NSTX

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Solenoid-free Plasma Start-up in NSTX using Transient CHI

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22nd IAEA Fusion Energy Conference
October 13-18, 2008, Geneva

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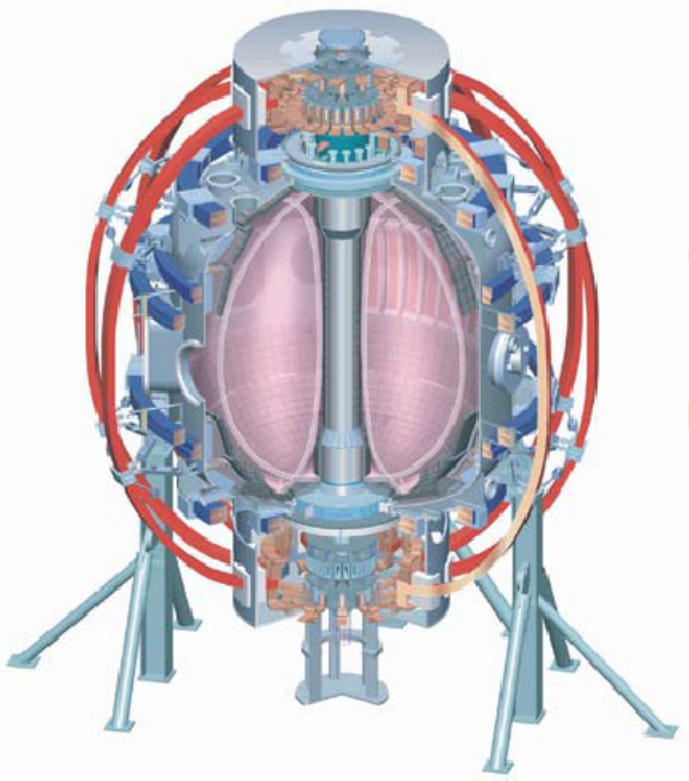
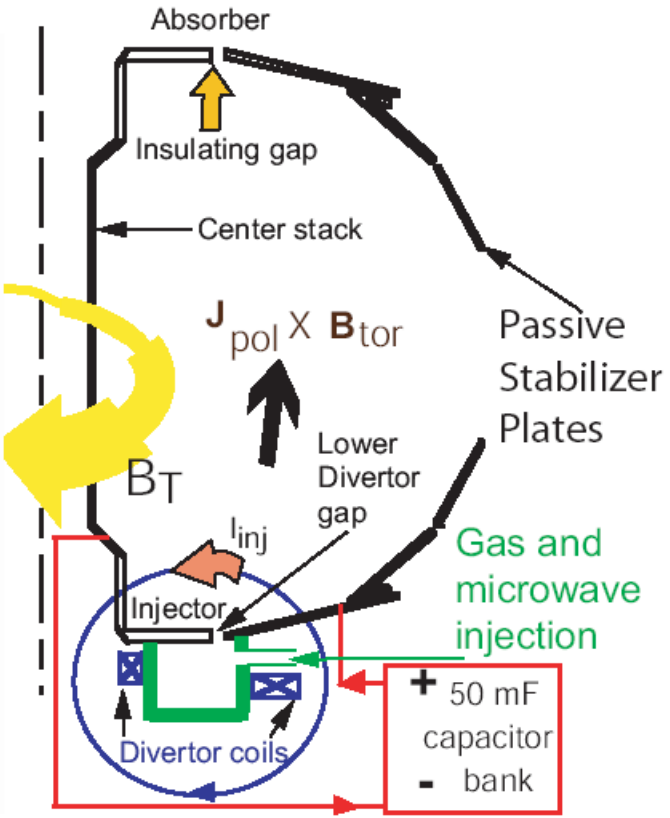
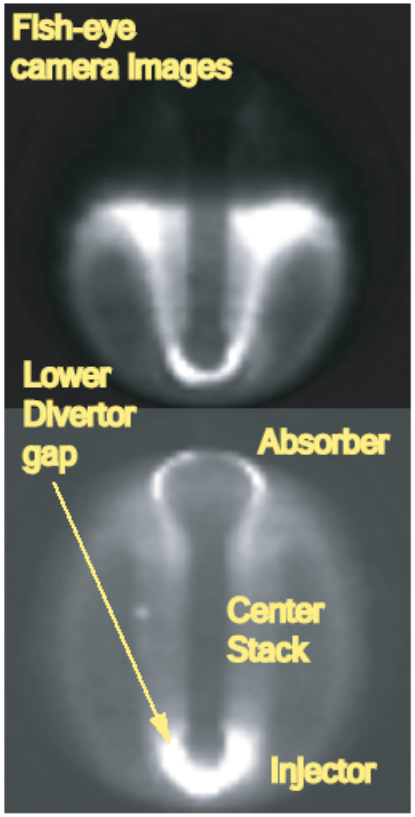
Motivation For Solenoid-Free Plasma Start-up

- The development of methods for solenoid-free current initiation would improve the prospects of the low aspect-ratio Spherical Torus as a CTF and fusion reactor
  - Could also aid ARIES-AT design
- Of the three large tokamaks in the US (DIII-D, NSTX, C-MOD) only NSTX is engaged in solenoid-free plasma start-up research
- Transient Coaxial Helicity Injection (CHI) created plasmas in toroidal equilibrium carrying significant plasma current on HIT-II at Univ. of Washington
- Method has now produced 160 kA closed-flux current in NSTX
  - World record for non-inductively generated start-up current in ST or tokamak

Transient CHI: Axisymmetric reconnection leads to formation of closed flux surfaces







- Demonstration of closed flux current generation
  - Aided by gas and EC-Pi 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

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

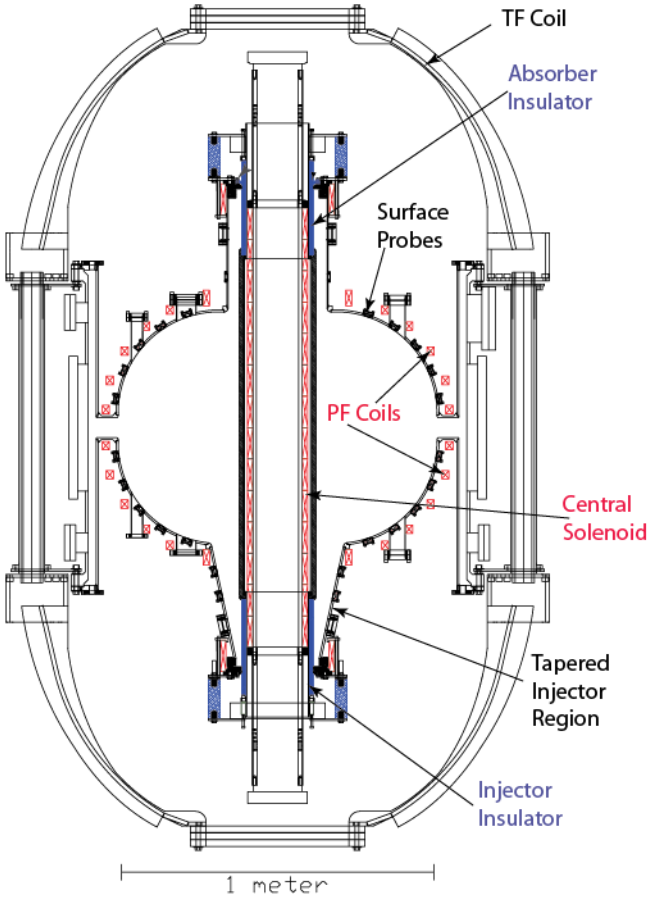
- Time needed to displace toroidal flux
  - For typical voltage at the injector after breakdown ~500V need ~1 ms to displace 600 mWb

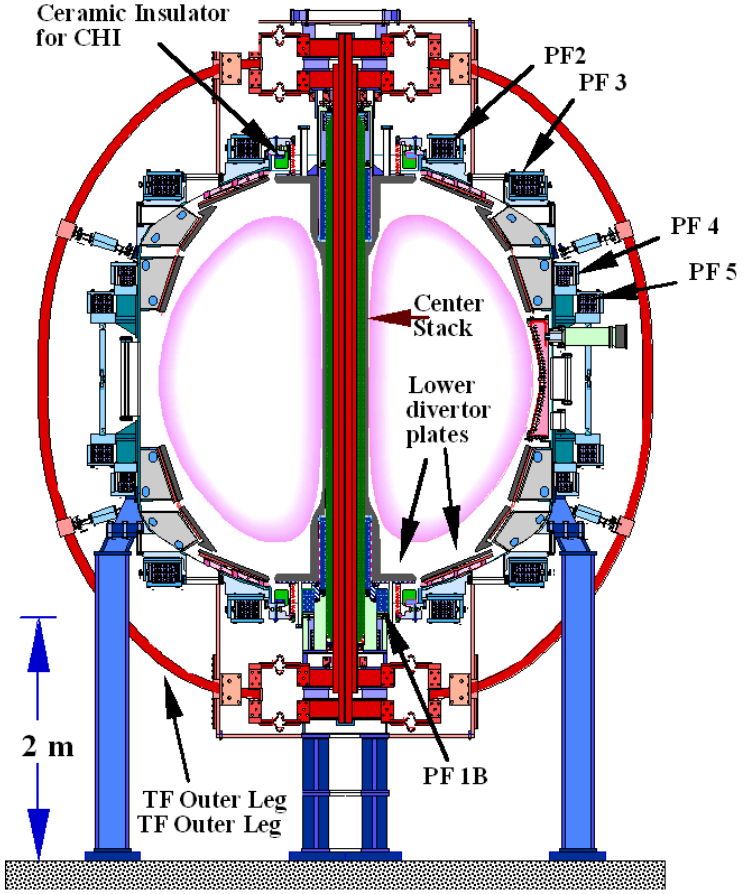
- Energy for peak toroidal current: $\frac{1}{2}CV^2 > \frac{1}{2}LI^2$

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

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

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





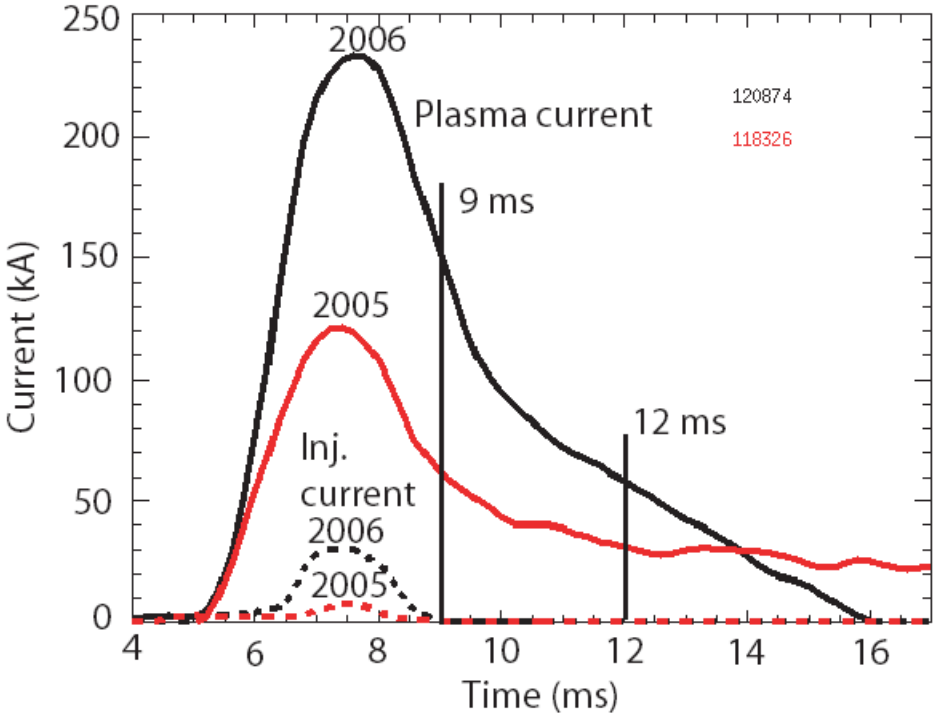
Concept exploration device HIT-II

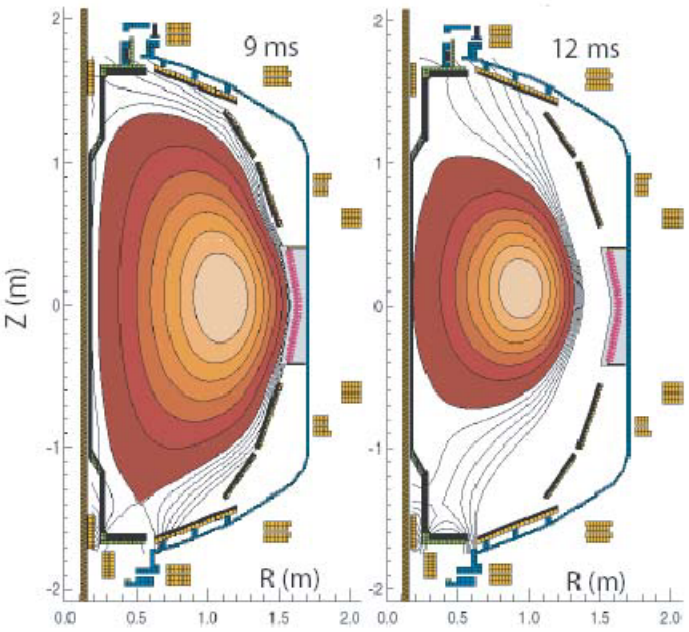
- Built for developing CHI
- Many Close fitting fast acting PF coils
- 4 kV CHI capacitor bank

Proof-of-Principle NSTX device

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

Very high current multiplication (~70) aided by higher Toroidal Field: $I_p = I_{inj}(\psi_{Tor}/\psi_{Pol})$





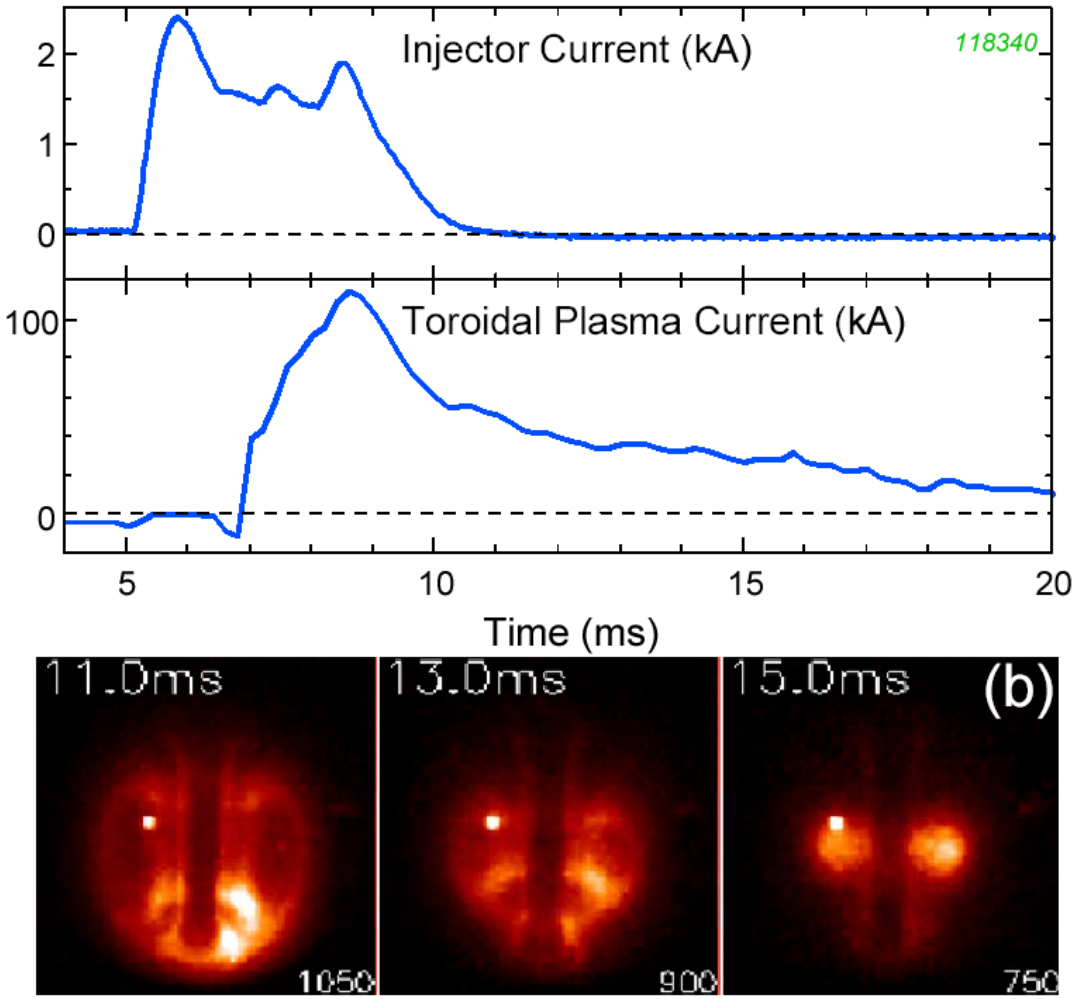
- 2006 discharges operated at higher toroidal field and injector flux
  - Record 160kA non-inductively generated closed flux current in ST or Tokamak produced in NSTX

- Used LRDFIT reconstructions

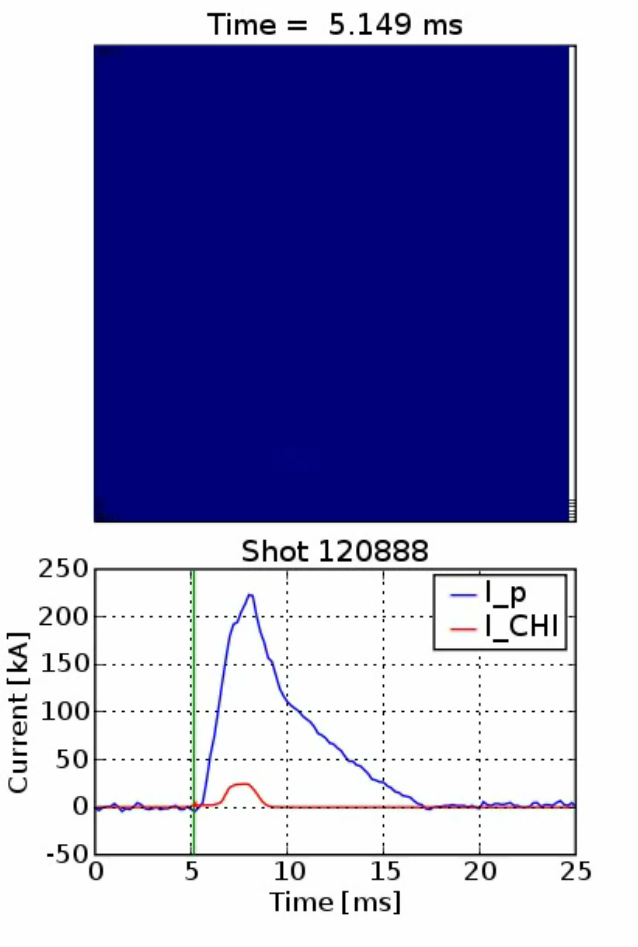
LRDFIT (J. Menard)

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

Discharges Without Absorber Arc Have High Current Multiplication Ratios (I_p/I_{inj} ~ 70)



Fast Camera Fish-eye Movie of CHI Started Discharge



Note:

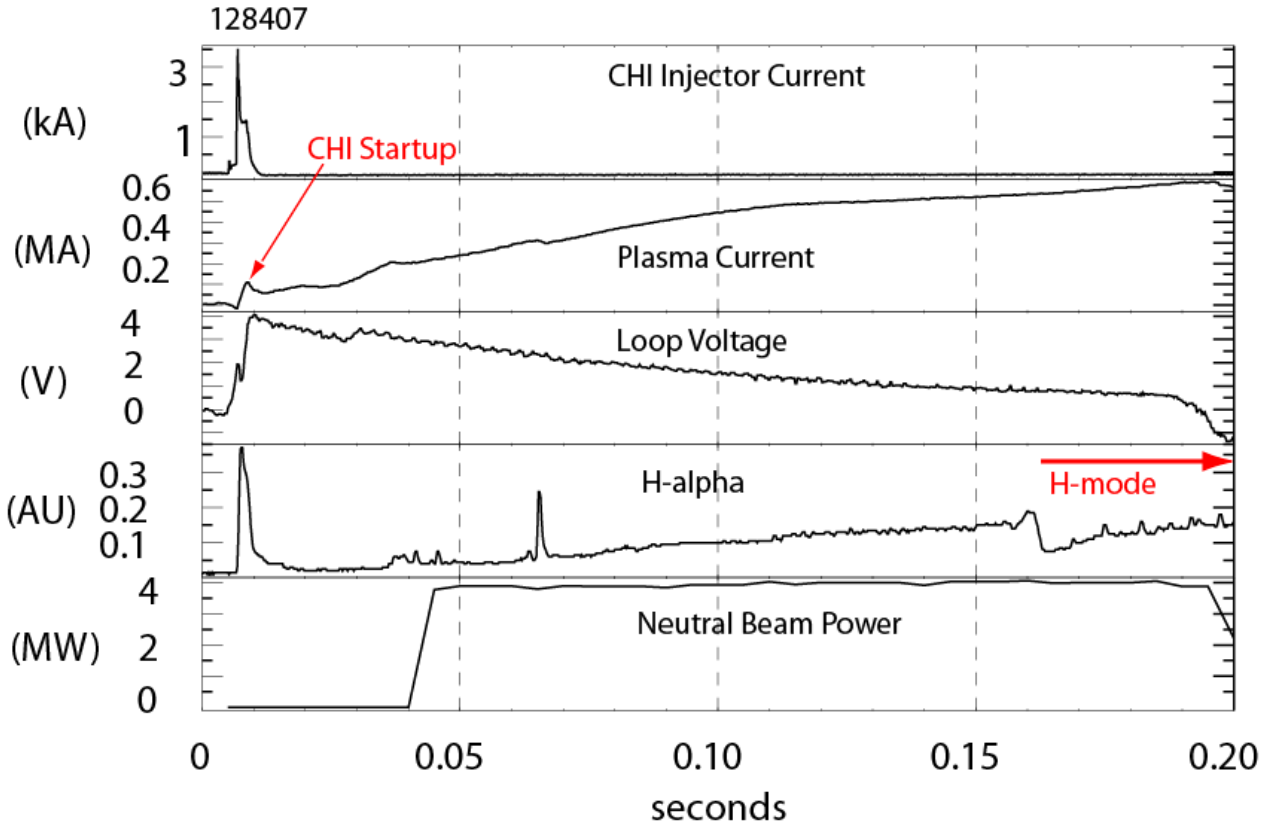
- CHI discharge evolution from the lower divertor plate region

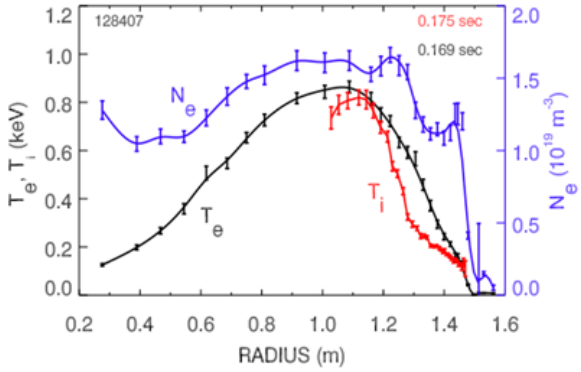
- Discharge contacting upper divertor region (Absorber arc)

- Detachment from the injector region

- Closed flux equilibrium decaying and shrinking in size

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

- Central T_e reaches 800eV
- Central T_i > 700eV

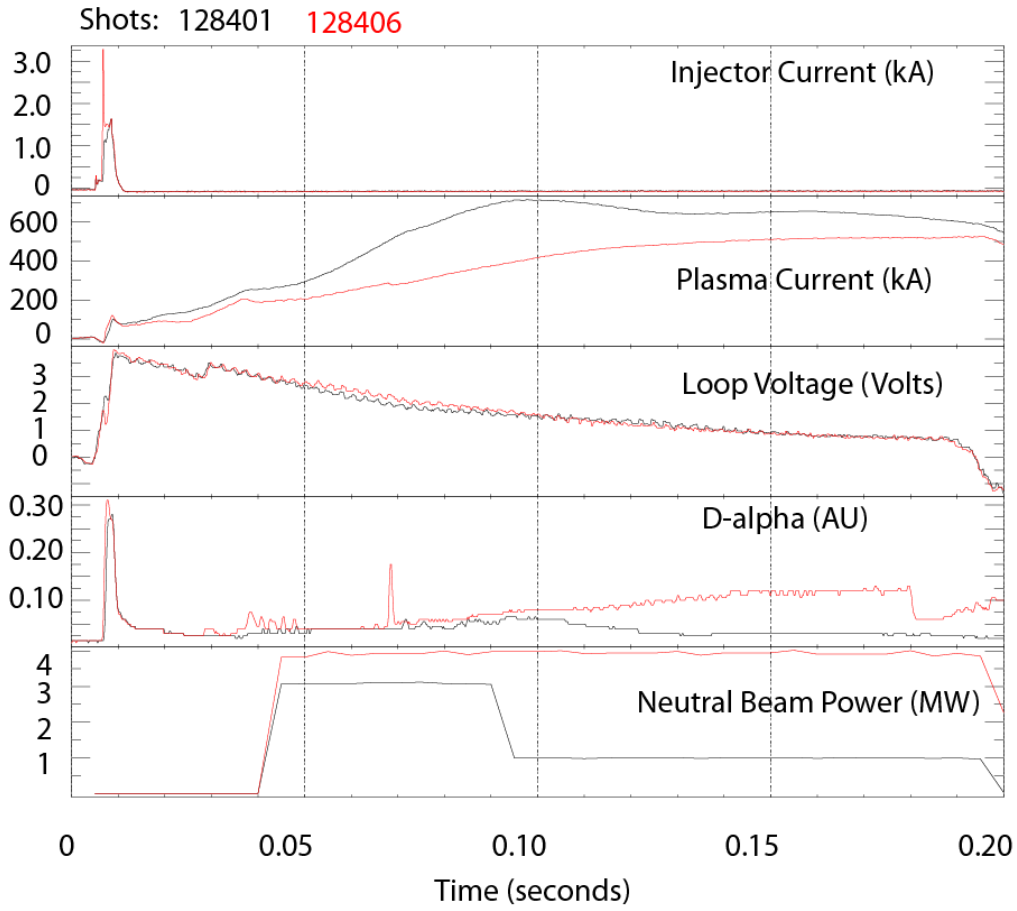
Note the broad density profile during H-mode phase

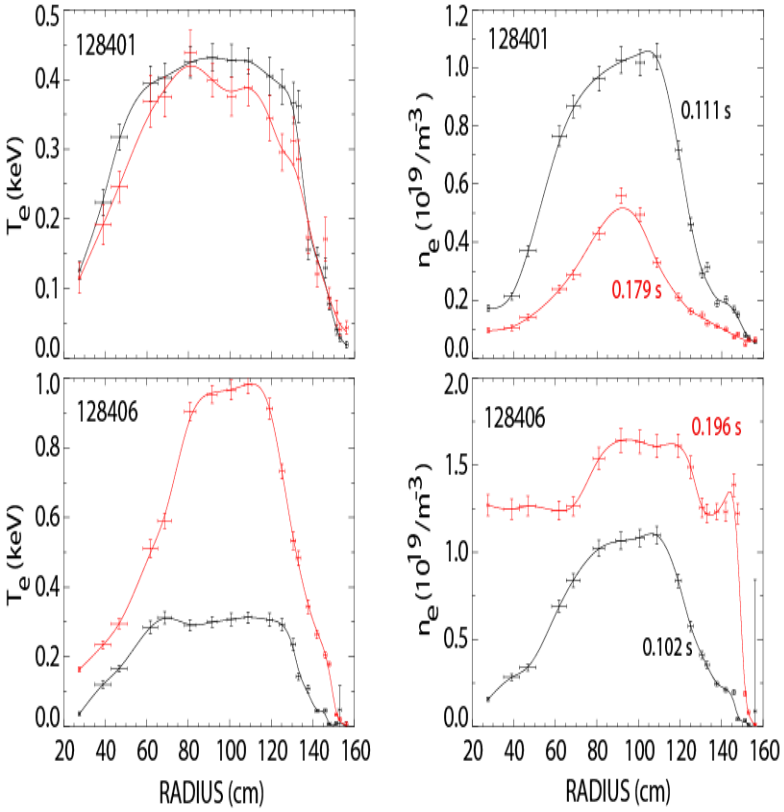
- Discharge is under full plasma equilibrium position control
  - Loop voltage is preprogrammed
- Projected plasma current for CTF >2.5 MA $[I_p = I_{inj}(\psi_{Tor}/\psi_{Pol})]$*
  - Based on 50 kA injected current (Injector current densities achieved on HIT-II)
  - Current multiplication of 50 (achieved in NSTX)

CHERS: R. Bell
Thomson: B. LeBlanc

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

CHI started discharges use <15 kJ of capacitor bank energy to generate 100kA start-up plasma

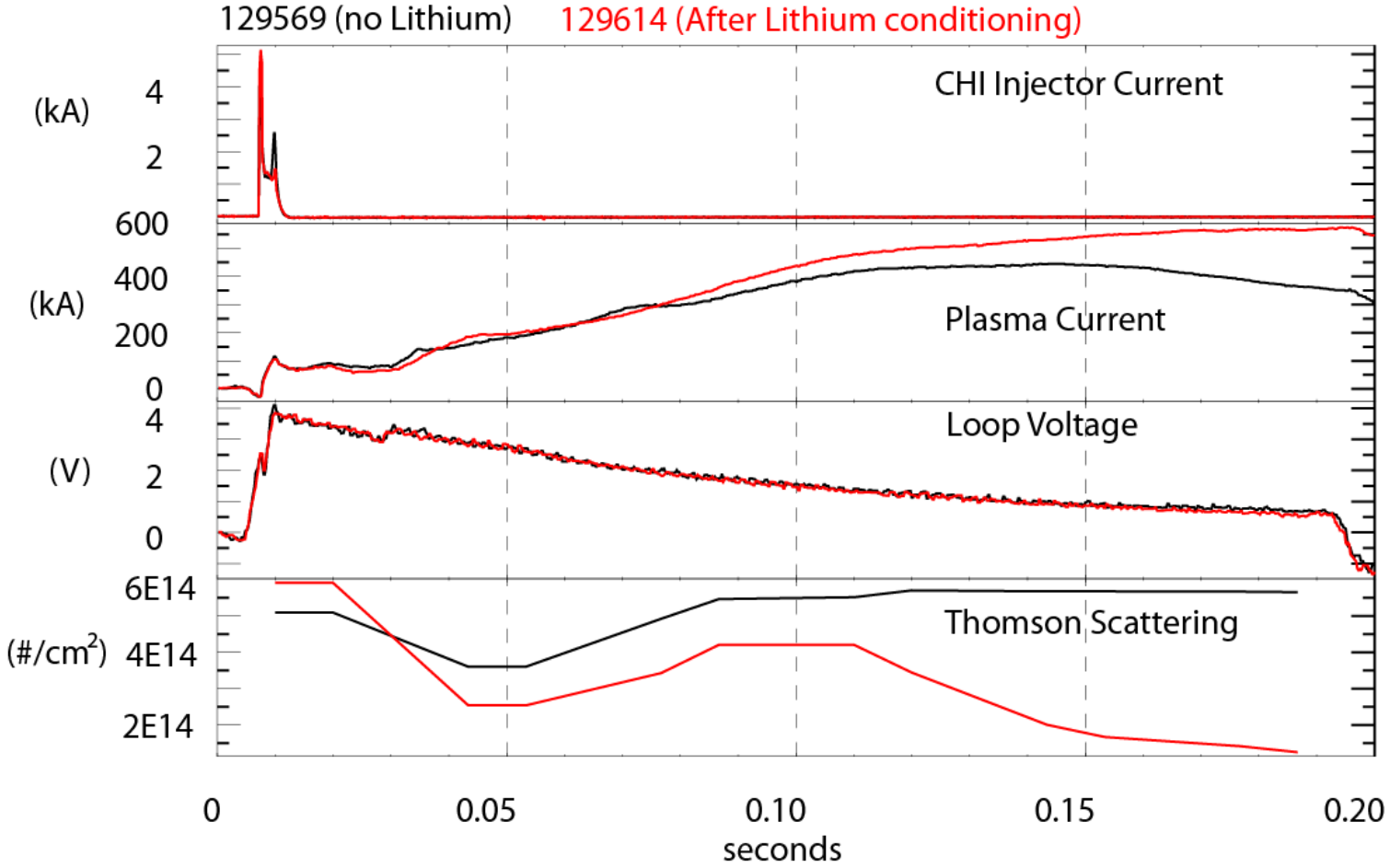




Discharge 128406 with center stack gas injection and higher NB power transitions to an H-mode

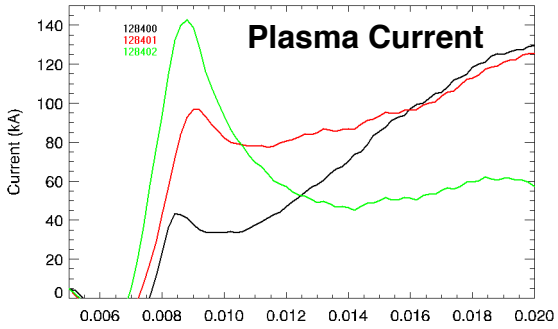
After the transition to H-mode in discharge 128406, T_e reaches 1 keV

Discharges produced after Li divertor plate conditioning are more reproducible and reach higher currents

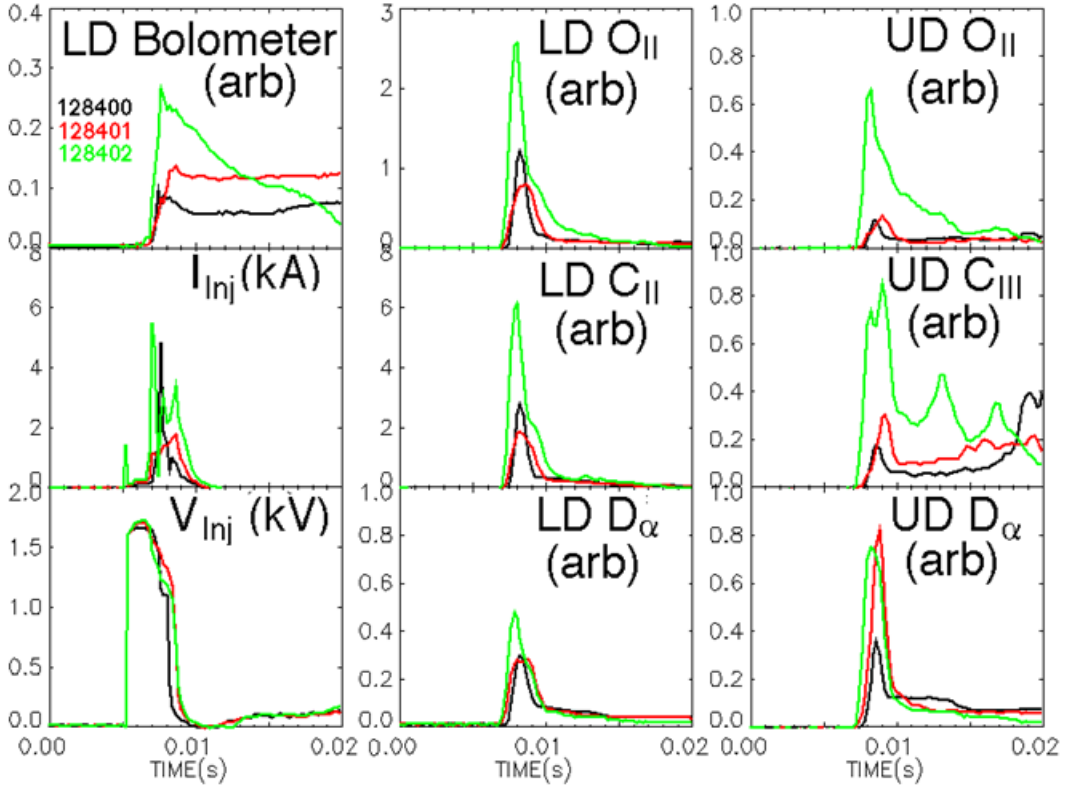


- Improved performance after coupling to induction is similar to that seen on HIT-II with Ti gettering
- The NB cryo-pumps were not used during either shot

Need auxiliary heating or metal divertor plates to compensate for increased radiated power with more capacitors

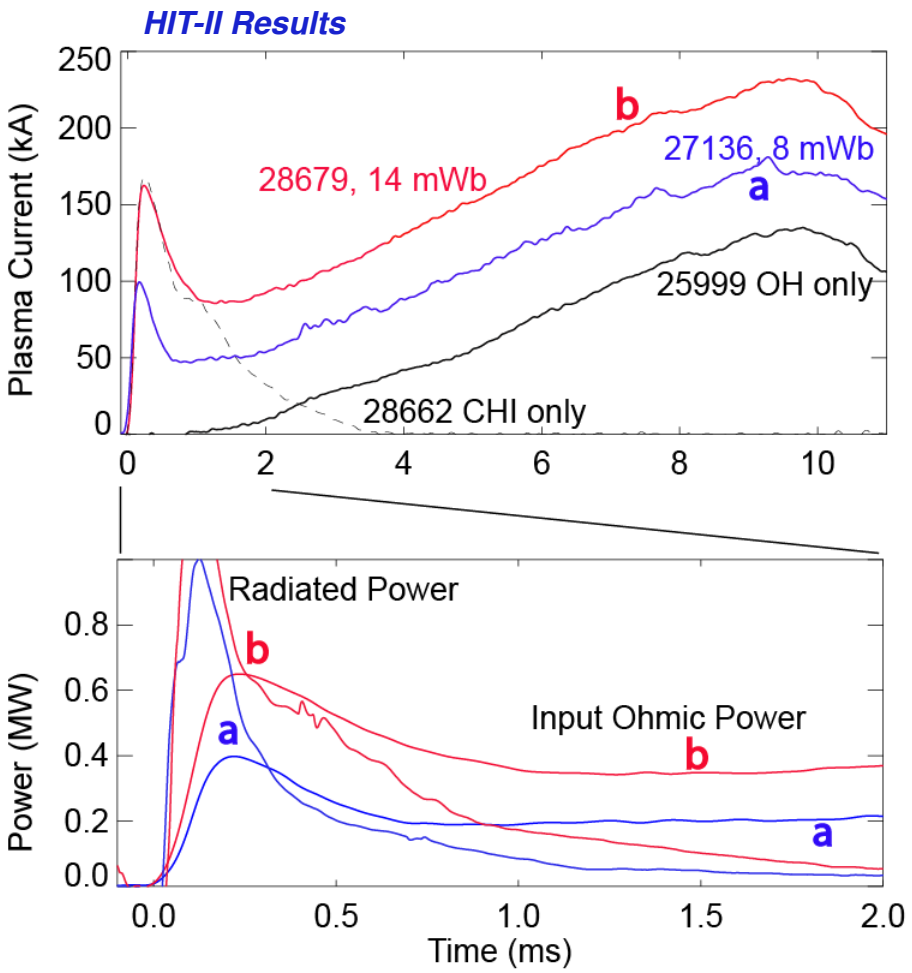


128400: 5mF (7.6kJ)
128401: 10mF (15.3kJ)
129402: 15mF (22.8kJ)



- Low-Z impurity radiation increases with more capacitors
  - High T_e in spheromaks (500eV) obtained with metal electrodes
  - Test with partial metal outer divertor plates during FY09
- Upper divertor (UD) radiation also increases with more capacitors
  - Need to reduce absorber arcs
  - Absorber field nulling coils to be used during FY09
- Assess benefits of partial metal plates + Absorber coils
  - Discharge clean divertor with high current DC power supply
  - Use 350kW ECH during FY11

In HIT-II nearly all CHI produced closed flux current is retained in the subsequent inductive ramp



- All three discharges have the identical loop voltage programming
- Coupling current increases as injected flux is increased
- Ip ramp-up begins after input power exceeds radiated power
  - Auxiliary heating would ease requirements on current ramp-up system
- 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

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

NSTX has Demonstrated a Viable Plasma Startup Method for the ST

1) 160 kA closed flux current generation in NSTX validates capability of CHI for high current generation in ST
   - *Modest requirements for increasing the CHI startup current to ~400kA*
     - *350 kW ECH to heat the CHI plasma*
     - *Metal divertor plates to reduce low-Z impurities*
     - *~20% increase in the capacitor bank voltage*
2) Successful coupling of CHI started discharges to inductive ramp-up & transition to an H-mode demonstrates compatibility with high-performance plasma operation

NSTX improvements over HIT-II

- demonstration of the process in a vessel volume thirty times larger than HIT-II on a size scale more comparable to a reactor,
- a 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.