Progress on CHI and MGI Experiments on NSTX

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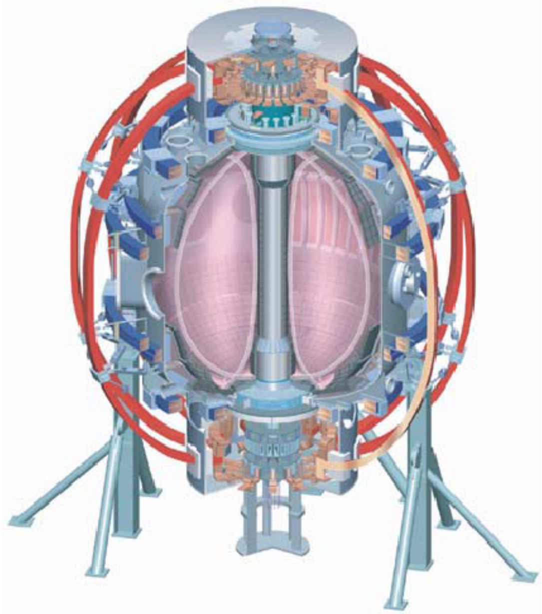
Coaxial Helicity Injection offers the possibility of eliminating the central solenoid in a tokamak

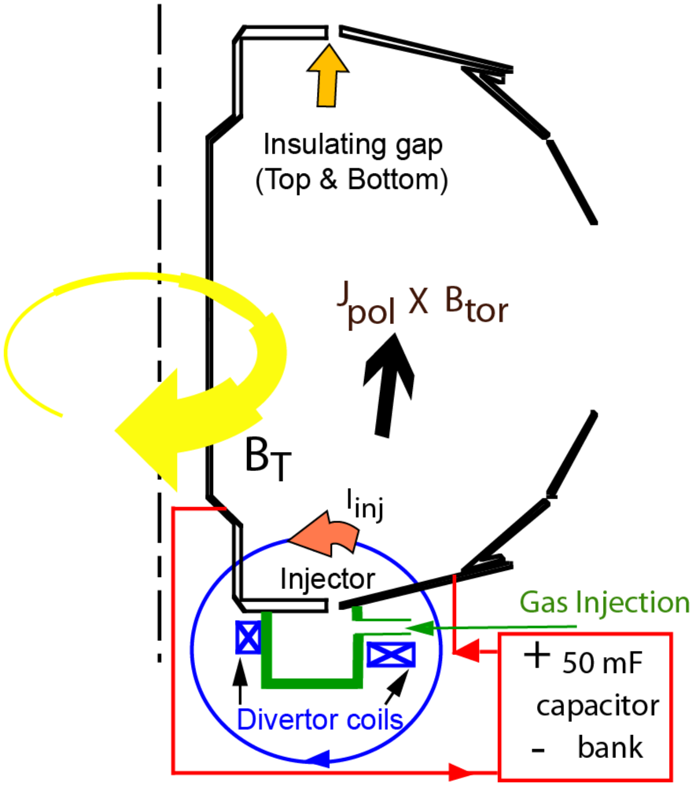
- Transient Coaxial Helicity Injection plasma startup method developed on HIT-II at U-Washington

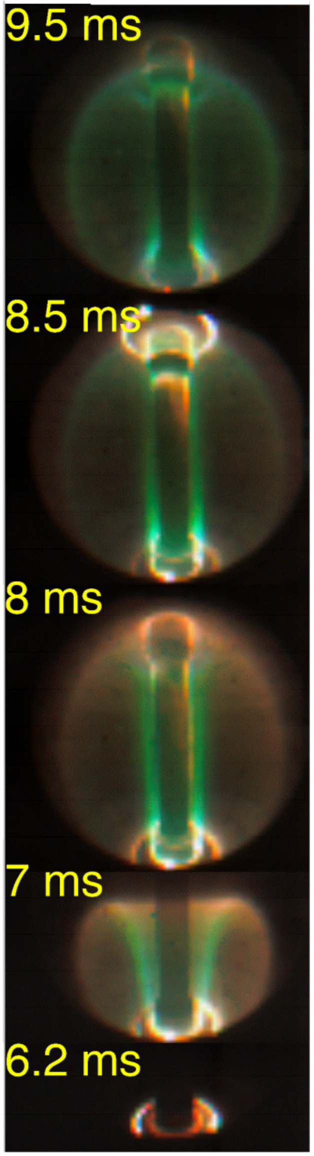
- Now successfully used on NSTX

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

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







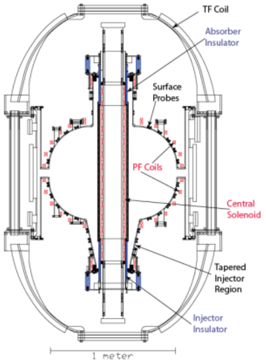
- **Parameters to consider**
  - **- Current multiplication factor**
  - **- Effect of toroidal field**
  - **- Magnitude of generated plasma current**
  - **- New desirable features?**

Fast camera: F. Scotti, L. Roquemore, (PPPL) R. Maqueda (Nova Photonics)

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**

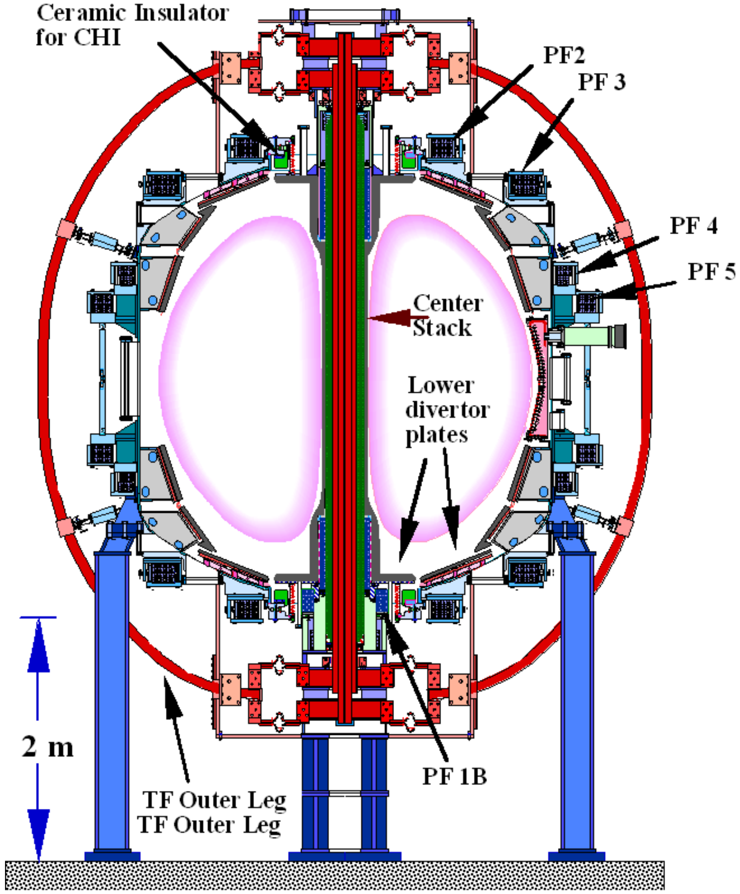
NSTX CHI Research Follows Concept Developed in HIT-II



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

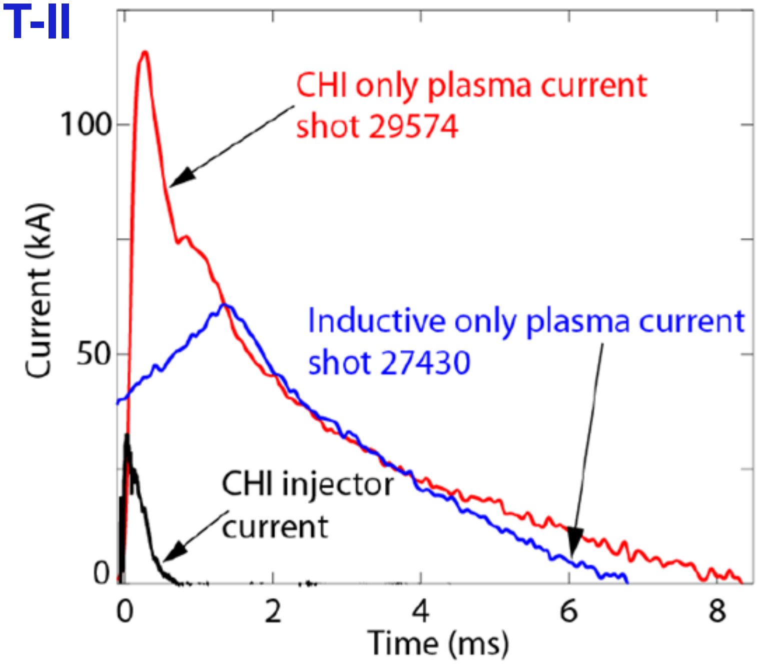


Proof-of-Principle NSTX device

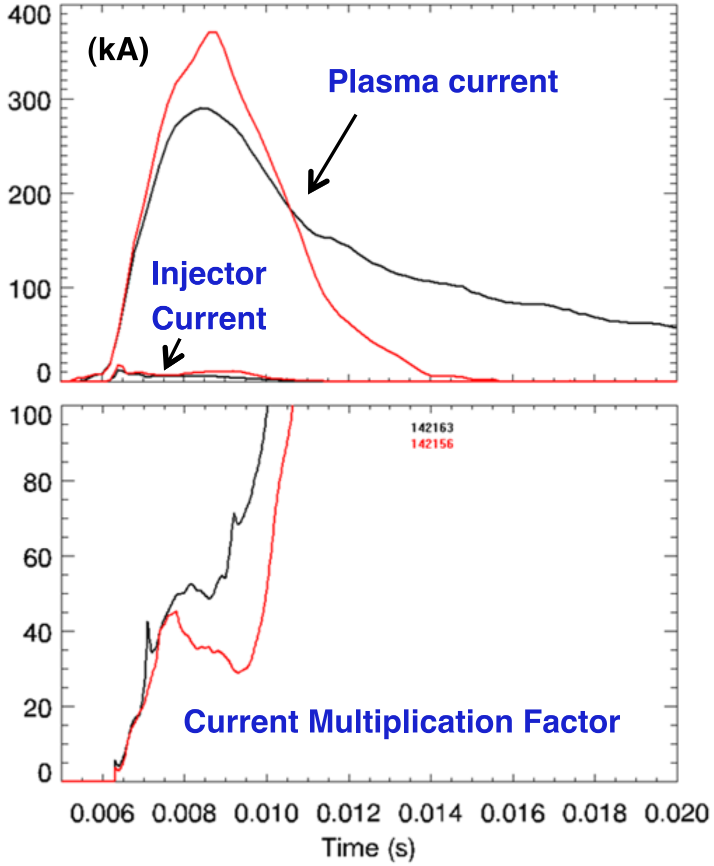
- Built with conventional tokamak components
- Few PF coils
- 1.7kV CHI capacitor bank

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 toroidal current persists when injector current reaches zero

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 Tokamak than in a Spheromak

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

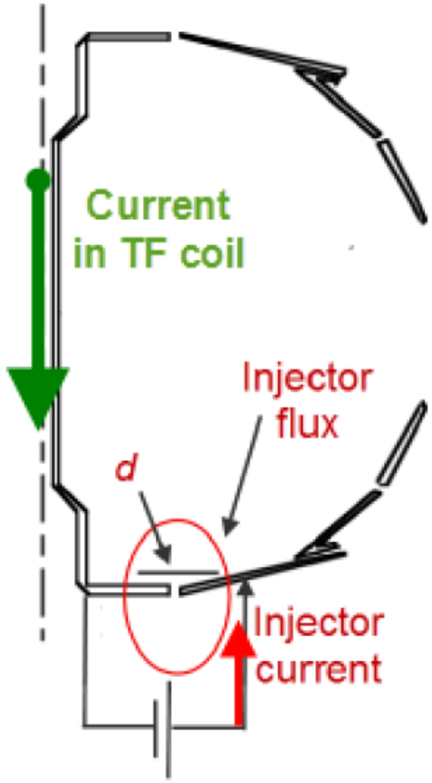
ψ_{inj} = injector flux

d = flux foot print width

I_{TF} = current in TF coil

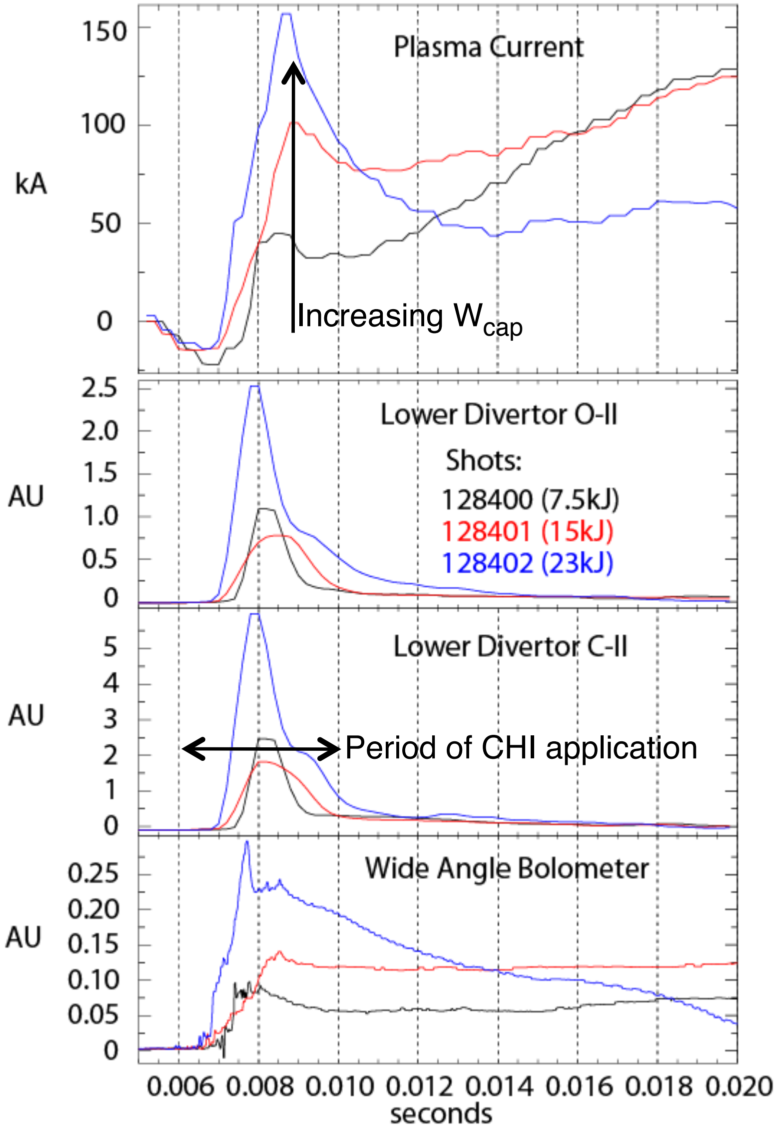
$$I_P = \overset{\text{Injector current}}{I_{inj}} (\overset{\text{Toroidal flux}}{\psi_T} / \psi_{inj})$$

- 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)

Low-Z Impurity Radiation Needs to be Reduced for Inductive Coupling

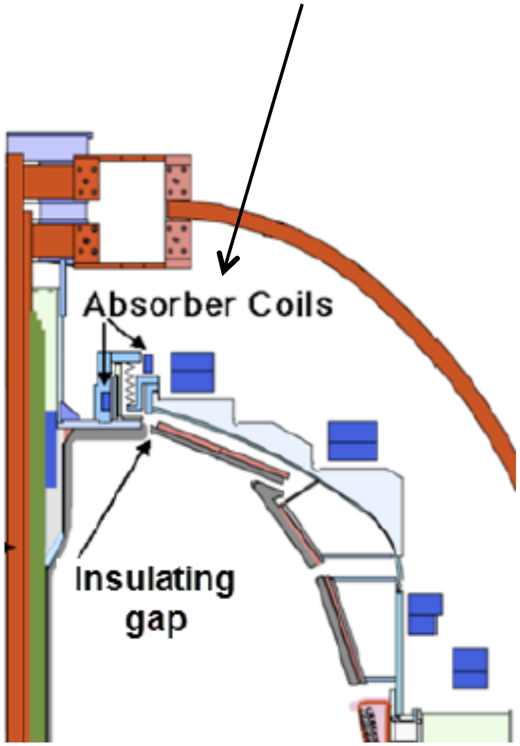


- Low-Z impurity radiation increases with more energy in CHI (more capacitors)
- Possible improvements
  - Metal divertor plates should reduce low-Z impurities
    - High T_e (500eV) obtained in spheromaks with metal electrodes
  - Discharge clean divertor with high current DC power supply
  - Apply auxiliary heating during the first 20ms

Filter scopes: V. Soukhanovskii (LLNL)

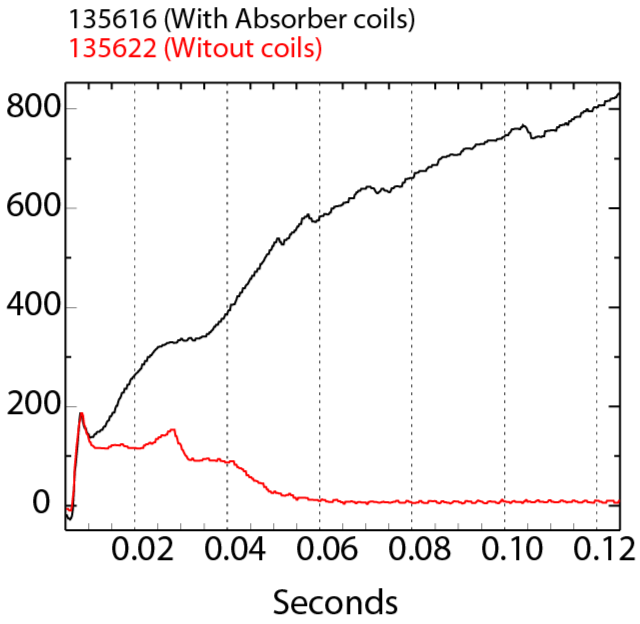
Low-Z Impurity Reduction using Four Techniques Improved CHI Performance in NSTX

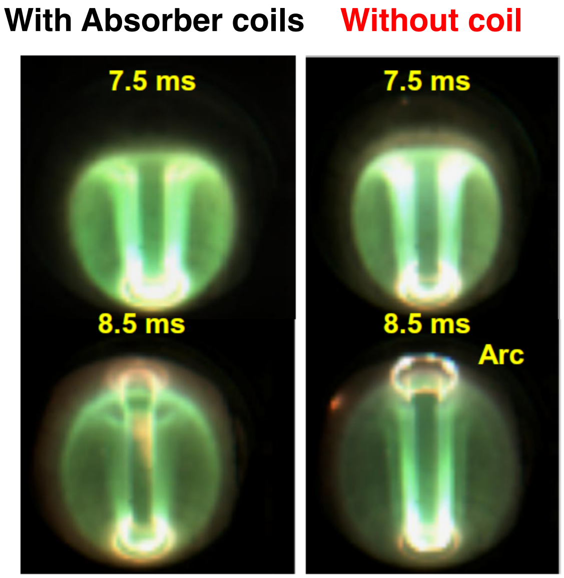
Absorber coils provide buffer field

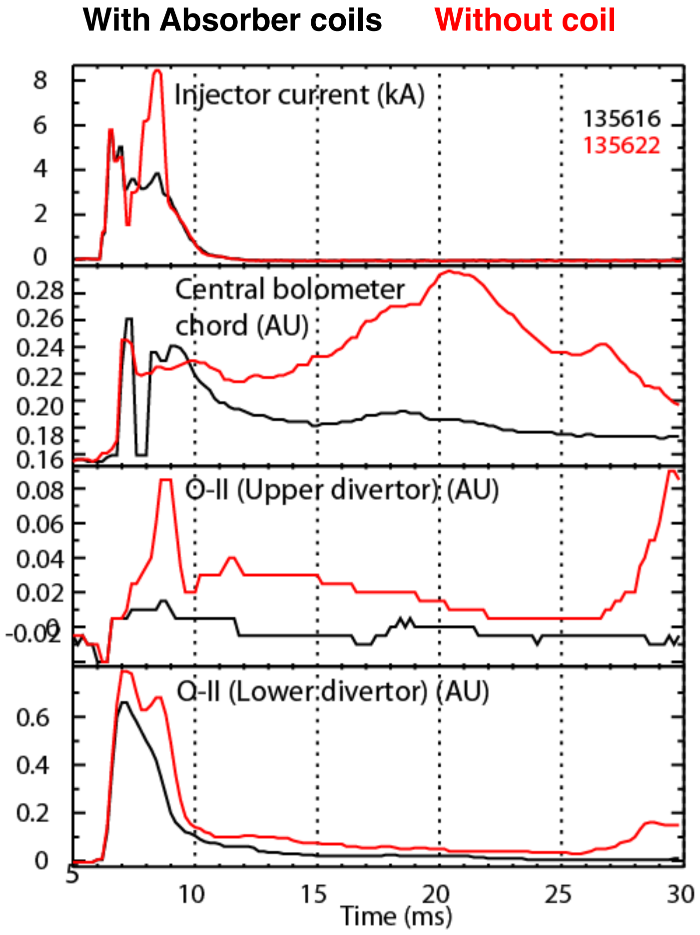


- Apply extended (400ms) CHI discharges with high injector flux to avoid "bubble-burst"
  - ablate low-Z impurities from lower divertor
- Employed deuterium glow discharge cleaning to chemically sputter and reduce oxygen levels
- Lithium evaporation on lower divertor plates improved discharge performance
- Applied "buffer field" using new PF coils located in the upper divertor region
  - reduced interaction of CHI discharge with un-conditioned upper divertor plates

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





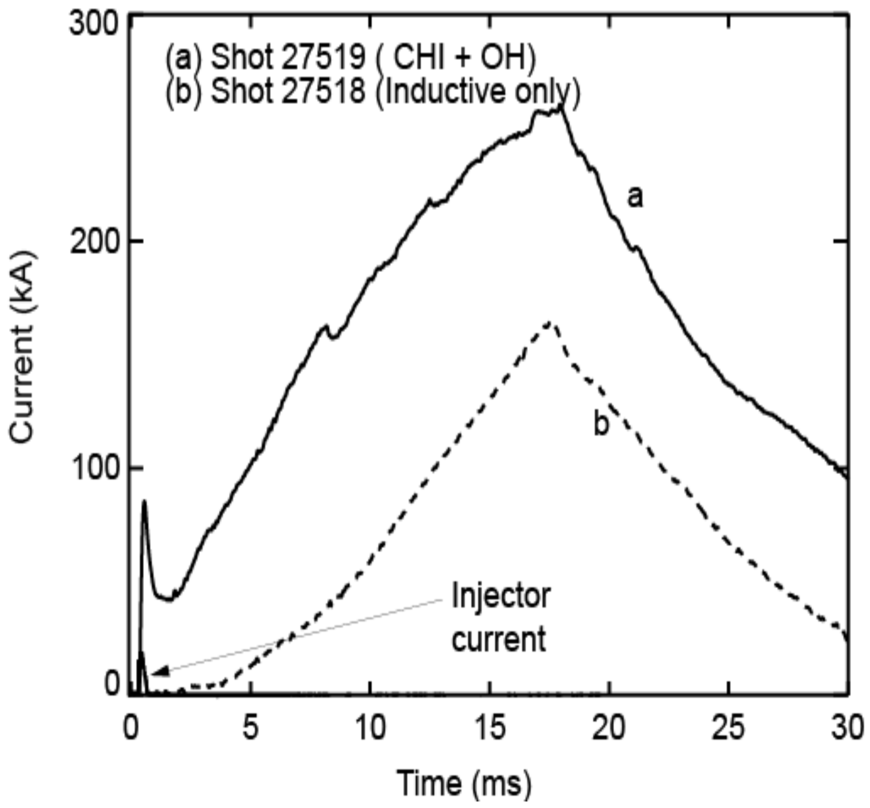


- **Divertor cleaning and lithium used to produce reference discharge**
- **Buffer field from PF absorber coils prevented contact of plasma with upper divertor**

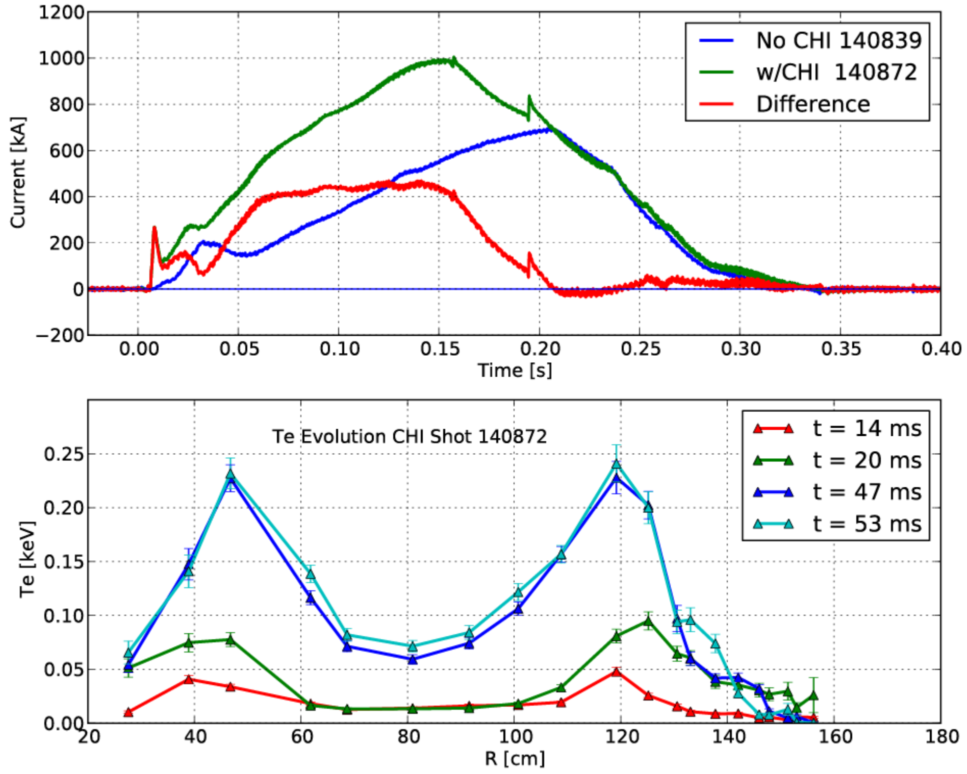
R. Raman, D. Mueller, B.A. Nelson, T.R. Jarboe, et al., PRL 104, (2010) 095003

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

HIT-II



NSTX



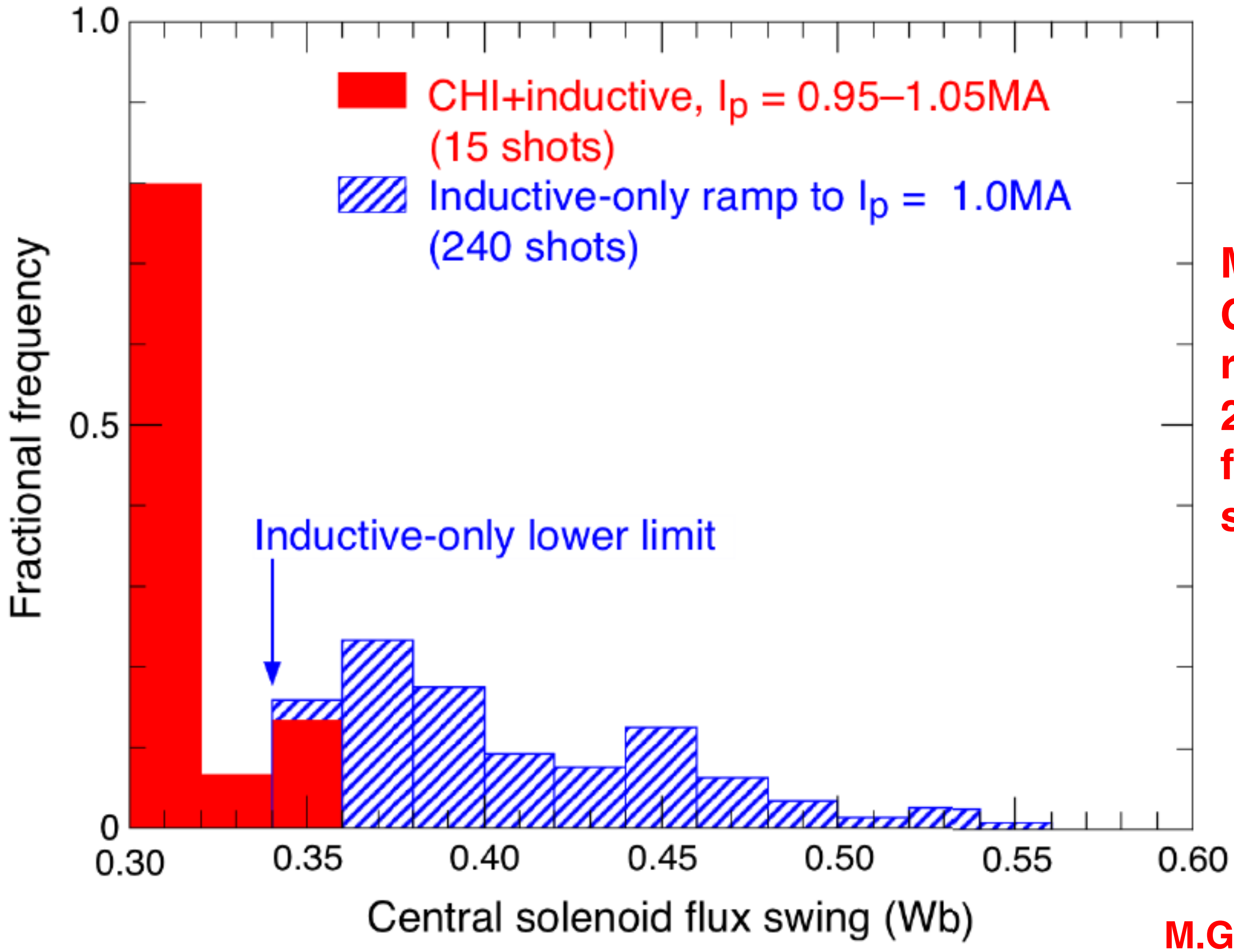
R. Raman, T.R. Jarboe, B.A. Nelson et al, Phys. Plasmas 14, 022504 (2007)

T_e measurement: B. LeBlanc (PPPL)

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

CHI Started Discharges Require Less Inductive Flux than Inductively Started Discharges in NSTX

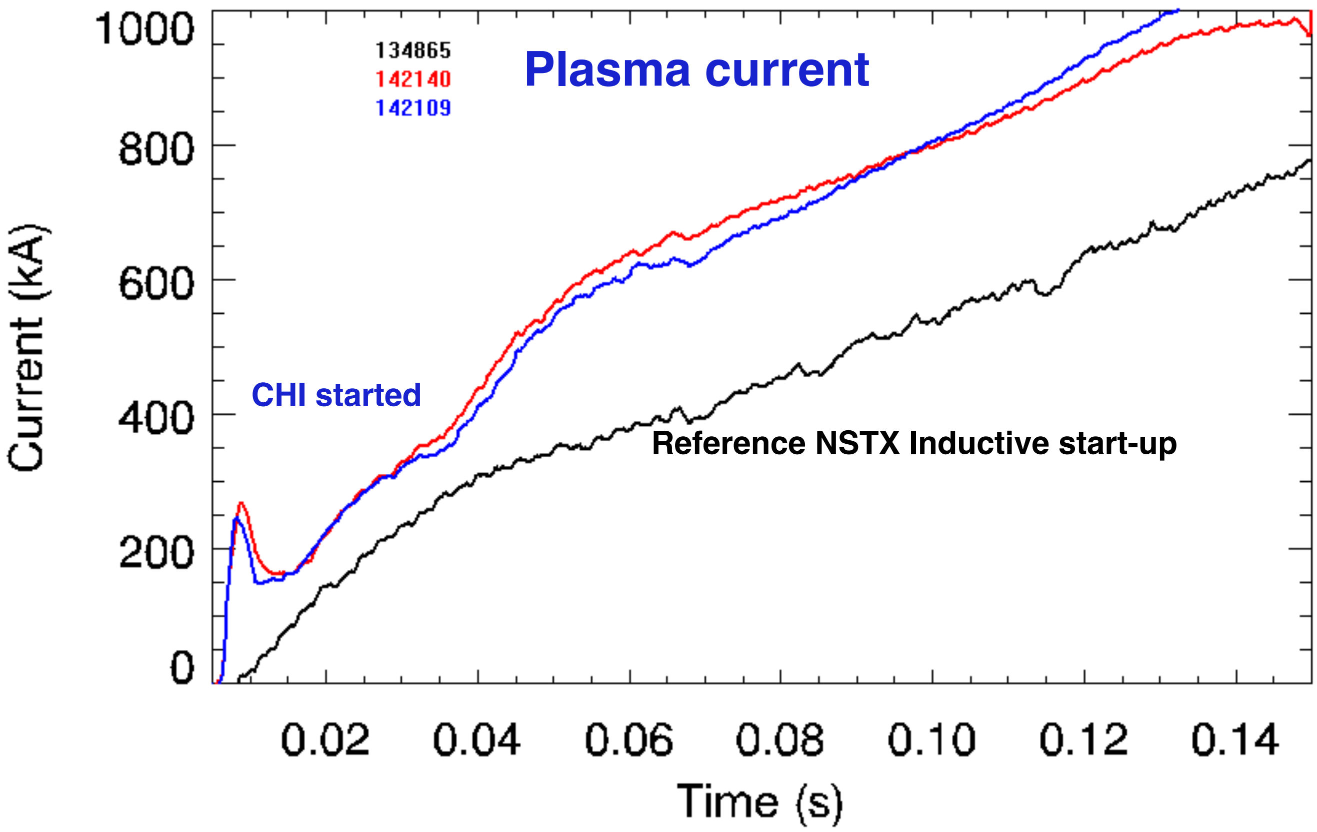
Comparison of CHI Startup to H-modes using more than 1 NBI source



More recent CHI discharges require only 258 mWb of flux (less than shown here)

M.G. Bell

CHI Started Discharge Requires ~30% Less Solenoid Flux to Reach 1MA than a Conventionally Started Discharge

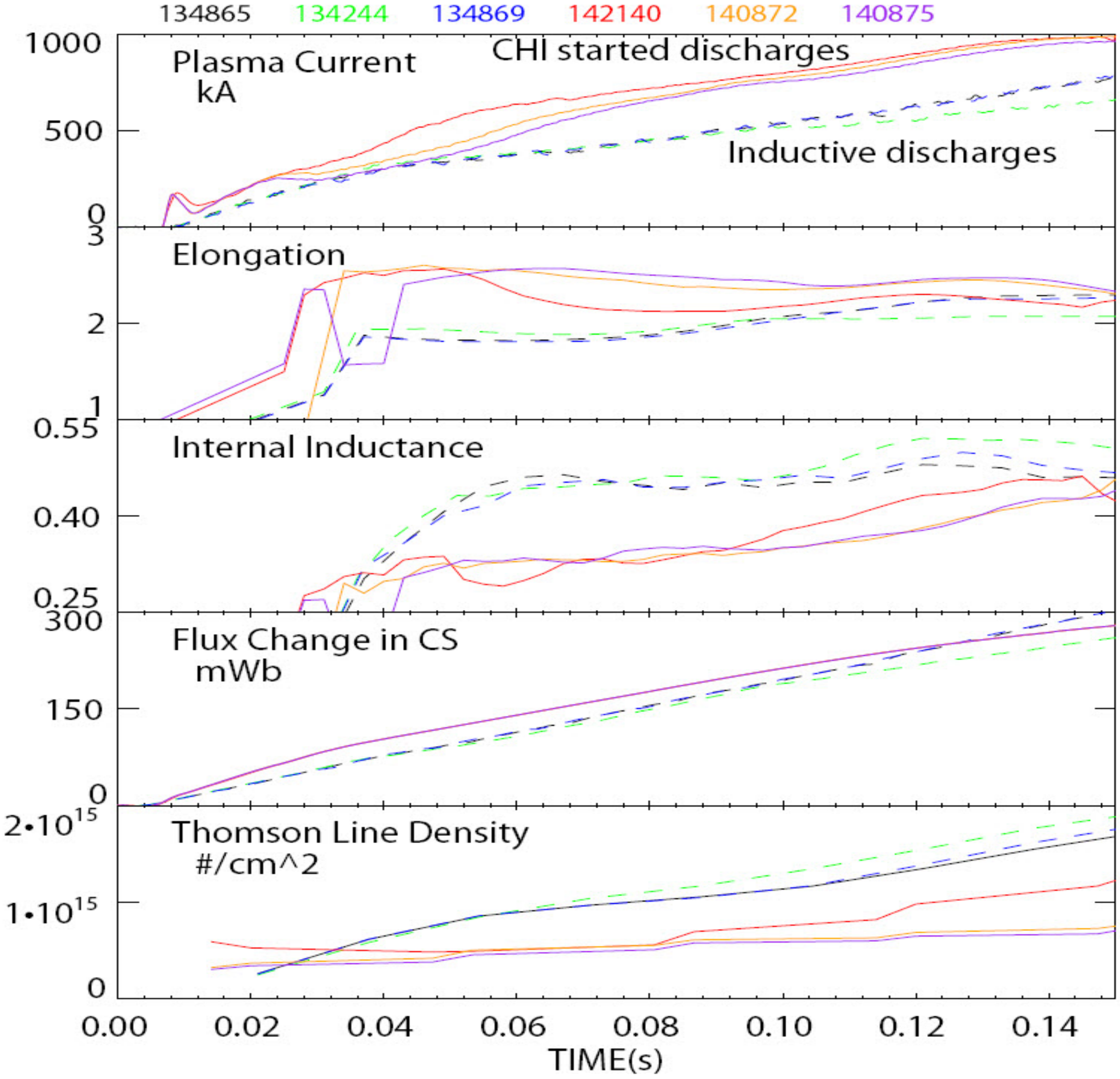


FY 11 Results

- **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 18, 092504 (2011)

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



FY 11 Results

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

CHI Start-up Parameters in NSTX and NSTX-U

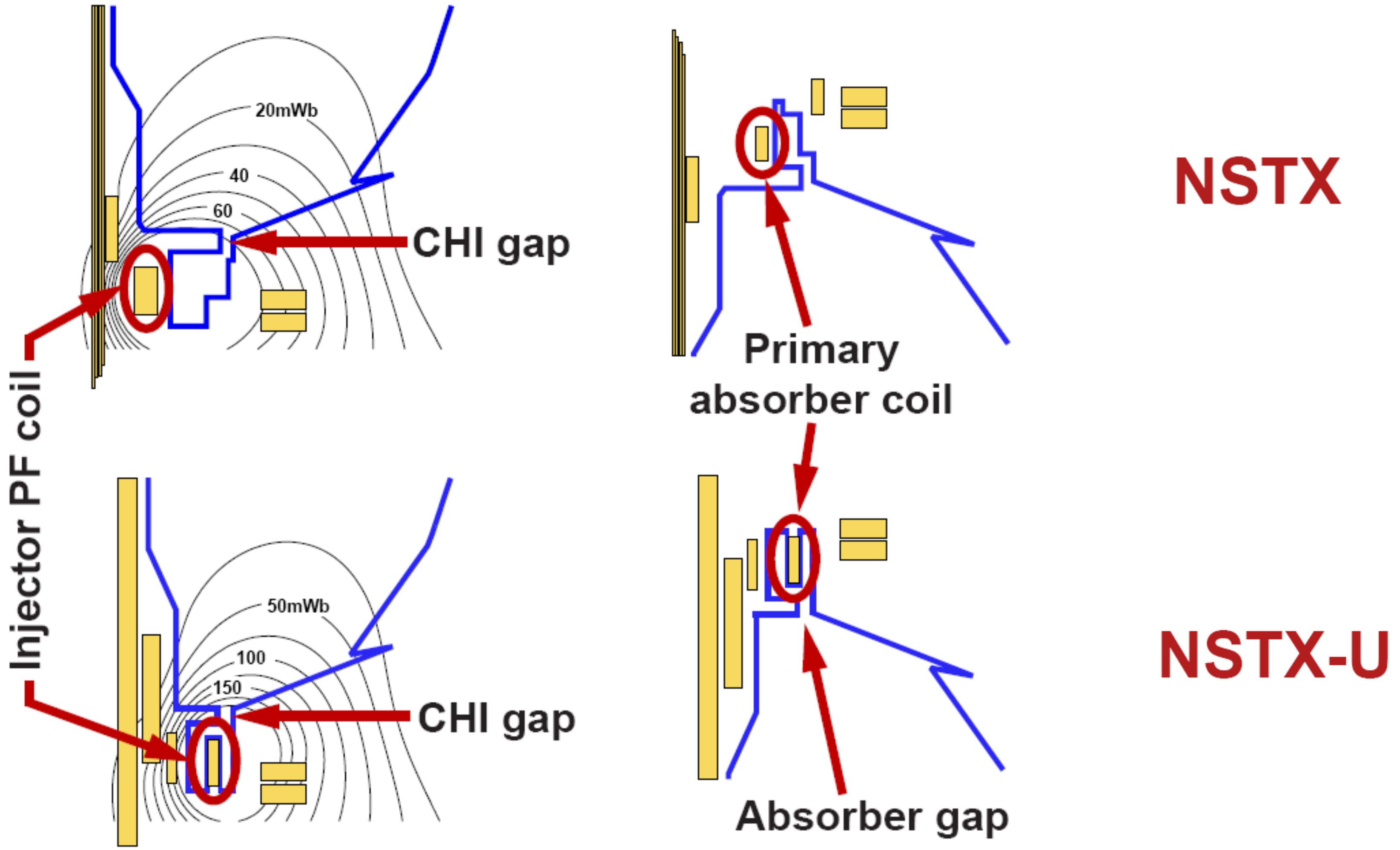
Parameters	NSTX	NSTX-U
R/a (m)	0.86 / 0.68	0.93 / 0.62
Toroidal Field (T)	0.55	1.0
Planned Non-Inductive sustained Current (MA)	0.7	1.0
Poloidal flux (mWb) contained in the plasma at non-inductive sustained current with internal inductance of 0.35 and at device major radius	132	206
Maximum available 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**

FY 11 Results

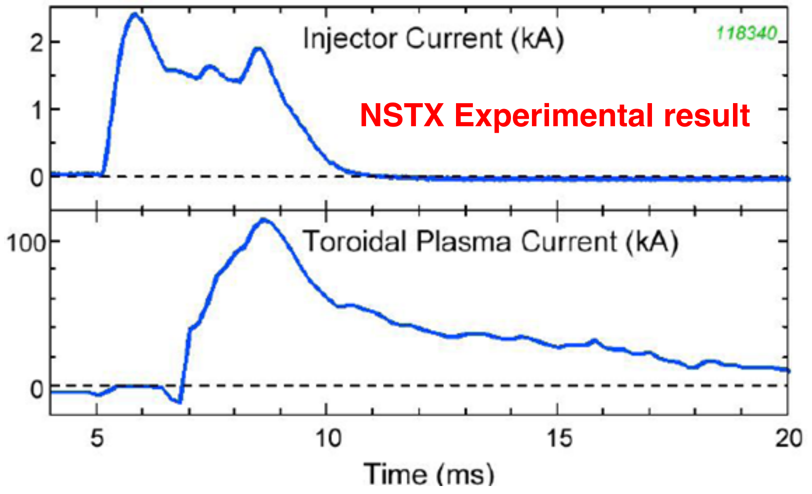
R. Raman, D. Mueller, T.R. Jarboe et al. Phys. Plasmas 18, 092504 (2011)

Higher Current Start-up Potential in NSTX-U is due to 2.5x More Injector Flux than in NSTX



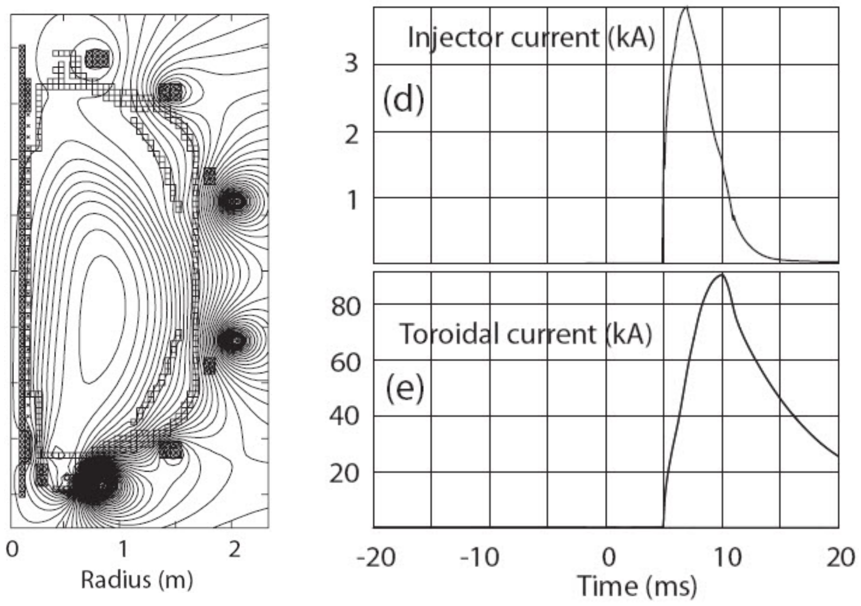
Absorber buffer coils are also better positioned in NSTX-U

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



NSTX Experimental result

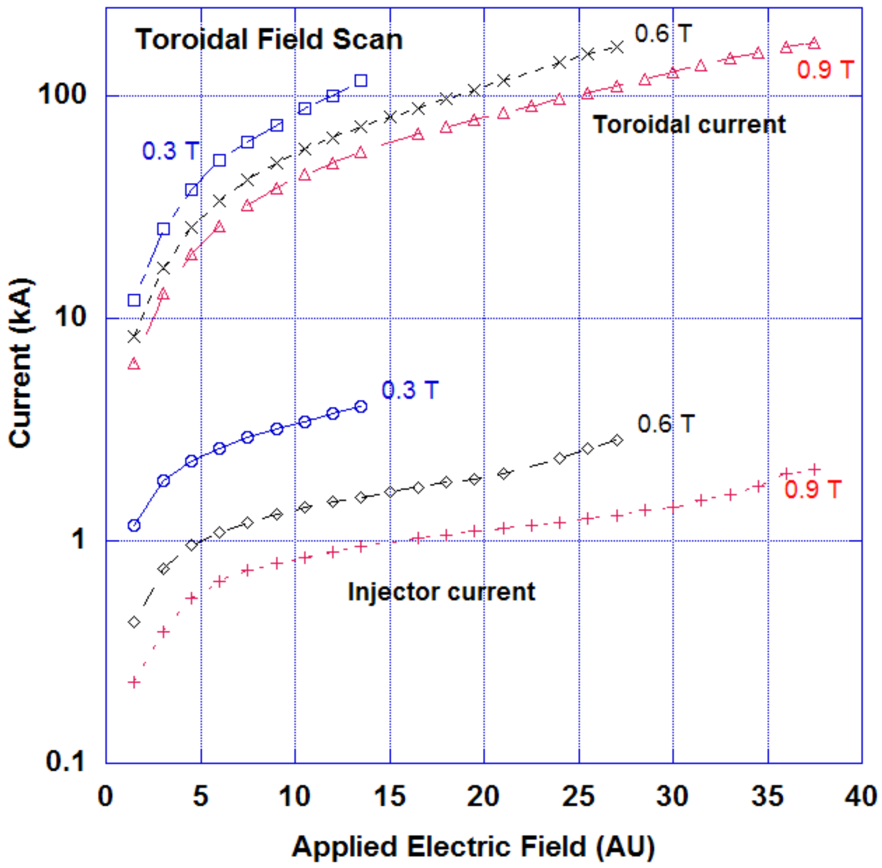
TSC simulation

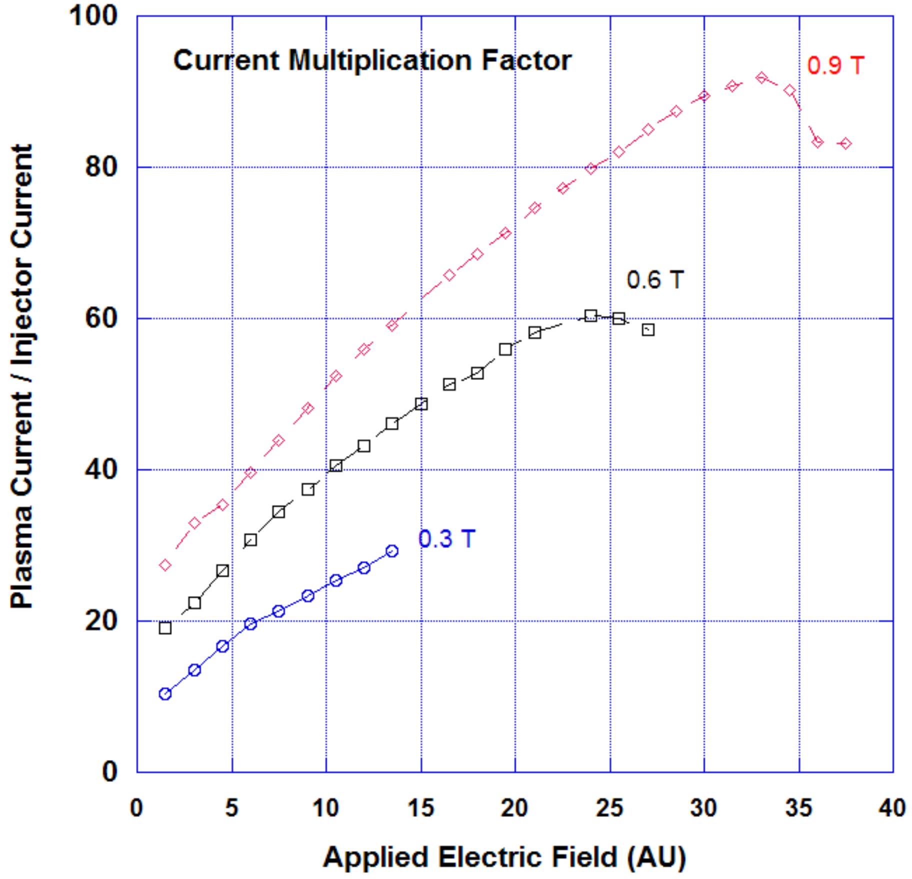


- Time-dependent, free-boundary, predictive equilibrium and transport
- Solves MHD/Maxwell's equations coupled to transport and Ohm's law
- Requires as input:
  - Device hardware geometry
  - Coil electrical characteristics
  - Assumptions concerning discharge characteristics
- Models evolution of free-boundary 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 desired injector current

TSC: Developed by S.C. Jardin

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

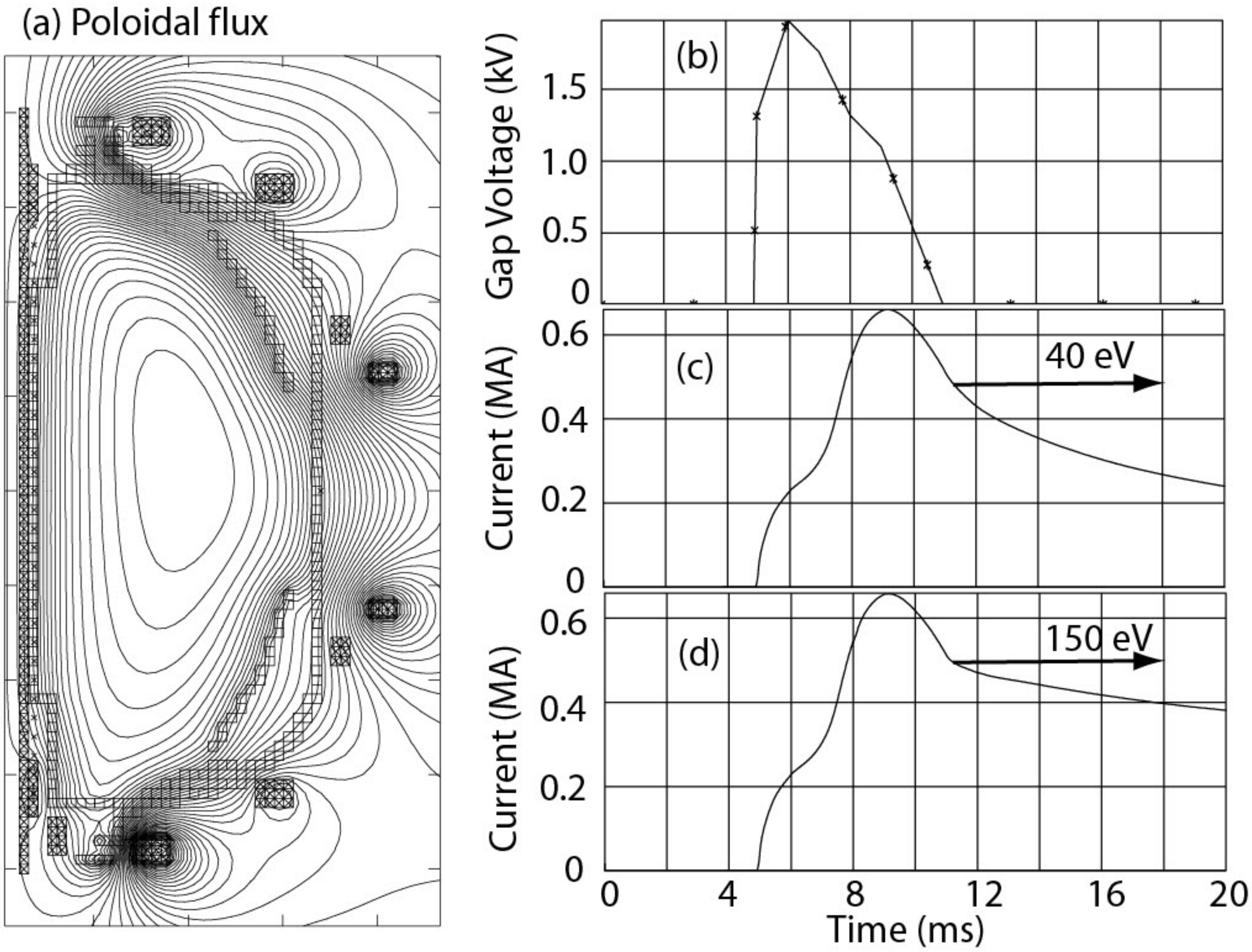




- **Observed current multiplication factors similar to observations in NSTX**
  - **- Higher toroidal field important as it reduces injector current requirement**

R. Raman, S.C. Jardin, J. Menard, T.R. Jarboe, et al., Nuclear Fusion 51, 113018 (2011)

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



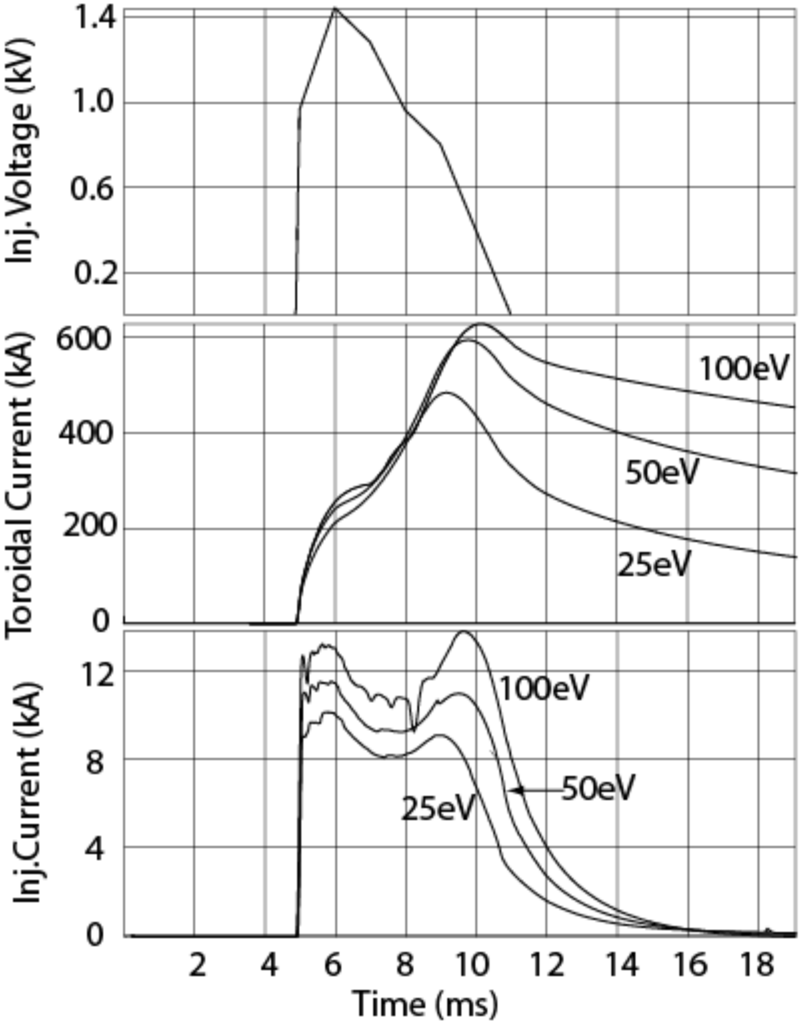
Projected plasma current for CTF >2.5 MA $[I_p = I_{inj}(\psi_{Tor}/\psi_{Pol})]$

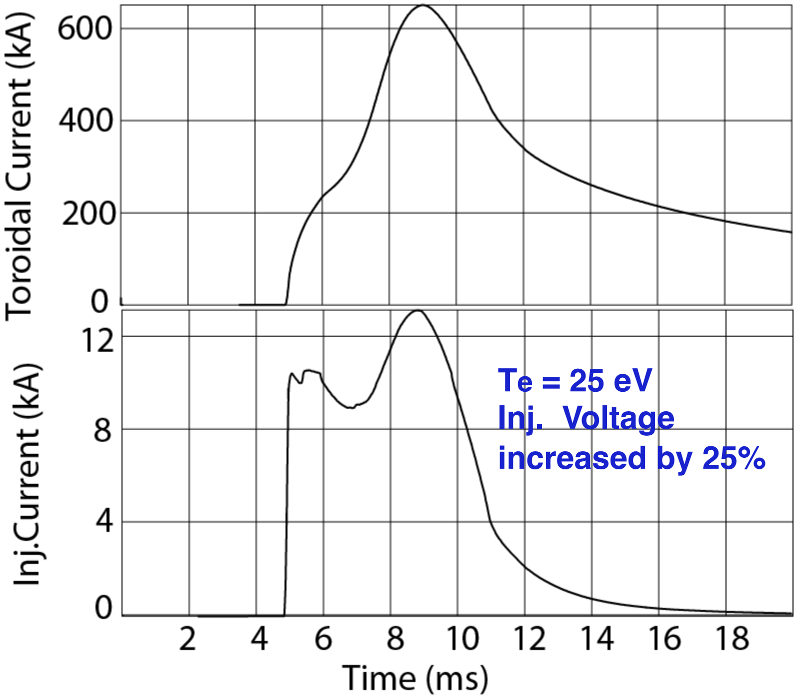
- Based on 50 kA injector current (1/5th of the current density previously achieved)
- Current multiplication of 50 (achieved in NSTX)

- **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**

Simulations Illustrate Importance of Auxiliary Heating and Higher Voltage for Discharge Performance Improvement

FY 11 Results





Te = 25 eV
Inj. Voltage increased by 25%

- With increasing T_e, I_p increases and current decay slows
  - Substantial at $T_e \sim 100$eV
- With 25% increases in voltage (at T_e = 25eV) peak I_p is restored
  - But current decay is still rapid

Disruption Mitigation Studies

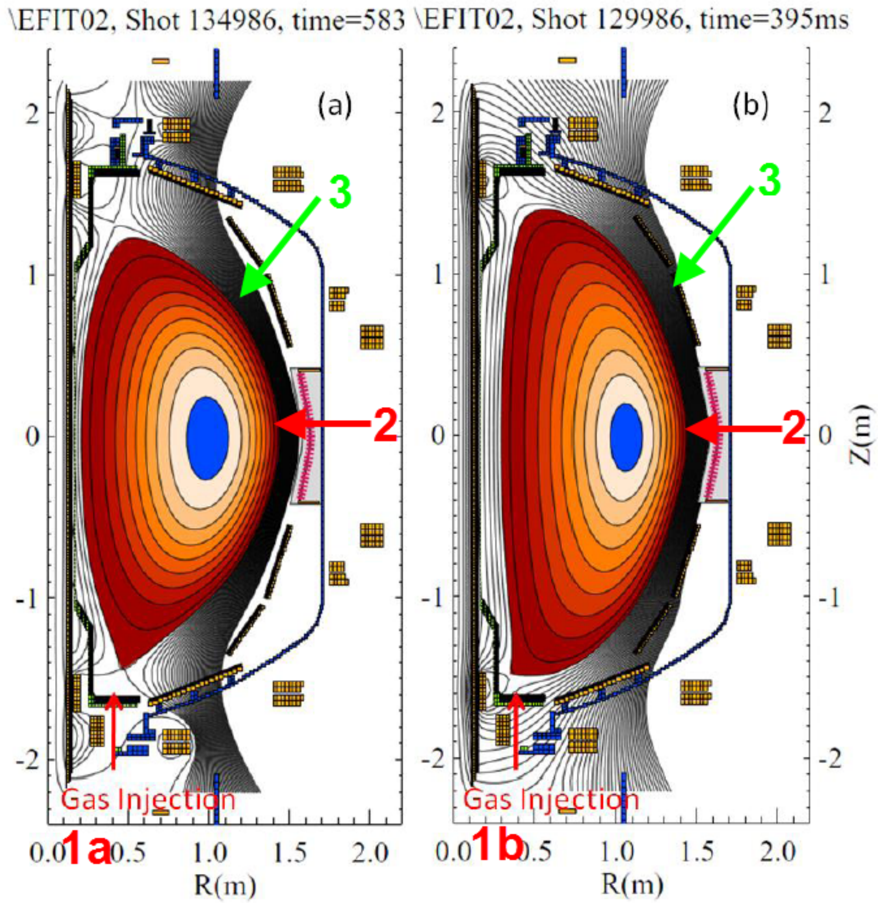
- In tokamaks and STs, disruptions may be unavoidable
- Without active intervention, disruptions can damage the structure of a large tokamak
- Requirements for the mitigation of disruption effects fall into three categories:
  - (1) Reducing thermal loads on the first wall;
  - (2) Reducing electromagnetic forces associated with “halo” currents, i.e. currents flowing on open field lines in the plasma scrape-off layer; and
  - (3) Suppressing runaway electron (RE) conversion in the current quench phase of the disruption.

At Present Massive Gas Injection Appears to be the Most Promising Method for Safely Terminating Discharges in ITER

- Massive Gas Injection (MGI) involves the rapid injection of gas with an inventory several times that of the plasma discharge. Some fraction will be a high-Z component such as Ar or Ne [1-4]
- For ITER it is projected that about 500 kPa-m^3 of helium with some noble gas fraction may be required
- Because of the large size of ITER and the presence of an energetic scrape-off-layer it is not known what fraction of this gas will reach the separatrix when gas is injected from the mid-plane as in present tokamak experiments.
- The amount of gas injected in MGI experiments in present tokamaks varies from 100 Pa.m^3 to over 2000 Pa.m^3, considerably less than the projections for ITER.
- The fraction of this gas that penetrates the separatrix also varies widely, with penetration efficiencies of over 20% being reported for cases that have a short MGI pulse [3].

(1) D. G. Whyte, et al., Journal of Nuc. Materials, 363-365 (2007) 1160-1167
(2) G. Pautasso, et al., Plasma. Phys. Cntrl. Fusion 51 (2009) 124056
(3) E.M. Hollmann, et al., Physics of Plasmas 17, 056117 (2010)
(4) D.G. Whyte, D.A. Humphreys, A.G. Kellman, Fusion Science and Technology, 48 (2005) 954

NSTX-U MGI Experiments will Vary the Poloidal Injection location



1a: Private flux region 1b: lower SOL

2: Conventional mid-plane injection

3: Variation in poloidal location

Unique capability of NSTX:

Asses benefits of injection into the private flux region & the high-field side region vs. LFS mid-plane

NSTX MGI Installation for
Private Flux Region Injection(May 2011)

- Now investigating feasibility of faster valves located closer to the vessel
- Modeling gas injection requirements for NSTX-U using DEGAS-2 simulations

Uniqueness of Planned NSTX-U Experiments

- Injection from the proposed location has two advantages.
- First, the gas is injected directly into the private flux region, so that it does not need to penetrate the scrape-off-layer.
- Second, because the injection location is located near the high-field side region, the injected gas should be more rapidly transported to the interior as known from high-field side pellet injection research and from high-field side gas injection on NSTX.
- By comparing gas injection from this new location to results obtained from injecting a similar amount of gas from the conventional outer mid-plane, NSTX-U results on massive gas injection can provide additional insight, a new database for improving computational simulations, and additional knowledge to disruption mitigation physics using massive gas injection.

DEGAS-2 Simulation Effort Initiated to Quantify Gas Penetration Fraction Through SOL

- To better quantify the amount of gas required in a MGI pulse we have initiated a DEGAS-2 Monte-Carlo code simulation effort to understand the extent of gas penetration through the SOL region and private flux regions.
- In addition to supporting NSTX-U needs, this simulation effort focuses on fundamentally studying the edge penetration issues to the separatrix, which is needed for predicting gas penetration efficiencies in ITER.
- A 1MA, 1MW NBI Lower Single Null NSTX discharge is used for the initial simulations
- Preliminary results indicate that the scrape-off-layer plasma may place limits on the achievable gas penetration fraction to the separatrix.

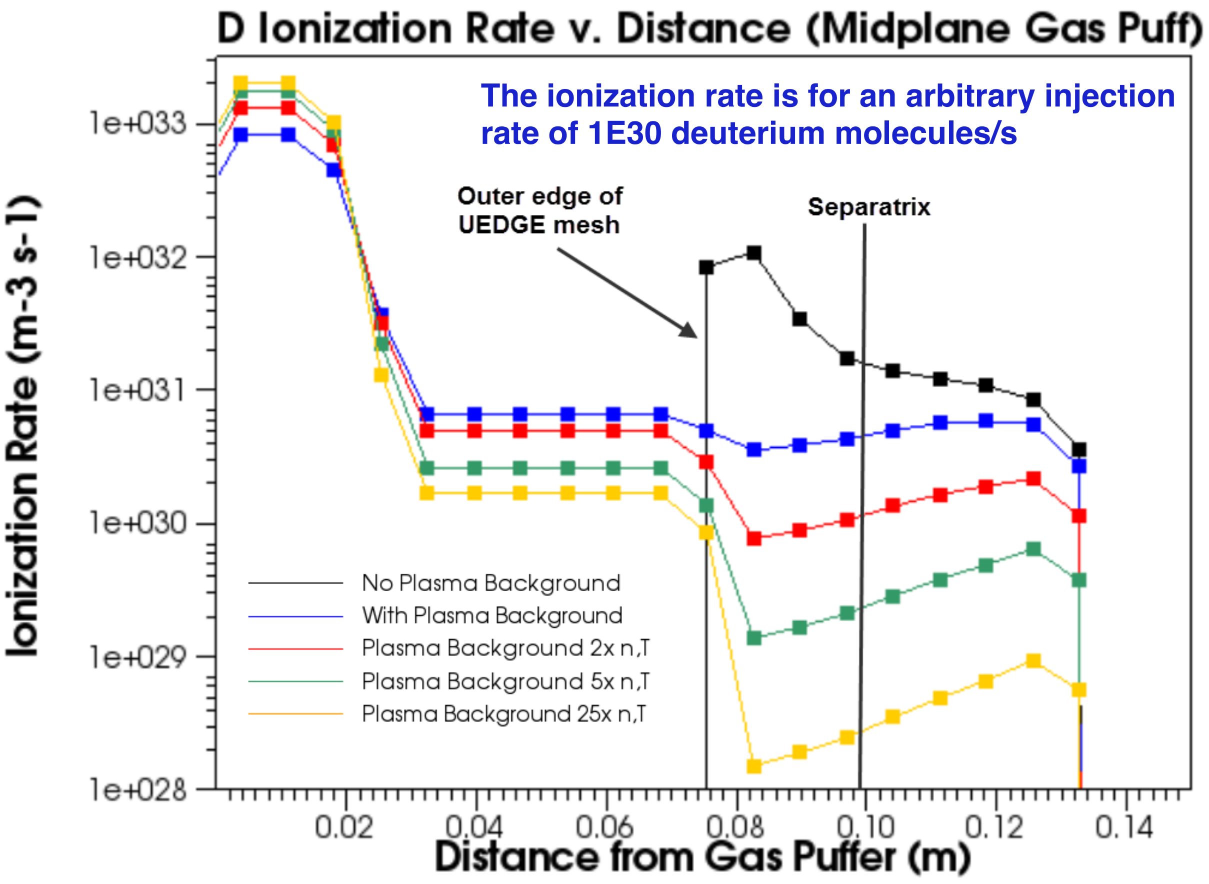
DEGAS-2 Simulations being conducted by T. Abrams and D.P. Stotler (PPPL)

DEGAS-2 Modeling (Monte Carlo code)

- As the first step in developing the full model to simulate the effect of increasing the SOL parameters we have conducted simulations in which the background plasma density and temperature are artificially increased, such as would happen when the auxiliary power of a plasma discharge is increased.
- In these preliminary simulations, deuterium molecules are launched from the mid-plane with a 300 K thermal energy distribution.
- As the molecules penetrate the plasma, they undergo ionization, dissociation, and elastic scattering; resulting molecular ions are assumed to be ionized, dissociated, or recombined immediately.
- Any product atoms are then tracked through the plasma and can undergo ionization and charge exchange.
- The particle track terminates upon ionization of the atom. Along the particles' paths, the volumetric source of plasma ions is accumulated in each computational zone.
- The penetration fraction is then the ratio of the volume integrated sum of those source rates over zones inside the separatrix to the gas puff rate.

Gas Penetration to Separatrix Rapidly Decreases for Modest Increases in Background Plasma Parameters

The background plasma is located between the UEDGE mesh and the vessel walls. In this region, a reference plasma density of 5 x 10^{18} m^{-3} and electron temperature of 25 eV were assumed.



- The background plasma density and temperature were increased to 2 times, 5 times and 25 times the reference values.
- The gas penetration fraction is 33% for the case with no background plasma.
- It drops to 16% for the case with the reference plasma and to 7%, 3% and 1% respectively for the cases of increasing plasma density and temperature.

Simulations: T. Abrams and D.P. Stotler (PPPL)

Simulation Work in Progress

- These results would suggest that more energetic plasma conditions in the SOL should make it more difficult for gas injected from the mid-plane to penetrate past the separatrix.
- However, if gas is injected directly into the private flux region, and does not need to cross the SOL, the penetration fraction should be higher so long as the private flux region plasma is much less energetic than plasma in the SOL.
- This should be the case as the bulk of the exhaust power from tokamak plasmas flows through the SOL, eventually being deposited on divertor plates.
- The SOL parameters will be better modeled and the MGI parameters better represented to provide improved estimates for MGI requirements on NSTX-U

NSTX-U Diagnostics Should be Capable of Measuring Several Parameters Related to MGI Studies

- Physics of gas penetration (fraction that penetrates separatrix)
  - Thomson scattering, Edge Thomson, Div. Thomson, Interferometer
- System response time (gas trigger time to first detection of injected gas interacting with the plasma edge)
  - H-alpha array, Ne, Ar, Kr filterscopes, Survey spectrometer, variable aperture LADA
- Divertor heat loads (spatial distribution)
  - Fast & Slow IR camera, Fast thermography & RT surf. emissivity, Eroding TCs
- Dependence on halo current amplitude on gas assimilation
  - Halo current sensors, Tile current sensors
- Thermal quench evolution
  - SXR/VUV imaging to obtain profile of cold front propagation
  - Multicolor tangential SXR (fast time scale T_e, pedestal collapse time)
  - Core radiated power time evolution (bolometer)
- Current quench evolution
  - Magnetics, fast diamagnetic loop, Vertical dynamics (SXR and visible cameras)

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)
- Results and TSC simulations suggest high current start-up capability in NSTX-U
- We are now developing the capability for MGI studies on NSTX-U