Demonstration of Plasma Start-up in NSTX Using Transient CHI

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M.J. Schaffer (GA), X. Tang (LANL), E.B. Hooper (LLNL)
and the NSTX Research Team

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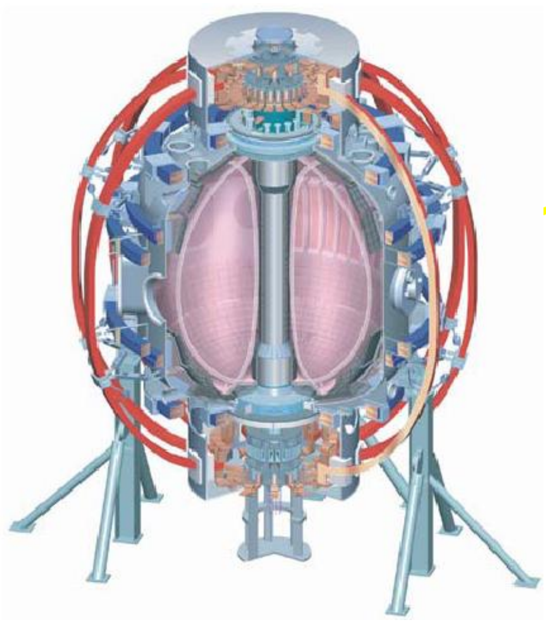
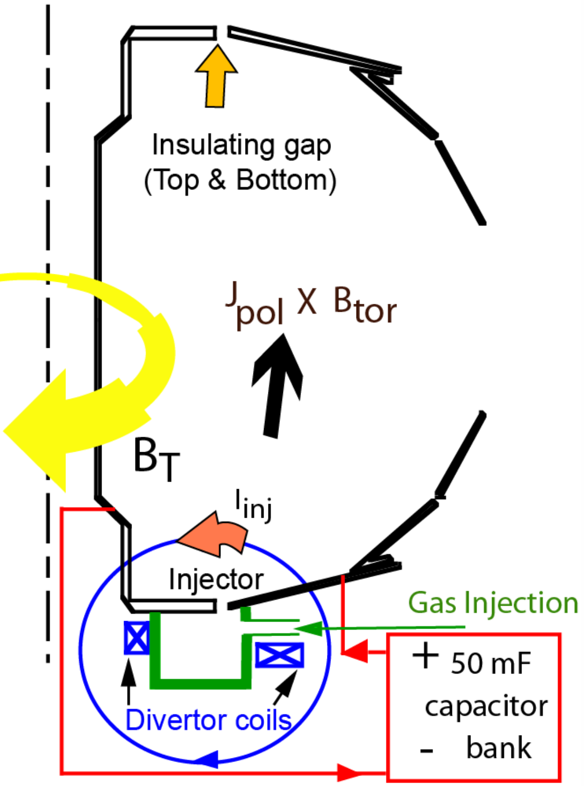
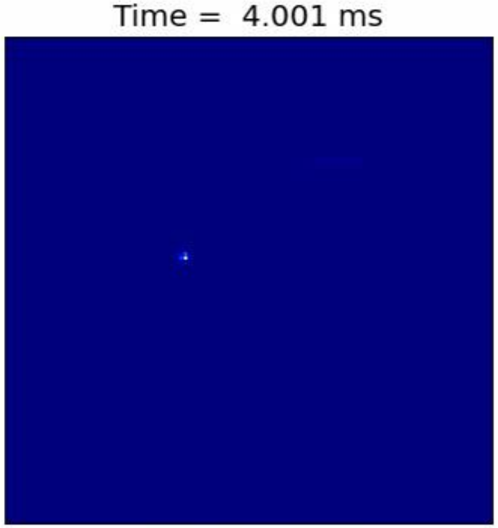
NSTX has now Demonstrated the Savings of Inductive Flux Equivalent to over 300kA Current

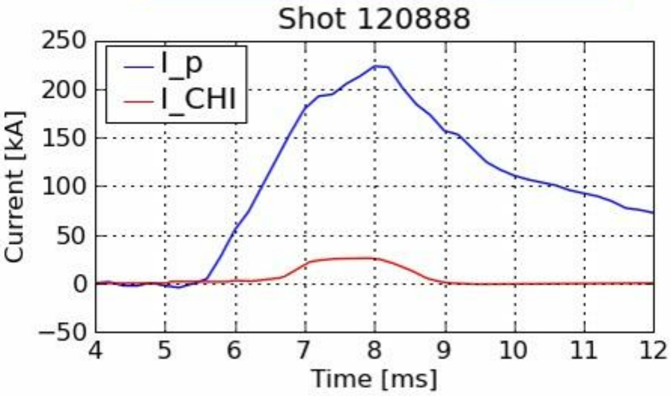
- Of the large machines, only NSTX actively engaged in solenoid-free plasma startup research
  - DIII-D is studying plasma start-up using the outer PF coils
- Transient Coaxial Helicity Injection plasma startup method developed on HIT-II at U-Washington
  - For plasma start-up, CHI is *now* unique to NSTX
- Enables lower aspect ratio configurations
  - Simplifies tokamak design

Transient CHI: Axisymmetric Reconnection Leads to Formation of Closed Flux Surfaces









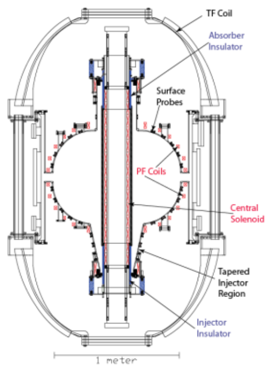
- Parameters to consider
  - Current multiplication factor
  - Effect of toroidal field
  - Magnitude of generated plasma current
  - New desirable features?

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

CHI for an ST: T.R. Jarboe, Fusion Technology, 15 (1989) 7

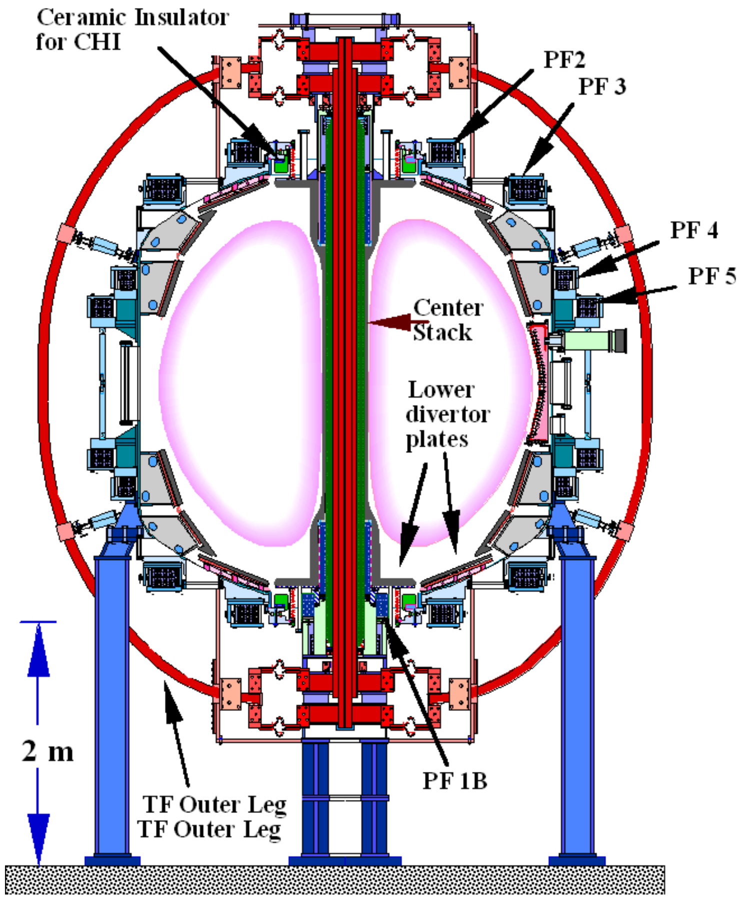
Transient CHI: R. Raman, T.R. Jarboe, B.A. Nelson, et al., PRL 90, (2003) 075005-1

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

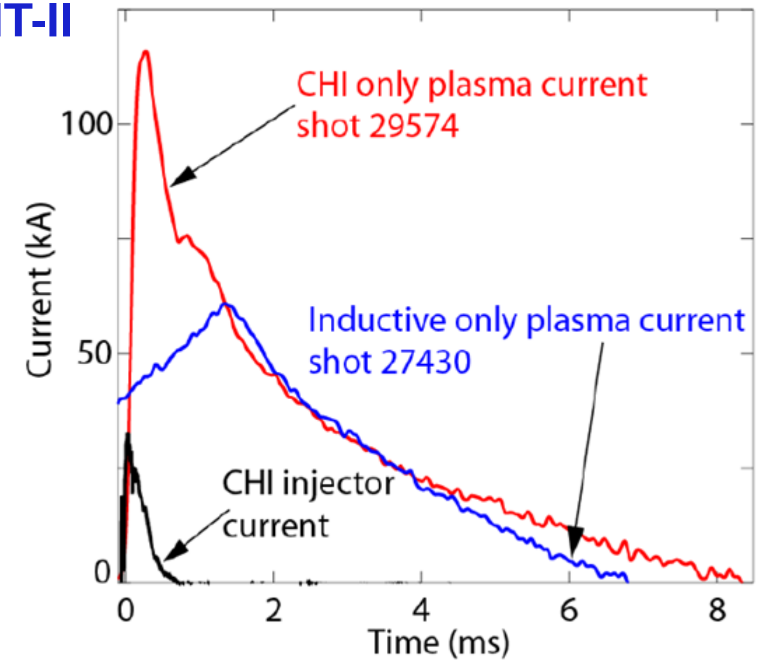
NSTX plasma is ~30 x plasma volume of HIT-II



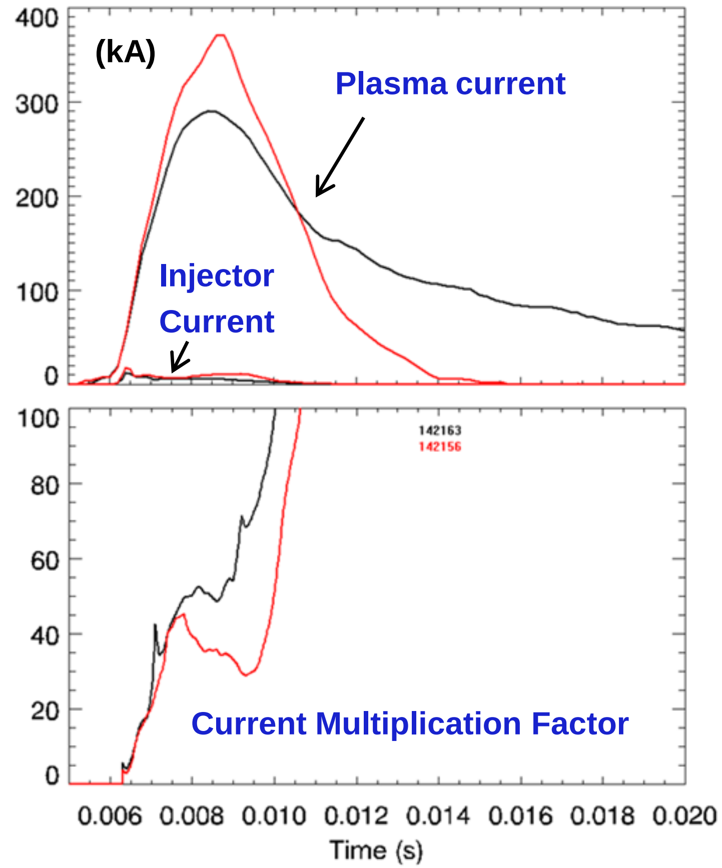
Proof-of-Principle NSTX device
- Built with conventional tokamak components
- Few PF coils
- 1.7kV CHI capacitor bank

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

HIT-II



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

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

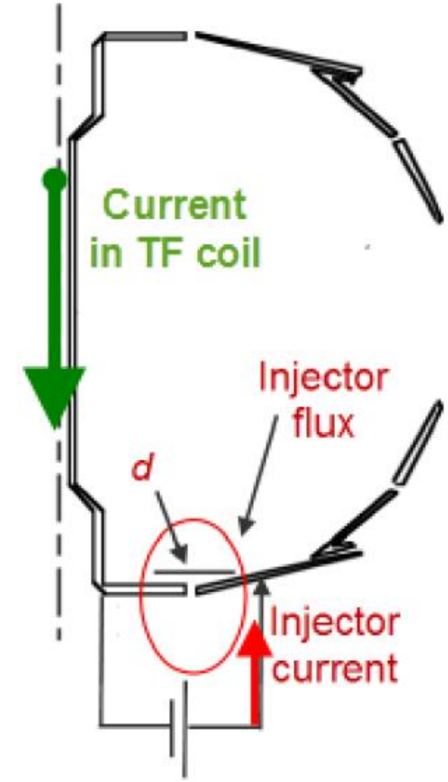
  d = flux foot print width

  I_{TF} = current in TF coil

Injector current → **Toroidal flux**

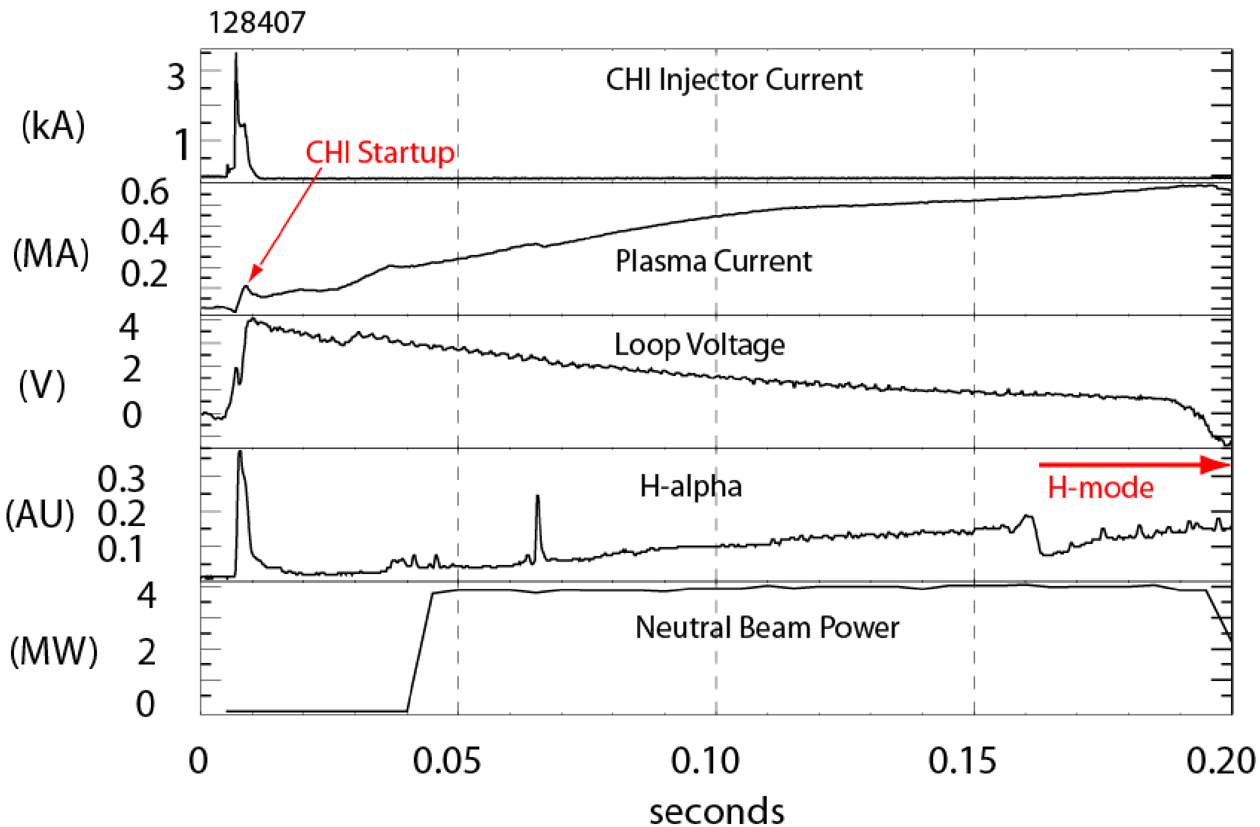
$$I_P = I_{inj}(\psi_T / \psi_{inj})$$

- 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



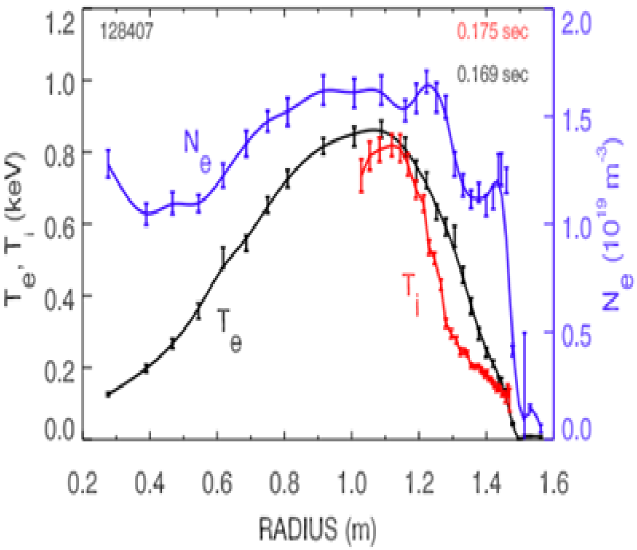
* T.R. Jarboe, Fusion Tech. 15, 7 (1989)

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

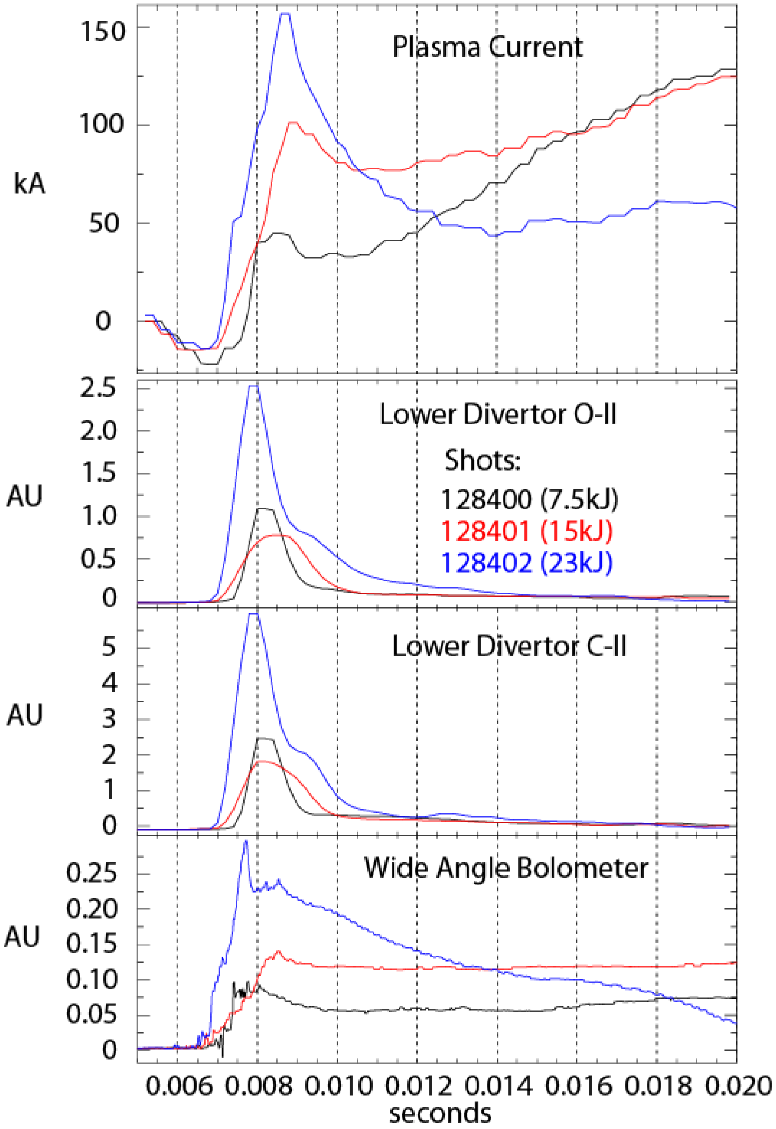


- Discharge is under full plasma equilibrium position control
  - Loop voltage is preprogrammed

CHERS : R. Bell

Thomson: B. LeBlanc

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

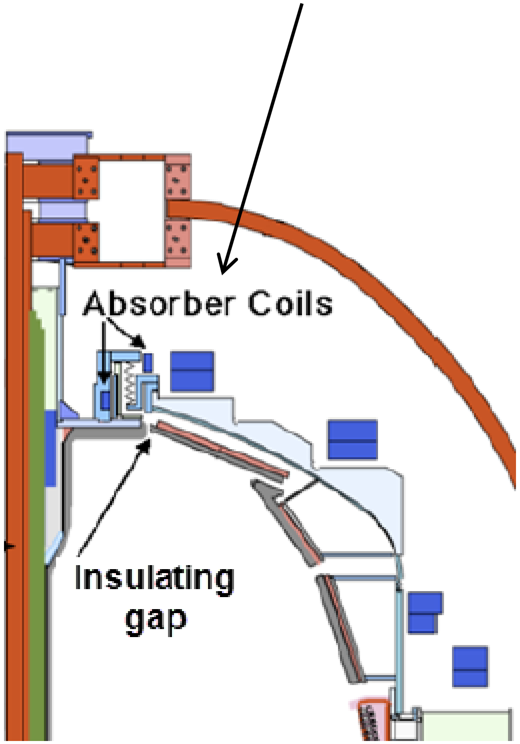


- Low-Z impurity radiation increases with more capacitors
- Possible improvements
  - Metal divertor plates should reduce low-Z impurities
    - High Te in spheromaks (500eV) obtained with metal electrodes
  - Discharge clean divertor with high current DC power supply
  - Use auxiliary heating during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

Filter scopes: V. Soukhanovskii

Flux Savings on NSTX Now Realized After Low-Z Impurity Reduction

Absorber coils provide buffer field



Long-pulse (400ms) CHI discharges with high injector flux to avoid “bubble-burst”

- ablate low-Z impurities from lower divertor

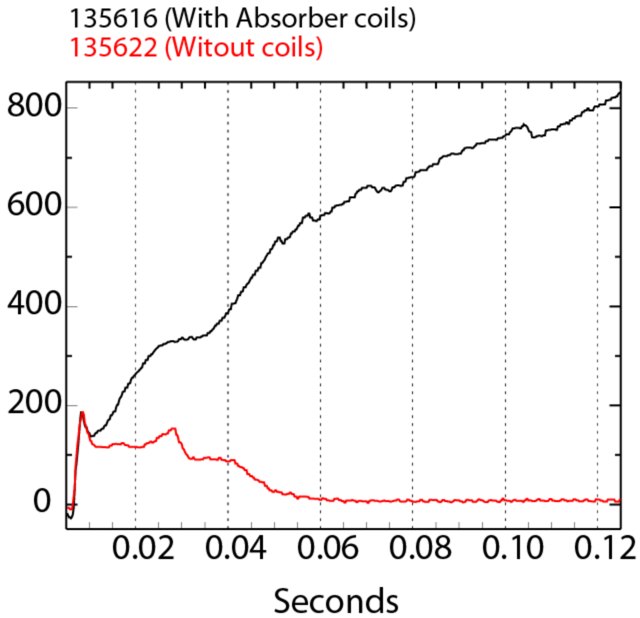
Deuterium glow discharge cleaning employed to chemically sputter and reduce oxygen levels

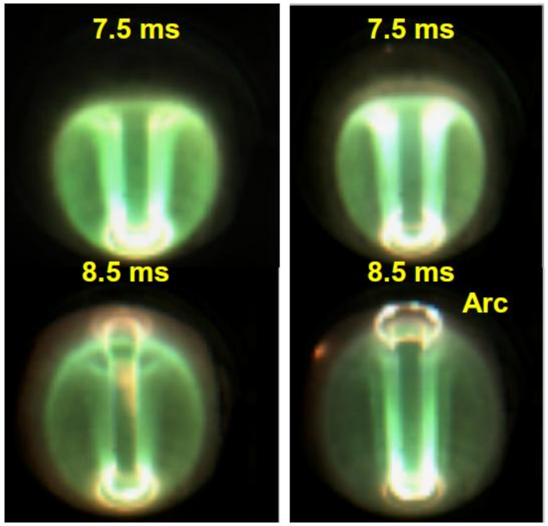
Lithium evaporation on lower divertor plates improved discharge performance

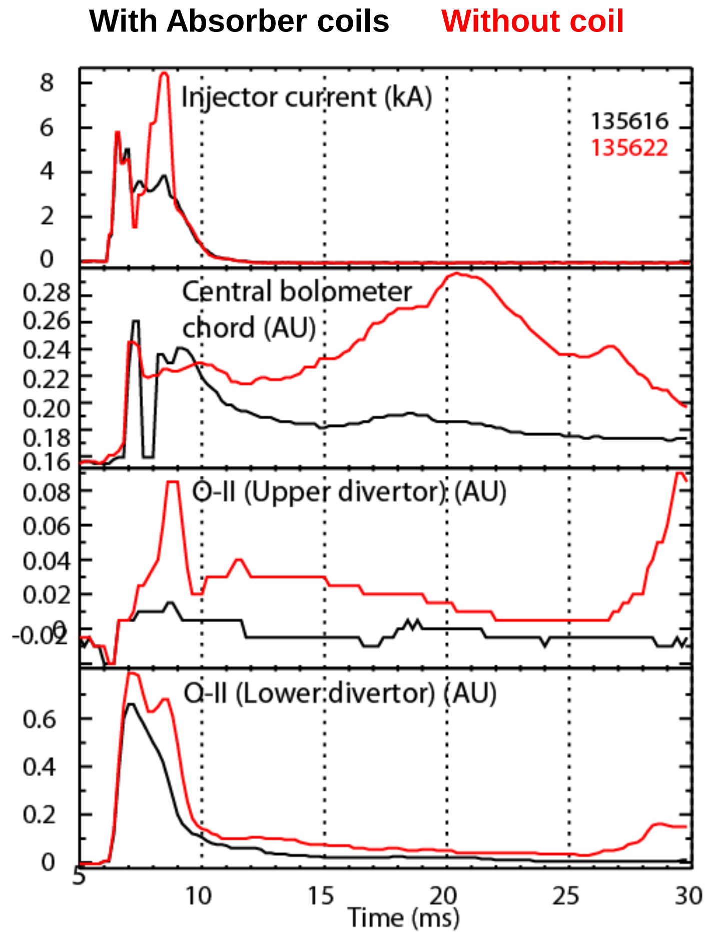
A buffer field was provided using new PF coils located in the upper divertor region

- reduced interaction of CHI discharge with un-conditioned upper divertor plates

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



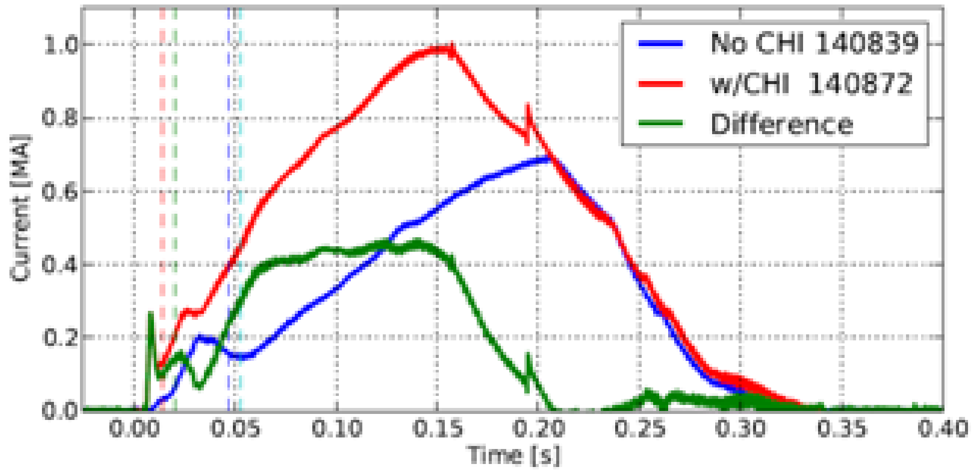


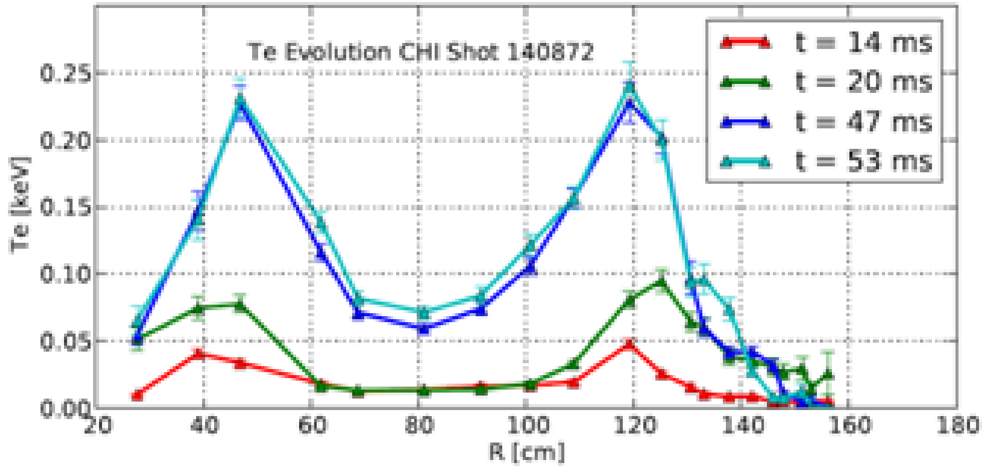


- Divertor cleaning and lithium used to produce reference discharge
- Buffer field from PF absorber coils prevented contact of plasma with upper divertor

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

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



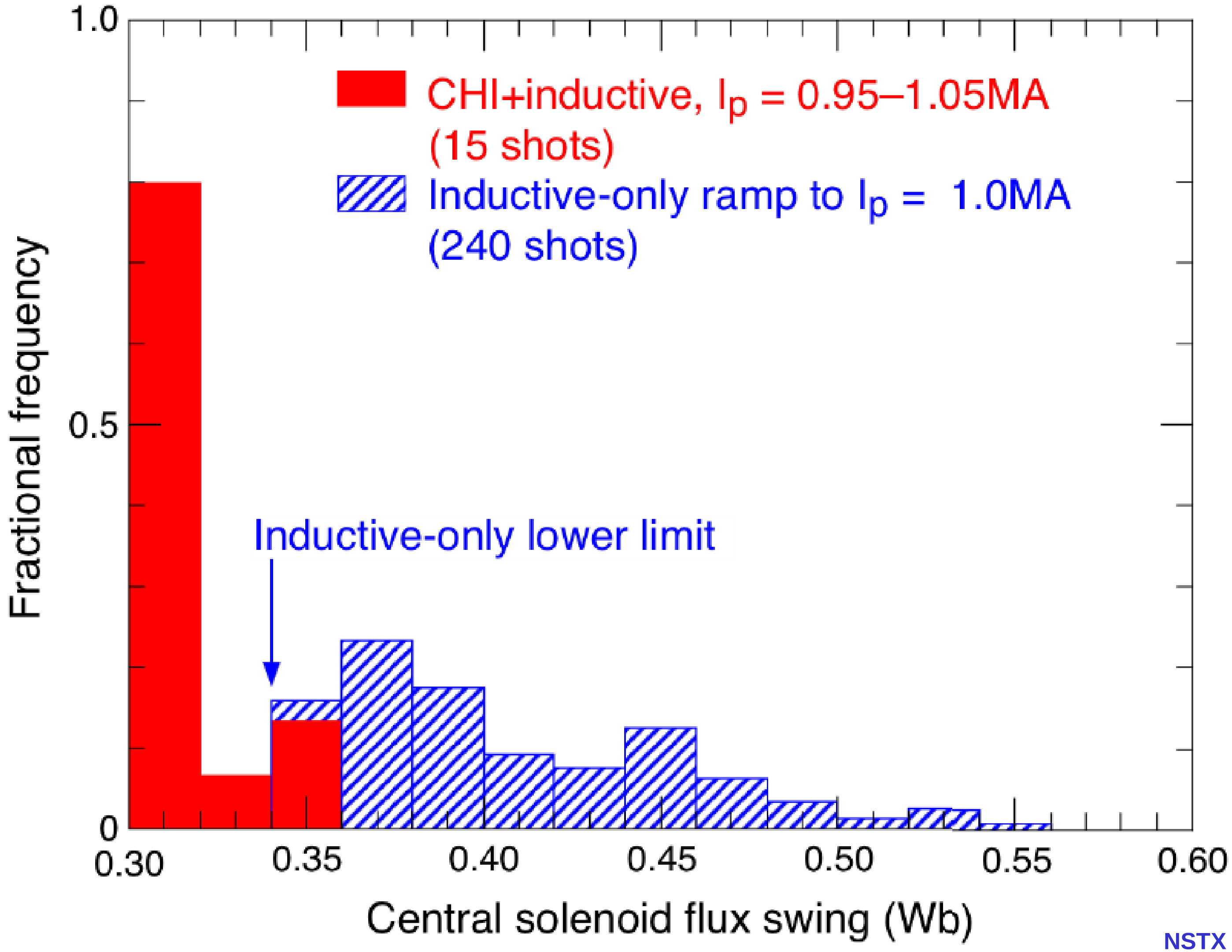


- Ramped up to 1MA after startup, using 0.3Wb change in solenoid flux
- Hollow electron temperature profile maintained during current ramp
  - Important beneficial aspect of using CHI startup

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

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

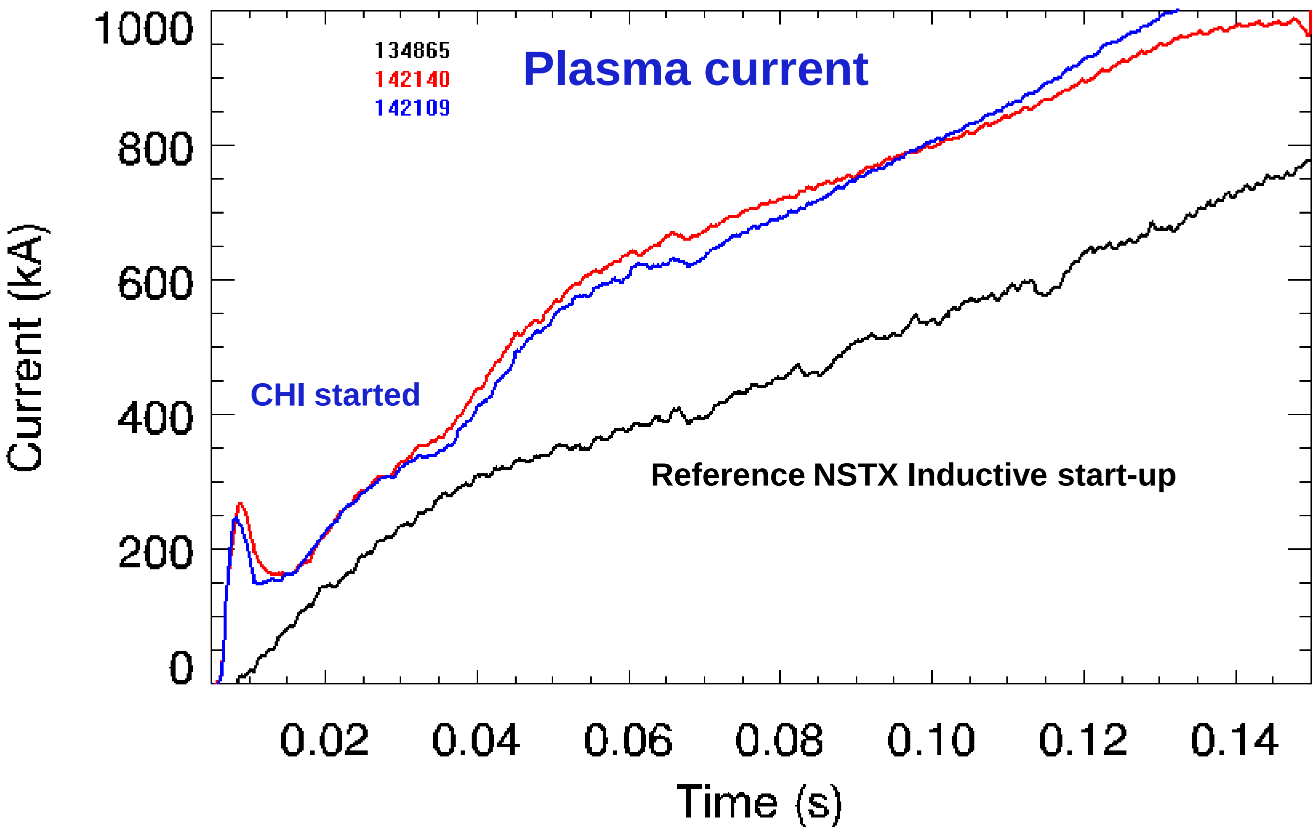
Comparison of CHI Startup to H-modes using more than 1 NBI source



Most recent CHI-started discharges require less flux than shown here

NSTX Data Base Analysis: **M. Bell**

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

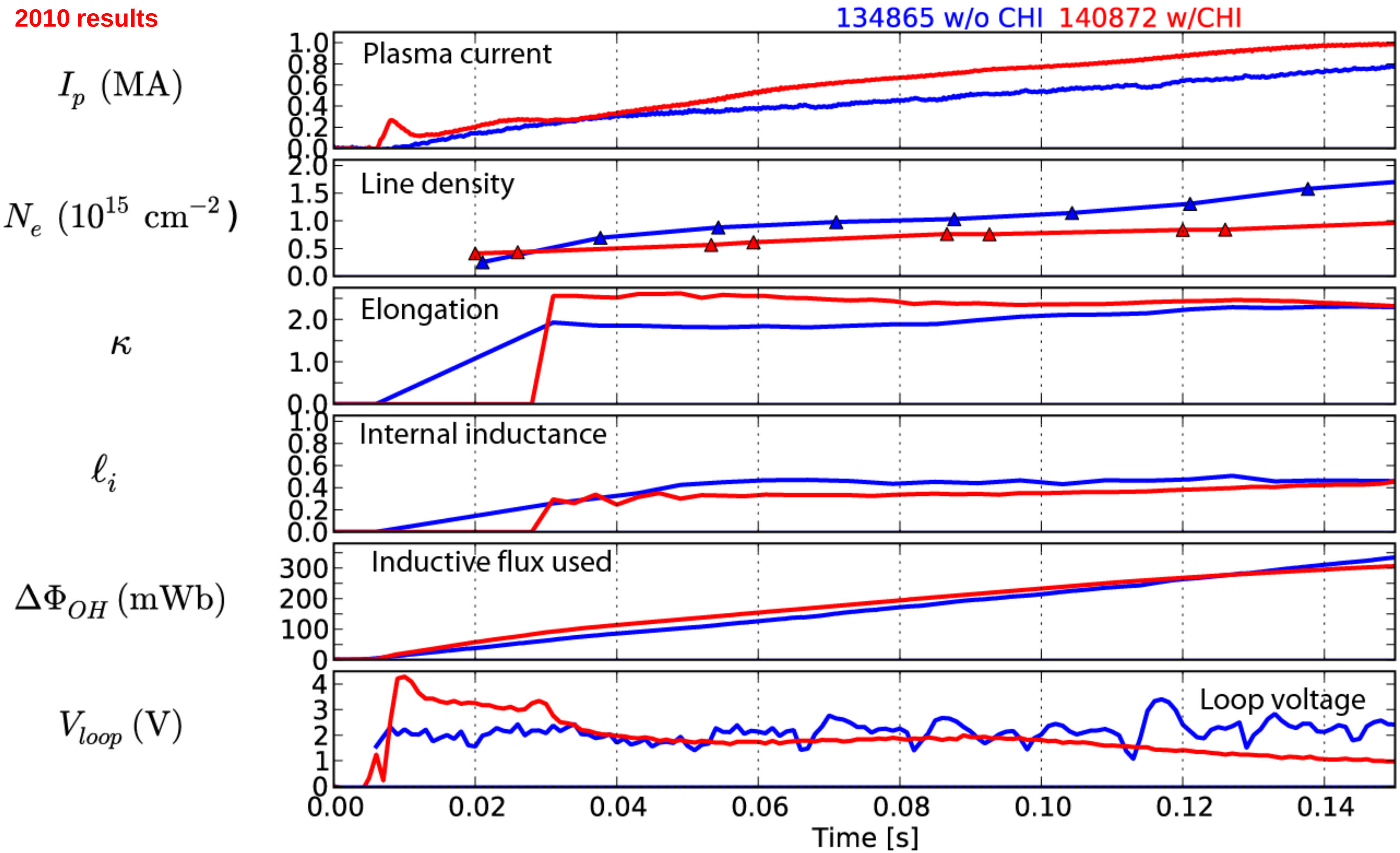


2010 results
Post IAEA

- **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)**

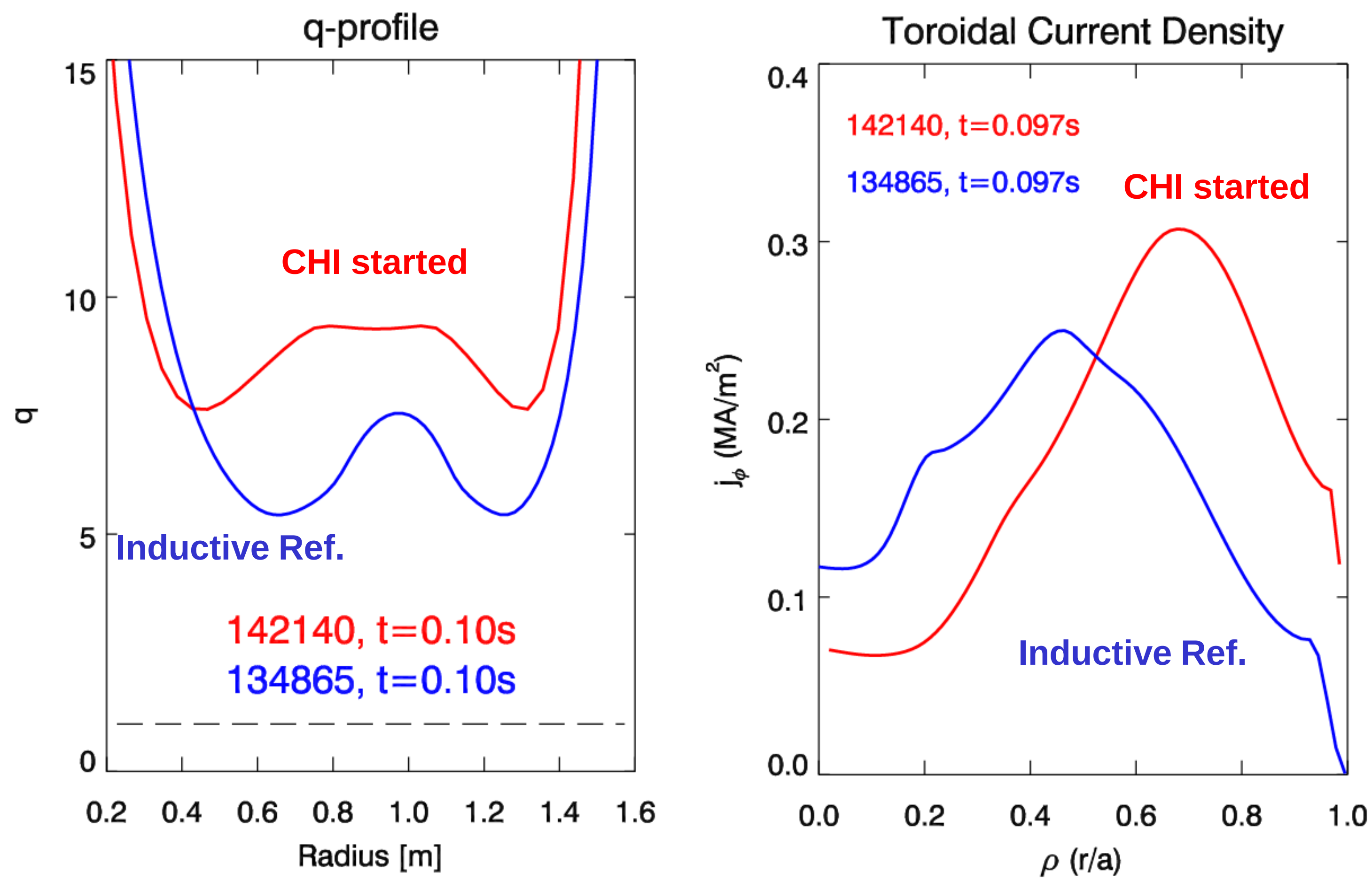
CHI Start-up Discharges have low Internal Inductance and Electron Density Starting from Early in the Current Ramp

2010 results



These are the type of plasmas needed to increase the neutral beam current drive fraction

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



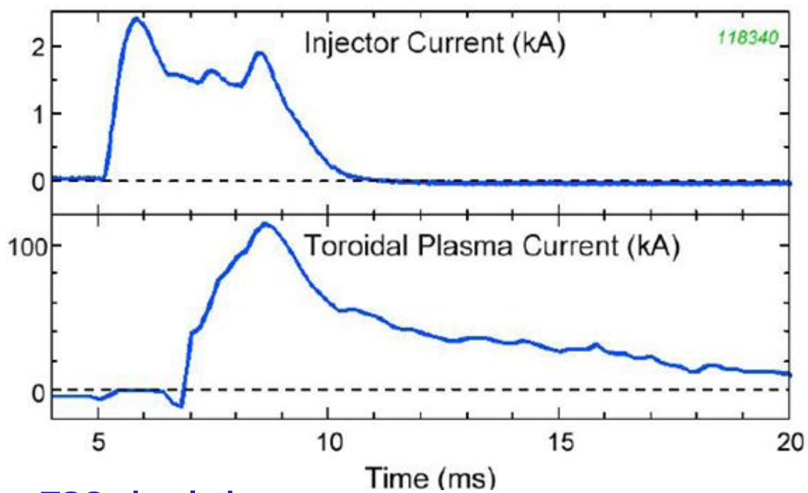
2010 results

These are the type of plasmas needed for advanced scenario operations

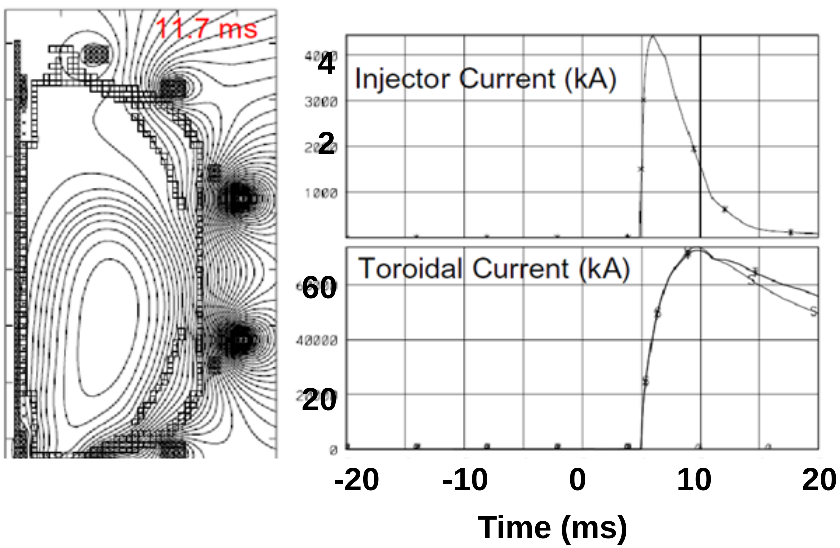
MSE & LRDFIT: H. Yuh, J. Menard, S. Gerhardt

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

NSTX Experimental result

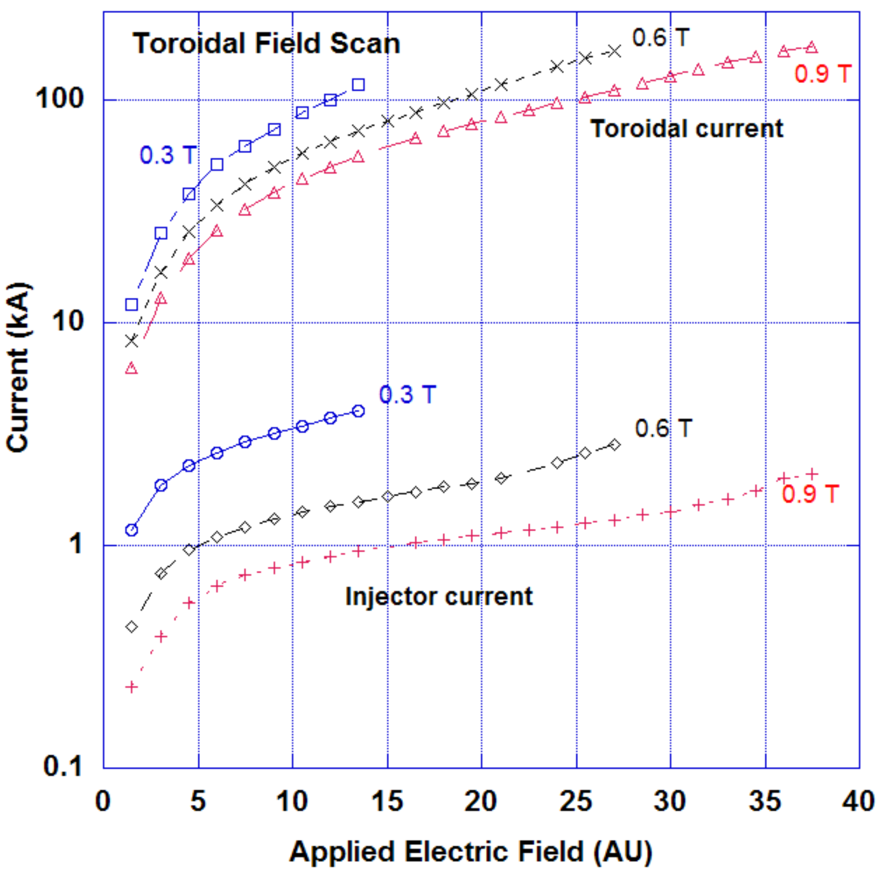


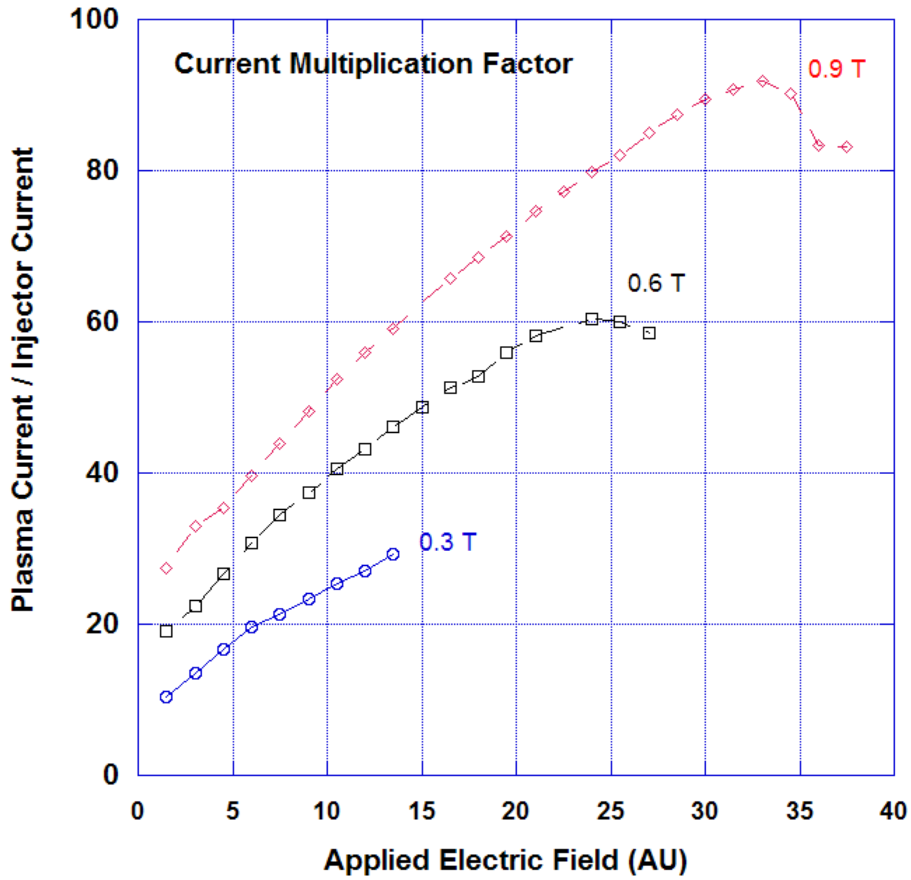
TSC simulation



- **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**

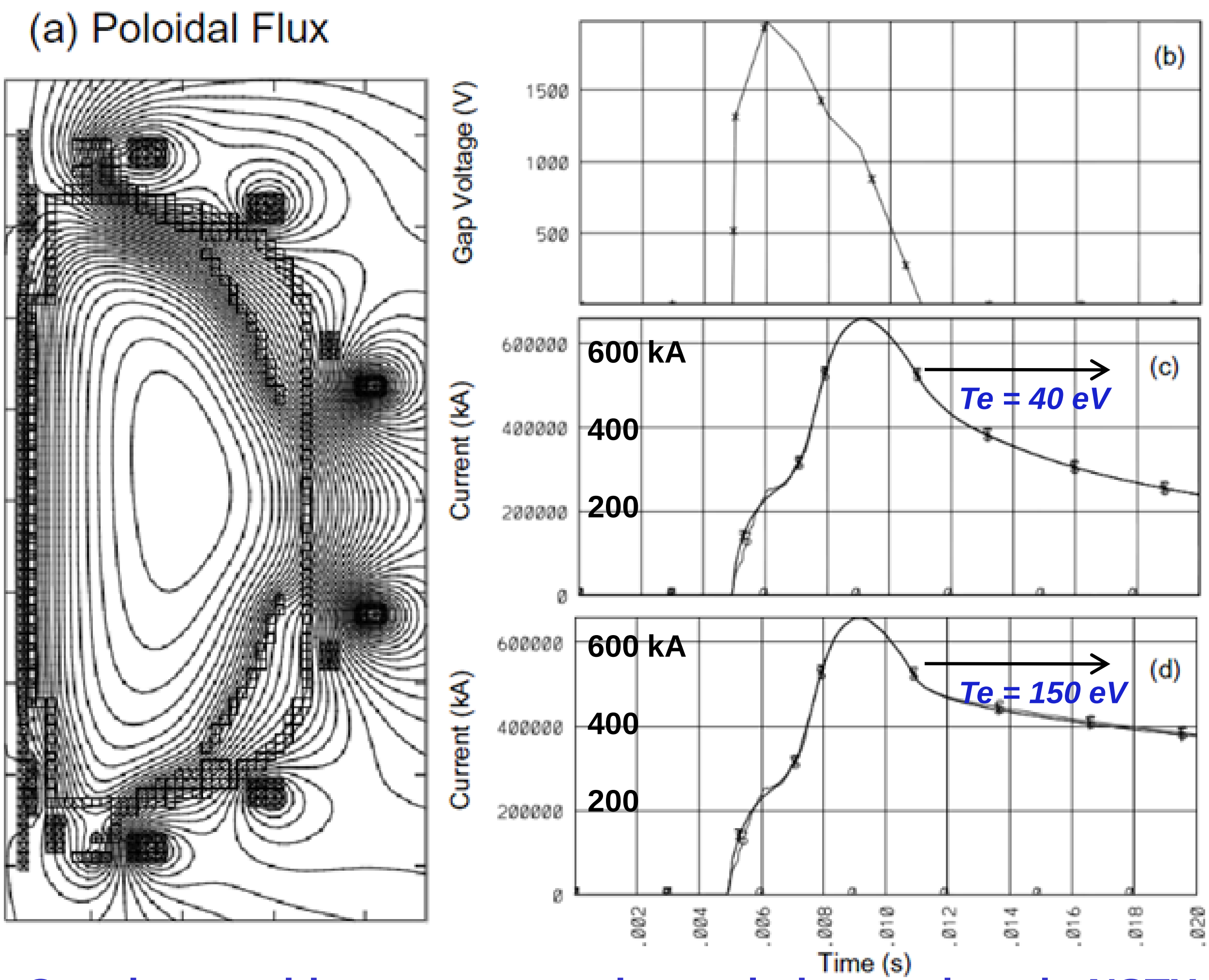
TSC Simulations Show Increasing Current Multiplication as TF is Increased (NSTX geometry)





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

TSC Simulations Show 600kA CHI Start-up Capability in NSTX as TF is Increased to 1T



Projected plasma current for CTF >2.5 MA [$I_p = I_{inj}(\psi_{Tor}/\psi_{Pol})$]

- Based on 50 kA injector current (1/5th of the current density previously achieved)
- Current multiplication of 50 (achieved in NSTX)

- **Consistent with present experimental observations in NSTX that attain >300kA at 0.5T**
- **NSTX-U will have B_T = 1T capability, ST CTF projected to have B_T about 2.5T**

NSTX has Made Considerable Progress Towards Developing a Viable Solenoid-Free Plasma Startup Method

- 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 observed experimentally and in TSC simulations

Next steps

- **Assess capability of auxiliary heating to increase T_e (RF and NBI)**
- **Increase the bank energy to increase the start-up current magnitude**
  - **- Assess initial current requirements for direct coupling to NBI**
  - **- Increase current magnitude in absorber coils**
  - **- Full Lithium coverage of the lower divertor plates**
  - **- Assess benefits of metal divertor plates**