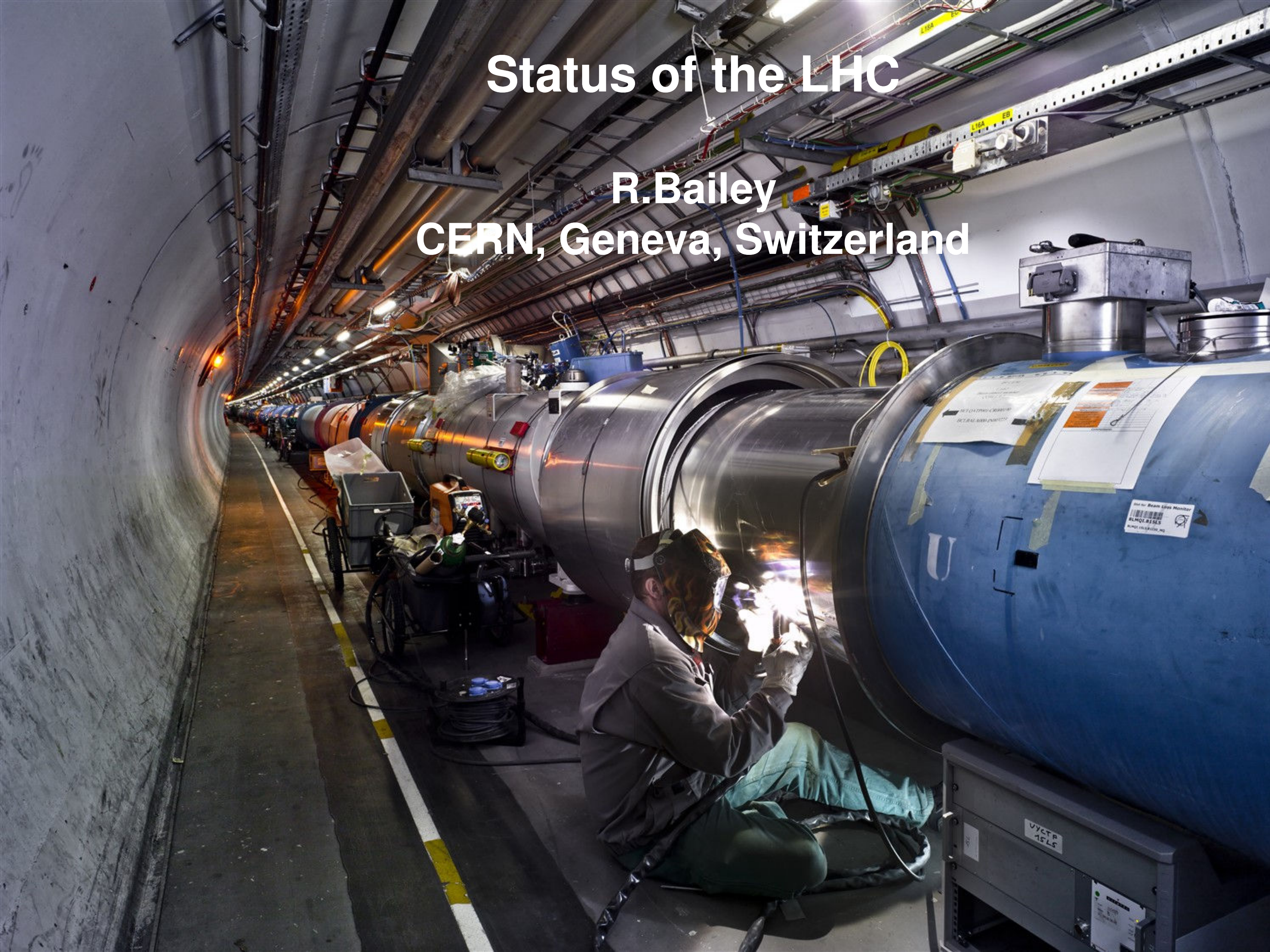
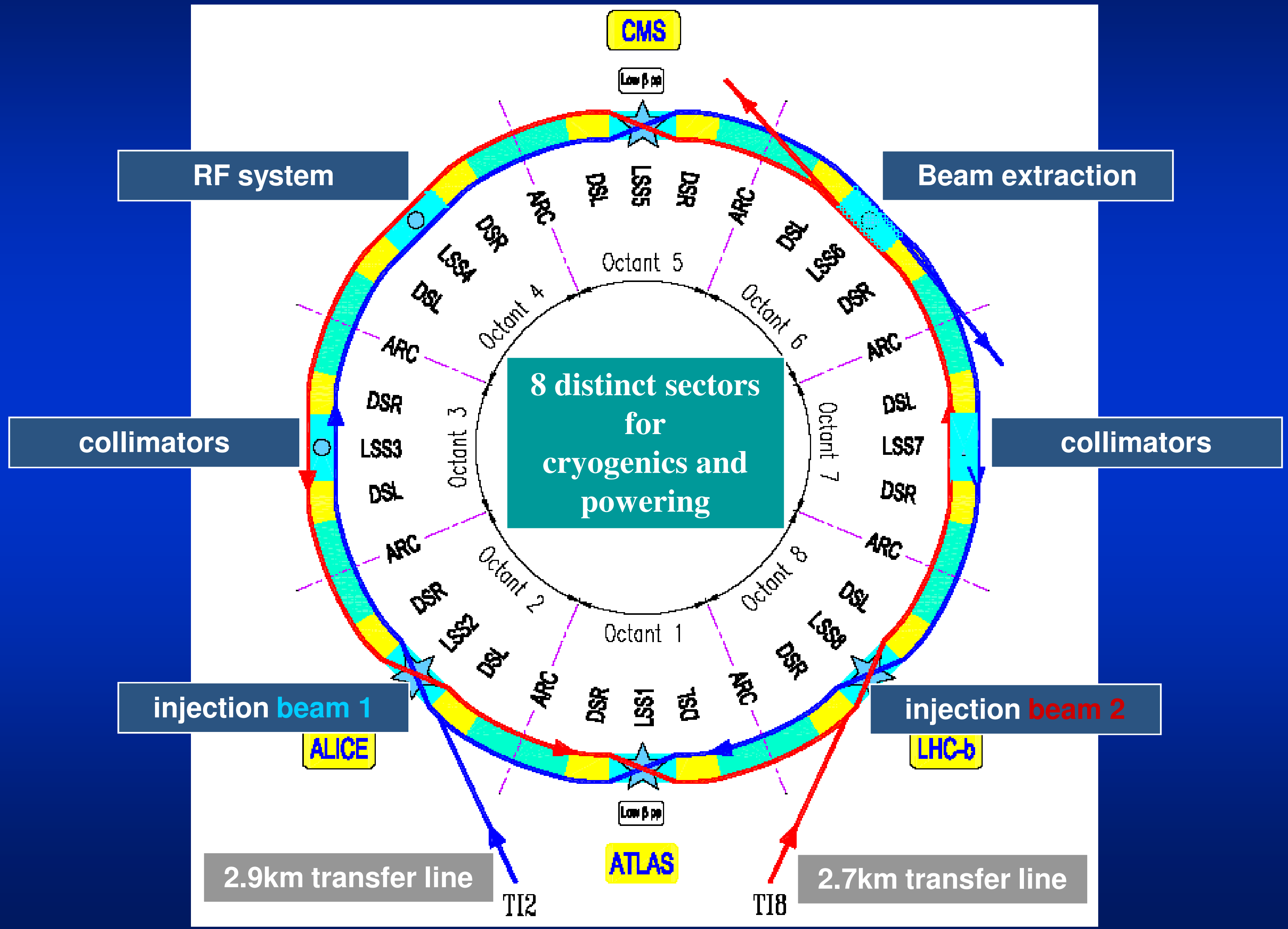
Status of the LHC

R.Bailey
CERN, Geneva, Switzerland

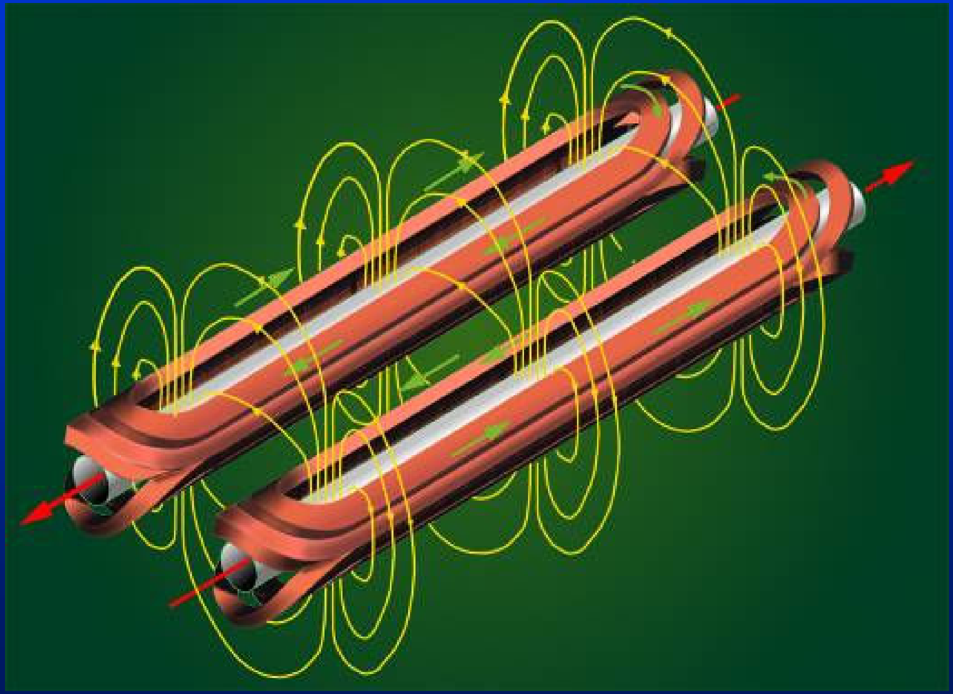


Schematic of the LHC



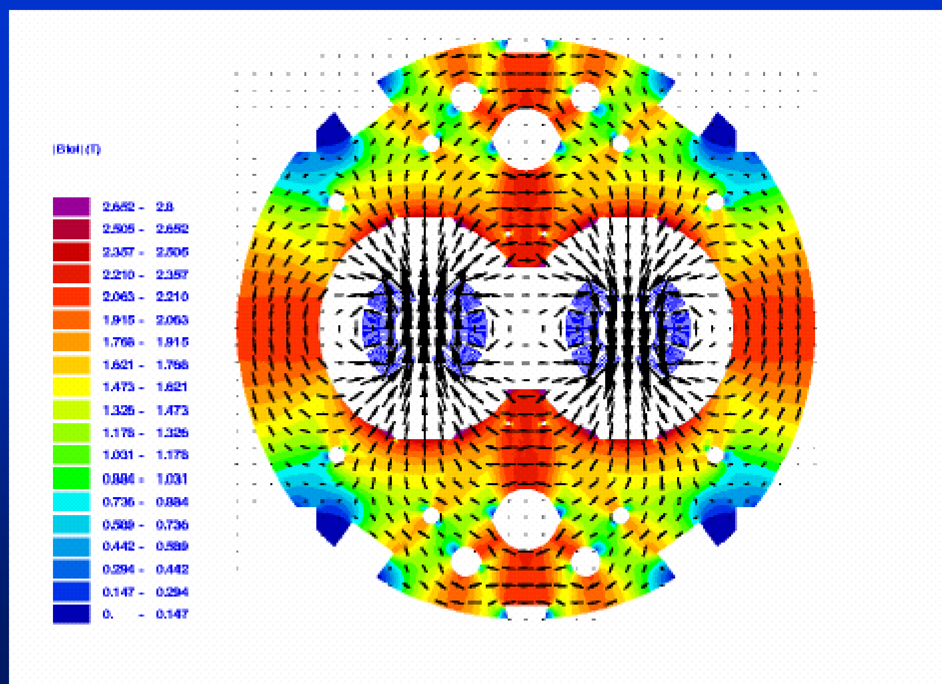
LHC design parameters

- Luminosity (defines rate of doing physics) 10^{34} cm^{-2} s^{-1}
  - Need lots of particles to achieve this rate
  - Hence proton – proton machine (unlike Tevatron or SppbarS)
  - Separate bending fields and vacuum chambers in the arcs

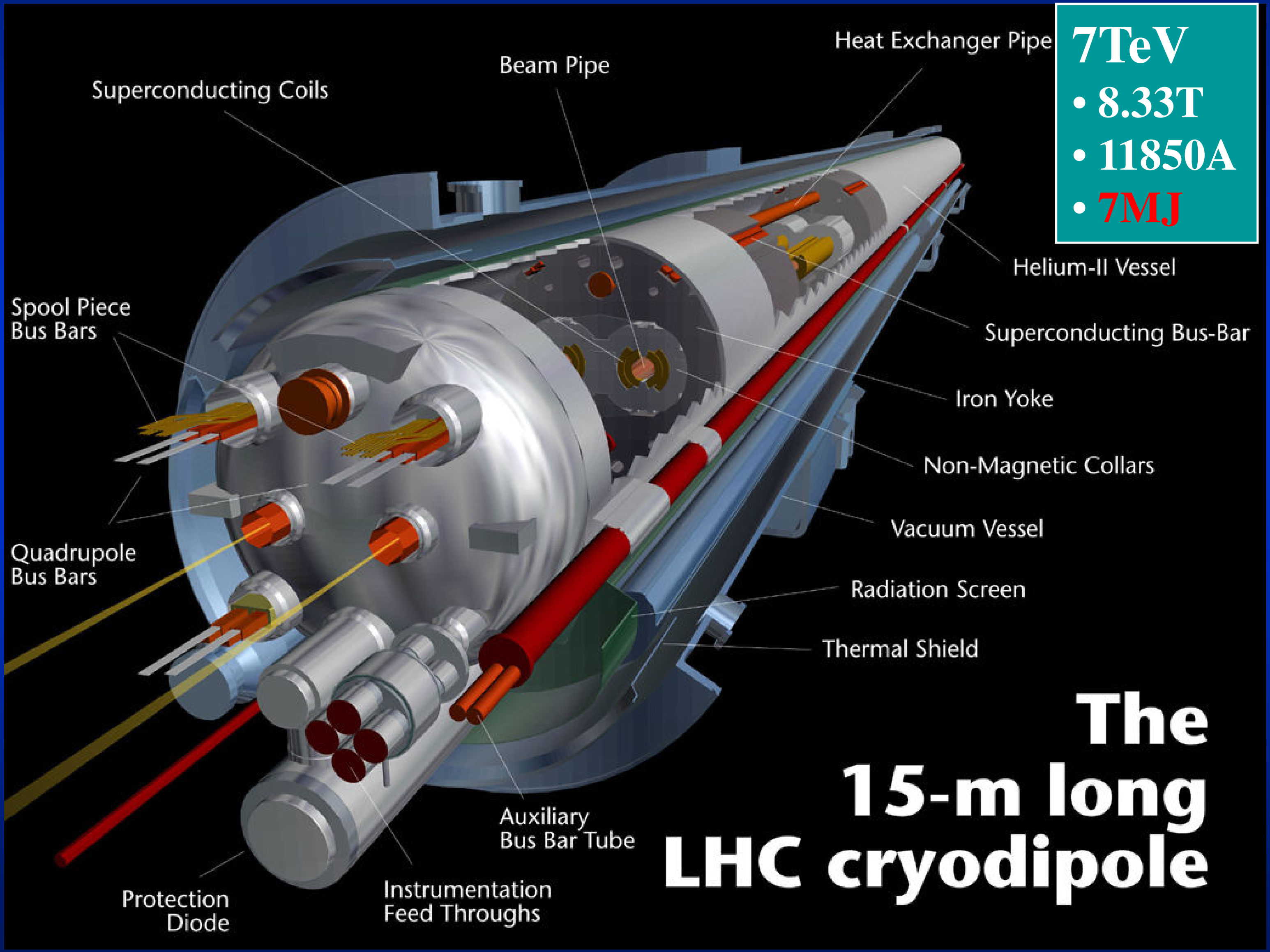


LHC design parameters

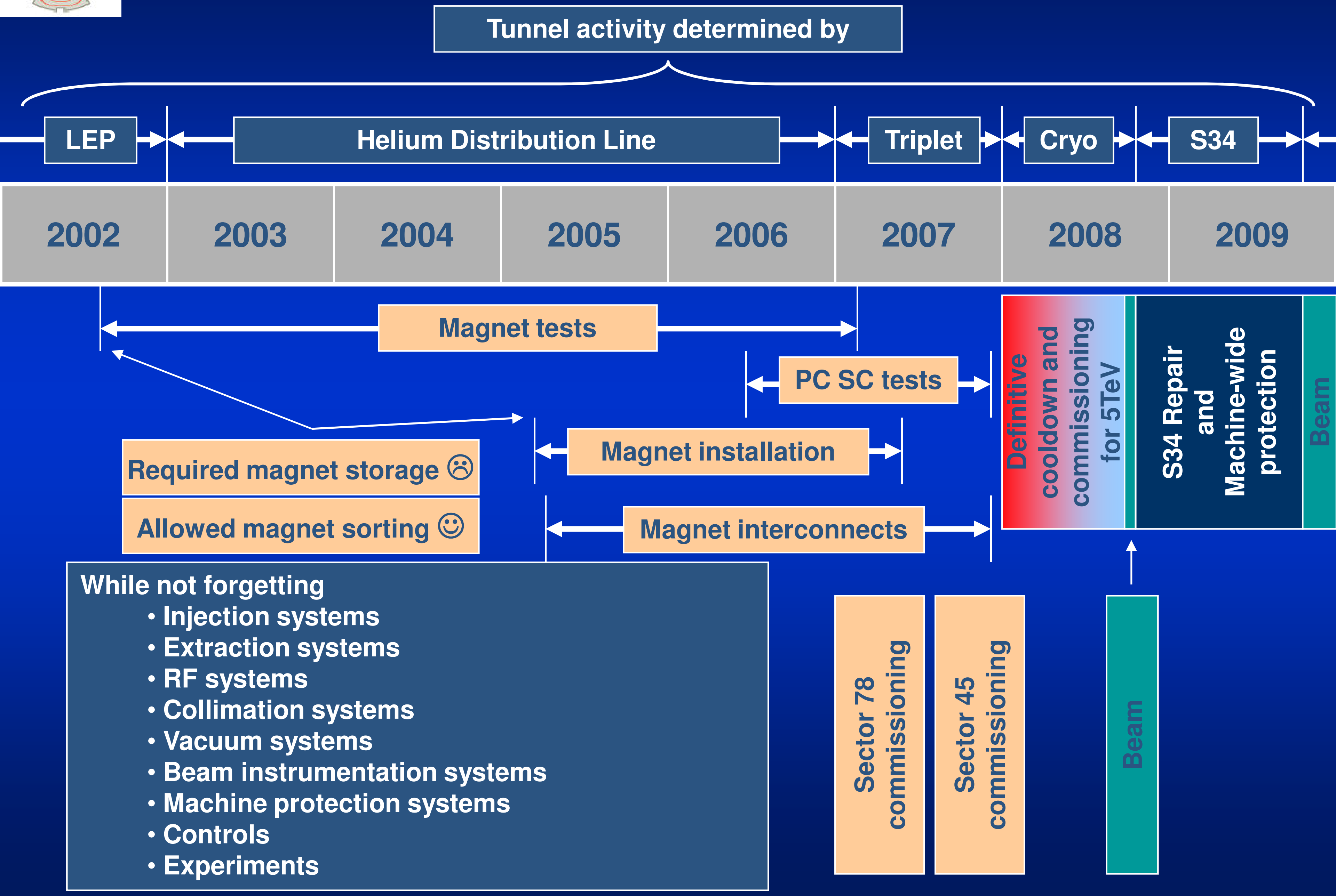
- **Energy   7TeV per beam ⇔ Dipole field 8.33Tesla**
  - **Superconducting technology needed to get such high fields**
  - **Tunnel cross section (4m) excludes 2 separate rings (unlike RHIC)**
  - **Hence twin aperture magnets in the arcs**



LHC dipoles (1232 of them) operating at 1.9K



Construction Commissioning Consolidation 2002-2009



Status of the LHC

The September 19th incident

Understanding the (extent of the) problem

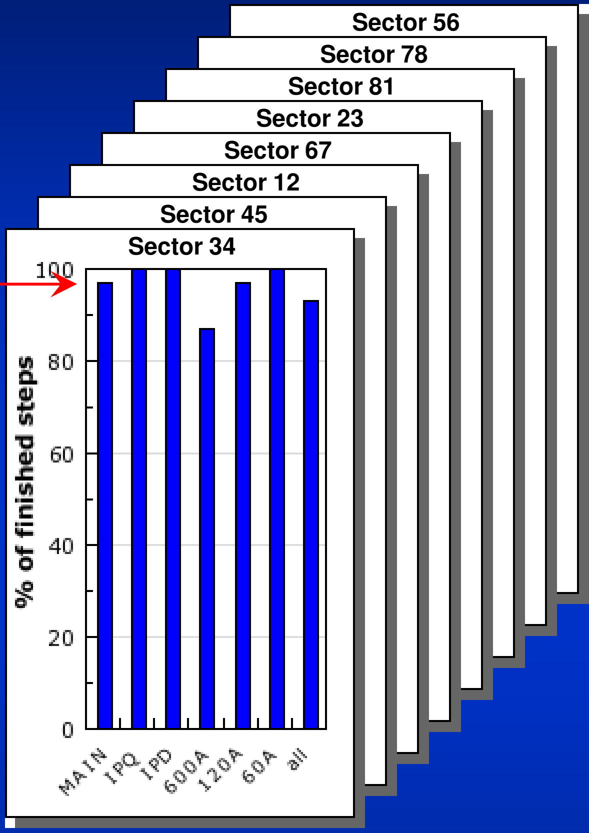
Making sure there is no repeat

Strategy for restart

Prospects for 2009 2010

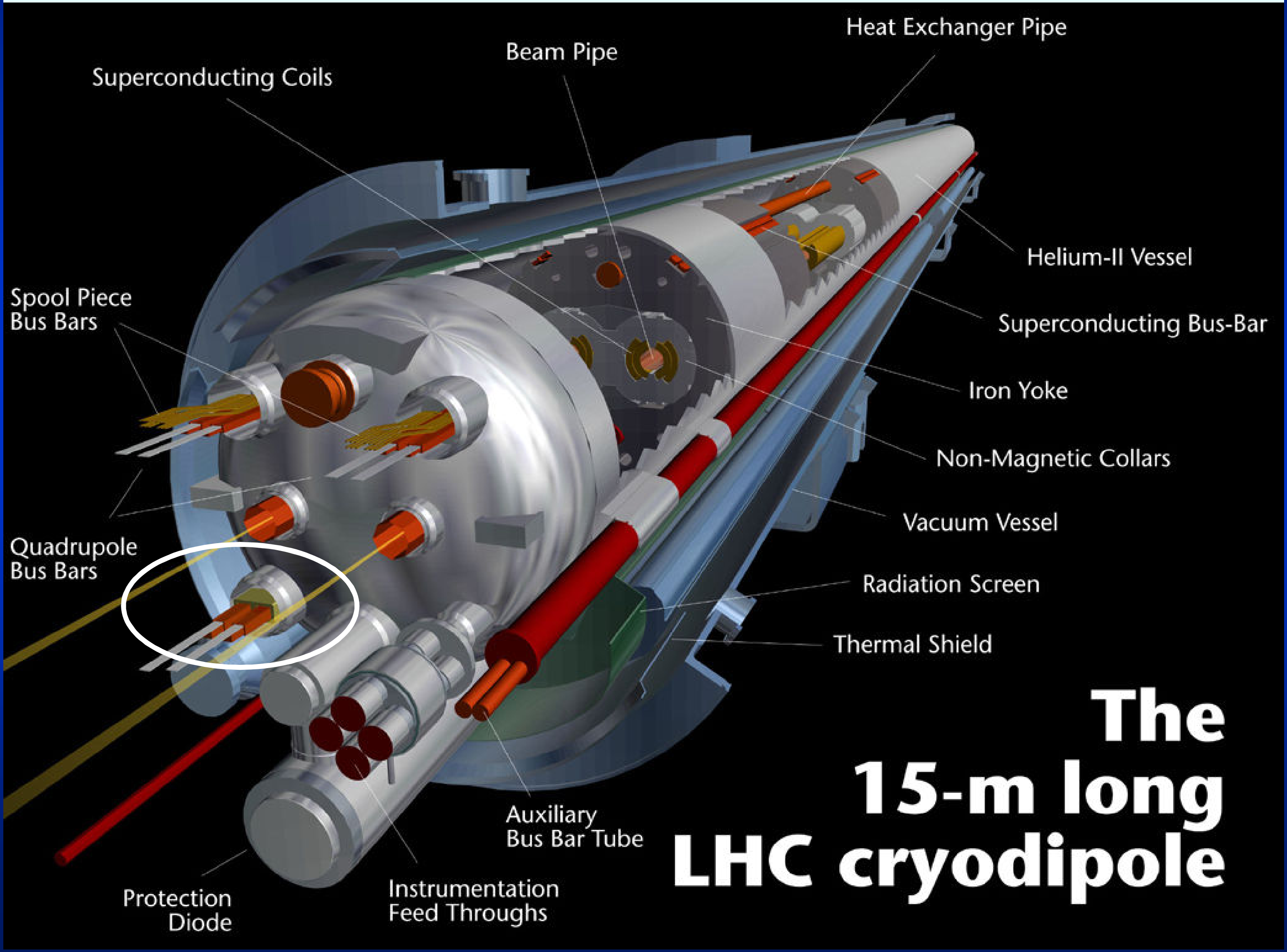
Incident of September 19th 2008

- During a few days period without beam while recovering from transformer failure
- Making the last step of the dipole circuit in sector 34, to 9.3kA
- At 8.7kA, development of resistive zone in the dipole bus bar splice between Q24 R3 and the neighbouring dipole
  - Later estimated (from cryogenic data on heat deposition) to be 220nΩ
- Electrical arc developed which punctured the helium enclosure, allowing helium release into the insulating vacuum
- Large pressure wave travelled along the accelerator in both directions

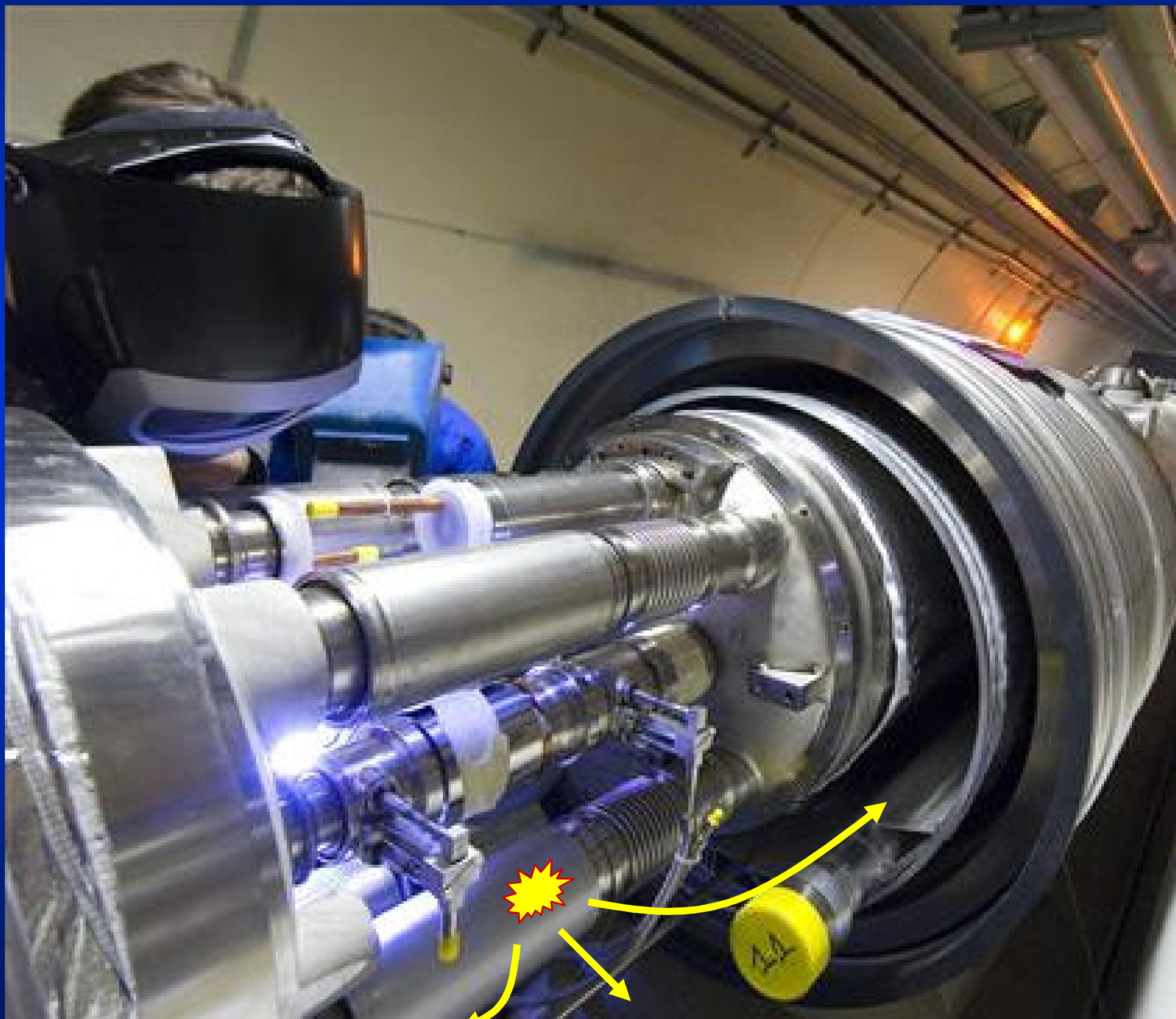


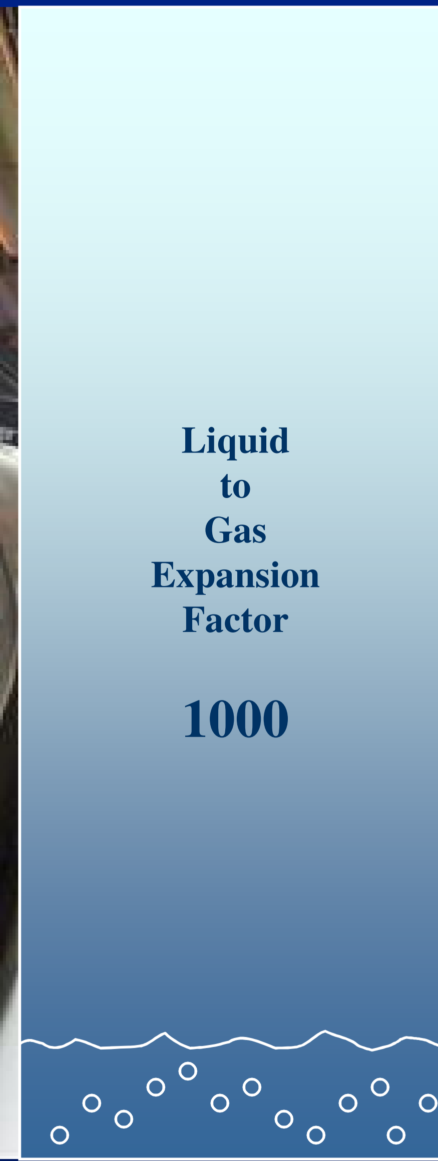
Development of resistive zone in dipole bus bar splice

1232 dipoles, 392 dipoles, 6 high current splices each

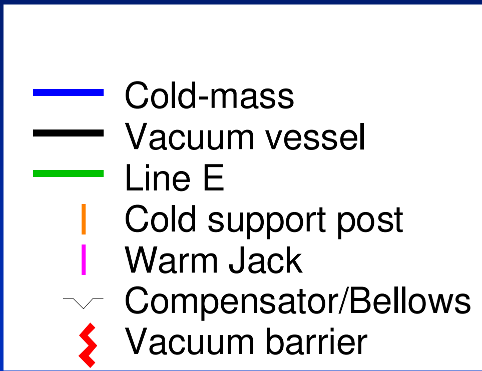


Arc and helium release into the insulating vacuum

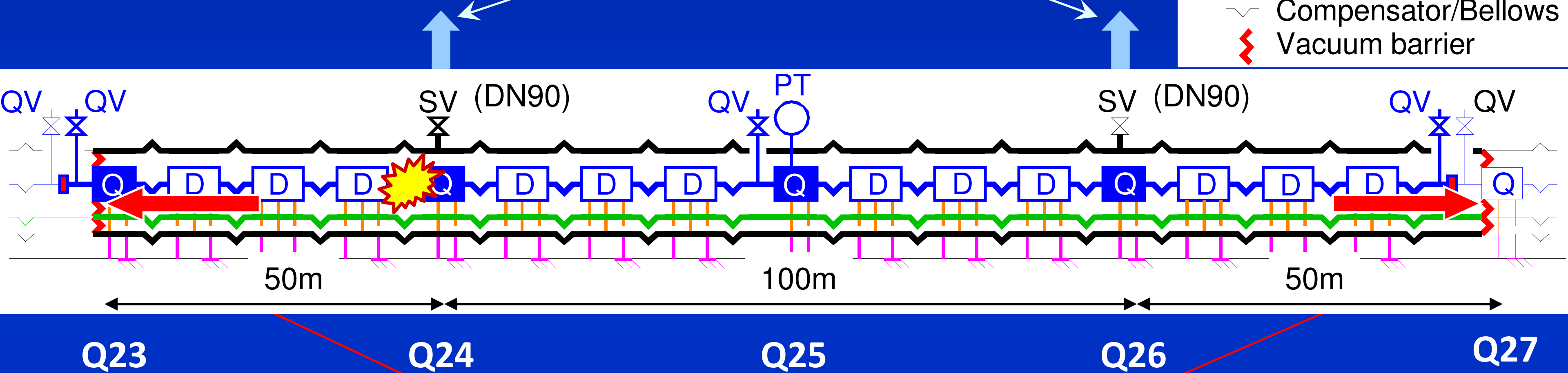




Large pressure wave travelled along the accelerator



Self actuating relief valves opened but could not handle all

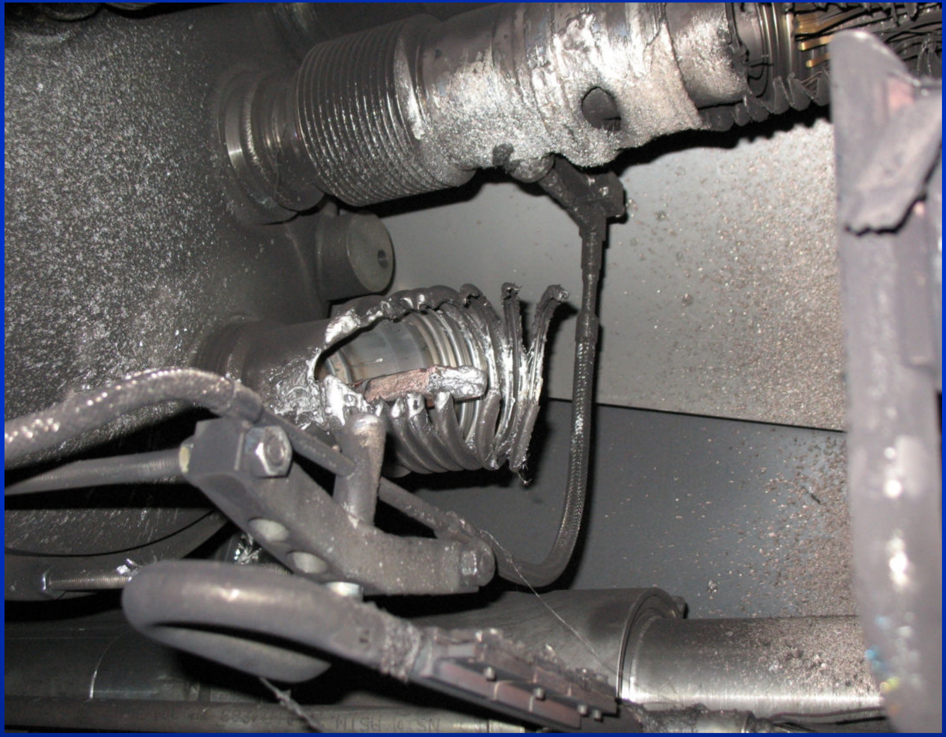


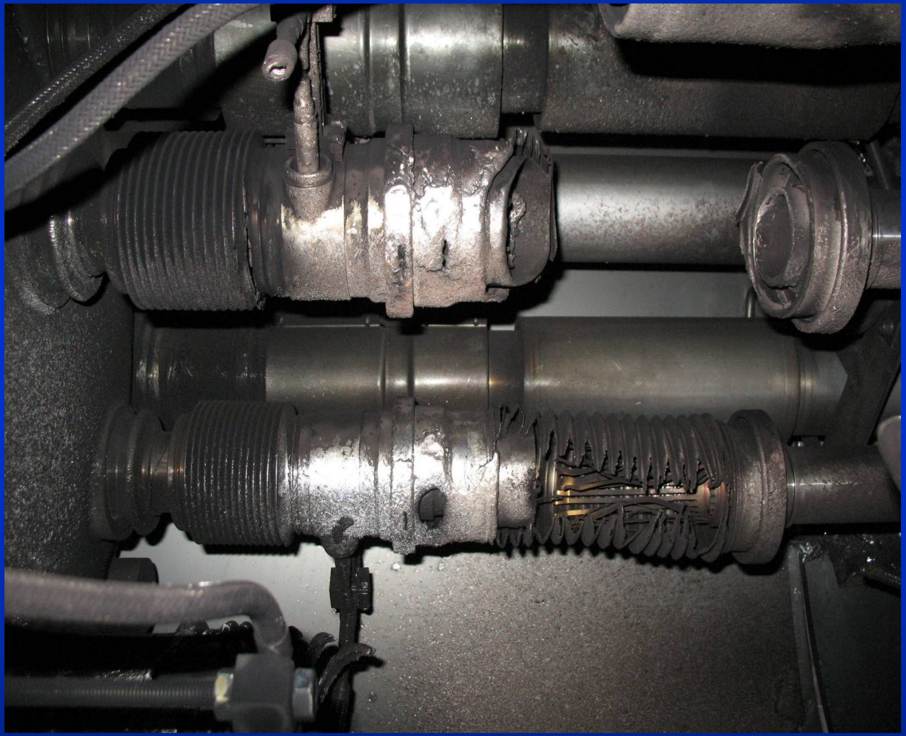
Large forces exerted on vacuum barriers located every 2 cells

Connections to cryogenic line also affected in several places

Beam vacuum system also affected

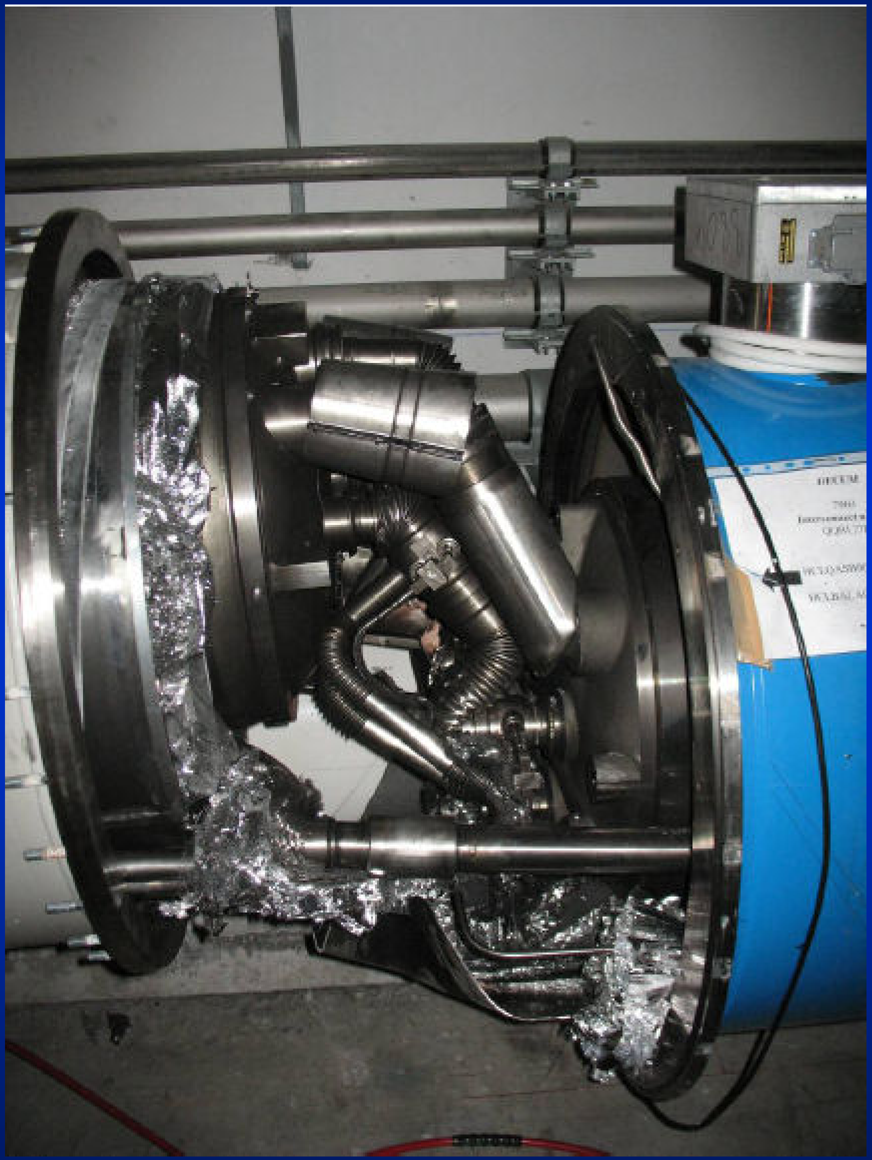
Multi kA electrical arc



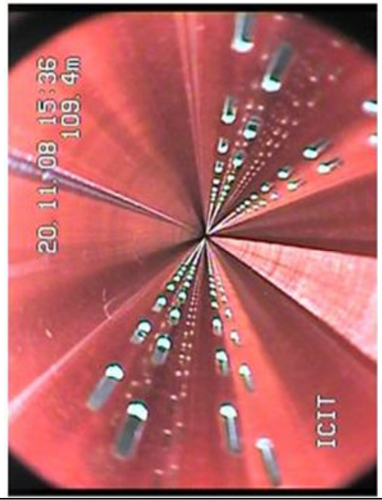
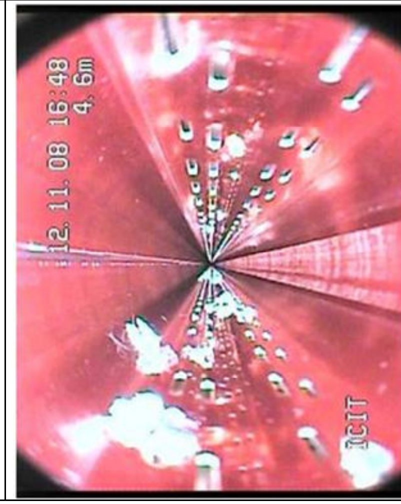
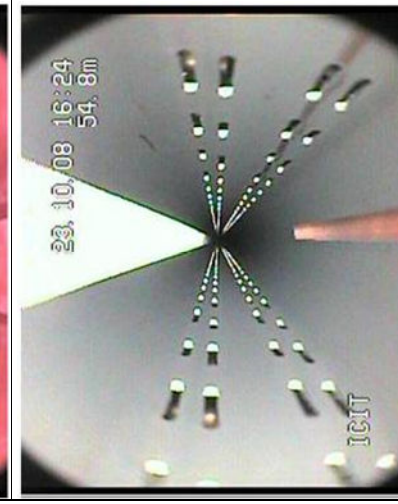


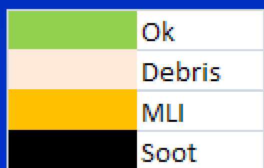
Consequences – Magnets displaced

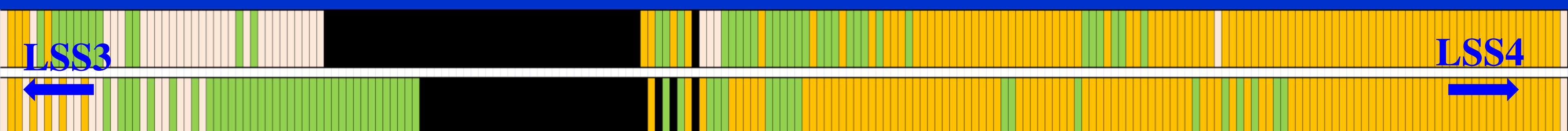
Consequences – Magnets displaced

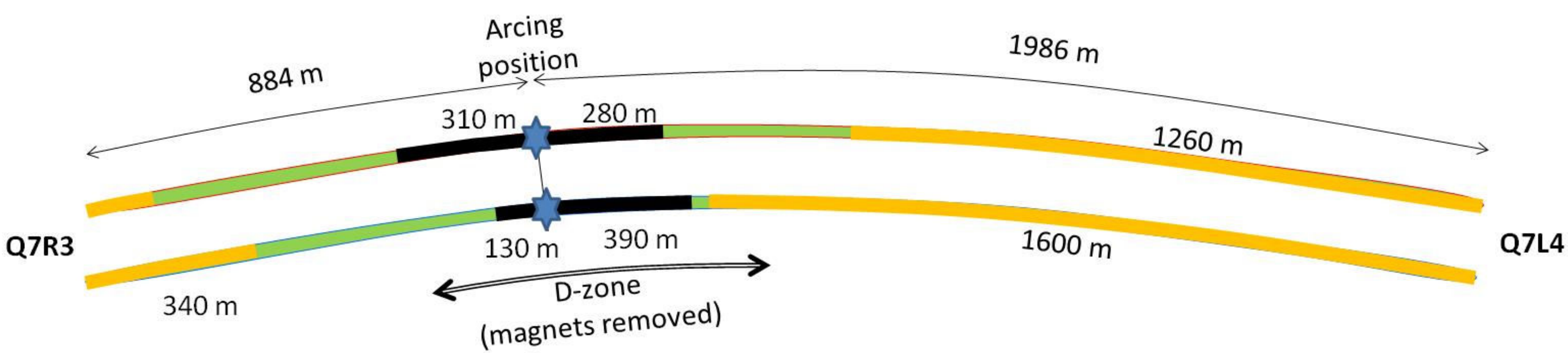


Beam vacuum

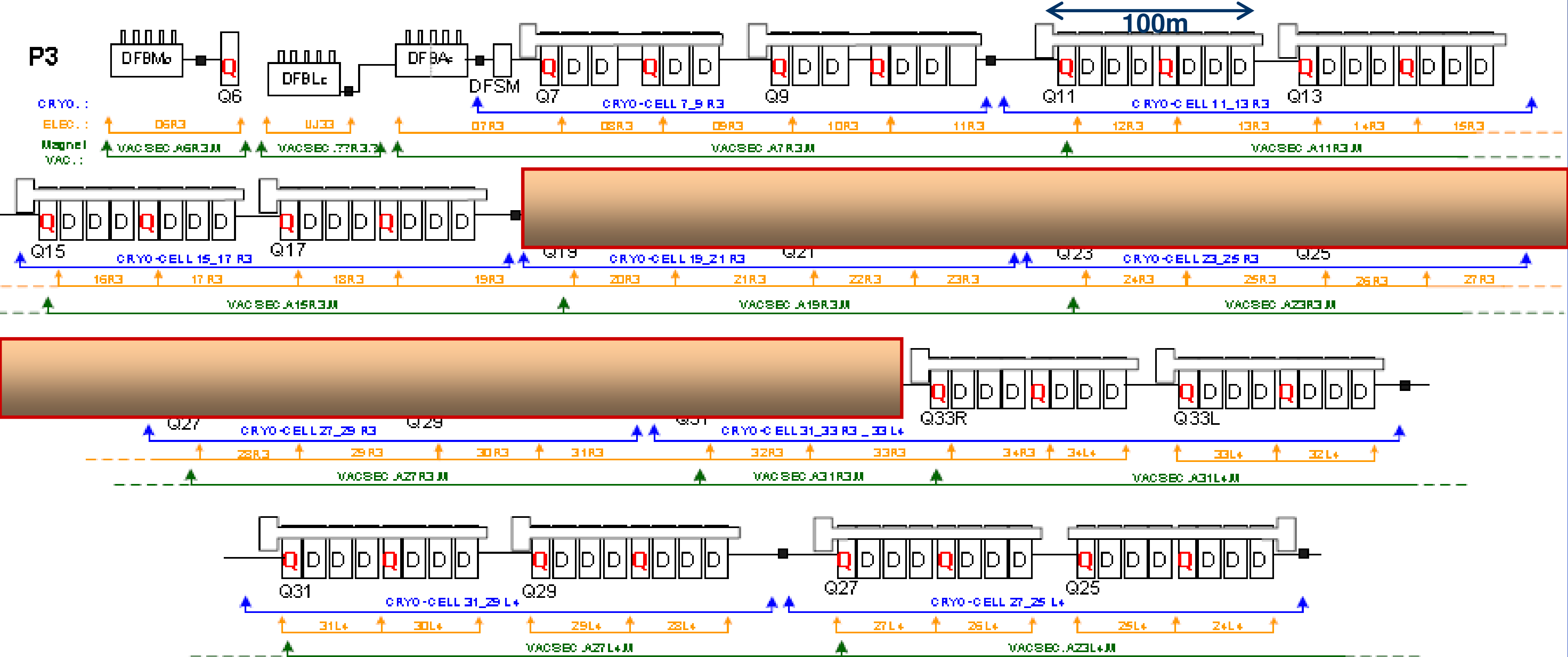
Beam Screen (BS) : The red color is characteristic of a clean copper surface	BS with some contamination by super-isolation (MLI multi layer insulation)	BS with soot contamination. The grey color varies depending on the thickness of the soot, from grey to dark.
		





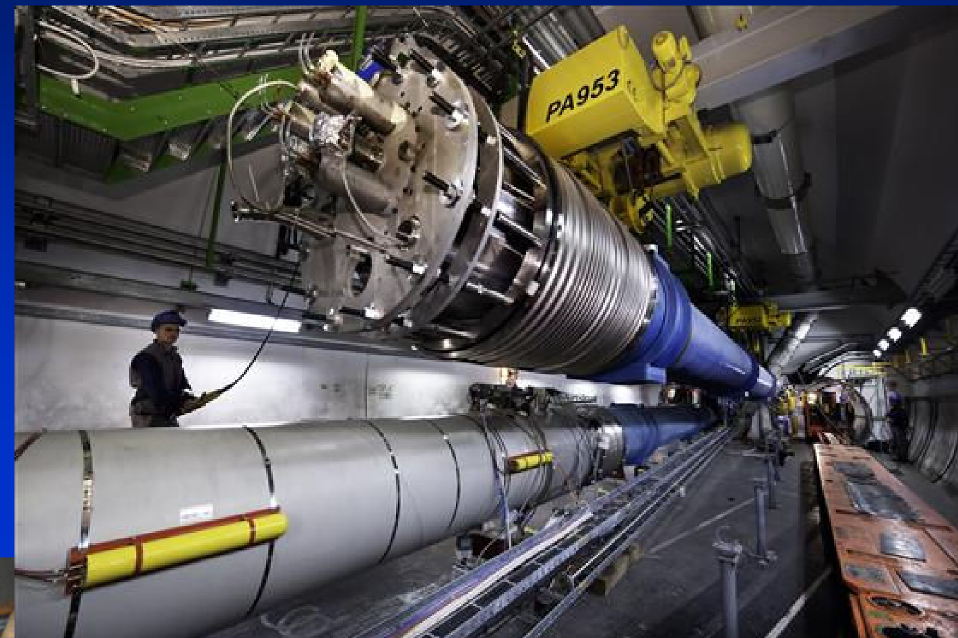


Repair



- Had to treat to lesser or greater degree all magnets Q19 to Q33
- 53 had to be brought to the surface (39 dipoles and 14 quads)
- Replaced with spare or refitted, then retested and reinstalled
- Huge enterprise; last magnet back in mid April
- Not forgetting cleaning the beam pipes
- Then have to align, make all interconnections, cool down, power test

Magnet removal



Underground logistics tricky at best

Special tooling needed for safe transport of damaged magnets

Surface activities

Status of the LHC

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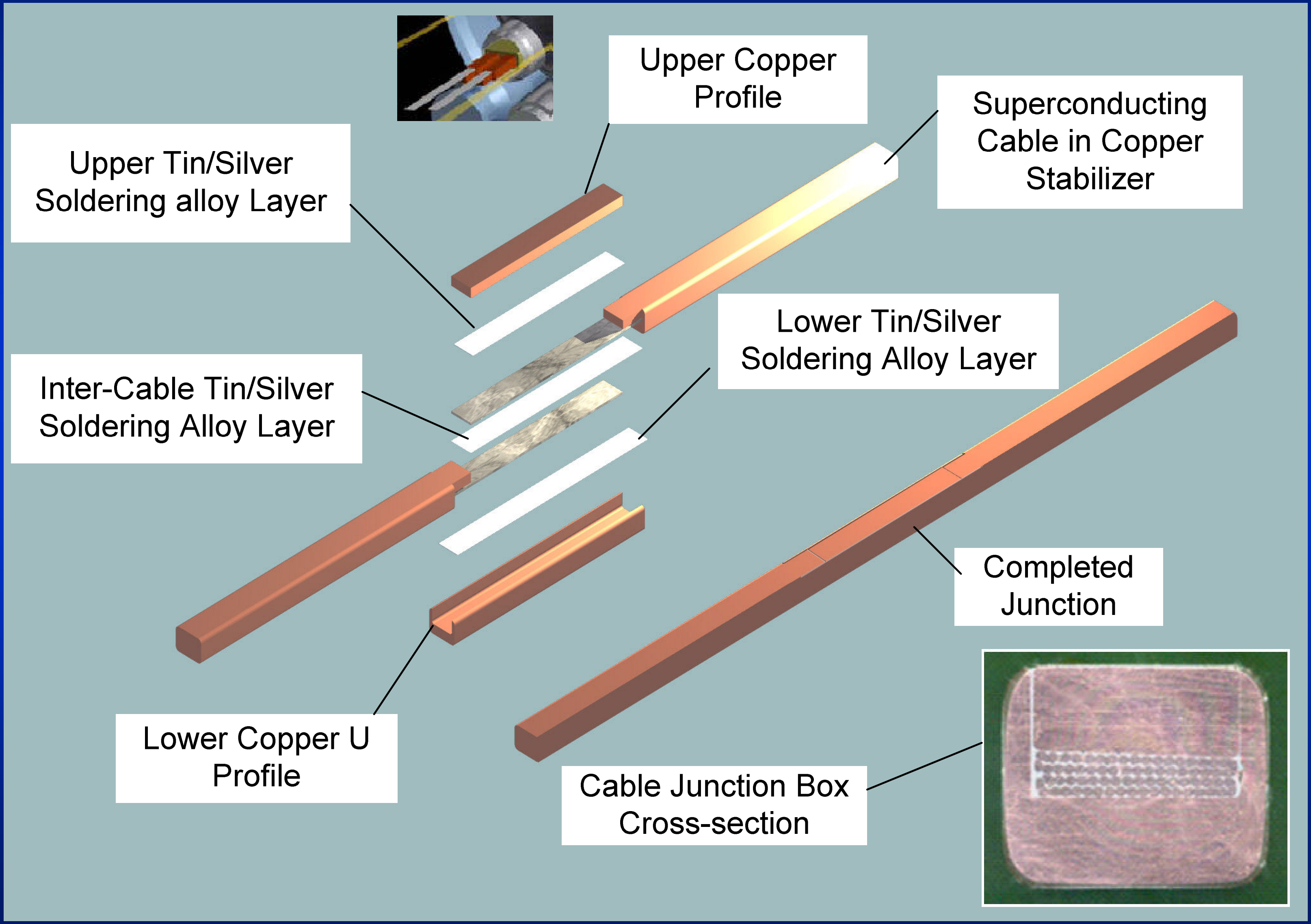
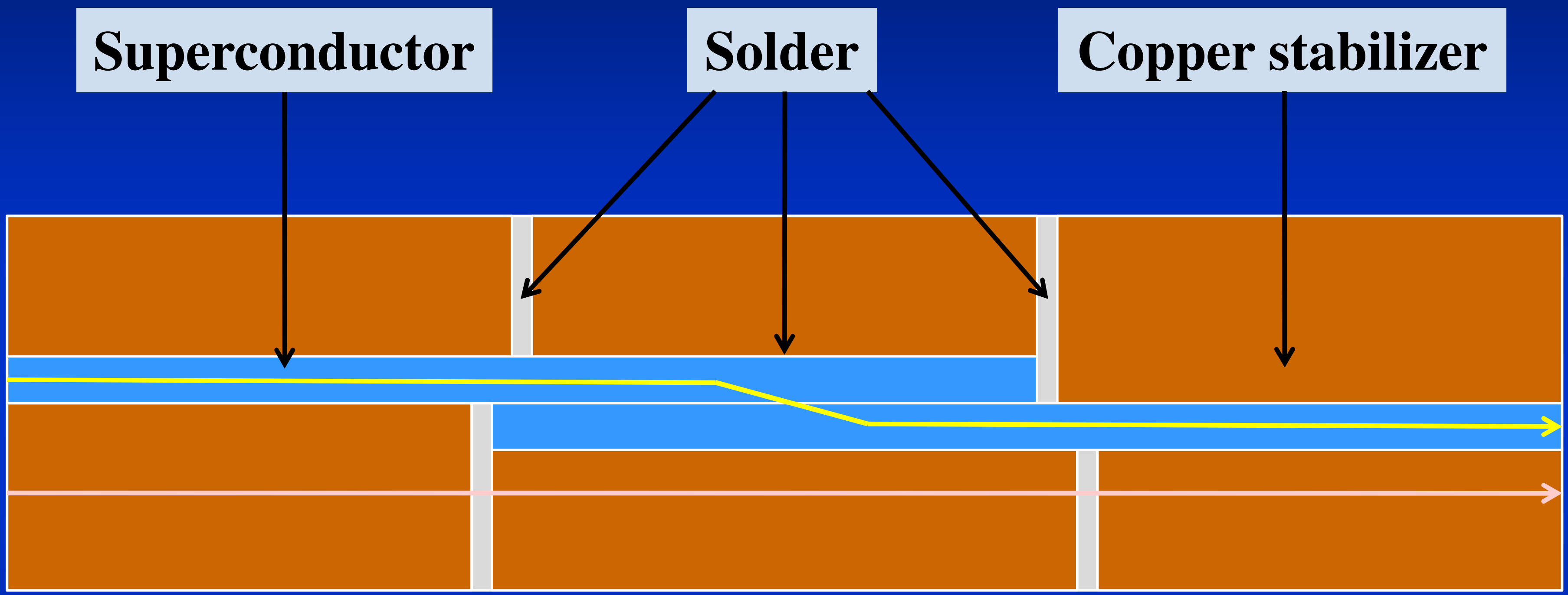
Strategy for restart

Prospects for 2009 2010

Bus bar splice construction



Interconnects



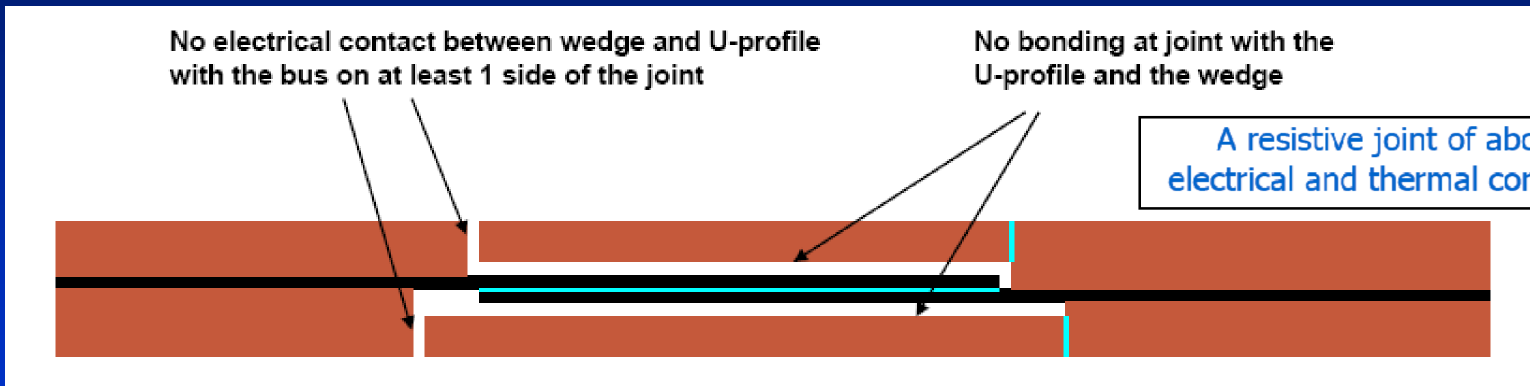
Current flow at 1.9K

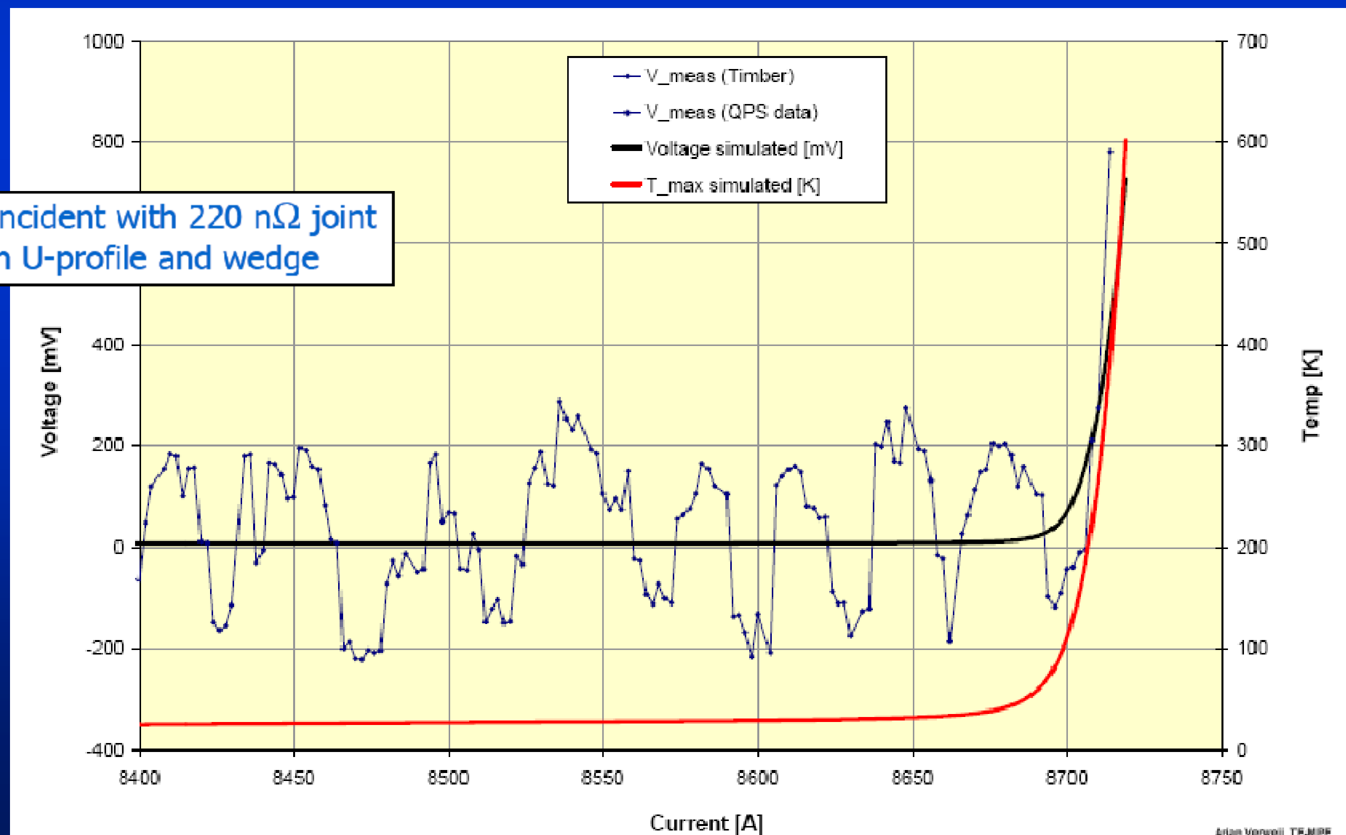
Good joint resistance < 1 nΩ

Current flow after a quench

Good joint resistance < 10 μΩ

Most likely explanation (after tests and simulations)



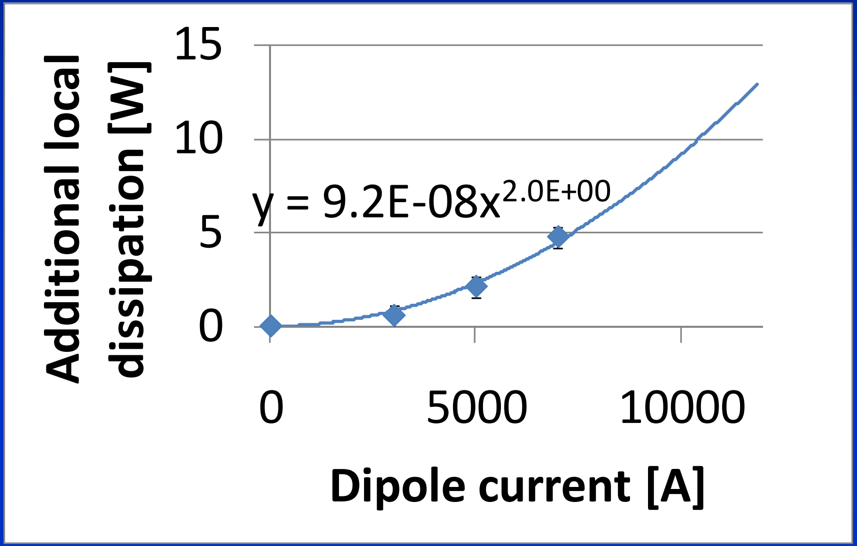


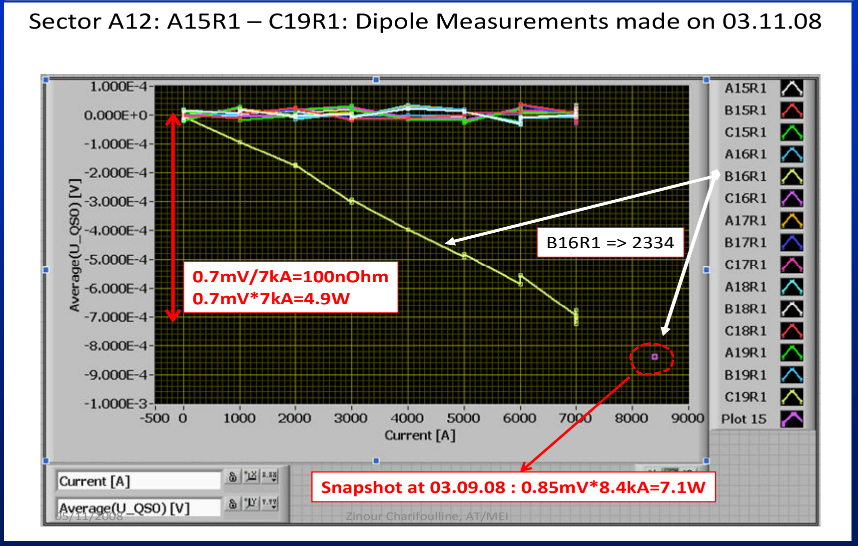
Measured vs simulated incident with 220 nΩ joint
and bad contact with U-profile and wedge

Arjan Verweij, TE-MPE

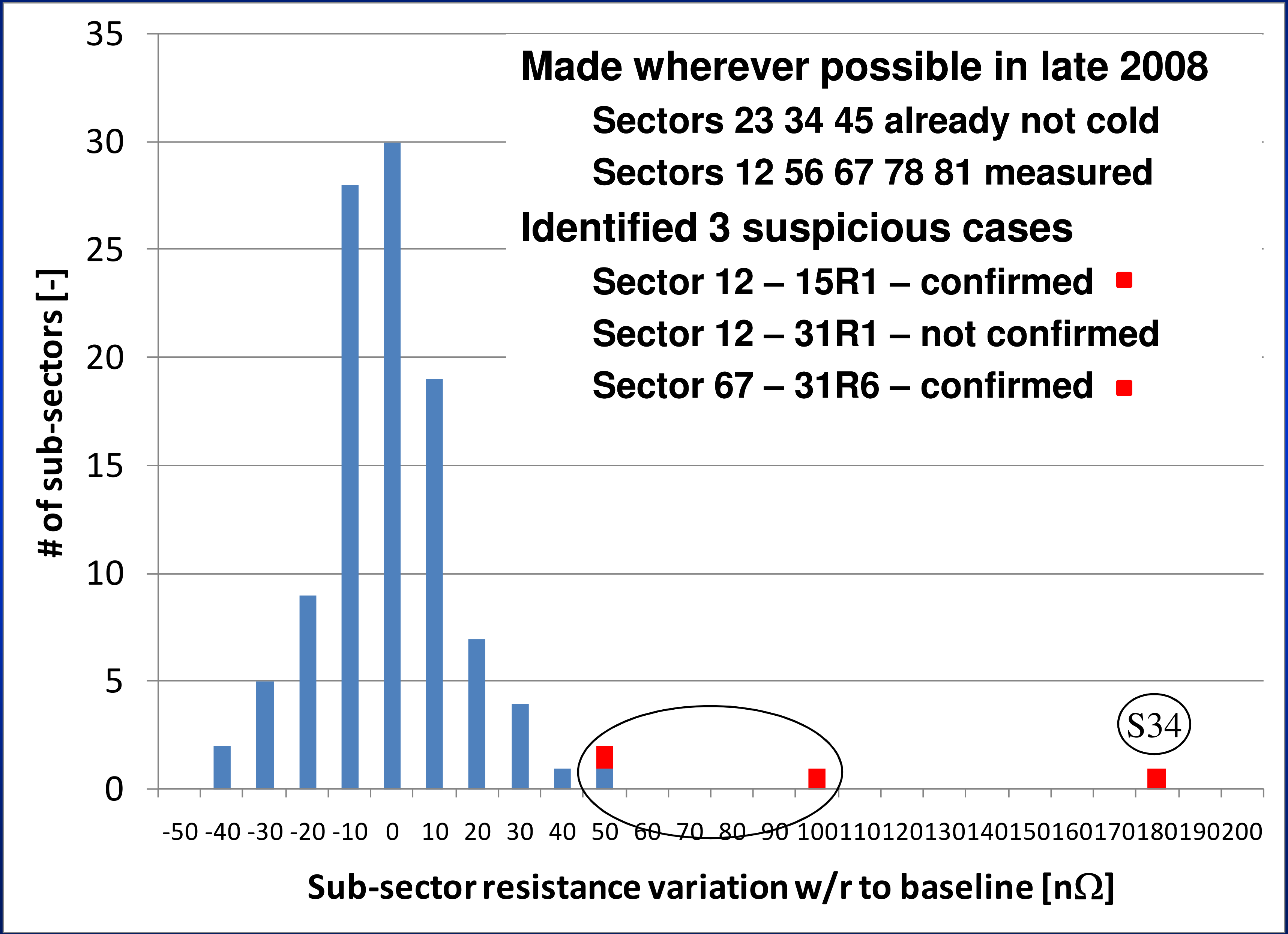
Machine wide investigations at cold Q4 2008

- Systematic scrutiny of all cryogenic data logged during power tests made in 2008
  - Gave pointers to trouble spots
- Controlled calorimetric measurements at cold where possible
  - Measured heat loads indicated problem areas
- Measure electrical resistance in suspect regions
  - Electrical resistance of joints between and inside magnets
- Fix anything obviously very wrong (means warming up)





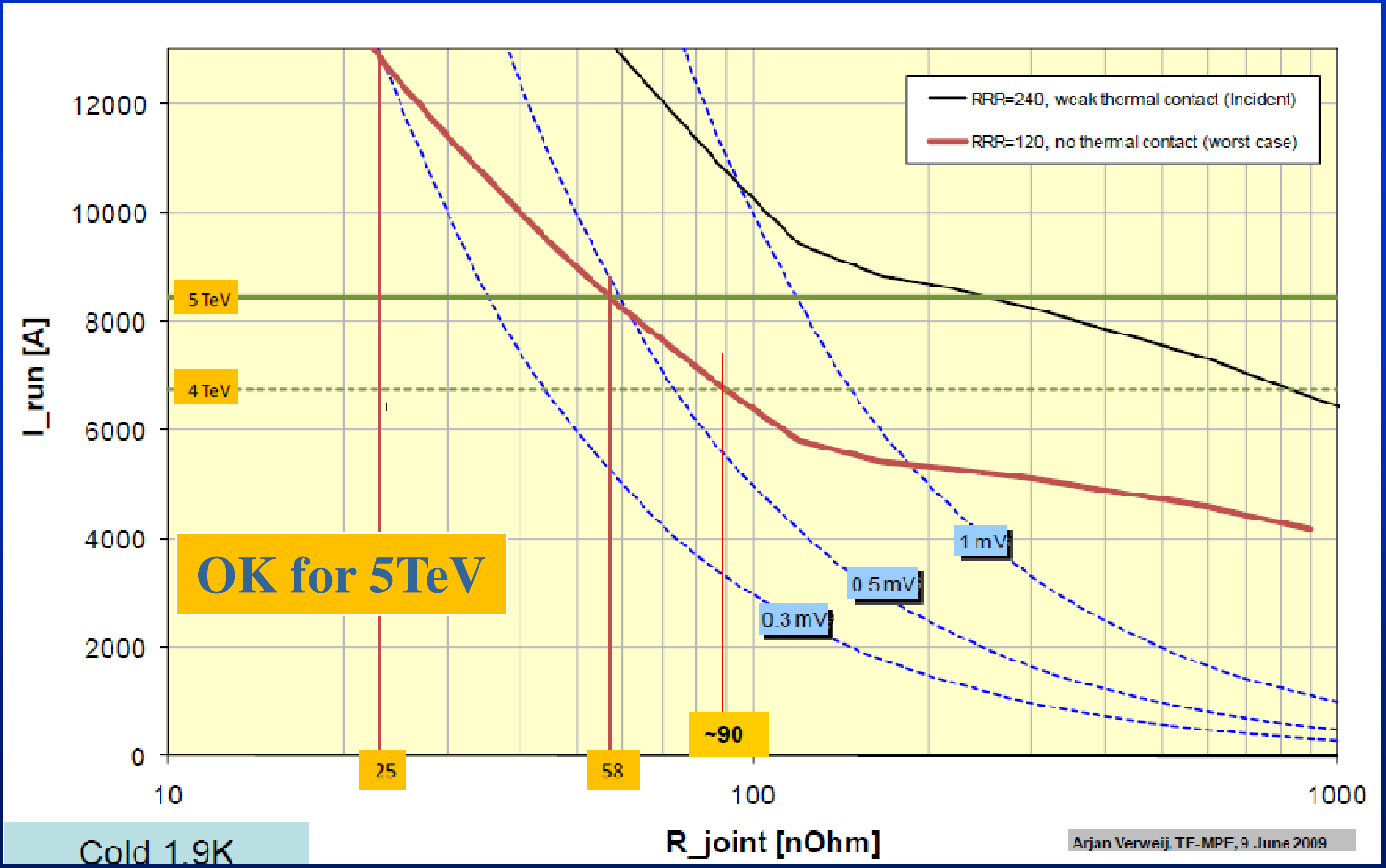
Calorimetric and electrical measurements summary



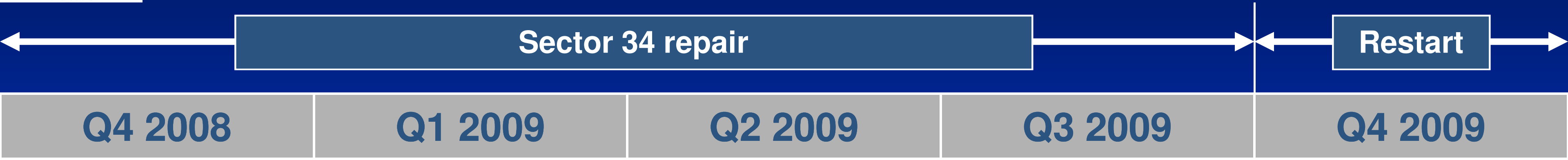
Splices (worst found 100nΩ, S12) (Chamonix)

SPLICES
23 34 45 not measured

- **All in sectors 12 56 67 78 81 fixed above**
  - **40 nΩ (magnets, no bad connection splices found)**
- **QPS threshold of 0.3 mV is needed to protect the dipole bus and the joints in all imaginable conditions**
- **Running at lower currents gives margin while new system is run in**



Decisions Q1 2009



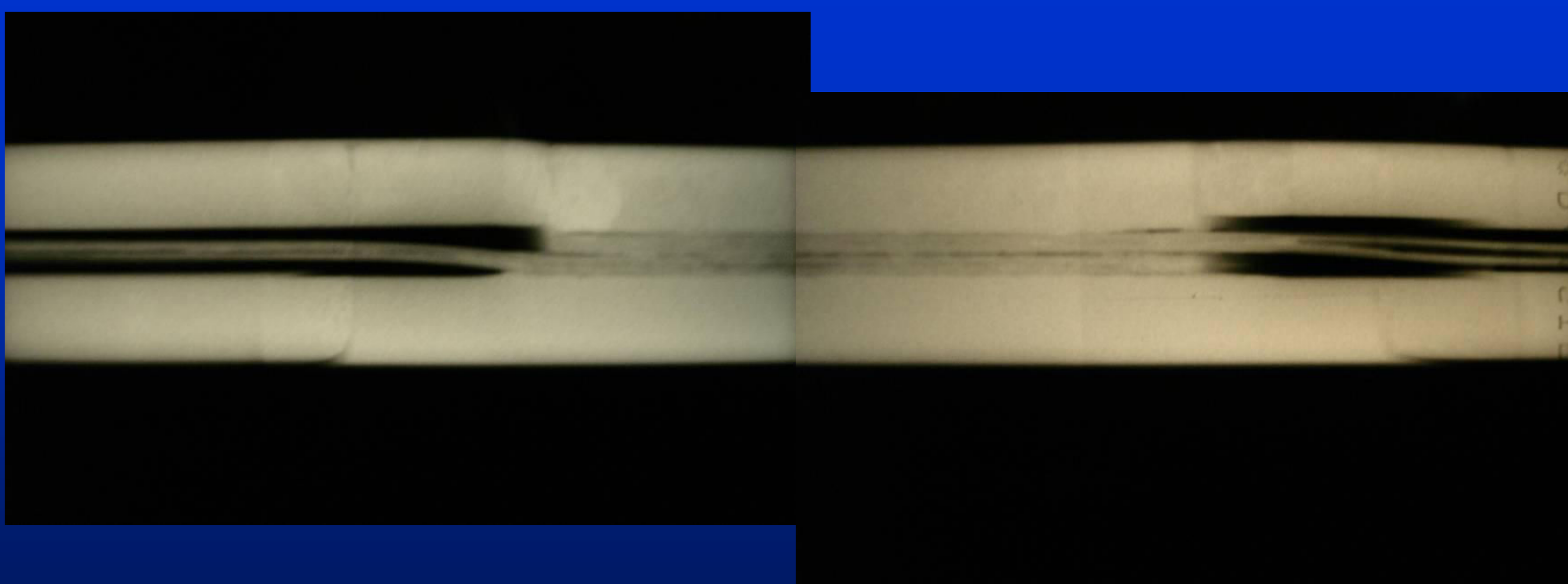
- Decided to warm up in 12 and 67 to replace faulty magnets
- Decided to warm up sector 56 in parallel for other reasons

- Warming up means
  - 3 weeks to get to 300K
  - Repair work
  - ELQA and other issues
  - 6 weeks to get to 2K

	Q4 2008	Q1 2009
12	Cold	Cold → Warm
23	< 100K	< 100K
34	Warm	Warm
45	< 100K	< 100K
56	Cold	Cold → Warm
67	Cold	Cold → Warm
78	Cold	< 100K
81	Cold	< 100K

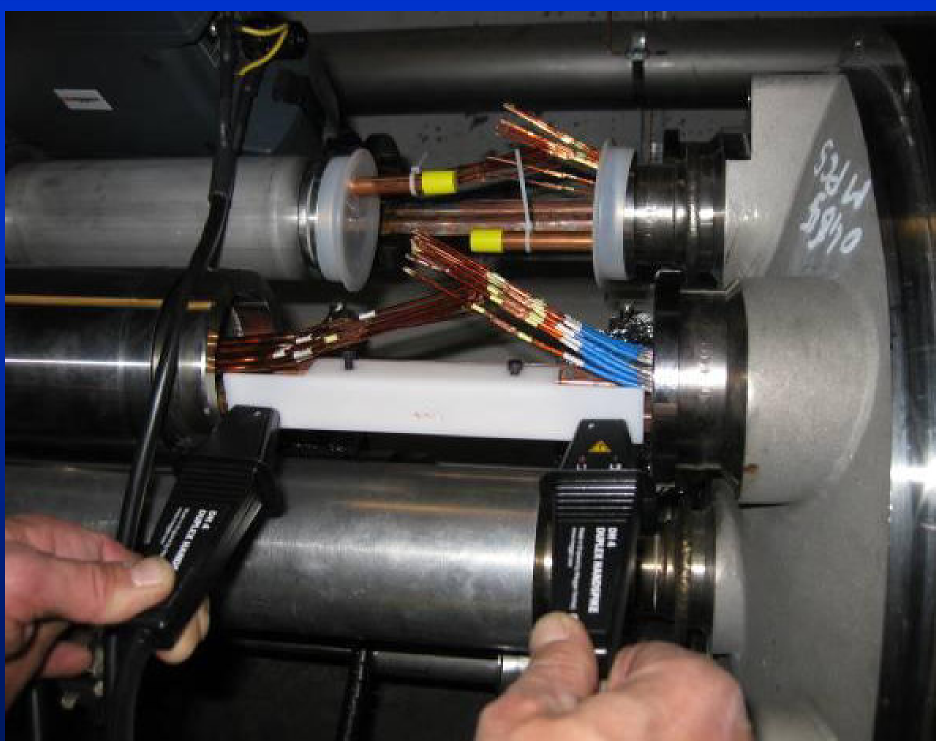
Investigations in sector 34 Q1 2009

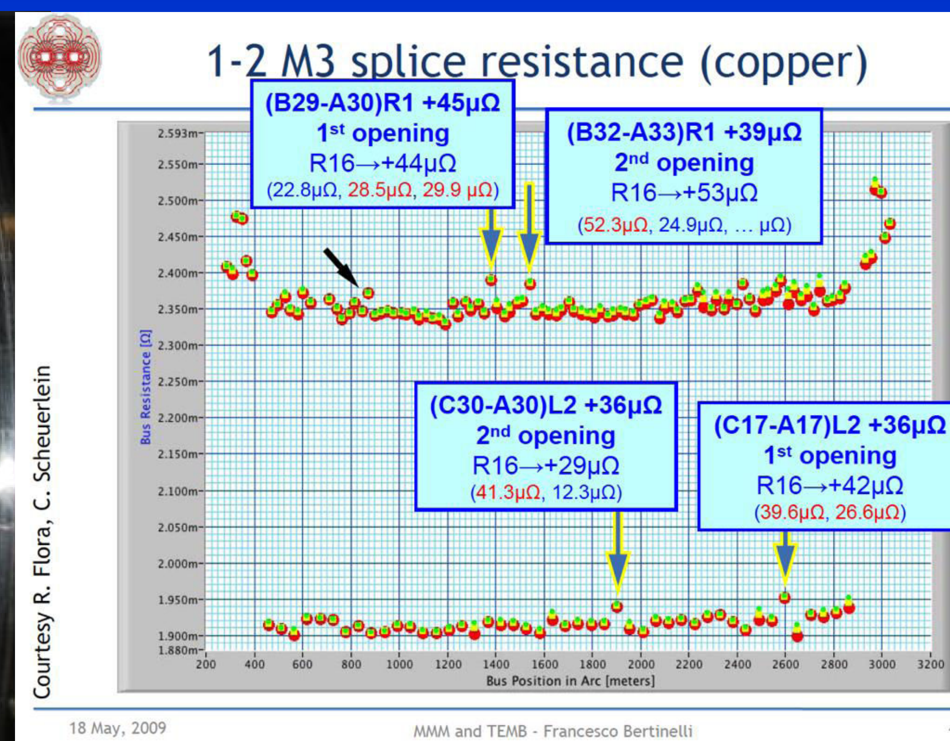
Bad surprise after gamma-ray imaging of the joints
Void is present in bus extremities because SnAg flowed out during soldering of the joint



Machine wide investigations Q2 2009

- Electrical measurements at warm on sectors 12 34 56 67
- Confirms new problem with the copper stabilizers
  - Non-invasive electrical measurements to show suspicious regions
    - Several bad regions found
  - Open and make precise local electrical measurements
    - Several bad stabilizers found (30μΩ to 50μΩ) and fixed





Machine wide investigations Q3 2009

Sector 34 repair | Restart

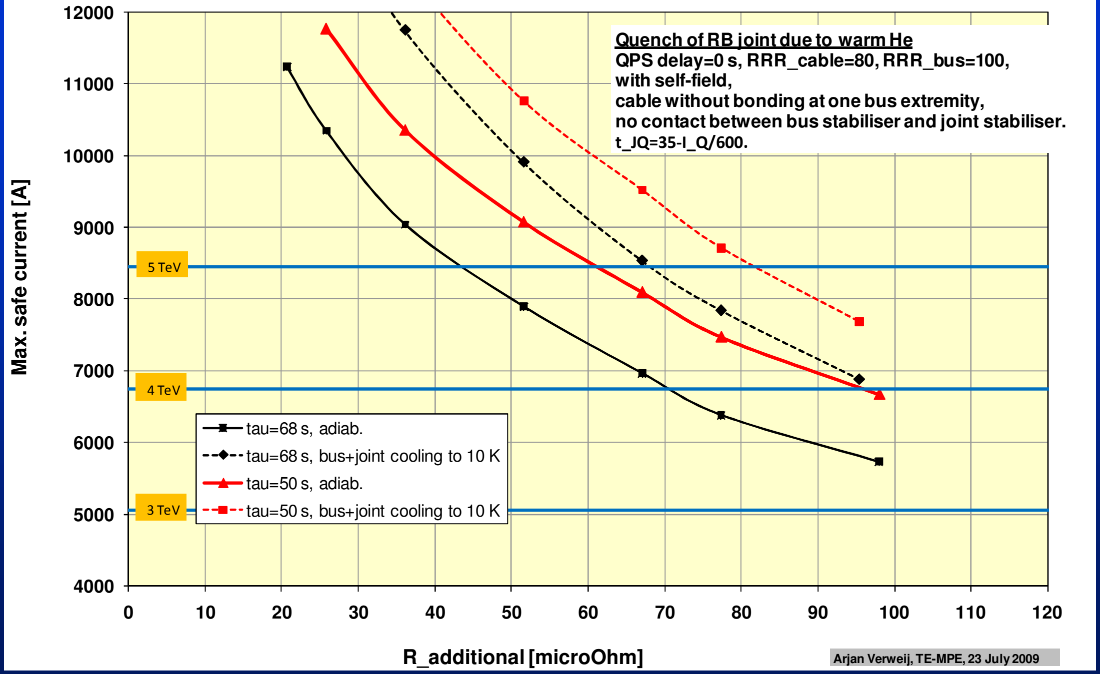
Q4 2008	Q1 2009	Q2 2009	Q3 2009	Q4 2009

- Electrical measurements at 80K on sector 45
  - Suspicious region found
  - Decided in June to warm up sector 45 to check
  - Problem confirmed and fixed
  - Other bad stabilizers found (~ 50μΩ) and fixed
- Electrical measurements at 80K on sectors 23 78 81
- Nothing significant found (but data in 78 and 81 very noisy)

	Q4 2008	Q1 2009	Q2 2009	Q3 2009	Q4 2009
12	Cold	Cold → Warm	Warm	Warm → Cold	Cold
23	< 100K	< 100K	< 100K → Cold	Cold → 80K → Cold	Cold
34	Warm	Warm	Warm	Warm → Cold	Cold
45	< 100K	< 100K	< 100K → Warm	Warm → Cold	Cold
56	Cold	Cold → Warm	Warm	Warm → Cold	Cold
67	Cold	Cold → Warm	Warm	Warm → Cold	Cold
78	Cold	< 100K	< 100K → 80K	80K → Cold	Cold
81	Cold	< 100K	< 100K → 80K	80K → Cold	Cold

Modeling and outcome

- Simulate effects of a bad copper stabilizer joint
- Input data needed
  - RRR 100 Conservative
  - Worst joint left 90µΩ Conservative
  - Time needed for energy extraction (easily modified)
  - Conditions at the joint when quench occurs
    - Essentially determined by quench propagation and cooling



68s OK for 3.5 TeV

51s OK for 4 TeV

Status of the LHC

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Prospects for 2009 2010

Quench Protection System upgrade

- New QPS to provide
  - Protection against symmetric quenches (problem noticed in summer 08)
  - Local bus bar measurements capable of detecting bad splices

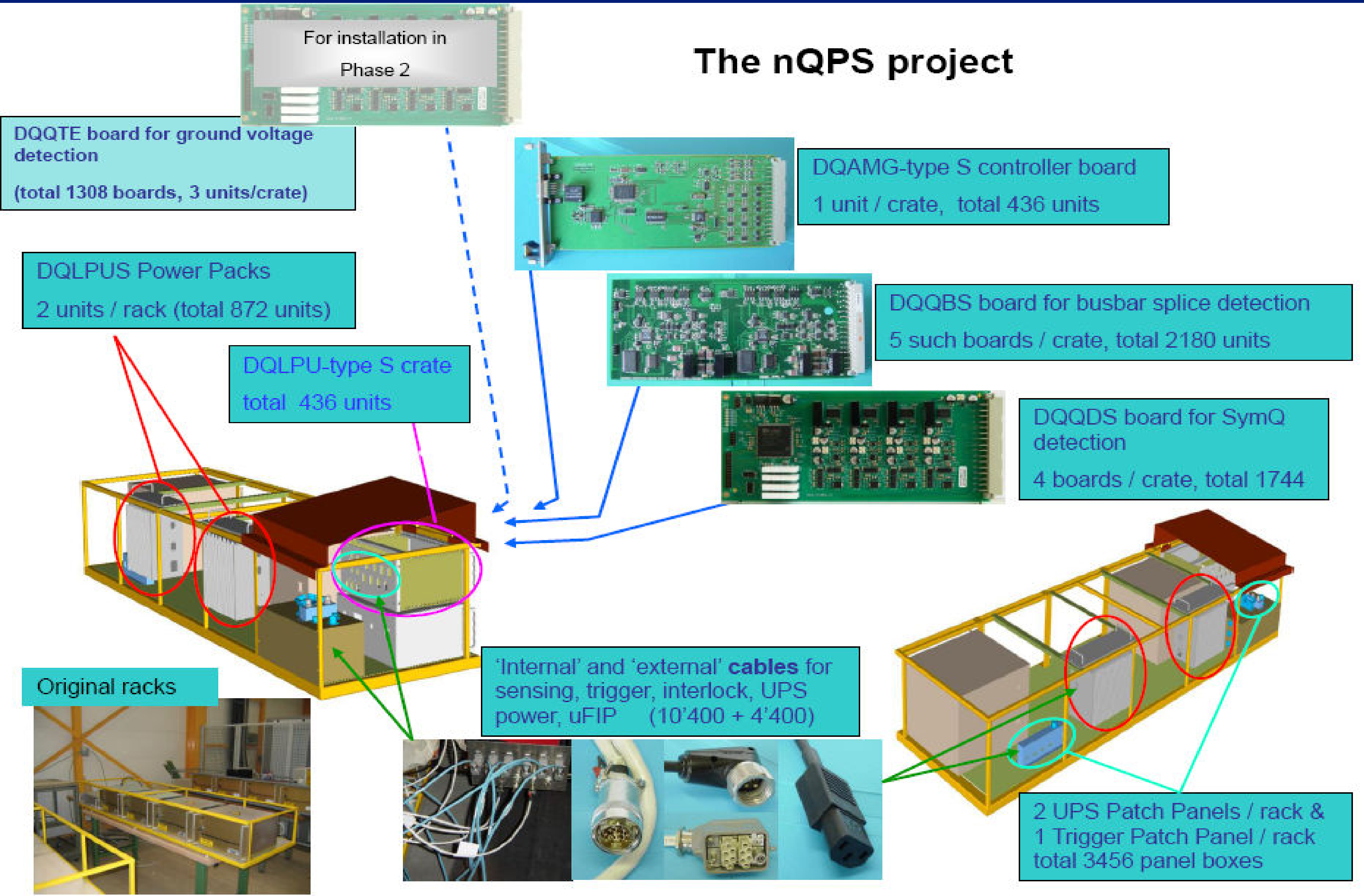
- Will also provide
  - Precision measurements of the joint resistances at cold (sub-nΩ range) of every busbar segment
    - complete mapping of the splice resistances (the bonding between the superconducting cables)
  - The basic monitoring system for future determination of busbar resistances at warm (min. 80 K)
    - measure regularly the continuity of the copper stabilizers

- Huge task
  - Has to be working before repowering (recommendation of external review)
  - On the critical path for restart
  - Will require extensive testing

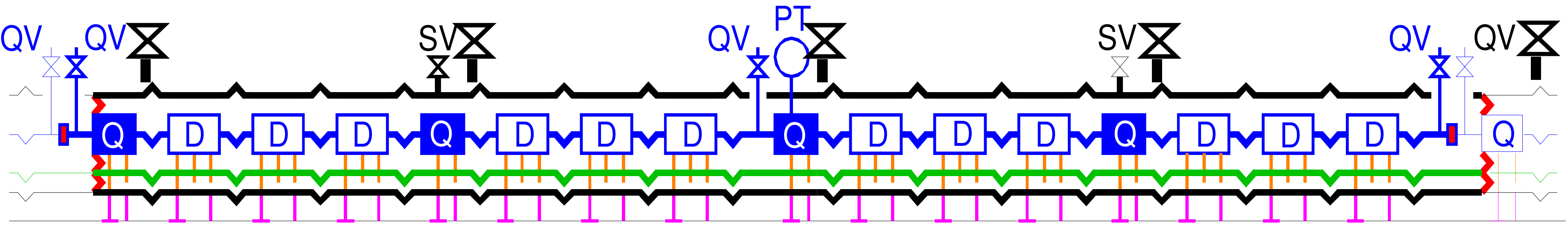
LHC Enhanced Quench Protection System Review

Quench Protection System upgrade

The nQPS project

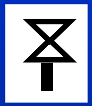


Mitigation – Relief valves arc SSS

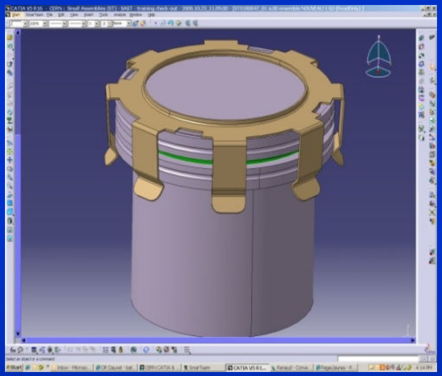


>1000 relief valves to install on existing flanges

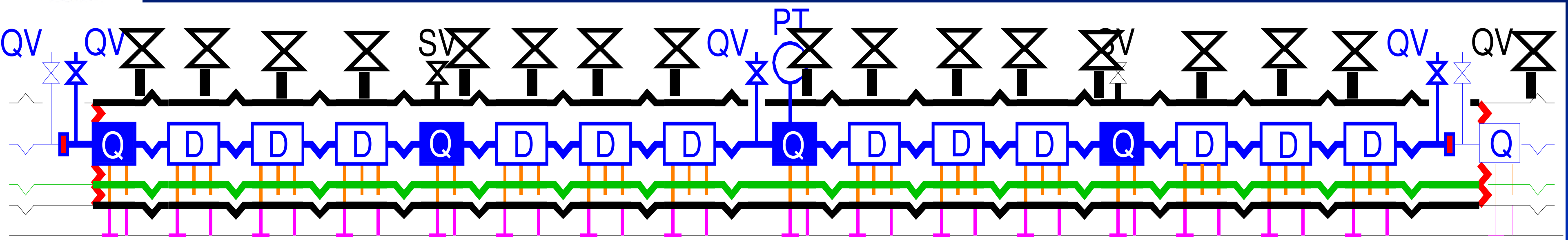
- **Keep existing 2 DN90 relief devices**
- **Per vacuum sub-sector**
  - **Mount relief springs on 5 DN100 vac. flanges**
  - **Mount relief springs on 8 DN100 BPM flanges**
  - **Mount relief springs on 4 DN63 cryo.instr. Flanges**



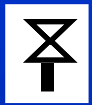
- **Can be done at cold**

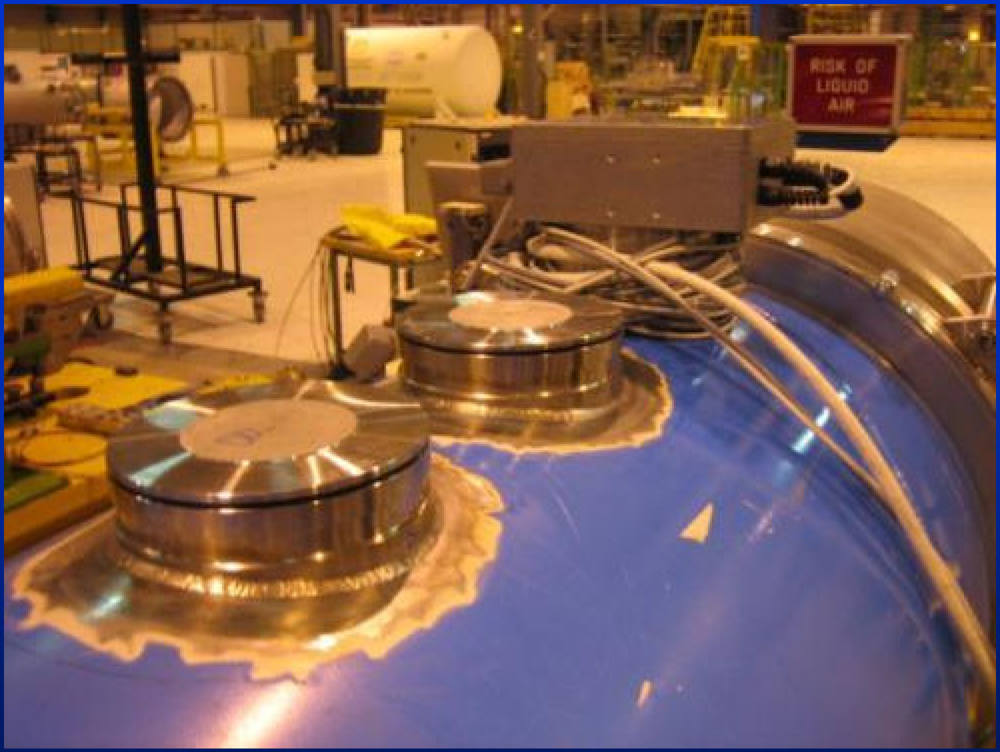


Mitigation – Relief valves arc Dipoles



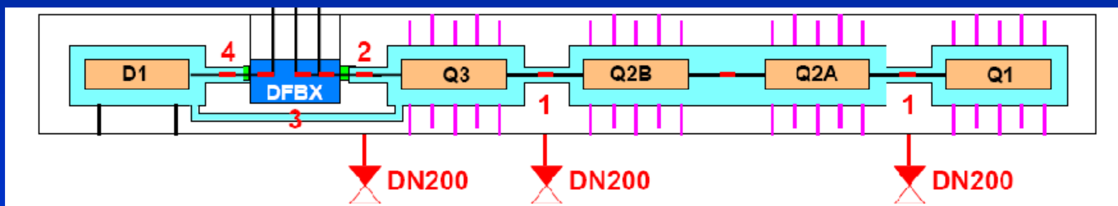
>1200 relief valves to install, each requires cutting

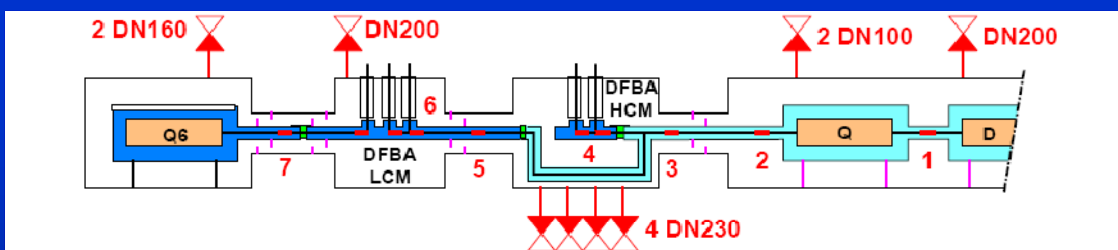
- Keep existing 2 DN90 relief devices
- Per vacuum sub-sector
  
  - Mount relief springs on 4 DN100 blank flanges
  - Add 12 DN200 new relief devices (1 per dipole)
  - Some cases need 2
- Can only be done at warm
  - 12 34 56 67

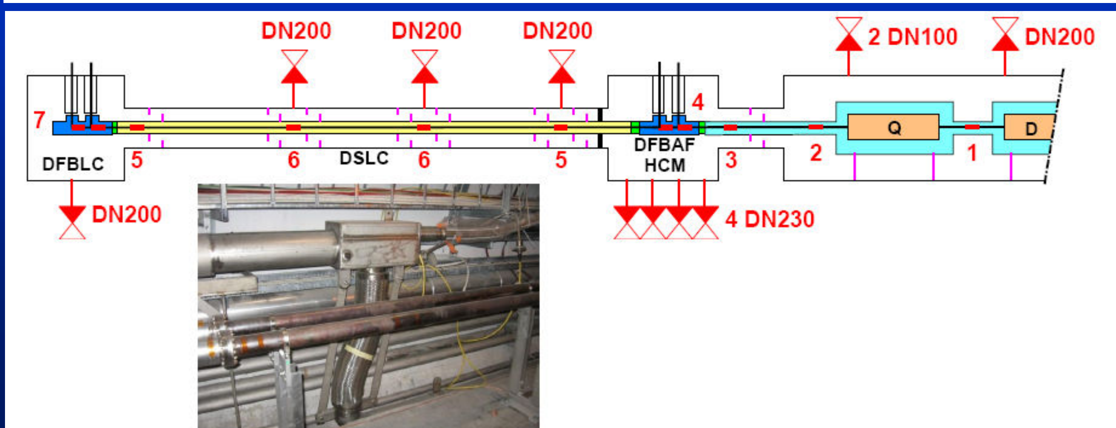


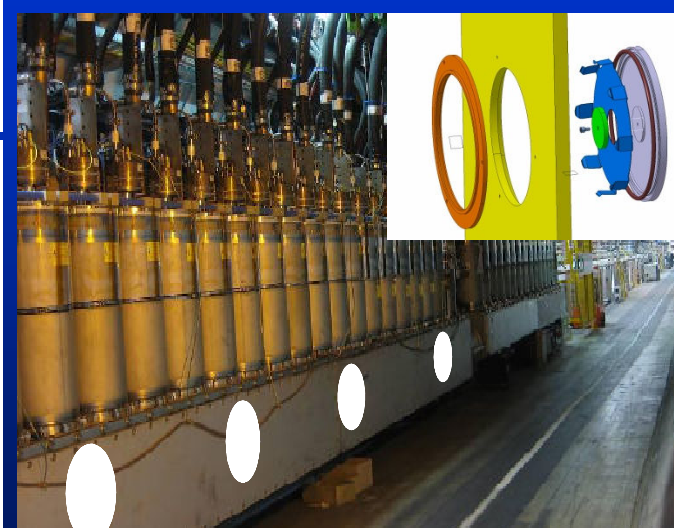
Mitigation – Relief valves Long Straight Sections

> 200 relief valves to install

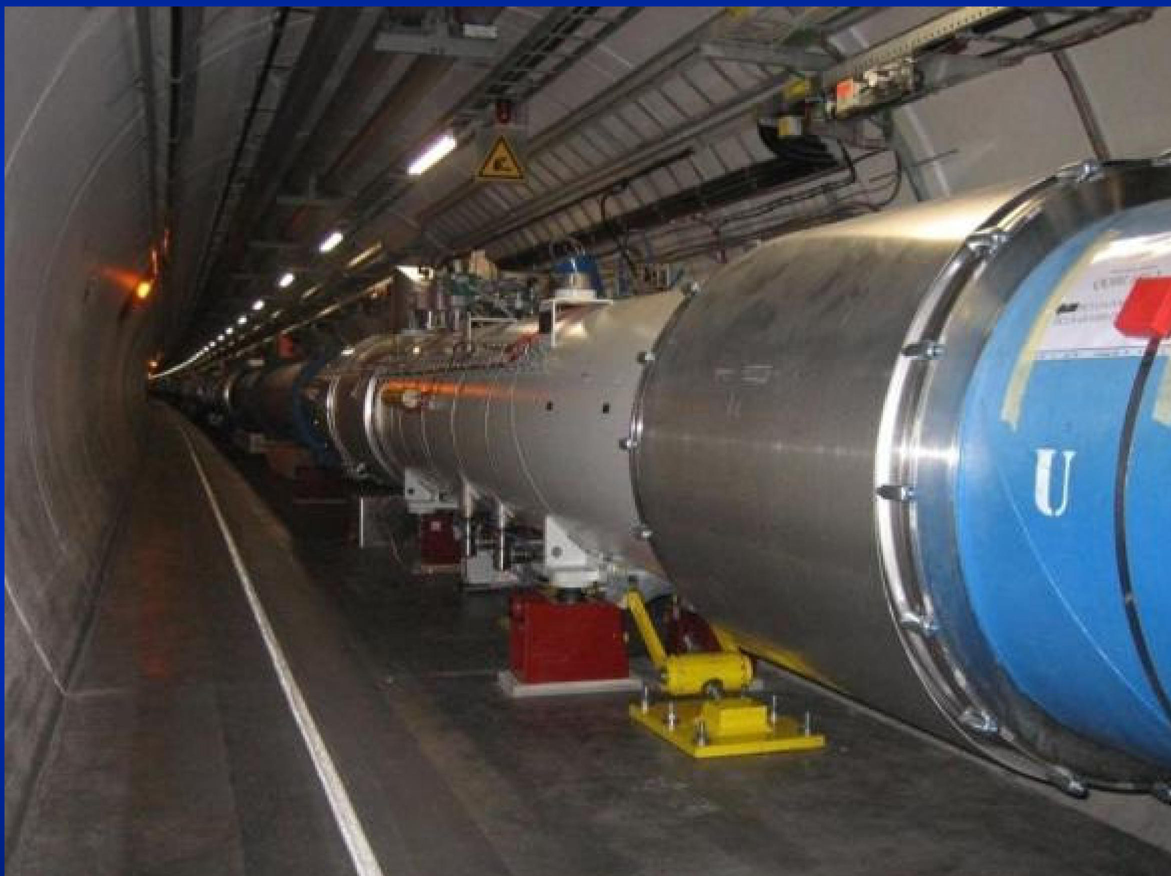








Mitigation – Anchoring



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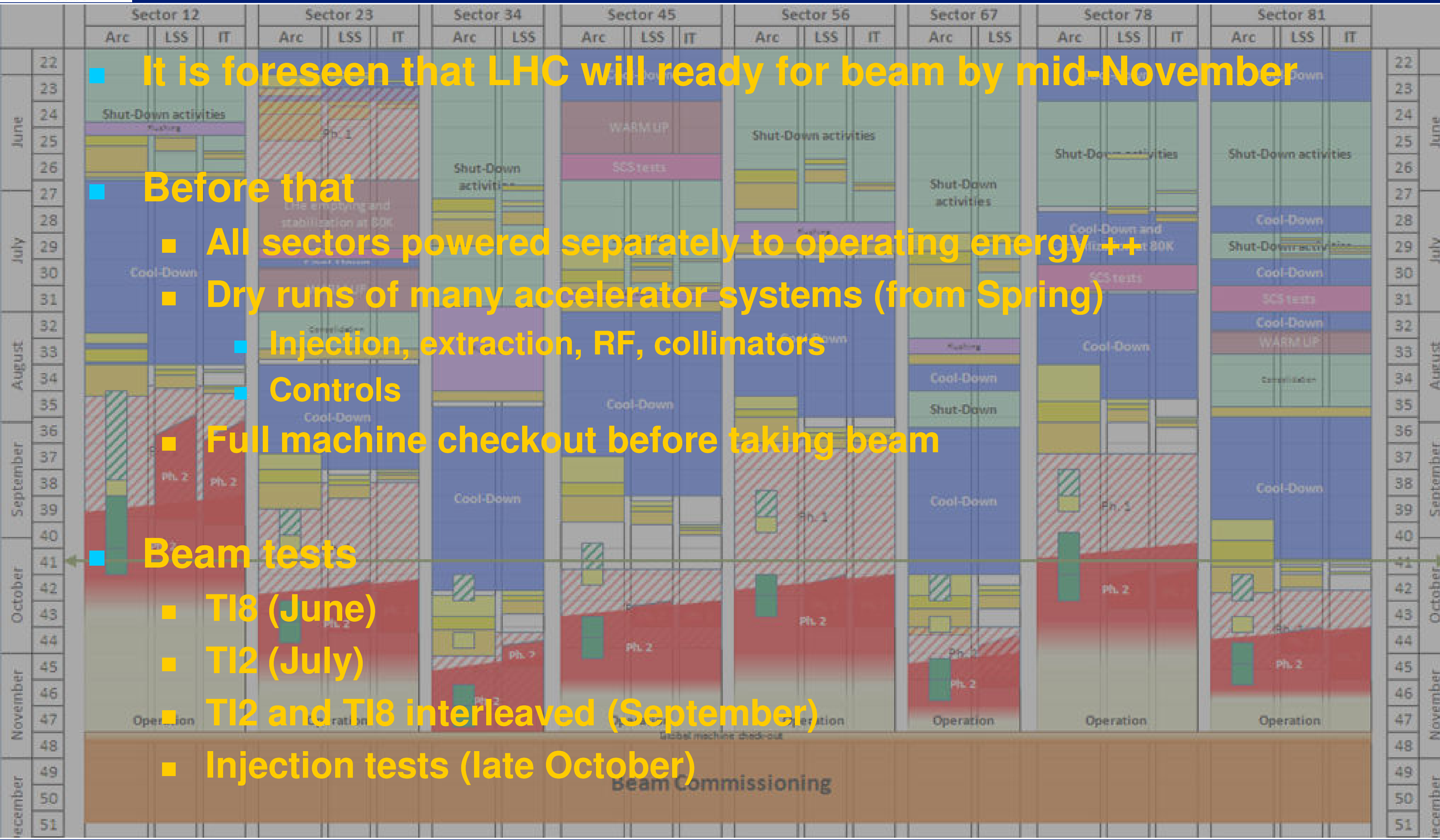
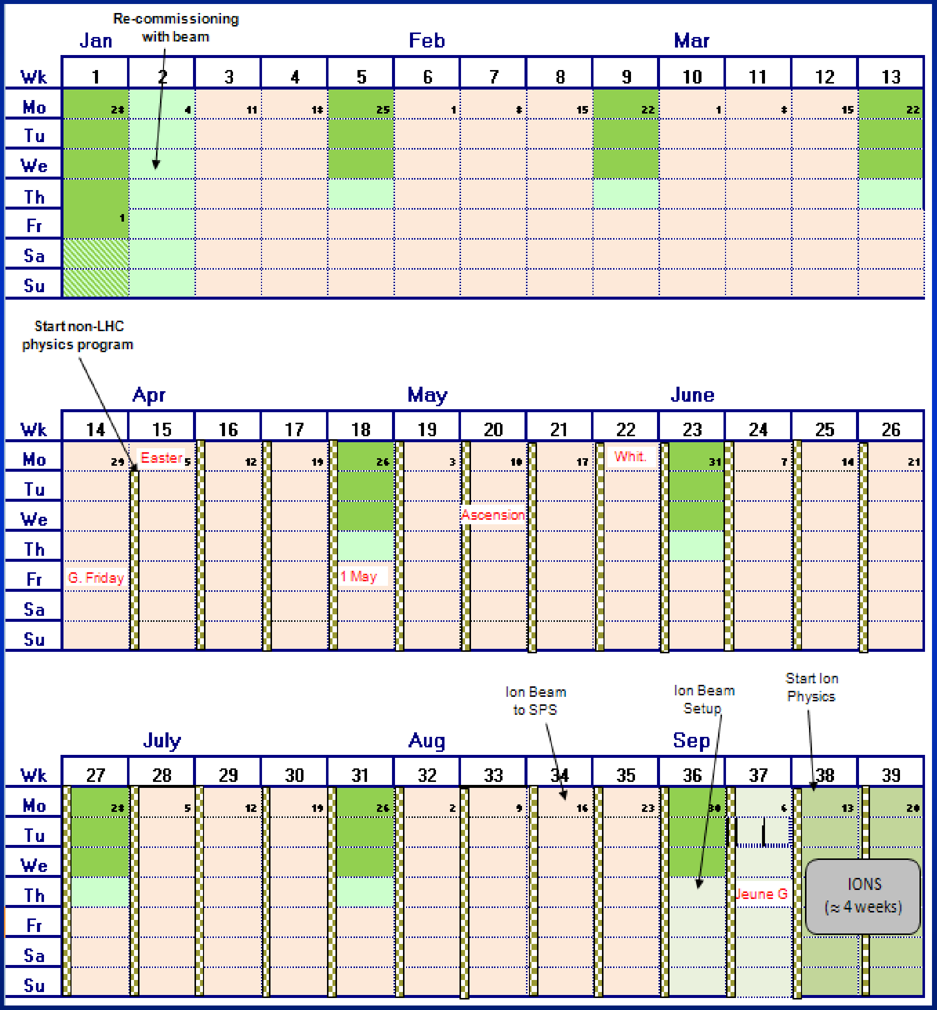
Schedule

- It is foreseen that LHC will ready for beam by mid-November
- Before that
  - All sectors powered separately to operating energy ++
  - Dry runs of many accelerator systems (from Spring)
    - Injection, extraction, RF, collimators
    - Controls
  - Full machine checkout before taking beam
- Beam tests
  - TI8 (June)
  - TI2 (July)
  - TI2 and TI8 interleaved (September)
  - Injection tests (late October)



Running through winter

- There will be no long shutdown 2009/10
  - Regular scheduled stops of LHC (as already foreseen)
  - Essential maintenance of injectors in the shadow of this
- Decided to stop over the end of the year 2009
  - Machine will be nowhere near operational
  - Would need full expert coverage in all areas
  - Standby from around December 19th to January 4th
  - Need to define standby conditions



Beam – recall 2008

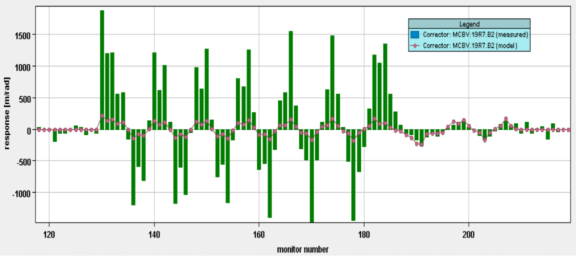
Commissioning plan 2008	
1	Injection and first turn
2	Circulating beam
3	450 GeV – initial commissioning
4	450 GeV – detailed optics studies
5	450 GeV increase intensity
6	450 GeV - two beams
7	450 GeV - collisions
8a	Ramp - single beam
8b	Ramp - both beams
9	Top energy checks
10a	Top energy collisions
11	Commission squeeze
10b	Set-up physics - partially squeezed

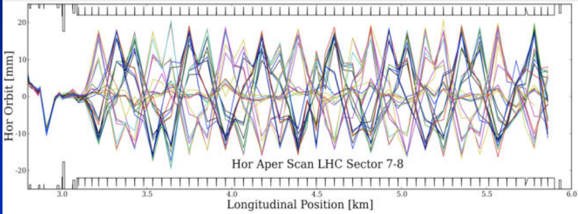
Lot done in 3 days

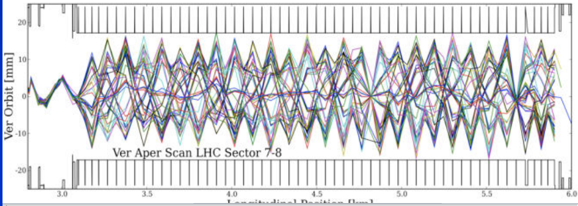
(after weeks of meticulous preparation)

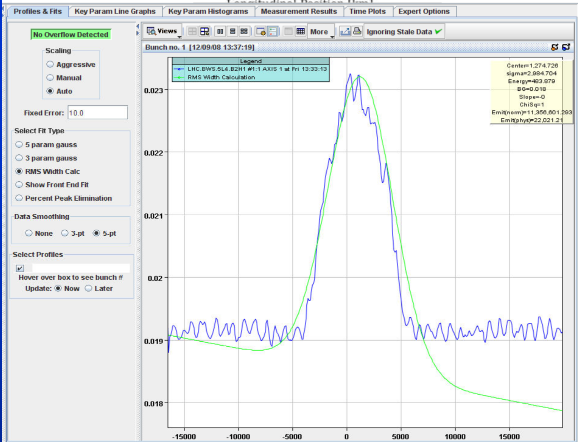
Settings
Controls
Instrumentation
RF capture
System commissioning
Aperture
Optics

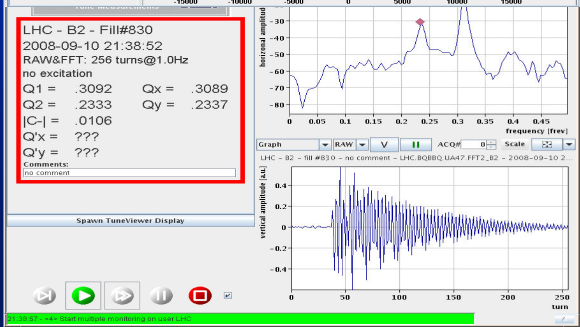
Working with very safe beam
Beam machine protection systems barely needed
System commissioning just started











Beam – mapping 08 onto 09

Key will be to increase intensity and energy
Move deep into Machine Protection territory
Phased approach using safe beams
For operational efficiency will also use safer beams

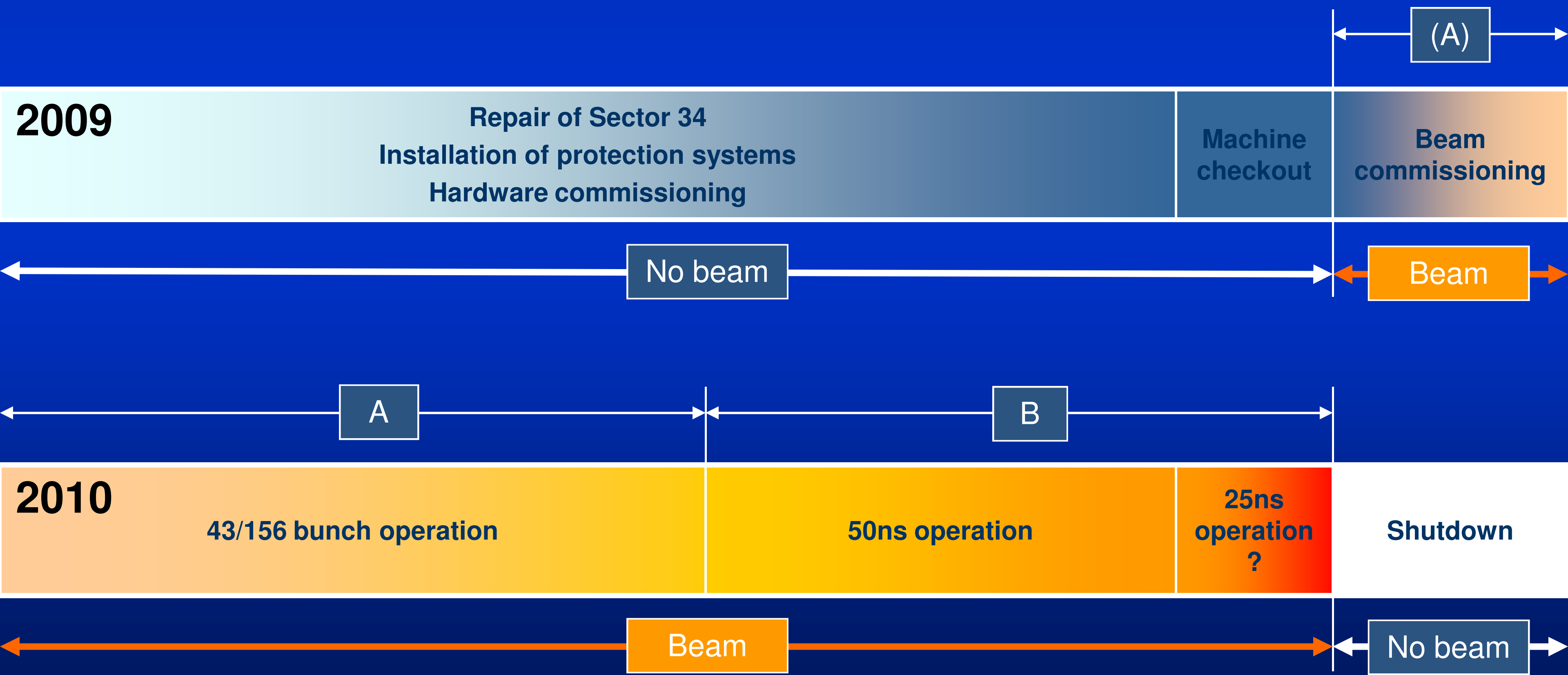
Energy	Safe	Safer
450 GeV	1e12	1e11
1 TeV	2e11	2e10
4 TeV	2e10	2e9

Commissioning plan 2009		Days*
Establish circulating beams	Repeat 2008	2
Essential 450 GeV commissioning	Instrumentation, optics, energy, capture	4
Machine protection commissioning 1	As needed for 450 GeV and 1TeV	4
450 GeV 2 beams and collisions	Commission experiment magnets	2
Ramp commissioning to 1 TeV	Master snapback, orbit, PLL	4
Machine protection commissioning 2	As needed for low intensity to high energies	3
Ramp to operating energy	Beam dump, instrumentation	2
First collisions		2
Full machine protection qualification	As needed for increased intensity	3
Increase intensity		2
Pilot physics		28
Squeeze		
* Estimate is for beam time – elapsed time will depend on machine availability – factor 2 ???		

Staged commissioning (as planned since 2005)

Three beam commissioning stages:

- **Stage A** → Simplest machine configuration (no crossing, moderate squeeze)
- **Stage B** → Up to intensity limit (fill pattern depends on experiment requests)
- **Stage C** → Towards nominal and ultimate performance



Status of the LHC

The September 19th incident

Understanding the (extent of the) problem

Making sure there is no repeat

Strategy for restart

Prospects for 2009 2010

Luminosity

$$L = \frac{N^2 k_b f}{4\pi\sigma_x\sigma_y} F = \frac{N^2 k_b f \gamma}{4\pi\varepsilon_n\beta^*} F$$

"Thus, to achieve high luminosity, all one has to do is make (lots of) high population bunches of low emittance to collide at high frequency at locations where the beam optics provides as low values of the amplitude functions as possible." PDG 2005, chapter 25

- **Nearly all the parameters are variable**
  - **Number of particles per bunch** N
  - **Number of bunches per beam** k_b
  - **Relativistic factor (E/m_0)** γ
  - **Normalised emittance** ε_n
  - **Beta function at the IP** β^*
  - **Crossing angle factor** F
    - **Full crossing angle** θ_c
    - **Bunch length** σ_z
    - **Transverse beam size at the IP** σ^*

$$F = 1/\sqrt{1 + \left(\frac{\theta_c \sigma_z}{2\sigma^*}\right)^2}$$

Performance

$$L = \frac{N^2 k_b f \gamma}{4\pi \varepsilon_n \beta^*} F$$

$$Eventrate / Cross = \frac{L \sigma_{TOT}}{k_b f}$$

Key parameters are γ N k_b β^* and they are strongly correlated

Need a crossing angle when k_b > ~ 150 (consequences for aperture)

γ	Energy not a free choice but has consequences for F N β^*
k_b	Number of bunches has consequences for F β^* and machine protection
N	Bunch intensity has consequences for beam-beam and pileup
β^*	Has consequences for N F and aperture

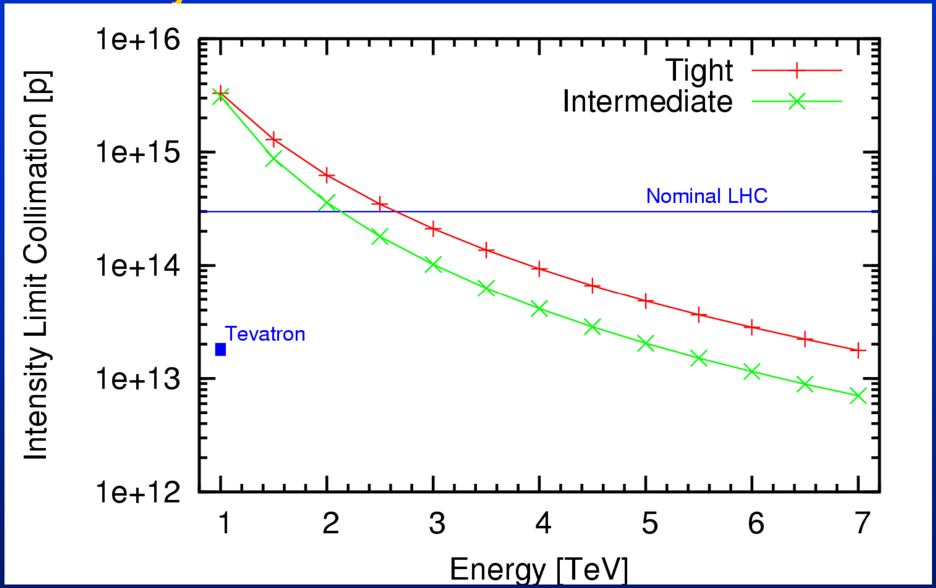
Smaller emittances ? Could be problems

$$\Delta Q \propto \xi = \frac{N \cdot r_o \cdot \beta^*}{4\pi\gamma\sigma^2} = \frac{N \cdot r_o}{4\pi\epsilon_n}$$

Boundary conditions 2009 2010

Conservative

- Energy will be initially limited to 3.5TeV
  - Safe current as decreed by splices to start with
  - nQPS running in for splice protection
  - Dipole training (0 quenches to 5TeV, 10 to 6TeV, 100 to 6.5TeV)
  - Recovery time from quenches during operation
- Intensity (nominal is 2808 bunches of 1.15 10^{11})
  - Machine protection considerations
  - Phase I collimation cleaning efficiency
    - Goes down with γ
    - Beam lifetime dips
    - Magnet quenches
      - 10% nominal at 5TeV
      - 25% nominal at 3.5TeV
    - Experience will tell !
- β^* (nominal is 0.55m)
  - Aperture considerations
  - Losses
    - Aim for 2m
    - Experience will tell !



Parameter space

		No Crossing Angle						Crossing Angle			NCA	Nom
Energy	TeV	0.45	0.45	3.50	3.50	3.50	3.50	3.50	3.50	3.50	5.00	7.00
Bunch intensity	1.E+10	1	4	4	4	4	9	9	9	9	9	11.5
Bunches		4	43	43	43	156	156	702	1404	2808	156	2808
Emittance	µm	3.75	3.75	3.75	3.75	3.75	3.75	3.75	3.75	3.75	3.75	3.75
β*	m	11	11	11	2	2	2	3	3	3	2	1
Luminosity	$cm^{-2} s^{-1}$	4.2E+26	7.2E+28	5.6E+29	3.1E+30	1.1E+31	5.6E+31	1.7E+32	3.3E+32	6.7E+32	8.0E+31	1.0E+34
Protons		4.0E+10	1.7E+12	1.7E+12	1.7E+12	6.2E+12	1.4E+13	6.3E+13	1.3E+14	2.5E+14	1.4E+13	3.2E+14
% nominal		0.0	0.5	0.5	0.5	1.9	4.3	19.6	39.1	78.3	4.3	100.0
Stored energy	MJ	0.0	0.1	1.0	1.0	3.5	7.9	35.4	70.8	141.5	11.2	361.7
Monthly (0.2)	pb-1	0.00	0.04	0.29	1.59	5.76	29.16	85.84	171.67	349.87	41.65	5231.88

(10^6 seconds @ <L> of 10^{33} cm^{-2} s^{-1} → 1 fb^{-1})

Delivered luminosities

- **Without crossing angle**

Could hit few 10^{31} cm^{-2} s^{-1} say <L> of 10^{31} cm^{-2} s^{-1}
40% efficiency for physics $\rightarrow$ 10^{6} seconds collisions per month
Integrated luminosity per month = 10 pb^{-1}

- **With crossing angle**

Could hit few 10^{32} cm^{-2} s^{-1} say <L> of 10^{32} cm^{-2} s^{-1}
40% efficiency for physics $\rightarrow$ 10^{6} seconds collisions per month
Integrated luminosity per month = 100 pb^{-1}

(10^{6} seconds @ <L> of 10^{33} cm^{-2} s^{-1} $\rightarrow$ 1 fb^{-1})

Summary

- From what we have seen with beam, we have a beautiful machine
- Gives us confidence that we know how to make it work

- September 19 cut us off at the knees
- Repair is well under way for restart late in 2009

- We now have a clear picture of what happened
- Checks all around the machine for similar problems

- Protection systems are being deployed to prevent recurrence
- Mitigation systems are being deployed to limit damage

- The way forward is clear for serious physics in 2010
- Experience will then tell us where to go next

We need to be careful, but we will make it work