NSTX-U

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The Electromagnetic Particle Injector for Disruption Mitigation in Tokamaks

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Desirable Requirements for a Reactor Disruption Mitigation System (DMS)

A DMS injects a radiative payload into the tokamak plasma to try to uniformly radiate the stored energy to the vessel walls, while trying to satisfy the TQ and CQ requirements

- Requires Fast Response Time < 10 ms
  - Overall response time (from first trigger to radiative payload reaching deep inside the plasma)

in combination with

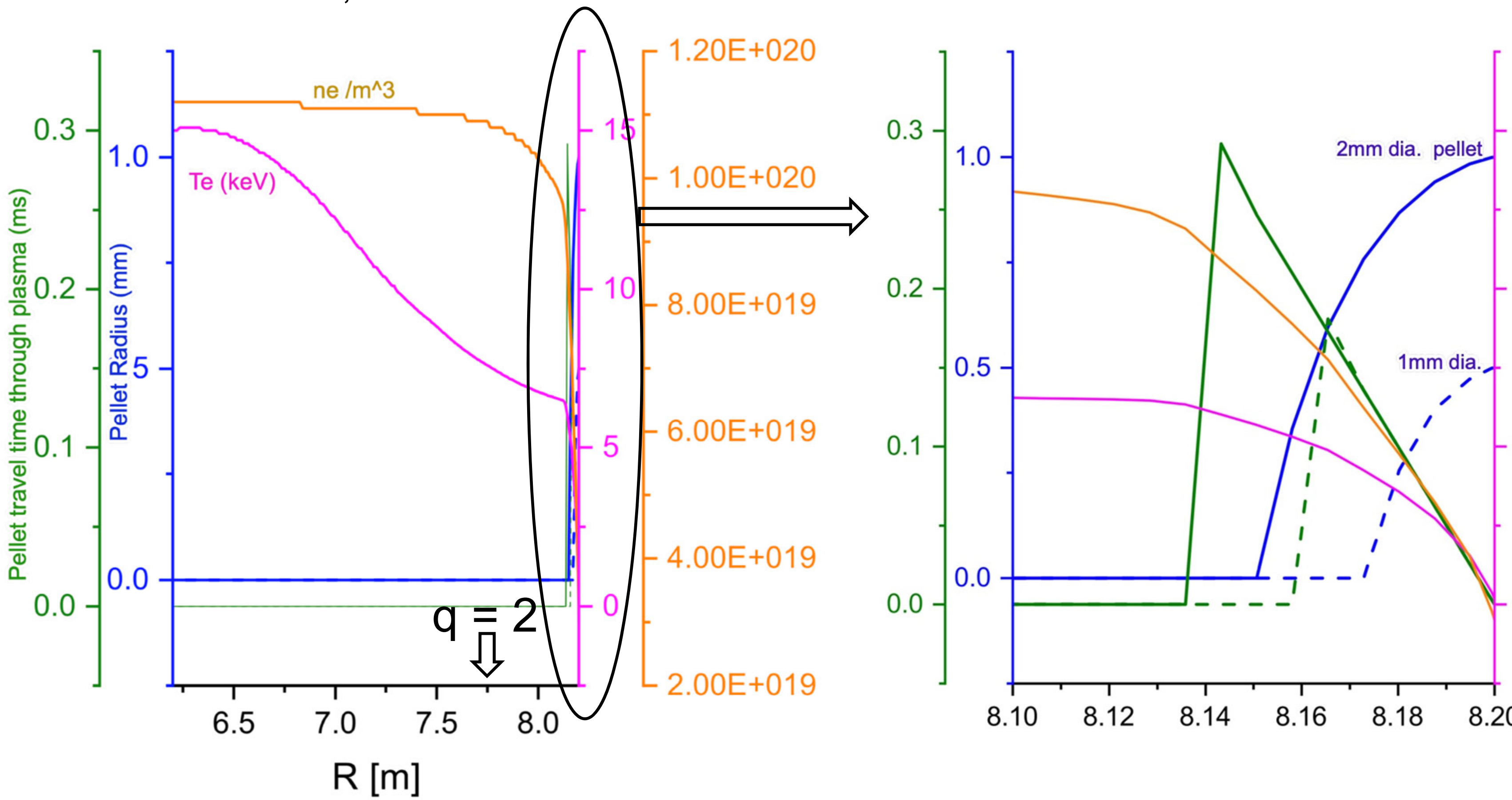
- High Velocity $\geq$ 1 km/s or higher
  - for deep payload penetration in reactor grade plasmas (at least beyond q = 2 surface)

Limitations of Present DM Systems

- SPI has been adopted by ITER as the baseline DMS
- The speed of the un-fragmented high-mass / high-Z SPI pellets is about 200 m/s (response time on DIII-D ~ 25ms)
  - After fragmentation, bulk of the Neon/Argon fragments are ~1-2mm in diameter
- Because of the slow speed and size of the fragmented particles, the penetration depth may be severely restricted in high power ITER discharges (M3D-C1 / NIMROD work in progress)
- Will the SPI fragments penetrate sufficiently deep into the much more energetic ITER H-mode pedestal or will SPI on ITER be more like MGI on present tokamaks?
  - Present methods rely on MHD to transport the radiative payload deep into the discharge
  - But, it would be desirable if the radiative payload could be deposited in the RE current generation region by the injection process itself

Simulations* Indicate 1 and 2 mm Ne Pellet (200 m/s) Penetration into ITER 350 MJ H-Mode Plasmas is Confined to a Region within the H-mode Pedestal

ITER-Profiles: A.R. Polevoi , ASTRA Code Simulations



- This calculation does not model SPI penetration. However, it provides an insight into how deep a single pellet could be expected to penetrate in high energy ITER plasmas.

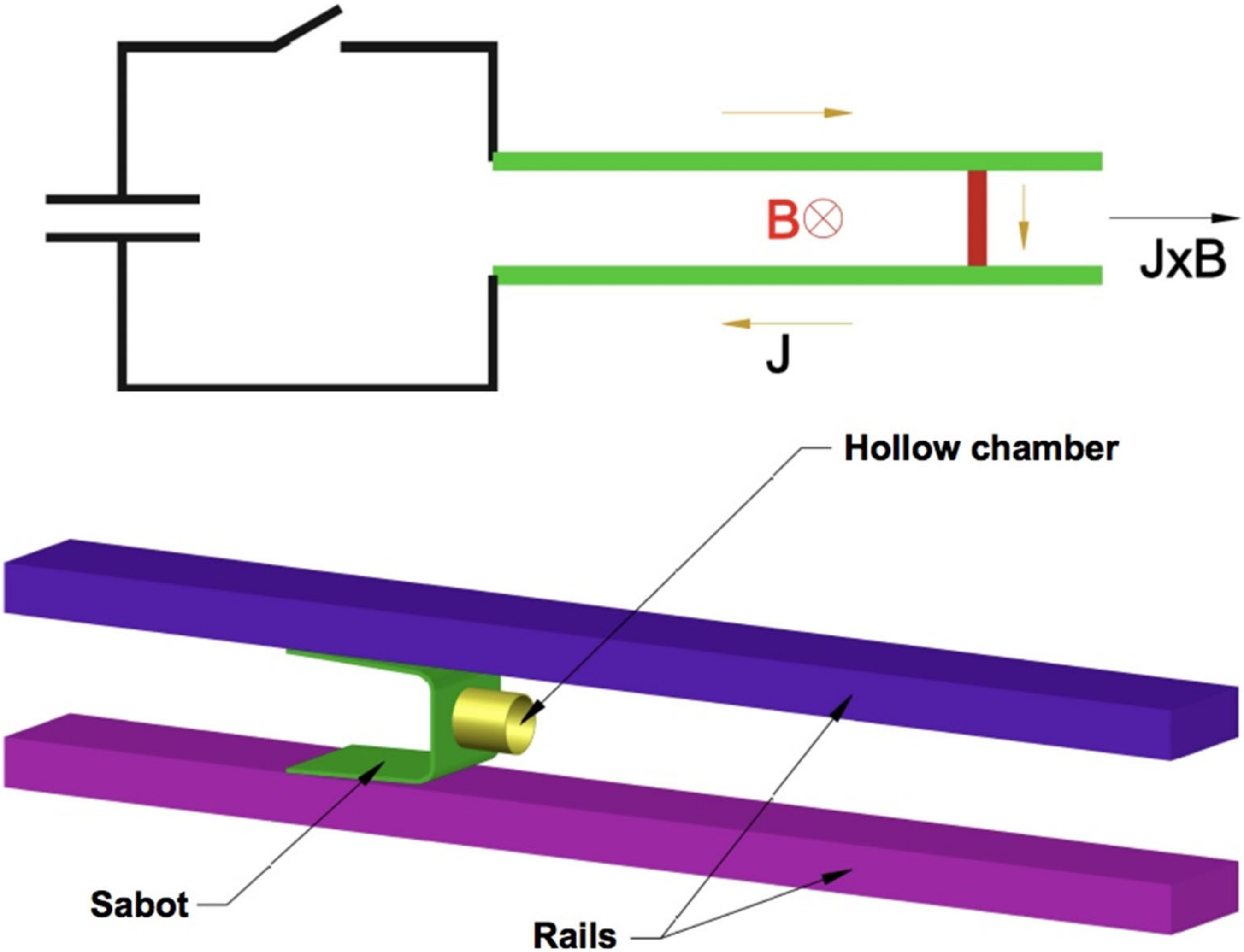
***ORNL Pellet Penetration Code:**
W. A. Houlberg, et al.,
Nuclear Fusion 28, 595 (1988)

How Does The Electromagnetic Particle Injector (EPI) Concept Address Present Limitations?

- The EPI accelerates a metallic capsule (a sabot) to high-velocity using an electromagnetic impeller.
  - At the end of the acceleration, within 2-3 ms, the sabot releases granules of known velocity and distribution – or a Shell Pellet
  - It can inject any impurities or a combination of impurities

- The **primary advantage** of the EPI concept over SPI and other gas propelled systems is its potential to meet **short warning time scales**, while accurately delivering the required particle size and materials at the velocities needed for achieving the required **core penetration** in high power ITER discharges.
  - Can deliver radiative payload to the the core where the RE channel is generated

The Ambient B-Field of a High-Field Tokamak such as ITER Can be Used to Improve Device Efficiency



- Injector can be positioned very close to the vessel, which further improves the system response time

- Use high-field SC boost coils (>8T) if located outside port plug

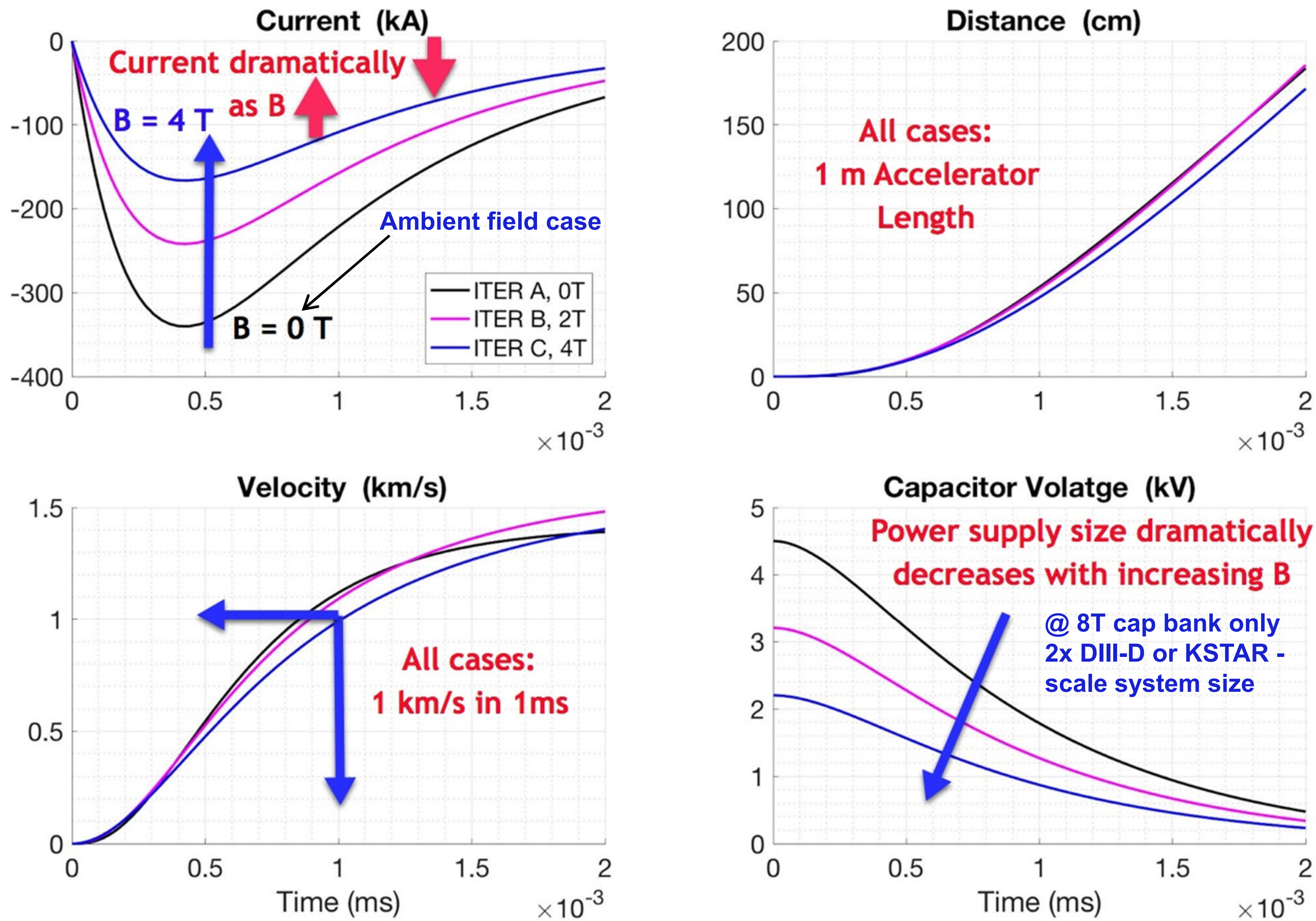
From: R. Raman, et al., Fusion Science & Technology, Vol.68 (Nov 2015) 797

EPI Satisfies Both Requirements (Fast Response Time & High Velocity)

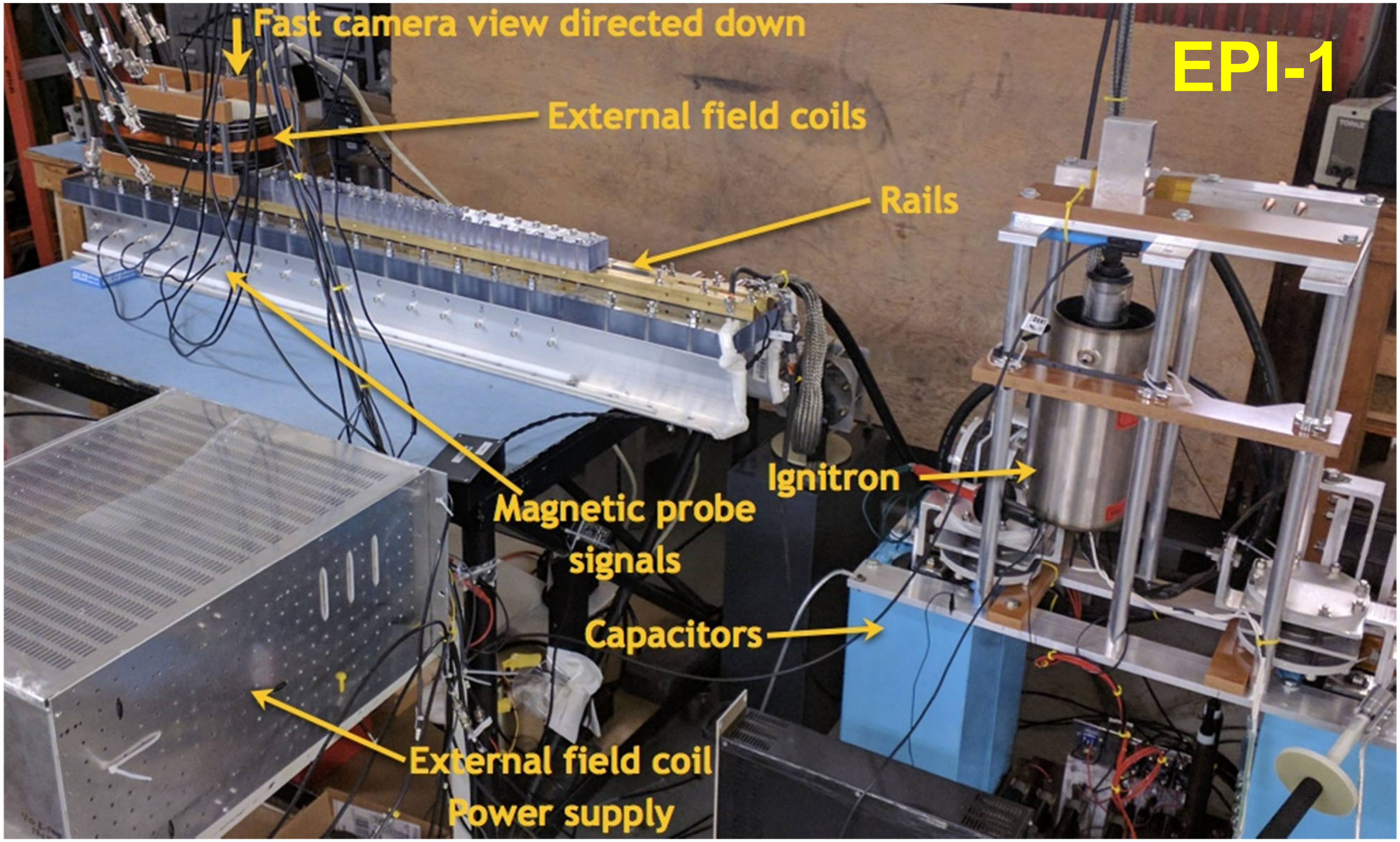
- EPI response time on ITER (from outside the port plug) will be <10ms (SPI response time on DIII-D is 25 ms)
- Present methods rely on MHD mixing to transport radiative materials to core, EPI has the potential for an inside to outside thermal quench
- Because EPI injects payload of known size and velocity, one can precisely calculate the needed parameters for penetrating to the center of any given plasma, including the ITER plasma

The present understanding (based on the theoretical work of Konavalov, et al., proceedings of the IAEA-FEC 2012 conference, ITR/P1-38) is that as little as 5g of Be may be adequate for both thermal quench and runaway electron mitigation in ITER. This radiative payload must be deposited sufficiently deep inside the plasma.

ITER Scale Injector Predicted to Attain 1 km/s in ~1 ms

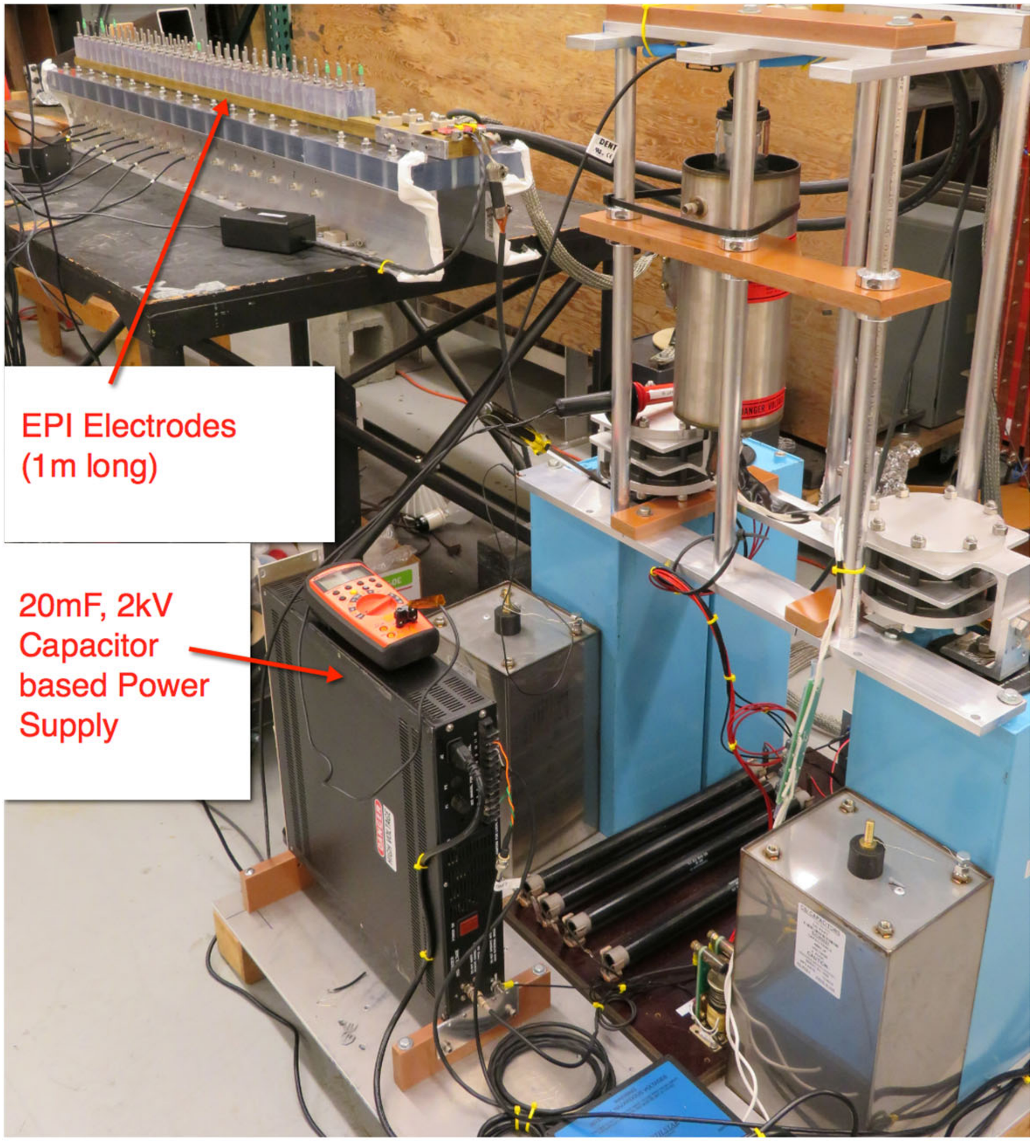


Small-scale System Used to Assess Critical Parameters & For Comparison With Projected Calculations

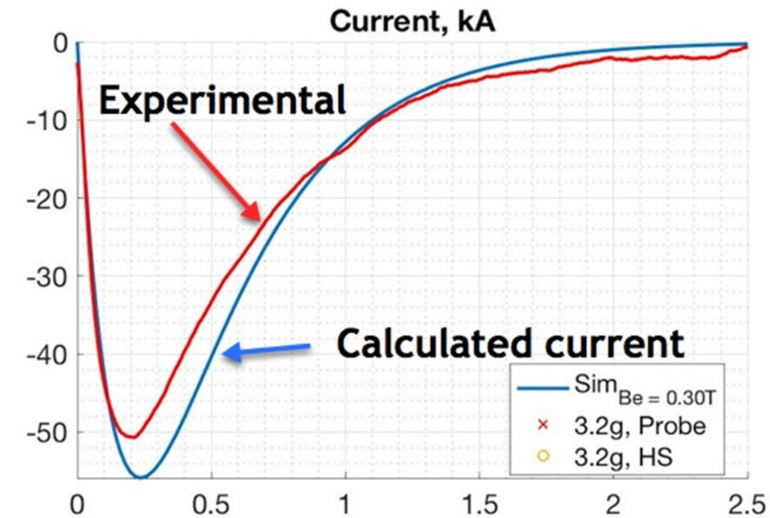


R. Raman, et al., Nuclear Fusion 59 (2019) 016021

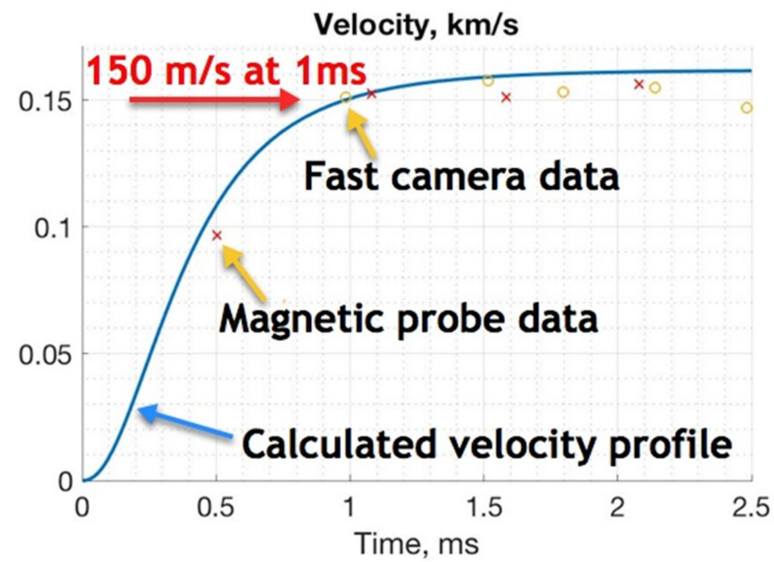
Measured EPI-1 system parameters with 0.3T B-field Augmentation in Agreement with Simulation Predictions



R. Raman, et al., Nuclear Fusion 59 (2019) 016021

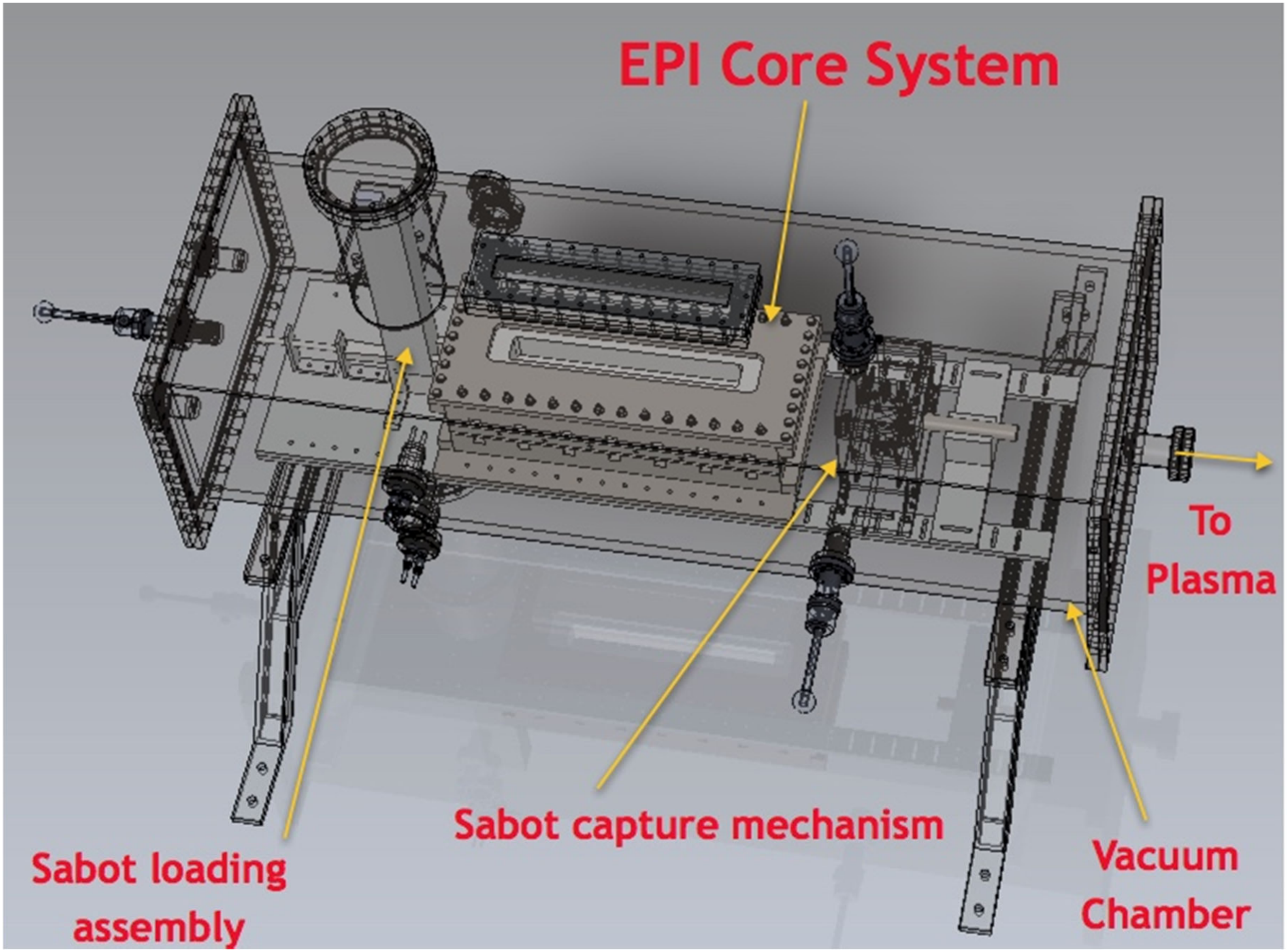


Maximum velocity limited by power supply limits

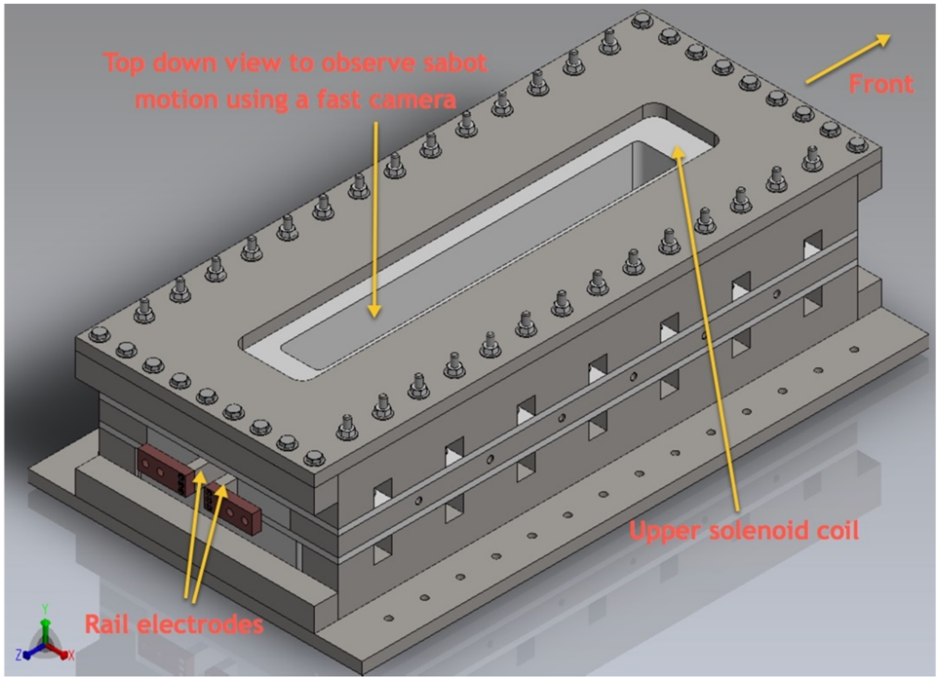


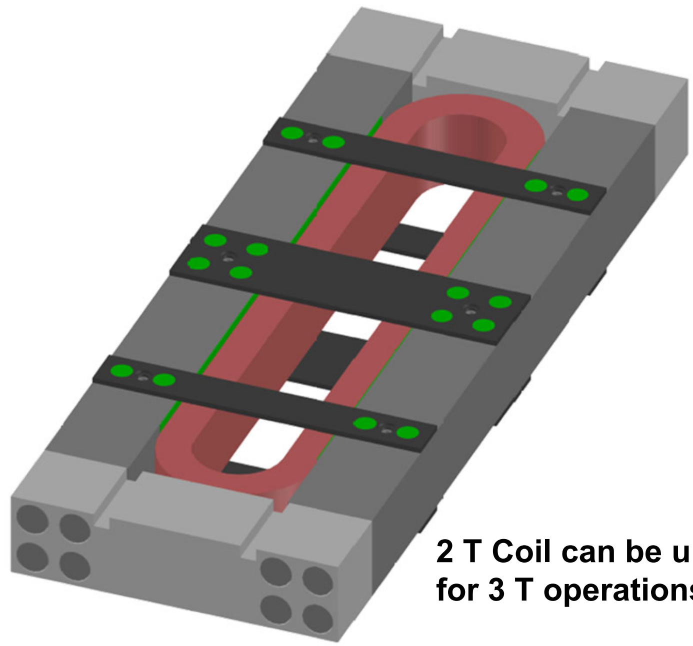
EPI-2 Design for a Tokamak Installation Test

Vacuum Chamber Dimensions (1.5m x 0.6m x 0.5m)



EPI-2 Core Region & High-Field Boost Coils Built and Tested





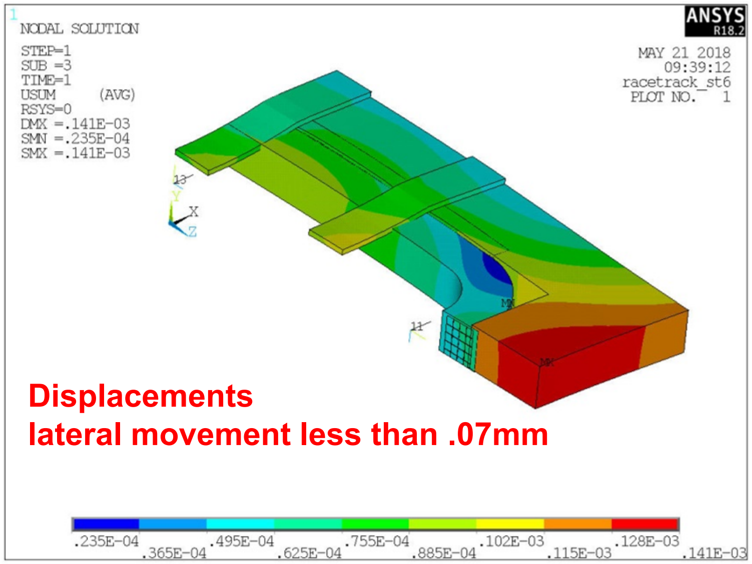
2 T Coil can be upgraded for 3 T operations

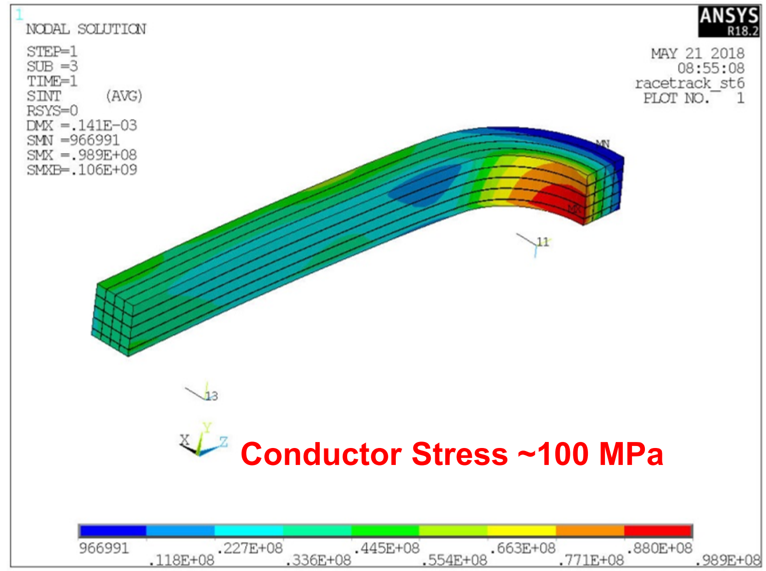
Coil Supports Designed to Restrain Coil Motion

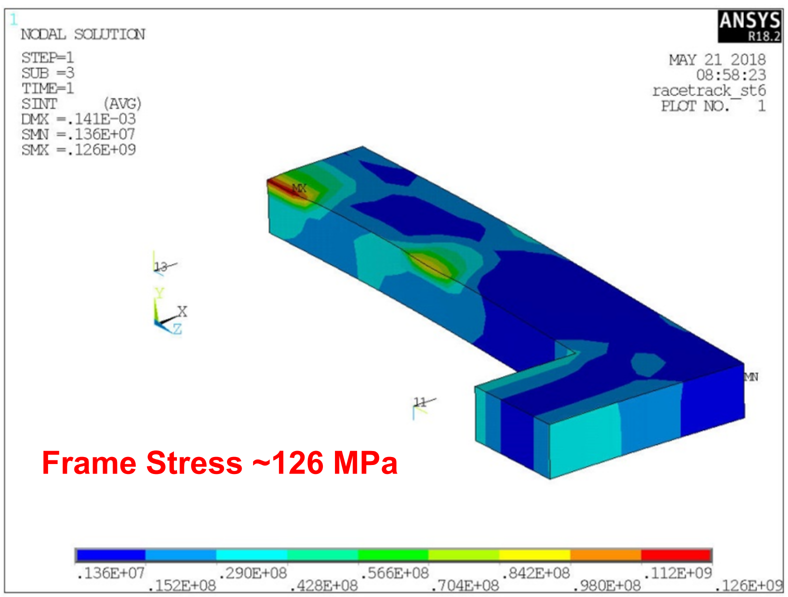
Work carried out using leftover funds from NSTX-U MGI deployment grant

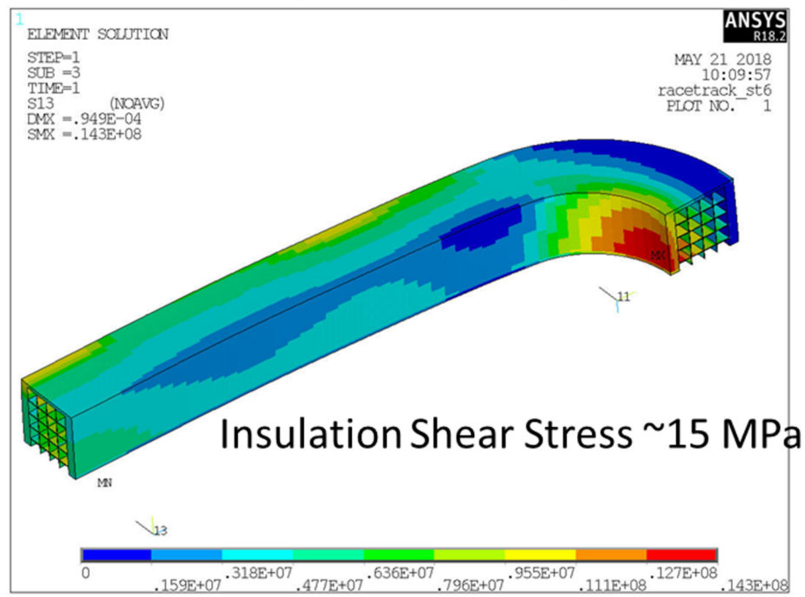
- Lateral Support added to Racetrack Coil
  - Inconel Frame 2”x2” bars bolted together
  - Titanium Straps top and bottom to strengthen & stiffen straight legs

Detailed Modeling of Coil Supports (A. Brooks, PPPL)

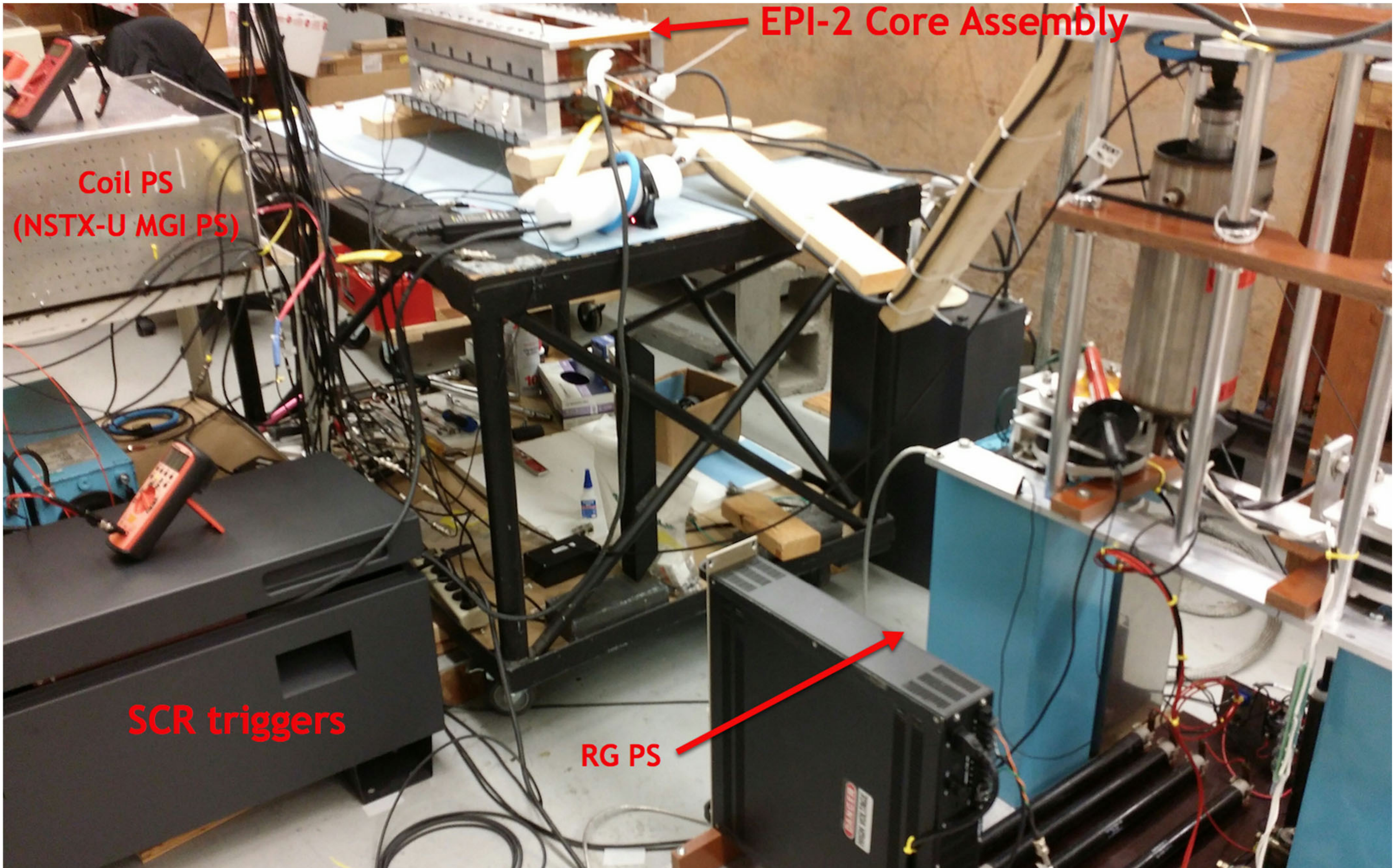




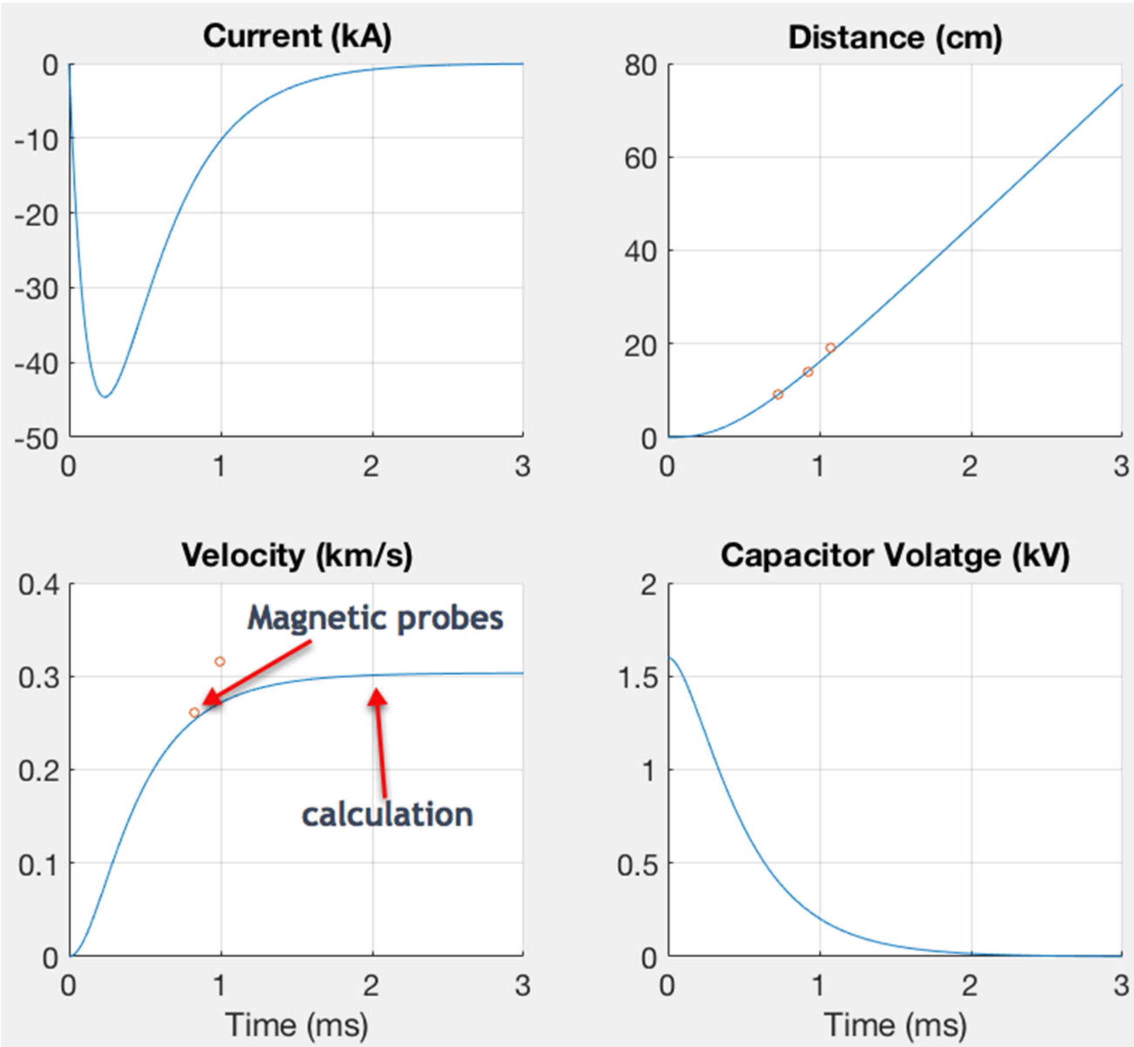




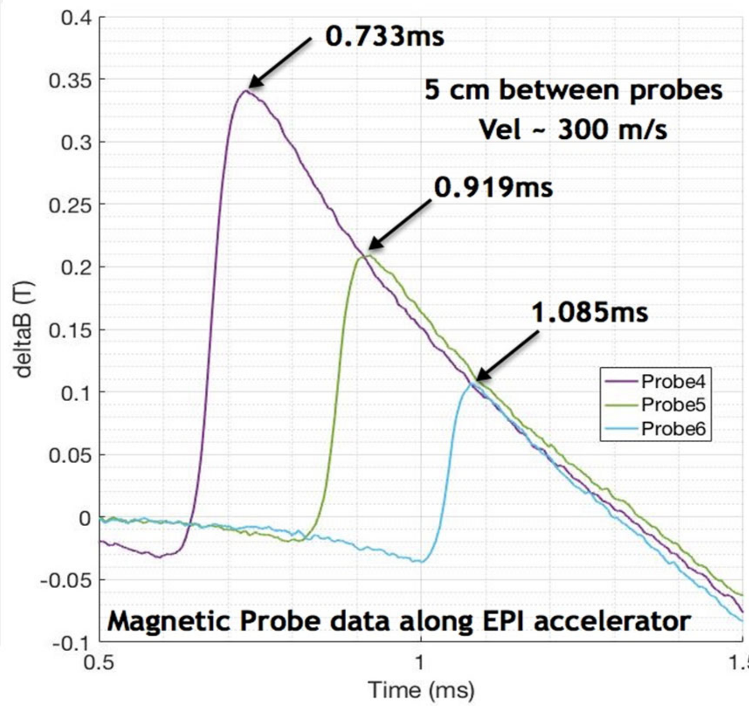
EPI-2 Assembly



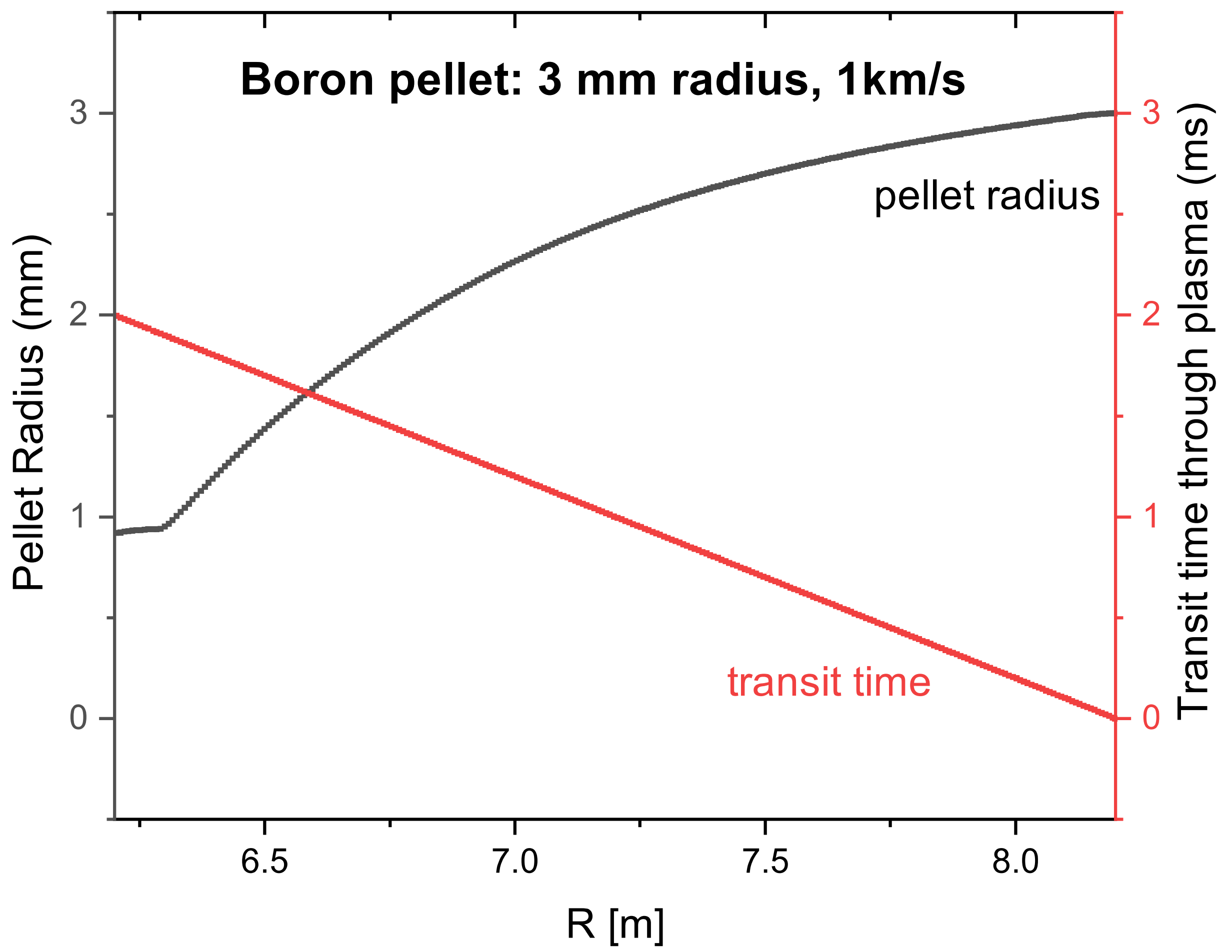
EPI-2 has easily attained 0.3 km/s with only 1.3T boost field (PS limited), consistent with calculations



Voltage (kV)	Velocity (m/s)
1000	170
1200	212
1400	259
1600	300 (65% EPI-1 @150m/s)



Single 6 mm diameter Boron Pellet at 1km/s reaches magnetic axis in ITER with sufficient payload mass left over



- EPI would inject many variable sized spheres of required composition and velocity
- Individual sphere sizes would be < 6mm (or it could be a single Shell Pellet)
- Spheres could be coated to minimize ablation until it reaches the required location

Realistic (Optimistic) Time Scale for Development of Alternate Technologies

2020-21	2022-23	2024-27	2028	2029-2030

Off-Line (EPI-2)

EPI-2, 1km/s

Build EPI-3 for Tokamak

Tokamak (EPI-3)

EPI-2 is Built & Ready to Support Operations

*Initial Tokamak Tests & Supporting M3D-C1, NIMROD verifications

Verify an inside to out Thermal Quench & compare to TQ induced by MHD mixing

ITER

Establish Payload Requirements for ITER (Simulations validated by Experiments)

ITER EPI Development & Testing (& addition / final testing on tokamaks

*Requires at least 4 Years of testing on at least two tokamaks

3 to 4 years of off-line work needed before tokamak deployment

DIII-D, JET, K-STAR: primary focus is SPI studies

Other tokamaks should being to develop alternate technologies

(diminishing returns on trying repeat SPI work done on DIII-D/JET/KSTAR – would be OK if we are convinced that SPI is the correct path forward, but this is not the case)

Future Tokamak-based Reactors & ITER Will Require the Level of Device Protection Capability Provided by EPI

- EPI concept for DMS relevant payload acceleration tested on EPI-1 at 0.3T
- EPI-2 core for off-line testing in support of a tokamak deployment built and tested at 1.3T and is now ready to support development tests
  - Basic aspects of sabot stopping and payload separation tested at 150 m/s and can be extrapolated to > 2km/s
- Following two years of development work, a system for deployment on a tokamak would be built during the third year
- At least four to five years of data are needed from at least two tokamaks and or STs to provide the experimental database for M3D-C1/NIMROD validation studies
- These simulations would be used to benchmark against present experiments and then to reliably extrapolate to the needs of ITER and future tokamaks/STs.
- It is important for tokamaks and STs to begin to develop alternate technologies now as several years of time would be needed for testing and validation on present tokamaks