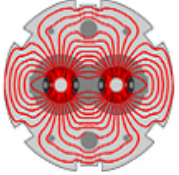
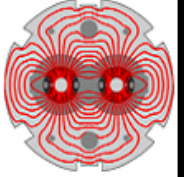
Status of LHC Commissioning

J. Wenninger
CERN Beams Department
Operation Group

On behalf of the LHC design, construction, installation and commissioning teams



Outline



Beam commissioning

Incident in sector 34

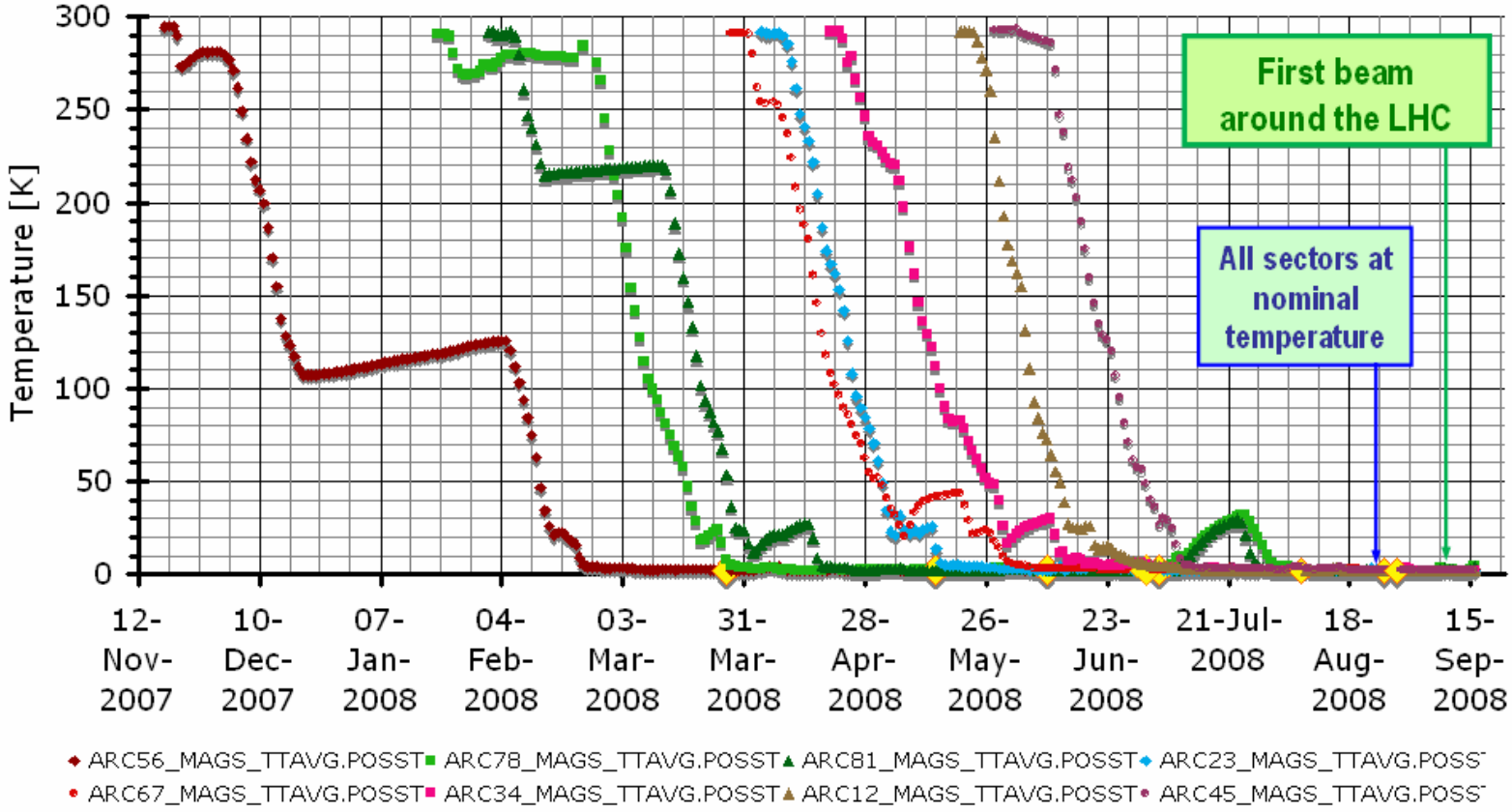
Repair and consolidation

2009/10 LHC run

Conclusions

LHC Cool-down

Cool-down time to 1.9 K ~ 4-6 weeks/sector
[sector = 1/8 LHC]



LHC Hardware Commissioning

April to September 2008:

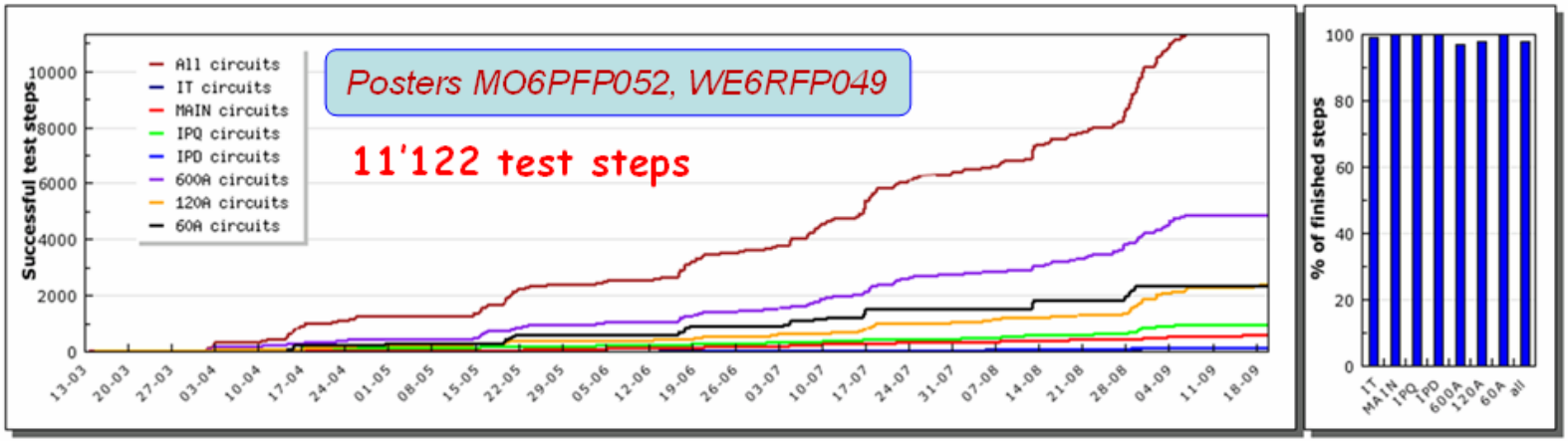
- (Re-)commissioning of the magnets & circuits (power converter, quench protection, interlocking..) following predefined test steps.

  1'700 circuits, 10'000 magnets

- LHC was commissioned to 5.5 TeV (5 TeV target for physics in 2008).

  Magnet re-training required above ~6 TeV.

ORAL by L. Rossi, TUE am



- Commissioning of beam related equipment (instrumentation, kicker, RF…).

Injection tests

August – September 2008:

- Injection tests of up to 4 adjacent sectors.
- Almost all HW systems involved in tests.
- Essential checks for:
  - Control system.
  - Beam instrumentation.
  - Optics (magnetic model) and aperture.

ORAL by M. Lamont, FRI am

Posters WE6PFP026, WE6PFP026

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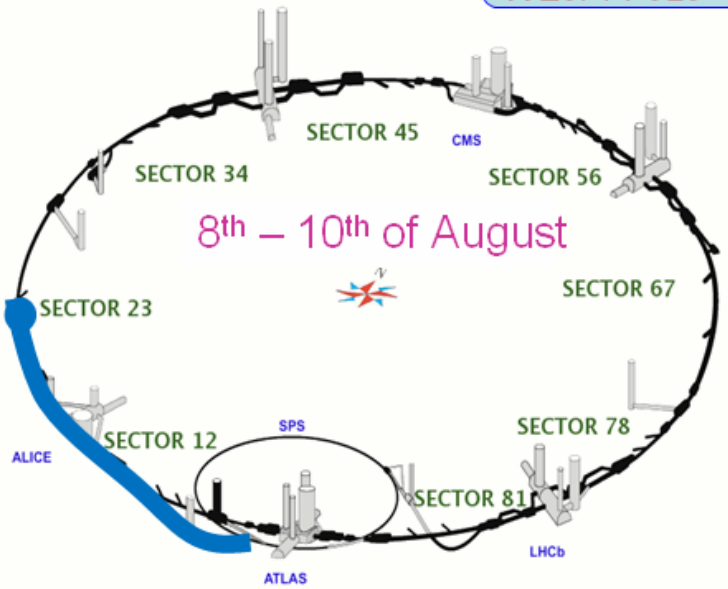

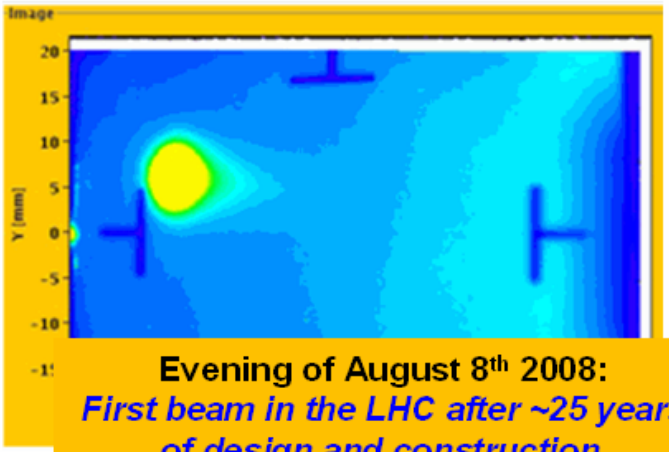

Evening of August 8th 2008:
First beam in the LHC after ~25 years of design and construction.

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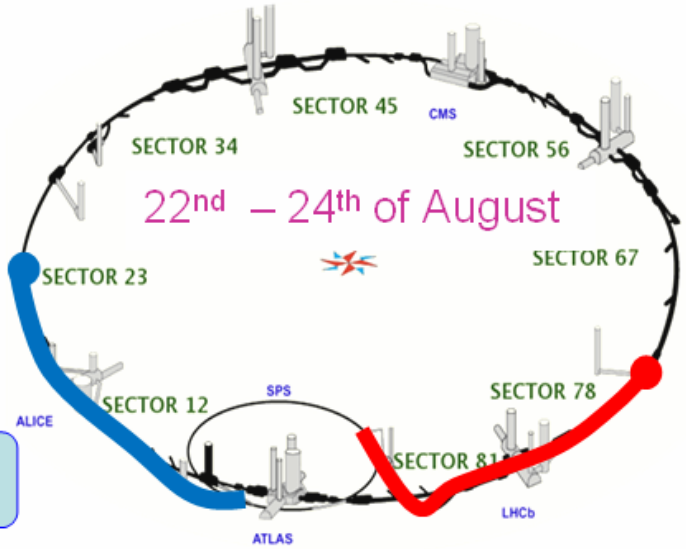

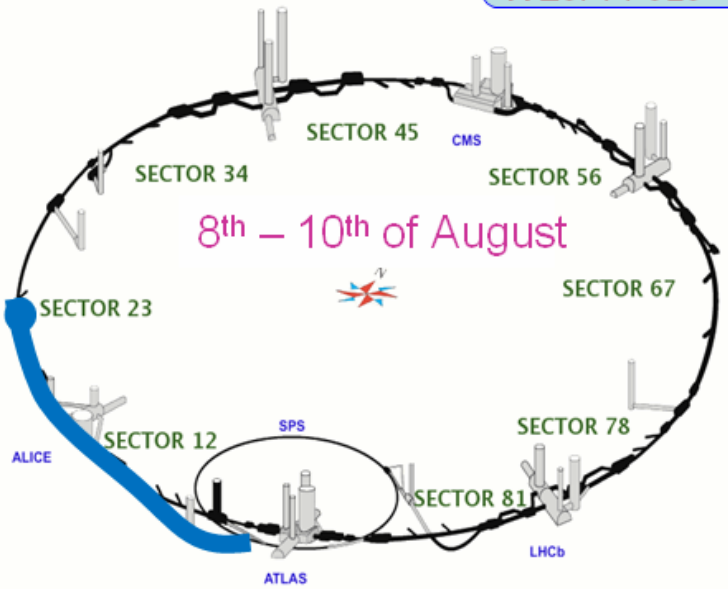

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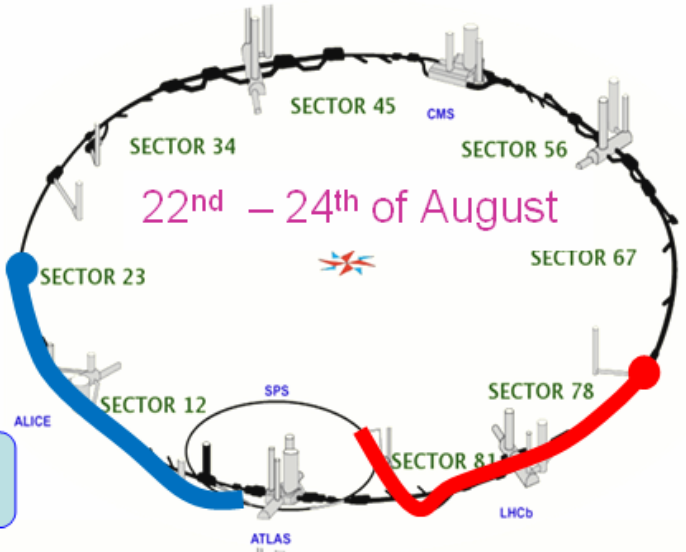

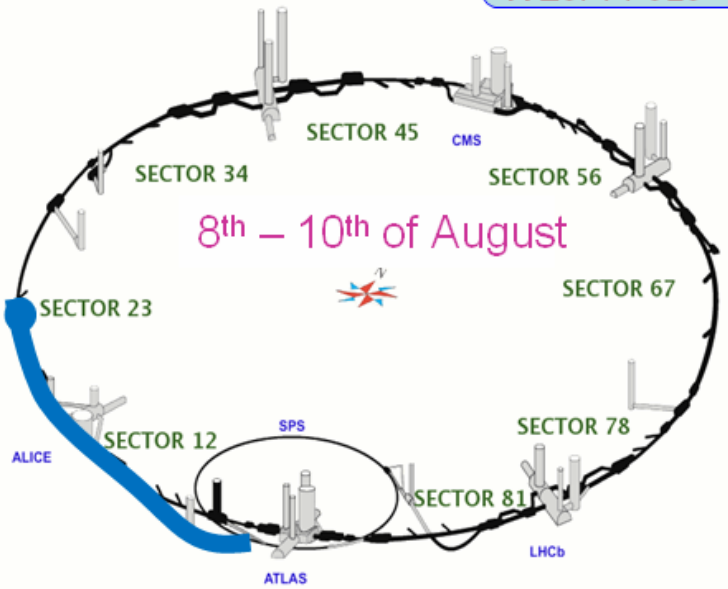

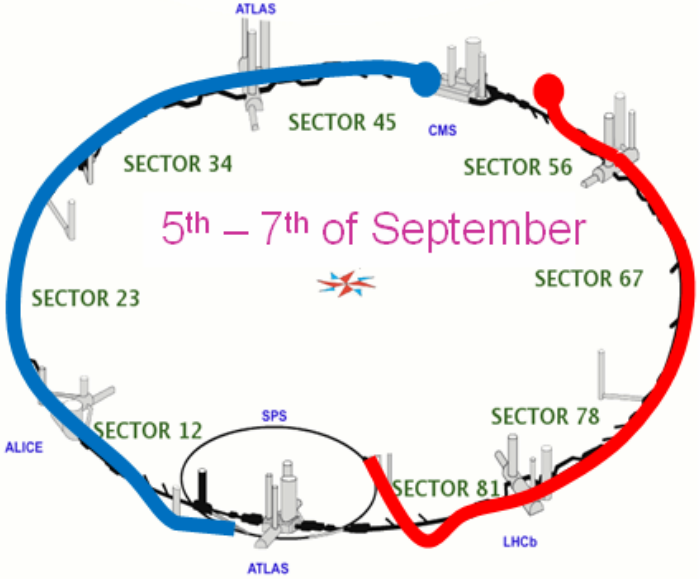

September 10th - control (show) room

Beam threading

Threading by sector:

- One beam at the time & one hour per beam.
- Collimators used to intercept the beam (1 bunch, 2×10^9 p - 2% of nominal bunch).
- Beam through 1 sector (1/8 ring), correct trajectory, open collimator and move on.

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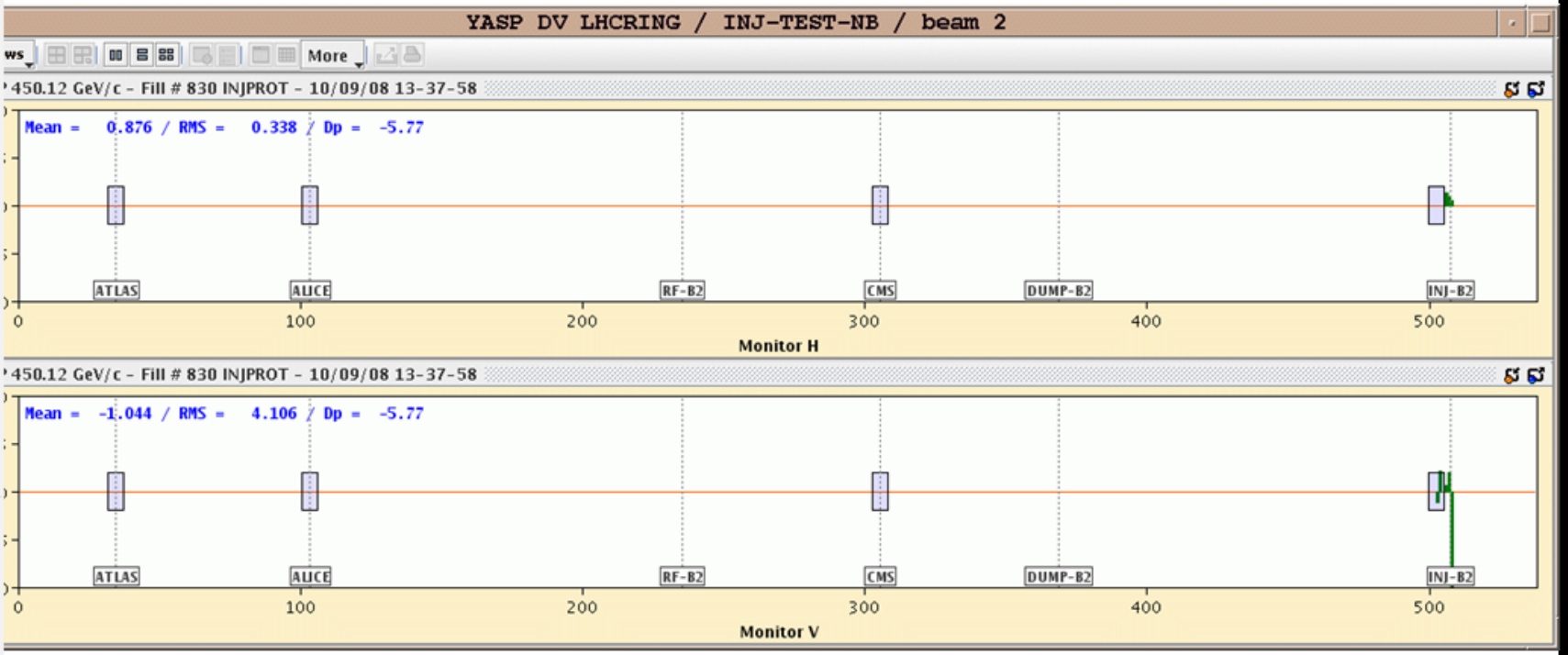

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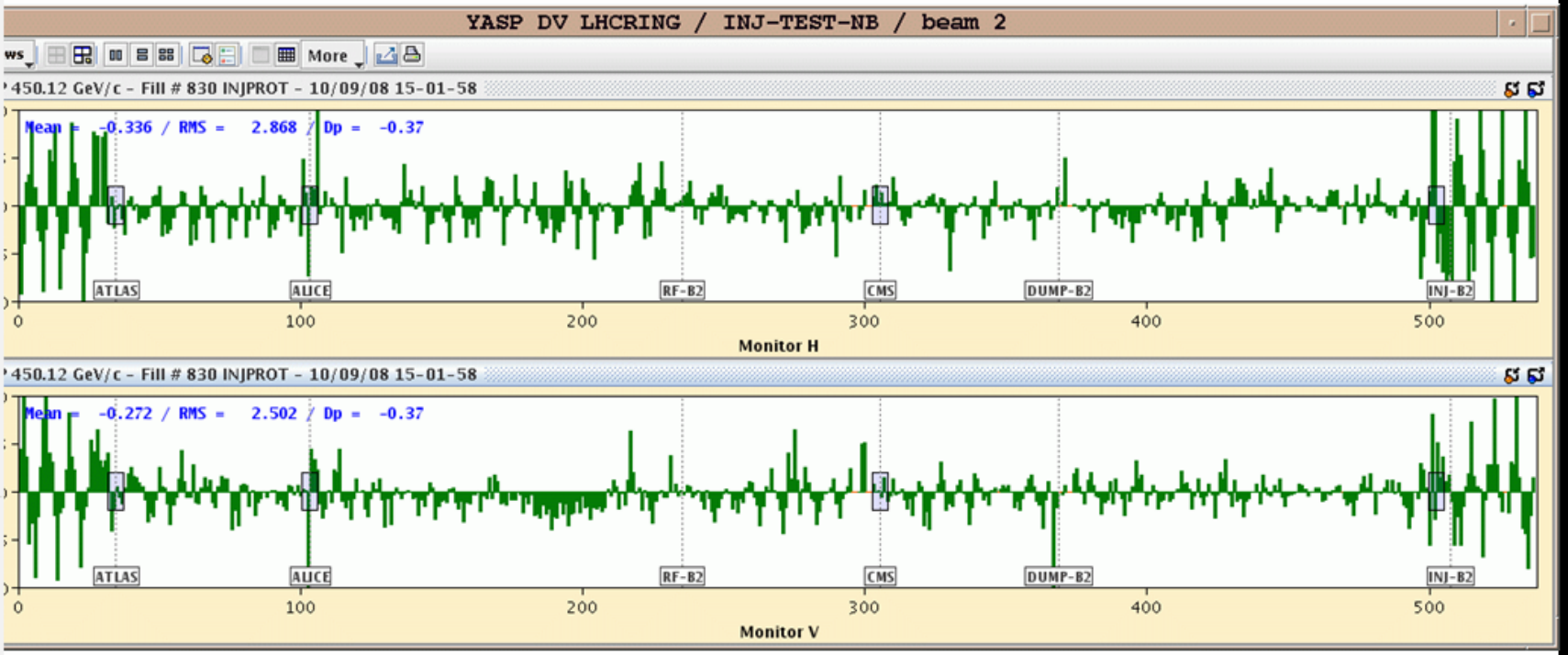
BPM availability ~ 99%

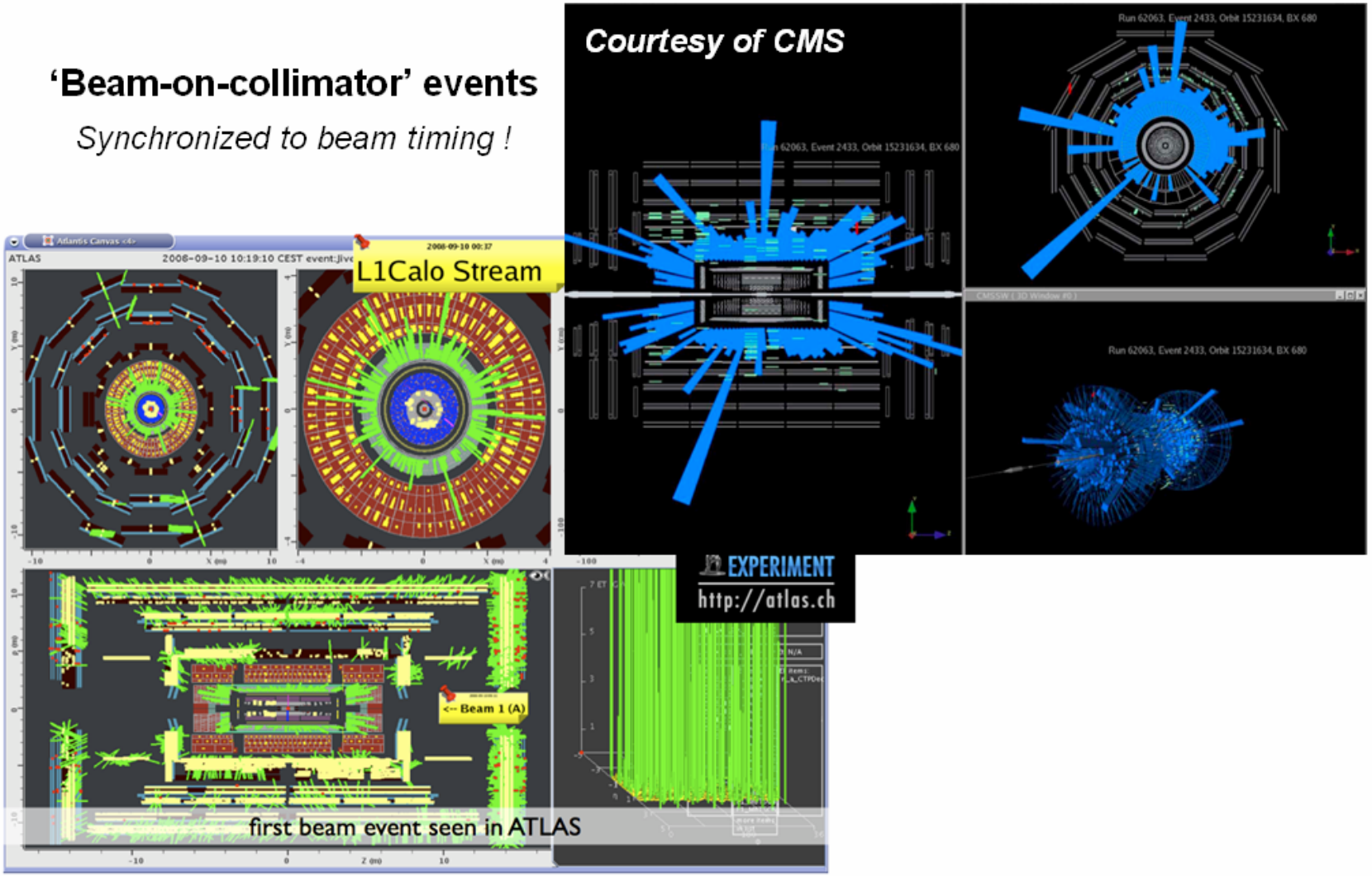
Beam 2 threading



ATLAS & CMS ‘events’

‘Beam-on-collimator’ events

Synchronized to beam timing !



Courtesy of ATLAS

Beam commissioning progress

September 10th :

- 10:30 : Beam 1 around the ring (in ~ 1 hour). Beam makes ~ 3 turns.
- 15:00 : Beam 2 around the ring, beam makes 3-4 turns.
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- Late evening: Beam 2 captured by RF.
- First emergency dump correctly executed.

September 12th :

- All base instrumentation operational : BPMs, BLMs, Tune, BCTs
- Good beam lifetime (> 1 hour).
- Beta-beating measured.

ORAL by R. Jones, WED pm

Posters TU6PFP058, TU6RFP023

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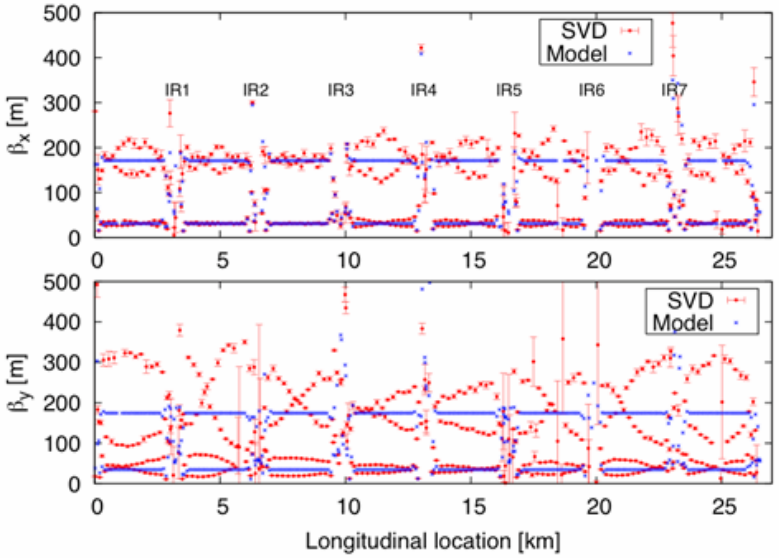

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Posters WE6PFP023, MO6PFP046

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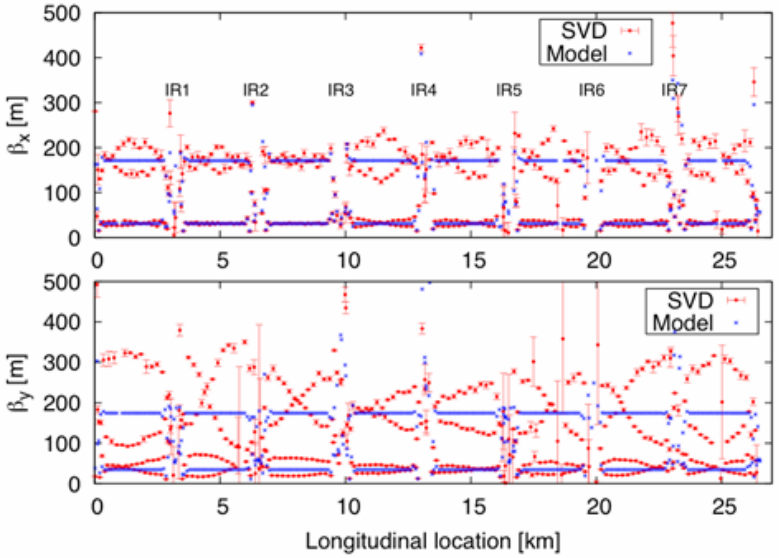

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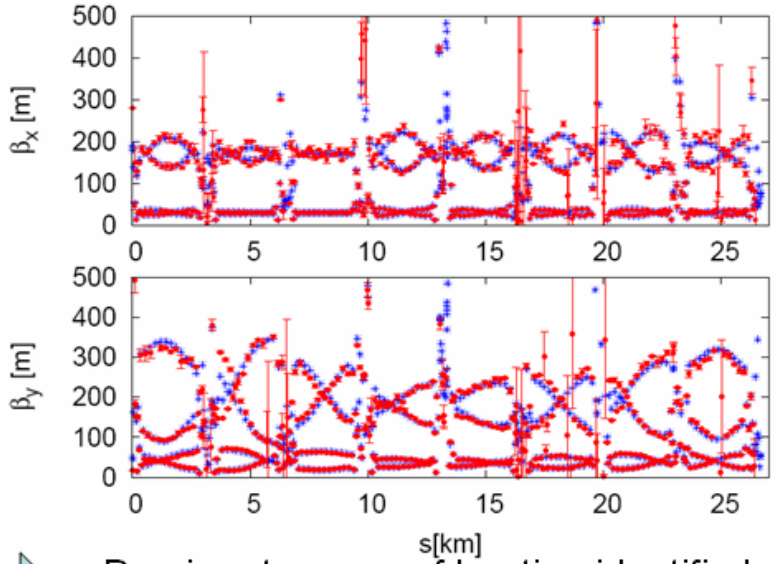

Dominant source of beating identified as trim quadrupole inversion between beam1 & beam2.

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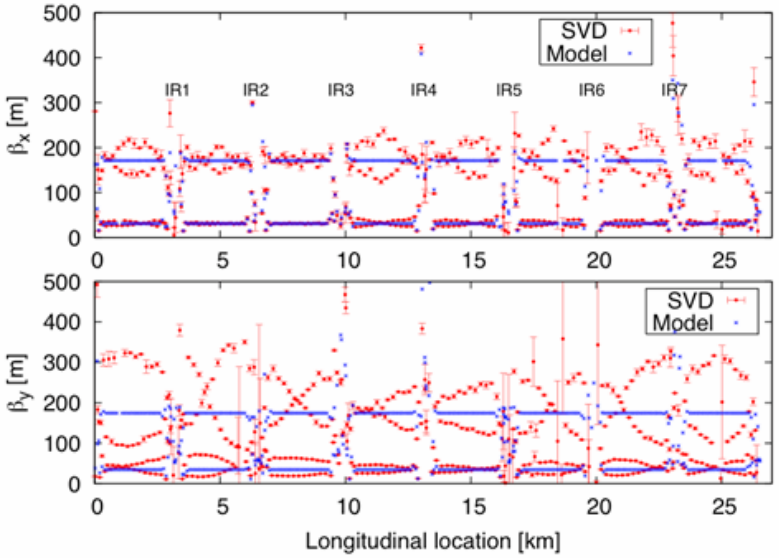

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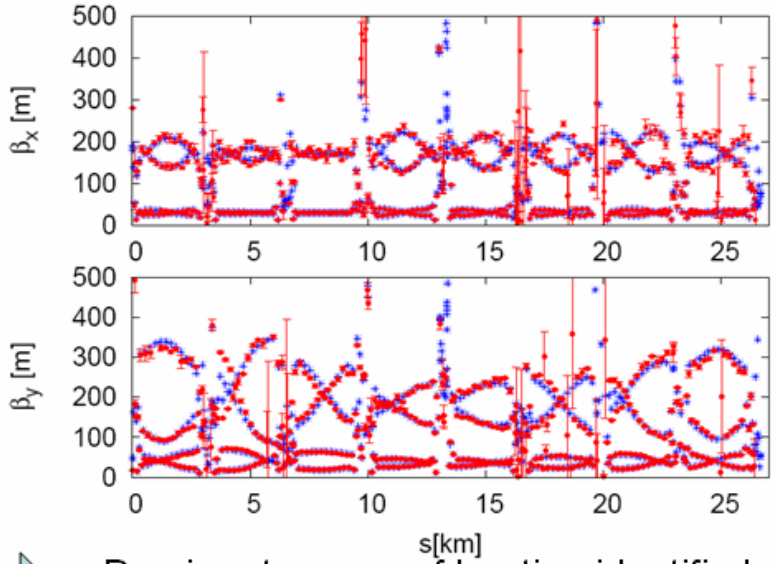

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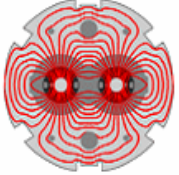
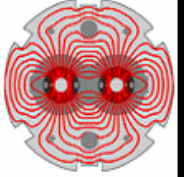

September 19th Incident

Event sequence on Sept. 19th

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- Last commissioning step of the main dipole circuit in sector 34 : ramp to 9.3kA (5.5 TeV).

- At 8.7kA an electrical fault developed in the **dipole bus bar** located in the interconnection between quadrupole Q24.R3 and the neighboring dipole.
  Later correlated to a local resistance of ~220 nΩ – nominal value 0.35 nΩ.

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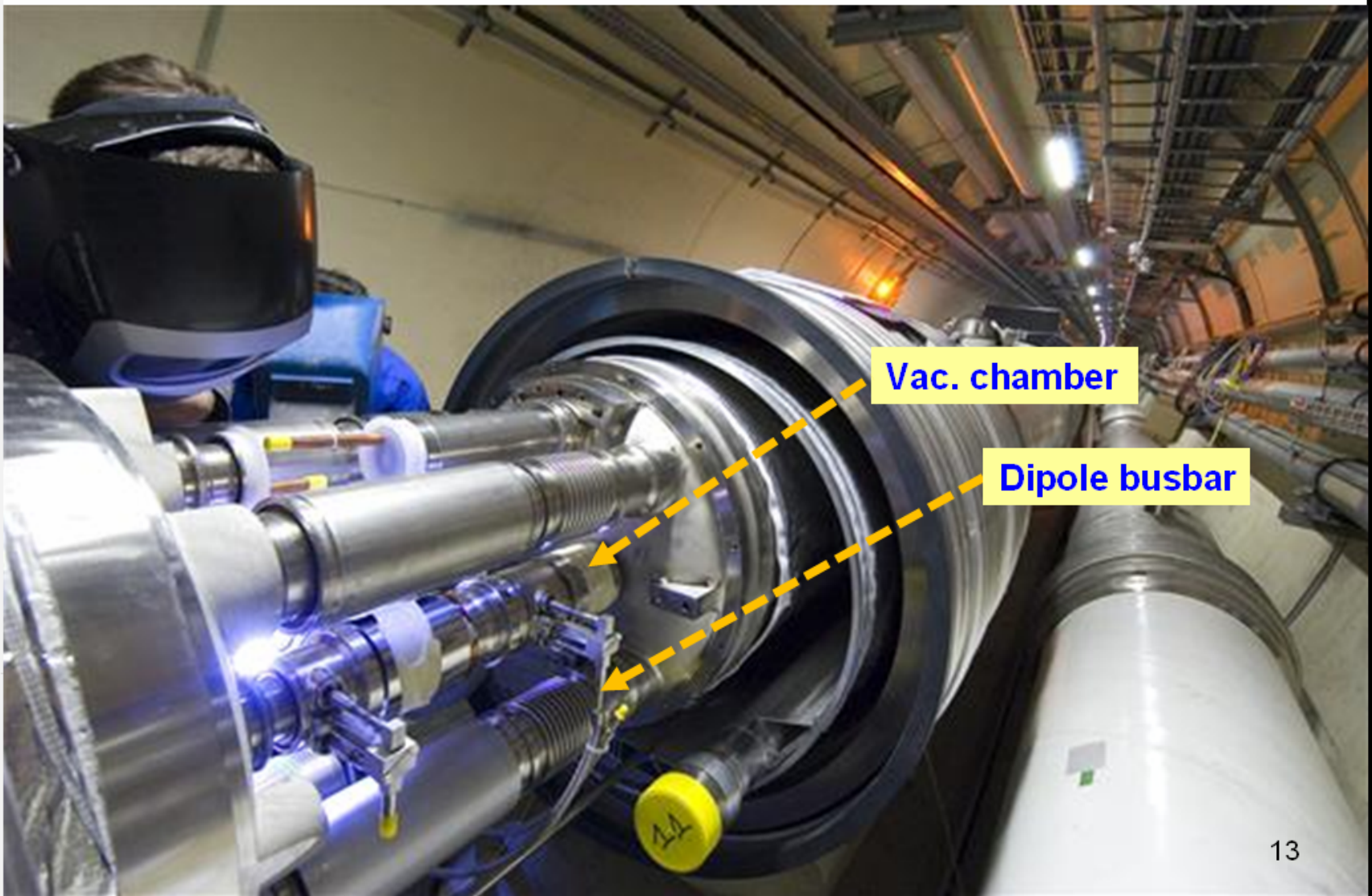
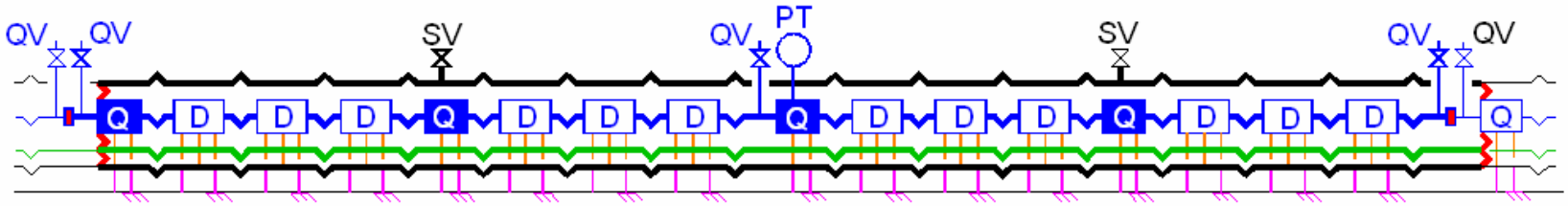
Inter-connection

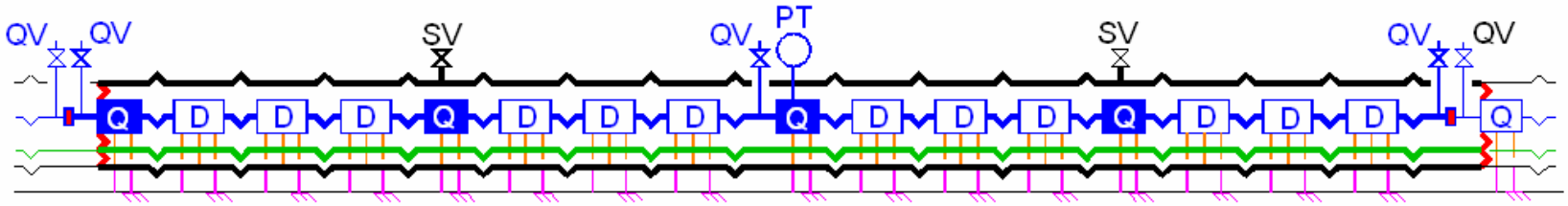


Pressure wave



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

Pressure wave



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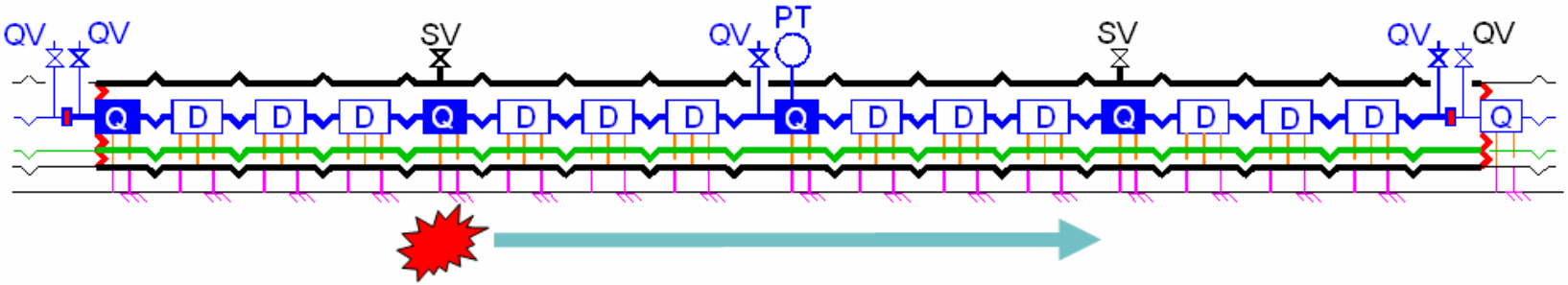

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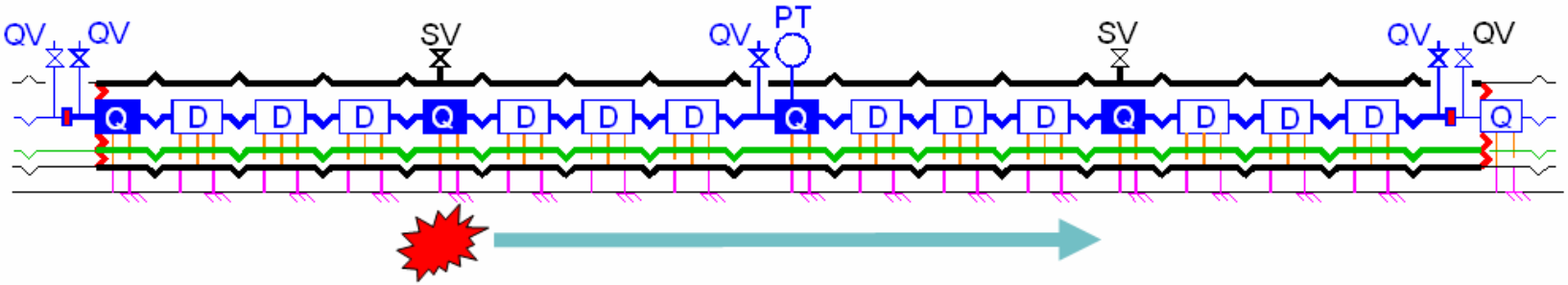

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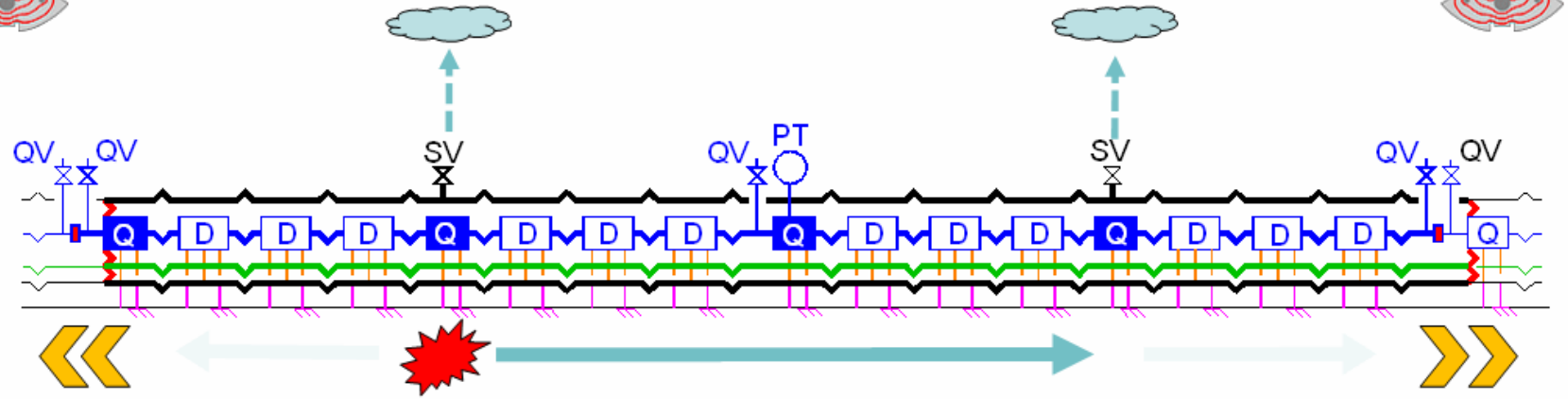

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  - Self actuating relief valves could not handle the pressure.
    designed for 2 kg He/s, incident ~ 20 kg/s.
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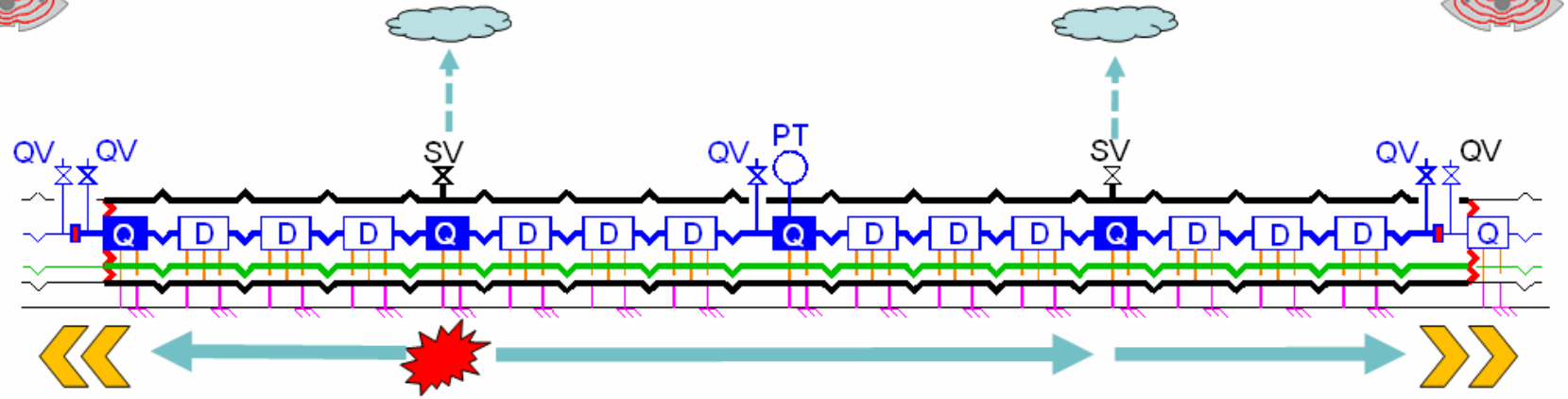
Pressure wave



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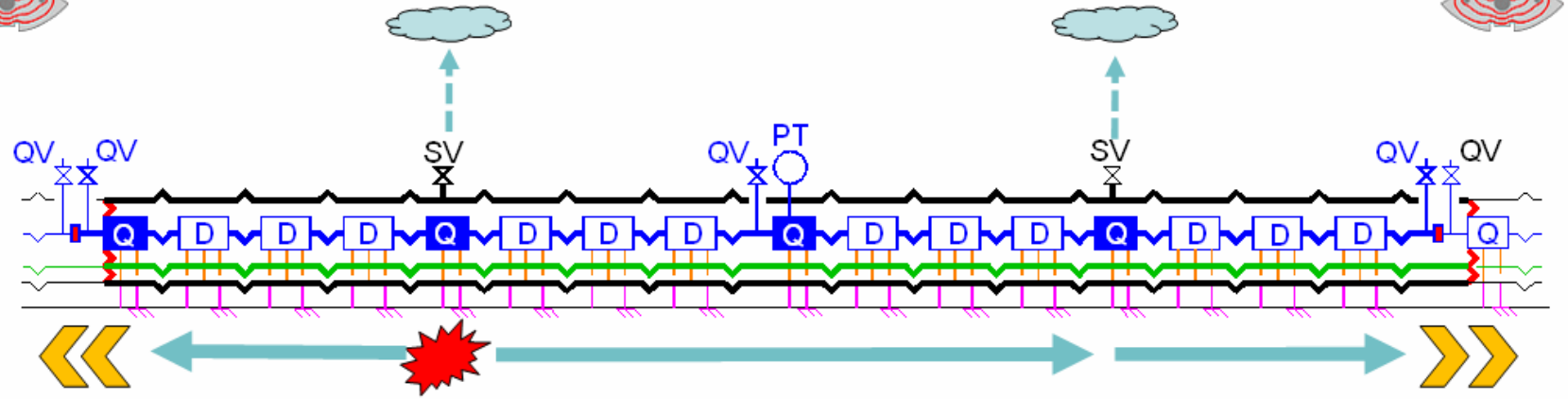

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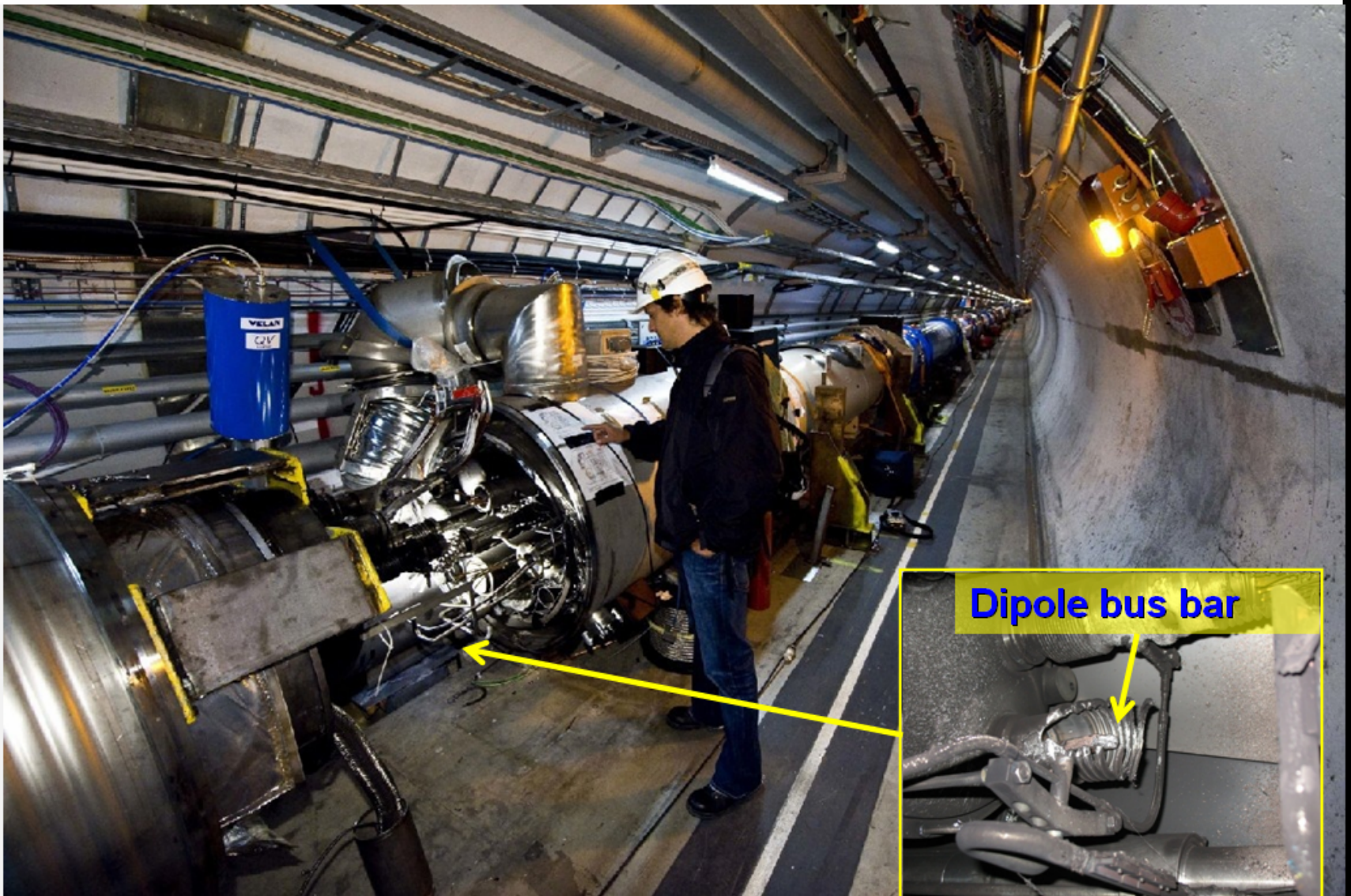
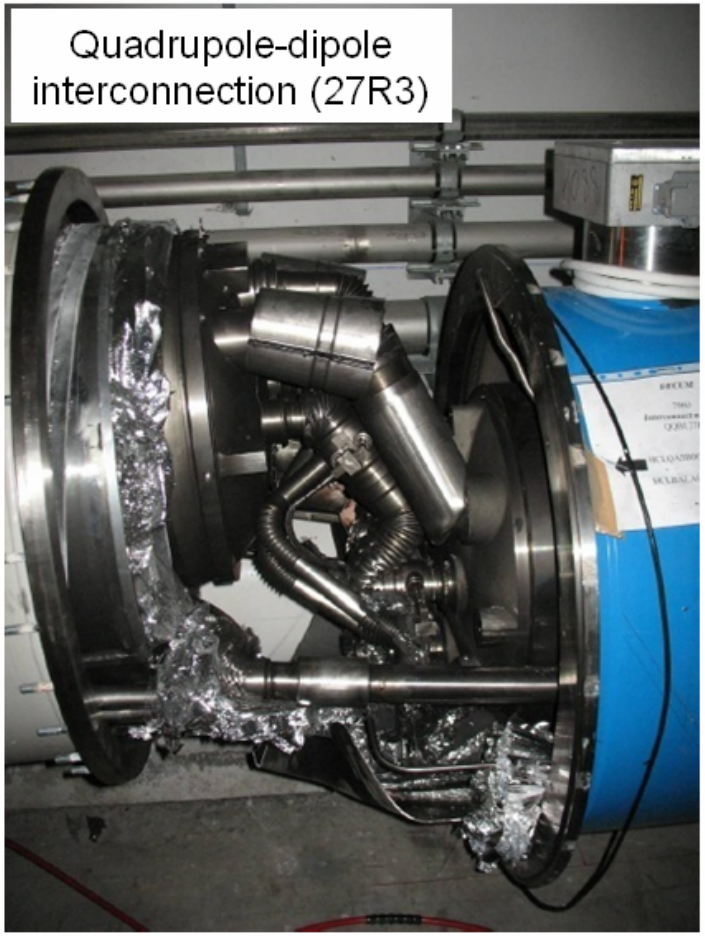


Collateral damage : displacements



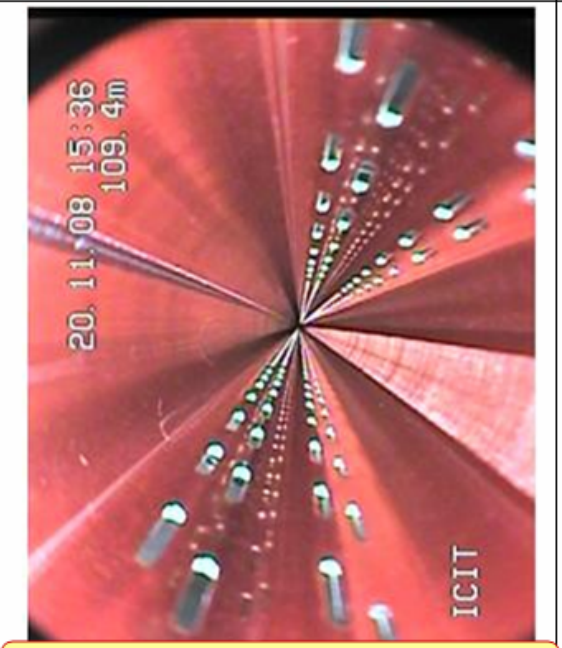
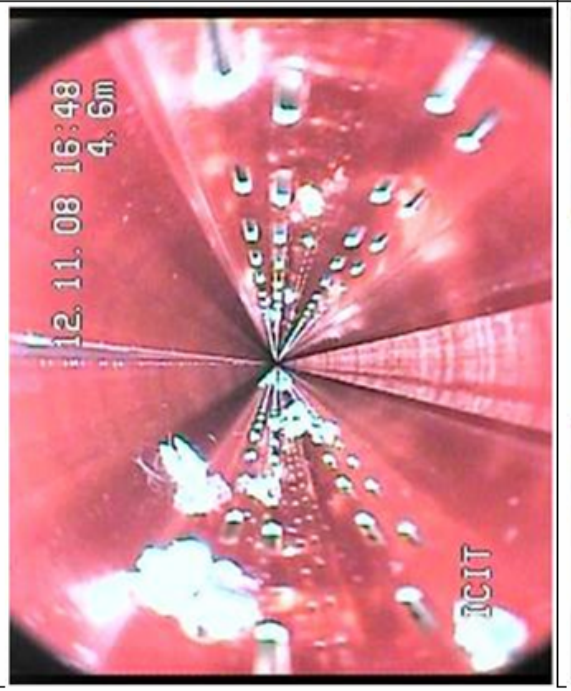
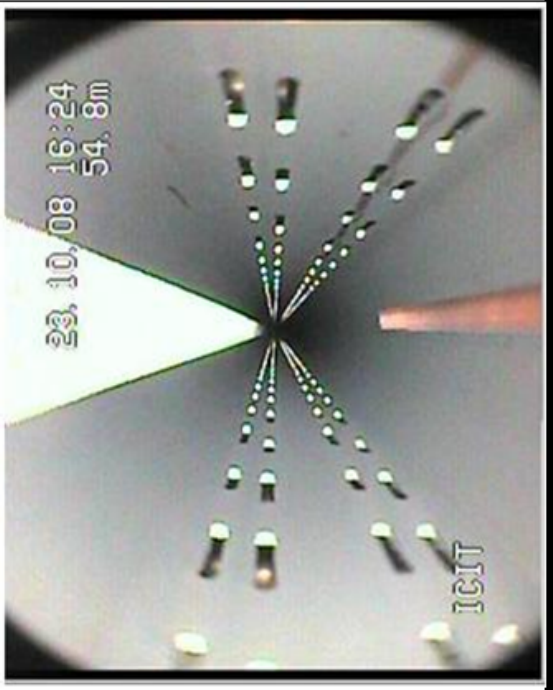
Main damage area ~ 700 metres.

- **39** out of 154 **dipoles**,
- **14** out of 47 **quadrupole** short straight sections (SSS)

  from the sector had to be moved to the surface for repair (16) or replacement (37).

Collateral damage : beam vacuum

Beam vacuum affected over entire 2.7 km length of the arc.

Beam screen with clean Copper surface.	Beam screen contaminated with multi-layer magnet insulation debris.	Beam screen contaminated with sooth.
		

ORAL by J. Jimenez, WED pm

≈ 60% of the chambers

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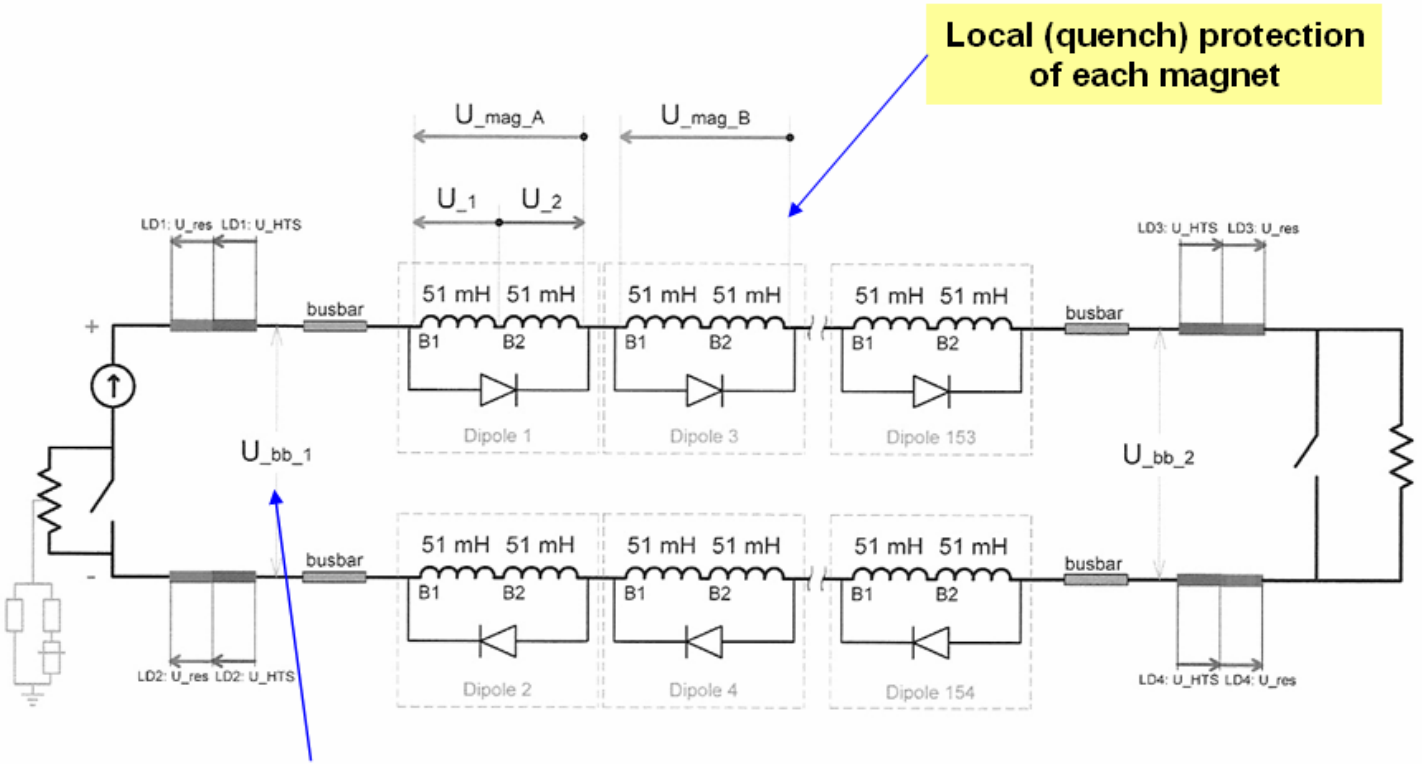
Schematic of the main dipole circuit



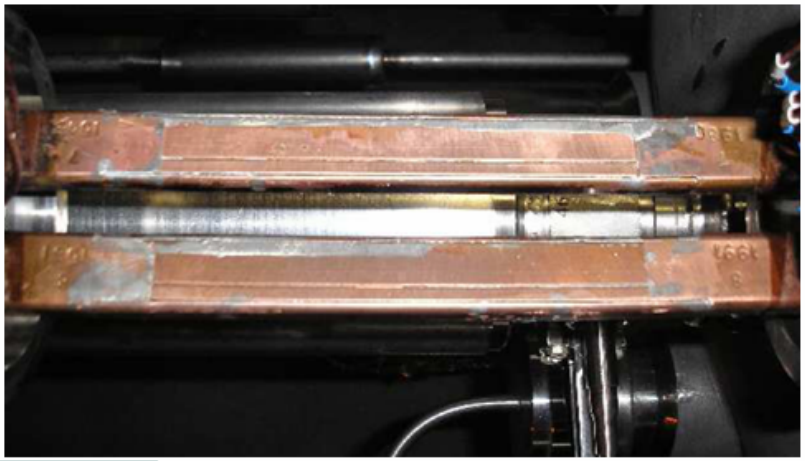
Global protection of the bus-bar and bus-bar joints (splices) between magnets.

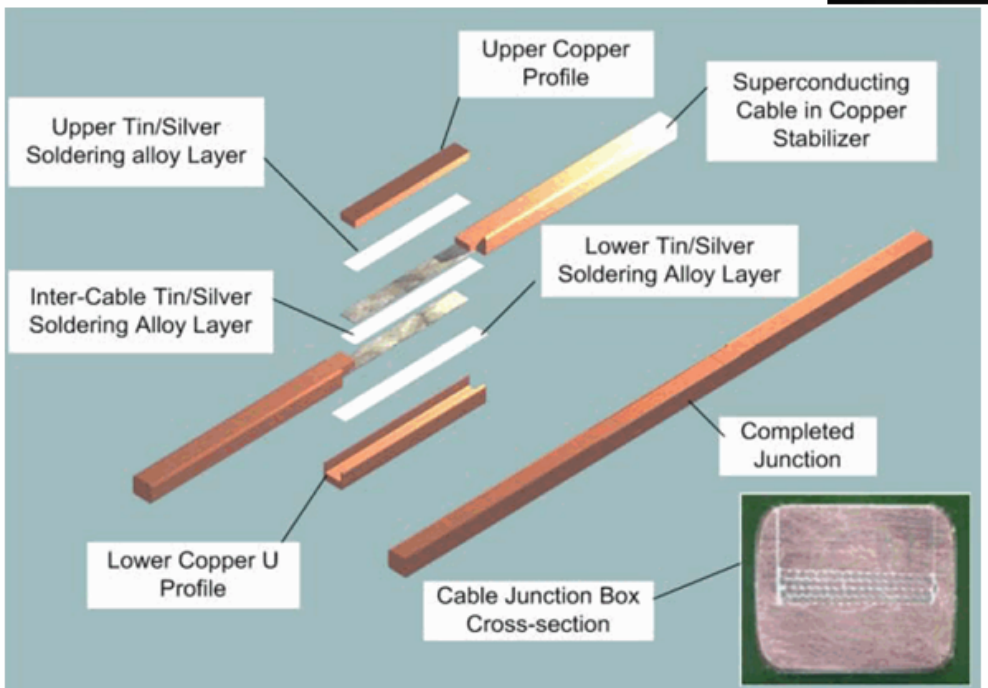
Protection threshold 1 V (160 V inductive voltage during ramp).
Bus-bar must cope with 100 second discharge time of circuit.

Bus-bar joint

- Superconducting cable embedded in Copper stabilizer.
- Bus bar joint is brazed (not clamped).
- Joint resistance ~0.35 nΩ (@ 1.9 K).
- Protected by global bus-bar protection system, no bypass diode.

  relies on good quality of the joint.

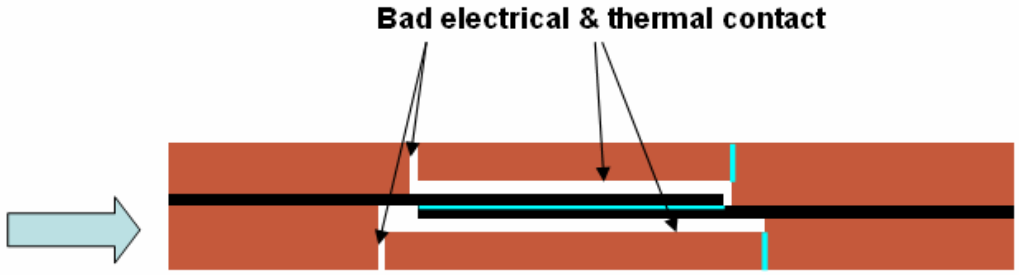




- Visual inspection after brazing.
- For the new joints (repair) the resistance is measured at room temperature to qualify the joint.

Likely incident cause : poor quality joint

- Cryogenic temperature data indicated a local anomalous resistance ~220 nΩ in the cell where the incident occurred.
- Joint model with poor electrical contact, R ~ 220 nΩ.



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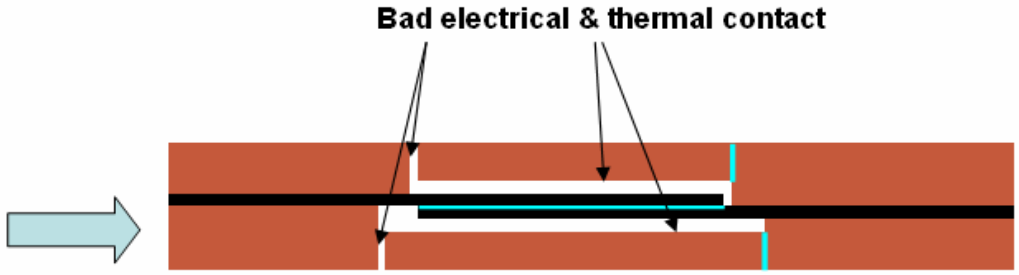

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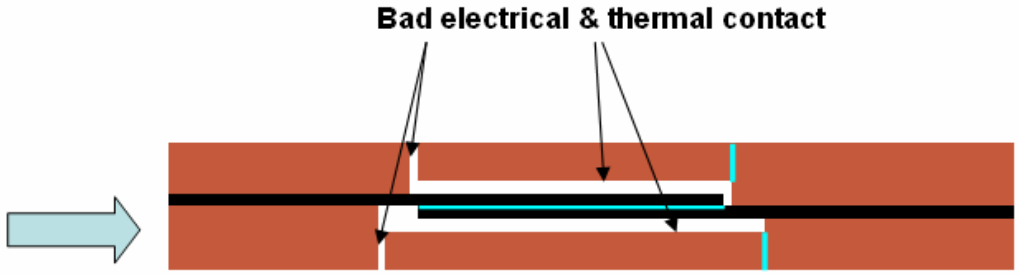
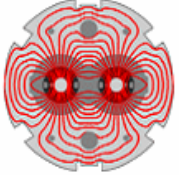
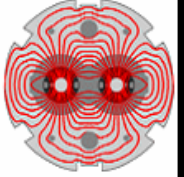


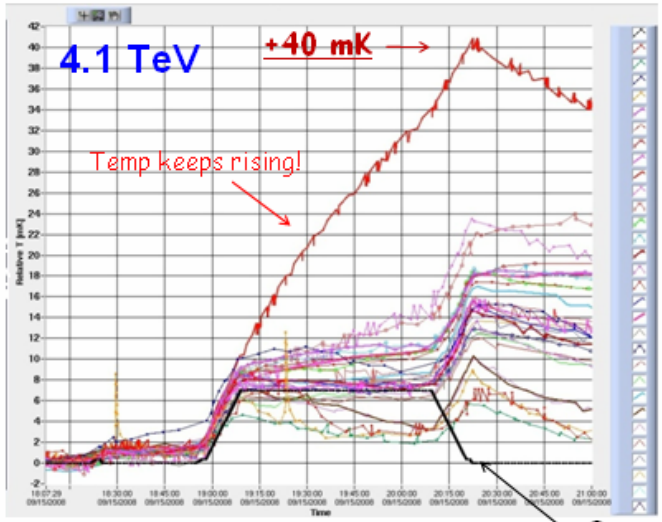
What about the other joints?

Calorimetric data

- Logged cryogenic data revealed a temperature anomaly of some 40 mK in the cell of the incident during a previous (lower current) powering cycle.

ΔT (mk)

7 kA test on **Sector 34**



5.5 TeV

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- Data from other powering tests indicated the presence of another anomaly in sector 12. Calorimetry suggested a **~100 nΩ resistance**.

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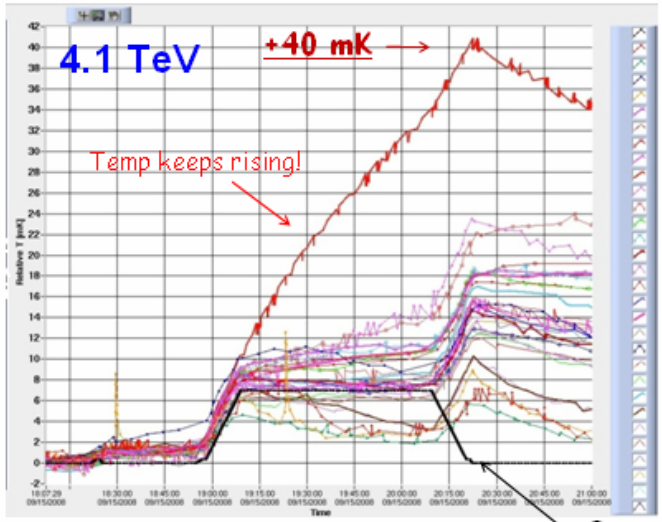
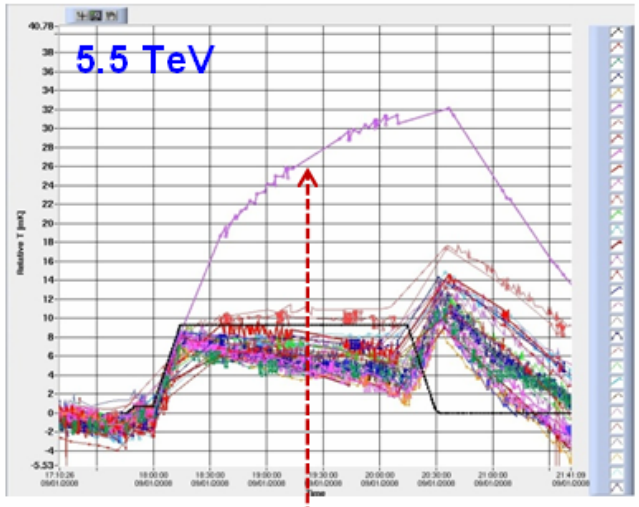


9.3 kA test on **Sector 12**



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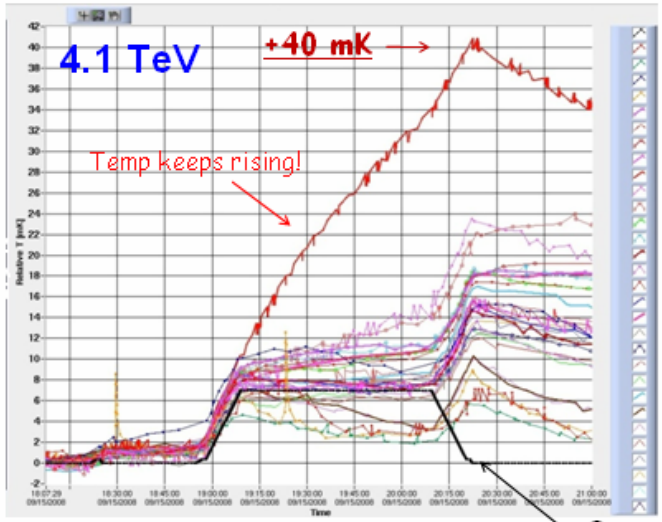

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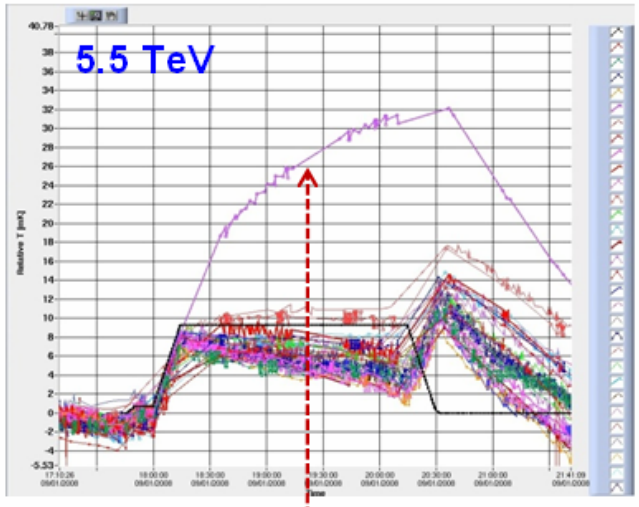

Suspicious cell in S12

Calorimetric and electrical measurements

Powerful diagnostics tools were developed:

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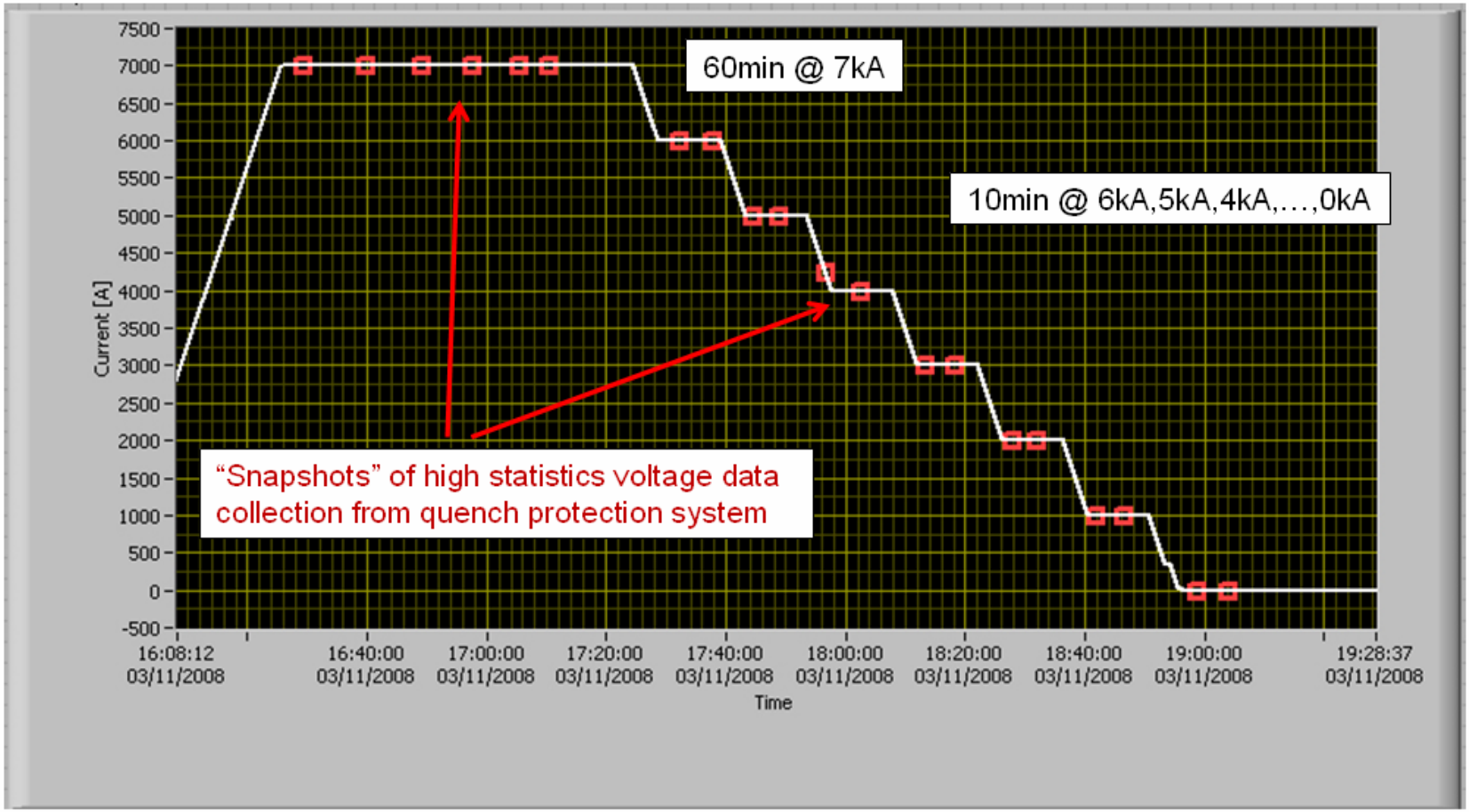
Outcome of the test campaign:

2 magnets were localized with **internal** resistances of **50** and **100 nΩ**.

- Both magnets had been tested to 12.4 kA (5% over nom.) before installation!

Electrical measurements



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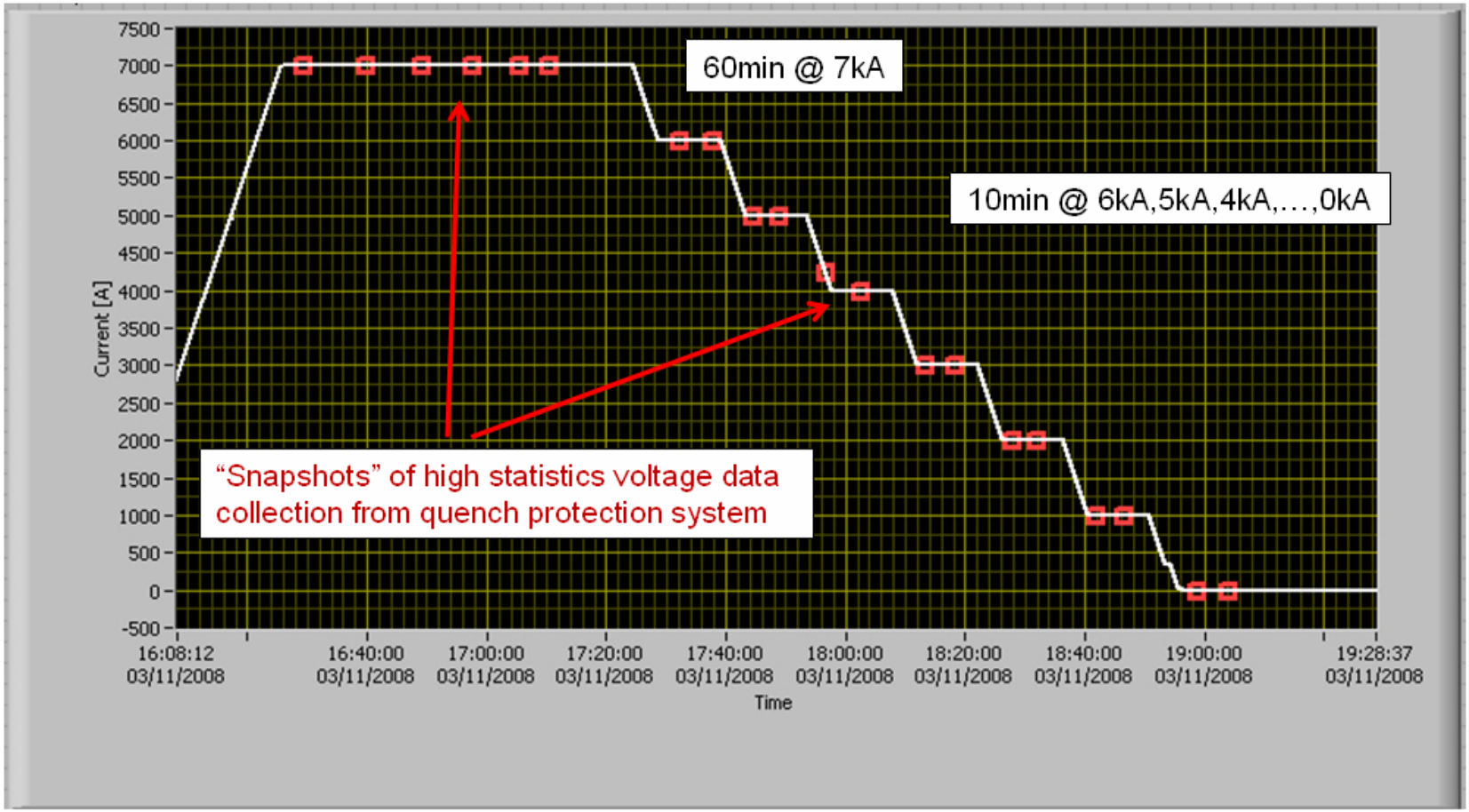

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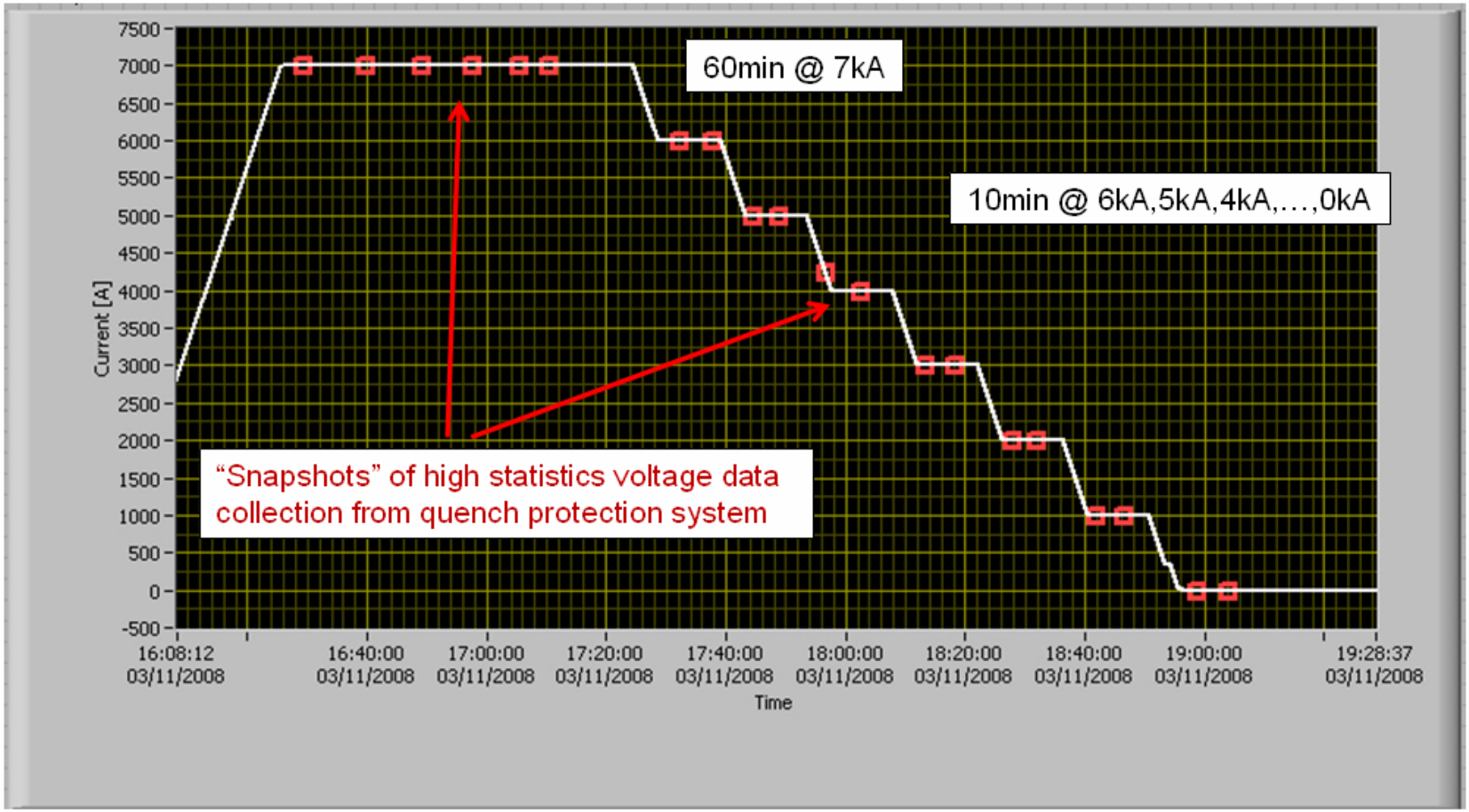
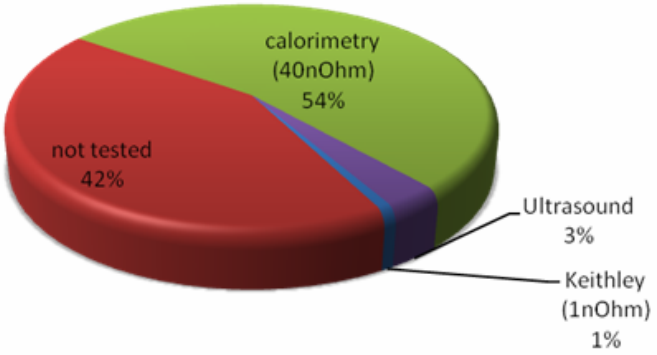


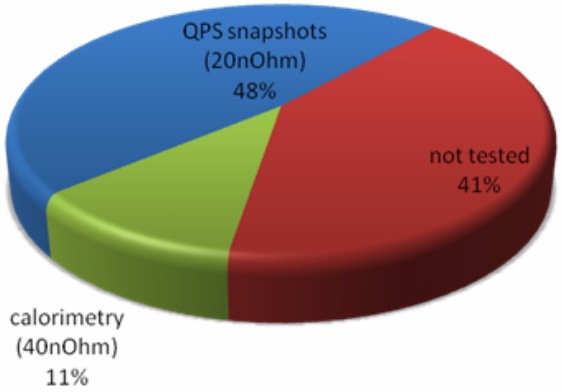
Joint test status

Interconnection joints



58% of 10080 tested

Magnet joints

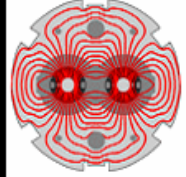
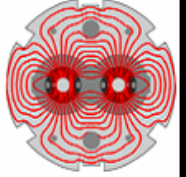


59% of 13796 tested

Poster MO6PFP049

Testing the remaining joints is a top priority of 2009 !

The untested joints have already been operated at 5.5 TeV !

Repair and consolidation

Repair (I)

- 39 dipoles and 14 quadrupoles short straight sections (SSS) brought to surface for repair (16: 9D + 7SSS) or replacement (37: 30D + 7SSS).

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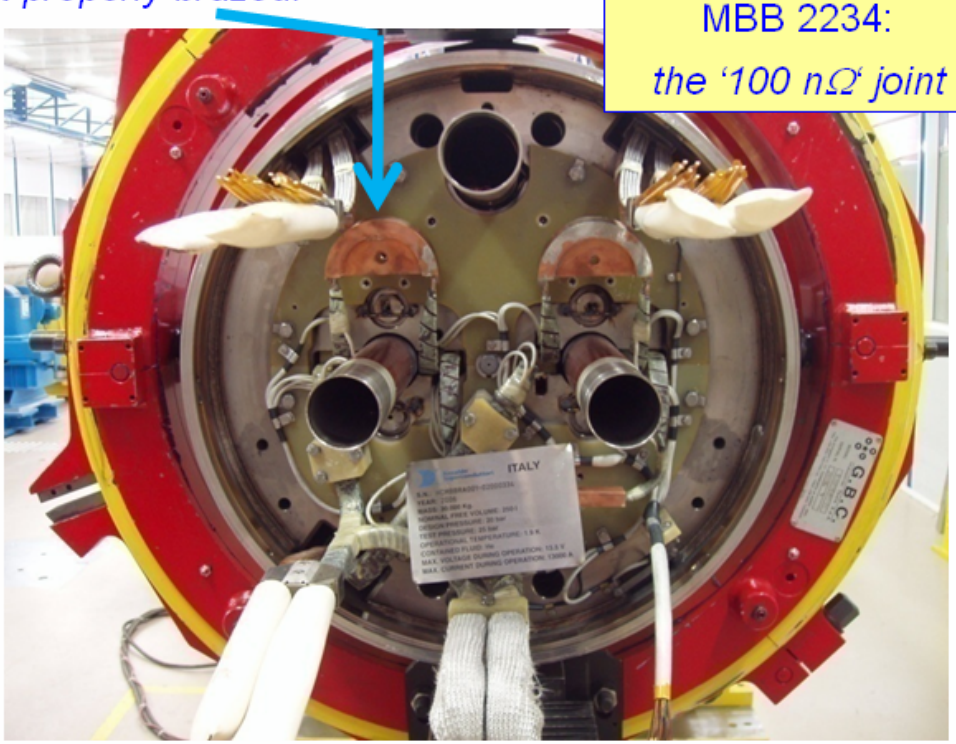
The 50 nΩ dipole will be stress tested on a bench.



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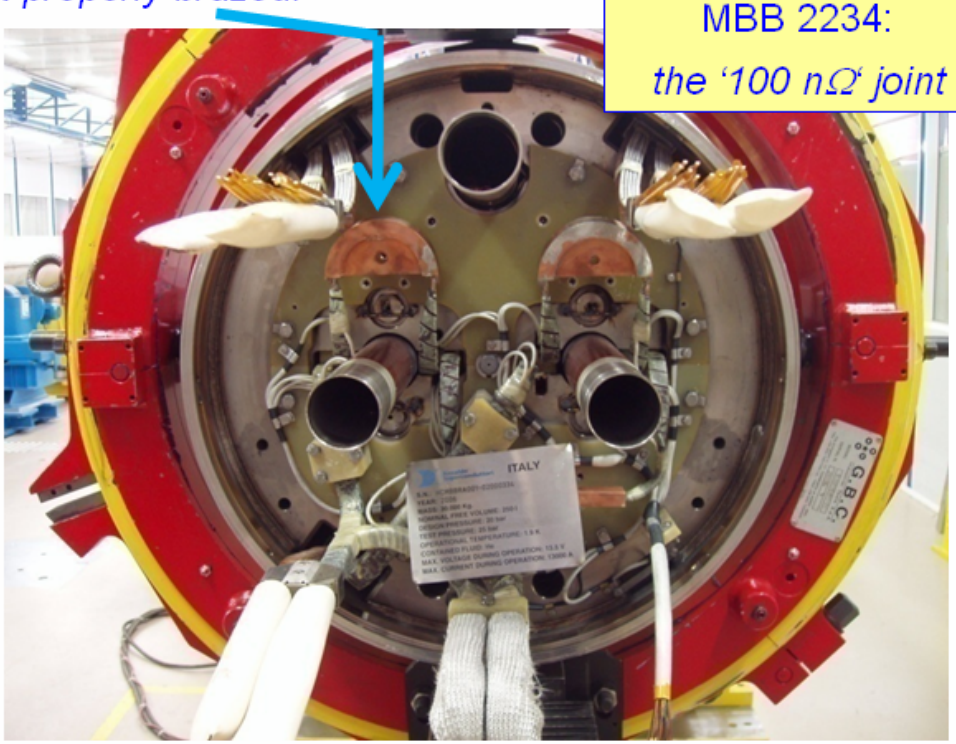

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- Major upgrade of the quench protection system.

Poster MO6PFP047

  - *Protection of the main quadrupole and dipole joints.*
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  - *High statistics measurement accuracy to < 1 nΩ.*

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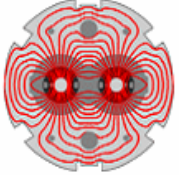
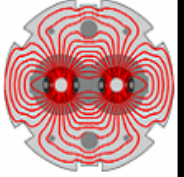
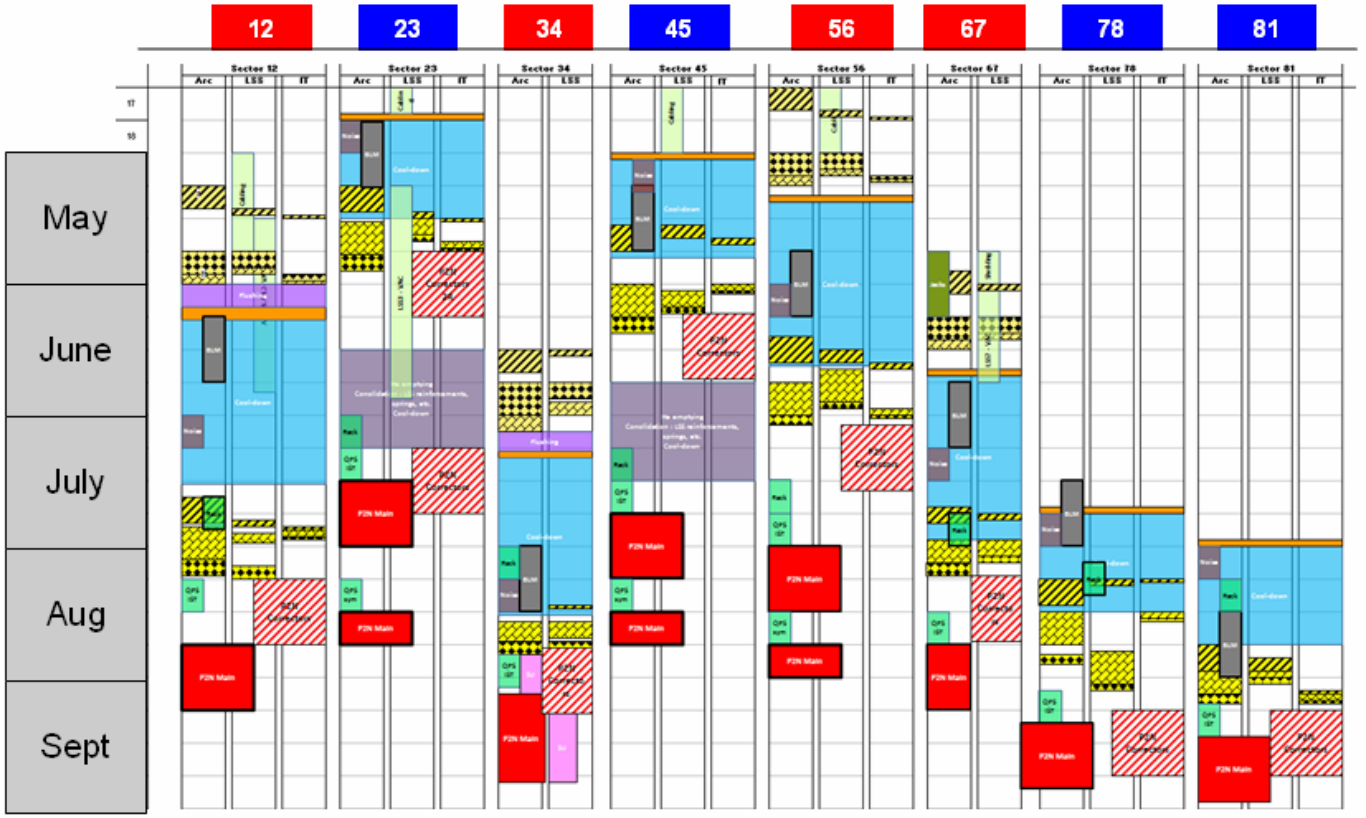



LHC run 2009/20010

Planning for 2009



…followed by a long LHC run until November 2010, with short break around Christmas/new year 2009/2010.

*Target beam energy for physics : **5 TeV**.*

LHC Experiments Desiderata

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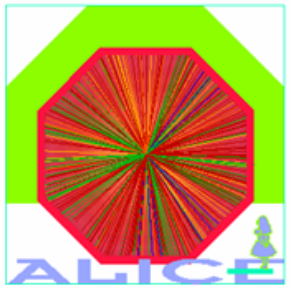
Many new limits set on hypothetical particles.



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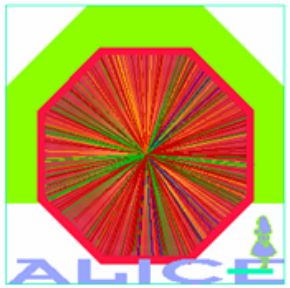

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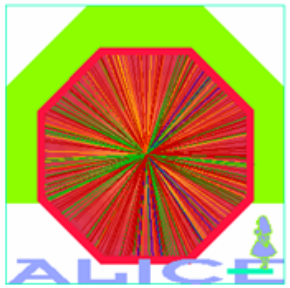

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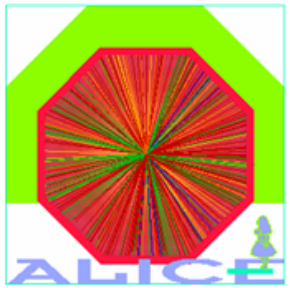

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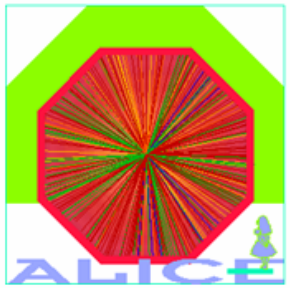

Luminosity Targets 2009/10

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ORAL by R. Assmann, TUE pm
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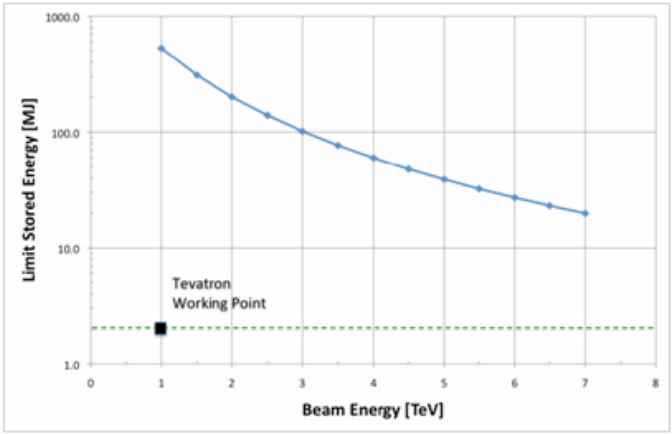

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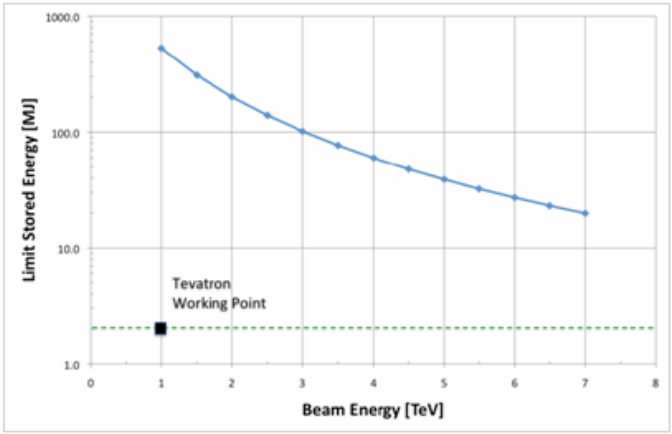

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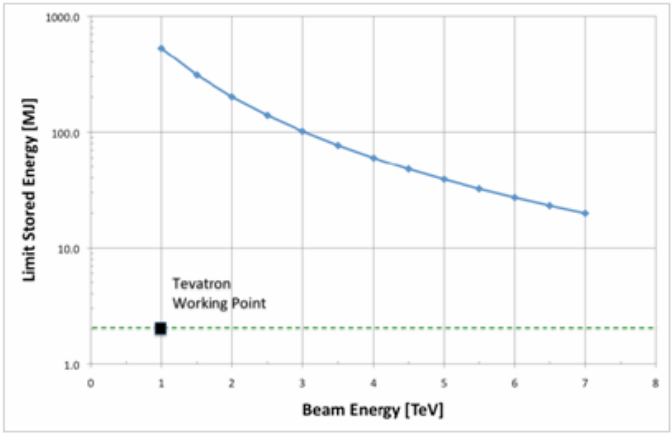

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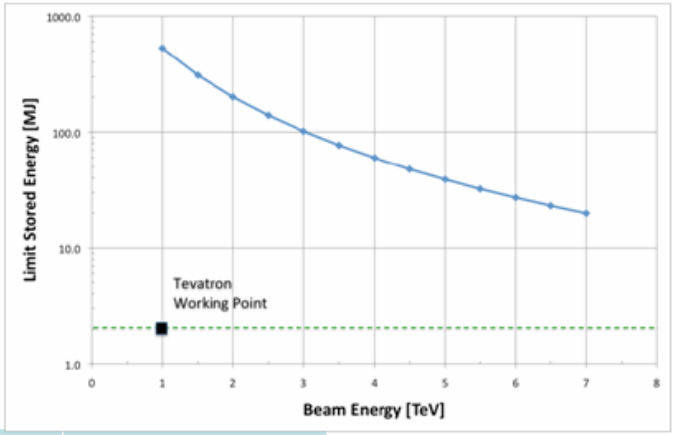


- Operation in 2009/10.

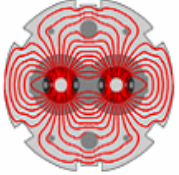
No. bunches/ beam	Protons/ bunch	% of nominal intensity	β* (m)	Peak L ($cm^{-2}\ s^{-1}$)
43	5×10^{10}	0.7	2	6.9×10^{30}
156	5×10^{10}	2.4	1	5.0×10^{31}
156	1×10^{11}	4.8	1	2.0×10^{32}
720 (50 ns)	5×10^{10}	11.1	2	1.2×10^{32}
2808	$\mathbf{1.15\times10^{11}}$	**100**	**0.55**	$\mathbf{1.0\times10^{34}}$

No crossing angle

Int. luminosity target achievable with ~40% availability

- Short Pb ion run foreseen end 2010.

Ion setup should be 'straight forward' as little difference wrt protons.



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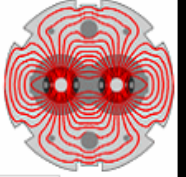

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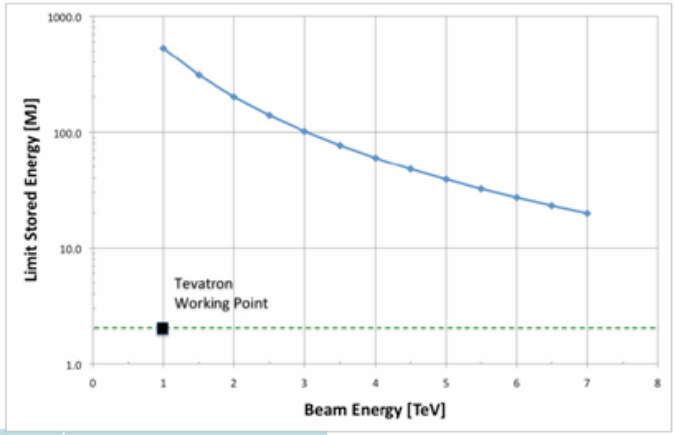

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720 (50 ns)	5×10^{10}	11.1	2	1.2×10^{32}
2808	$\mathbf{1.15\times10^{11}}$	**100**	**0.55**	$\mathbf{1.0\times10^{34}}$

No crossing angle

Int. luminosity target achievable with ~40% availability

- Short Pb ion run foreseen end 2010.

Ion setup should be 'straight forward' as little difference wrt protons.

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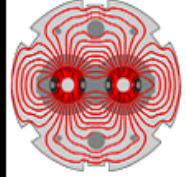
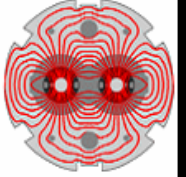
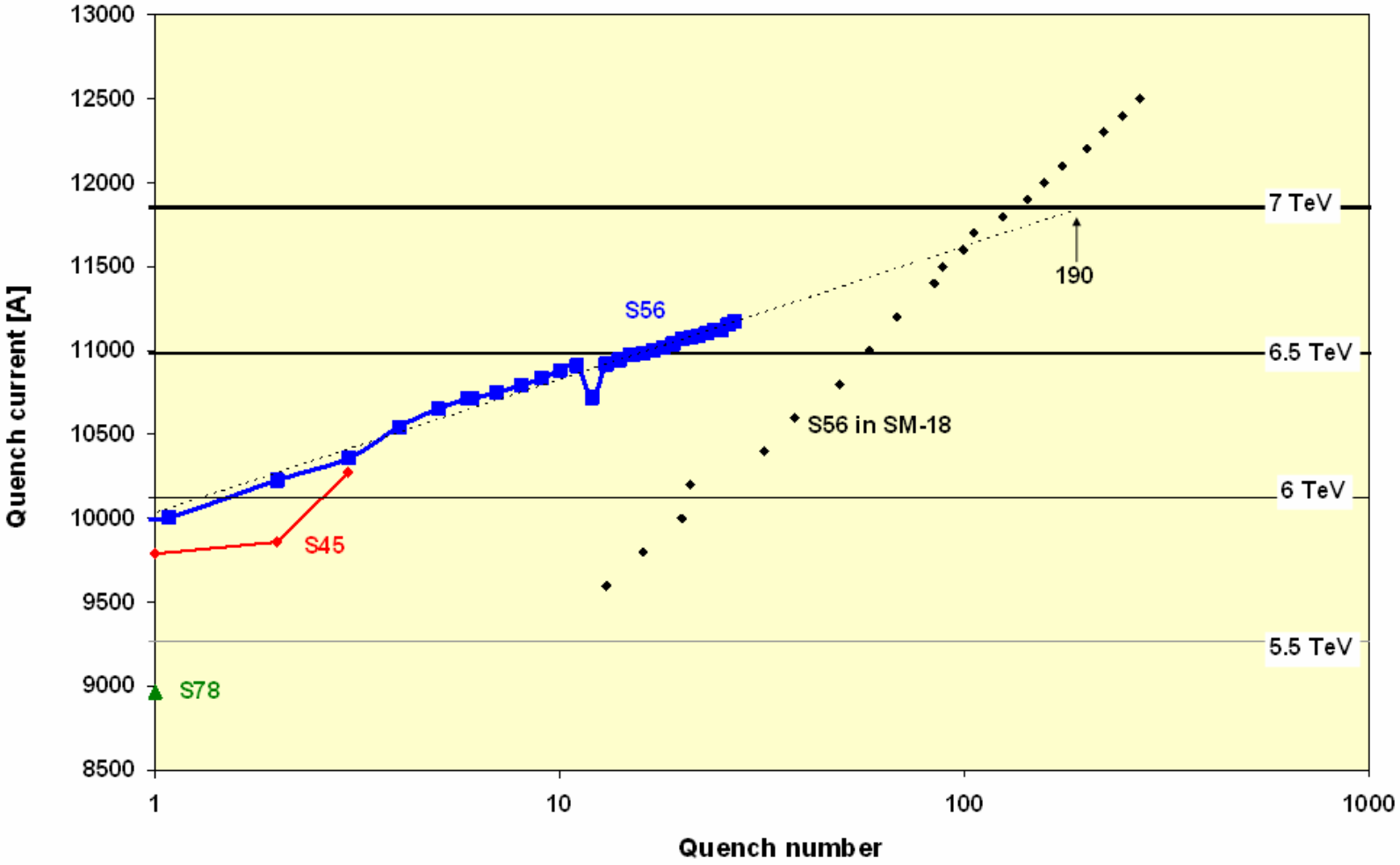
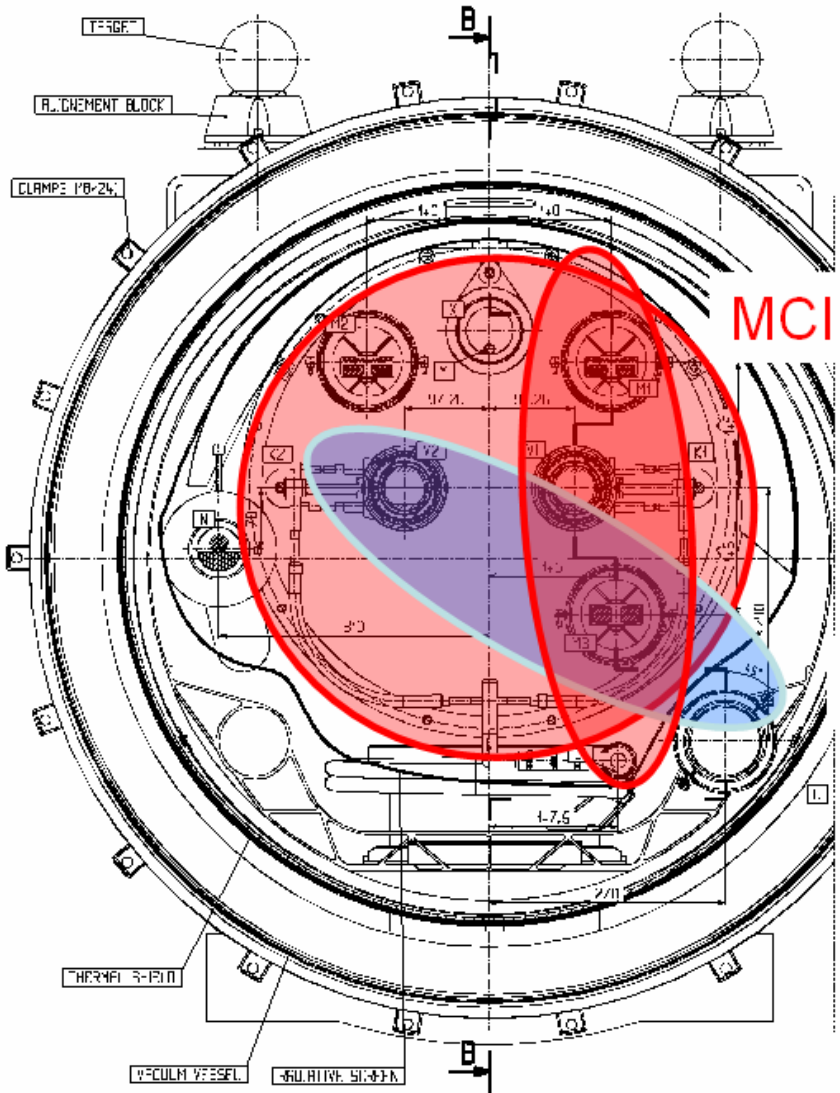



Reserve slides

Magnet training to 7 TeV



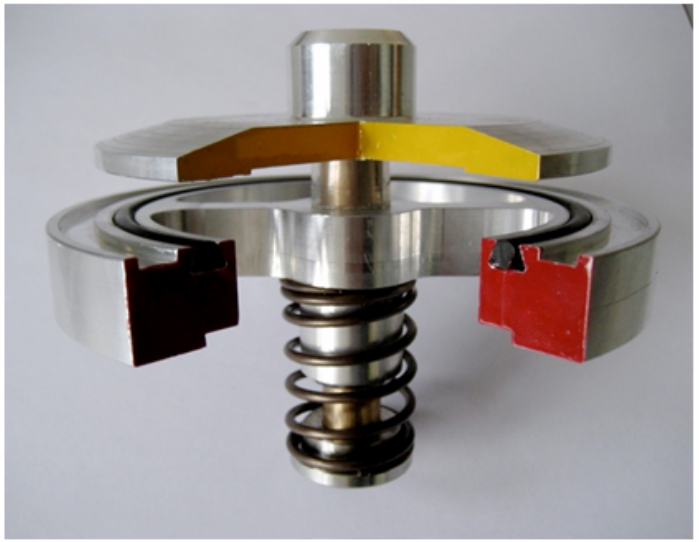
Maximum Conceivable Incident



MCI ?

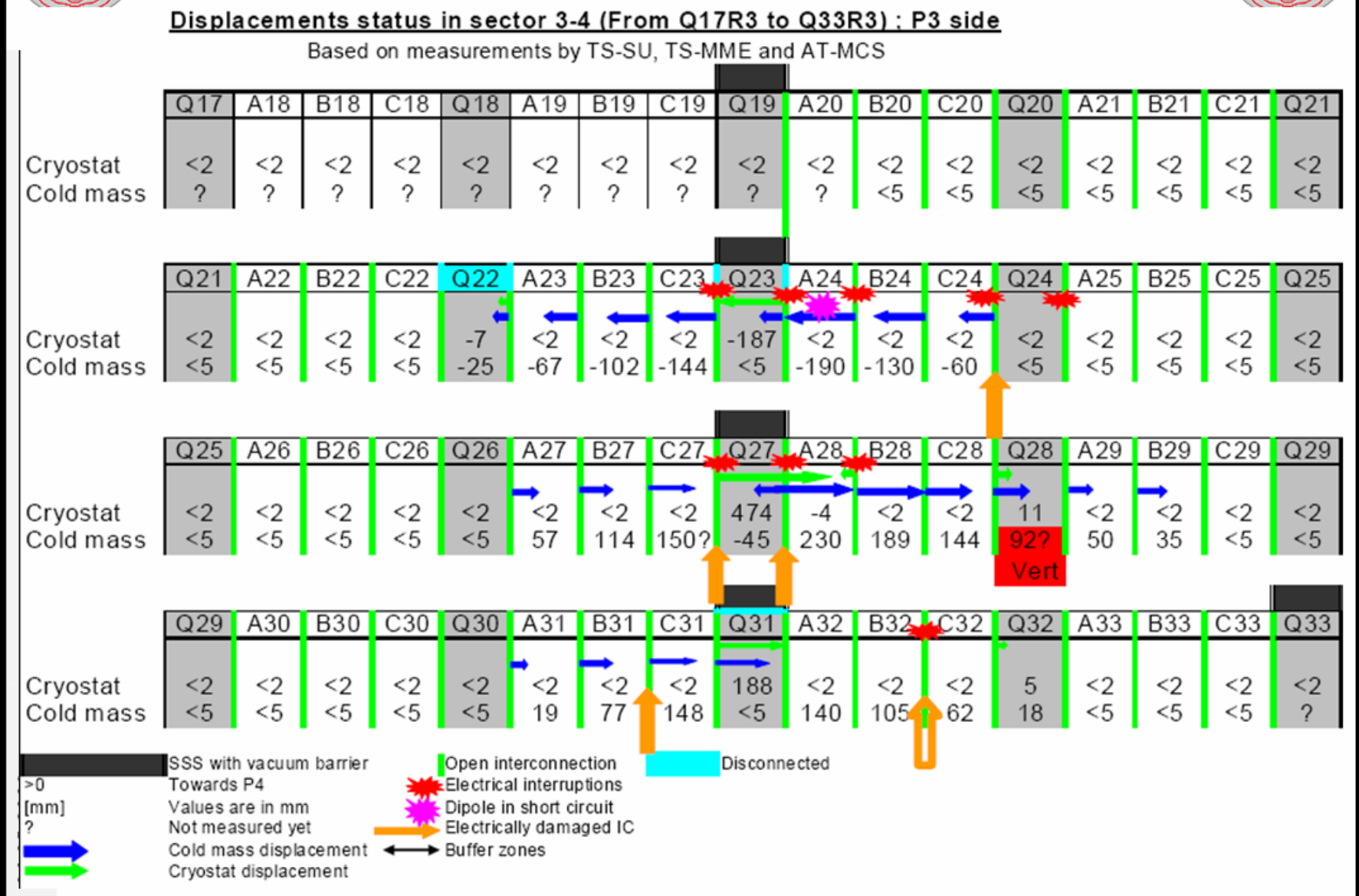
Sect.3-4 incident

Existing relief valves (quadrupoles)



- Designed for He flow of 2 kg/s
- Estimate for incident is ~ 20 kg/s

Damage area


Displacements status in sector 3-4 (From Q17R3 to Q33R3) : P3 side
Based on measurements by TS-SU, TS-MME and AT-MCS
Q17 A18 B18 C18 Q18 A19 B19 C19 Q19 A20 B20 C20 Q20 A21 B21 C21 Q21
Cryostat <2 <2 <2 <2 <2 <2 <2 <2 <2 <2 <2 <2 <2 <2 <2 <2 <2
Cold mass ? ? ? ? ? ? ? ? ? ? <5 <5 <5 <5 <5 <5 <5
Q21 A22 B22 C22 Q22 A23 B23 C23 Q23 A24 B24 C24 Q24 A25 B25 C25 Q25
Cryostat <2 <2 <2 <2 -7 <2 <2 <2 -187 <2 <2 <2 <2 <2 <2 <2 <2
Cold mass <5 <5 <5 <5 -25 -67 -102 -144 <5 -190 -130 -60 <5 <5 <5 <5 <5
Q25 A26 B26 C26 Q26 A27 B27 C27 Q27 A28 B28 C28 Q28 A29 B29 C29 Q29
Cryostat <2 <2 <2 <2 <2 <2 <2 <2 474 -4 <2 <2 11 <2 <2 <2 <2
Cold mass <5 <5 <5 <5 <5 57 114 150? -45 230 189 144 92? Vert 50 35 <5 <5
Q29 A30 B30 C30 Q30 A31 B31 C31 Q31 A32 B32 C32 Q32 A33 B33 C33 Q33
Cryostat <2 <2 <2 <2 <2 <2 <2 <2 188 <2 <2 <2 5 <2 <2 <2 <2
Cold mass <5 <5 <5 <5 <5 19 77 148 <5 140 105 62 18 <5 <5 <5 ?
SSS with vacuum barrier
Towards P4
>0
Values are in mm
[mm]
Not measured yet
?
Cold mass displacement
Cryostat displacement
Open interconnection
Electrical interruptions
Dipole in short circuit
Electrically damaged IC
Buffer zones
Disconnected

Summary of joint measurements

Sectors	Arc dipole			Arc Quadrupoles			IPQ		
Tests	Calorimetric	Magnet	Bus-bar (on request)	Calorimetric	Magnet	Bus-bar (on request)	Calorimetric	Magnet	Bus-bar (on request)
1-2	(2)	1							
2-3									
3-4									
4-5									
5-6	(0)	0		(0)	0				
6-7	(1)	1		(1)	0				
7-8	(1)	0	0	(1)	0				
8-1	(1)	0	0	(0)	0				

(1) suspected cases from calorimetric measurements

1 confirmed cases by electrical measurement

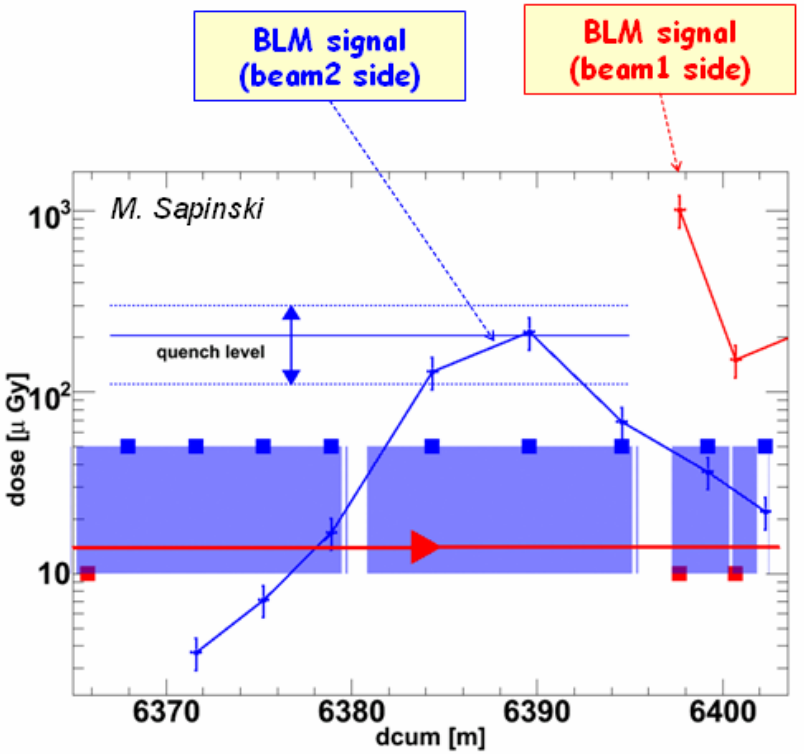
‘Quenches’ with beam

- The quench protection system (QPS) was triggered with fast losses of 2×10^9 and 4×10^9 protons, only *one part in 10’000 of the nominal beam*.

  Without force-quenching by the QPS with the quench heaters, the magnets would have recovered spontaneously

- Simulations agree within a factor ~2 with the expectations from the magnet model on the energy density to quench:
  - Measurement ~ 15 mJ/cm^3
  - Expectation ~ 30 mJ/cm^3

Beam commissioning with a single bunch of 2×10^9 p.



Magnetic model

- Momentum (b_1 [US=b0]):
  - LHC average momentum = 450.5 ± 0.2 GeV
  - Δb_1 between rings ≈ 1.5×10^{-4}
  - Δb_1 among 8 sectors ≈ 3×10^{-4}

- Tune (b_2 [US=b1]):
  - Measured tunes are within 0.15 of nominal ones.
  - Corresponds to an error of 25×10^{-4} on b2, expected $\pm20\times10^{-4}$.