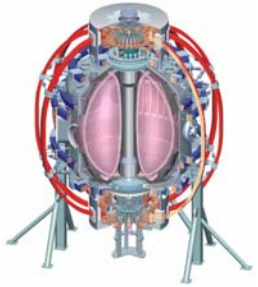
Supported by

Office of Science

NSTX

Plasma Start-up In NSTX Using Transient CHI



Roger Raman, Univ. of Washington

For the NSTX Team

48th Annual Meeting of the DPP

Monday–Friday, October 30–November 3, 2006

Philadelphia, Pennsylvania

Acknowledgments

T.R. Jarboe, D. Mueller, B.A. Nelson, M.G. Bell, M. Ono, M.J. Schaffer

Institutions

Univ. of Washington, PPPL, ORNL, GA, Nova Photonics

College W&M
Colorado Sch Mines
Columbia U
Comp-X
General Atomics
INEL
Johns Hopkins U
LANL
LLNL
Lodestar
MIT
Nova Photonics
New York U
Old Dominion U
ORNL
PPPL
PSI
Princeton U
SNL
Think Tank, Inc.
UC Davis
UC Irvine
UCLA
UCSD
U Colorado
U Maryland
U Rochester
U Washington
U Wisconsin

Culham Sci Ctr
U St. Andrews
York U
Chubu U
Fukui U
Hiroshima U
Hyogo U
Kyoto U
Kyushu U
Kyushu Tokai U
NIFS
Niigata U
U Tokyo
JAERI
Hebrew U
Ioffe Inst
RRC Kurchatov Inst
TRINITI
KBSI
KAIST
ENEA, Frascati
CEA, Cadarache
IPP, Jülich
IPP, Garching
ASCR, Czech Rep

Outline

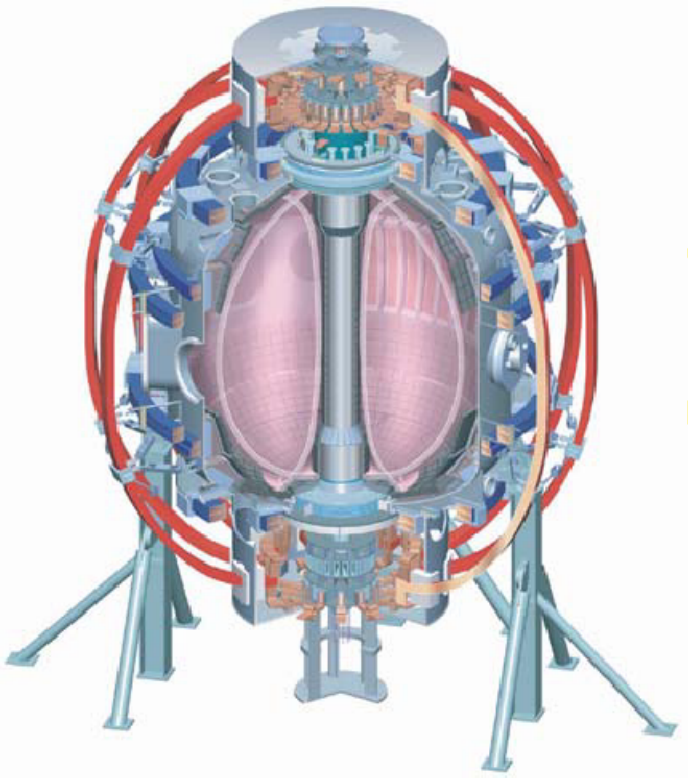
- Motivation for solenoid-free plasma startup
- Implementation of Coaxial Helicity Injection (CHI) in NSTX
- Requirements for Transient CHI
- Experimental results from NSTX
- Brief summary of HIT-II results

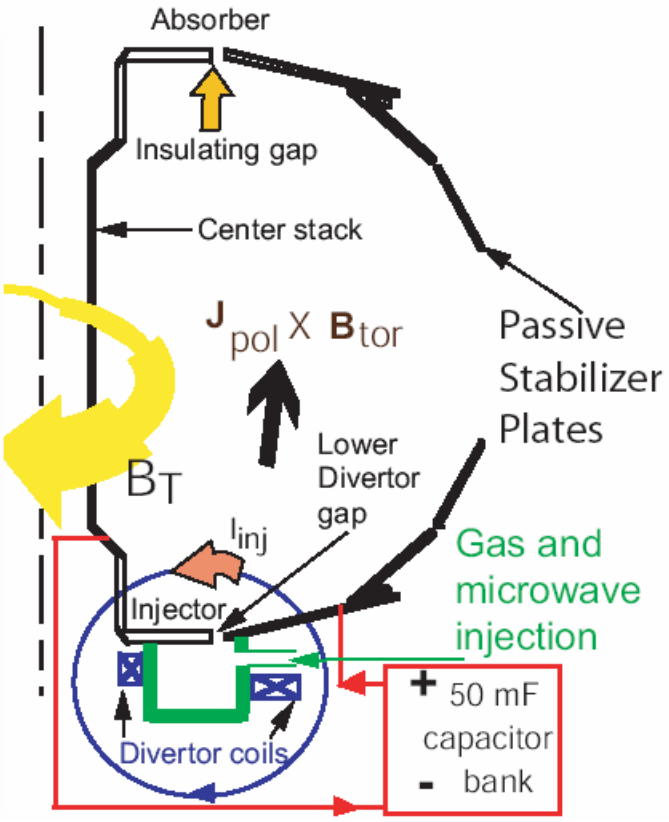
160 kA of closed flux current produced in NSTX, without using a solenoid

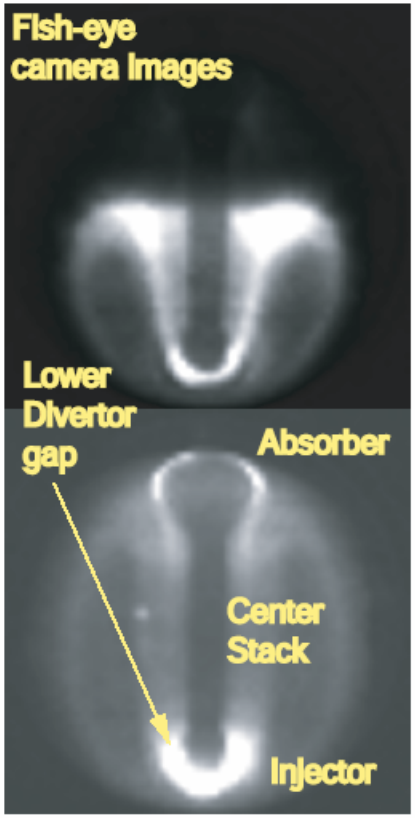
- Transient Coaxial Helicity Injection (CHI), previously demonstrated on HIT-II* at U- Washington
- Important step in the production of a starting equilibrium for solenoid free operation
- Conventional tokamak uses solenoid
  - ARIES-AT has no solenoid
- ST has advantages of high β and good τ_E
  - ST reactor cannot use solenoid
  - Alternate method for plasma startup is essential for ST concept
  - Could also reduce the cost of a future tokamak reactor

*R. Raman, T.R. Jarboe, B.A. Nelson *et al.*, Phys Rev. Lett. **90** 075005 (2003)

NSTX incorporates toroidal insulation breaks to enable CHI operation







Transient CHI: Axisymmetric reconnection leads to formation of closed flux surfaces.
Driven (Steady State) CHI: Non-axisymmetric modes needed for closed flux generation

Fast Camera (R. Maqueda, Nova Photonics & L. Roquemore, PPPL)

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

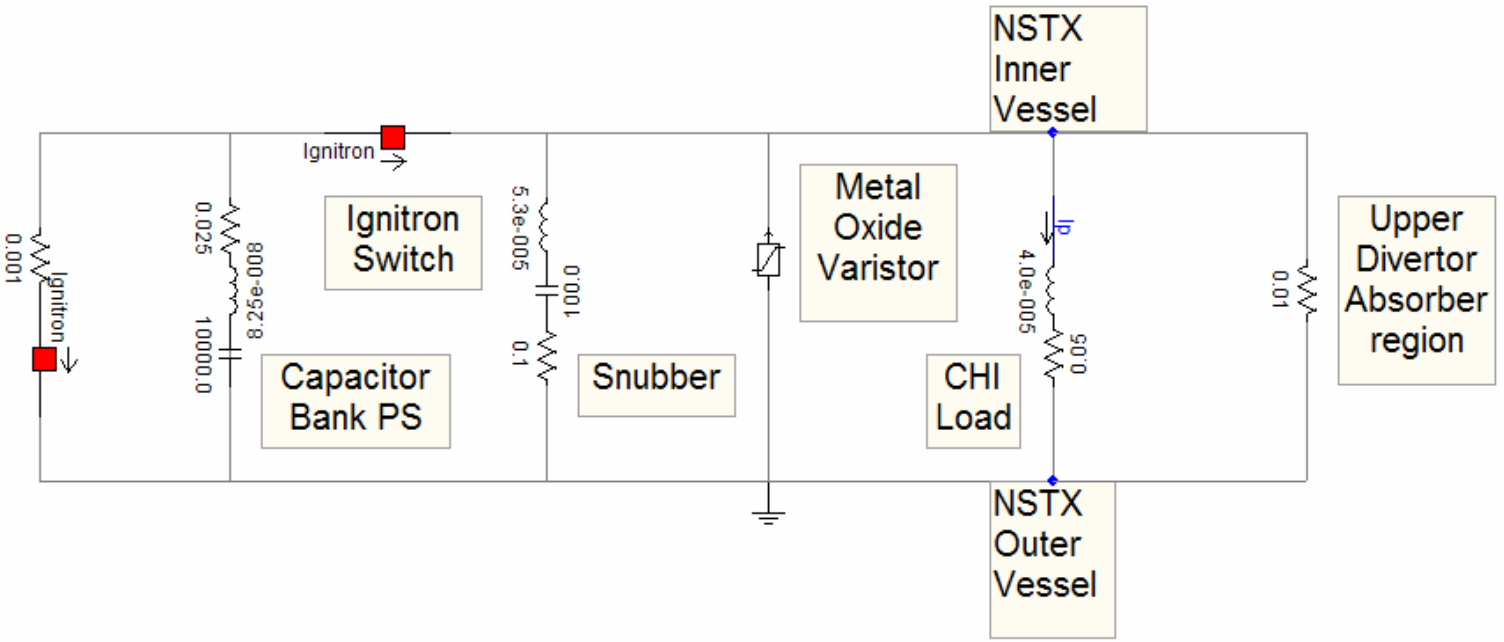
- Time needed to displace toroidal flux
  - For typical voltage at the injector after breakdown ~500V need ~1 ms to displace 600 mWb

- 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

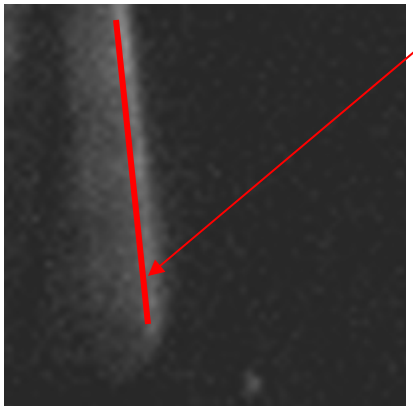
* T.R. Jarboe Fusion Tech. **15**, 7 (1989)

Upgrades that enabled progress in Transient CHI

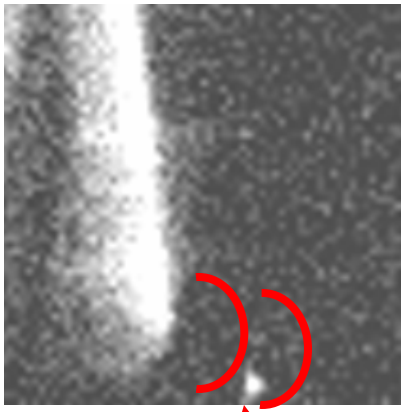


- Replaced rectifier PS with capacitor PS
- Added MOV and Snubber
- Gas & microwave injection from lower divertor region
- Improved Absorber insulator design
- Discharge resistor across capacitor bank

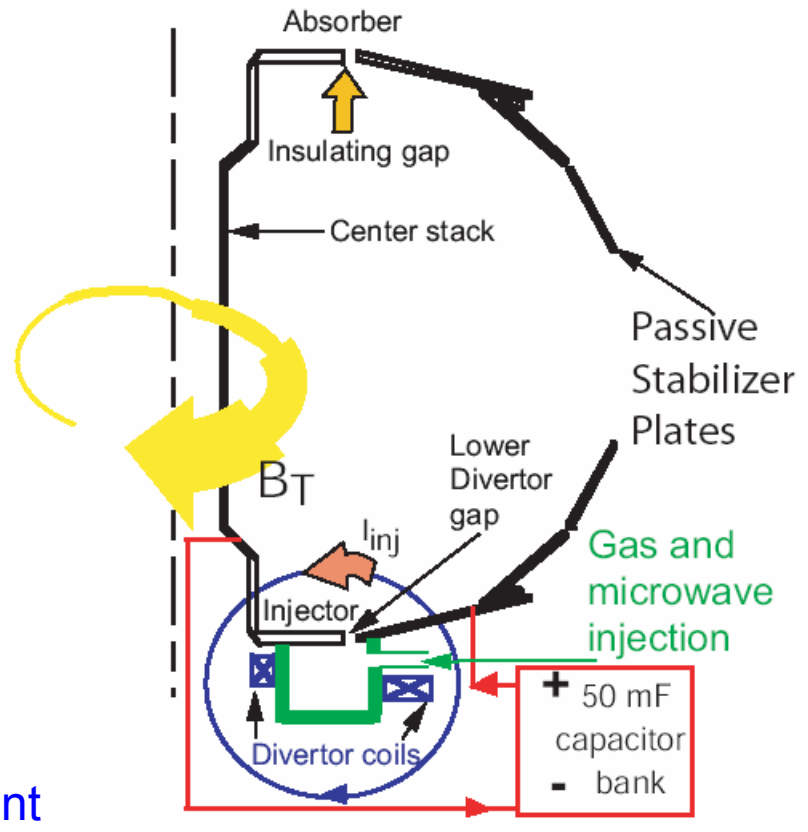
Improved pre-ionization to a level that results in injected gas 10 times less than in 2004



Location of center stack



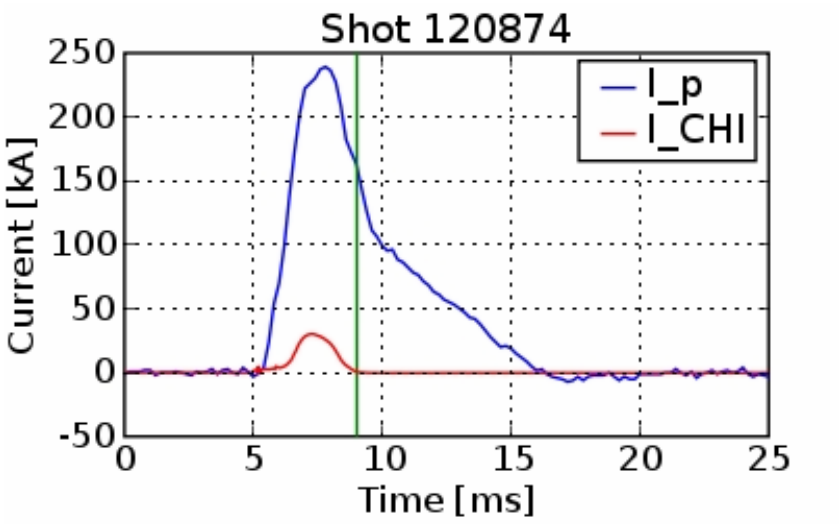
Divertor gap

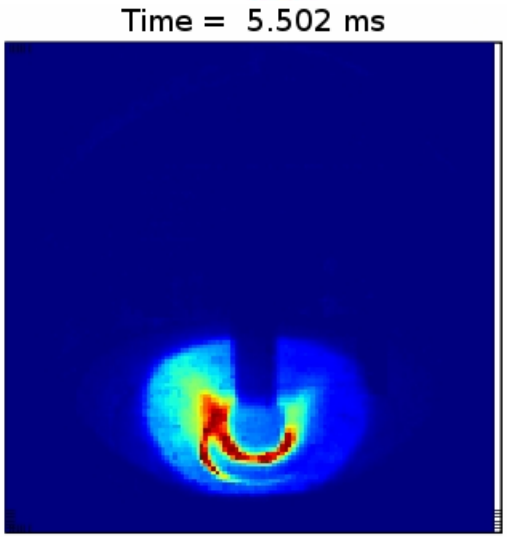


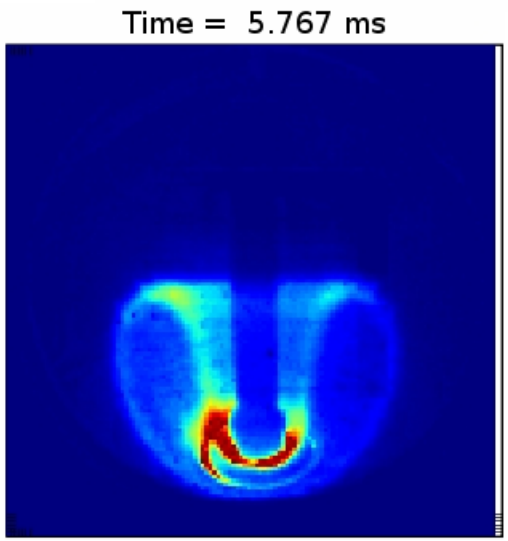
Injected gas amount now same as that used for inductive discharges

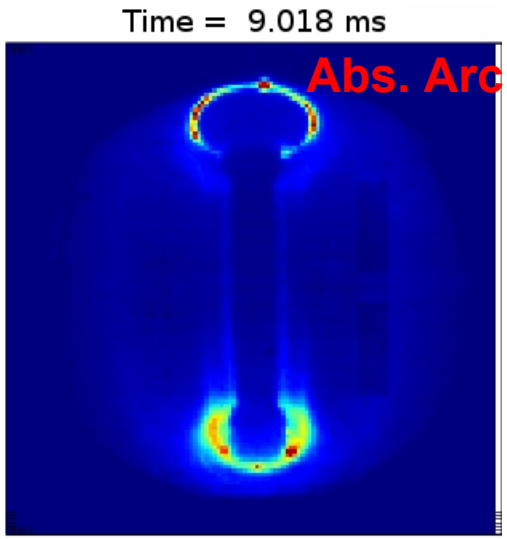
ECH: T. Bigelow (ORNL)

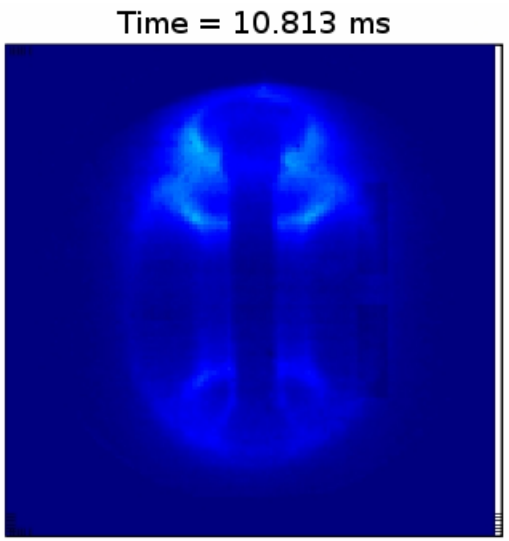
Closed flux current generation by Transient CHI





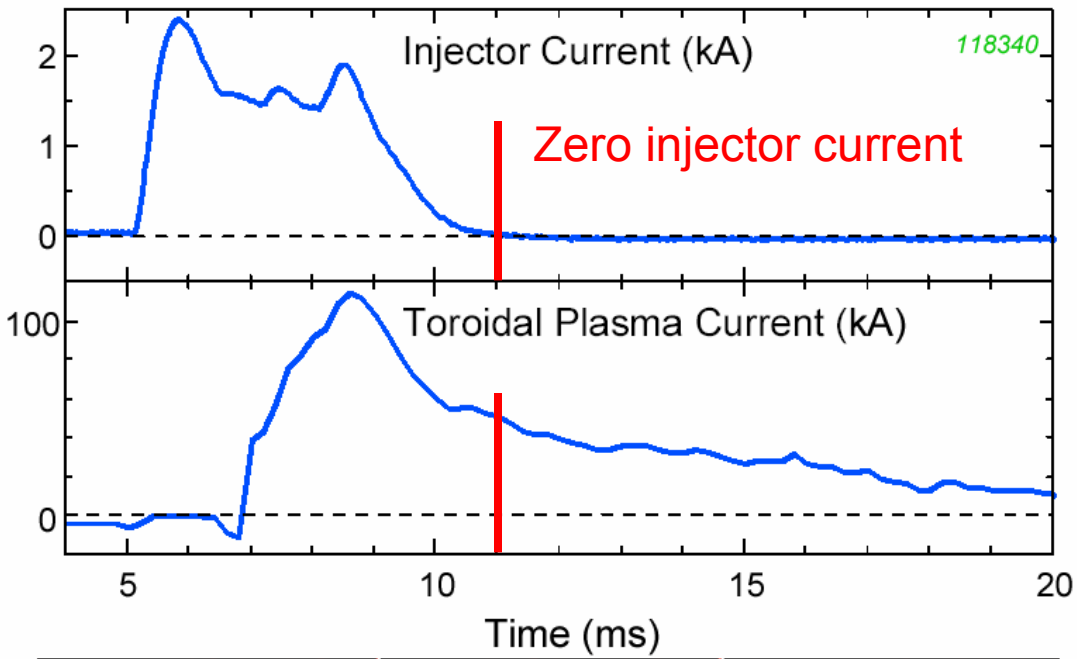




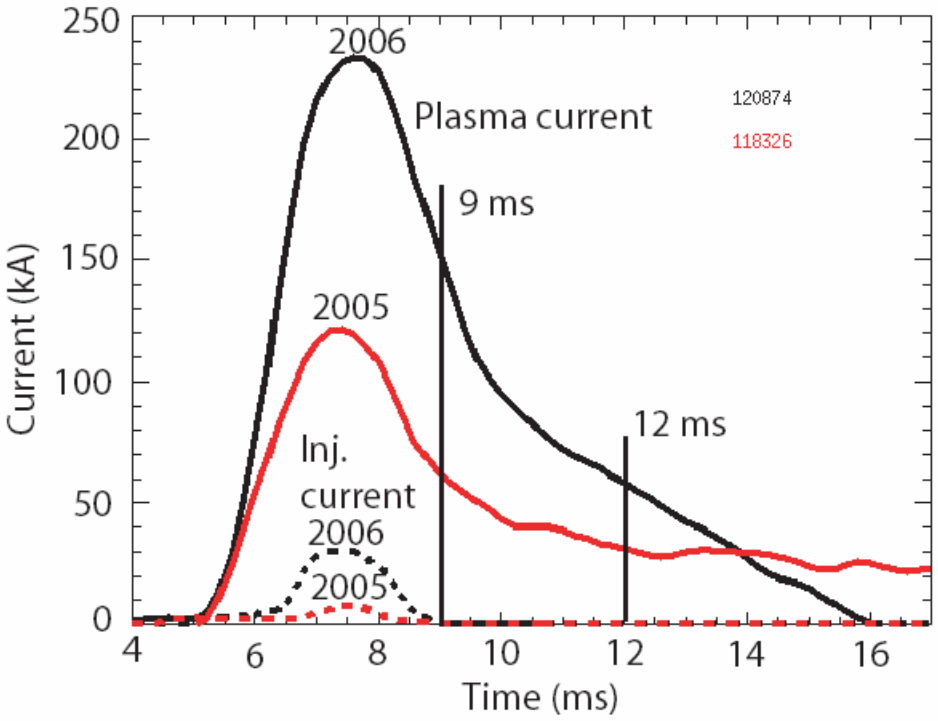


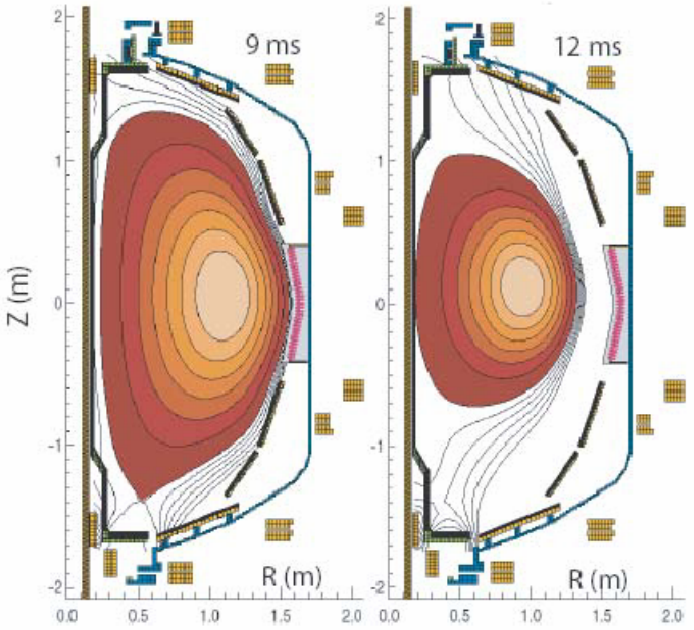
R. Raman, B.A. Nelson, MG.Bell, *et al.,* PRL **97**, 175002 (2006)

Discharges without an absorber arc show high current multiplication ratios of 60



Improvement in high current generation due to operation at higher voltage



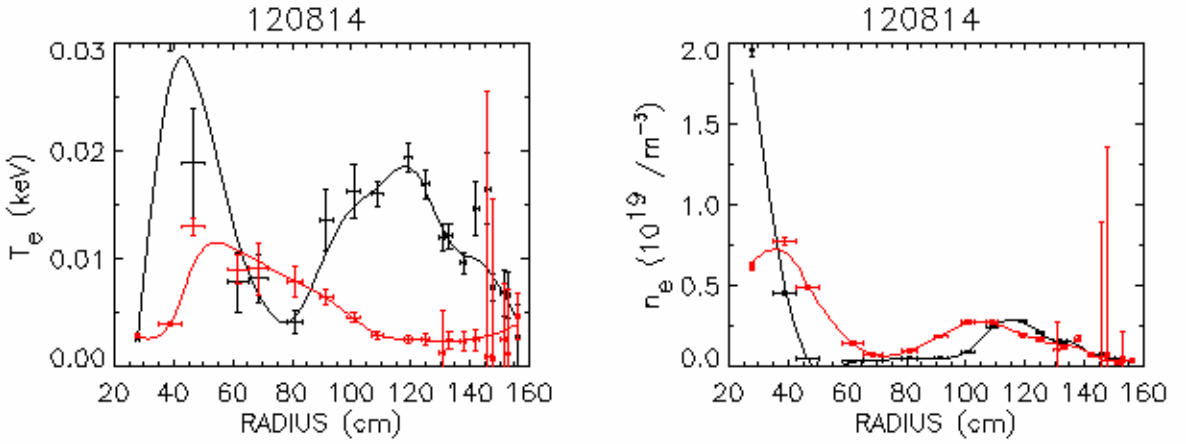


- 2006 discharges operated at higher toroidal field and injector flux
- EFIT is done when no injector current is present
- Magnetic sensors and flux loops used in reconstruction

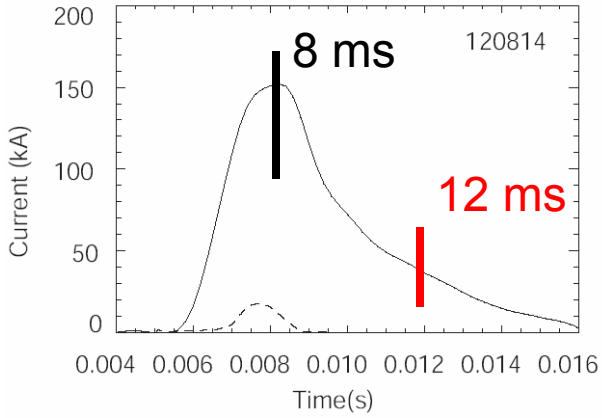
LRDFIT (J. Menard)

Electron temperature and density profiles become less hollow with time

120814: Black: 8ms, Red: 12ms



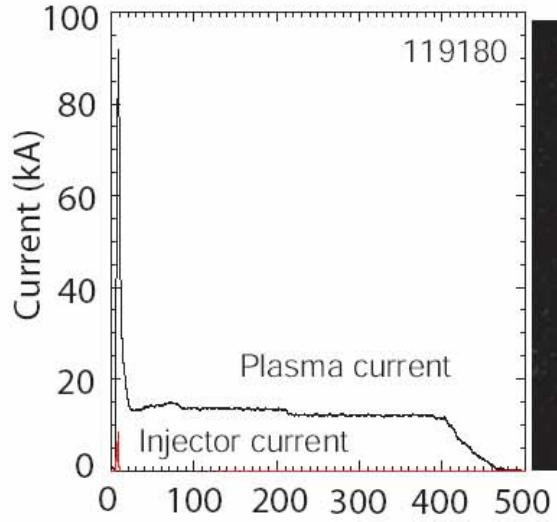
Profile becomes less hollow with time

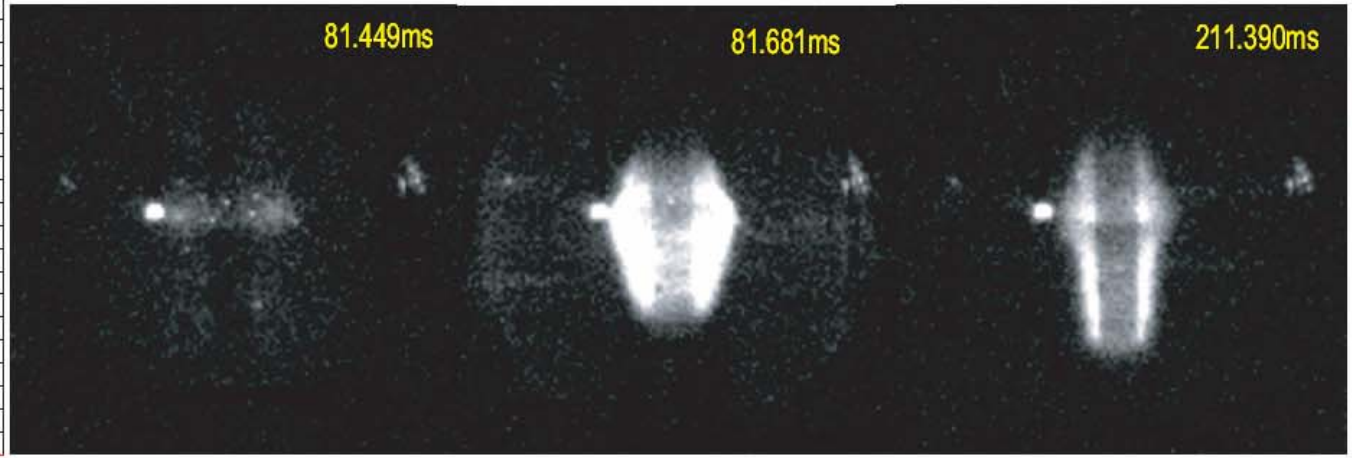


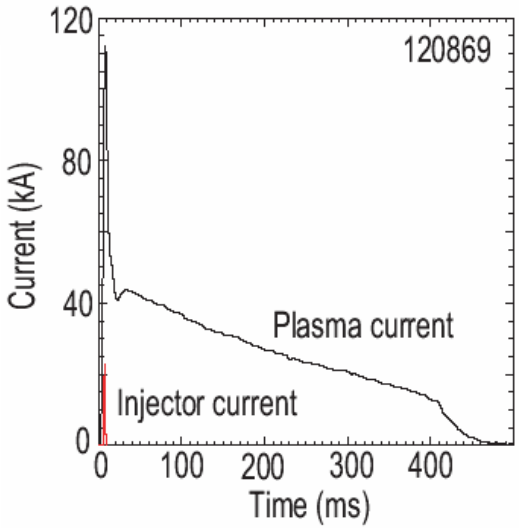
Plasma and Injector current

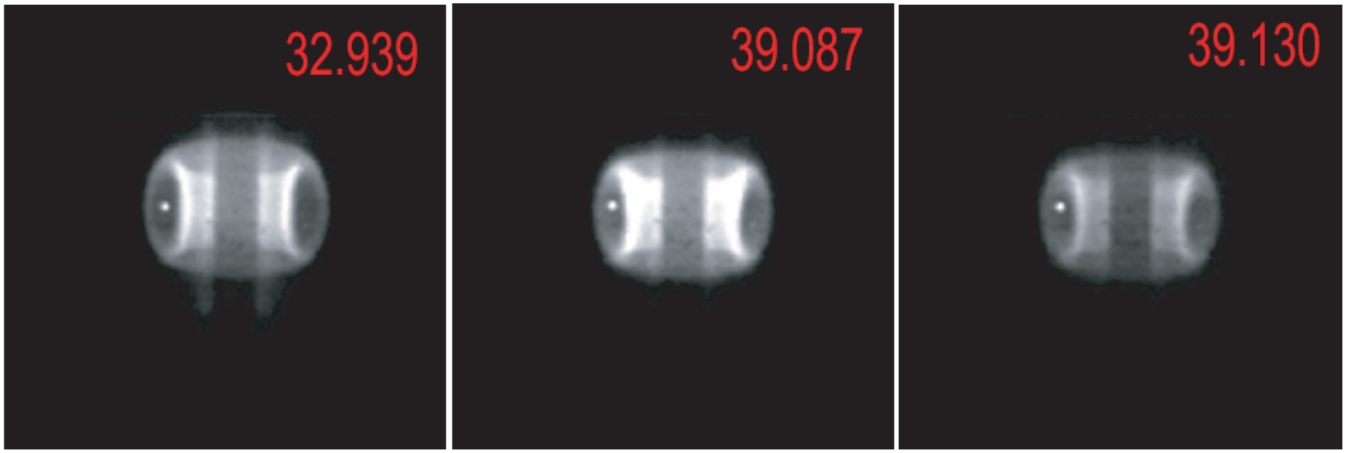
Thomson Scattering (B. LeBlanc)

Some discharges persist for as long as the equilibrium coil currents are maintained.





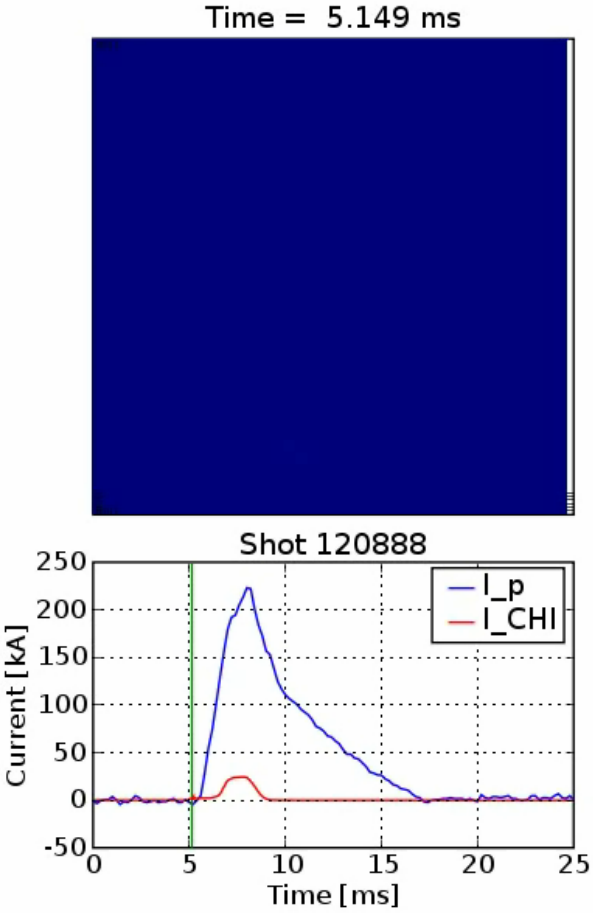




These discharges are sensitive to gas pressure

Fast camera: R. Maqueda

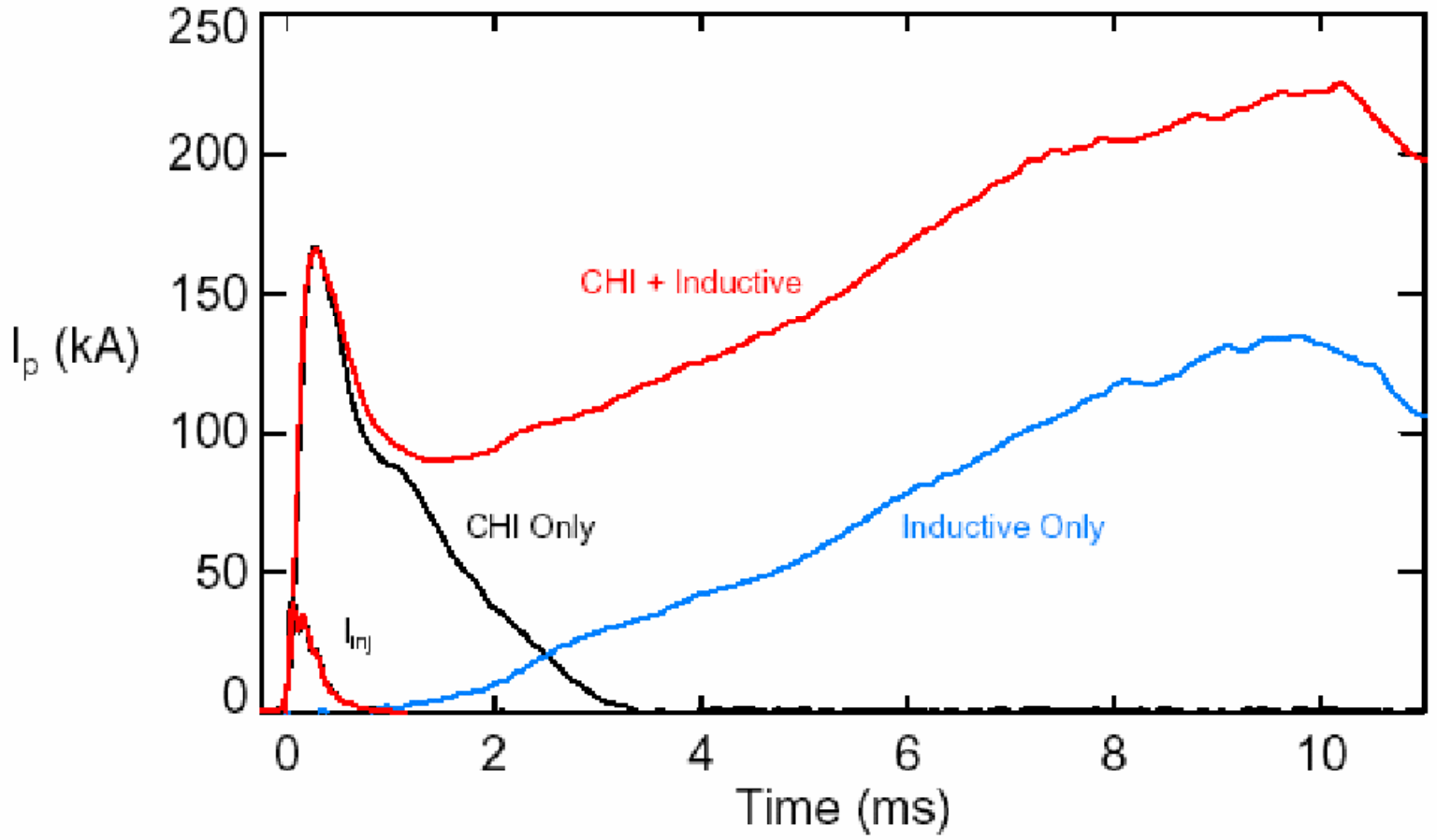
Movie of a high current discharge.



Fast Camera:
R. Maqueda &
L. Roquemore

Nearly all Transient CHI produced closed flux current couples to the subsequent inductive drive

HIT-II



Both discharges have identical loop voltage programming

Current multiplication needed for larger machines achieved on NSTX

- Attainable current multiplication (CM) is given as:

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

- For similar values of B_T, toroidal flux,

$$\psi_T^{NSTX} \sim 10 \cdot \psi_T^{HIT-II}$$

- So CM in NSTX should be 10x HIT-II, which is observed

- CM is understood from HIT-II and NSTX results

- No reason to believe CM will get worse in a larger machine (may get better)

Maximum injector currents determined by system voltage limits

- Assuming constant resistivity on field lines,

  For similar values of ψ_{inj} , at the same voltage,

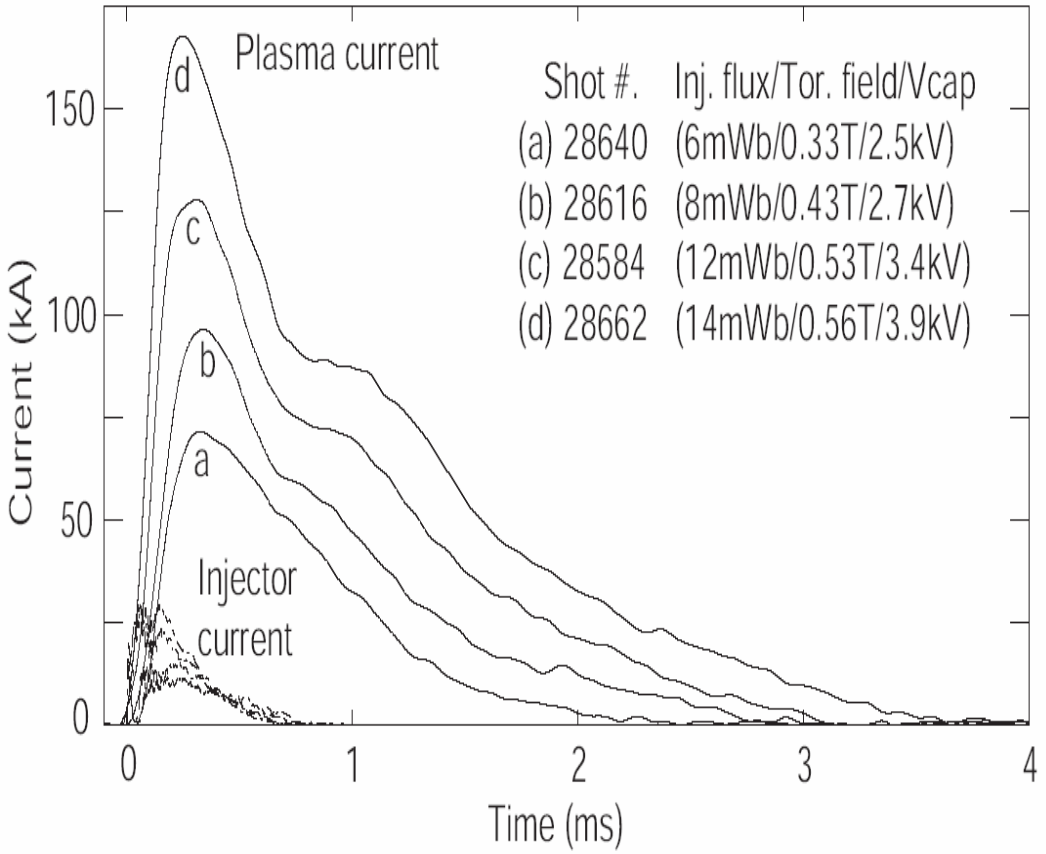
  $$I_{inj} \propto V_{inj} \cdot (\psi_{inj} / \psi_T)$$

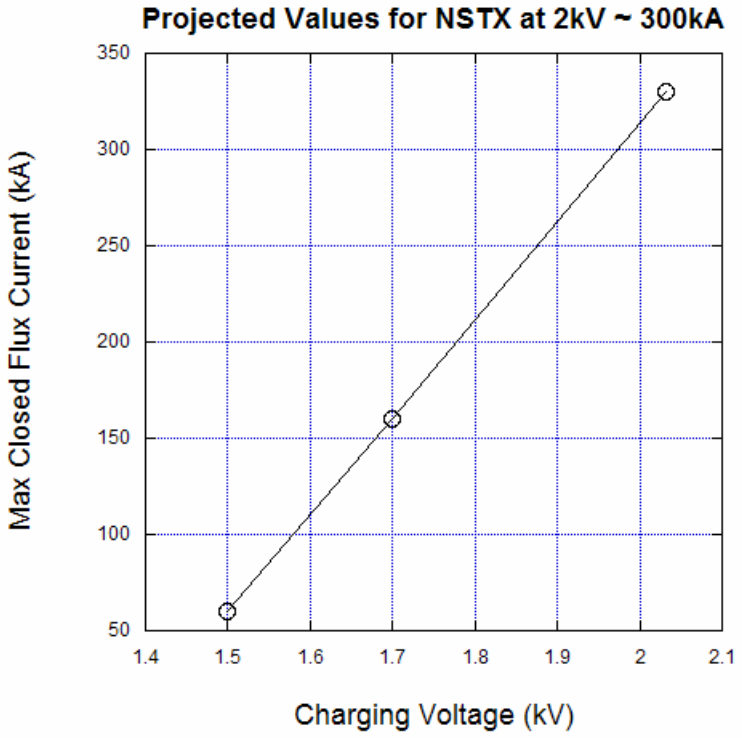
  I_{inj} in HIT-II should be ~10 x NSTX

- Consistent with observed I_{inj} ~15-30kA in HIT-II vs ~2-4 kA in NSTX
- Also consistent with the bubble burst relation, which requires 10x more current in HIT-II than in NSTX

- With 10-20kA of injector current MA levels of startup current should be possible in larger STs

Full 2kV capability in NSTX would increase Ip ~ 300kA.





HIT-II data: R. Raman, T.R. Jarboe *et al.*, Nuclear Fusion, **45**, L15-L19 (2005)

Voltage, flux optimization allowed HIT-II to increase closed flux current as capacitor charging voltage was increased

160kA closed flux current in NSTX validates feasibility of CHI for high current generation

- NSTX has addressed the plasma startup issue for the ST by demonstrating a viable alternate plasma startup method

1) demonstration of the process in a vessel volume thirty times larger than HIT-II on a size scale more comparable to a reactor,
2) a remarkable multiplication factor of 60 between the injected current and the achieved toroidal current, compared to six in previous experiments,
3) results were obtained on a machine designed with mainly conventional components and systems,
4) indicate favorable scaling with machine size
5) HIT-II results indicate efficient coupling to other current drive methods is feasible

- Future experiments in NSTX to explore coupling to OH
  - 200kW ECH to heat the CHI plasma
  - Coupling to RF and NBI