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

• 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.

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

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

**Current (kA)**
- Current dramatically as B
- B = 4 T
- B = 0 T

**Distance (cm)**
- All cases: 1 m Accelerator Length

**Velocity (km/s)**
- All cases: 1 km/s in 1ms

**Capacitor Volatge (kV)**
- Power supply size dramatically decreases with increasing B
- @ 8T cap bank only 2x DIII-D or KSTAR - scale system size
Small-scale System Used to Assess Critical Parameters & For Comparison With Projected Calculations

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

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

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

Coil Supports Designed to Restrain Coil Motion

2 T Coil can be upgraded for 3 T operations

Work carried out using leftover funds from NSTX-U MGI deployment grant
Detailed Modeling of Coil Supports (A. Brooks, PPPL)

Displacements
lateral movement less than .07mm

Conductor Stress ~100 MPa

Frame Stress ~126 MPa

Insulation Shear Stress ~15 MPa
EPI-2 Assembly

Coil PS (NSTX-U MGI PS)

SCR triggers

EPI-2 Core Assembly

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

<table>
<thead>
<tr>
<th>Year</th>
<th>EPI-2, 1km/s</th>
<th>Build EPI-3 for Tokamak</th>
<th>*Initial Tokamak Tests &amp; Supporting M3D-C1, NIMROD verifications</th>
<th>Establish Payload Requirements for ITER (Simulations validated by Experiments)</th>
<th>Verify an inside to out Thermal Quench &amp; compare to TQ induced by MHD mixing</th>
<th>ITER EPI Development &amp; Testing (&amp; addition / final testing on tokamaks)</th>
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<tbody>
<tr>
<td>2020-21</td>
<td>EPI-2 is Built &amp; Ready to Support Operations</td>
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<td>2029-2030</td>
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*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 be 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