Session 3 - Optimise Interventions and Recovery from Collateral Damages on Cold Sectors

Means to limit the collateral damages in the beam vacuum chambers

J.M. Jimenez

On behalf of TE-VSC group

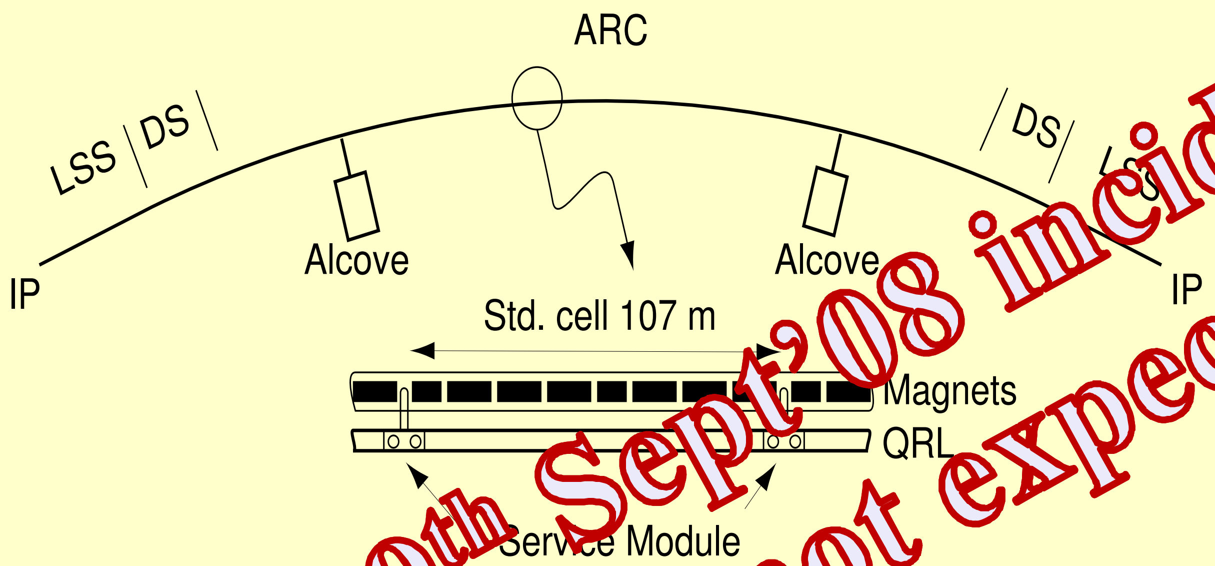
Thanks to V. Baglin, P. Coly, P. Cruikshank, C. Garion, J. Strait, L. Tavian, R. Veness and R. Van Weelderen for their help

Main Topics

- Introduction
- Review of the Vacuum Failure modes
- Expected consequences
- Mitigation solutions
- Closing remarks

Introduction
LHC Beam Vacuum Sectorisation

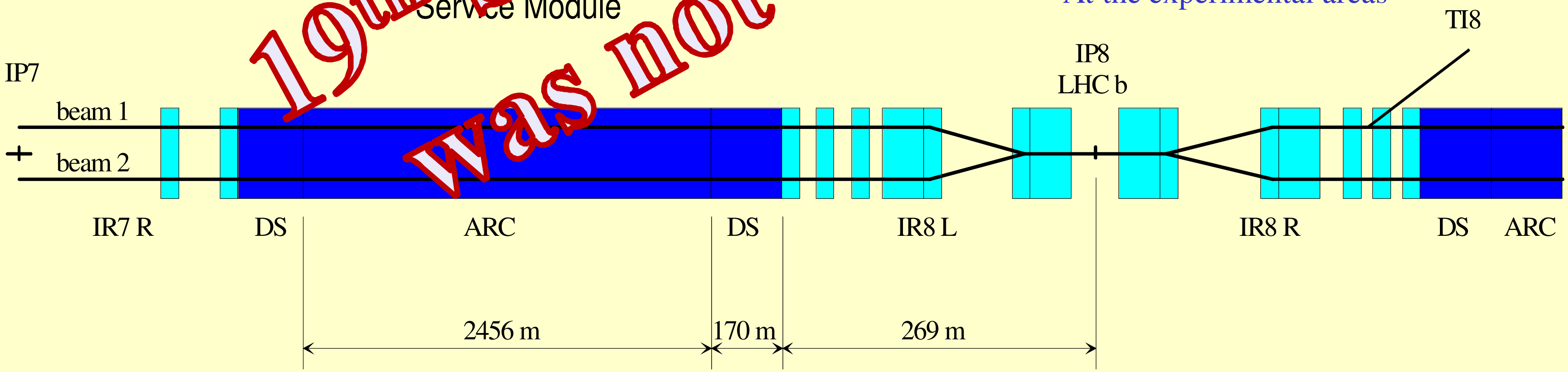
- **Brief history:** Beam Vacuum system has been designed to limit, whenever possible, the impact of *small* air or helium leaks: welds, seals, feedthroughs, holes in beam screen capillaries, etc.



LHC Beam Vacuum Sectorisation

- 8 arcs and 8 straight sections
- Separation of cold and RT vacuum system
- Create vacuum sectors in long/fragile RT zones
- Equipment which need and ex-situ conditioning
- At the experimental areas

19th Sept'08 incident was not expected



Introduction
Risk Analysis of the LHC cryogenic system (1/4)

- **Reference document: LHC-project note 177:**

LHC Project Note 177

1999-01-12

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Preliminary risk analysis of the LHC cryogenic system

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Summary

The objective of the study is to identify all risks to personnel, equipment or environment resulting from cryogenic failures that may accidentally occur within the cryogenic system of Large Hadron Collider in any phase of the machine operation, and that could not be eliminated by design. We then formulate recommendations concerning lines of preventive and corrective defence, as well as further, more detailed studies.

Courtesy L. Tavian

Introduction
Risk Analysis of the LHC cryogenic system (2/4)

Table 6: Credible failures of the cryogenic elements located in the tunnel and their causes

Element	Failure	Failure causes
R1. LHC machine cryostat	**R1.1.** Air flow to cryostat insulation vacuum	Mechanical impact on a vacuum tapping Bellows failure Weld non-tight
	R1.2. Helium flow to cryostat insulation vacuum	Bellows failure Weld non-tight
	R1.3. Air flow to sub-atmospheric helium Venting to helium of cryostat insulation vacuum	Break of instrumentation capillary
	R1.4. Helium flow to environment	Break of instrumentation capillary
	R1.5. Air flow to beam vacuum	Break of warm beam tube e.g. due to beam escape. Bellows failure
	R1.6. Helium flow to beam vacuum	Break of beam screen cooling pipe or cold beam tube e.g. due to beam escape.
	R1.7. Pressurized helium flow to sub-atmospheric helium	Bellows failure
	R1.8. Energy release due to a sector quench	Control system failure Utilities failure
	R1.9 Energy release due to electrical arc	Low dielectric resistance of helium

Courtesy
L. Tavian

Introduction
Risk Analysis of the LHC cryogenic system (3/4)

Table 7b: Recognized failures of the LHC elements located in the tunnel and their consequences (part 2)

Failure	Events	Danger to personnel	Risk to equipment	Information/ detection	Preventive defence	Corrective defence
R1.5. Air flow to beam vacuum **Gravity 1**	Air propagation to the cold bore. Air condensation and heat flow to the cold mass. A quench may be provoked.	No	Contamination of the beam vacuum space	Beam vacuum gauges	Actively cooled beam screen	Intervention necessary
R1.6. He flow to beam vacuum **Gravity 3b**	Beam vacuum filling with cold helium along whole machine. The pressure may rise above the set pressure for rupture disc and helium may flow to the tunnel. A quench may be provoked.	Freezing of tissue	Contamination of beam vacuum space	Beam vacuum gauges	Actively cooled beam screen	Intervention necessary
R1.7. Press. He flow to sub-atm He **Gravity 1**	Increase of the saturation He pressure and cold mass temperature. A quench may be provoked.	No	No	Temperature and pressure sensors	Redundancy of cold compressors capacity	Intervention necessary
R1.8. Sector quench [12 ,13] **Gravity 1**	Dissipation of magnetic energy in the cold mass, helium expulsion to header D through SRV valves Pressurisation of header D to 20 bar, helium flow to HP storage	No	No	Rise of magnet temperature	High capacity cold header D	Not linked to the cryogenic system
R1.9. Energy release – electrical arc **Gravity 3b**	Electrical arc between superconducting cables or busbars may result in local thermal energy release of MW order. Cold mass helium will pressurise and vent through quench relief valve. It may be followed by destruction of cold mass enclosure and helium flow to insulation vacuum (see R1.2).	See R1.2	See R1.2	Voltage taps, voltage across current leads	High dielectric resistance of pressurised He II	Not linked to the cryogenic system

Gravity 3b: Helium is blown out of the machine in confined areas while access to these areas is allowed, under controlled conditions

Courtesy L. Tavian

Introduction
Risk Analysis of the LHC cryogenic system (4/4)

Table 8: Gravity 3b failures at the nodes located in the tunnel

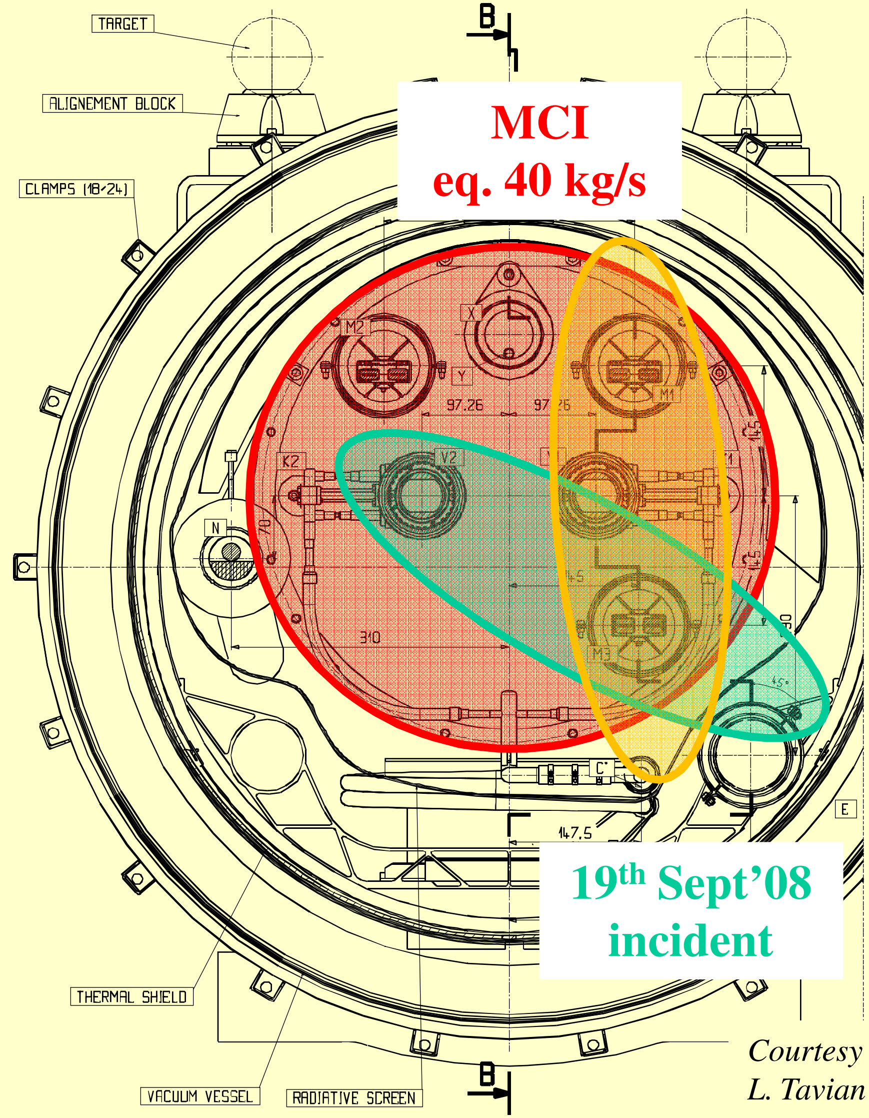
Failure	Maximum amount of helium relieved to the tunnel [kg]/ approximate flow rate [kg/s]	Recommendations
R1.2 LHC cryomagnets: He flow to cryostat insulation vacuum	475 / below 2	Further analysis necessary
R1.4 LHC cryomagnets: He flow to air	475 / He flow of a leak order	Consequences of the failure fully covered by R1.2 and R2.4
R1.6 LHC cryomagnets He flow to beam vacuum	475 / to be calculated	Further analysis necessary
R1.9 LHC cryomagnets energy release – electrical arc	475 kg / flow rate similar to R1.2	Not directly related to cryogenics, consequences covered by R1.2
R2.2 He flow to QRL insulation vacuum, assumption of header C break	3300 kg / lower than 2	Second, after R2.4 worst case scenario, further modelling of helium expulsion to the tunnel as well as helium propagation in the tunnel is necessary
R2.4 He flow to air, assumption of jumper connection break	4250 / about 20. About 600 kg are discharged in the first 60 s. After this time the mass flow-rate reduces by an order of magnitude.	Worst case scenario, further modelling of helium expulsion to the tunnel as well as helium propagation in the tunnel is necessary

Courtesy L. Tavian

Introduction
Experience from SM18 String Test & MCI

- **Following the electrical problem produced on the String experiment (see LHC-XMS-ER-0002 rev 1.0), no special warning was triggered at the time concerning the large collateral damages that could be created.**

- **MCI is equivalent to a discharge of 40 kg/s even in case the M1, M2 and M3 lines are damaged simultaneously**



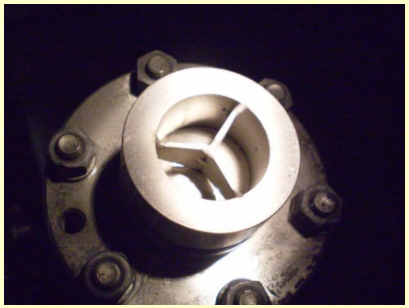
Courtesy L. Tavian

Introduction

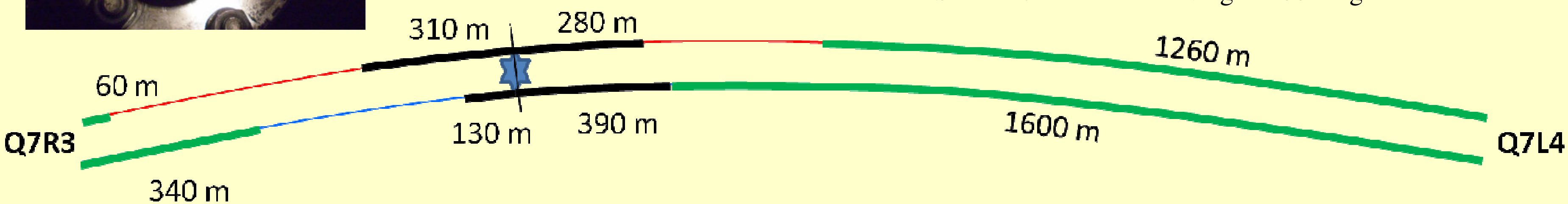
19th Sept'08: Damages to the Beam Vacuum

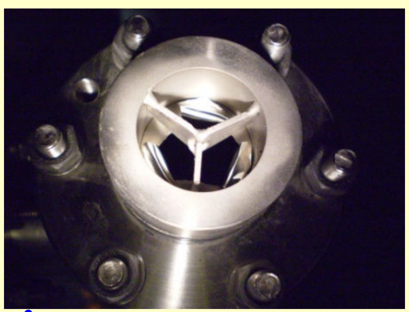
Status	V1 Magnet	V2 Magnet	V1 %	V2 %	Total %
Ok	54/49	39/30	26/31	18/19	22/25
MLI	124/111	129/124	58/69	61/78	59/73
Soot	35/0	45/6	16/0	21/4	19/2
Total	213/160	213/160	100	100	100

Second % is after removing the 53 magnets of the D-zone

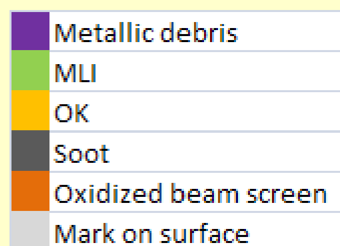


Q8R3 V1: rupture disk deformed but not perforated

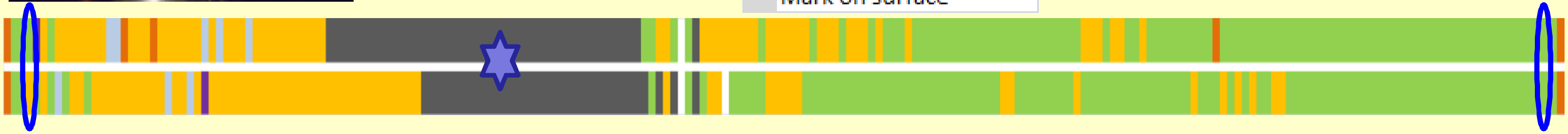




Q8R3 V2: rupture disk blown



Q8L4 V1/V2: rupture disk deformed but not perforated



Introduction
« As built » situation

- **Arcs Insulation vacuum**
  - Vacuum barriers (204 m)
  - Spring relief valve (2 by vacuum subsector eq. DN90)

- **Arc Beam vacuum**
  - Rupture disks (30 mm aperture) available at each arc extremity (~3 km)
  - No vacuum sectorisation !
- **Long straight sections Warm vacuum sectors**
  - Vacuum sector valves (Warm sectors can always be isolated from SAM)
- **Long straight sections Standalone Magnets (SAM)**
  - Insulation vacuum
    - Spring relief safety valve

  - Beam vacuum
    - Rupture disks (30 mm aperture) available at each SAM extremity (max. length in triplets)
    - Vacuum sector valves at each extremities (isolate from the warm vacuum sector)
- **Experimental areas**
  - Vacuum sector valves at Q1 (each side) and to isolate the central beam pipes
  - Pressure relief valve (only in LHCb Velo)

Introduction
Situation after the 3-4 Incident

- **Arcs Insulation vacuum**
  - Vacuum barriers (204 m)
  - Spring relief valve (2 by vacuum subsector eq. DN90)
  - Safety relief valves (DN200) and/or declamped flanges (DN63 and DN100)
  - By-pass installed across all vacuum barriers (5 arcs completed/8)
- **Arc Beam vacuum**
  - Rupture disks (30 mm aperture) available at each arc extremity (~3 km)
  - No vacuum sectorisation !
- **Long straight sections Warm vacuum sectors**
  - Vacuum sector valves (Warm sectors can always be isolated from SAM)
- **Long straight sections Standalone Magnets (SAM)**
  - Insulation vacuum
    - Spring relief safety valve
    - Safety relief valves (DN200) and/or declamped flanges (DN63 and DN100)
  - Beam vacuum
    - Rupture disks (30 mm aperture) available at each SAM extremity (max. length in triplets)
    - Vacuum sector valves at each extremities (isolate from the warm vacuum sector)
- **Experimental areas**
  - Vacuum sector valves at Q1 (each side) and to isolate the central beam pipes
  - Pressure relief valve (only in LHCb Velo)
  - Rupture disks (30 mm aperture) at each extremity of each Experimental area (close to Q1)

Review of the Vacuum Failure modes
Beam Vacuum

- **Electrical arcing inside the cold mass**
  - Making a hole on the cold bore: short on the lira or on the magnet coil
    - ☞ Fast helium venting and pressurisation of the Beam vacuum chambers
- **Beam loss on warm or cold sectors**
  - Expected effects are different between warm/cold and interconnect/cold mass
    - ☞ More critical when occurring in the cold mass than at the interconnect
    - ☞ Fast helium venting and pressurisation of the Beam vacuum chambers
    - ☞ Beam loss in warm sectors will result in an air venting and requires a bake out
- **Collateral effect of an incident which occurred in the Insulation Vacuum**
  - Mechanical buckling and rupture of the bellows (PIMs and nested) induced by an external pressurisation
  - Physical displacement of the magnets destroying the bellows (PIMs and nested bellows)
  - Electrical arcing inducing melted metal projections or direct arcing which damage the bellows (PIMs and nested) ⇨ More critical when it induces:
    - A brutal venting and pressurisation of the Beam vacuum
    - An injection of contaminants: MLI, soot, metallic debris

Expected consequences
Accidental venting of Beam vacuum

- Brutal venting is a worsen factor – will enhance the other effects

- **Air leaks**
  - Are expected to develops *slowly*
    - Condensation of oxygen on cold surfaces implies safety measures
  - In Arcs, SAM and IT: will require a total warm up
  - In LSS RT sectors: will require a bake out
    - Long shutdown for Experimental areas
- **Helium leak without pressurisation/contamination**
  - Will require the warming up of the cold sectors (arcs, SAMs and ITs)
    - Implies the removal of *at least* a magnet if the leak is in the cold mass, in the beam screen capillaries or not accessible in the cryostat.
  - In LSS RT and Experimental areas
    - Dry helium does not saturate the NEG coatings ⇨ pump down could be enough

Expected consequences
Mechanical damages to Beam vacuum

- **External pressurisation or displacement (only on cryo-magnets)**
    - Buckling and rupture of the bellows by an external pressurisation of the insulation vacuum
    - Damage and rupture of vacuum components and bellows resulting from a displacement of the magnet cryostat or cold mass
    - Damages and holes due to accidental Beam losses
  - In Arcs, SAM and ITs: will require a total warm up
    - Implies the removal of damaged magnets and replacement of components
- **Mechanical damages resulting from an internal pressurisation**
    - Will require a total warm-up
  - Arcs, SAM and ITs: Buckling of bellows is critical for the nested bellows on the beam screen since it implies removing the magnet from the tunnel
  - Experimental areas: Bellows, chambers and supports in the Experimental areas could fail resulting from the build-up of longitudinal forces not considered during the design. Some components are more fragile like thin-wall beam pipes and envelopes, aluminum bellows, VELO detector and LHCb Aluminum window.
  - In LSS warm sectors: Implies a replacement of damaged components and requires a bake out

Expected consequences
Contamination

- Contamination of the upstream and downstream vacuum sector is expected
- More critical in arcs (warm-up) and Experimental areas (cleaning, bake out)

- **Failure originated in the Insulation vacuum**
    - Contamination is injected through the damaged interconnection (PIMs/nested bellows)
    - *Heavy* soot contamination implies the exchange of components/magnets as light contamination can be cleaned in situ. Removal of all dust is not granted.
  - In case of an electrical arc
    - Soot, metallic and MLI debris
  - If resulting from an external pressurisation or displacement
    - MLI debris only
- **Failure originated in the Beam vacuum**
    - *Heavy* soot contamination implies the exchange of components/magnets as light contamination can be cleaned in situ ⇨ Removal of all dust is not granted.
  - At the interconnection (Beam loss)
    - Soot and metallic debris (few)
  - In the cold mass (Beam loss, lira and coil shorts)
    - Soot, metallic and Kapton debris

Technology Department TE Vacuum Surfaces & Coatings

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Expected consequences
Today's situation (includes approved consolidations)

1 Direct effect
2 Indirect effect

	Mitigations								
	Already implemented/approved							Additonal	
	Vacuum sector valves	Machine Protection System	nQPS (limit the risk of arcing and the power in the plasma)	Quench relief valves on the cryolines (avoids that the helium pressure rise above xx bars)	Reinforcement of the support of the SSS with Vacuum barriers	Pressure relief valves on Insulation Vacuum vessels (limits the internal pressurisation)	Rupture disks on Beam Vacuum (limits the internal pressurisation)	Two half-shells to protect the bellows	Fast-closing valves on Beam Vacuum (protect other components)
Failure modes for the Beam Vacuum									
Direct effects									
Air leak provoked by a failure of warm components (gauges, bellows, rupture disks)	1								
Helium leak inside the Beam Vacuum	1								
Electrical arcing inside the magnet cold mass (coil or lira)			1						
Hole provoqued by a beam loss		1	1	2					
Brutal venting to helium and propagation to the entire machine	1						2		
Buckling of bellows (PIMs and nested bellows) by an internal helium pressurisation			2	2			1		
Contamination (metallic debris, soot and Kapton) and propagation to the entire machine by the brutal venting	1		1	2					
Indirect effects: Helium pressurisation from Insulation Vacuum									
Buckling and rupture of bellows (PIMs and nested bellows) by an external pressure (rupture of a cryo-line)				1	2	1			
Physical displacement of the magnets destroying the bellows				1	1	1			
Brutal venting to helium and propagation to the entire machine	1								
Buckling of bellows (PIMs and nested bellows) by an induced internal helium pressurisation			2	2	2	1	1		
Contamination (MLI) and propagation to the entire machine by the brutal venting	1		2	1		1			
Projection of melted metal resulting from an electrical arc			1						
Brutal venting to helium and propagation to the entire machine	1								
Buckling of bellows (PIMs and nested bellows) by an induced internal helium pressurisation			2	2	2	1	1		
Contamination by an arcing (metallic debris, soot and MLI) and propagation to the entire machine by the brutal venting	1		1	2	2	1			

Expected consequences
With additional mitigation measures

1 Direct effect
2 Indirect effect

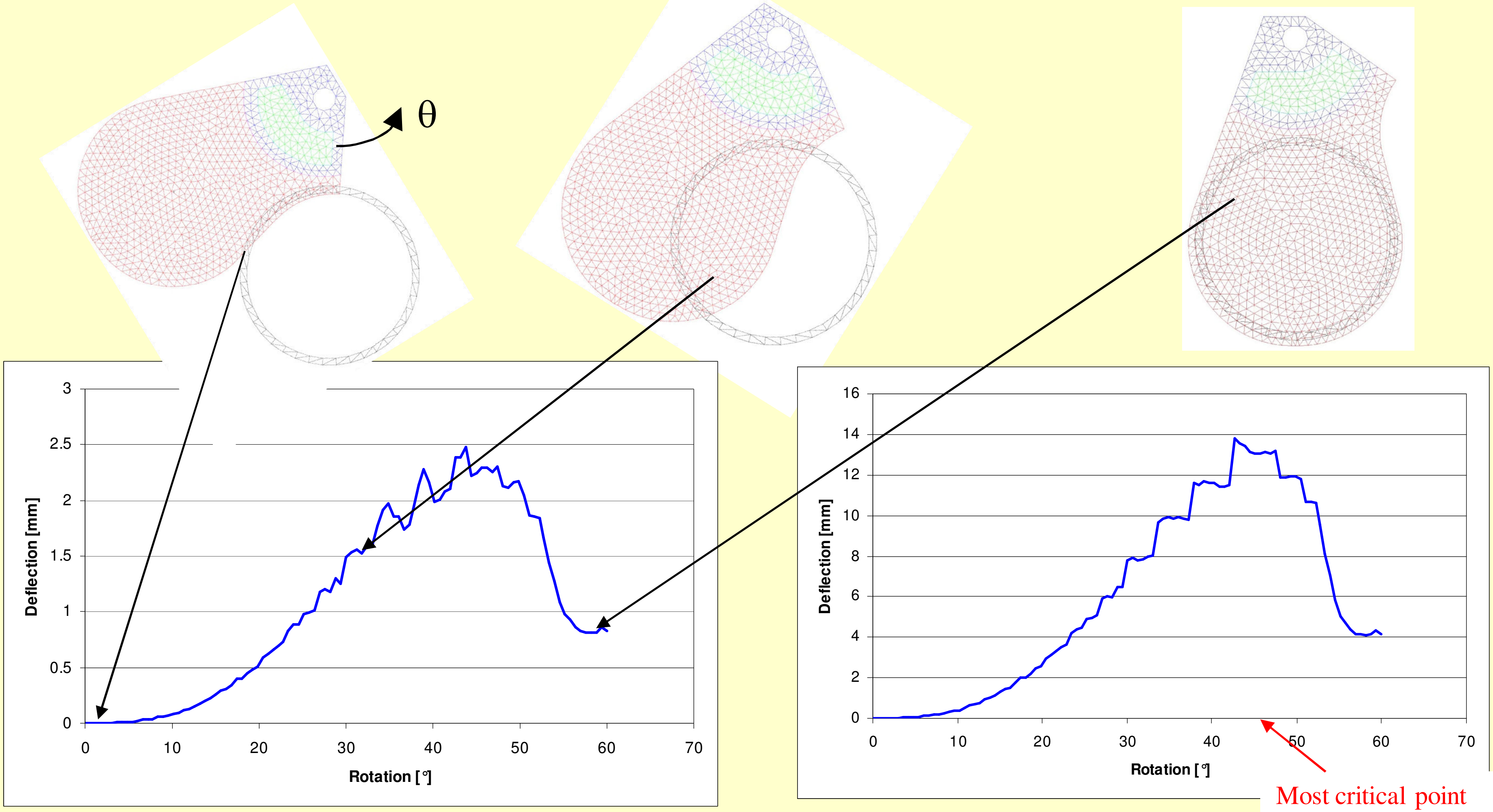
	Mitigations								
	Already implemented/approved							Additonal	
	Vacuum sector valves	Machine Protection System	nQPS (limit the risk of arcing and the power in the plasma)	Quench relief valves on the cryolines (avoids that the helium pressure rise above xx bars)	Reinforcement of the support of the SSS with Vacuum barriers	Pressure relief valves on Insulation Vacuum vessels (limits the internal pressurisation)	Rupture disks on Beam Vacuum (limits the internal pressurisation)	Two half-shells to protect the bellows	Fast-closing valves on Beam Vacuum (protect other components)
Failure modes for the Beam Vacuum									
Direct effects									
Air leak provoked by a failure of warm components (gauges, bellows, rupture disks)	1								1
Helium leak inside the Beam Vacuum	1								1
Electrical arcing inside the magnet cold mass (coil or lira)			1						
Hole provoqued by a beam loss		1	1	2					
Brutal venting to helium and propagation to the entire machine	1						2		1
Buckling of bellows (PIMs and nested bellows) by an internal helium pressurisation			2	2			1	1	
Contamination (metallic debris, soot and Kapton) and propagation to the entire machine by the brutal venting	1		1	2					1
Indirect effects: Helium pressurisation from Insulation Vacuum									
Buckling and rupture of bellows (PIMs and nested bellows) by an external pressure (rupture of a cryo-line)				1	2	1		1	
Physical displacement of the magnets destroying the bellows				1	1	1			
Brutal venting to helium and propagation to the entire machine	1								1
Buckling of bellows (PIMs and nested bellows) by an induced internal helium pressurisation			2	2	2	1	1	1	
Contamination (MLI) and propagation to the entire machine by the brutal venting	1		2	1		1		1	1
Projection of melted metal resulting from an electrical arc			1					1	
Brutal venting to helium and propagation to the entire machine	1								1
Buckling of bellows (PIMs and nested bellows) by an induced internal helium pressurisation			2	2	2	1	1	1	
Contamination by an arcing (metallic debris, soot and MLI) and propagation to the entire machine by the brutal venting	1		1	2	2	1		1	

Mitigation solutions
Technical solutions: Efficiency & Feasibility

- **Two half-shells in Vetronite or equivalent**
  - Shall protect the bellows (PIMs and nested) in the interconnections
    - Increase resistance to plasma discharge (high temperature resistance)
    - Avoid damages induced by the projections of melted metal
    - Limit the injection of MLI in the Beam Vacuum
  - Shall use insulating material to repulse the plasma/arcing risk
  - ☞ Easy to retrofit during the consolidation of the splices
- **Fast-closing valves**
  - Shall not be necessarily leak tight
  - Shall close within 20-50 ms
  - Shall use a low-Z material for the sealing plate
    - Transparent to the beam in case the valve closes while beams are still circulating
    - Faster since lighter
    - Spring or pyrotechnic actuator
  - ⇨ Requires reliable interlock signals
    - Beam loss monitors
    - Pressure gauges or nQPS in the absence of circulating beams
  - ☞ Needs a complete development and validation tests

Mitigation solutions
Technical solutions: Efficiency & Feasibility

Fast-closing valves: reusing LEP type valves

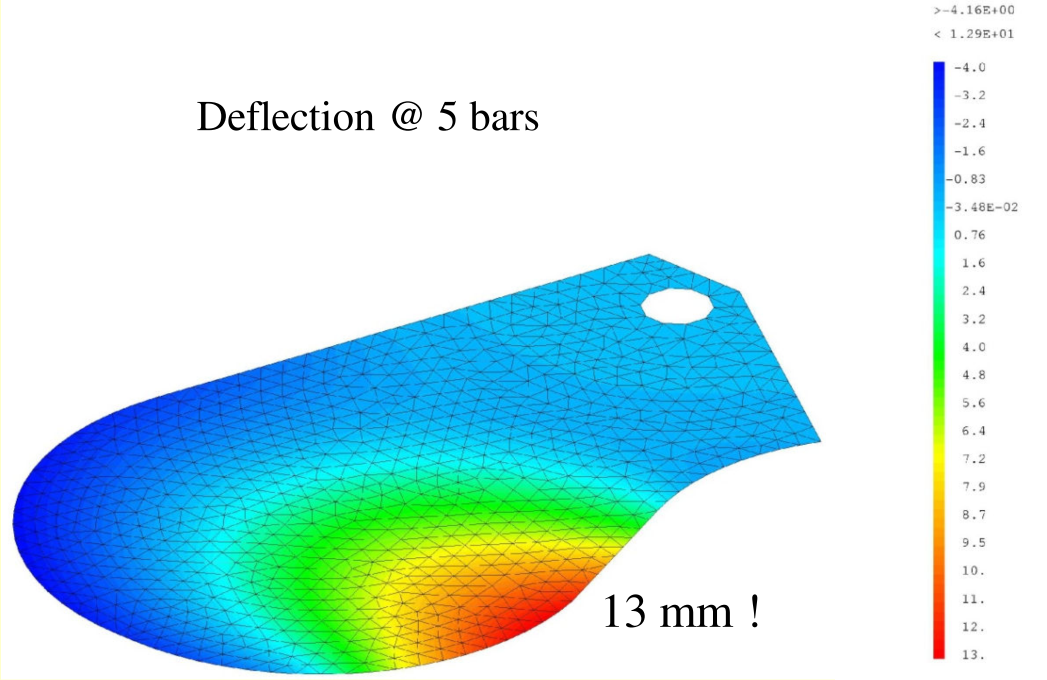


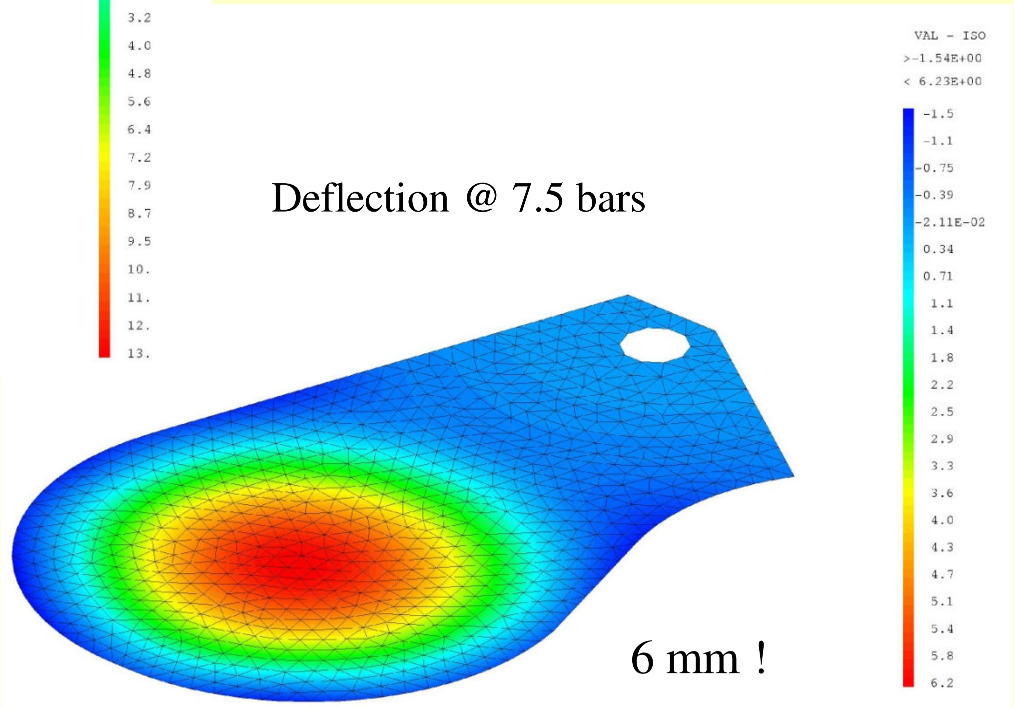
Maximum deflection for p = 1 bar

Maximum deflection for p = 5 bar

Mitigation solutions
Technical solutions: Efficiency & Feasibility

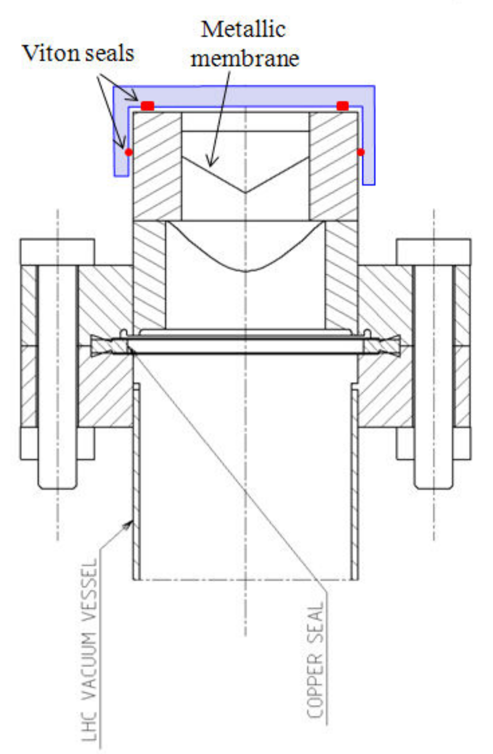
Fast-closing valves: reusing LEP type valves



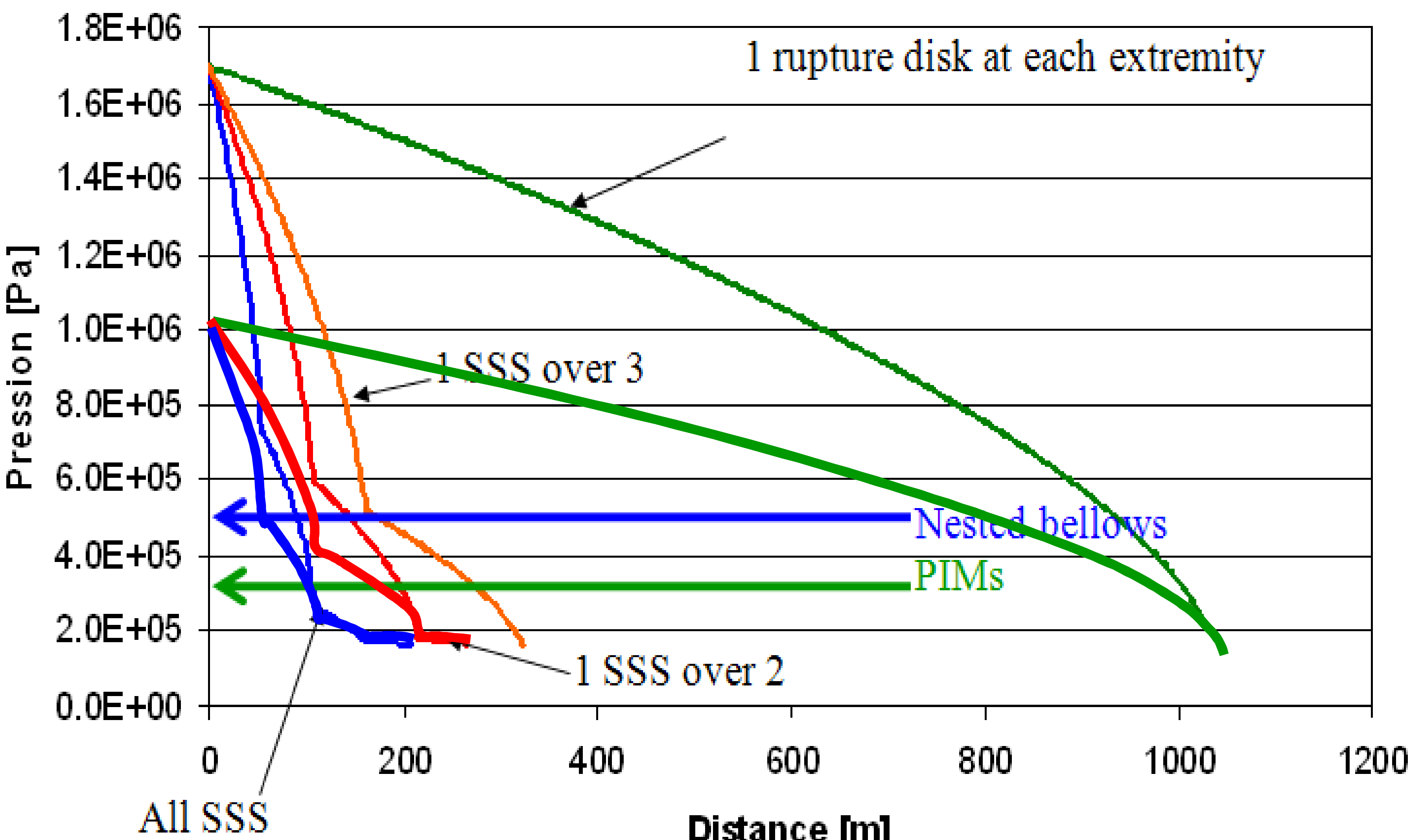


Mitigation solutions
Technical solutions: Efficiency & Feasibility

- **Rupture disks**
  - Shall be modified to limit the impact of a failing membrane
    - Spring-based cap is being studied
  - Shall equip all vacuum sectors in the Experimental areas
    - Put back to operation the two central vacuum sector valves of the Experimental areas
  - Limits the buckling of the bellows (PIMs and nested) in case of an internal pressurisation
  - Can be retrofitted:
    - In the arc during the consolidation of the splices (require a warm up)
    - In the Experimental areas using a small over pressure of dry Neon



Mitigation solutions
Rupture disks efficiency (1/2)



Mitigation solutions
Technical solutions: Efficiency & Feasibility

Rupture disks

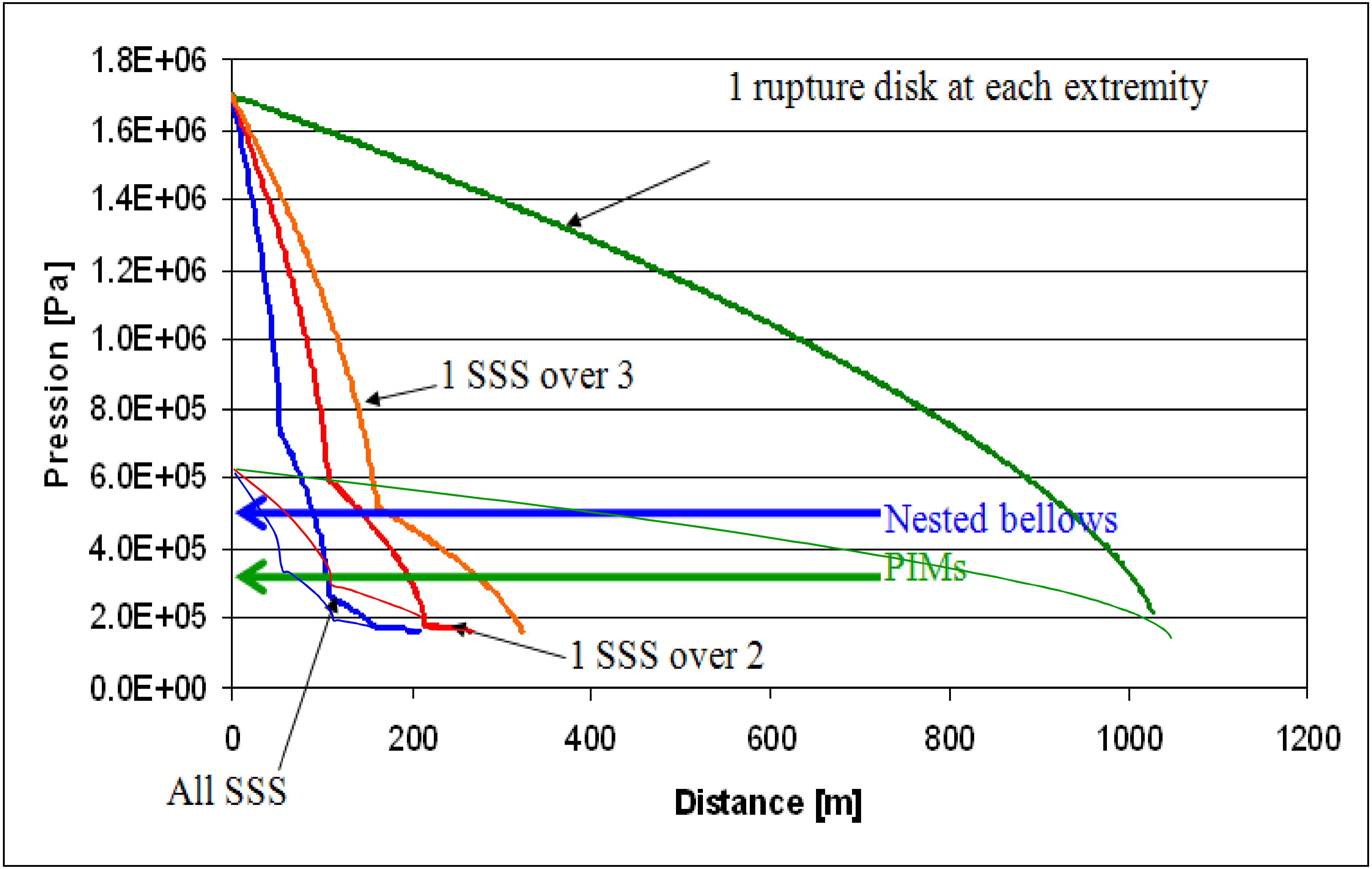
– 17 bars (max)
- 2 periods (200 m) if rupture disks are installed on all SSS
- 4 periods (400 m) if rupture disks are installed on 1 SSS over 3

– 10 bars (set quench relief valves on cryo-lines)
- 1 period (100 m) if rupture disks are installed on all SSS
- 2 periods (200 m) if rupture disks are installed on 1 SSS over 3

☞Limitation in conductance of the cold bore limits the effect of the rupture disks.

Mitigation solutions

Rupture disks efficiency (2/2)



Closing Remarks

- **Prerequisites and required time to implement**
  - Half-shells are easy to install and can be coupled with the consolidation of the splices
  - Additional rupture disks sounds a good idea
    - For all Experimental areas ⇨ Needs a venting to dry Neon
    - In the arcs ⇨ Needs a warm up and can be coupled with the consolidation of the splices
  - ☞ Reliability and limitation of collateral damages in case of a membrane failure is the determinant factor
  - Fast-closing valves need a technical development and validation ⇨ A minimum of 1 year of development is expected
  - ☞ Can be implemented in warm sectors to protect RF cavities, kickers and Experimental areas provided that means are found to trigger their closure
  - ☞ Implementation in the arcs seems difficult
- **Protections implemented in other accelerators**
  - Many discussions with US Colleagues (thanks to them and to J. Strait)
  - ☞ Nothing specific is implemented in the US accelerators. Contamination is not worrying them

Closing Remarks

- **Do the proposed solutions fill the requirement in case of a MCI?**
  - YES, as complementary measures to the Machine Protection system, nQPS, pressure relief valves, vacuum sector valves, adjustment and triggering of the quench relief valves
  - ☞ Protective half-sells for the PIMs and nested bellows, additional rupture disks (quantities and positions still to be defined) and fast valves will help to limit the collateral damages
  - ☞ Difficult to see them as primary systems

- **Arcing in the interconnections or in cold mass will result in contamination problems**

- **Pressure relief valves and rupture disks will prevent from other collateral damages like buckling of bellows**

Abstract

The incident in the sector 3-4 has pointed out the need to limit whenever possible the propagation of the contamination by soot, MLI and other debris to an entire arc. Indeed, the subsequent endoscopic inspection and cleaning imply about 6 months of shutdown and requires opening the interconnections every 200 m.

Following a brief review of the 3-4 incident, the impact of a similar incident at other locations in the LHC ring will be discussed together with the expected impact onto the upstream and downstream vacuum sectors. Expected pressure profiles will be presented. Some proposal to limit the induced overpressure and the propagation of dusts will be discussed.

Their feasibility and drawbacks as well as the prerequisite and time required for their implementation will be discussed and compared to solutions implemented in other accelerators. The applicability to the recently defined MCI will be commented.

Review of potential incidents
Expected collateral damages to beam vacuum (1)

- **Catastrophic beam vacuum failure (no access to the tunnel)**
  - Failure beam vacuum windows
    - Dump line
      - Dump bloc must be kept at an atmospheric pressure of nitrogen to avoid a fire
        - » Combination of beam dump + air leak
    - ☞ Failure of the dump window
        - » Limited effect onto the main ring beam vacuum
        - » Dump line will become a "contaminated" area
    - Rupture disks
      - 2 per beam line / arcs (4 in total) and 1 per beam line / SAM (2 in total)
      - Failure of the rupture disk
        - » Cold sector will have to be warmed-up to ambient temperature to remove the condensed water
          - » 3 weeks for the SAM
          - » > 6 weeks for the arcs
        - » Small leaks will not be detected before magnet will quench due to beam losses induced by beam-gas scattering
        - » Replacement shall be scheduled (limited lifetime?)

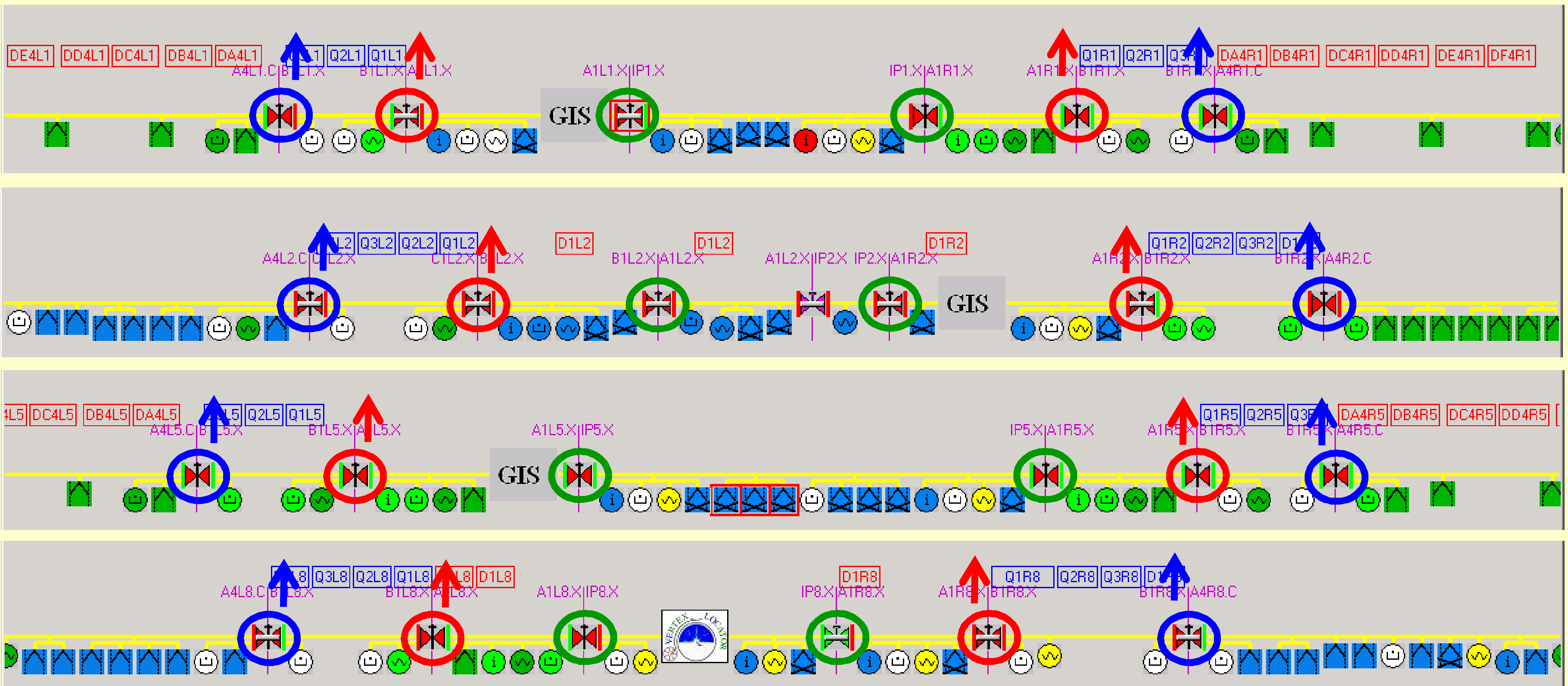
Review of potential incidents
Expected collateral damages to beam vacuum (2)

- **Catastrophic beam vacuum failure (personnel accessing the tunnel)**
  - Bellows and feedthroughs are the most exposed
    - All activities around the beam pipe are concerned including the vacuum activities !
  - Expected consequences
    - Cold beam vacuum are the most critical since a warm-up to ambient temperature will be required to remove the condensed water
      - 3 weeks for the SAM
      - > 6 weeks for the arcs
    - NEG beam vacuum sectors are critical only during the activation process (24 h/1 week). An air leak occurring at T > 180 °C will destroy the NEG coating…
      - ~5-6 weeks for LSS warm sector
      - ? months for Detector beam pipes

- **Alternative repair solutions exist for non catastrophic leaks**
  - Varnishing, differential pumping, re-welding in situ, etc.

Follow-up of Chamonix'09 recommendations
Proposals for Experimental Areas

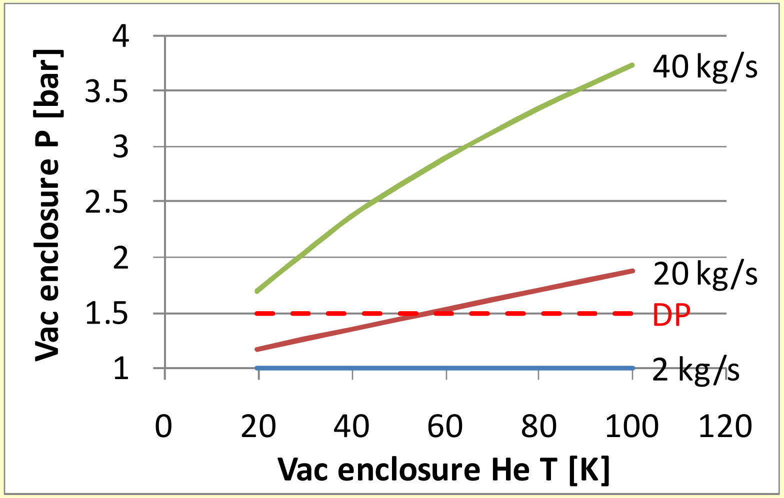
- **Modification of the sequence of closure of the sector valves**
  - Blocking the central experimental beam sector valves
- **Installation of two "protected" rupture disks at each extremity of the experimental beam pipes**



No change | Do not close | Close faster | Existing rupture disk | New rupture disk

Limiting collateral damages
Pressurization of the beam pipes: Arcs and SAM (5)

- Protection on cold sub-sectors: 13 DN100, 2 DN90, 4 DN63



- Protection on warm sub-sectors: 12 DN200, 4 DN100, 2 DN90