NSTX-U Contributions to Disruption Mitigation Studies in Support of ITER

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Outstanding Issues for ITER and FNSF

- MGI / SPI* / Shell Pellet** impurity penetration & system response time
  - Much larger size, and much more energetic edge plasma in ITER, will make impurity penetration much more difficult
    - Fraction of injected MGI gas that will penetrate sufficiently deep in ITER?
    - Size and velocity of SPI fragments required for deep penetration in ITER?
    - Size, composition, and fragmentation requirements for Shell Pellet to obtain sufficiently wide impurity dispersal?
- Radiation asymmetries and MHD response of the plasma
  - Good continuing progress in this area
- RE Mitigation, CQ/VDE physics
  - Good progress, need to understand JET MGI results

***   Cryogenic Shatter Pellet containing high-z noble gas***
***** Shell Pellet capsule containing solid low-z impurity particles***

Some Disruptions in ITER may have Warning Times <10ms

The ITER DM System must be designed to handle this possibility

- For warning times < 10 ms, conventional MGI/SPI may not be a viable option
  - For MGI/SPI located 6-7m away, system response time would be 20-30ms (so we know this alone is inadequate for all disruptions)

- Rupture disk system installed close to vessel wall may work if it could be made reliable (being studied)

- Particulate matter injection using new methods may be a likely means to achieve the required fast response time by the DMS
  - New methods being developed and considered, are:
    - Shell Pellet injection (DIII-D)
    - Plasma injection (possibly on DIII-D)
    - Others concepts

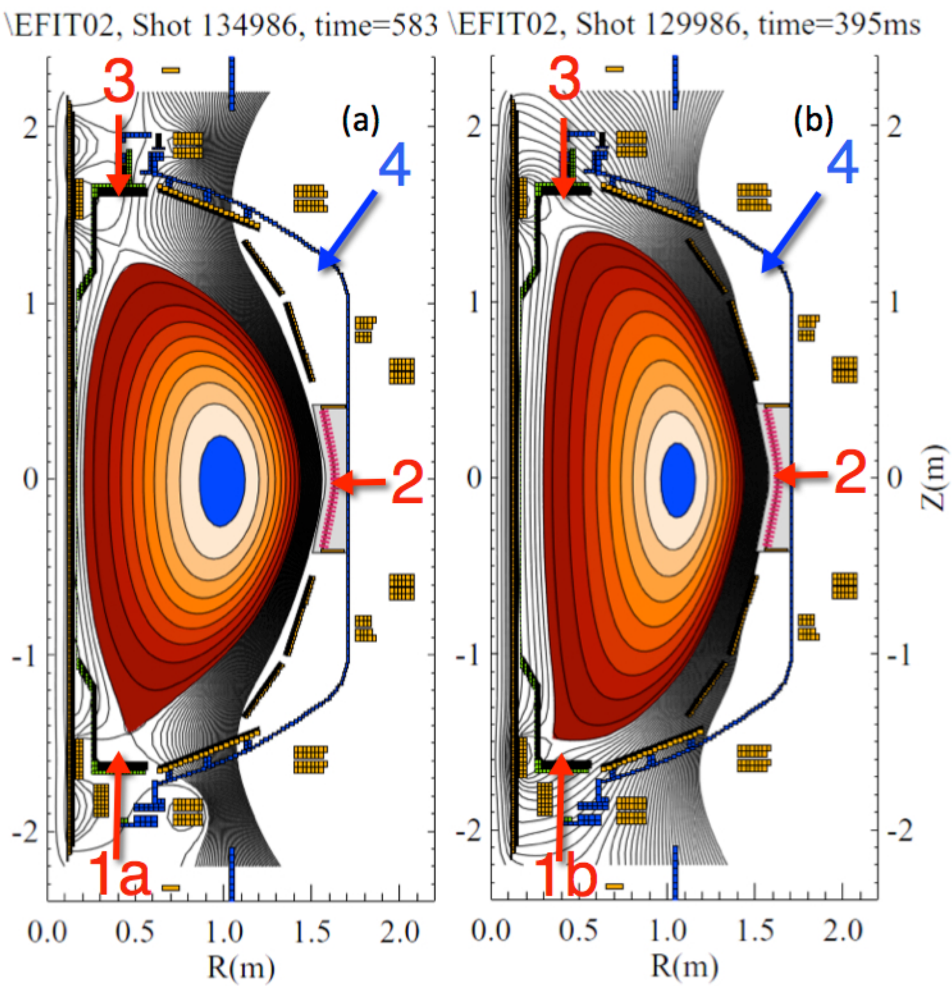
NSTX-U Plans for Disruption Mitigation Studies

1. Massive Gas Injection (MGI) studies in NSTX-U will initially study effect of poloidal injection location variation and model the gas penetration and assimilation results using 3D MHD code

2. Off-line MGI studies at Univ. of Washington will contribute to MGI valve development using ITER-type MGI valve

3. Electromagnetic Particle Injector (EPI) is being developed as a means for fast time-scale impurity injection into a tokamak plasma
    - Off-line development work in progress
    - Plan to test injector on NSTX-U and/or another tokamak

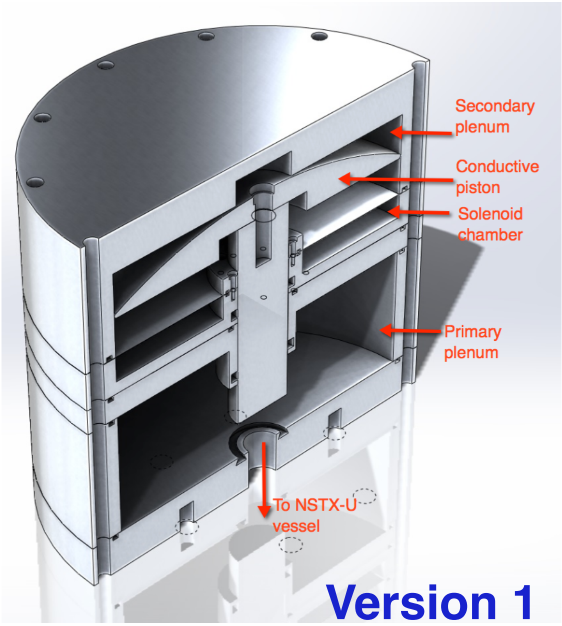
NSTX-U MGI will Study Poloidal Injection Location Variation using Identical MGI Valves and Gas Transit Piping

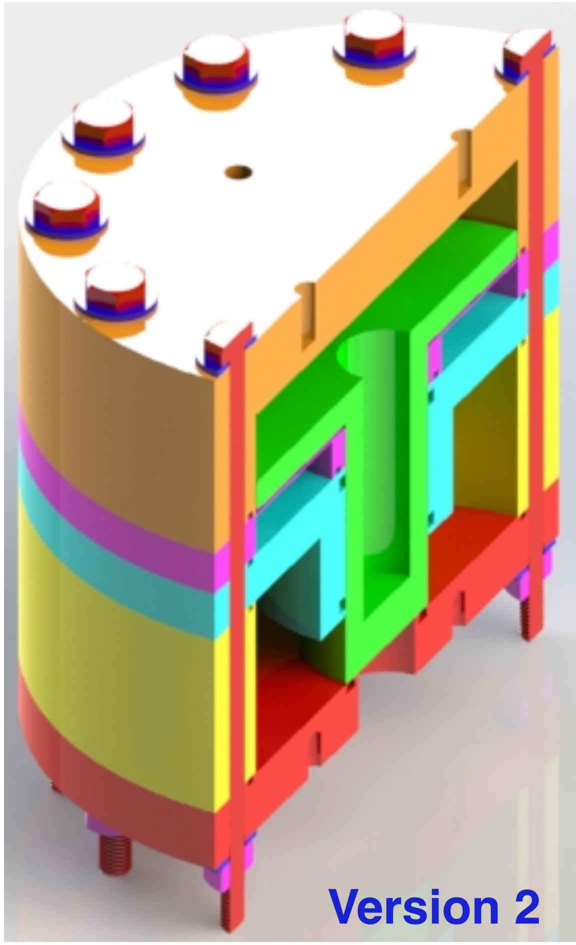


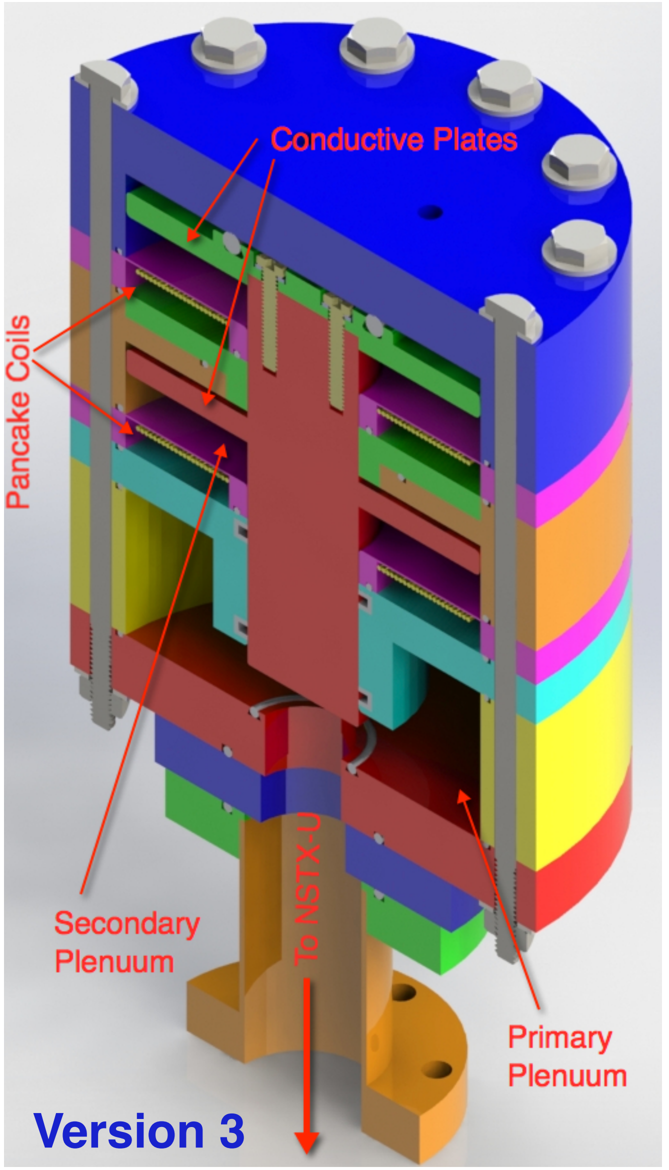
- Assess benefits of injection into the private flux region & the high-field side region vs. LFS mid-plane
- Quantify MGI gas assimilation fractions and extend model to larger machines

1a: Private flux region
1b: Lower SOL, Lower Divertor
2: Conventional mid-plane
3: Upper divertor
4: Future installation

Off-line MGI Studies will Contribute to MGI Valve Development







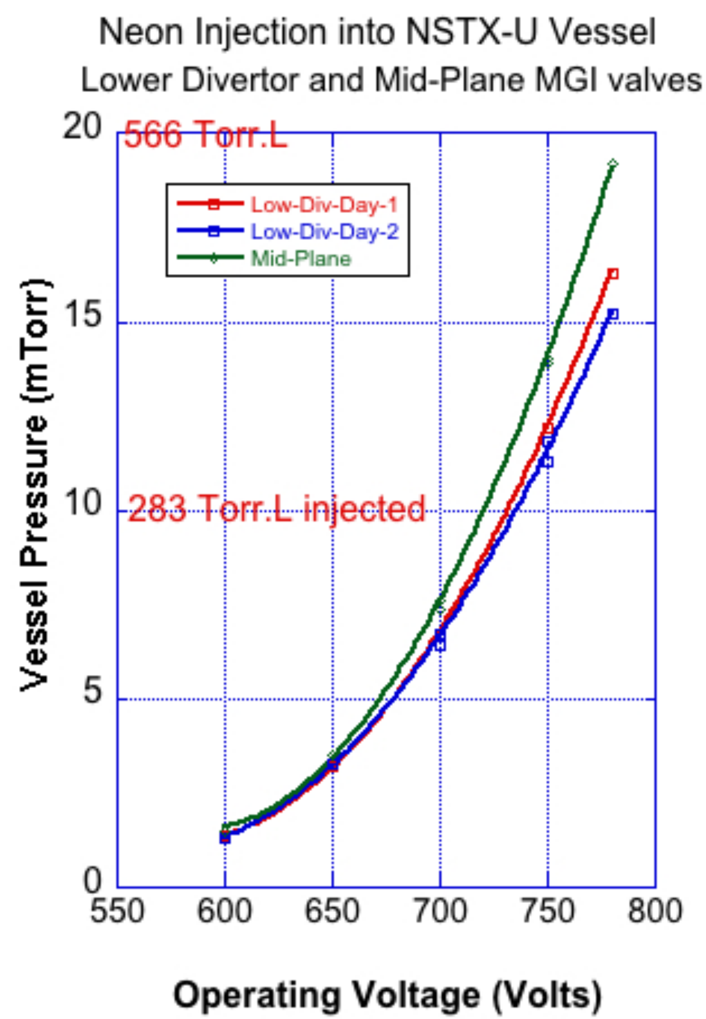
MGI valve design based on TEXTOR / JET MGI concept

New double solenoid MGI design – V3 (zero net J x B torque) based on ORNL ITER MGI concept

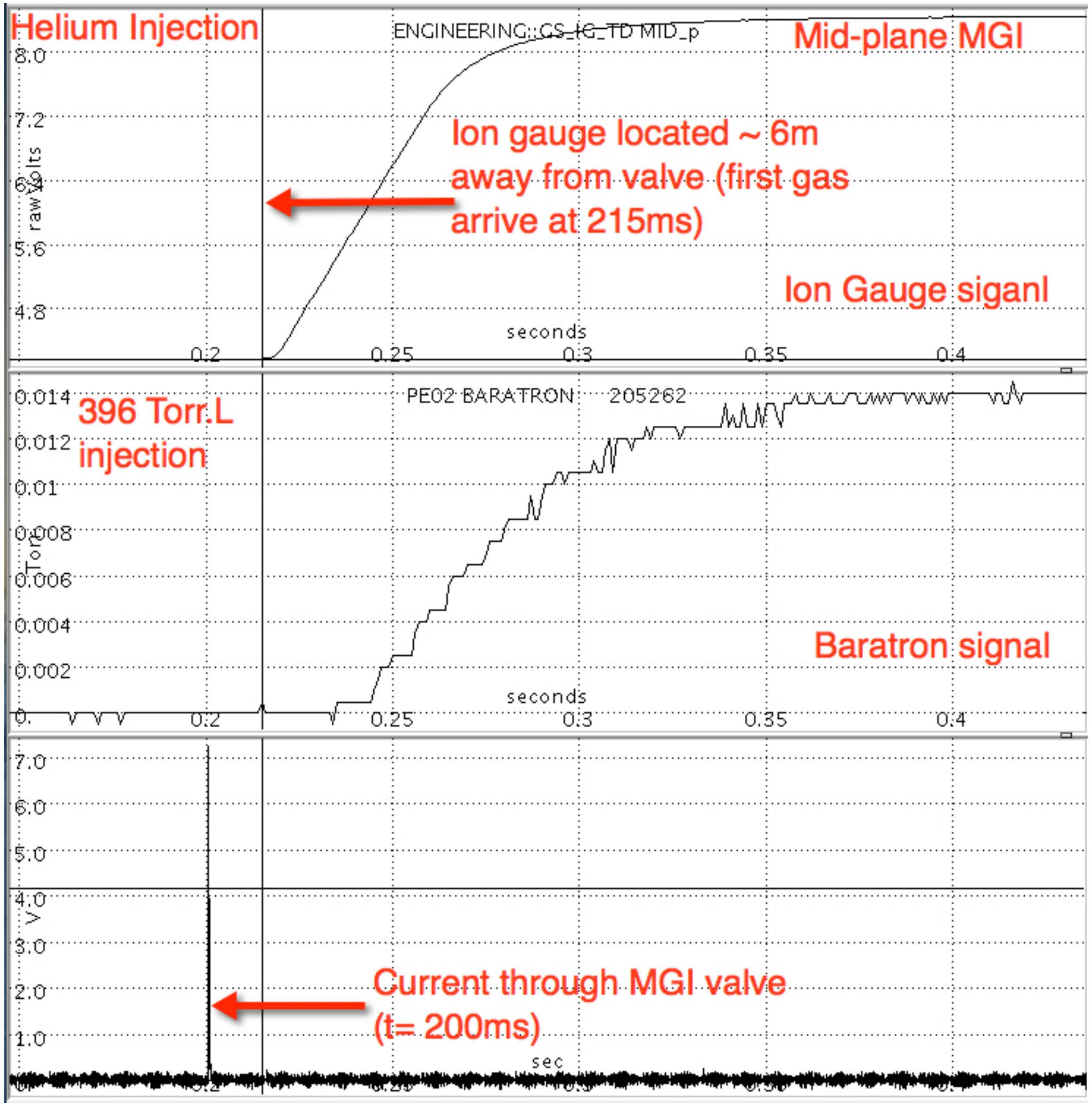
 R. Raman, et al., RSI, 85, 11E801 (2014)

Mid-Plane & Divertor MGI Valves ready to support Plasma Operations

- The Pre-operational Test Procedure (PTP) for both MGI valves were completed
- Valve power supplies operated at 1kV during PTP
- Both valves were calibrated in Nitrogen, Helium and Neon at the full operating pressure (200 Psig)
- During these tests 400Torr.L of neon was injected into the NSTX-U vessel, this is about twice the amount of neon injection planned for the first MGI experiments to be conducted on NSTX-U



Gas Arrival Times as Measured by Slow Pressure Gauges Roughly Consistent with Sound Speed of Gas



200 Psig Plenum pressure

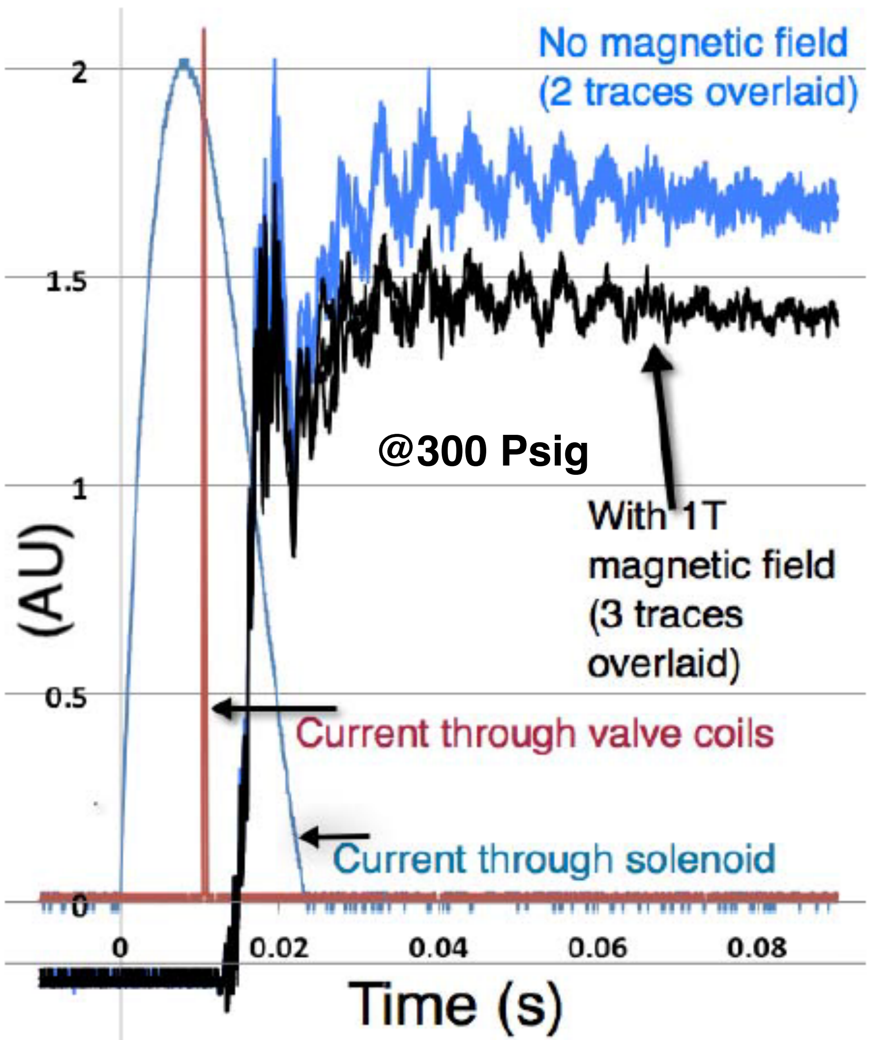
MGI gas travels through 2m long tube with bends.

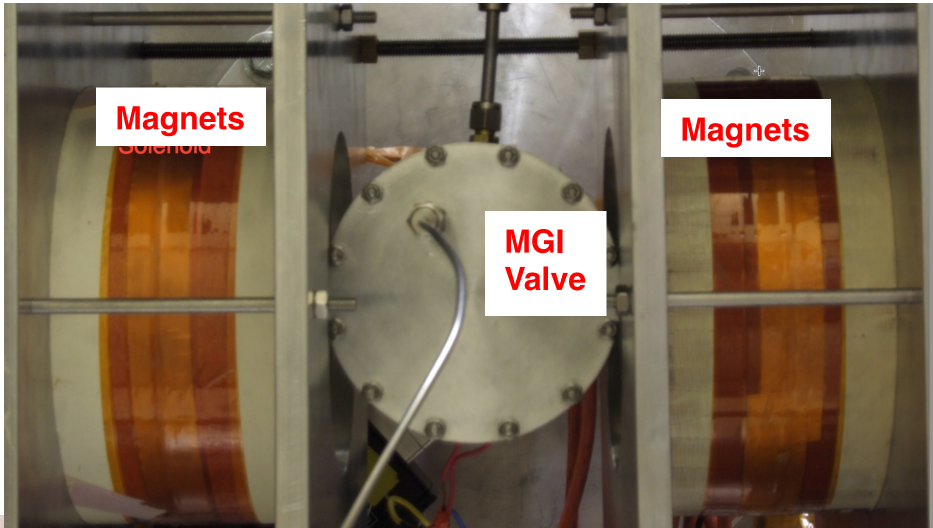
Future experiments will inject gas using a short connecting tube (to compare to Upper Divertor MGI configuration)

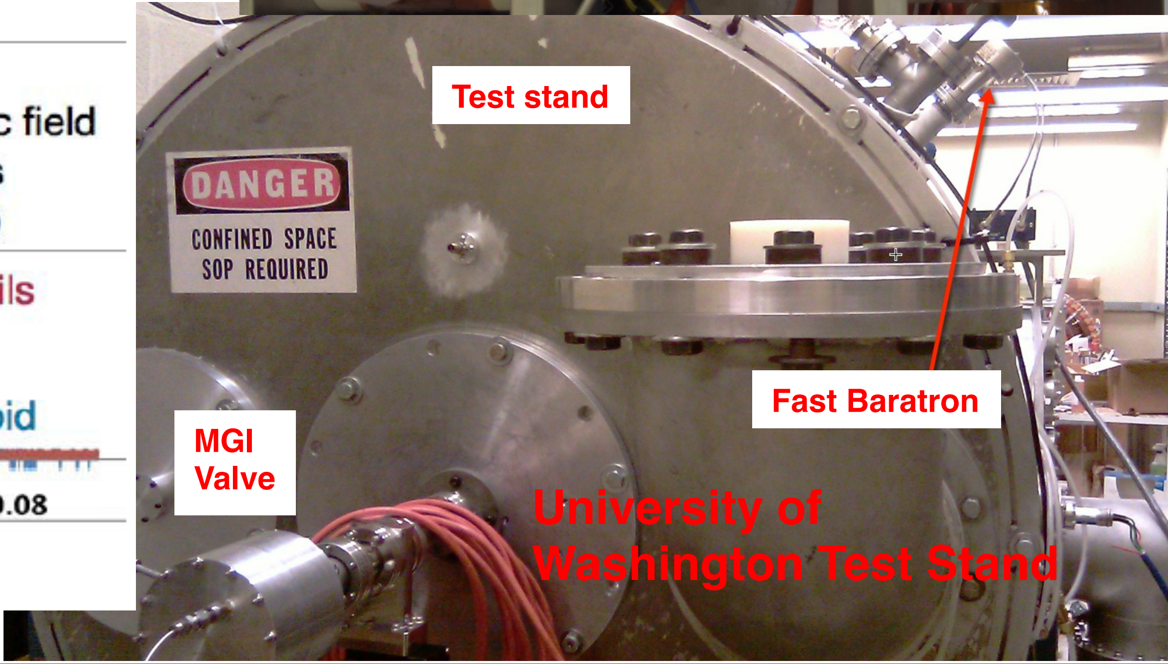
Sound speed:
He : ~972 m/s
Neon: ~461 m/s
Nitrogen: ~354 m/s

Off-line Tests to Study Reliability and Magnetic Field Limits on Valve Operation

Baratron traces with and without magnetic field







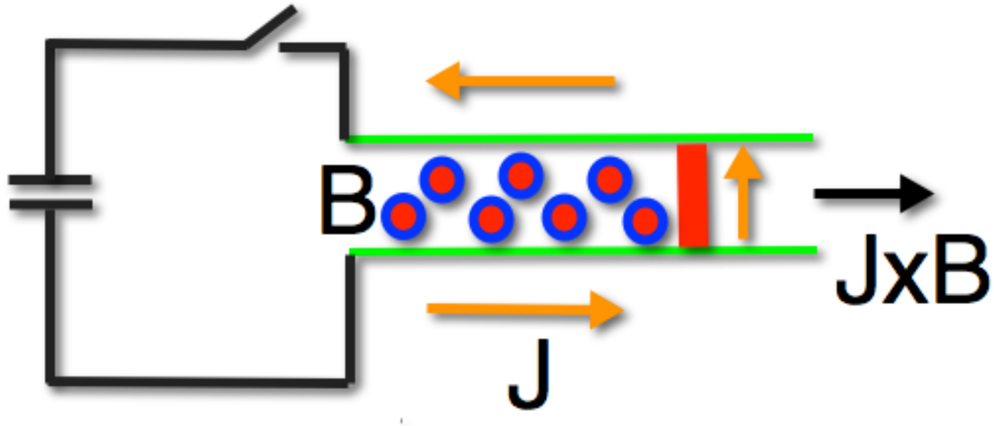
R. Raman, et al., IEEE-PS 44, 1547 (2016)

EPI can Deliver Impurity Particles Deep into the Tokamak Plasma on a Fast Time-scale

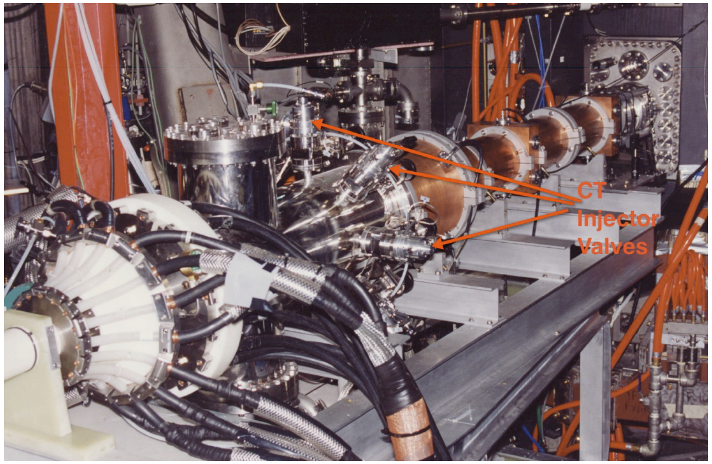
- Electromagnetic Particle Injector (EPI) concept is based on acceleration of a pellet using a linear Rail Gun injector

- Compared to the Shell Pellet concept, the primary difference is the <u>Pellet Delivery Mechanism</u>
  - 1) Size of pellets, 2) particle species, 3) size of particle inside pellet - share many commonalties with the Shell Pellet concept
  - Effort needed to model pellet ablation physics inside a plasma with varying energy content

Linear Rail Gun is Especially Well Suited for Operation in High-Ambient Magnetic Fields



CT Injector on TdeV



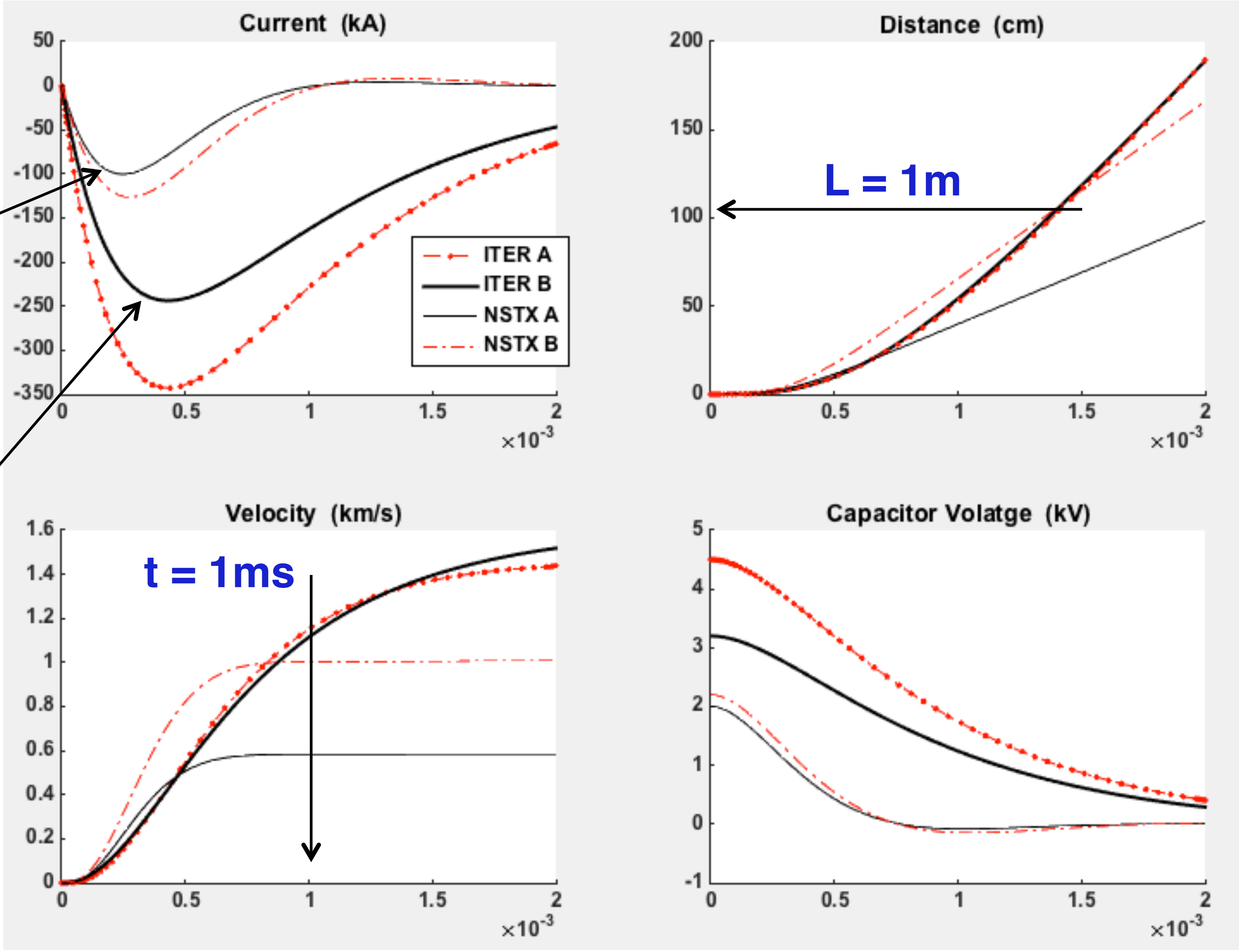
- In a simple rail gun, the magnetic field is produced by the current flowing along the rails
- To increase the JxB force accelerating the projectile, the current along the rails needs to be increased
- An important advantage of a linear rail gun is that the ambient magnetic field in ITER can be used to increase the gun efficiency
- Injector can to be positioned very close to the vessel, which further improves the system response time and efficiency

 R. Raman, et al., FST 68,797 (2015)

External Magnetic Field Augmentation Substantially Reduces Electrode Current and PS Requirements

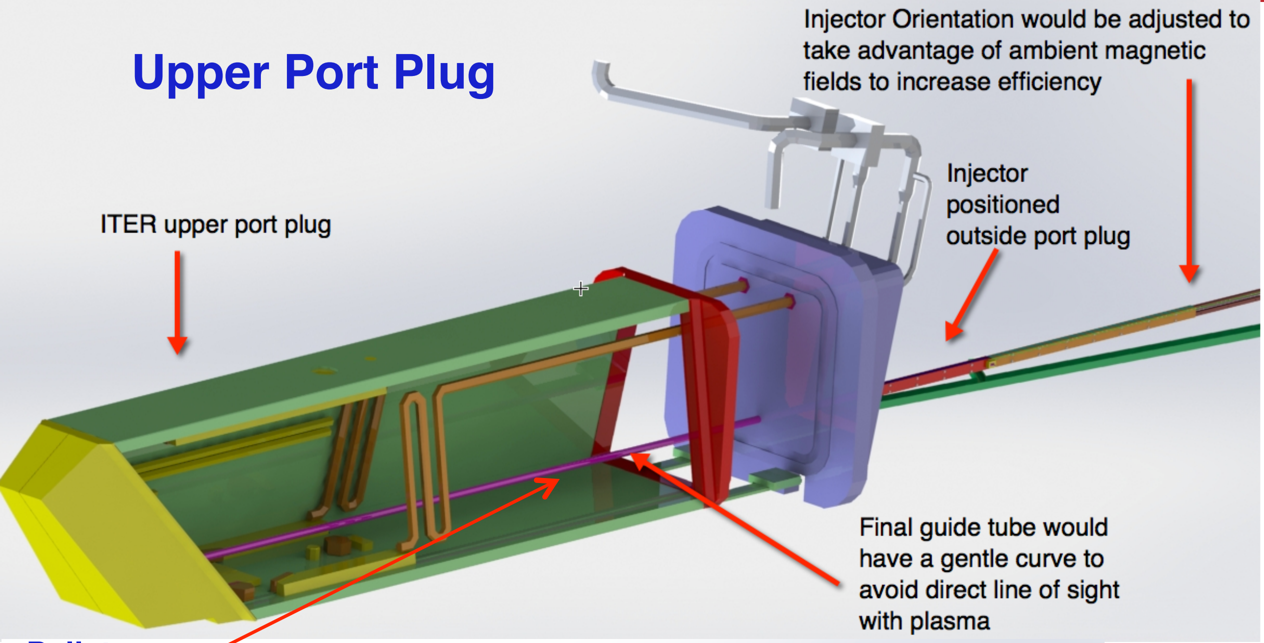
NSTX-U
20 mF, 2kV

ITER
2T external magnetic field augmentation, 100mF, 3.2kV



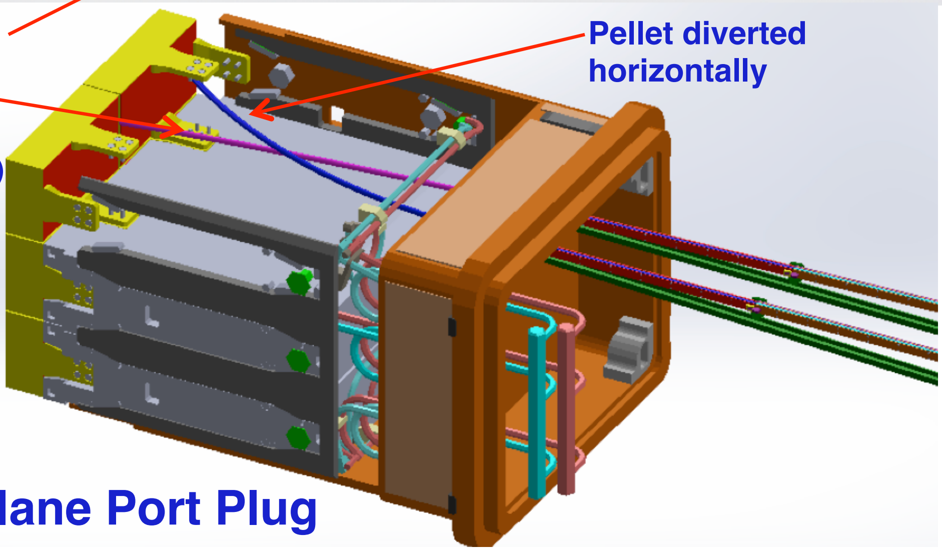
Scoping Studies Suggest that an EPI Installation on ITER should be feasible*

Upper Port Plug



Pellet diverted vertically (poloidal direction)

Pellet diverted horizontally

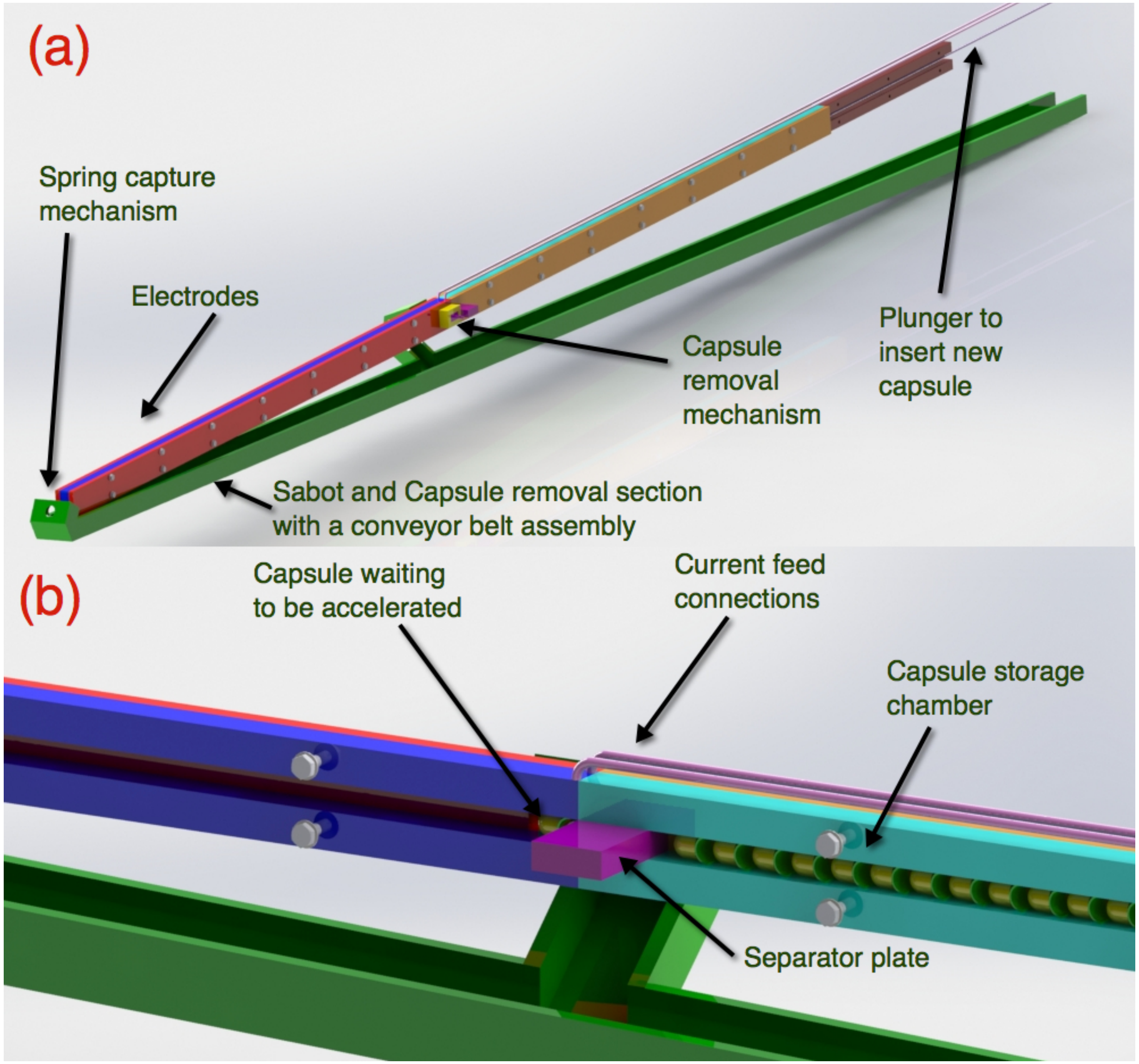


Mid-plane Port Plug

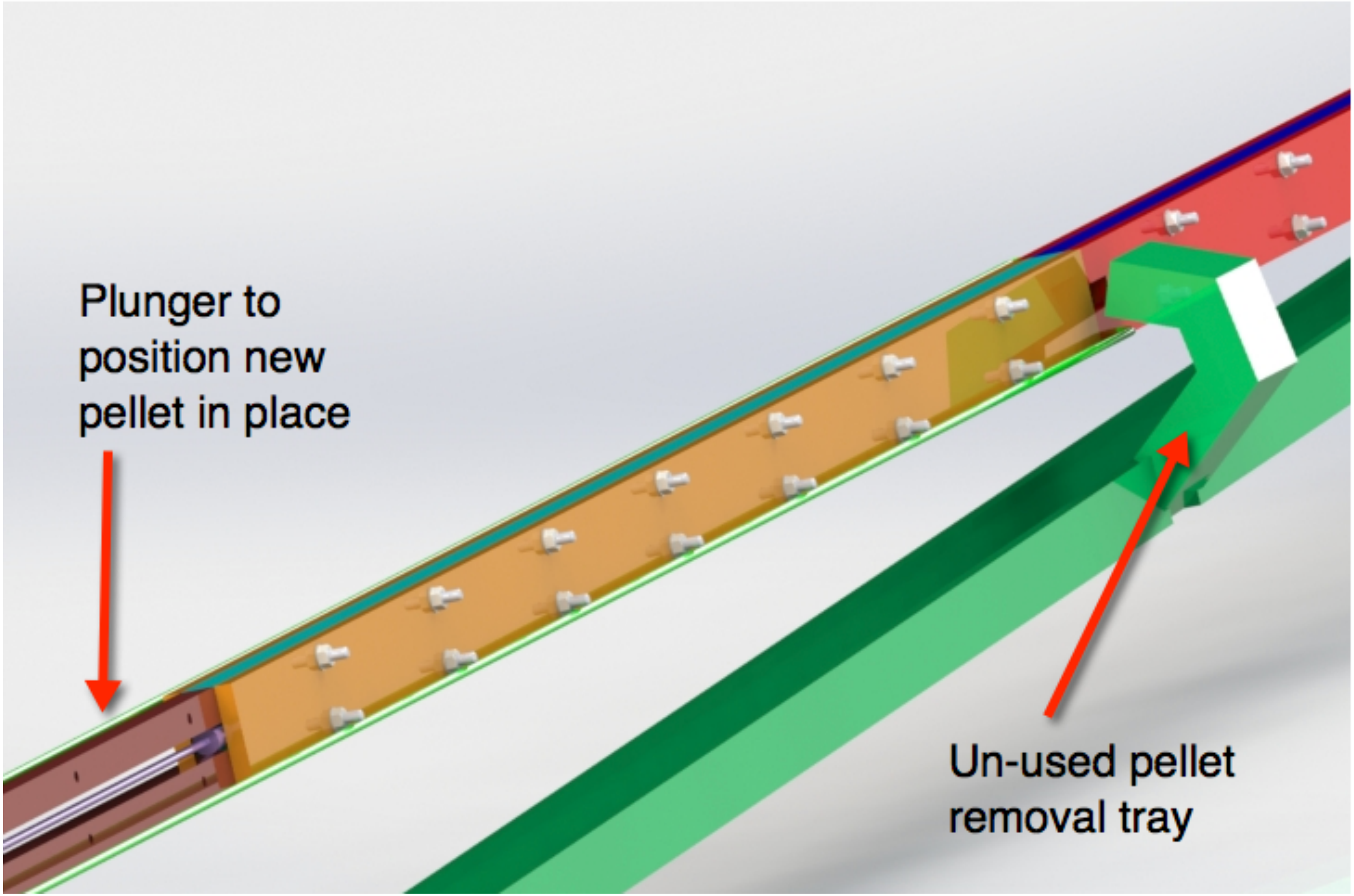
***In FNSF, inclusion of EPI from early design phase should allow installation closer to the wall to benefit from high toroidal field**

R. Raman, T.R. Jarboe, J.E. Menard, et al., Fusion Science and Technol. (2015)

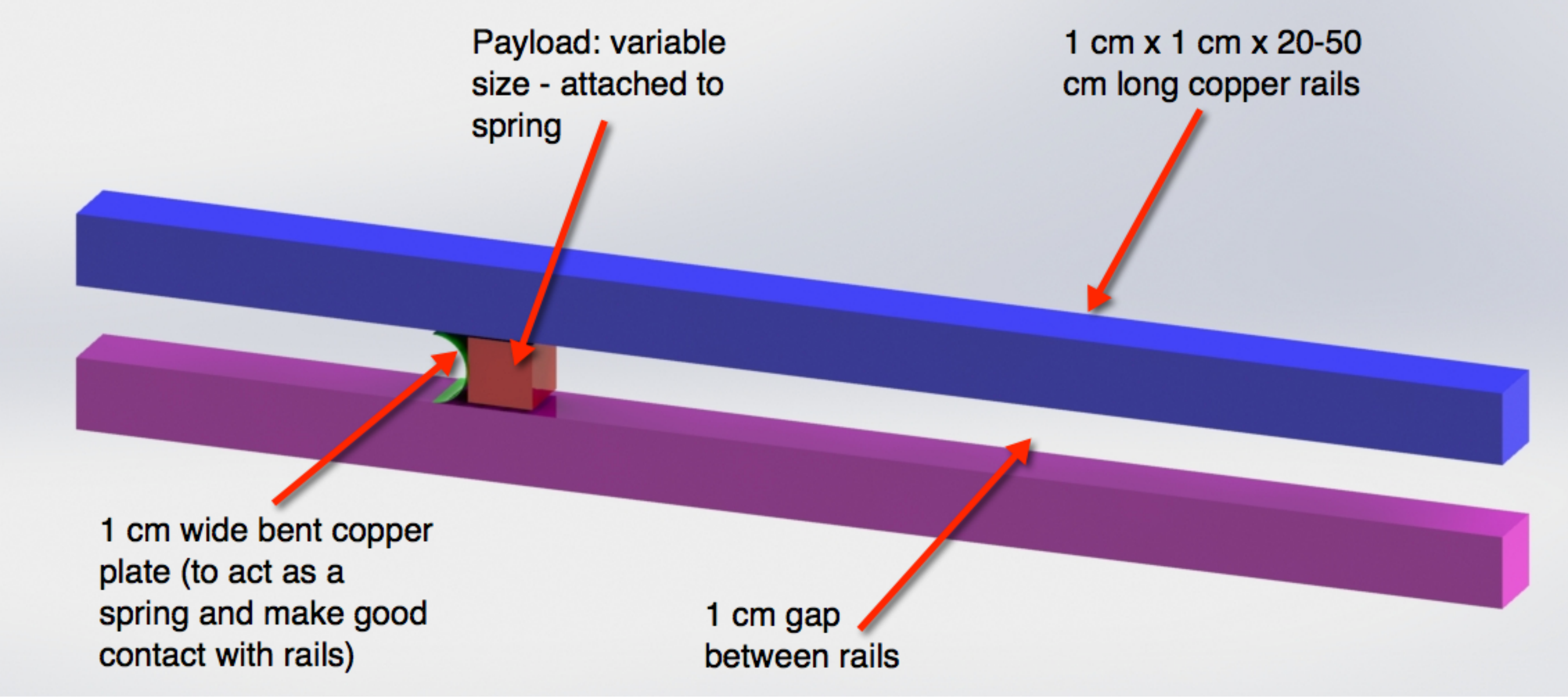
Primary Components of an EPI System for ITER



Unused Pellet Removal System and New Pellet Insertion

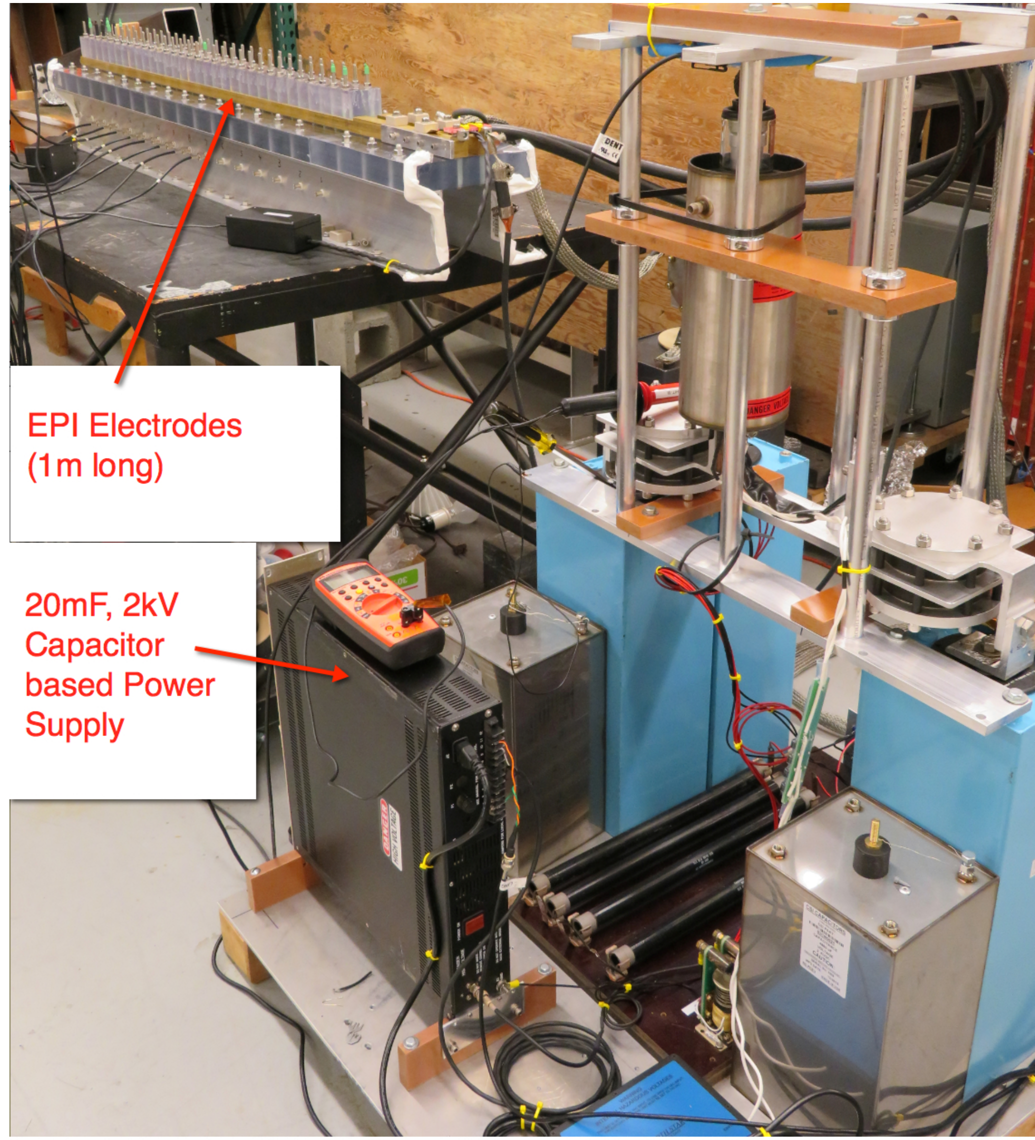


Initial Tests at U-Washington will Accelerate 2 to 5g payloads

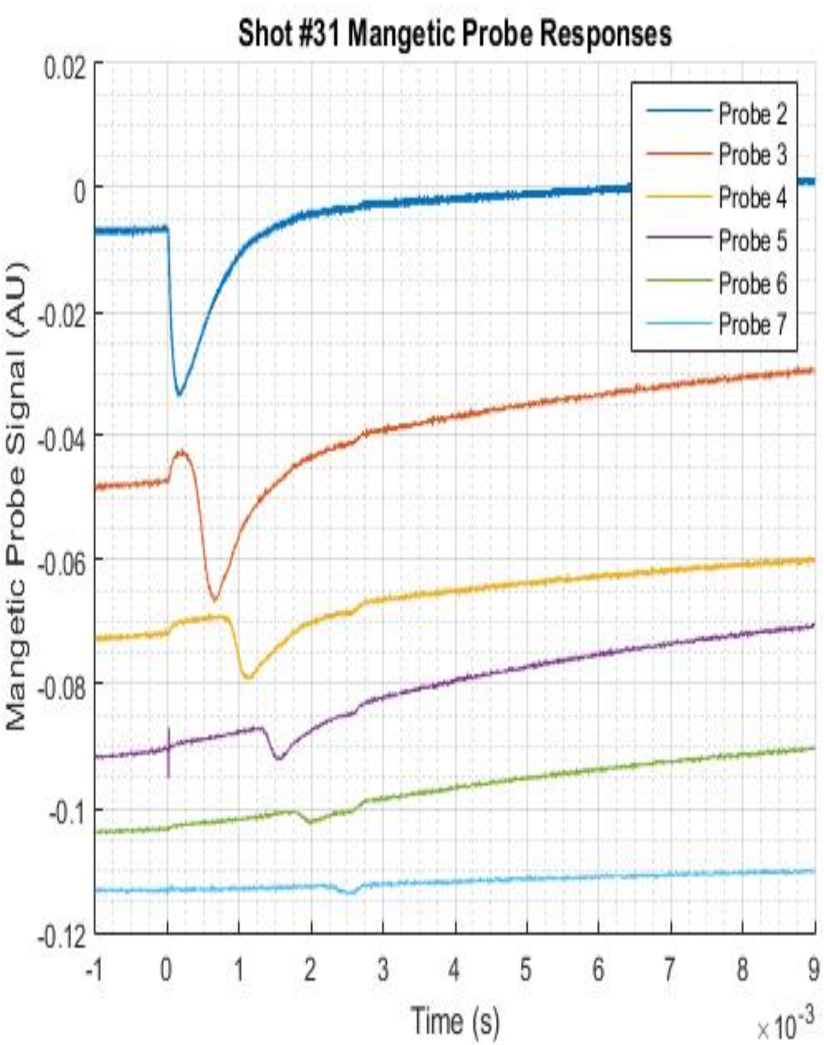


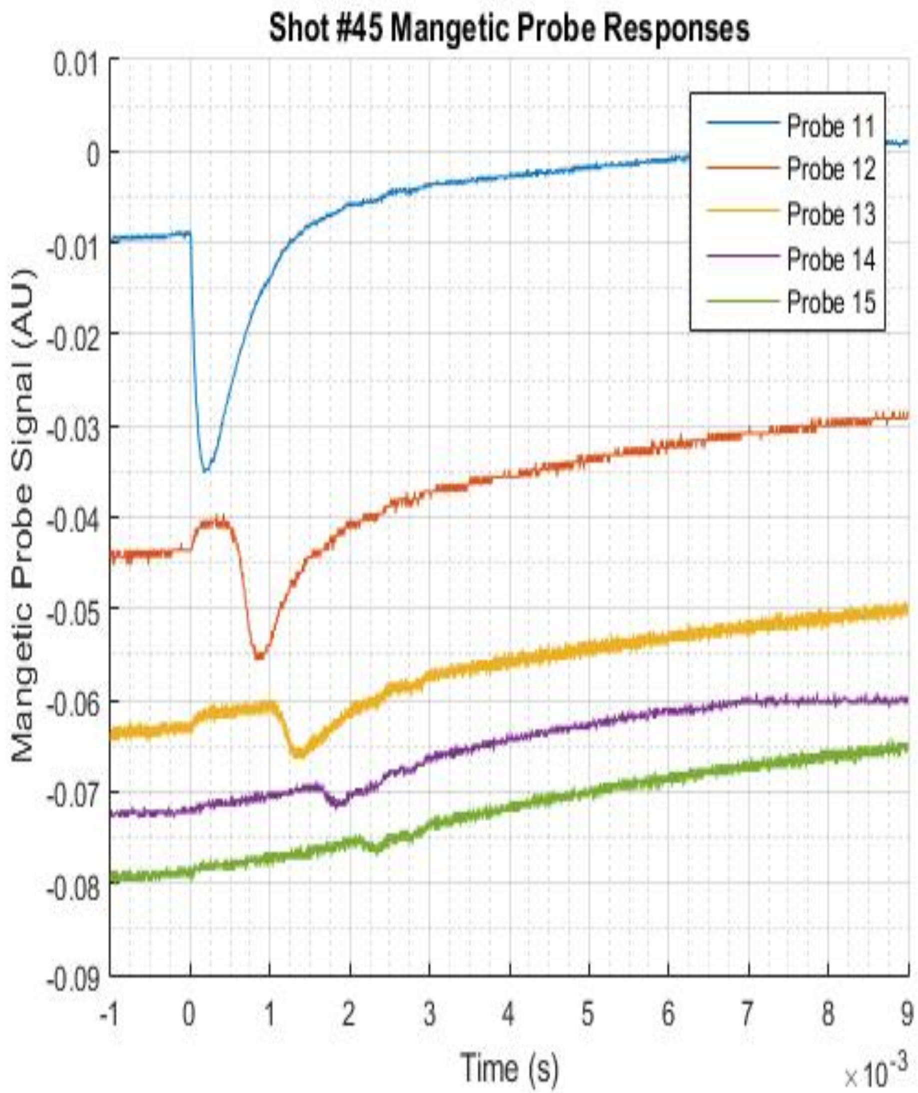
Rails will be sandwiched between insulating plates and powered using a 20mF, 2kV capacitor bank

External Field Augmentation (~25%) Provided by Two Magnetic Field Coils



Sabot Position Tracking using Magnetic Probes Indicates Attainment of Maximum Velocity in <2ms after Trigger Time





Velocity Measurements using Fast Camera Images are Consistent with Results from Magnetic Probe Signals

Shot 45

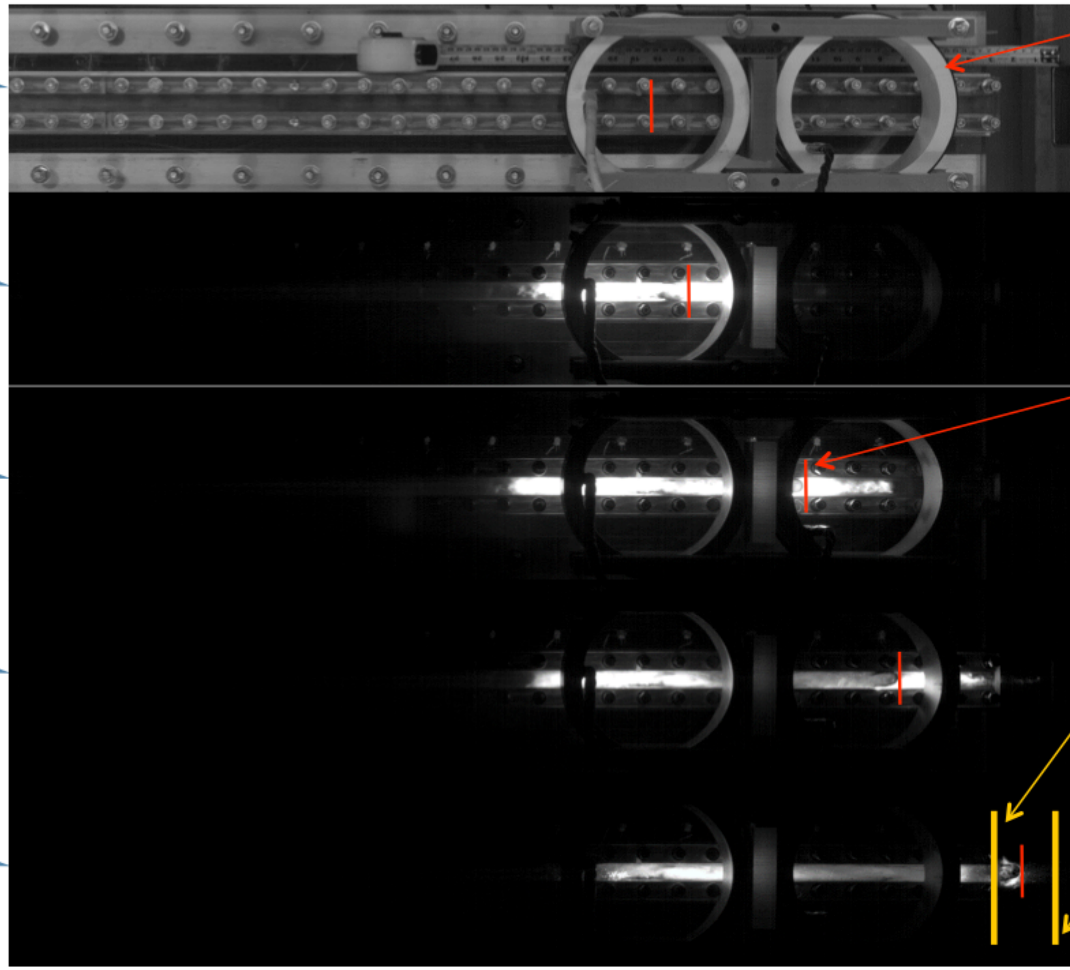
Time: 0.140ms
Distance: 0mm

Time: 0.577ms
Distance: 38.1mm

Time: 1.452ms
Distance: 152.4mm

Time: 2.140ms
Distance: 228.6mm

Time: 3.077ms
Distance: 342.9mm



Magnetic coils to enhance magnetic field

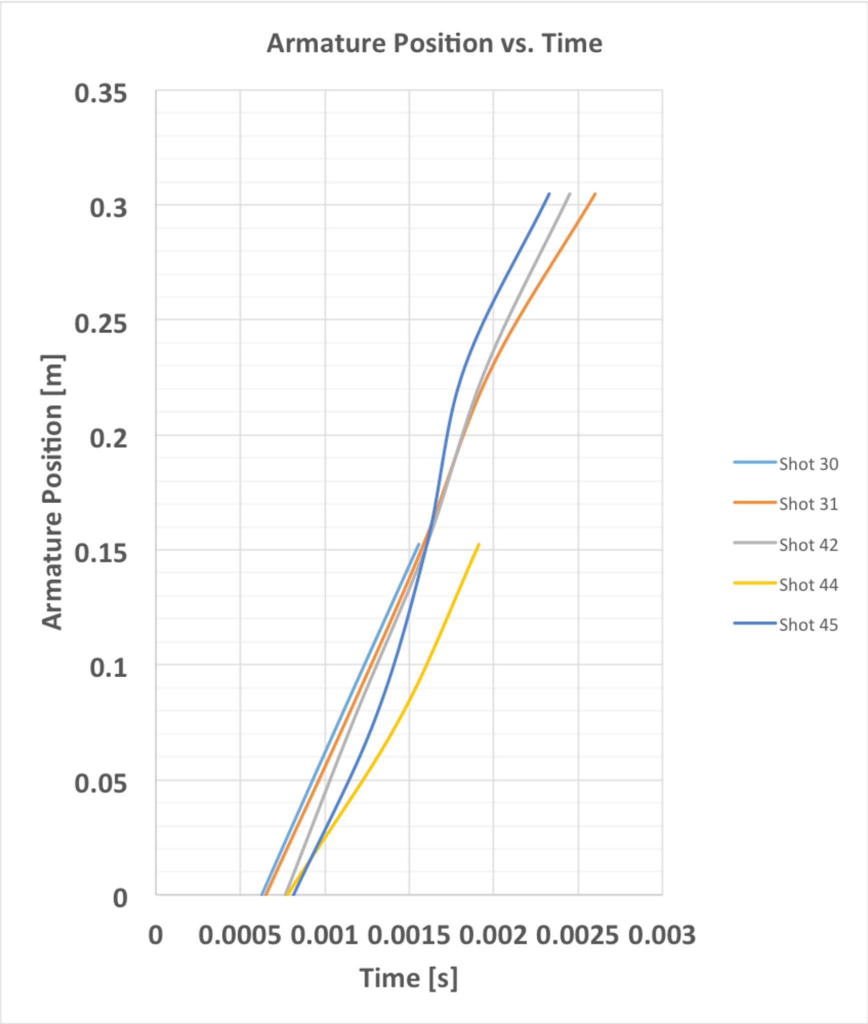
Still camera image to show full assembly

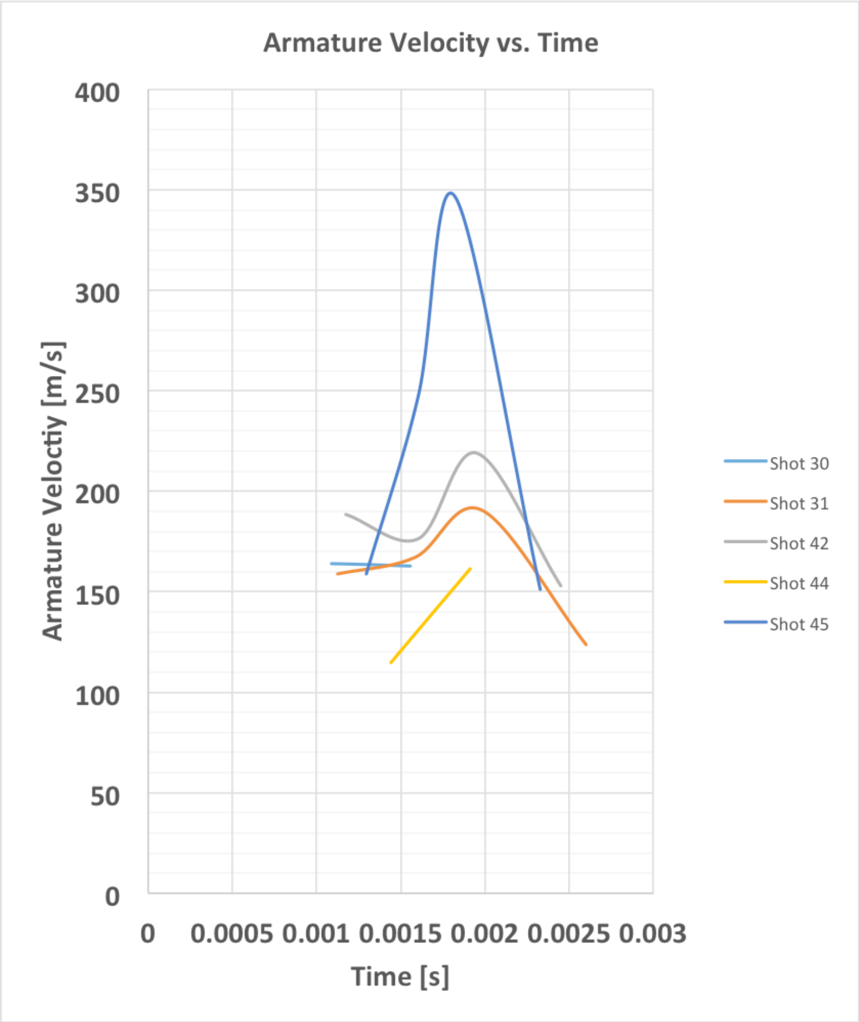
Location of sabot

End of accelerator

Start of sabot capture chamber

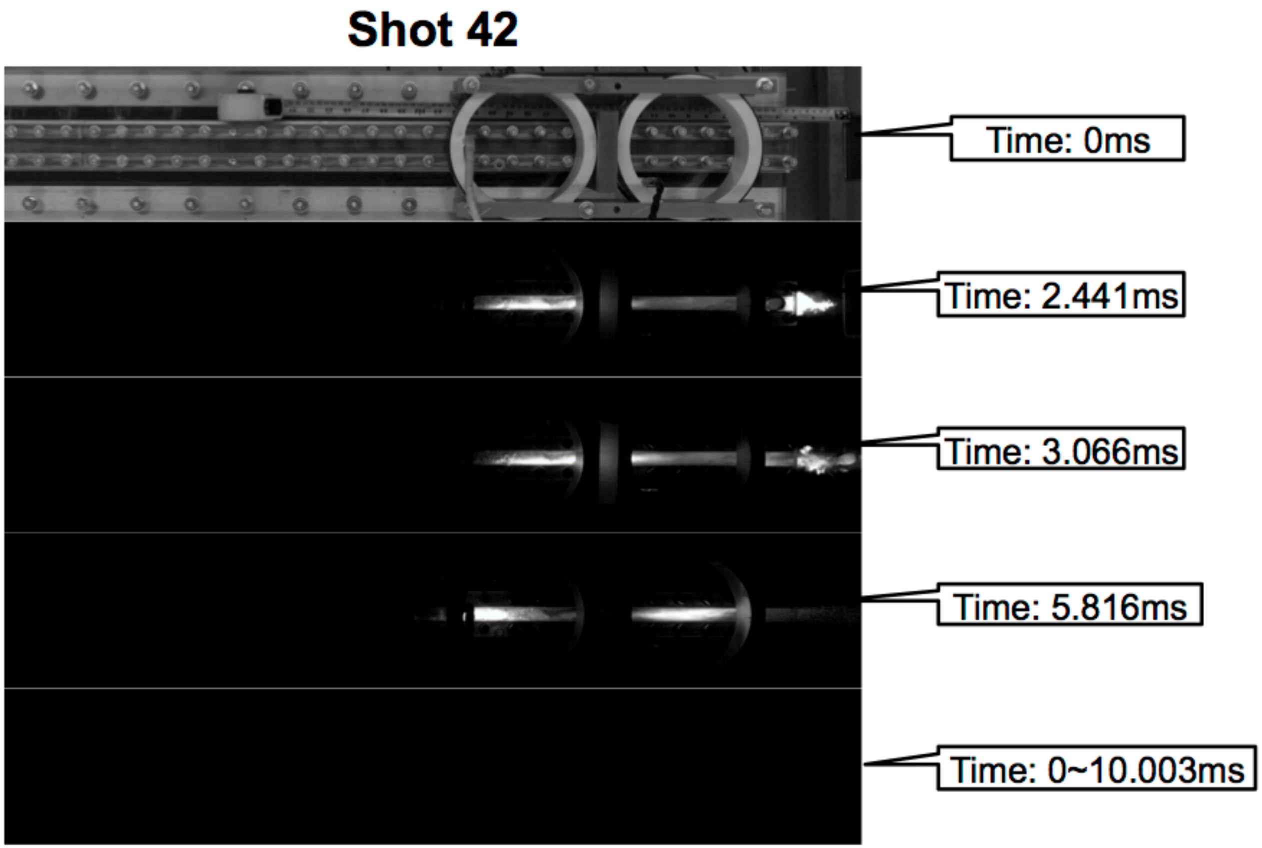
Attained Velocities and Accelerator Length Roughly Consistent with Calculations in Initial (un-optimized) Tests





Accelerator dimensions and circuit parameters need to be optimized to avoid velocity droop after attainment of peak velocity

High-velocity Shots Indicate Creation of a Partial Vacuum Behind 3 g Accelerating Sabot



Note plasma / gas outside the injector region, and less plasma near the injector exit

All the plasma / gas outside the exit has been pulled back into the injector.

This means that the sabot is traveling faster that the speed with which the region behind the sabot can be re-filled with atmospheric pressure air

- Generation of partial vacuum behind projectile indicates sabot is pushing against significant atmospheric pressure
- Injector will be operated in vacuum for tokamak test, which should further improve acceleration parameters

NSTX-U DM Research Aims to Develop MGI and EPI Technologies in Support ITER and FNSF

- ITER-type MGI valve will be used on NSTX-U in a configuration to do nearly exact comparison experiments
  - Same valve & piping configuration at each poloidal location
  - NSTX-U MGI valves operated at 1T in off-line tests
  - Three MGI valves installed on NSTX-U, and two valves fully commissioned on NSTX-U, and are ready to support plasma operations
- Experimental results to be studied using M3D C1 to develop capability for understanding gas assimilation fraction by the plasma so that it could be used to project to ITER plasmas
- The EPI system has several attractive features
  - Rapid delivery of impurities deeper into plasma with fast time-response
    - < 5ms from trigger to delivery at 7m from plasma
    - ~ 2ms delivery time, if installed closer to vessel (FNSF)
    - >10ms for Shell Pellet (>20ms for high-z MGI)
  - Efficiency of system improves in a magnetic field environment
  - Well suited for long stand-by mode operation (single power supply and no moving parts in system)
  - Can be located close to vacuum vessel