Disruption Mitigation System Developments and Design for ITER


Oak Ridge National Laboratory
*ITER Organization

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Outline

• DMS Requirements
• DMS Design for ITER
• Design Challenges
• Design Progress-to-Date
• 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)

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?
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 – can be used as MGI
- 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 acceleration 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

• Calculations for Ne and D$_2$ with a 28mm valve/tube size
• D$_2$ and Ne 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

- 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**

Up to 100 kPa-m³ for runaway electron suppression and dissipation

MGI fast gas valves use a stainless steel valve seat with Vespel polyimide plugs
MGI and SPI for RE Suppression/Dissipation
Installed Outside Equatorial Port Plug for Reliability and Maintainability

- 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

Up to 100 kPa-m³ for runaway electron suppression and dissipation

MGI and SPI DMS

Stainless steel valve seat with Vespel valve plugs

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

- 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

Injector has multiple barrels
Combination of MGI and SPI is possible

Single shot SPI pellets frozen in short cold section of guide tube
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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 D$_2$ and neon pellet formation/acceleration.
- SPI uses MGI valves to accelerate pellets and can be used as MGI system when no pellet is formed.

View of freezing process from end of barrel
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 34mm diameter pellets for RE suppression
Disruption Mitigation – Laboratory Testing of Neon Pellet Shattering

Pellet in transit

Plume of the shattered neon pellet after passing through bent tube
Disruption Mitigation – Field Testing of Neon Shattered Pellet

- Additional pumping capacity added eliminates issues with leading edge propellant

Disruption mitigation experiments carried on DIII-D in 2014 – results presented at APSDPP 2014

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

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

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

Need Reliable Simulation/Prediction of DMS Performance
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

• 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

Disclaimer:
The views and opinions expressed in this paper do not necessarily reflect those of the ITER Organization.
Thank you
BACKUP ONLY
Milestone: Complete Disruption Mitigation System PDR (November 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
Massive Gas Injection Valve Prototype

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.

Full size - 8 kPa*m³ injected gas mass
Massive Gas Injection on DIII-D

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.
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