# Prototype Tests of the Electromagnetic Particle Injector Concept Demonstrate Its Primary Advantages for Fast Time Response Disruption Mitigation in Tokamaks

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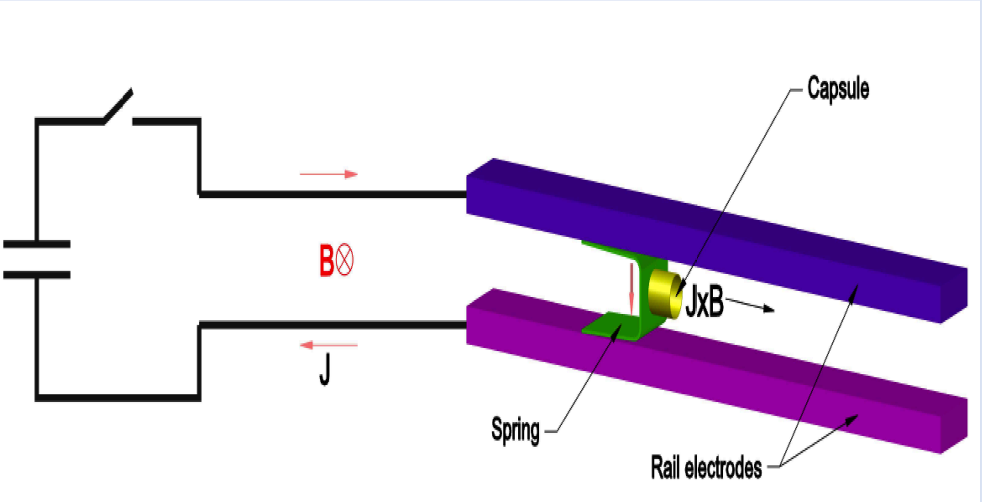
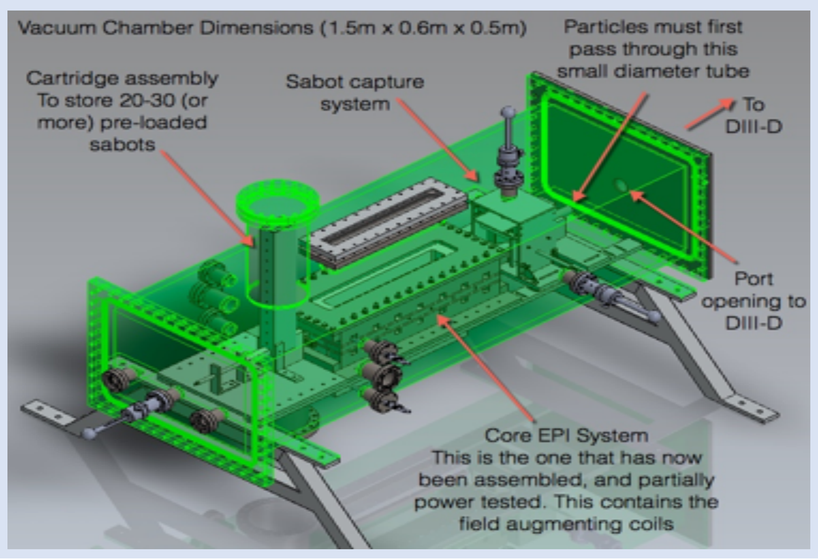
## ABSTRACT


- Some disruptions with short warning times may be unavoidable in ITER
- The Electromagnetic Particle Injector (EPI) is being developed to meet this need (<10 ms overall response time, > 1km/s payload injection speed in ITER)
- Off-line tests have shown attainment of 0.6 km/s in 1ms
- Because of the large size difference between ITER and present experiments, 3d MHD simulations benchmarked with present experiments is necessary to reliably project to ITER
- M3D-C1 is being modified to model the injection of solid pellets

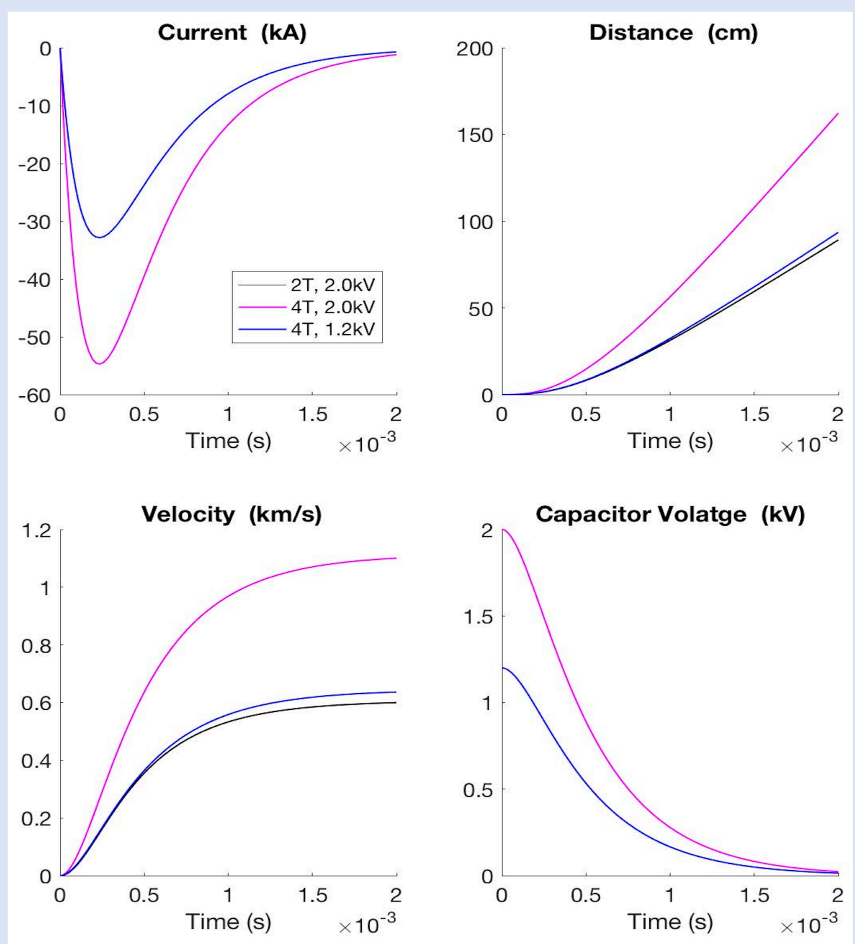

## BACKGROUND

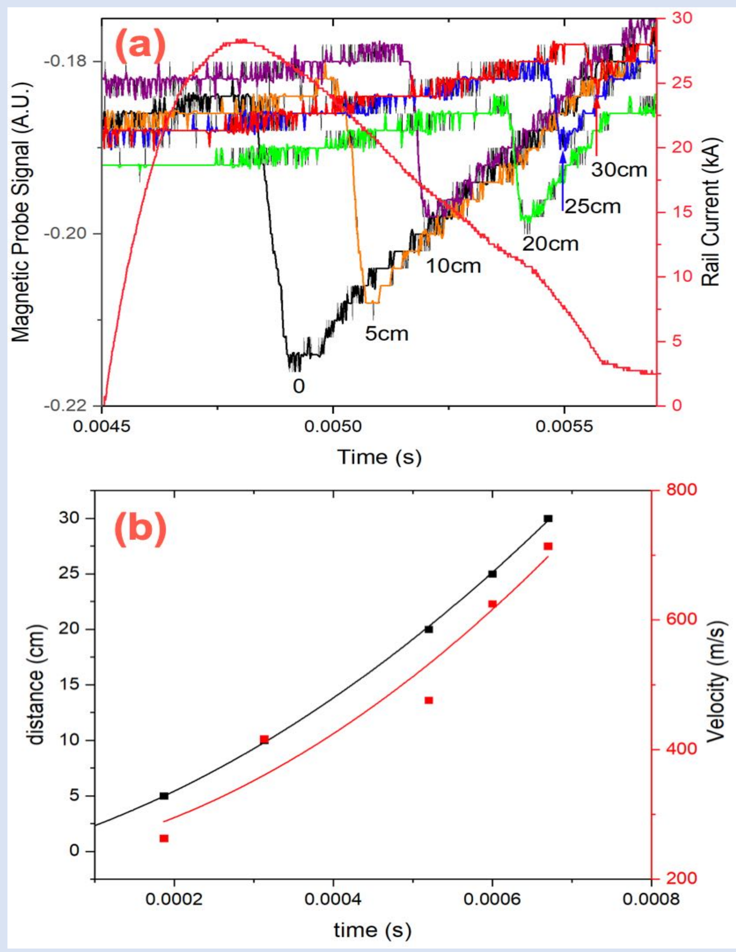
- Shattered Pellet Injection (SPI) has response time of 25 ms on DIII-D, and will have >30ms response time on ITER [1,2]
- Gas load from SPI impact fracturing [3] could trigger early Thermal Quench (TQ) before fragments penetrate deep into ITER
- Fragmentation, gas load [3] combined with variable fragment size and velocity makes SPI penetration modeling challenging
- EPI overcomes these issues by relying on simple electromagnetic propulsion system without the limitations of gas-based systems
- In EPI, a metallic sabot is accelerated to high velocity (>1 km/s in <2 ms) at which point the sabot releases well defined particles or a Shell Pellet




(Left) Cartoon showing the EPI electrical circuit, EPI rail electrodes, the sabot, and the chamber that would contain the radiative payload. A JxB interaction between the current through the sabot and the magnetic field between the rails accelerates the sabot. B can be increased using magnetic coils. (Right) The core EPI that was used in the off-lines tests is shown inside the total system that could be deployed on a tokamak. It contains the boost magnetic field coils currently capable of operation at 3T. The front region contains a sabot capture mechanism, which would retain the sabot inside the green vessel and the payload would travel through a small opening into the target tokamak. Behind the core EPI system is a remote sabot and payload loading mechanism. The overall length of the total system is about 1.5m.

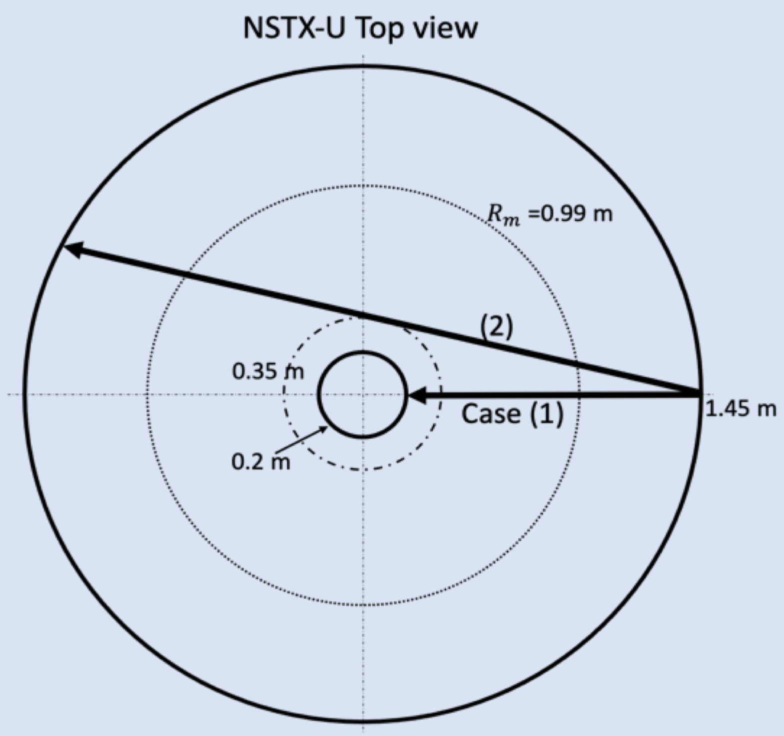


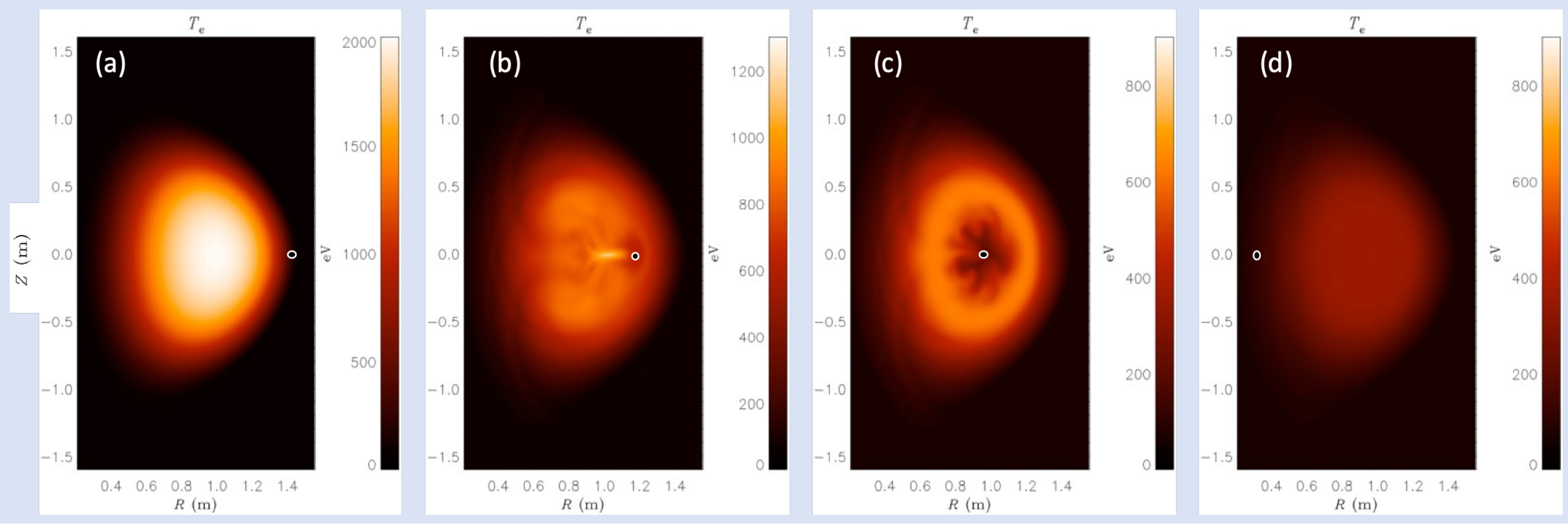

(Left)- Calculated parameters for near term tokamak test. With 4T boost magnetic field, velocities of 0.5 to 1km/s can be attained. (Right) -In a test of velocity potential using 2g sabot, 0.6 km/s was attained in < 1ms. The top right figure shows expanding magnetic field pulse behind the sabot as it moves along the accelerator. The bottom right plot shows distance traveled and velocity of the sabot as a function of time.

## M3D-C1 Simulations

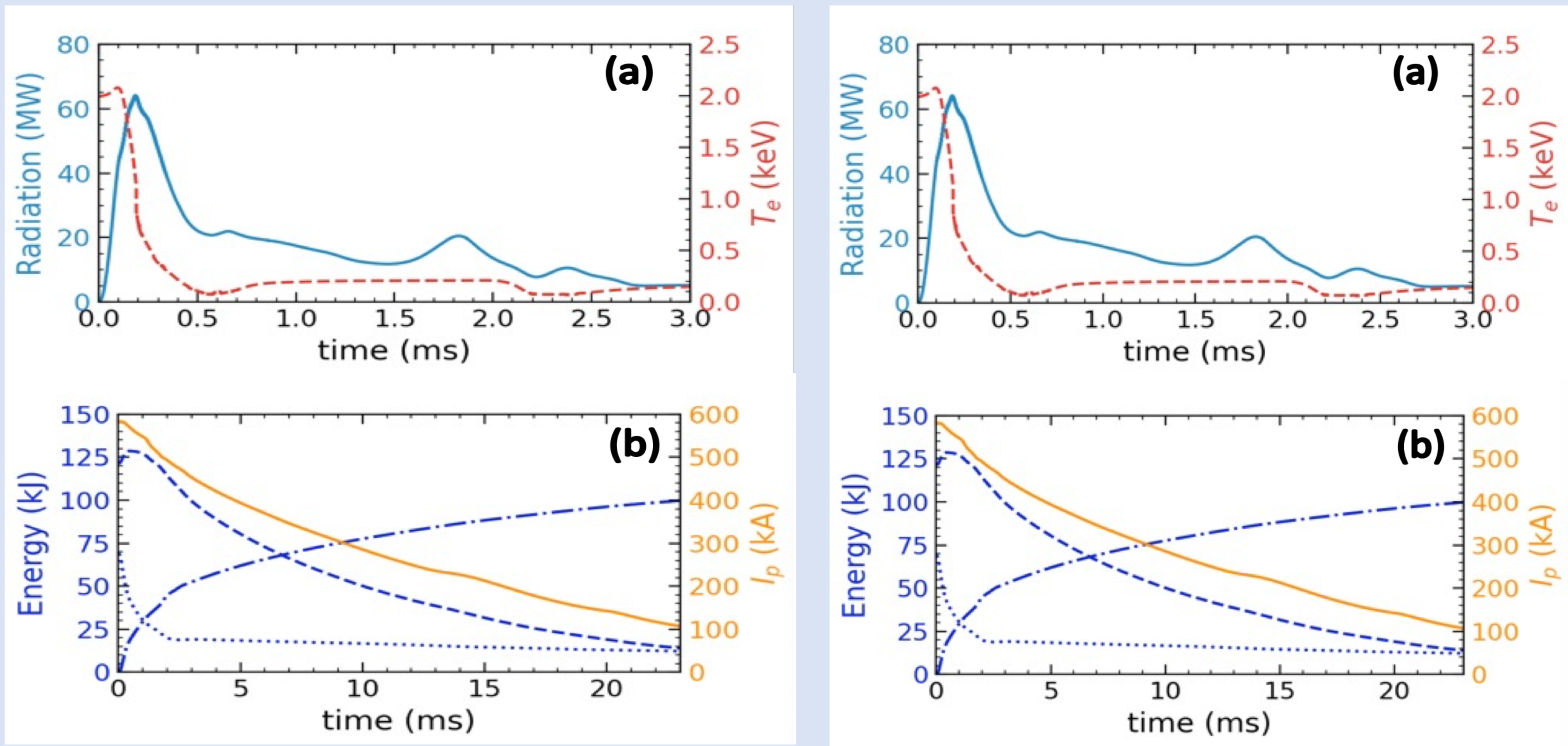
New capabilities being added to M3D-C1 [4] will also be capable of modelling SPI penetration for ITER. The target plasma configuration used for these simulations for the injection of solid carbon pellets is NSTX-U. The ablation model is based on a neutral gas shielding approach (NGS) [5,6] in which the key quantity is the shielding factor $\delta = q_p/q_0$, where $q_p$ is the plasma heat flux that has reached the pellet surface and $q_0$ is the plasma heat flux before entering the pellet neutral cloud. For both strong ($\delta \ll 1$) and weak ($\delta \lesssim 1$) shielding, analytic expressions can be derived [5,6] and interpolated expression that covers both limits proposed in Ref [5] was incorporated in M3D-C1.




Top-down view showing the carbon pellet injection geometry. **Case 1** is for pure radial injection, which minimizes the pellet propagation time to the magnetic axis. **Case 2** is for a shallow injection cases, such as that which is likely to be used in the EPI configuration as in the absence of a plasma, the pellet could leave the vessel through a port at the opposite end of the pellet trajectory. This would avoid the pellet impacting the center stack of the tokamak.




The plasma electron temperature for different time slices (a-d corresponding to 0, 0.235, 0.438, and 1.09 ms respectively) for Case-1 with Velocity of pellet = 1000 m/s. The small circle within the frame shows the pellet position at each time. At t = 0.235 ms, the pellet has propagated to the q = 2.4 surface. The core $T_e$ has dropped from ~ 2 keV to ~1 keV. Central $T_e$ is falling sharply. Field lines at the pellet position are now linked to the plasma core but not to the edge. Pellet radiation is coming primarily from the core and, $T_e$ becomes hollow. At = 0.438 ms, the pellet has reached the magnetic axis. $T_e$ at magnetic axis drops to ~200 eV. At this point the stochastization spreads to the edge and therefore the temperature at the center starts rising due to the hotter edge plasma. Finally, at t = 1.09 ms, the pellet is almost exiting the plasma. Resulting plasma reforms and has a nearly uniform $T_e$ above 250 eV.




(Left Top) Radiated power (solid lines) and $T_e$ (dashed lines) (b) Thermal Energy (TE) is shown by the solid lines and radiated energy by the dashed lines. These are as a function of time for the three injection velocities in Case-1. The total ablated material in these cases ranged from 11% (for 1000 m/s) to 21% (for 300 m/s), leading to a partial thermal quench. (Right) (a) The total radiated power and the central electron temperature for the case of a tangential shell pellet injection at 1 km/s, for the pellet trajectory shown as Case 2 (b) Shown are traces for the plasma current (solid), plasma thermal energy (dotted), plasma magnetic energy (dashed) and total radiated energy (dash-dotted). the total ablated material was ~32%. This was done to increase the effective surface area and to increase the ablation rate.

## CONCLUSION

- Response time: EPI trigger to core payload deposition would be <10 ms in ITER [7]
- Payload size, composition, and velocity are well defined in EPI permitting reliable modeling
- Core deposition would permit inside-out TQ & Runaway Electron suppression (Konavalov, IAEA-FEC 2012, ITR/P1-38)
- Materials used in EPI are fully compatible with ITER requirements
- M3D-C1 simulations show even 300m/s carbon pellets do not fully ablate in 2keV central $T_e$ plasmas, giving confidence that encasing the payload inside a shell (which could be tungsten for ITER purposes) may be a viable way to transport the radiative payload to the core before initiating a thermal quench that first starts outside the q=2 surface
- Tokamak test and parallel MHD modeling efforts are necessary next steps for concept validation

## ACKNOWLEDGEMENTS / REFERENCES

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