Demonstration of 300 kA CHI Startup Current Coupling to Transformer Drive on NSTX

B. A. Nelson, R. Raman, T.R. Jarboe
University of Washington (UW)

M.G. Bell, D. Mueller, B. LeBlanc, A.L. Roquemore
Princeton Plasma Physics Laboratory (PPPL)

V. Soukhanovskii
Lawrence Livermore National Laboratory (LLNL)

23rd IAEA Fusion Energy Conference 2010
Daejon Korea
October 2010

Abstract, Part I

Discharges started by Transient Coaxial Helicity Injection (CHI) in NSTX [R. Raman et al., Nuc. Fus., 49, (2009)] have attained peak currents up to 300 kA for the first time. These discharges are coupled to induction, producing up to 200 kA additional current over inductive-only operation. For the first time, the CHI-produced toroidal current that couples to induction has continued to increase with the energy supplied by the CHI power supply. CHI in NSTX has shown to be energetically quite efficient, producing a plasma current of about 10 A/Joule of capacitor bank energy. These results indicate the potential for substantial current generation capability by CHI in NSTX and in future toroidal devices.

In earlier work, up to 50 kA of toroidal plasma current produced by the non-inductive method of CHI was successfully coupled to inductive ramp-up in NSTX. In those experiments, the CHI current that could be successfully coupled was limited by impurity production in the divertor region and the occurrence of absorber arcs (i.e. parasitic discharges across the insulating gap in the upper divertor). More recently, extensive conditioning of the divertor plates (CHI electrodes) greatly reduced impurity production during CHI. Further, by energizing, for the first time, the axisymmetric absorber

Abstract, Part II

field-nulling coils located near the upper divertor in NSTX, the absorber arcs could be delayed or suppressed. Also, the use of evaporated coatings of lithium on the plasma facing components in NSTX [H.W. Kugel et al., J. Nuc. Mat., 1 (2009)] increased the current at the hand-off from CHI to induction to nearly 200 kA. Later in the inductive ramp-up, the discharges with CHI applied reached significantly higher plasma current than discharges with only the inductive loop voltage applied.

These results represent a factor of four improvement in the magnitude of current that was ramped up by induction, a factor of three increase in the initial start-up current, and the first results demonstrating flux savings in NSTX. The CHI started discharge, when coupled to induction produces about 60% more current than the comparison inductive-only case. These results confirm that CHI could be an important tool for non-inductive start-up in next-step STs.

This work supported by U.S. DOE Contracts # DE-AC02-09CHI1466 and DE-FG02-99ER54519 AM08.

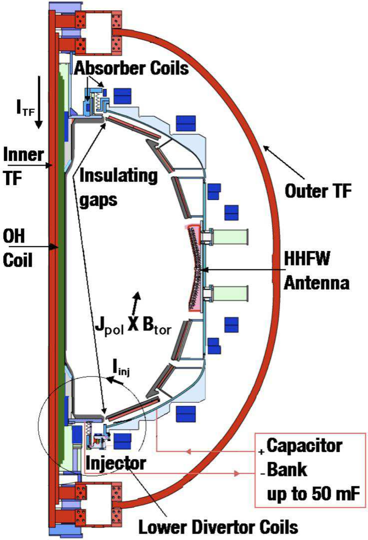
Outline

1. Introduction
   - Coaxial Helicity Injection and non-Inductive Startup
   - The NSTX Experiment
2. Transient CHI
   - Implementation & Scaling
   - Importance of Surface Conditioning
3. CHI-Startup / OH Ramp-up
   - Successful Coupling to OH Drive
   - Demonstrated Flux Savings
4. Summary and Future Work

Solenoid-Free Startup is Crucial for the ST Concept

- Limited space for the central column in an ST requires alternative start-up and current drive methods
  - There is no room for a transformer in CTFs or reactor-scale STs
- Transient CHI produces short-duration high-quality startup plasmas that can couple to other methods of current drive
  - Developed on HIT–II (Univ. Wash.), implemented on NSTX (PPPL)
  - Transient CHI produces over 160 kA of closed-flux startup current
  - Transient CHI demonstrates flux-savings (HIT–II and NSTX) and transitions to H-mode plasmas (NSTX)
- High quality plasma is required before it can be driven inductively
  - Use the plasma's ability to "couple to induction" as criterion for the quality of the plasma needed for non-inductive ramp up
  - Plasmas with high impurity content decay resistively despite application of inductive loop voltage

The NSTX Experiment (PPPL)

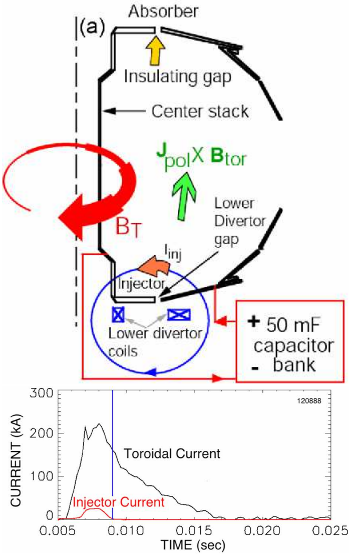


- $R = 0.85$ m
- $a = 0.67$ m
- $A = 1.27$
- $B_{TOR} \sim 0.6$ T
- $\kappa \sim 2.5$
- $\delta \sim 0.8$
- $I_p \sim 1.5$ MA
- Heating and Current Drive
  - Induction: 0.6 Vs
  - NBI (100 keV): 7 MW
  - HHFW (30 MHz): 6 MW
  - CHI: 0.4 MA
- Pulse Length: 1.8 s

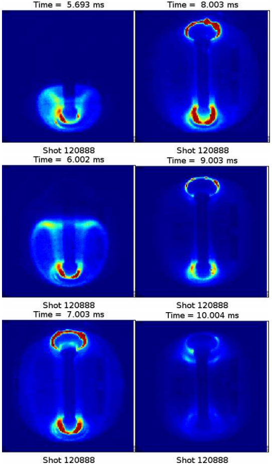
Transient CHI: Small Capacitor Bank Produces a Short CHI Pulse and Closed Flux

NSTX CHI Cap Bank

- 10 $\times$ 5 mF, 2 kV caps
- Three ignitron switches
- Fast crowbar



TV images (R. Maqueda)



CHI Scaling Implies High I_p/I_{inj} in NSTX

1. From helicity and energy conservation, for a Taylor minimum energy state $\lambda_{inj} \geq \lambda_{tok}$
   - $\lambda_{inj} = \mu_0 I_{inj}/\psi_{inj}$; ψ_{inj} = poloidal cathode-to-anode injector flux
   - $\lambda_{tok} = \mu_0 I_p/\Phi_{TOR}$; Φ_{TOR} = vessel toroidal flux

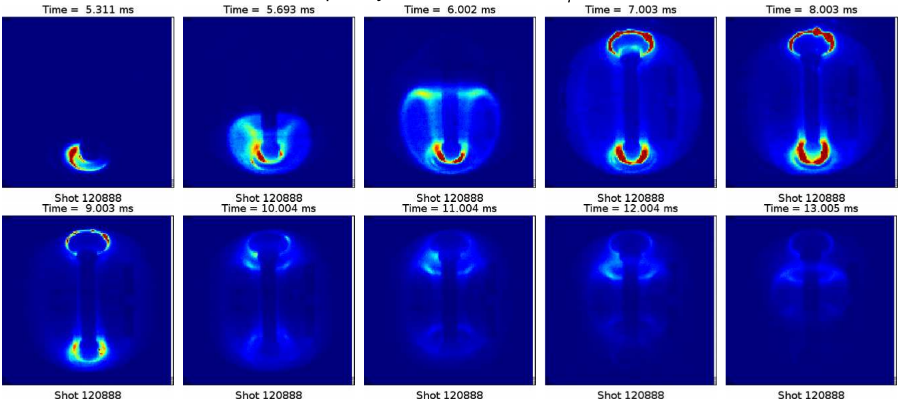
$\therefore\ I_p \leq I_{inj}\left(\Phi_{TOR}/\psi_{inj}\right)$

2. For similar B_T NSTX has $10 \times \Phi_{TOR}$ of HIT–II
3. I_{inj} requirement to stretch out ψ_{inj}, or "bubble burst" condition:
   - $I_{inj} = 2\psi_{inj}^2/\left(\mu_0^2 d^2 I_{TF}\right)$
   - For HIT-II, $\psi_{inj} = 8$ mWb, $d = 8$ cm (flux footprint width)
   - For NSTX, $\psi_{inj} = 10$ mWb, $d = 16$ cm
   - $I_{inj} \geq 15$ kA for HIT-II, $I_{inj} \geq 2$ kA for NSTX

$\Rightarrow$ Achieve much higher I_p/I_{inj} in NSTX

TV View of Plasma Shows Expansion, Reconnection, Then Closed Flux

CHI Startup Only, Peak Closed-flux $I_p = 160$ kA



TV images from R. Maqueda, LANL

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

- Long-pulse (400 ms) 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 is 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 improves discharge performance

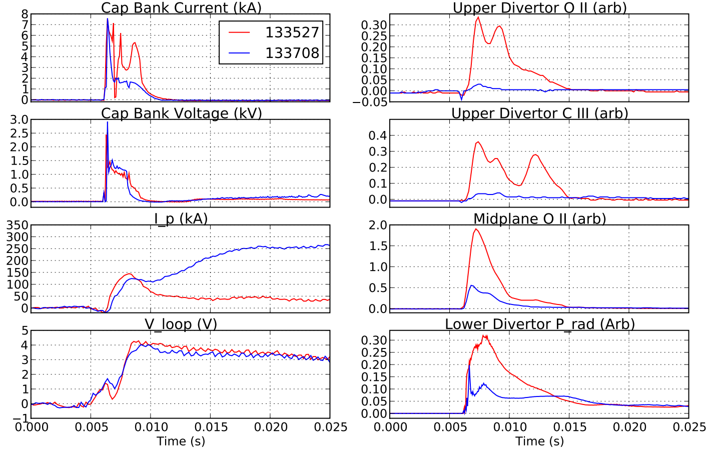
Conditioning Critical for CHI Startup and Handoff

(Handoff defined as when $I_{CHI} \sim 0$)

- Active divertor conditioning campaign:
  - Preparatory CHI conditioning:
    - Run DC CHI supply, $I_{\text{inj}} \sim 5 - 6$ kA, $\sim$0.4 s
    - ψ_{inj} and I_{inj} maintained at or below “bubble-burst” level
    - DC D_2 glow between conditioning shots
  - Li deposition while running (LITER)
- Operational results with CHI handoff to Ohmic:
  - Handoff successful with low O II levels
  - Handoff over 150 kA
  - Handoff with more than one cap (successful with two and three)
  - Demonstrated flux savings

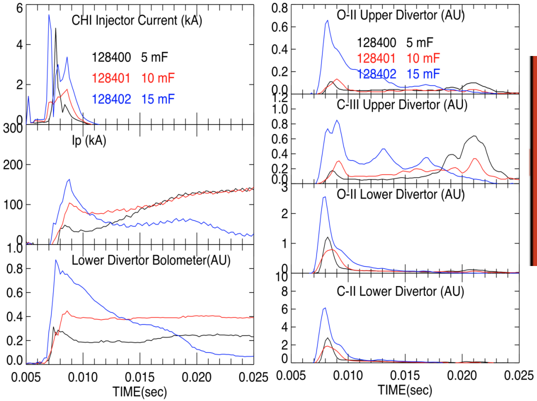
Conditioning of Divertors Improves CHI Handoff

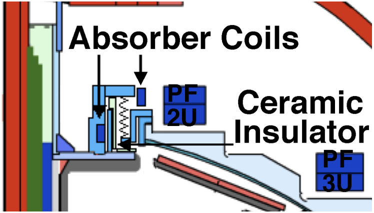
After conditioning / Before conditioning
(2 $\times$ 5 mF caps)



Without conditioning, (PDC, Li deposition, *etc.*) Ohmic drive doesn't ramp up

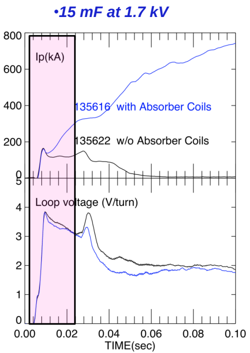
Absorber Coils Provide "Buffer Flux" to Plasma Flow

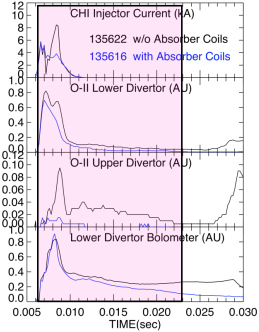


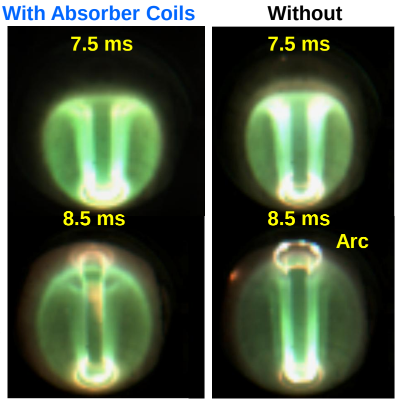


- As the discharges grow upwards to fill the vessel absorber arcs occur.
- CHI discharges exhibit low Z impurities that increase with increasing capacitor energy
    - The absorber coils have provided buffer flux to prevent arcs

Absorber Coil Radial Fields Help Prevent Arcing

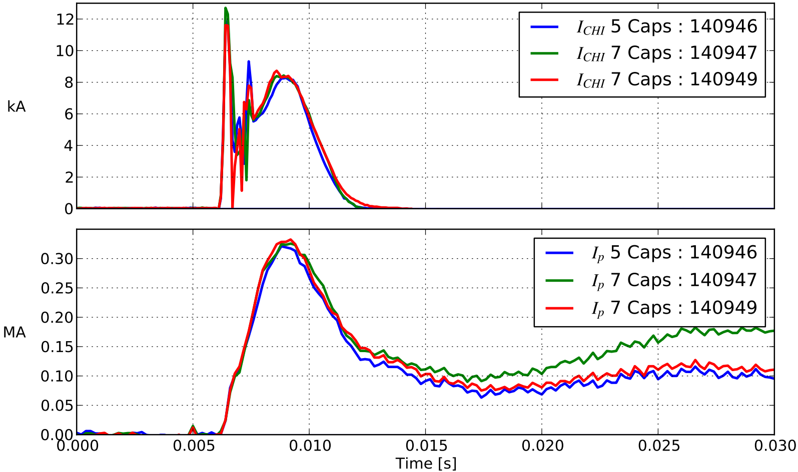






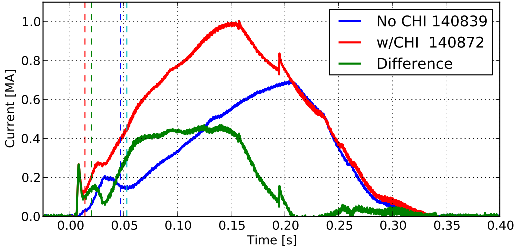
- Only the discharge without the absorber arc couples to inductive ramp-up
- Even without an arc, low Z impurities limit the ability to couple to ramp-up
- It is important to condition the lower divertors

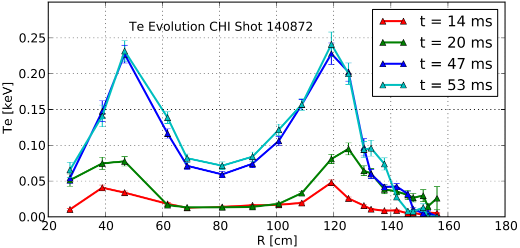
Absorber-arc-free Plasmas Produced w/up to 7 Caps



⇒ Improved conditioning and operation of absorber field coils

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





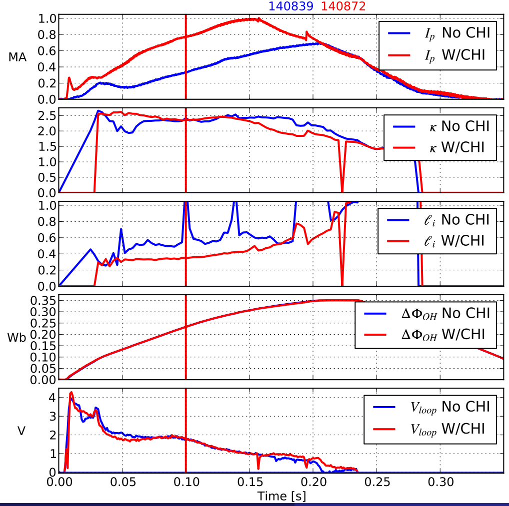
- Ramped up to 1 MA after startup, using 0.3 Wb change in OH coil current
- Hollow electron temperature profile maintained during current ramp

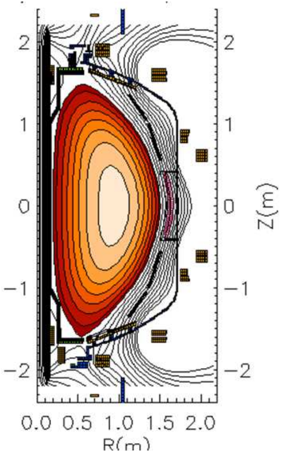
Discharges with early high T_e ramp-up to higher current

CHI Start-up has Low Internal Inductance (ℓ_i), from Beginning of Discharge

Same V_{loop} programming

With CHI : Without CHI



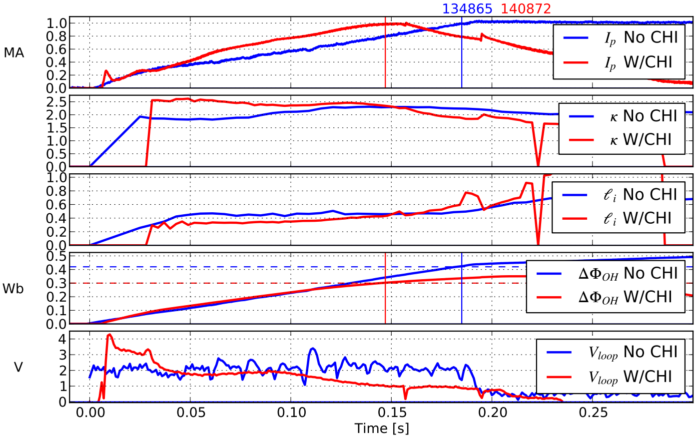


EFIT reconstruction for

CHI start-up at t=100 ms

CHI Start-up Ramps to 1 MA Using 40% less Ohmic Flux than a Standard L-mode NSTX Discharge

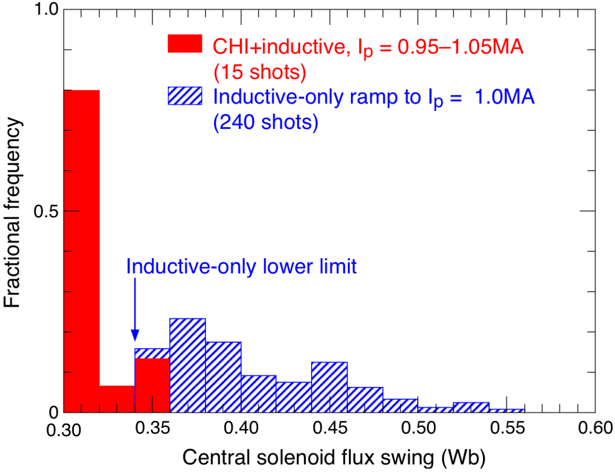
- CHI start-up uses ∼0.3 Wb of OH, OH-only uses ∼0.42 Wb to get to 1 MA (40% less flux)
- Comparison to a standard NSTX L-mode discharge using 1 NBI source at 2 MW



⇒ 40% flux generates ∼360 kA

CHI Startup Plasmas Require Less Inductive Flux Swing to Ramp to 1 MA

Comparison of CHI Startup to H-modes using more than 1 NBI source



Characteristics of CHI Startup Plasmas

- CHI startup plasmas:
  - CHI startup $T_e \sim 30 - 40$ eV (similar to OH startup at same time and current levels) with hollow profiles that remain during the discharge
  - CHI works best with low gas puff and divertor conditioning
- CHI startup with Ohmic ramp-up plasmas:
  - Improved overall discharge evolution, ramping to 1 MA using less inductive flux that has ever been done on NSTX
  - Compared to CHI started discharges, inductive L-mode discharges in NSTX require $\sim$40% more inductive flux to ramp to 1 MA.
    $\Rightarrow$ 40% inductive of flux typically generates 360 kA of current
  - Can produce CHI start-up discharges using 5 and 7 capacitors without absorber arcs

Summary

- Transient CHI startup has demonstrated on NSTX:
  - Ramp-up of CHI plasma to over 1 MA with demonstrated flux savings
  - Startup plasmas with $T_e \sim 30 - 40$ eV (similar to Ohmic)
  - Compatibility with high-performance H-mode discharges
- Active divertor conditioning improves performance
  - Long-pulse CHI conditioning
  - Lithium deposition and discharge cleaning
- Absorber coils help prevent absorber arcs

  $\Rightarrow$ Better coupling and performance

Future Work

- 5 and 7 cap CHI plasmas are ready to be coupled to induction
- Further improve the early discharge phase
- Increase NBI power input, adding it earlier in time to heat the early phase of the CHI plasma
- Continued performance improvement