Status and Plans for Transient CHI and MGI Experiments on NSTX-U

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Outline of Poster

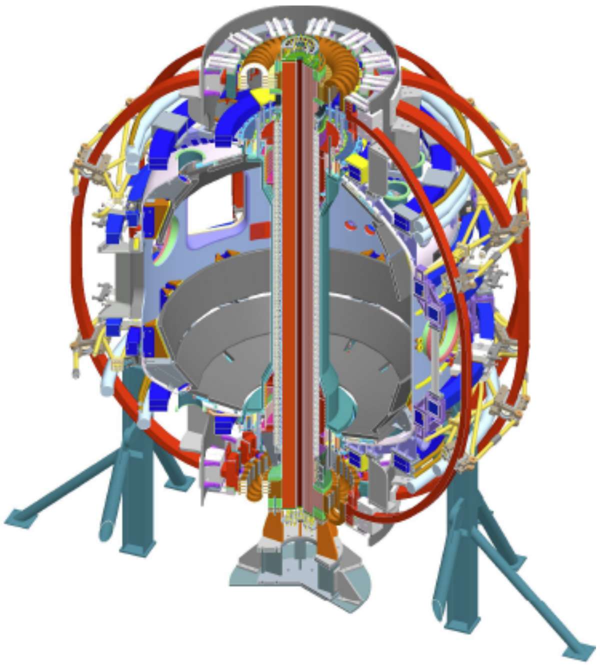
PART-I: Transient Coaxial Helicity Injection (CHI)

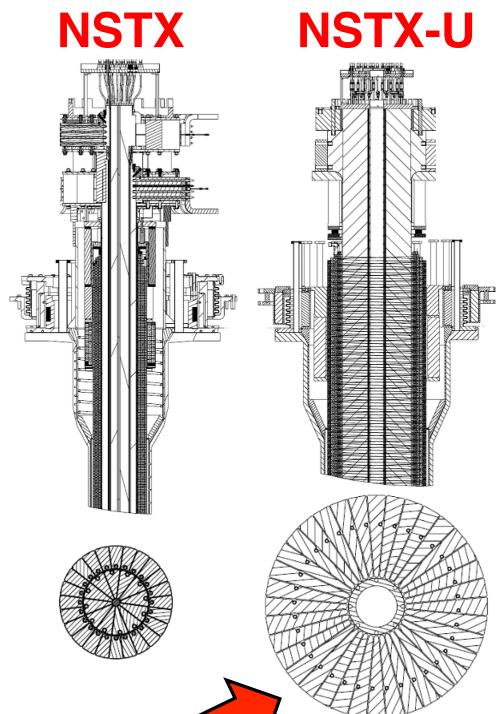
- Solenoid-free Plasma Start-up and Ramp-up Plans on NSTX-U
- Brief summary of Experimental results from NSTX
- How CHI works and why the current generation factor is much higher in NSTX-U?
- Why NSTX-U needs ECH heating for non-inductive current ramp-up?
- TSC simulations show that NSTX-U can generate 400 kA of start-up current using CHI
- NIMROD simulations also generation of closed flux current in NSTX-U

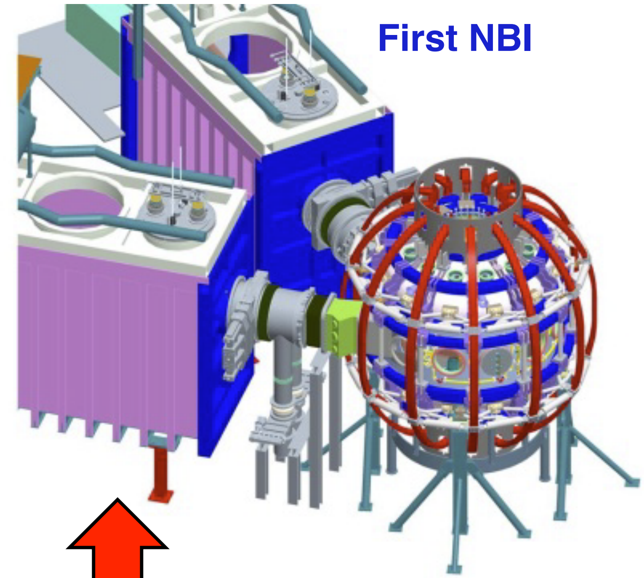
PART-II: Massive Gas Injection Experiments (MGI)

- Motivation for MGI research
- Primary goals of MGI research on NSTX-U & gas injection locations
- NSTX-U MGI valve similar in concept to proposed ITER MGI valves
- Experimental results from valve design for NSTX-U, fabrication, and testing

NSTX-U Research will Advance the ST as a Candidate for a Fusion Nuclear Science Facility (FNSF)







Second tangential Neutral Beam in NSTX-U enables development of

- Non-inductive current ramp-up and 100% NI sustained operation

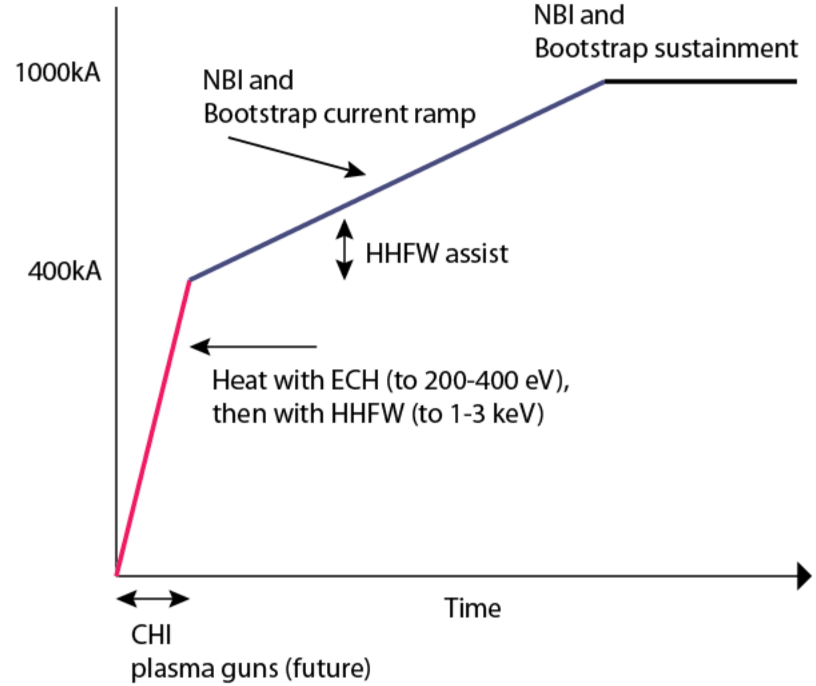
New large center stack in NSTX-U enables

- B_T: Increases from 0.55 to 1 T
- Plasma current: 1 to 2 MA
- Discharge pulse duration: 1s to 5 s

NSTX-U Aims to Develop and understand non-inductive start-up/ramp-up to project to ST-FNSF operation

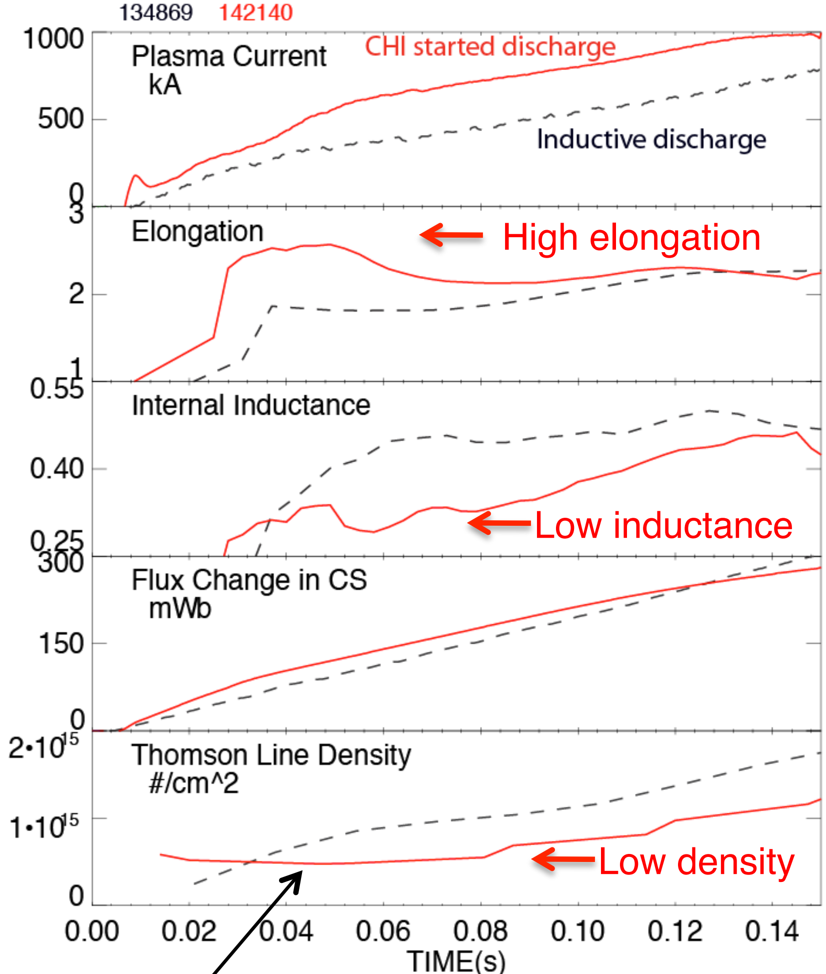
- Establish physics basis for ST-FNSF, and non-inductive start-up is essential in ST
  - Simplify the tokamak concept to reduce cost
- NSTX-U is striving for fully non-inductive operations
  - Transient Coaxial Helicity Injection (CHI) start-up is the front end of that objective
  - Plasma guns and EWB will be tested after those systems are technically ready

NSTX-U Start-up and Ramp-up strategy



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 so that ECH could be used to heat these plasmas

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)

Externally Produced Toroidal Field makes CHI much more Efficient

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

  ψ_{inj} = injector flux

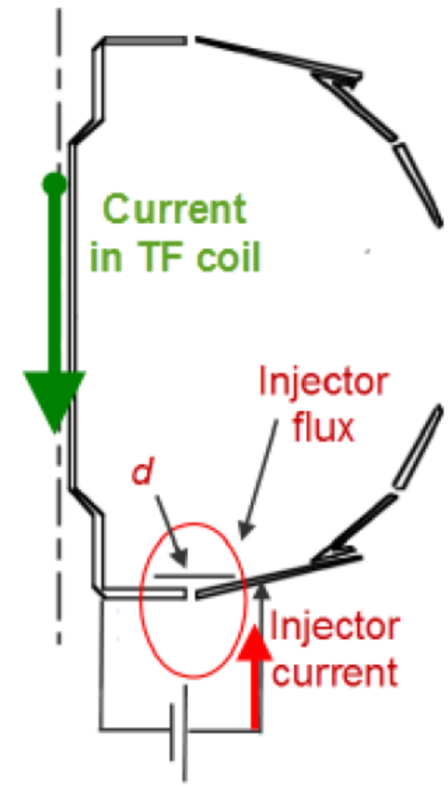
  d = flux foot print width

  I_{TF} = current in TF coil

Injector current **Toroidal flux**

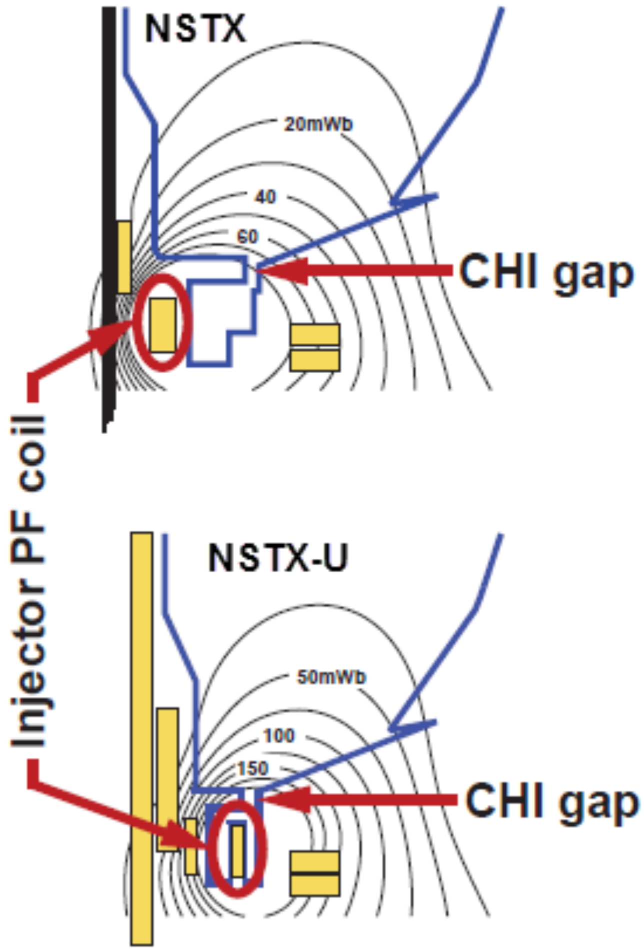
$$I_P = I_{inj}(\psi_T / \psi_{inj})$$

- 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)

CHI start-up to ~0.4MA is projected for NSTX-U, and projects to ~20% start-up current in next-step STs



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

Parameters	NSTX	NSTX-U	ST-FNSF	ST Pilot Plant
Major radius [m]	0.86	0.93	1.2	2.2
Minor radius [m]	0.66	0.62	0.80	1.29
B_T [T]	0.55	1.0	2.2	2.4
Toroidal flux [Wb]	2.5	3.9	15.8	45.7
Sustained I_p [MA]	1	2	10	18
Injector flux (Wb)	0.047	0.1	0.66	2.18
Projected Start-up current (MA)	0.2	0.4	2.0	3.6

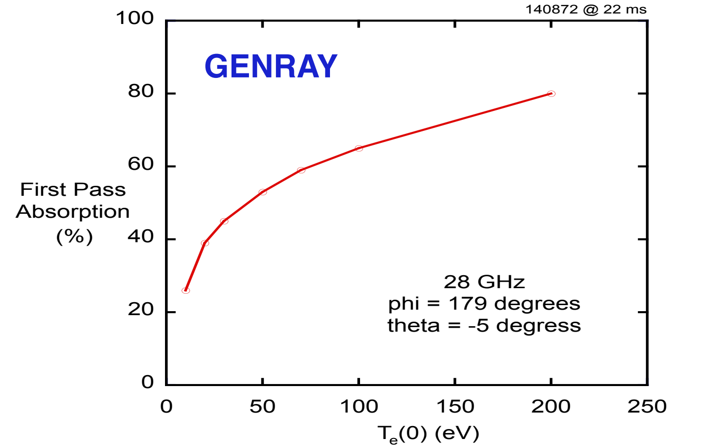
Transient CHI Scaling:

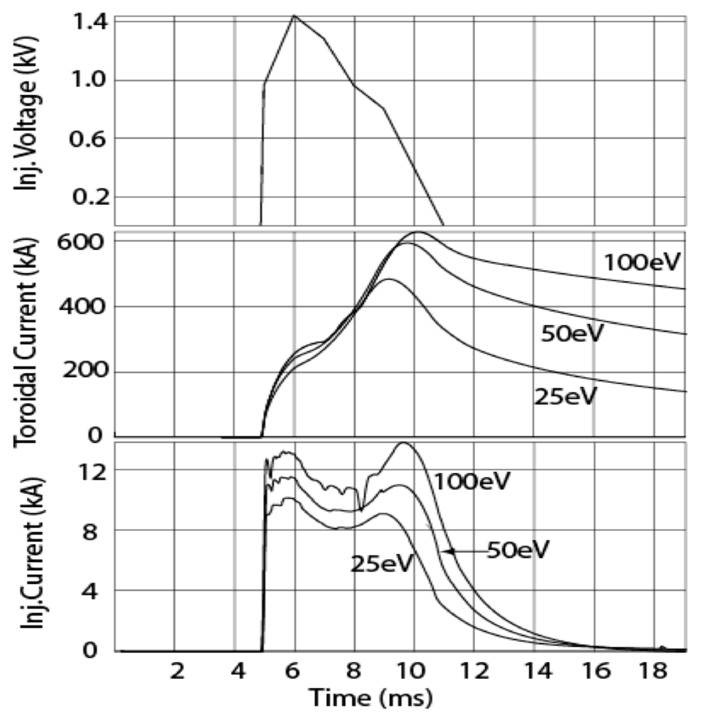
Generated Toroidal Current is proportional to Injector Flux

Ramp-up strategy significantly benefits from 1-2 MW ECH to heat CHI plasma

•GENRAY

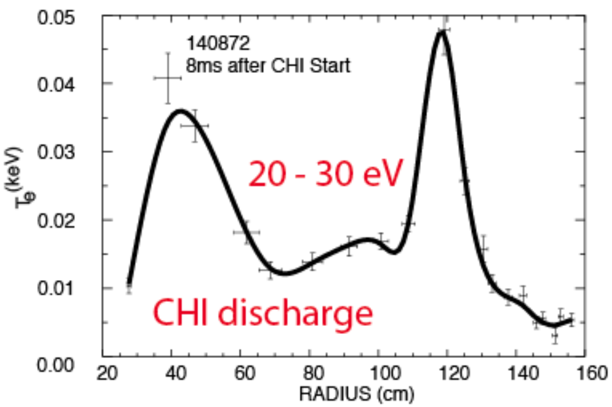
- In a 500kA decaying inductive discharge, TSC* simulations indicate 0.6MW of absorbed ECH power could increase T_e to ~400eV in 20ms (with 50% ITER L-mode scaling)
  - ECH absorption and deposition profile being modeled using GENRAY
  - CHI discharge densities at T_e = 70 eV would allow 60% first-pass absorption by 28 GHz ECH in NSTX-U
- Increased T_e predicted to significantly reduce I_p decay rate
  - ECH heated plasma can be further heated with HHFW
  - Maximum HHFW power < 4MW, higher B_T in NSTX-U would improve coupling
  - HHFW has demonstrated heating a 300 kA / 300 eV plasma to > 1 keV in 40ms



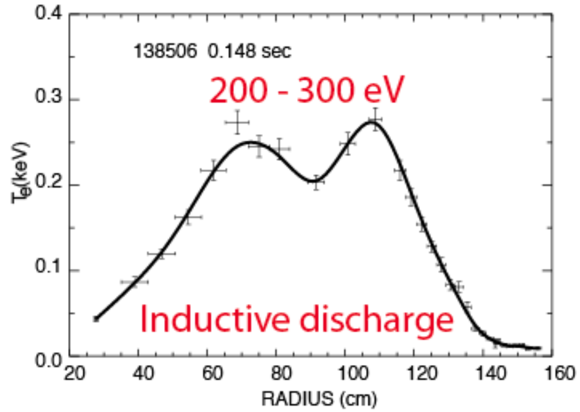


*S.C. Jardin., et al., J. Comput. Phys. 66, 481 (1986)

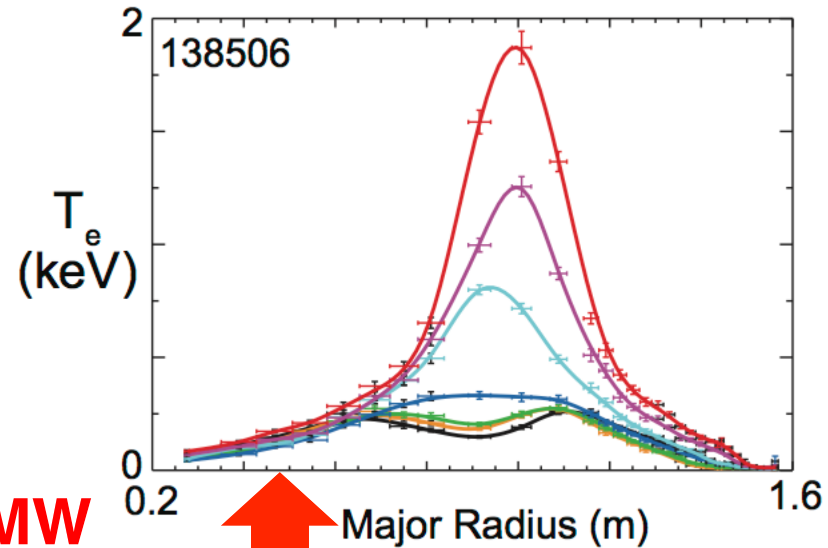
Bridge Electron Temperature Gap Between CHI Start-up and Current Ramp-up Requirements with ECH Heating

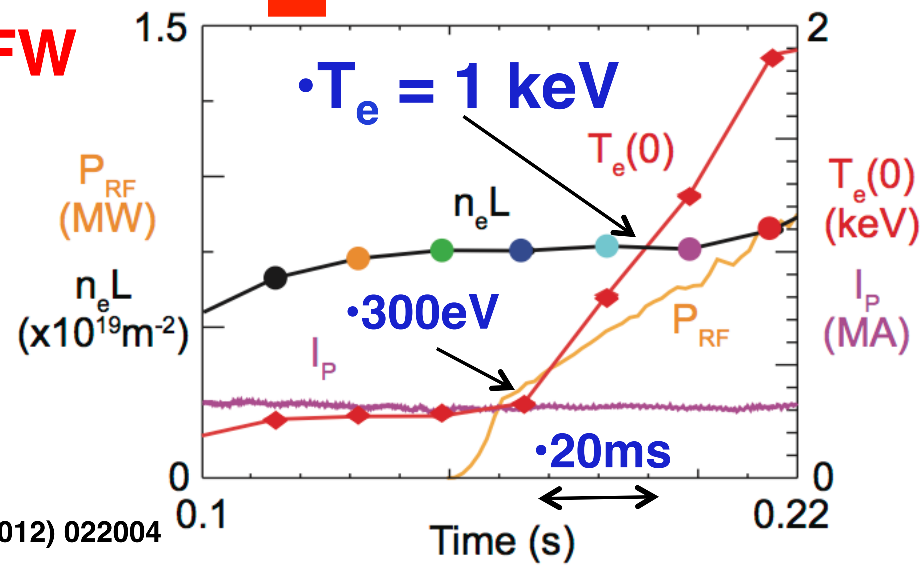


1MW ECH



1-2 MW HHFW





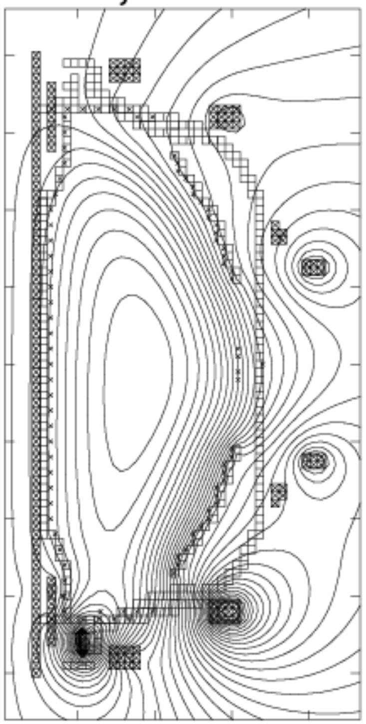
G. Taylor, et al.,
Phys. Plasmas 19 (2012) 022004

TSC simulations are being used to develop initial start-Up scenarios for NSTX-U

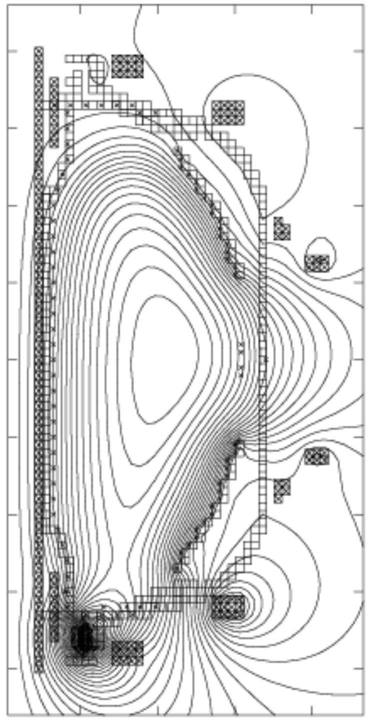
- Time-dependent, free-boundary, predictive equilibrium and transport
- Solves MHD/Maxwell’s equations coupled to transport and Ohm’s law
- Requires as input:
  - Device hardware geometry
  - Coil electrical characteristics
  - Assumptions concerning discharge characteristics
- Models evolutions of free-boundary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

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

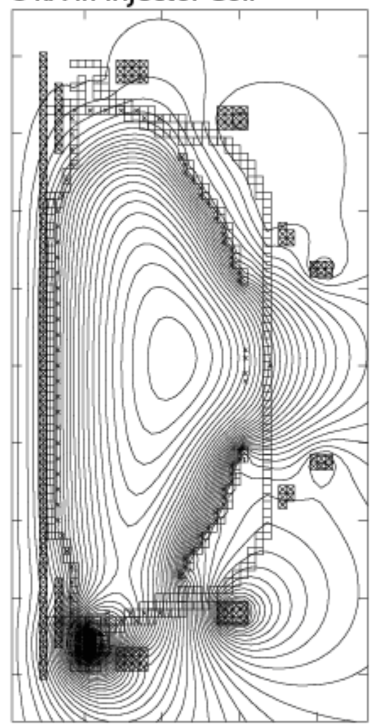
Poloidal Flux at 15 ms
2 kA in Injector Coil



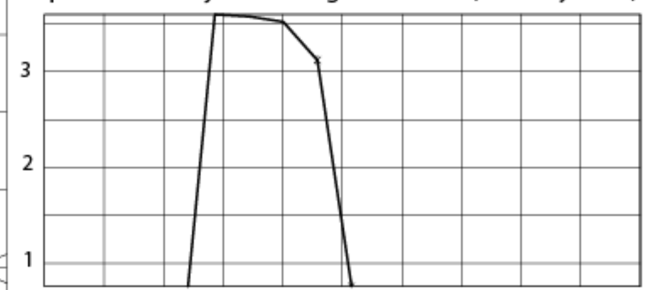
4 kA in injector Coil



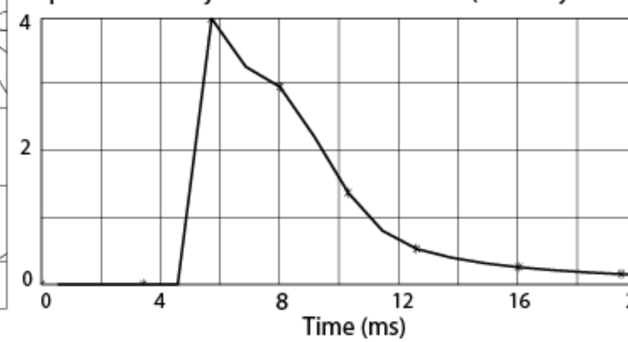
8 kA in Injector Coil



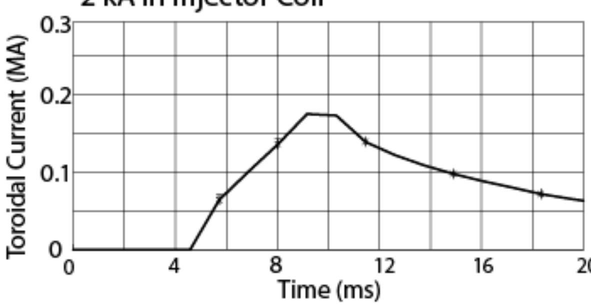
Representative Injector Volatge Waveform (Arbitrary Units)



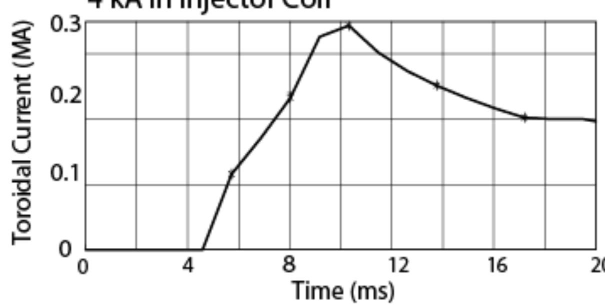
Representative Injector Current Waveform (Arbitrary Units)



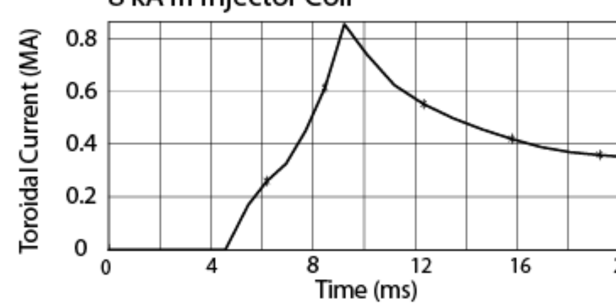
2 kA in Injector Coil



4 kA in injector Coil

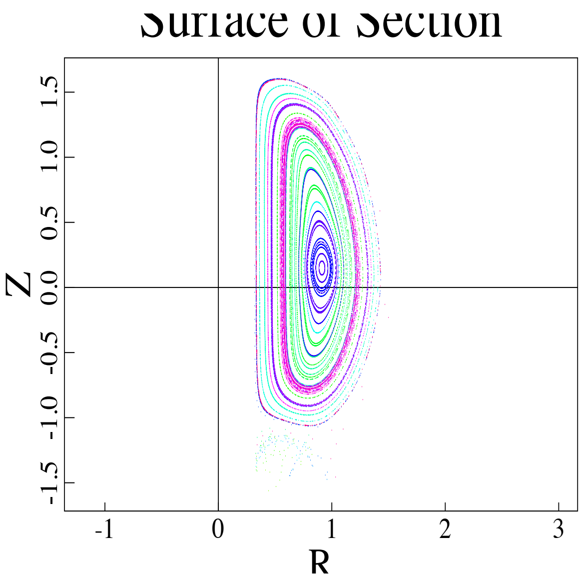


8 kA in Injector Coil

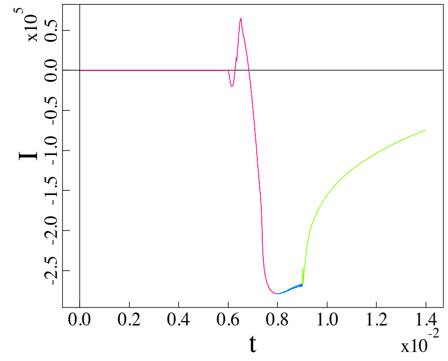


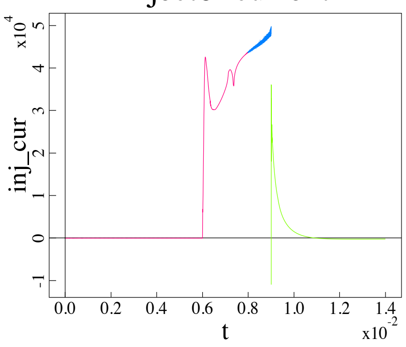
Raman, et al., IEEE Transactions on Plasma Science, Vol 42, No. 8 2154 (2014)

Full flux closure is obtained in MHD simulations of NSTX-U



- Resistive MHD NIMROD simulations are performed in NSTX-U geometry at Te ~ 15eV.
- Some features of reconnection process is similar to NSTX, i. e. closed flux surfaces expand in the NSTX global domain through a local Sweet-Parker type reconnection with an elongated current sheet in the injector region [F. Ebrahimi et al. PoP 2013, 2014]
- The fraction of closed flux current in NSTX-U is much higher (almost 100%) than what obtained in the simulations of NSTX.





CHI Summary: NSTX-U Aims to Develop Full Non-inductive Start-up and Current Ramp-up in support of FNSF and next step Tokamaks

- 0.2MA closed flux 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 & transitioning to an H-mode demonstrates compatibility with high-performance plasma operation
- TSC simulations show that closed flux surfaces begin to form soon after a positive toroidal loop voltage is generated. Physically, this loop voltage is generated due to the decaying poloidal flux on open field lines, and is analogous to the large loop voltage that is predicted to form in ITER immediately following a thermal quench, as the poloidal flux in ITER decays.
- In NIMROD simulations closed flux formation during transient CHI is consistent with 2-D Sweet-Parker type reconnection, and 3-D modes do not seem to be important (F. Ebrahimi, PoP 2014)
- 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)

Massive Gas Injection Studies on NSTX-U

Massive Gas Injection (MGI) is the most developed disruption mitigation system to-date and will be implemented on ITER to protect internal ITER components during unplanned tokamak disruptions. However, much research is still required from existing facilities to better understand massive gas injection requirements for ITER, and gas penetration past the ITER SOL and pedestal regions. NSTX-U research will offer new insight by studying gas assimilation efficiencies for MGI injection from different poloidal locations using identical gas injection systems. In support of this activity, we have built and tested an inductive electromagnetic valve for implementation on NSTX-U. The valve is similar in design to the MGI valve that is being considered for ITER, and our design for NSTX-U is motivated by the work of Lehnen[1]. The valve has similarities in design to several valves we built for a Compact Toroid (CT) injector[2] but draws on some of the design features used in the TEXTOR valve[3,4]. The valve operates by repelling a conductive piston due to eddy currents induced on it by a rapidly changing magnetic field created by a pancake disk solenoid positioned beneath the piston. Two gas plenums are used to adjust the pressure across the piston so as to make valve operation nearly independent of the gas pressure in the primary plenum that evacuates into the tokamak upon piston activation. The first-generation valve used a 1.08 cm orifice, and additional seals to isolate the pancake solenoid from the gas plenums. The second-generation valve (to be implemented on NSTX-U) increased the orifice diameter to 2.3 cm and considerably improved the solenoid seals by fabricating the entire solenoid chamber from a single block of metal. Both these changes dramatically improved the efficiency to an extent that the required operating voltage was significantly reduced while the gas flow rate substantially improved. A fast baratron (MKS 617A), with a rated time response of about 1ms, was used to monitor the pressure in a 1.3m^3 vessel. The design of both valves, and experimental results from MGI valve calibrations for NSTX-U that will inject 200-1000 Torr.L of gas, including valve operation in an externally imposed magnetic field, will be described.

[1] M. Lehnen, "Massive Gas Injection – Valve Developments and Application Toward ITER, US Disruption Mitigation Workshop, General Atomics, San Diego, March 12-13, 2103

[2] J.C. Thomas, D.Q. Hwang, R.D. Horton, J.H. Rogers, and R. Raman, Review of Scientific Instruments **64** 1410 (1983)

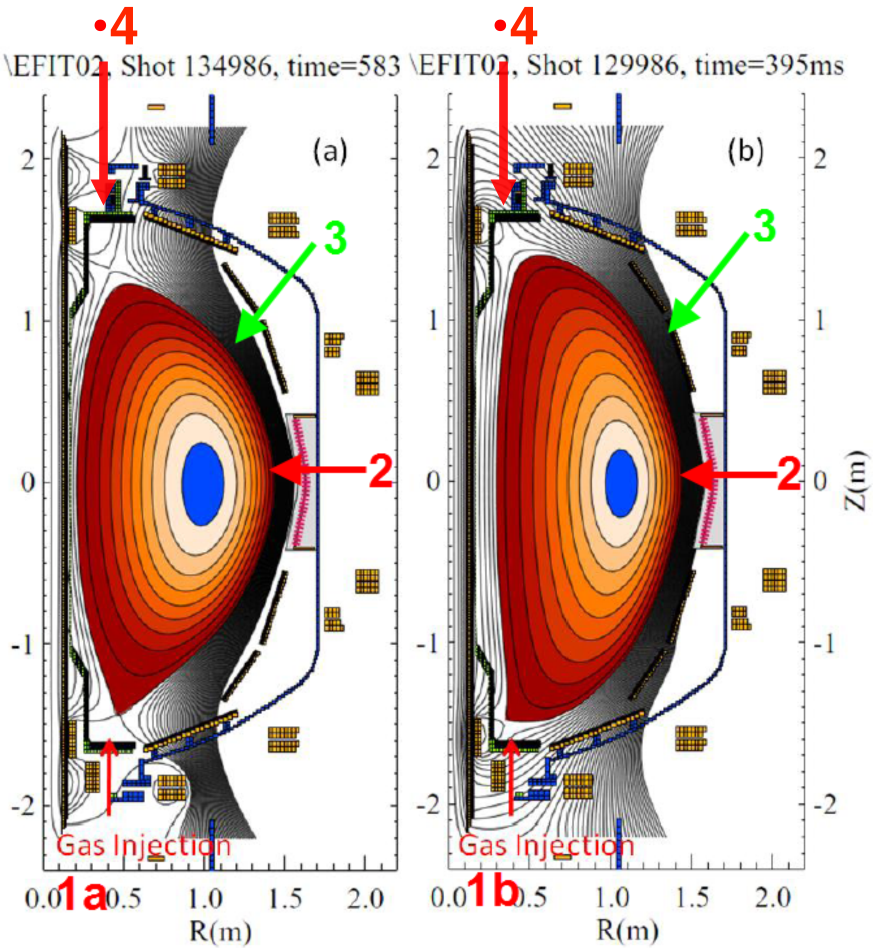
[3] S.A. Bozhenkov, K-H. Finken, M. Lehnen, and R.C. Wolf, Review of Scientific Instruments **78** 033503 (2007)

[4] K.H. Finken, M. Lehnen and S.A. Bozhenkov, Nuclear Fusion **48** 115001 (2008)

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.

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



Low triangularity High triangularity

- MGI Research Plans for FY15
  - Operate valves at ~5000 Torr (200 Torr.L Neon)
  - Compare mid-plane and PFR locations for gas assimilations studies using identical gas injection set-up
  - Possible Poloidal injection effect on VDE (multi-machine experiment with DIII-D & C-MOD)
  - 3 valves to be installed for FY15 Experiments

1a: Private flux region 1b: lower SOL

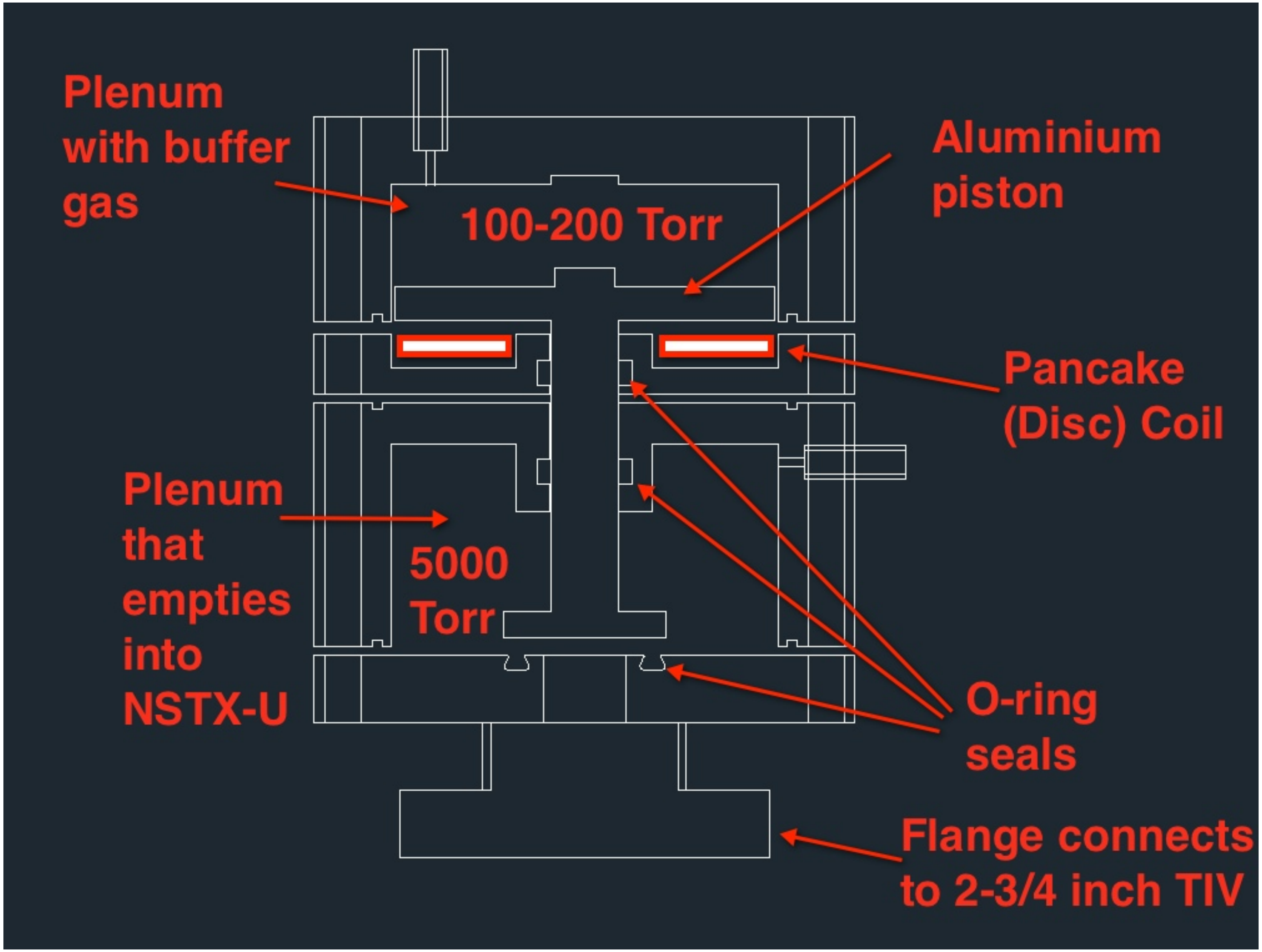
2: Conventional mid-plane injection

3: Variation in poloidal location

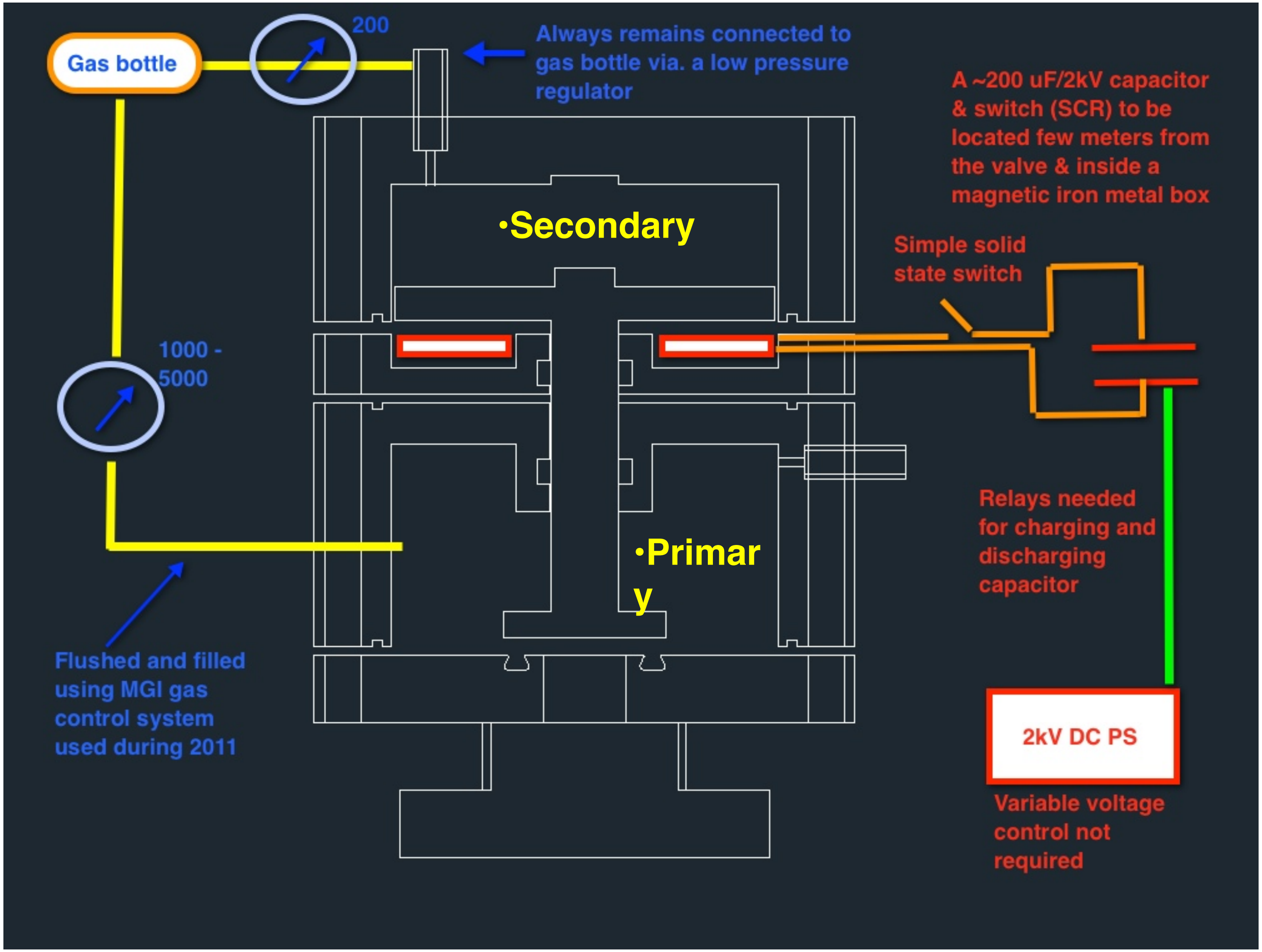
4: Injection from the upper divertor region

Plasma shape will be varied to access locations 1a and 1b

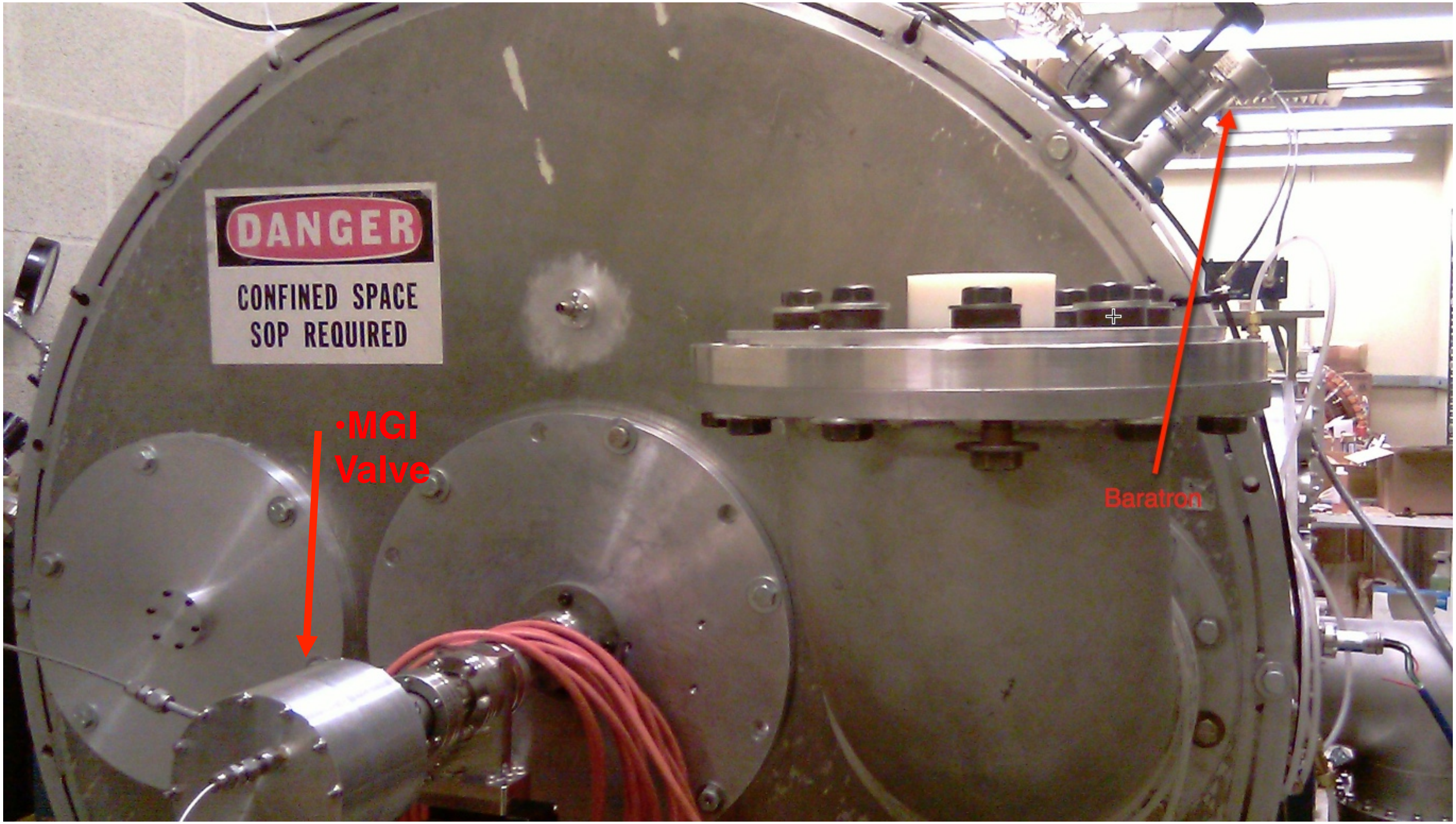
Primary Components of NSTX-U MGI Valve



Valve Operating Sequence: 1) Secondary Plenum and 2) Primary Plenum filled, 3) Energized capacitor discharged



MGI valve evacuated into 1.3 m^3 test chamber and vessel pressure increase monitored using fast baratron

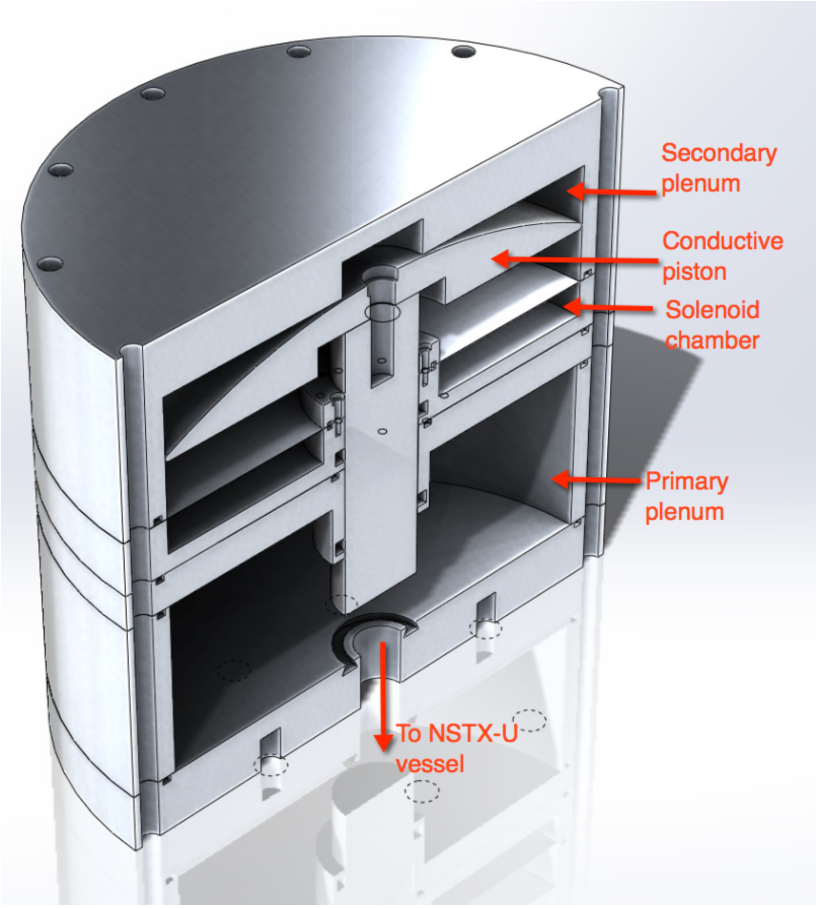


Four Versions of MGI Valves Built and Tested

1. V1: Solenoid cavity composed of several components, orifice size: 1.08 cm
2. V2: Solenoid cavity fabricated out of a single block of SS304L (to be replaced with Inconel 625)
3. V3: Orifice size increased of 2.3 cm
4. V4: Valve uses U-Cup Lip Seals (instead of O-ring seals) for the sliding piston.
   - Parker Lip seals composed of high-performance Nitroxile compound (highest grade self-lubricated, wear resistant, low friction, sealing material rated for use at up to 120C)
   - Dupont Krytox LVP high-performance O-ring lubricant rated for 300C use, not necessary for this seal, but used in these initial tests (Vapor pressure 1×10^{-5} Torr at 200C & 1×10^{-13} Torr at 20C)

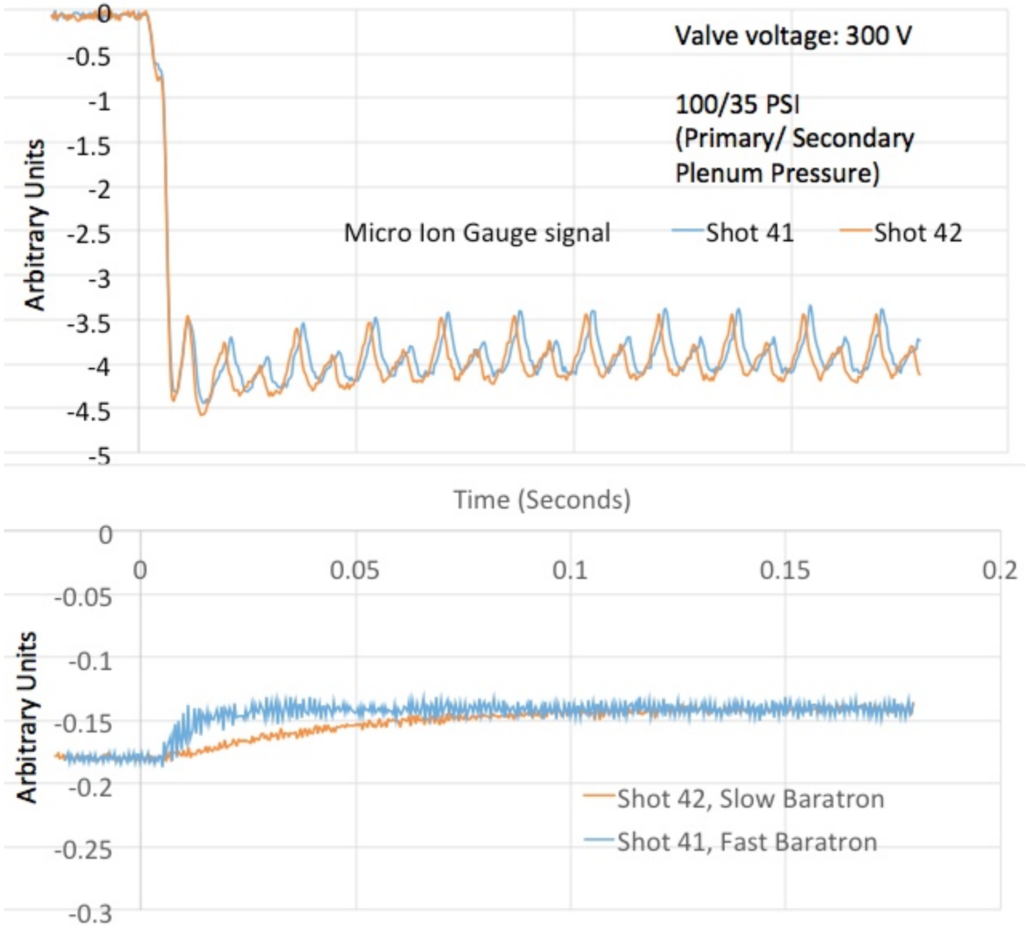
•Parker U-Cup Lip Seal

Version 1 Valve used 1.08 cm diameter orifice and O-ring Seals for sliding piston

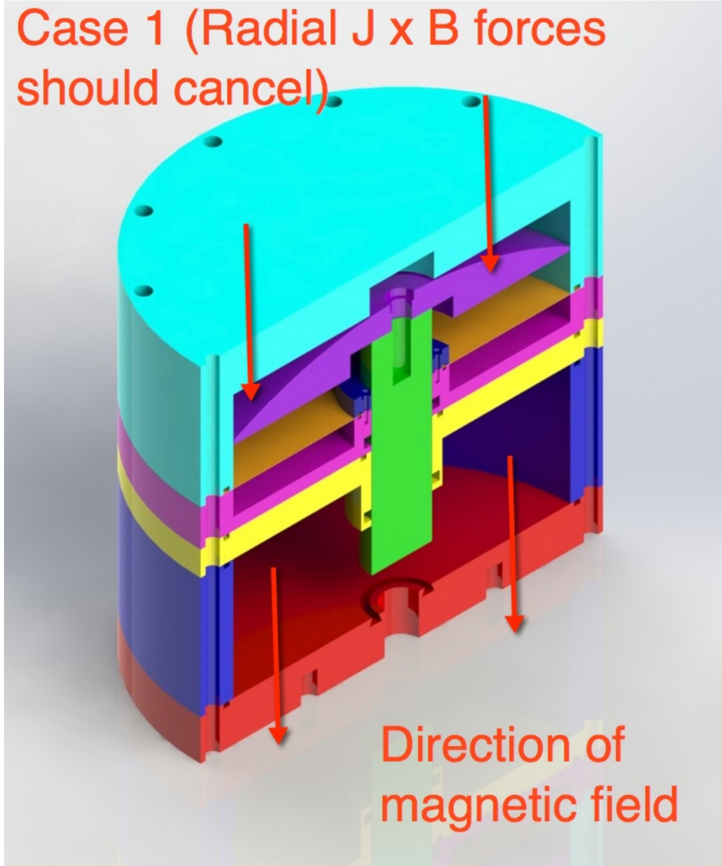


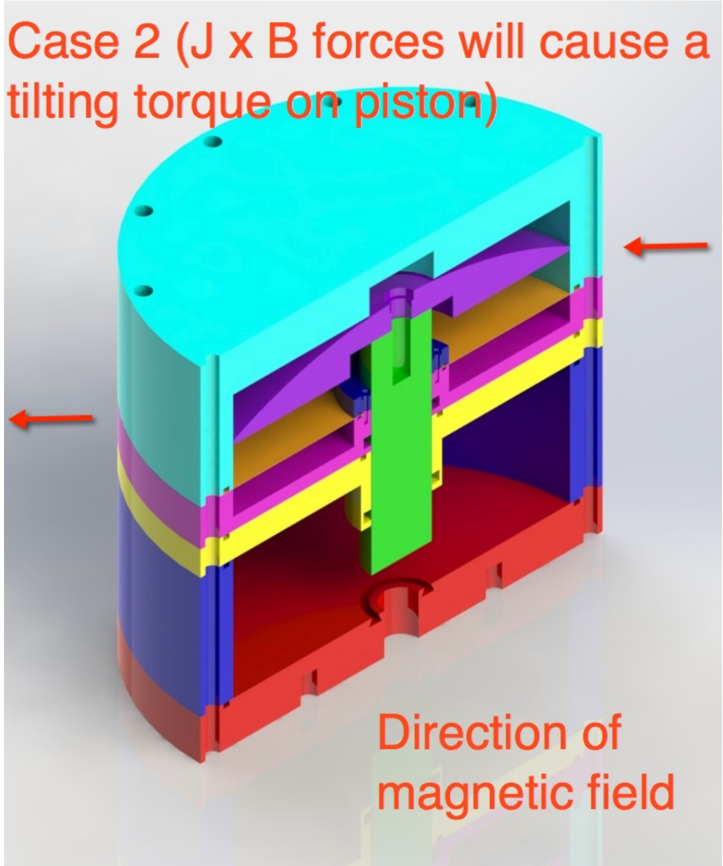
Solenoid chamber composed of several components

- Comparison of pressure signals using:
- 1) Fast Micro Ion Gauge 2) Slow Baratron and 3) Fast Baratron

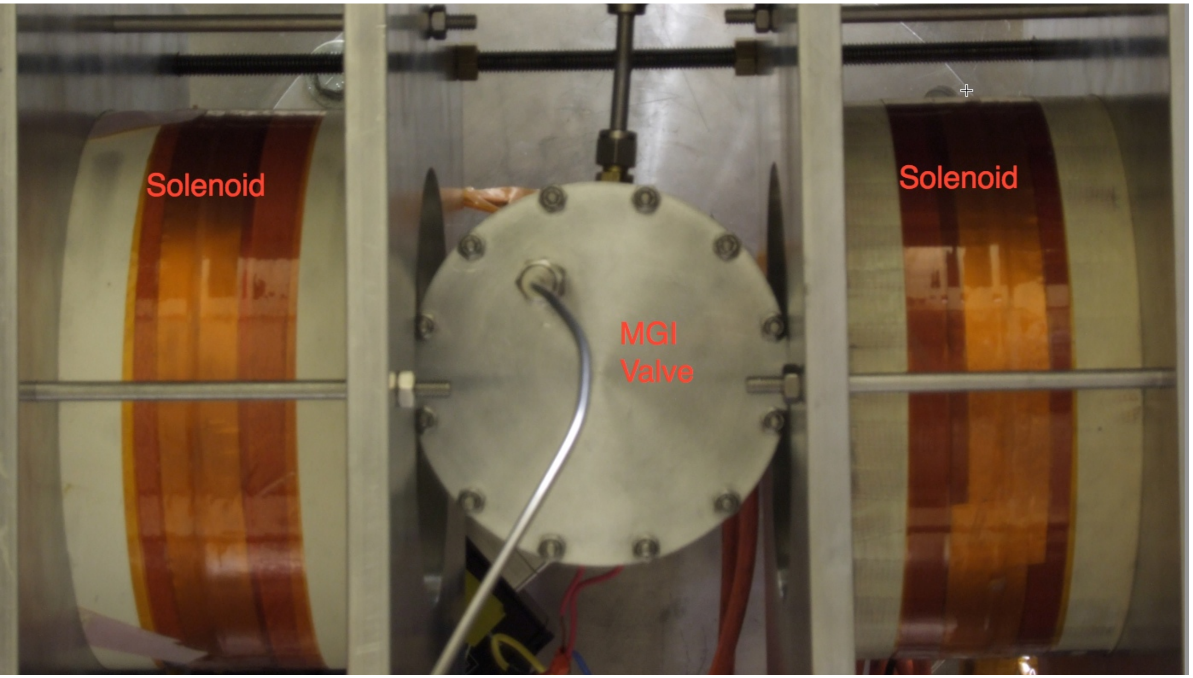


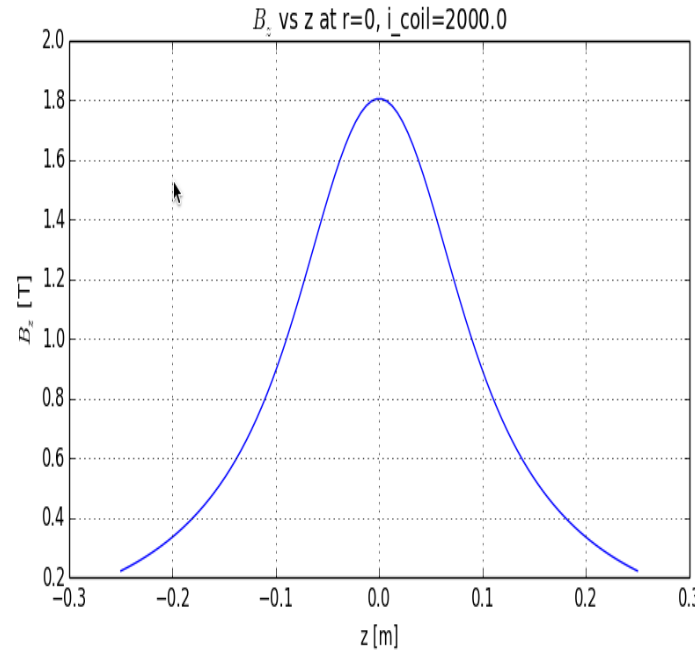
Forces experienced by Valve in a Tokamak environment





MGI Valve Operated in Magnetic Fields <0.4T

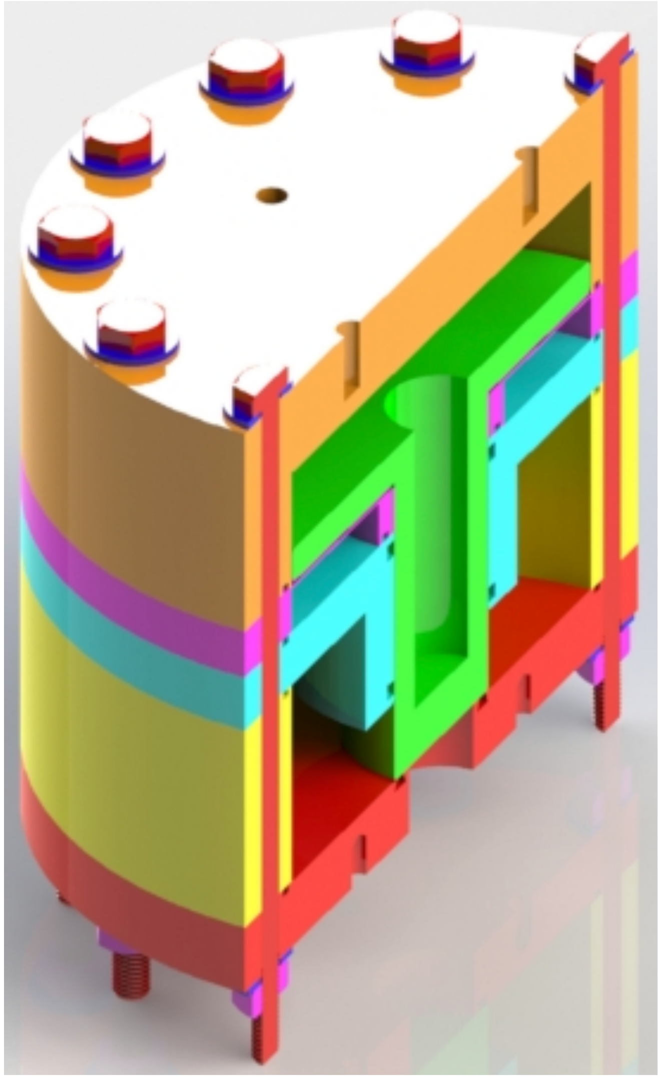


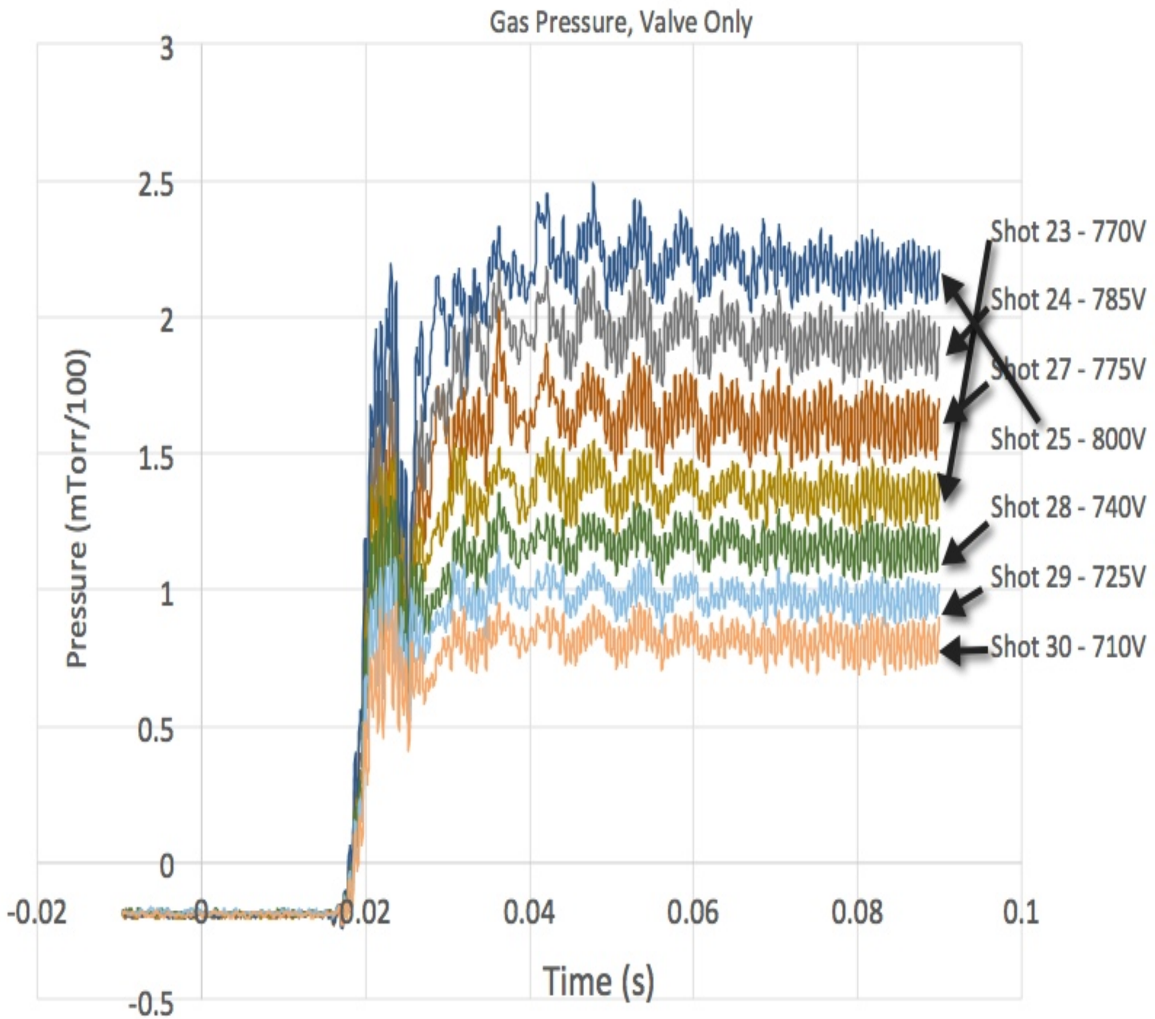


- Solenoid driven using a 10 mF, 1kV Capacitor bank
- Field between the two coils is 1.8T at 2kA coil current

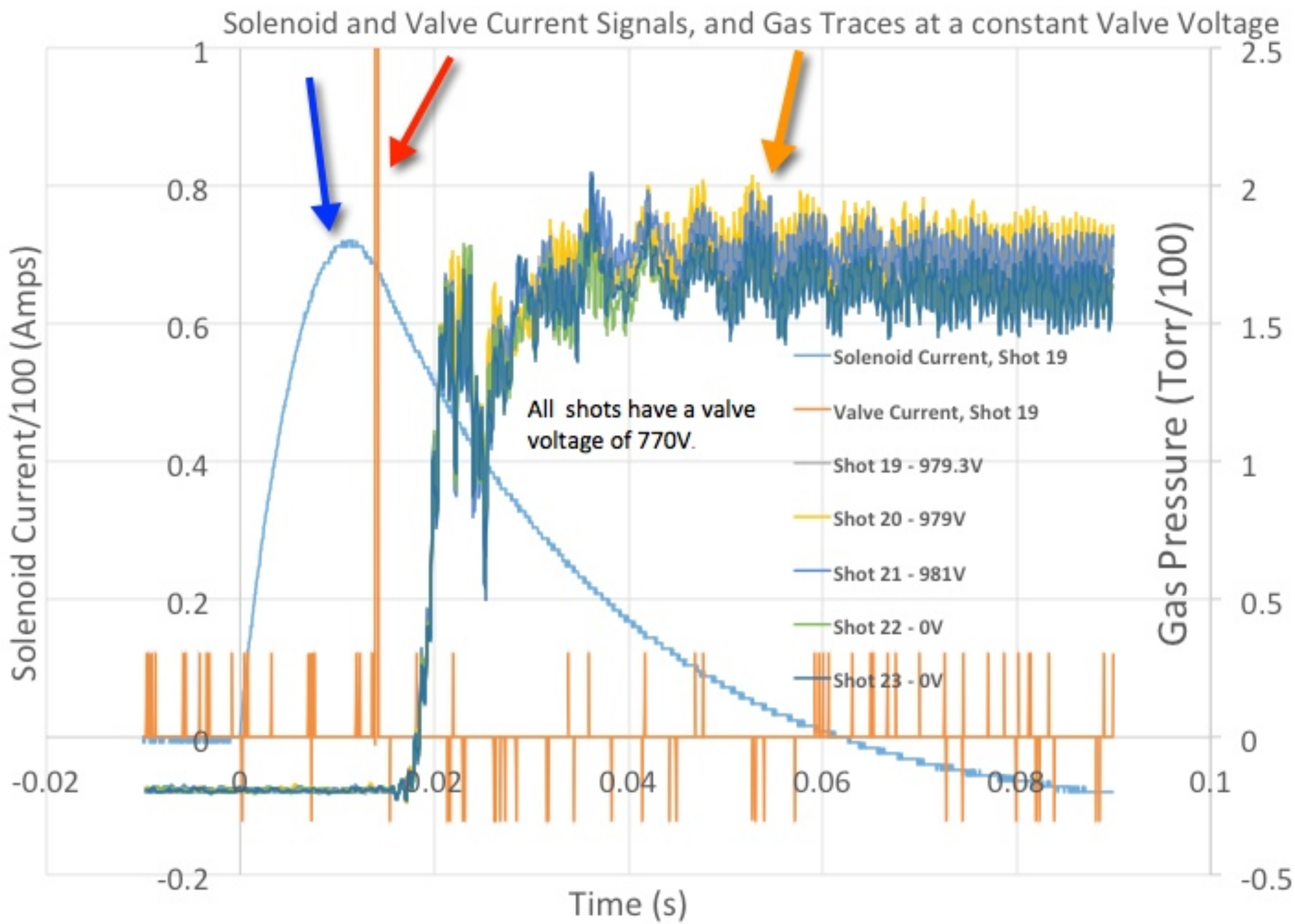
Version 4 Valve evacuates into chamber in < 3ms, for gas injection amounts of 200 Torr.L N_2

- NSTX-U MGI Valve





Valve has same time response for operation in <0.4T magnetic fields



- Shots 19,20, 21 are with solenoid energized
- Shots 22 and 23 are comparison shots without solenoid

- Vacuum solenoid field is 0.67T
- Skin depth in Al is 2.2cm, valve wall thickness is 1cm. Fields inside valve side wall ~0.4T
- Future tests will use SS304L valve and further slow down solenoid current waveform

MGI Summary: MGI Valve of the Type to Used on ITER will be used for NSTX-U MGI Experiments

- Electromagnetic valve built and tested for NSTX-U installation
- - Uses new Lip Seals instead of conventional O-ring seals
- Valve performance at 7000 Torr adequate to support FY2015 Experiments on NSTX-U
- - >200 Torr.L N_2 injected
- - Gas pulse rise times of <3 ms, ~2 m away from injection location
- Valve operating pressure can be increased to >10,000 Torr to achieve similar or better gas pulse rise times for >200 Torr.L gas injection for FY16 and beyond experiments
- - Off line test will continue valve development work
- Valve also tested at moderate magnetic fields typical of those to be experienced during FY15 NSTX-U operations, with no significant observable effects on gas pulse response time
- - Higher field tests to continue as part of valve development work
- 3 valves to be installed on NSTX-U for FY15 Operations