Research Thrust for Plasma Startup and Ramp-up

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ReNeW - Theme V
Optimizing the ST Configuration
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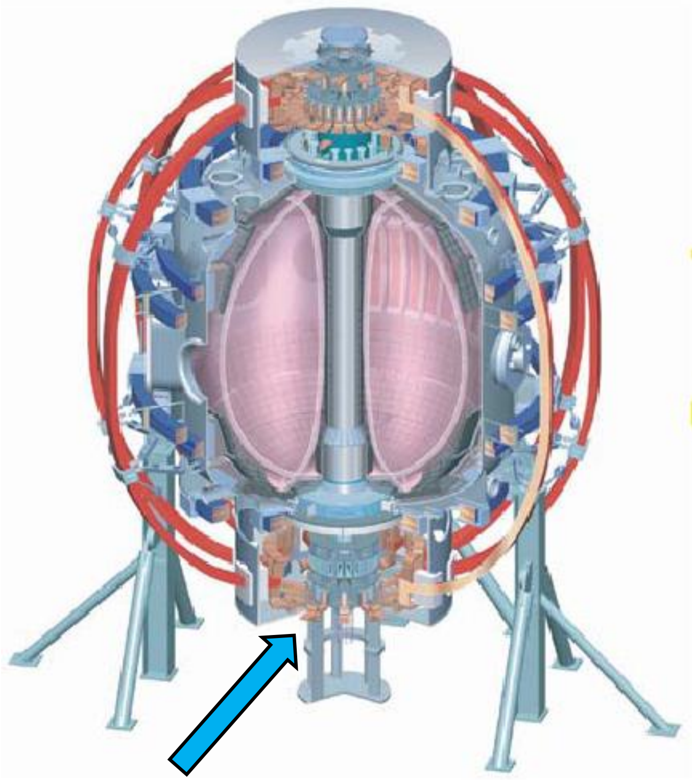
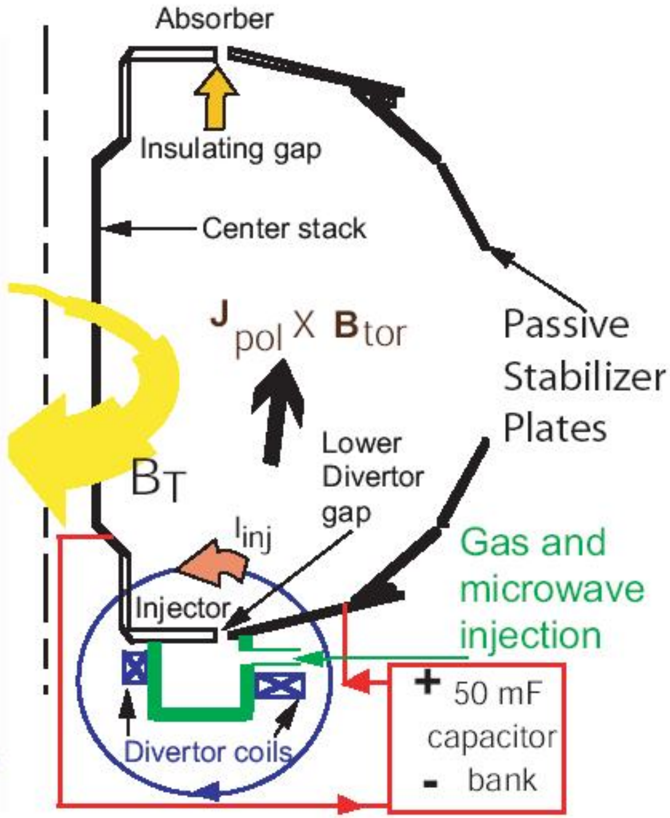
Motivation For Solenoid-Free Plasma Startup

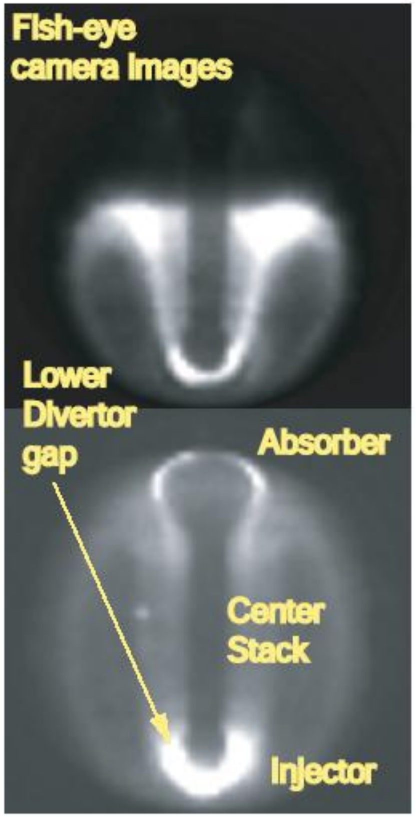
- The development of methods for solenoid-free current initiation would improve the prospects of the low aspect-ratio Spherical Torus as a CTF and fusion reactor
  - Tokamak (OH+TF) —*simplify*→ ST (TF, no OH) —*simplify*→ CT (no TF, no OH)
- Removal of the central solenoid would also simplify the tokamak design and provide access to lower aspect ratio configurations
  - Cross-cuts with Theme II by removing an expensive component not needed for steady-state operation (ST Contribution to Tokamaks)
- Transient Coaxial Helicity Injection (CHI) has demonstrated start-up and coupling to induction in both HIT-II and NSTX
  - Cross-cuts with the CT Theme (CT Contribution to STs and Tokamaks)
- Method has now produced 160 kA closed-flux current in NSTX
  - World record for non-inductively generated closed flux current in ST/Tokamak
  - CHI started discharges successfully coupled to induction, transitioning to an H-mode in NSTX, demonstrating viability for high-performance operation

Transient CHI: Axisymmetric reconnection leads to formation of closed flux surfaces



Large Coaxial Plasma Gun





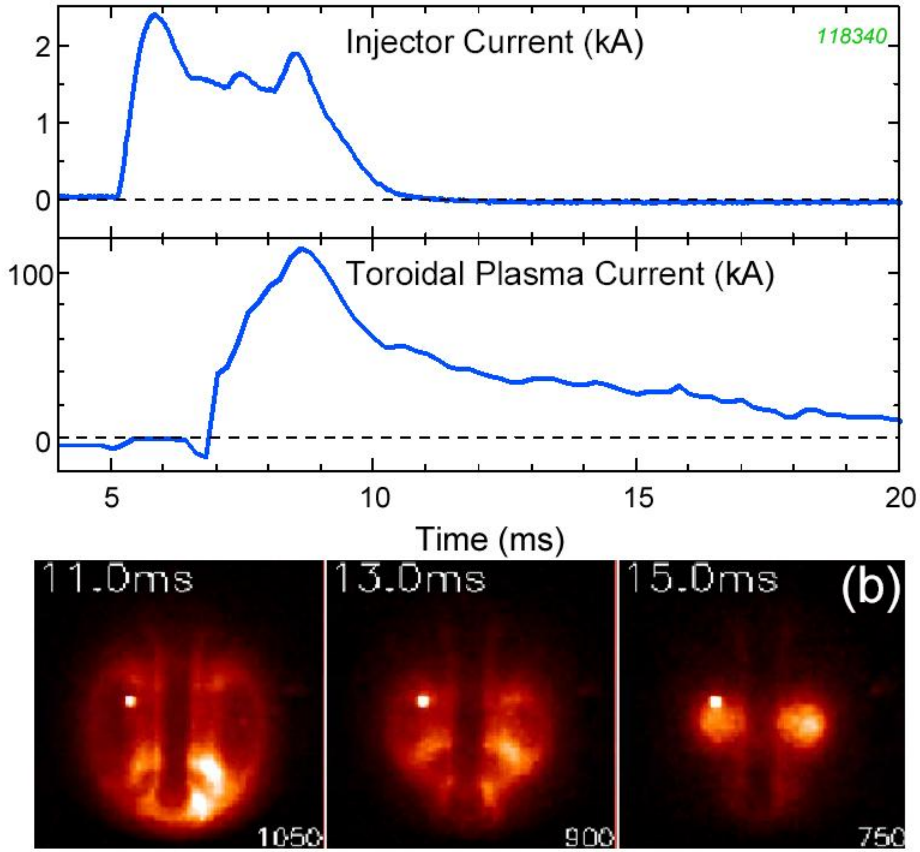
- Method is an outgrowth of spheromak research (CT Contribution to STs)
- Toroidal field considerably improves efficiency of CHI (ST contribution to CTs)

CHI for an ST: T.R. Jarboe, Fusion Technology, 15 (1989) 7

Transient CHI: R. Raman, T.R. Jarboe, B.A. Nelson, et al., PRL 90, (2003) 075005-1

Discharges Without Absorber Arc in NSTX Have High Current Multiplication Ratios (I_p/I_{inj} ~ 70)

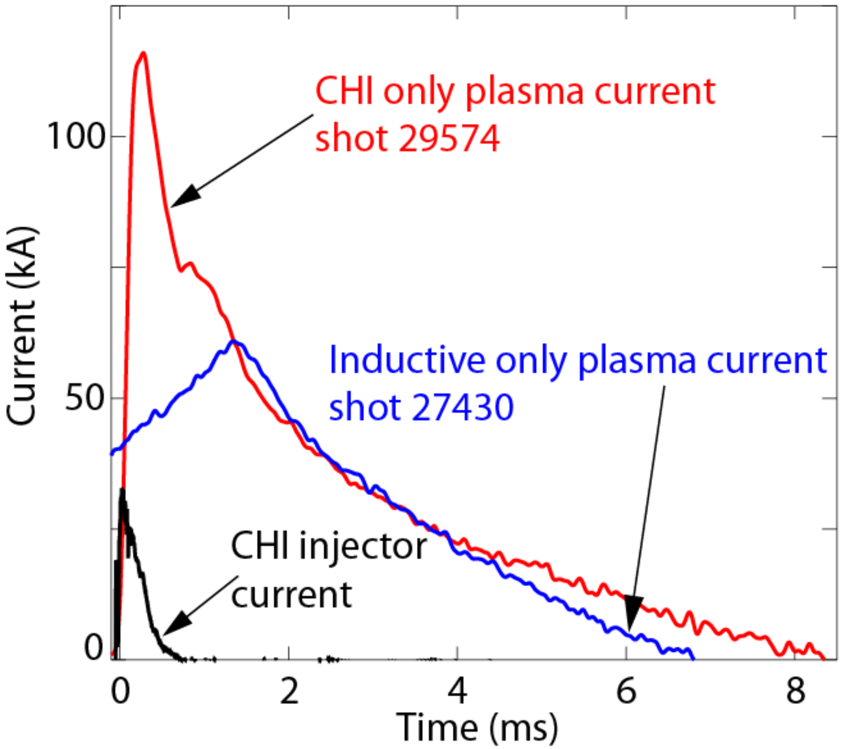
NSTX



I_{inj} ~1.5 kA generates I_p ~100 kA

- due to Higher Toroidal Flux in NSTX

HIT-II



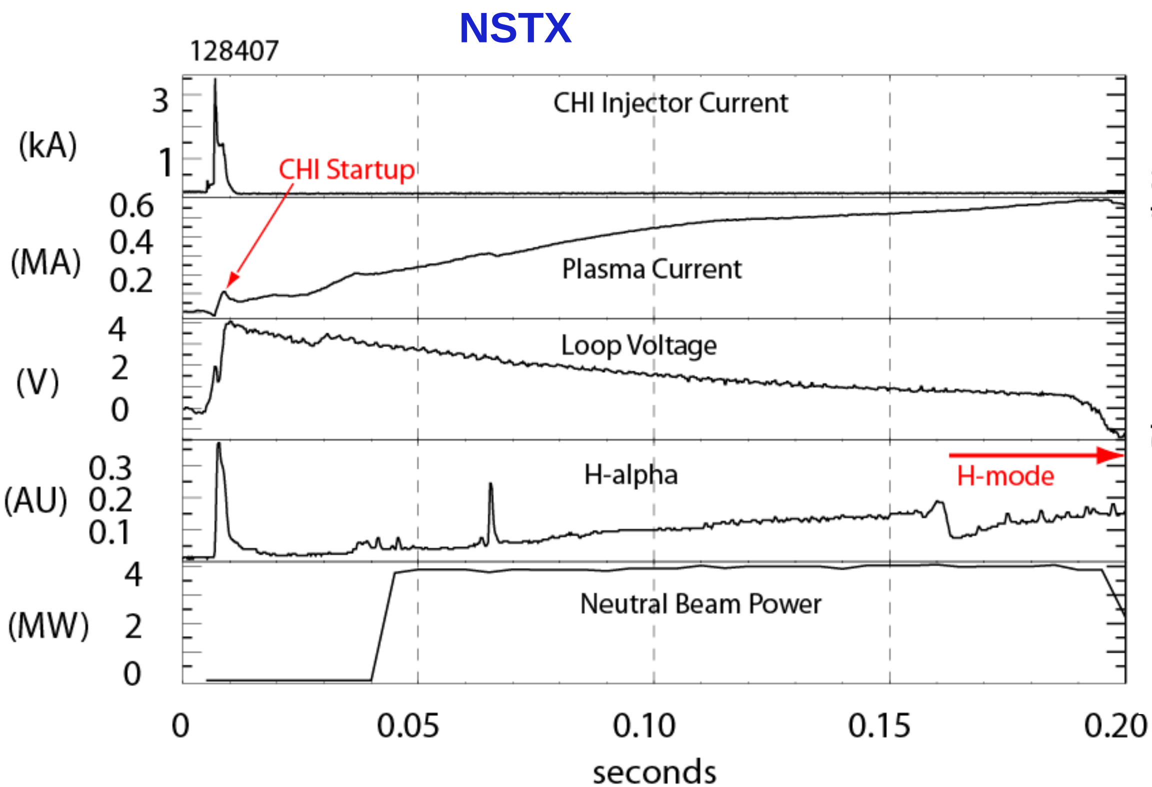
I_{inj} ~30 kA generates Ip ~120kA

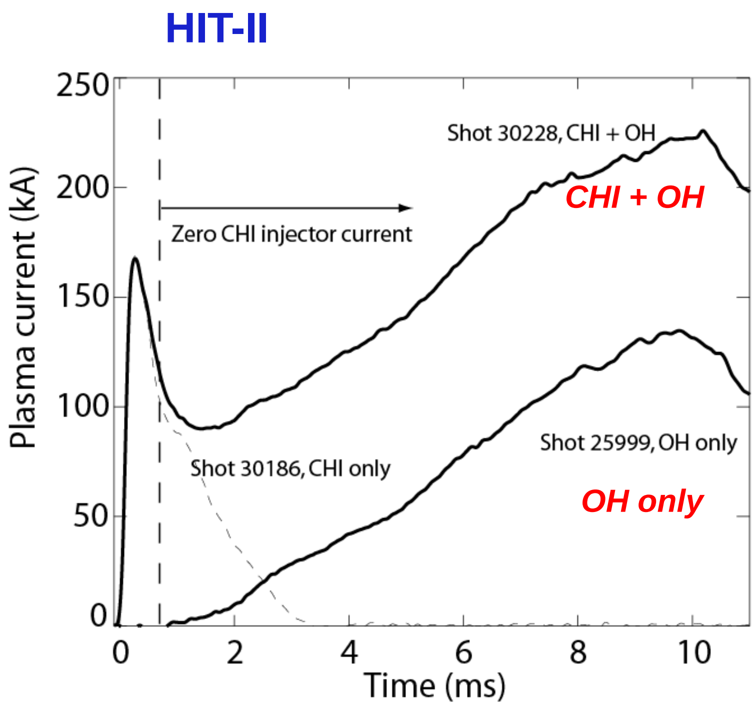
Best current multiplication is ~6-7

R. Raman, T.R. Jarboe, R.G. O'Neill, et al., NF 45 (2005) L15-L19

R. Raman, B.A.Nelson, D. Mueller, et al., PRL 97 (2006) 17002

NSTX CHI discharges couple to induction and transition to an H-mode demonstrating compatibility with high-performance plasma operation





Discharge is under full plasma equilibrium position control

- Loop voltage is preprogrammed

All of the CHI started current is retained in the subsequent inductive ramp

Higher current startup in NSTX requires reduction of low-Z impurities

Transient CHI Scales Very Well to Larger Machines

- 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 (Advantage of TF and ST contribution to CTs)

- Current Multiplication can be very large! $I_P = I_{inj}(\psi_{Tor} / \psi_{Pol})$
  - HIT-II: Current multiplication factor ~6
  - NSTX: I_{inj}~1.5kA generates I_P ~ 120kA (~60-70)

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

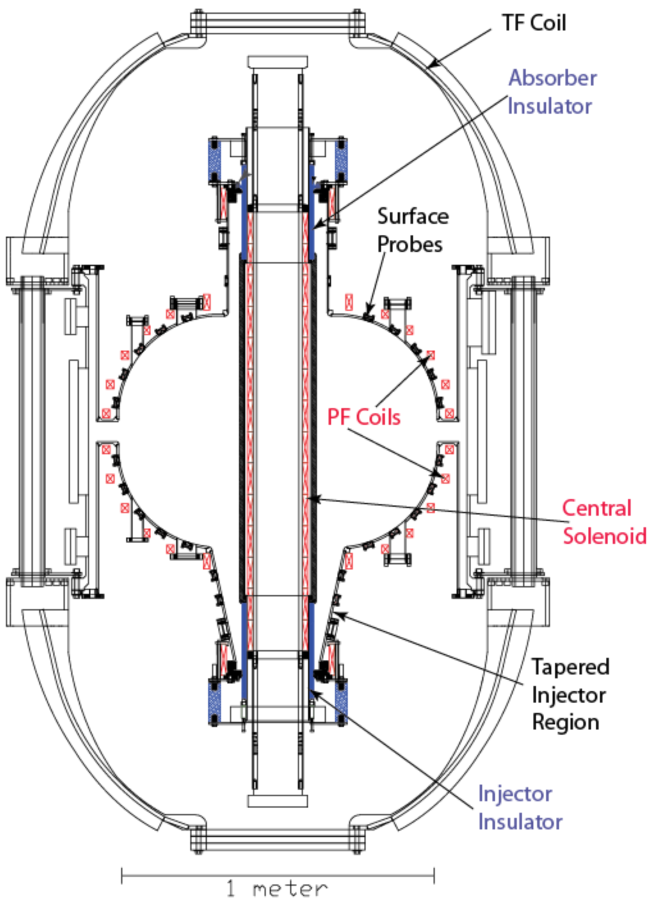
Transient CHI is Capable of Very High Current Generation in ST CTF and in ST Reactors!

- Projected plasma current for CTF >2.5 MA

  $[I_p = I_{inj}(\psi_{Tor}/\psi_{Pol})]$

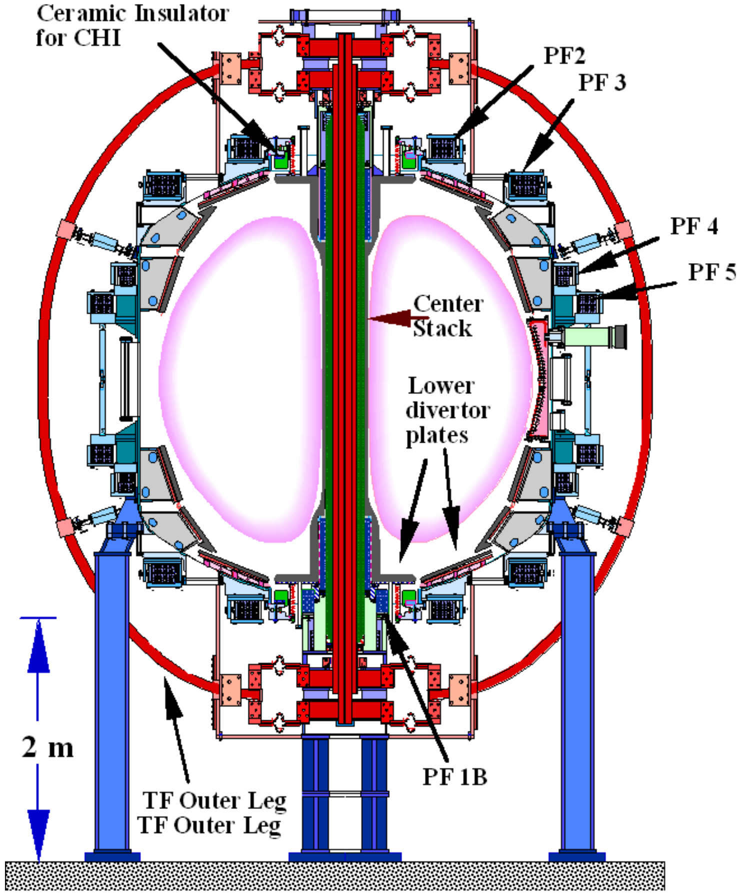
  - Based on conservative 50 kA injected current (30 kA Injector current densities achieved on HIT-II translates to ~250kA in ST CTF).
  - Current multiplication of 50 (70 achieved in NSTX, and can be expected to improve in a larger machine with more toroidal flux)
  - ***NOTE: Start-up currents much higher that 2.5 MA is possible***

NSTX Plasma is ~ 30 x Plasma Volume of HIT-II



Concept exploration device HIT-II

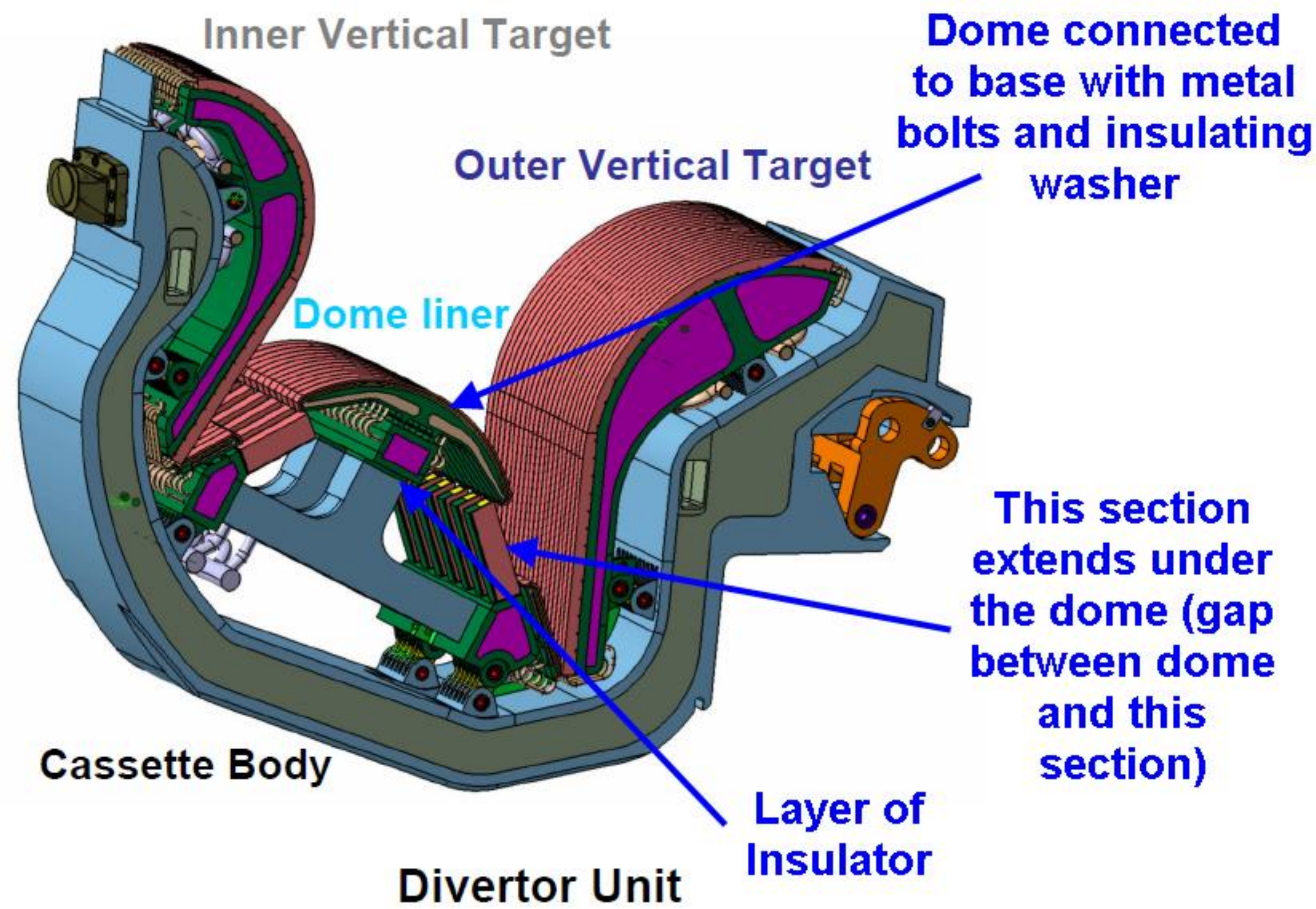
- Built for developing CHI
- Many Close fitting fast acting PF coils
- 4 kV CHI capacitor bank



Proof-of-Principle NSTX device

- Built with conventional tokamak components
- Few PF coils
- 1.7 kV CHI capacitor bank

One Example of CHI Insulator Installation in a Reactor (The Dome region is insulated from the vessel)



Insulator is under compression and shielded from neutron

(Concept is similar to the biased ring electrode on DIII-D, but because of the short pulse length, and because of the lack of a pre-existing plasma, the requirements on the insulator are considerably less demanding than on DIII-D)

Requirements for the CHI Insulator are Less Demanding than the Insulation Requirements for a Mineral Insulated Solenoid

- Insulator Resistance >1 Ohm
- Resistance to be maintained ***only*** during the plasma start-up phase (< 30ms in duration)
- The actual high-voltage phase < plasma start-up phase
- During the plasma startup phase, there is no pre-existing plasma that can short-out insulator (CHI current path is controlled by pre-programmed vacuum field line pattern)
- After the high-voltage phase, insulator could be shorted-out, if necessary
- Between now and the construction of a ST-CTF or a DEMO, improvements in insulator technology would further simplify CHI insulator requirements

Because the Insulator Resistance is very low (few times the plasma impedance) other possibilities exist

For example:

- Thin resistive metal coated with an insulating layer is a possibility
- Powdered, weakly bonded, insulator sandwiched between two metal plates is another possibility
- The HIT-SI device uses an insulator spray to achieve insulation *in a plasma environment* in a more complicated vessel geometry

Required Improvements for CHI Start-up

- Low-Z impurities are an issue for startup
  - Test with full metal divertor plates in NSTX
    - Spheromaks with metal walls reach Te ~500 eV

- Test CHI with insulated divertor plates
  - As part of NSTX-Upgrade,

    the lower divertor plates could be insulated

    - This has the added benefit for ST research of being able to measure induced currents on divertor plates during a disruption

Research Gaps in Solenoid-free Start-up

Method	Advantages	Reactor Requirements	Research Gaps
Transient CHI (NSTX is the only device at this time with CHI capability)	Compatible with superconducting (SC) PF coils Very favorable scaling to larger devices (>2.5MA projected for ST CTF)	Either the inner, outer or dome region of the divertor needs to be insulated from the rest of the vessel, but present insulators could meet this need	Experiments needed in a metal electrode configuration to reduce low-Z impurities Demonstration of Ip > 500kA and coupling to NBI and RF to ramp Ip >1MA
Plasma Gun Startup	Gun sources could be removed from reactor after plasma startup Possibly compatible with SC PF coils	Number of gun sources and size of guns	Current scaling needs to be understood
Outer PF startup	No new components needed	Requires sufficient loop-voltage capability from outer PF coils	Effect of blankets and other conductive components between PF coils and plasma on the available loop volts
EBW	Easy to install Compatible with SC PF coils	Requirements on RF capability for desired current levels	Scaling with microwave power and coupling to other non-inductive current drive methods High current generation to be demonstrated
Mineral Insulated Solenoid	Solenoid is a 40yr old system	Insulation requirements, especially under repeated pulsing after neutron bombardment cycles	Insulation and solenoid capability under repeated neutron fluence cycles is not known
Iron core solenoid	Passive component with some electrical insulation Requires non-SC PF coils	Insulation and installation requirements	Maximum attainable currents?

Research Thrust on Plasma Start-up & Ramp-up (Other Methods): TAP Tier 1 Issue

- Pegasus – Plasma Gun Startup
  1)Current scaling to larger machines
  2)Scaling with respect to number of gun sources and gun size
  3)Test on NSTX & coupling to NBI and RF

- DIII-D – Outer PF Start-up
  1)Because of the higher TF, high ECH power and good feed-back plasma control capabilities, DIII-D is best suited to study the potential of this method for plasma startup
  2)Modeling effort to study the impact of conductive structures between the PF coils and the plasma & required PF coil(s) current ramp rates

- MAST – EBW Start-up
  1)Test of high current generation
  2)Current scaling and power requirements for future machines

- Predictive modeling – NIMROD & TSC
  1)develop models for integrated startup and ramp-up
  2)validate models against experimental data

Research Thrust on Plasma Start-up & Ramp-up (CHI Start-up): TAP Tier 1 Issue

•NSTX – Transient CHI

1)Use metal divertor electrodes to reduce the influx of low-Z impurities

2)Optimize CHI startup with Li walls

• NSTX-U – Transient CHI

1)Use the 1T capability to further validate scaling relations

2)Using improved electrical insulation with insulated divertor plates and metal electrode surfaces increase the CHI produced current to ~500kA

•At 500kA, and at the higher toroidal field TSC simulations show that non-inductive current ramp-up and sustainment should be possible using NBI and HHFW *– such a demonstration would fulfill a primary ST goal of realizing full non-inductive start-up and ramp-up. This would be a useful contribution of STs to Tokamaks.*

•Predictive modeling – NIMROD & TSC

1)develop models for integrated startup and ramp-up

2)validate models against experimental data