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HIT-II

Solenoid free plasma startup in HIT-II and NSTX by Coaxial Helicity Injection*

Speaker: Roger Raman

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2004 ST Workshop
28 – 30 September 2004
Kyoto University, Kyoto, Japan

***Research supported by U.S. DOE contract numbers. DE-FG03-96ER54361, DE-FG03-99ER54519**

Outline

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

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

NSTX

- Elimination of the central solenoid simplifies the engineering design of tokamaks (Re: ARIES AT & RS)
- CHI is capable of both plasma start-up and edge current in a pre-established diverted discharge
  - Edge current profile for high beta discharges

CHI research on NSTX focuses on three areas

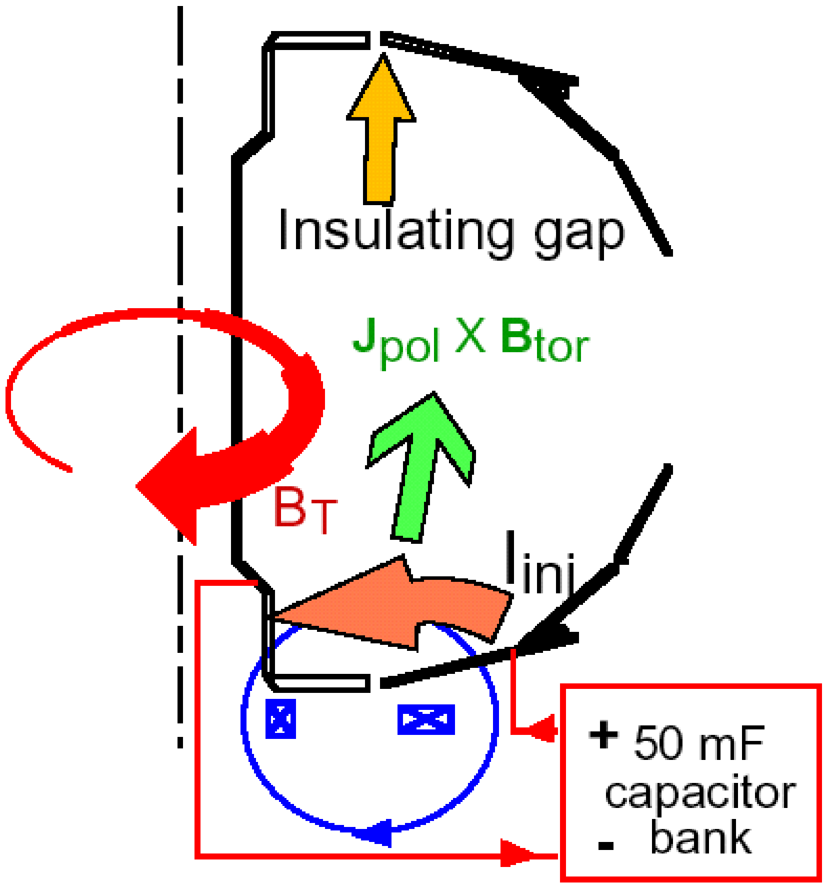
1. Solenoid-free plasma startup
   - New method referred to as ***Transient CHI*** * is being implemented

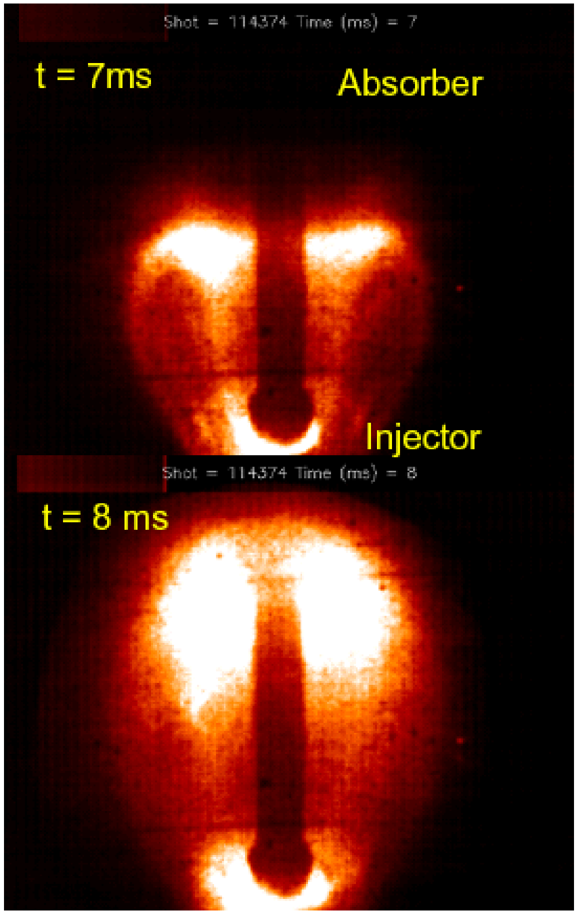
2. Edge current drive
   - Controlling edge SOL flows
   - Improving stability limits
   - Induce edge rotation

3. 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: C. Bush (ORNL)

Capacitor bank requirements for Transient CHI

NSTX

Bubble burst current that is equal I_{inj}

- $I_{inj} \propto \Psi^2_{inj}/\Psi_{toroidal}$ (easily met)*

Volt-seconds to replace the toroidal flux

- For $\Psi_{toroidal}$ 600 mWb, at ~500V need ~1.2ms just for current rampup - *OK, but will improve at higher voltage*

Energy for peak toroidal current ($LI^2/2$, $L=1\mu H$)

- Maximum possible Ip (at 17.5 kJ) ~ 190 kA (achieved ~ 140 kA)
- *Need to increase Ecap*

Energy for ionization of all injected gas and heating to 20eV (~50eV/D)

- At lowest gas pressure 16.8 Torr.L injected, need ~21kJ just to ionize and heat – *Need to reduce total injected gas*

* 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
- The initial injector flux with a narrow enough footprint and high enough value so that λ_{inj} is higher than the target λ_{ST}.

$$\lambda_{inj} = \mu_o I_{inj} / \Psi_{inj} \qquad \lambda_{ST} = \mu_o I_p / \Psi_{toroidal}$$

Gas puff provides the following:

- Just enough gas for breakdown (need $j/n > 10^{-14}$Am, Greenwald)
- Highest density at the injector

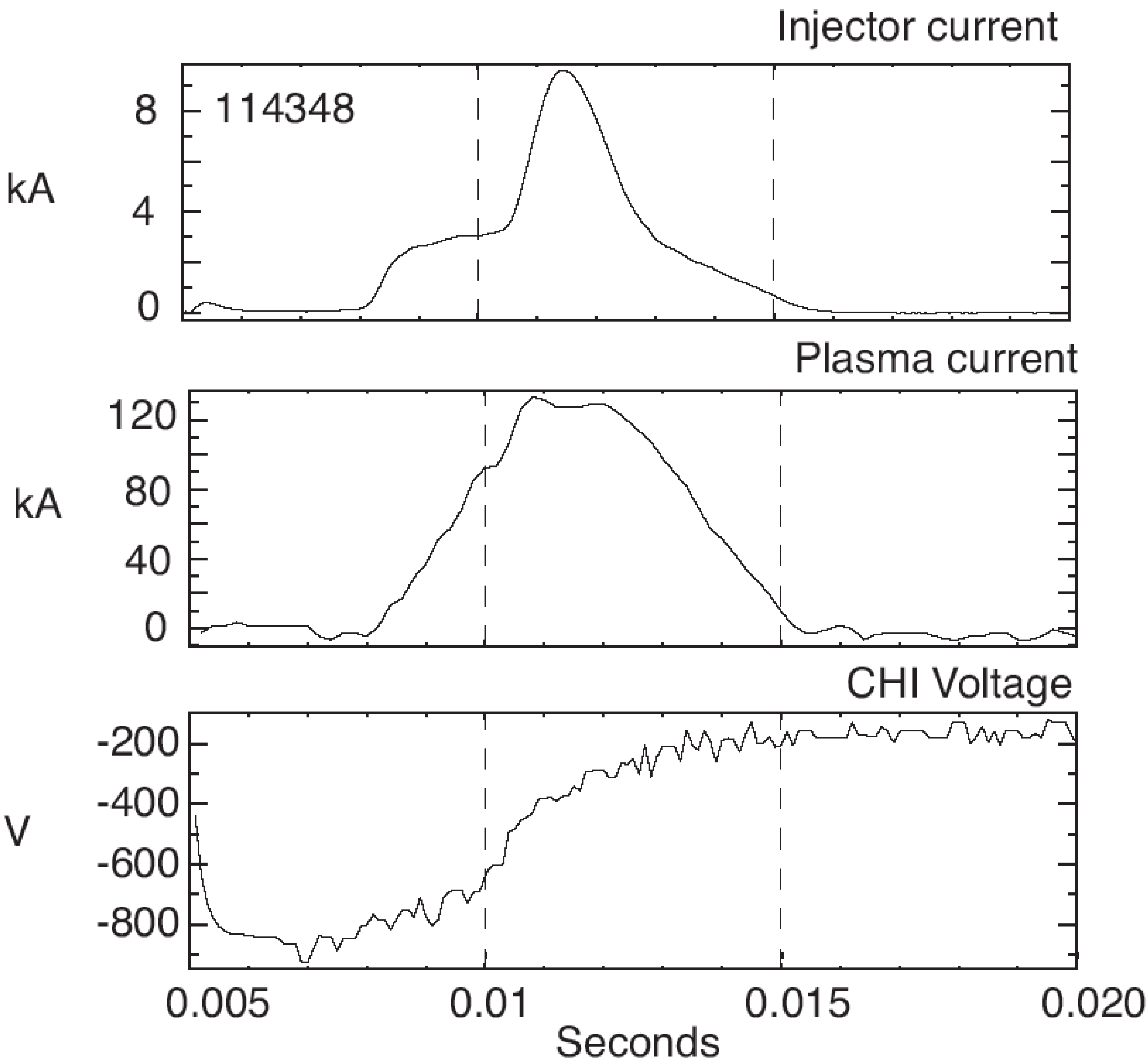
ECH provides the following:

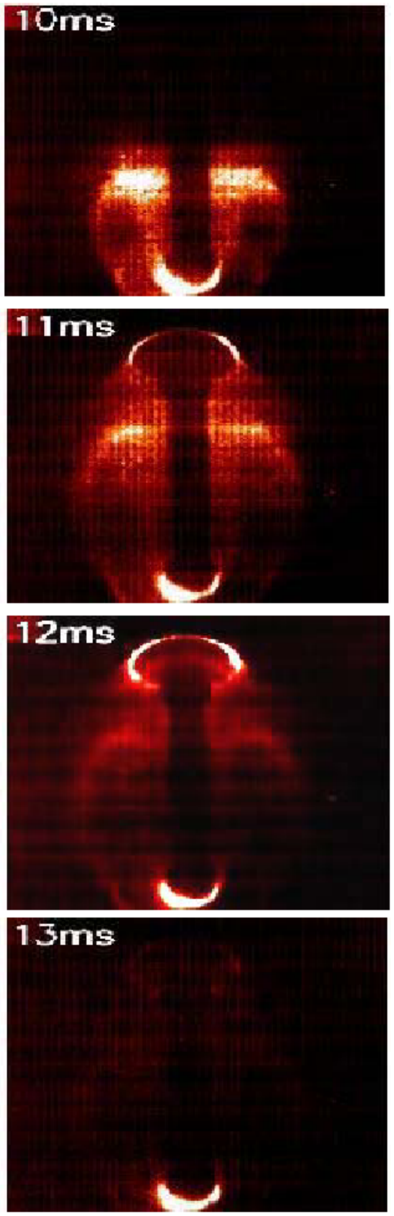
- Pre-ionization for rapid and repeatable breakdown
- Initial plasma in the injector gap

Capacitor bank for Transient CHI commissioned

- Maximum rating:
  50 mF (10 caps), 2 kV
- Operated reliably at up to 1kV (7 caps, 17.5 kJ)
- Produced reliable breakdown at ~ 1/ 3rd the previous gas pressure
  - Constant voltage application allowed more precise synchonization with gas injection
  - HHFW used for Pi assist

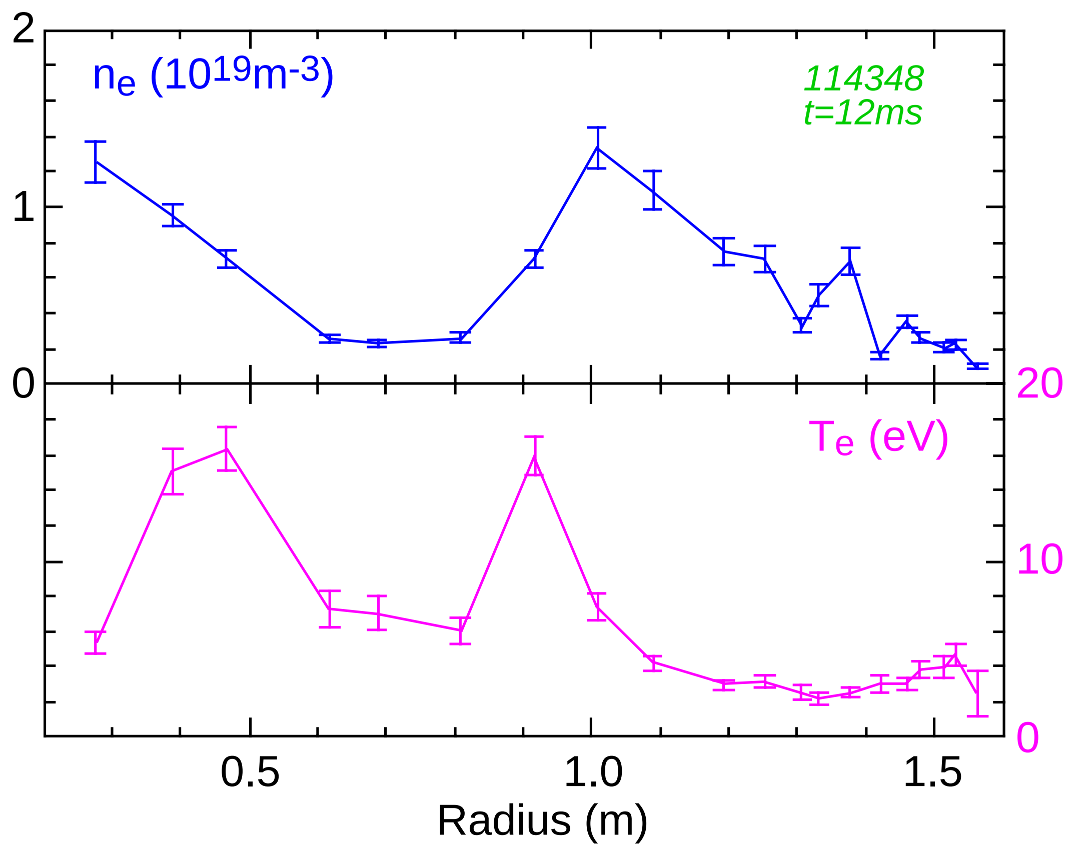
Initial transient CHI discharge in NSTX





Current persistence not yet observed

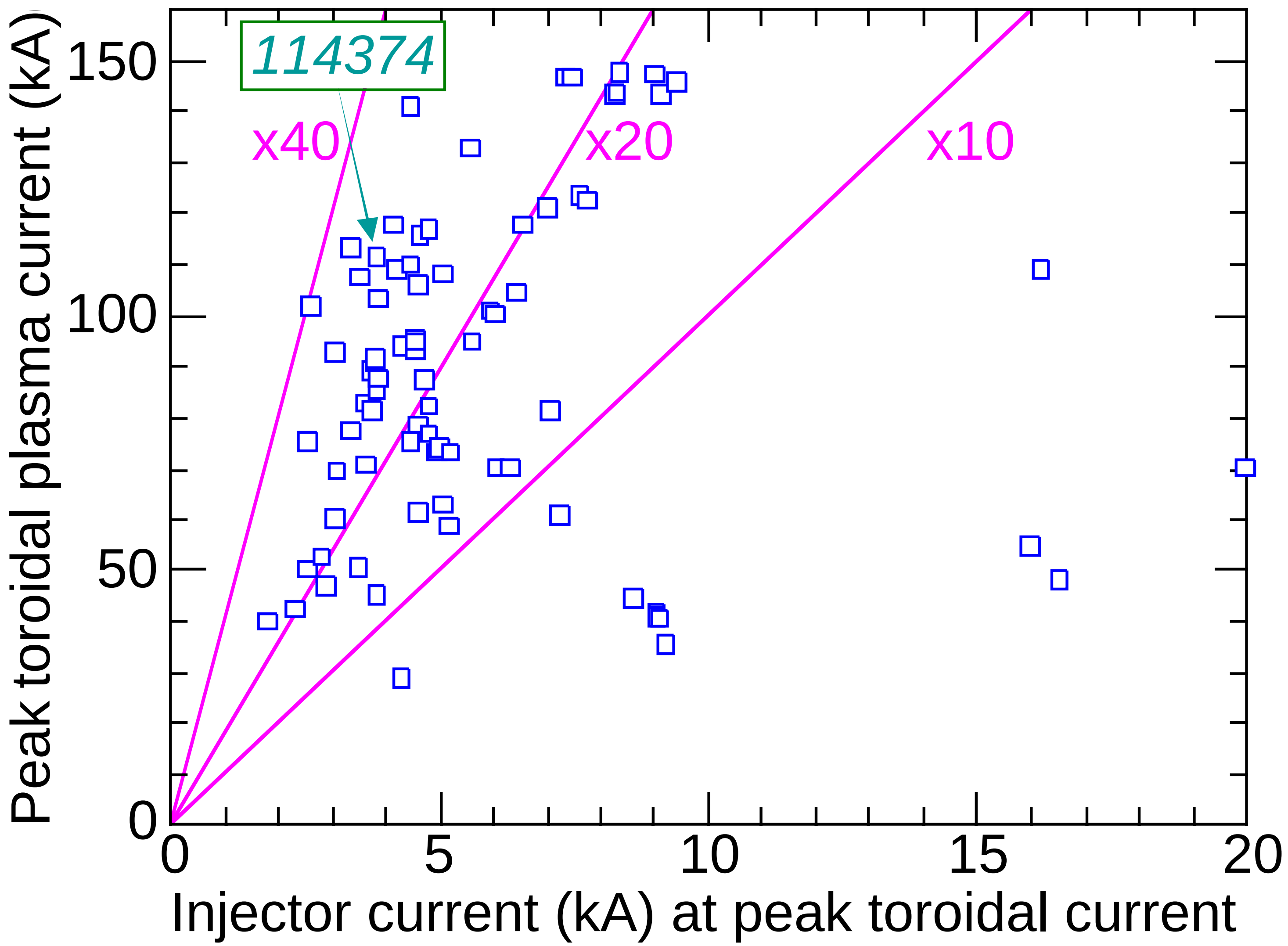
Te ~ 16eV measured in lowest neutral pressure discharge



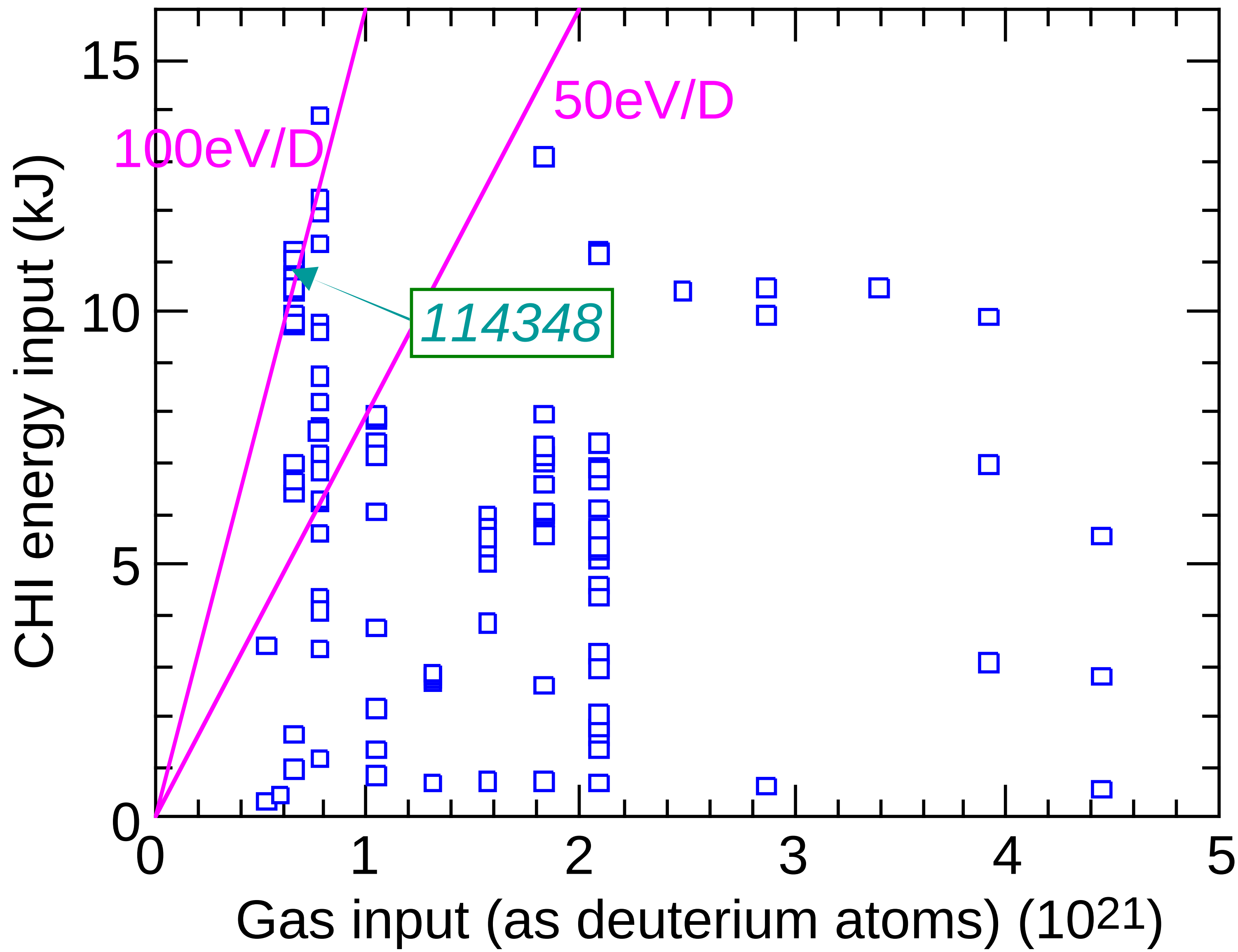
- Te increases with reduction in fill pressure
- Breakdown constraints prevented operation at the more optimal low pressures.

Thomson: B. Leblanc (PPPL)

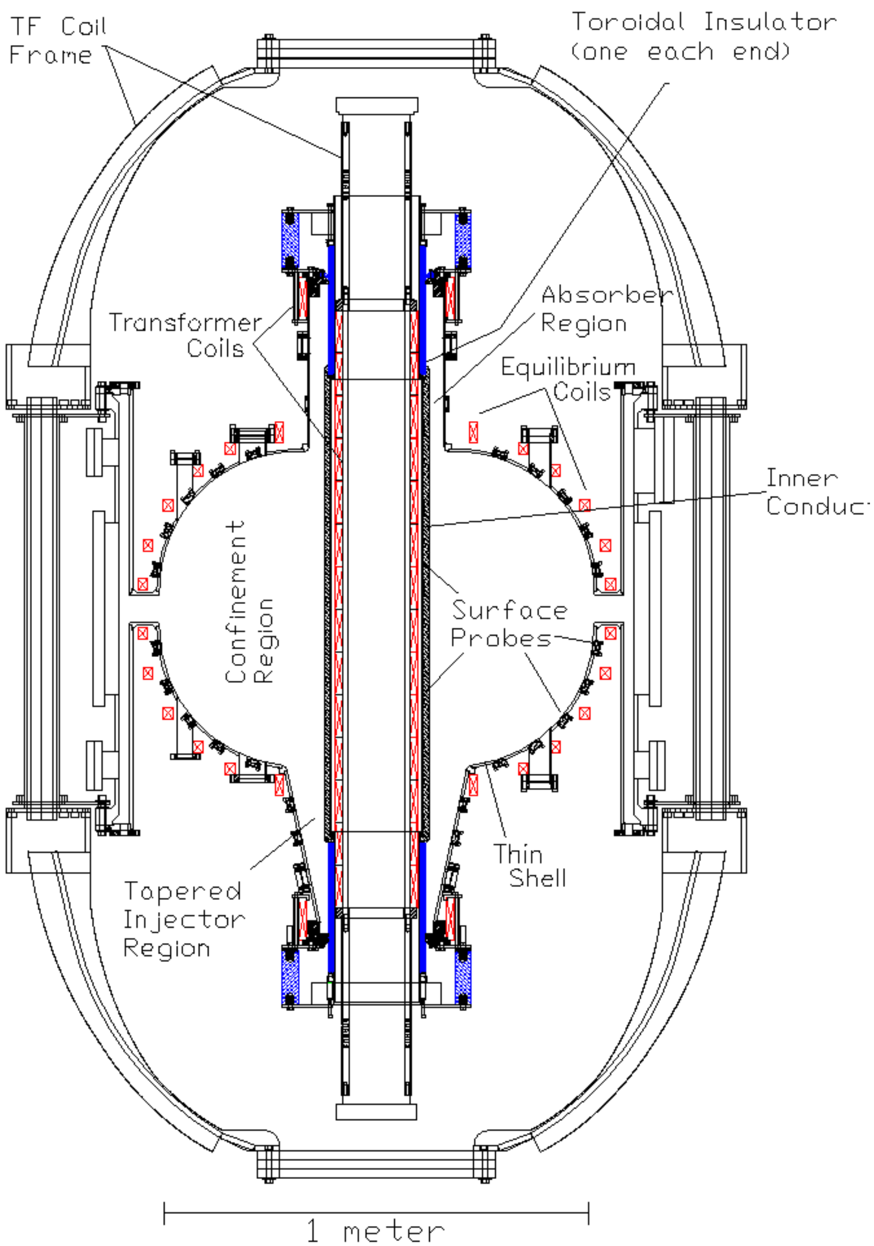
Highest current multiplication obtained in discharges with the lower injector current (these also have lower Ψ_{inj})



Capacitor bank energy was barely adequate to ionize only those discharges with the lowest gas input

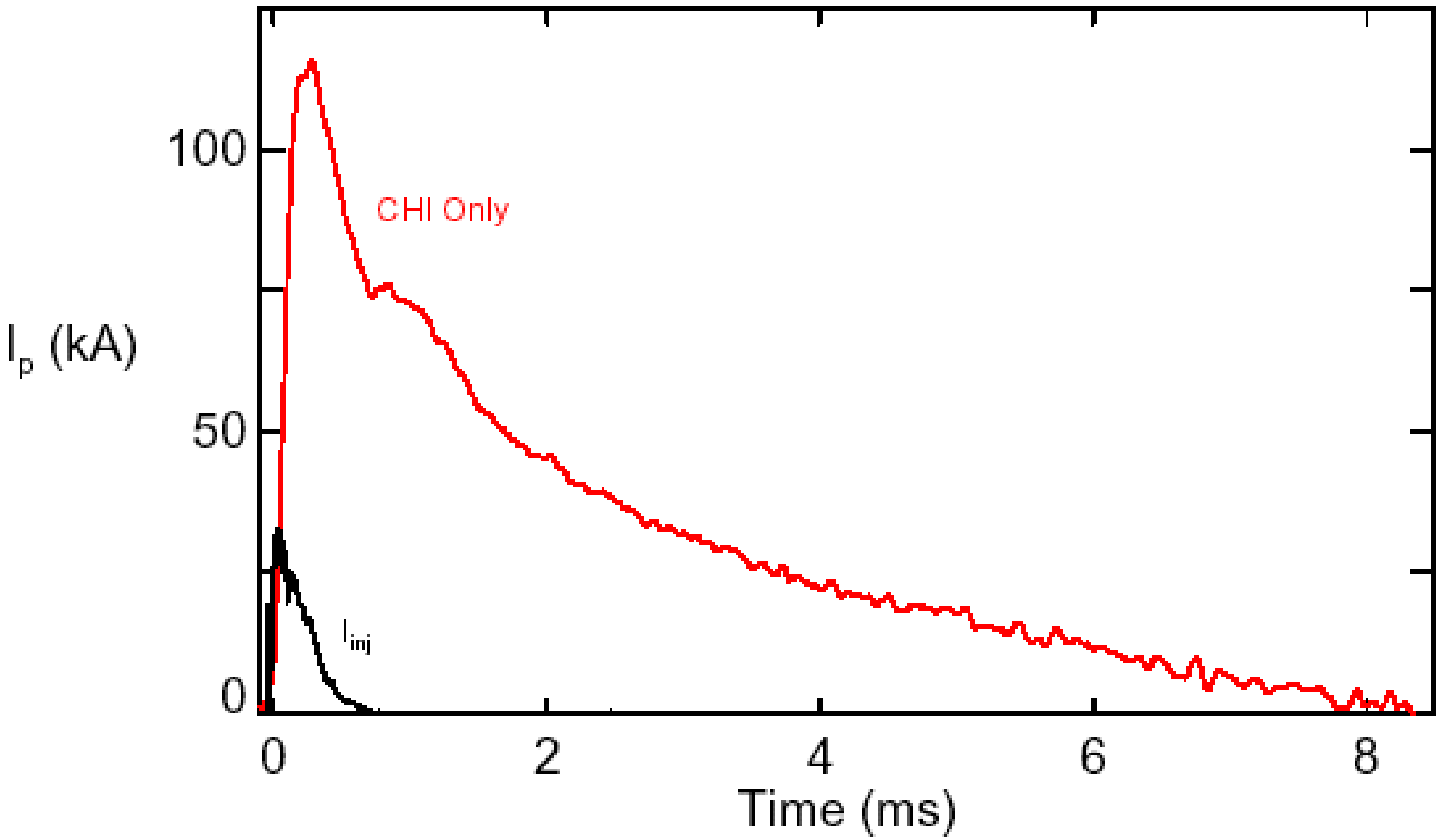


HIT-II attained machine parameters



- 24 feedback controlled PF coils maintain prescribed boundary condition
  - R = 0.3m
  - a = 0.2m
  - B_T ~ 0.4T
  - elongation ~ 1.5

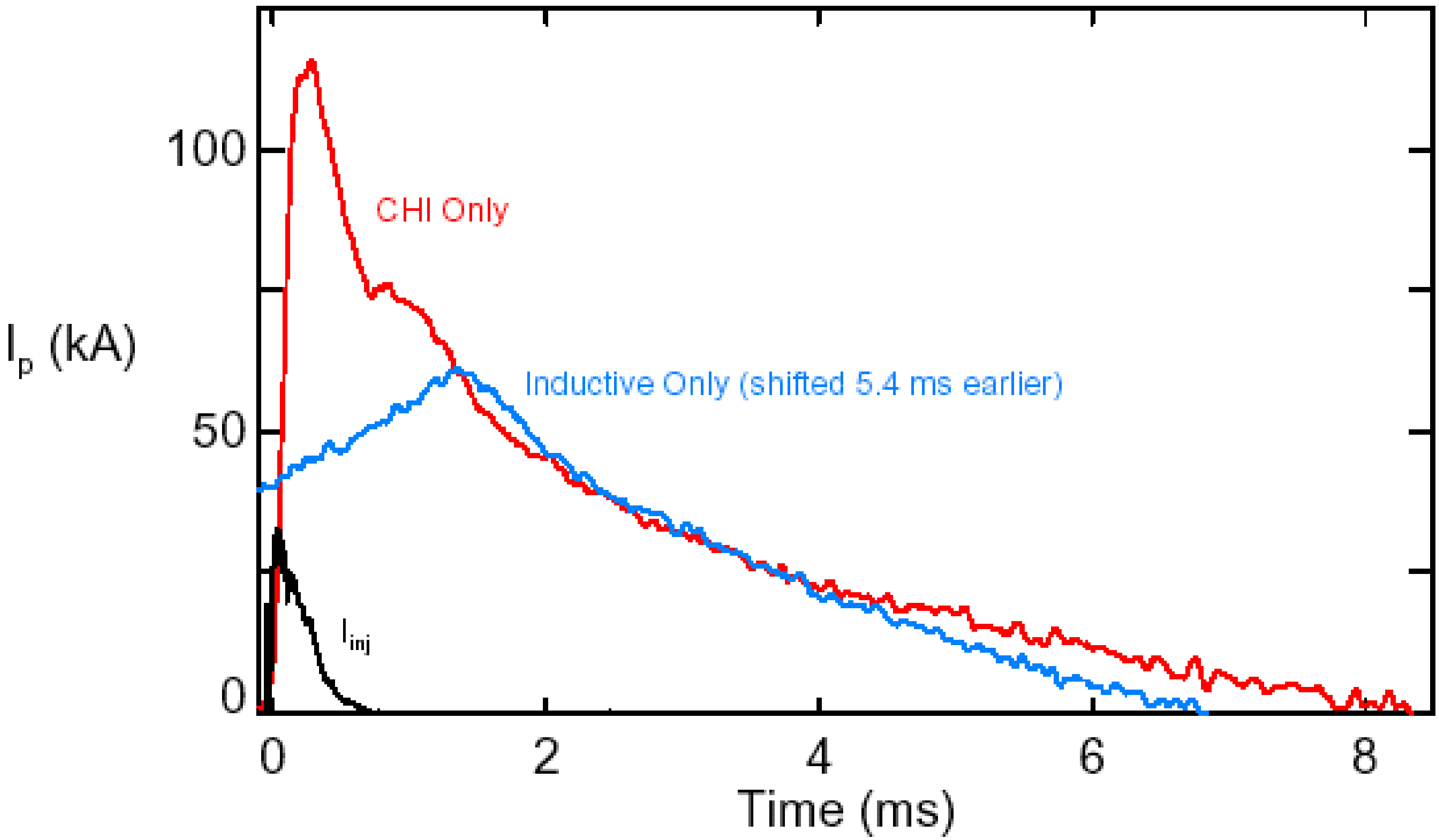
Transient CHI: Small capacitor bank power supply is used to apply a short voltage pulse to the injector electrodes



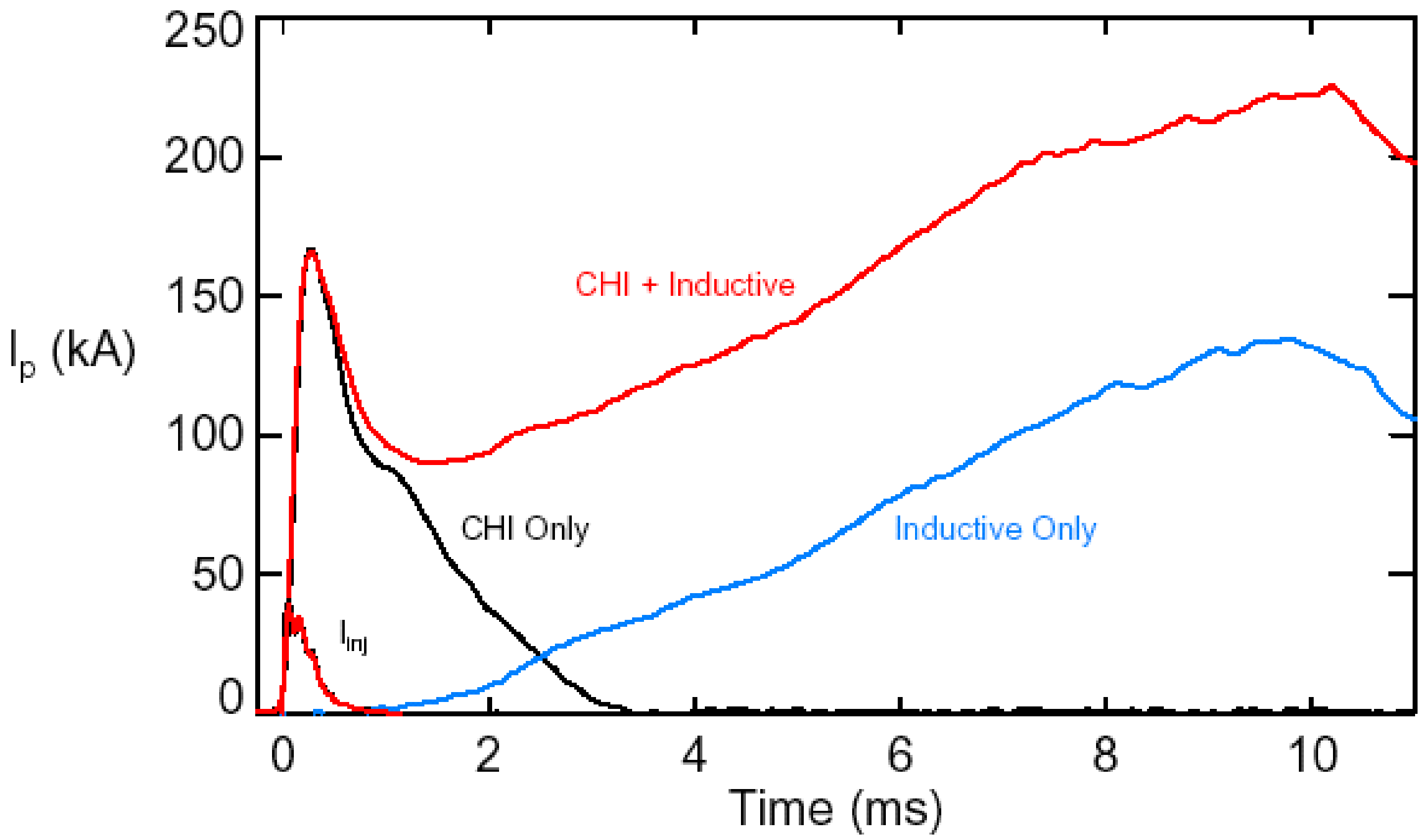
Note the persistence of CHI plasma current after the injector current has been reduced to zero

CHI produced plasmas have current decay times similar to those produced using induction

HIT-II



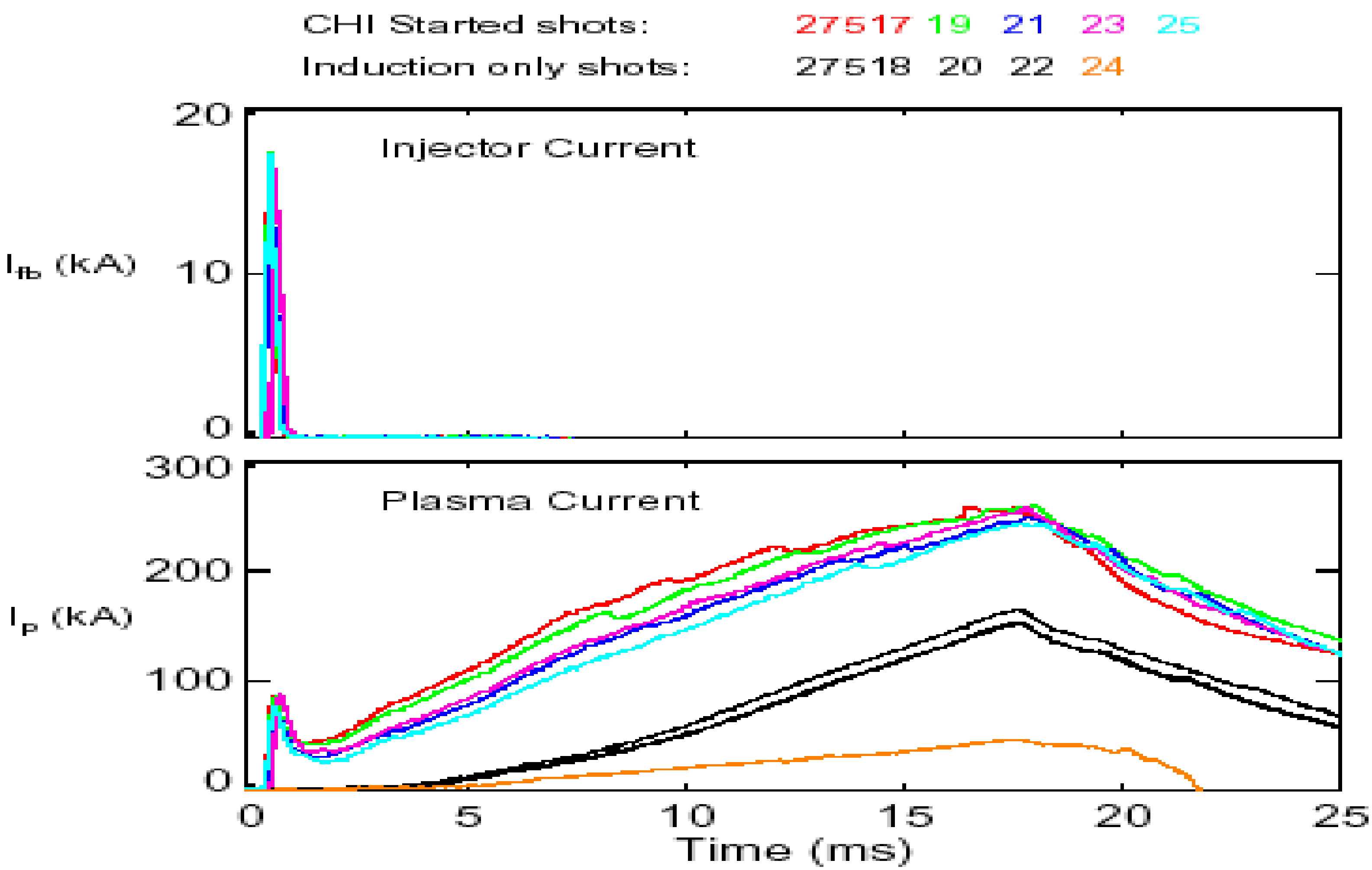
Nearly all Transient CHI produced closed flux current couples to the subsequent inductive drive



Both discharges have identical loop voltage programming

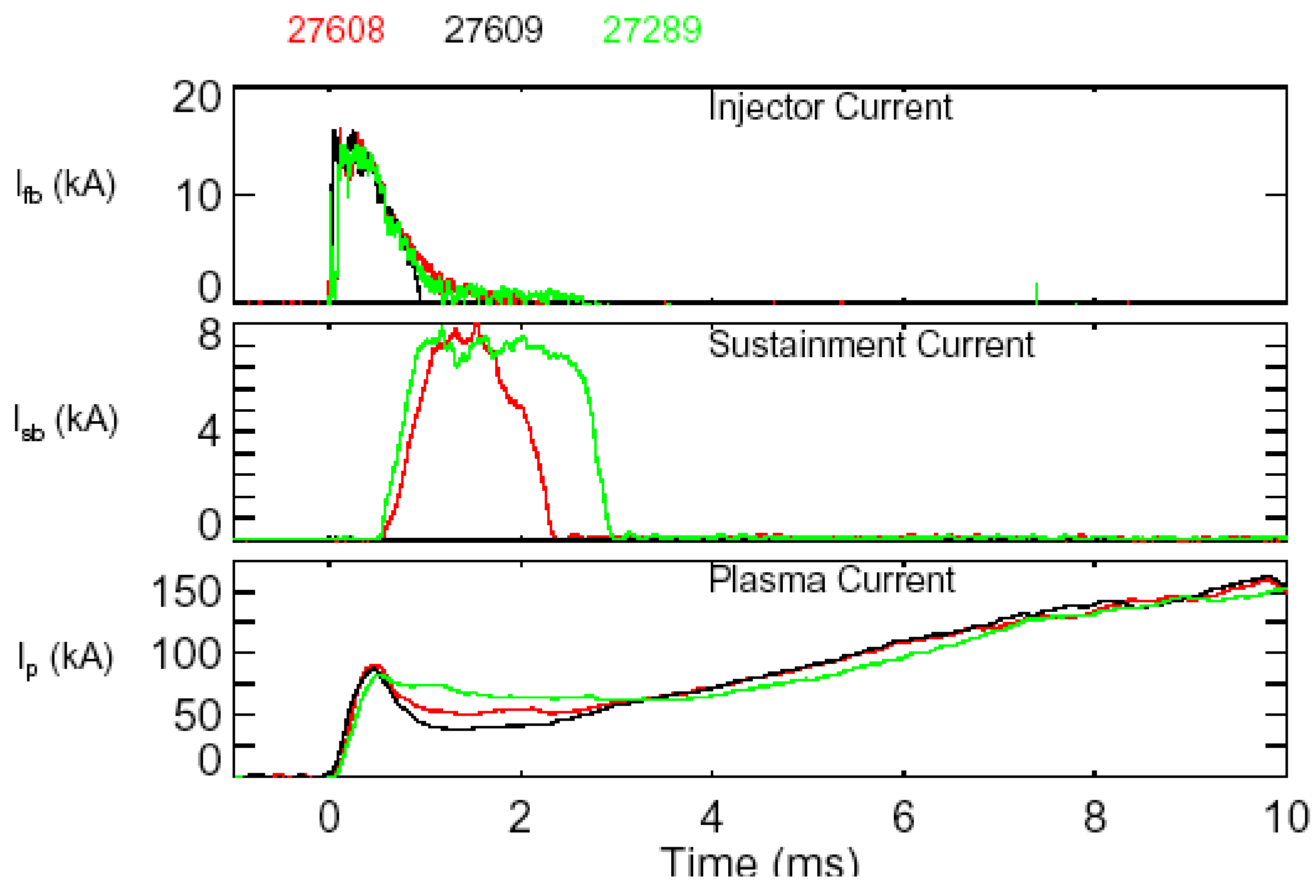
CHI startup is also compatible with pre-charged solenoid operation and is more reproducible than inductive only operation

HIT-II



Improves performance and saves volt-seconds

Edge current drive during the plasma startup increases handoff current



- Neutral Beam power absorption increases with plasma current
- Small edge current may increase stability limits
- Investigation of current profile changes is possible in NSTX

Experimental Demonstration of plasma start-up by coaxial helicity injection, R. Raman, T.R. Jarboe, B.A. Nelson et al., Physics of Plasmas, **11**, 2565 (2004)

Summary

CHI start-up works very well on HIT-II

-Improves the quality of inductive discharges

The initial seed current produced by transient CHI could be used by other solenoid-free current drive methods to boost the start-up current level

The decay time of the transient CHI discharge is similar to that of inductive discharges

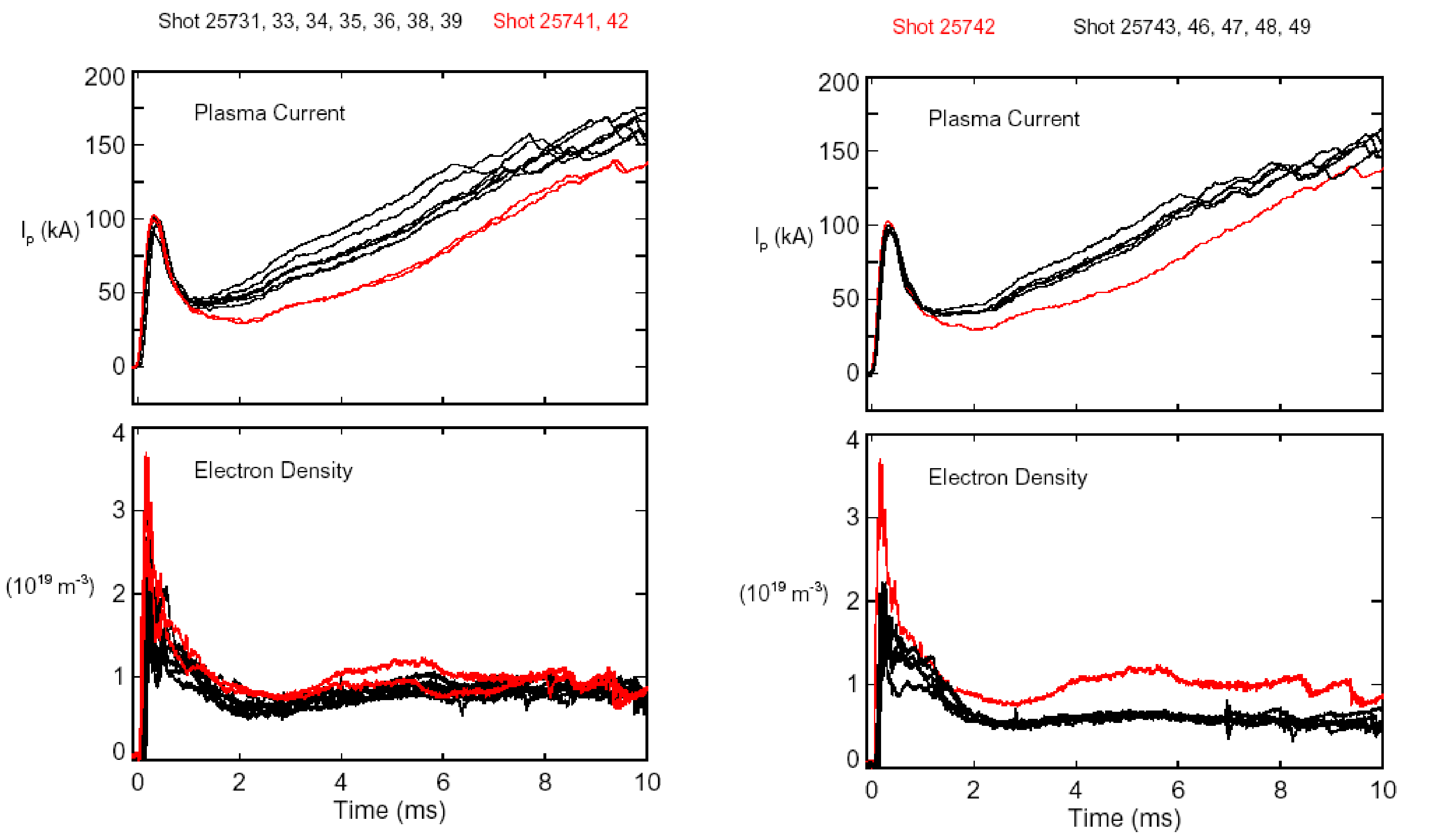
- On larger machines, auxiliary heating power can be used to increase the CHI produced plasma temperature

Initial results from NSTX are consistent with our understanding of Transient CHI

Conclusions

- CHI produces an attractive closed-flux startup equilibrium
- CHI startup saves volt-seconds with Ohmic follow-up
- CHI startup allows more repeatable discharges
- Hardware improvements are being implemented on NSTX
  - Improved pre-ionization
  - Higher voltage operation
  - Absorber PF coils

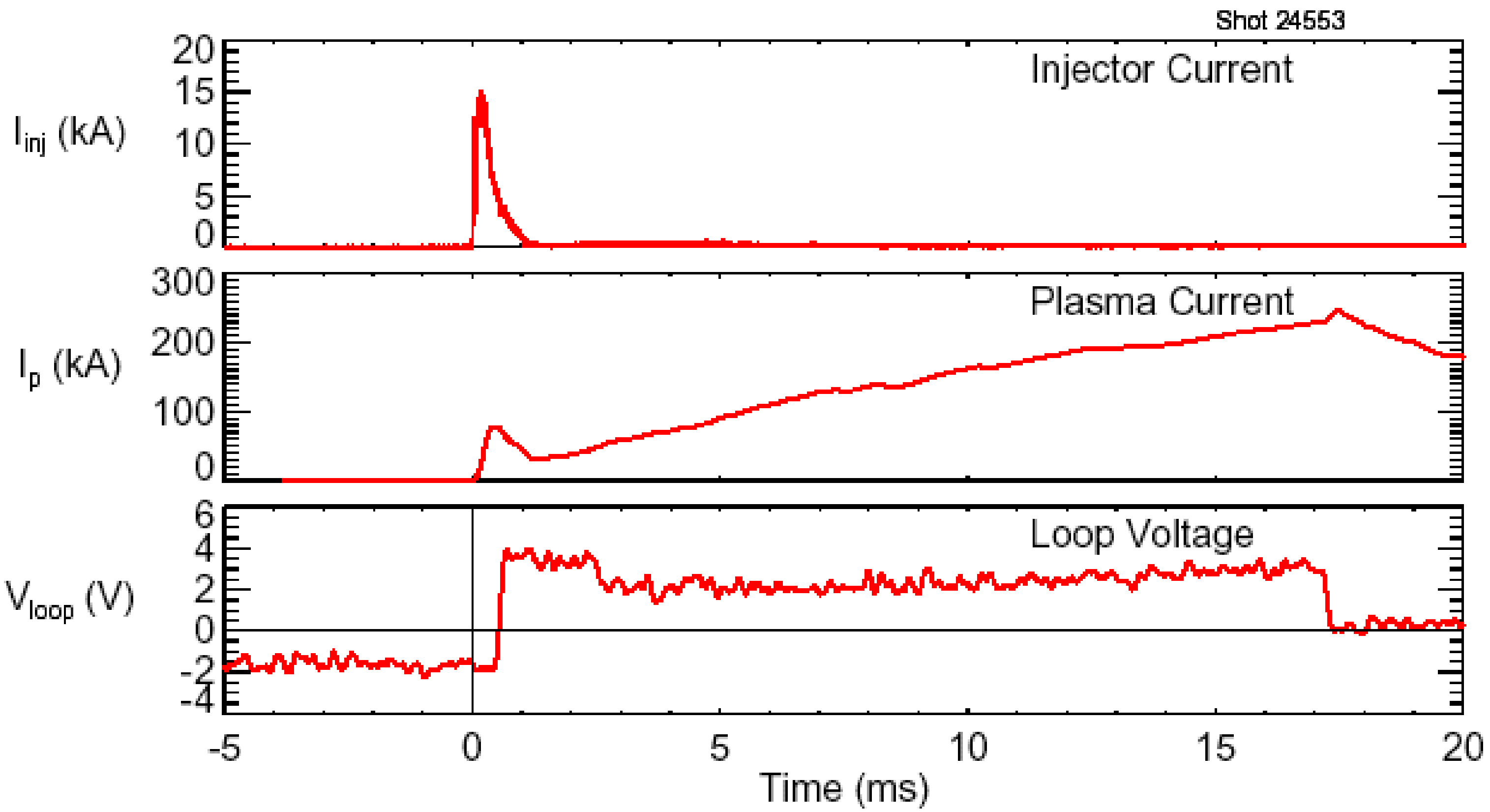
Increased electron density causes lower plasma current



- Improved pre-ionization needed to initiate CHI at low pressure
- RF waves could be used in larger machines

Interferometer: R. G. O'Neill

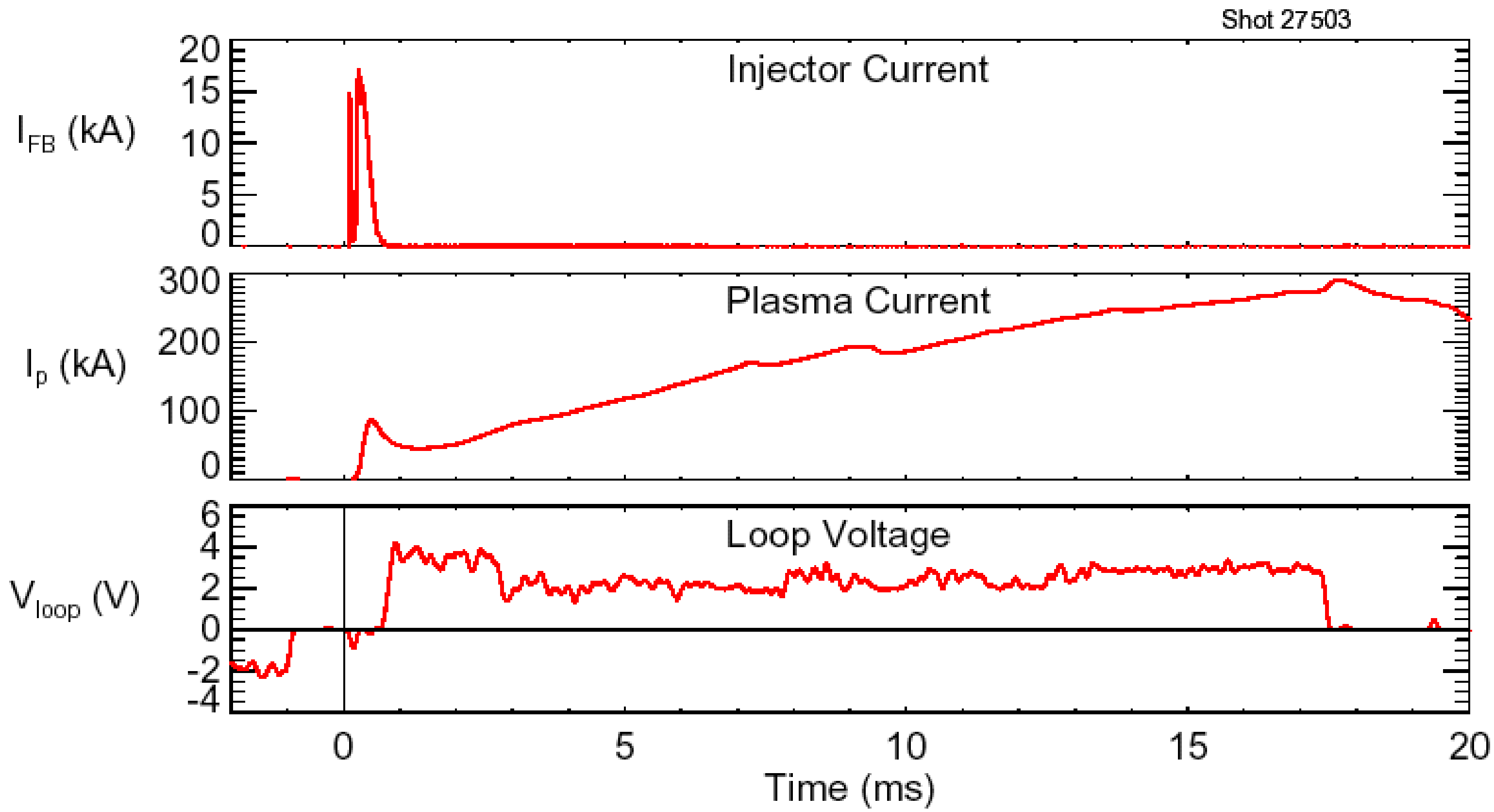
CHI can be initiated while the central transformer is in the process of being pre-charged



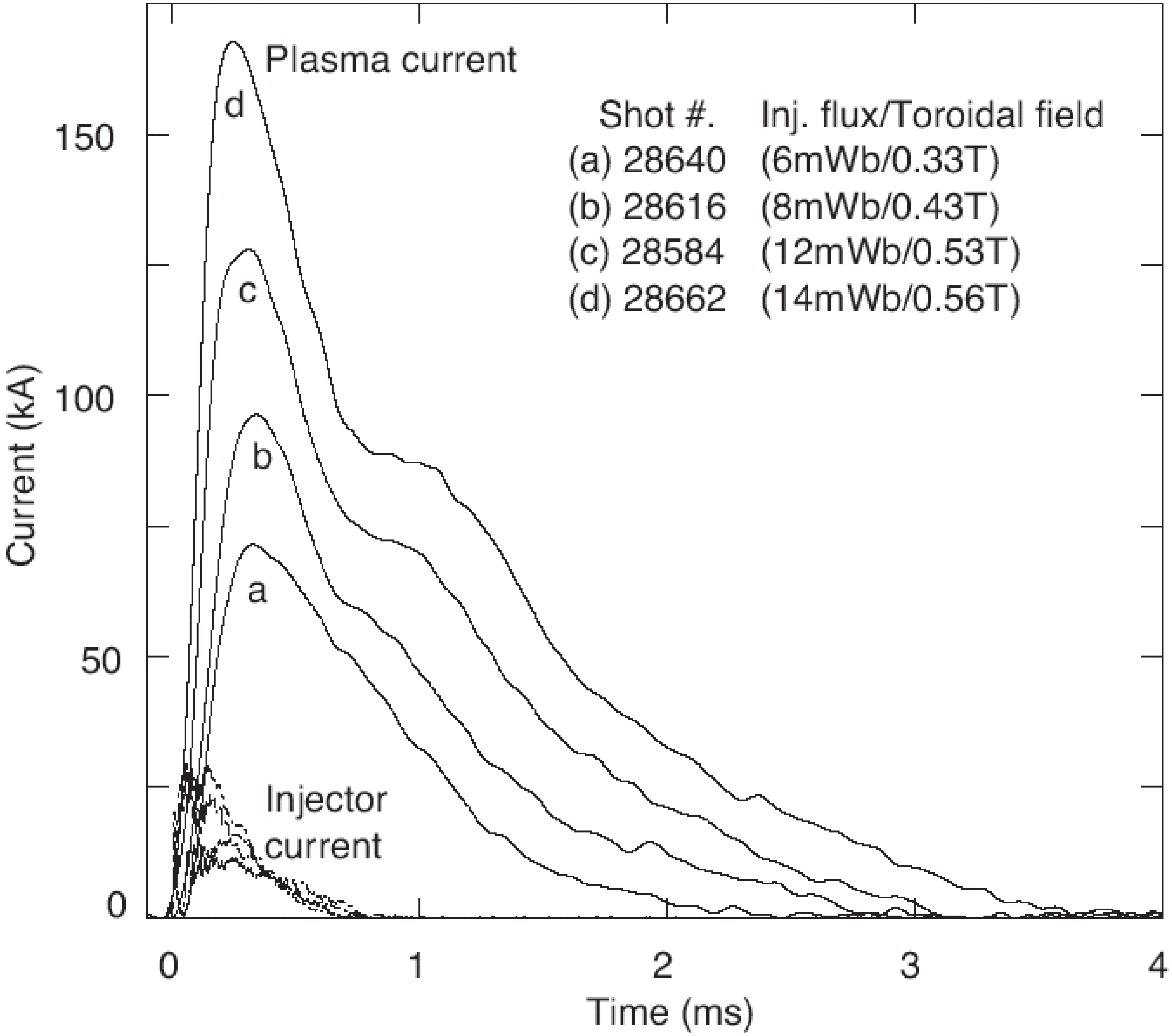
Important for a burning plasma reactor that may contain a small central transformer

Experiment suggested by M. Ono (PPPL)

Record plasma currents produced on HIT-II using CHI start-up



290 kA Record current for Ohmic plasmas in the Concept Exploration class STs


Plasma current
d
c
b
a
Shot #. Inj. flux/Toroidal field
(a) 28640 (6mWb/0.33T)
(b) 28616 (8mWb/0.43T)
(c) 28584 (12mWb/0.53T)
(d) 28662 (14mWb/0.56T)
Injector current
Current (kA)
150
100
50
0
0
1
2
3
4
Time (ms)