# LHC Status
# (since September 2008)

Steve Myers

HEPAP 11th March 2010

# Topics

- The Accident
- The Repair and consolidation
- First beam operation at end of 2009
- Chamonix10
  - Running in 2010-2011
  - LHC Upgrades
- After Chamonix
- Present status with beam

- The Accident
- The Repair and consolidation
- Hardware Commissioning
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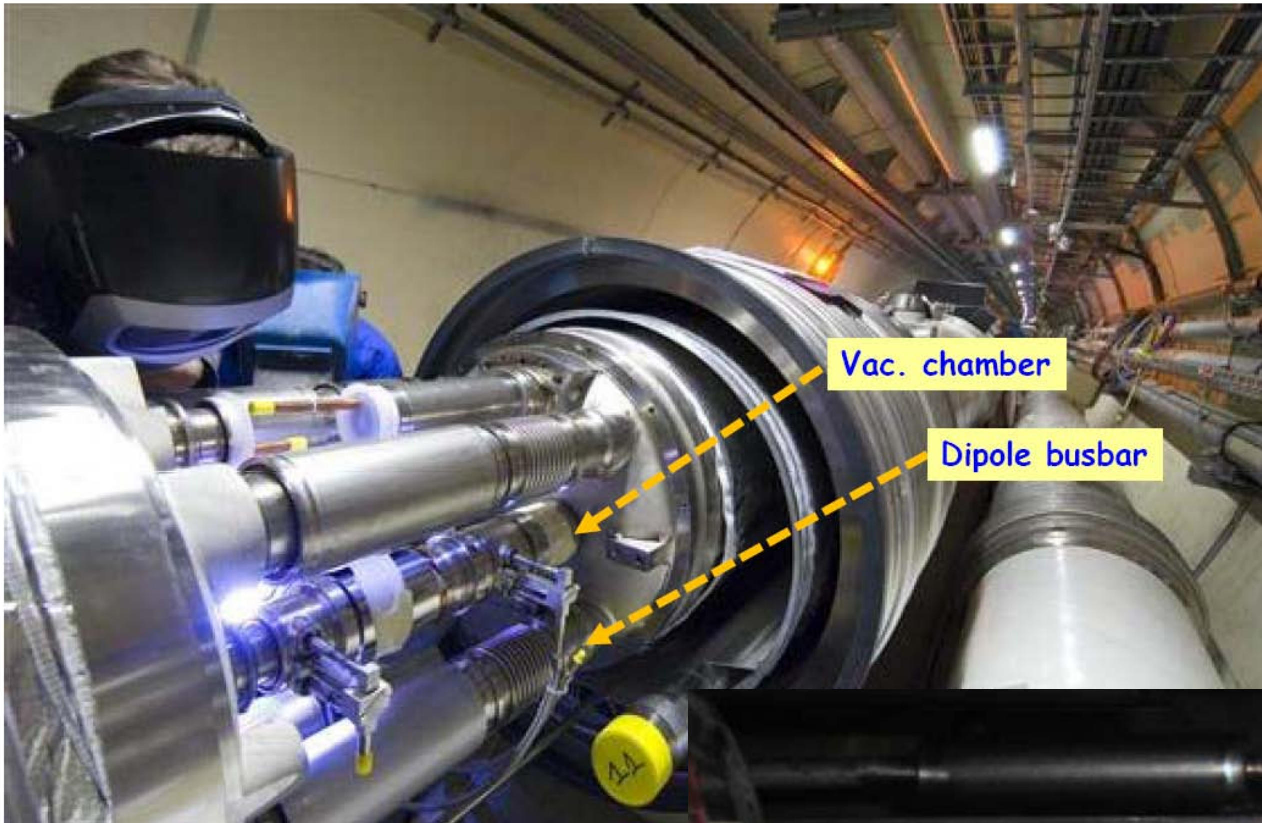
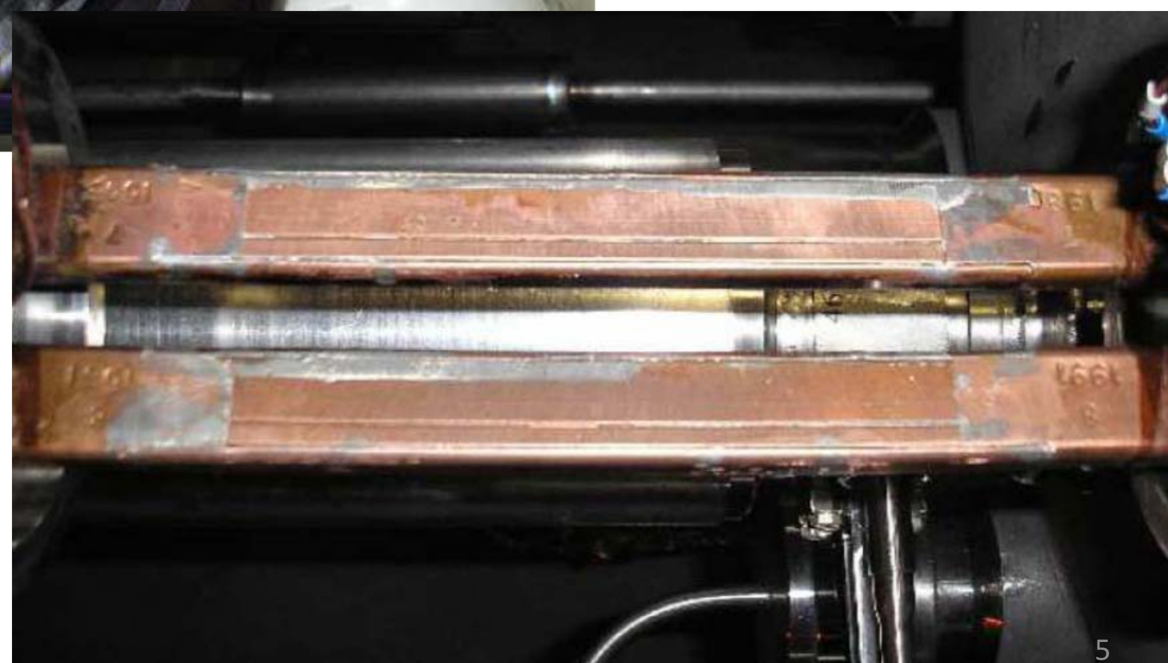
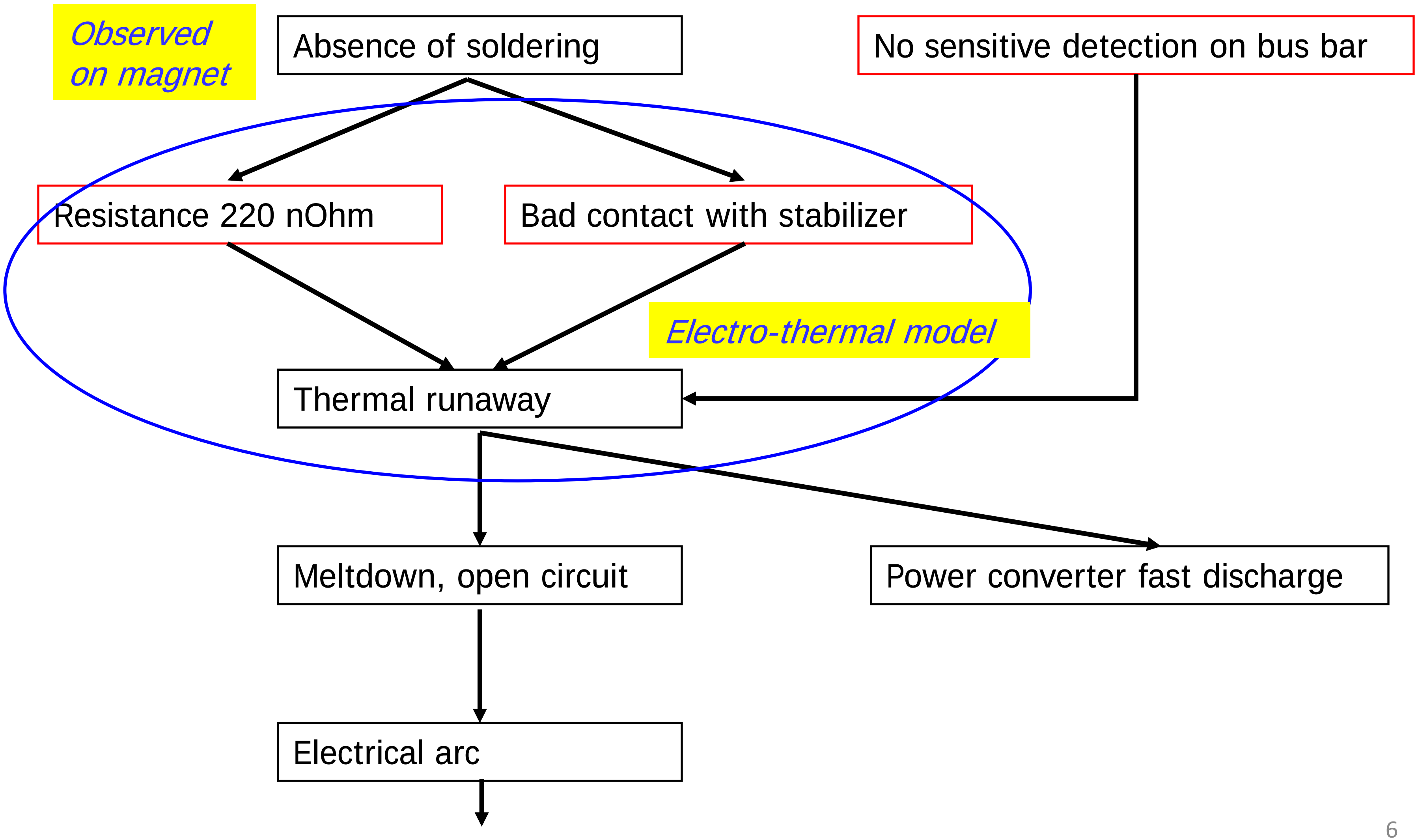
# Accident of September 19th 2008

- During a few days period without beam
- Making the last step of 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
- Electrical arc developed which punctured the helium enclosure

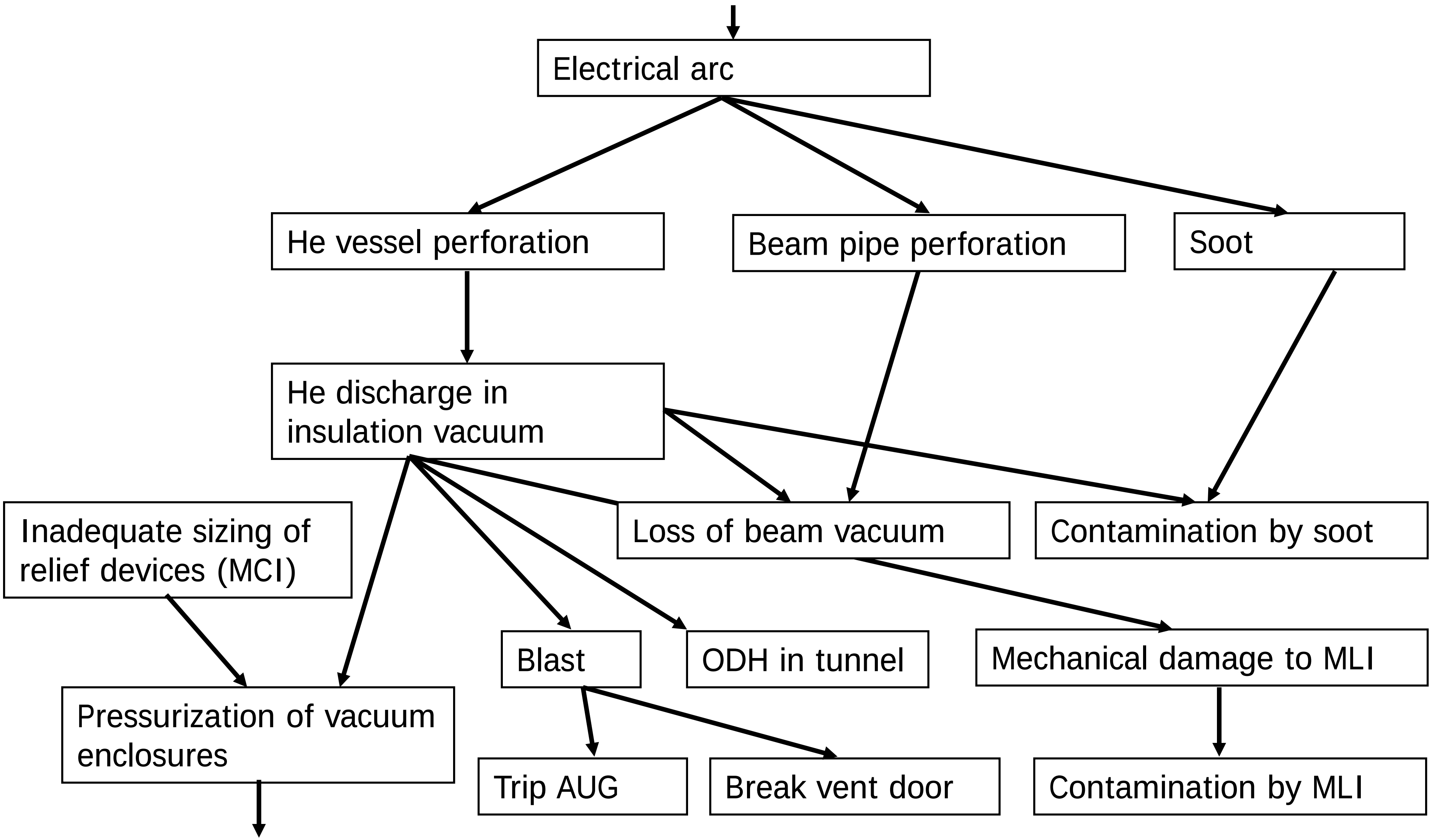

Vac. chamber
Dipole busbar



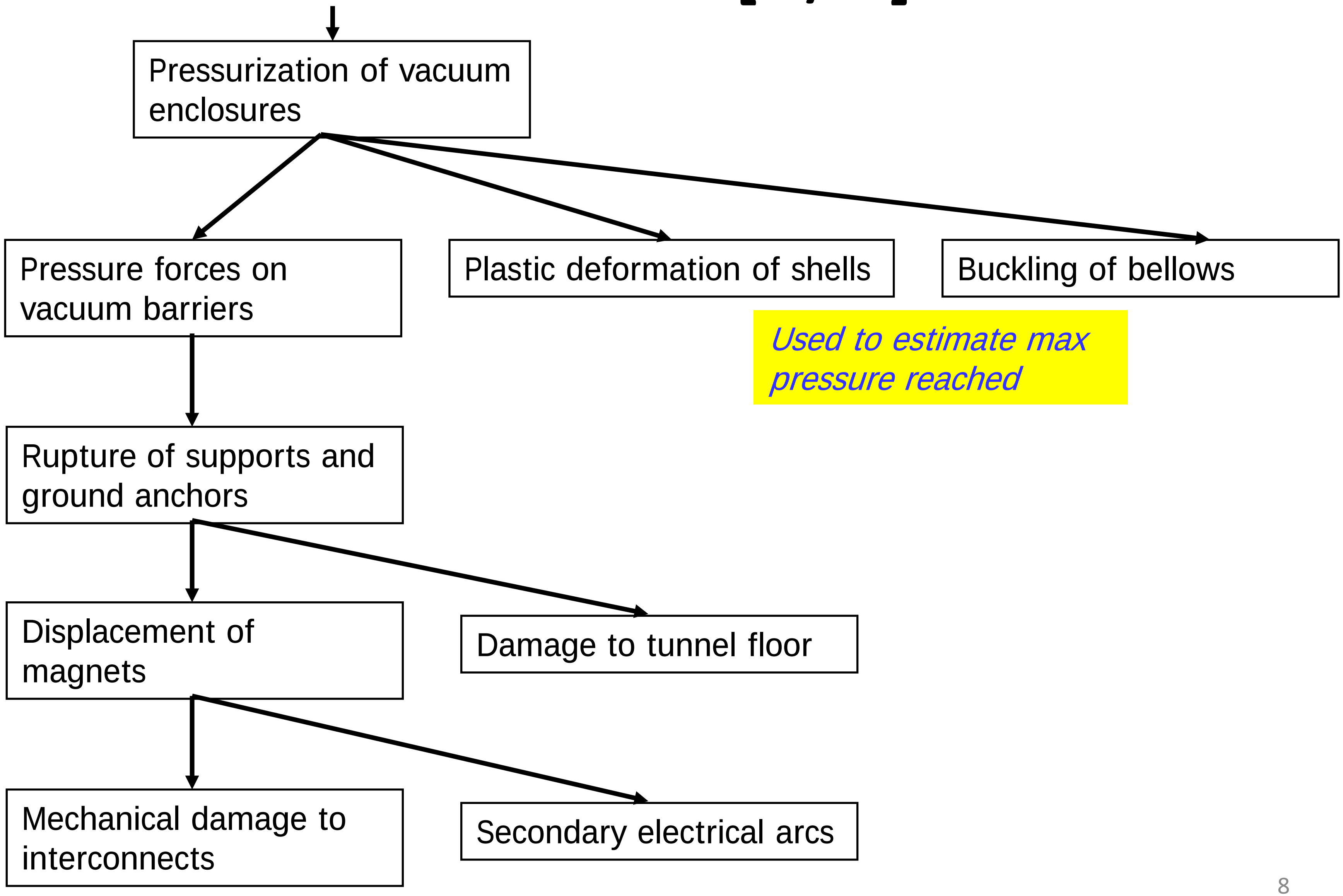
# Fault tree [1/3]



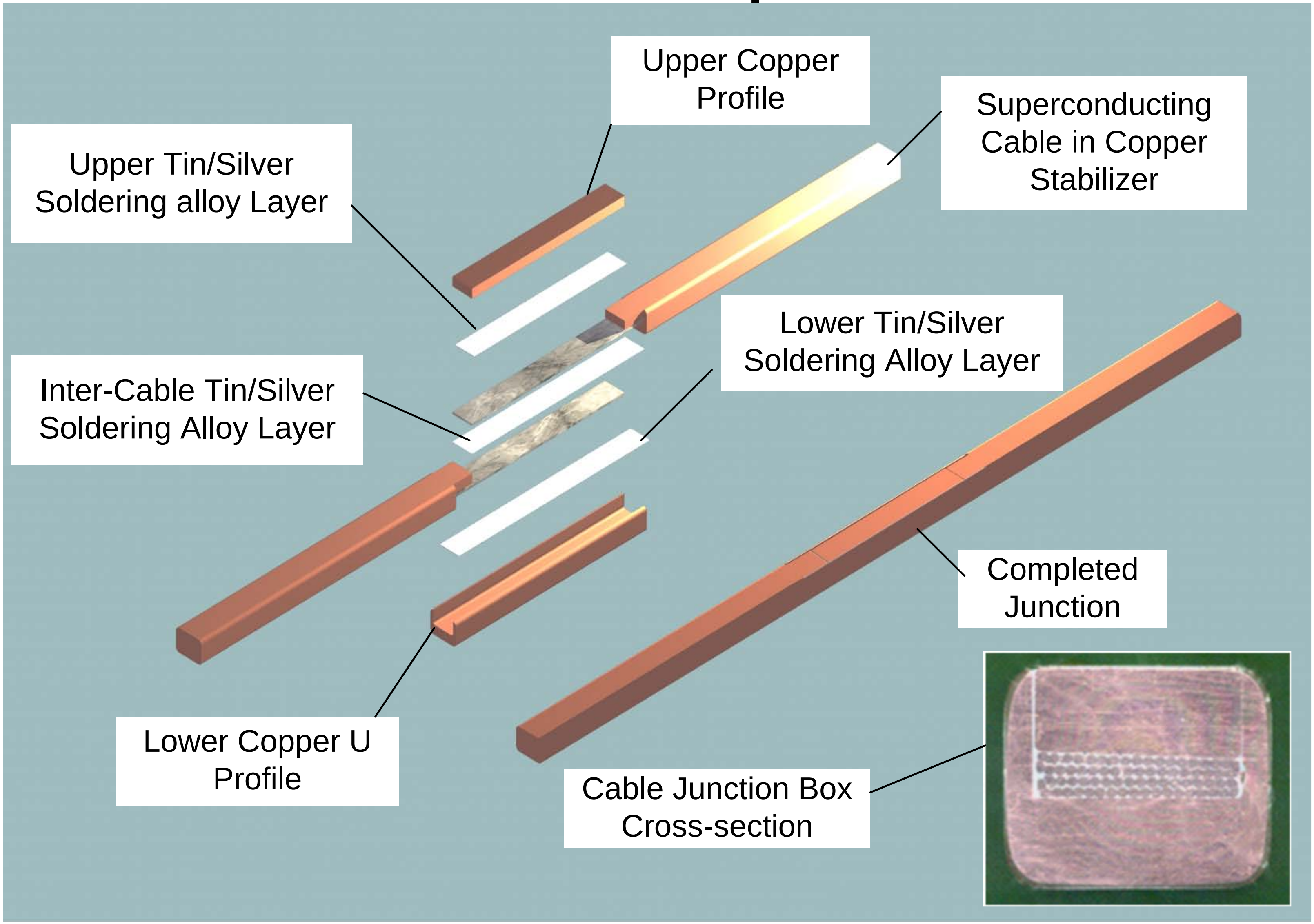
# Fault tree [2/3]



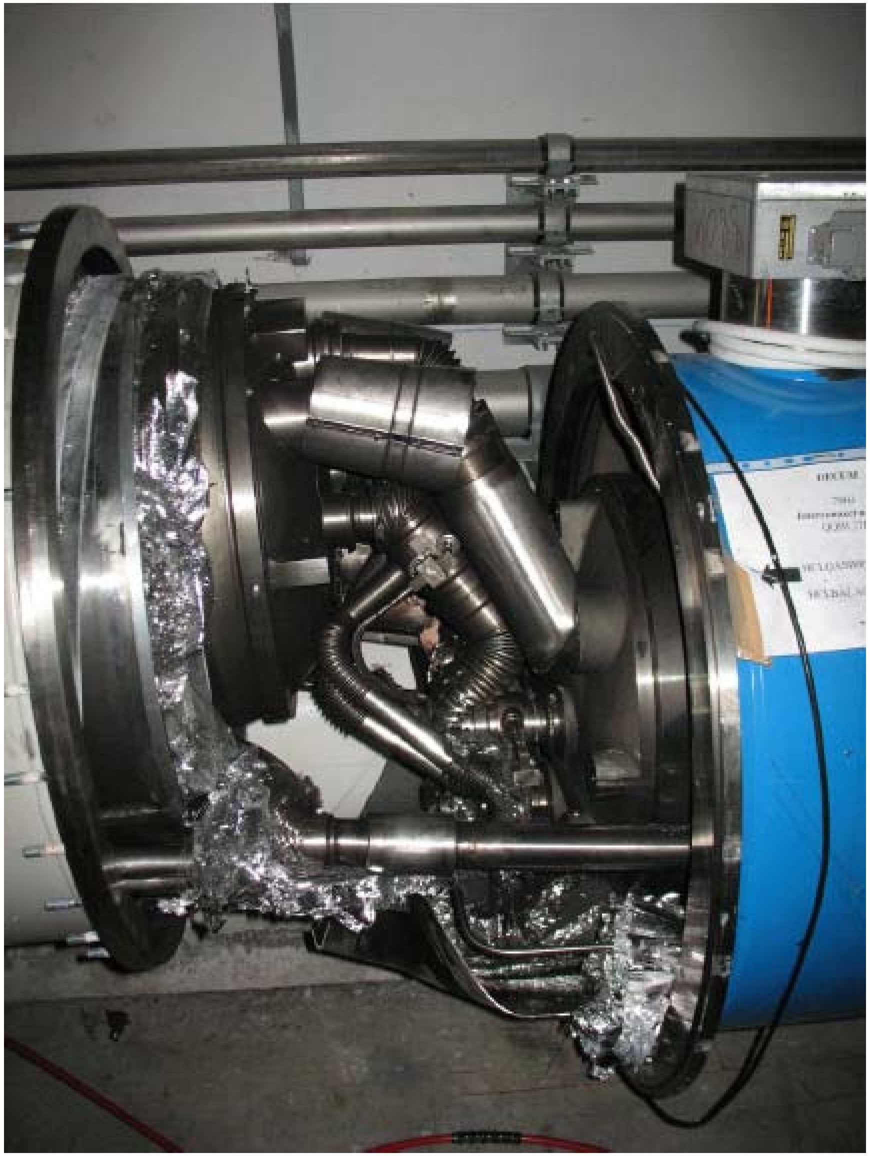
# Fault tree [3/3]



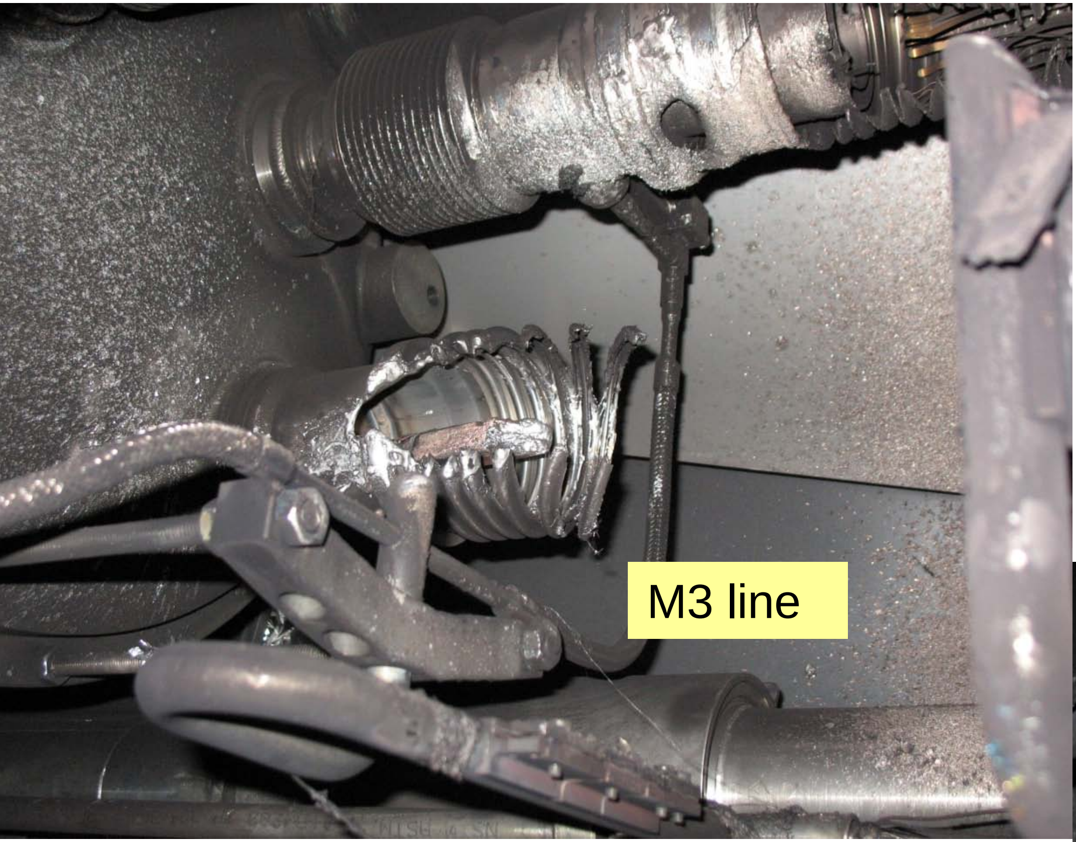
# Bus bar splice



# Consequences

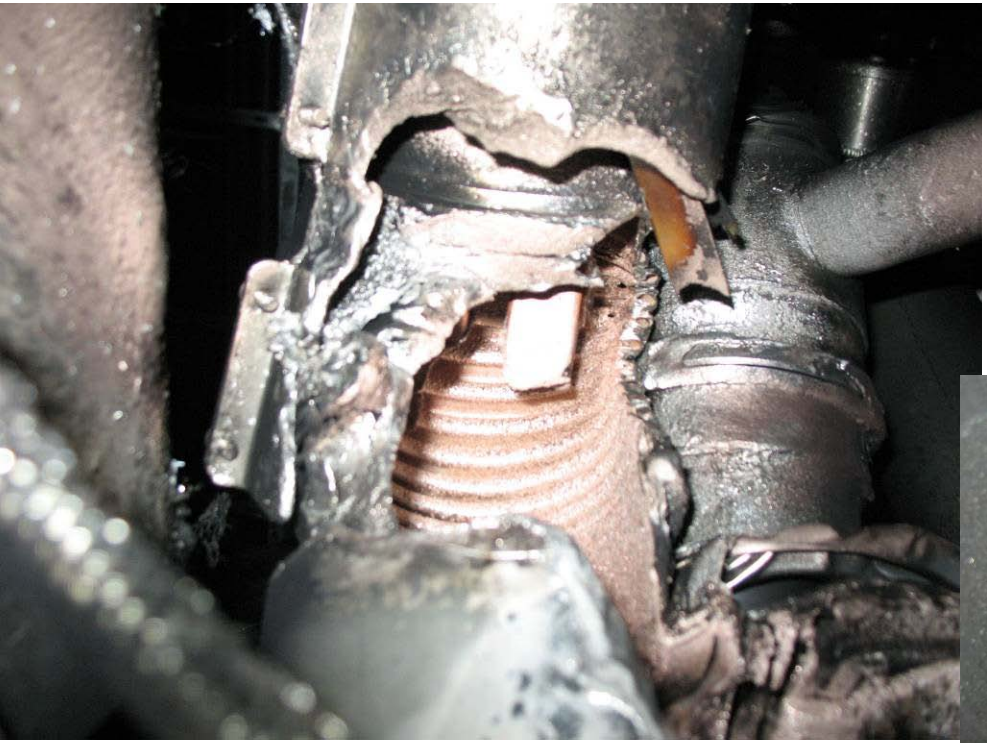


# Electrical arc between C24 and Q24



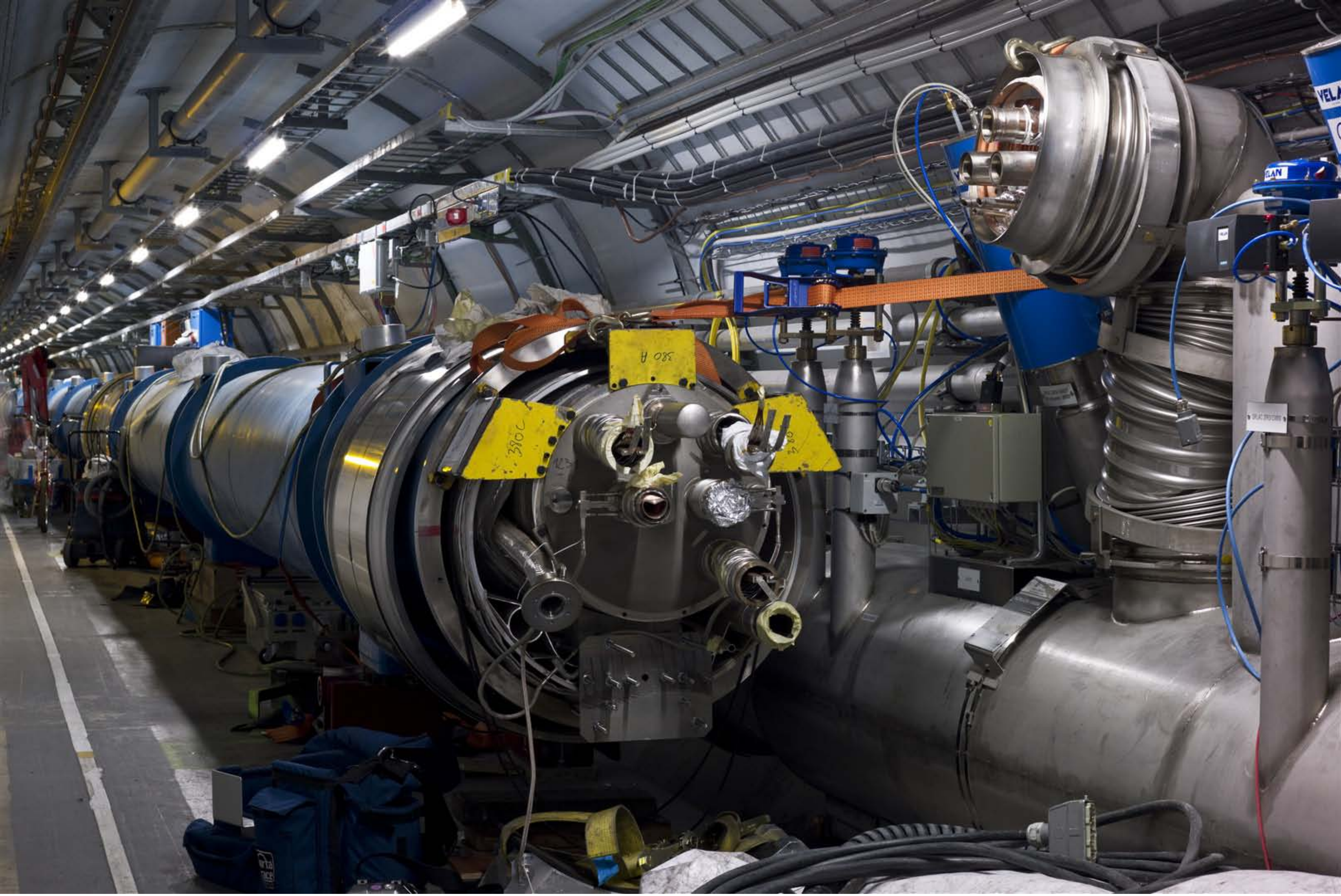

V lines

# Collateral damage: secondary arcs



QQBI.27R3 M3 line

QBBI.B31R3 M3 line



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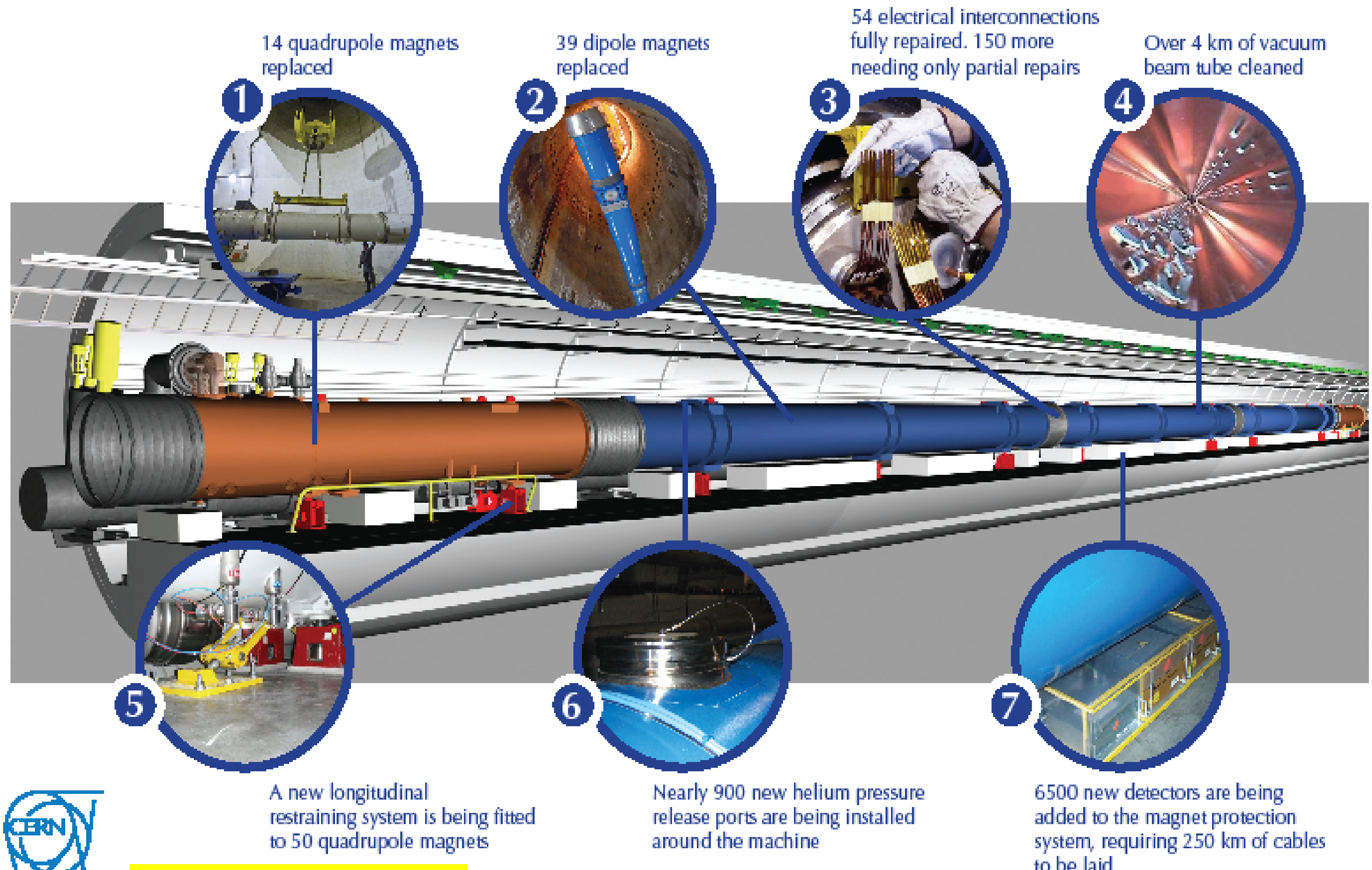
Phase 1 +2

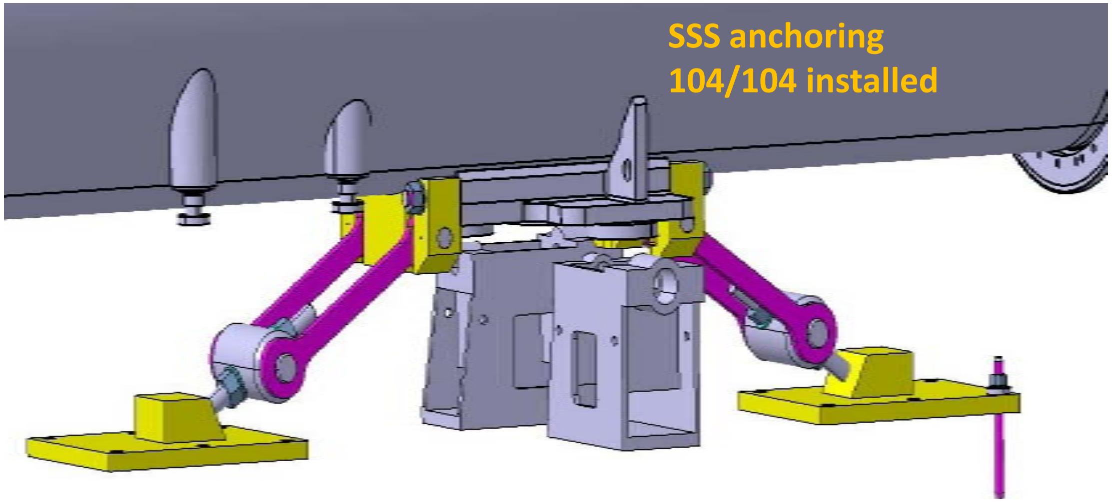
# The LHC repairs in detail




+ 8 cryogenics!

# Magnet protection and anchoring



- The Accident
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- **Hardware Commissioning**
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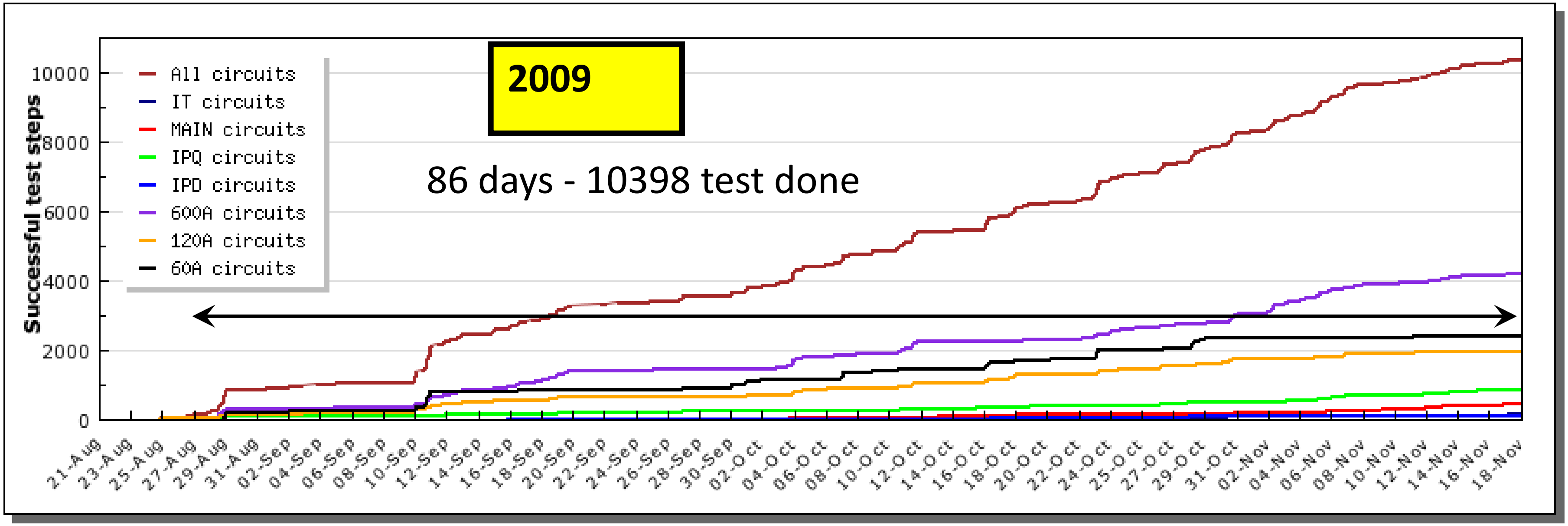
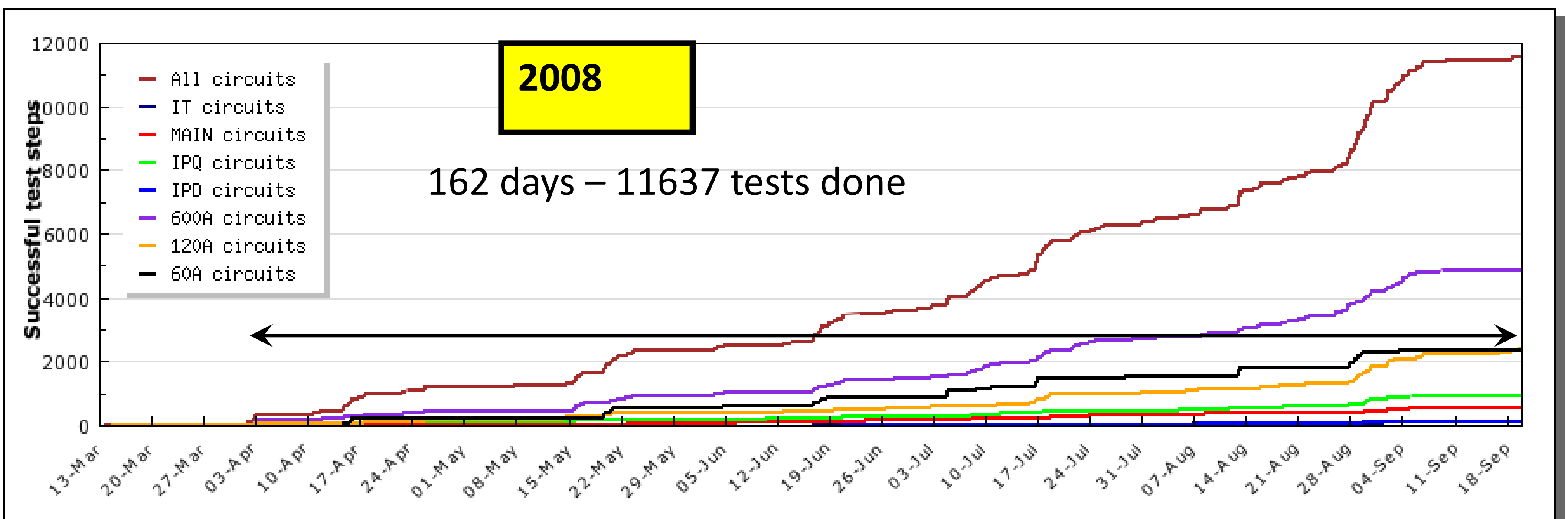
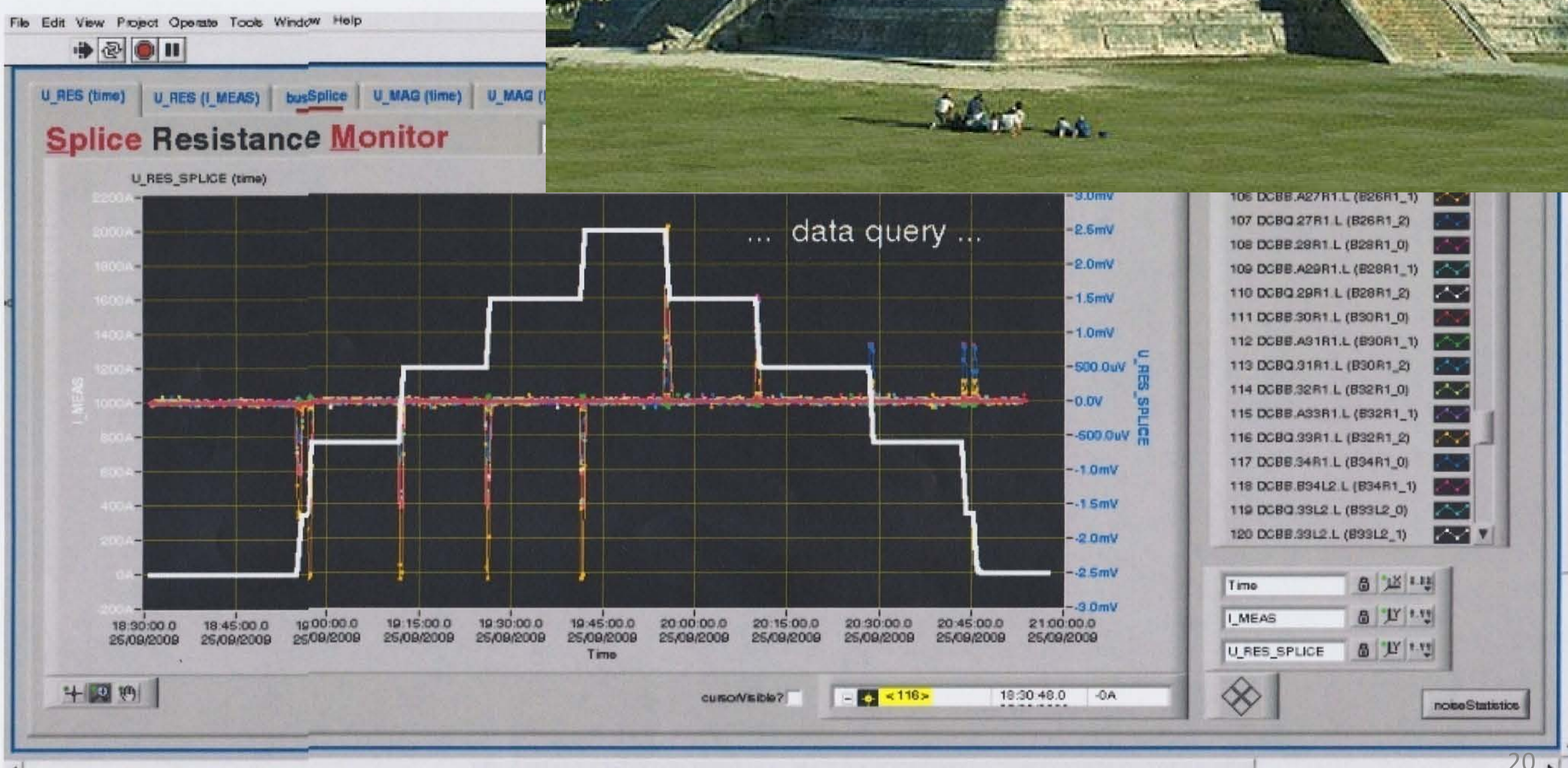
# Powering Tests overview



# Pyramid for Splice Mapping

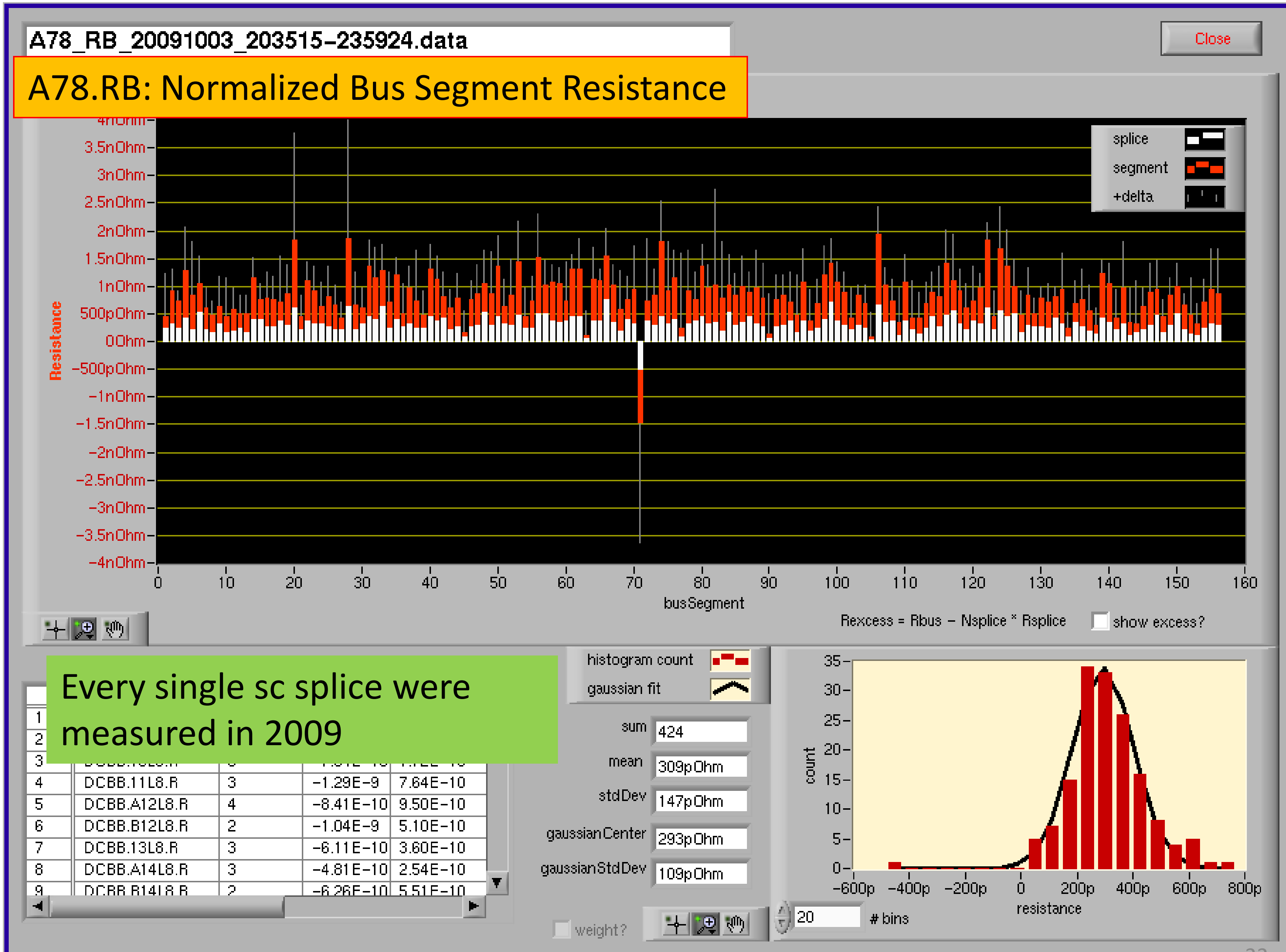

Current in the Dipoles as function of time

Splice Mapping of Dipoles

QPS team


First Dipole Busbar Resistances from first scan to 2 kA

# A78.RB: Normalized Bus Segment Resistance




Every single sc splice were measured in 2009

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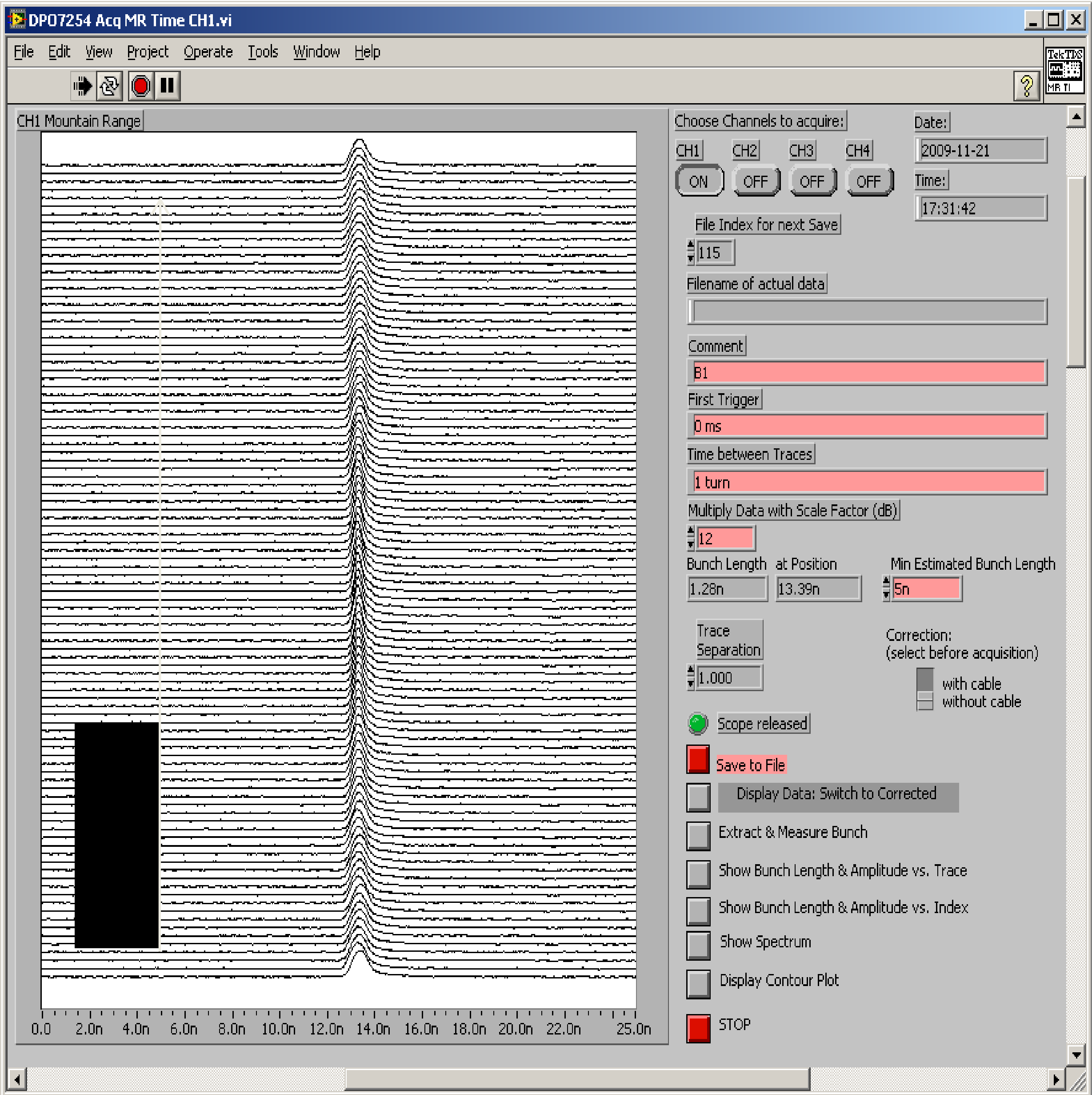
November 20, 2009

LHC back on line!

# To This

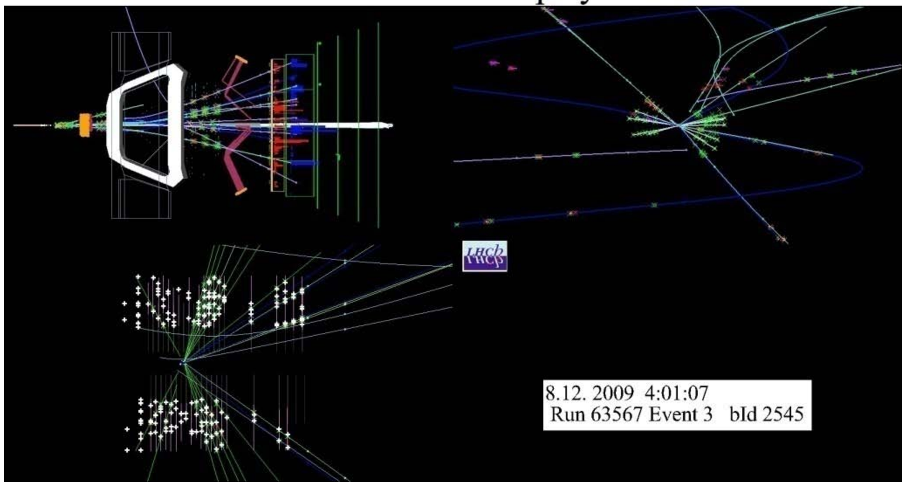


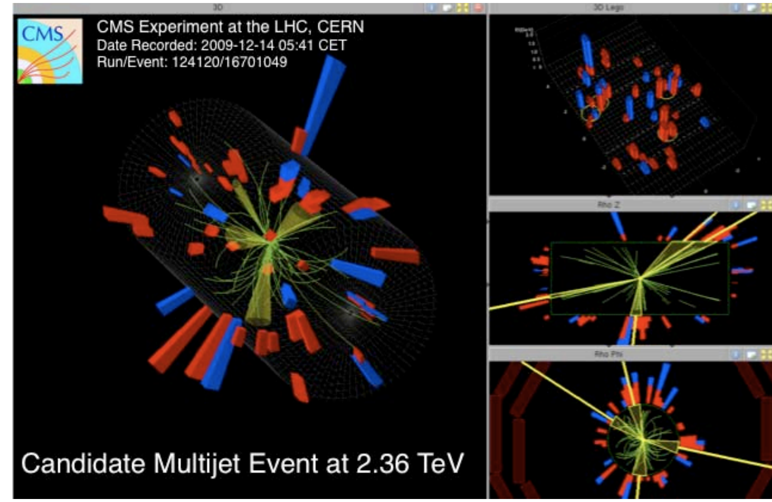

Beam is circulating and stable

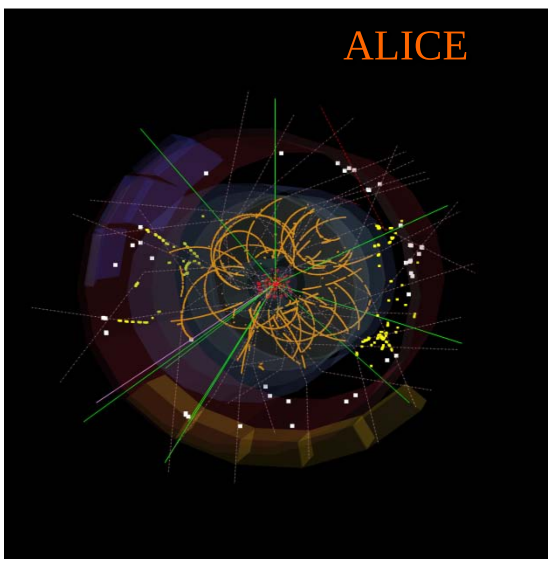
- magnets
- power supplies
- vacuum
- RF
- cryogenics
- all infrastructure
- optics
- injection

# And of course this

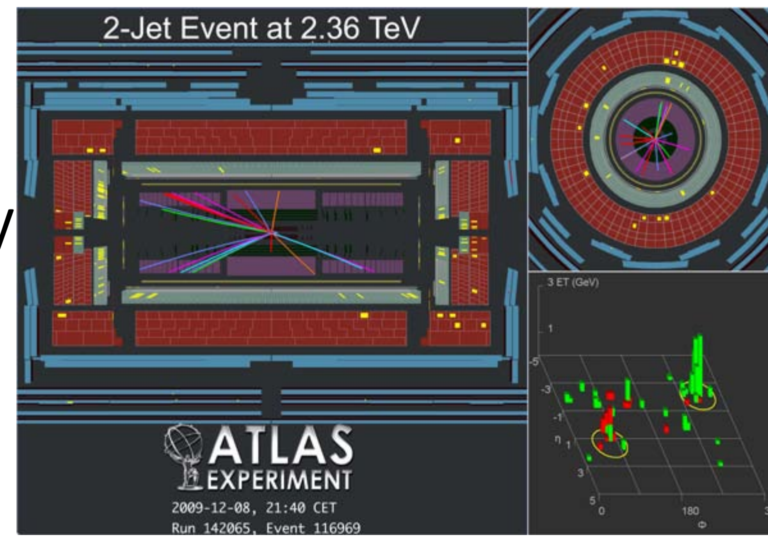
LHCb Event Display




First collisions events at 0.9 TeV and 2.36 TeV

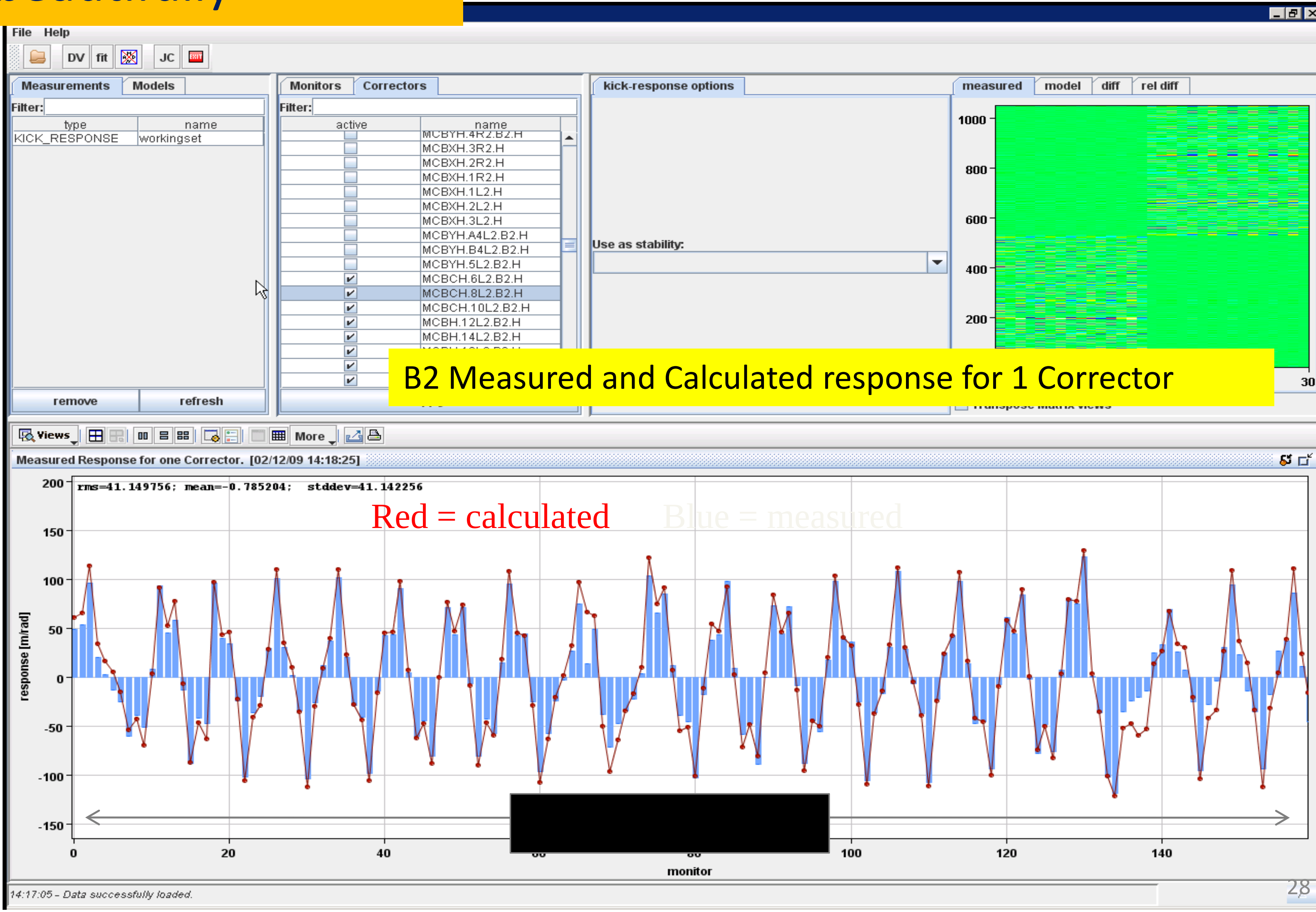


# Milestones

| Date | Day | Achieved |
|---|---|---|
| Nov 20 | 1 | Each beam circulating. Key beam instrumentation working. |
| Nov 23 | 4 | First collisions at 450 GeV. First ramp (reached 560 GeV). |
| Nov 26 | 7 | Magnetic cycling established (reproducibility). |
| Nov 27 | 8 | Energy matching. |
| Nov 29 | 10 | Ramp to 1.18 TeV. |
| Nov 30 | 11 | Experiment solenoids on. |
| Dec 04 | 15 | Aperture measurement campaign finished. LHCb and ALICE dipoles on. |
| Dec 05 | 16 | Machine protection (Injection, Beam dump, Collimators) ready for safe operation with pilots. |
| Dec 06 | 17 | First collisions with STABLE BEAMS, 4 on 4 pilots at 450 GeV, rates around 1Hz. |
| Dec 08 | 19 | Ramp colliding bunches to 1.18 TeV |
| Dec 11 | 22 | Collisions with STABLE BEAMS, 4 on 4 at 450 GeV, > $10^{10}$ per bunch, rates around 10Hz. |
| Dec 13 | 24 | Ramp 2 bunches per beam to 1.18 TeV. Collisions for 90mins. |
| Dec 14 | 25 | Collisions with STABLE BEAMS, 16 on 16 at 450 GeV, > $10^{10}$ per bunch, rates around 50Hz. |
| Dec 16 | 27 | Ramp 4 on 4 to 1.18 TeV. Squeeze to 7 m. |

# All systems worked beautifully

# Optics Checks ($2^{nd}$ Dec)



# LHC back on line!

26 days of highly successful beam commissioning due to

- Meticulous planning
- High availability of all accelerator and detector components

# In conclusion

It was a truly remarkable 26 days.

Many firsts for the LHC and the detectors

On the longer time scale, it has been a fantastic effort, with five impressive phases:
1) repair; 2) consolidation; 3) hardware commissioning; 4) preparation for beam; and 5) beam operation.

The final phase was highly visible, and widely reported by the media, but would not have been possible without the other phases.

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- Hardware Commissioning
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# Splices and Beam Energy: Statements

- Simulations for safe current used pessimistic input parameters (RRR......) but have no safety margins
- For 2010, 3.5 TeV is safe
    - **Measure the RRR (asap) to confirm the safety margin for 3.5TeV/beam**
- Without repairing the copper stabilizers, **5 TeV is risky**
- For confident operation at 5TeV we would need
    - Repairs to the “outlier” splices
    - Better knowledge of the input parameters (RRR...)
    - With present input parameters the “limit” splice resistances are **43 μΩ (RB)** and **41 μΩ (RQ)**
      **NOTE: these values are close to the limit of the resolution of our measurements made for the RBs at 300K**

# 7TeV/beam Splices : Statements

- For confident operation at 14TeV we need
  - To replace all splices with new clamped shunted ones!

► F. Bertinelli, A. Verweij, P. Fessia (unaminous)

For safe running around 7 TeV/beam, a shunt has to be added on all 13 kA joints, also on those with small $R_{addit}$. Joints with high $R_{addit}$ or joints with large visual defects should be resoldered and shunted.

A Cu-shunt with high RRR and a cross-section of 16x2 $mm^2$ is sufficient, if soldered at short distance from the gap. Experimental confirmation by means of a test in FRESCA should be foreseen.

# Two Possible Scenarios 2010-2011

1. Run at 3.5 TeV/beam up to a predefined integrated luminosity with a date limit. Then consolidate the whole machine for 7TeV/beam.
    - Need to determine the needs for the shutdown (resources, coactivity etc)

# Upgrades: Foreword

Studies have been launched about one year ago and are ongoing

- Performance Aim
  - To maximize the useful integrated luminosity over the lifetime of the LHC
- Targets set by the detectors are:

  3000$fb^{-1}$ (on tape) by the end of the life of the LHC

  → 250-300$fb^{-1}$ per year in the second decade of running the LHC

- Goals
  - Check the performance of the present upgrades
  - Check the coherence of present upgrades wrt
    - » Accelerator performance limitations,
    - » Detector requirements,
    - » manpower resources,
    - » shutdown planning for all activities

# Performance: Injector Upgrades

- Present Peak Performance Situation

| Intensity Limitations ($10^{11}$ protons per bunch) | | |
|---|---|---|
| | Present | |
| Linac2/LINAC4 | 4.0 | |
| PSB or SPL | 3.6 | |
| PS or PS2 | 1.7 | |
| SPS | ~1.2 | |
| LHC | 1.7-2.3? | |

**Conclusion 1: SPS is the bottleneck!**

# SPS Bottleneck

- Other injectors are limited by a fundamental limitation, the space charge effect ($\Delta Q_{sc} = 0.3$)
- In the SPS at injection: $\Delta Q_{sc} = 0.07$! (no fundamental limitation)
- Actual Intensity Limitation in SPS (mitigaton)
  - Electron cloud (vacuum chamber coating)
  - Transverse Mode Coupling Instability (Impedance reduction and/or transverse feedback)
  - RF effects such as beam loading etc (redesign of existing RF or build new system)

Immediately after Chamonix a hardware task force has been set up to investigate the removal of this SPS bottleneck (led by Volker Mertens)

# Injectors Performance (Availability)

- From the LINAC2 to the SPS we have ageing machines
  - We need consolidation or replacement
- Proposed scenario (White Paper, 2006) is to replace LINAC2, PSB and PS
  - LINAC4, SPL, and PS2
- Recent study shows time scale for operation of the PS2 is at earliest 2020 and likely 2022.
  - Conclusion 2: We need to aggressively consolidate the existing injector chain to allow reliable operation of the LHC until at least 2022.
  - Task force set up late last year. (Simon Baird)
- BUT: **Resources** needed for the consolidation of the existing injectors are in direct competition with those needed for the construction of SPL/PS2
- Question: What would be the LHC performance implications of not constructing SPL/PS2??

# Summary of Intensity Limits

| Intensity Limitations ($10^{11}$ protons per bunch) | | | |
|---|---|---|---|
| | Present | SPL-PS2 | |
| Linac2/LINAC4 | 4.0 | 4.0 | |
| PSB or SPL | 3.6 | 4.0 | |
| PS or PS2 | 1.7 | 4.0 | |
| SPS | 1.2 | >1.7? | |
| LHC | 1.7-2.3? | 1.7-2.3? | |

It would be wonderful to be able to afford these additional margins and flexibility! Also an asset to CERN for future high intensity proton project proposals

# Performance Limitations without SPL/PS2

- Alternative scenario to SPL/PS2
  - Consolidate existing injectors for the life of the LHC (2030)
  - During the same consolidation, improve the performance of PSB/PS as injectors for the LHC
- New "Idea"
  - Increase the extraction energy of the PSB which allows increase of the injection energy of the PS.
  - 2GeV injection energy in the PS allows ~$3x10^{11}$ ppb with the same space charge tune shift (preliminary study presented in Chamonix)

**"Project" set up immediately after Chamonix**

# Intensity Limits

| Intensity Limitations ($10^{11}$ protons per bunch) | | | |
|---|---|---|---|
| | Present | SPL-PS2 | 2GeV in PS |
| Linac2/LINAC4 | 4.0 | 4.0 | 4.0 |
| PSB or SPL | 3.6 | 4.0 | 3.6 |
| PS or PS2 | 1.7 | 4.0 | 3.0 |
| SPS | 1.2 | >1.7? | >1.7? |
| LHC | 1.7-2.3? | 1.7-2.3? | 1.7-2.3? |

# Running Present injector Chain for > 20 years

- Very detailed list of consolidation items to ensure reliable running of the present injector chain
  - Machines, experimental areas, services and infra-structure
- Points of Note
  - Consolidation programme includes all experimental areas
    - Doing this for the SPL/PS2 upgrade will incur substantial additional resources

# Possible Improvements in Existing Injector Chain: Summary

- Increase PSB (PS injection) energy to 2 GeV
  - Possibility to generate LHC bunches of up to $2.7\times10^{11}$ p (or even up to $3\times10^{11}$ p) with 25 ns spacing.
- Time line for implementation of new PSB extraction energy:
  - Three to four years (design and construction of new hardware)
  - One to two shutdowns (hardware installation)

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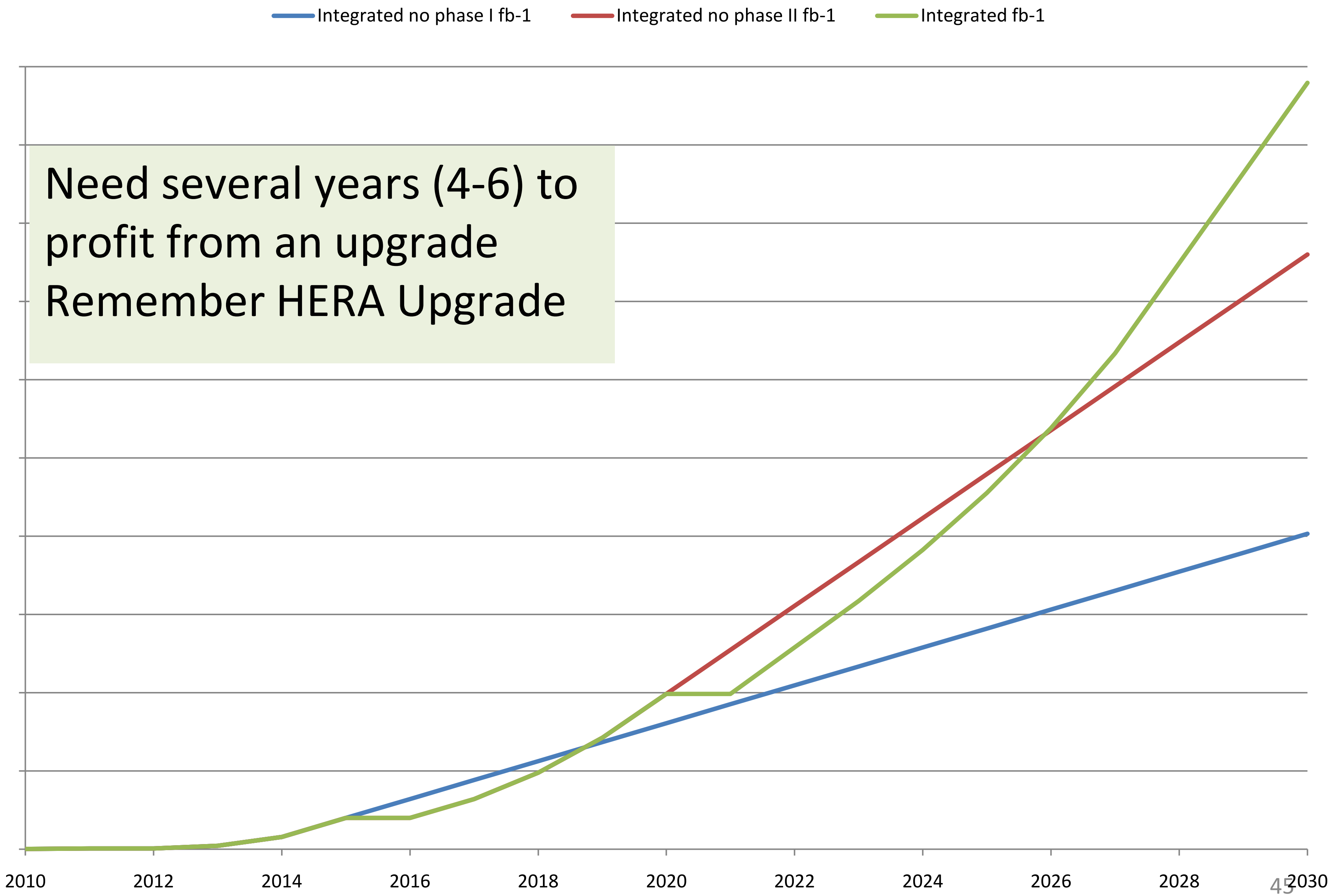
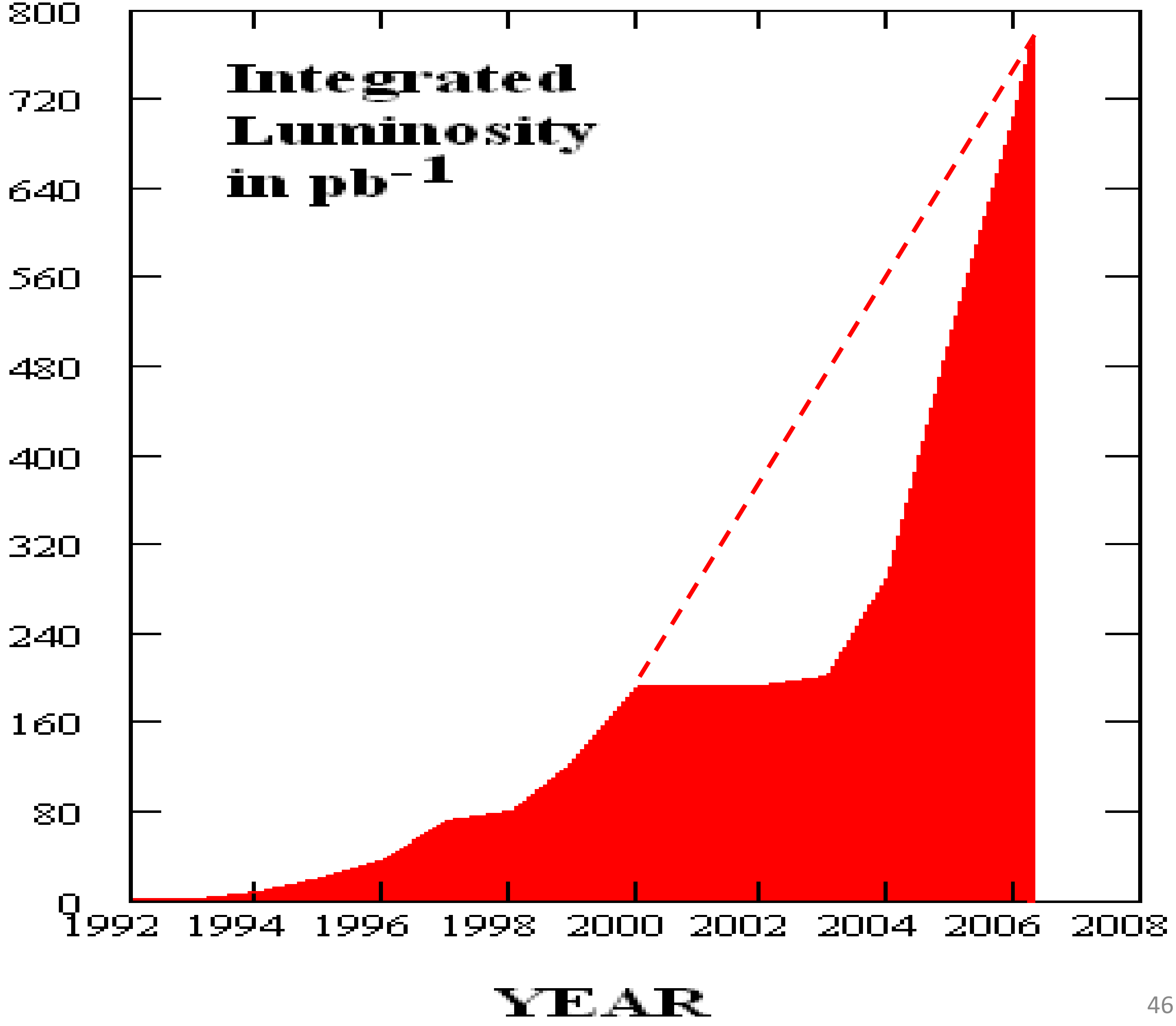
# IR/Optics Upgrade or not



HERA II



Integrated Luminosity in $pb^{-1}$
800
720
640
560
480
400
320
240
160
80
0
1992
1994
1996
1998
2000
2002
2004
2006
2008
YEAR

# Insertion Upgrade Plans

- IT Upgrade "phase 1"
  - Goal: reliable operation at $2x10^{34}cm^{-2}s^{-1}$ , intensity < ultimate and > nominal
  - ? Same resources for splice consolidation

Very similar to "ultimate"

Tough Questions:

1. Will the phase 1 upgrade produce an increase in useful integrated luminosity?
    - Installation time and recomissioning a new machine afterwards
2. Do we have the resources to complete on a time scale which is reasonable with respect to phase 2?

Task force set up immediately after Chamonix (Lucio Rossi) 4-5 weeks to answer above questions (mid-end March). Task force will then define the parameters for sLHC

# Future Upgrade Scenarios “Phase 2”

- Luminosity Optimization and Levelling
  - For LHC high luminosities, the luminosity lifetime becomes comparable with the turn round time.. Low efficiency
  - Preliminary estimates show that the useful integrated luminosity is greater with
    - a peak luminosity of 5-6x$10^{34}$ $cm^{-2}$ $s^{-1}$ and luminosity levelling
    - than with $10^{35}$ and a luminosity lifetime of a few hours
  - Luminosity Levelling by
    - Beta*, crossing angle, crab cavities, and bunch length

Detector people have also said that their detector upgrade would be much more complicated and expensive for a peak luminosity of $10^{35}$ due to

- Pile up events
- Radiation effects

# Some additional Remarks

- Collimation (highest priority after the splice repair)
- Radiation to Electronics

- We also need to study
  - How to give LHCb $5x10^{33}cm^{-2}s^{-1}$
  - Higher luminosity with lead collisions (ALICE)

# Conclusions

- The Luminosity Targets set by the detectors are:
    - 3000fb$^{-1}$ (on tape) by the end of the life of the LHC
    - → 250-300fb$^{-1}$ per year in the second decade of running the LHC
- The Upgrades needed to attack these goals are
    - SPS performance improvements to remove the bottleneck
    - Aggressive consolidation of the existing injector chain for availability reasons
    - Performance improvement of the injector chain to allow phase 2 luminosities
    - a newly defined sLHC which involves
        - luminosity levelling at ~5-6x 10$^{34}$cm$^{-2}$s$^{-1}$ (crab cavities etc…)
        - At least one major upgrade of the high luminosity insertions

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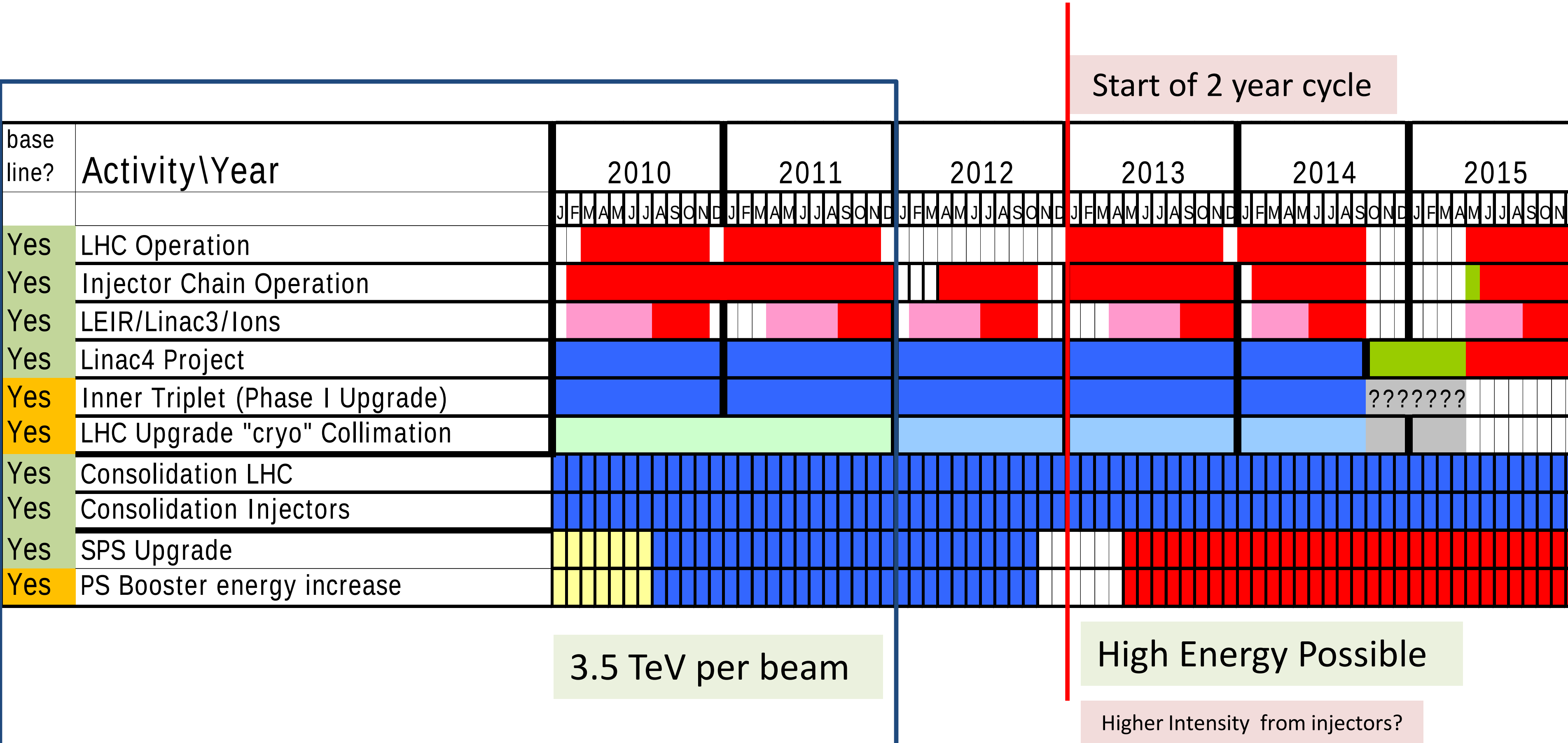
# Time lines (Very Preliminary)



# LHC Performance Pre-amble

- The nominal parameters of the LHC (as quoted in the LHC design report) are challenging both for the machine and the experiments. A staged approach to commissioning the LHC with proton beams was first proposed in Chamonix 2006
- This approach aimed at finding a balance between robust operations (efficiency and machine protection) and satisfying the experiments (luminosity and event pileup). The number of bunches, bunch intensity and $\beta^*$ are the key parameters varied throughout the period of commissioning to ensure safe and efficient operation.
- The LHC commissioning will be carried out in stages with performance being gradually increased up to the nominal parameters. The 2009 run constituted a first stage, starting with a pilot run at 0.45 and 1.18 TeV/beam and low intensities.
- In 2010 and 2011 we will be operating at 3.5TeV/beam and pushing intensities and luminosities but along a safe line.

# Luminosity

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

- Nearly all the parameters are variable (and not independent)
  - Number of particles per bunch $N$
  - Number of bunches per beam $k_b$
  - Relativistic factor ($E/m_0$) $\gamma$
  - Normalised emittance $\varepsilon_n$
  - Beta function at the IP $\beta^*$
  - Crossing angle factor $F$
    - Full crossing angle $\theta_c$
    - Bunch length $\sigma_z$
    - Transverse beam size at the IP $\sigma^*$

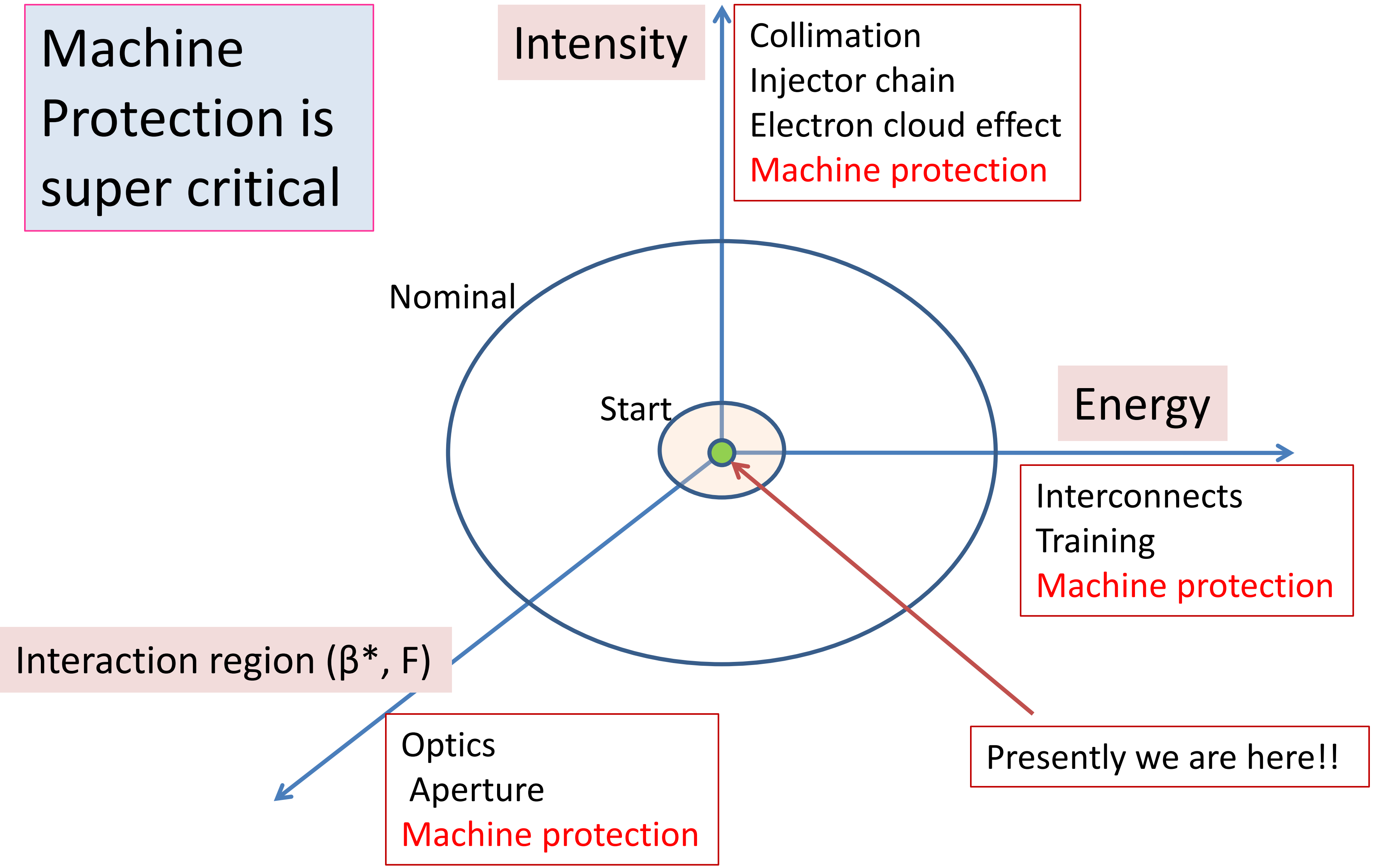
Intensity ($N$, $k_b$)

Energy ($\gamma$)

Interaction Region ($\beta^*$, $F$, $\theta_c$)

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

# LHC performance drivers/limiters



# β* and F in 2010

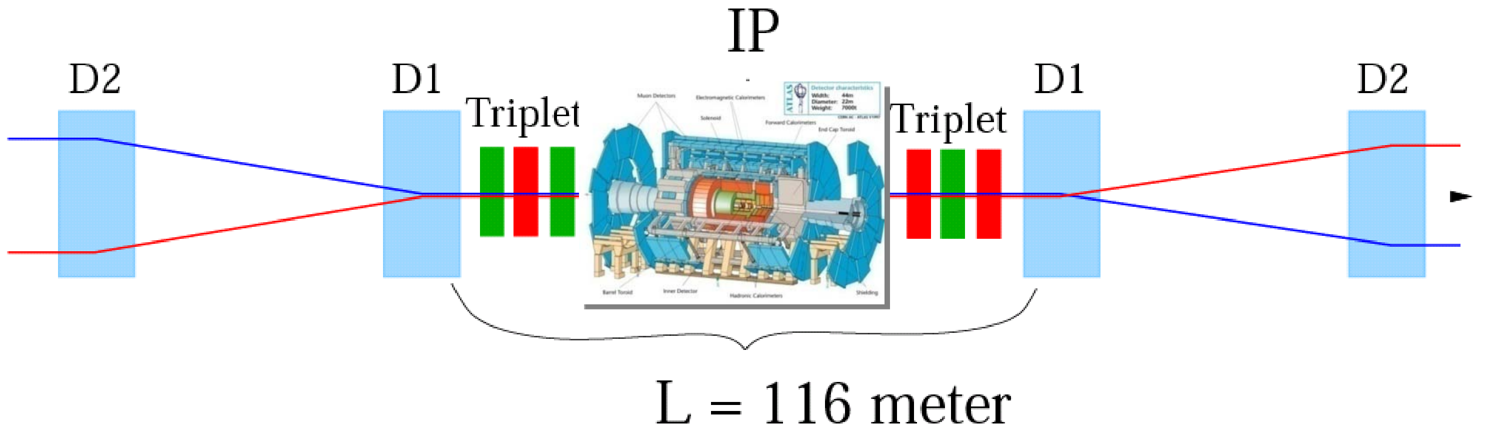
- Lower energy means bigger beams $\varepsilon_n = \varepsilon\gamma$ $\sigma = \sqrt{\varepsilon\beta}$
  - Less aperture margin
  - Higher β*

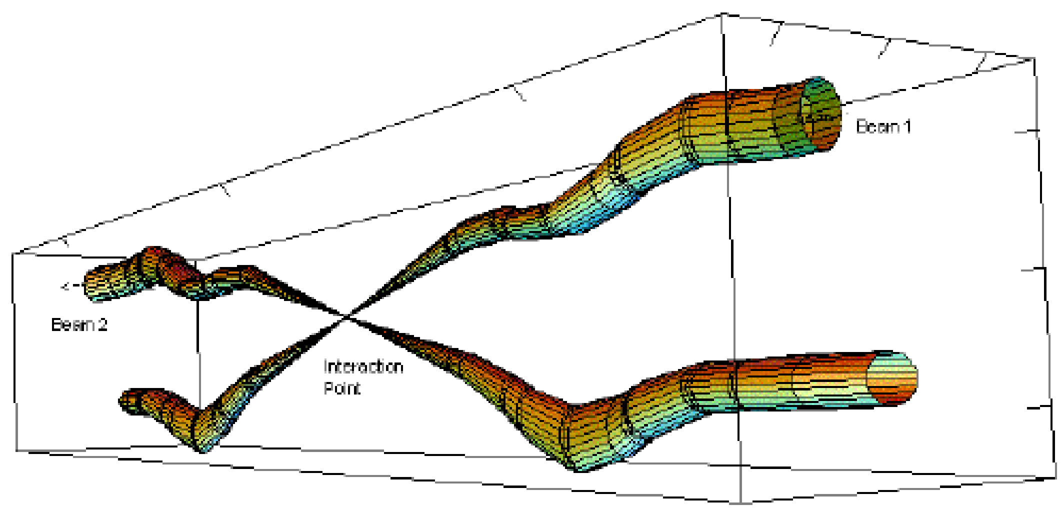
At max

- > 150 bunches requires crossing angle (beam-beam)
  - Requires more aperture
  - Higher β*

- Targets for 3.5TeV
  - 2/2.5 m without/with crossing angle in 2010
  - 2m with crossing angle in 2011

# Interaction Region - F

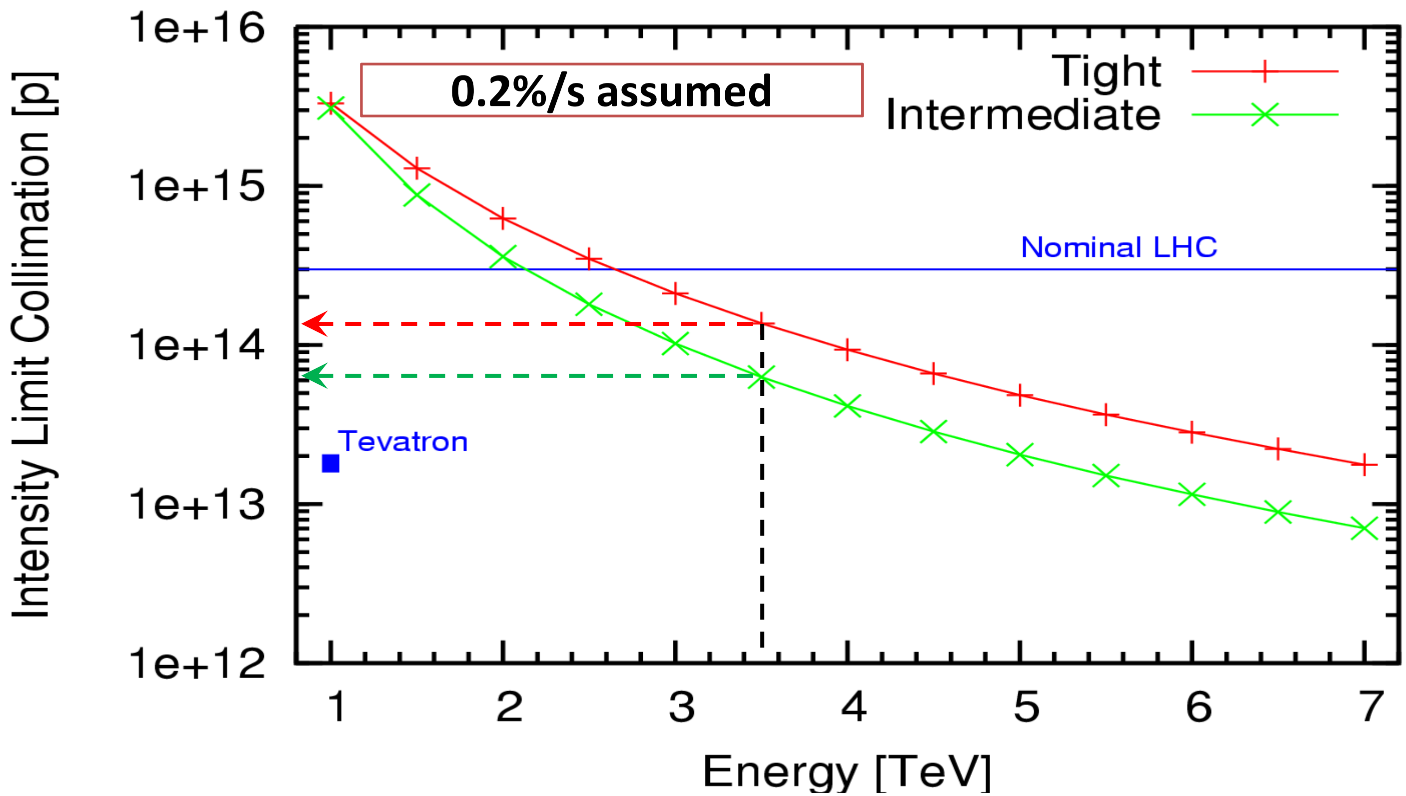



Relative beam sizes around IP1 (Atlas) in collision

**With > 150 bunches per beam, need a crossing angle to avoid parasitic collisions**

# “Intensity limits” Collimation (2010)




Collimator “limit” around 6 $10^{13}$ protons per beam at 3.5TeV with “intermediate” settings (about 20% nominal intensity)

**33.6 MJ stored beam energy**

Soft limit, not yet well defined, 0.2%/s loss rate totally arbitrary (8 minute lifetime)

# Strategy for Increasing the Beam Intensity

- The magic **number for 2010/11 is 1 $fb^{-1}$**. To achieve this, the LHC must **run flat out at $2x10^{32}$ $cm^{-2}s^{-1}$ in 2011**,
  - Correspond to 8e10 ppb, 700 bunches, with a stored energy of 35 MJ (with $\beta$*=2 m and nominal emittance).

# Intensity increase – Summary

- Maximum intensity increase versus stored energy:
  - Up to 0.25 MJ — typical factor ~2, max 4
  - Up to 1-2 MJ — max. factor ~2
  - Above 1-2 MJ — ≤ ~2 MJ per step

# Progression (1)

| Stage | Ib (protons) | Nb | Stored E (kJ) | Stored E step | Peak L (Hz cm-2) |
|---|---|---|---|---|---|
| 4 pilots | 5.00E+09 | 4 | 11.2 | 1.00 | 4.77E+27 |
| 4 bunches | 2.00E+10 | 4 | 44.8 | 4.00 | 7.63E+28 |
| 4 bunches | 5.00E+10 | 4 | 112.0 | 2.50 | 4.77E+29 |
| 8 bunches | 5.00E+10 | 8 | 224.0 | 2.00 | 9.54E+29 |
| 4x4 bunches | 5.00E+10 | 16 | 448.0 | 2.00 | 1.91E+30 |
| 8x4 bunches | 5.00E+10 | 32 | 896.0 | 2.00 | 3.81E+30 |
| 43x43 | 5.00E+10 | 43 | 1204.0 | 1.34 | 5.13E+30 |
| 8 trains of 6 b | 8.00E+10 | 48 | 2150.4 | 1.79 | 1.33E+31 |
| 50 ns trains | 8.00E+10 | 96 | 4300.8 | 2.00 | 2.67E+31 |

$\beta^*$ = 2 m, nominal emittance

2 weeks between energy steps = 10 days + margin for MD, access etc

# 2011

## 3.5 TeV: run flat out at ~100 $pb^{-1}$ per month

| | No. bunches | ppb | Total Intensity | Beam Stored Energy (MJ) | beta* | Peak Lumi | Int Lumi per month [$pb^{-1}$] |
|---|---|---|---|---|---|---|---|
| 50 ns | 432 | 7 e10 | 3 e13 | 17 | 2 | 1.3 e32 | ~85 |
| Pushing intensity limit | 720 | 7 e10 | 5.1 e13 | 28.2 | 2 | 2.2 e32 | ~140 |
| Pushing bunch current limit | 432 | 11 e10 | 4.8 e13 | 26.6 | 2 | 3.3 e32 | ~209 |

With these parameters we should be able to deliver 1 $fb^{-1}$

# Summary

- To achieve an integrated luminosity of $1fb^{-1}$ in 2010/2011 we must reach a peak of luminosity of $2x10^{32}cm^{-2}s^{-1}$ in 2010.
- To do this there must be a rapid progression in stored beam energy in parallel to a lot of commissioning activities.
  - Much faster than in previous machines, with the potential to cause damage !
  - Coupled to an excellent machine uptime.

- The Accident
- The Repair and consolidation
- Hardware Commissioning
- First operation end 2009
- Chamonix10
  - Running in 2010-2011
  - LHC Upgrades
- After Chamonix
- Present status

- Beam is back
- Machine is highly reproducible
- Plan for first collisions at 7TeV cm by the end of March

Thank you

# A Question to better define the risk

- What exactly will happen if we have exceed the "limit" values for the splices while running at 3.5TeV/beam
  - New situation with pressure release valves
  - New dump resistors
  - New QPS protection
    - Fast intermagnet splice protection
    - Asymetric quench protection
  - Evaluation of the damage
  - Evaluation of the repair time

This question is being pursued following the LMC of 3 February

# Comparison of Scenarios

- Scenario 1 (Minimum Risk)
  - Probably the more efficient over the LHC lifetime
    - **+ ALARA**
    - **determine the needs for the shutdown (resources, coactivity etc)**
    - **Re-design/testing of the splices; timing is “reasonable”**
- Scenario 2 (Higher Risk)
  - Reduced running in 2010, long shutdown 2010-2011, delays operation at the highest energy
    - **-- ALARA**
    - **-- Urgently needs a more accurate measurement of warm resistance (thermal amplifier) which has not yet been developed**
    - **? --May need nearly as much shutdown time as scenario 1 and the repair is only good for 5TeV/beam**

What to do if we have an unforeseen stop e.g. S34 vacuum?

# To increase the PSB extraction energy

- PSB:
  - Main magnets
  - Main power supply
  - RF
  - Septa and kickers
- Transfer and measurement line
  - Magnets
  - Septa and kickers
  - Power converters
- PS injection:
  - Septum and kicker
  - Injection slow bump

NB: in this proposal the extraction energy for the ISOLDE beams is unchanged.

## **Special criteria** before any intensity increase,

- **Stability** is an issue for going above 0.25 MJ.
  - The **optics stability** should be better than about ~10%
  - The **orbit stability** should be better than <0.5 mm to 0.2 mm. (The actual tolerances would depend on the measured "n1" and on the collimator setting.)
  - **1-2 MJ of beam energy** is close to 1% of nominal performance.
    - The **MPS performance should be reviewed at this beam energy**.
- Bunch Spacing
  - For most of the time one could operate with **50-ns trains**, initially based on 6, and then 12 bunches per train (and not 36).

# Procedure

- How would the **green light for an intensity increase** be given?
  - The minimum running time at a given intensity is about **10 days with at least 10 fills/dumps**.
  - A **mini-review prior to every intensity step** would discuss any issue and document the decision.
  - There was the exception of requiring **at least 3-4 weeks of running at an intensity around 1-2 MJ**, possibly **in two different configurations** (43 bunches and trains).
  - The **losses** should always be small enough to avoid the risk of frequent quench.
  - A number of **tests or verifications are needed after each intensity increase**:
    - the **diagnostics** should be shown to be fully operational, and t
    - **beam cleaning** adequate.
    - **beam dump** would be tested at injection.
  - **Optics changes** like introducing a crossing angle or squeeze would **require additional verifications**, e.g. related to the collimation set up (to be adjusted), and to the asynchronous dump failure check