NSTX Supported by U.S. DEPARTMENT OF ENERGY Office of Science

Design Description of the Coaxial Helicity Injection (CHI) System on NSTX-U

R. Raman, T.R. Jarboe, B.A. Nelson
(University of Washington, Seattle, WA)

D. Mueller, S.C. Jardin, C. Neumeyer, M. Ono, J.E. Menard
(Princeton Plasma Physics Laboratory, Princeton, NJ)

and the NSTX Research Team

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Motivation for CHI Start-up

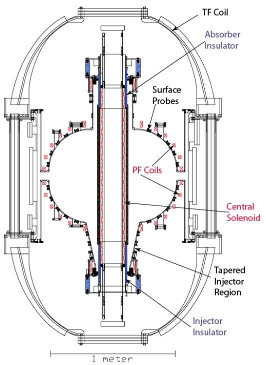
- A FNSF based on the Spherical Torus (ST) concept will have very restricted space for a central solenoid
  - A method for solenoid-free start-up is very likely required

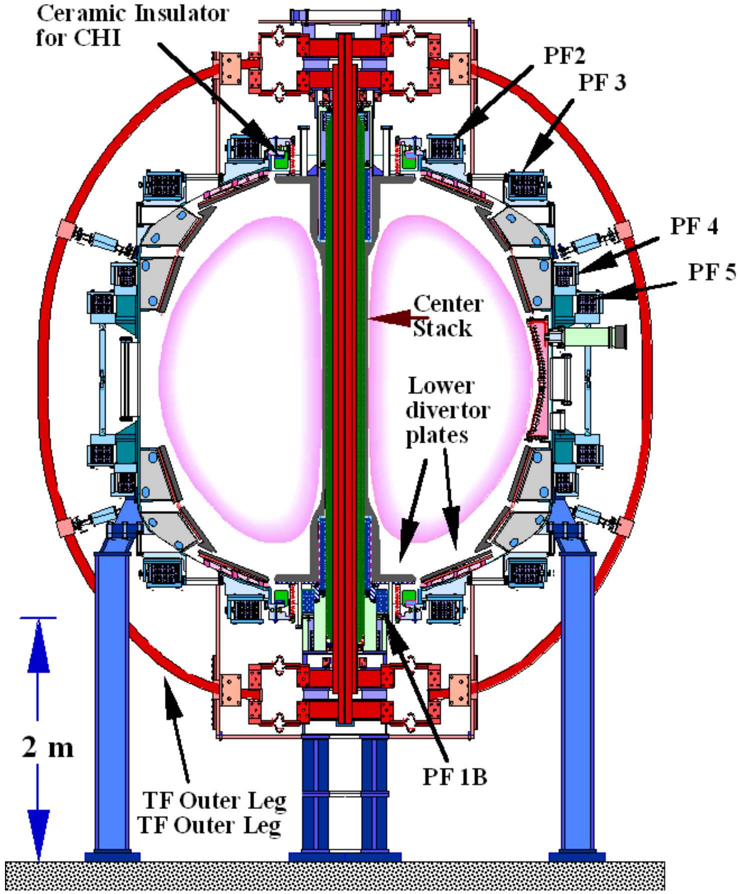
- Eliminating the solenoid also simplifies the tokamak concept
  - Solenoid not needed during steady-state operation
  - Provides greater flexibility in the choice of the aspect ratio

- 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

NSTX and NSTX-U CHI Research Follows Concept Developed in HIT-II

Both machines shown approximate to scale





Concept exploration device HIT-II

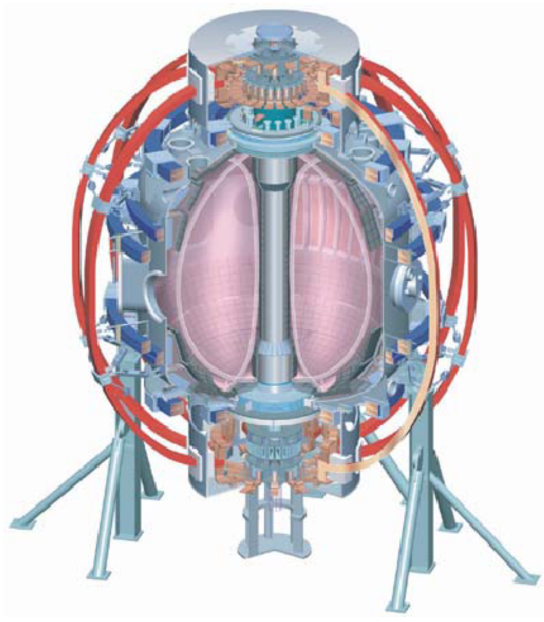
- Built for developing CHI
- Many close fitting fast acting PF coils
- 4kV CHI capacitor bank

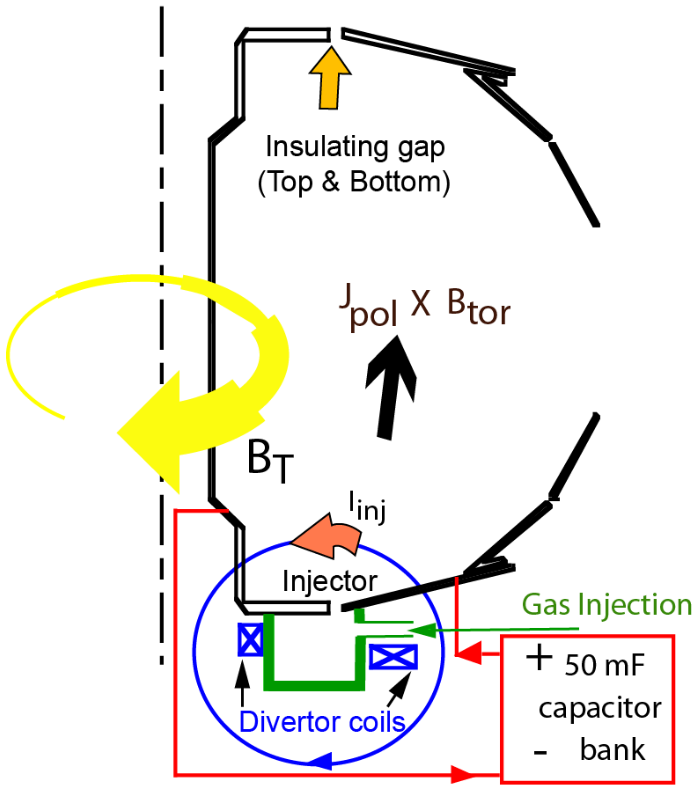
NSTX plasma is ~30 x plasma volume of HIT-II

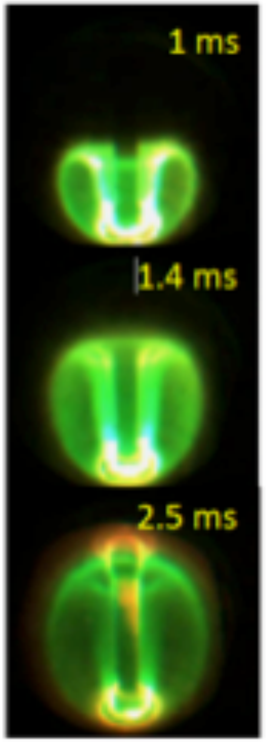
Proof-of-Principle NSTX device

- Built with conventional tokamak components
- Few PF coils
- 1.7kV CHI capacitor bank (2-3kV on NSTX-U)

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







- Transient CHI Start-up
  - Generate injector poloidal flux using divertor coils
  - Ensure divertor flux footprints are narrow
  - Inject 2 Torr.L of D2 below divertor plate gap
  - Discharge 25-50mF capacitor bank (2 kV)
  - Injected current rapidly decays
  - Toroidal plasma currents remains on closed flux surfaces

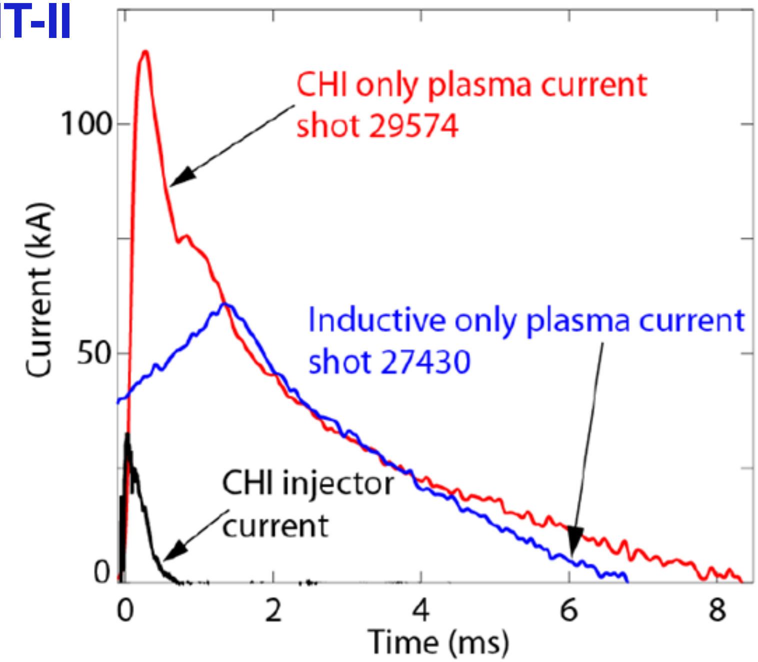
Fast camera: F. Scotti, L. Roquemore, R. Maqueda

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

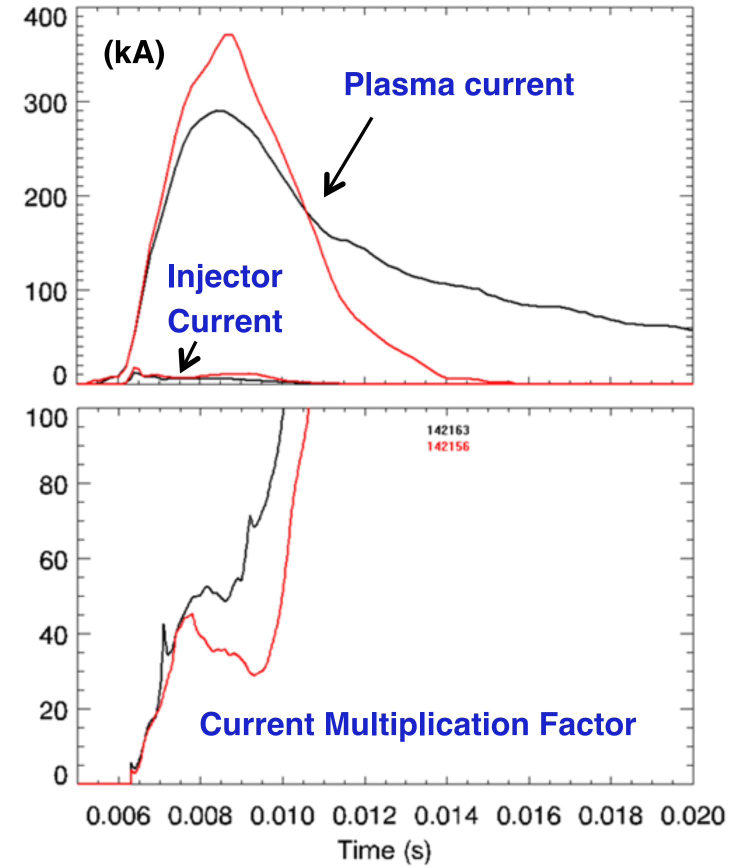
Transient CHI: R. Raman, T.R. Jarboe, B.A. Nelson, et al., PRL 90, (2003) 075005-1

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

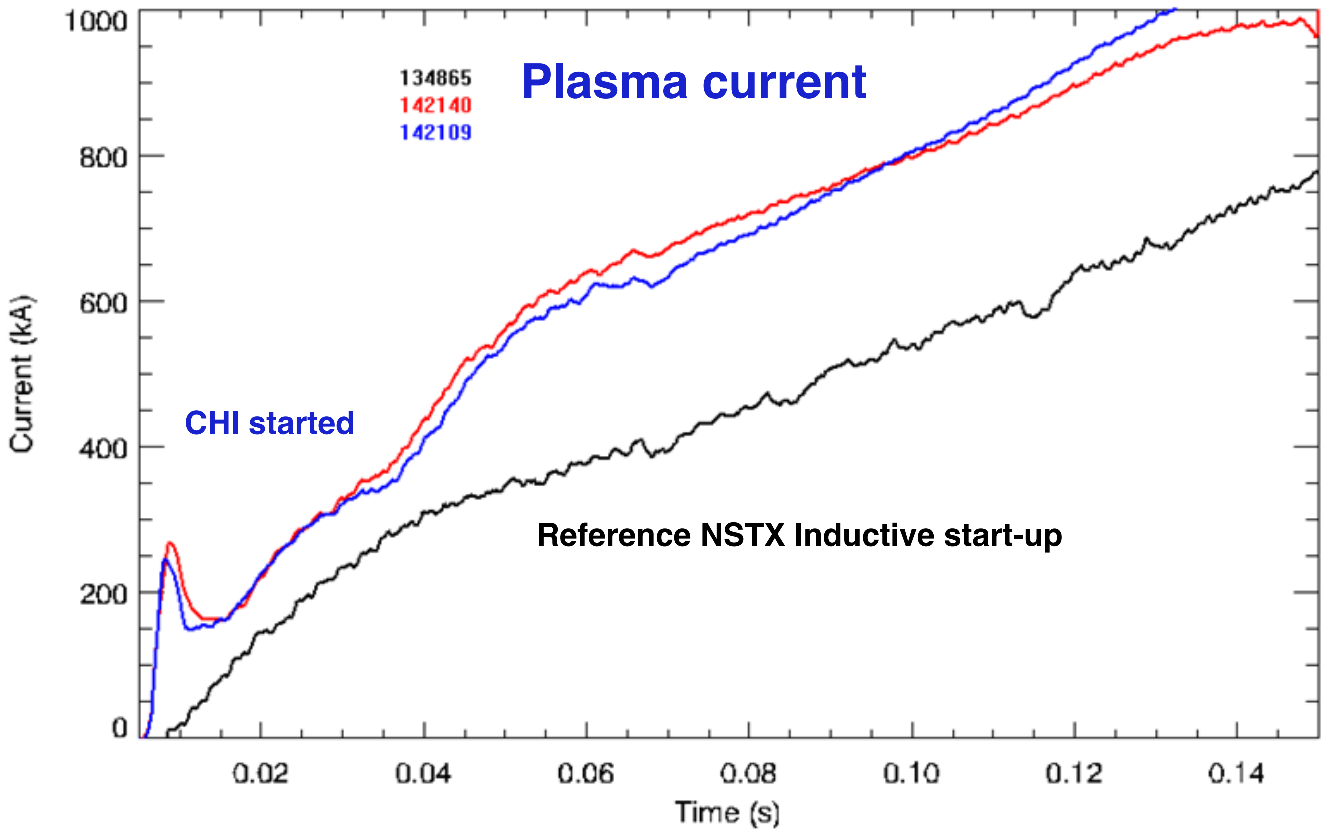
-Best current multiplication factor is 6-7

-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

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



2010 results

Reference Inductive discharge: Uses 396mWb to get to 1MA

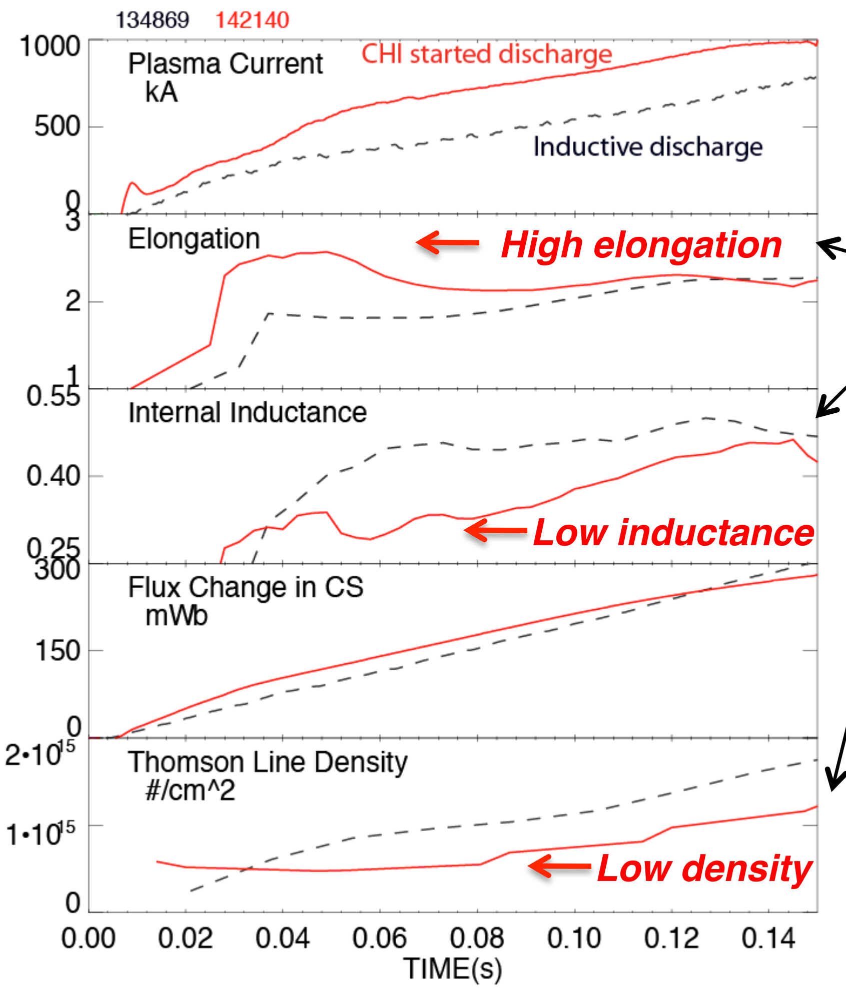
CHI started discharge: Uses 258 mWb to get to 1MA (53% less flux)

NSTX inductive start-up: 138mWb flux typically generates 400kA of plasma current

Best CHI-startup discharges: 138mWb flux generated 650kA

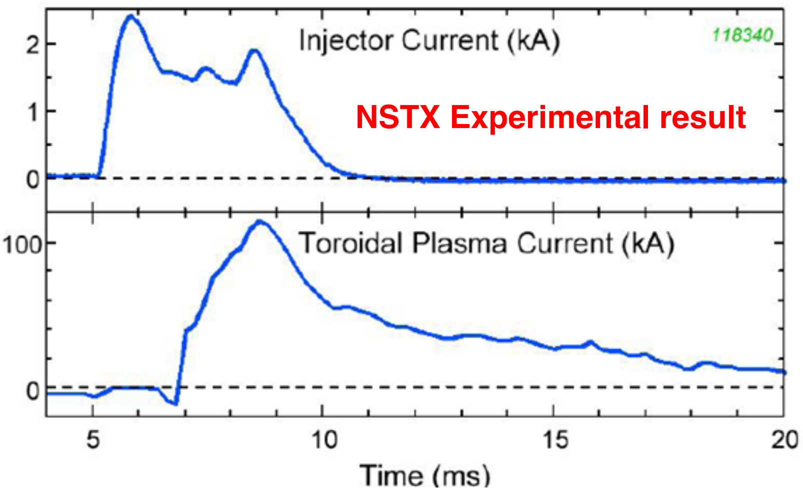
Plasma discharge ramping to 1MA requires 35% less inductive flux when coaxial helicity injection (CHI) is used

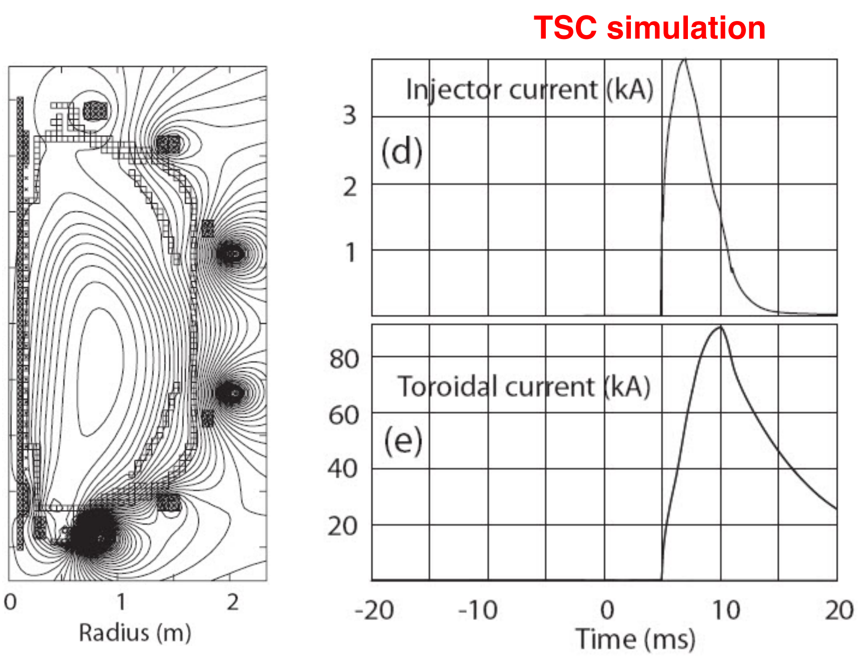
CHI assisted startup in NSTX



- CHI generates plasmas with high elongation, low l_i and n_e
- Results imply a doubling of closed flux current > 400kA in NSTX-U

TSC Simulations are being used to Understand CHI-Scaling with Machine Size (NSTX)





- 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

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

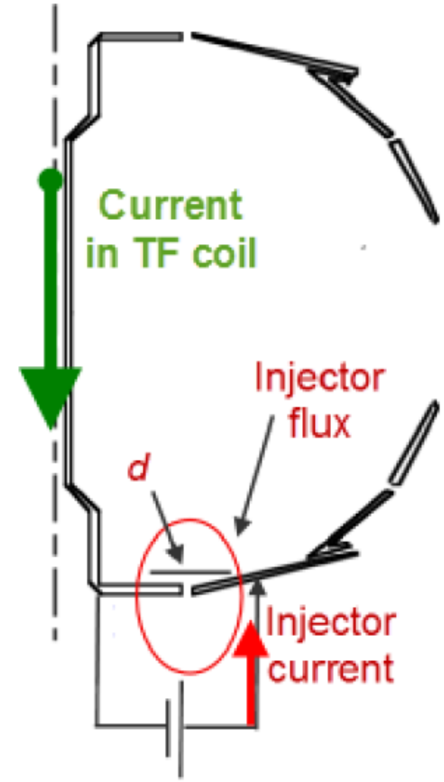
  d = flux foot print width

  I_{TF} = current in TF coil

Injector current → I_{inj} ; **Toroidal flux** → ψ_T

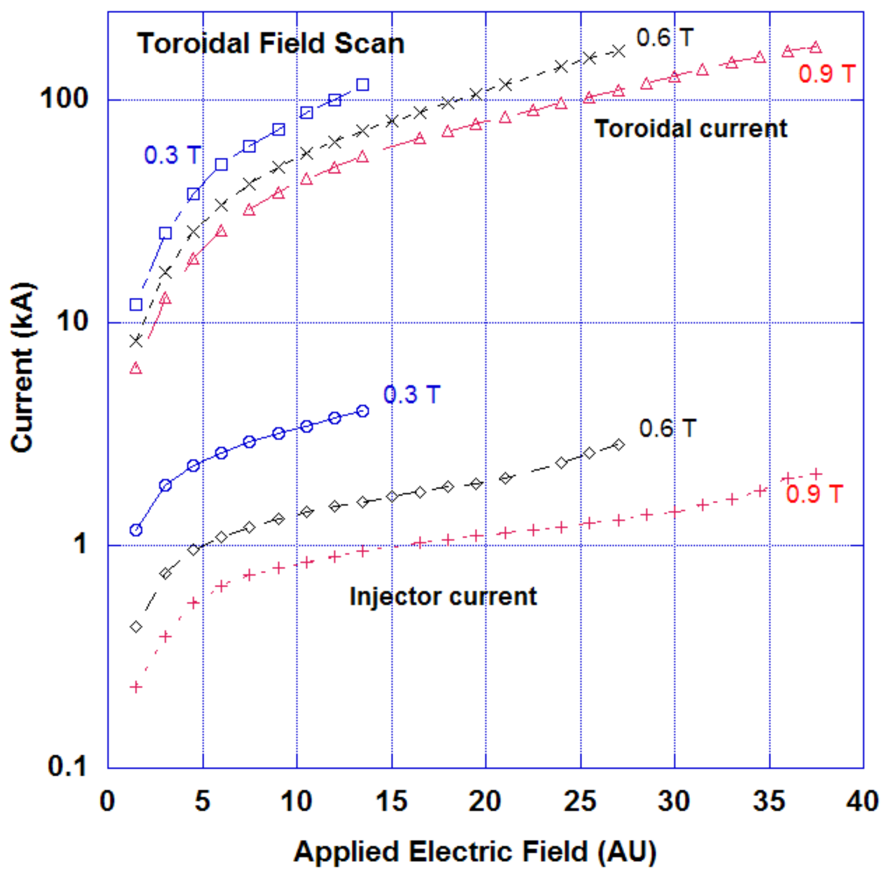
$$I_P = I_{inj}(\psi_T / \psi_{inj})$$

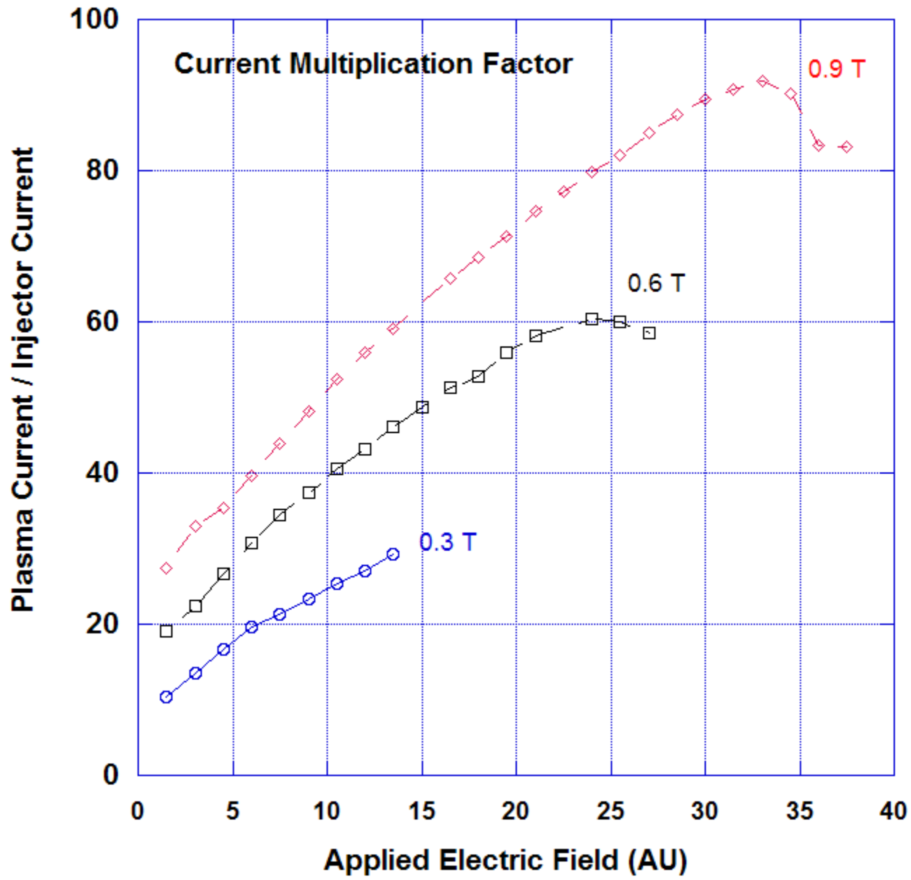
- Current multiplication increases with toroidal field
  - Favorable scaling with machine size
  - Increases efficiency (10 Amps/Joule in NSTX)
  - Smaller injector current to minimize electrode interaction



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

TSC Simulations Show Increasing Current Multiplication as TF is Increased





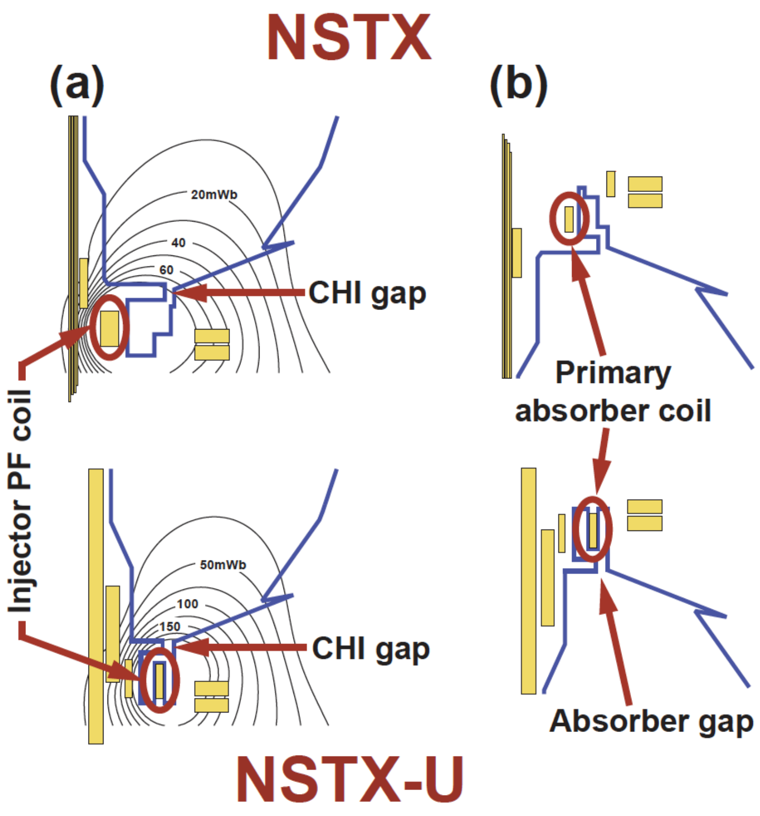
- Observed current multiplication factors similar to observations in NSTX
  - Higher toroidal field important as it reduces injector current requirement

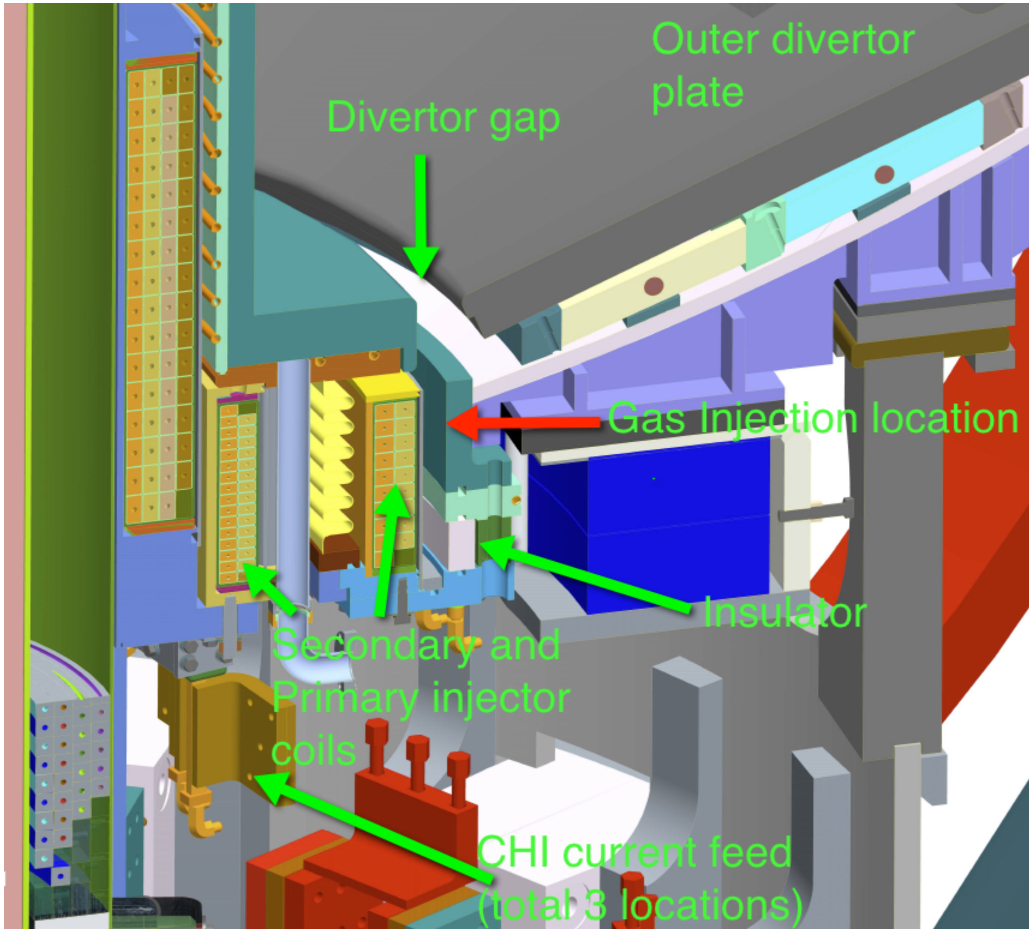
R. Raman, S.C. Jardin, J. Menard, T.R. Jarboe et al., Nuclear Fusion 51, 113018 (2011)

NSTX-U Upgrades that Facilitate CHI Start-up

NSTX-U Machine Enhancements for CHI

- > 2.5 x Injector Flux in NSTX (proportional to I_p)
- Absorber coil much better positioned to suppress spurious arcs



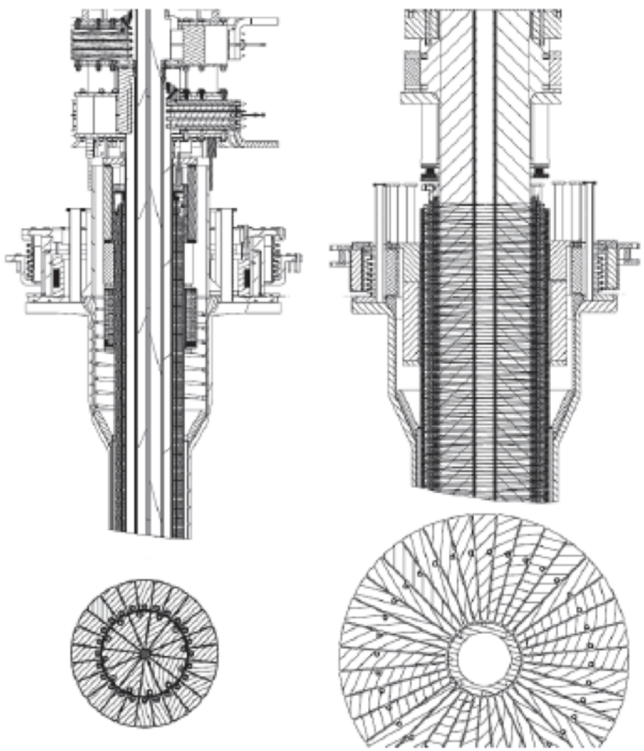


Increased TF and ECH Beneficial for Increasing Electron Temperature in CHI-Started Discharges

TF increased to 1T (0.55 T in NSTX)

- Increases current multiplication factor defined as plasma current/capacitor bank current (facilitated by larger center stack)

Present CS New CS

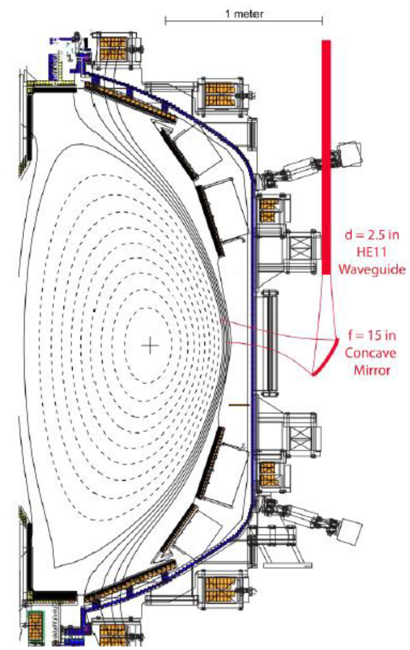


20 cm OD 40 cm OD

28 GHz (1 MW) ECH system

- Will increase electron temperature

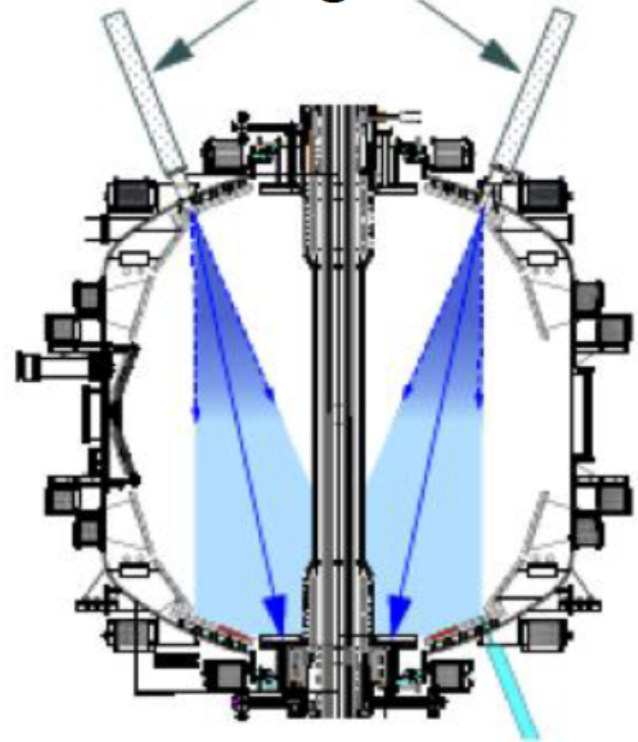
28 GHz, 1.5 MW Tsukuba Gyrotron



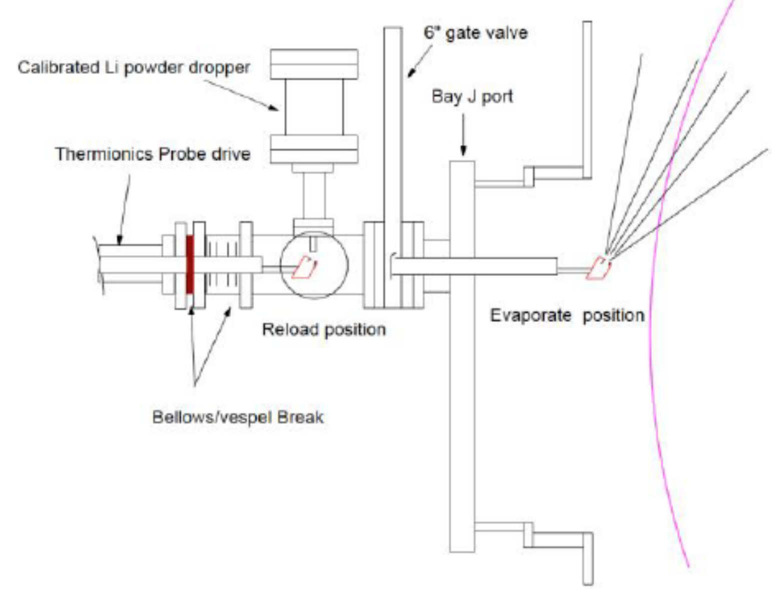
28 GHz ECH/EBWH waveguide and mirror concept

Increased Li Coverage of Vessel to Reduce Low-Z Impurities

Existing LITERS



New Upward Evaporating LITER

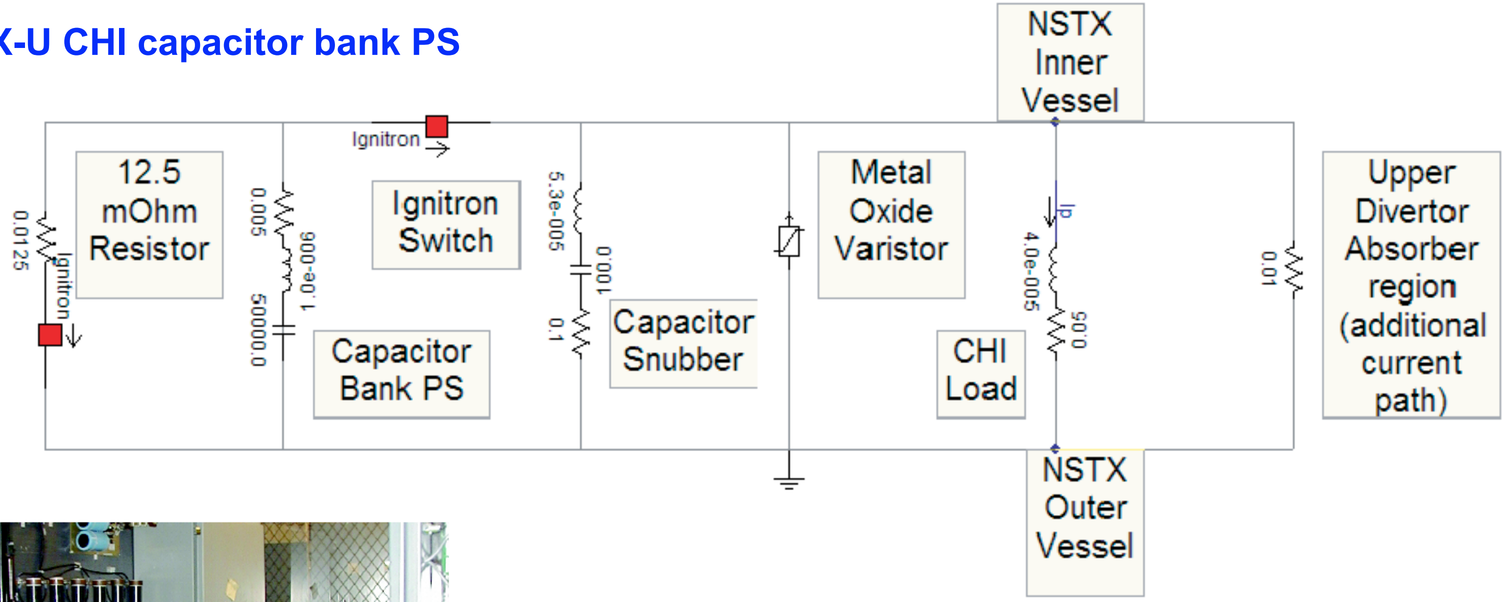


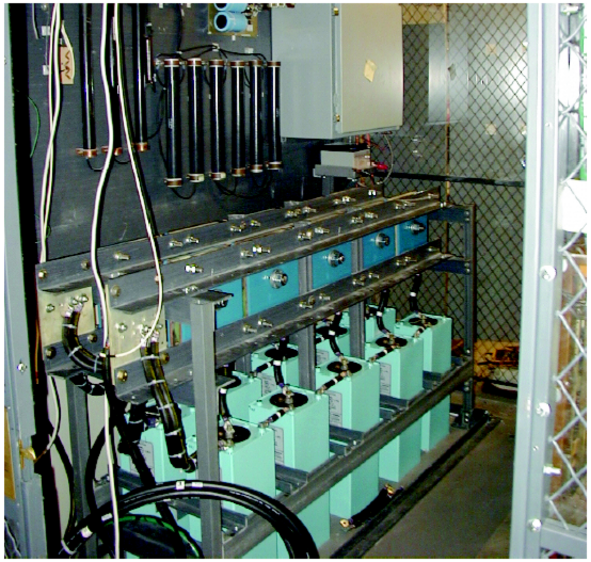
- Upward Evaporating LITER to increase Li coverage for increased plasma performance

Metal divertor plates and Cryo Pump Upgrades (post FY2016) Will allow CHI plasma temperature to increase as a result of reduced low-Z impurity influx and plasma density pump-out

2-3kV Capacitor Bank Upgrades Allow Injection of More Poloidal Flux into NSTX-U (Injector Flux is Proportional to Ip)

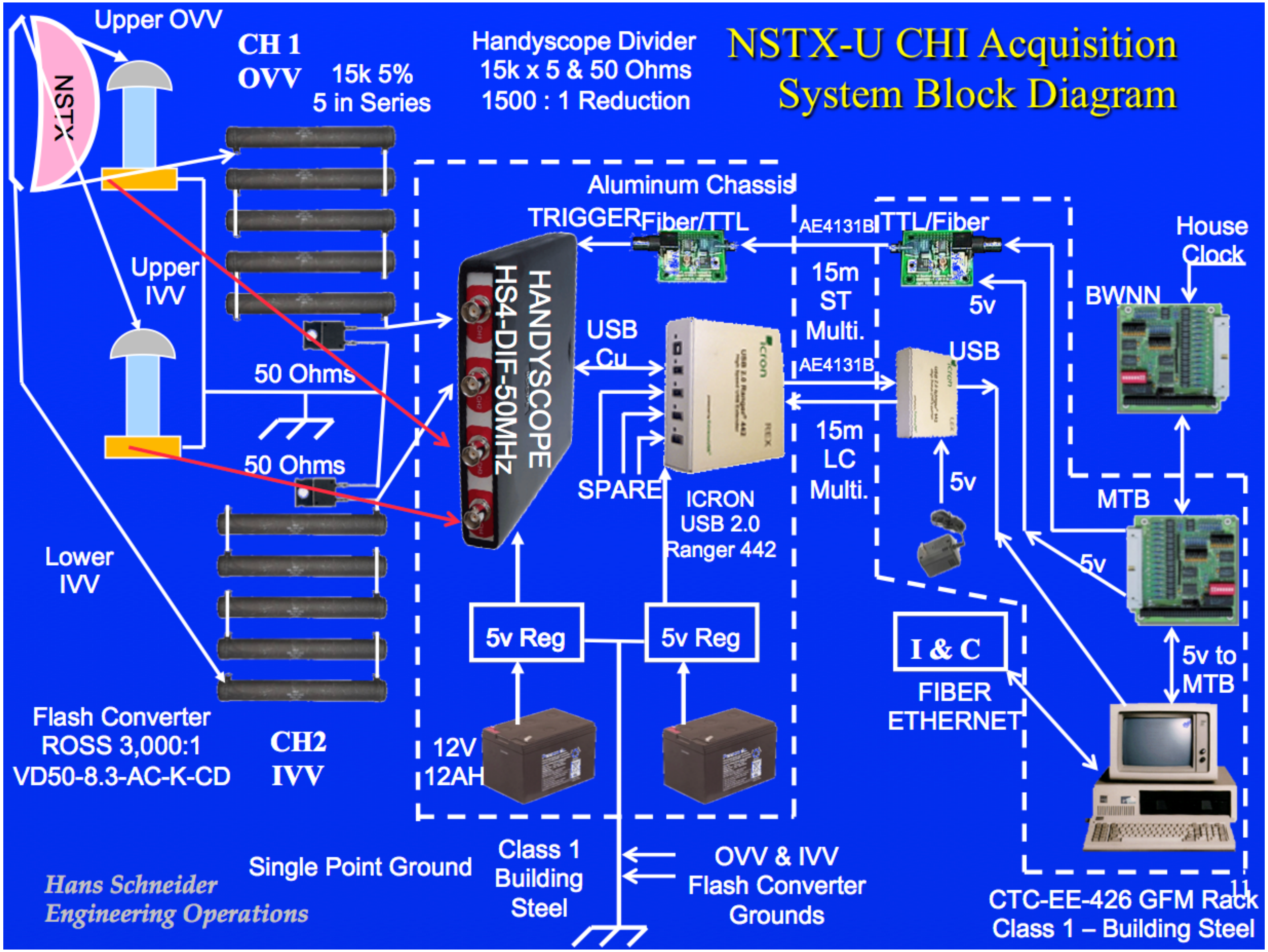
NSTX-U CHI capacitor bank PS





- 50mF, 2.0 kV capacitor bank (5mF x 10): 100kJ
- Present plans to upgrade to 3kV capacitors in FY2017 to allow capability to inject more poloidal injector flux
- Fast crowbar system to interrupt injector current
- Three, variable capacitance, and individually triggered modules to shape injector voltage waveform
- Programmable thyristor power supply (2kV, 50kA) also available to support steady-state type CHI discharges

Dual 1 MHz Vessel Voltage Monitors based on Ross Voltage Monitors and Resistive Dividers (H. Schneider)



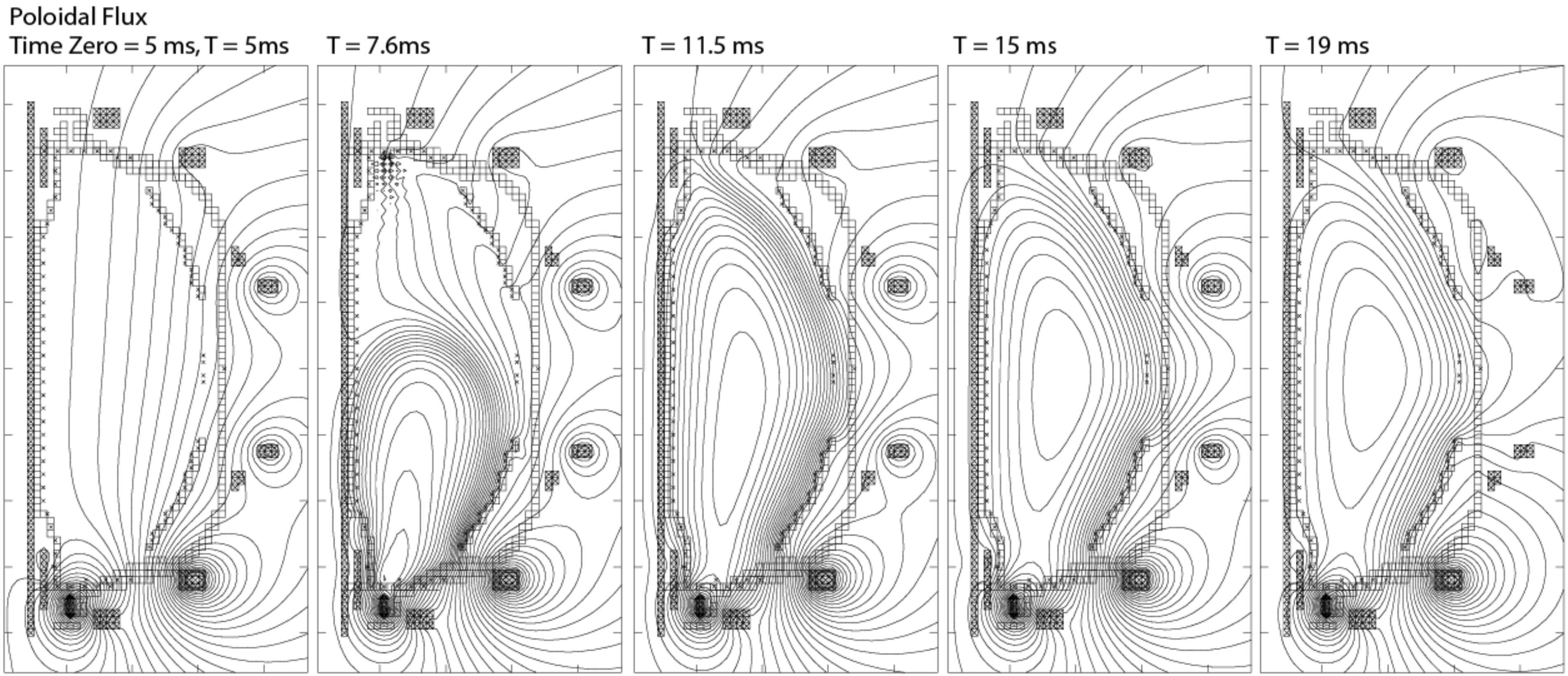
CHI Injector and Absorber Poloidal Field Coil Parameters (NSTX and NSTX-U)

Coil	R (cm)	# Turns	L (mH)	R (mΩ)	kA-Turns (min)	kA-Turns (max)	kA.Turns/ms and Voltage (kV)
NSTX							
PFAB1	43.06	48	3.93	129.7	-48	48	+/- 4.8 [1 kV]
PFAB2	63.18	48	6.46	190.2	-48	48	+/- 4.8 [1 kV]
PF1B	30.5	32	0.673	3.15	0	+320	+19 [2 kV]
PF2L	80	28	1.98	7.32	-560	+560	+/- 25.3 [2 kV]
NSTX-U							
PF1AU,L	32.4	64	2.03	8.93	-460	1172	56.2 [2 kV]
PF1BU,L	40.4	32	1.14	9.19	-192	416	+45.8 [2 kV]
PF1CU,L	55.05	20	0.72	4.49	-100	318	+41.1 [2 kV]
PF2L	80	28	1.98	7.32	-308	420	+25.3 [2 kV]

Injector coil is positioned much closer to CHI gap (R = 57-61.6 cm) in NSTX-U

Absorber buffer coils have much higher current slew rates

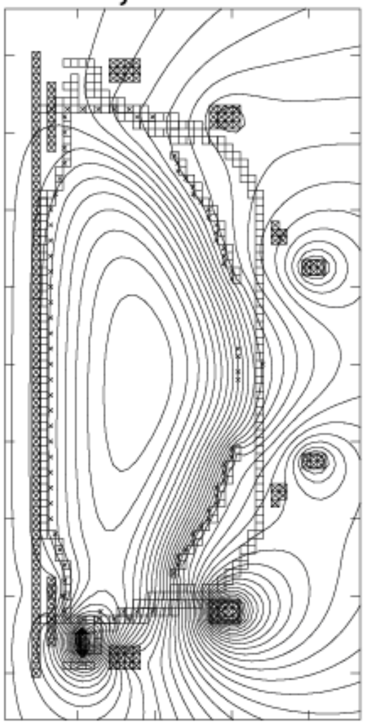
Initial CHI Start-up Scenario in NSTX-U (TSC Simulations in NSTX-U Geometry – Static Coil Currents)



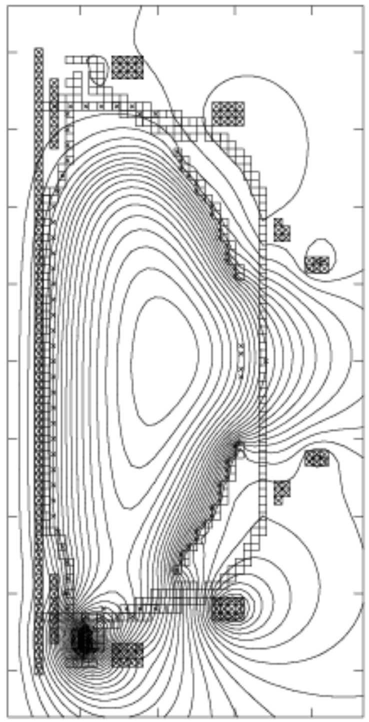
- Initial Transient CHI discharges in NSTX-U will start with low levels of current in the Primary PF1CL injector coil
- CHI discharge will be grown into a magnetic well suitable for the final CHI plasma equilibrium
- Poloidal flux evolution (shown above) is for for constant (in time) coil current values of:
    - PF1CL (2 kA, Max available 15 kA), PF1AL (-0.4 kA), PF2L (-0.35 kA), PF3L (-0.5 kA),
    - PF5 (-0.15 kA), PF3U (-0.07 kA), and Zero current in the other coils
    - Absorber arc suppression may require low levels of current in the PF1CU coil

CHI Produced Toroidal Current Increases with Increasing Levels of Current in the CHI Injector Coil (NSTX-U)

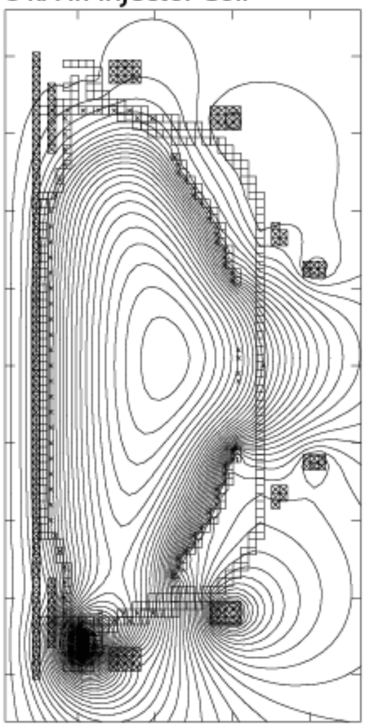
Poloidal Flux at 15 ms
2 kA in Injector Coil



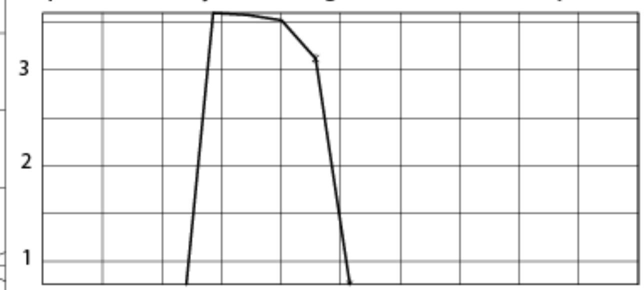
4 kA in injector Coil



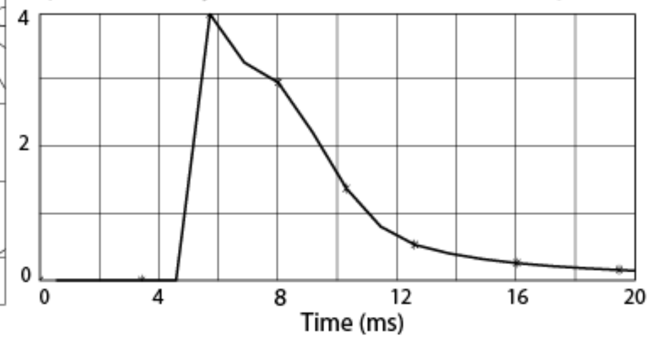
8 kA in Injector Coil



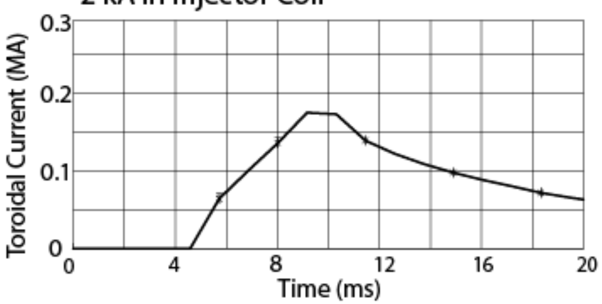
Representative Injector Volatge Waveform (Arbitrary Units)



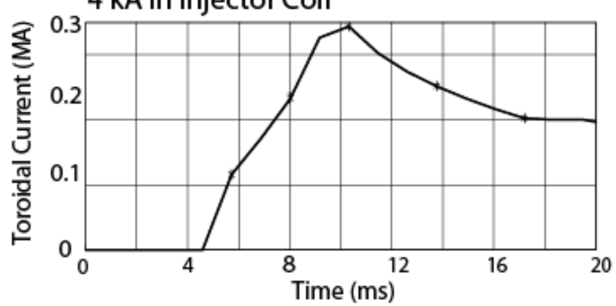
Representative Injector Current Waveform (Arbitrary Units)



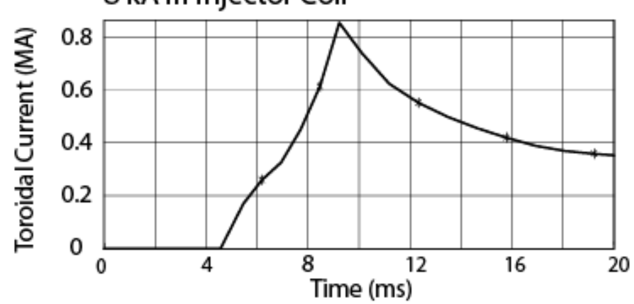
2 kA in Injector Coil



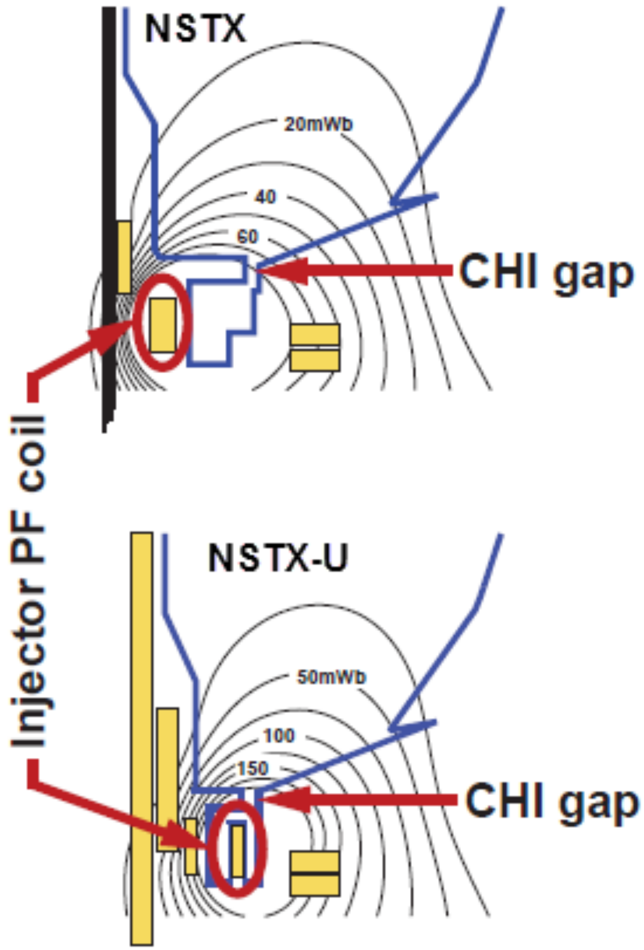
4 kA in injector Coil



8 kA in Injector Coil



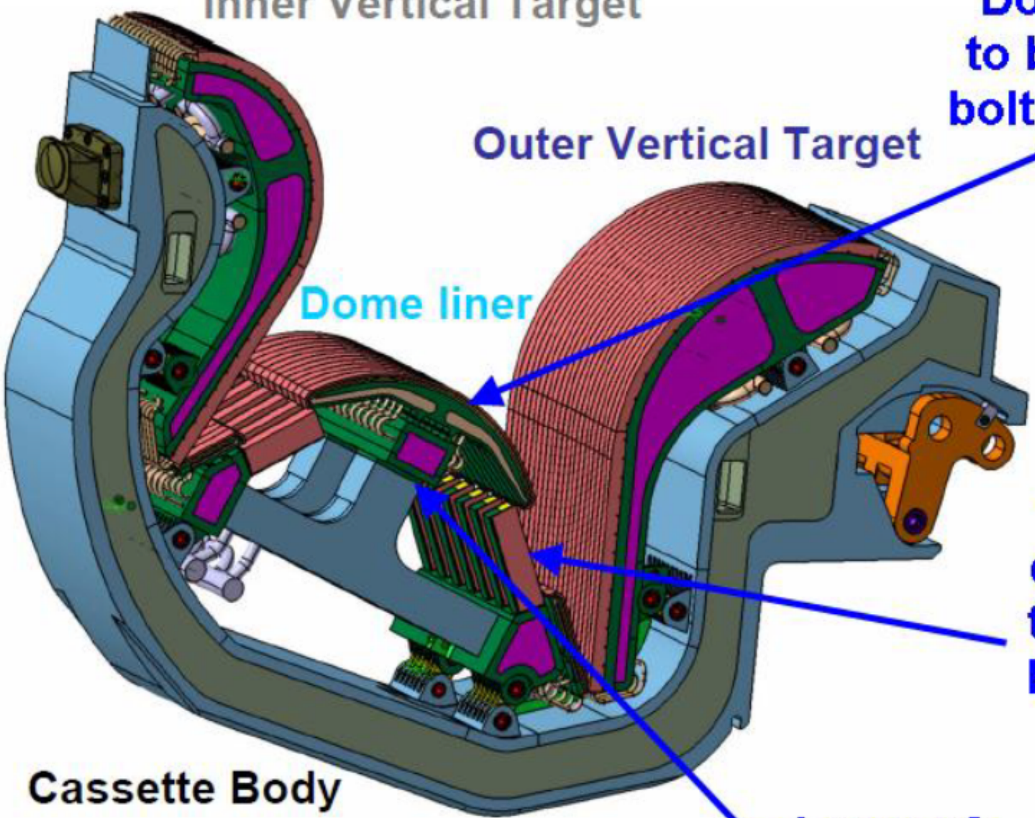
CHI Start-up to ~0.4MA is Projected for NSTX-U, and Projects to ~20% Start-up Current in Next-step STs



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

Example of CHI Insulator Installation in a Reactor
(In ITER, the Dome Region would be 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 (<30 ms in duration)
- The actual high-voltage phase < plasma start-up phase
- During the plasma start-up phase, there is no pre-existing plasma that can short out the insulator (and CHI current path is controlled by pre-programmed vacuum field line pattern)
- After the high-voltage phase, insulator could be shorted-out, if necessary

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

- Layers of thin resistive metal coated with insulating layers
- Powdered, weakly bonded, insulator sandwiched between two metal plates
- The HIT-Si device used an insulator spray to achieve insulation *in a plasma environment* in an more complicated vessel geometry
- …. Other possibilities (including conventional insulator technology currently planned for next step machines to insulate PF coils and other components)
- Insulator could be hidden behind metallic structure as on NSTX-U

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)
- TSC Simulations for NSTX-U geometry suggest Transient CHI start-up may be more efficient due to improved injector coil positioning
- Successful coupling of CHI started discharges to inductive ramp-up & transition to an H-mode in NSTX 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)
- 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