Progress on CHI Plasma Start-up and MGI Experiments on NSTX

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This work is supported by US DOE contract numbers FG03-96ER5436, DE-FG02-99ER54519, DE-SC0006757, and DE-AC02-09CH11466

39th EPS Conference on Plasma Physics
16th International Congress on Plasma Physics
Stockholm, Sweden, 2-6 July 2012
Presentation: P2.008 (Tuesday July 3, 2012)

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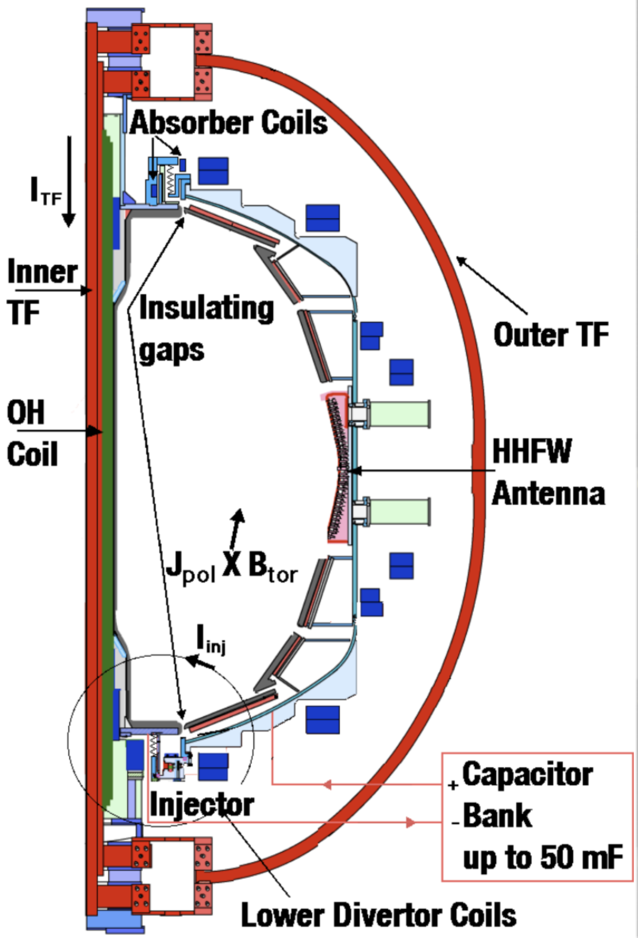
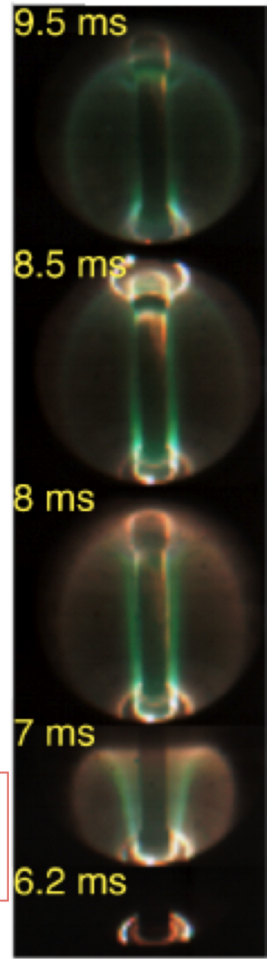
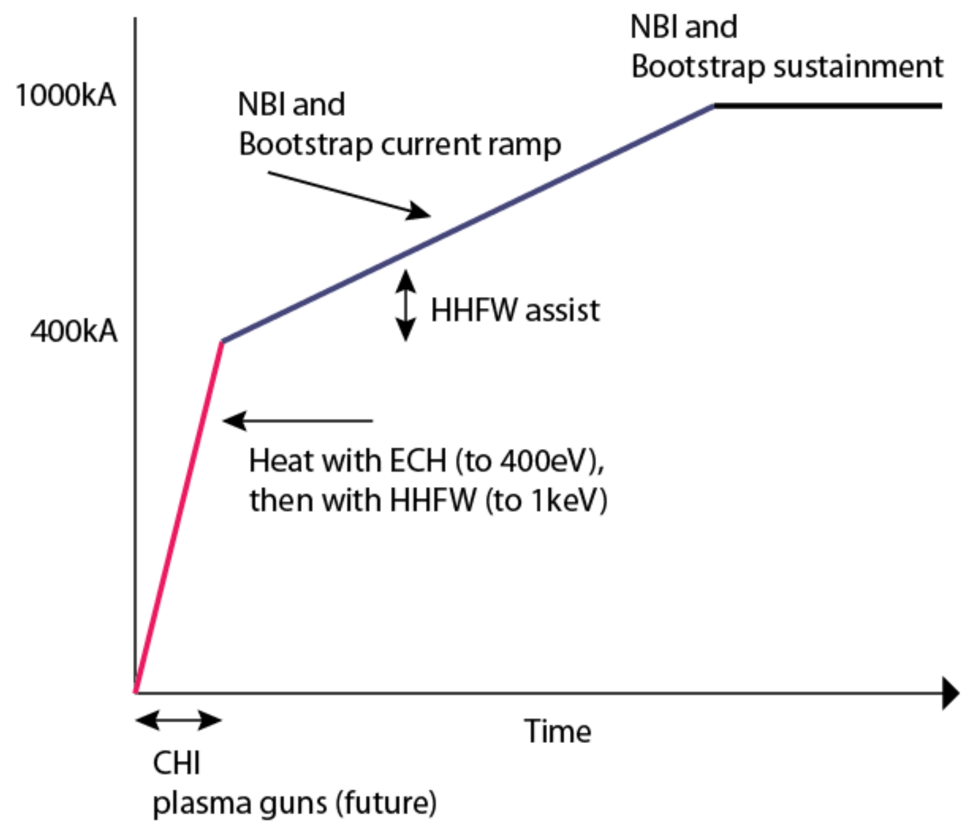
CHI is Planned to be Used as Initial Current Seed for Subsequent Non-inductive Current Ramp-up in NSTX-U

CHI in NSTX/NSTX-U



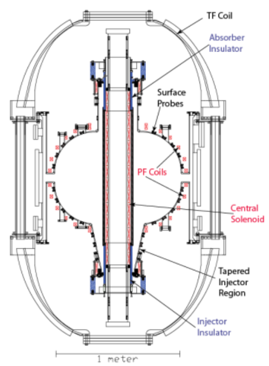


NSTX-U Start-up and Ramp-up strategy



NSTX-U goal is to demonstrate and understand solenoid-free current start-up and ramp-up

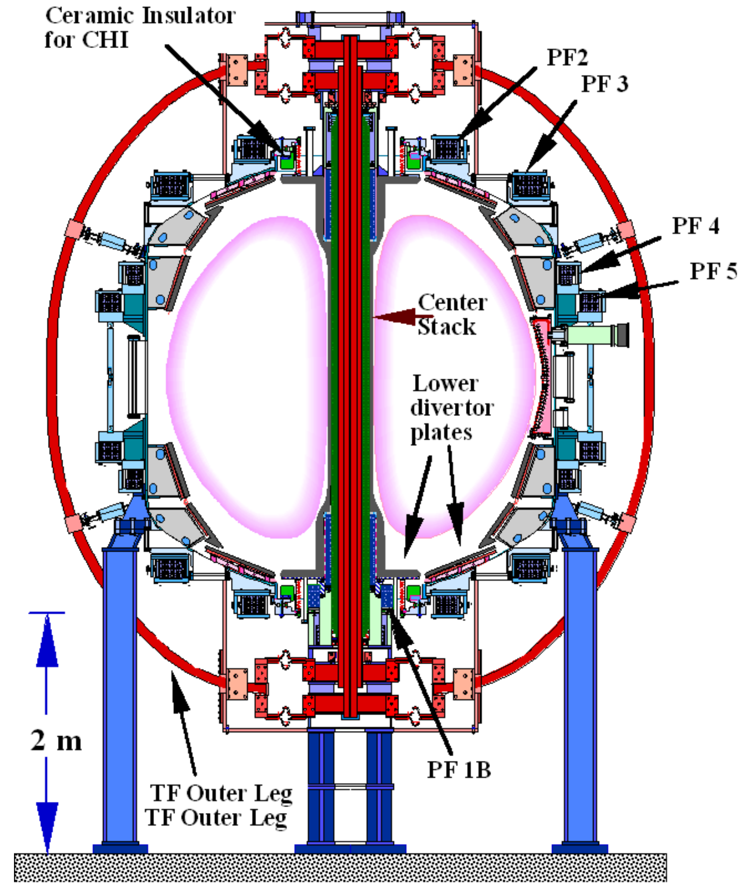
NSTX CHI Research Follows Concept Developed in HIT-II



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

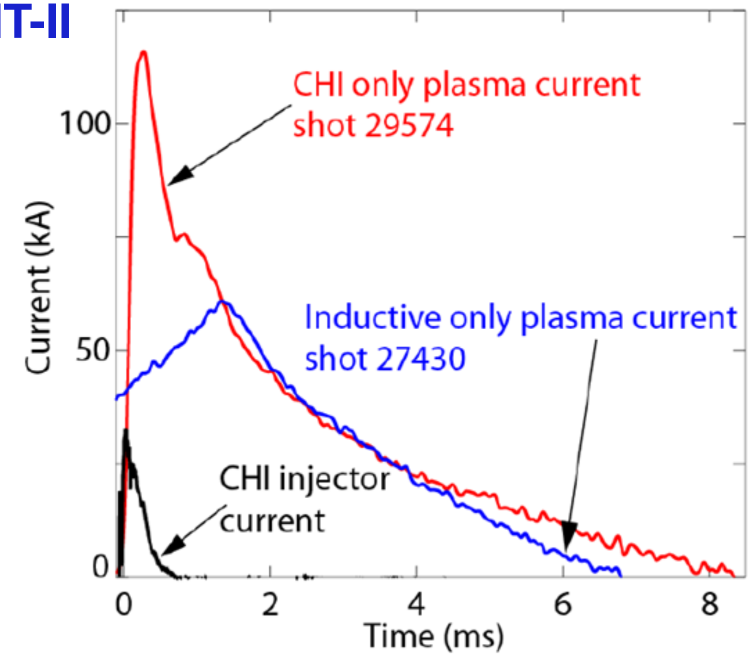


Proof-of-Principle NSTX device

- 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

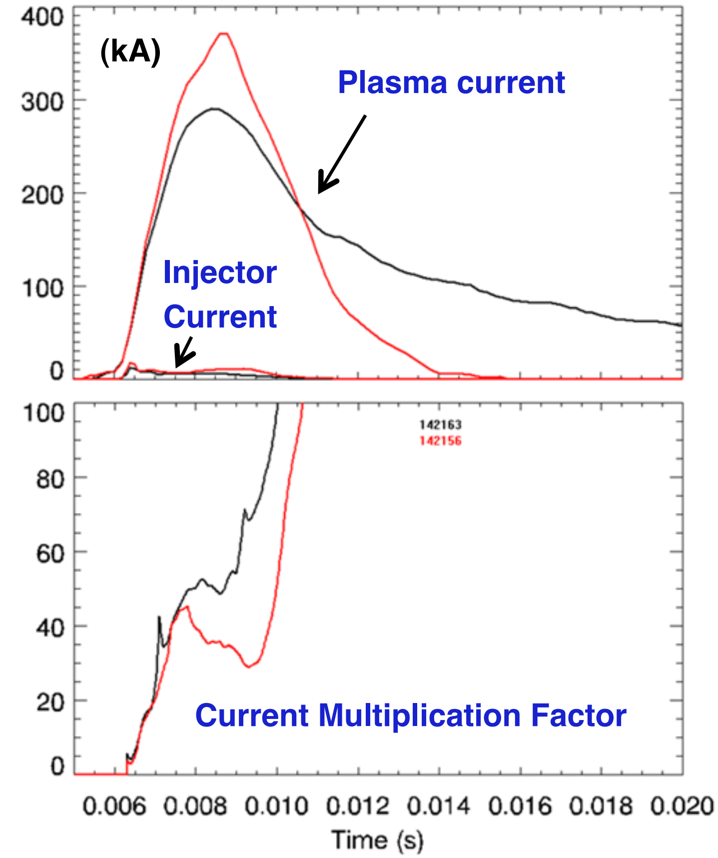


-30kA of injector current generates 120kA of plasma current

-Best current multiplication factor is 6-7

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

NSTX



- 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

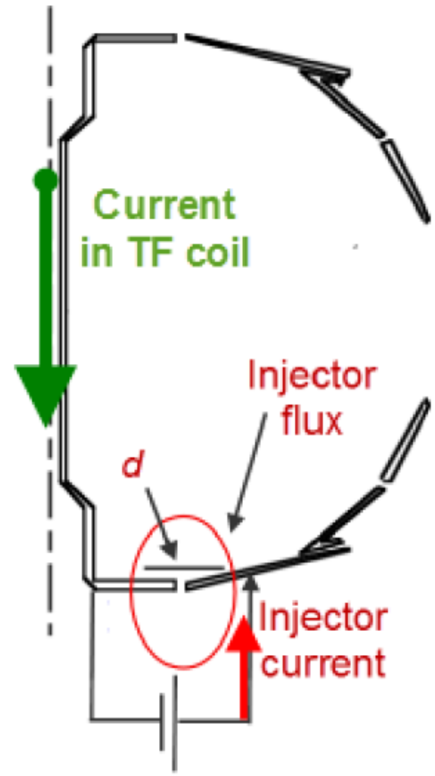
$$I_P = \underbrace{I_{inj}}_{\text{Injector current}} (\underbrace{\psi_T}_{\text{Toroidal flux}} / \psi_{inj})$$

- Current multiplication increases with toroidal field

  - Favorable scaling with machine size

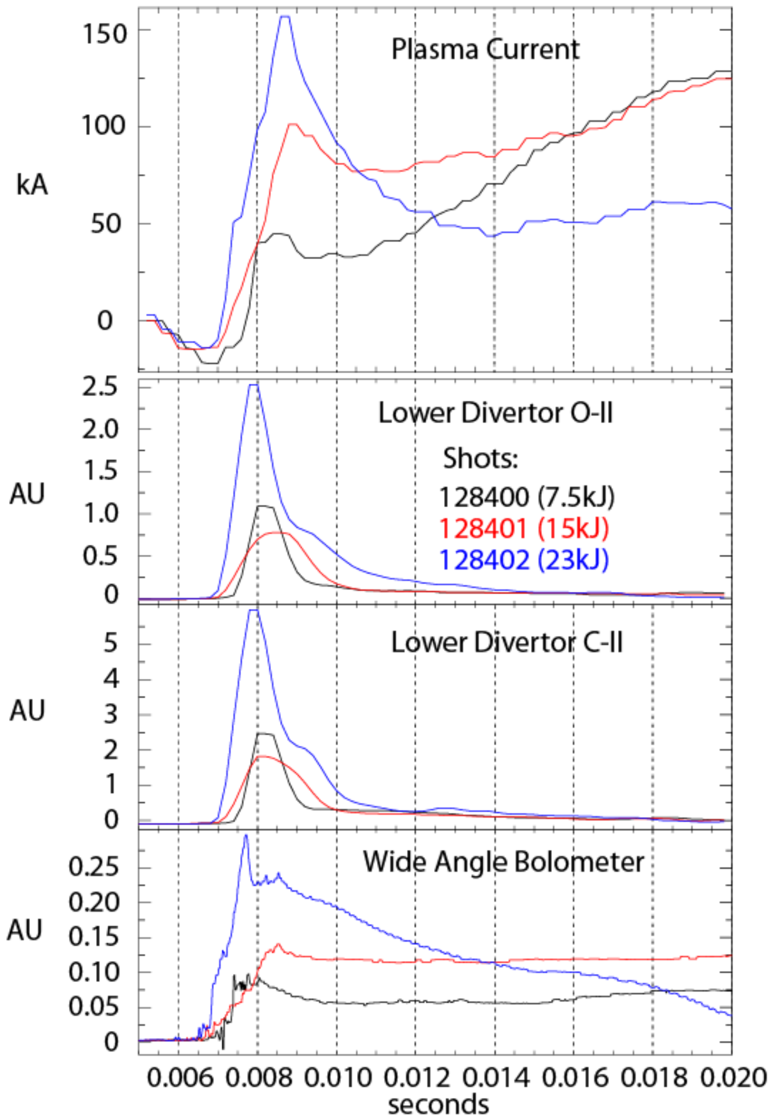
  - Increases efficiency (10 Amps/Joule in NSTX)

  - Smaller injector current to minimize electrode interaction



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

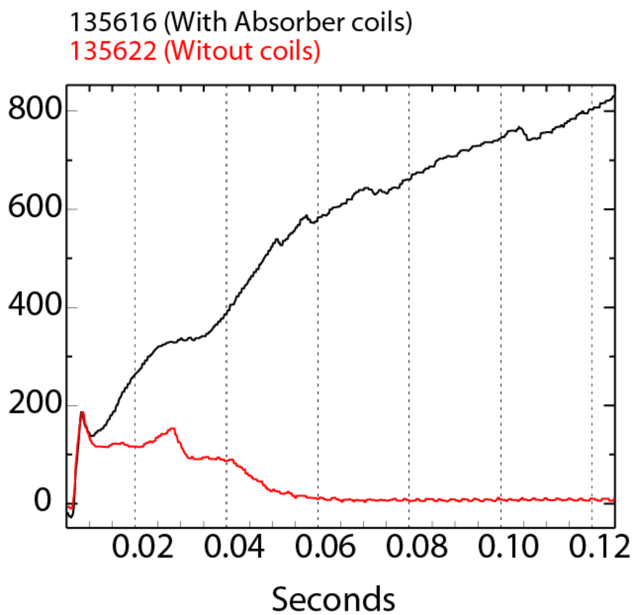
Low-Z Impurity Radiation Needs to be Reduced for Inductive Coupling

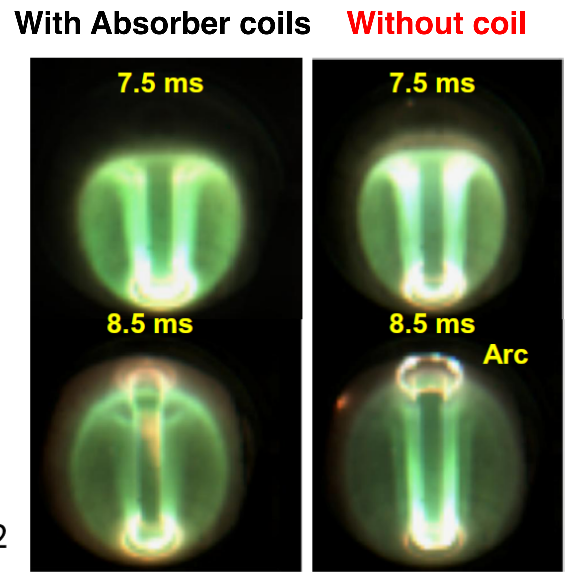


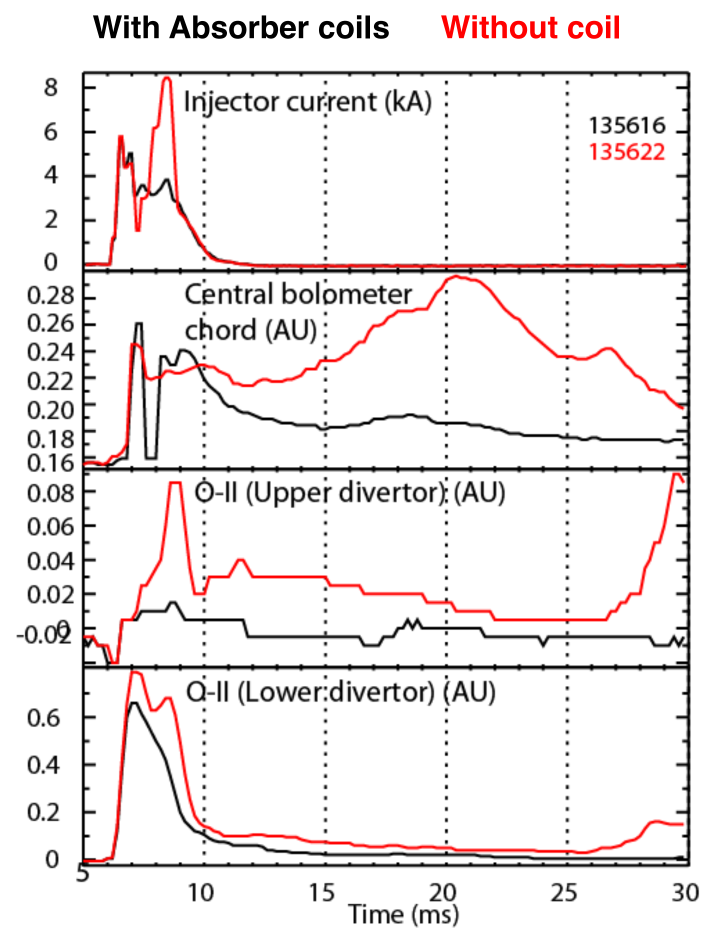
- Low-Z impurity radiation increases with more capacitors
- Possible improvements
  - Metal divertor plates should reduce low-Z impurities
    - High Te in spheromaks (500eV) obtained with metal electrodes
  - Discharge clean divertor with high current DC power supply
  - Use auxiliary heating during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

Filter scopes: V. Soukhanovskii (LLNL)

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







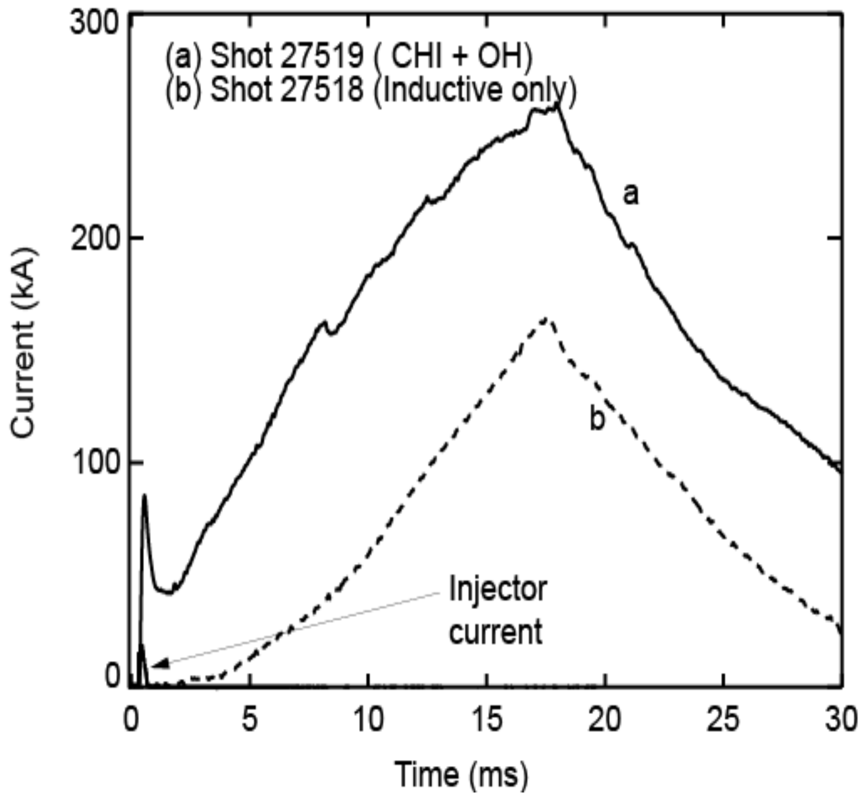
- Divertor cleaning and lithium used to produce reference discharge

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

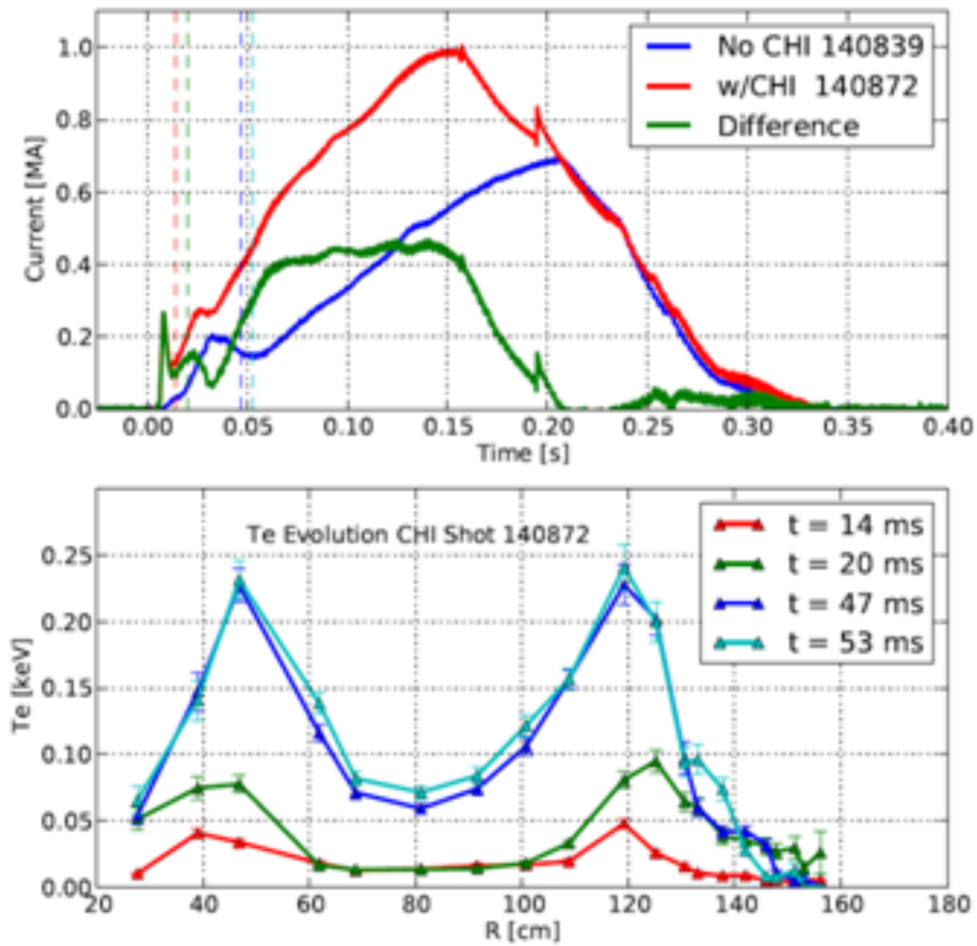
R. Raman, D. Mueller, B.A. Nelson, T.R. Jarboe, et al., PRL 104, (2010) 095003

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

HIT-II



NSTX

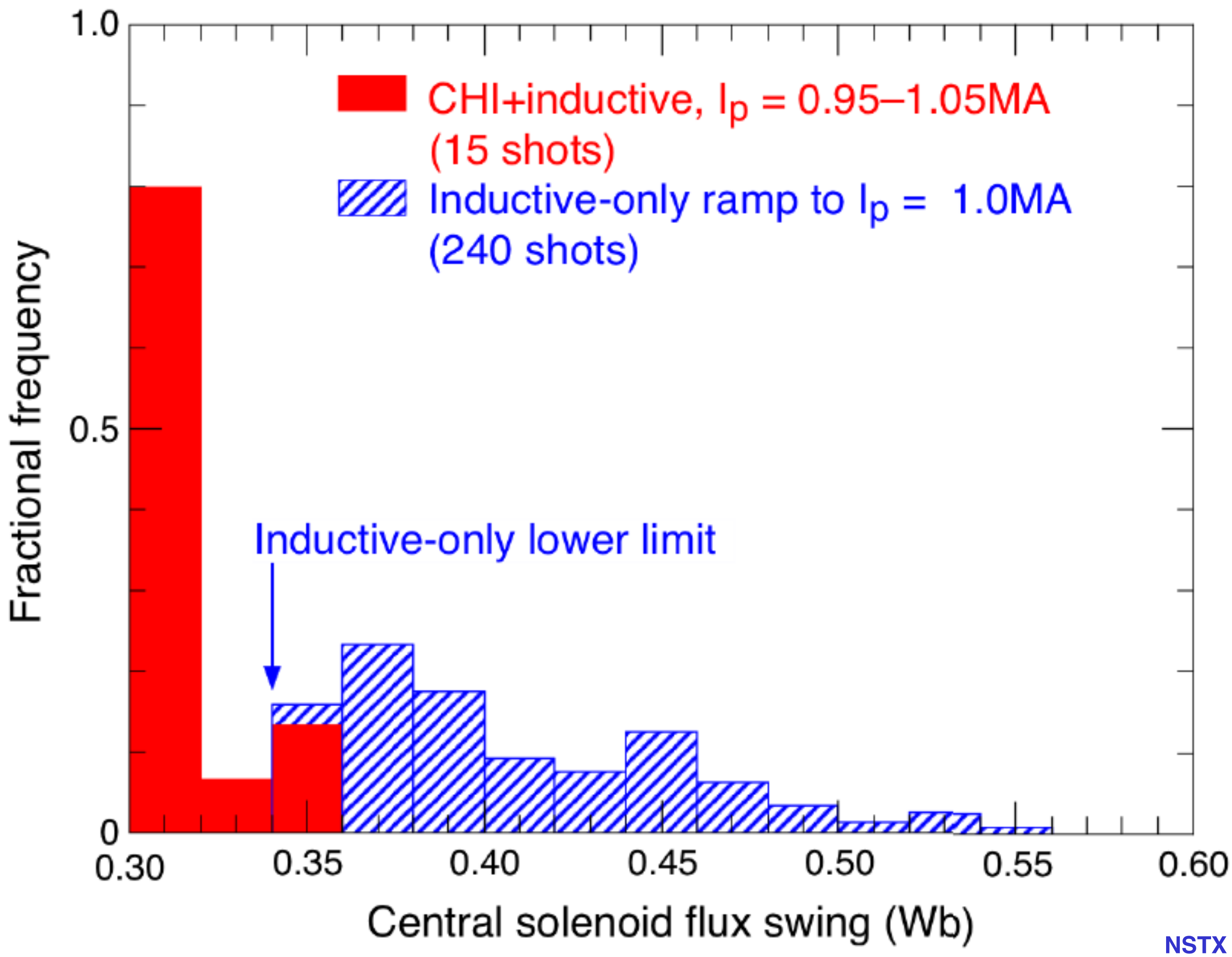


R. Raman, T.R. Jarboe, B.A. Nelson et al, Phys. Plasmas 14, 022504 (2007)

Thomson: B. LeBlanc (PPPL)

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

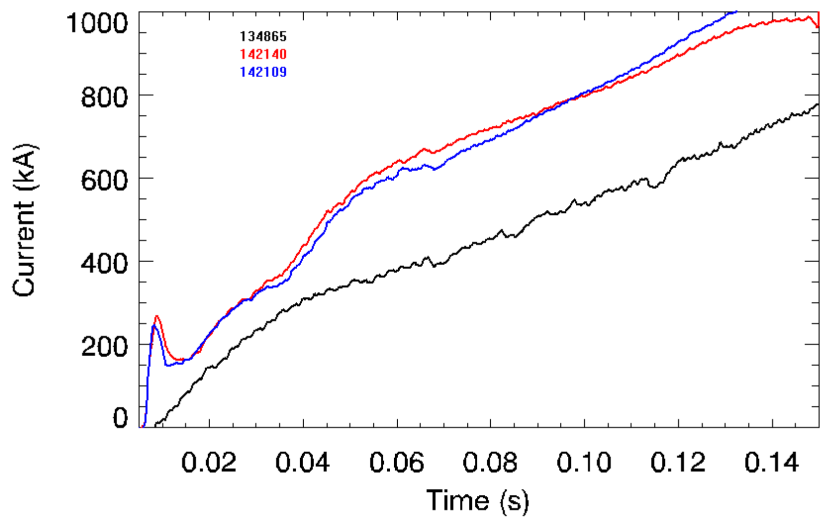


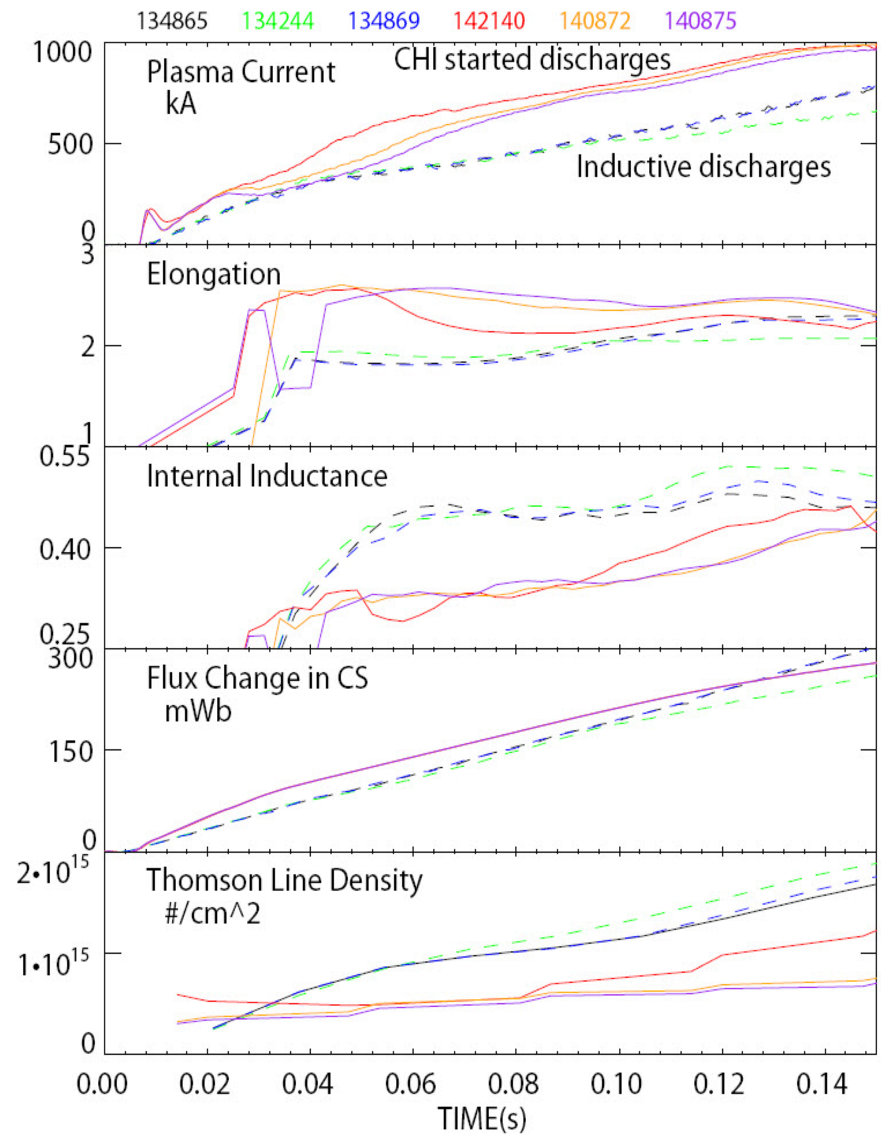
FY11 discharges require 258 mWb of flux

(less flux than shown here)

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

NSTX has made Considerable Progress in Developing CHI as a Method to Start-up an ST

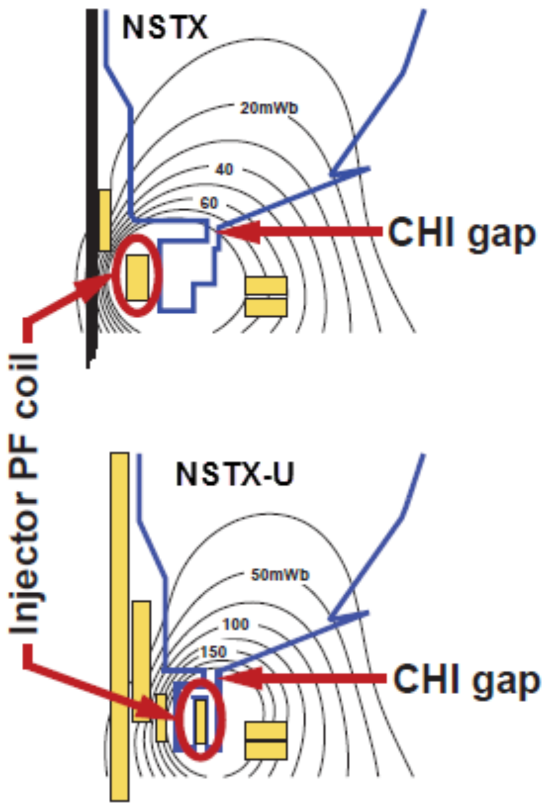




- Best inductive plasma (from 10 YR NSTX data base) uses 340 mWb of solenoid flux to get to 1MA
- Un-optimized CHI started discharges require 258 mWb
- Full non-inductive start-up and ramp-up will be developed on NSTX-U

R. Raman, et al., Phys Plasmas, 18, 092504 (2011)

CHI Start-up to ~0.4MA is Projected for NSTX-U, and is Projected to Scale Favorably to Next-step STs

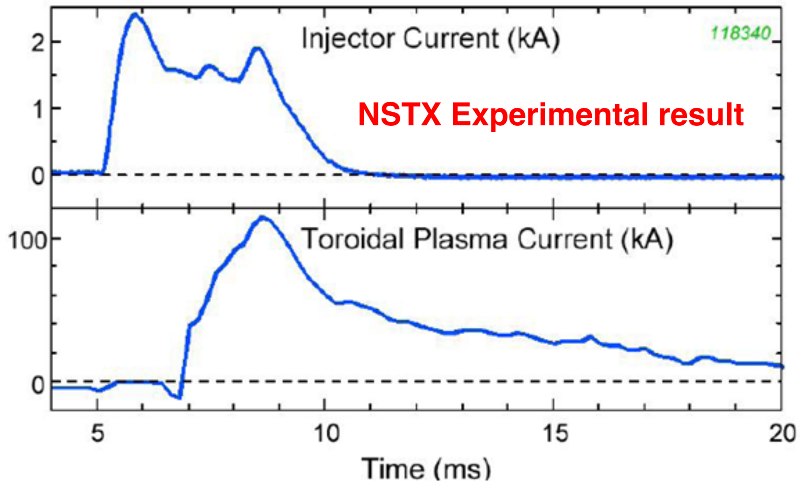


Injector flux in NSTX-U is ~ 2.5 times higher than in NSTX → supports increased CHI current

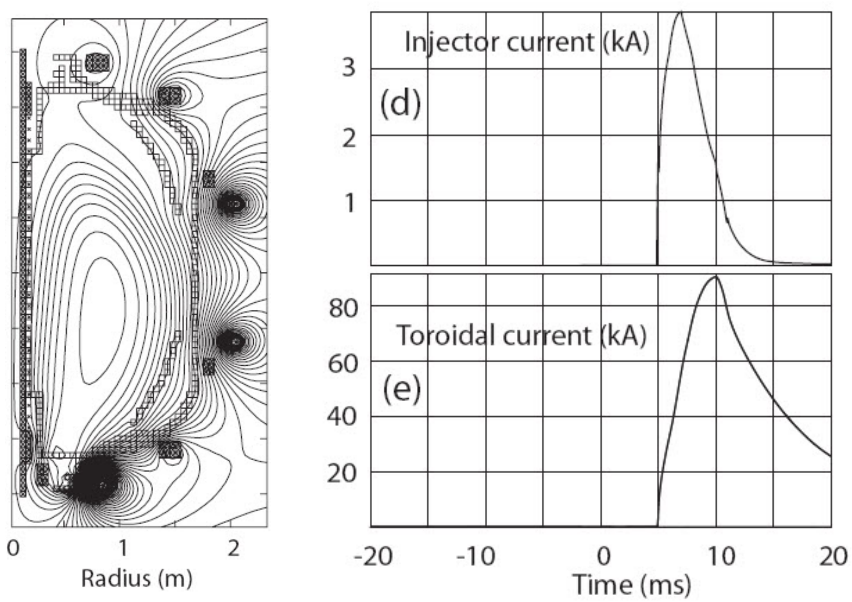
J.E. Menard, et al., Nuclear Fusion (accepted)

Parameters	NSTX	NSTX-U	ST-FNSF	ST Pilot Plant
Aspect ratio: A	1.30	1.50	1.50	1.70
Elongation: κ	2.6	2.8	3.1	3.3
Major radius: R_0 [m]	0.86	0.93	1.2	2.2
Minor radius: a [m]	0.66	0.62	0.80	1.29
Toroidal field at R_0: B_T [T]	0.55	1	2.2	2.4
TF rod current: I_{TF} [MA]	2.4	4.7	13.2	26.4
Toroidal flux: Φ_T [Wb]	2.5	3.9	15.8	45.7
Reference maximum sustained plasma current: I_{PS} [MA]	1	2	10	18
Start-up plasma normalized internal inductance: l_i	0.35	0.35	0.35	0.35
Injector flux footprint: d [m]	0.6	0.56	0.73	1.17
Injector flux for projecting start-up current: ψ_{inj} [Wb]	0.047	0.10	0.66	2.18
Bubble-burst current: I_{bb} [kA]	3.3	9.0	79	165
Injector current: I_{inj} [kA]	4.0	10.8	95	198
Start-up plasma flux: ψ_p [Wb]	0.04	0.08	0.53	1.74
Start-up plasma current achieved or projected: I_P [MA]	0.20	0.40	2.00	3.60
Current multiplication: I_P / I_{inj}	50	37	21	18
Multiplication limit: Φ_T / ψ_{inj}	53	38	24	21
Injector current density [kA/m^2]	4.9	12	63	39

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

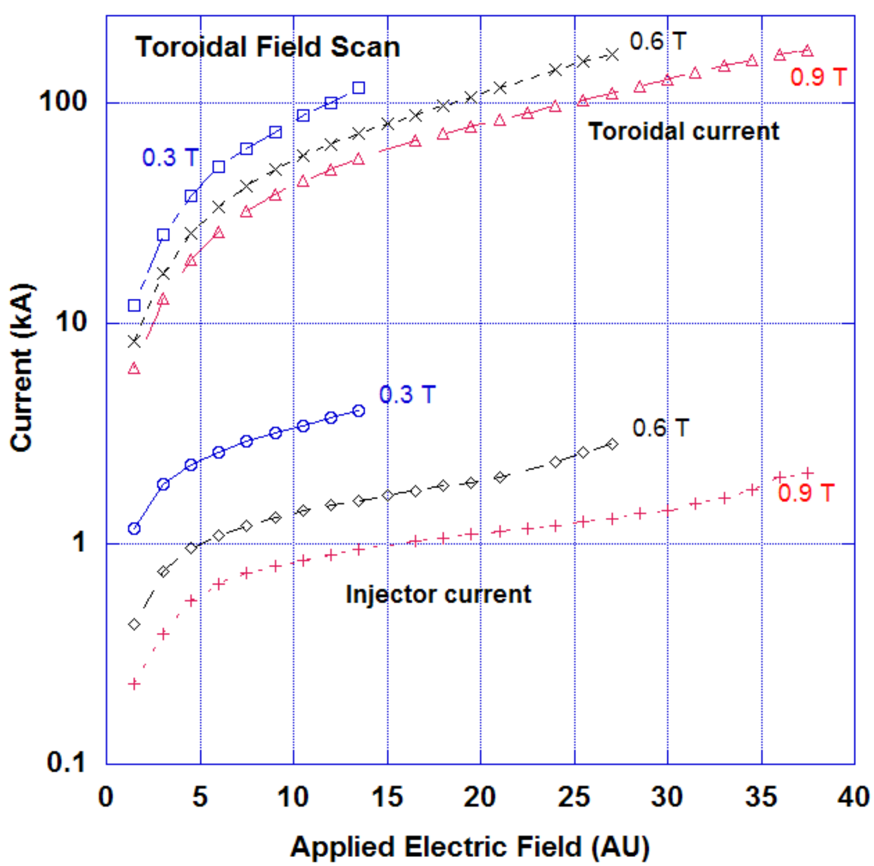
- Requires as input:
  - Device hardware geometry
  - Coil electrical characteristics
  - Assumptions concerning discharge characteristics

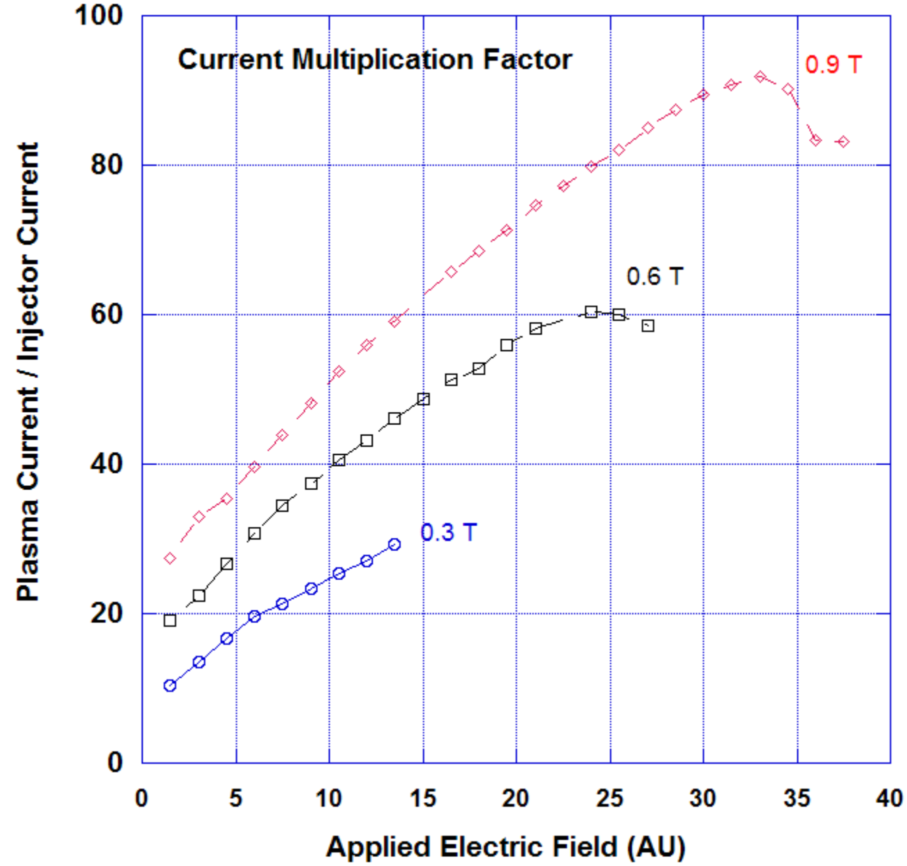
- Models evolutions of free-boundary axisymmetric toroidal plasma on the resistive and energy confinement time scales.

- 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: Developed by S.C. Jardin (PPPL)

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





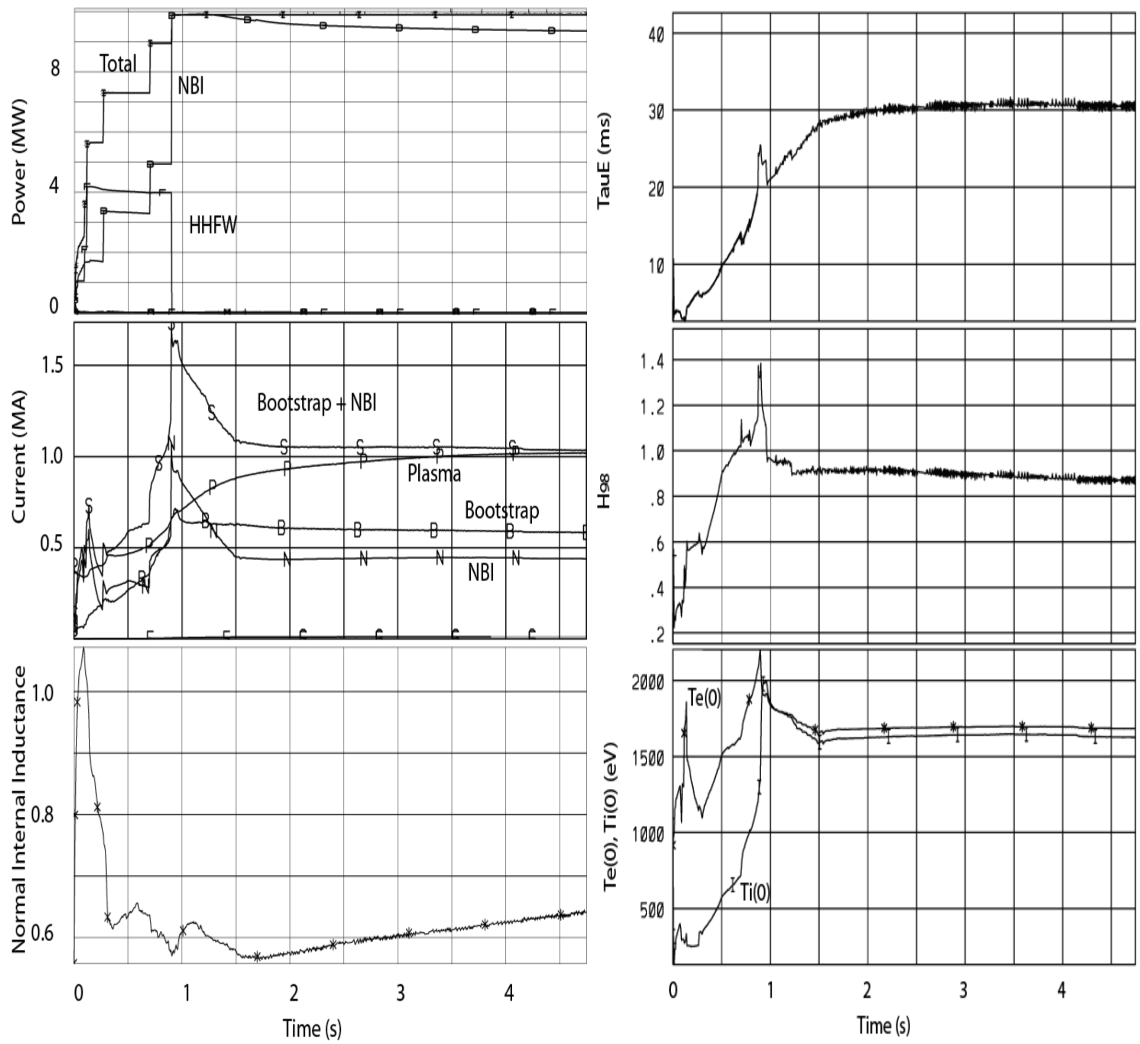
- Observed current multiplication factors similar to observations in NSTX
  - Higher toroidal field important as it reduces injector current requirement

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

Preliminary Scenario for Ramping to 1MA in NSTX-U

- Initial 400 kA low inductance target is heated by HHFW
  - H-mode initiated at 150ms
  - NBI power programmed to increase with I_p
  - HHFW is turned off at 0.9s
  - Starting from 1.5s, f_{GW} of 0.5 and central temperature of 1.7 keV is maintained until 5s
  - Bootstrap current overdrive and NB current increases I_p to 1 MA at 3.5s

Simulations in progress would use a TSC generated CHI start-up plasma to replace the 400kA low inductance plasma used in this simulation



Massive Gas Injection for Disruption Mitigation Studies in NSTX-U

- In tokamaks and STs some disruptions may be unavoidable
- For these discharges a safe plasma termination method is needed
- 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.

Motivation for Massive Gas Injection (MGI) Studies

- At present MGI appears to be the most promising method for safely terminating discharges in ITER [1-4]

- MGI involves the rapid injection of gas with an inventory several times the inventory of the plasma discharge. Some fraction of it contains a high-Z component such as Ar or Ne

- For ITER it is projected that about 500 kPa-m^3 of helium with some noble gas fraction may be required

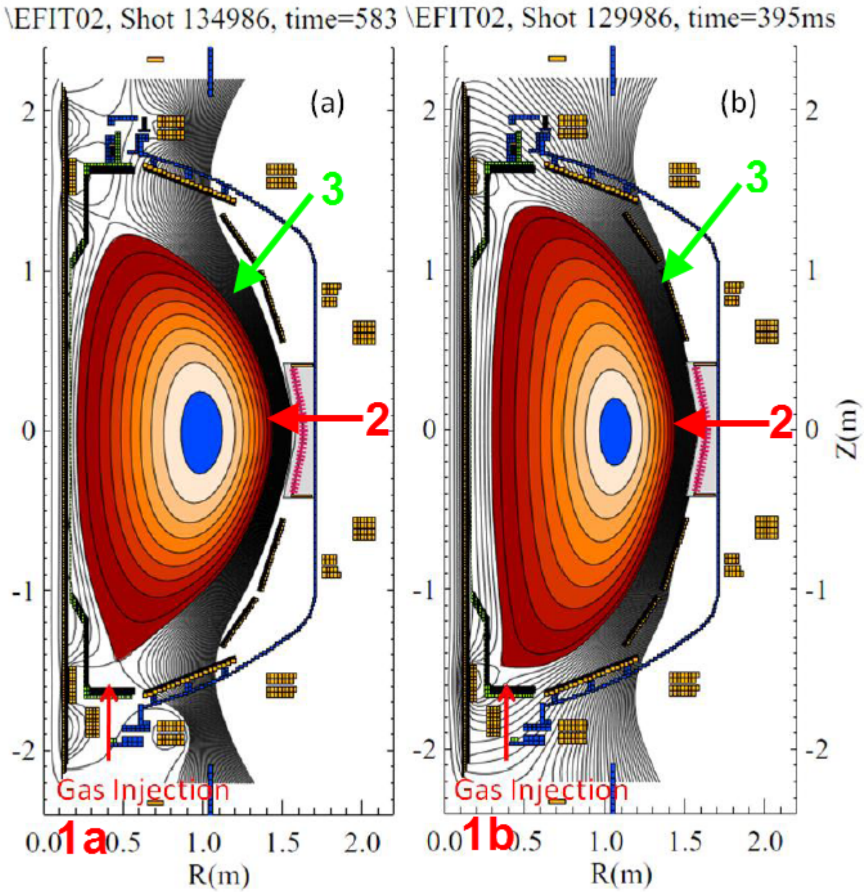
- Because of the large size of ITER and the presence of an energetic scrape-off-layer it is not known what fraction of this gas will reach the separatrix when gas is injected from the mid-plane as in present tokamak experiments.

- 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.

(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) **R.S. Granetz, et al., Nuclear Fusion 47 (2007) 1086**

The Poloidal Injection Location can be Varied in NSTX-U MGI Studies



Unique capability of NSTX:

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

1a: Private flux region 1b: lower SOL

2: Conventional mid-plane injection

3: Variation in poloidal location

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

DEGAS-2 (Monte Carlo) Simulation Effort Initiated to Quantify Gas Penetration Fraction Through SOL

- Recent work from C-MOD, ASDEX-U, DIII-D and other facilities shows that most of the gas that is assimilated by the plasma is that which is injected during the first 1ms of the gas pulse
- SOL plasma parameters increase substantially in ITER
- Modeling the gas penetration efficiency as a function of SOL parameters, distance of the gas injector from the separatrix and the injection gas pressure are needed to predict the gas assimilation efficiency that could be expected in ITER for both Massive Gas Injection and Rupture Disk injection systems.
- A full DEGAS-2 simulation using the full plasma shape is beyond our present man-power resources. A simplified slab model should be capable of providing reasonable estimates for the gas penetration efficiency that could then be compared to measured efficiencies in present experiments.
  - The slab model results would be useful for improving the design of the NSTX-U MGI system and in characterizing the fraction of noble gases required in a carrier low-Z gas
- Typical SOL and PFR parameters in DIII-D* and ITER*
  - PFR (ITER) ~1 to 2 eV and 2 E20 /m^3
  - PFR (DIII-D) <1 eV, <5 E19 /m^3
  - SOL (ITER) ~100 eV, 2 E19 /m^3
  - SOL (DIII-D) ~20 eV, < 3 E 18 /m^3

***V. Kotov, D. Reiter and A.S. Kukushkin, "Numerical study of the ITER divertor plasma with the B2-EIRENE code package," Bericht des Forschungszentrums Julich, Jul-4257, November (2007)**

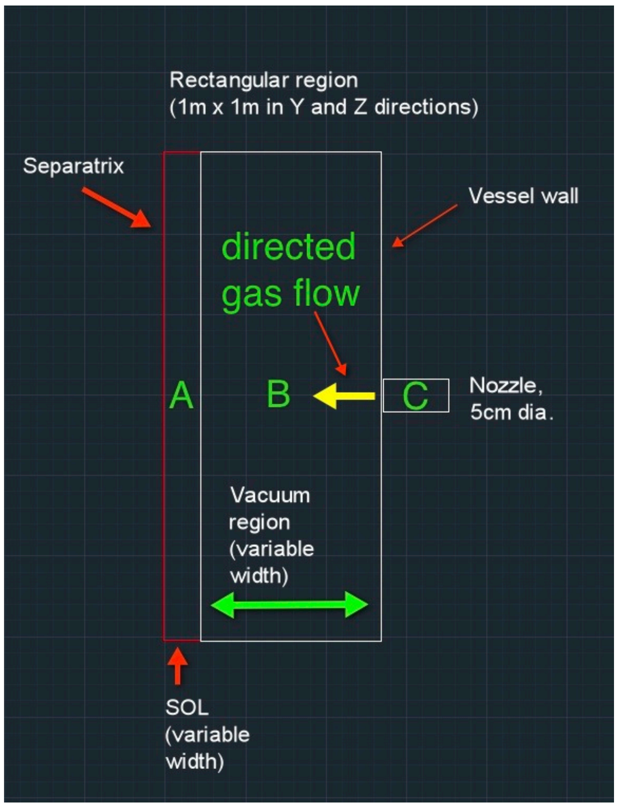
***S.L. Allen, Rev. Scientific Instrum. 68 (1997) 1261**

***A.S. Kukushkin, et al., Nuclear Fusion, 47 (2007) 698**

***D.L. Rudakov, et al., Nuclear Fusion, 45 (2005) 1589**

Simplified DEGAS-2 Model to Characterize Gas Penetration through SOL and Private Flux Region

- The SOL (region A) and the region between the SOL and vessel wall (region B) is represented by a rectangular box (1m x 1m x variable depth along X direction)
- Gas nozzle is located at the vessel wall



- 1ms pulse of gas is injected from the nozzle in the –X direction towards the separatrix
- Initial simulations will use a single gas species
  - Future simulations may include smaller fractions of higher Z gases along with D2 or He as the primary carrier gas
- Region B is a vacuum region
- Region A is filled with plasma with parameters in the range of 1 eV to 100 eV and an electron density of 3E18 to 2E20 #/m^3
  - The parameters in this region would be varied to simulate SOL and PFR conditions
  - In addition to neutral-neutral collisions, electron neutral collisions, ion-neutral collisions and recombination are modeled
  - In regions B and A - atoms, molecules, ions that pass the boundaries along the Y and Z directions are assumed to be lost
  - Neutrals and ions that penetrate the separatrix are assumed to be assimilated by the plasma
  - Particle inventories and spatial distribution in sub milli-second time scale will be computed

DEGAS-2: D. P. Stotler and C. F. F. Karney, Contrib. Plasma Phys. 34, 392 (1994).

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