ITER Disruption Mitigation System Design Status

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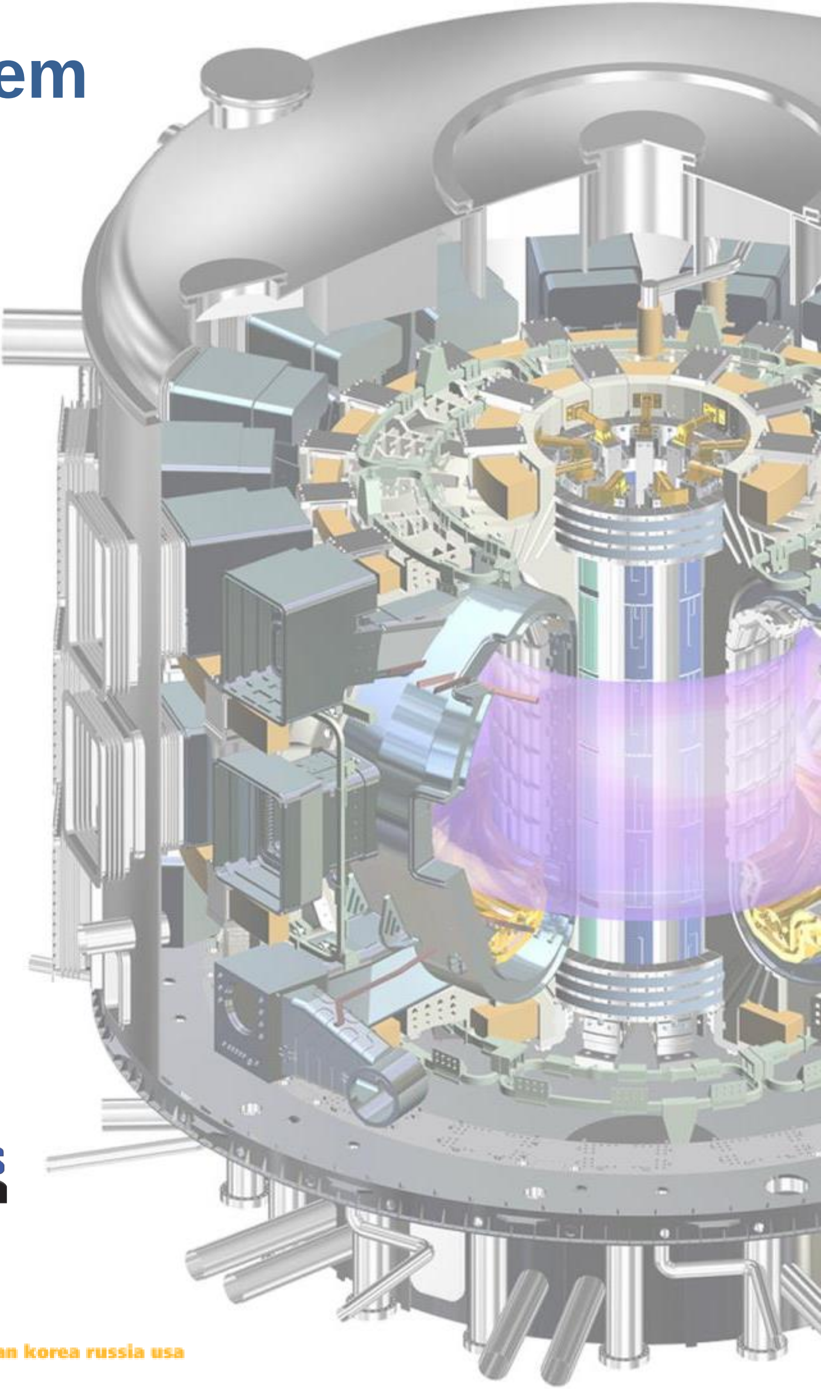
Oak Ridge National Laboratory
*ITER Organization

IEA Workshop on the Theory and Simulation of Disruptions

July 13-15, 2015



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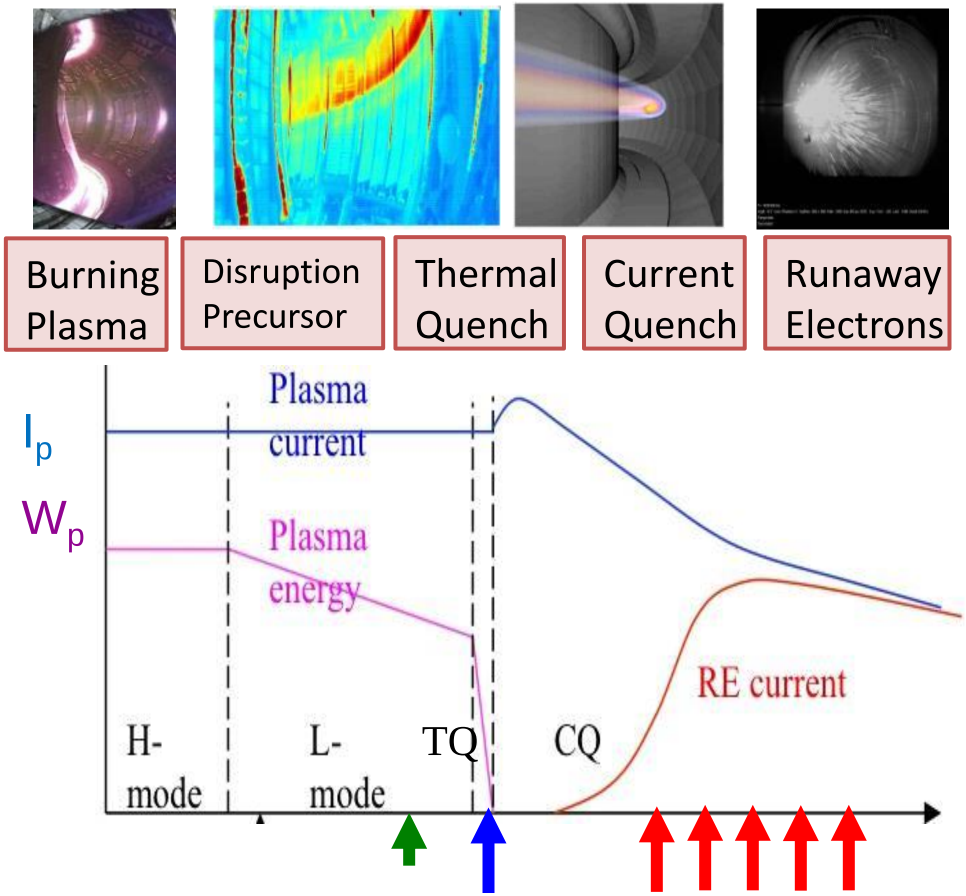
Outline

- DMS Purpose & Requirements
- Technology Developments for DMS
- DMS Preliminary Design Details and 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)**



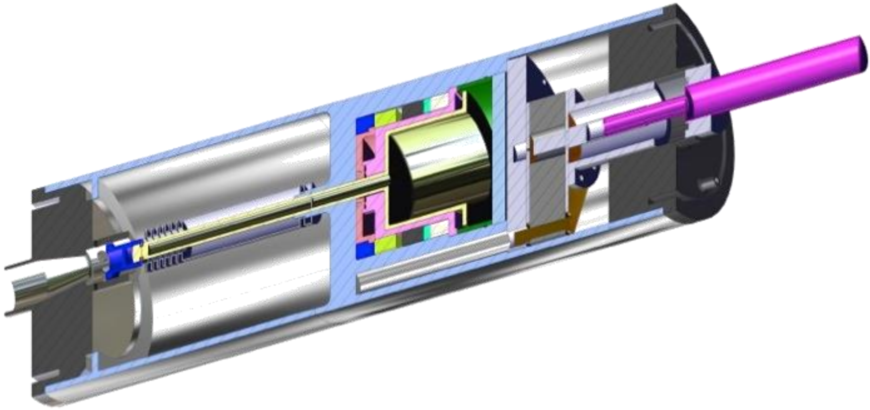
Preventive SPI and MGI of material for **Thermal Mitigation** and **Runaway Electron Suppression**

MGI and SPI **RE Dissipation**

Disruption Mitigation System Material Injection Requirements

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

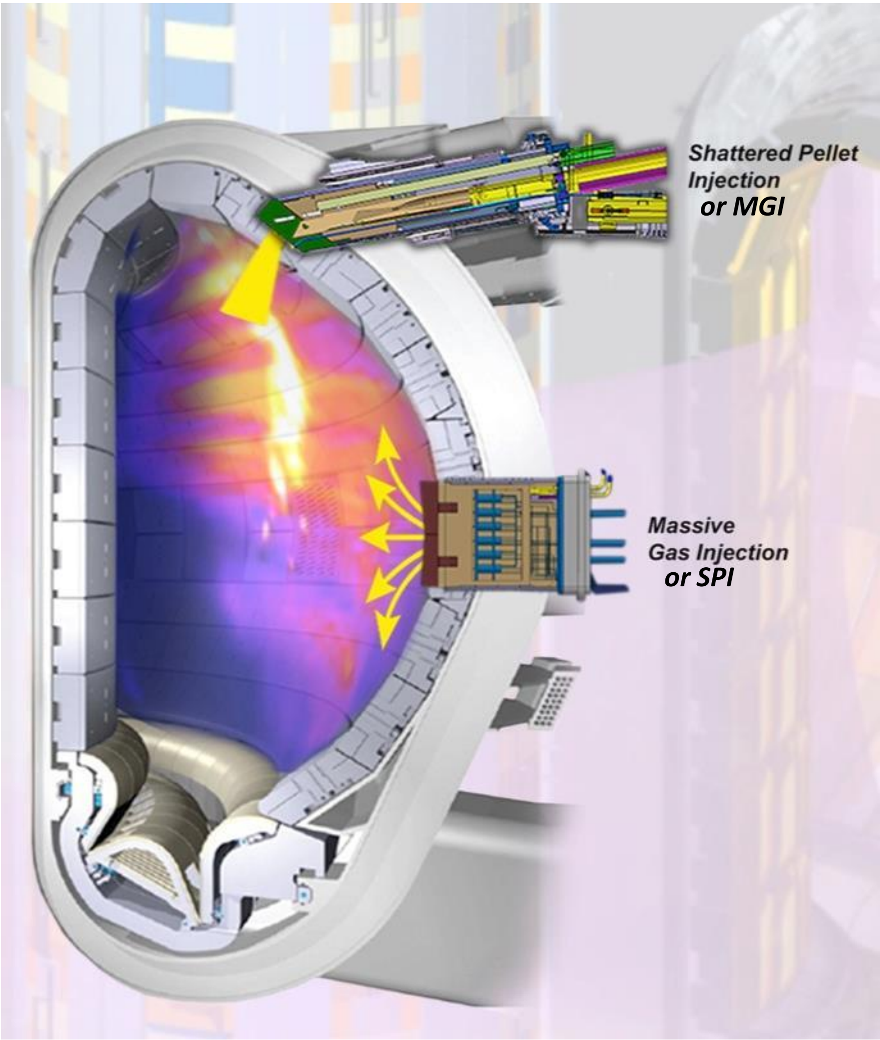
- Limit impact of plasma disruption thermal and mechanical loads on walls and vacuum vessel – up to 10 kPa-m^3 (100 bar-L) of D_2, Ar, Ne, He in < 20 ms
- Suppress the formation and dissipate high energy runaway electrons with multiple injections – up to 100 kPa-m^3 (1000 bar-L) in < 10 ms after TQ
- Reliability, Redundancy, and **Maintainability**



Massive Gas Injection Valve

Shattered Pellet Injector

Disruption Mitigation System Configuration



DMS Configuration:

- Shattered pellet injector (hybrid SPI/MGI) located in 3 upper ports with pellet shattered near plasma edge
- SPI has multiple barrels for redundancy and adjusting amount injected
- Multiple SPI located in 1 equatorial port for runaway electron mitigation
- Combinations of MGI and SPI are possible with hybrid injectors
- Injectors located outside port plugs for maintenance access.
- 1 dedicated close coupled MGI in upper port plug for non-nuclear phase

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 Preliminary Design Review consideration of viable candidates**
  - Down selection to shattered pellet injection with hybrid injectors
- **Technology development in laboratory**
  - Fast massive gas injection valves
  - Production and long term sustainment of **large** deuterium and neon mixture 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)

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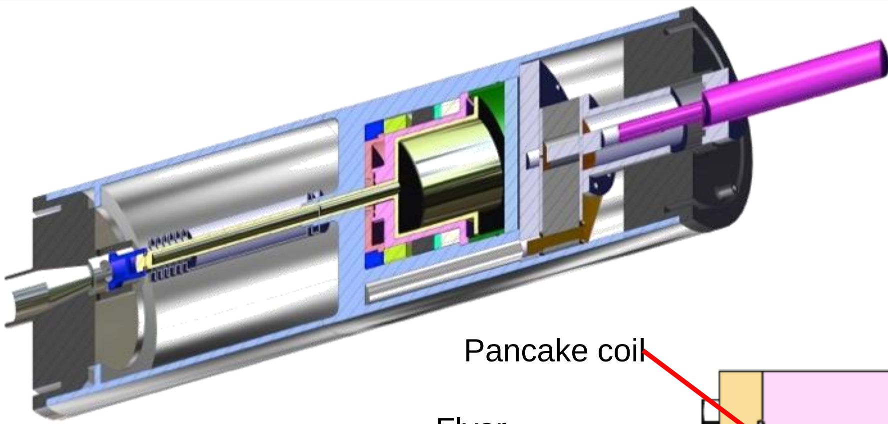
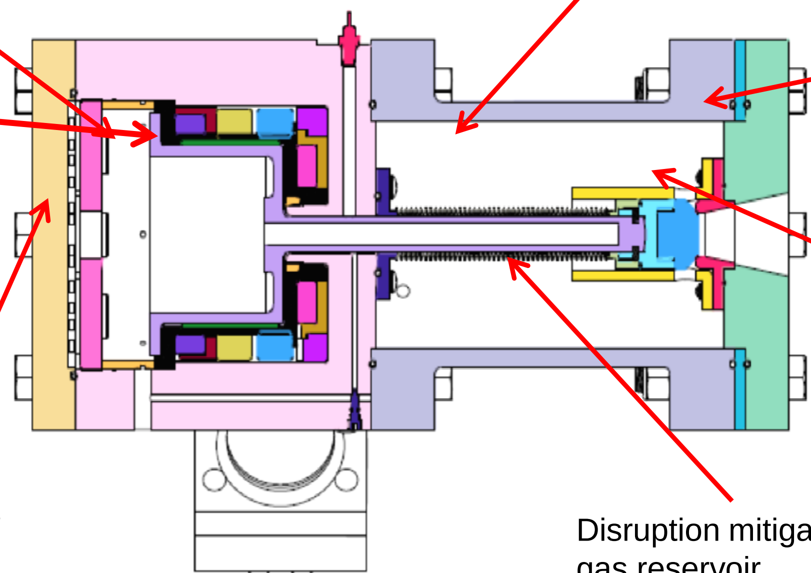
Massive Gas Injection Valve Prototype Design

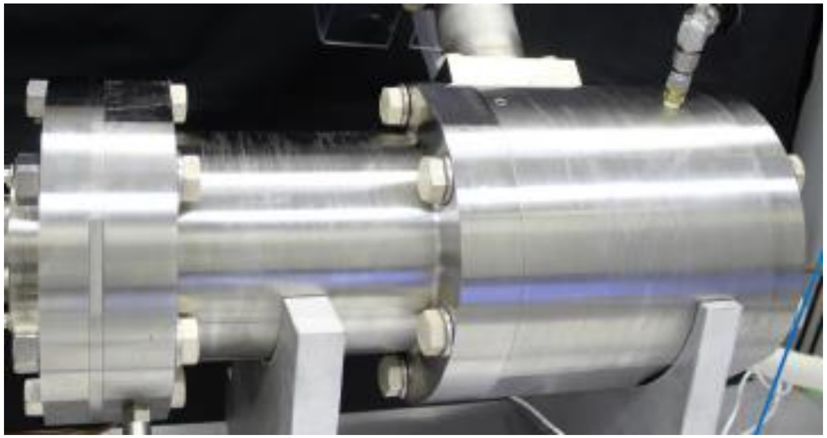


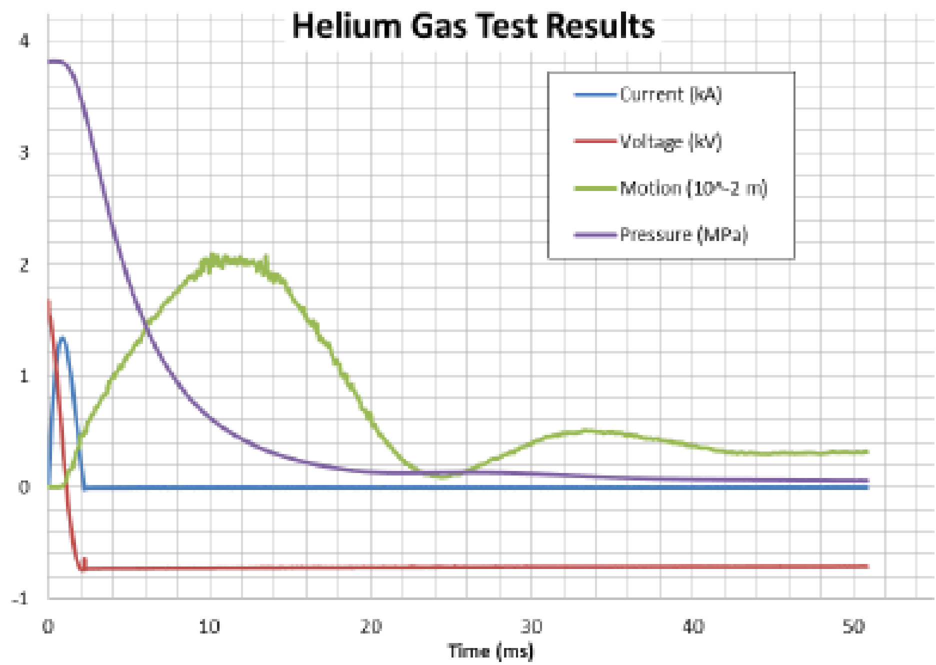
Full size - 8 kPa*m^3 injected gas mass



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

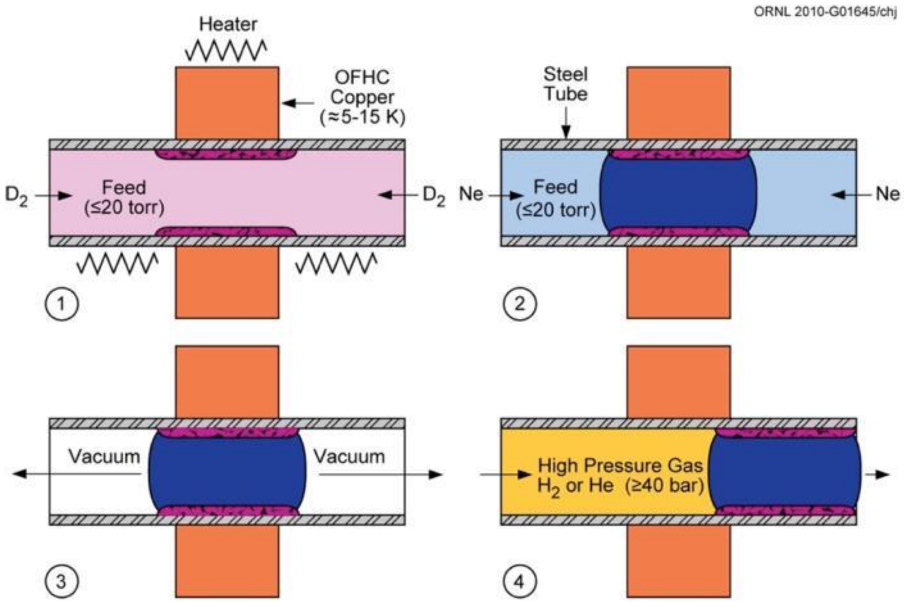
Massive Gas Injection Valve Prototype Fabricated and Tested





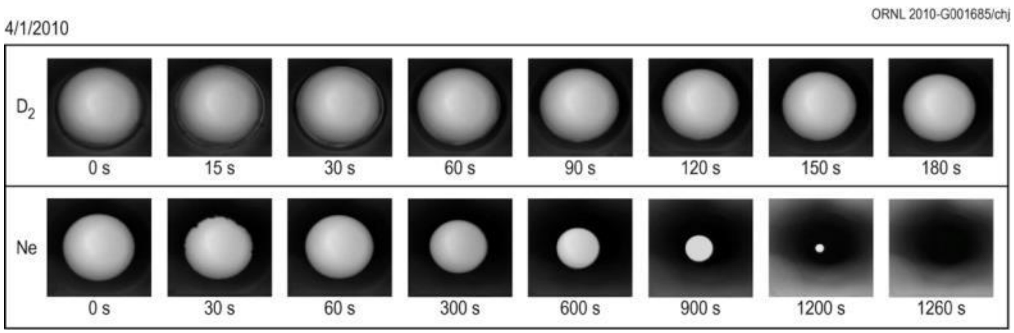
The valve includes a tip design and all-metal valve stem sealing for compatibility with tritium and high neutron and gamma fluxes. Helium leak rate of tip to seat < 2×10^{-6} mbar-L/s after 3000 cycles.

SPI 3-Barrel Prototypes Completed and Tested



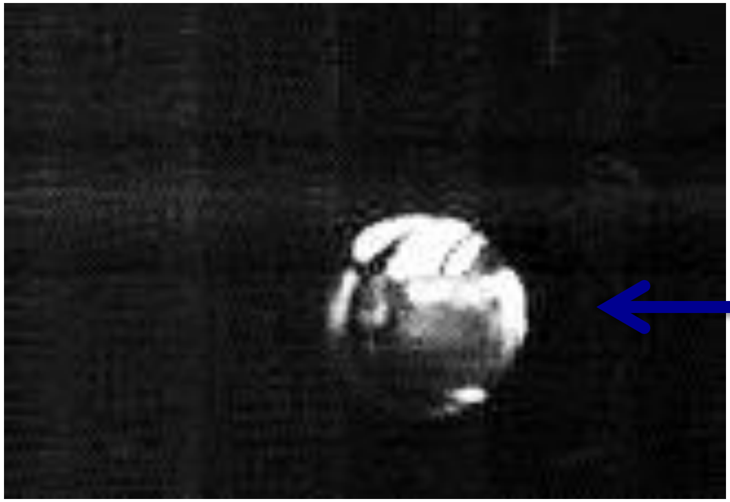
- **Barrel inner diameter increased to 24.4 mm (from 16 mm diameter) in order to study scaling of freezing/forming of D_2 and neon pellets.**

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

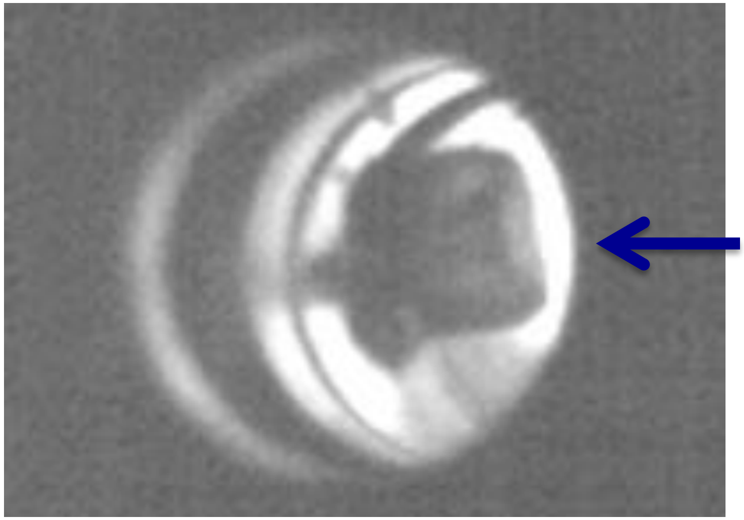


25 mm D_2 and Neon Pellets Formed and Accelerated from 3 Barrels

- **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**
- **Pellet maintained in the barrel ready to fire for over 6 hours**

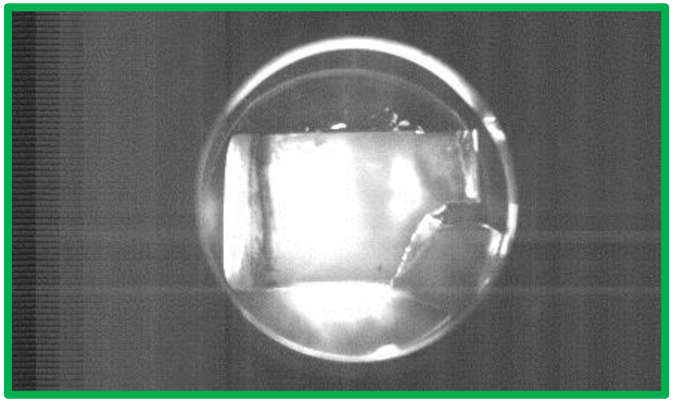


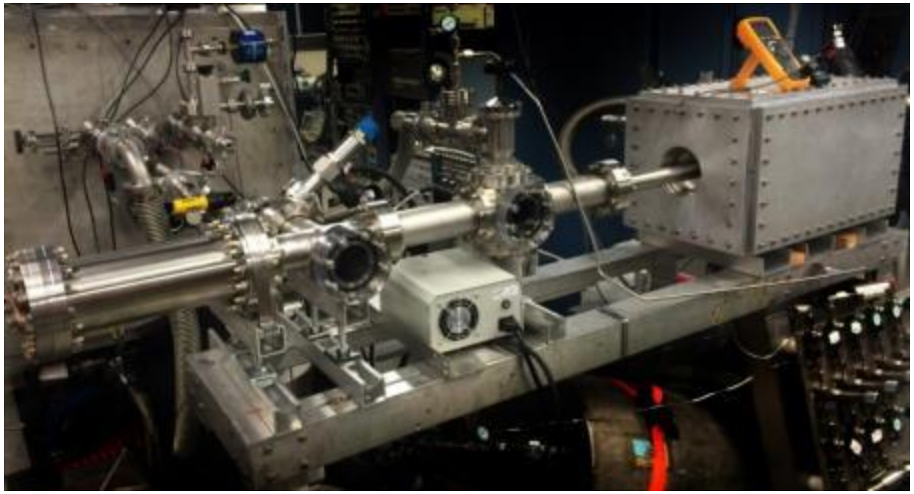
25 mm neon



25 mm D_2

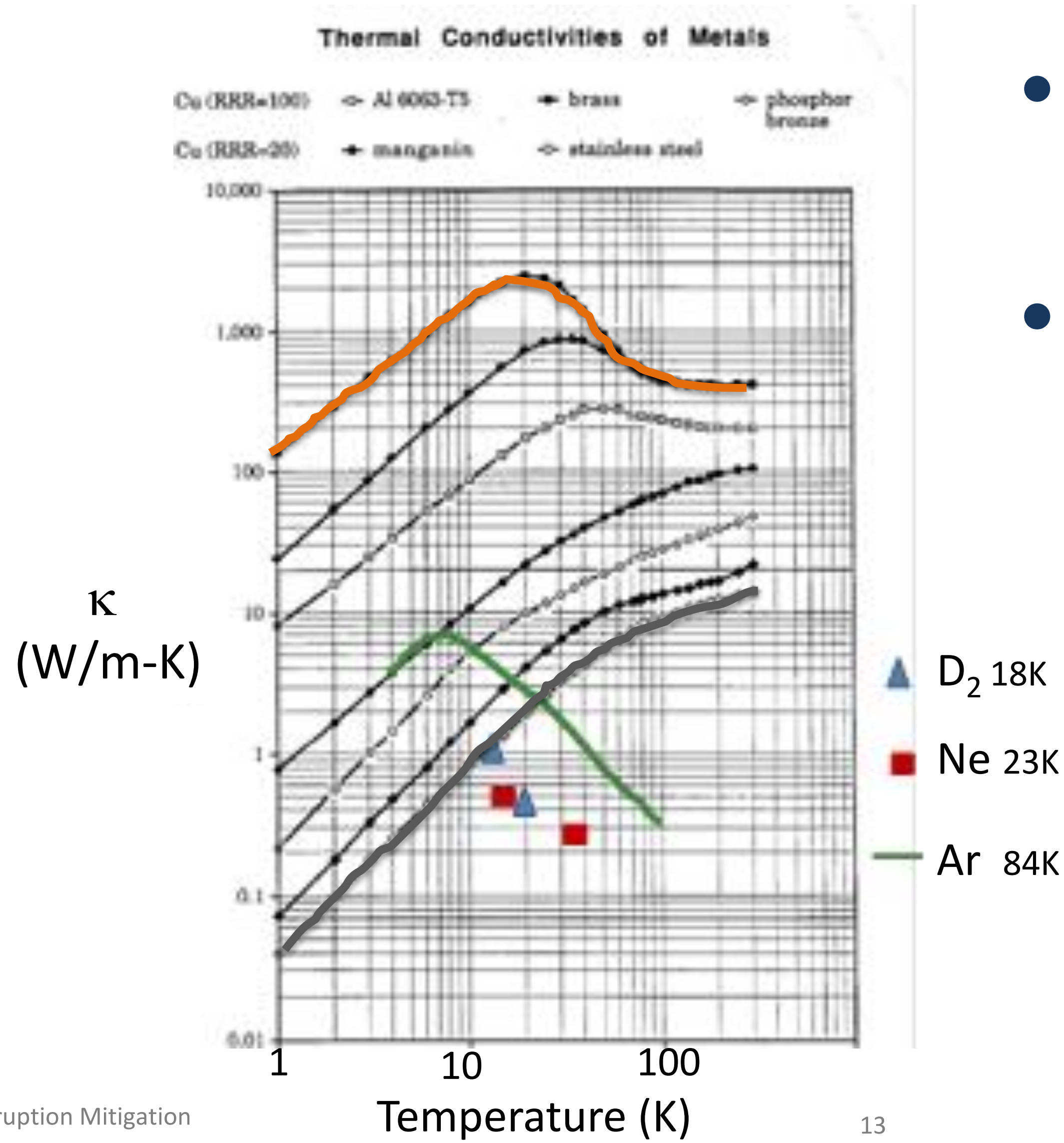
34 mm D_2 Pellets Formed and Accelerated from 1 Barrel



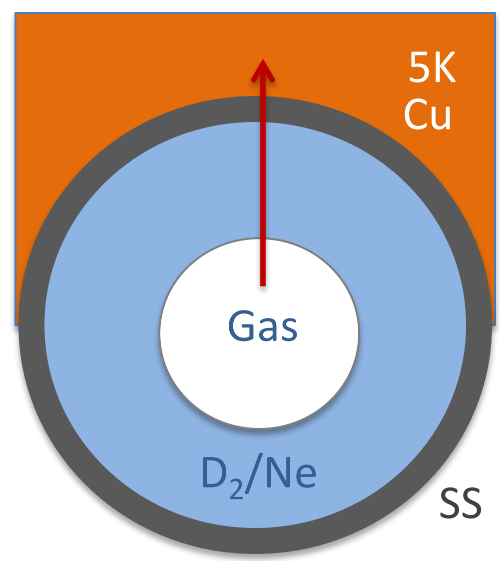


- A 34 mm diameter pellet with L/D ratio of 1.7 is the World's Largest D_2 pellet.
- Formation time of ~ 1hr due to poor thermal conductivity of solid D_2.
- Smaller sizes to be employed for ITER.

Thermal Conductivity is an Important Aspect of Forming Large Pellets

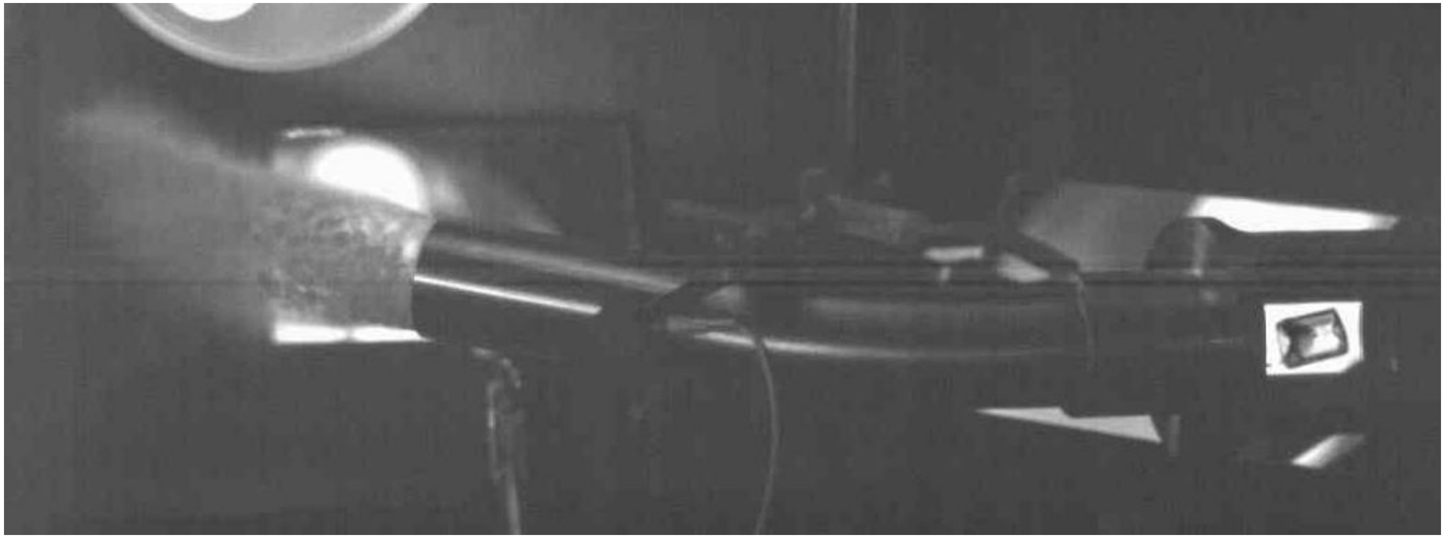


- Low thermal conductivity of pellet material dictates the time to produce large pellets.
- Feed gas pressure must be low to limit conduction heating.



$q = \kappa/D \, \Delta T$

Shattering Occurs from Transit Through Bent Tube Results in a ~15^o Dispersion for Neon



Ne Pellet in 20^o Shatter Tube

Foil Impacts Indicate < 15^o Dispersion of Spray

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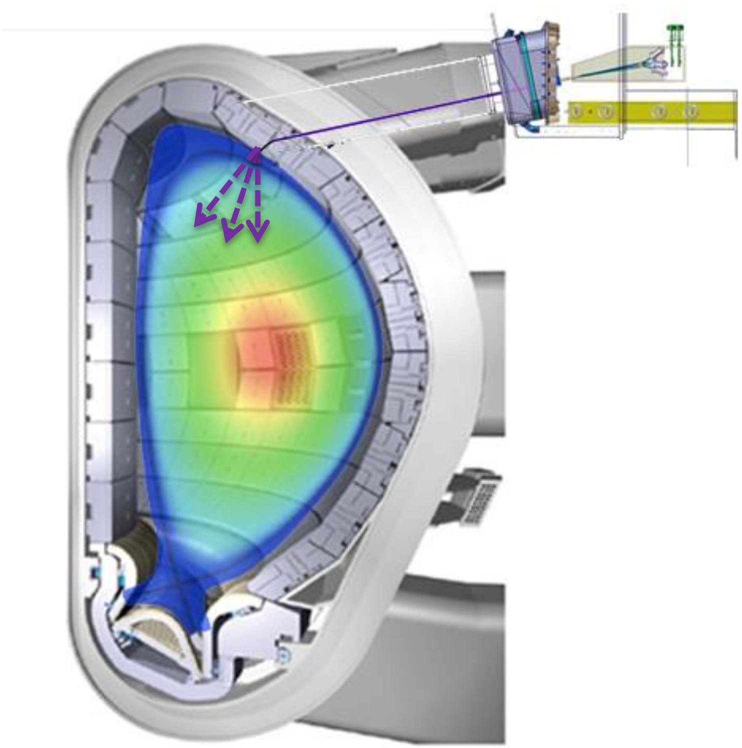
Disruption Mitigation System Design Status and Plans

- **CDR and Systems PDR complete**
- **Design underway** for
  - Shattered cryogenic pellet injection (SPI/MGI)
  - Massive gas injection (MGI non-nuclear phase)
- **Hardware for SPI and MGI subsystems must be tested on fusion experiments to determine effectiveness**
  - Experiments are performed by fusion community with their resources
  - Tests of DMS techniques and technologies for ITER underway in lab and at DIII-D
  - SPI experience on another machine is badly needed
  - U.S. ITER and OFES supports SPI and MGI experiments with hardware
  - Simulations to determine effectiveness on ITER are still needed

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

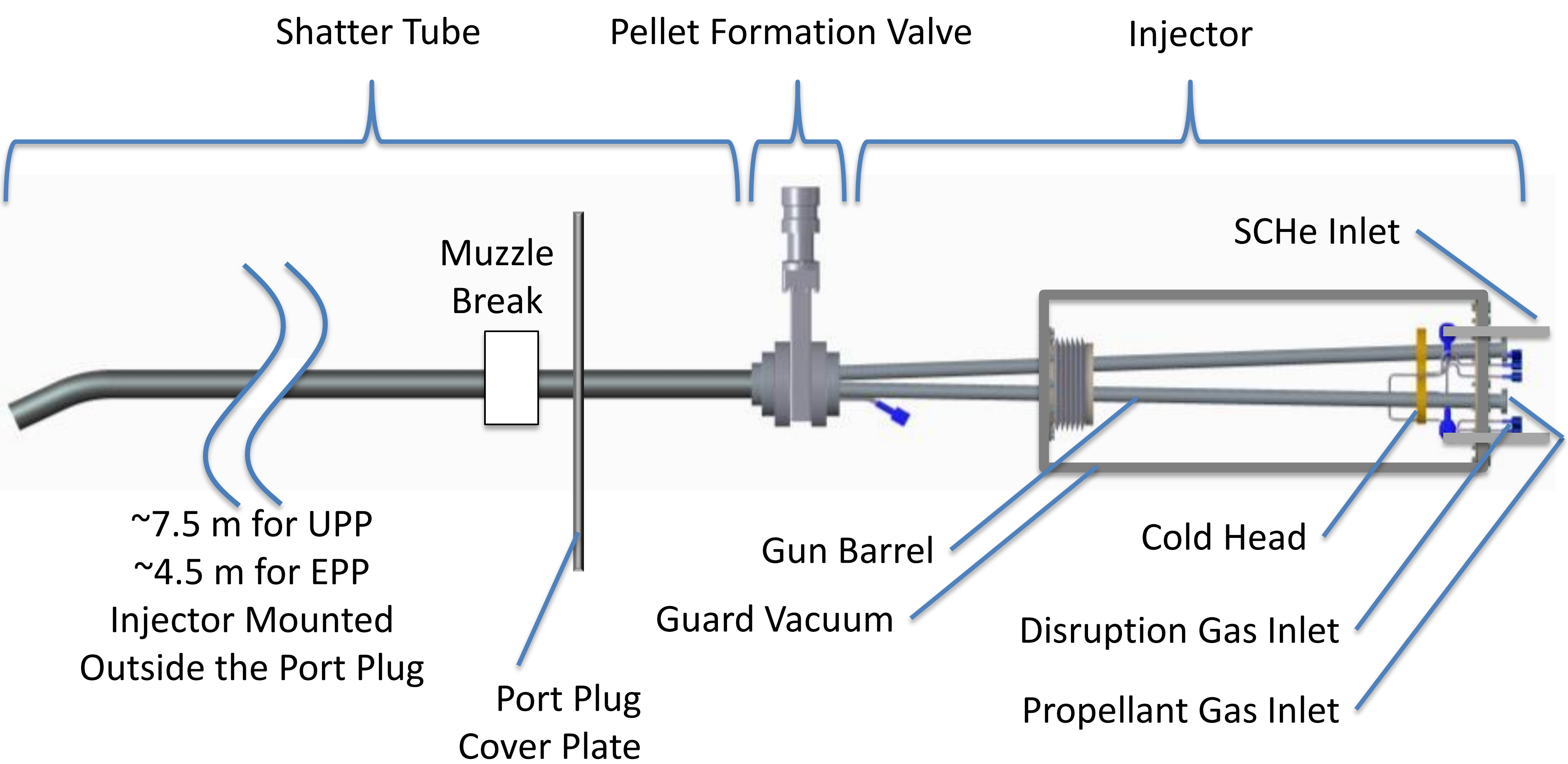


Injector has multiple barrels
Combination of MGI and SPI is possible

SPI pellets formed 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**

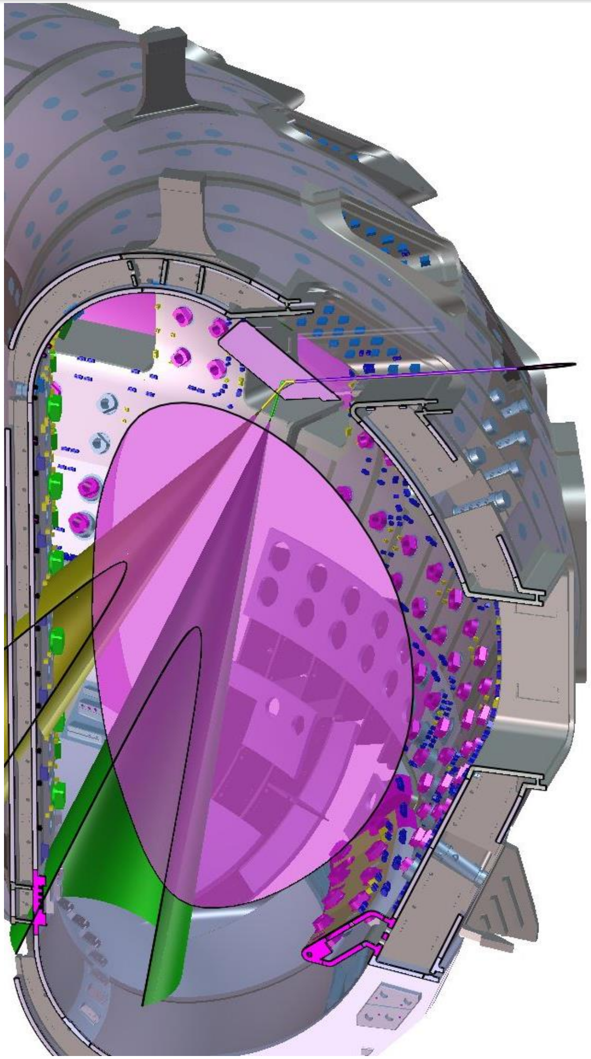
Basic SPI Design for ITER



SPI can be used as MGI with no pellet formed in the barrel

MGI valve is used to accelerate the pellet or inject gas

ITER DMS– Upper SPI Injection Angles

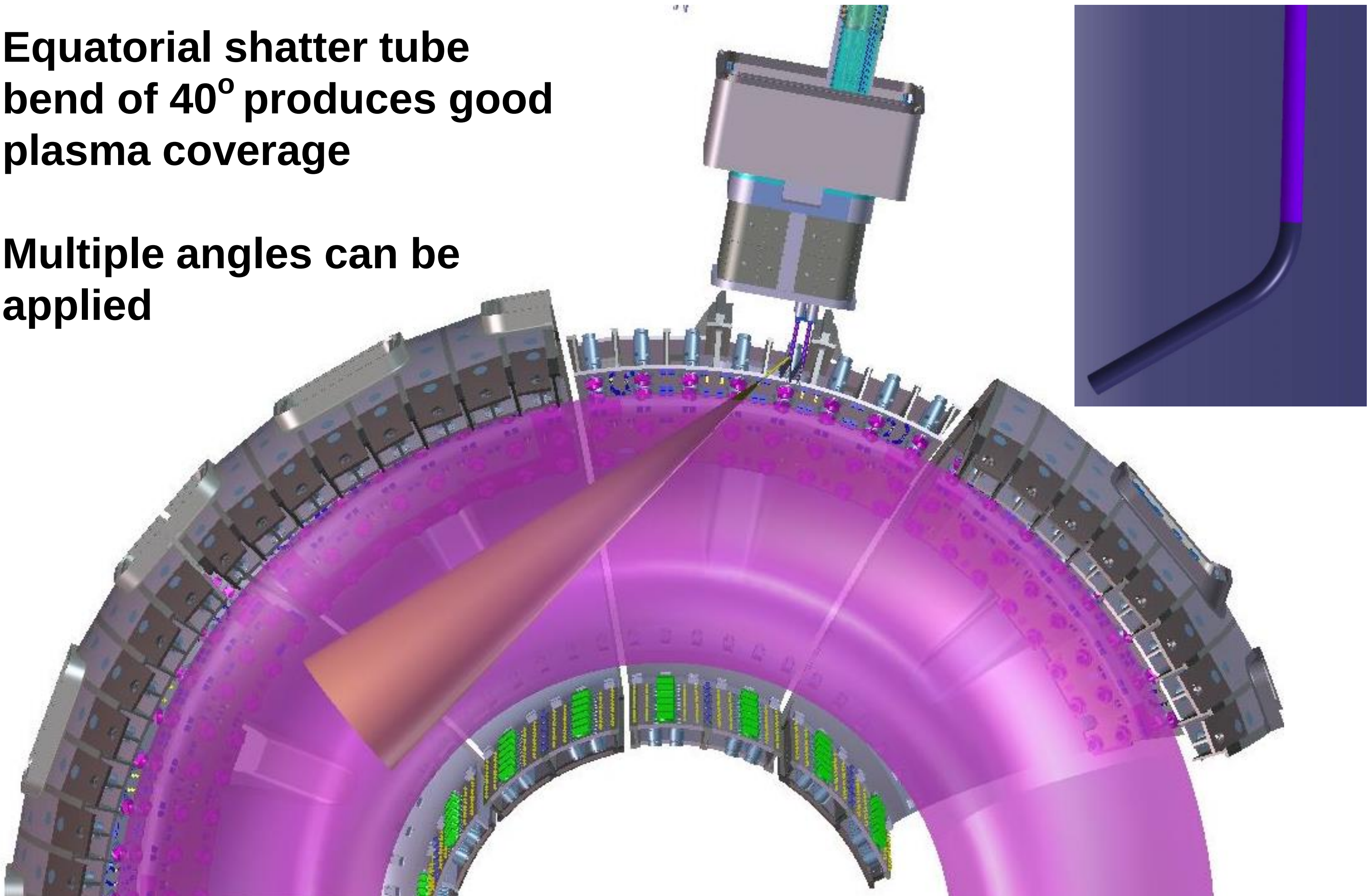


- CAD model image of upper SPI injection on ITER.
- Cones of incidence from a 20° and 40° bend shatter tube in ITER upper port plugs.
- Lab testing at sharper bend angles needs to be performed.
- Future research plan is to quantify the shattering process from ITER relevant bends and materials.

ITER DMS– Equatorial SPI Injection for RE Mitigation with Toroidal Angle can Reach Axis with Long Path Length

Equatorial shatter tube bend of 40^{o} produces good plasma coverage

Multiple angles can be applied



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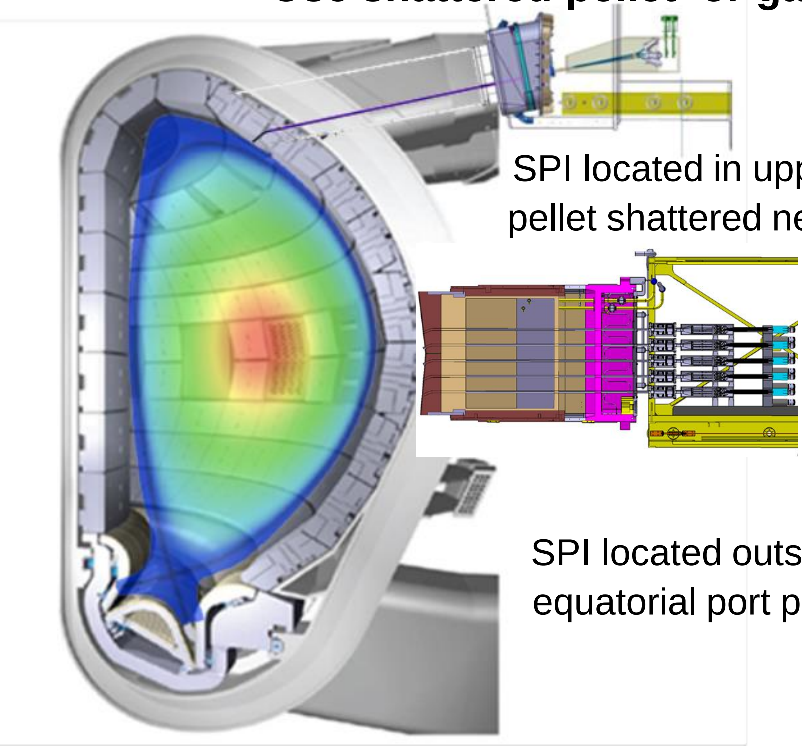
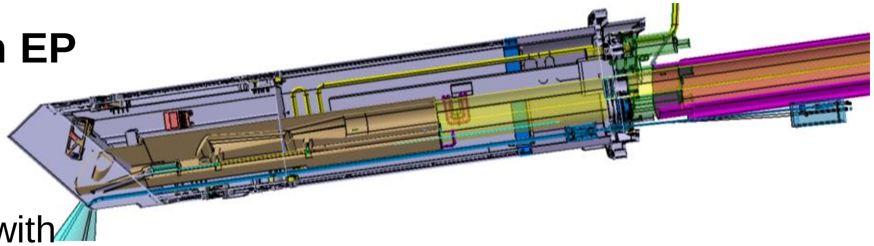
Disruption Mitigation Uses Injection of Pellets Shattered at Plasma Edge and Gas Injection through Delivery Tubes

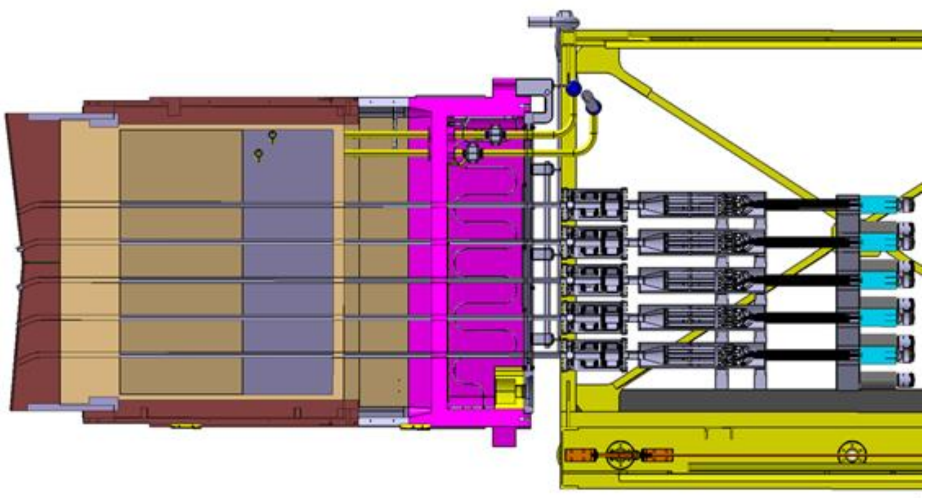
- **Mitigate impact of the disruption thermal and current quench**
  - **Use large shattered pellets composed of neon deuterium mixture in UP**
- **Suppress and dissipate runaway electrons**
  - **Use shattered pellet or gas injection EP**



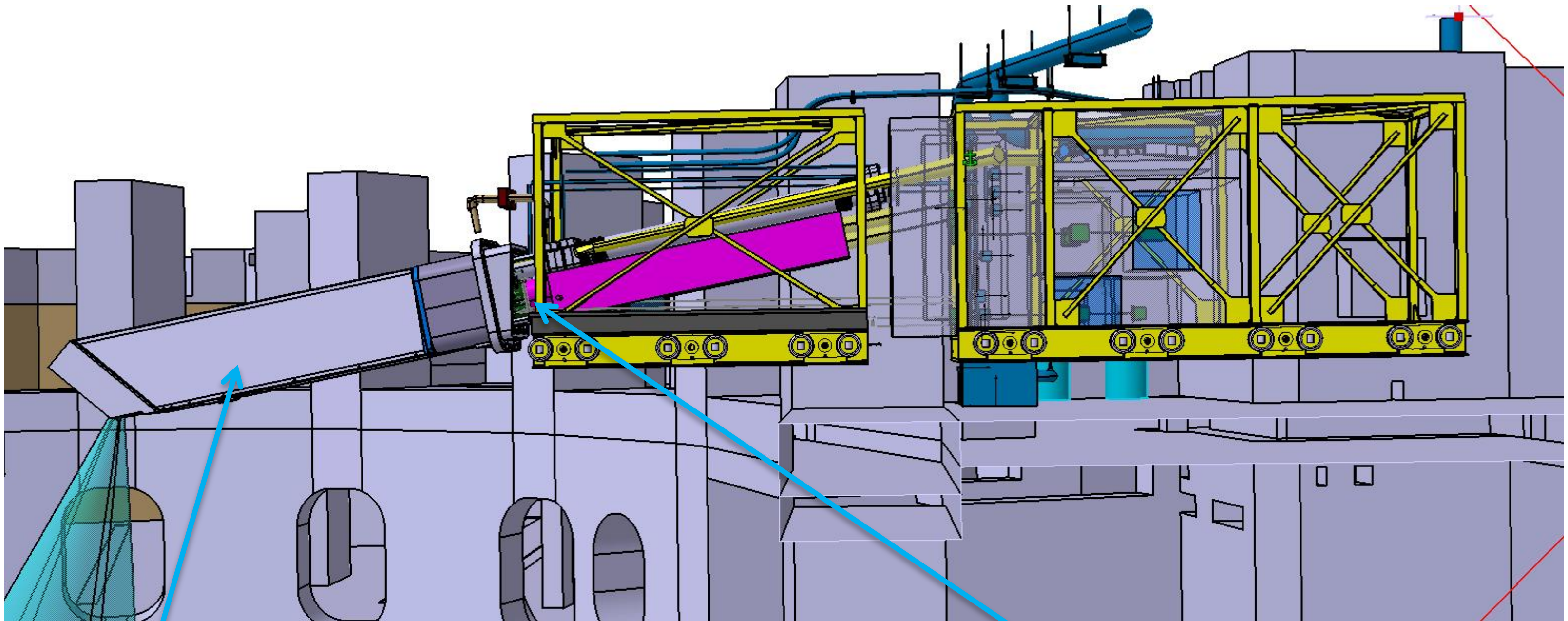


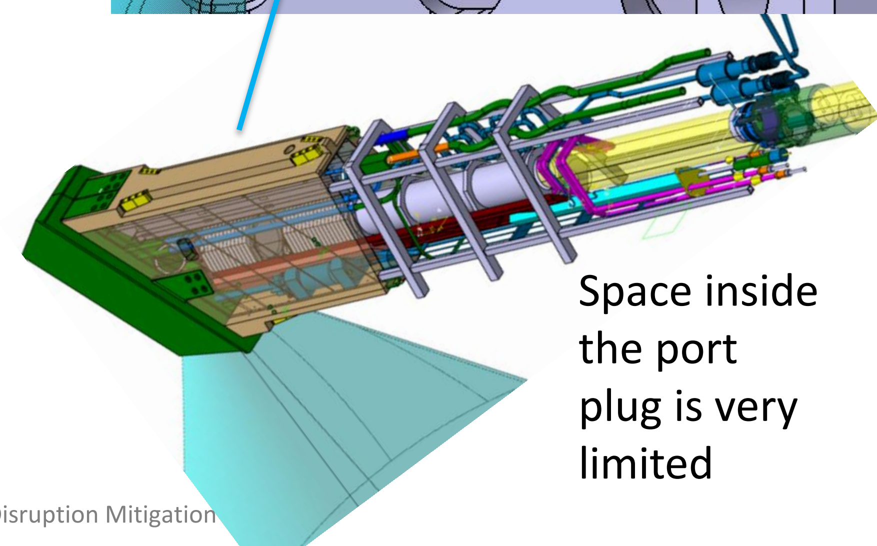
SPI located in upper port cell with pellet shattered near plasma edge

SPI located outside equatorial port plug



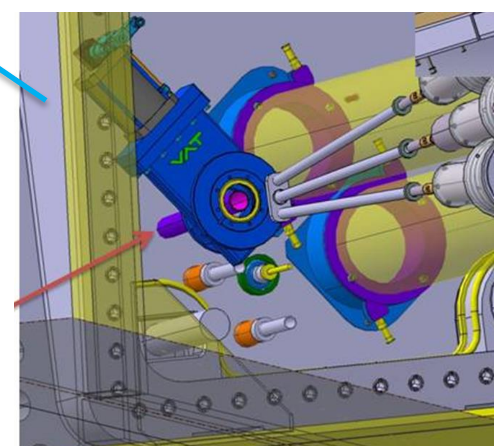
3D Layout of the Upper Ports for DMS Is Challenging





Space inside the port plug is very limited

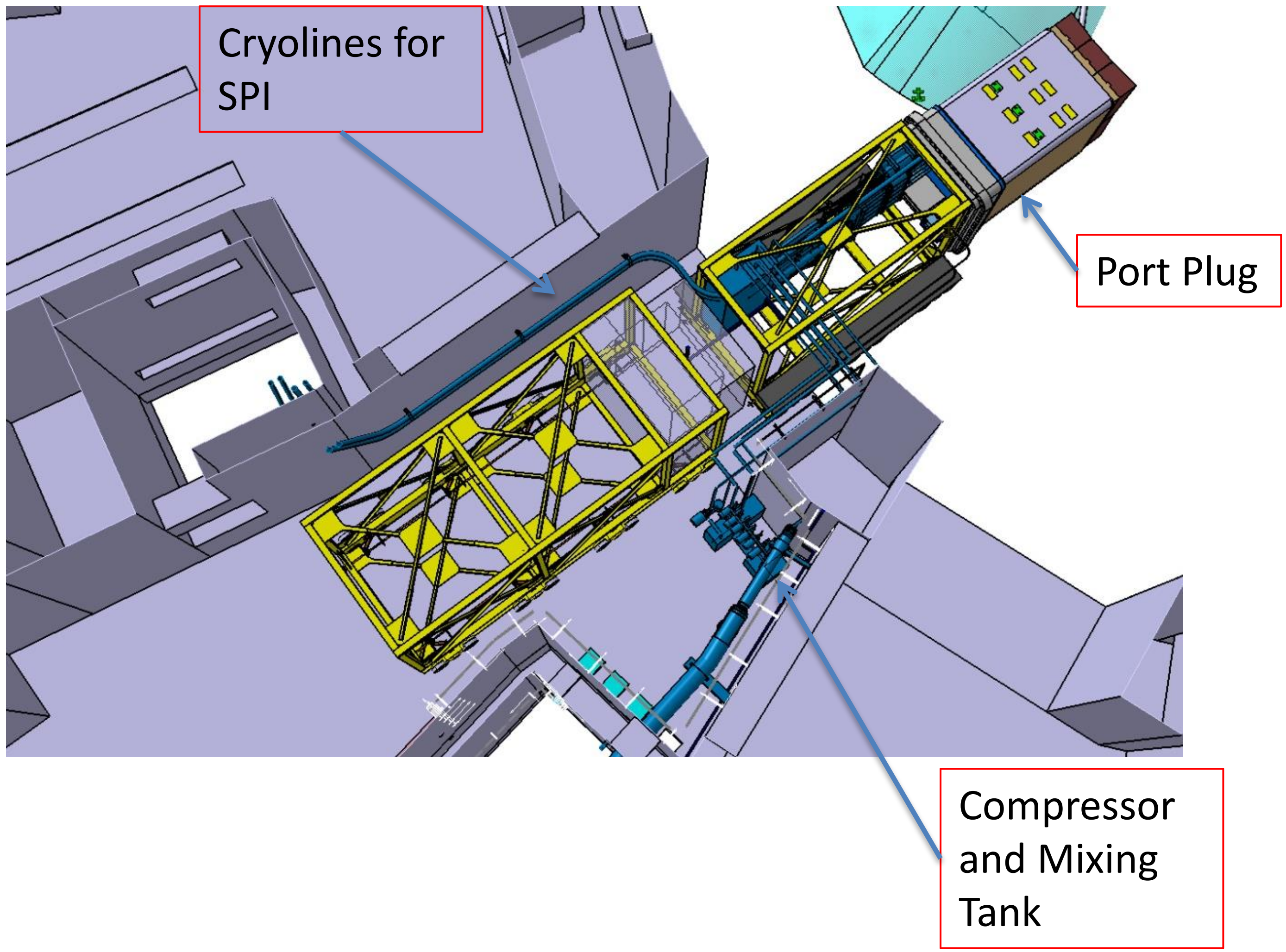
Interfacing with the PP cover plate is extremely challenging



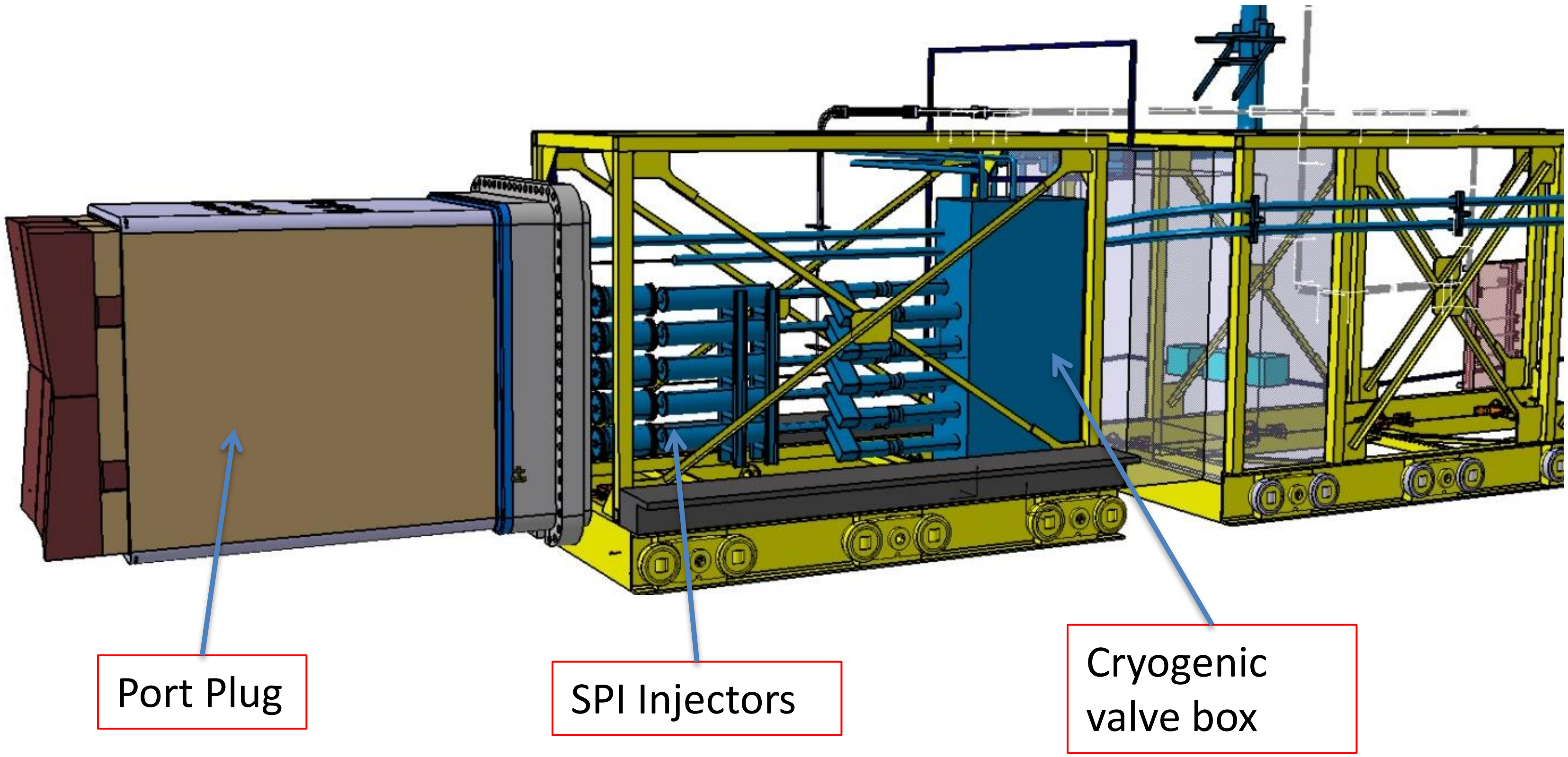
3D Layout of the Equatorial Port

EQ port is much easier in integration point of view, since the DMS placed into one dedicated drawer (1/3 of port plug).

1/3 of the interspace volume is also available for use.



3D Layout of the Equatorial Port for DMS



Completed Disruption Mitigation System PDR (November 2014)

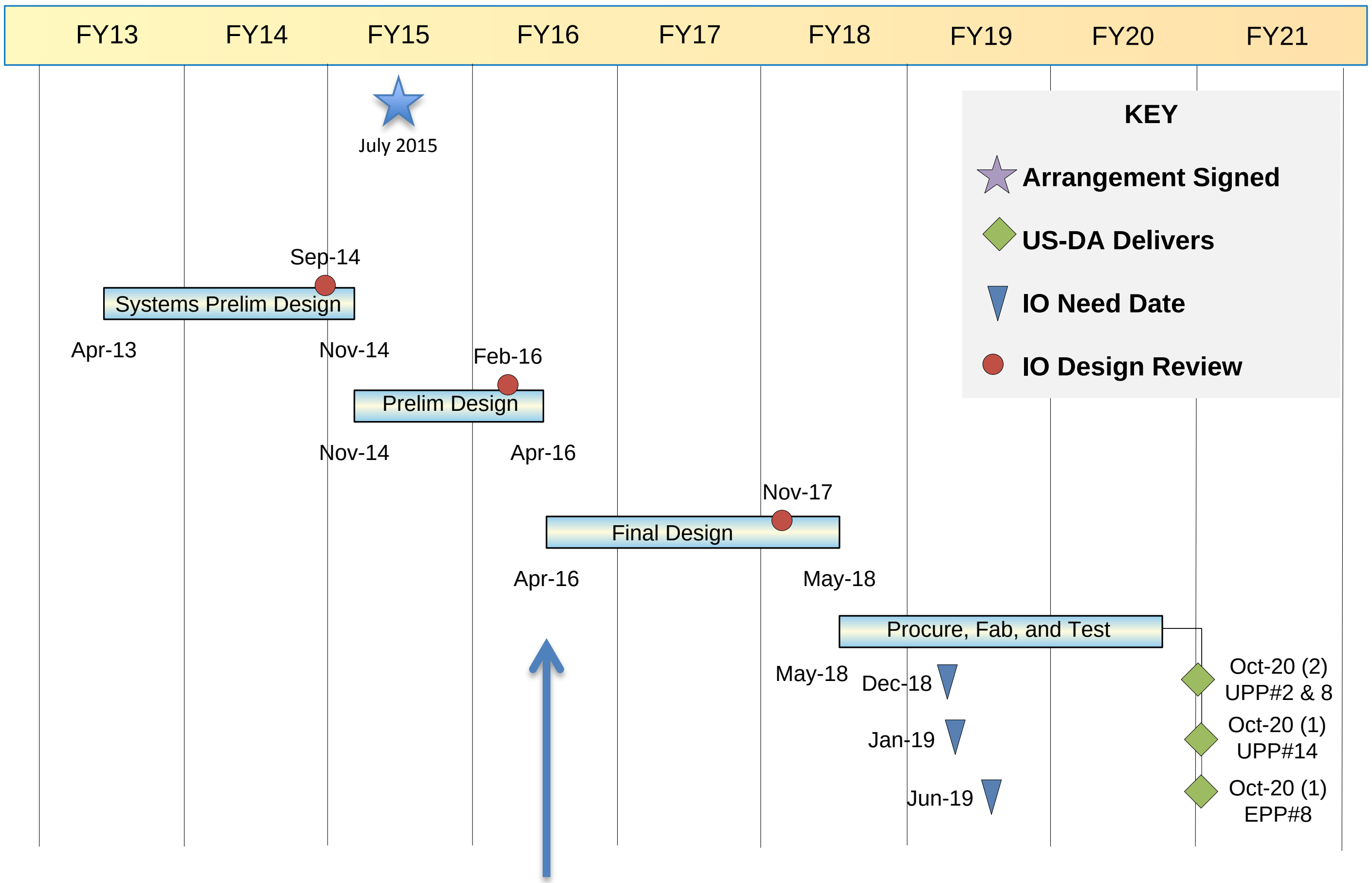
SPDR tasks and responsible parties

- IO performed physics studies to determine maximum allowable response time
- IO completed PCR to reserve space for outside of the port plug locations
- Tokamak experiments and IO analysis provide guidance on MGI vs SPI material assimilation, TQ, CQ and RES effectiveness and injection locations
- US completed P&IDs for MGI and SPI options
- US performed 3-barrel injector tests
- US determined the maximum obtainable pellet speed
- US completed the design, fabrication and initial testing of the MGI valve

SPDR Outcomes

- Most promising DM technology identified at SPDR becomes basis for remaining Preliminary Design and port plug interfaces
- Backup DM technology design (MGI) placed on hold
- **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 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 and SPDR Complete
  - Down selection to SPI/MGI hybrid following Nov 2014 SPRD
  - Hardware for SPI and MGI being designed, fabricated and tested
  - International fusion community is actively engaged
  - Design and qualification testing with DMS research partners
  - Cost is capped by agreement with IO
- Present Challenges
  - Interface with upper port plug closure plates – tight squeeze
  - Develop argon mixture pellet formation and optimize shatter tube geometry
  - Minimum response time for runaway electron suppression and dissipation
- **More simulation and modeling needed to validate design choices**
  - Needed for Final Design of DMS

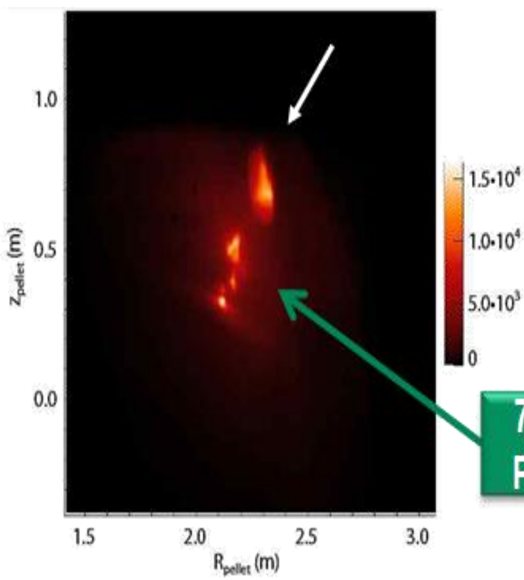
BACKUP ONLY

Disruption Mitigation – Field Testing of Neon Shattered Pellet

SPI Injection Line Pumping

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

Disruption mitigation experiments planned on DIII-D throughout 2014



7 mm Neon Shattered Pellet in DIII-D Plasma

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

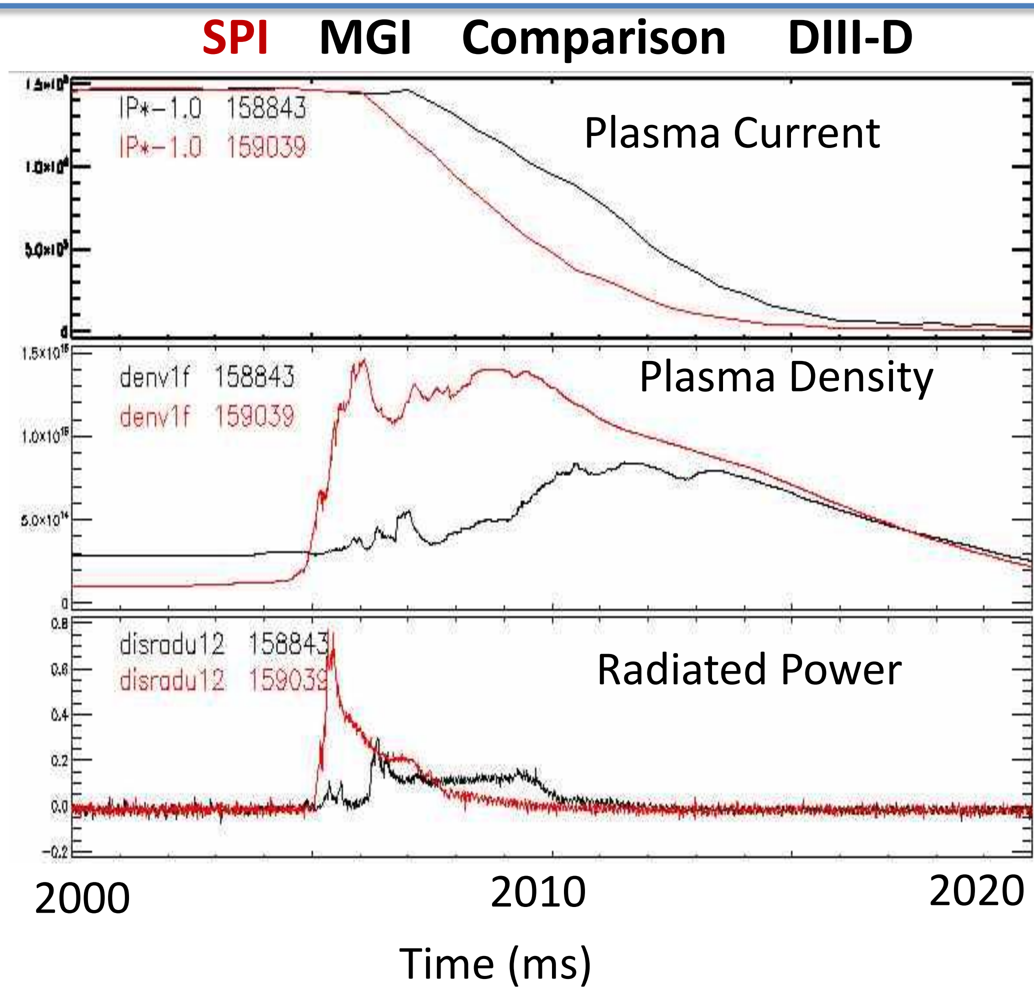
S.J. Meitner, C.R. Foust, S.K. Combs, N. Commaux, B. Dannels, A.R. Horton, D. Shirake, L.R. Baylor

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

DIII-D Thermal Mitigation Faster with Neon SPI than MGI

Experiments with Neon Shattered Pellet Injection carried out to Study Thermal Mitigation

- 7mm neon pellets injected to shut down plasma (red) and compared with similar amount of gas injection (black)
- Pellets: T ~ 10 K, ~ 250 m/s
- 1.4 MA H-mode plasma terminated by SPI or MGI
- Highly reliable operation of SPI leads to much faster shutdown than with neon gas from MGI.
- Faster time response and deeper penetration of SPI is favorable for the ITER DMS thermal mitigation application.



Highlight courtesy of Commaux, Shiraki, APSDPP 2014

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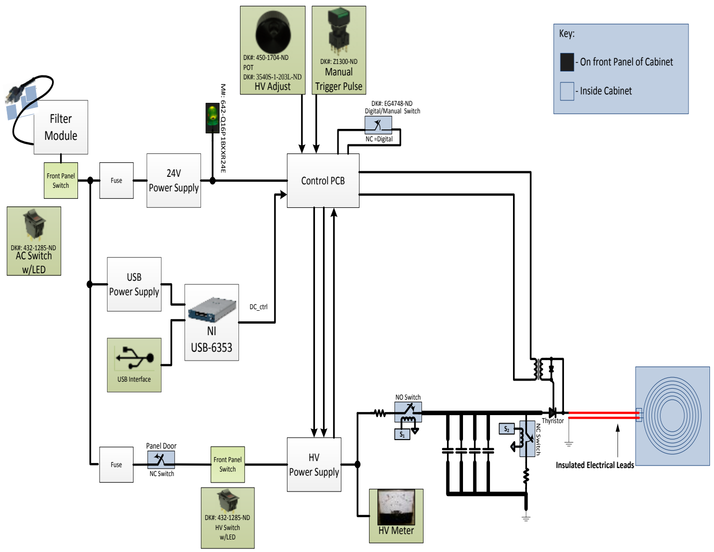
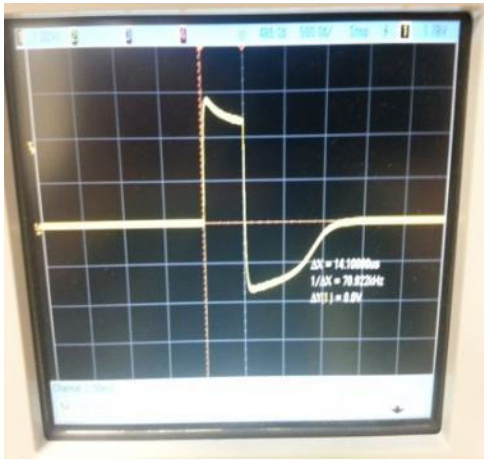
Design, Fabrication and Testing of MGI Power Supply Completed





SCR Triggering Requirements:

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