Disruption Mitigation System Design for ITER

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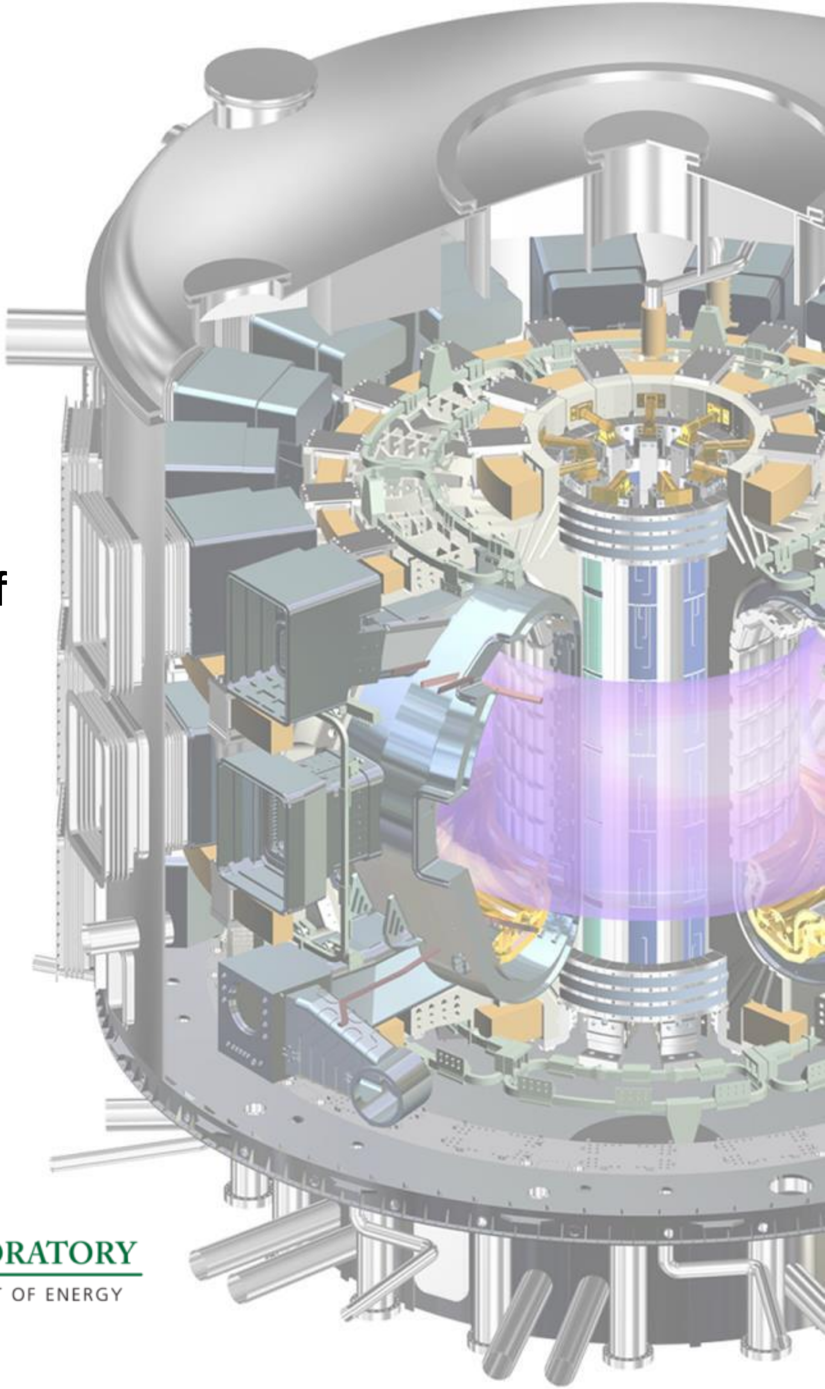


Theory and Simulation of Disruptions Workshop
July 9-11, 2014

US iter

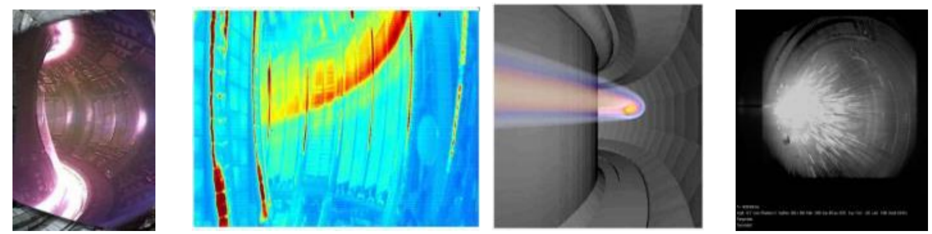
OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE DEPARTMENT OF ENERGY

Outline

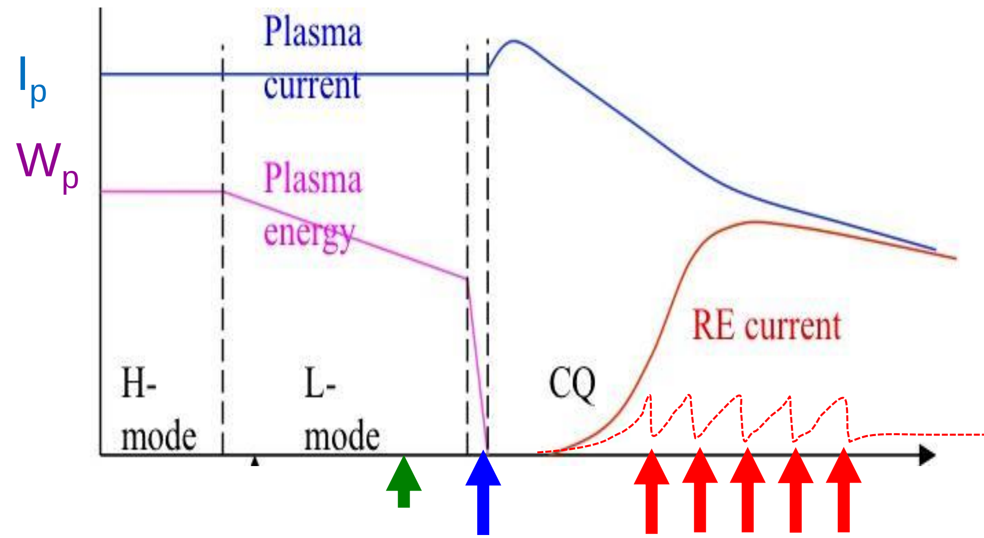
- DMS Requirements
- DMS Design for ITER
- Design Challenges
- Design Progress-to-Date & Schedule
- Summary

Mitigation of Disruptions is a Challenge for ITER

- **Large Thermal Loads occur during Thermal Quench – TQ peak heat loads need reduction of > 10 X**
- **Large Mechanical Loads on plasma facing components and vessel during Current Quench - CQ decay time must be controlled within limits of 50-150 ms**
- **Runaway electrons can be generated during Current Quench - RE current must be suppressed or dissipated to less than 2 MA**
- **Mitigate with solid and gas injection of deuterium, argon, neon and helium**
- **Developing tools and techniques for:**
  - **Massive gas injection (MGI)**
  - **Shattered pellet injection (SPI)**



Burning Plasma	Disruption Precursor	Thermal Quench	Current Quench	Runaway Electrons



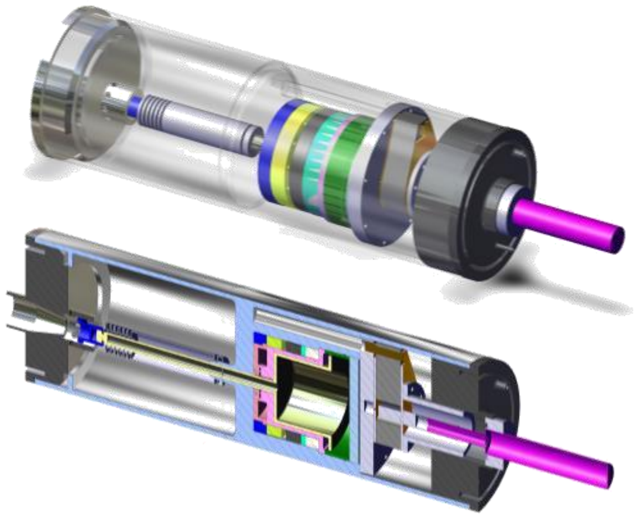
Preventive SPI and MGI of material for **Thermal Mitigation** and **Runaway Electron Suppression**

MGI and SPI **RE Dissipation**

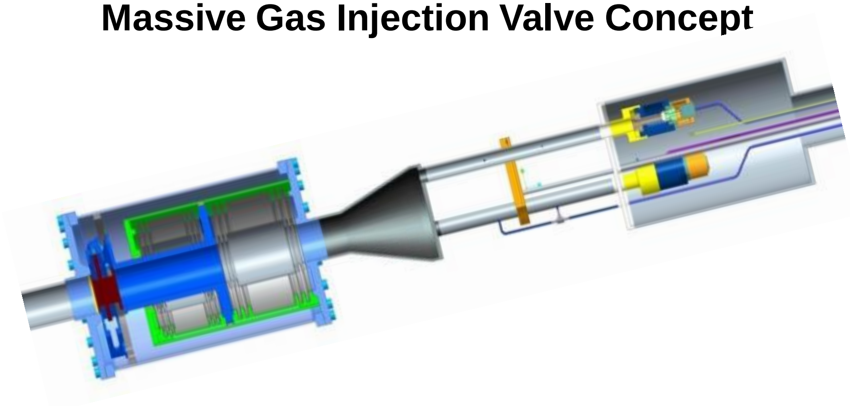
Disruption Mitigation System Material Injection Requirements

DMS Requirements: Deliver rapid shattered pellet and massive gas injection systems to

- Limit impact of plasma disruption thermal and mechanical loads on walls and vacuum vessel – up to 10 kPa-m^3 of D_2, Ar, Ne, He in < 20 ms
- Suppress the formation and effects of high energy runaway electrons – up to 100 kPa-m^3 in < 10 ms
- Reliability and Maintainability
- Are these requirements compatible?

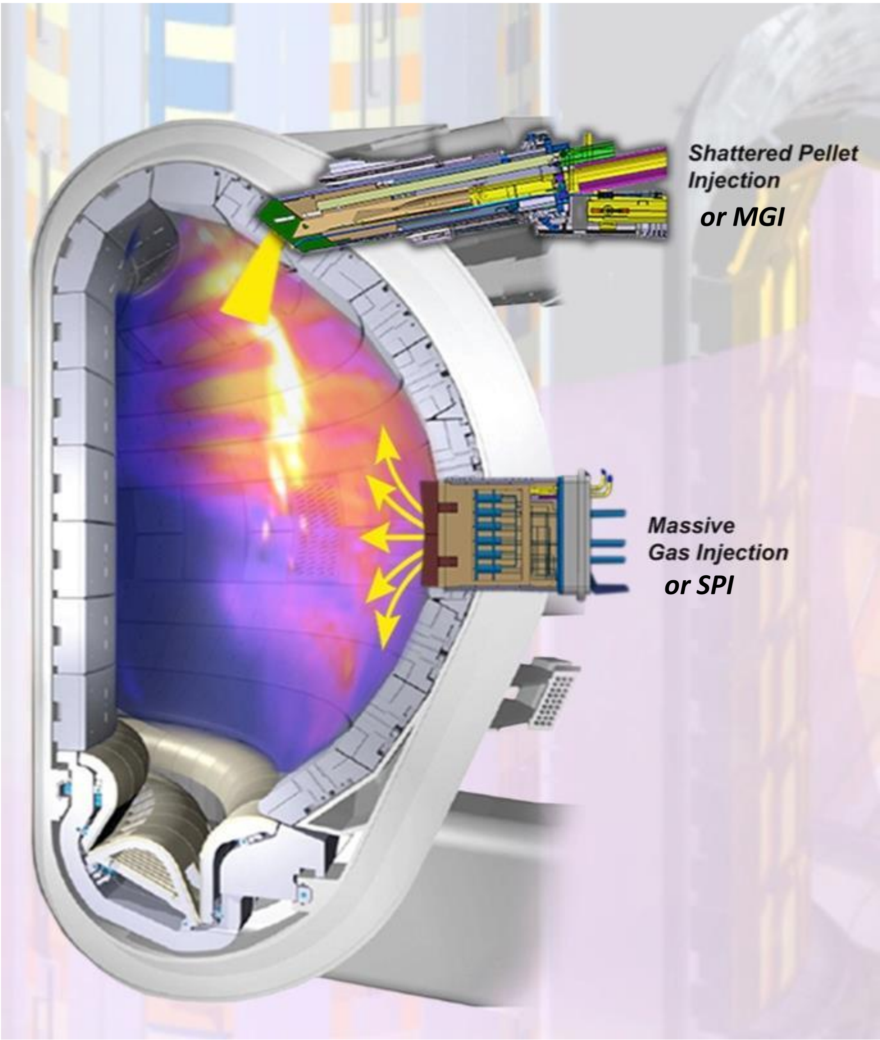


Massive Gas Injection Valve Concept



Shattered Pellet Injector Concept

Disruption Mitigation System Configuration



DMS Configuration:

- Shattered pellet injector (SPI) or Massive gas injection (MGI) located in 3 upper ports with pellet shattered near plasma edge
- SPI has multiple barrels for redundancy and adjusting amount injected
- MGI or SPI located in 1 equatorial port for runaway electron mitigation
- Combinations of MGI and SPI are possible

Significant Design and Technical Achievements

- **Requirements defined by IO with input from ITPA and fusion community**
- **Fusion science and technology community workshop**
  - Identification of candidate technologies & techniques for effective mitigation
- **DMS Conceptual Design Review and consideration of viable candidates**
  - Down selection to massive gas injection and shattered pellet injection
- **Technology development in laboratory**
  - Fast massive gas injection valves
  - Production and long term sustainment of large deuterium and neon pellets
  - Optimization of pellet shatter geometry
- **Technology deployment and demonstration on fusion devices**
  - Initial demonstrations of thermal mitigation and runaway electron dissipation
  - Argon pellet injector deployed for controlled triggering of REs in disruptions
- **Modeling of technology and disruption mitigation experiments**
  - Models of gas flows, pellet fragmentation and assimilation in disruption plasma
  - Modeling of effects of ITER DMS (yet to be achieved)

Disruption Mitigation System Design Status and Plans

- CDR complete
- Design underway for
  - Massive gas injection (MGI)
  - Shattered cryogenic pellet injection (SPI)
- Hardware for SPI and MGI subsystems must be tested on fusion experiments to determine effectiveness
  - Experiments are performed by fusion community with their resources
  - Initial tests of DMS techniques and technologies for ITER underway in lab and at DIII-D
  - U.S. ITER and VLT supports SPI and MGI experiments with hardware
  - Simulations to determine effectiveness on ITER are needed

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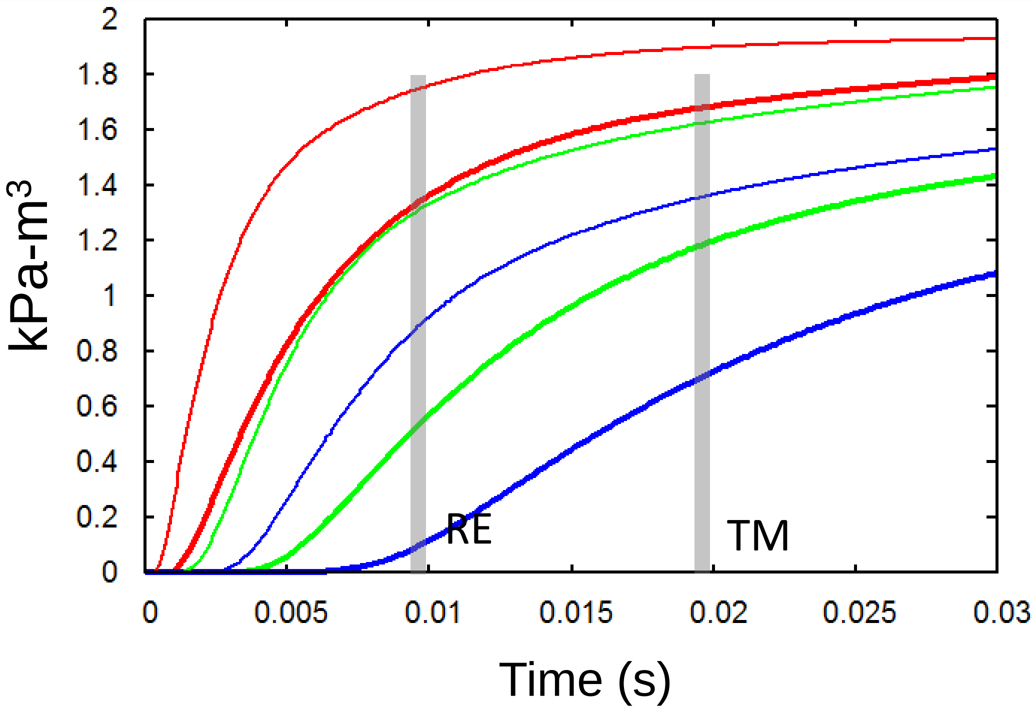
MGI Integrated Mass Flow into Plasma for Different Gases/Distances



28mm valve orifice and tube I.D.

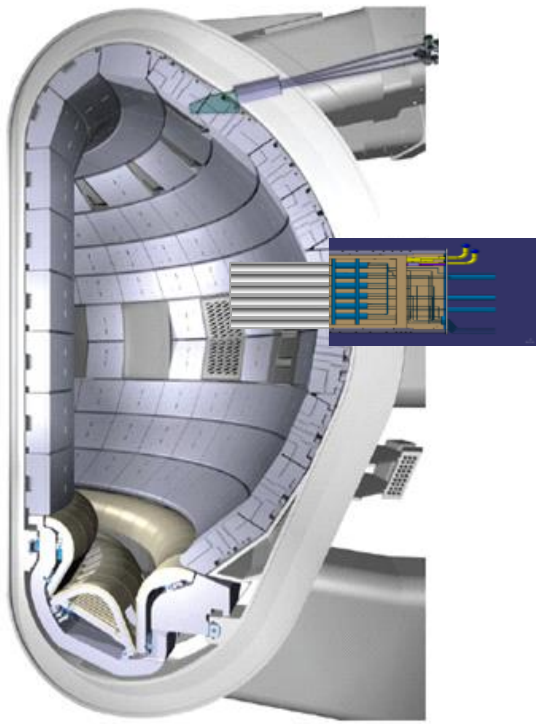
2 kPa-m^3 in reservoir

Ideal opening valve assumed.

- Ne and D_2 calculations for a 28mm valve/tube size
- D_2 and Neon at 1m achieves the 90% injection within 20ms – the specified response TM cannot be achieved with neon MGI at 4m, 60% is possible

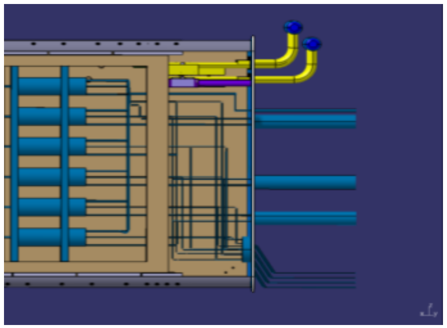
CFD calculations – SonicFOAM

MGI and SPI for RE Suppression/Dissipation Installed **Inside** Equatorial Port Plug to Meet Injection Time Requirements



Up to 100 kPa-m^3 for runaway electron suppression and dissipation

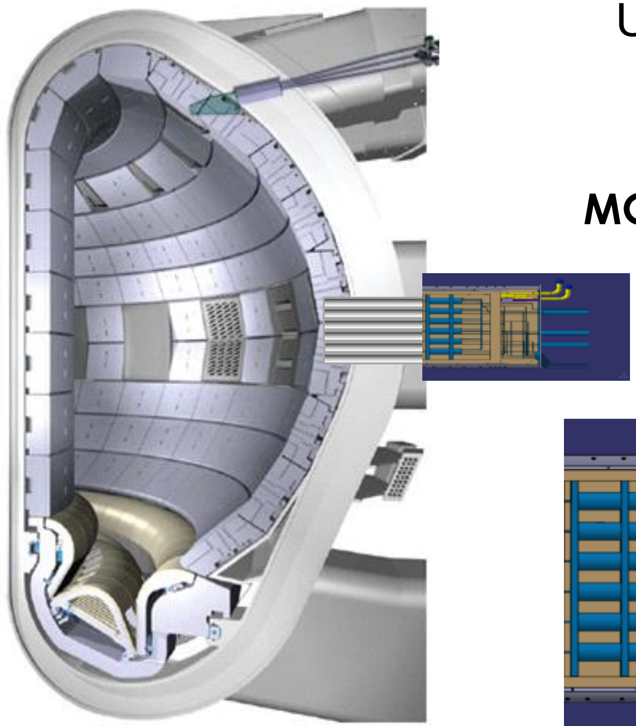
MGI and SPI DMS



MGI fast gas valves use a stainless steel valve seat with Vespel polyimide plugs

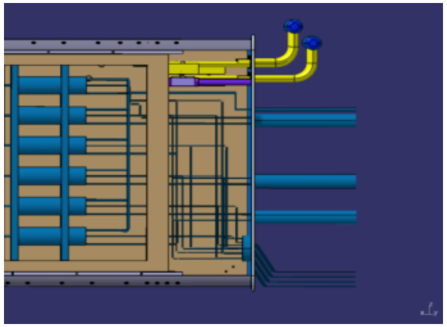
- MGI located in one equatorial port plug for runaway electron suppression/dissipation to meet injection time requirement - limited by sound speed of gas
- Combination of SPI and MGI is possible
- **Design challenges with active MGI components located inside port plug**

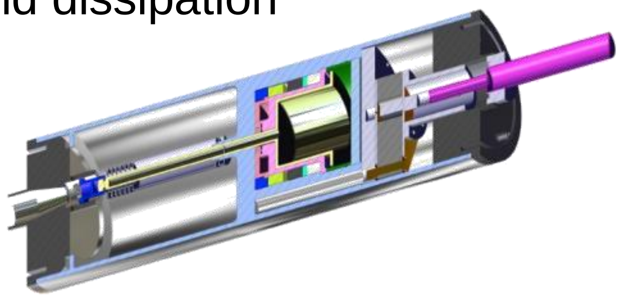
MGI and SPI for RE Suppression/Dissipation Installed **Outside** Equatorial Port Plug for Reliability and Maintainability



Up to 100 kPa-m^3 for runaway electron suppression and dissipation

MGI and SPI DMS

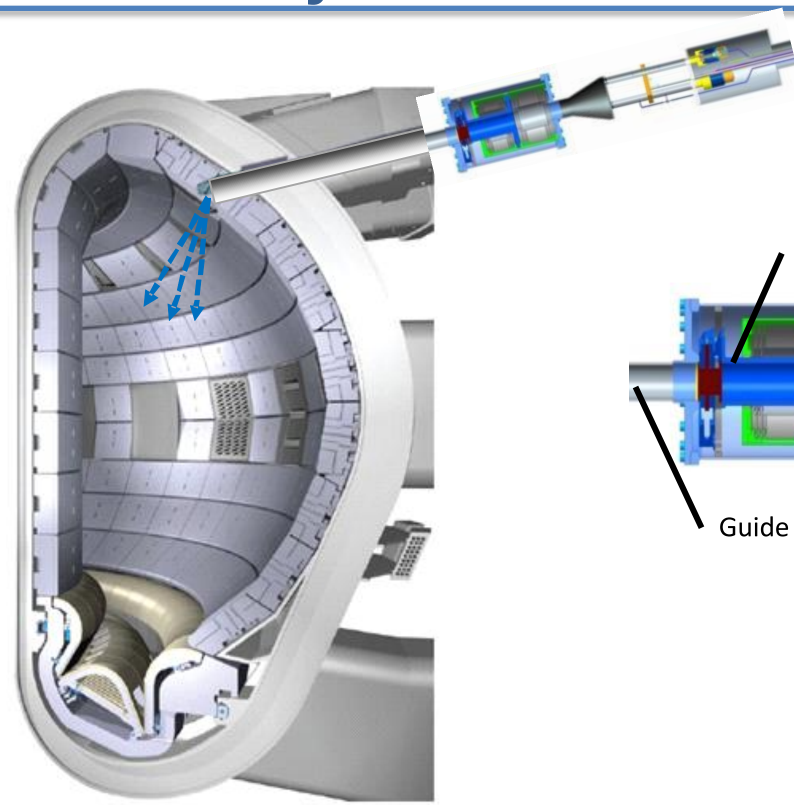




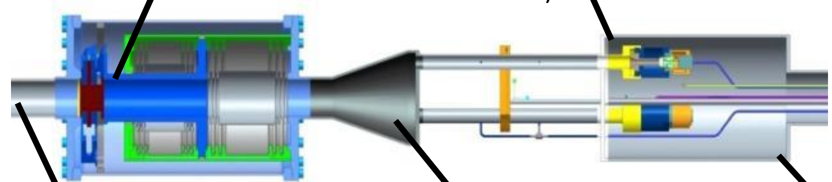
Stainless steel valve seat with Vespel valve plugs

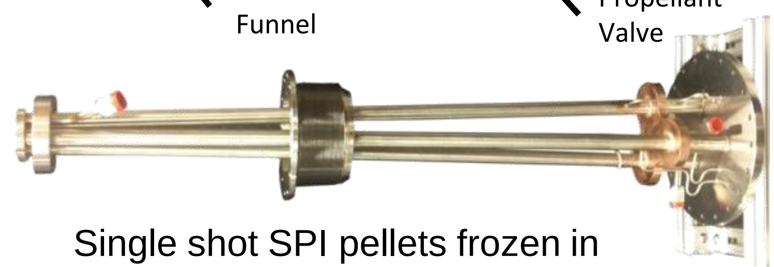
- MGI located in one equatorial port plug for runaway electron suppression/dissipation
- Combination of SPI and MGI is possible
- **Design challenges decrease with active components located outside port plug, but time response is longer**

Shattered Cryogenic Pellet Injection Active Components Installed **Outside** Upper Port Plugs for Reliability and Maintainability



Injector has multiple barrels
Combination of MGI and SPI is possible





Single shot SPI pellets frozen in
short cold section of guide tube

- SPI located in upper port plug(s) with pellet shattered near plasma edge
- Injector has multiple barrels for redundancy and adjusting amount injected – combination of MGI and SPI is possible
- **Challenges decrease with active SPI components located outside port plug**
- **Injection time is marginal to meet 20ms requirement for TM**

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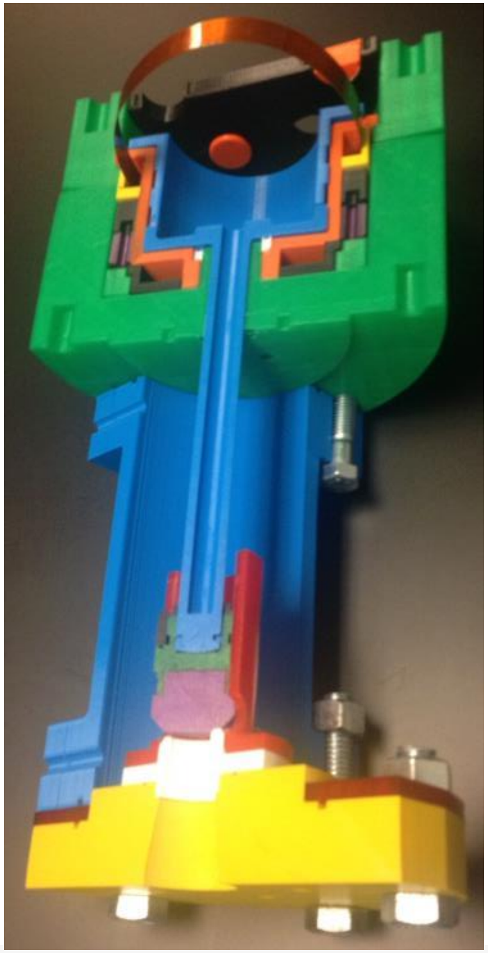
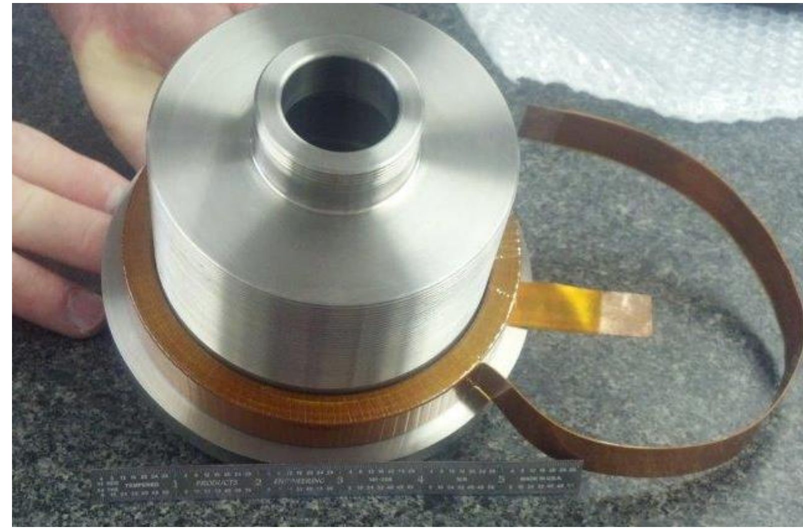
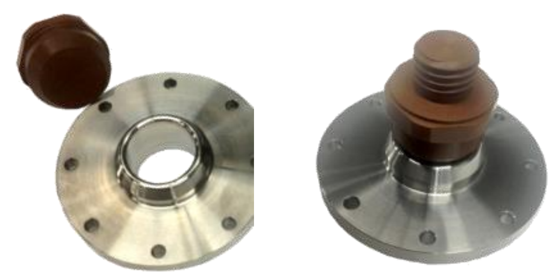
Massive Gas Injection Valve Prototype

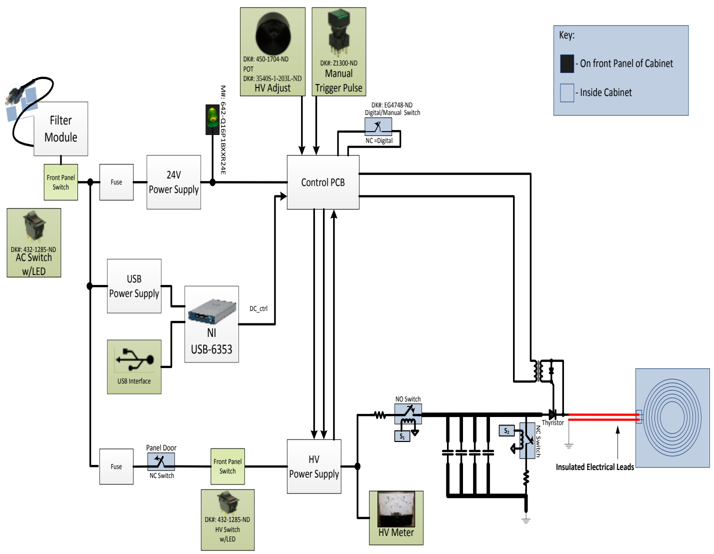


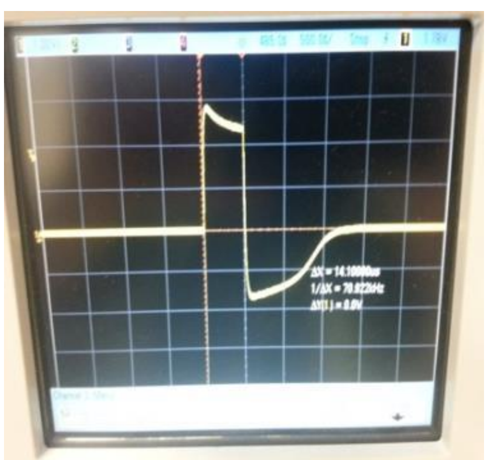




Valve based on a design used on JET, but modified for ITER tokamak environment and injection requirements. MGI Valve uses Flyer Plate to Achieve Fast Opening Time and incorporates T compatible components

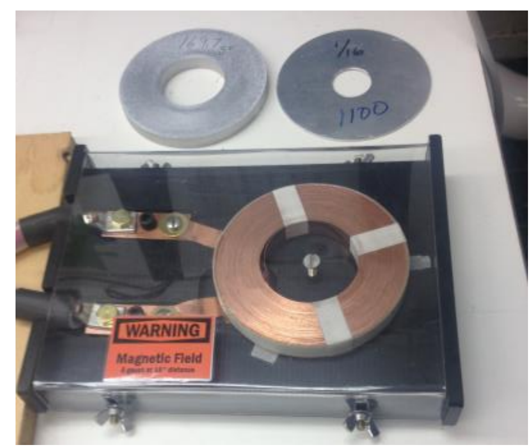
Design, Fab and Test of MGI Power Supply Completed



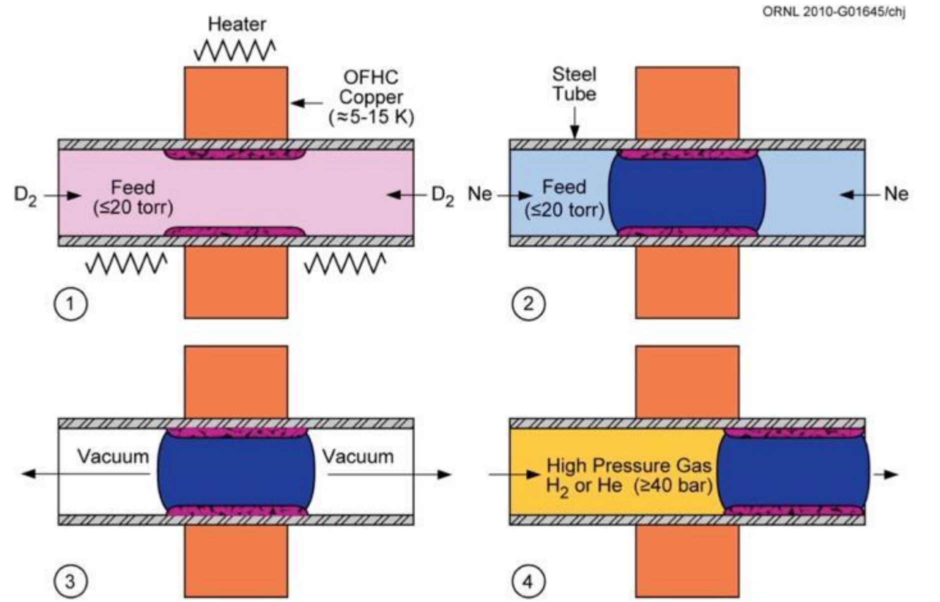


SCR Triggering Requirements:

- ~5V, ~300mA, ~100μs duration
- ~15 ohm load

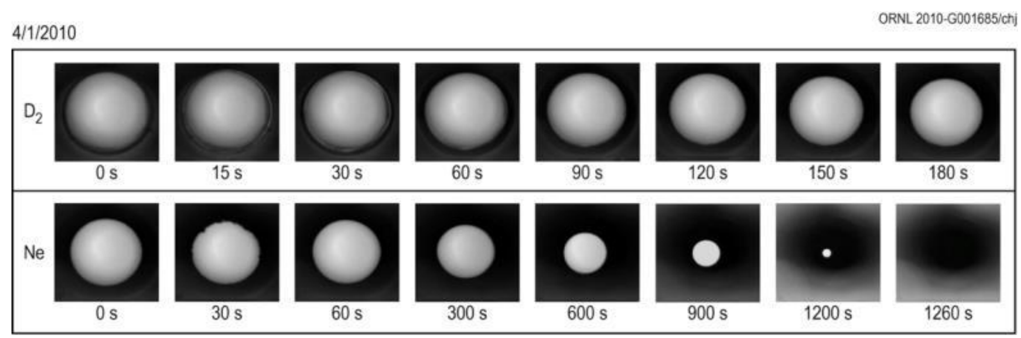


SPI 3-Barrel Prototype Completed



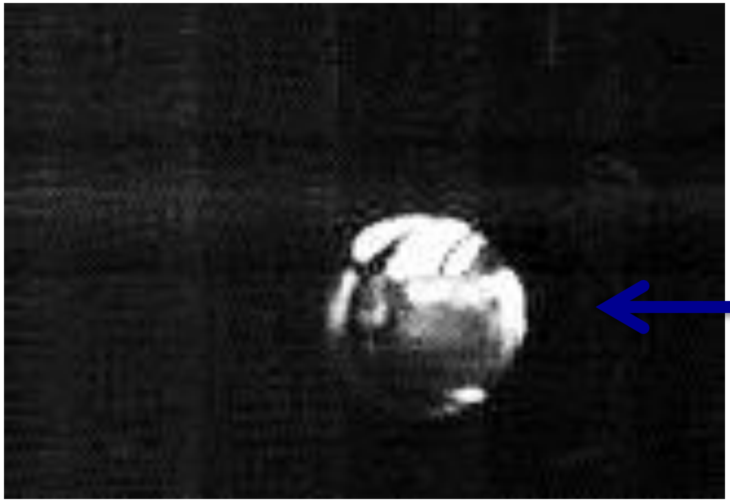
- **Barrel inner diameter increased to 24.4 mm (from 16 mm diameter) in order to study scaling of freezing/forming of D_2 and neon pellets.**

- **Larger size will reduce the number of barrels needed for DMS.**

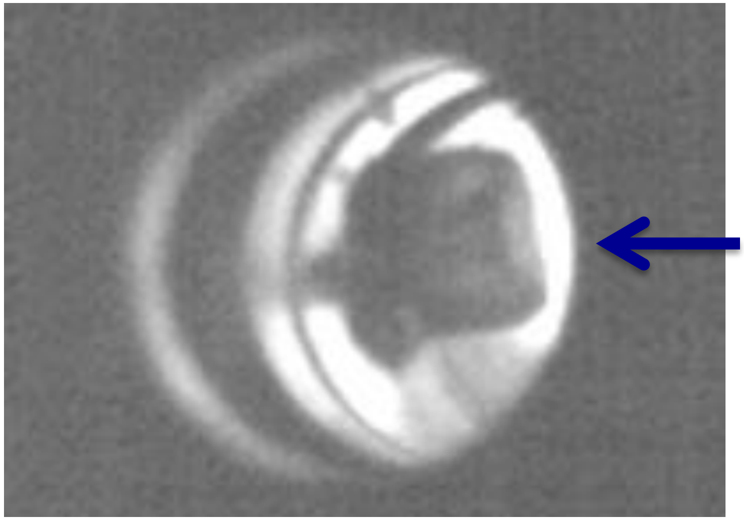


25 mm D_2 and Neon Pellets Formed and Accelerated from 3 Barrels

- **3 ea. ~ 25 mm pellets formed and accelerated to 330 m/s**
- **1.5 kPa-m^3 of deuterium each. 2 pellets exceed the requirement of 2 kPa-m^3 for thermal mitigation**
- **Future testing planned for 41mm diameter pellets**



25 mm neon

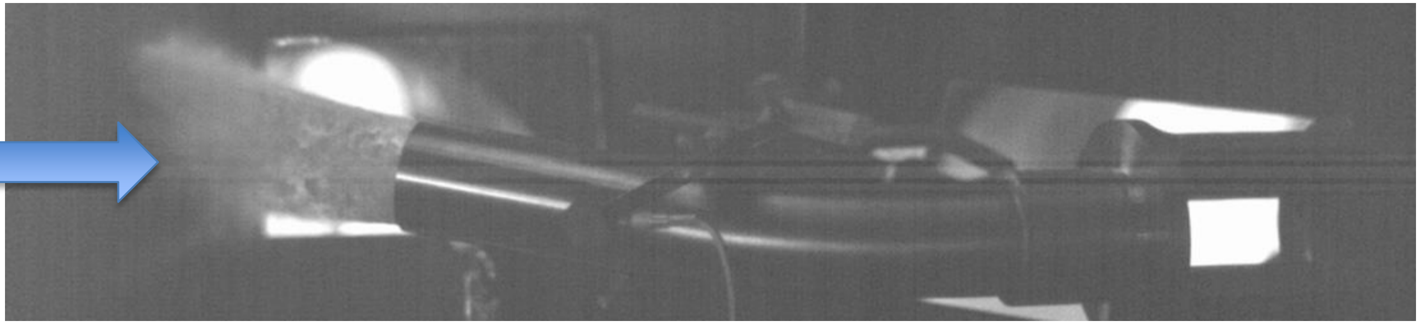


25 mm D_2

Disruption Mitigation – Laboratory Testing of Neon Pellet Shattering

Pellet in transit

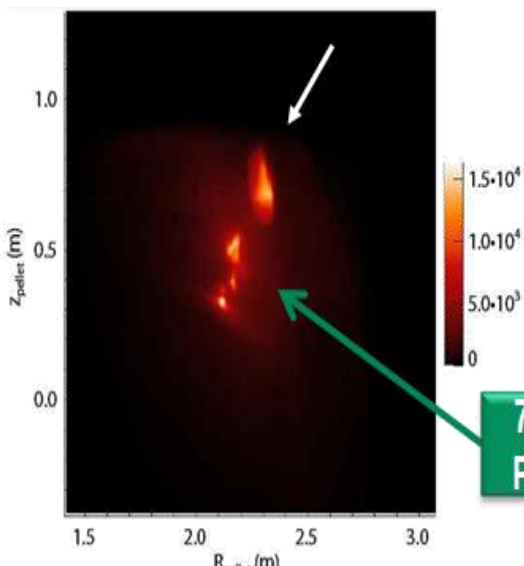
Plume of the shattered neon pellet after passing through bend



Disruption Mitigation – Field Testing of Neon Shattered Pellet

- **Additional pumping capacity eliminates issues with leading edge propellant**

Disruption mitigation experiments planned on DIII-D throughout remainder of 2014



- **Barrel diameter downscaled to 7 mm for thermal mitigation testing on DIII-D**

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Milestone: Complete Disruption Mitigation System PDR (September 2014)

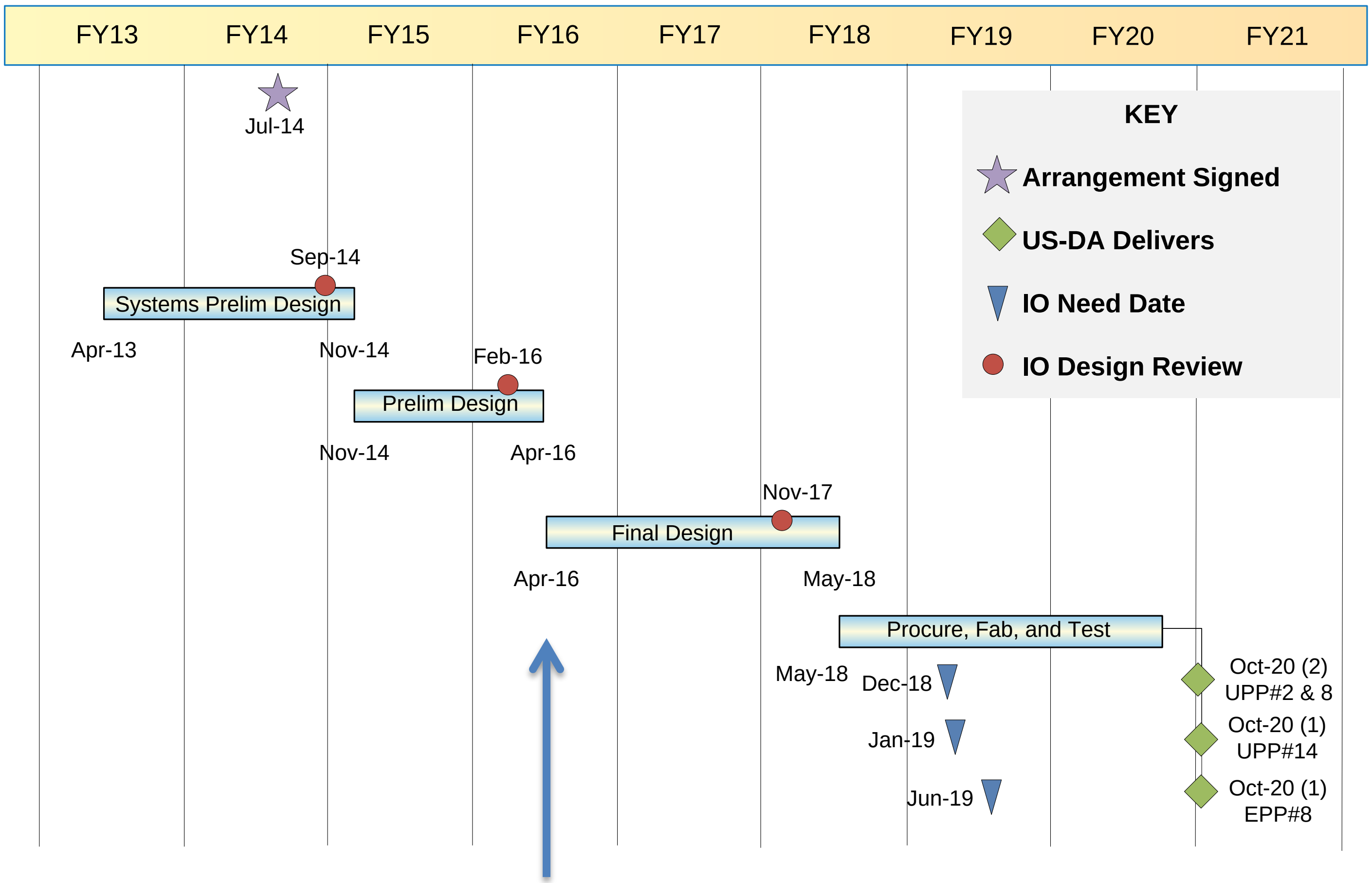
Pre-SPDR tasks and responsible parties

- IO completes physics studies to determine maximum allowable response time
- IO completes PCR to reserve space for outside of the port plug location
- Tokamak experiments and IO analysis provide guidance on MGI vs SPI material assimilation, TQ, CQ and RES effectiveness and need for multiple toroidal and/or poloidal injection locations
- US completes P&IDs for MGI and SPI options
- US performs 3-barrel injector tests
- US determine the maximum obtainable pellet speed
- US completes the design, fabrication and initial testing of the MGI valve
- US completes the design and fabricate MGI valve firing electronics

SPDR Outcomes

- Most promising DM technology identified at SPDR becomes basis for remaining PD and port plug interfaces
- Backup DM technology design placed on hold and minimum hardware and design needed for associated port plugs
- Update Systems Requirements to reflect latest physics and hardware understanding

Disruption Mitigation Summary Schedule (based on detailed schedule with 321 activities)



Need Reliable Simulation/Prediction of DMS Performance

Schedule Drivers:

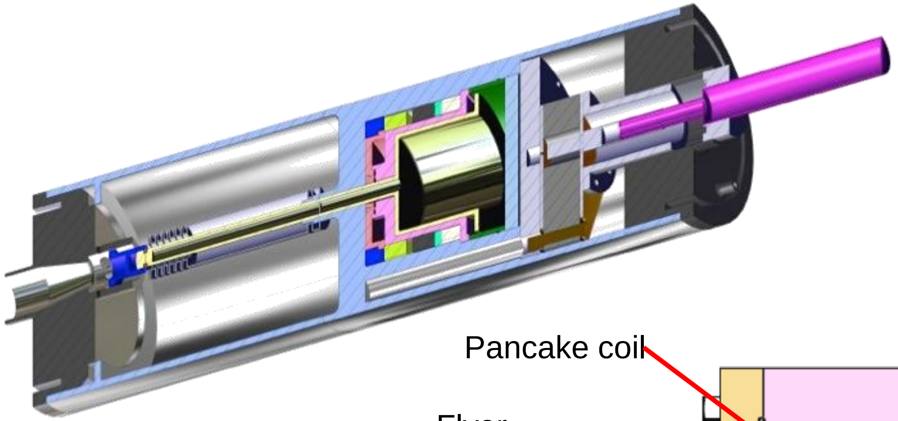
- Final design of components that meet response time and interface requirements
- Fabrication durations for specialized components
- Requires experimental time on DIII-D, JET, etc. to deploy and qualify DMS components
- Critical path
  - Test program
  - Funding profile

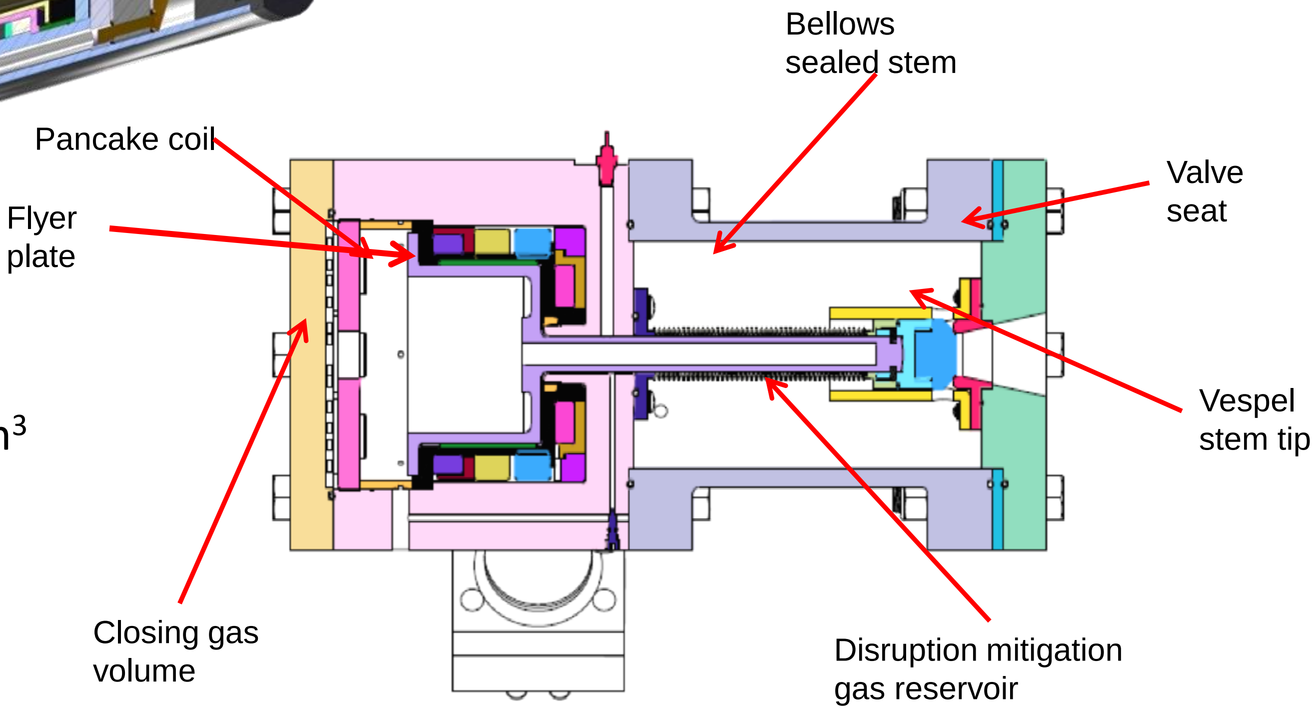
Summary

- DMS scope and schedule are well defined and being executed
  - CDR Complete
  - Down selection to SPI and MGI following December 2012 CDR
  - Hardware for candidate SPI and MGI being designed, fabricated and tested
  - International fusion community is actively engaged
  - Design and qualification integrated with DMS research partners
  - Cost is capped by agreement with IO
- Present Challenges - Injection response vs Reliability
  - Harsh port plug environment and reliability requirements
  - Minimum response time for runaway electron suppression and dissipation
- **More simulation and modeling needed to resolve requirement issues**
  - Needed for Final Design of DMS

BACKUP ONLY

Massive Gas Injection Valve Prototype





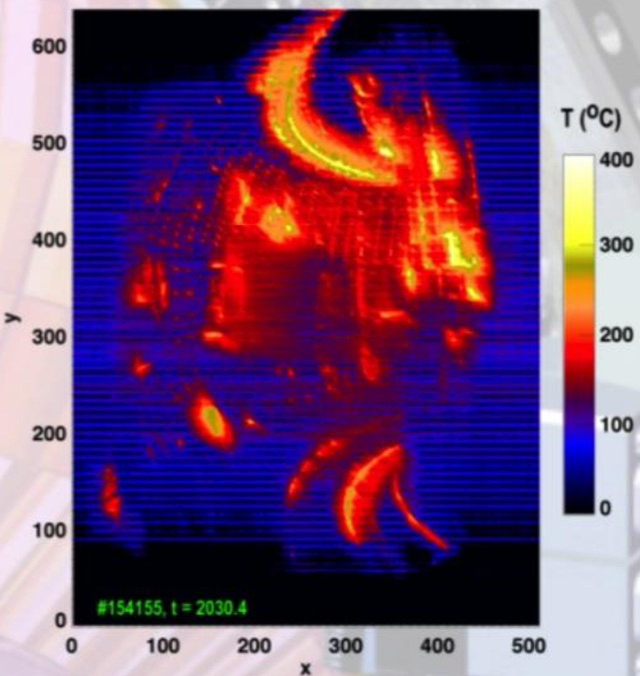
Full size - 8 kPa*m^3 injected gas mass

Valve based on a design used on JET but modified for ITER tokamak environment and injection rate requirements. Modified Valve uses Flyer Plate to Achieve Fast Opening Time and incorporates T compatible components

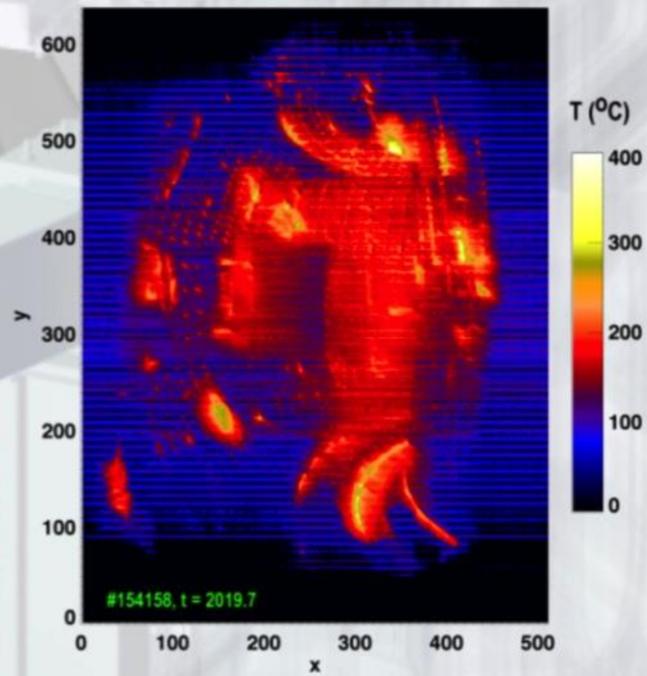
Massive Gas Injection on DIII-D

Experimental Progress

Effective mitigation of thermal quench with massive gas injection has been demonstrated on JET, DIII-D, ASDEX-U and C-MOD tokamaks. Mitigation with shattered pellet injection has also been demonstrated on DIII-D.

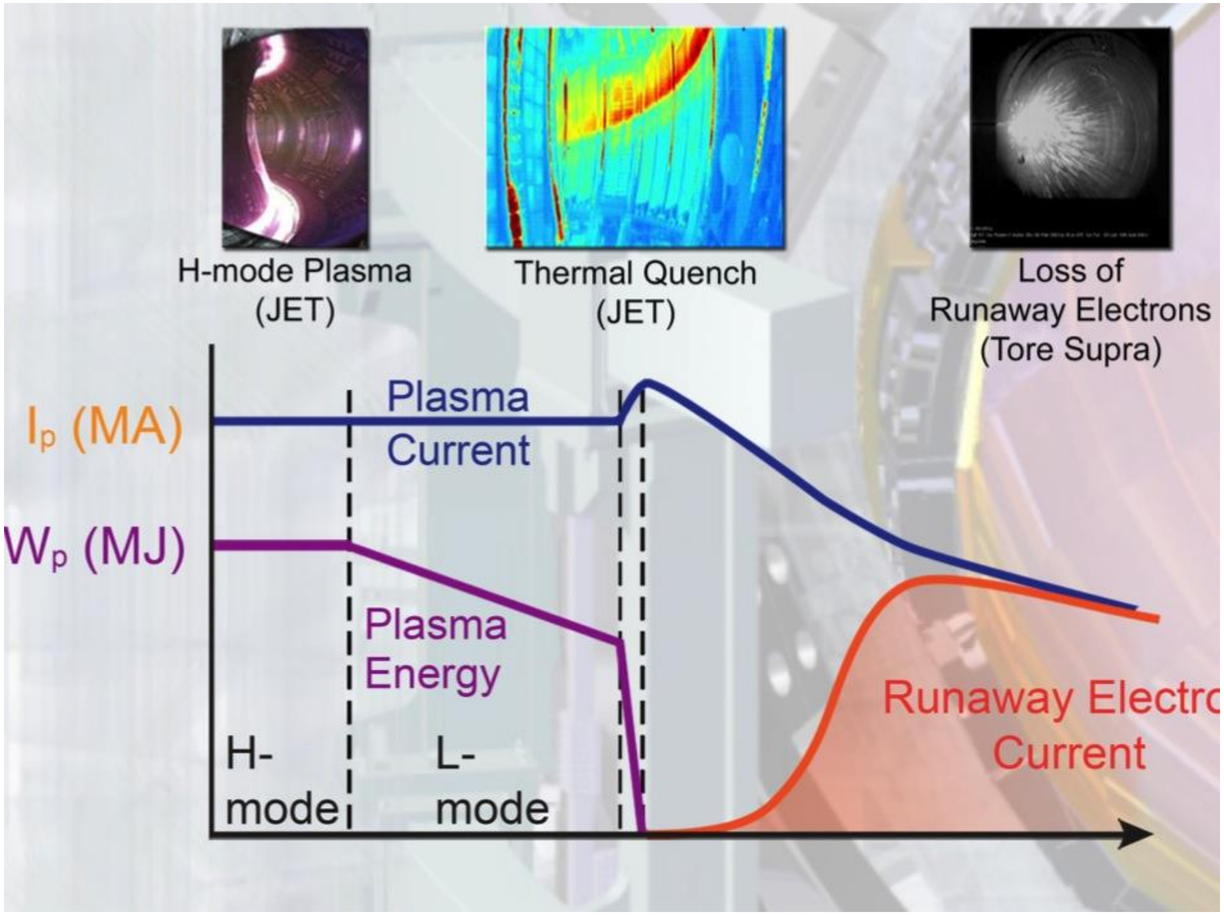


Unmitigated Upward Vertical Displacement Event on DIII-D



Mitigated Upward Vertical Displacement Event on DIII-D

Disruption Mitigation System

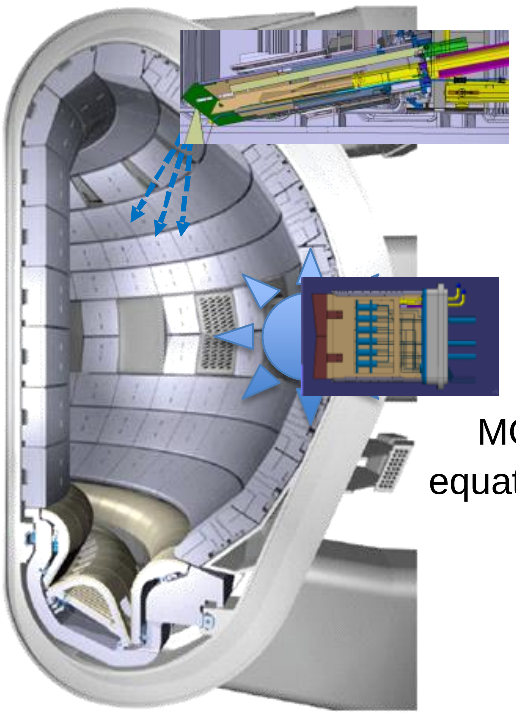


Requirements:

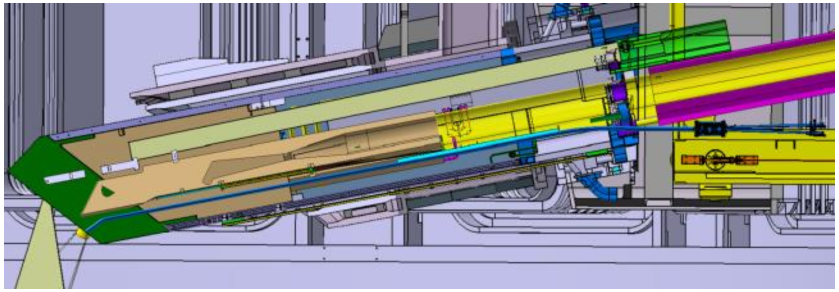
- Mitigate heat loads from rapid plasma thermal quench (response time ~10 ms)
- Mitigate mechanical loads from plasma current quench (response time ~200 ms)
- Suppress or dissipate runaway electron current (response time ~500 ms)

Disruption Mitigation Includes Injection of Pellets Shattered at Plasma Edge and Gas Injection through Delivery Tubes

- **Mitigate impact of the disruption thermal and current quench**
  - **Use large shattered pellets composed of neon with a deuterium shell**
- **Suppress and dissipate runaway electrons**
  - **Use massive gas or shattered pellet injection**



SPI located in upper port plugs with pellet shattered near plasma edge



MGI located in equatorial port plugs