Chamonix 2011 LHC Performance Workshop,
Session 04: Beam Energy

Consequences of a hypothetical incident for different sectors (with beam energy up to 5 TeV)

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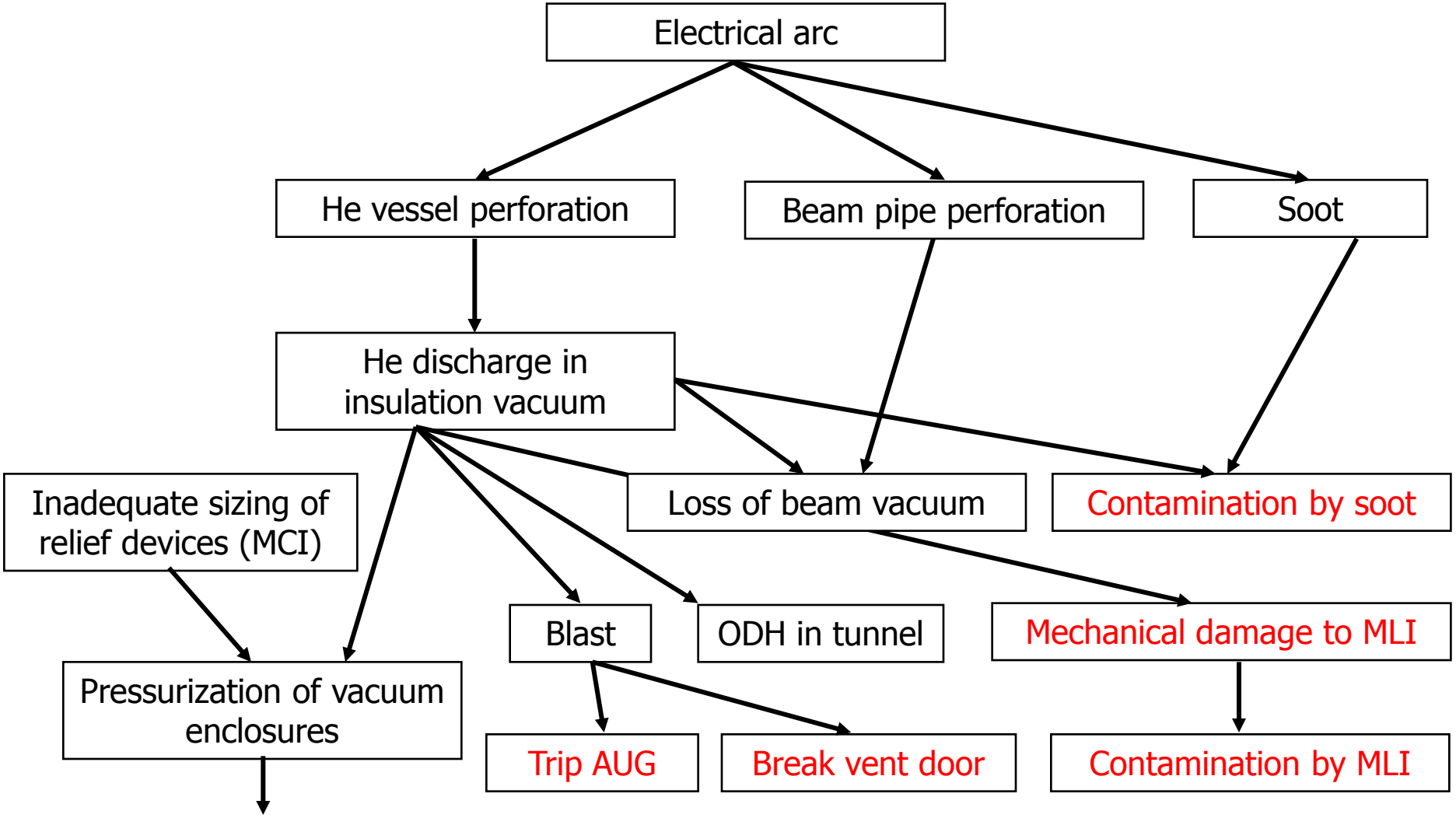
Content

- Introduction
  - Recall of the 19th Sept'08 fault tree
  - Recall of sector consolidation status for 2011/12 operation
- Updated fault trees and consequences in case of:
  - A hypothetical electrical arc in a cryo-magnet interconnect for beam energy up to 5 TeV
  - A hypothetical electrical arc in a magnet cold-mass for beam energy up to 5 TeV
- Conclusion

Fault tree of 19 Sept 2008 incident at the LHC

Cryogenic effects [1/2]



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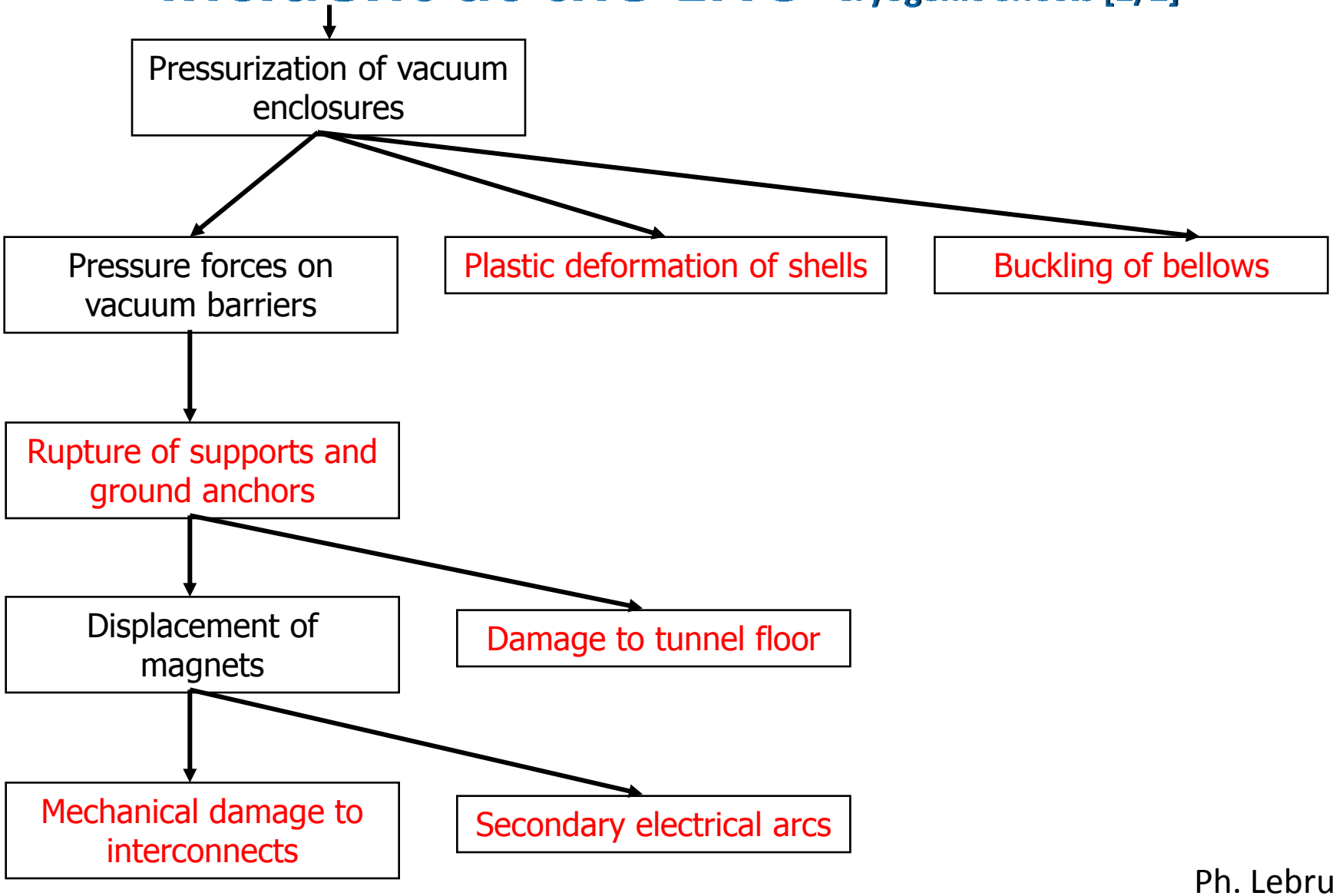
Fault tree of 19 Sept 2008 incident at the LHC

Cryogenic effects [2/2]



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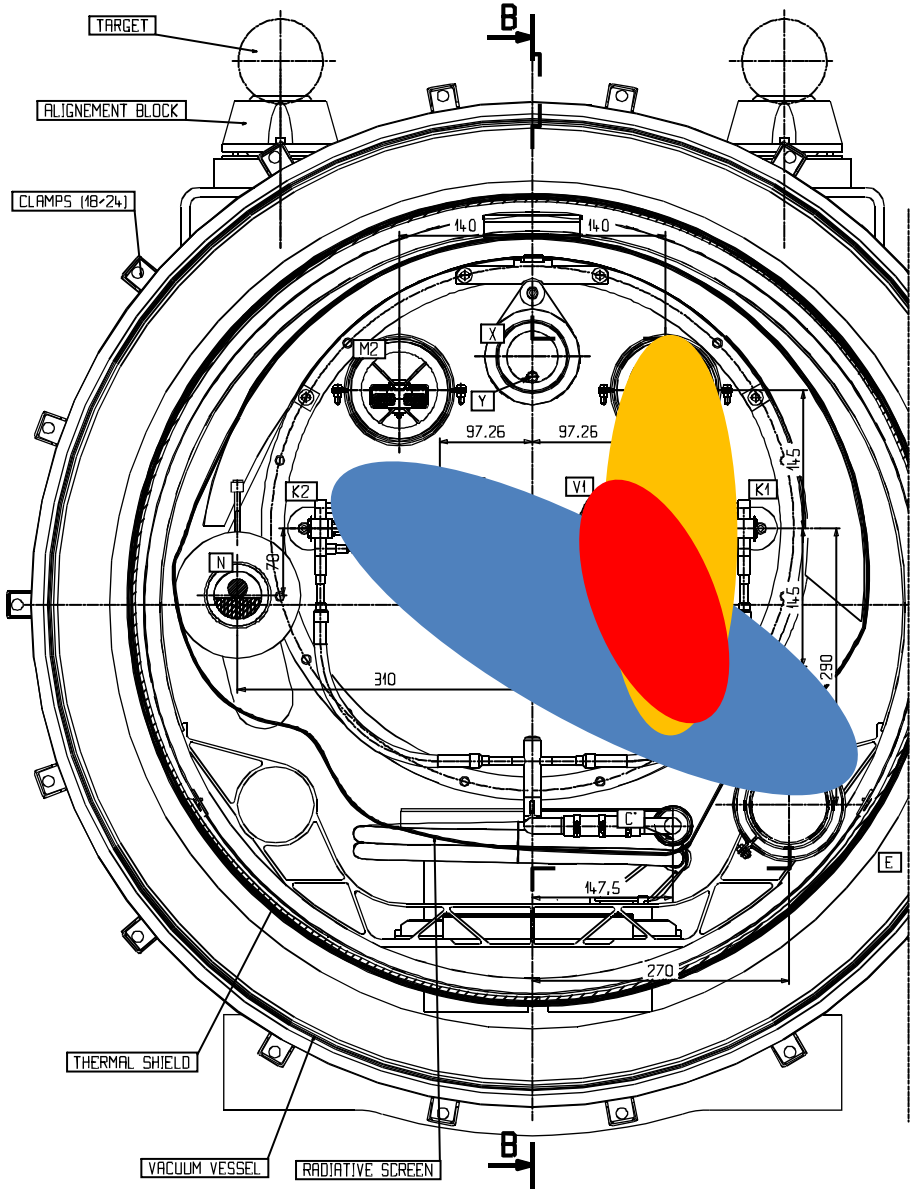
Sub-sector inventory

(Ref. CERN ATS Note 2010-057)

MCI in case of electrical arc in an interconnect



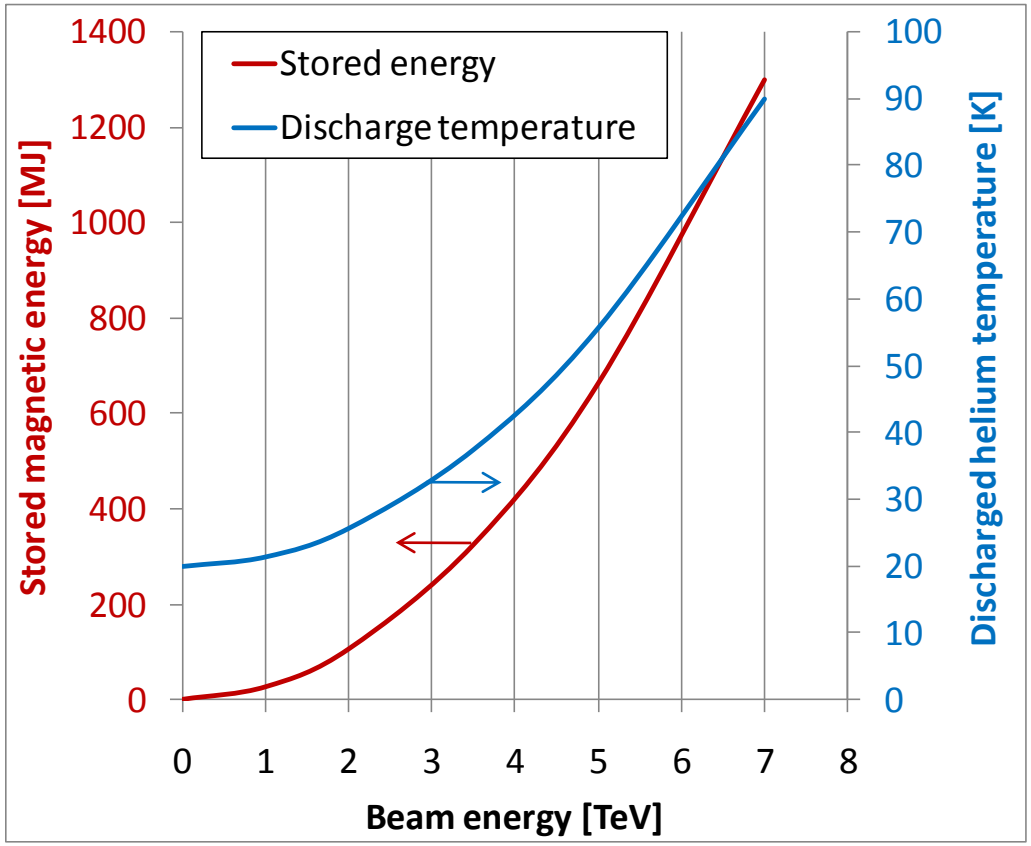
With “smaller” electrical arc (i.e. lower magnetic stored energy and/or lower discharge time constant), perforation of the beam pipe can not be excluded with the present consolidation status. (Electrical insulation of the beam pipe interconnect foreseen in 2013/12)

080919 accident (~ 5 TeV)

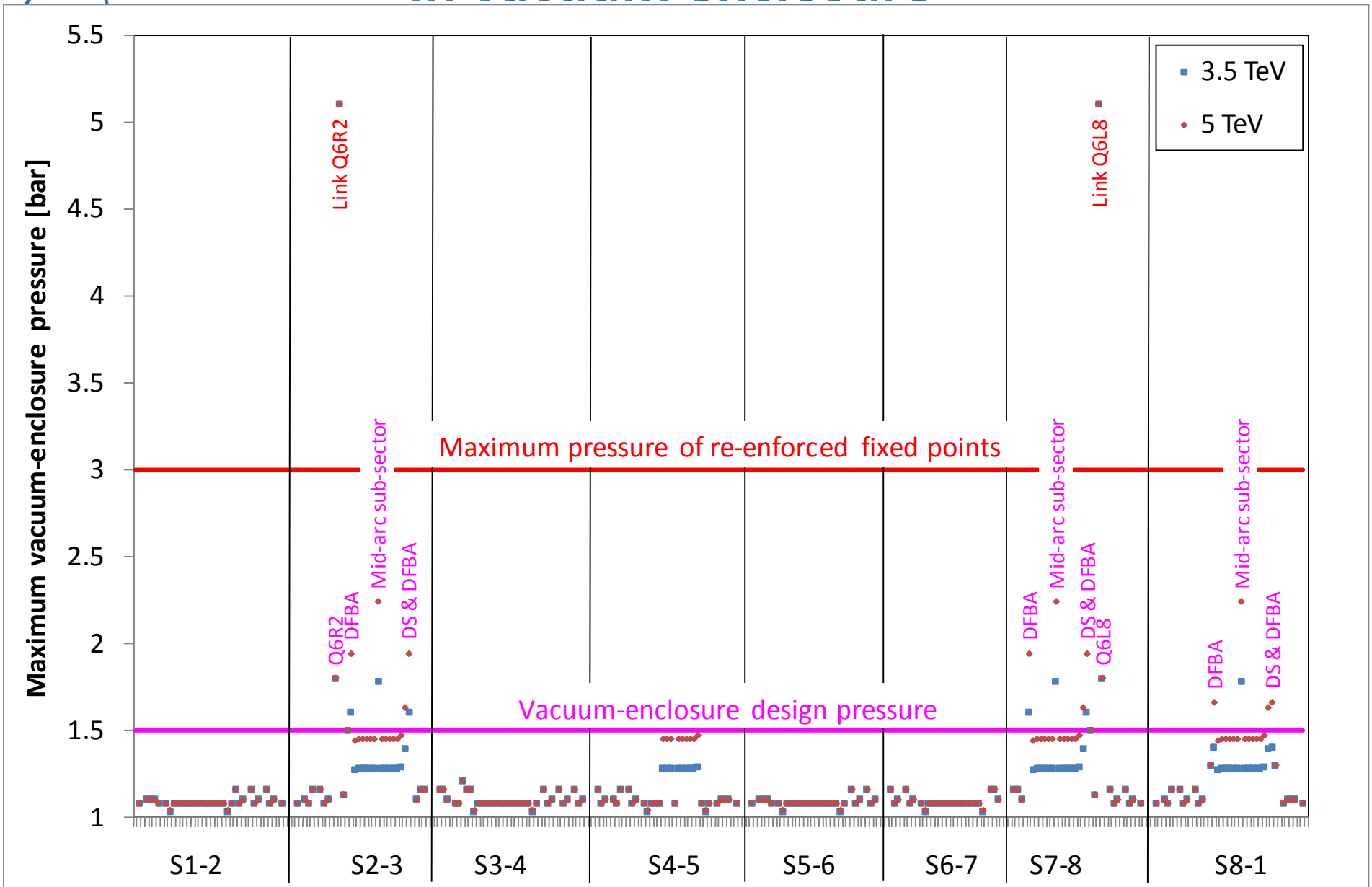
Discharge conditions through safety devices vs beam energy

- Mass flow → MCI flow (already at 3.5 TeV, an electrical arc is able to create the MCI breaches (2 x 60 cm^2)), e.g. 30 kg/s in the continuous cryostat.

- Temperature of helium heated by the electrical arc power and discharged through the safety devices depends on:
  - the stored magnetic energy
  - The current discharge time constant
  - The heat transferred by convection from the environment.



Maximum pressure build-up in vacuum enclosure



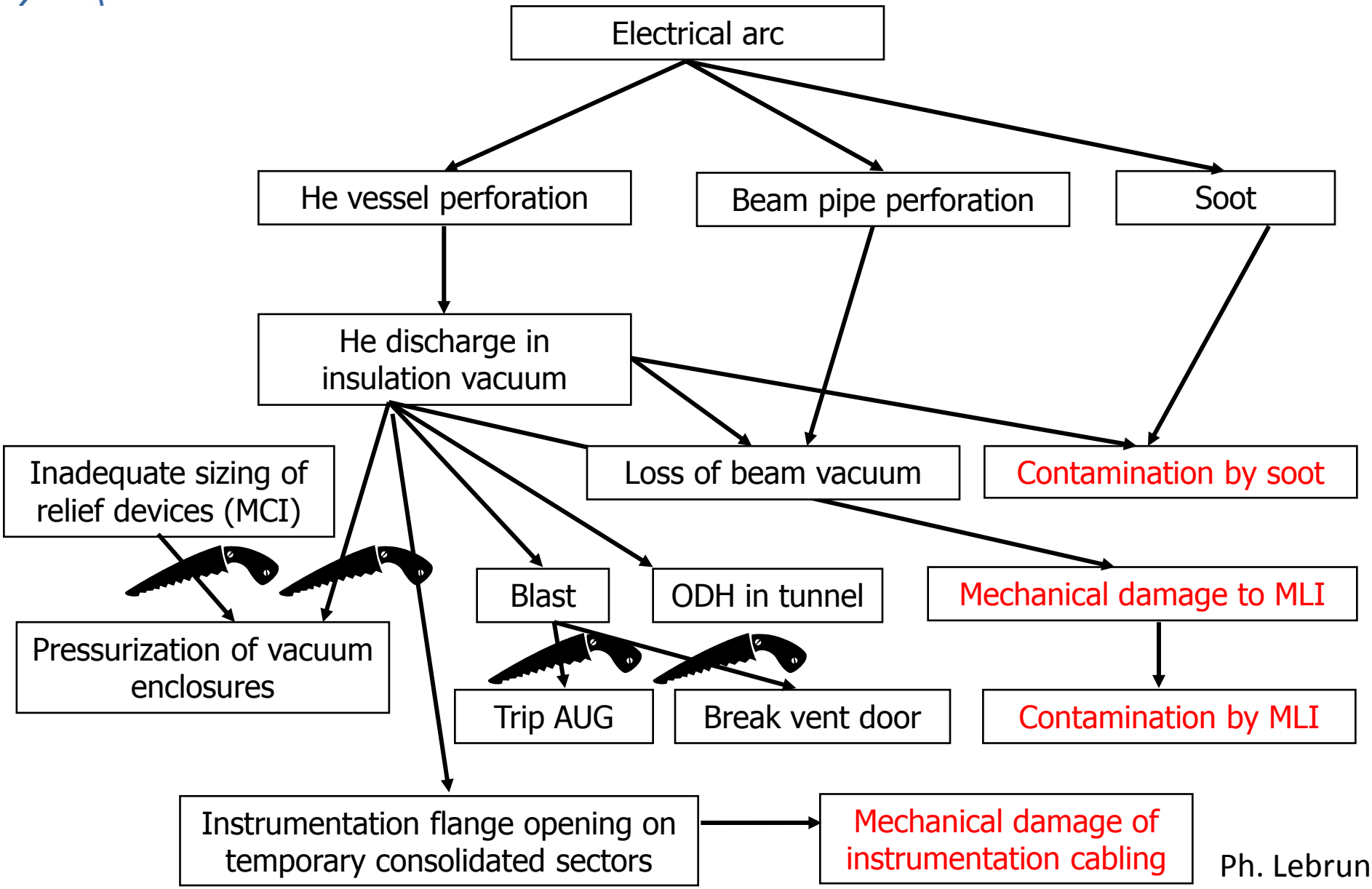
Off-design remaining cases

Vacuum sub-sector	P max [bar]		Remarks
	3.5 TeV	5 TeV	
Link Q6R2 & Q6L8	5.1	5.1	Compatible with vacuum enclosure design margin (DN200 link)
Q6R2 & Q6L8	1.8	1.8	Compatible with vacuum enclosure design margin
Mid-arc S2-3, S7-8 & S8-1	1.8	2.3*	Compatible with vacuum enclosure design margin and re-enforced fixed points on SSS
DFBA HCM R2, L3, R7 & L8	1.6	2.0	Compatible with vacuum enclosure design margin and re-enforced fixed points on DFBA
DFBA HCM R8 & L1	1.4	1.7	Compatible with vacuum enclosure design margin and re-enforced fixed points on DFBA
DS L3, L8 & L1	1.4	1.6	Compatible with vacuum enclosure design margin and re-enforced fixed points on SSS and DFBA

*: Above 1.9 bar, plastic deformation of SSS vacuum barrier could occur (pressure test under preparation)

Conclusion: Up to 5 TeV, no longer **mechanical** collateral damages in adjacent sub-sectors!

Updated fault tree up to 5 TeV



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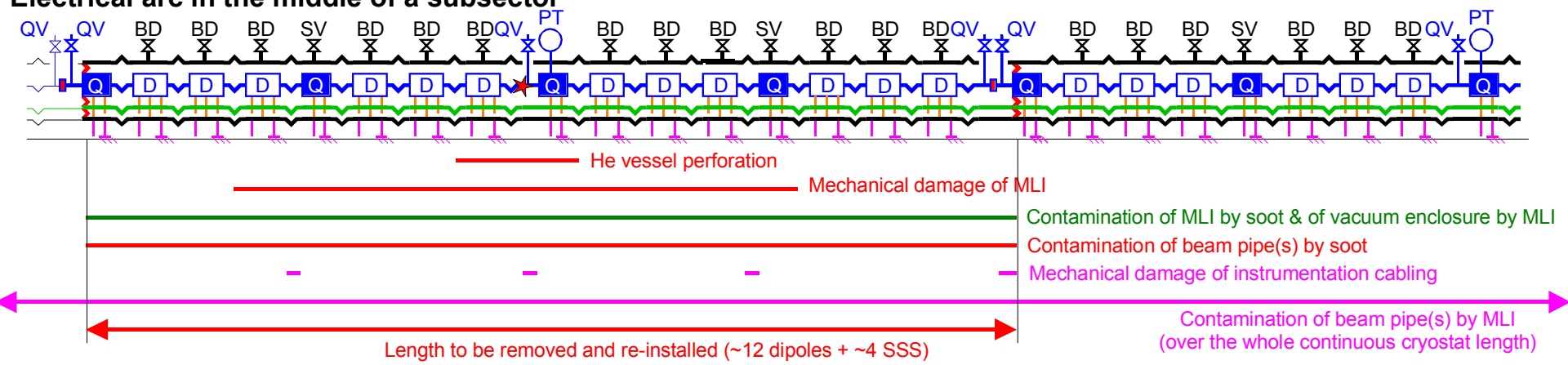
Damages in case of a hypothetical electrical arc in an interconnect (up to 5 TeV)

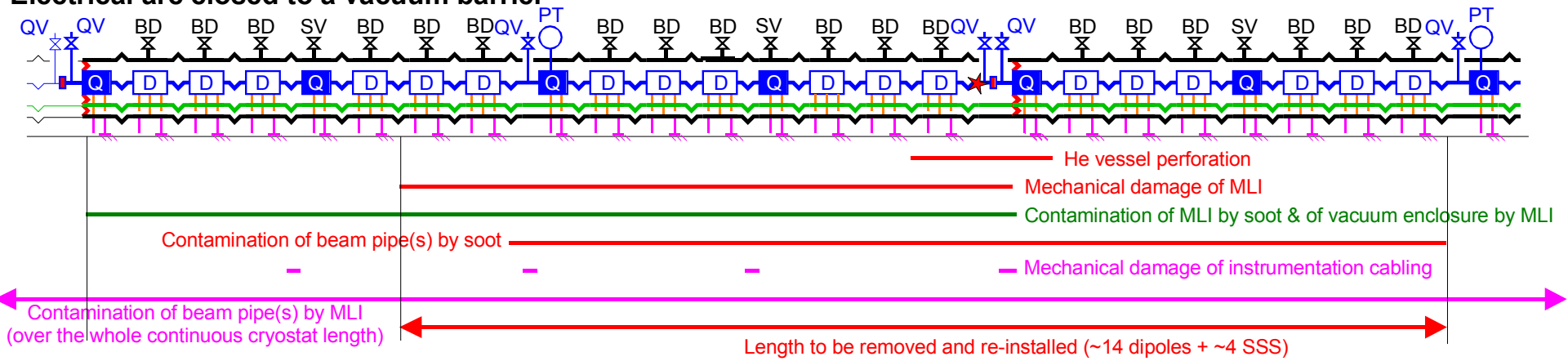
- Sept'08 damages which are mitigated by the 2009 consolidations:
  - Plastic deformation of shells
  - Buckling of bellows
  - Rupture of supports and ground anchors
  - Damage to tunnel floor
  - Mechanical damage to interconnects
  - Secondary electrical arcs
- Damages still present up to 5 TeV
  - He vessel and beam pipe perforation
  - Mechanical damage of MLI
  - Contamination by soot of MLI and beam pipes
  - Contamination by MLI of vacuum enclosure and beam pipes
  - Mechanical damage of BPM cabling

Expected damages in case of a hypothetical incident

Electrical arc in the middle of a subsector



Electrical arc closed to a vacuum barrier



Cold-mass
Vacuum vessel
Line E
Cold support post
Warm Jack
Compensator/Bellows
Vacuum barrier

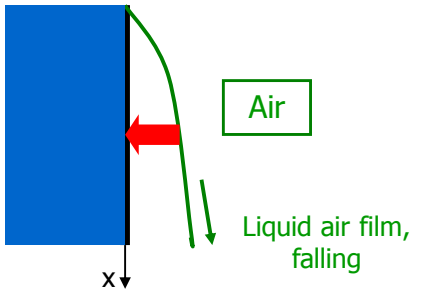
To be exchanged or repaired (surface) before operation restart
To be repaired in-situ before operation restart
Consolidation can wait the next long shut-down
Electrical arc position

Mechanical damage of MLI (1)

- Without MLI, cold mass enclosure are not protected against pressure build-up in case of break of the insulation vacuum with air.

Heat transfer by condensation of air on cold wall

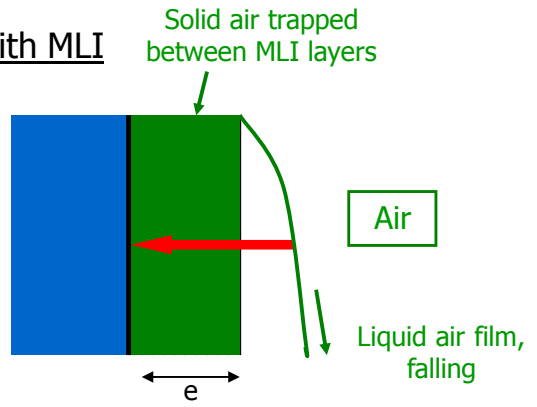
Bare wall



Heat transport limited by conduction across falling film

- From a calculation by Nusselt
  - $h \approx 0.943\ (\rho^2\ g\ k^3\ L_v/\eta\ x\ \Delta T)^{0.25}$
- Assimilating air to nitrogen
  - $h \approx 680\ W/m^2\ K$
  - heat flux $h\ \Delta T \approx 50'000\ W/m^2$
  - average thickness of film ≈ 0.2 mm

with MLI



Heat transport limited by conduction across solid air

- Multi-layer insulation
  - take e = 10 mm
- Conduction in solid nitrogen
  - conductivity integral from 77 to 4 K ≈ 50 W/m
  - Heat flux $h\ \Delta T \approx 5'000\ W/m^2$

Not compatible with the cold-mass pressure relief system !

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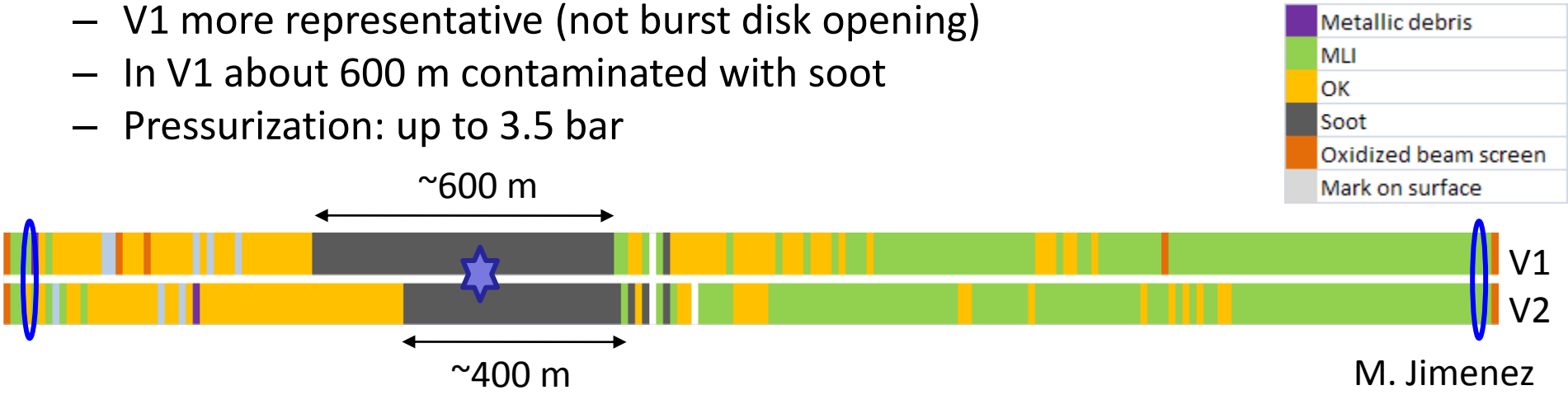
Mechanical damage of MLI (2) Affected length?

- S3-4 incident: ~ 2/3 of the total affected length (22 cryo-magnets over 2 sub-sectors)
- New incident ?:
  - MLI damage goes with ρv^2 or m^2/ρ or m^2T/P
    - S3-4 incident 30 kg/s – 6 bar – 70 K
    - New incident 3.5 TeV: 30 kg/s – 1.1 to 1.3 bar – 40 K → **factor 3 to 2.6**
    - New incident 5 TeV: 30 kg/s – 1.1 to 1.5 bar – 60 K → **factor 4.5 to 3.5**
  - But the distribution of the safety devices allows a faster decrease of the flow along the length
  - Let's assume the same damage ratio (2/3) for a new incident i.e.:
    - **~ 10/16 cryo-magnets to be repaired**
      → use of spares for dipoles
      → re-cryostating of SSS (no spare)
  - **Question: Can we safely operate with only missing MLI on SSS? (if yes, the heavy SSS re-cryostating could wait the next long shutdown!)**

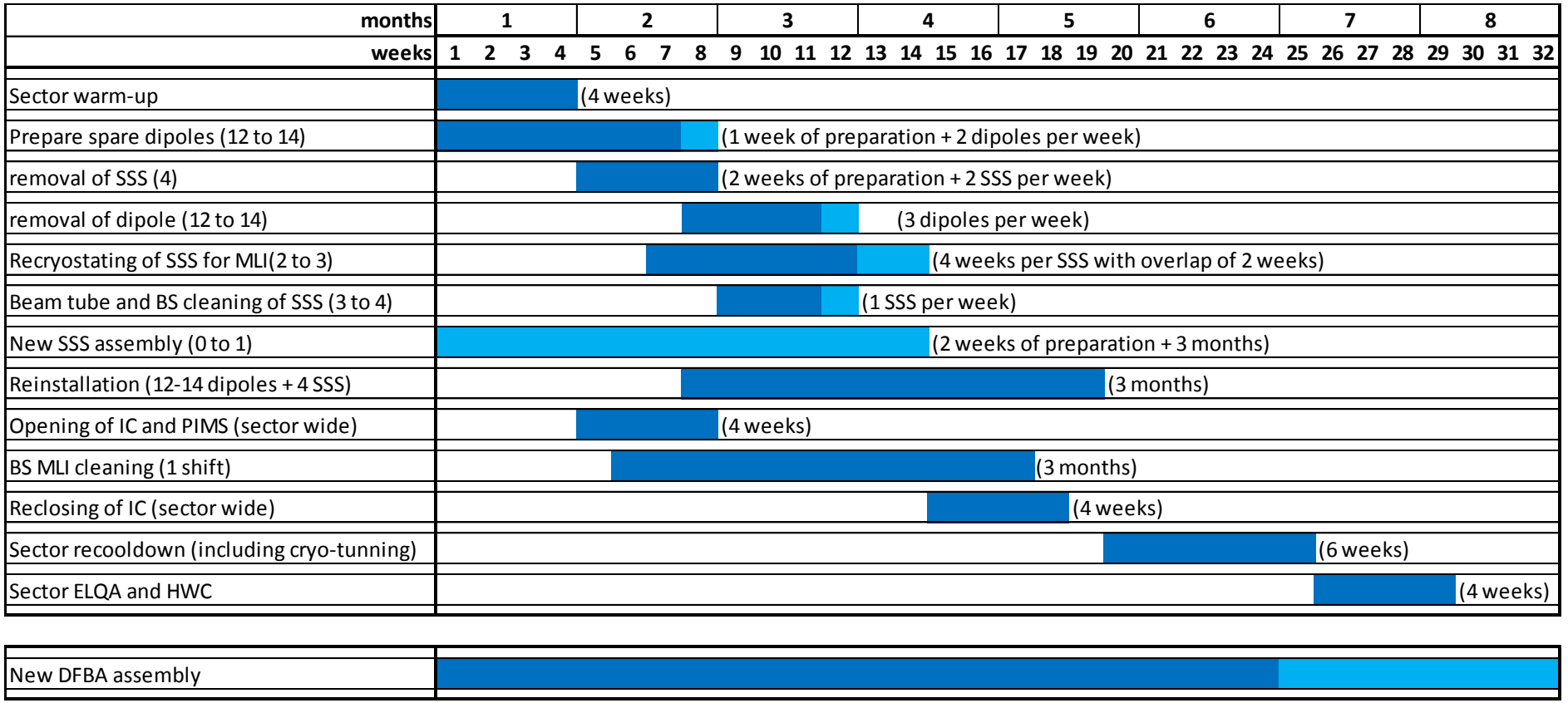
Contamination by soot of beam pipes: Affected length?

- Experience return from S3-4
  - V1 more representative (not burst disk opening)
  - In V1 about 600 m contaminated with soot
  - Pressurization: up to 3.5 bar



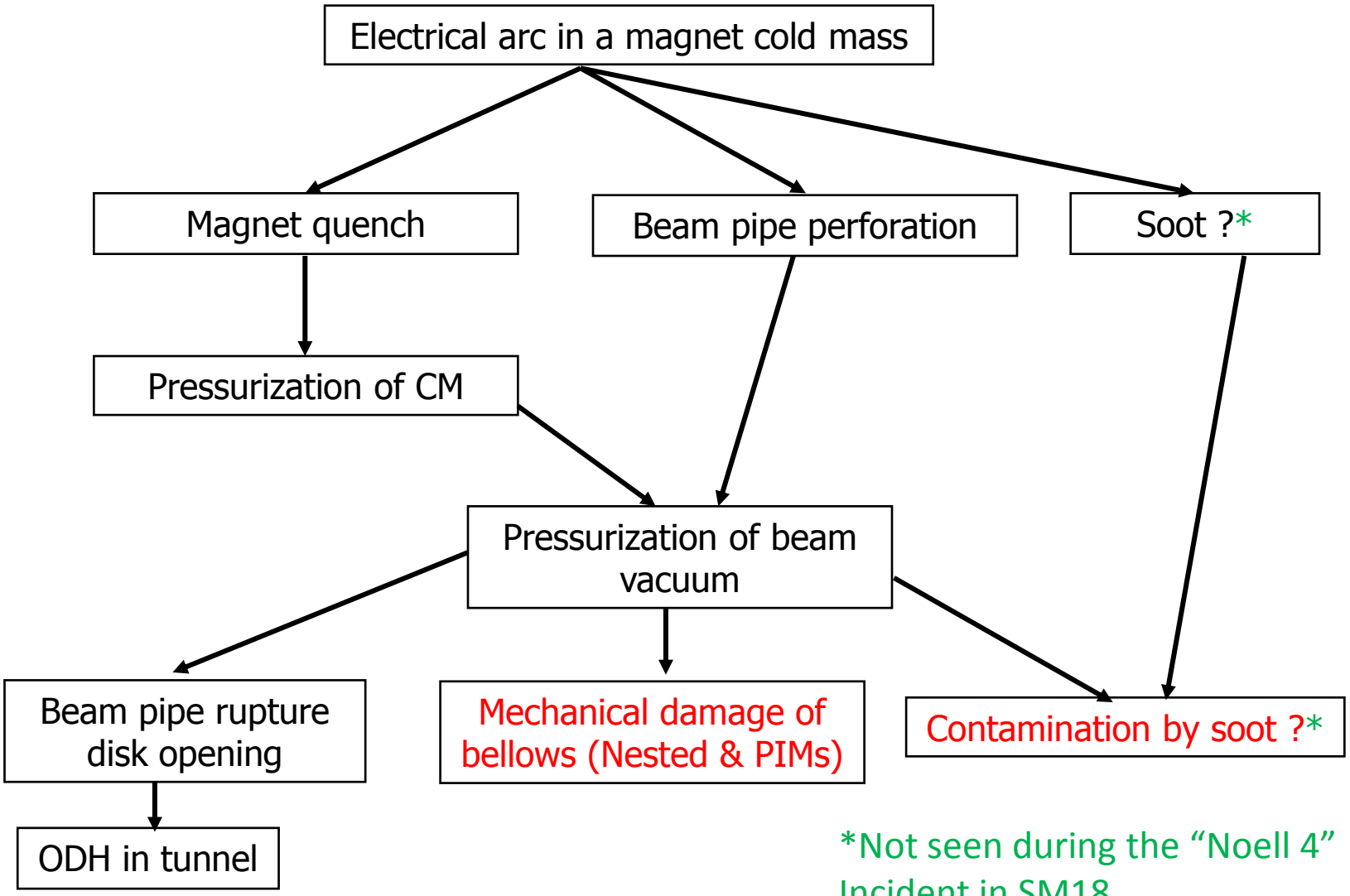
- New incident expectation: Affected length is assumed to be proportional to the quantity of soot introduced:
  - For most sub-sectors, pressurization limited to 1.1-1.5 bar:
    → quantity of soot introduced in the beam pipes divided by 2.3 to 3
    → 250 to 200 m of magnet could be affected
  - For the specific mid-arc subsectors (3/8), pressurization limited to 1.8 -2.3 bar:
    → quantity of soot introduced in the beam pipe divided by 2 to 1.5
    → 300 to 400 m of magnet could be affected

Repair schedule following a hypothetical interconnect electrical arc



Remark: In case of a hypothetical electrical arc in an Inner Triplet, soot contamination of the detector beam pipe cannot be excluded (Fast shutter valves installation only in 2013/12 long shutdown) → Long and heavy repair work if NEG coatings are damaged! (4 to 6 months)

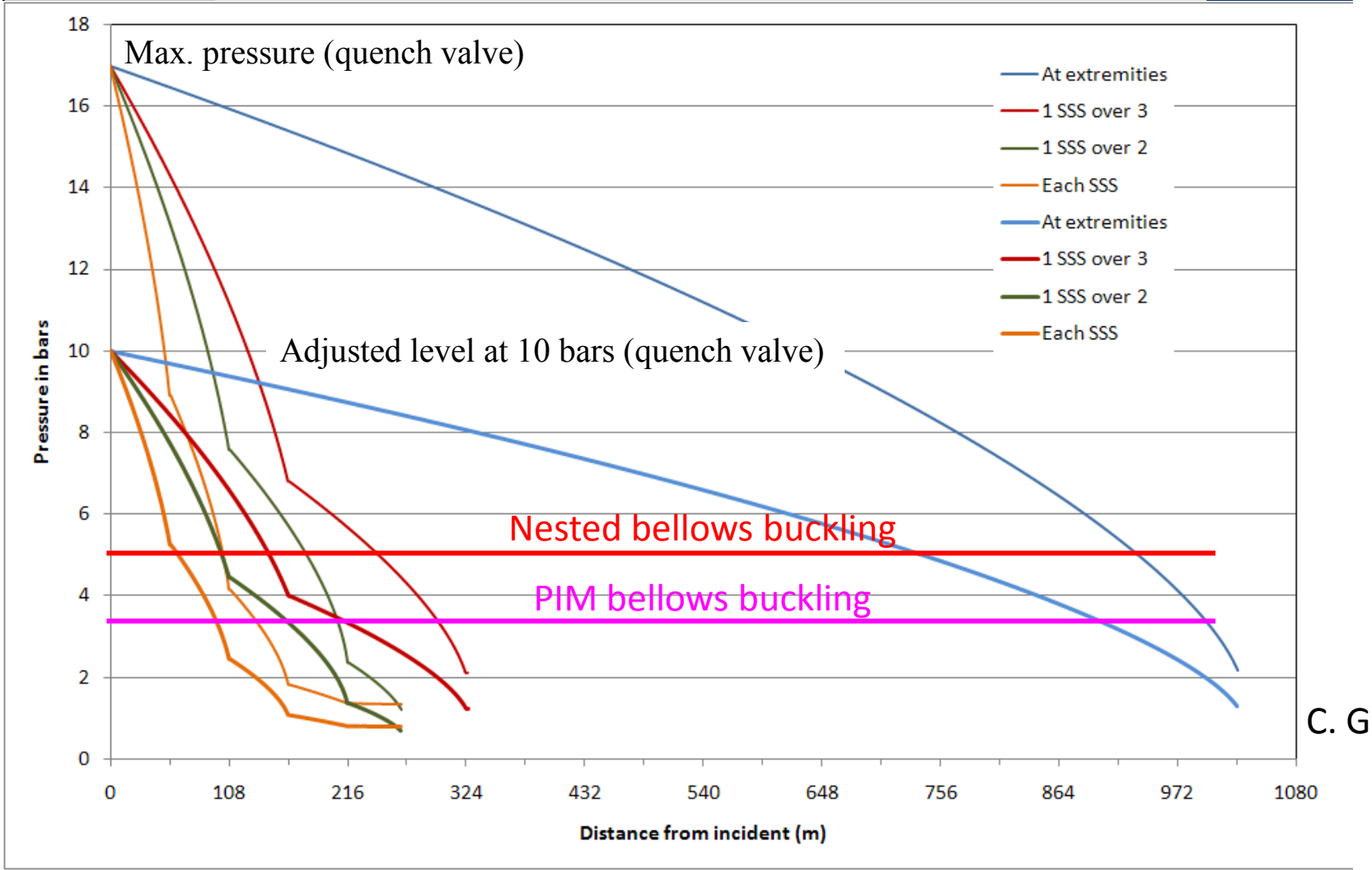
Fault tree of an electrical arc in magnet coil
(caused by a short circuit or by a catastrophic beam loss)



*Not seen during the "Noell 4" Incident in SM18

Damage due to a hypothetical electrical arc in a magnet coil

Mitigation solutions
Rupture disks (3/4)



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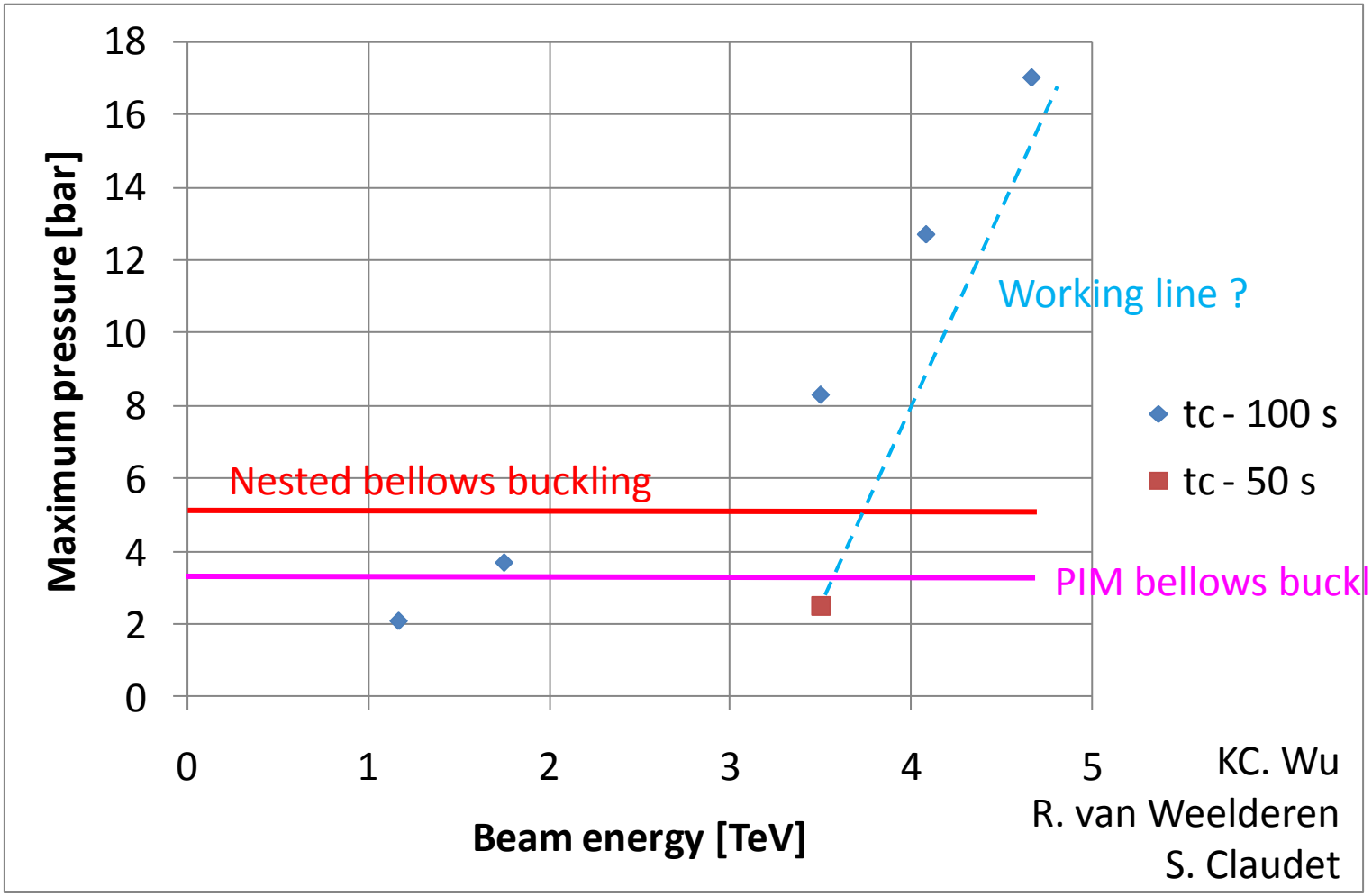
Maximum pressure following a dipole quench (measurements)



Damages in case of a hypothetical electrical arc in a magnet coil

- Beam pipe perforation of a single magnet (Reminder: the downtime for a single dipole exchange is about 4 months)
- Plastic deformation (rupture ?) of nested & PIM bellows:
  - No damage at 3.5 TeV (with 50 s time constant)
  - Could become critical above 3.5 TeV especially if we increase the discharge time constant.
    - PIMs can be repaired in-situ
    - Nested bellow repair requires magnet removal.

Conclusion

- Electrical arc in an interconnect:
  - The present consolidation, up to 5 TeV, will suppress **mechanical** collateral damages in adjacent sub-sectors.
  - Nevertheless, mechanical damage of the MLI in the concerned sub-sector as well as contamination of the beam pipe(s) could require heavy repair work.
  - With the present consolidation status, a new incident will still have big impact on the machine down time (8 to 12 months)

- Electrical arc in a dipole coil:
  - Limited impact at 3.5 TeV (but at least 4 months of downtime to exchange one dipole)
  - Could be more critical above 3.5 TeV (damage of bellows over several sub-sectors)

- A hypothetical incident caused by an electrical arc during the 2011/12 operation could seriously impact the LHC physics program:
  → Corresponding risks must be carefully assessed.