LHC Commissioning at Higher Energy

On Behalf of the whole LHC Team & International Collaborators

Paul Collier, Beams Department, CERN

Outline

- Run 1 Recap
- Long Shutdown 1
- Cool-down & Powering Tests
- Preparing for Beam
- Beam Commissioning

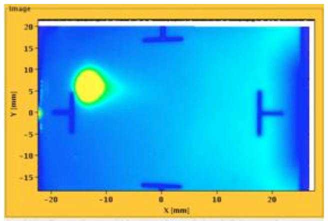
Acknowledgements

- To the many people who worked on the machine during LS1
- The teams from inside and outside CERN who contributed to the Hardware Commissioning and individual system tests
- … and the LHC teams who are working on the Beam Commissioning

All of whom have freely lent me information for this talk.

LHC Run 1 Timeline

August 2008
First injection test

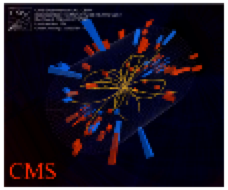


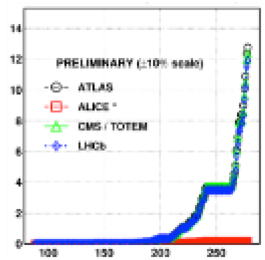
September 10, 2008
First beams around

September 19, 2008
Disaster
Accidental release of 600 MJ stored energy in one sector of LHC dipole magnets

November 29, 2009
Beam back

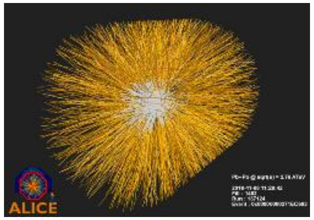
March 30, 2010
First collisions at 3.5 TeV





October 14, 2010
$1\times10^{+32}$, 248 bunches

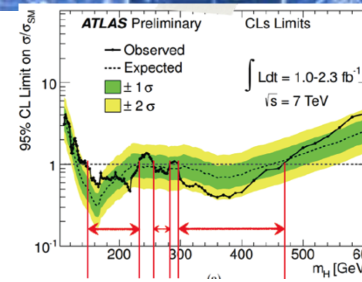
November 2010
First lead ion run



June 28 2011
1380 bunches

1380

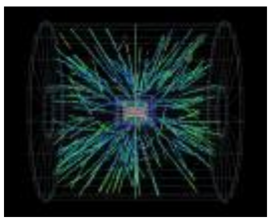
August, 2011
First Hints!



April 5, 2012
First collisions at 4 TeV

4 July, 2012
Higgs Discovery

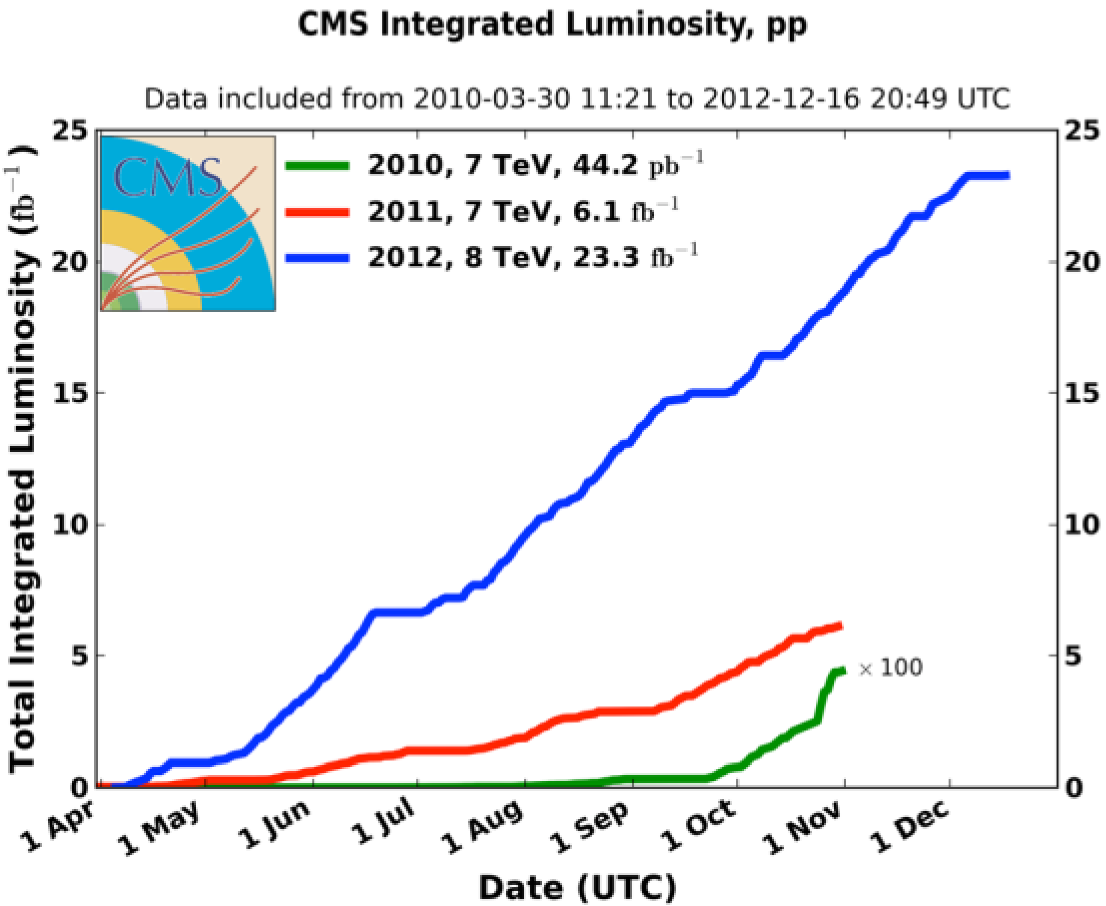
20 Jan, 2013
First Proton-Lead Collisions



14 February, 2013
Start of Long Shutdown 1 (LS1)

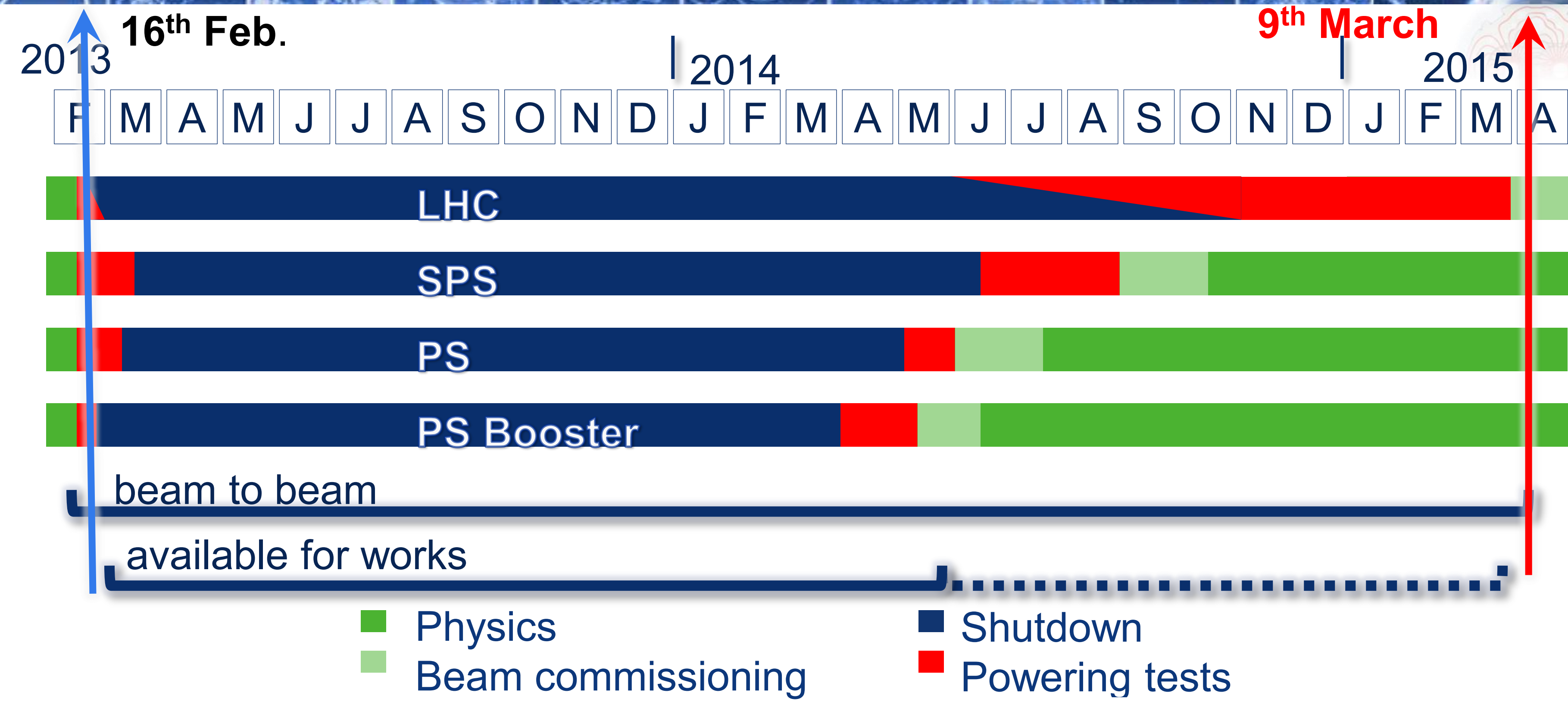
2008 | 2009 | 2010 | 2011 | 2012 | 2013

Performance, 2010-2012



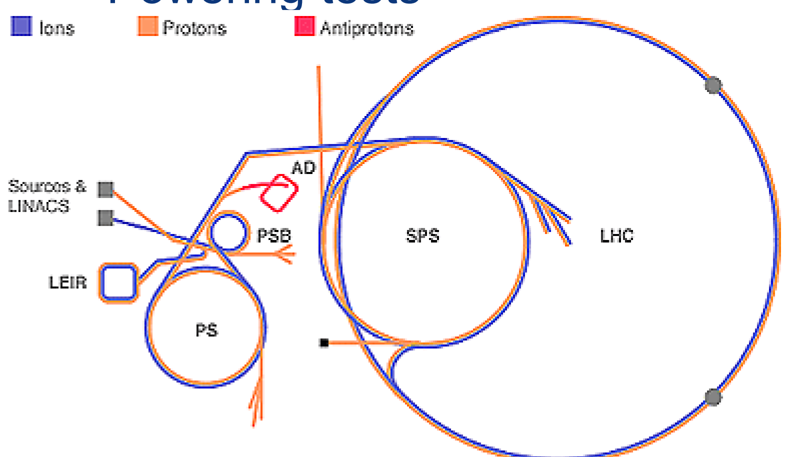
- **2010: 0.04 fb^{-1}**
  - 7 TeV CoM energy
  - Commissioning
- **2011: 6.1 fb^{-1}**
  - 7 TeV CoM energy
  - Exploring the limits
- **2012: 23.3 fb^{-1}**
  - 8 TeV CoM energy
  - Production

Long Shutdown 1: Feb 2014-April 2015



Over 1 Million Hours Worked in the LHC Tunnel

Safety First,
Quality Second,
Schedule Third.



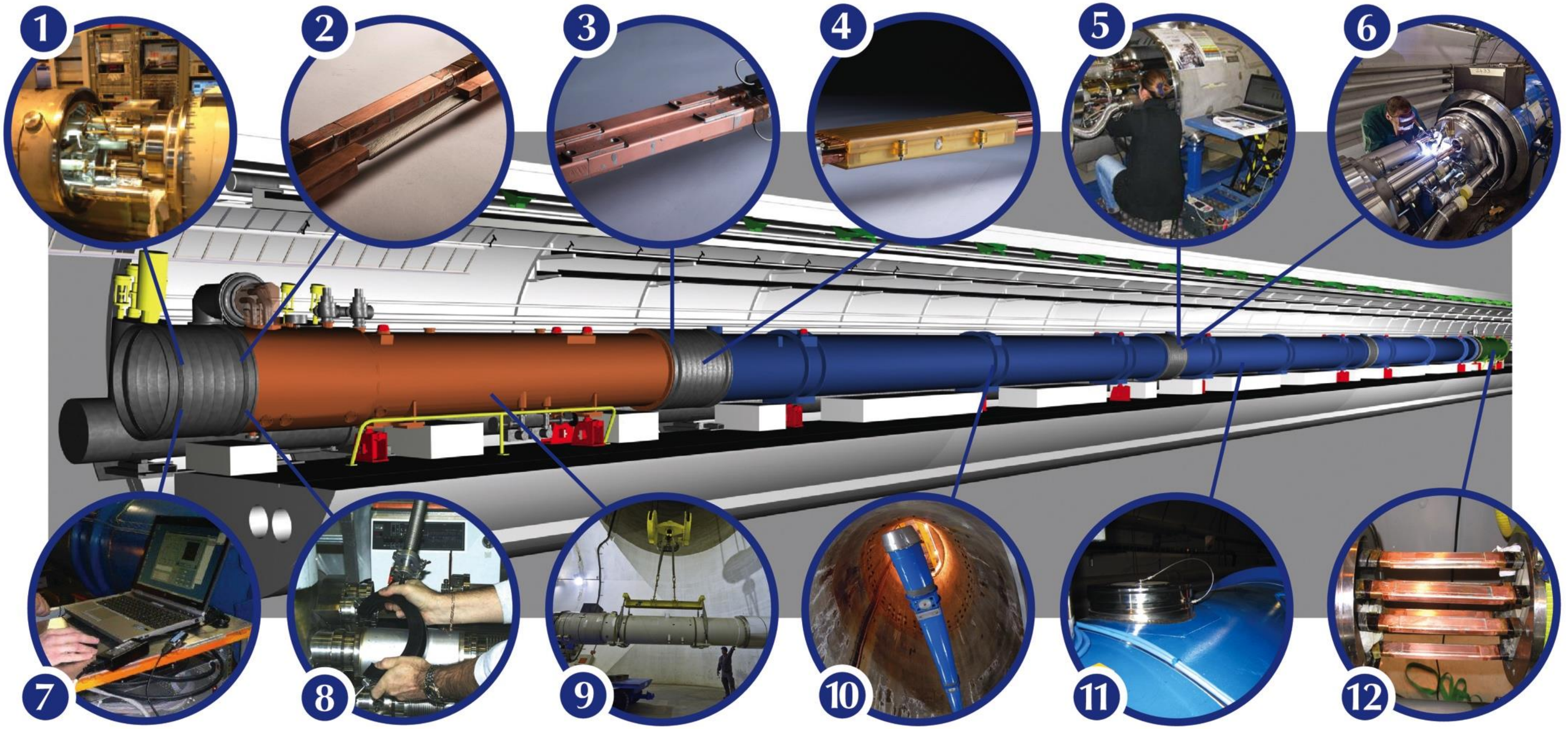
LS1 Main Activities

- Repair and consolidation of the magnet interconnections,
- Replacements of 'weak' magnets,
- Relocation of electronics to reduce the impact of radiation (Single Event Upsets),
- General maintenance of the cooling-ventilation system and of the cryogenic plants,
- Upgrades, changes and fixes in essentially all systems !

After LS1 we have a 'new' machine
(but with experience on how to run it !)

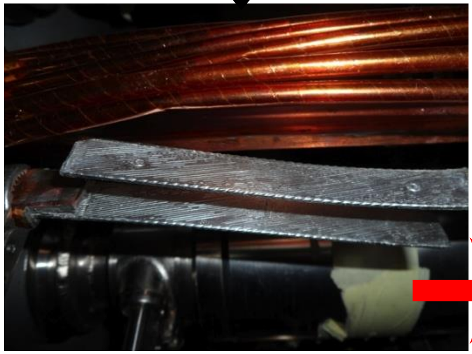
The Main LHC Consolidation

1. 1695 Openings and final reclosures of the interconnections
2. Complete reconstruction of 3000 of these splices
3. Consolidation of the 10170 13kA splices, installing 27 000 shunts
4. Installation of 5000 consolidated electrical insulation systems
5. 300 000 electrical resistance measurements
6. 10170 orbital welding of stainless steel lines

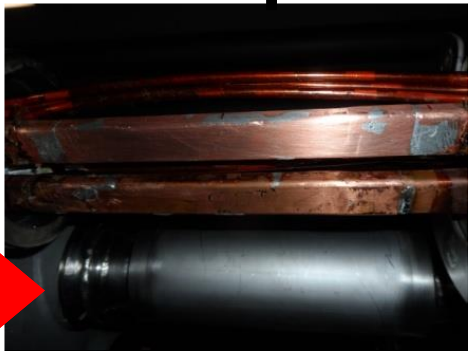


7. 18 000 electrical Quality Assurance tests
8. 10170 leak tightness tests
9. 3 quadrupole magnets to be replaced
10. 15 dipole magnets to be replaced
11. Installation of 612 pressure relief devices to bring the total to 1344
12. Consolidation of the 13 kA circuits in the 16 main electrical feed-boxes

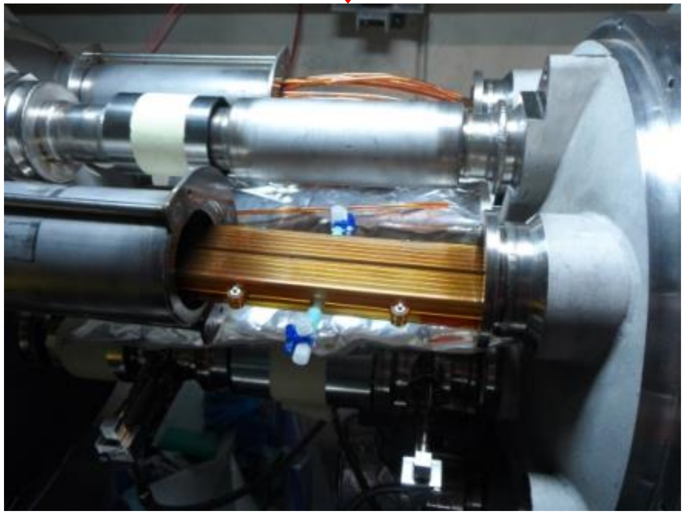
13kA Busbar Splices



« Cables »



« New Splice »

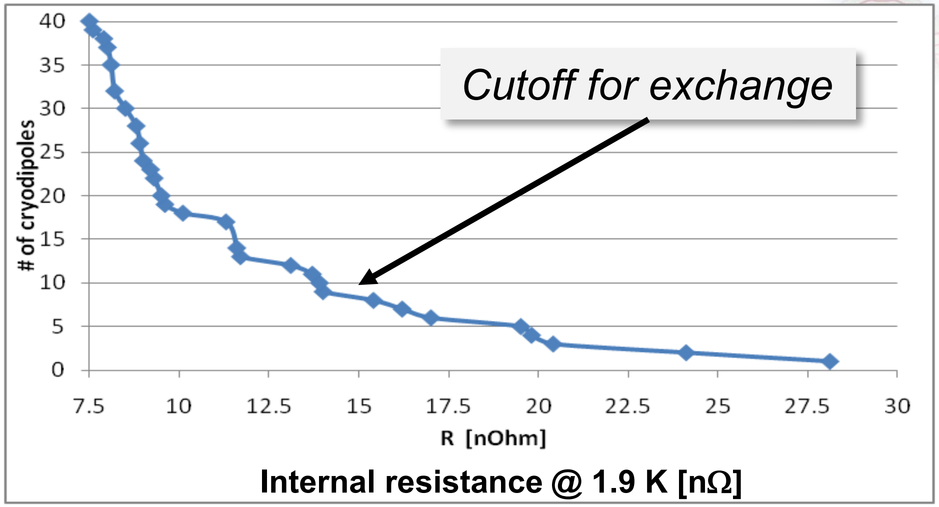


« Insulation box »

- **Total interconnects in the LHC:**
  - **1,695 (10,170 high current splices)**
- **Number of splices redone: ~3,000 (~30%)**
- **Number of shunts applied: > 27,000**

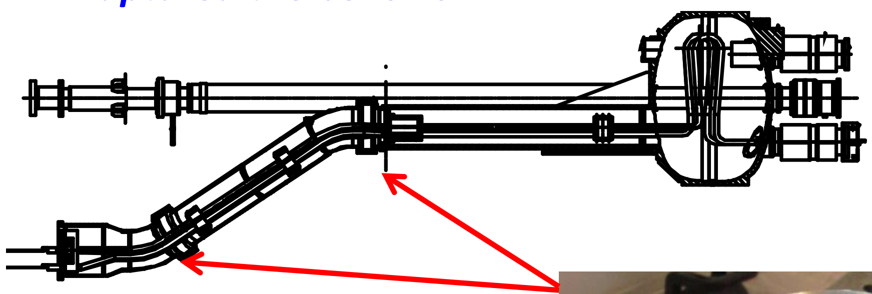
Magnet Exchange

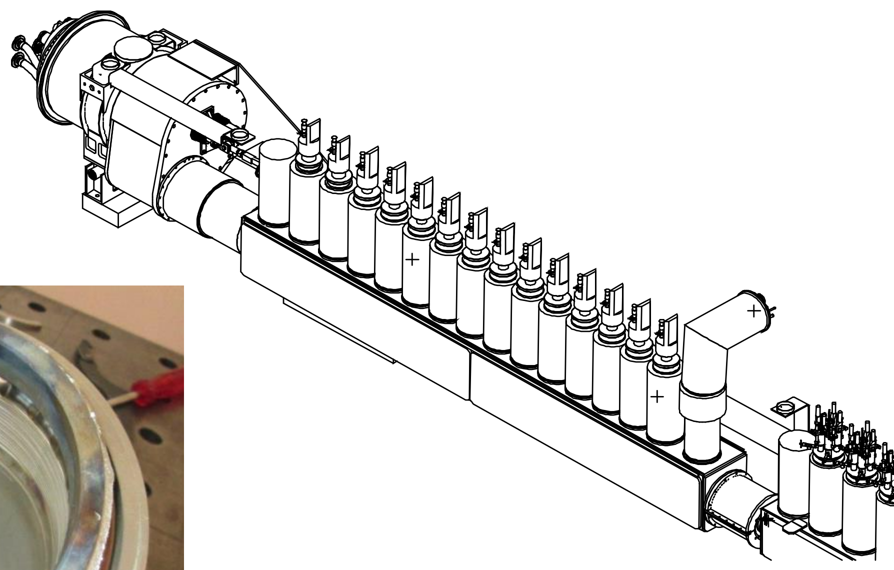
- 18 cryo-magnets were exchanged:
  - *Large internal resistance @ 1.9 K.*
    - Confirmed by inspections: imperfect soldering.
  - *Problems with quench protection, electrical isolation.*
- 15 additional magnet will be exchanged in LS2 (2018).

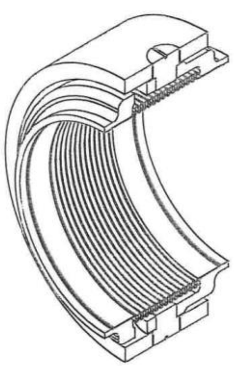


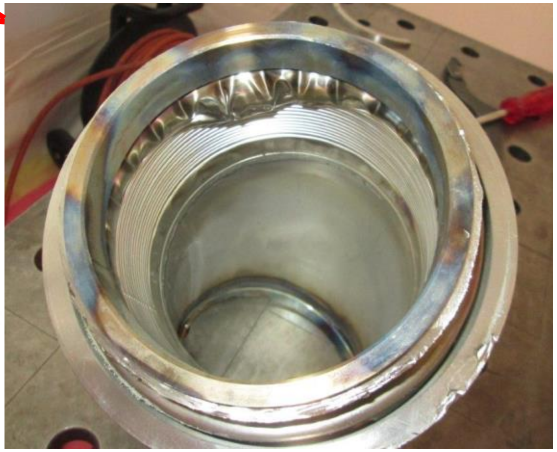
Unexpected Issues

- **After warm up a problem was diagnosed on some bellows inside the Cryogenic Feed Boxes (DFB).**
- **Bellows were found 'imploded' on 4 of them, 2 requiring repair on the surface in a workshop.**
    - ***Cold Helium most likely diffused (through cracks in the welds) between the sheets of the multi-sheet bellows. During warm up the Helium was trapped, building up an over-pressure that ruptured the bellows.***

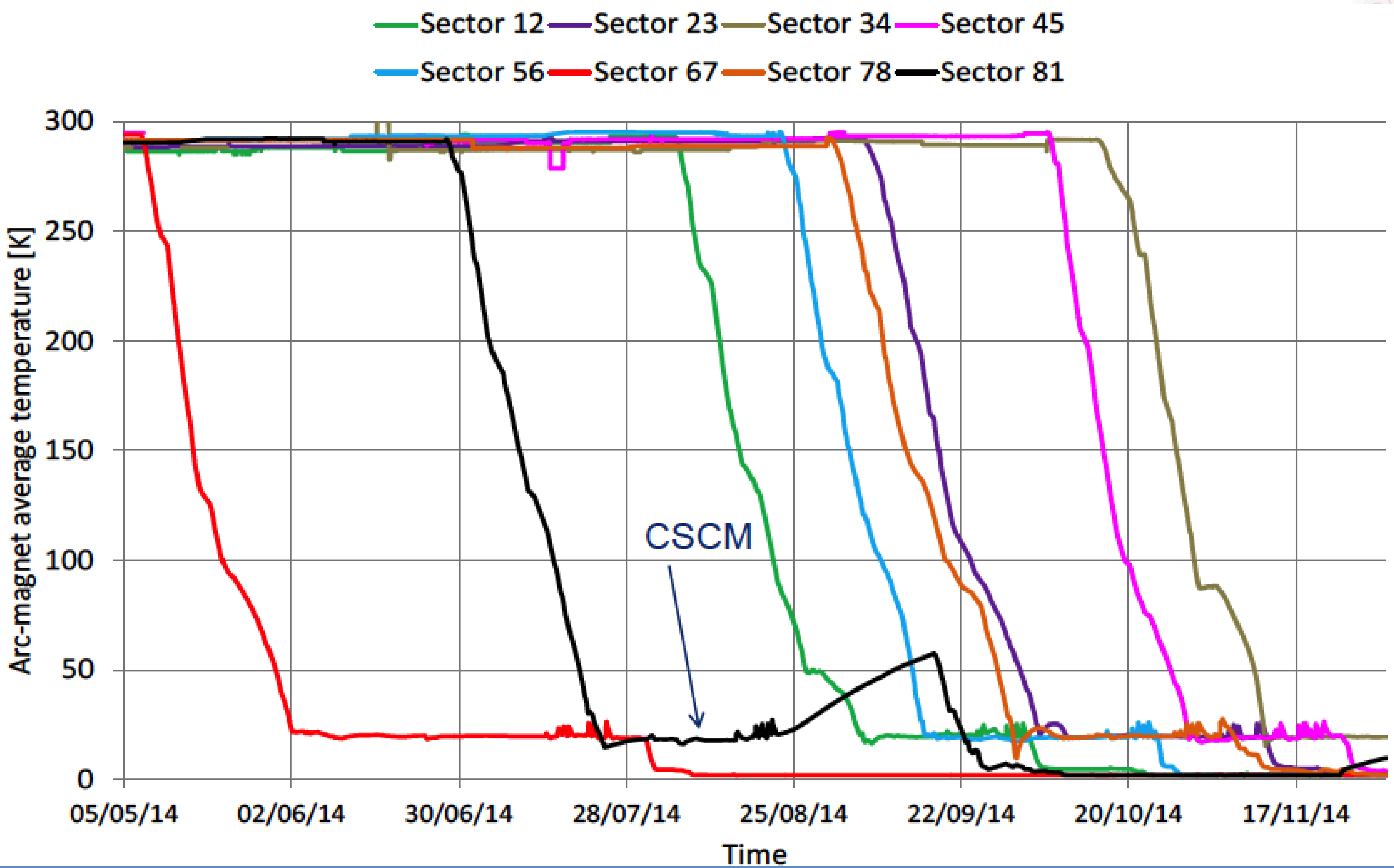






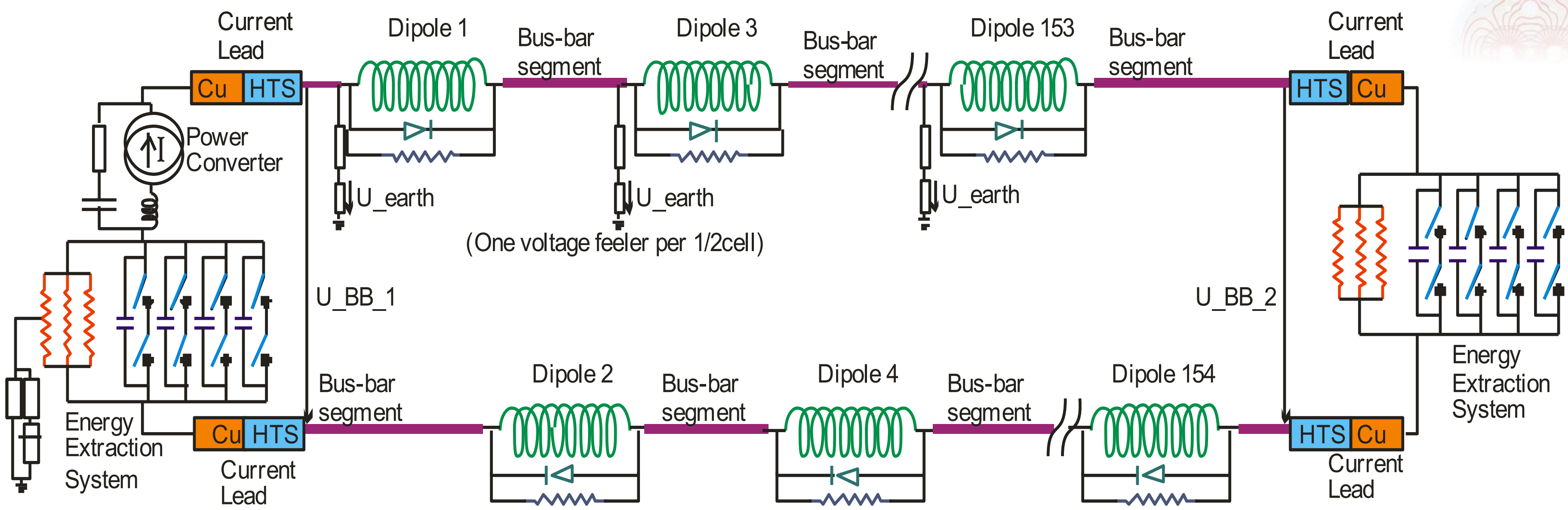


Cool Down



10,000 t of Nitrogen to pre-cool the machine, 130 t LHe Inventory

Copper Stabiliser Continuity Measurement (CSCM)



- Each of the large dipole and quadrupole circuits have a large number of discontinuities which can be external or internal to the magnets.
  - *The 8 dipoles circuits have ~28'000 discontinuities !*
- The discontinuities between magnets (interconnects) as well as the bypass diodes of the quadrupoles were checked and consolidated during LS1.
- The main unchecked discontinuities were in the dipole bypass diodes.
  - *New test developed to test the whole of the bus-bar part of the circuit - CSCM*

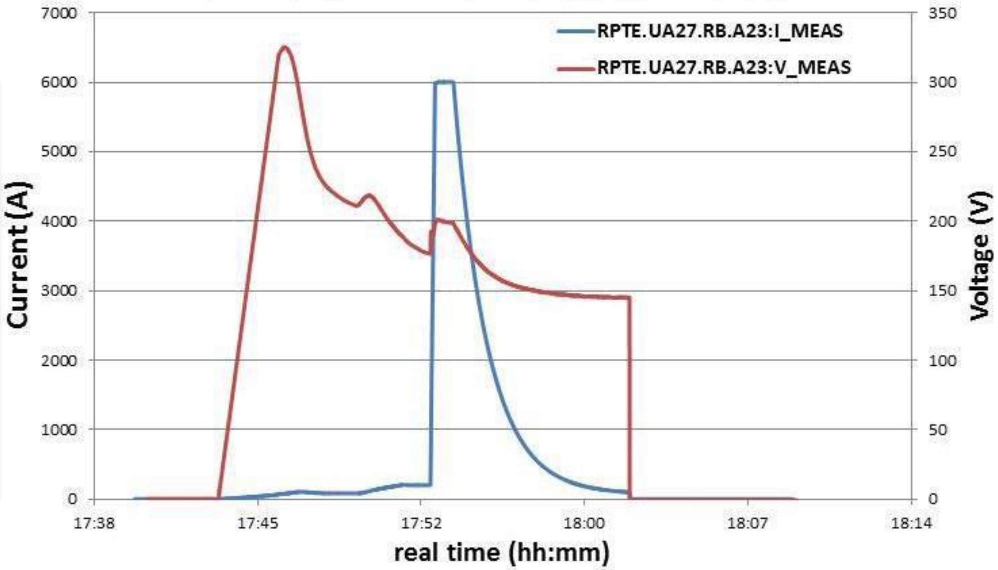
CSCM Tests

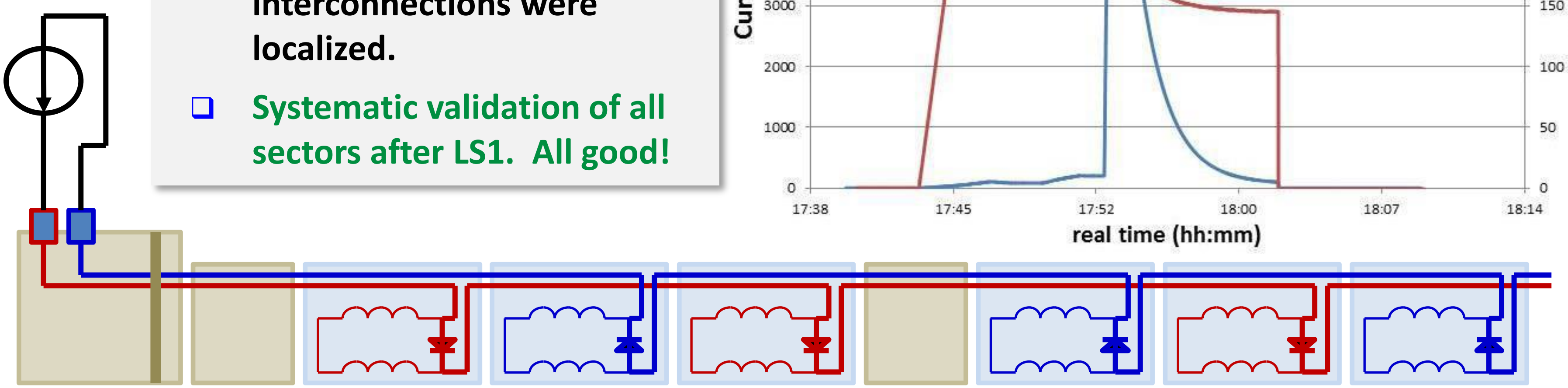
The CSCM is a test to fully qualify the complete bus-bar of the main dipole circuits and ***ensure*** that the current can safely bypass the magnets in case of a quench.

- Stabilize a sector around 20 K, ***the magnets and bus-bars are not superconducting***.
- Reconfigure the power converters: 2, 6kA/200 V in series (→ 400V)
- Use a Voltage pulse to fire all the diodes in the circuit
- Send a current pulse of up to 11 kA (then decay with τ = 100s).
- Excessive resistance leads to thermal run-away and increasing voltage → observe voltages over interconnections.

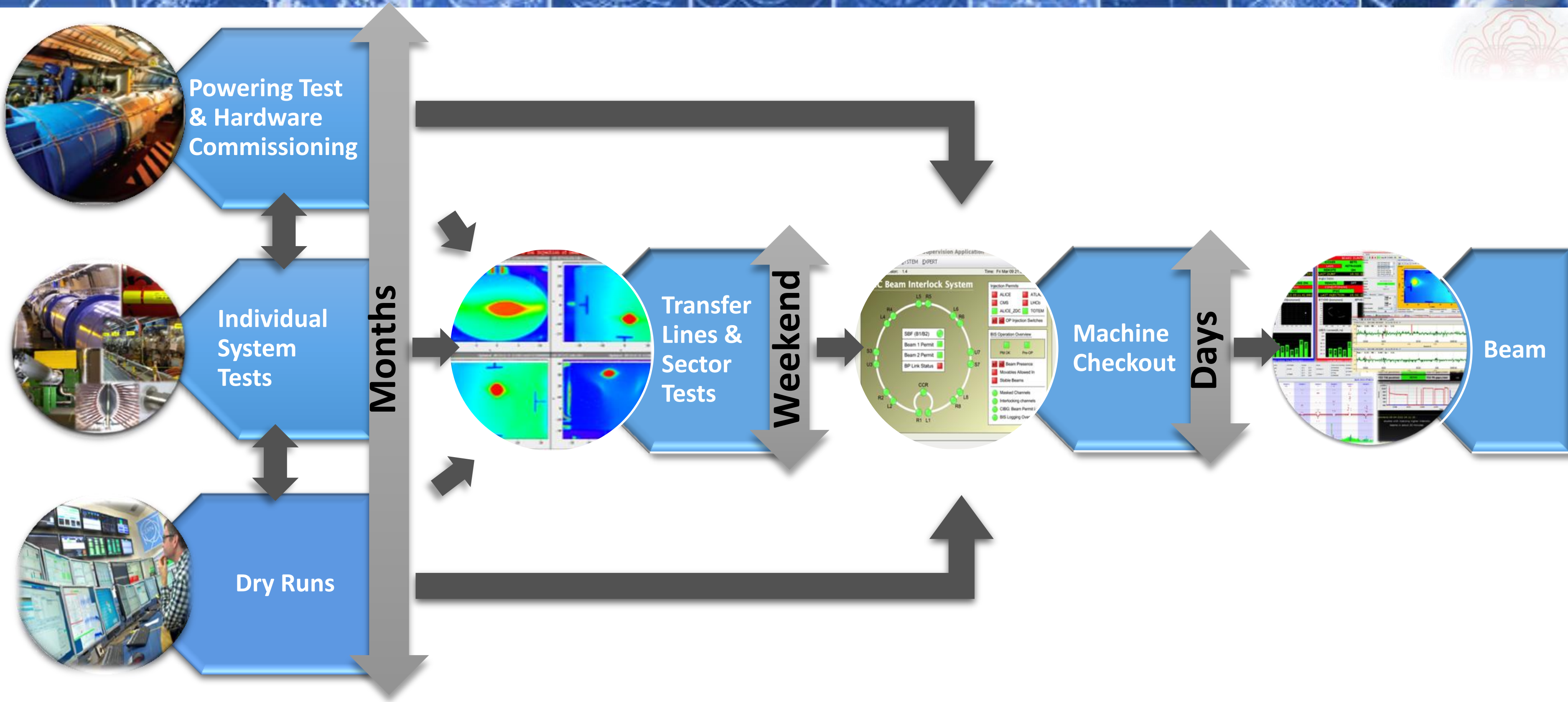
Status

- Type test in one sector before LS1, Three bad interconnections were localized.
- Systematic validation of all sectors after LS1. All good!





Preparing for Beam



Powering & HWC :

- ✧ Covers SC and Warm Magnet circuits (& associated protection systems)

Individual System Tests:

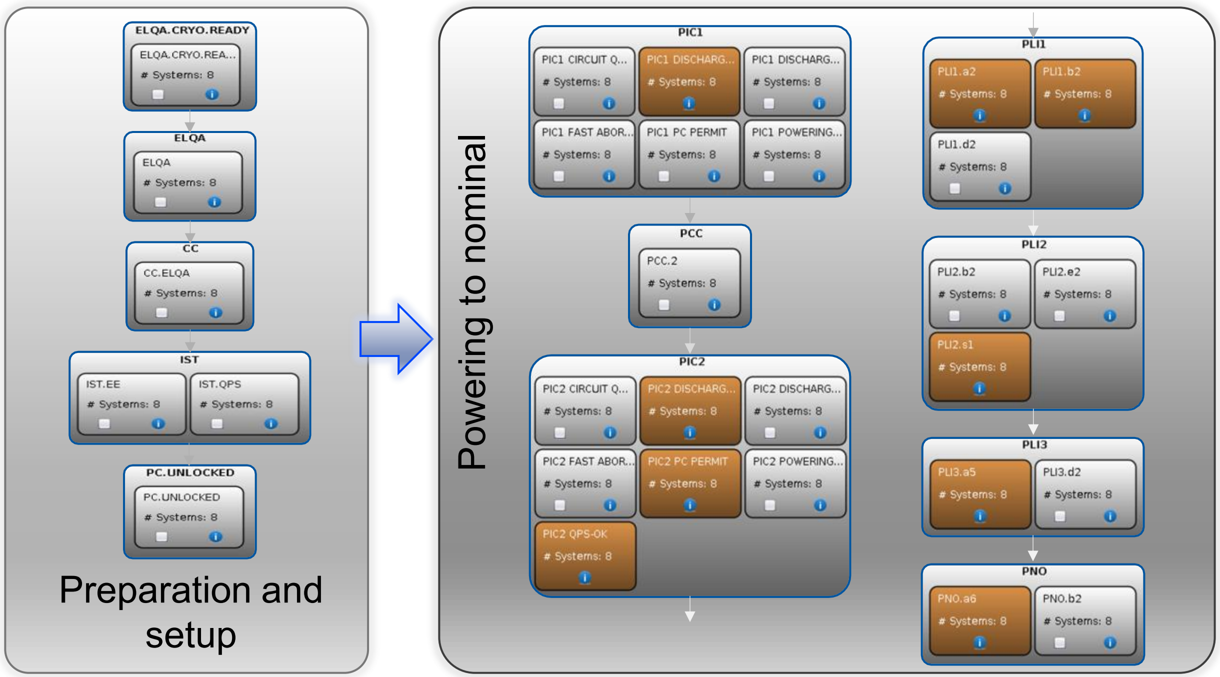
- ✧ Everything else. E.g. RF, BI, Vacuum, Injection & Dump systems,

Dry Runs:

- ✧ Integration of systems into operational processes

Powering Tests

- Electrical Quality Assurance (ElQA = check of insulation integrity) followed by a series of current cycles to test the powering interlocks, the protection functionality and the capability of all magnets to reach the requested current



Example of the testing flowchart for the RB circuits

What was tested?

Almost 1600 circuits

- **24 Main circuits**
  - **8 dipoles**
  - **16 quadrupoles**
- **8 Inner Triplets**
- **94 Individually Powered 4-6 kA circuits**
  - **78 IPQs**
  - **16 IPDs**
- **410 x 600 A circuits**
- **284 x 80-120A circuits**
- **752 x 60 A circuits**

A total of **more than 6000 interlock test steps + 11,000 test steps** with current in about 5 months!!

Powering Tests

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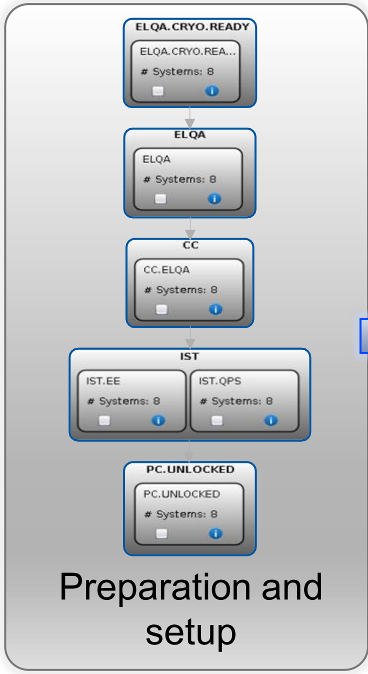

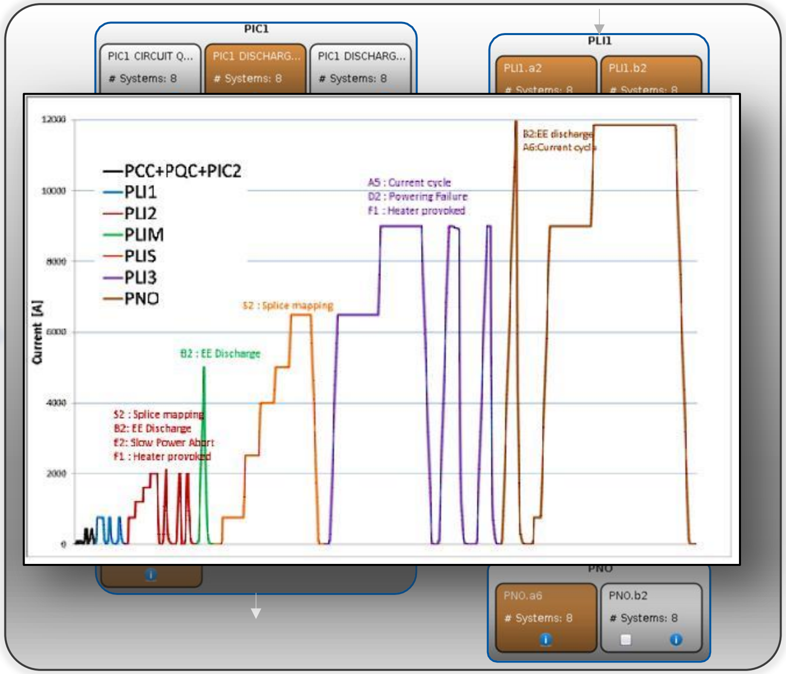

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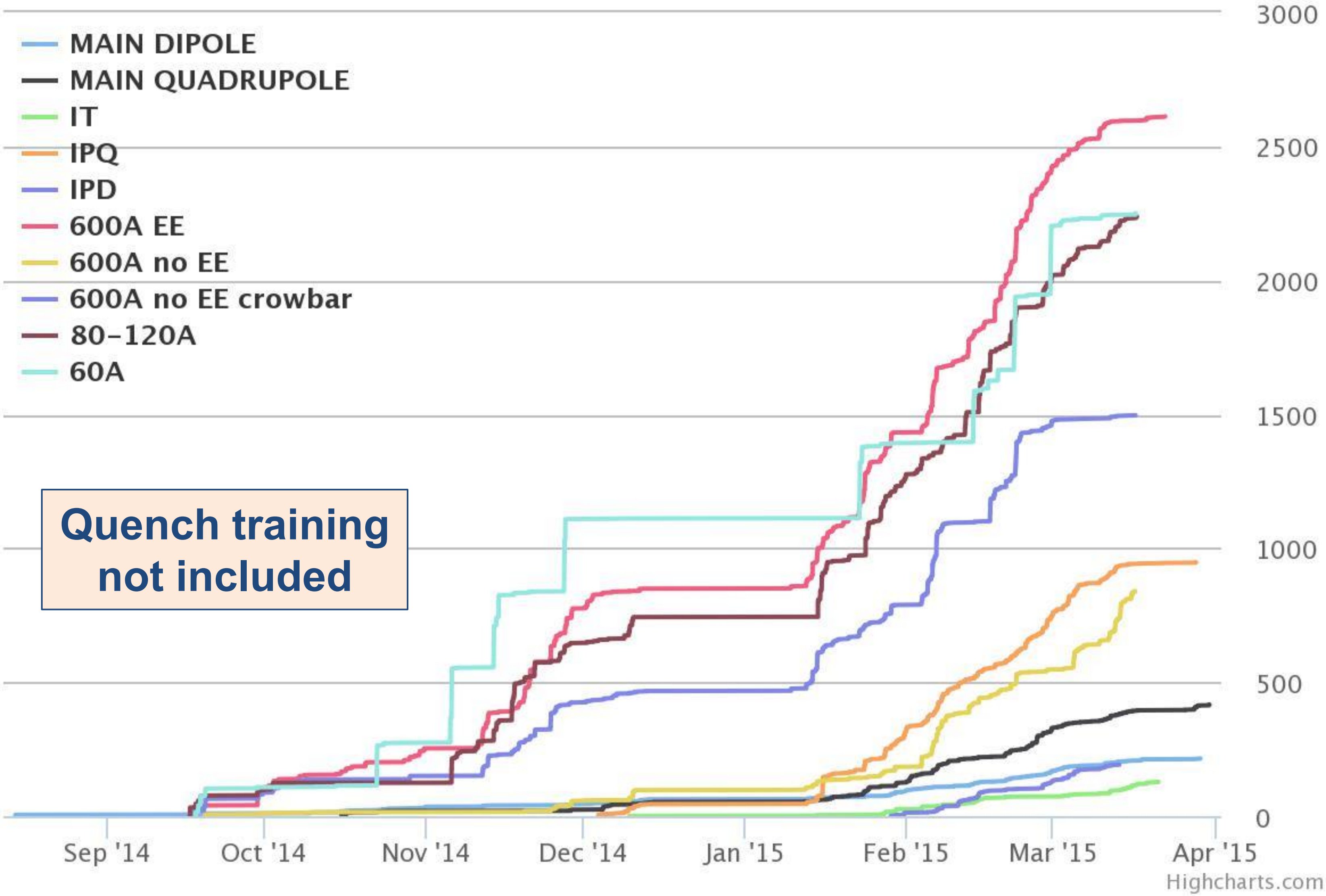
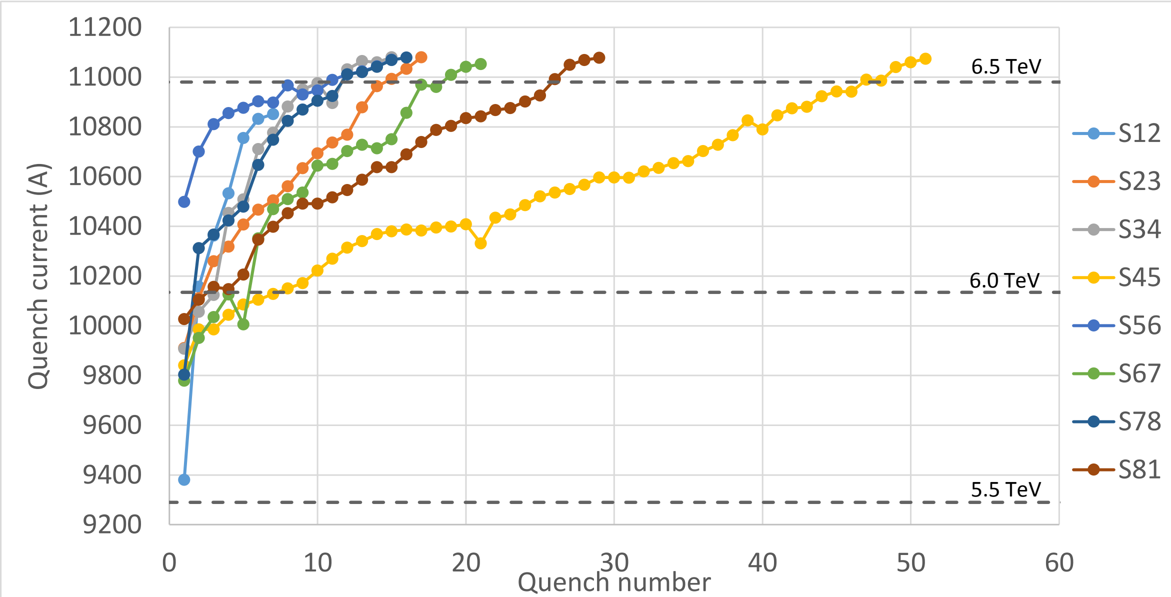
Powering Tests



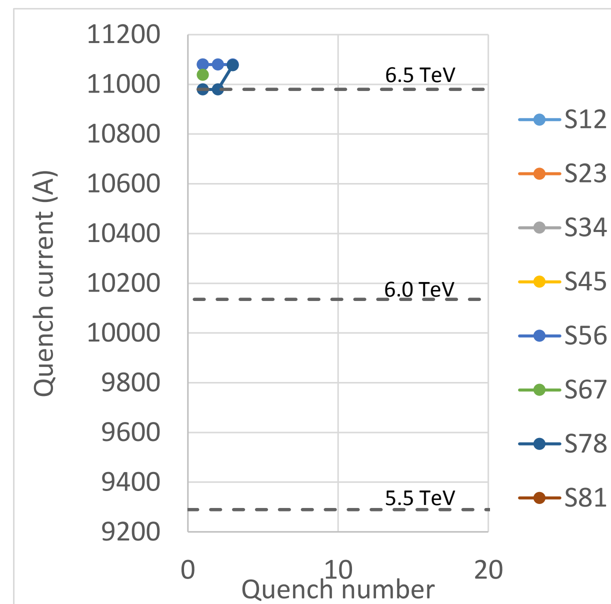
Quench training not included

Dipole Training Campaign



Each Sector Trained to 6.56TeV (11080A)
(100 A above the operational field)

A few quenches at flat top, after training



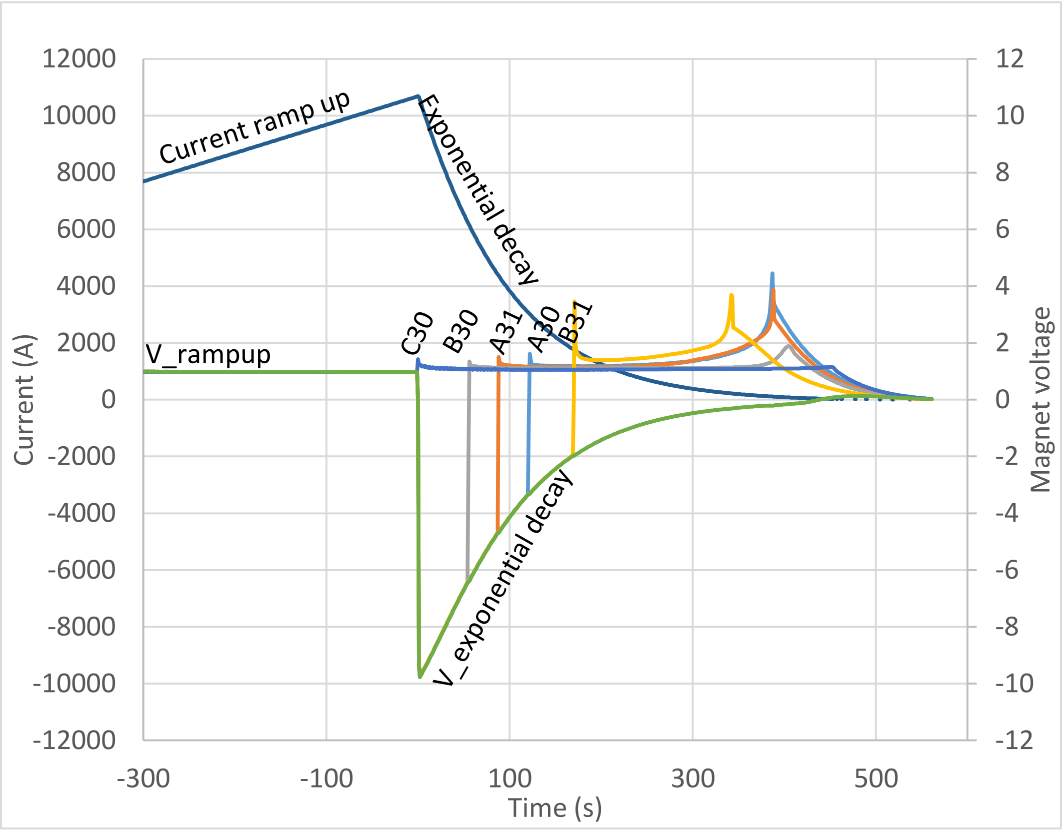
Sector	# Training quench	Flattop quenches
S12	7	0
S23	17	0
S34	15	1
S45	51	0
S56	18	3
S67	22	1
S78	19	3
S81	29	0
Total	171	8

Large variation in number of training quenches per sector, between 7 and 51 quenches!

Detailed Analysis in Progress!

Quench Propagation

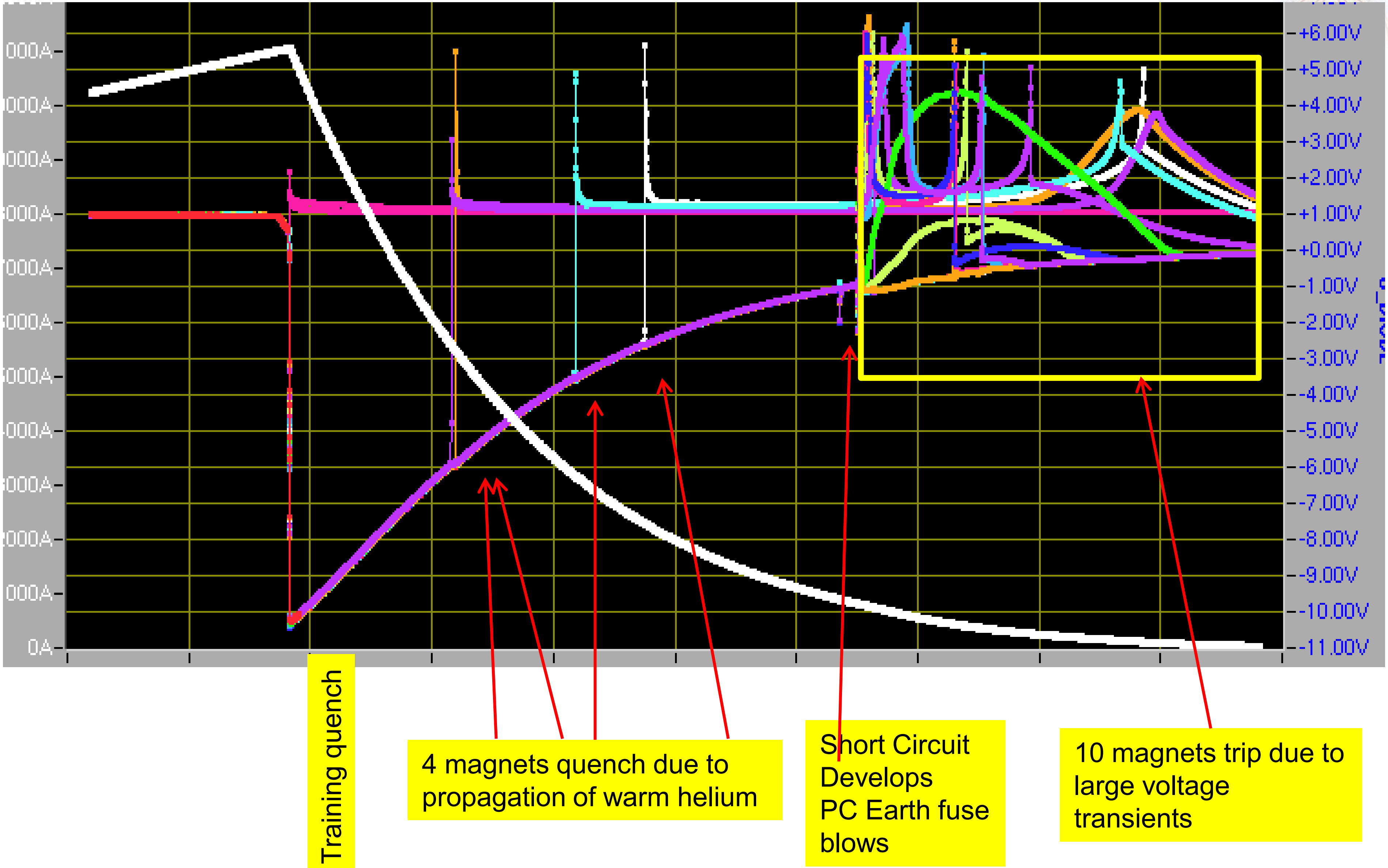
Typical quench event during the HWC campaign (sector 8-1, position C30)



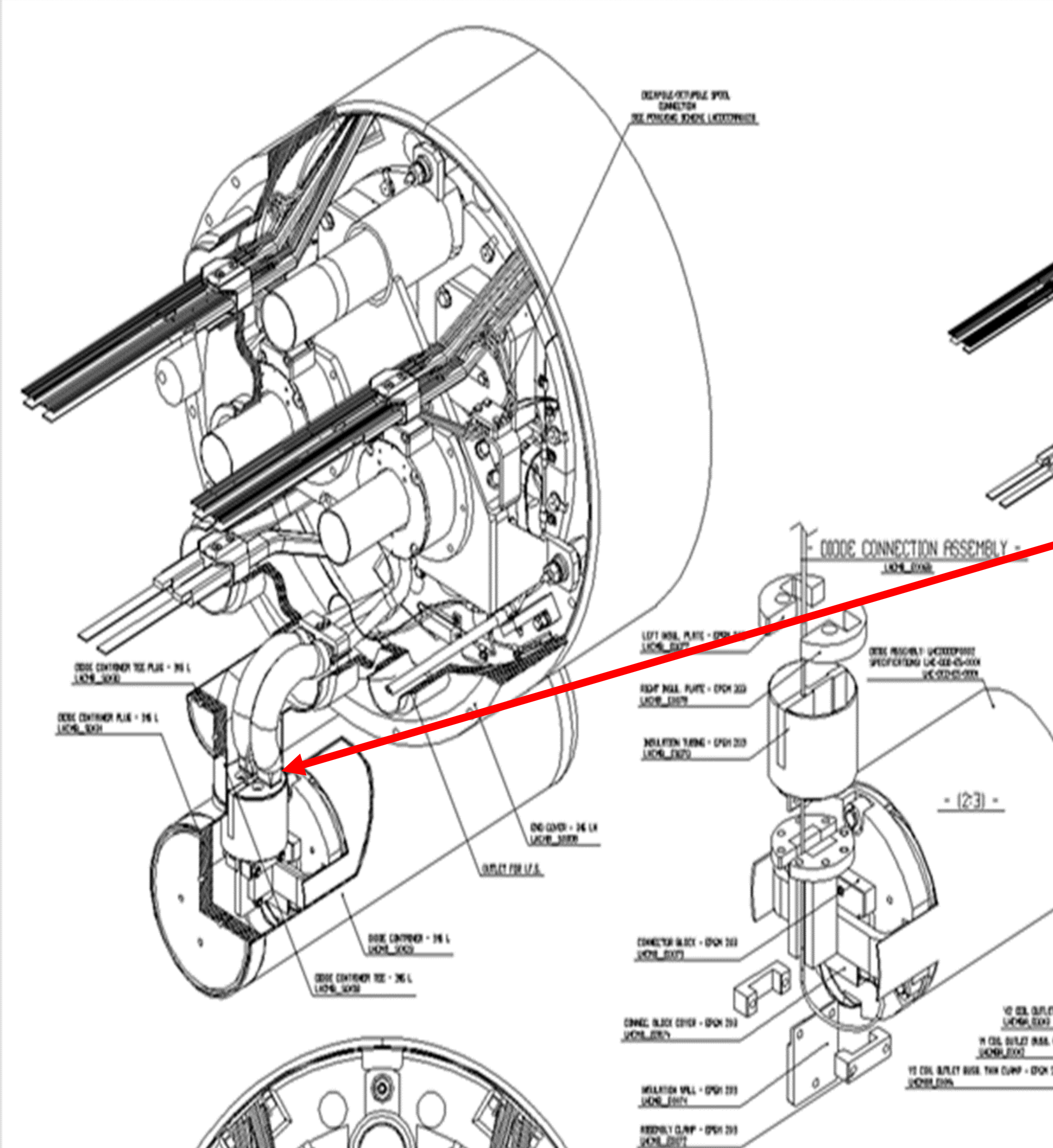
- **154 magnets in series**
- **Quench in a magnet triggers energy extraction opening. Current in the circuit decays exponentially with $\tau = 100$ s.**
- **Negative inductive voltage across each <u>superconducting magnet</u>.**
- **Positive voltage across <u>quenched magnet</u> when current goes through bypass diode.**

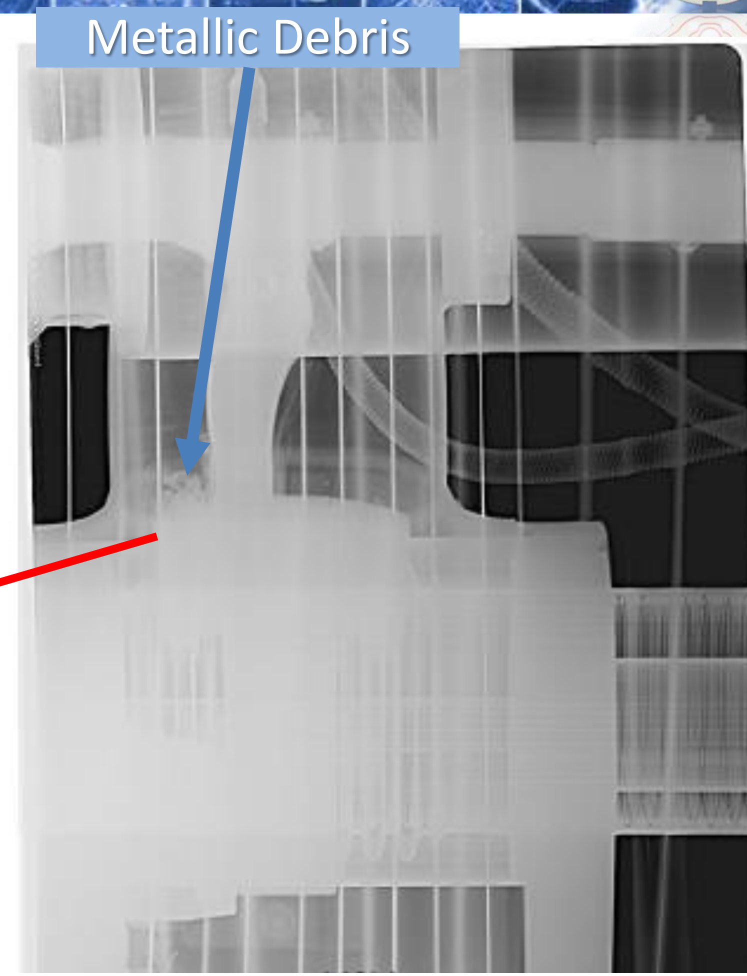
Typically a training quench is followed by secondary quenches through heat propagation.

Short Circuit in a Main Dipole (sector 3-4)



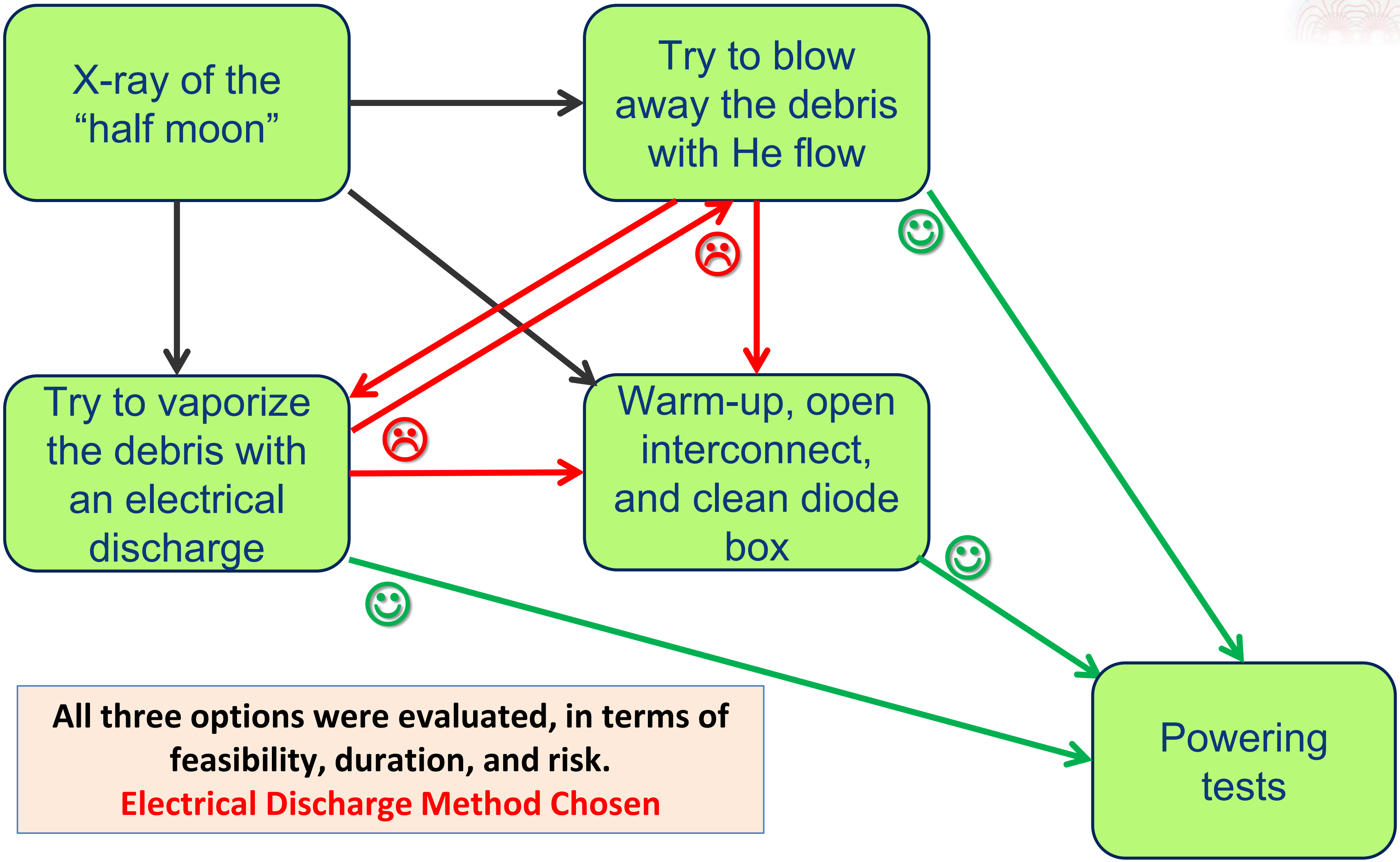
Diode Short-Circuit



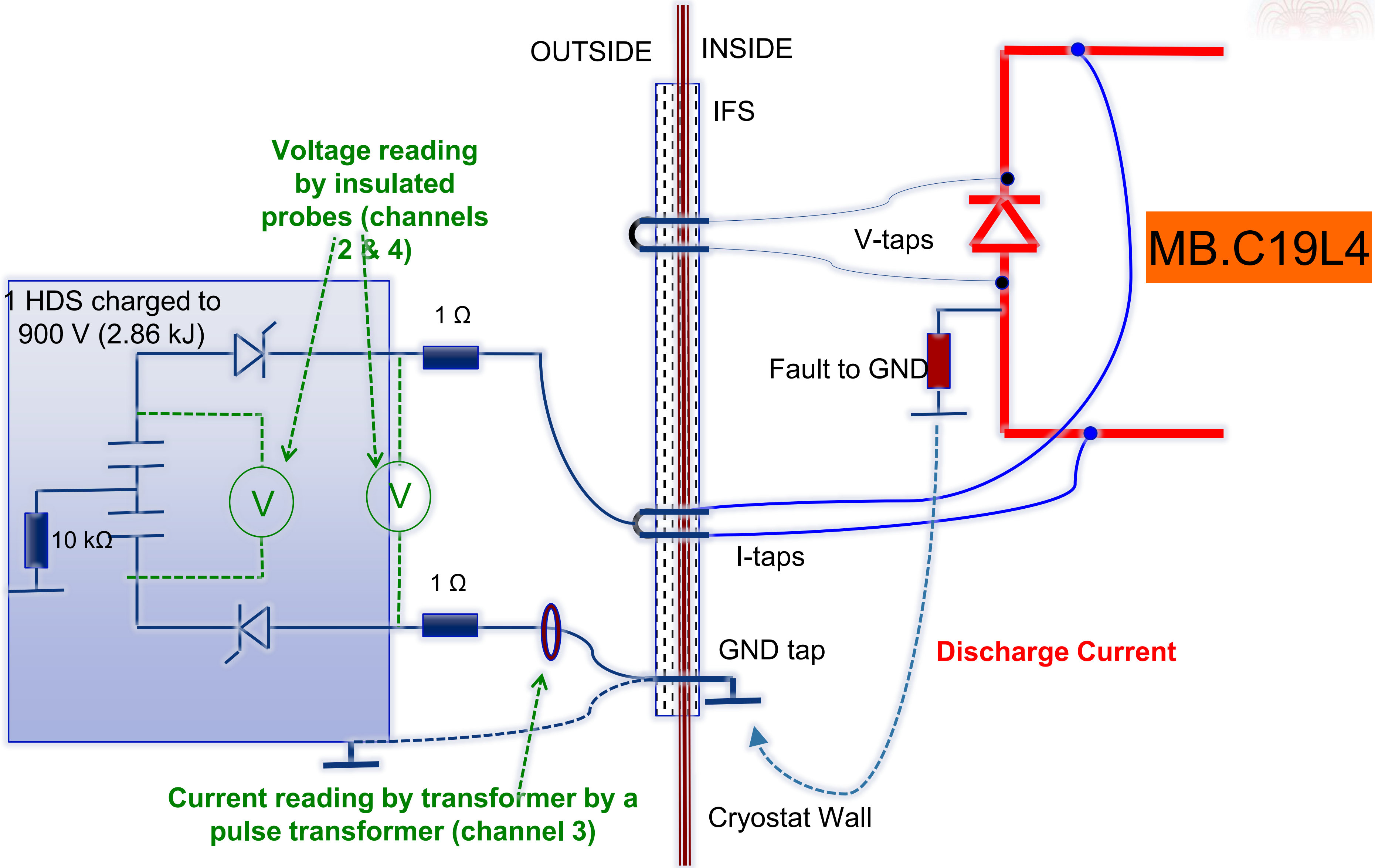


Unfortunately can not see the debris in the affected magnet

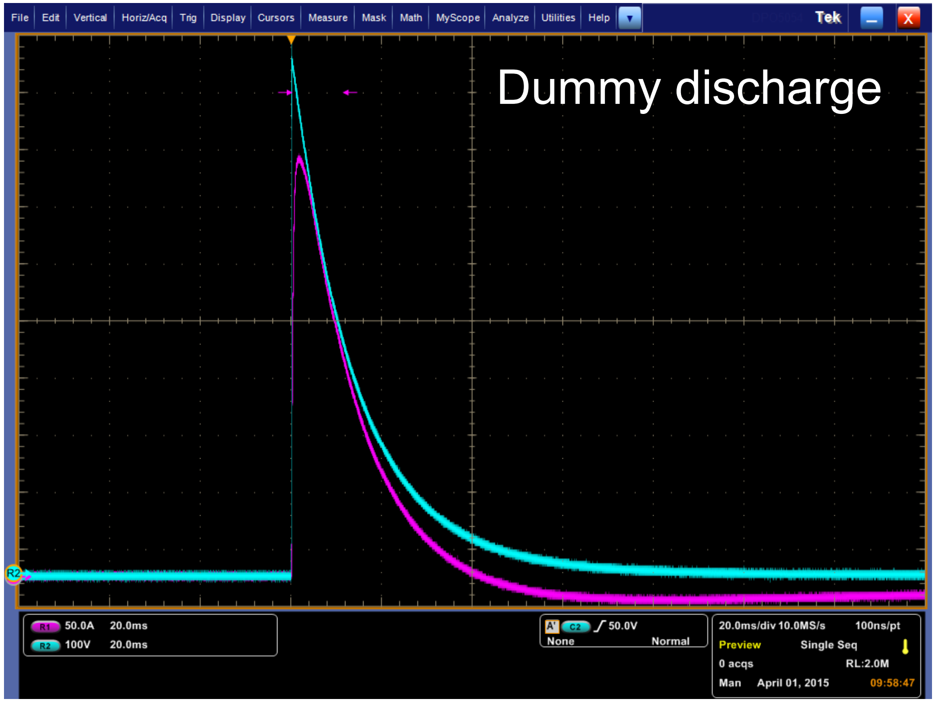
Next Steps

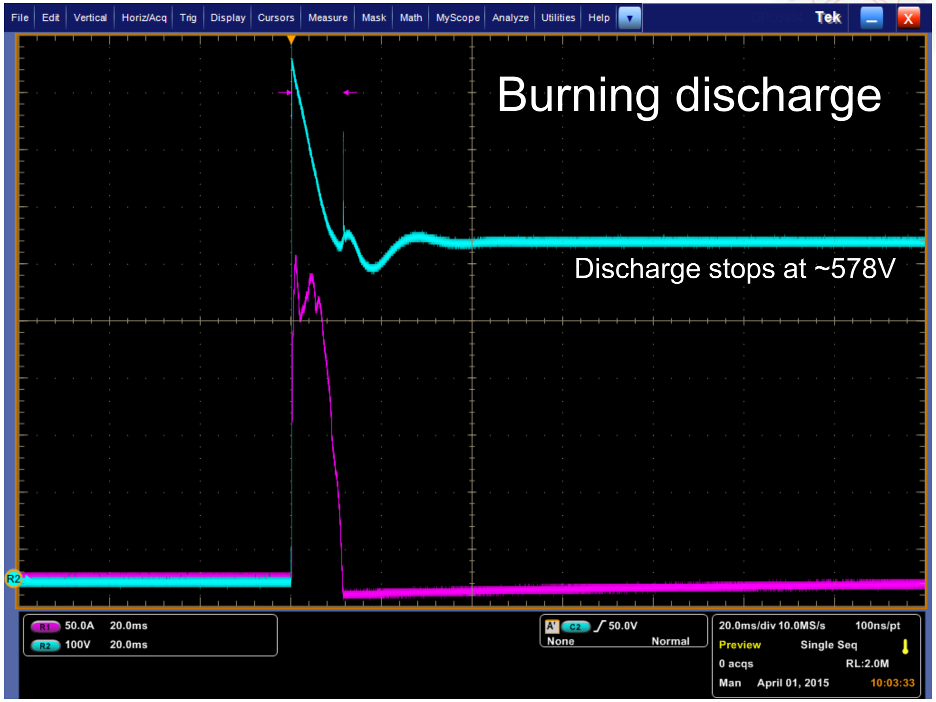

X-ray of the "half moon"
Try to blow away the debris with He flow
Try to vaporize the debris with an electrical discharge
Warm-up, open interconnect, and clean diode box
Powering tests
All three options were evaluated, in terms of feasibility, duration, and risk.
Electrical Discharge Method Chosen

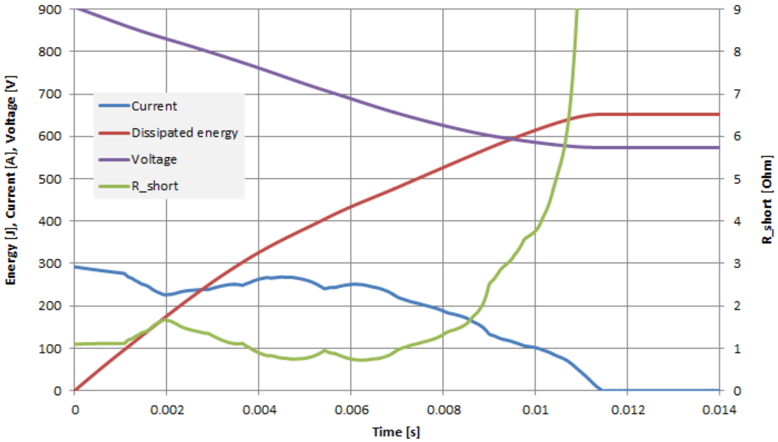
Discharge Set-Up



How It Worked

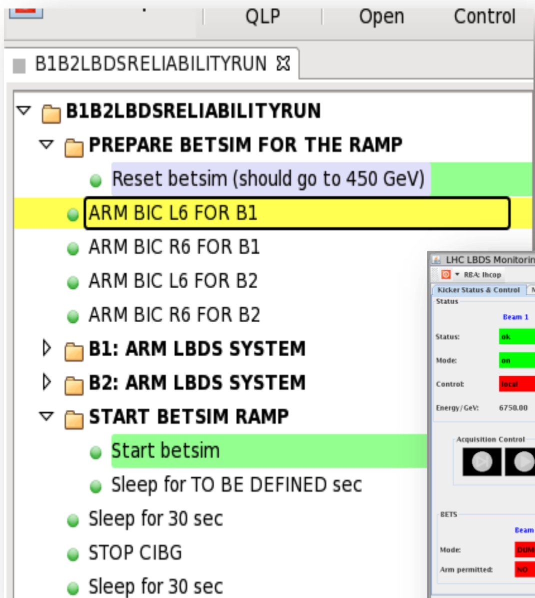






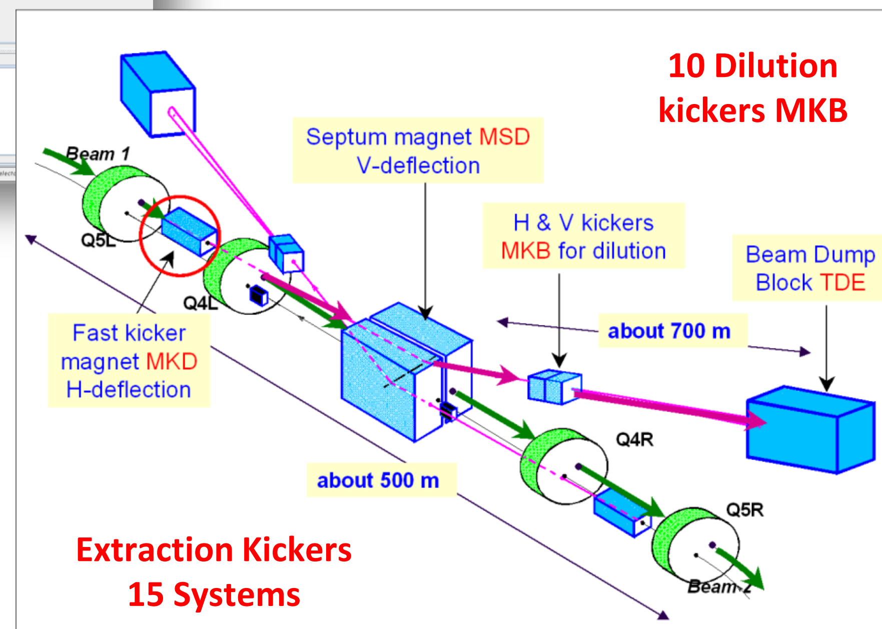
Discharge time:	**~11.5 ms**
Discharge voltage:	**906 V to 578 V**
Dissipated energy:	**~1.5 kJ**
Balancing resistors:	**2x1 Ohm**
Short resistance:	**~1 Ohm**
Energy dissipated in short:	**~500 J**

Dry Runs



Beam dump reliability run

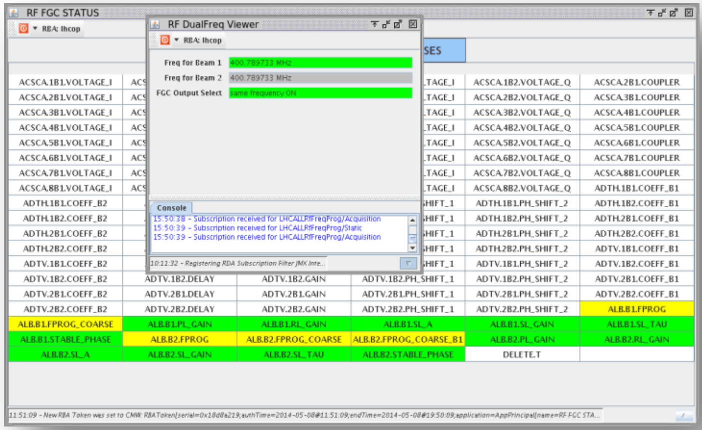
Early test campaigns of operational procedures by OP team from the control room



Remote reliability run:

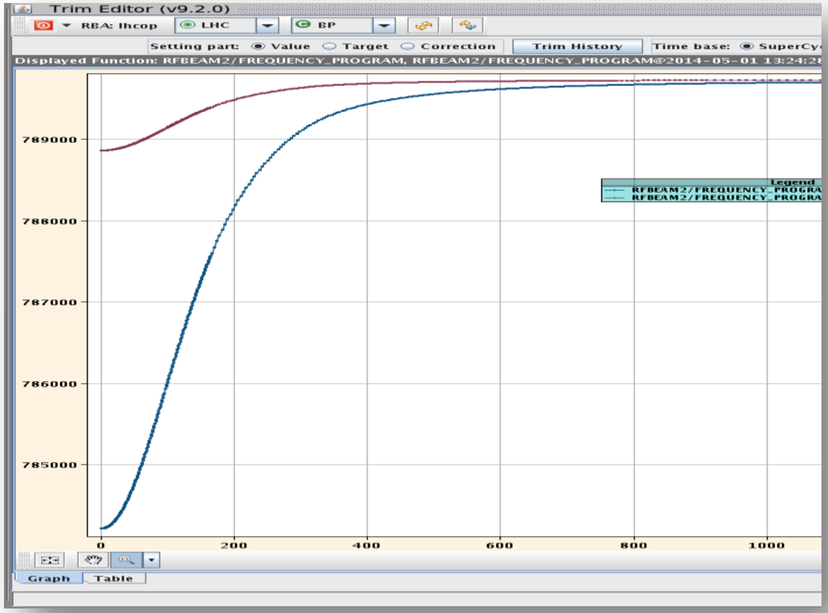
- New arming sequence
- With local Beam interlock loop
- Energy ramp with energy tracking simulator
- Sequence to arm/ramp/dump that was played in a loop for several weeks.

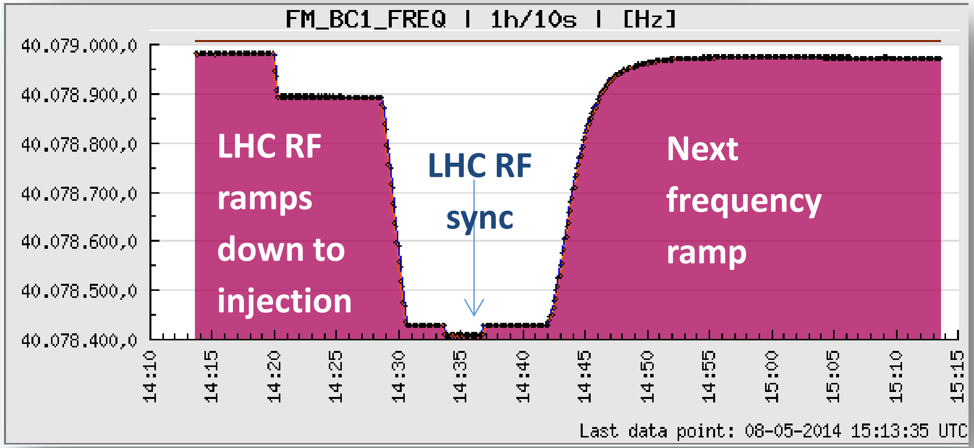
RF Synchronization & Frequency Ramp



Frequency monitoring Checks

Proton and ions frequency settings for 6.5 TeV ramp





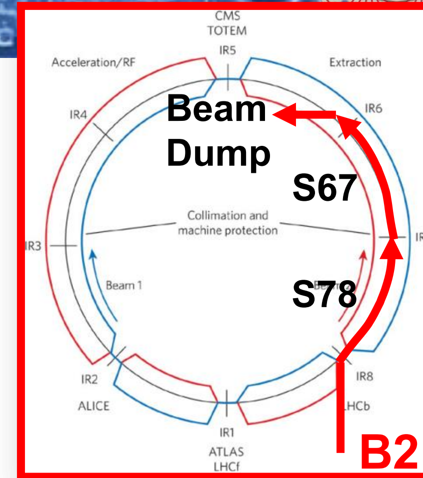
Ensure:

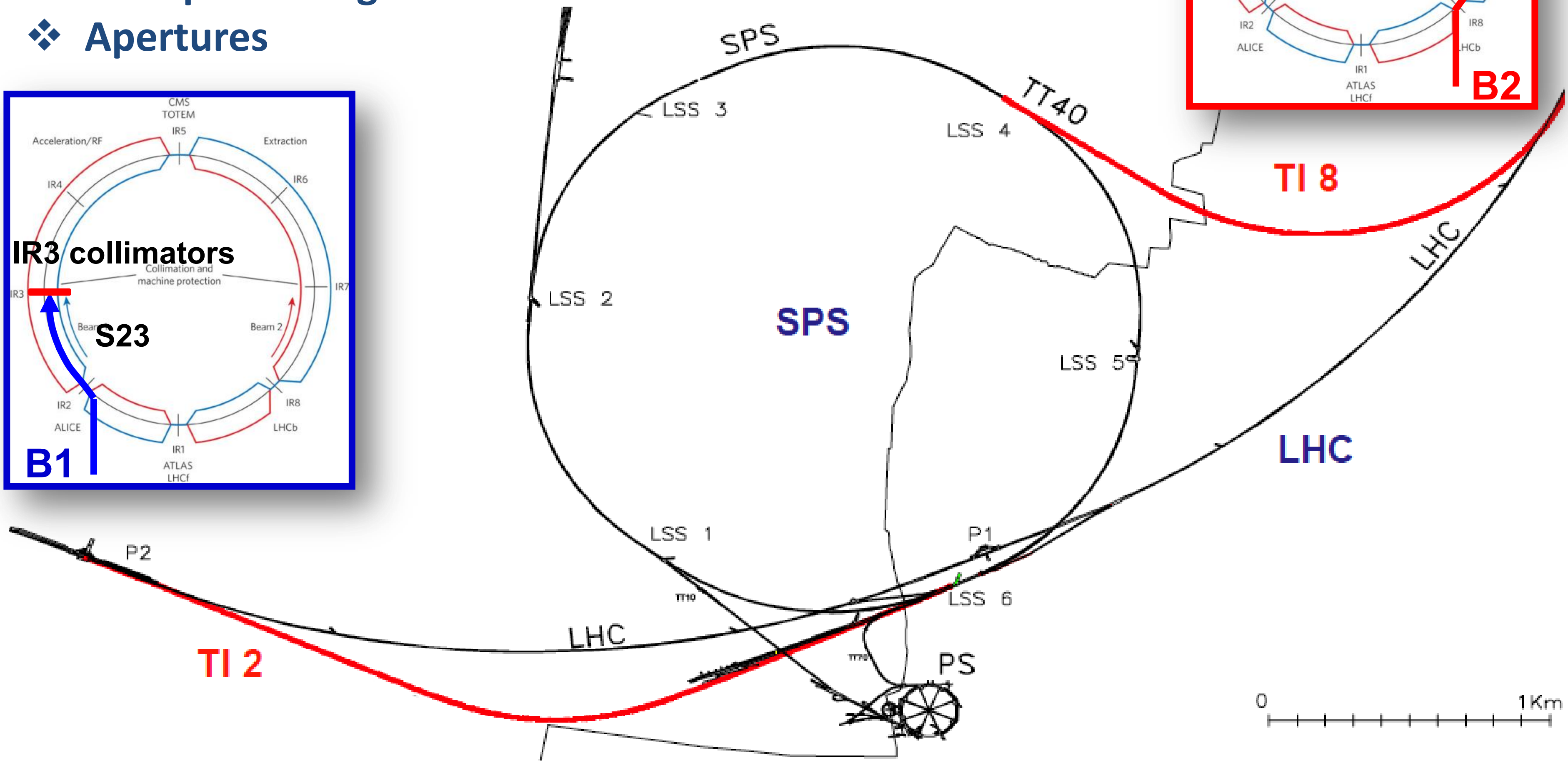
- **Frequency is properly received by the experiments**
- **Resynchronisation of beam control successful.**

Sector Tests

The Beam is the Best Diagnostic tool!

- Test beam transfer and Synchronization
- Linear Optics Checks (TL+ Ring Matching)
- Pickup and Magnet Polarities
- Apertures

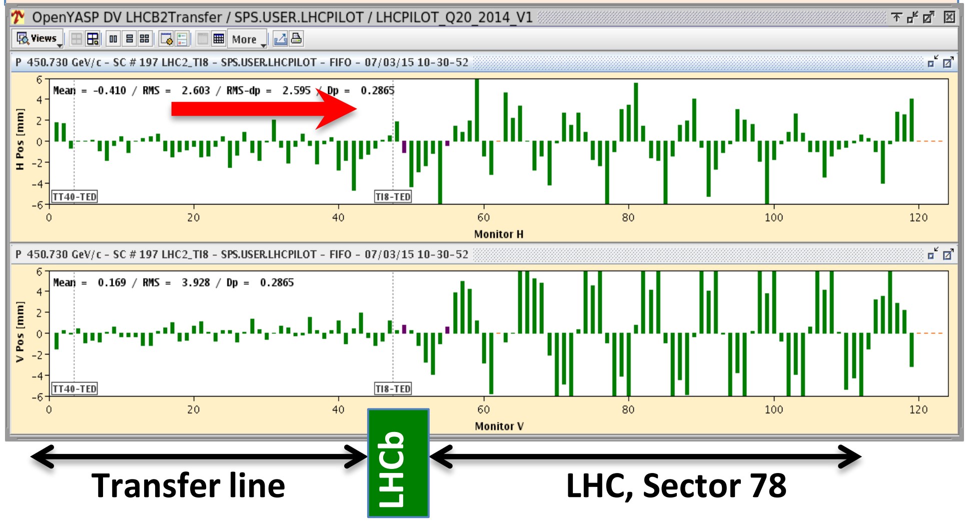


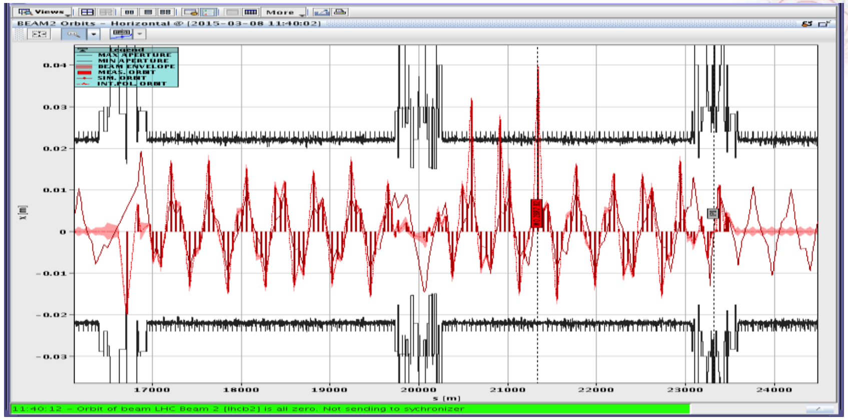


Sector Test, 7th March 2015

Beam Back into LHC

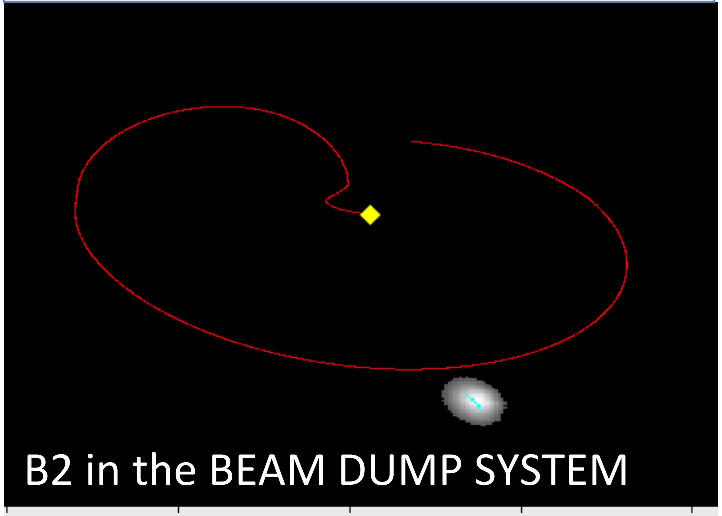
FIRST BEAM INTO LHC AFTER RUN 1



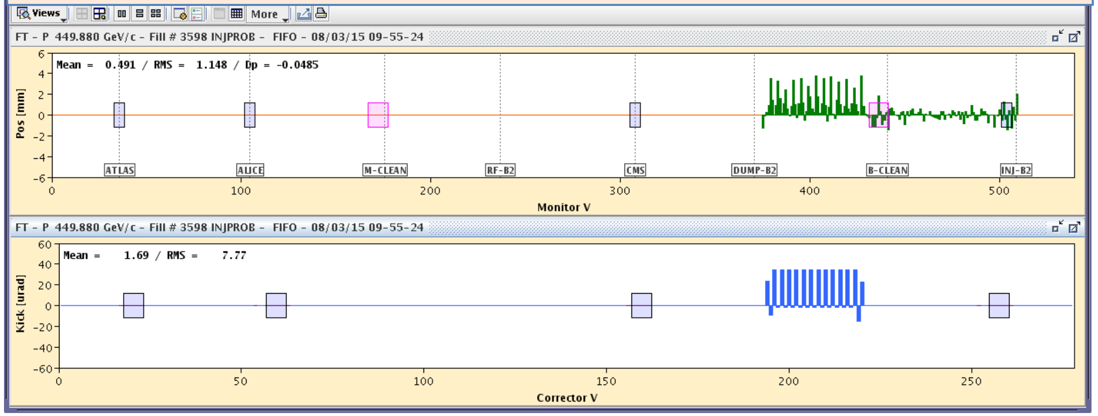


Aperture Checks

Inject and Dump on the 1st Turn (1/4 circumference)



BPM and orbit correctors polarity checks



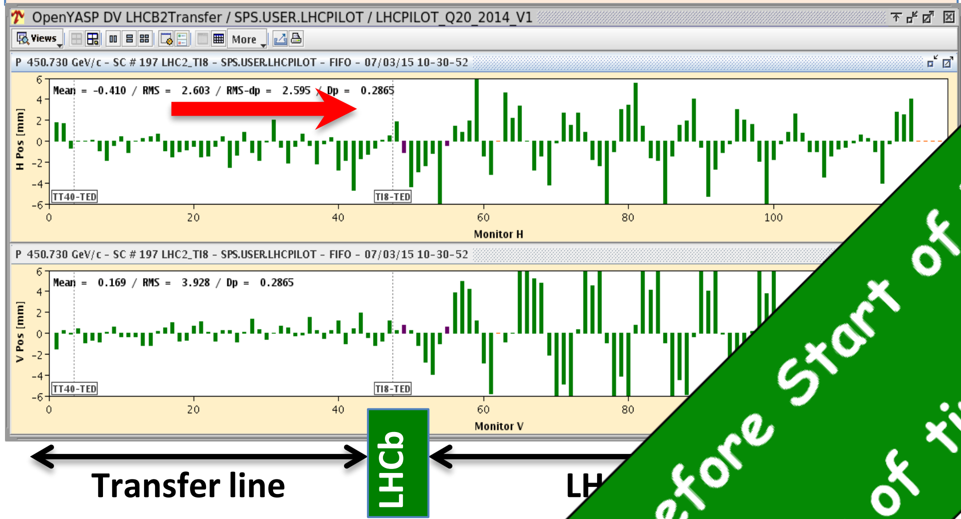
Sector Test, 7th March 2015

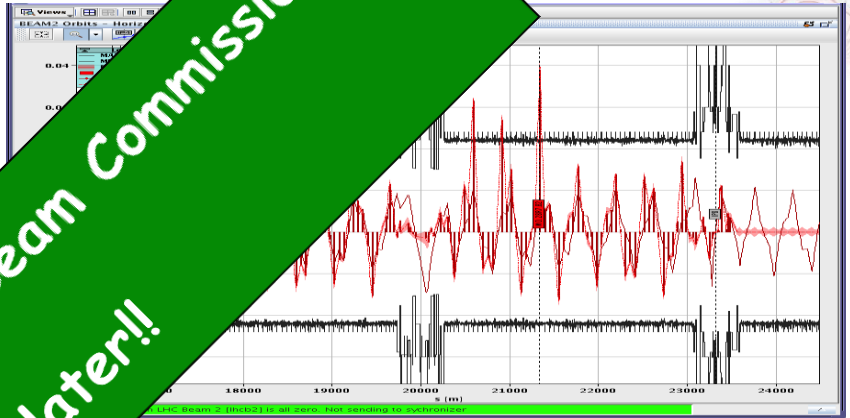
Beam Back into LHC

Vital Test, 1 Month before Start of Beam Commissioning

Saved a lot of time later!!

FIRST BEAM INTO LHC AFTER RUN 1





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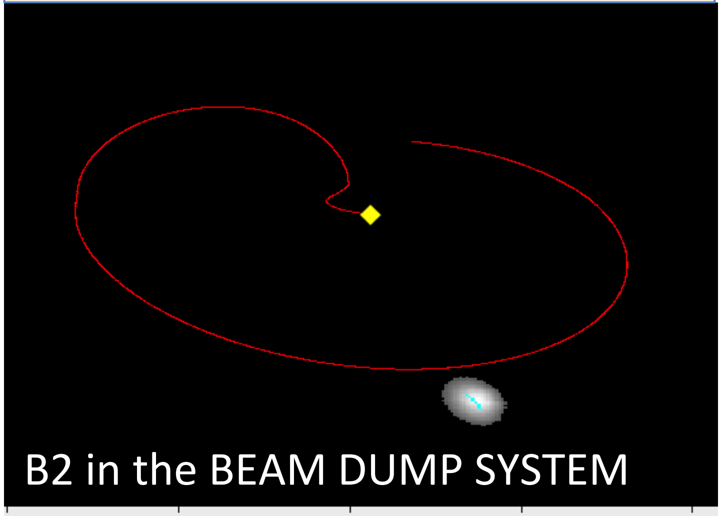
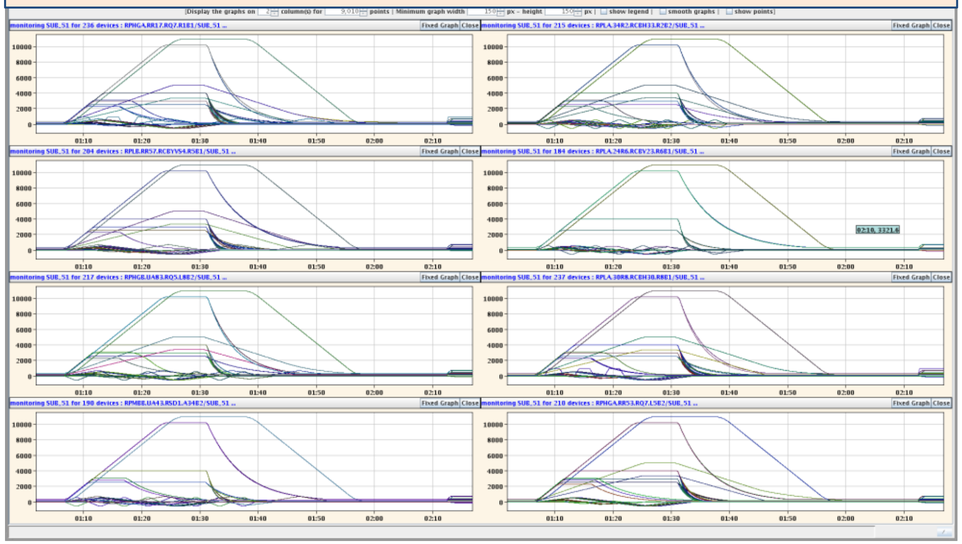


BPM and orbit ... checks

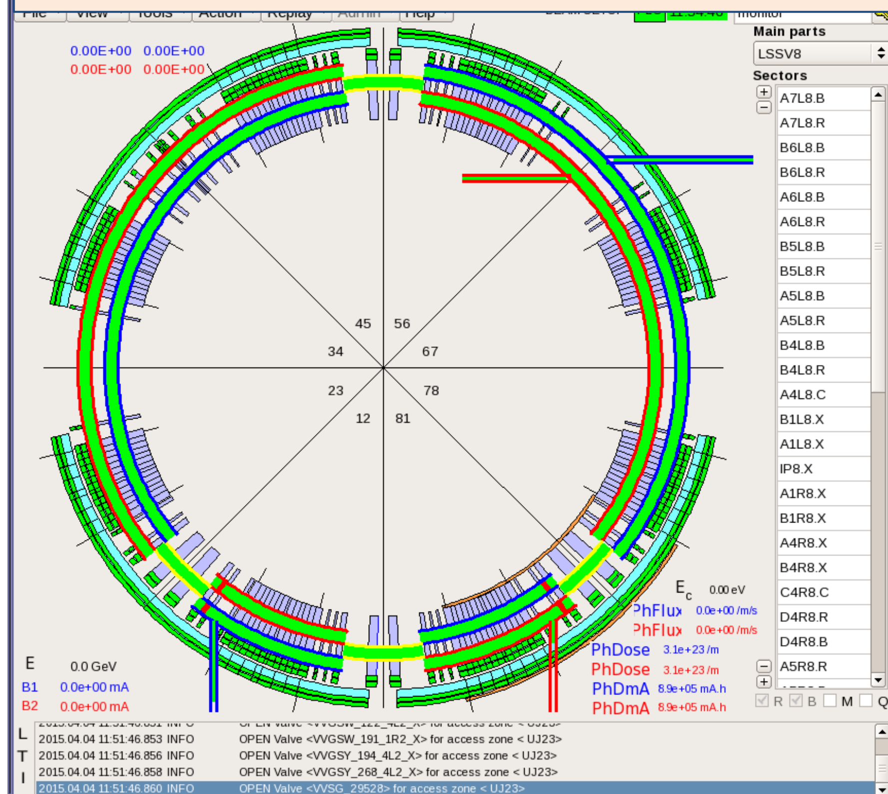
Final Preparations: Cold Checkout

First Cycle of the Complete Machine

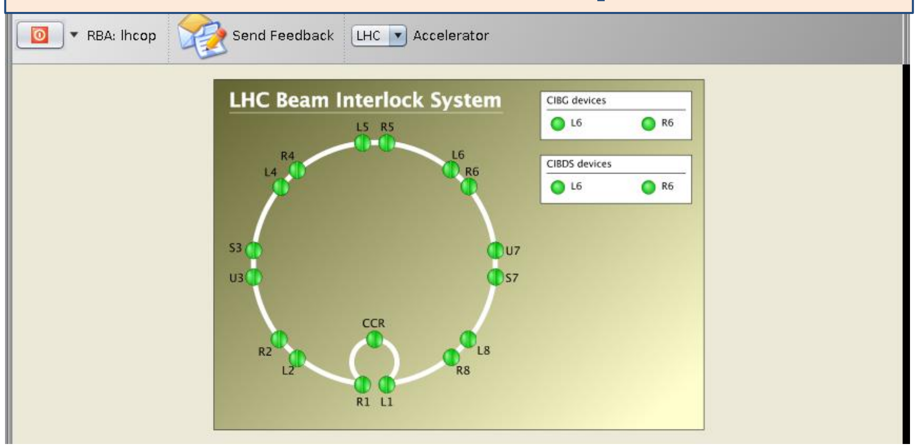


Talk about last minute!
… the night before first beam!

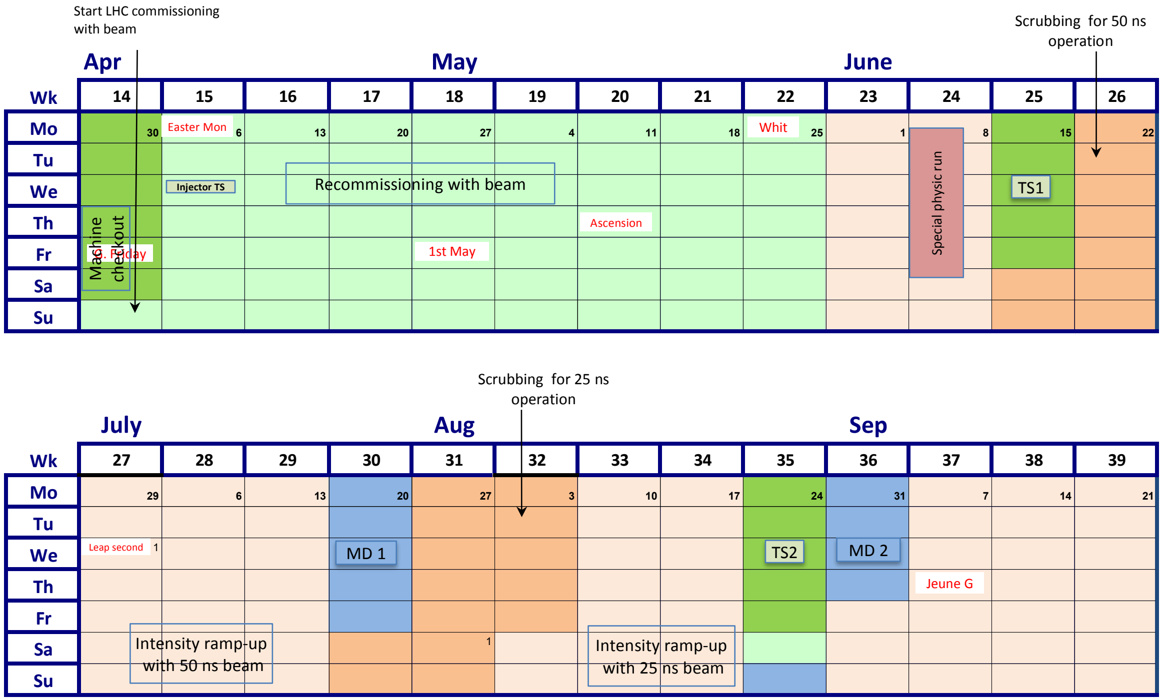
Vacuum Valves Open



Beam Interlock Loop Closed



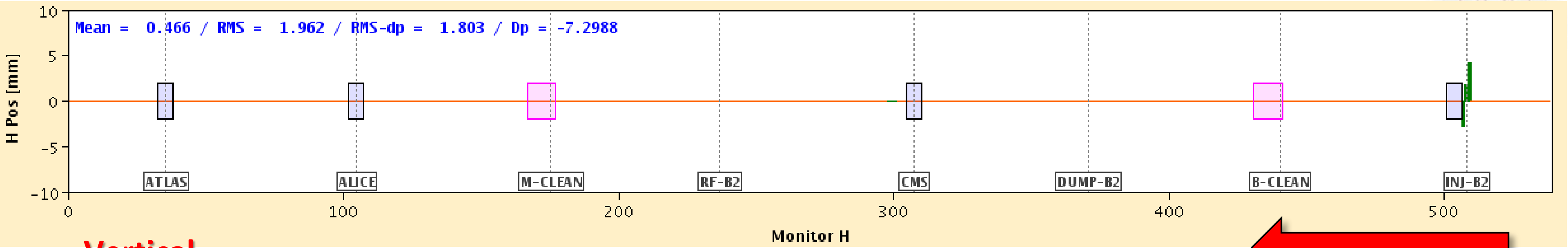
2015 Commissioning Strategy



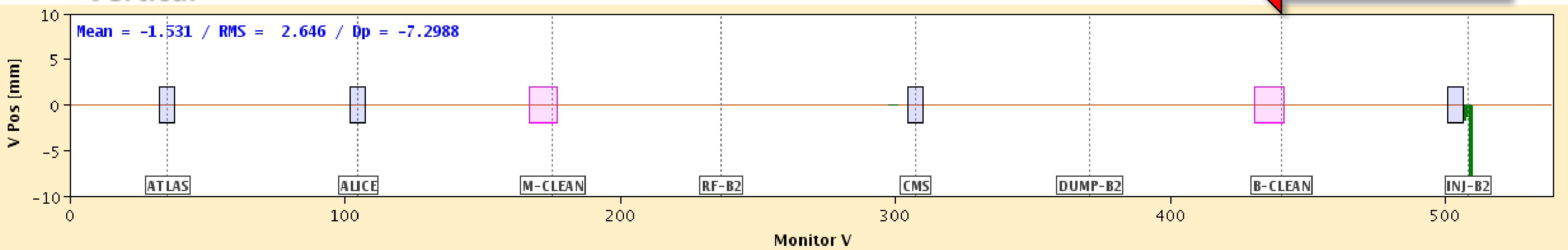
- ✧ Low intensity commissioning of full cycle – 8 weeks
- ✧ First stable beams – low number of bunches
- ✧ Special physics: LHCf and Luminosity calibration
- ✧ Scrubbing for 50 ns
- ✧ Intensity ramp-up with 50 ns
  Characterize vacuum, heat load, electron cloud, losses, instabilities, UFOs, impedance
- ✧ Scrubbing for 25 ns
- ✧ Ramp-up 25 ns operation with relaxed beta* (80cm), but commission to 40cm
- ✧ 25 ns operation

First Beam: 5th April

Horizontal

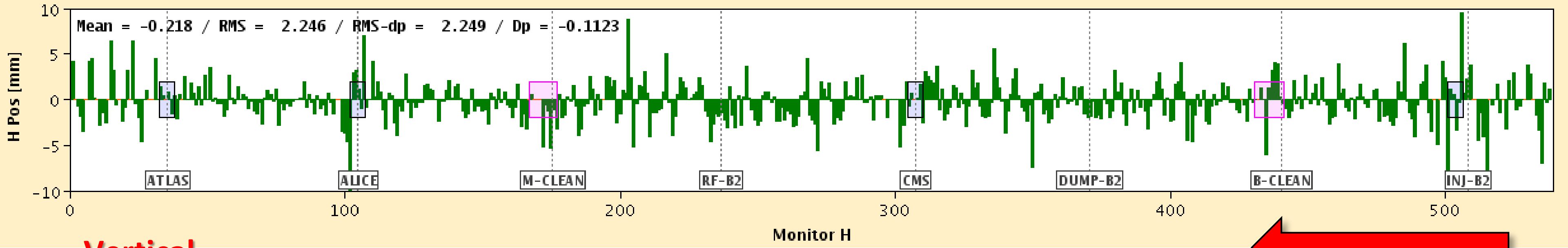


Vertical

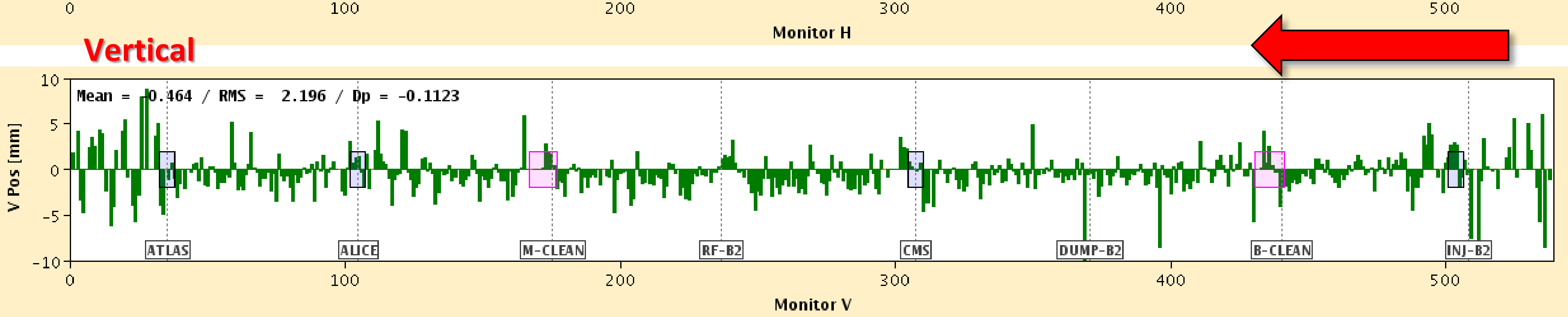


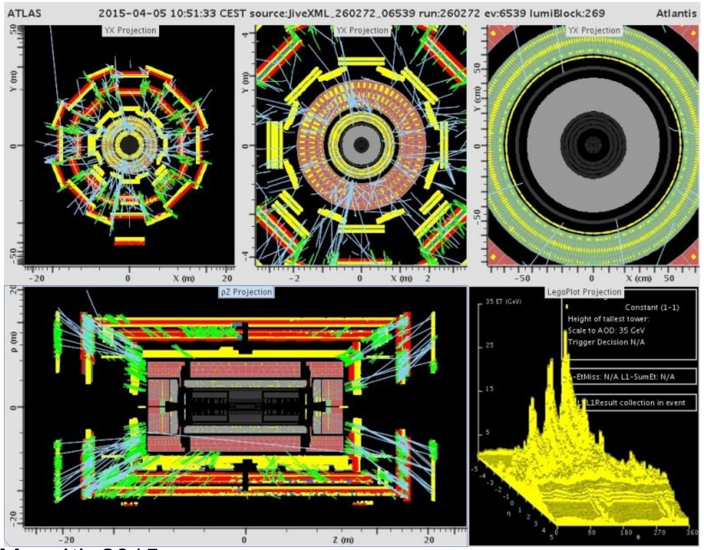
First Beam: 5th April

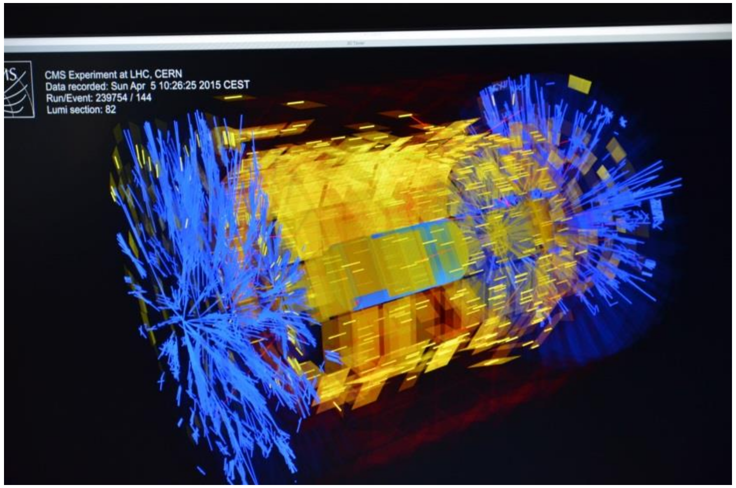
Horizontal



Vertical

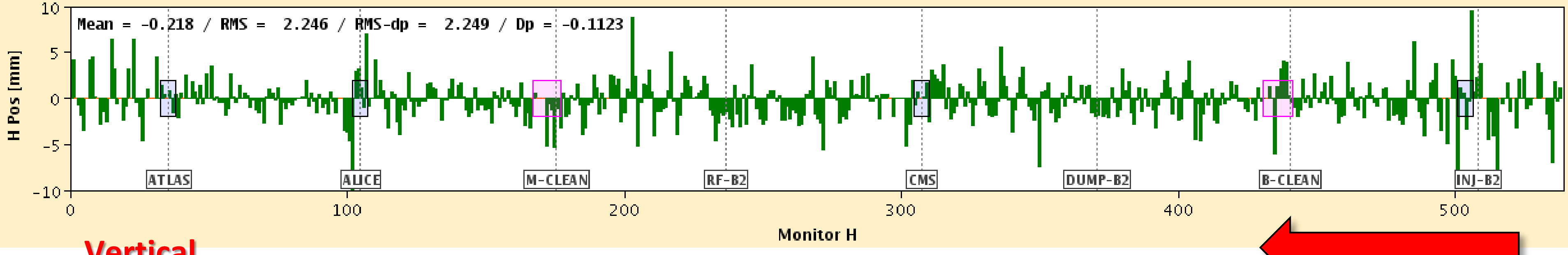




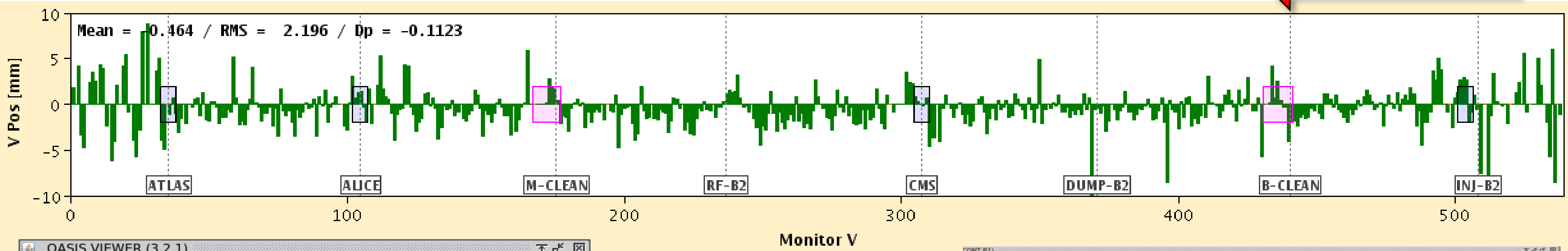


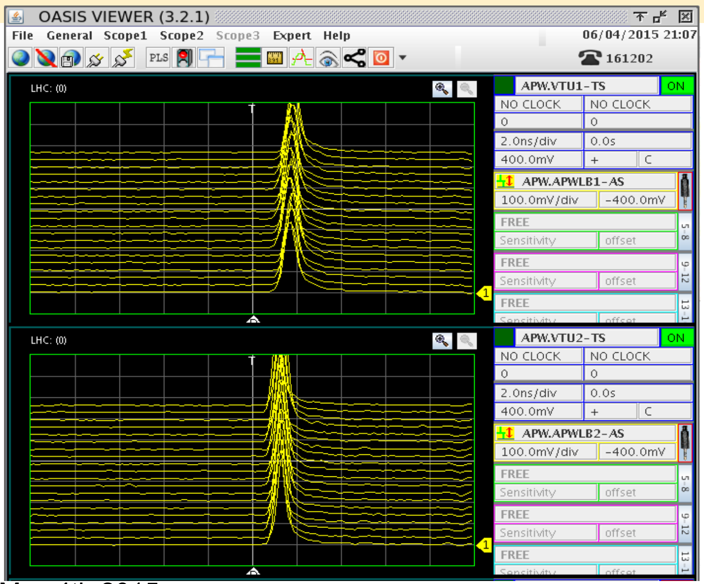
First Beam: 5th April

Horizontal

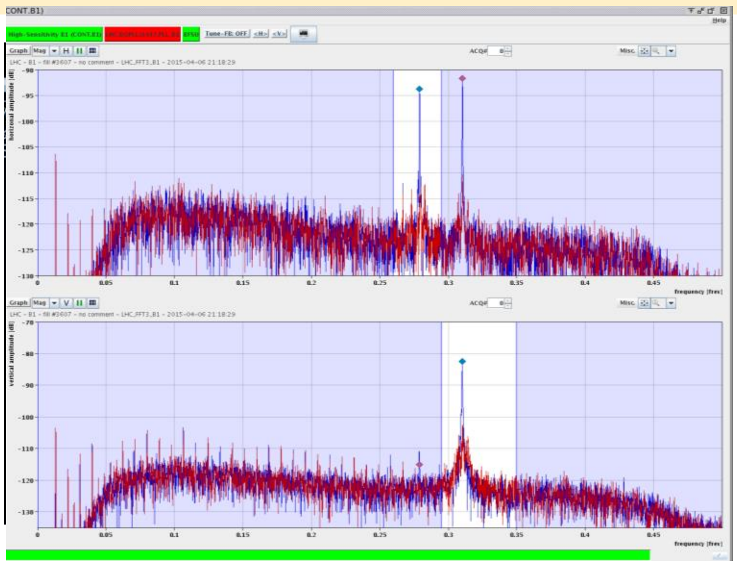


Vertical

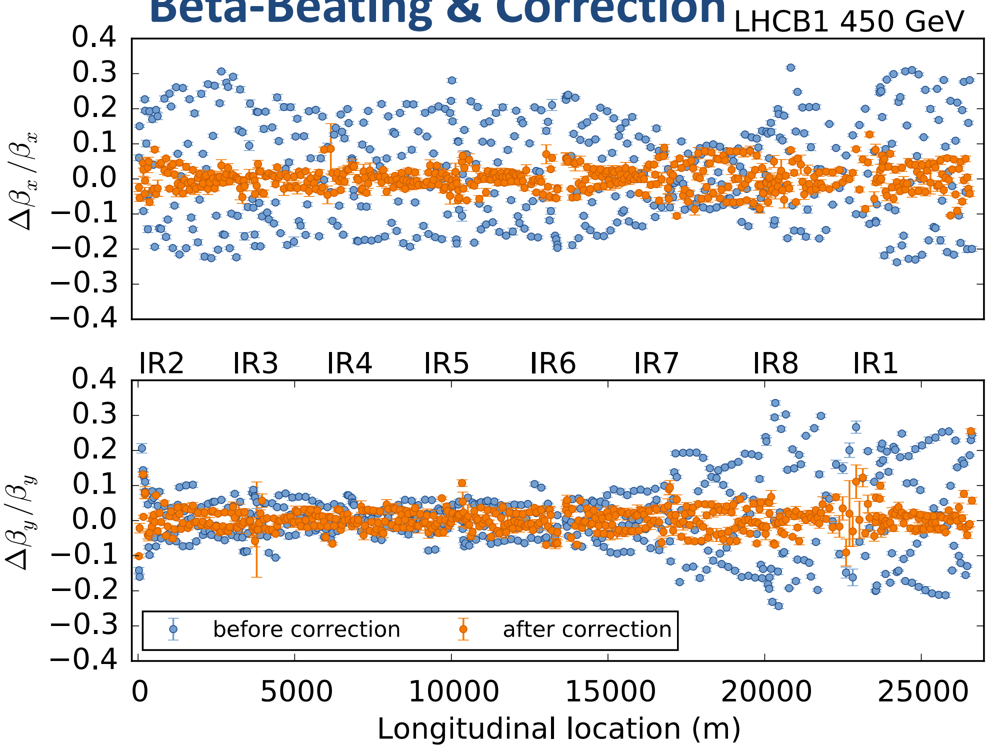




Soon After RF Capture, closed orbit and first measurements

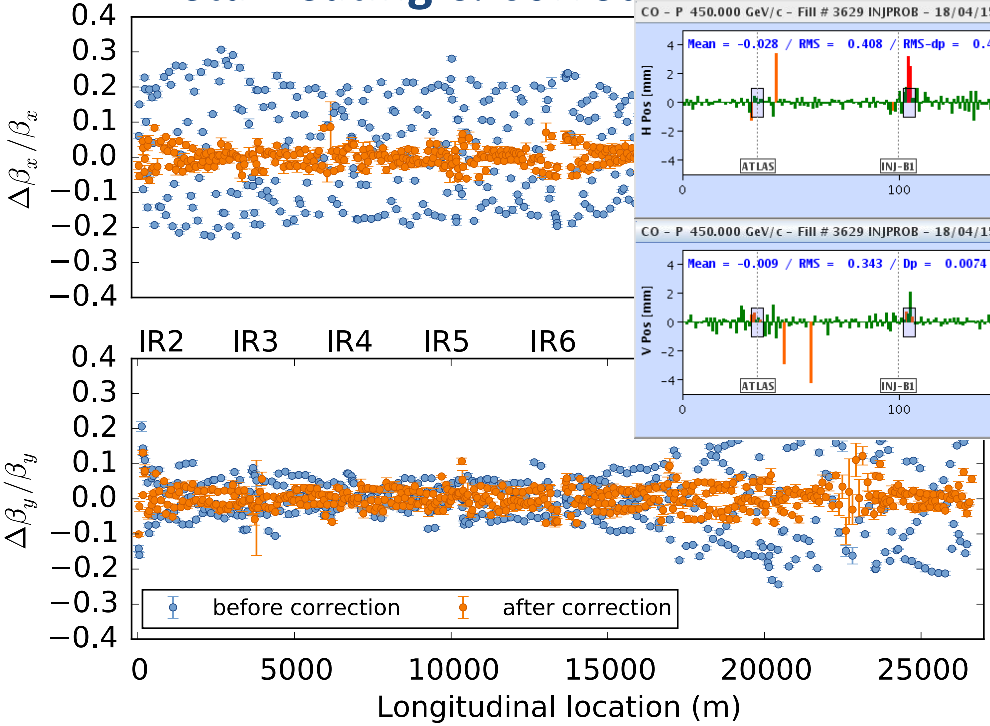


Beta-Beating & Correction

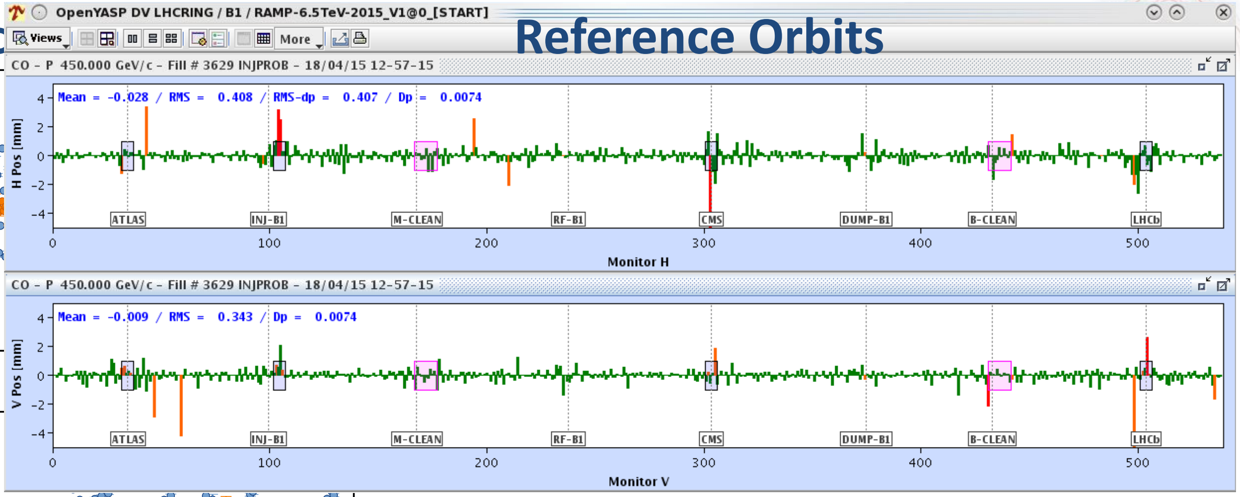


Commissioning

Beta-Beating & Correc

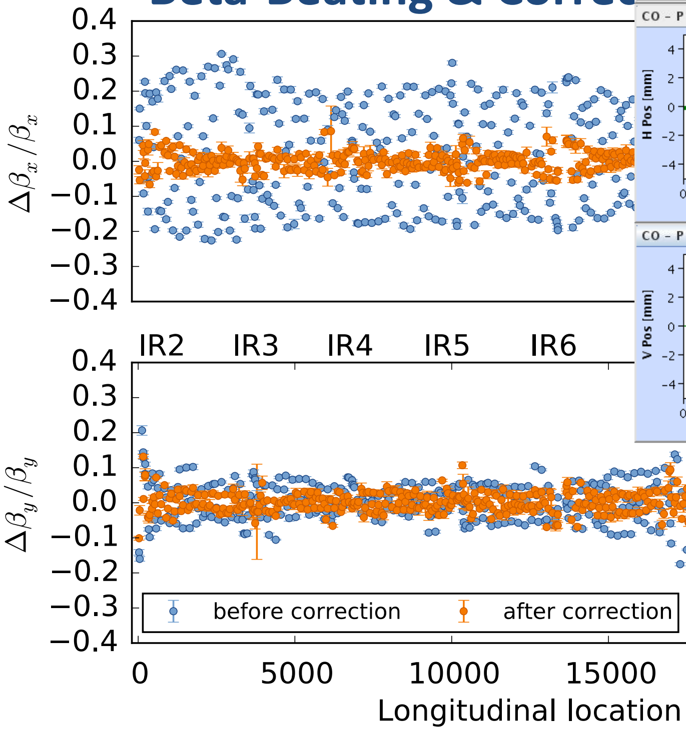


Reference Orbits

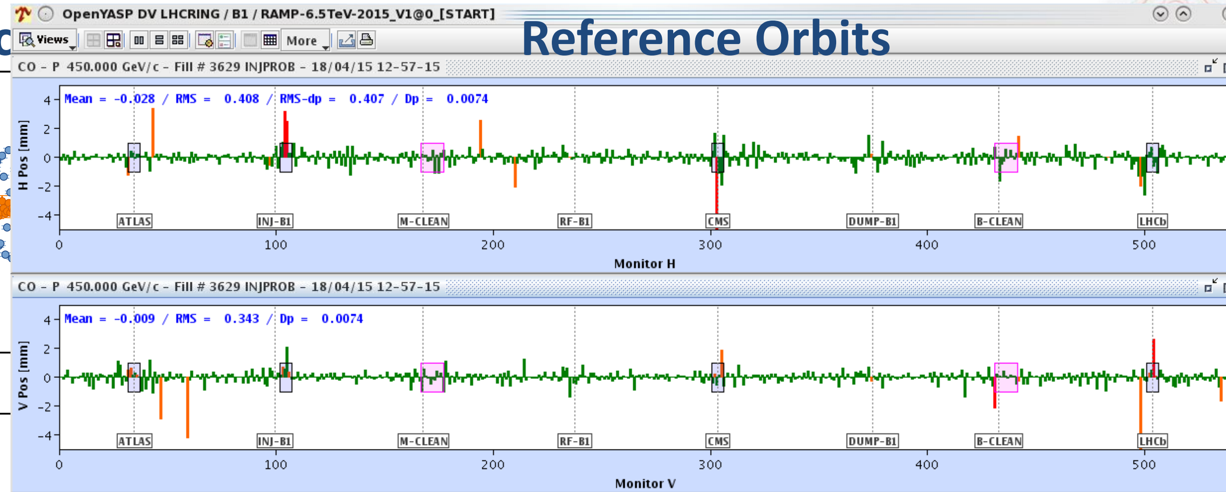


Commissioning

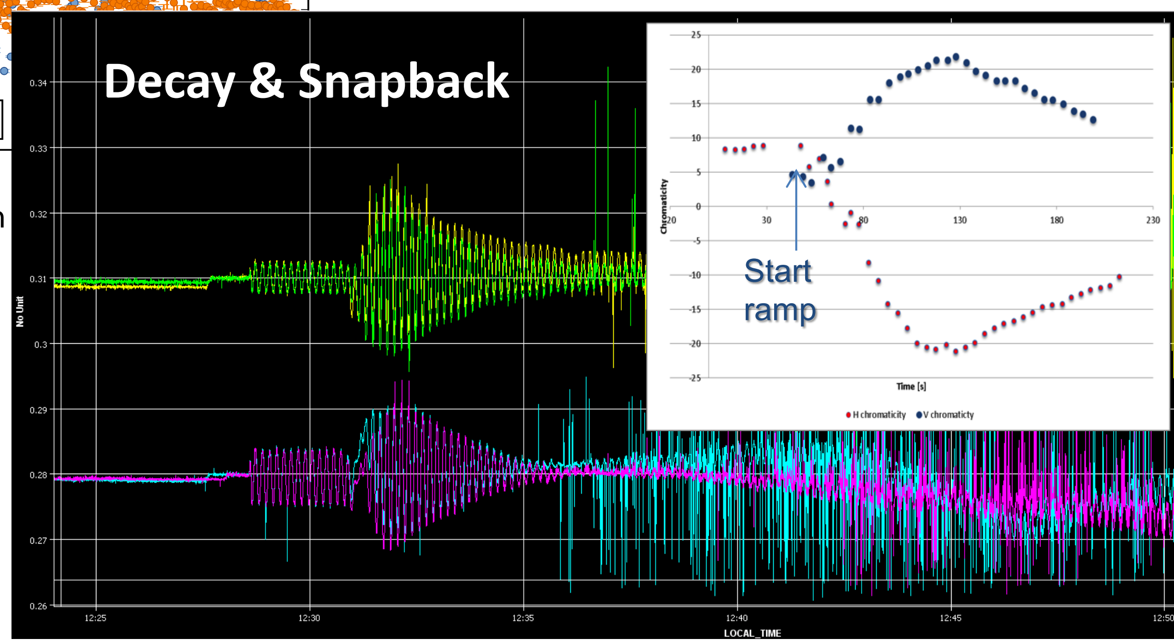
Beta-Beating & Correc



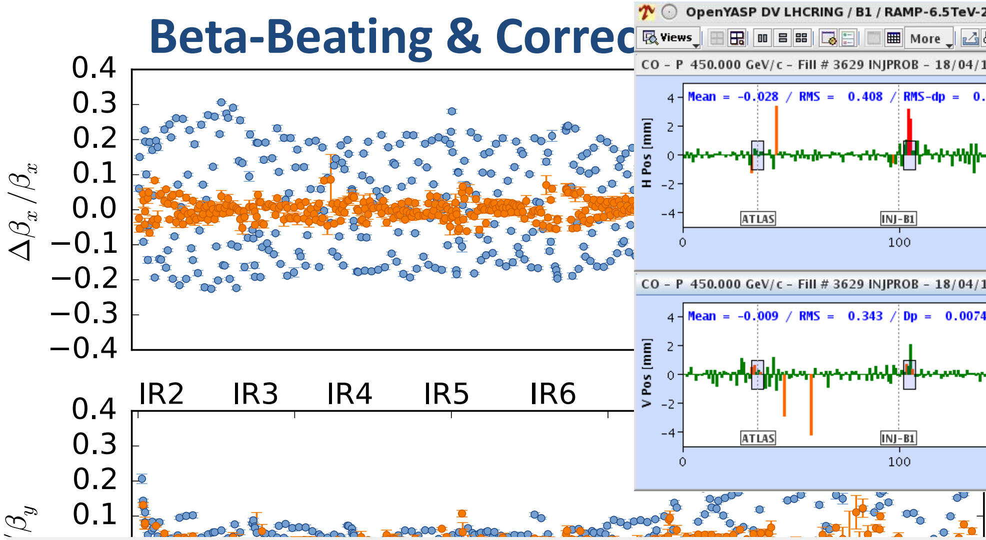
Reference Orbits

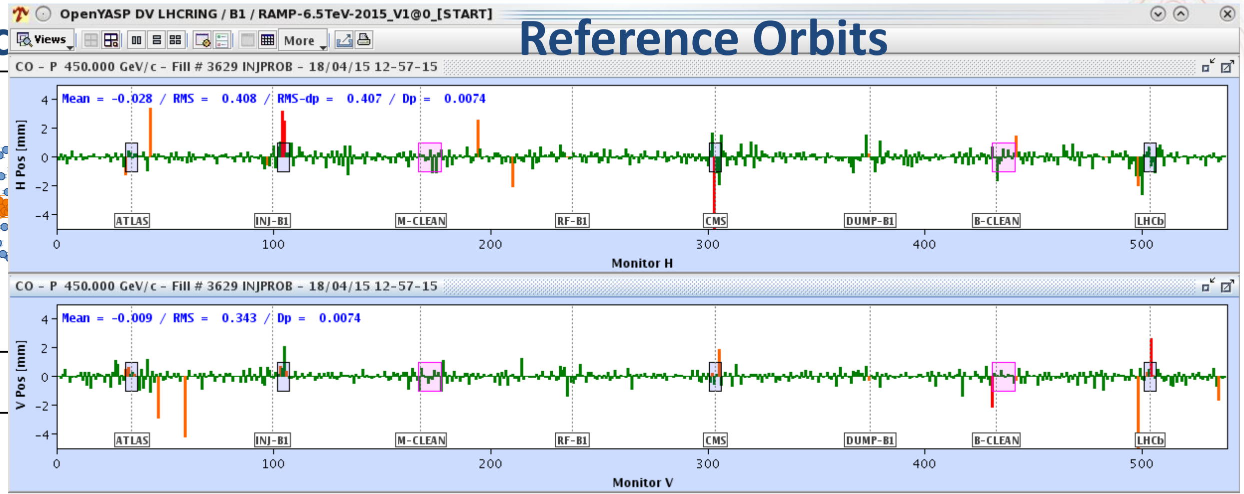


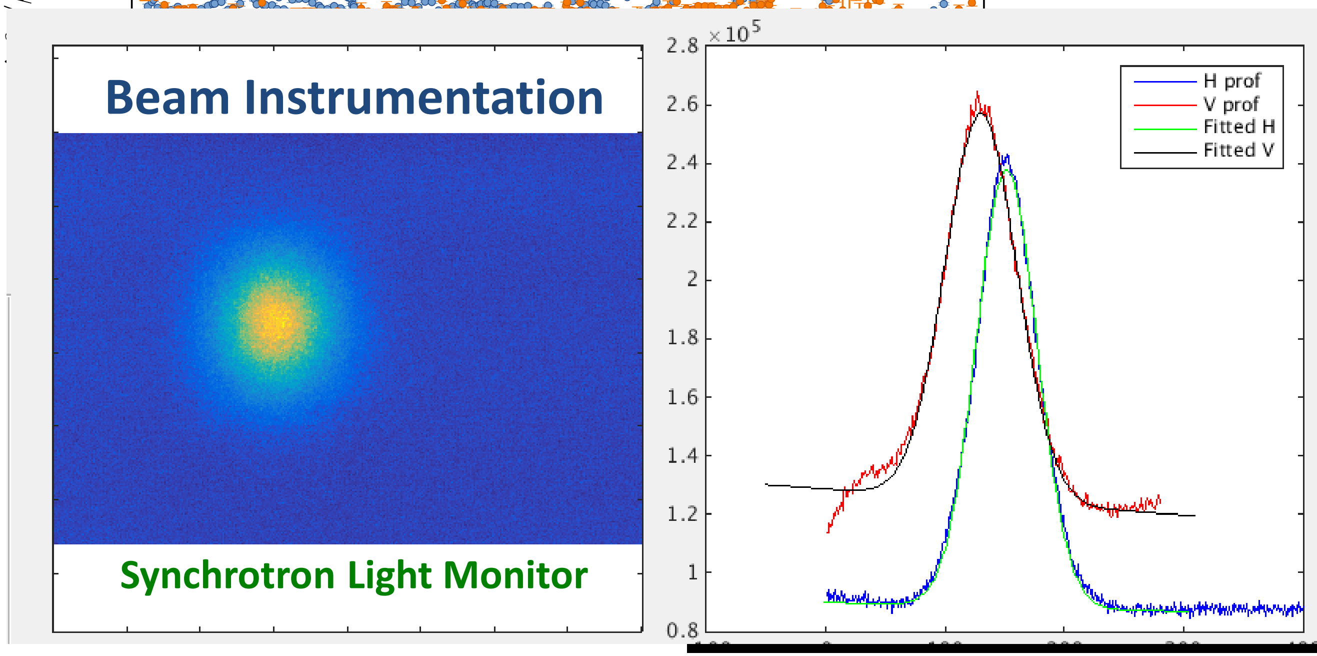
Decay & Snapback

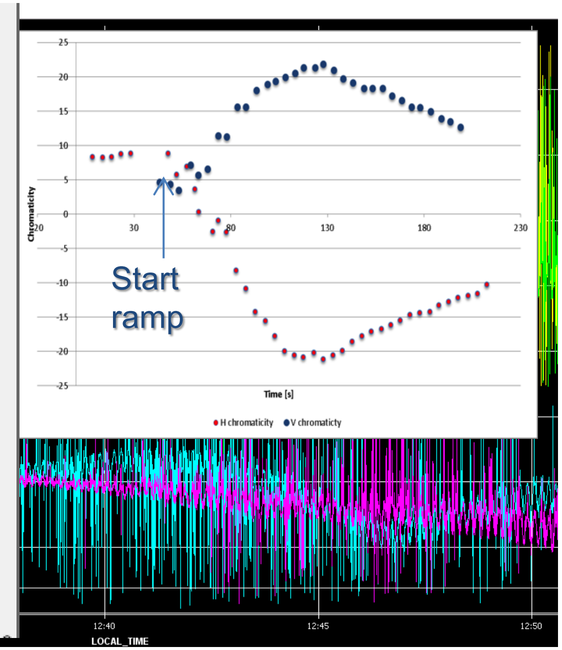


Commissioning

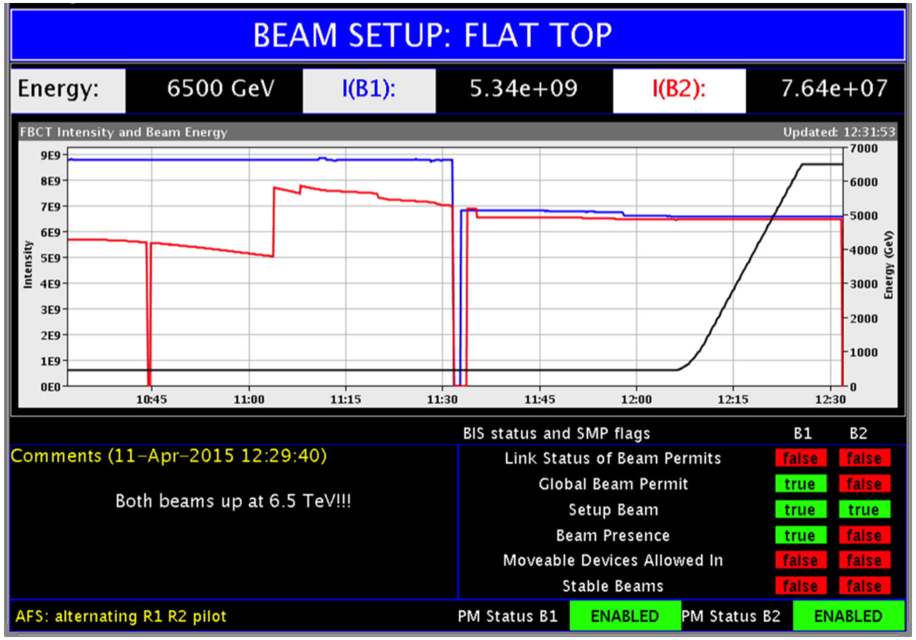








Beam at 6.5 TeV



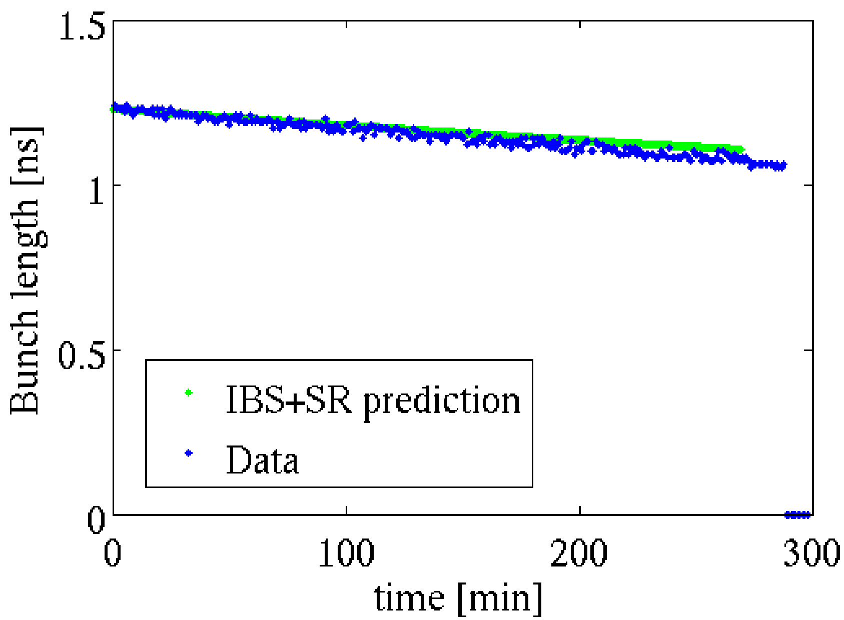
First Beam at 6.5 TeV !

Later, first observation of Synchrotron Radiation Damping with Protons

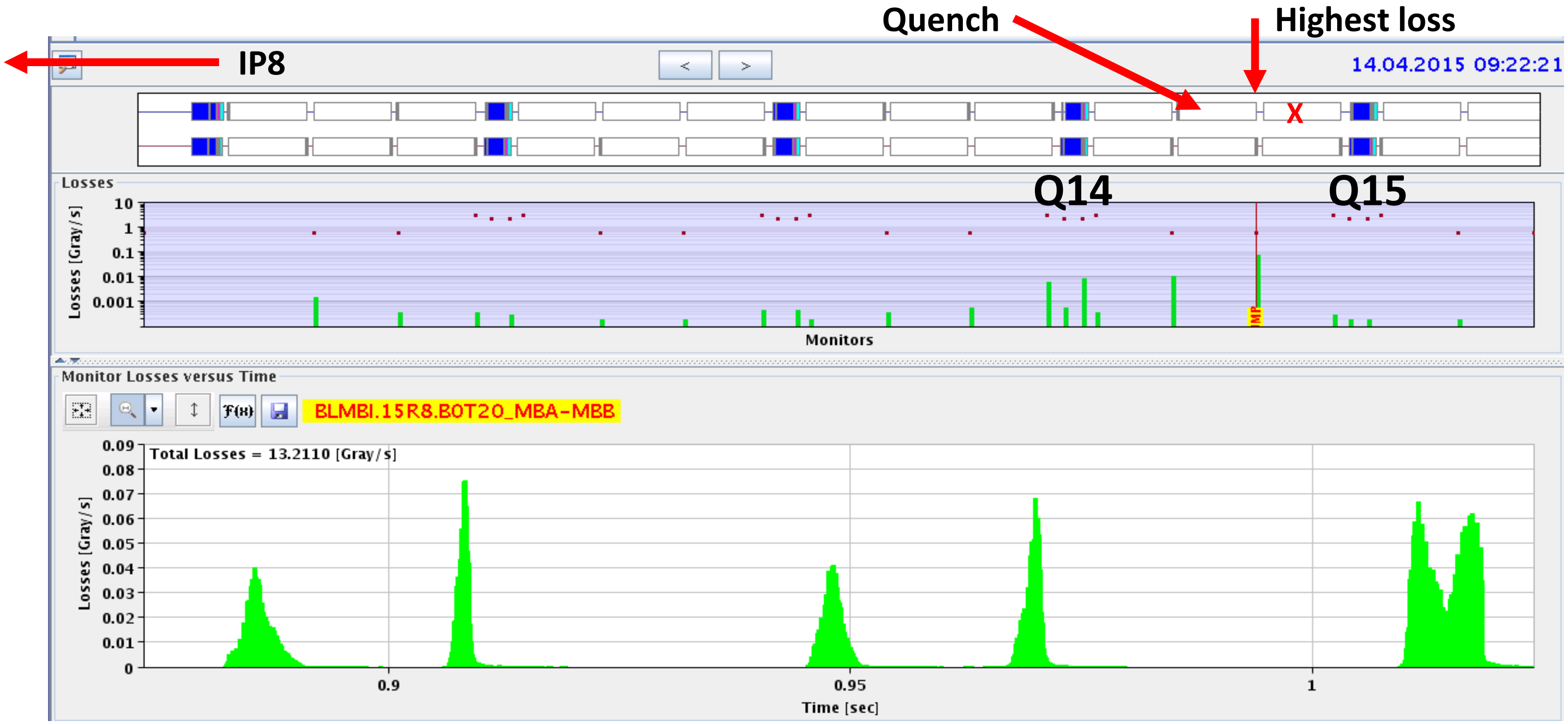
In 3 hours bunch length at 6.5 TeV drops from 1.25 ns to 1.07 ns in a 12 MV bucket.

Pilot intensity & negligible intensity loss.

Comparison with simulations including IBS and SR show that indeed is caused by SR.



Not everything is plain sailing! Aperture in 15R8



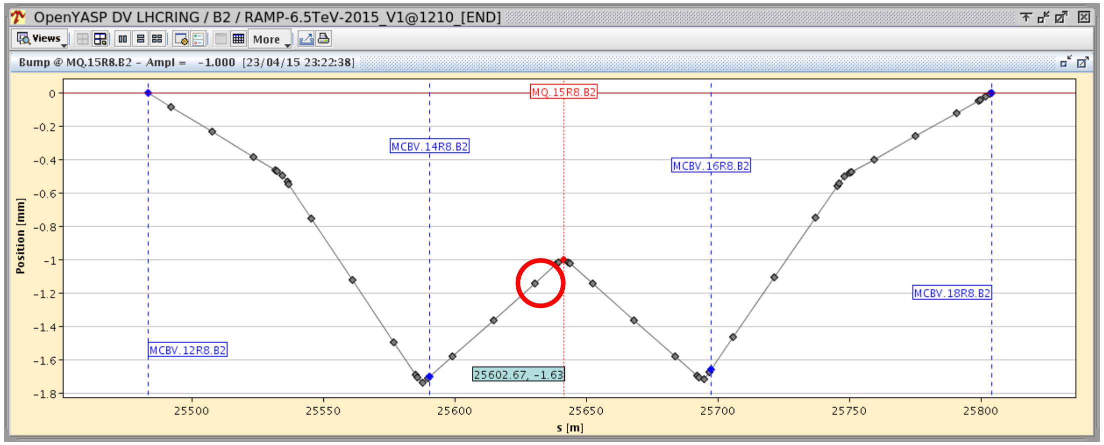
Initial Situation

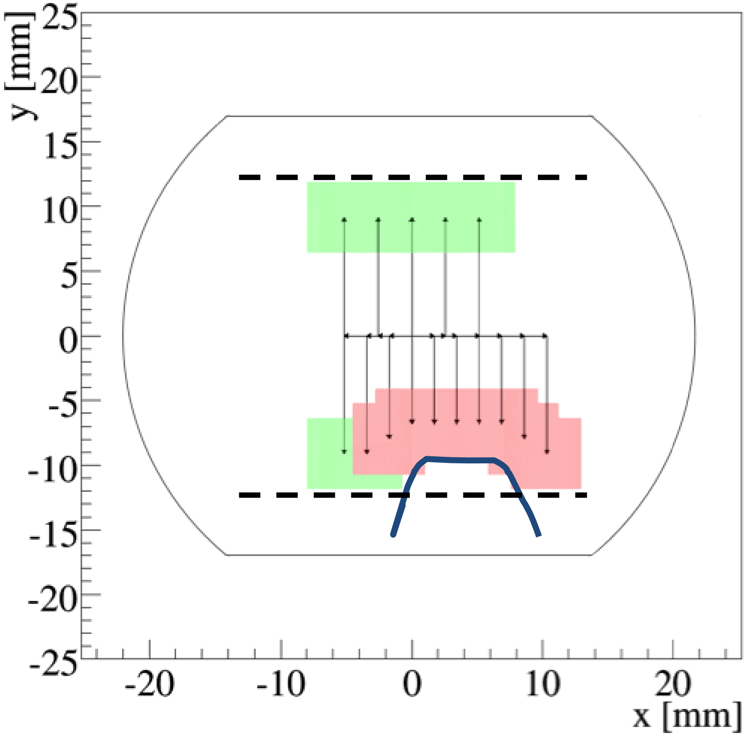
- Multiple loss events after a short time at 6.5 TeV – compatible with particles falling into the beam
- Loss patterns point to a specific position in the middle of a dipole magnet
- Aperture scans do not show a restriction
- Much less activity at injection

Beam screen warmed to ~80K in this half cell and kept there for several hours before re-cooling.

Aperture in 15R8 (2)

After beam-screen warm up …





…Clear Aperture restriction seen

- Measured at injection and 6.5 TeV
- UFO stopped then restarted
- Probably not a limiting aperture for operation
- But stability of the object remains a concern

…to come

- How does it behave with higher intensities?, bunch trains?

A very active area of study at the moment!

Conclusions

LHC Is Back!

- An enormous amount of work was achieved during LS1, thanks to the efforts of many people
- Re-commissioning of the circuits went well – even though we had some surprises!
- Training of the magnets roughly according to expectations – deeper analysis is now needed to understand the behaviour
- Initial commissioning went well
- … Some surprises here too!

… And (Hopefully) Still on Schedule to deliver Physics in June

- Initially low luminosity and special runs
- Then 50ns intensity ramp up (~ 1fb-1)
- Switch to 25ns during the summer
- First Pb-Pb at the end of the year.

CERN