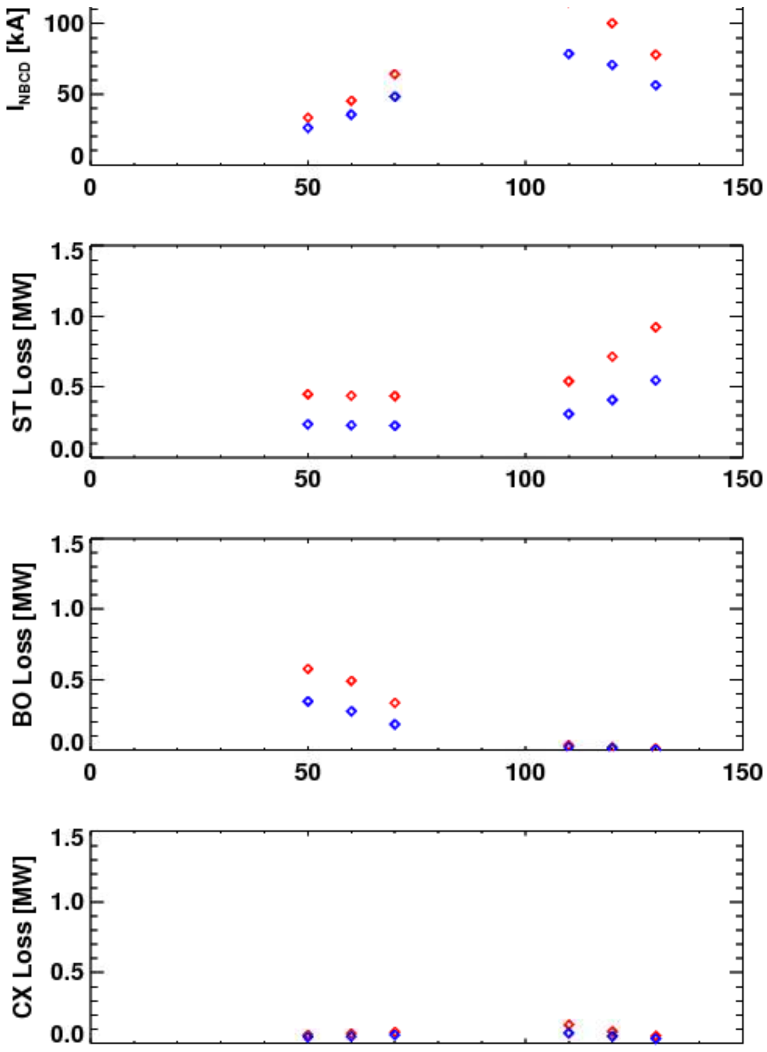
- Insulator Resistance > 1Ohm
- Resistance to be maintained only during the plasma start-up phase (<30 ms in duration)
- The actual high-voltage phase < plasma start-up phase
- During the plasma start-up phase, there is no pre-existing plasma that can short out the insulator (CHI current path is controlled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

Because the 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)

Stefan TRANSP Calculations (300kA, 2MW NBI single source, Blue: 65kV, Red 80kV)

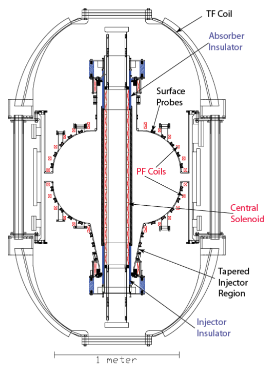
shot	Beam	Voltage	runID
140353	50	80	N10
140353	60	80	N11
140353	70	80	N12
140353	110	80	N13
140353	120	80	N14
140353	130	80	N15
140353	50	65	N20
140353	60	65	N21
140353	70	65	N22
140353	110	65	N23
140353	120	65	N24
140353	130	65	N25

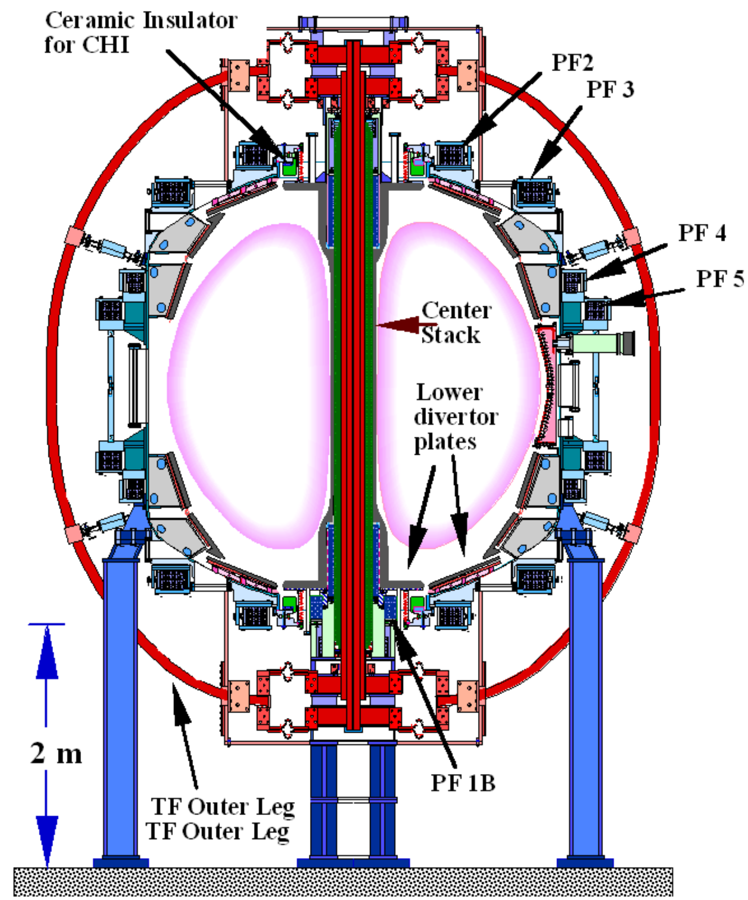


These runs have the NUBEAM output for a single (slightly reversed) q-profile, Greenwald fraction, confinement level,…

Thomson line density is 1 – 1.5E15 /cm^2 = 1-1.5E13 /cm^3
About twice that for a CHI discharge

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

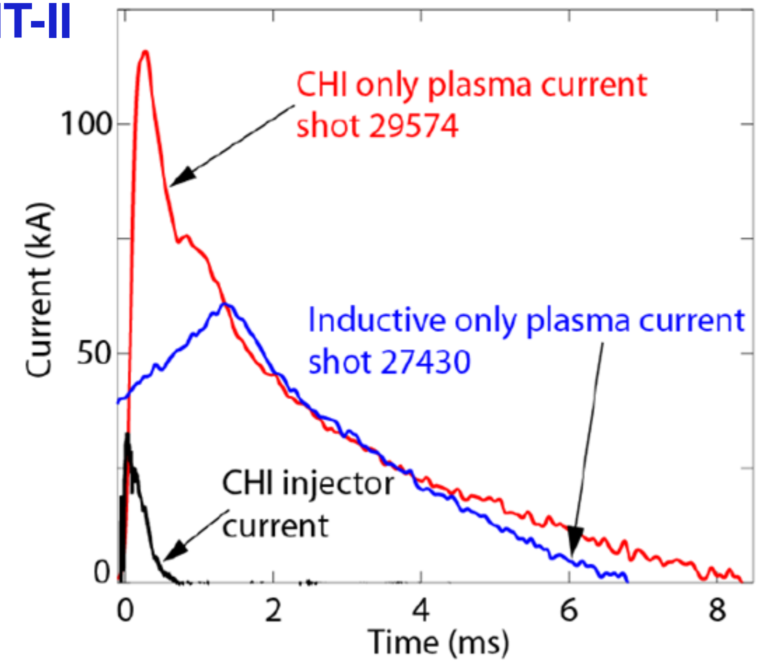
Proof-of-Principle NSTX device

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

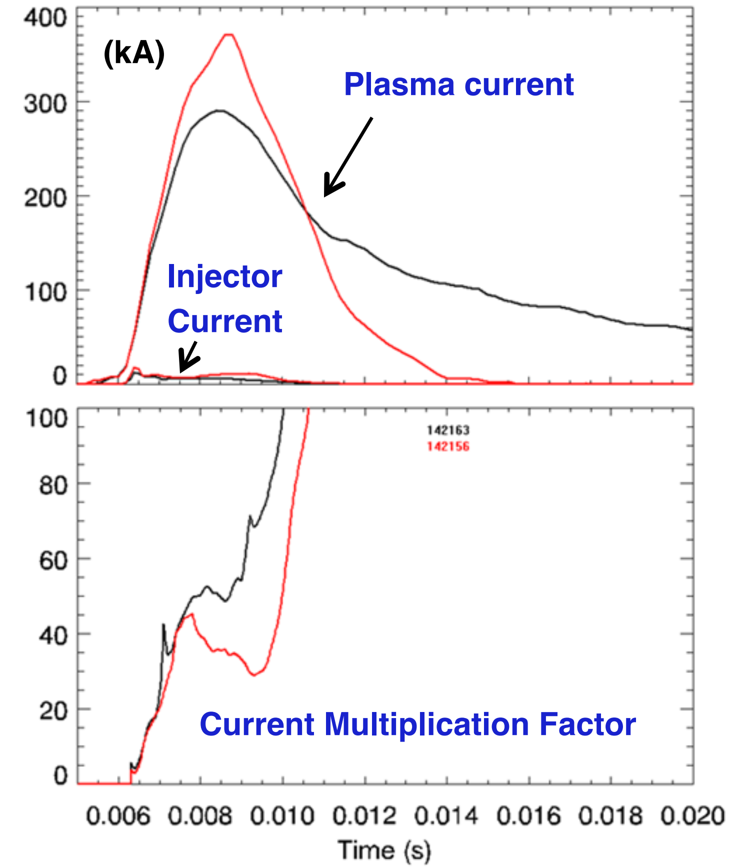
NSTX plasma is ~30 x plasma volume of HIT-II

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

HIT-II



NSTX



-30kA of injector current generates 120kA of plasma current

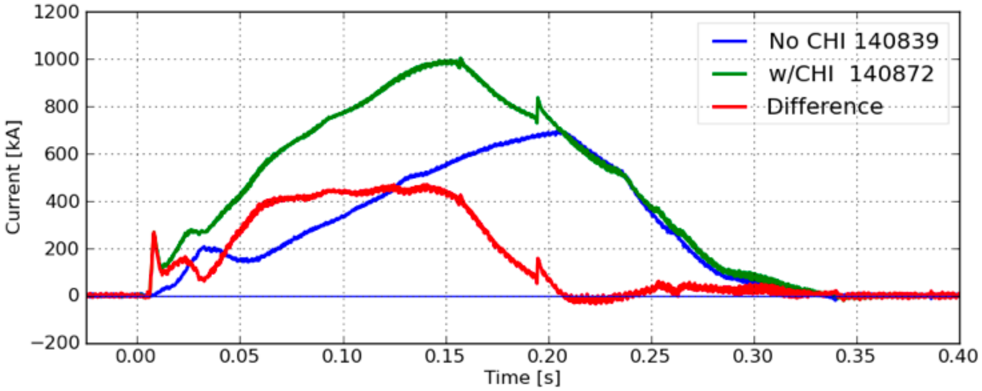
-Best current multiplication factor is 6-7

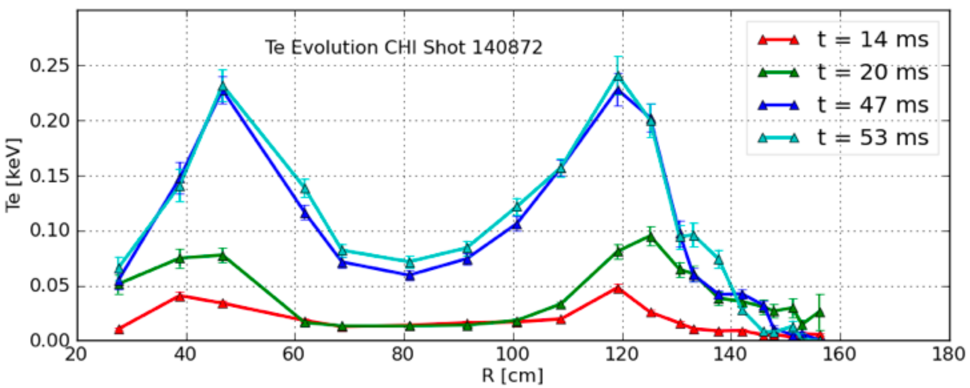
-Current multiplication factor in NSTX is 10 times greater than that in HIT-II

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

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

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

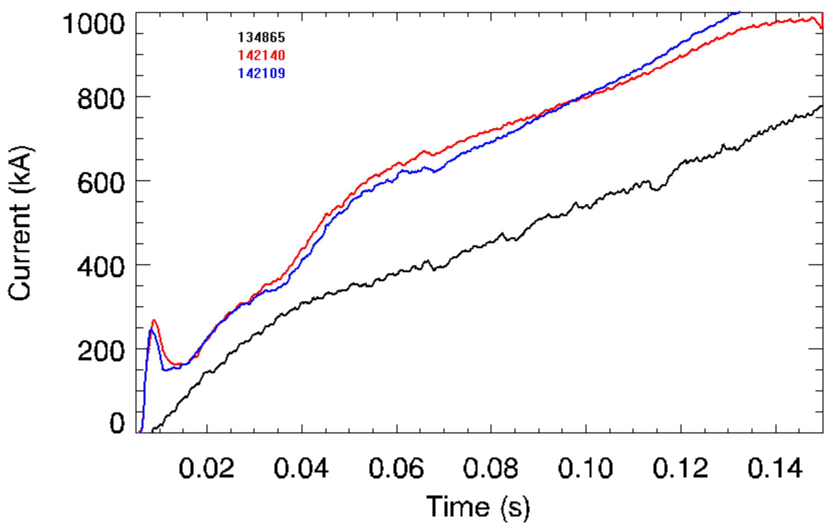


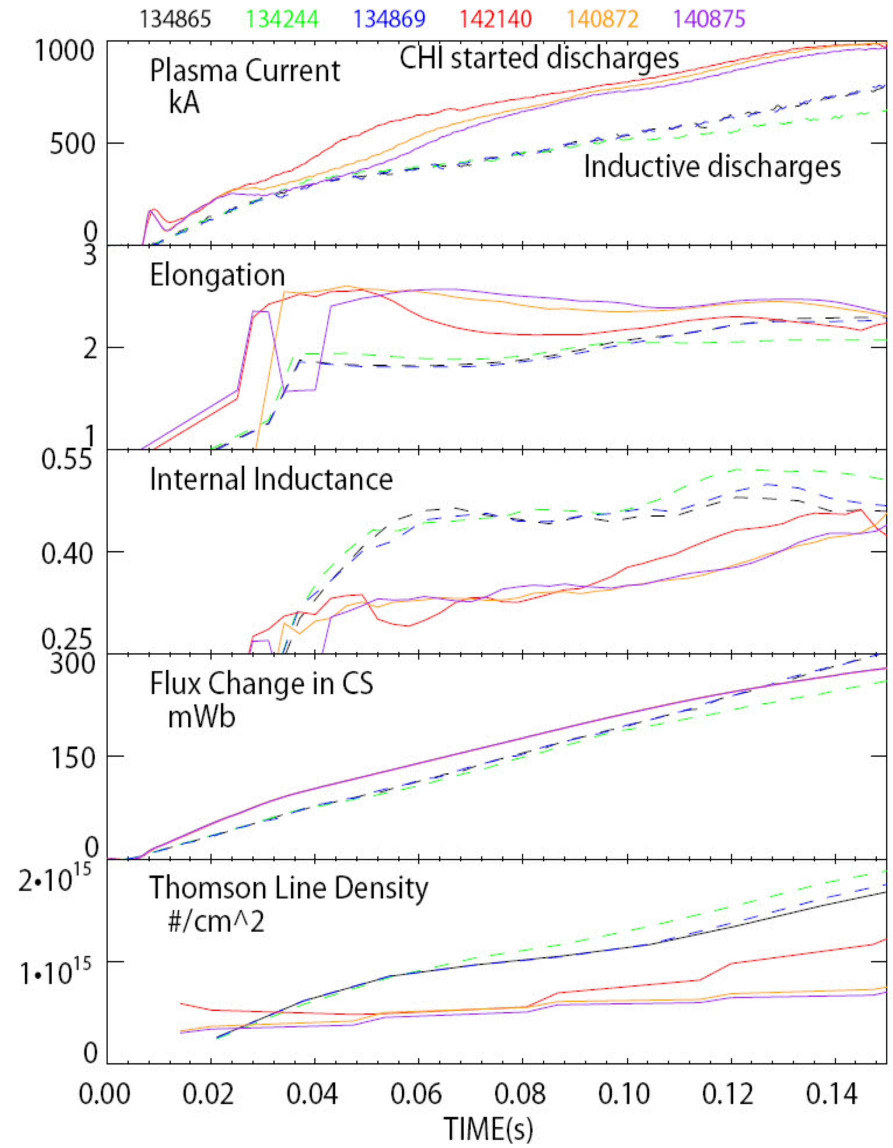


- Ramped up to 1MA after startup, using 0.3Wb change in solenoid flux
- Hollow electron temperature profile maintained during current ramp
  - Important beneficial aspect of using CHI startup

- Discharges with early high T_e ramp-up to higher current

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



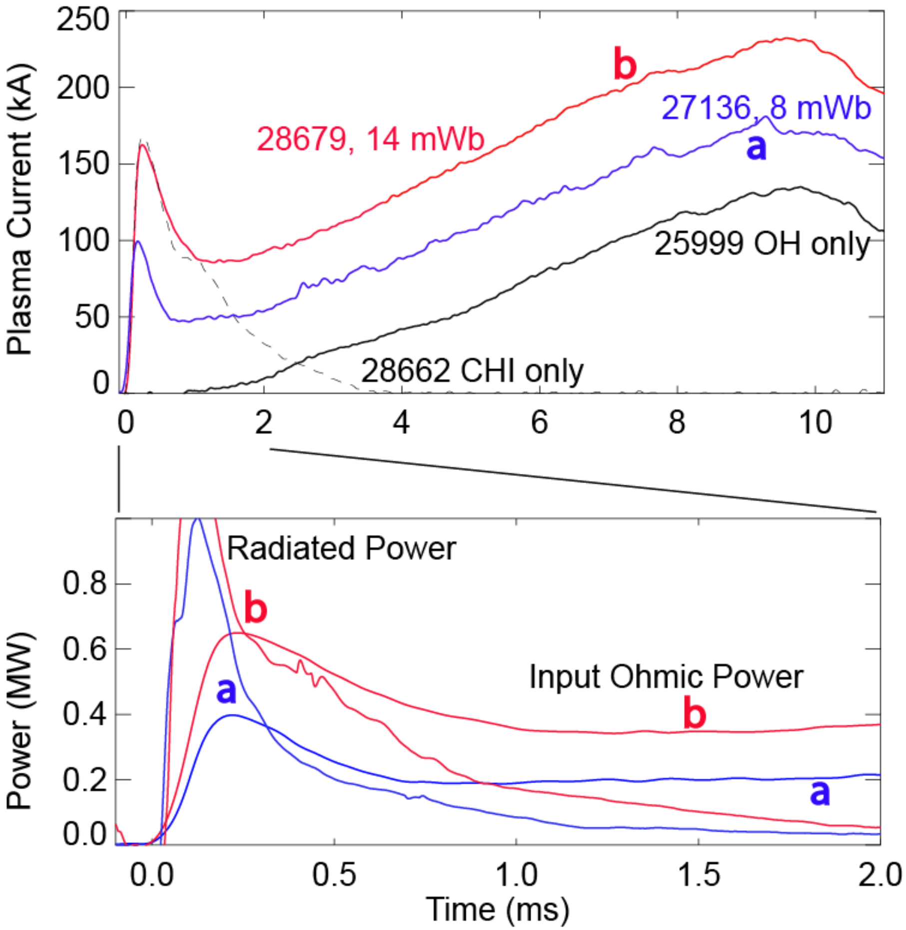


- Best inductive plasma (from 10 YR NSTX data base) uses 340 mWb of solenoid flux to get to 1MA
- Un-optimized CHI started discharges require 258 mWb
- Full non-inductive start-up and ramp-up will be developed on NSTX-U

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

Inductively Coupled Current Ramps-up After Input Power Exceeds Radiated Power

HIT-II Results

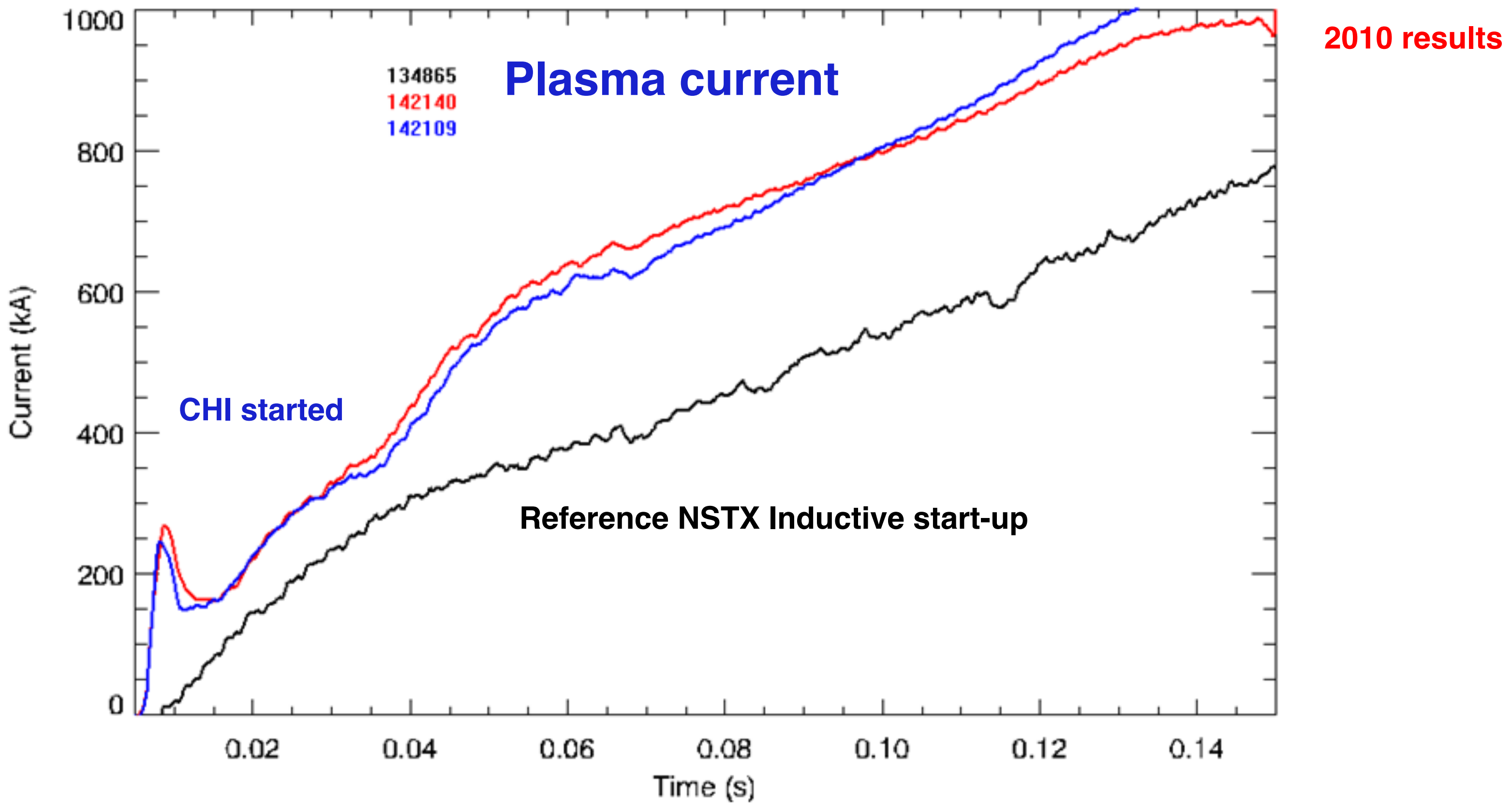


- Identical loop voltage programming for all cases
- Coupling current increases as injector flux is increased
- Radiated power can be decreased by using W or Mo target plates
  - Start-up plasma (inductive or CHI) is cold (few 10s of eV)
    - ➢ Reduce Low-z line radiation
  - Auxiliary heating would ease requirements on current ramp-up system

R. Raman, T.R. Jarboe, R.G. O'Neill, et al., NF 45 (2005) L15-L19

R. Raman, T.R. Jarboe, W.T. Hamp, et al., PoP 14 (2007) 022504

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



Reference Inductive discharge: Uses 396mWb to get to 1MA

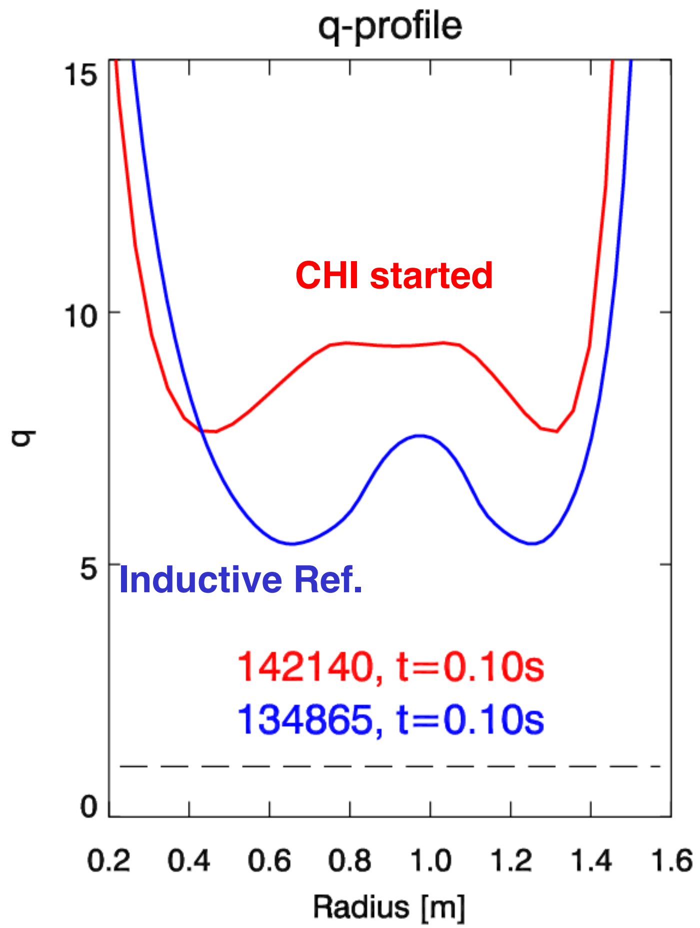
CHI started discharge: Uses 258 mWb to get to 1MA (53% less flux)

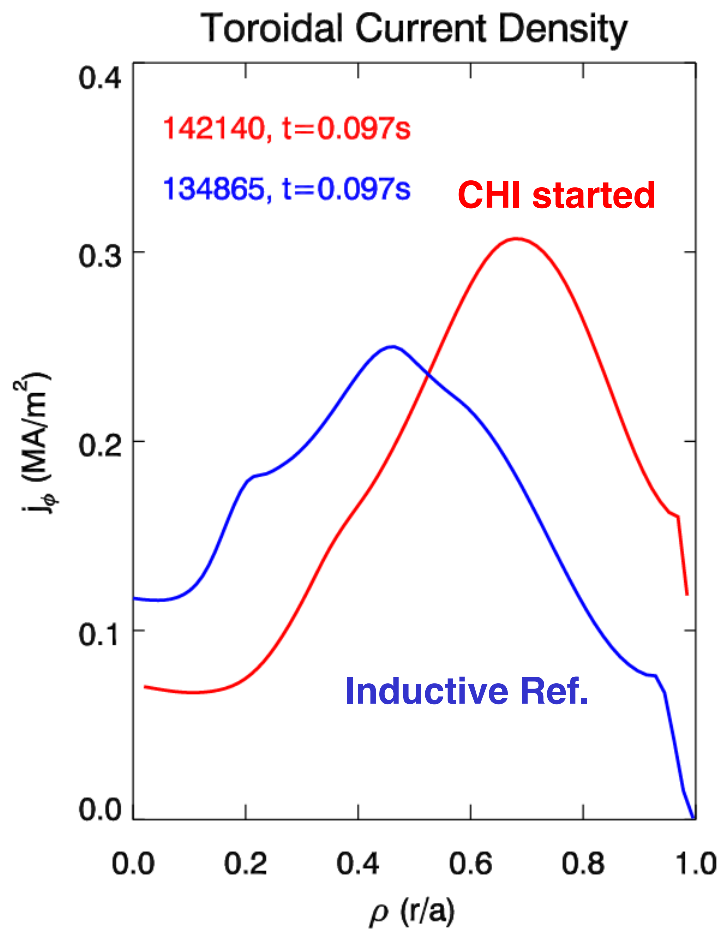
NSTX inductive start-up: 138mWb flux typically generates 400kA of plasma current

Best CHI-startup discharges: 138mWb flux generated 650kA

CHI Start-up Discharges Show Plasma Current Driven at Large Radius

2010 results





These are the type of plasmas needed for advanced scenario operations

MSE & LRDFIT: H. Yuh, J. Menard, S. Gerhardt