NSTX

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

Efficient Generation of Closed Magnetic Surfaces Using CHI

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and the NSTX Research Team

2009 US-Japan Workshop on
Innovative Confinement Concepts based on Self-Organization and Active Control
September 8-10, 2009
Gunma University, Japan

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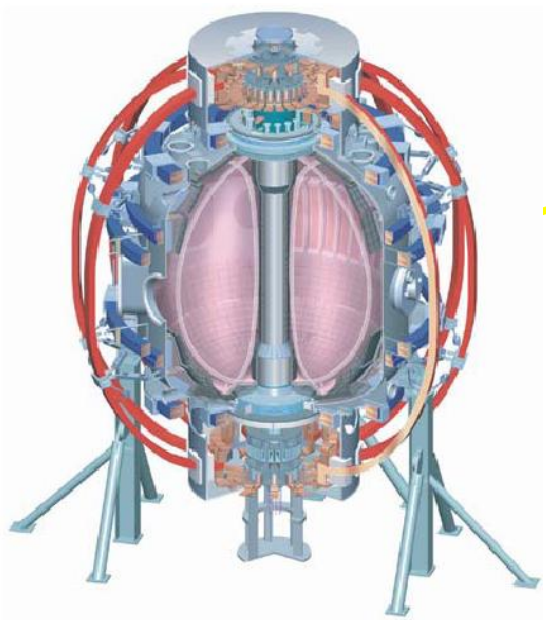
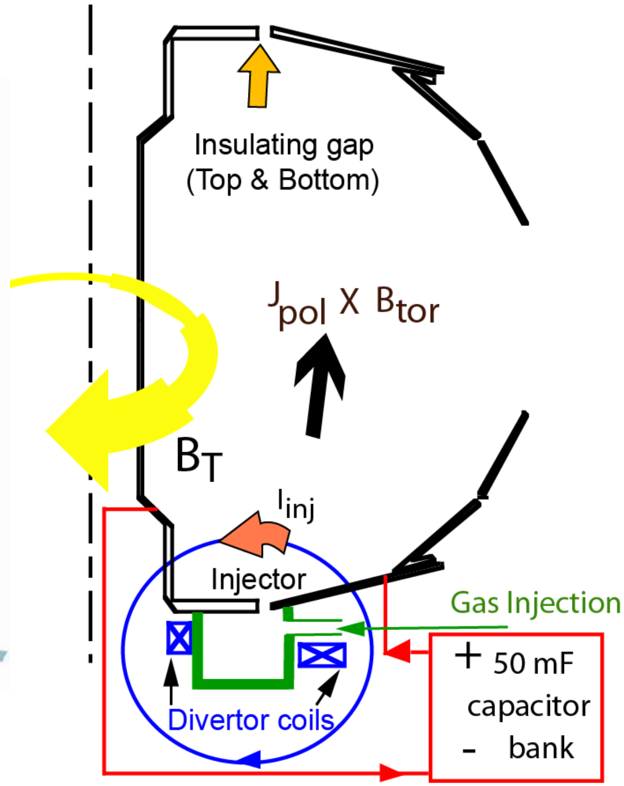
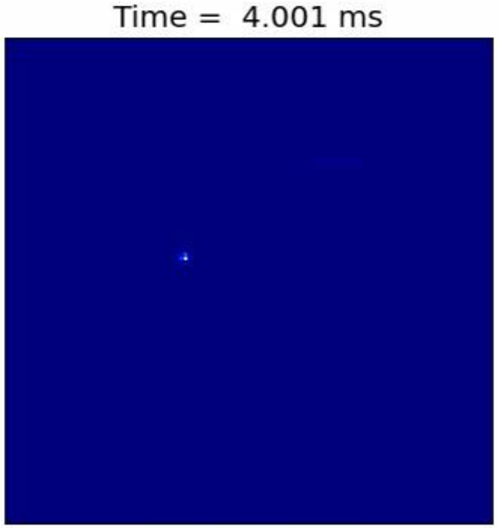
Solenoid-Free Current Initiation would Improve the Prospects of the ST as a CTF and Fusion Reactor

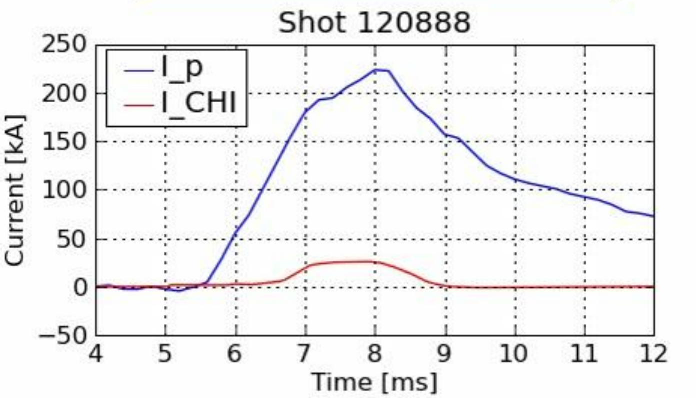
- Could also aid Tokamak designs
  - Access lower aspect ratio configurations & reduce cost
- Of the three large tokamaks in the US, only NSTX is actively engaged in solenoid-fee plasma startup research
- Transient Coaxial Helicity Injection plasma startup method developed on HIT-II at U-Washington
- NSTX has now demonstrated the savings of 200kA equivalent solenoid flux after coupling CHI started discharges to induction

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







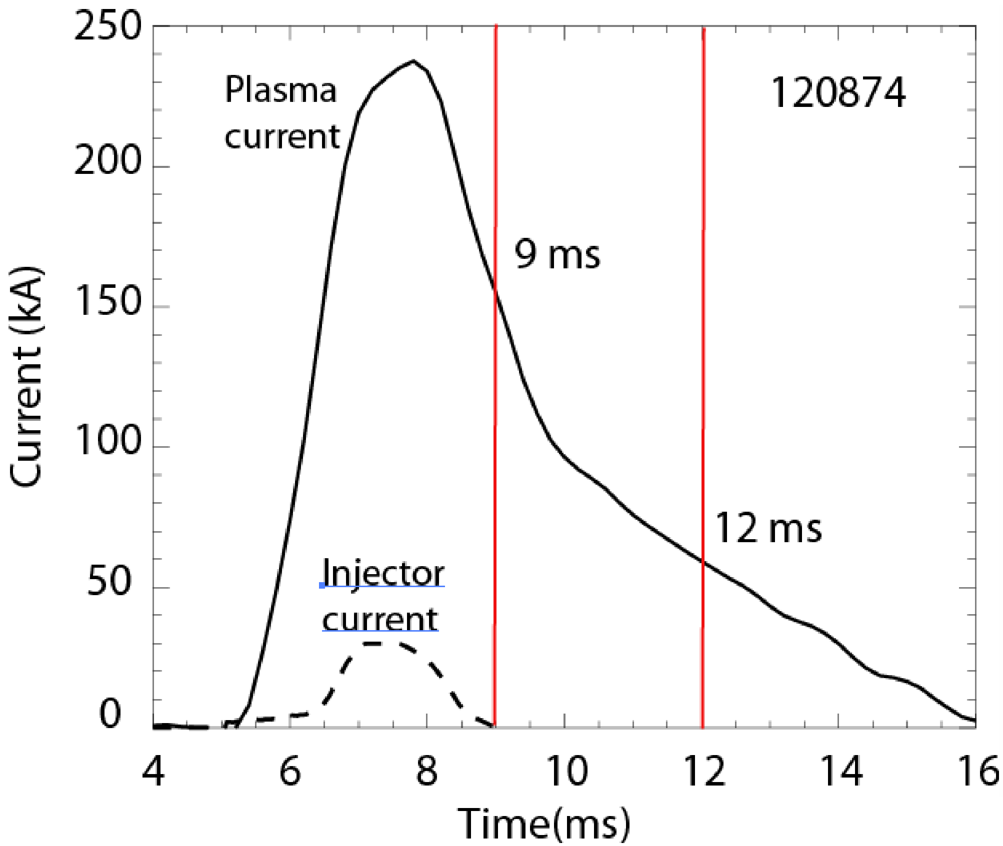


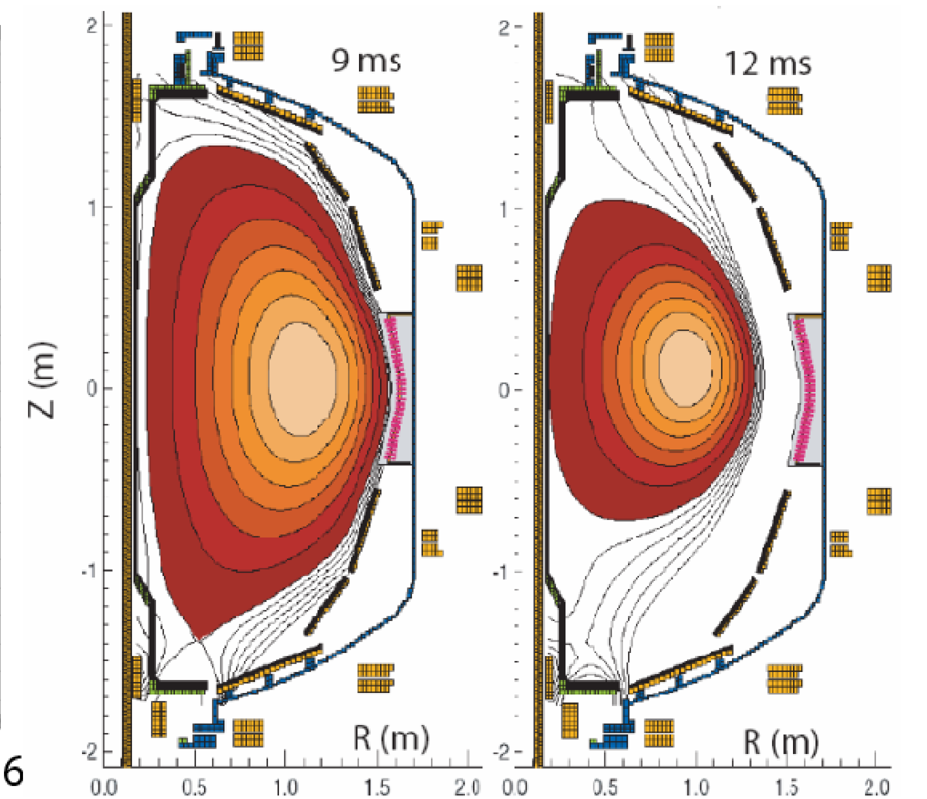
- Demonstration of closed flux current generation
  - Aided by gas and EC-Pre-ionization injection from below divertor plate region
- Demonstration of coupling to induction (2008)
  - Aided by staged capacitor bank capability

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

Very high current multiplication (~70) aided by higher Toroidal Flux

$$I_p = I_{inj}(\psi_{Tor} / \psi_{Pol})$$





Record 160kA non-inductively generated closed flux current in ST or Tokamak produced in NSTX

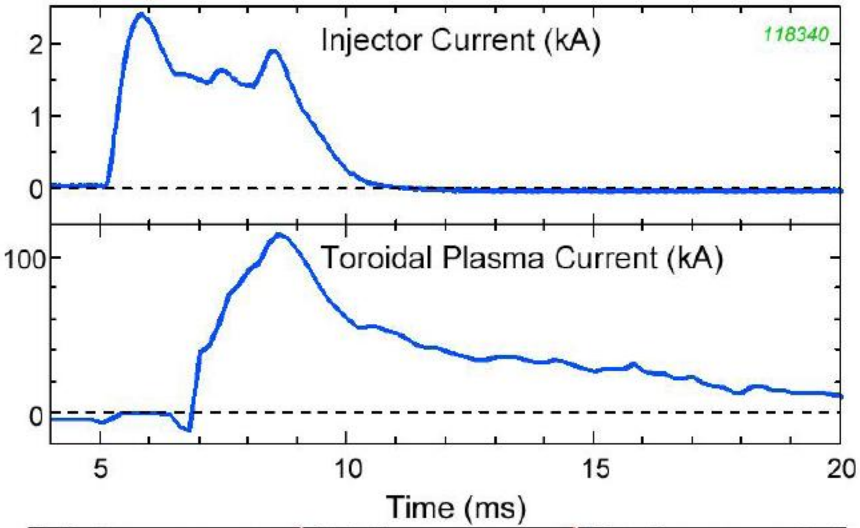
Used LRDFIT reconstructions

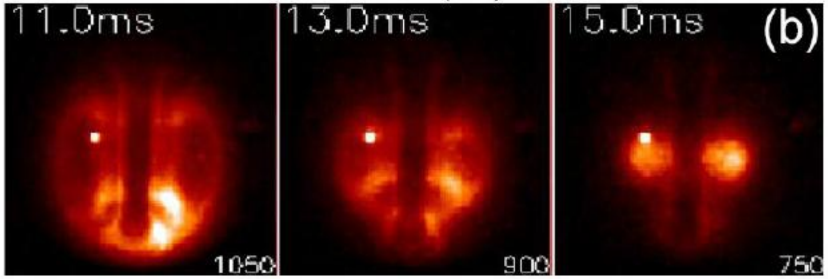
LRDFIT (J. Menard)

R. Raman, B.A. Nelson, M.G. Bell et al., PRL 97, 175002 (2006)

Current Multiplication in NSTX is ~10x than in HIT-II

NSTX

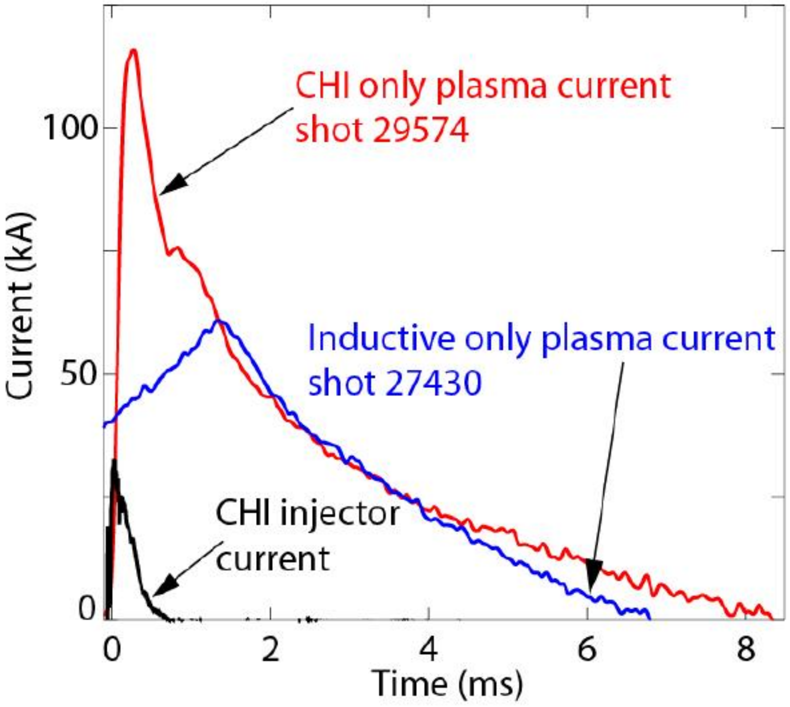




I_{inj} ~1.5 kA generates I_p ~100 kA

- due to Higher Toroidal Flux in NSTX

HIT-II



I_{inj} ~30 kA generates Ip ~120kA

Best current multiplication is ~6-7

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

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

Externally Produced Toroidal Field Makes CHI Much More Efficient in a ST (Compared to Spheromak)

- 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 (Advantage of TF and ST contribution to CTs)

- Current Multiplication can be very large! $I_P = I_{inj}(\psi_{Tor} / \psi_{Pol})$
  - HIT-II: Current multiplication factor ~6
  - NSTX: I_{inj}~1.5kA generates I_P ~ 120kA (~60-70)

As the magnitude of the toroidal field increases:

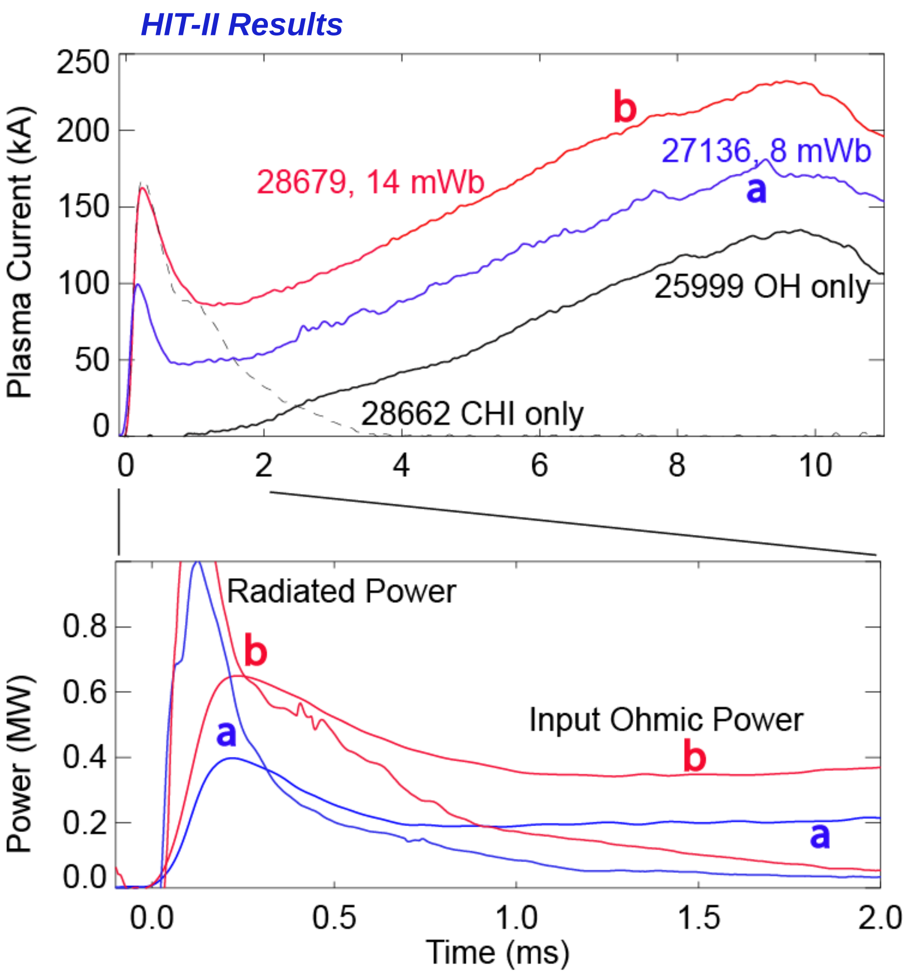
- Less injector current is needed for a given injector flux

- Current multiplication factor improves

⇨ Favorable scaling with machine size

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

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

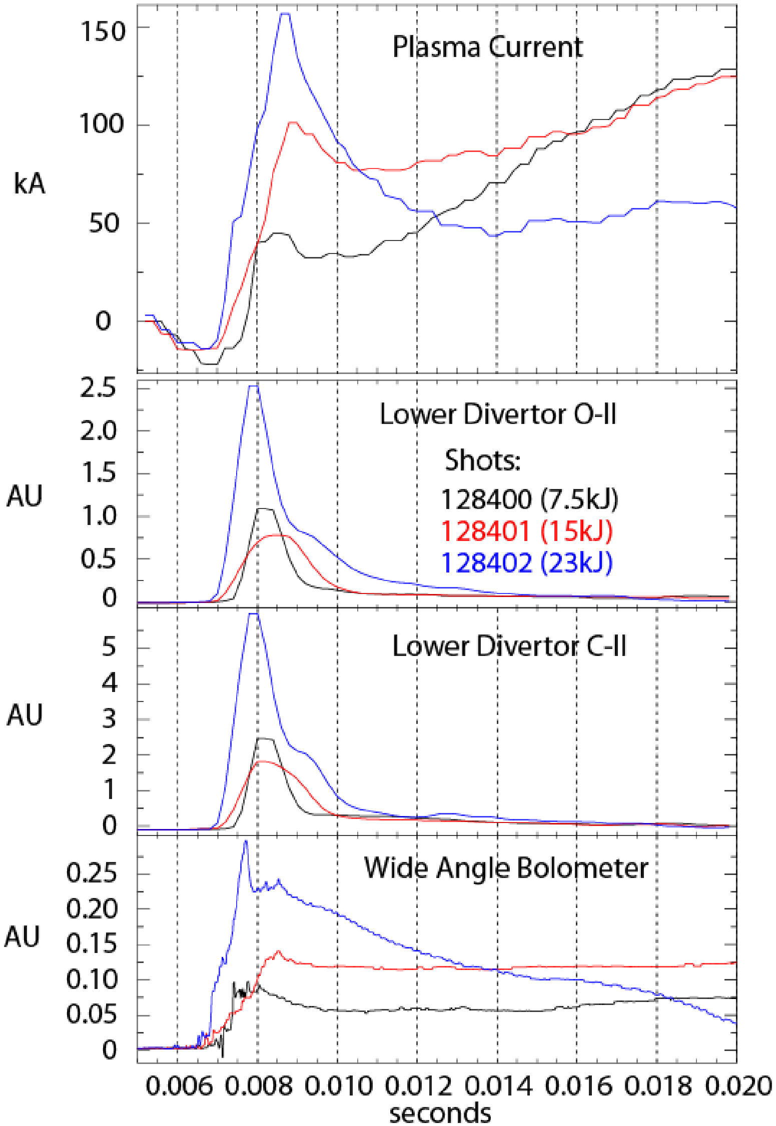


- Identical loop voltage programming for all cases
- Coupling current increases as injector flux is increased
- Radiated power can be decreased by using W or Mo target plates
  - Start-up plasma (inductive or CHI) is cold (few 10s of eV)
    - Reduce Low-z line radiation
  - Auxiliary heating would ease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

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

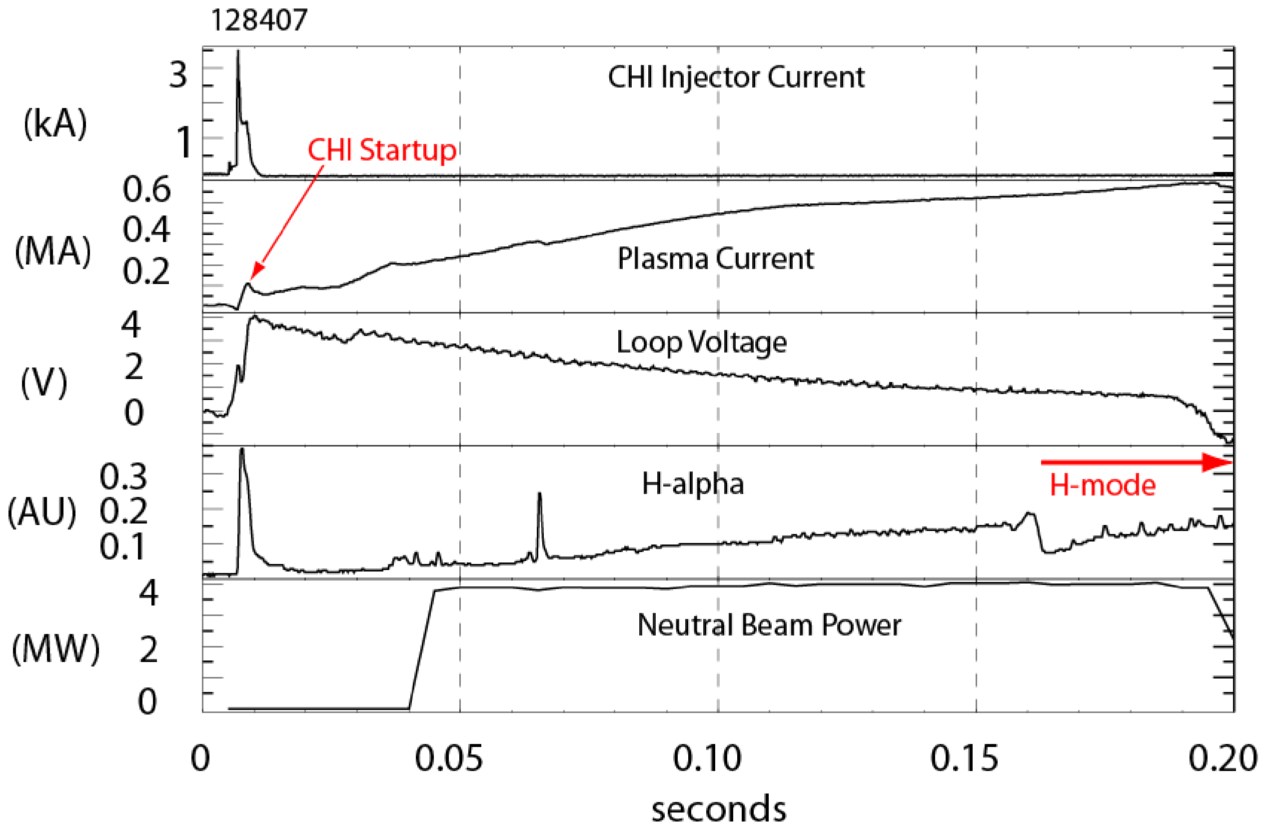
R. Raman, T.R. Jarboe, W.T. Hamp, et al., PoP 14 (2007) 022504

Low-z Impurity Radiation Should be Reduced for Inductive Coupling



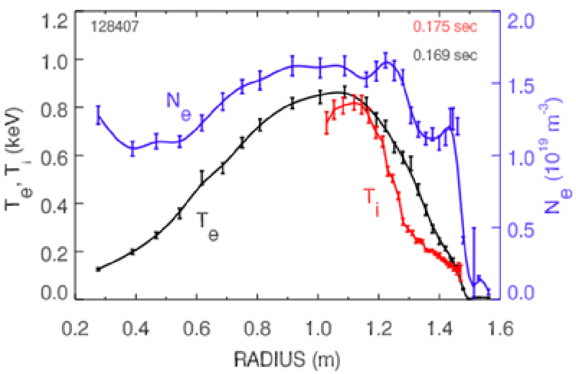
- Low-z impurity radiation increases with more capacitors
- Possible improvements
  - Test CHI in NSTX with partial metal outer divertor plates as part of liquid Li divertor upgrades
    - High Te in spheromaks (500eV) obtained with metal electrodes
  - Discharge clean divertor with high current DC power supply
  - Use ~350kW ECH to heat CHI started plasma

CHI started discharge couples to induction and transitions to an H-mode demonstrating compatibility with high-performance plasma operation



Te & Ne from Thomson

Ti from CHERS



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

- Projected plasma current for CTF >2.5 MA

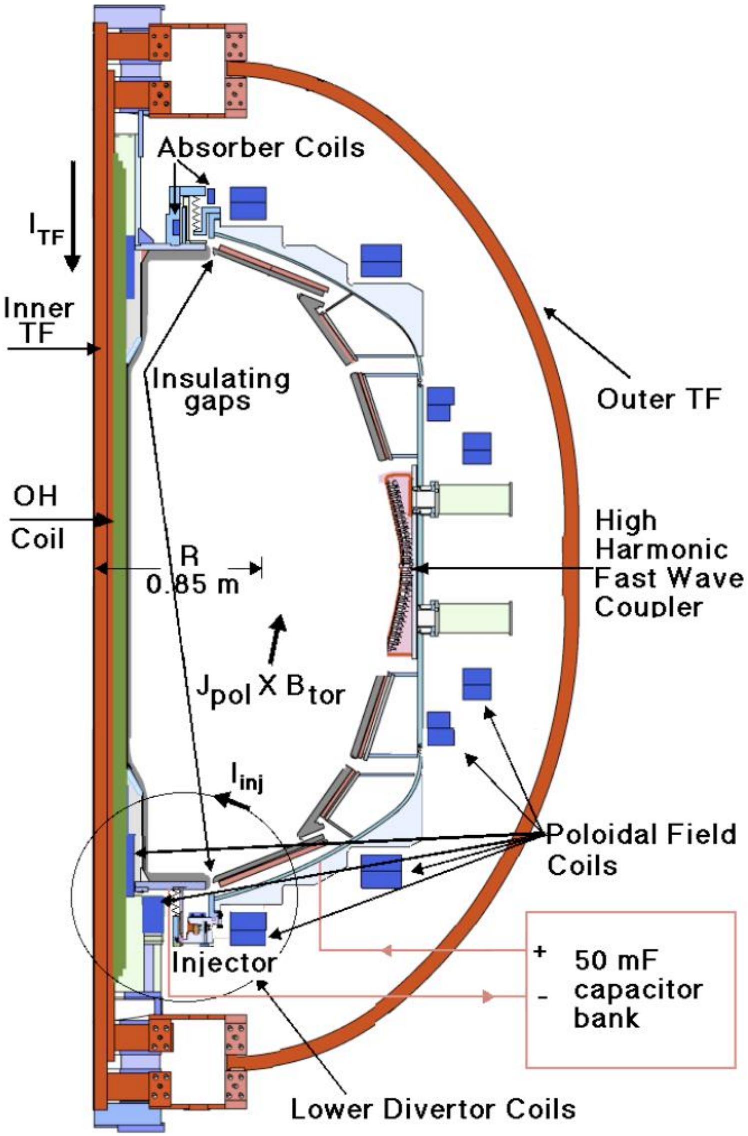
  $[I_p = I_{inj}(\psi_{Tor}/\psi_{Pol})]$*
  - Based on 50 kA injector current (250kA equivalent achieved on HIT-II)
  - Current multiplication of 50 (70 achieved in NSTX)

CHERS: R. Bell

Thomson: B. LeBlanc

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

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



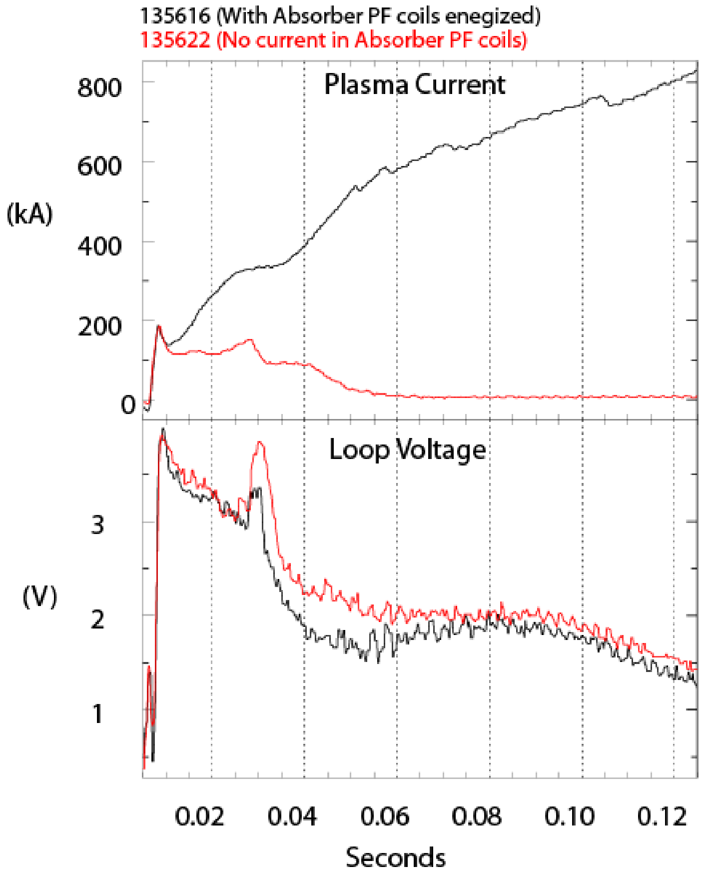
Long-pulse (400ms) CHI discharges in a 'stuffed- injector' current mode used to ablate Low-Z impurities from lower divertor

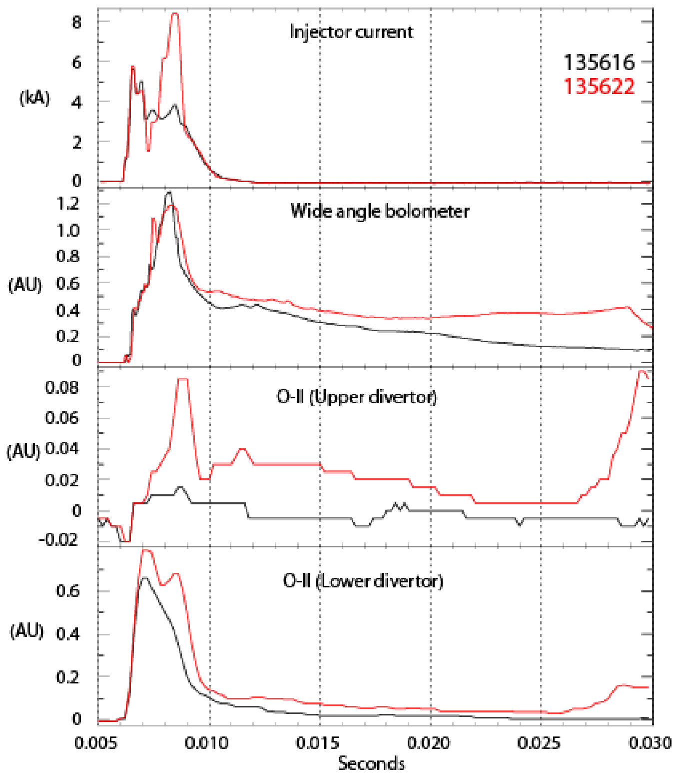
Deuterium Glow Discharge cleaning employed to chemically sputter and reduce oxygen levels

A buffer field was provided using new PF coils located in the upper divertor region (Absorber region) to reduce interaction of CHI discharge with un-conditioned upper divertor plates

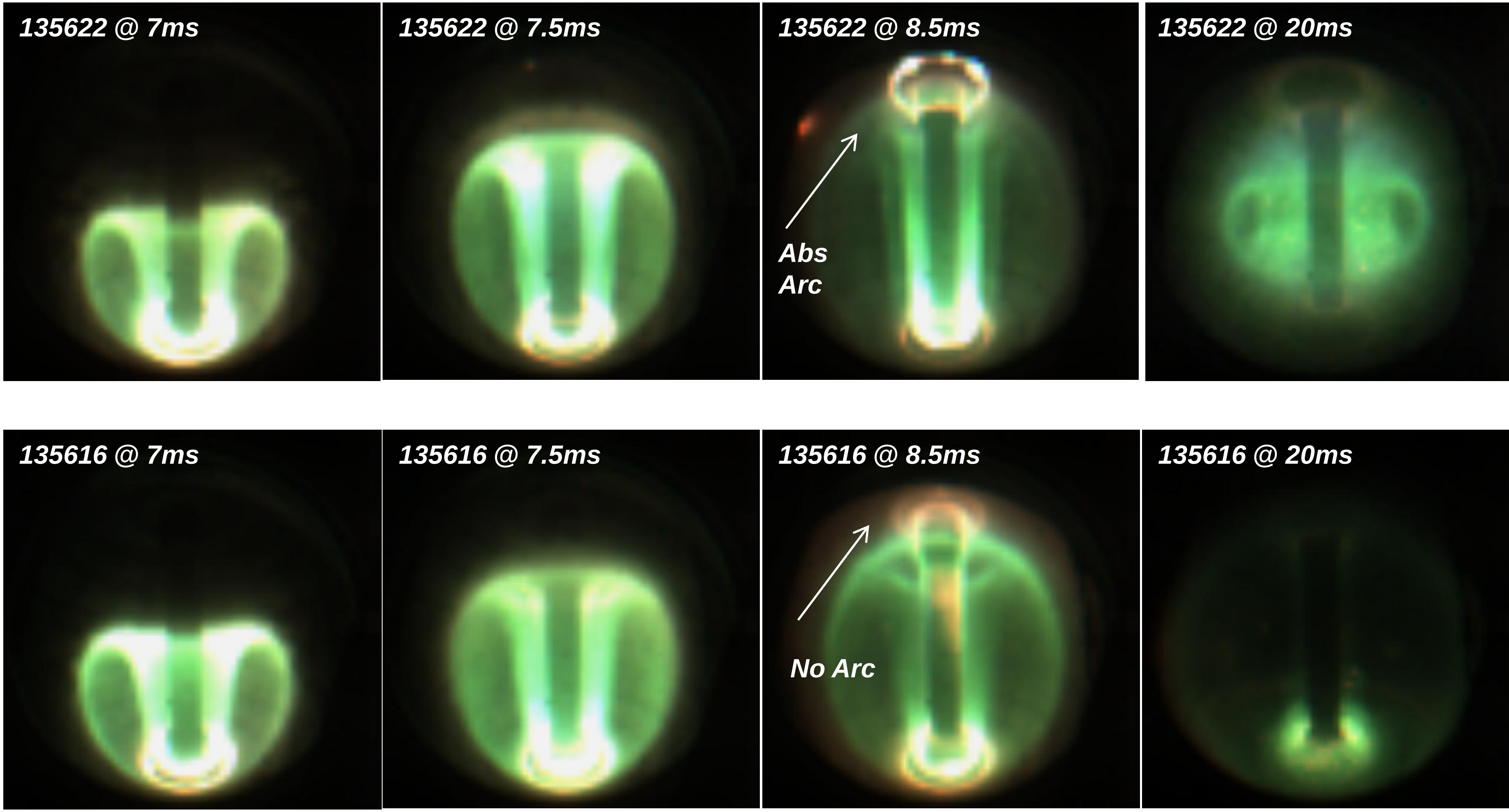
Lithium evaporation on lower divertor plates improved discharge performance

Absorber PF Coils Have Reduced Influx of Oxygen Impurities From Upper Divertor



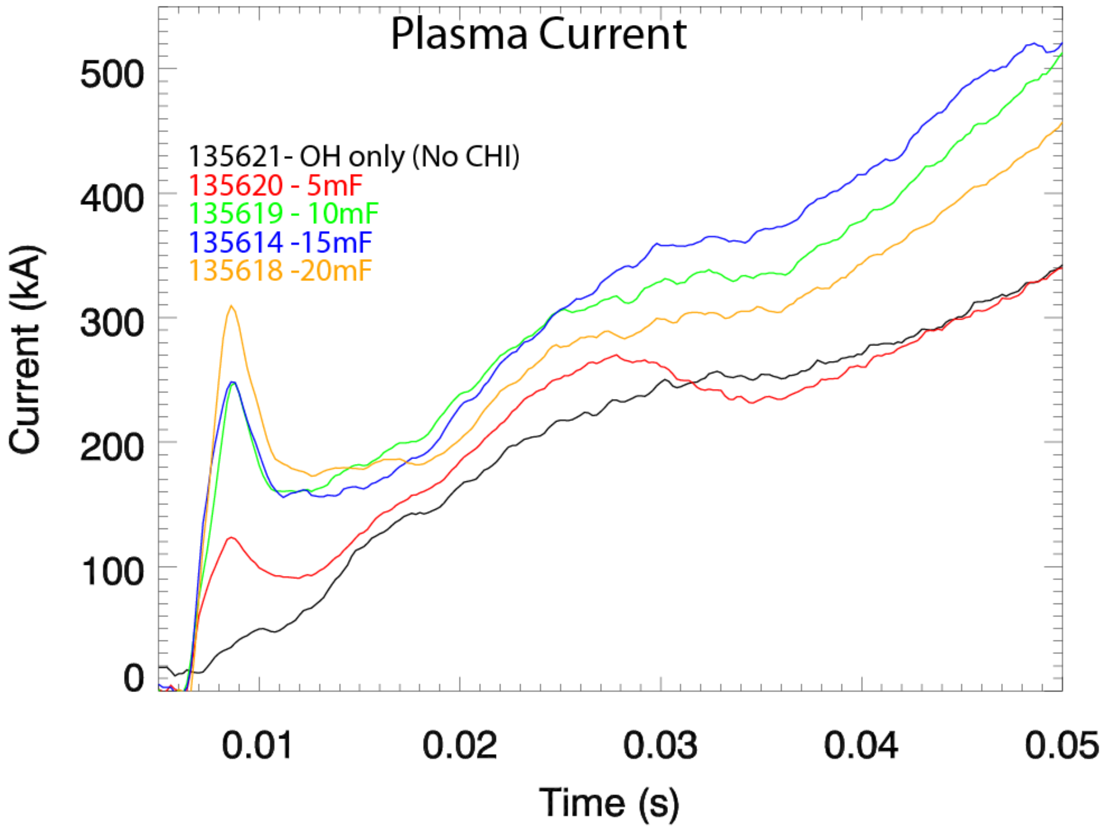


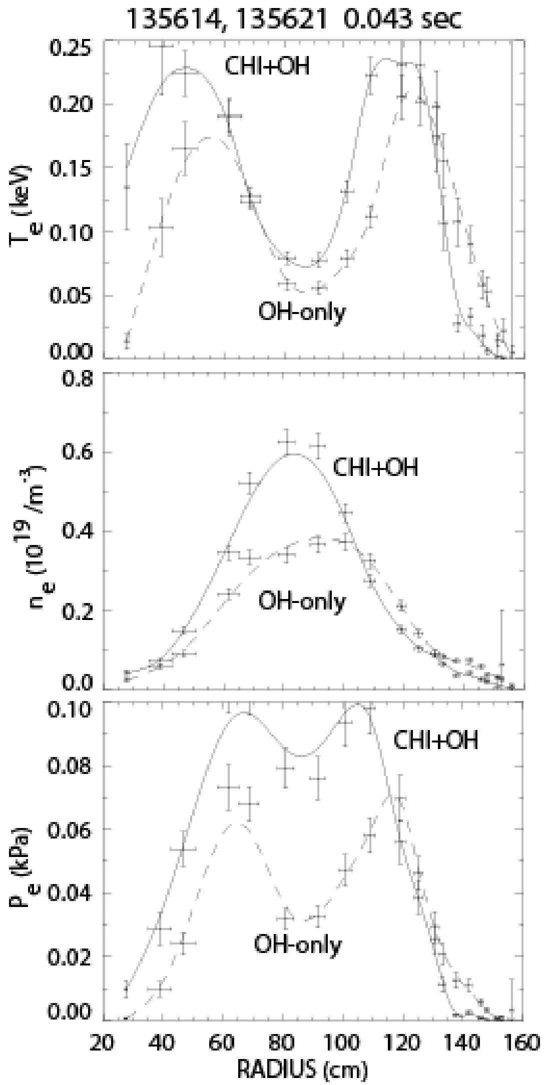
Avoidance of Absorber Arc Clearly Seen in Fast Camera Images



- **Discharge with Absorber Arc (135622) shrinks in size after coupling to induction**
- **Discharge without Absorber Arc heats-up and visible emission decreases**

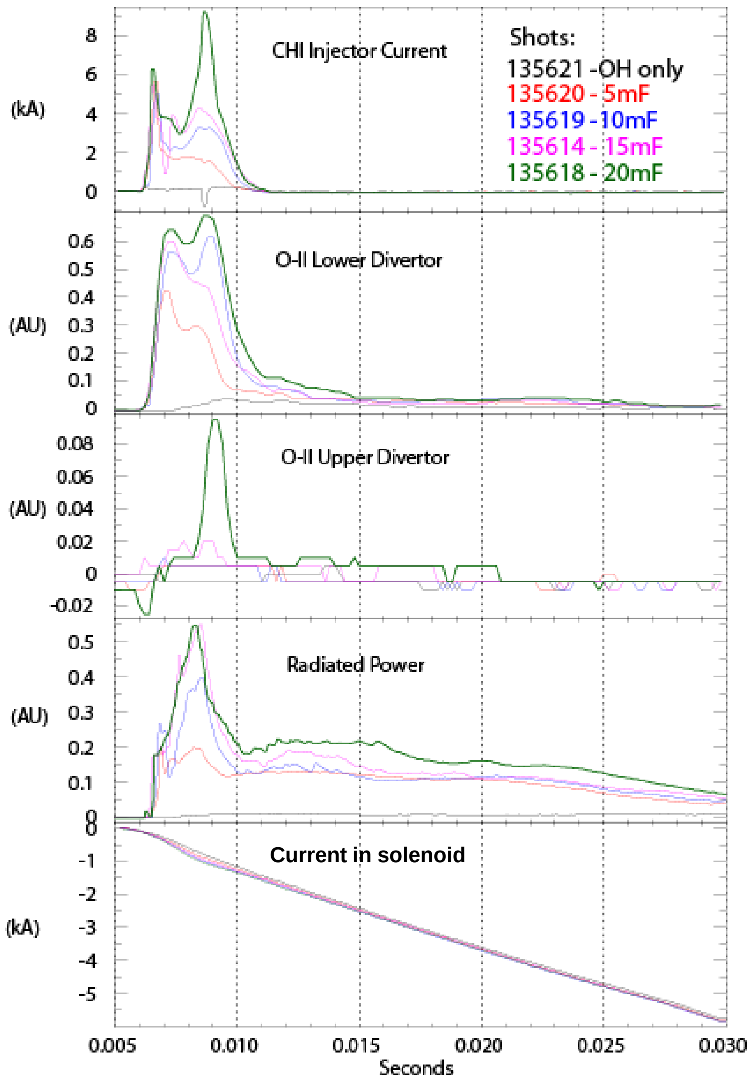
Using Only 25kJ of Capacitor Bank Energy 300kA of CHI Started Discharge Generated and Coupled to Induction

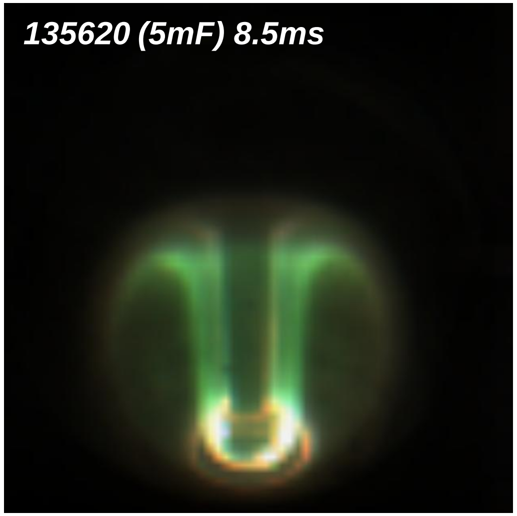


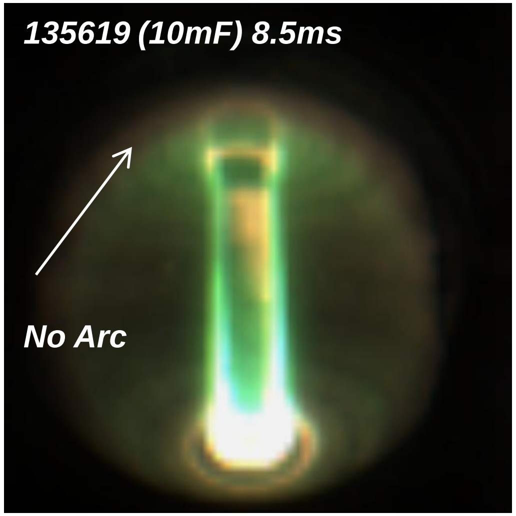


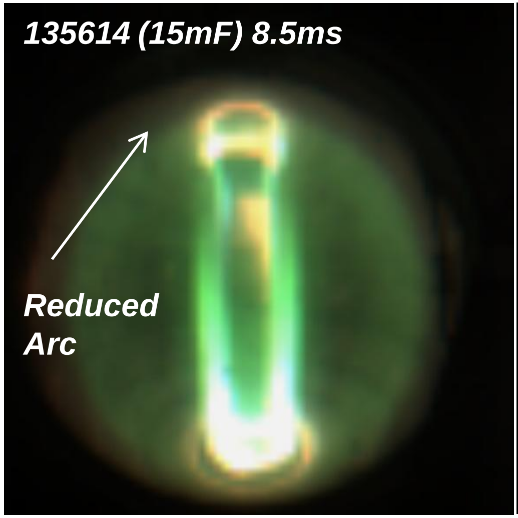
- All discharges used 0.11Vs of Central Solenoid Flux
- Te and ne, both are higher in CHI-started discharge
- Discharges with 3-capacitors (20kJ) reaches 525kA
    - -200kA higher than induction-only discharge
    - -Induction-only discharge reaches only 325kA

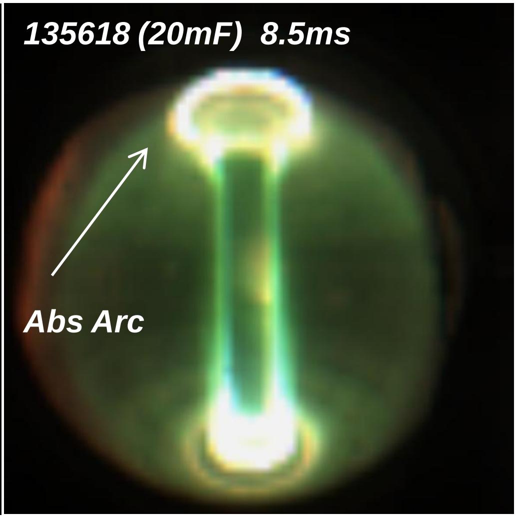
Weak Absorber Arc During Operation with 20mF Capacitor Responsible for Reduced Coupling to Induction



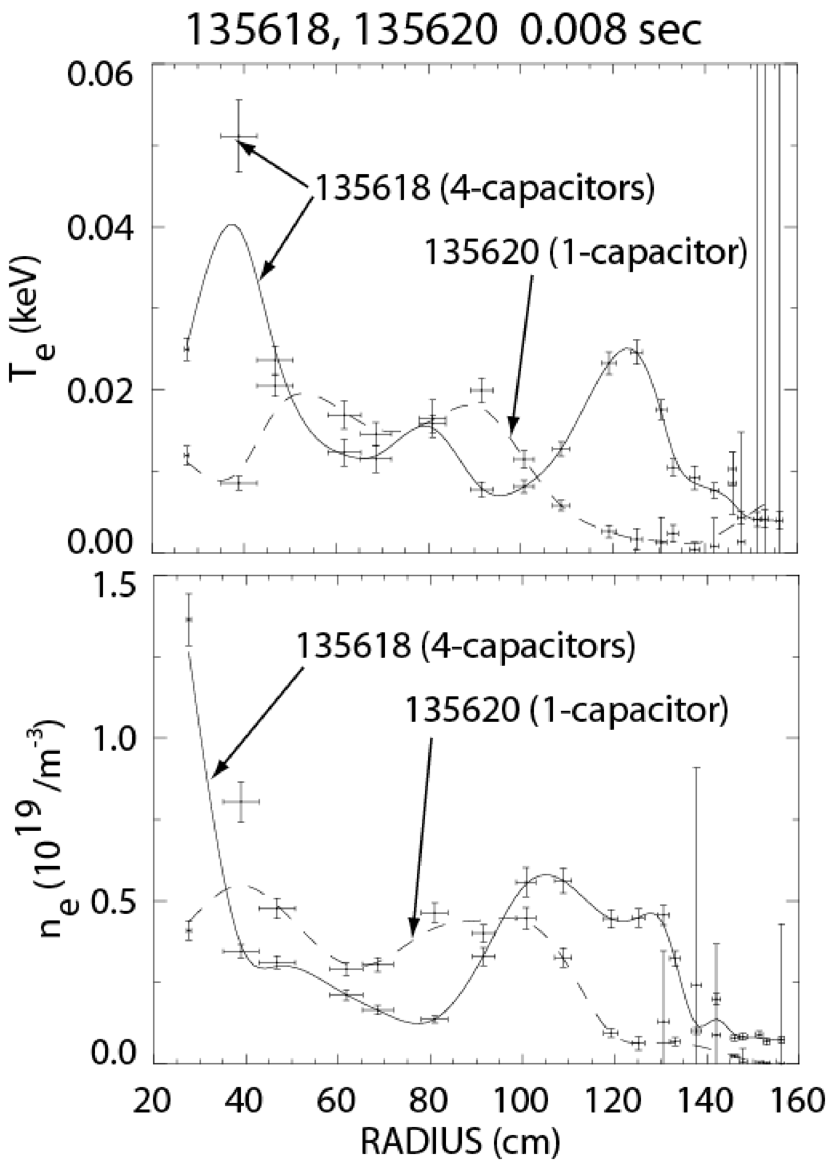








For the First Time in NSTX CHI Discharges up to 50eV Electron Temperatures Measured by Thomson Scattering



- **Now for the First Time in NSTX CHI discharges the electron temperature is seen to increase with increasing capacitor bank energy**
- **This indicates burn-through of oxygen impurities (due to reduction in oxygen levels)**
- **At temperatures>20eV, flux savings should be realized and this is now seen in NSTX CHI started discharges**

NSTX has Demonstrated a Viable Solenoid-Free Plasma Startup Method for the ST

- Demonstration of the process in a vessel volume thirty times larger than HIT-II on a size scale more comparable to a reactor
- Remarkable multiplication factor of 70 between the injected current and the achieved toroidal current, compared to six in previous experiments
- Results were obtained on a machine designed with mainly conventional components and systems
- Favorable scaling with increasing machine size

1) 0.3MA current generation in NSTX validates capability of CHI for high current generation in ST
2) Successful coupling of CHI started discharges to inductive ramp-up & transition to an H-mode demonstrates compatibility with high-performance plasma operation

Back-up slides

Simultaneous Requirements for Transient CHI

- 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

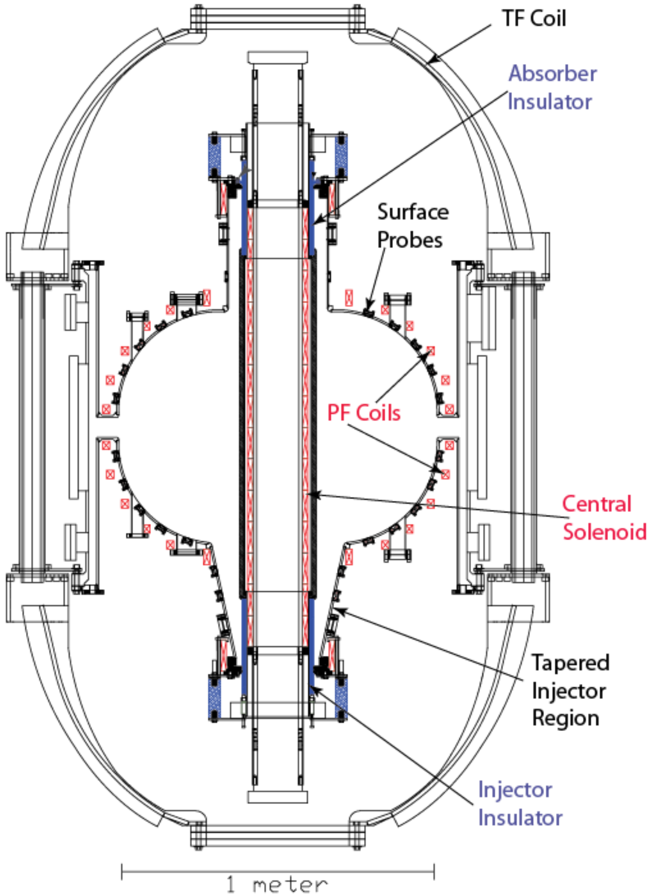
  I_{TF} = current in TF coil

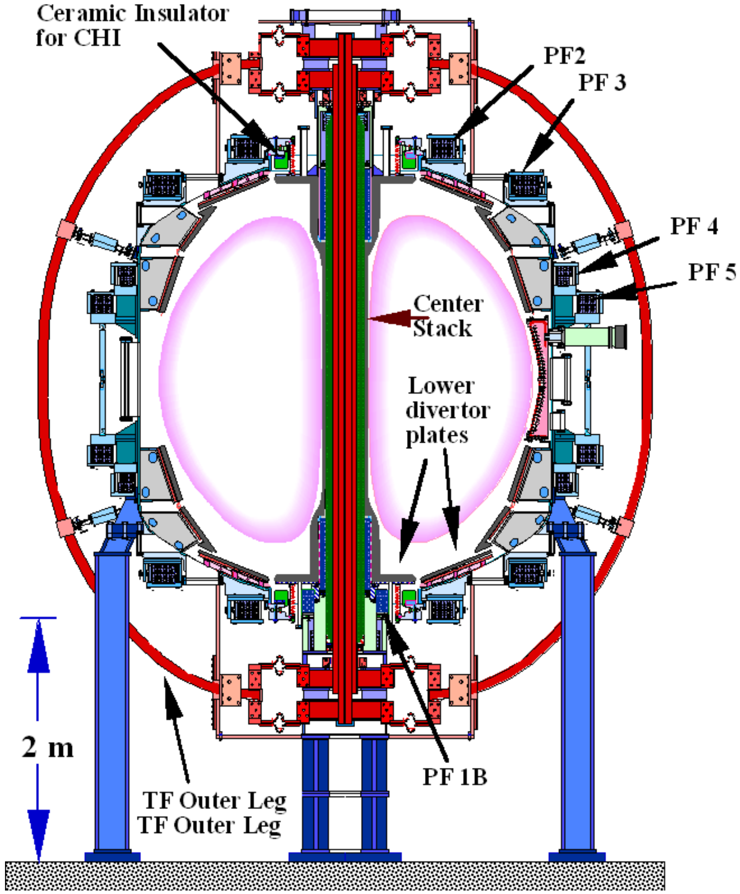
- Time needed to displace toroidal flux
  - For typical voltage at the injector after breakdown ~500V need ~1 ms to displace 600 mWb

- Energy for peak toroidal current: $\frac{1}{2}CV^2 > \frac{1}{2}LI^2$

- Exceed Energy for ionization and heating to 20eV (~50eV/D)
  - For 2 Torr.L injected, need ~2kJ

NSTX Plasma is ~30 x Plasma Volume of HIT-II





Concept exploration device HIT-II

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

Proof-of-Principle NSTX device

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