Coaxial Helicity Injection Non-inductive Startup on NSTX

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Abstract

Transient Coaxial Helicity Injection (CHI) has demonstrated current startup and coupling to subsequent inductive current ramp-up, a crucial technology for future spherical torus/tokamak designs. Up to 160 kA of closed current has been produced solely by CHI [Raman *et al.*, Phys. Plas., **14**, p056106, 2007] on the National Spherical Torus Experiment (NSTX). Further studies have produced currents on the order of 100 kA that couple to inductive drive. With the addition of neutral-beam and high harmonic fast wave (HHFW) heating, these plasmas ultimately reach over 800 kA and H-mode transition with $T_e > 800$ eV. The resulting plasma has low inductance, which is preferred for long-pulse discharges. This demonstrates the compatibility of CHI startup with high-performance discharges. The initial CHI plasmas have $T_e \sim 10-30$ eV with $n_e \sim 0.6-1.0 \times 10^{19}$ m^{-3}, which are consistent with values for inductive startup at the same current levels. Operation with lithium wall conditioning generally improves operation, but higher CHI currents tend to liberate more low-Z impurities from the graphite divertors, limiting the resistive diffusion time of the startup current. The next NSTX CHI campaign includes better conditioning of the divertor plates, upgraded lithium conditioning, and improved flux control at the upper CHI insulator. Progress with these improvements will be reported.

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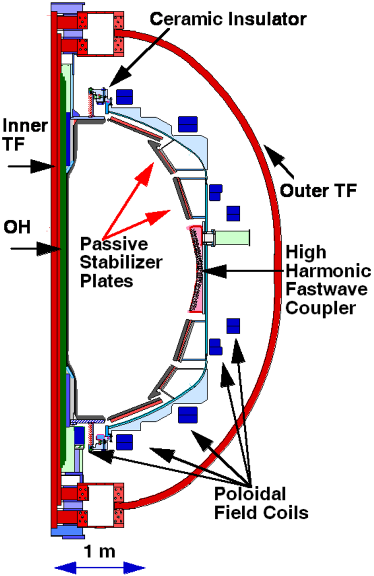
Outline

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 160 kA of closed-flux startup current
  - Transient CHI demonstrates flux-savings (HIT–II and NSTX) and transitions to H-mode plasmas (NSTX)

The NSTX Experiment (Princeton Plasma Lab, NJ)

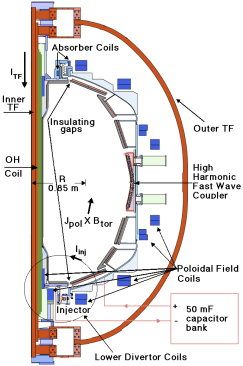


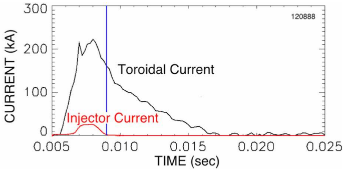
- $R = 0.85$ m
- $a = 0.67$ m
- $A = 1.27$
- $B_{\mathrm{TOR}} \sim 0.6$ T
- $\kappa \sim 2.5$
- $\delta \sim 0.8$
- $I_p \sim 1.5$ MA
- Heating and Current Drive
  - Induction: 0.6 Vs
  - NBI (100 keV): 7 MW
  - HHFW (30 MHz): 6 MW
  - CHI: 0.4 MA
- Pulse Length: 1.8 s

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

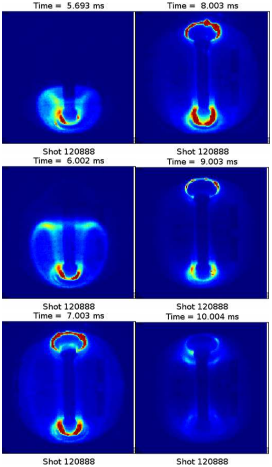
NSTX CHI Cap Bank

- 10 × 5 mF, 2 kV caps
- Three ignitron switches
- Fast crowbar





TV images (R. Maqueda)

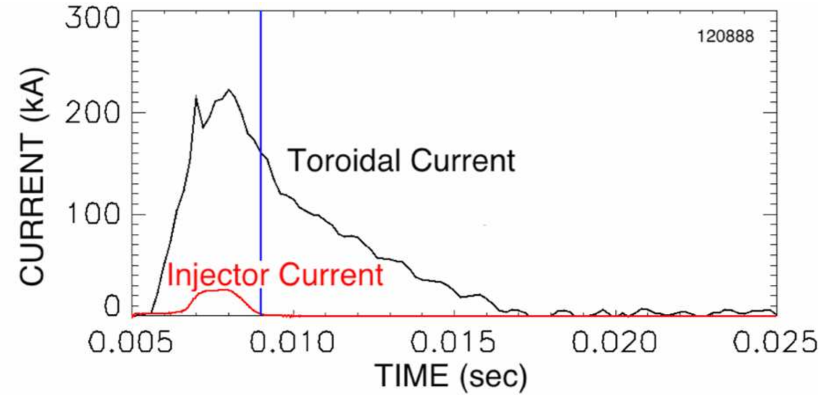


CHI Scaling Implies High I_p/I_{inj} in NSTX

- From helicity and energy conservation, for a Taylor minimum energy state $\lambda_{\text{inj}} \geq \lambda_{\text{tok}}$
  - $\lambda_{\text{inj}} = \mu_0 I_{\text{inj}}/\psi_{\text{inj}}$; $\psi_{\text{inj}} =$ poloidal injector flux
  - $\lambda_{\text{tok}} = \mu_0 I_p/\Phi_{\text{TOR}}$; $\Phi_{\text{TOR}} =$ vessel toroidal flux
- $I_p \leq I_{\text{inj}} \left(\Phi_{\text{TOR}}/\psi_{\text{inj}}\right)$
- For similar B_T NSTX has $10 \times \Phi_{\text{TOR}}$ of HIT–II
- Bubble burst condition: $I_{\text{inj}} = 2\psi_{\text{inj}}^2/\left(\mu_0^2 d^2 I_{TF}\right)$
  - For HIT-II, $\psi_{\text{inj}} = 8$ mWb, $d = 8$ cm (flux footprint width)
  - For NSTX, $\psi_{\text{inj}} = 10$ mWb, $d = 16$ cm
  - $I_{\text{inj}} \geq 15$ kA for HIT-II, $I_{\text{inj}} \geq 2$ kA for NSTX

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

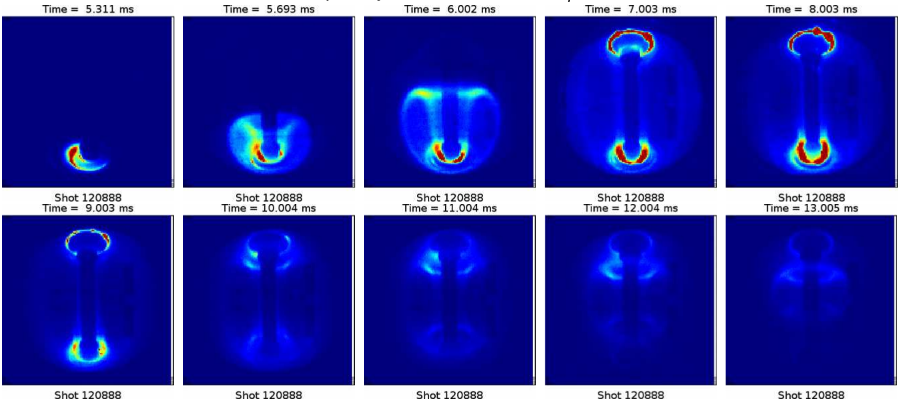
Highest non-inductive Startup Current of 160 kA



Persistent $I_p = 160$ kA plasma after $I_{\rm inj}$ is zero
(parasitic absorber current near I_p peak)

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

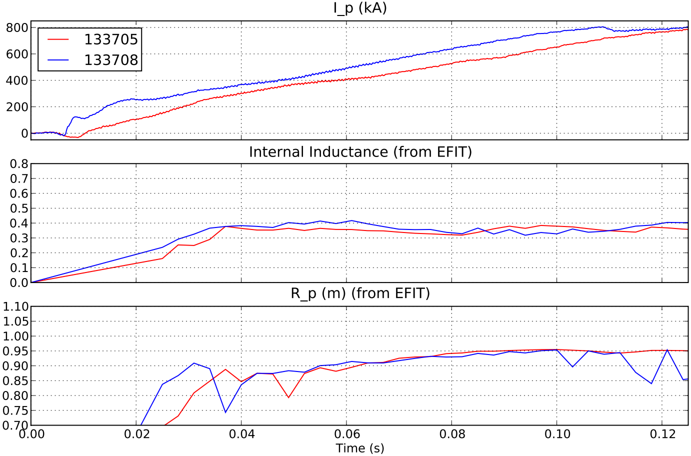
CHI Startup Only, Peak Closed-flux $I_p = 160$ kA



TV images from R. Maqueda, LANL

CHI Startup Demonstrates Flux Savings

Same V_{loop} programming: With CHI / Without CHI

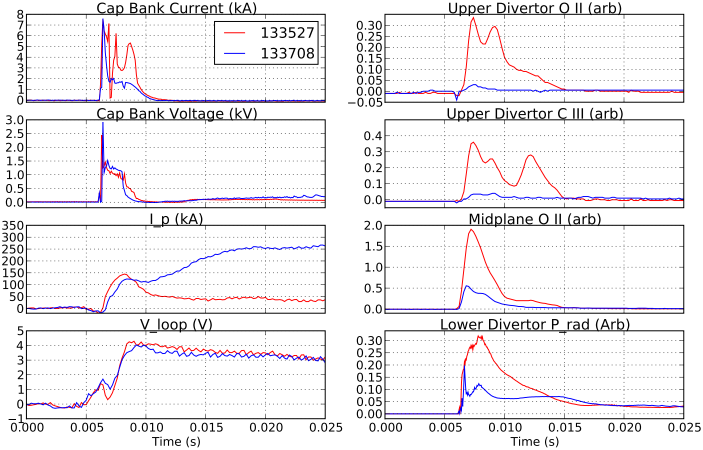


$\Delta I_p \gtrsim 100$ kA with same EFIT ℓ_i and R_p

(until after IREs, $t > 0.11$ s)

Conditioning of Divertors Improves CHI Handoff

After conditioning / Before conditioning



Without conditioning, Ohmic drive doesn't ramp up

(2 $\times$ 5 mF caps)

Conditioning Critical for CHI Startup and Handoff

- 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 up to $\sim$ 140 kA
  - Handoff with more than one cap (successful with two and three)
  - Demonstrated flux savings

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 initially hollow profiles that later fill in
  - CHI works best with low gas puff and divertor conditioning
- CHI Startup with Ohmic ramp-up Plasmas:
  - Can handoff up to 140 kA, with proper conditioning
  - Can handoff with up to three capacitors in CHI bank
  - CHI-startup / OH-ramp-up plasmas over 800 kA, several hundred eV, and H-mode (with NBI)
  - Demonstrated flux savings with two caps

Summary

- Transient CHI startup has demonstrated on NSTX:
  - Record 160 kA of non-inductive closed-flux current
  - Startup plasmas with $T_e \sim 30 - 40$ eV (similar to Ohmic)
  - Demonstrated flux savings
  - Compatibility with high-performance H-mode discharges
- Active divertor conditioning improves performance
  - Long-pulse CHI conditioning
  - Lithium deposition and discharge cleaning

Future Work

- 2009 Campaign
  - Continued conditioning (long-pulse CHI, Li)
  - Additional auxiliary power (NBI, HHFW)
  - Attempt higher transient CHI closed-flux and handoff current
  - Bring absorber coils online to reduce/eliminate absorber current
- 2010 Campaign
  - Lithium electrodes (and reverse CHI polarity)
  - Optimize absorber coils
  - Continued performance improvement

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