NSTX

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# Non-inductive Plasma Current Start-up in NSTX using Transient CHI and subsequent Non-inductive Current Ramp-up Scenario in NSTX-U


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# Motivation for Coaxial Helicity Injection (CHI) Start-up

- A FNSF based on the Spherical Torus (ST) concept will have very restricted space for a central solenoid
  - A method for solenoid-free start-up is very likely required
- Eliminating the solenoid also simplifies the tokamak concept
  - Solenoid not needed during steady-state operation
  - Provides greater flexibility in the choice of the aspect ratio
- Transient CHI has generated 200kA of high-quality plasma current in NSTX
  - When induction is applied, the current ramped-up to 1MA, while requiring 35% less inductive flux than a discharge without CHI start-up

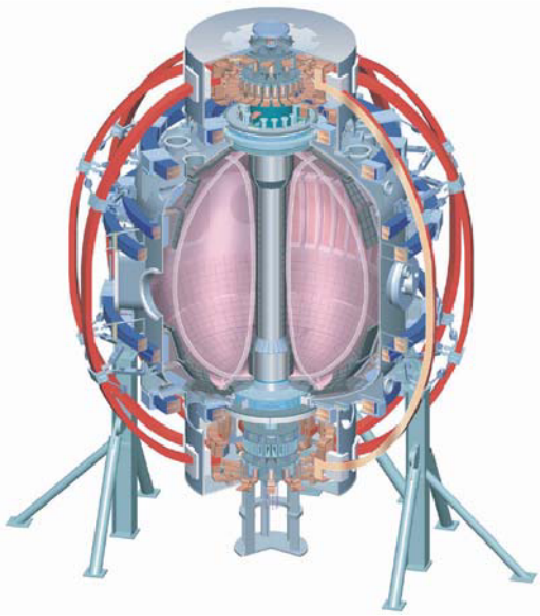
# Outline

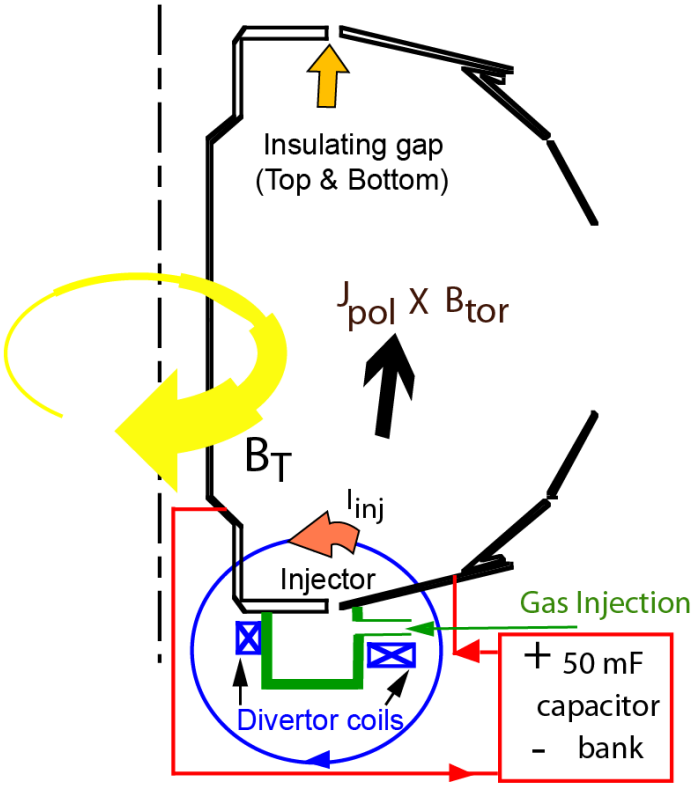
1) Transient CHI Plasma Start-up

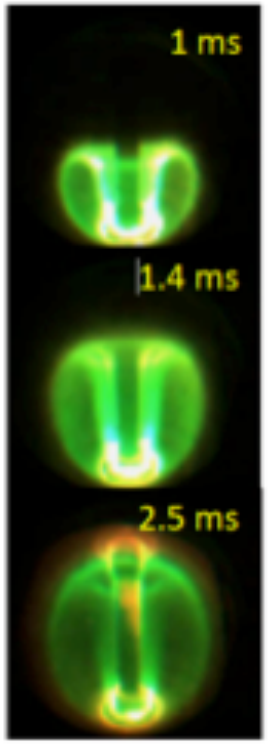
2) Coupling CHI to inductive current drive in NSTX

3) NSTX-U plans on coupling CHI to NBI current drive

# NSTX-U Will Use Transient CHI For Solenoid-free Plasma Start-up With Subsequent Current Ramp-up Using NBI






- Parameters to consider
  - Current multiplication factor
  - Effect of toroidal field
  - Magnitude of generated plasma current
  - New desirable features?

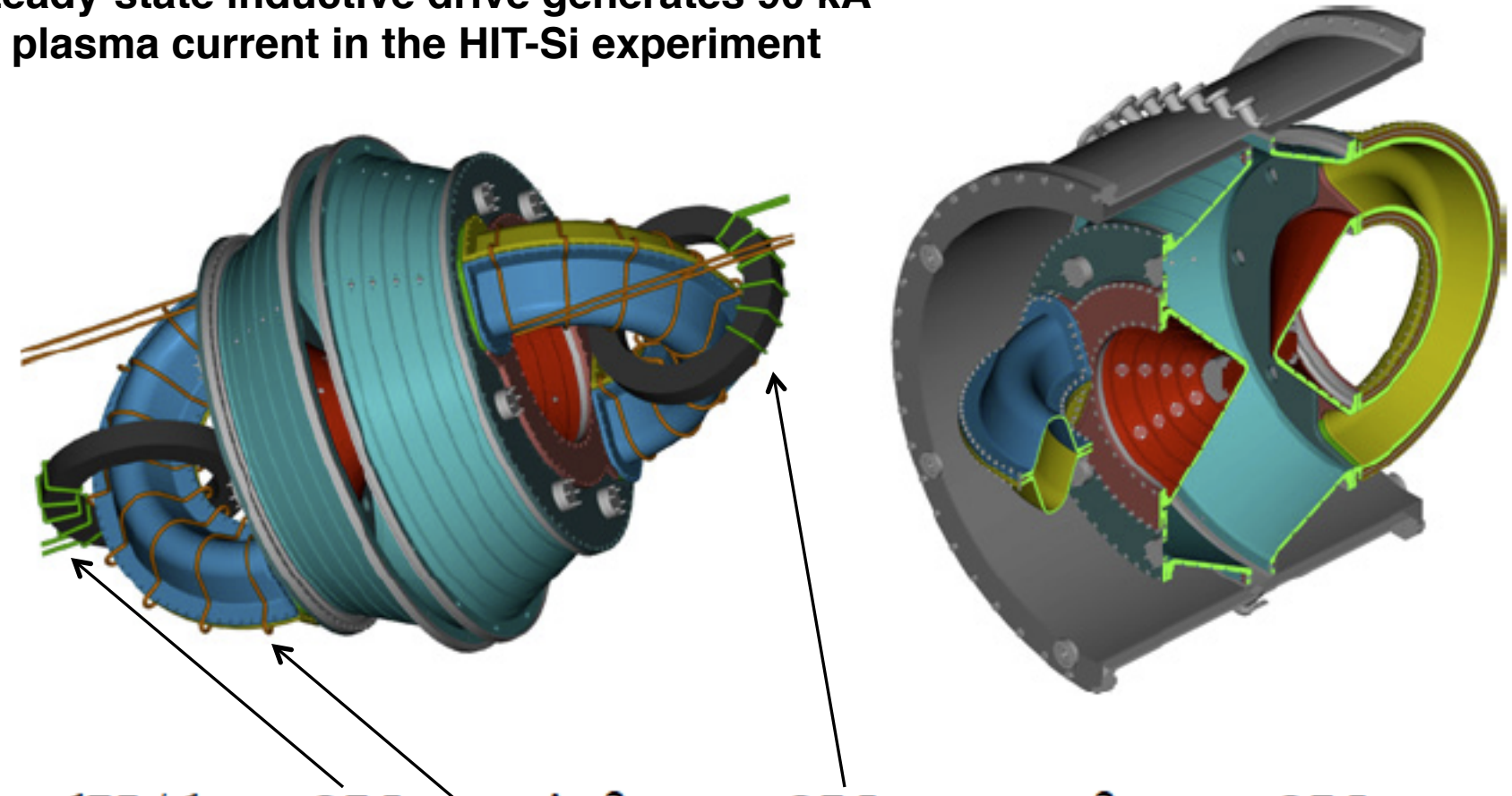

**Fast camera:** F. Scotti, L. Roquemore, R. Maqueda

**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

# Imposed-dynamo Current Drive Levies Controlled Fluctuations on Open Field Lines around a Stable Equilibrium

**Steady-state inductive drive generates 90 kA of plasma current in the HIT-Si experiment**

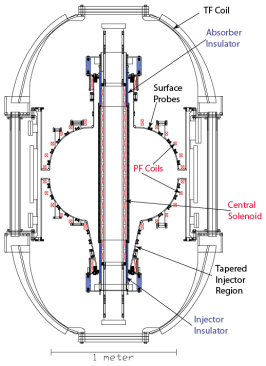


$$dK/dt = 2V_o\psi_o\sin^2\omega t + 2V_o\psi_o\cos^2\omega t = 2V_o\psi_o$$

**University of Washington**

T.R. Jarboe, et al., Nucl. Fusion **52** (2012) 083017
B.S. Victor et al., Phys. Rev. Lett. **107** (2011) 165005

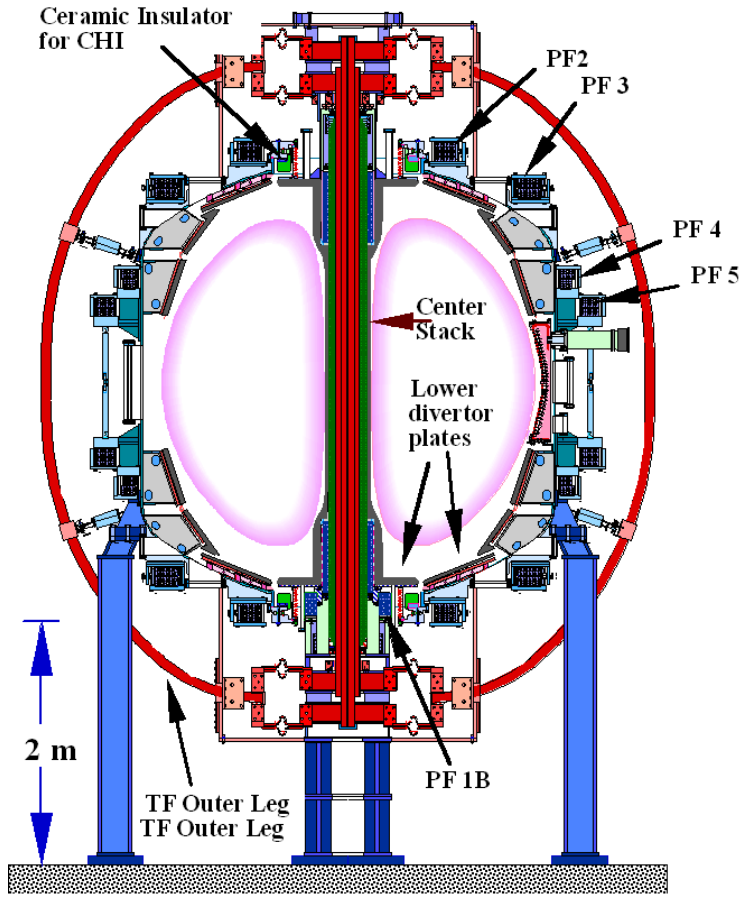
# NSTX CHI Research Follows Concept Developed in HIT-II




**Concept exploration device HIT-II**

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

**NSTX plasma is ~30 x plasma volume of HIT-II**

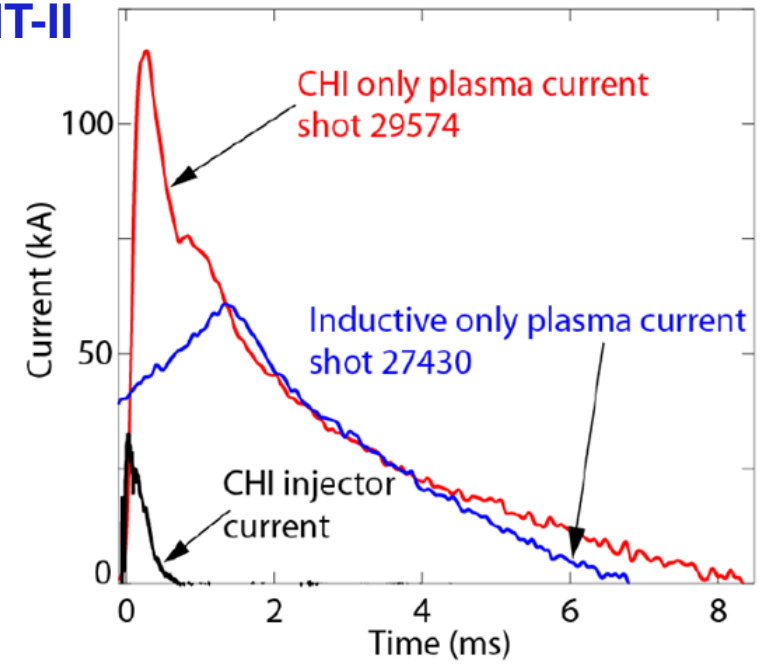



**Proof-of-Principle NSTX device**

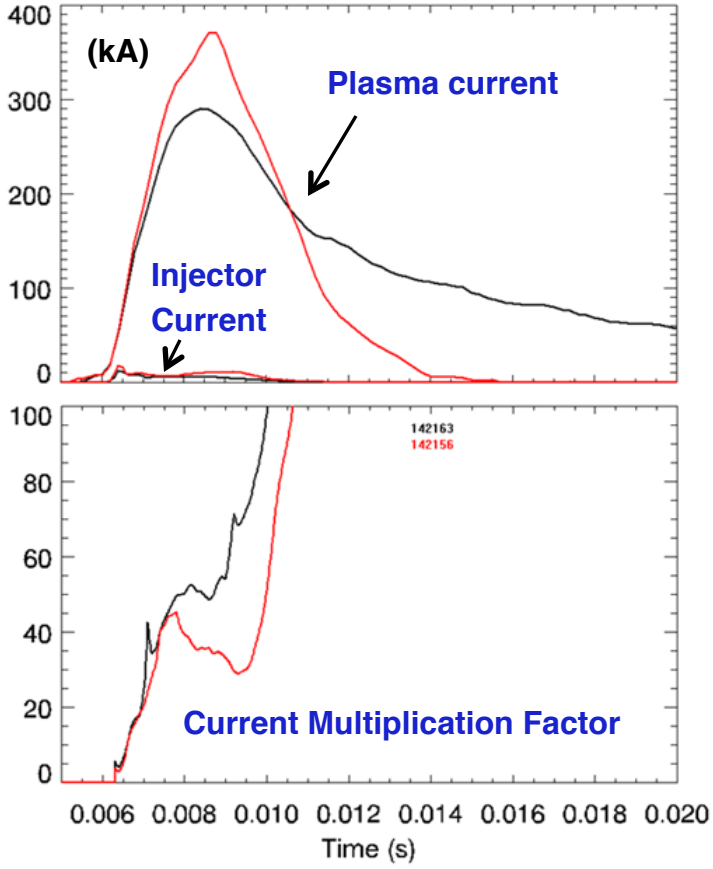
- Built with conventional tokamak components
- Few PF coils
- 1.7kV CHI capacitor bank

# Very High Current Multiplication (Over 70 in NSTX) Aided by Higher Toroidal Flux

**HIT-II**




**NSTX**




**-30kA of injector current generates 120kA of plasma current**

**-Best current multiplication factor is 6-7**

**-Current multiplication factor in NSTX is 10 times greater than that in HIT-II**

**- Over 200kA of current persists after CHI is turned off**

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

# Externally Produced Toroidal Field makes CHI much more Efficient in a Lower Aspect Ratio Tokamak

- Bubble burst current*: $I_{inj} = 2\psi_{inj}^2 / (\mu_o^2 d^2 I_{TF})$

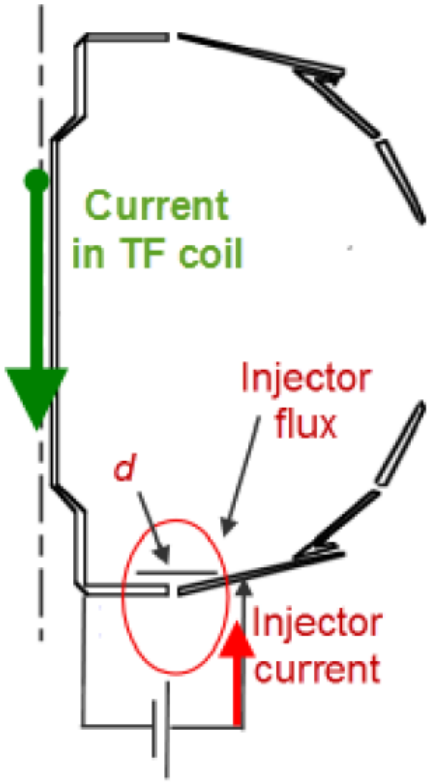
  $\psi_{inj}$ = injector flux

  $d$ = flux foot print width

  $I_{TF}$ = current in TF coil

**Injector current** **Toroidal flux**

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

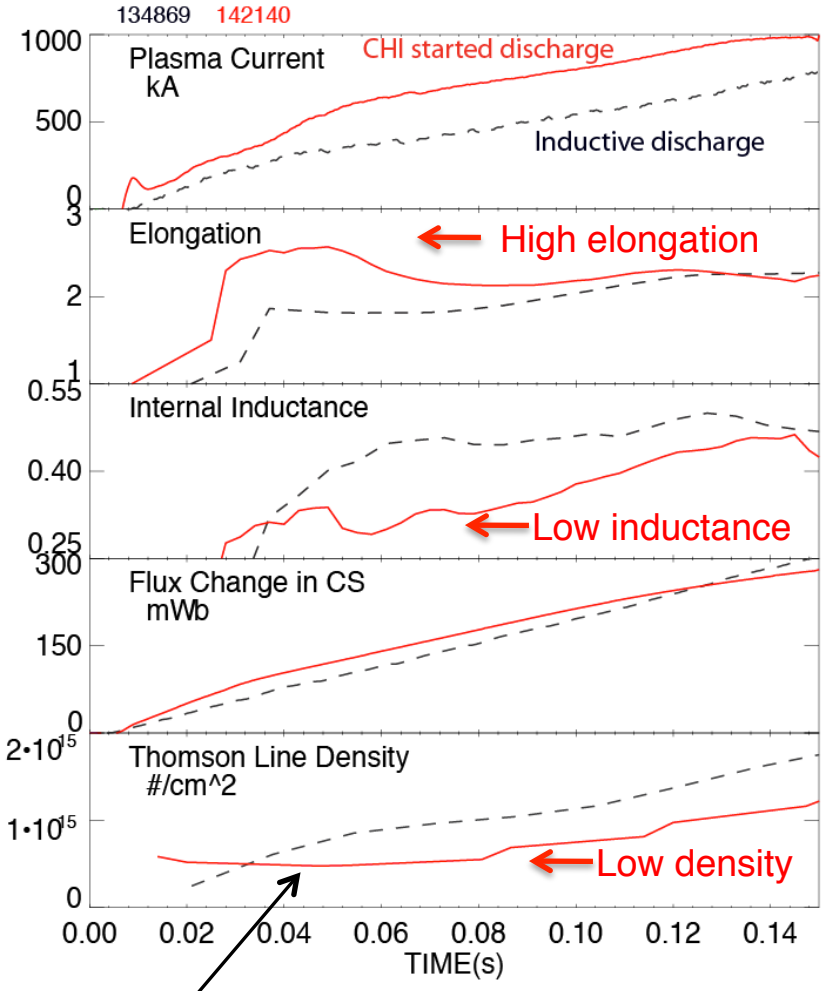



- Current multiplication increases with toroidal field
  - Favorable scaling with machine size
  - Increases efficiency (10 Amps/Joule in NSTX)
  - Smaller injector current to minimize electrode interaction

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

# Plasma Discharge Ramping to 1MA Required 35% Less Inductive Flux when Coaxial Helicity Injection (CHI) is Used

CHI assisted startup in NSTX




CHI generates plasmas with low $n_e$ below ECH cut-off

27 kJ of stored capacitor bank energy used for CHI plasma start-up

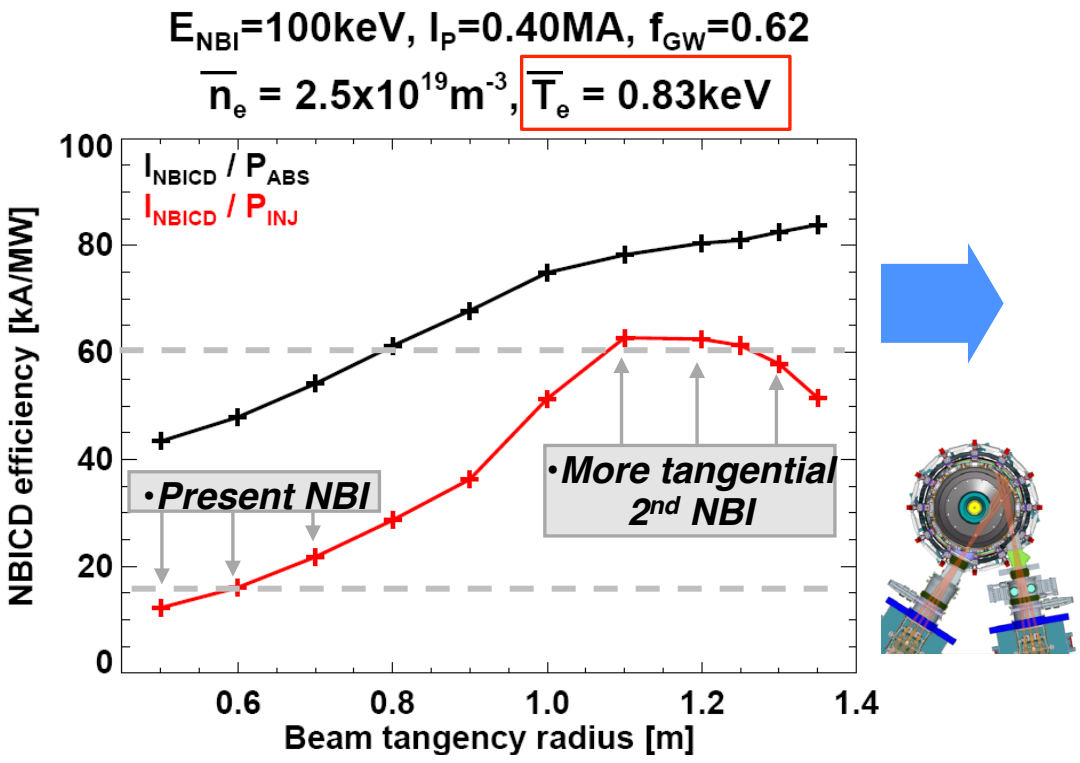
CHI produced plasma is clean

(Discharges have transitioned to H-mode after coupling to induction)

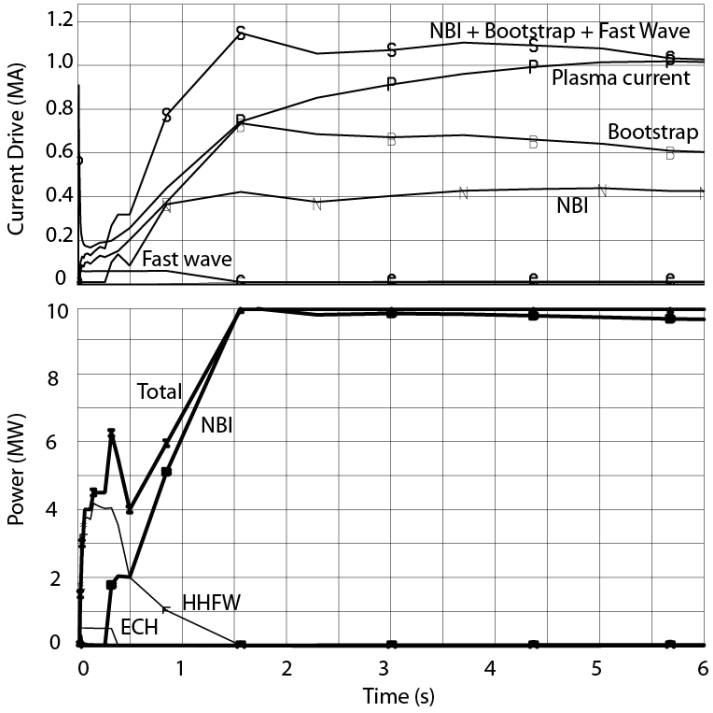
# NSTX-U Plans for coupling Transient CHI plasma to Neutral Beam current drive

# Non-inductive Ramp-up from ~0.4MA to ~1MA Projected to be Possible with More Tangential 2nd NBI

- **More tangential NBI provides 3-4x higher CD at low $I_P$:**
  - 1.5-2x higher current drive efficiency, plus
  - 2x higher absorption (40→80%) at low $I_P$ = 0.4MA

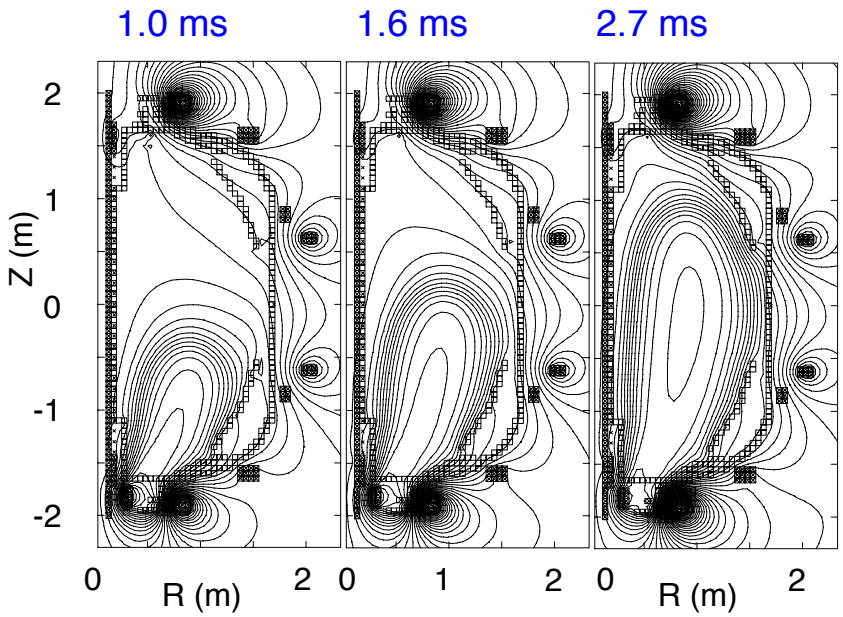


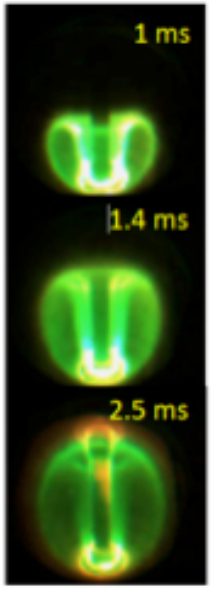

- **TSC simulation of non-inductive ramp-up from initial CHI target**
  - Simulations now being improved to use TRANSP/NUBEAM loop within TSC
  - Experimental challenges:
    - Maximum NBI power in low inductance CHI plasma



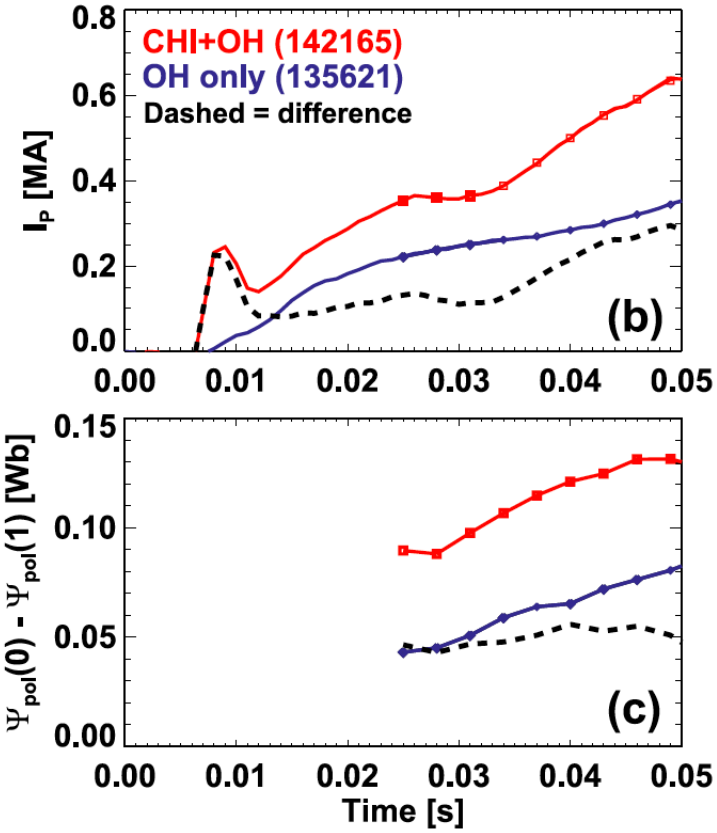
# Simulations Using TSC, coupled to TRANSP/NUBEAM and GENRAY being used for Current Ramp-up Simulations

TSC (axisymmetric 2D ) simulation



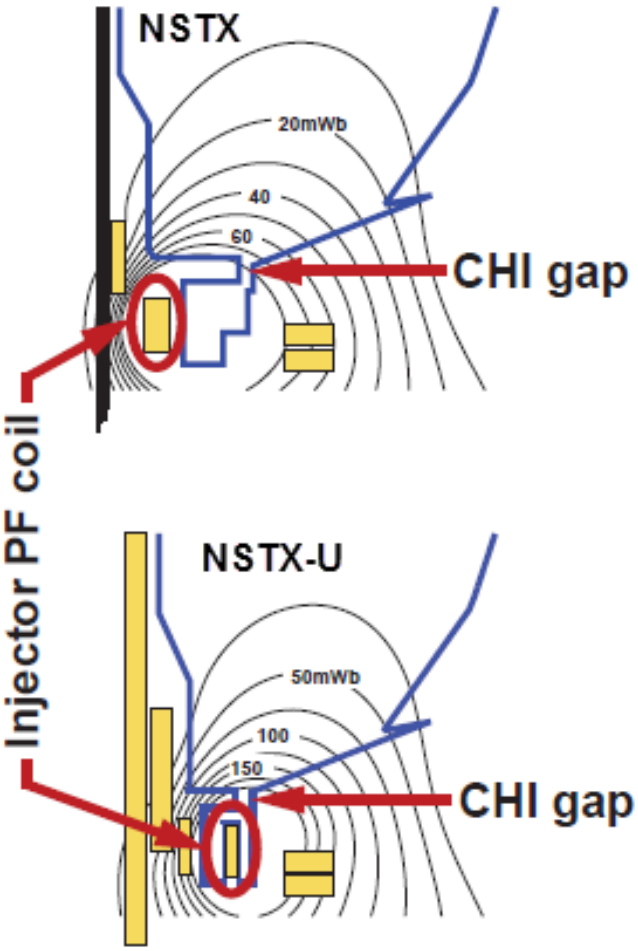

CHI produces closed flux change of ~ 50 mWb




## New Tools for CHI on NSTX-U

- > 2.5 x Injector Flux (proportional to $I_p$ )
- TF = 1 T (increases current multiplication)
- ECH (increases $T_e$)
- > 2kV CHI voltage (increases flux injection)
- Full Li coverage (reduces low-Z imp.)
- Metal divertor, Cryo pump (increases $T_e$)

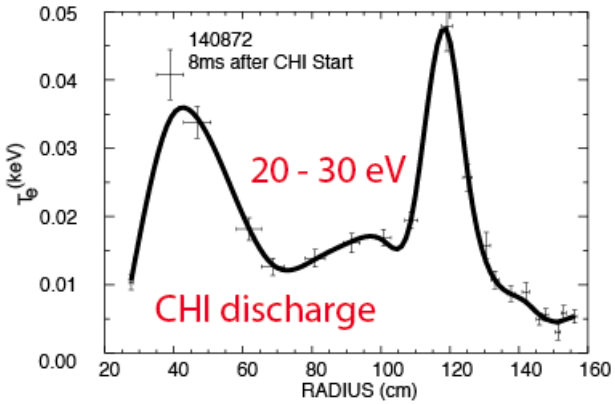
# CHI Start-up to ~0.4MA is Projected for NSTX-U, and Projects to ~20% Start-up Current in Next-step STs



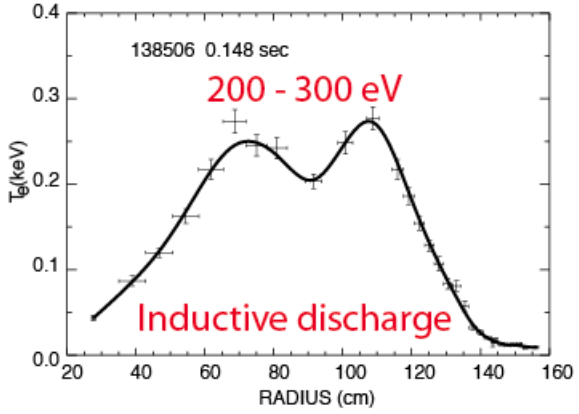

| Parameters | NSTX | NSTX-U | ST-FNSF |
|---|---|---|---|
| Major Radius [m] | 0.86 | 0.93 | 1.2 |
| Minor Radius [m] | 0.66 | 0.62 | 0.80 |
| $B_T$ [T] | 0.55 | 1.0 | 2.2 |
| Toroidal Flux [Wb] | 2.5 | 3.9 | 15.8 |
| Plasma current [MA] | 1 | 2 | 10 |
| Projected Start-up Current (MA) | 0.2 | 0.4 | 2.0 |
| Poloidal Flux [Wb] | 0.04 | 0.08 | 0.53 |
| Injector Flux [Wb] | 0.047 | 0.1 | 0.66 |

**Injector flux in NSTX-U is ~ 2.5 times higher than in NSTX → supports increased CHI current**

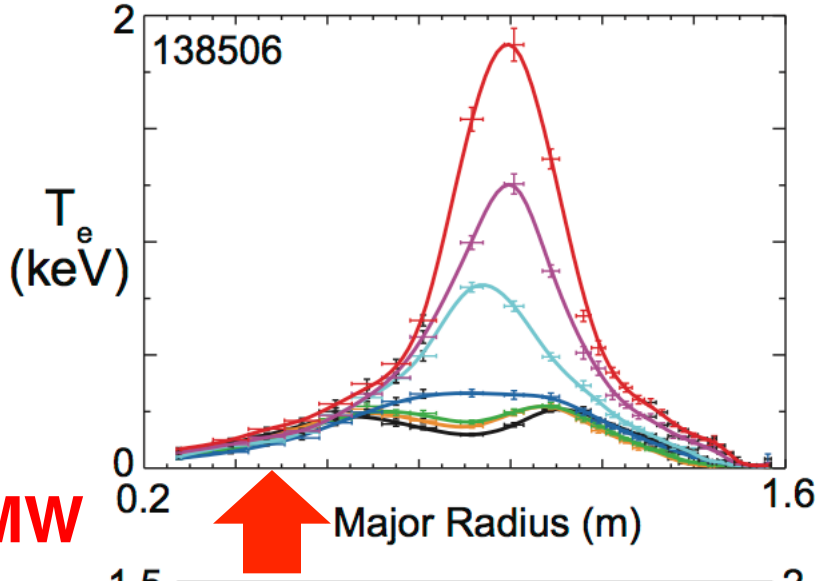
# Bridge Electron Temperature Gap Between CHI Start-up and Current Ramp-up Requirements with ECH Heating

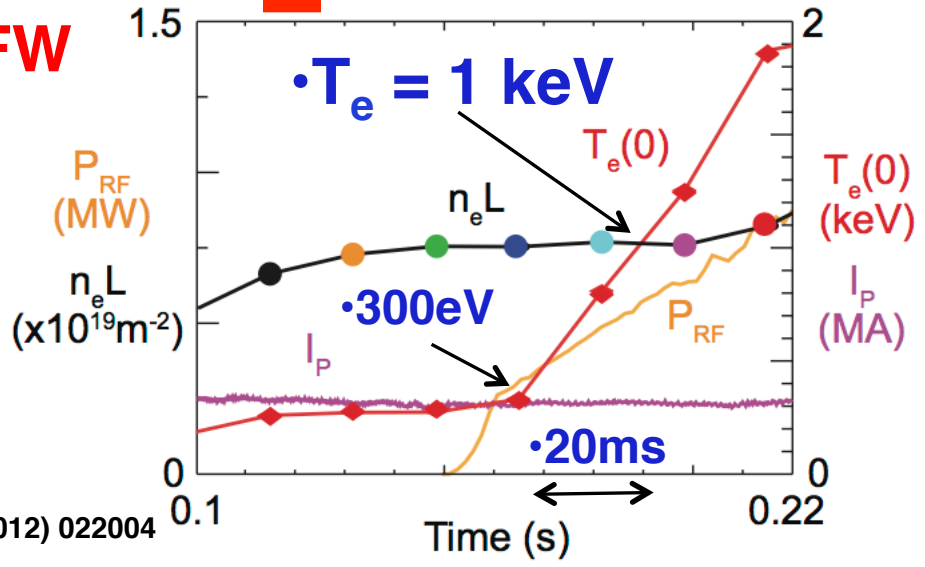



1MW ECH




1-2 MW HHFW




G. Taylor, et al., Phys. Plasmas 19 (2012) 022004

# NSTX-U will Develop Full Non-inductive Start-up and Current Ramp-up in support of FNSF and next step Tokamaks

- 0.3MA current generation in NSTX validates capability of CHI for high current generation in a ST (>400 kA projected for NSTX-U)
- Successful coupling of CHI started discharges to inductive ramp-up & transition to an H-mode demonstrates compatibility with high-performance plasma operation
- CHI start-up has produced the type of plasmas required for non-inductive ramp-up and sustainment (low internal inductance, low density)
- Favorable scaling with increasing machine size (from two machines of vastly different size, HIT-II and NSTX and in TSC simulations)
- Initial full discharge simulations (CHI start-up + NBI CD) using TSC provides viable scenarios for current ramp-up to 1MA
- NSTX-U is well equipped with new capabilities to study full non-inductive start-up and current ramp-up

  - 2x Higher TF, 1MW ECH, Second Tangential NBI for CD, 2x higher CHI voltage, >2.5x more injector flux, Improved upper divertor coils

# Back-up Slide

# Preliminary Scenario for Ramping to 1MA in NSTX-U

- Initial CHI target is generated by TSC
  - CHI phase ends at 17ms
  - Horizontal and vertical position control of CHI-started discharge initiated at 20 and 30ms
  - 0.5 MW ECH (absorbed power) maintained for 0.5s to heat CHI target
  - Initial 4 MW HHFW power ramped down to zero by 1.5s
  - H-mode initiated at 500ms
  - $\tau_E$ maintained at < 40ms, consistent with NSTX experimental results
  - Bootstrap current overdrive and NB current increases $I_p$ to 1 MA at 6s
  - Normalized internal inductance (not shown)maintained below 0.6 during current ramp