NSTX

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Demonstration of Plasma Start-up in NSTX Using Transient CHI

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and the NSTX Research Team

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The Joint Meeting of
5th IAEA Technical Meeting on Spherical Tori
16th International Workshop on Spherical Torus (ISTW2011)
2011 US-Japan Workshop on ST Plasma
September 27-30, 2011

National Institute for Fusion Science, Toki, Japan

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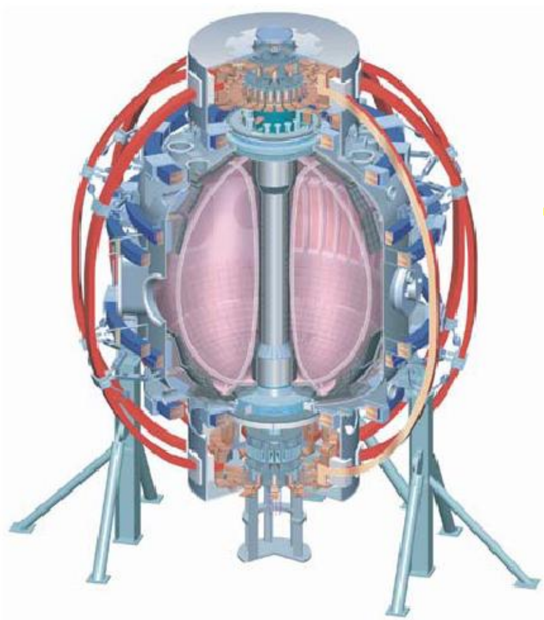
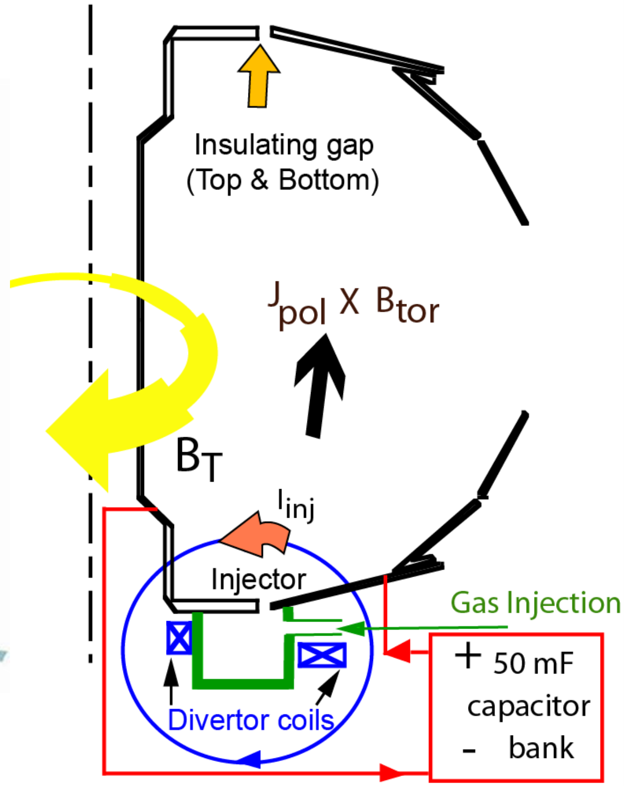
Tokamak Design Simplified by Eliminating Solenoid

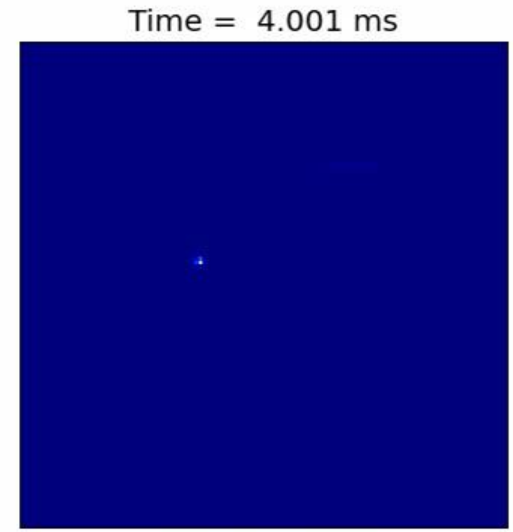
- Transient Coaxial Helicity Injection plasma startup method developed on HIT-II at U-Washington
  - Now successfully used on NSTX

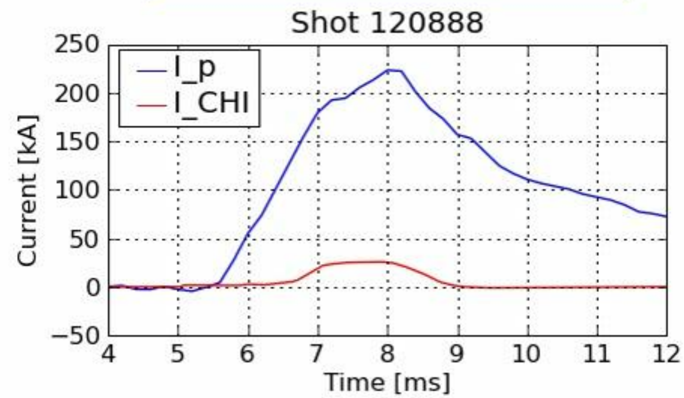
- Demonstrated the savings of inductive flux equivalent to over 300 kA current

Transient CHI: Axisymmetric Reconnection Leads to Formation of Closed Flux Surfaces









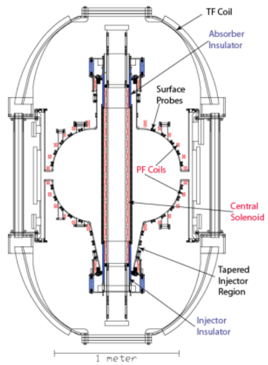
- Parameters to consider
  - Current multiplication factor
  - Effect of toroidal field
  - Magnitude of generated plasma current
  - New desirable features?

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

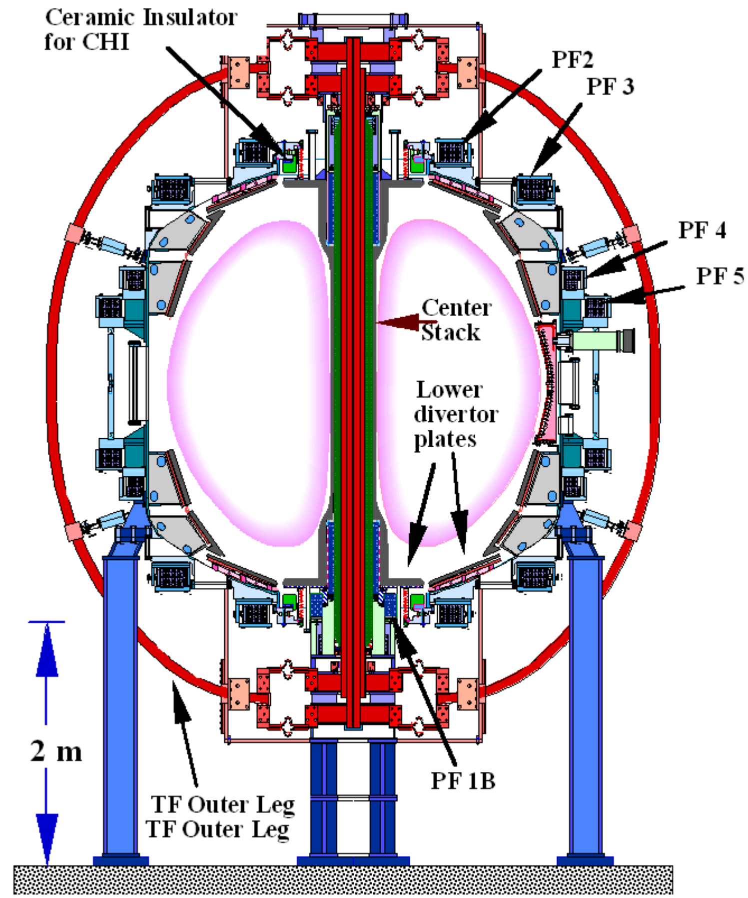
NSTX CHI Research Follows Concept Developed in HIT-II



ICC 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

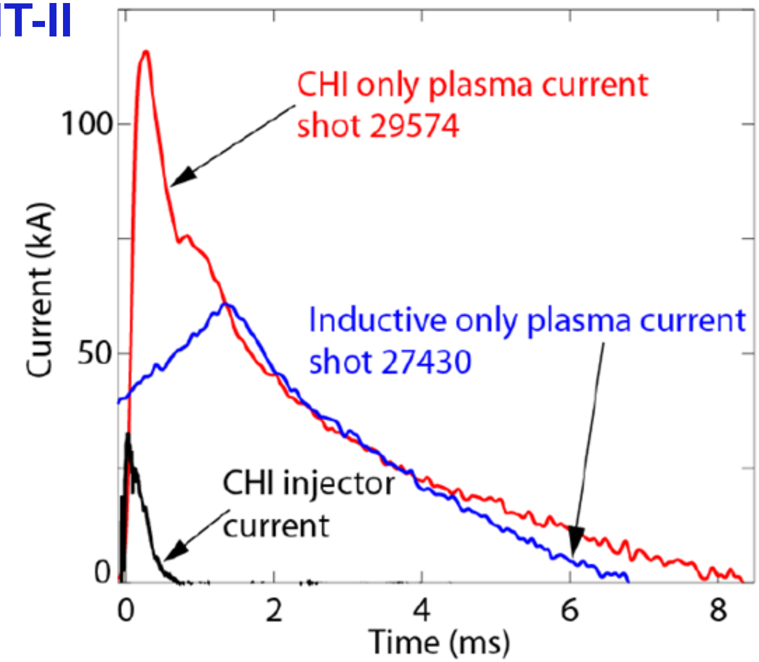


Proof-of-Principle NSTX device

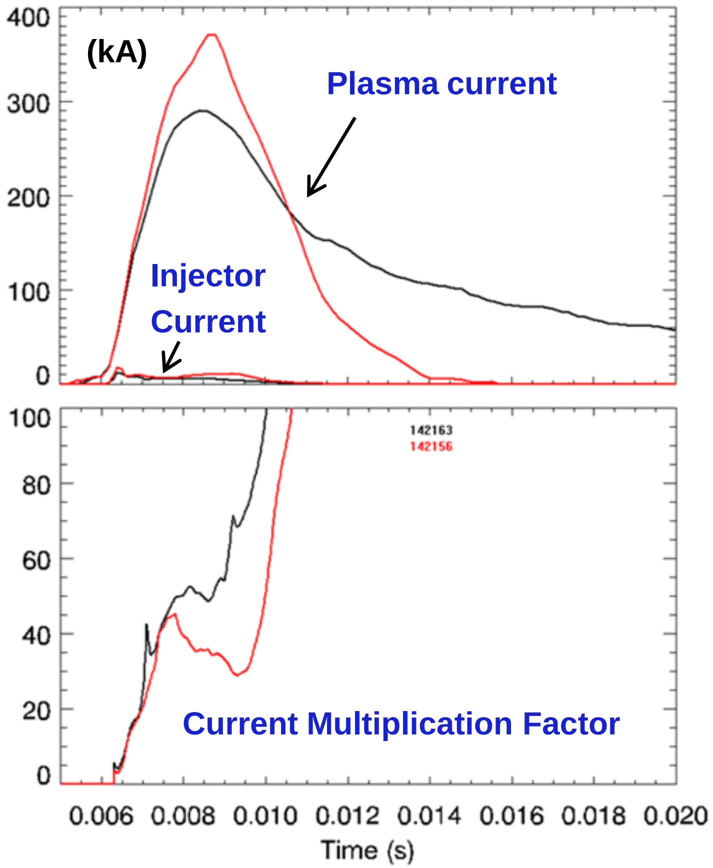
- Built with conventional tokamak components
- Few PF coils
- 1.7kV CHI capacitor bank

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 et al, Nuclear Fusion 45, L15-L19 (2005)

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

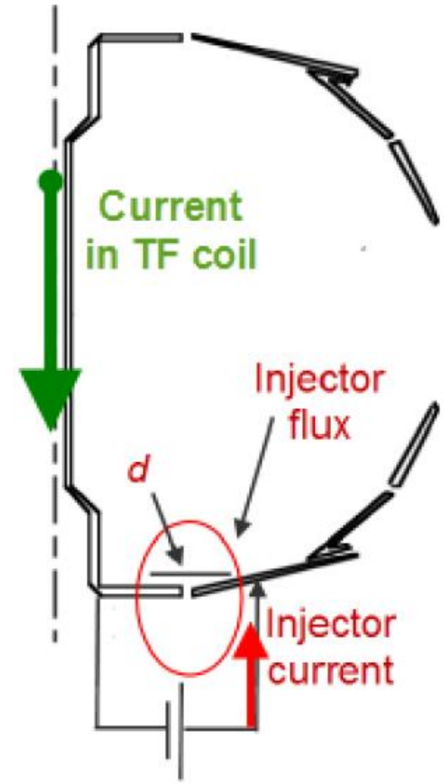
  ψ_{inj} = injector flux

  d = flux foot print width

  I_{TF} = current in TF coil

Injector current **Toroidal flux**

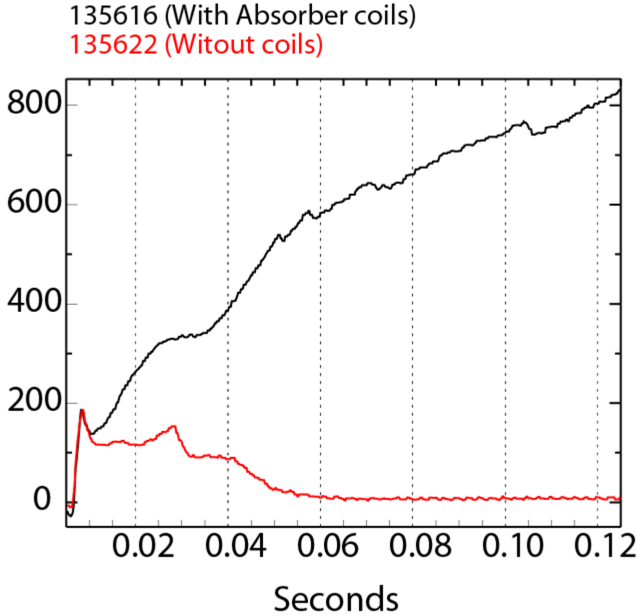
$$I_P = I_{inj}(\psi_T / \psi_{inj})$$

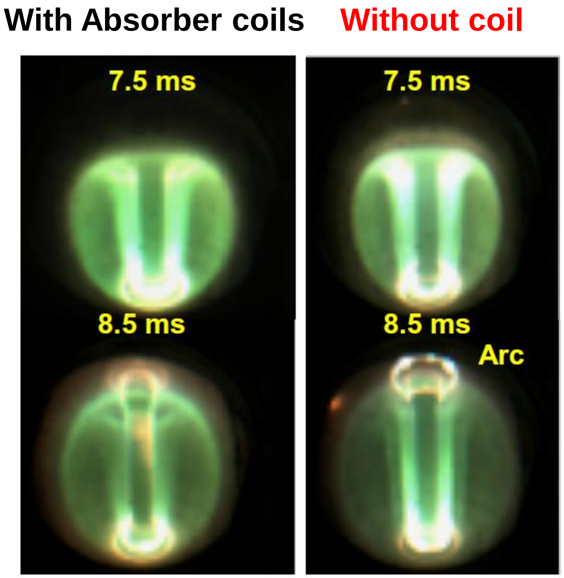


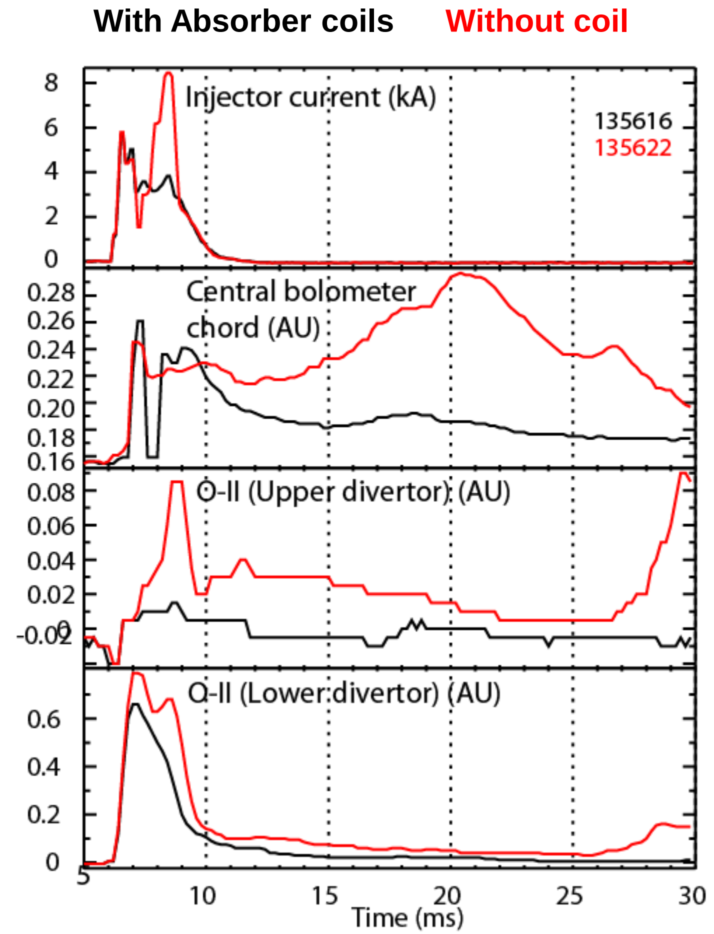
- Current multiplication increases with toroidal field
  - Favorable scaling with machine size
  - Increases efficiency (10 Amps/Joule in NSTX)
  - Smaller injector current to minimize electrode interaction

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

Absorber Coils Suppressed Arcs in Upper Divertor and Reduced Influx of Oxygen Impurities







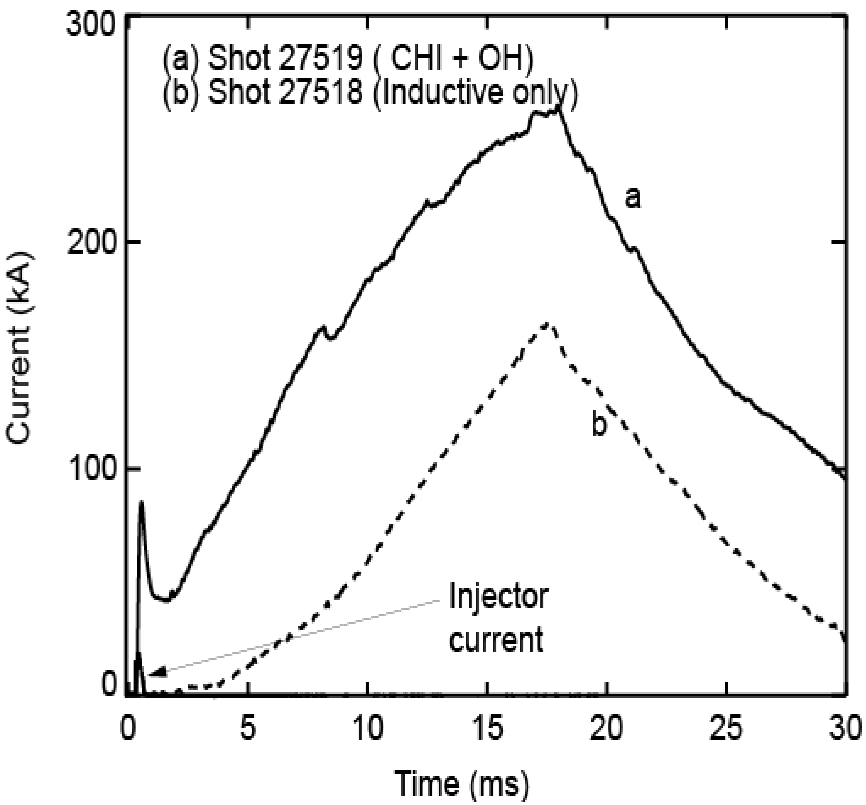
- Divertor cleaning and lithium used to produce reference discharge

- Buffer field from PF absorber coils prevented contact of plasma with upper divertor

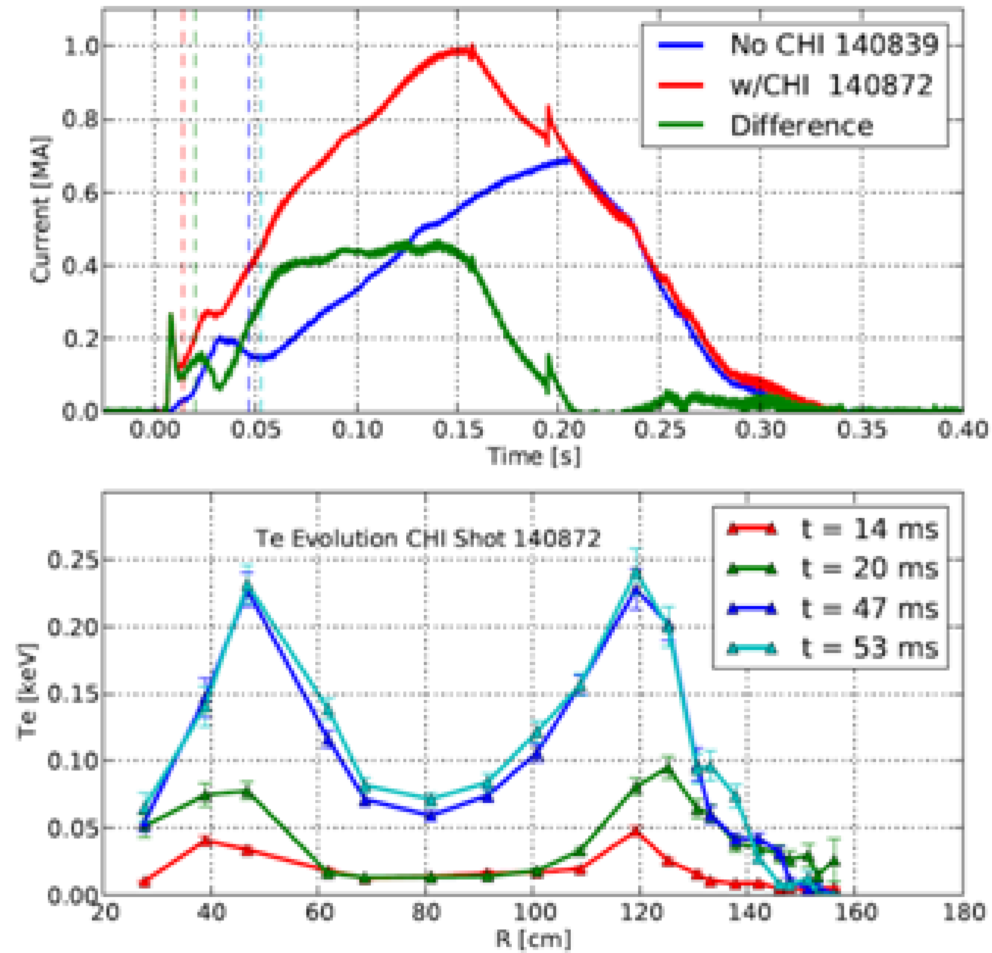
R. Raman, D. Mueller, B.A. Nelson, T.R. Jarboe, et al., PRL 104, (2010) 095003

In NSTX Using Only 27kJ of Capacitor Bank Energy CHI Started a 300kA Discharge that Coupled to Induction

HIT-II



NSTX

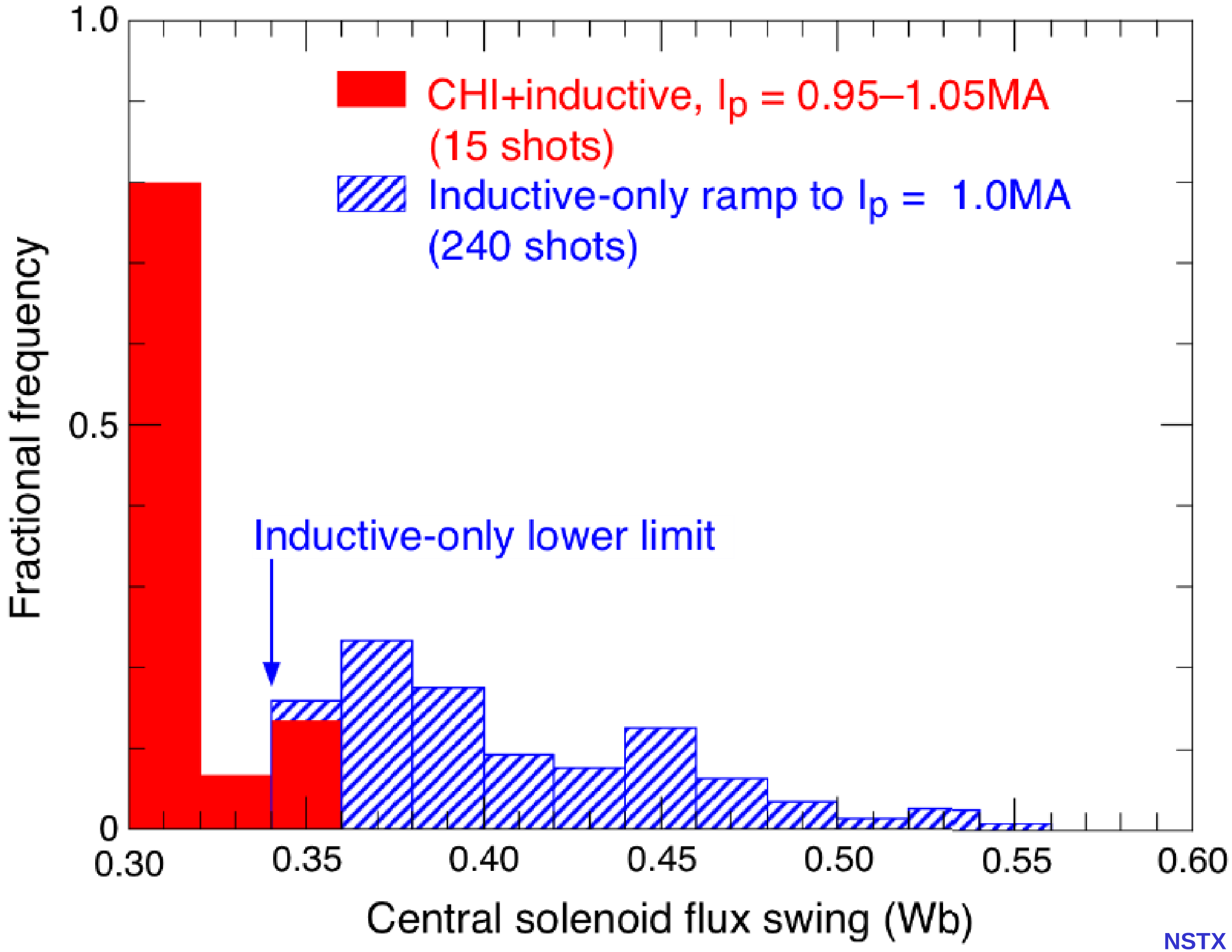


R. Raman, T.R. Jarboe, B.A. Nelson et al, Phys. Plasmas 14, 022504 (2007)

B.A. Nelson et al, Nuclear Fusion 51, 063008 (2011)

CHI Started Discharges Require Less Inductive Flux than Discharges in NSTX Data Base

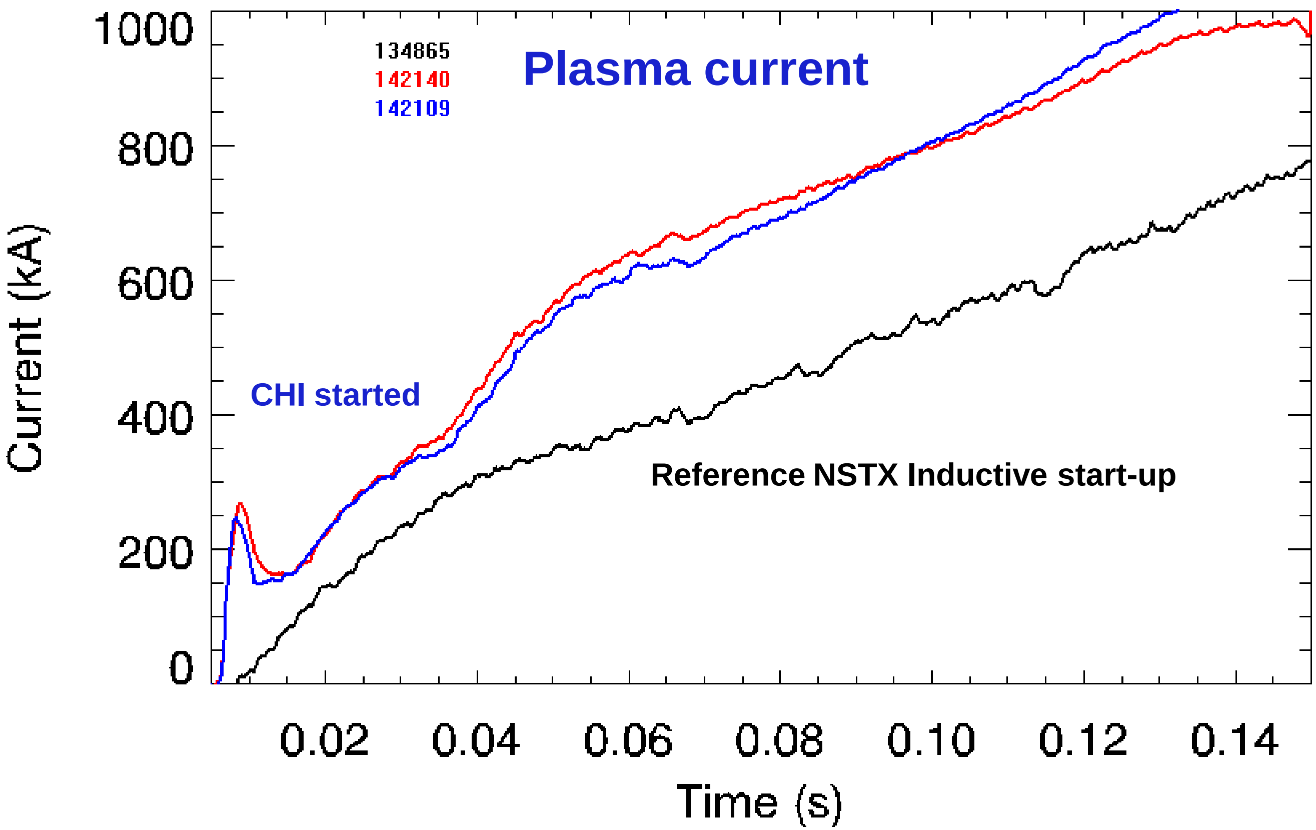
Comparison of CHI Startup to H-modes using more than 1 NBI source



Most recent CHI-started discharges require less flux than shown here

NSTX Data Base Analysis: **M. Bell**

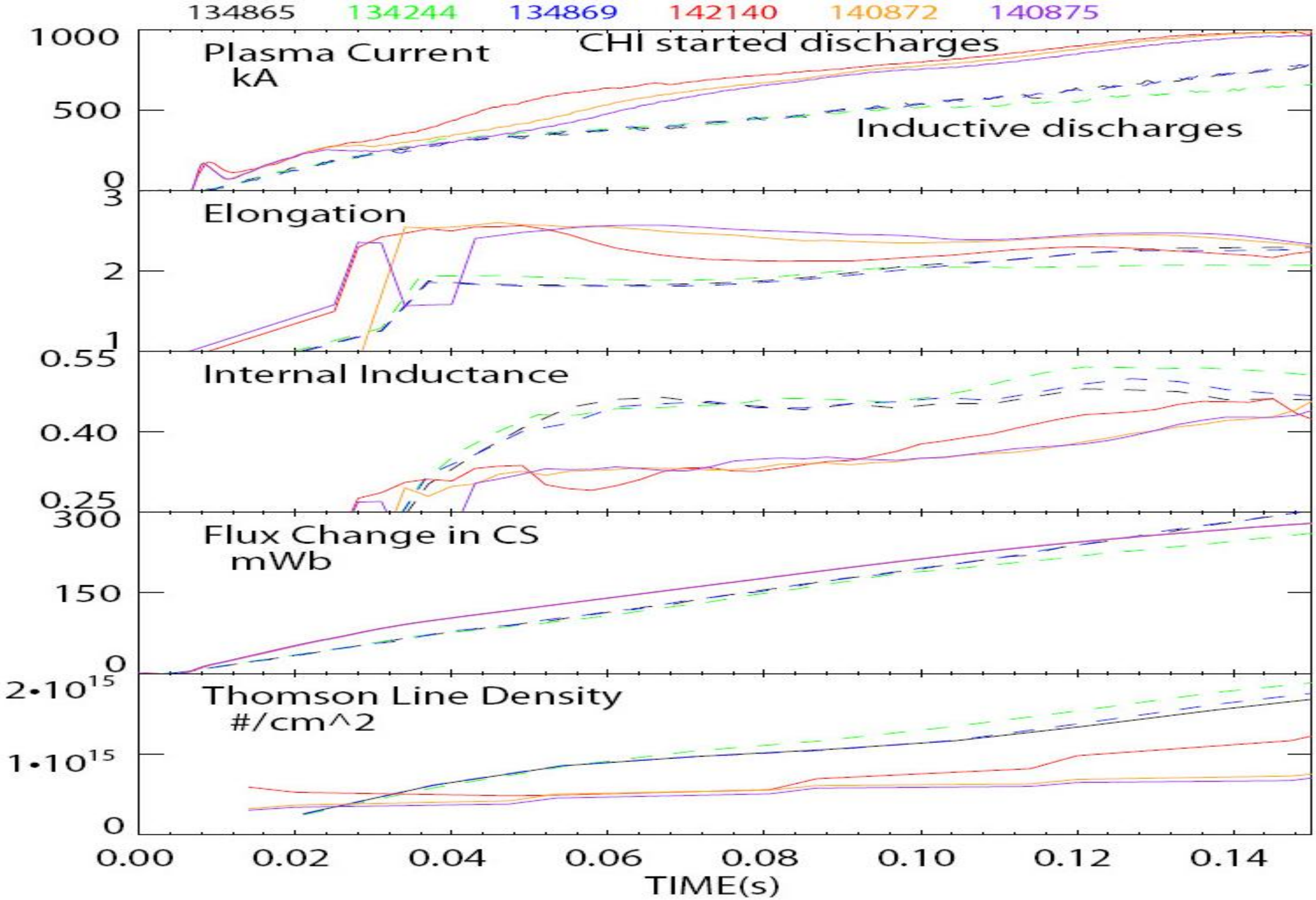
Standard L-mode NSTX Discharge Ramps to 1MA Requiring 50% More Inductive Flux than a CHI Started Discharge



- Reference inductive discharge
  - Uses 396mWb to get to 1MA
- CHI started discharge
  - Uses 258 mWb to get to 1MA (138 mWb less flux to get to 1MA)

R. Raman, D. Mueller T.R. Jarboe et al. Phys. Plasmas (2011) - accepted

CHI Start-up Discharges have low Internal Inductance and Electron Density Starting from Early in the Current Ramp



These are the type of plasmas needed to increase the neutral beam current drive fraction

NSTX-U has the Potential for 1 MA CHI Start-up

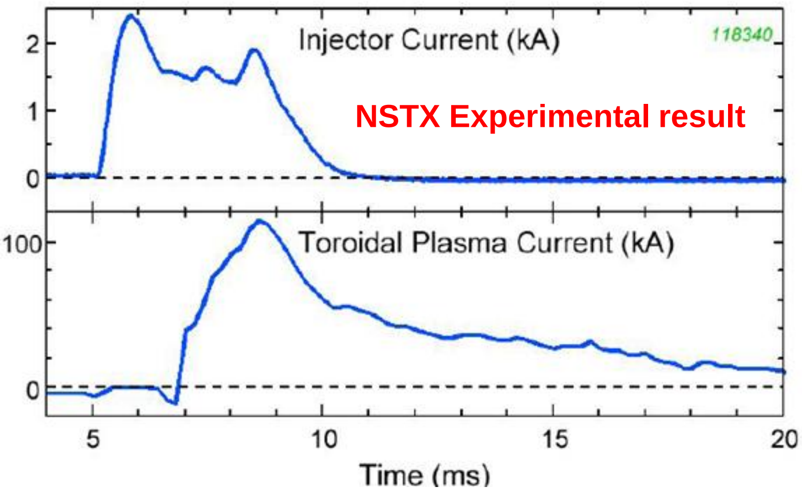
CHI Start-up Parameters in NSTX and NSTX-U

Parameters	NSTX	NSTX-U
R/a (m)	0.86 / 0.68	0.93 / 0.62
Toroidal Field (T)	0.55	1.0
Planned Non-Inductive sustained Current (MA) I_{PS}	0.7	1.0
Poloidal flux at I_{PS} (mWb)	132	206
Maximum available injector flux (mWb)	80	340
Maximum startup current potential (MA)	0.4	~1
Req. Injector current for max. current potential (kA)	10	27*

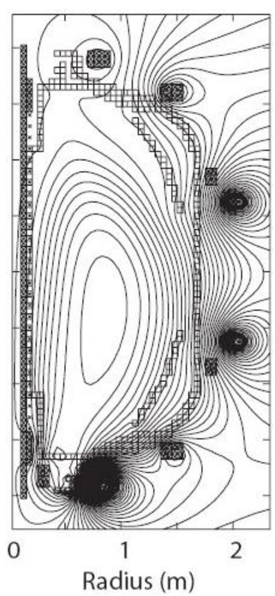
*** HIT-II routinely operated with 30kA injector current without impurity issues**

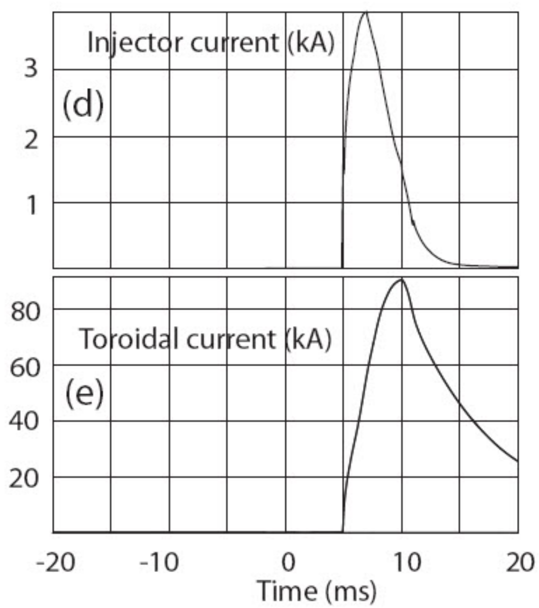
R. Raman, D. Mueller T.R. Jarboe et al. PoP (2011) - accepted

TSC Simulations are being Used to Understand CHI-Scaling with Machine Size



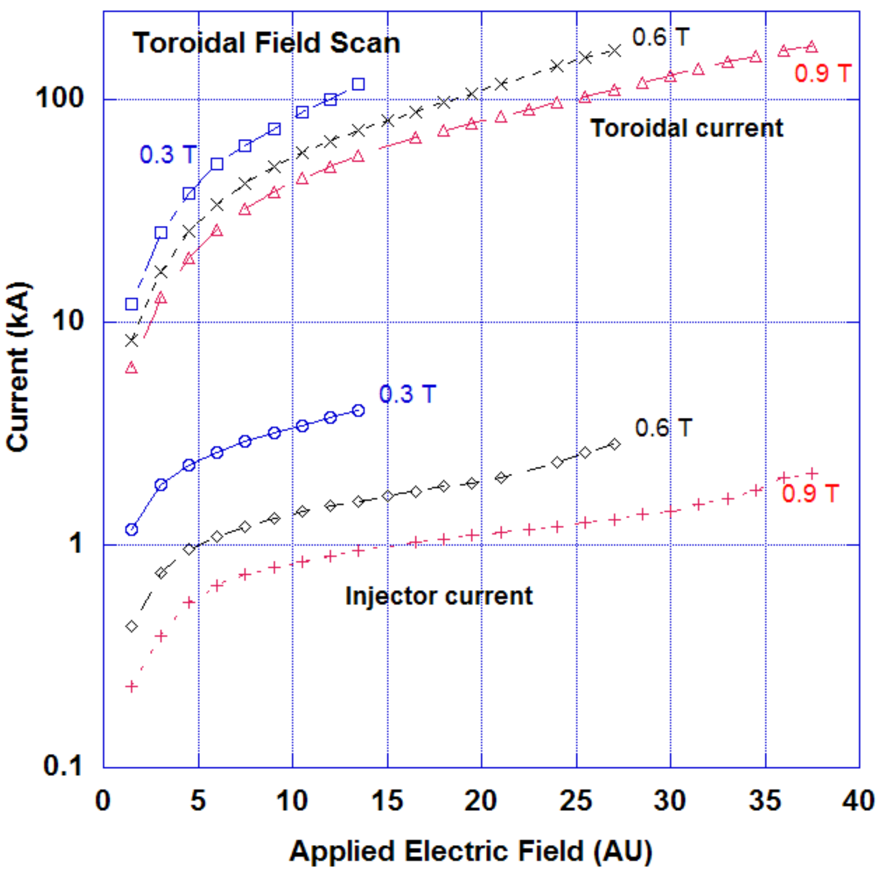
TSC simulation

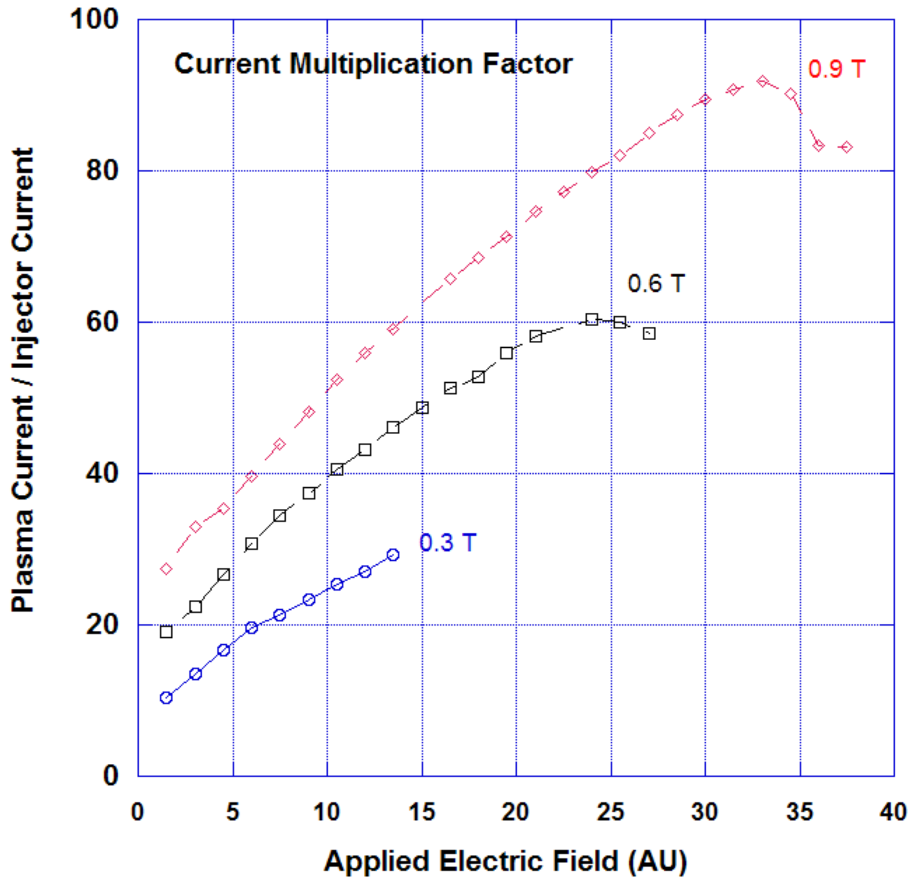




- **Time-dependent, free-boundary, predictive equilibrium and transport**
- **Solves MHD/Maxwell's equations coupled to transport and Ohm's law**
- **Requires as input:**
  - **- Device hardware geometry**
  - **- Coil electrical characteristics**
  - **- Assumptions concerning discharge characteristics**
- **Models evolutions of free-boundary axisymmetric toroidal plasma on the resistive and energy confinement time scales.**
- **NSTX vacuum vessel modeled as a metallic structure with poloidal breaks**
  - **- An electric potential is applied across the break to generate the desired injector current**

TSC Simulations Show Increasing Current Multiplication as TF is Increased (NSTX geometry)

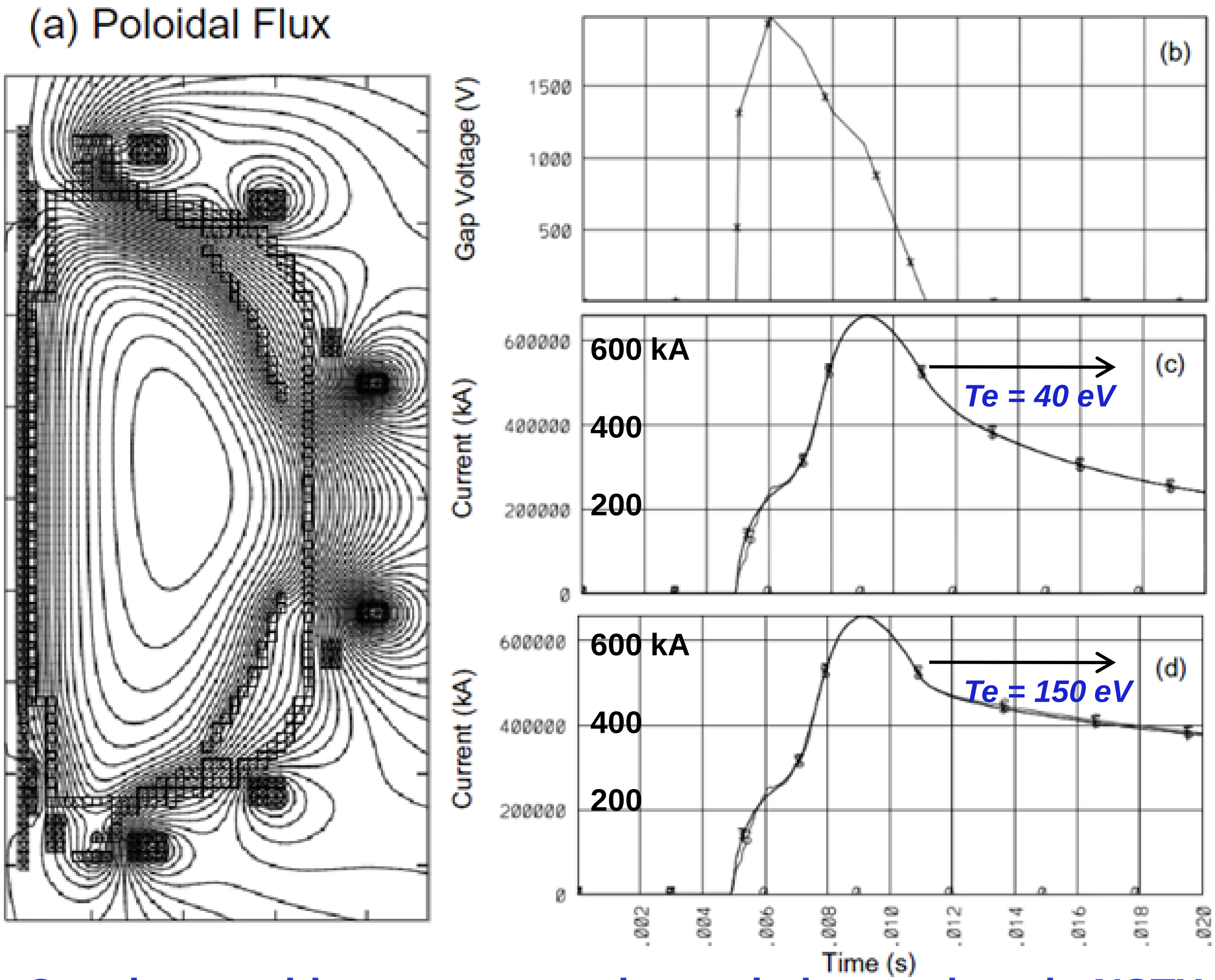




- **Observed current multiplication factors similar to observations in NSTX**
  - **- Higher toroidal field important as it reduces injector current requirement**

R. Raman, S.C. Jardin, J. Menard, T.R. Jarboe et al., Nuclear Fusion (2011) - accepted

TSC Simulations Show 600kA CHI Start-up Capability in NSTX as TF is Increased to 1T



Projected plasma current for CTF >2.5 MA
$[I_p = I_{inj}(\psi_{Tor}/\psi_{Pol})]$

- Based on 50 kA injector current (1/5th of the current density previously achieved)
- Current multiplication of 50 (achieved in NSTX)

- **Consistent with present experimental observations in NSTX that attain >300kA at 0.5T**
- **NSTX-U will have B_T = 1T capability, ST CTF projected to have B_T about 2.5T**

NSTX and HIT-II Results Demonstrate Viability of CHI as a Solenoid-free Plasma Startup Method for the Tokamak/ST

- 0.3MA current generation in NSTX validates capability of CHI for high current generation in a ST
- 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 and in TSC simulations)