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Solenoid-free Plasma Start-up in HIT-II and NSTX using Transient CHI

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Outline

- Motivation for solenoid-free plasma startup
- Implementation of CHI in NSTX
- Requirements for Transient CHI
- Experimental results from HIT-II & NSTX
- Summary and Conclusions

Solenoid-free plasma startup is essential for the viability of the ST concept

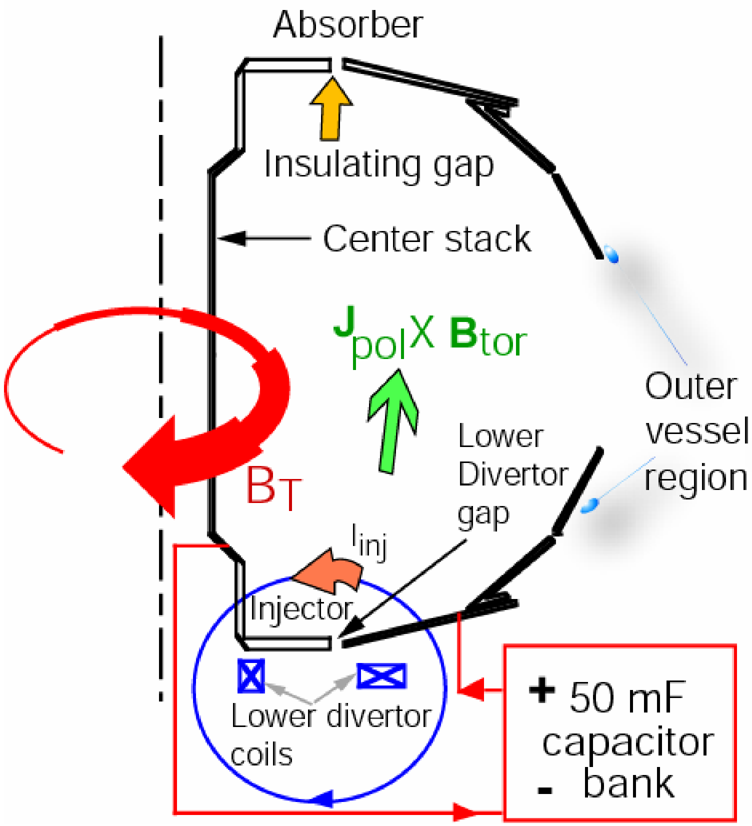
- Elimination of the central solenoid simplifies the engineering design of tokamaks (Re: ARIES AT)
- CHI is capable of both plasma start-up and edge current in a pre-established diverted discharge
  - Edge current profile for high beta discharges
  - SOL modification (ELMs, SOL flows, detachment)
  - Physics of relaxation current drive

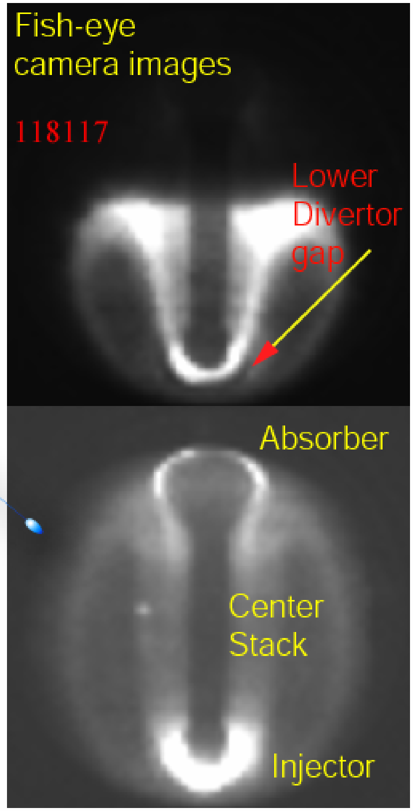
CHI research on NSTX focuses on three areas

- Solenoid-free plasma startup
  - ***Transient CHI ****
- Edge current drive
  - Controlling edge SOL flows
  - Improving stability limits
  - Induce edge rotation
- Steady-state CHI
  - SS relaxation current drive

*Demonstration of plasma start-up by coaxial helicity injection,
R. Raman, T.R. Jarboe, B.A. Nelson et al., Physical Review Letters, **90**, 075005 (2003)

Implementation of Transient CHI





Expect axisymmetric reconnection at the injector to result in formation of closed flux surfaces

Fast camera: R. Maqueda

Requirements for optimizing Transient CHI

- "Bubble burst" current that is equal I_{inj}
  - $I_{inj} \propto \Psi^2_{inj}/\Psi_{toroidal}$ (*easily met*)*
  - [I_{inj} is the injector current, and Ψ is the poloidal flux]
- Volt-seconds to replace the toroidal flux
  - For $\Psi_{toroidal}$ 600 mWb, at ~500V need ~1.2ms just for current ramp-up
    - *Condition met*
    - *Will improve at higher voltage*
- Energy for peak toroidal current ($LI^2/2$, L~1μH)
  - Maximum possible I_p (with 3 caps at 1.5kV - 17 kJ used in 2005) ~ 190 kA is possible (experiment achieved ~ 150 kA)
  - *Adequate available energy, will improve as V_{cap} is increased*
- Energy for ionization of injected gas and heating to 20eV (~50eV/D)
  - At lowest gas pressure 2 Torr.L injected during 2005, need ~2kJ
  - *Condition adequately satisfied*

* T.R. Jarboe,"Formation and steady-state sustainment of a tokamak by coaxial helicity injection," *Fusion Technology* **15**, 7 (1989).

Equilibrium and pre-ionization requirements

- The equilibrium coil currents provide the following:
  - An equilibrium for the target closed current when the open field line current is back to zero
  - Define $\lambda_{inj} = \mu_o I_{inj} / \Psi_{inj}$ $\lambda_{ST} = \mu_o I_p / \Psi_{toroidal}$
  - The initial injector flux with a narrow enough footprint and with $\lambda_{inj} > \lambda_{ST}$.

- Gas puff provides the following:
  - Just enough gas for breakdown (need j/n > 10-14Am, Greenwald)
  - Highest density at the injector

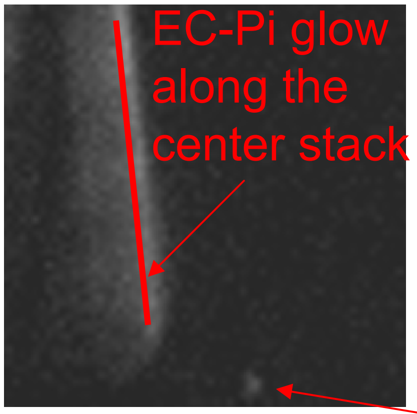
- ECH provides the following:
  - Pre-ionization for rapid and repeatable breakdown
  - Initial plasma in the injector gap

Capacitor bank used in Transient CHI Experiments

Maximum rating:

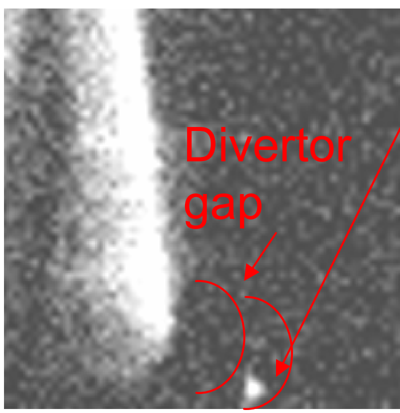
- 50 mF (10 caps), 2 kV
- Operated reliably at up to 1.5kV (4 caps)
- Produced reliable breakdown at ~ 1/3rd the previous gas injection amount
  - Constant voltage application allowed more precise synchronization with gas injection
  - EC-Pi and gas injection below divertor used for Pre-ionization assist

Last year we improved pre-ionization to a level that results in injected gas 10 times less than in 2004



Shot 116565
603.4ms
B_T = 0.35T
1.4 Torr.L gas injection

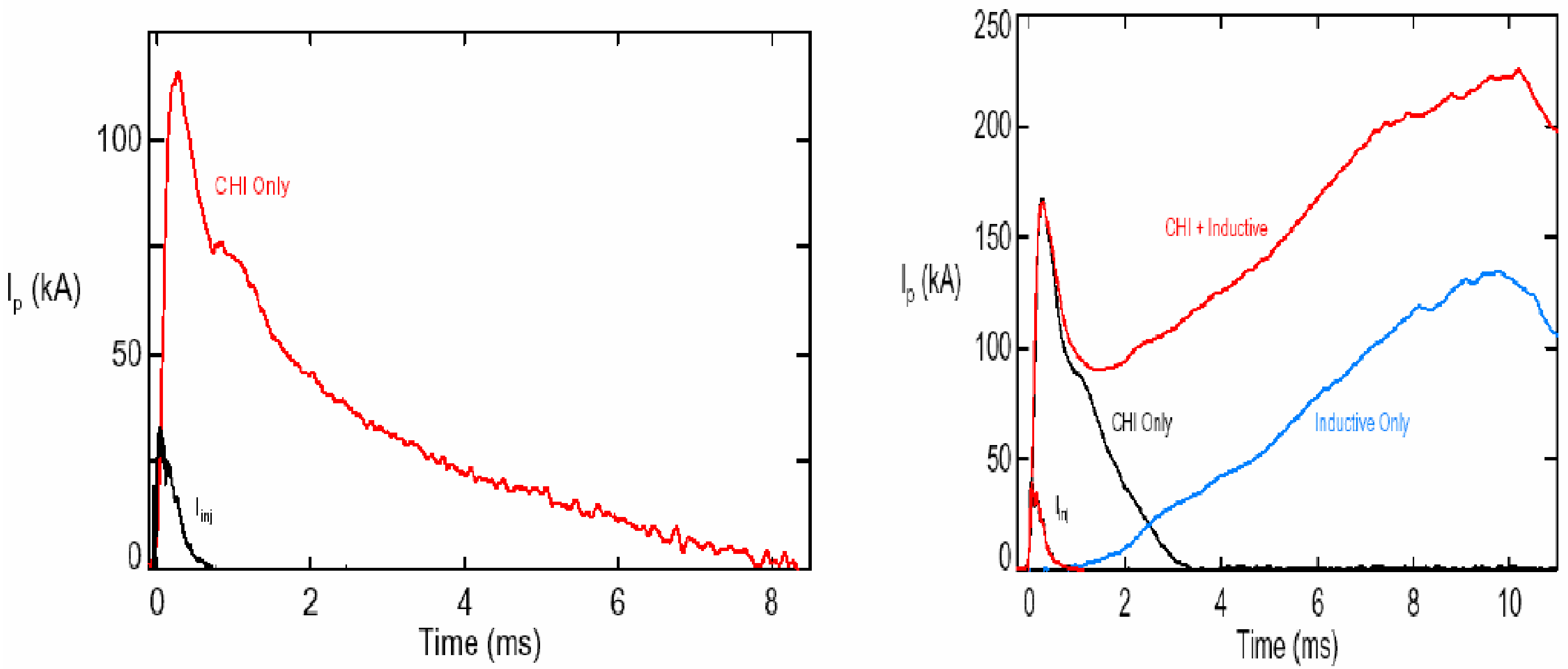
The small glow shown by the arrow is in the gap between the lower divertor plates and it is produced solely by EC-Preionization of the gas injected below the lower divertor plates. No voltage is applied.



Shot 116570
602.2ms
B_T =0.35T
0.7 Torr.L gas injection

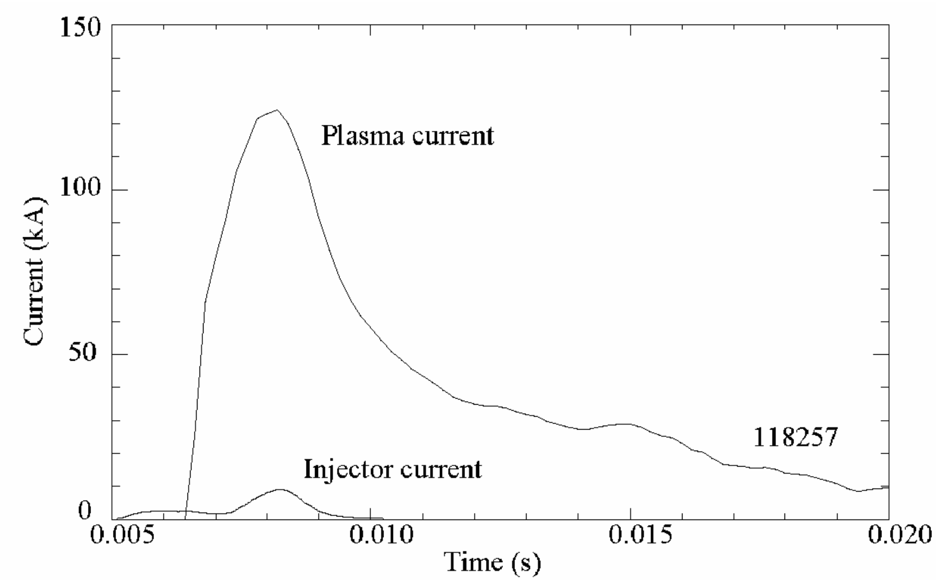
- Novel pre-ionization system
  - Injects gas and 10-20kW of 18GHz ECH in a cavity below the lower divertor gap
  - Successfully tested, achieved discharge generation at injected gas amount of < 2 Torr.Liter
- Fast Crowbar system
  - Rapidly reduces the injector current after the CHI discharge has elongated into the vessel.

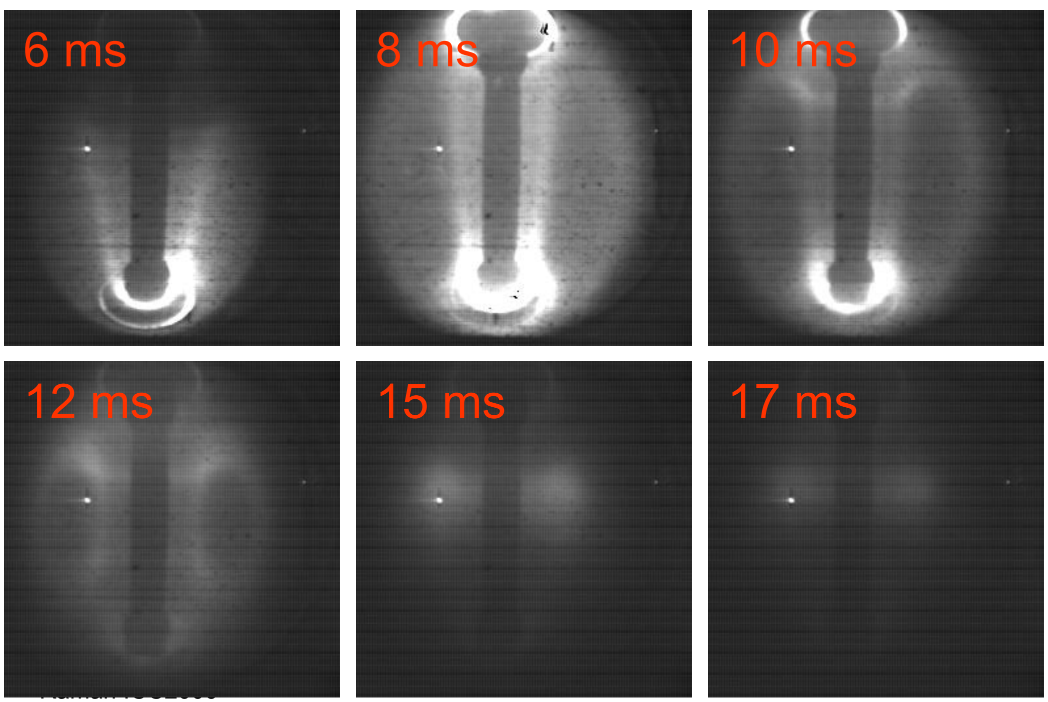
In HIT-II, nearly all of the closed flux current is retained by the subsequent inductive drive



- Note the persistence of CHI plasma current after the injector current has been reduced to zero
- Both discharges have identical loop voltage programming

Closed flux current generation by Transient CHI

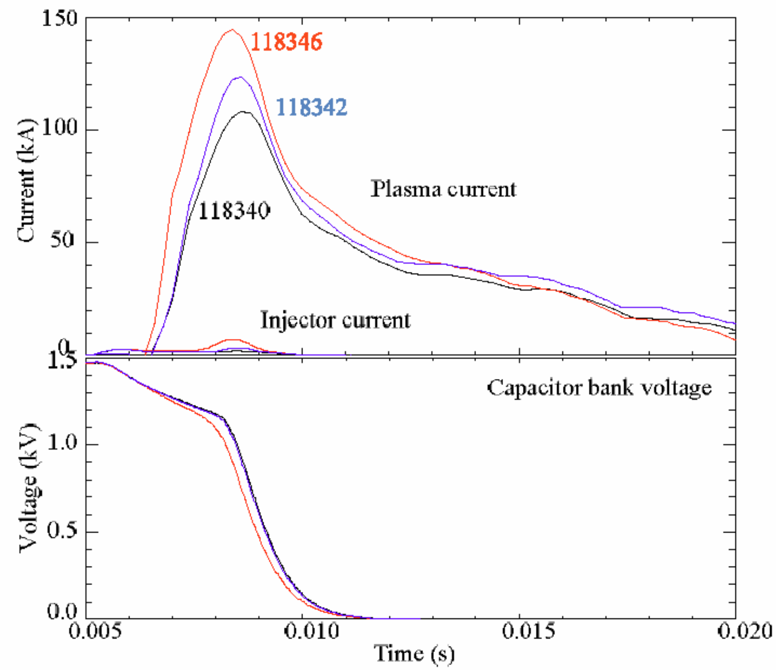


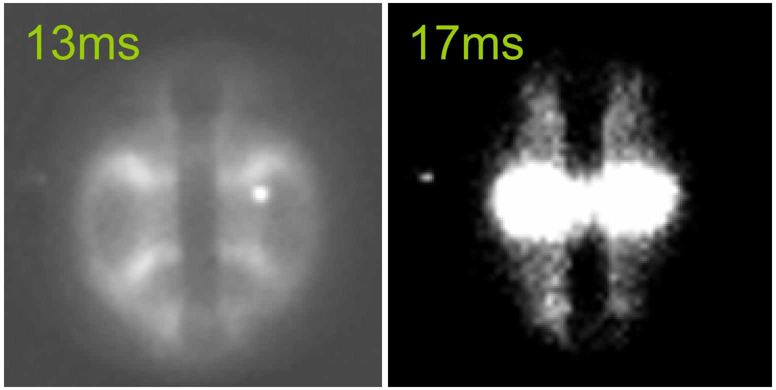


- Plasma current amplified many times over the injected current.
- The sequence of camera images shows a fish eye image of the interior of the NSTX vacuum vessel. The central column is the center stack, which contains the conventional induction solenoid. The lower bright region seen at 6ms is the injector region.

Hiroshima University (N. Nishino) Camera Images: R. Kaita (PPPL)

Fast camera images and Thomson data from CHI current persistence shot 118342





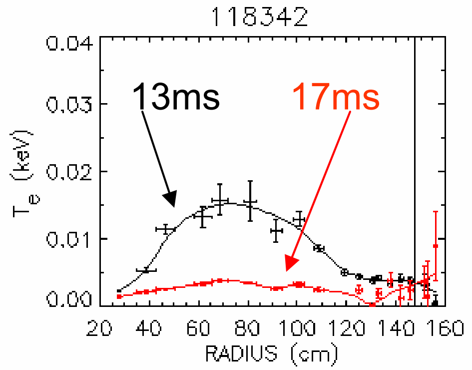
Good Thomson T_e and n_e profiles obtained when fast camera shows presence of closed flux region

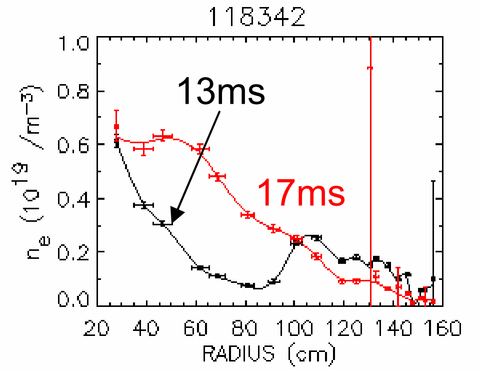
Movement of discharge towards CS seen in the Thomson density profile, consistent with the camera image

Te measurements made when cap bank current is zero

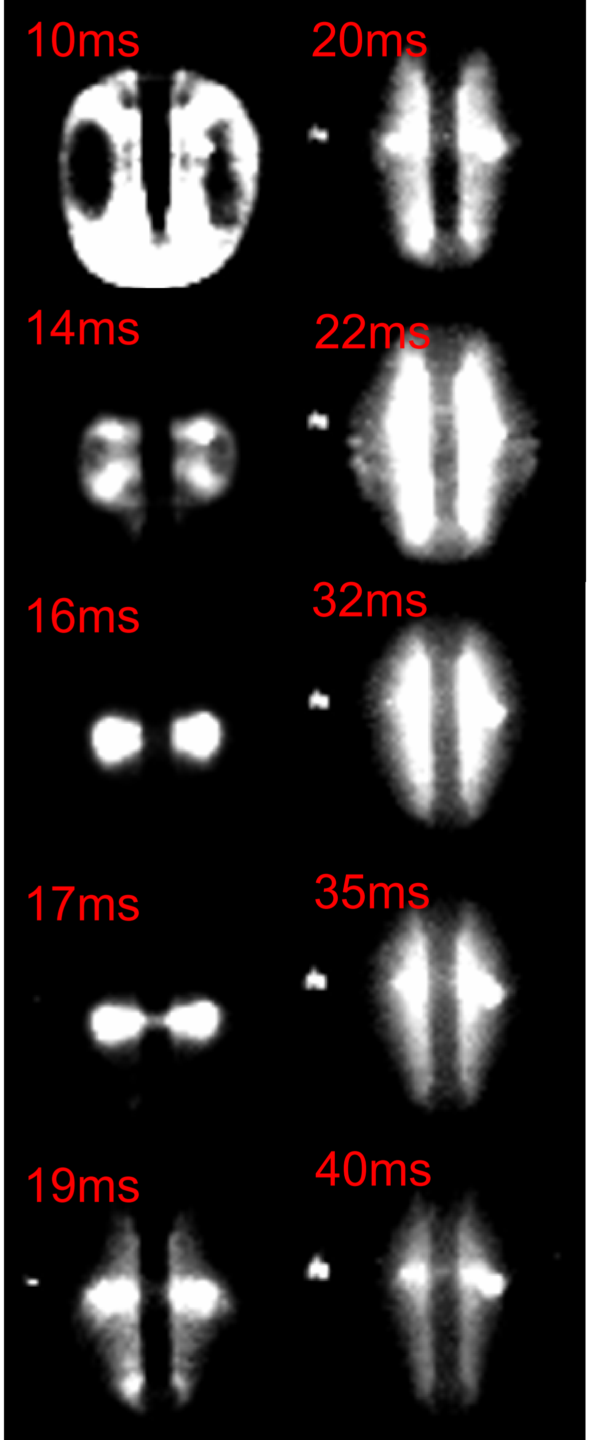
>60kA of closed flux current generated using Transient CHI

Unambiguous closed flux current generation is clearly demonstrated in these discharges.

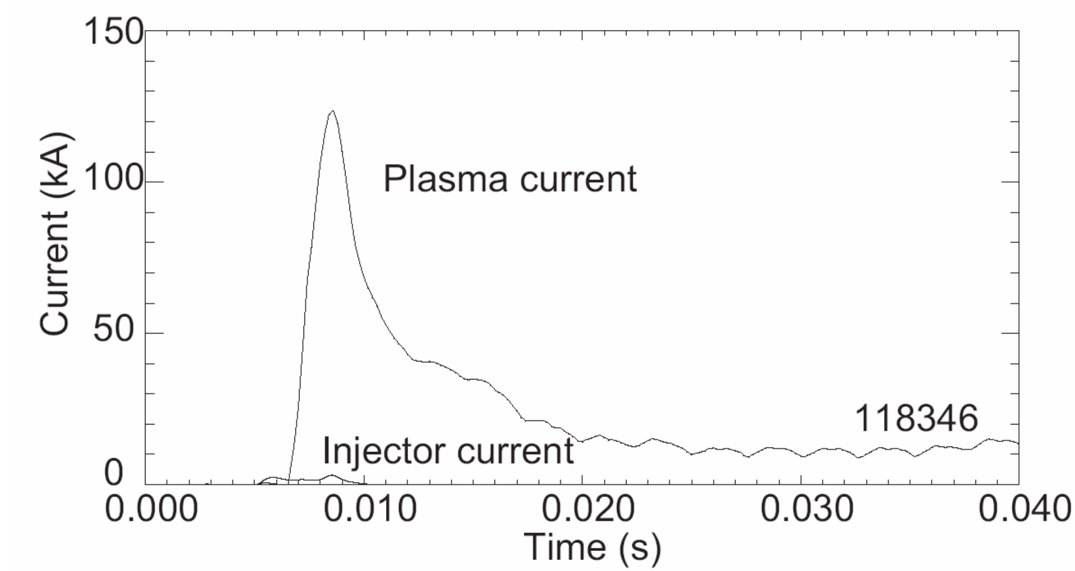




Phantom Camera Images: R. Maqueda (Nova Photonics)
Thomson: B. LeBlanc (PPPL)

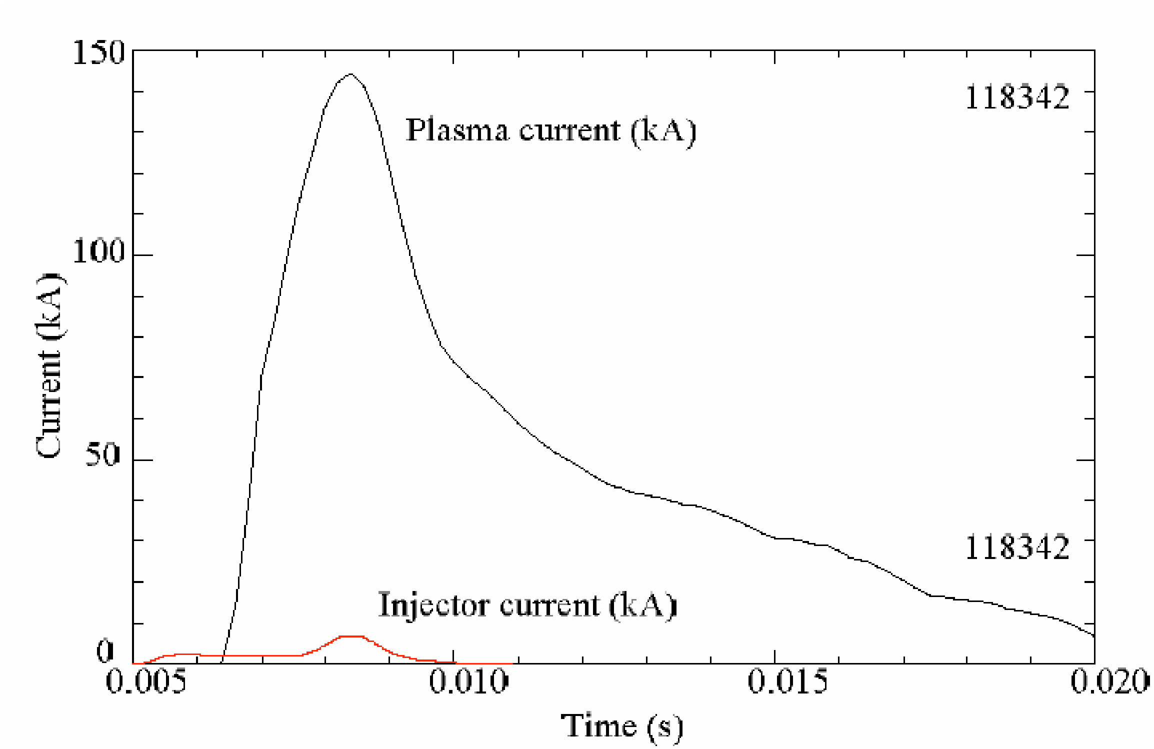


Some discharges have current persistence well beyond 20ms

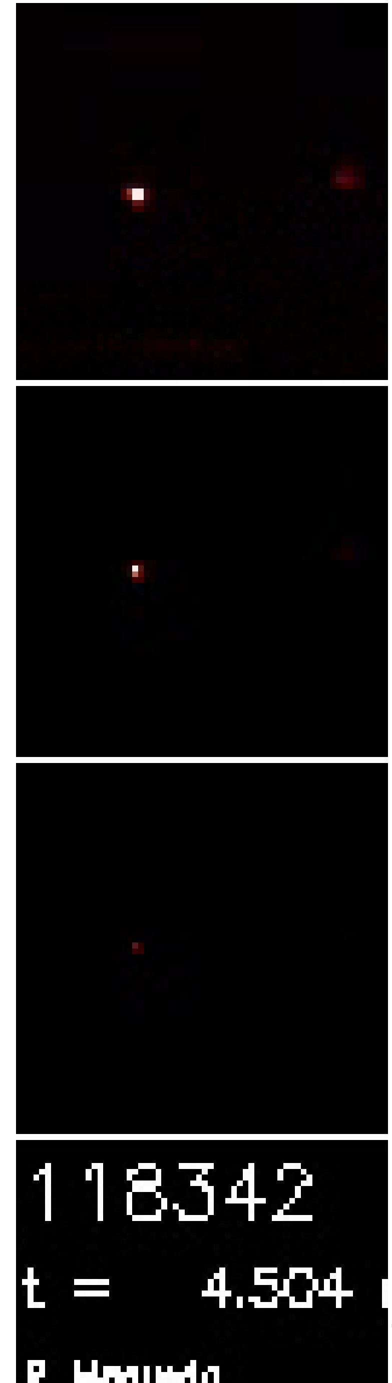


Until t=19ms, the plasma continues to shrink in size along the CS. Then for the subsequent 15ms, it becomes diffuse and spreads along the center column. As seen at 22ms, there are diffuse structures indicating field lines at larger major radius near the mid-plane, Then starting at about 35ms, the elongation shrinks and it once again becomes a small more discharge localized to the mid-plane for the subsequent 200 to 400ms.

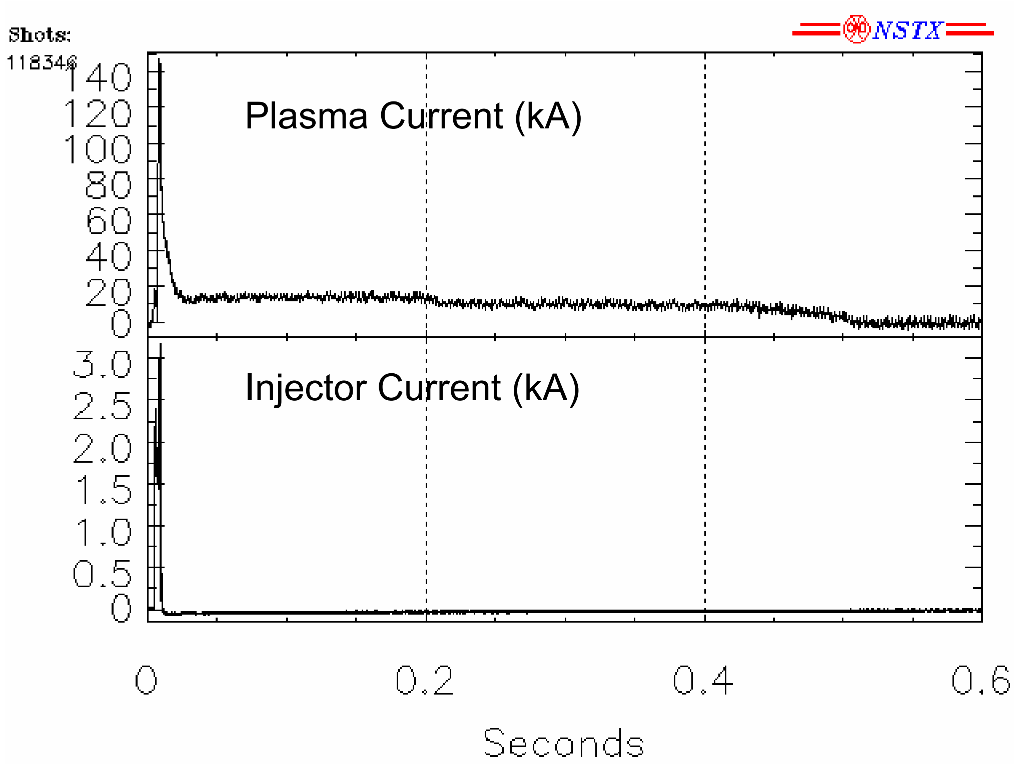
Fast camera movie of a short duration transient CHI discharge (shot 118342)

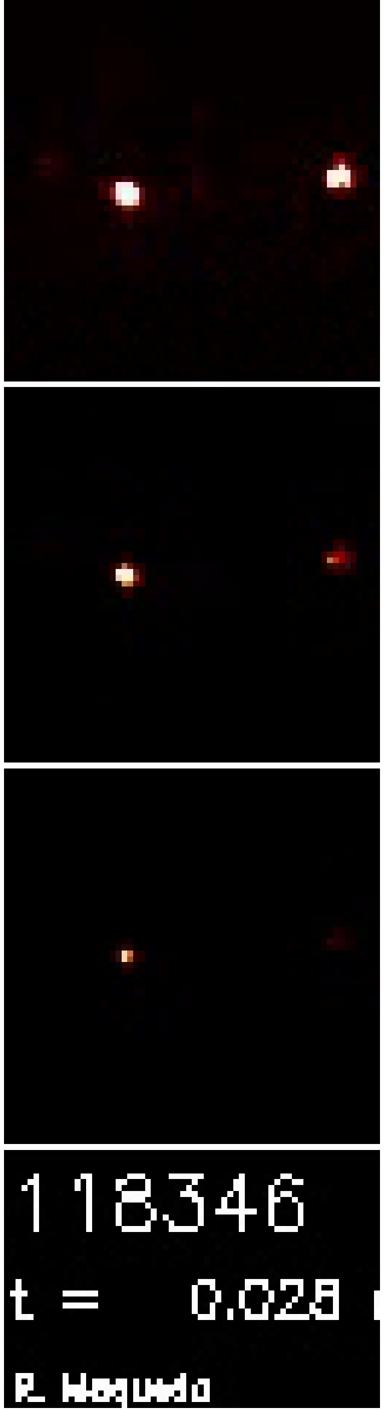


As time progresses, the CHI produced plasma gradually shrinks in size and forms a ring around the center stack



Some discharges persist for t > 200ms (shot 118346)





- In this discharge, the after the plasma shrinks to a small size, it continues to persist for nearly 400ms.

- Plasma parameters for this persisting plasma have not yet been measured.

Summary and Conclusions

- Generation of closed flux current in a ST, without the use of a solenoid now demonstrated by CHI
- 100kA of closed flux current generated in HIT-II
  - This current is retained during an inductive ramp
  - Demonstrates CHI can produce discharges of quality comparable to inductive discharges
  - On HIT-II CHI capability almost doubles what induction alone can achieve
- In initial experiments, 60kA of closed flux current generated in NSTX
  - 7kJ of capacitor bank energy used for this process
  - Very high current multiplication factors of 60 achieved in NSTX, which bodes well to extrapolation to larger machines
- In some discharges, the current channel shrinks to a small size and persists for more than 200ms
- **CHI is a method that was originally developed by the ICC program. It has now been usefully implemented on a large ST to address an issue essential to the viability of the ST concept.**