Implications of Disruption Mitigation for the ITER Vacuum System

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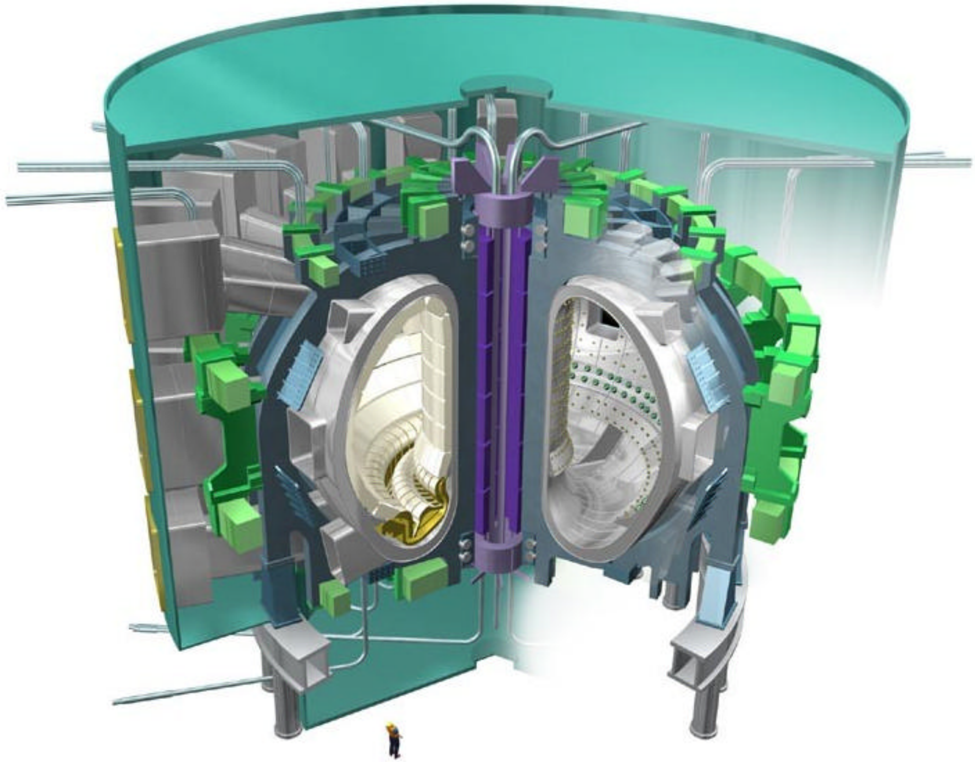
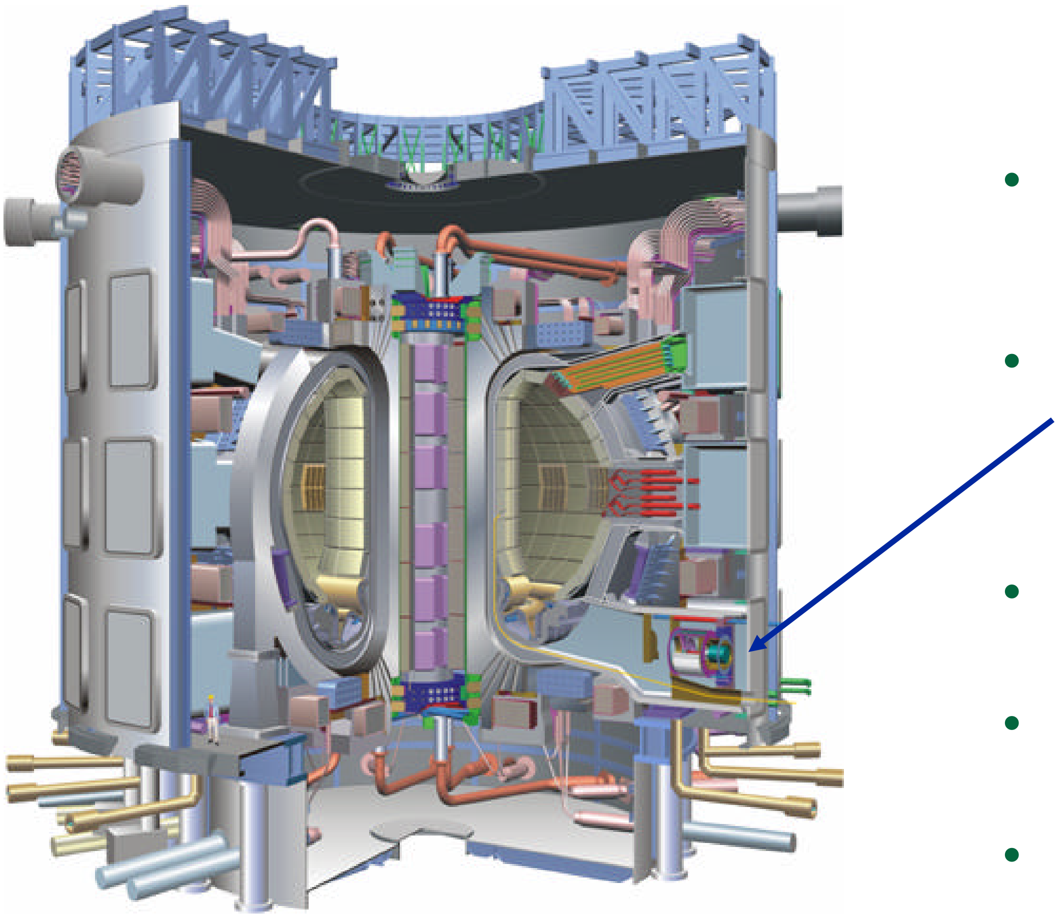
ORNL, *FZK, # ITER IO



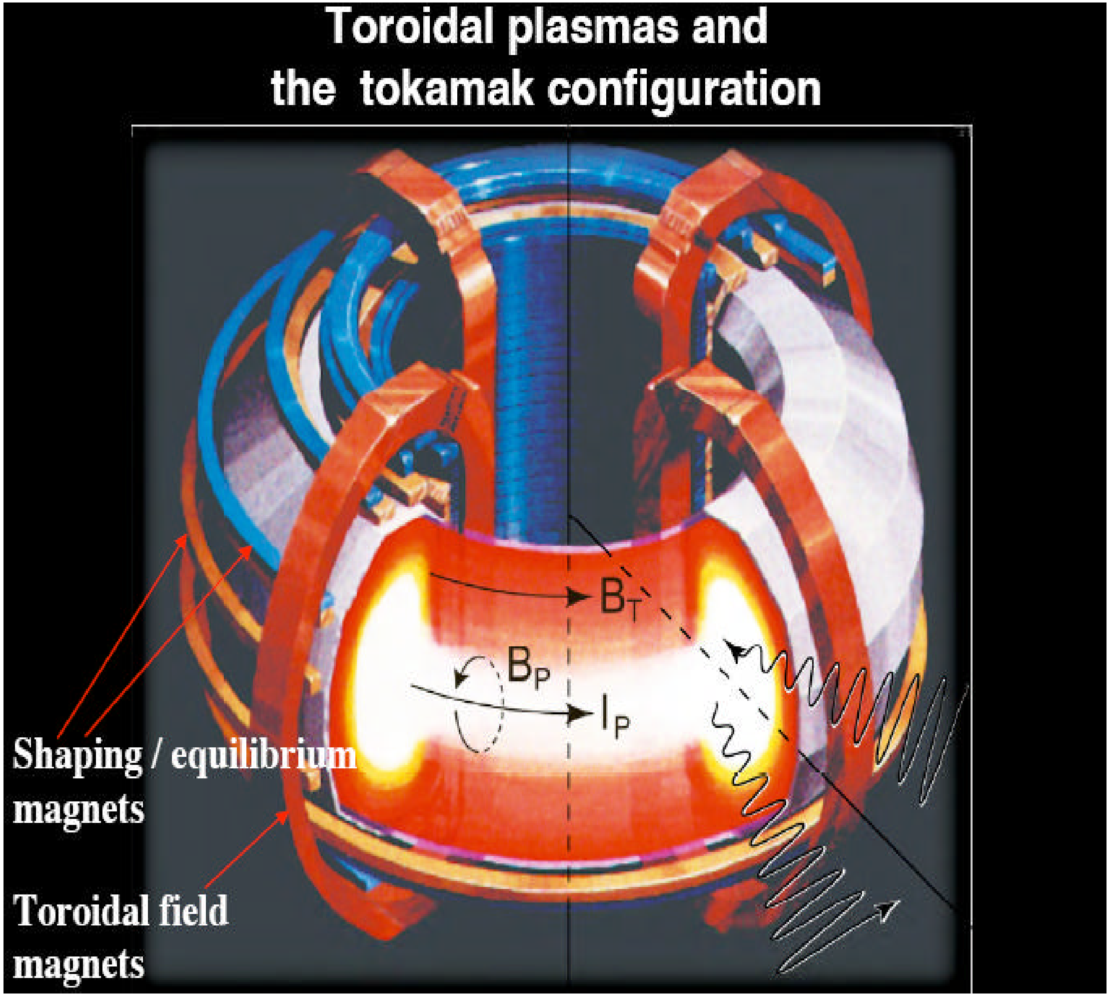
ITER – Worlds Largest Fusion Experimental Reactor



ITER Highlights

- ~1400 m^3 vacuum vessel volume, neutral beam, cryostat and service vacuum system [1].
- 8 Cryopumps backed by large roughing pump system [2] (P. Ladd, 2001, C. Day, IAEA 2004, D. Murdoch IVC2007, …)
- Plasma contains ~2 bar-L equivalent gas
- Tritium compatibility of all systems from day one
- Operational 2016

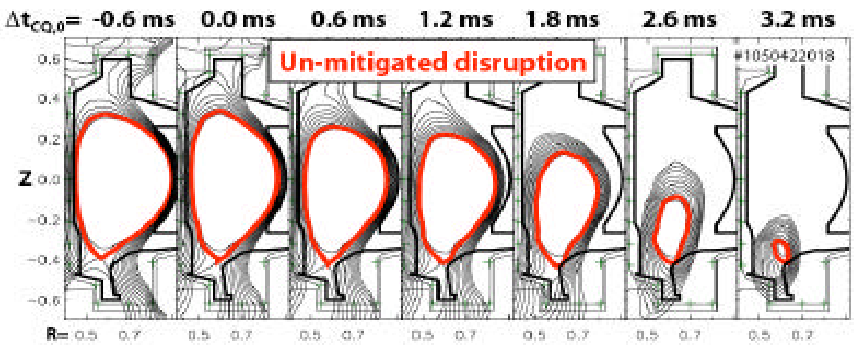
ITER has up to 15 MA of Plasma Current

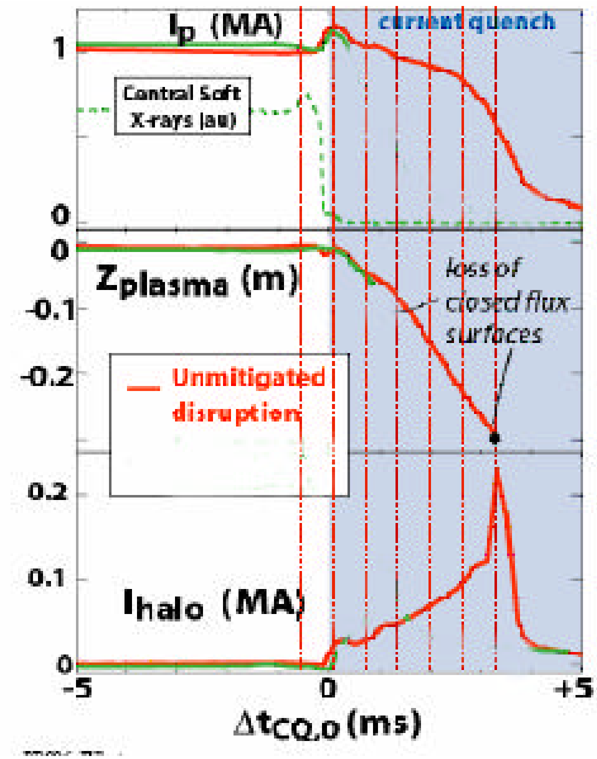


What is a Disruption?

- ITER is a tokamak with a plasma current of 15 MA.
- MHD instabilities can cause plasma to become unstable and collide against chamber. (This is called a disruption)
- Plasma current is dissipated in ~30 ms in a disruption causing thermal and structural design challenges [3].
  - Structural problems can be handled by careful design
  - Thermal excursion of first wall can lead to damage
- Runaway electrons can be generated by Coulomb-collisions during the current decay phase of the disruption
  - ITER could have up to 10 MA of RE current in MeV range of energies
  - Component melting and water leaks are possible [4]

Example of a 1 MA Disruption on Alcator C-Mod





- Unmitigated 1 MA disruption in C-Mod with 3ms current quench [5]

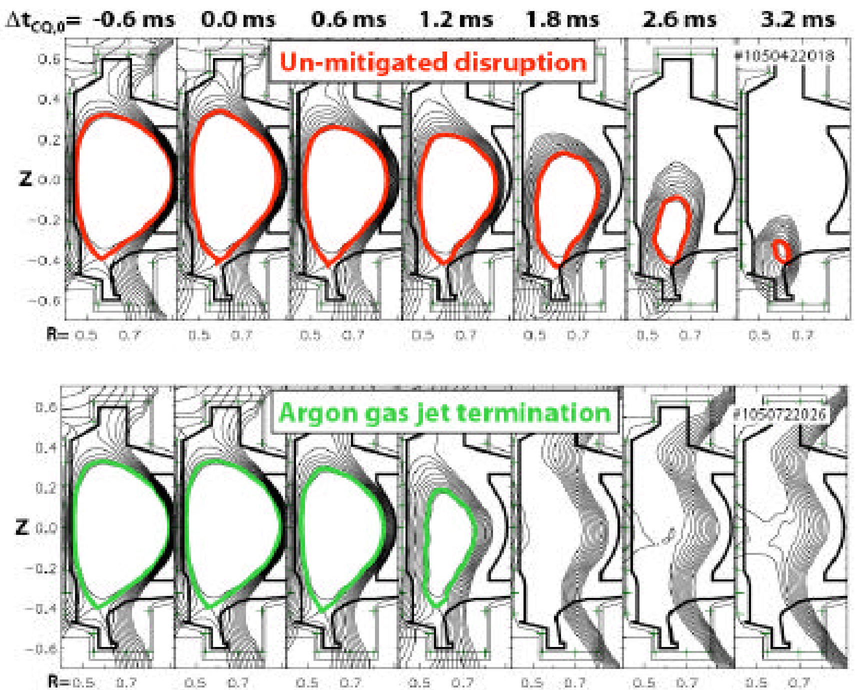
D. Whyte, EPS 2006

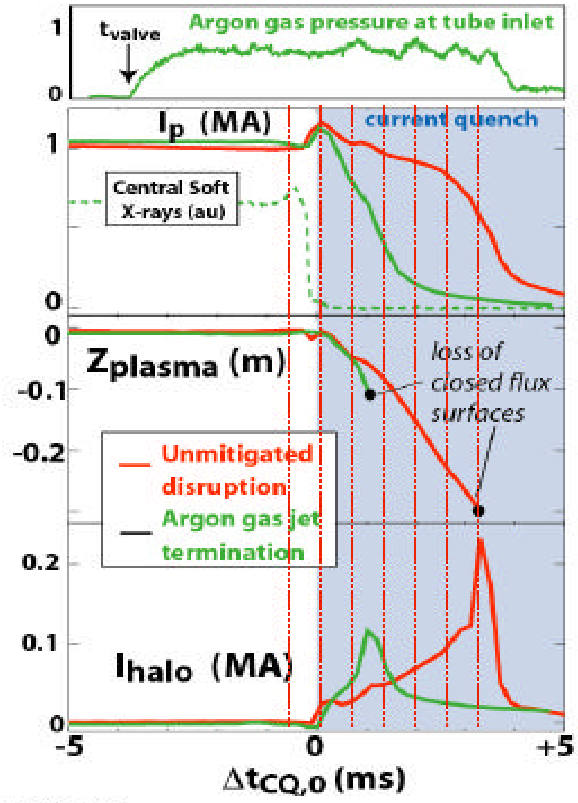
Alcator C-Mod

How is a Disruption Mitigated ?

- Large increase of plasma density during disruption can lower the plasmas temperature and thus mitigate effects of thermal damage
- Particles must penetrate into the current channel during the current quench to prevent runaway electron formation
- Methods to increase the density are:
  - Gas injection: Large burst of gas from a fast valve
  - Pellet injection: Solid pellets accelerated by gas
  - Liquid jet: Cryogenic liquid forced through a nozzle
- The ITER current quench time scale is estimated to be 30-35 ms [1].
- See the example in the following slide showing faster current quench with gas jet mitigation in C-Mod [5].

Example of Disruption Mitigation on Alcator C-Mod

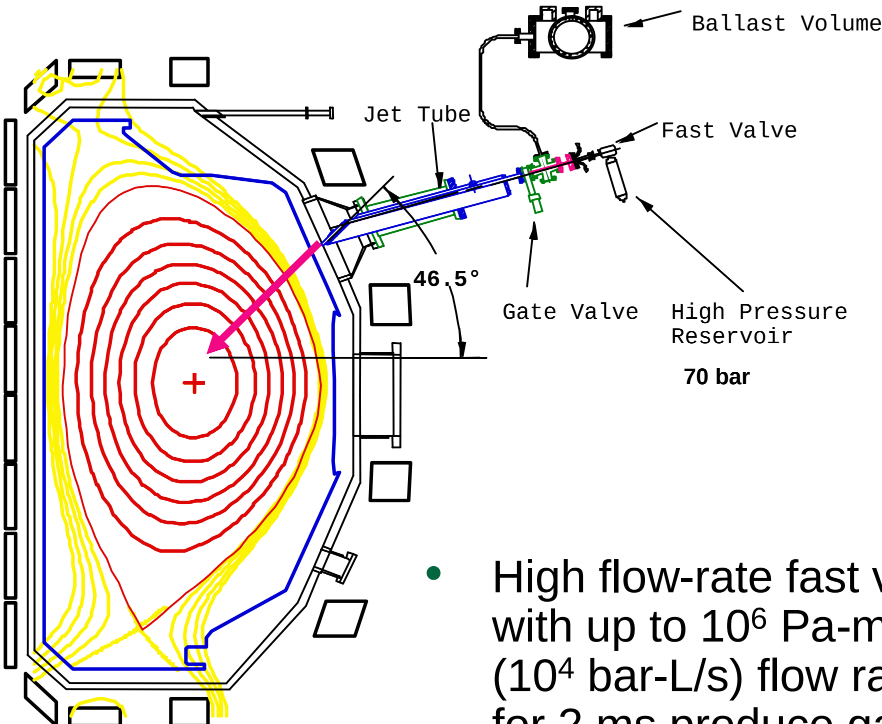


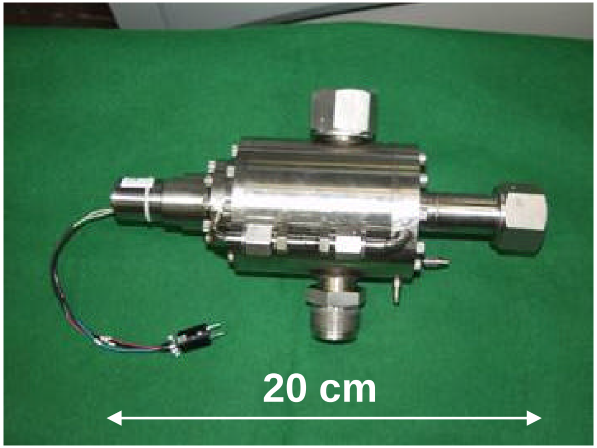


- Comparison of unmitigated disruption with Ar gas jet mitigation showing faster current quench. [5]

D. Whyte, EPS 2006

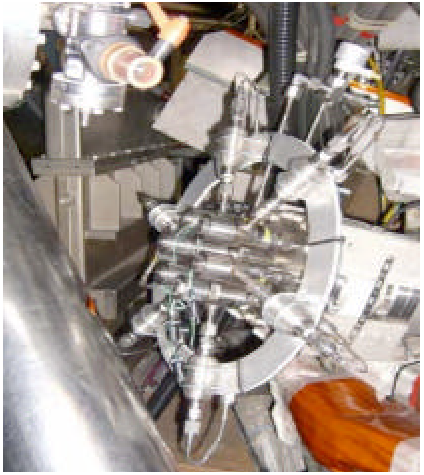
How is a Disruption Mitigated ?





Jumbo Valve – 10^6 Pa-m^3/s

- High flow-rate fast valves with up to 10^6 Pa-m^3/s (10^4 bar-L/s) flow rates for 2 ms produce gas jet into plasma [6].
- Impurity or large D_2 pellets (3cm) can also be used.



Medusa Valve – $3x10^5$ Pa-m^3/s

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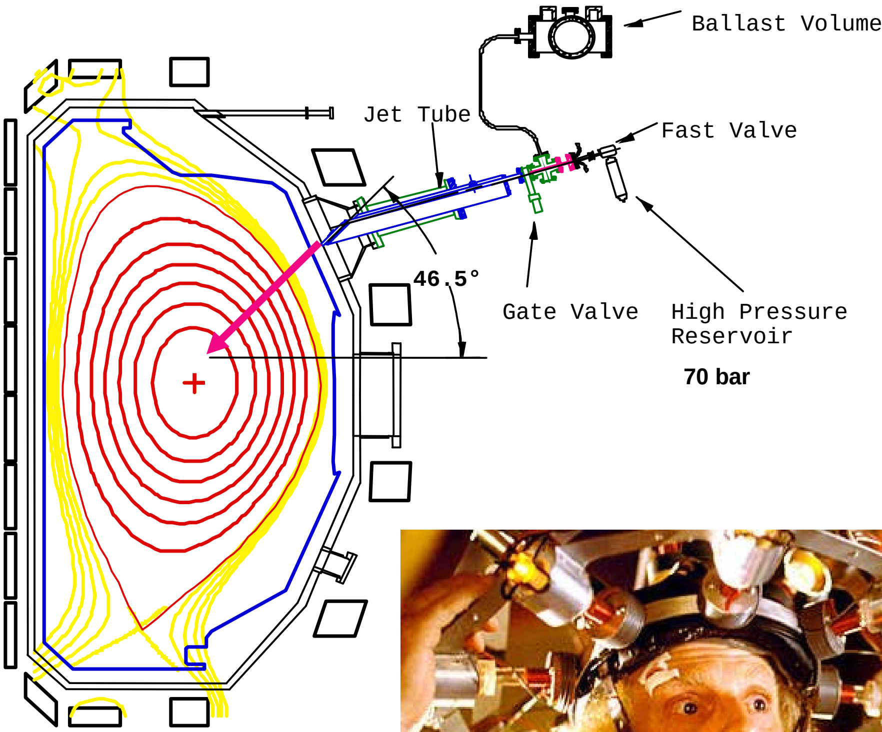

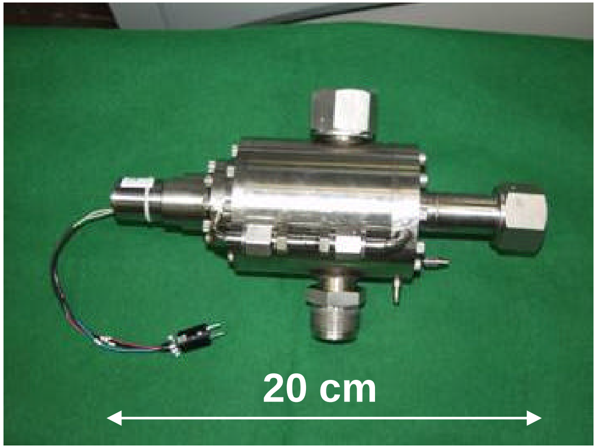

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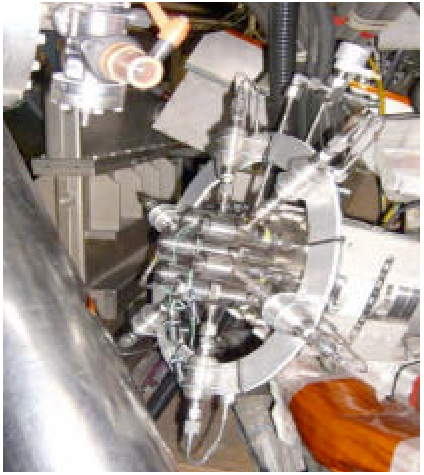


Medusa Valve – $3x10^5$ Pa-m^3/s

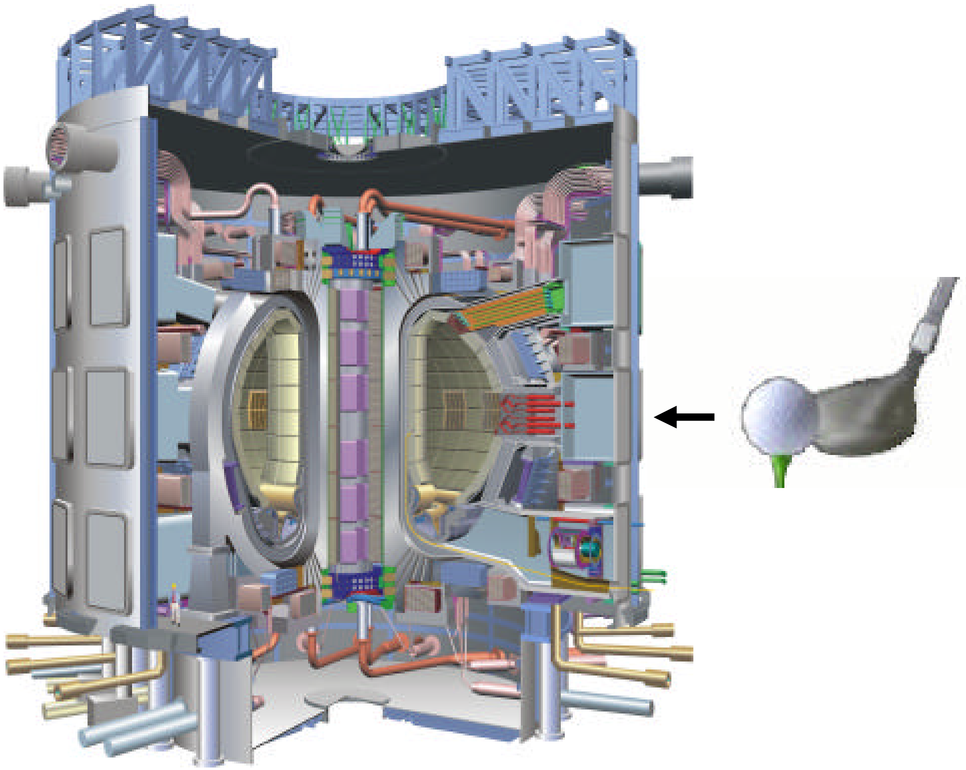
How Many Particles are Needed in ITER ?

- Table based on avalanche growth model by Rosenbluth-Putvinski [7] and a plasma current of 15 MA and 35 ms current decay time [8].
- Higher Z than Ar is not useful because of slower sound speed and is more likely to generate runaway electrons. (R. Granetz, C-Mod, APS2006 [9])

Species	AMU	N	Pa-m3	Resulting Press (Pa)
D_2	4	$1.7x10^{25}$	$6.5x10^4$	65
He	4	$1.7x10^{25}$	$6.5x10^4$	65
Ne	20	$3.5x10^{24}$	$1.3x10^4$	13
Ar	40	$1.9x10^{24}$	$7.2x10^3$	7

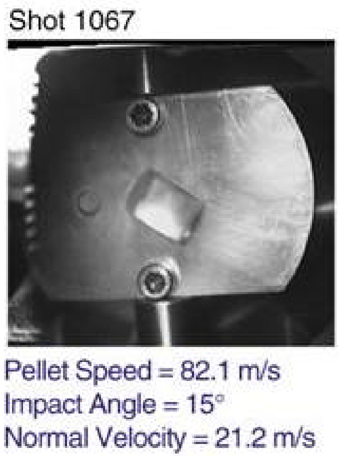
- Assimilation of gas is at best 10% in present experiments, so as much as 10x more may be needed if the avalanche model is correct.
- Pellet sizes of 30 mm for D_2 and 2.5 mm for Ar would provide the needed number of electrons.

ITER Pellet Disruption Mitigation Scheme

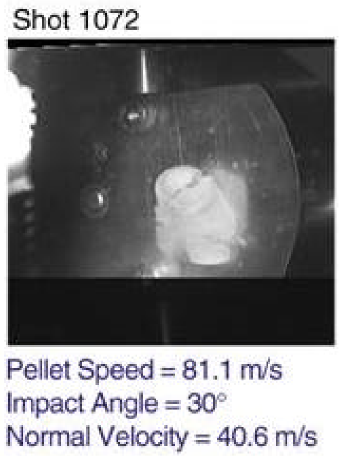


- **A large "golf ball size" pellet made with D_2 or some combination of D_2 and Ne or other impurity is a possible option to mitigate disruptions in ITER.**
- **A reliable single stage gas gun can accelerate the pellet to 1 km/s speed. (Alternatively a 460 cc driver with T. Woods)**

ITER Pellet Disruption Mitigation Scheme



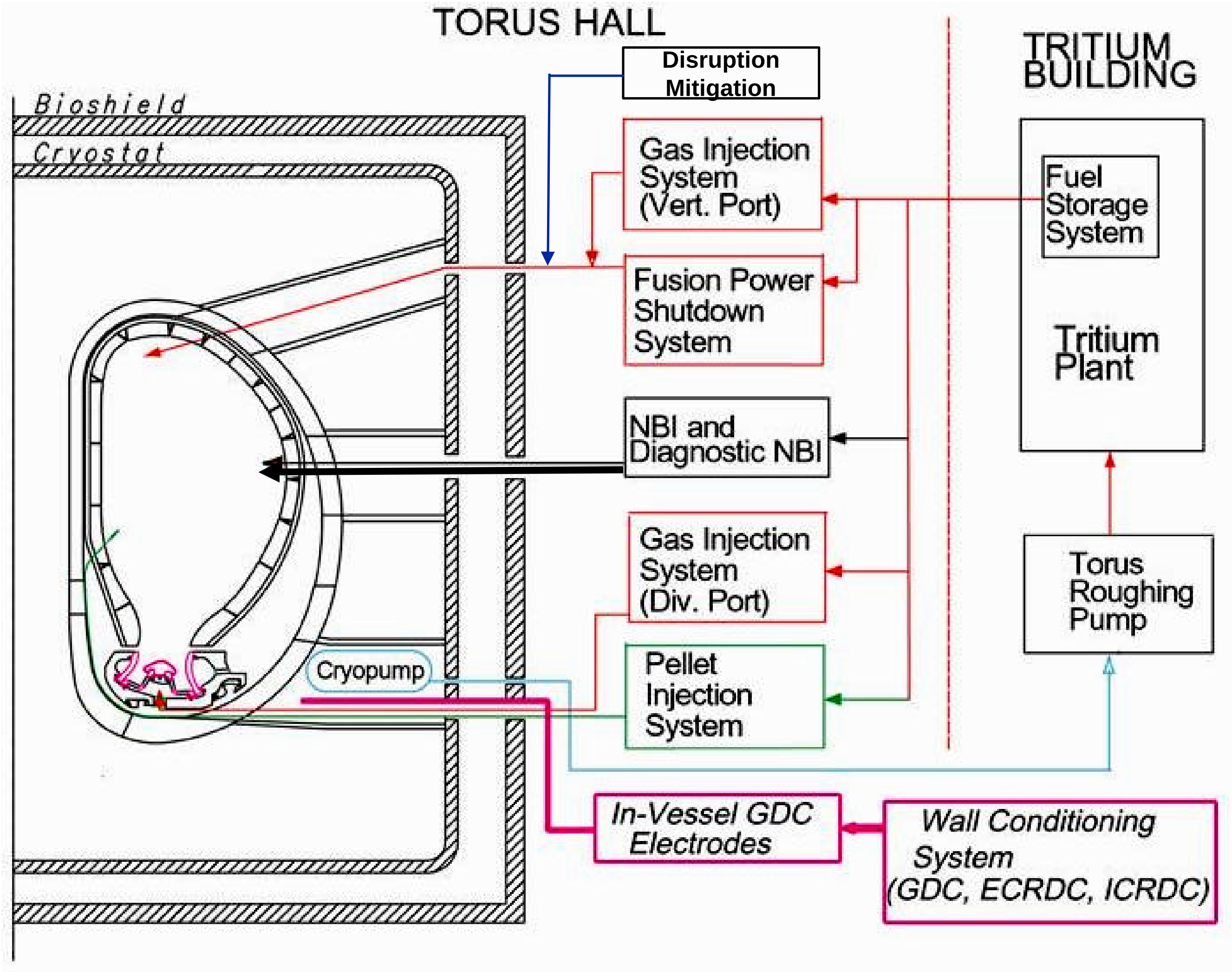
10 mm pellet



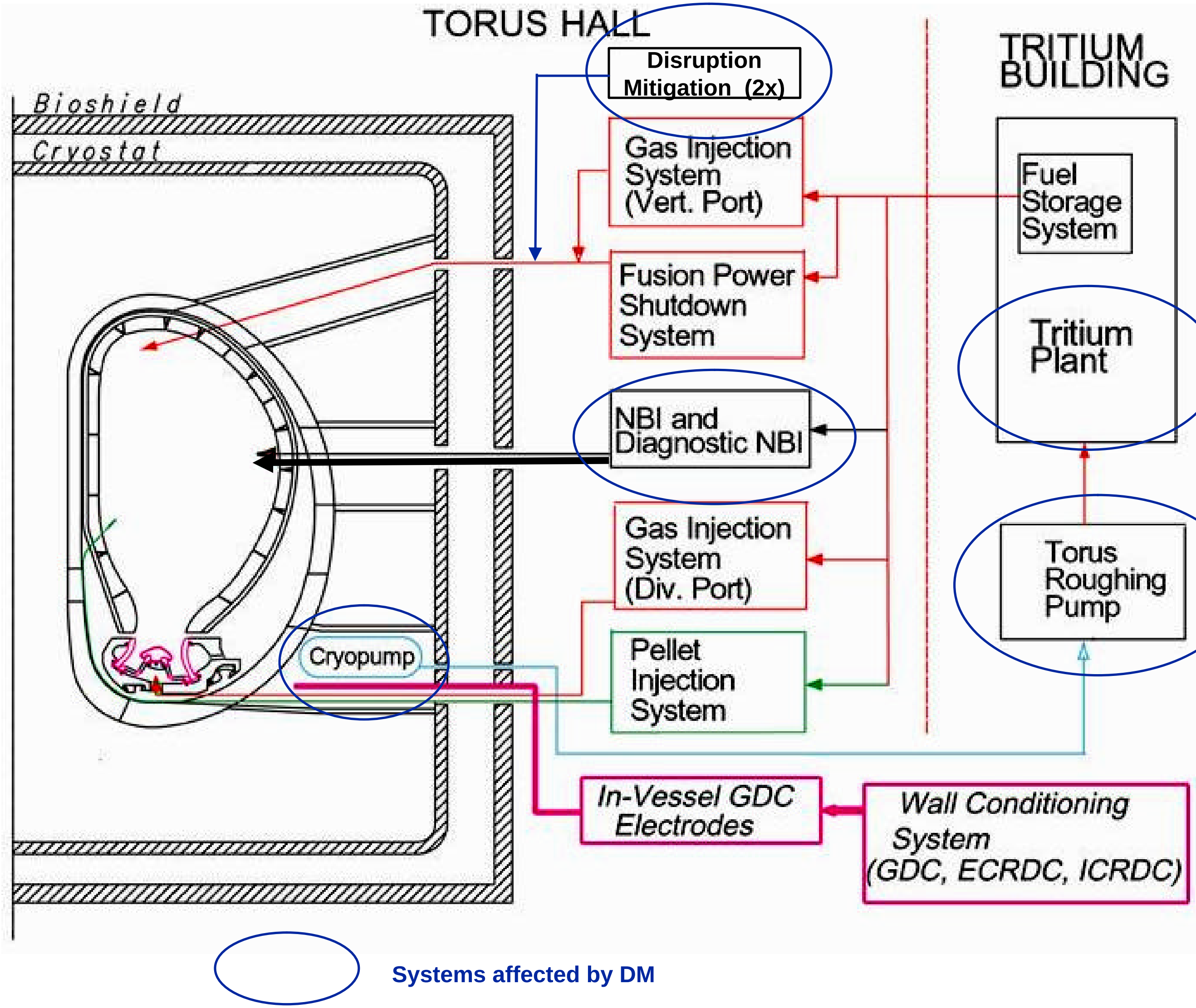
10 mm pellet purposely shattered

- **A large "golf ball size" pellet made with D_2 or some combination of D_2 and Ne or other impurity is a possible option to mitigate disruptions in ITER.**
- **A reliable single stage gas gun can accelerate the pellet to 1 km/s speed.**
- **10 mm pellets have been produced easily and larger sizes are possible.**
- **Pellets can be shattered to minimize risk of damage to inner wall.**

ITER Fuel Cycle Block Diagram



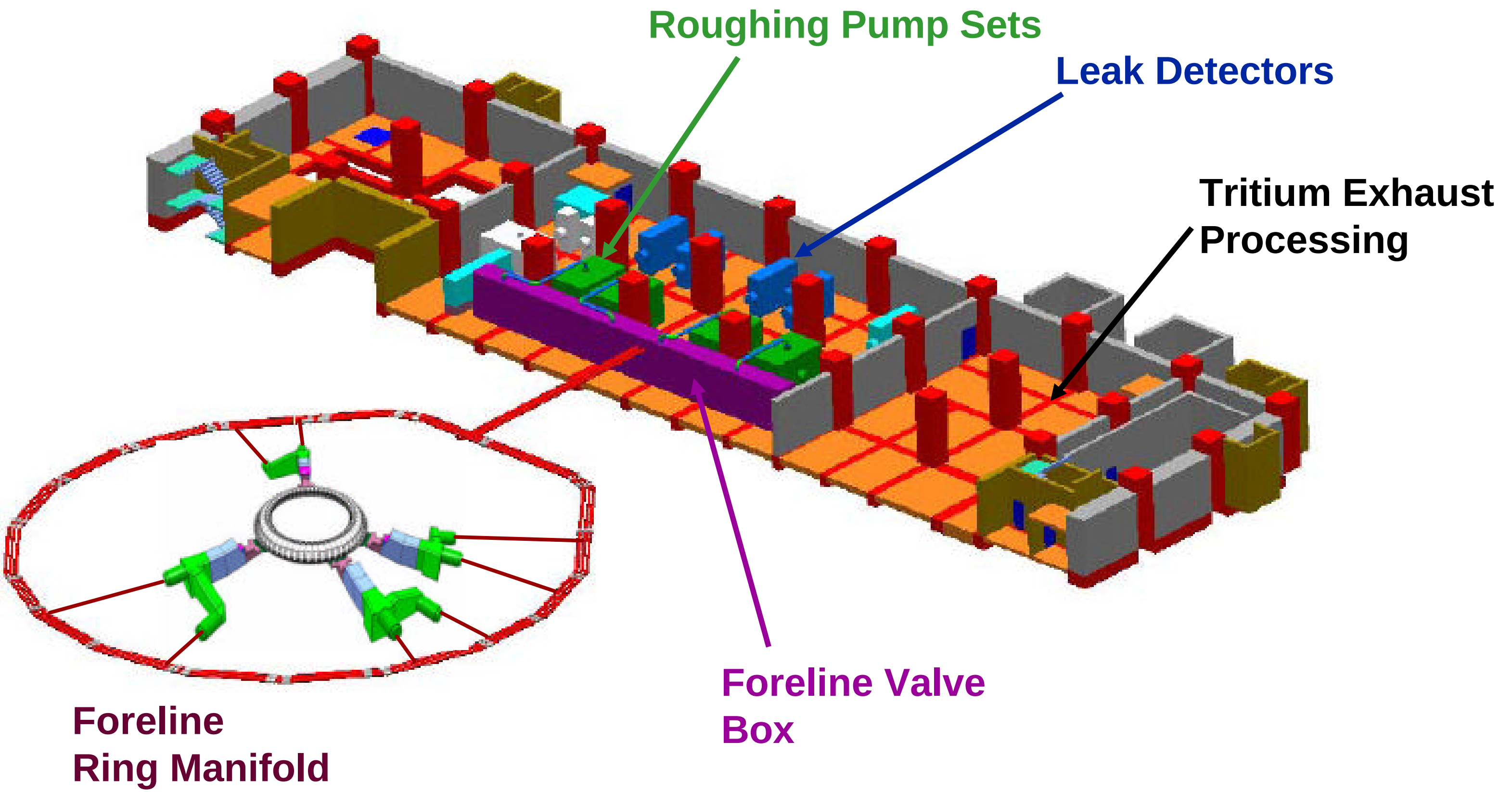
ITER Fuel Cycle Block Diagram



ITER – Vacuum Issues for Disruption Mitigation

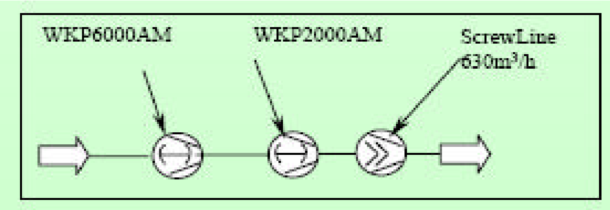
- Gas type must be compatible with pumping system and avoid activation from fusion neutrons
- Cryopumps for the torus and neutral beams may regenerate and allow pumped impurities back into torus
- Roughing Pumps must be able to handle the additional load in a timely fashion
- Neutral Beam Injectors (NBI) must be switched off when DMS is actuated and gate valves closed (several seconds).
- Tritium Plant must be able to process the extra DMS exhaust gas in a timely fashion

ITER Torus Pumping System

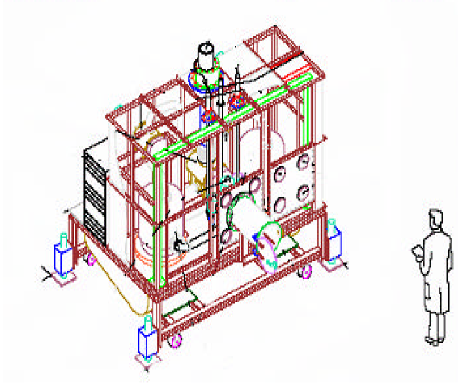


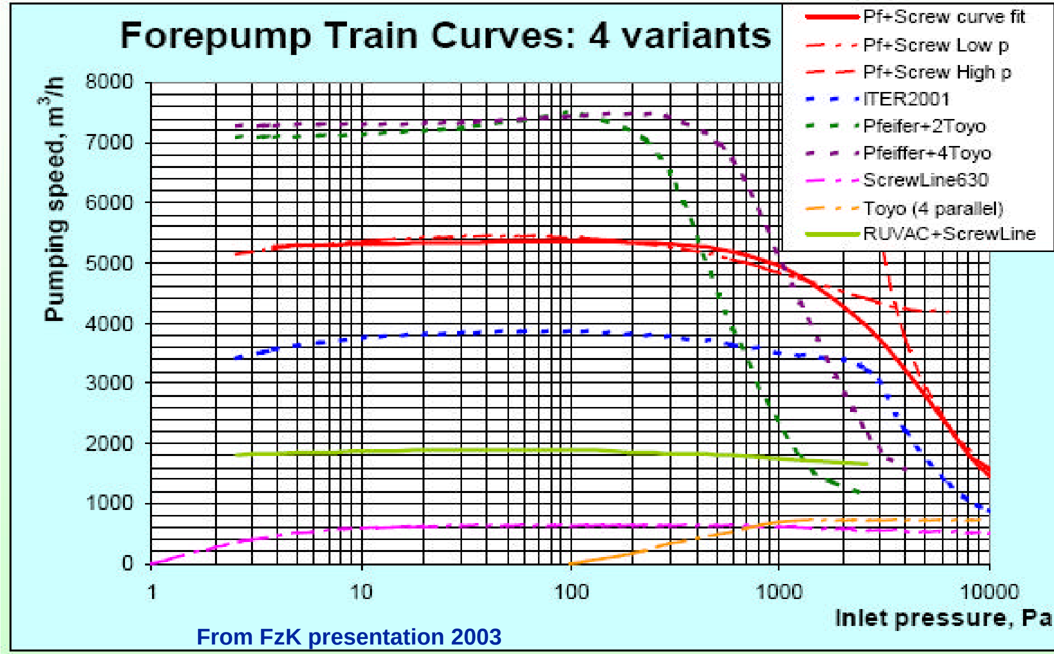
- Cartoon (not to scale) of the torus pumping system showing the cryopumps and divertor ring and foreline manifold connection to the roughing pumps.

ITER Roughing Pump System



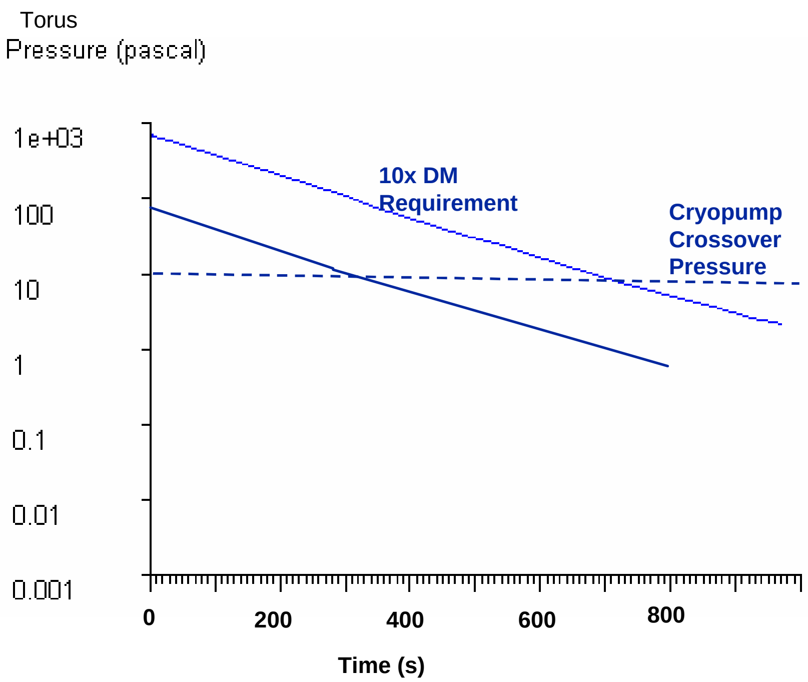
Roots Blowers + Screw Pump

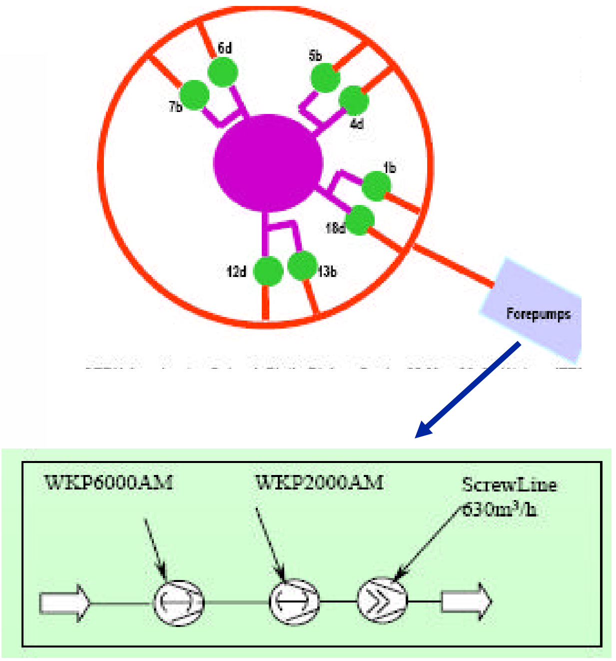




- Roots blowers are used as the first two stages in all the pump train options that are under consideration.
- One attractive option uses a screw pump to back the roots pumps.
- Pumping speed of 5000 m^3/h is possible with this configuration

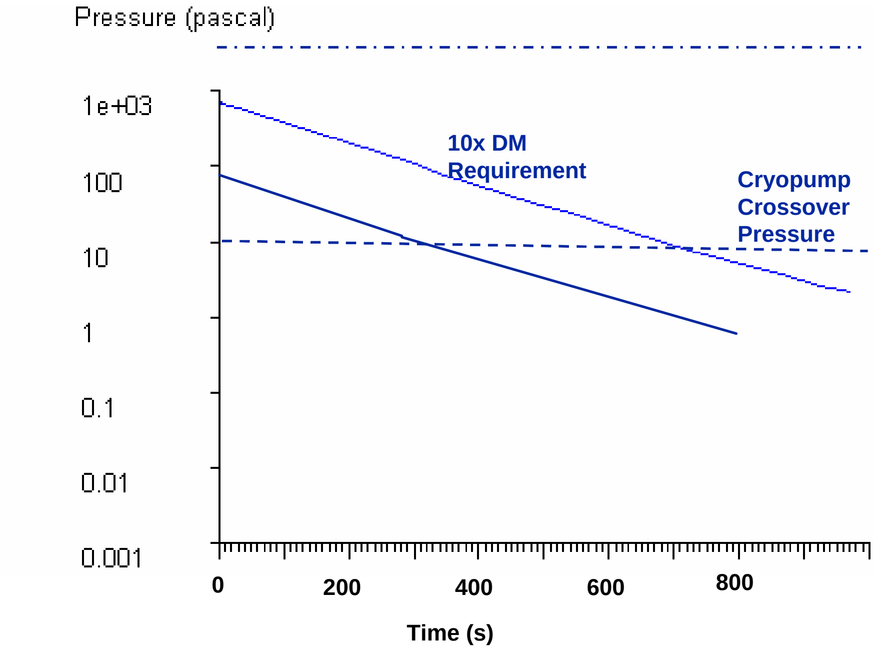
Pumpdown Time Scale After DM

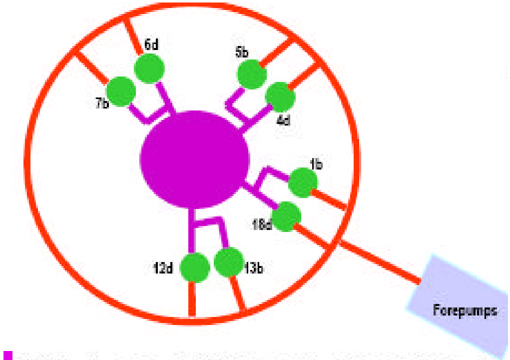


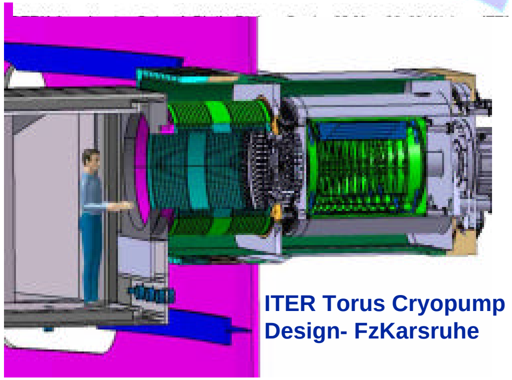


- ITERVAC [9] calculation (C. Day) shows pumpdown time when cryopumps regenerated of 150 sec.
- Crude VACSIM calculation shows time scale if 10x gas is introduced to be > 10 minutes. More detailed ITERVAC simulation is needed to for accurate pumpdown time.

Cryopump Regeneration After DM







ITER Torus Cryopump Design- FzKarsruhe

- Disruption mitigation is unlikely to cause torus cryopumps to regenerate spontaneously. Valves can be throttled and pumps regenerated naturally after pumpdown.
- NBI cryopumps will likely regenerate since valves are totally open and take seconds to close. If normal cryogenic flow is available then pumps can resume operation in ~20 minutes.

Summary

- Disruption mitigation is an important subsystem for ITER machine protection, but hopefully will be used infrequently
  - High reliability and redundancy are needed
- Technology to both detect disruptions and mitigate them in ITER are under development
- DM will introduce large amount of particles (gas or pellet) into the torus from 2 upper ports during the current decay in a few ms.
- Cryopumps for the neutral beams will likely regenerate, but probably not the torus cryopumps (4 that are pumping during disruption).
- Roughing pumps can handle the gas in a timely fashion – probably less than 20 minutes to get back into operational state.
- NBI systems can recover as soon as cryopumps are cooled down which takes ~20 minutes.
- Tritium Plant must be able to process the gas in a timely fashion
  - Capable only of 150 Pa-m3/s, so could be ~2 hours for 10X gas load

References

- [1] ITER Design Description Document
- [2] ITER Vacuum System Description (P. Ladd, Fus. Eng. Design, 58, 2001, 377, C. Day, IAEA 2004, D. Murdoch IVC 2007)
- [3] Parker, R.R., Nucl. Fusion 40 (2000) 473.
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