IBIC14 – Monterey, California, USA.

The Beam Instrumentation and Diagnostic Challenges for LHC Operation at High Energy

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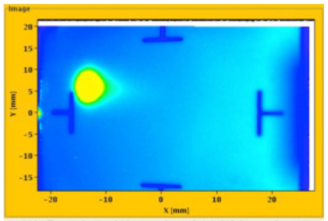
YEARS / ANS CERN

Outline

- LHC Performance during Run I
- Consolidation during the Long Shutdown
- Main challenges facing LHC Operation at 7TeV
- How these challenges can be addressed with beam instrumentation

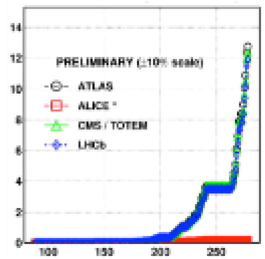
LHC Timeline

August 2008
First injection test



September 10, 2008
First beams around

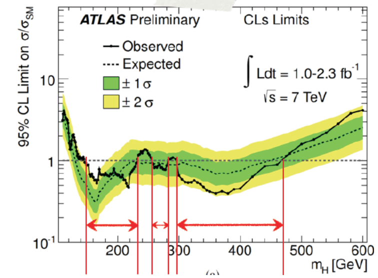
November 29, 2009
Beam back



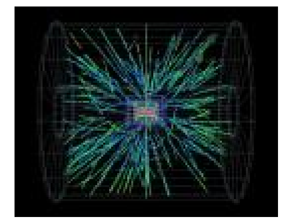
October 14, 2010
Goal reached 1e32 248

June 28 2011
1380 bunches

1380



August, 2011
2.3e33, 2.6 fb^{-1}
1380 bunches

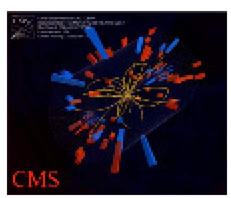


20 Jan, 2013
First Proton-Lead Collisions

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

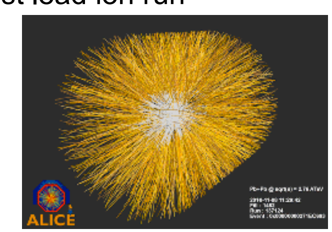
2008 | 2009 | 2010 | 2011 | 2012 | 2013

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



March 30, 2010
First collisions at 3.5 TeV

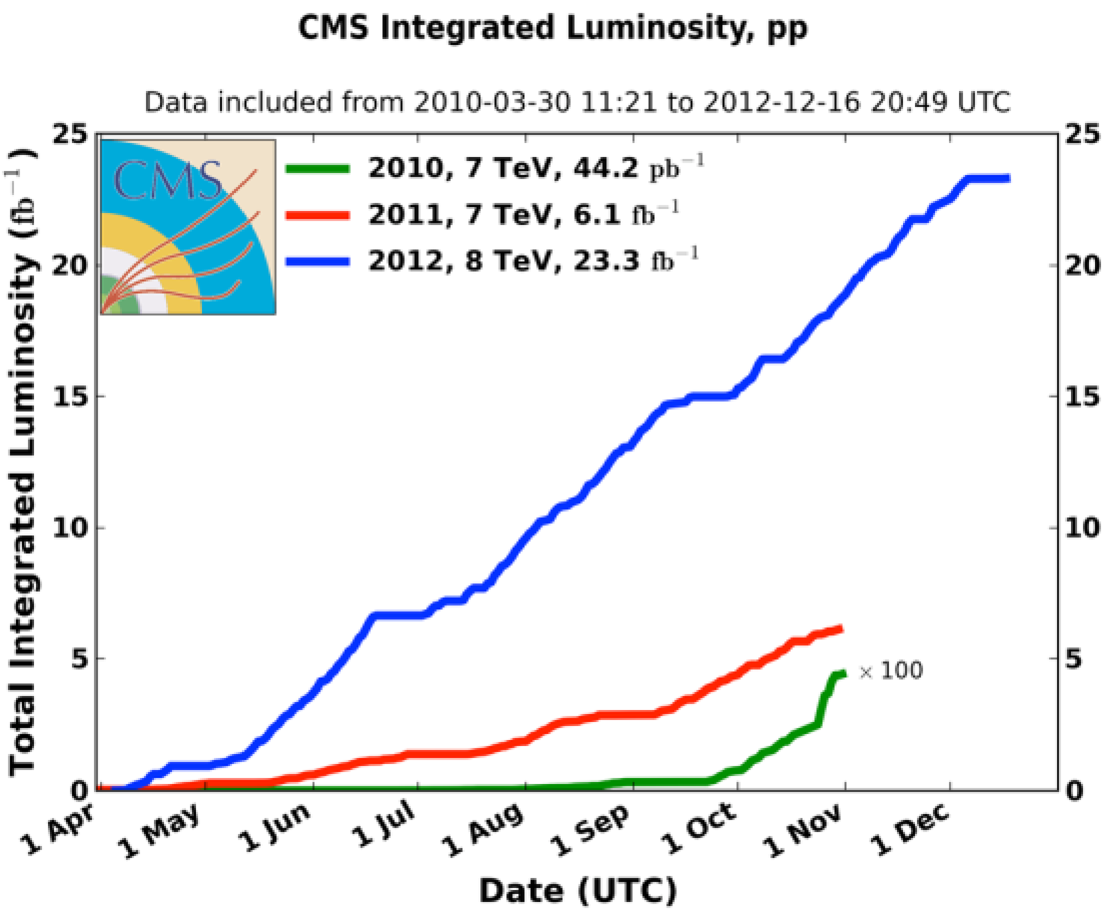
November 2010
First lead ion run



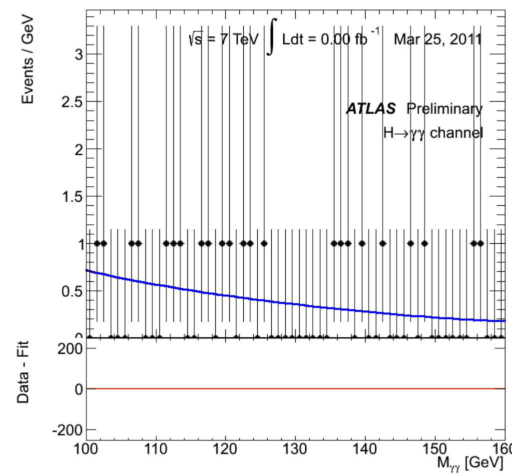
April 5, 2012
First collisions at 4 TeV

4 July, 2012
Higgs Discovery

Integrated luminosity 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



LHC Long Shutdown 1 : 2013-2014

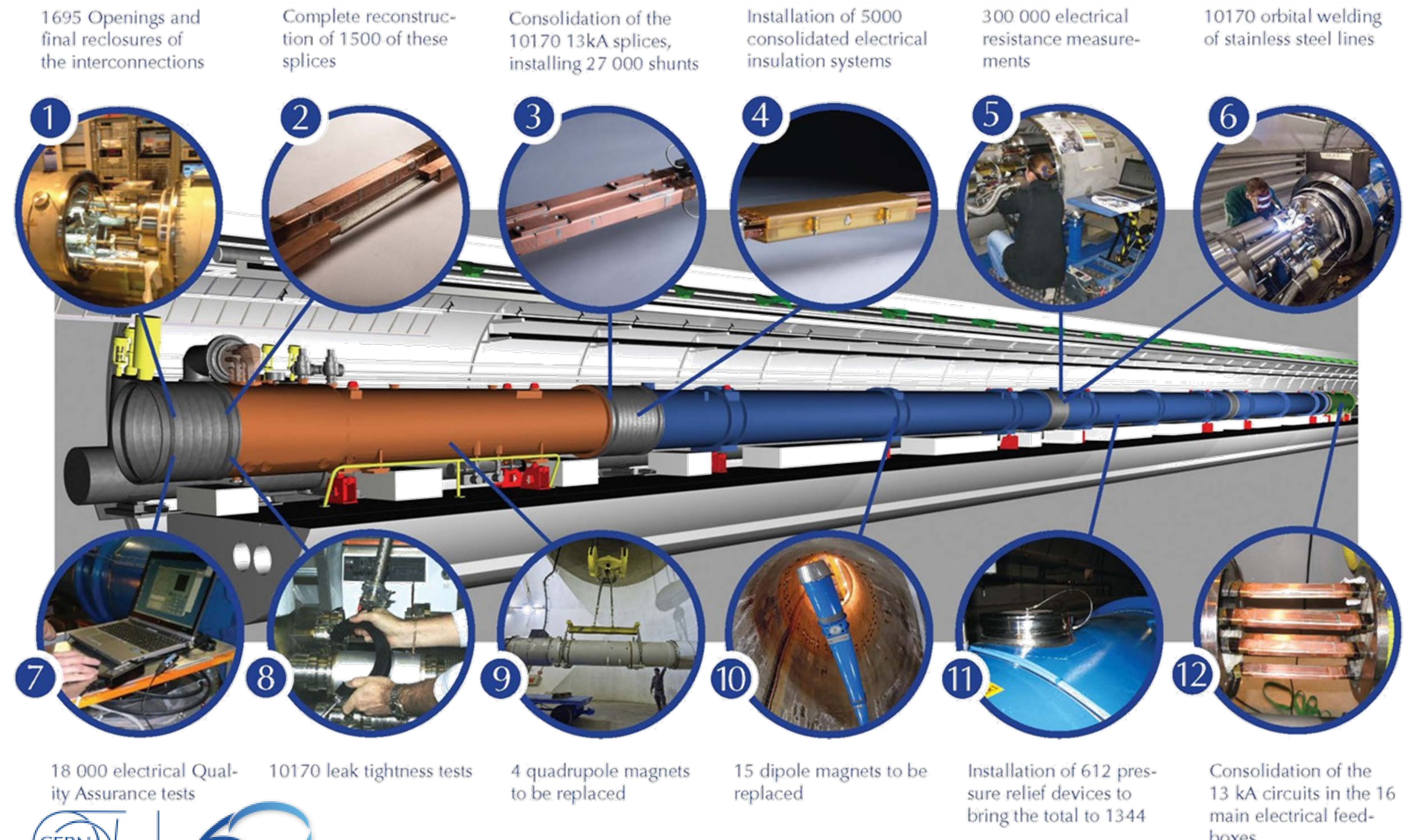
Primary aim

- Consolidation to allow running at high energy

Three main tasks

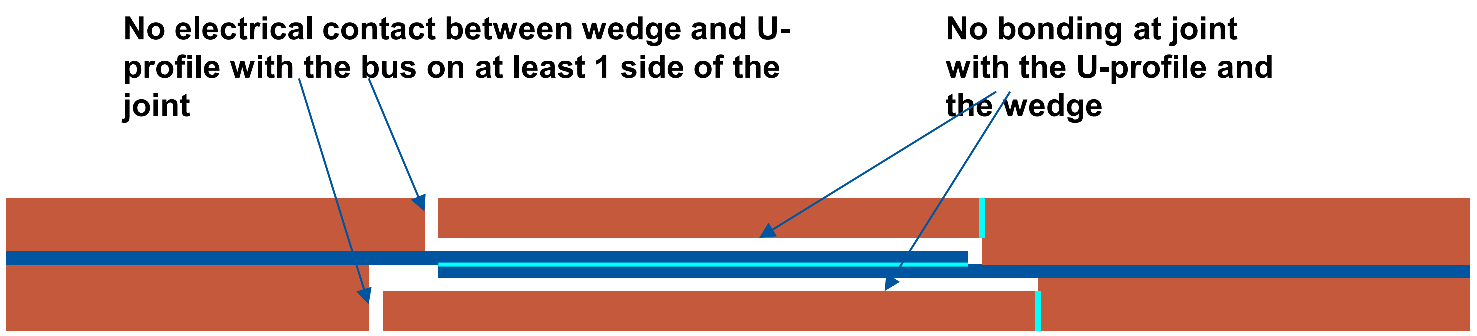
- Superconducting magnet and circuit consolidation
- Reducing effect of radiation on electronics
- Full maintenance of all equipment including majority of beam instrumentation

Main 2013-2014 Consolidation

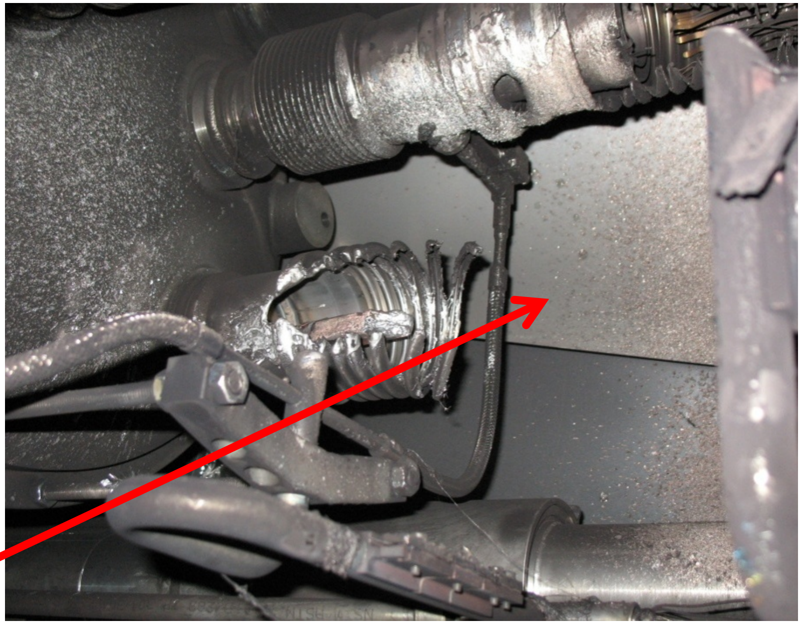


2008 - What happened?

Theory: A resistive joint of about 220 nΩ with bad electrical and thermal contacts with the stabilizer

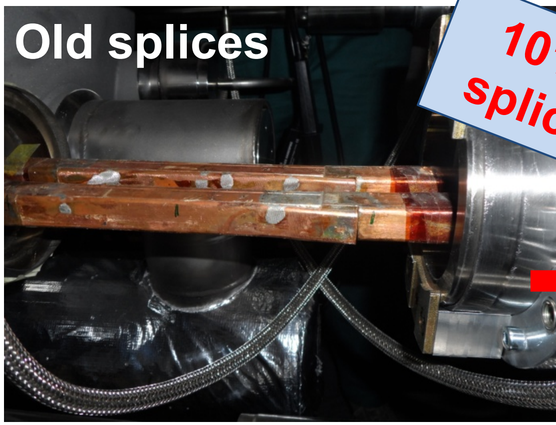


- Loss of clamping pressure on the joint and between joint and stabilizer
- Degradation of transverse contact between superconducting cable and stabilizer
- Interruption of longitudinal electrical continuity in stabilizer

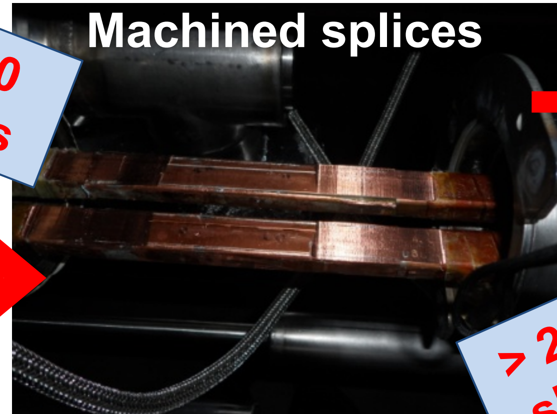


Problem: this is where the evidence used to be

Splice Consolidation Process

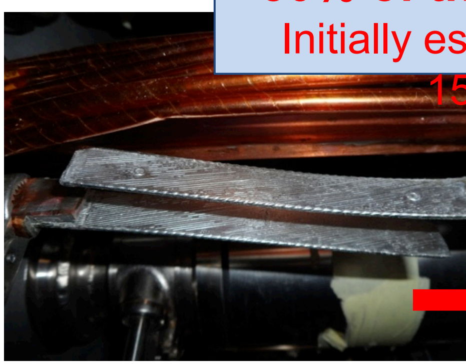


10170 splices

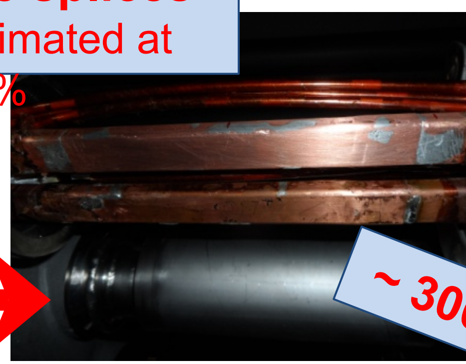


> 27000 shunts

30% of the splices
Initially estimated at 15%

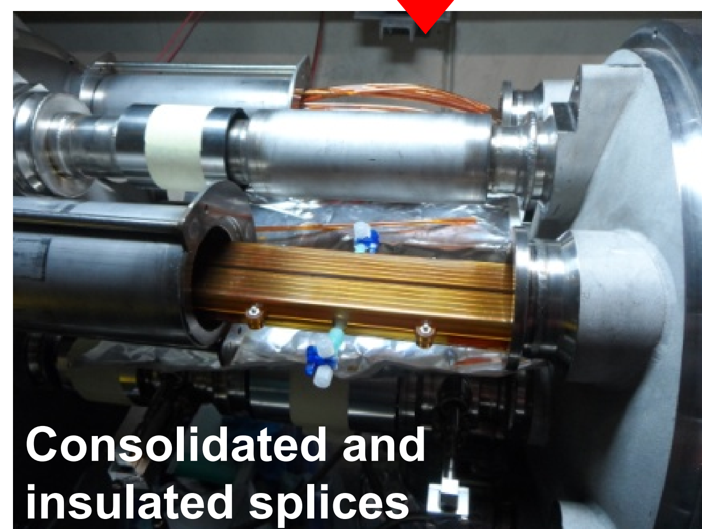


Unsoldering of splice and superconducting cables



~ 3000

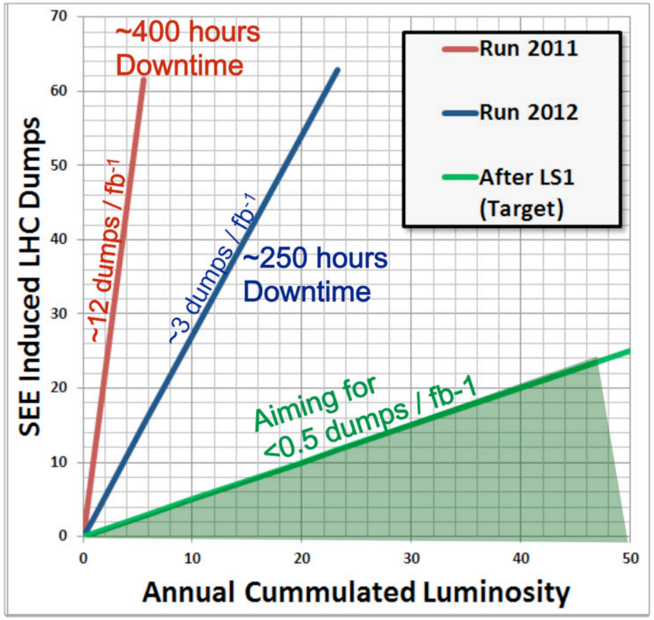
Reconstruction and soldering of splice and superconducting cables



Minimising Radiation to Electronics

- Major effort - 70 weeks and combined effort of ~150 persons
- Main activities around high luminosity experiments and collimation regions

Relocation & Shielding



Equipment Upgrades

Monitoring

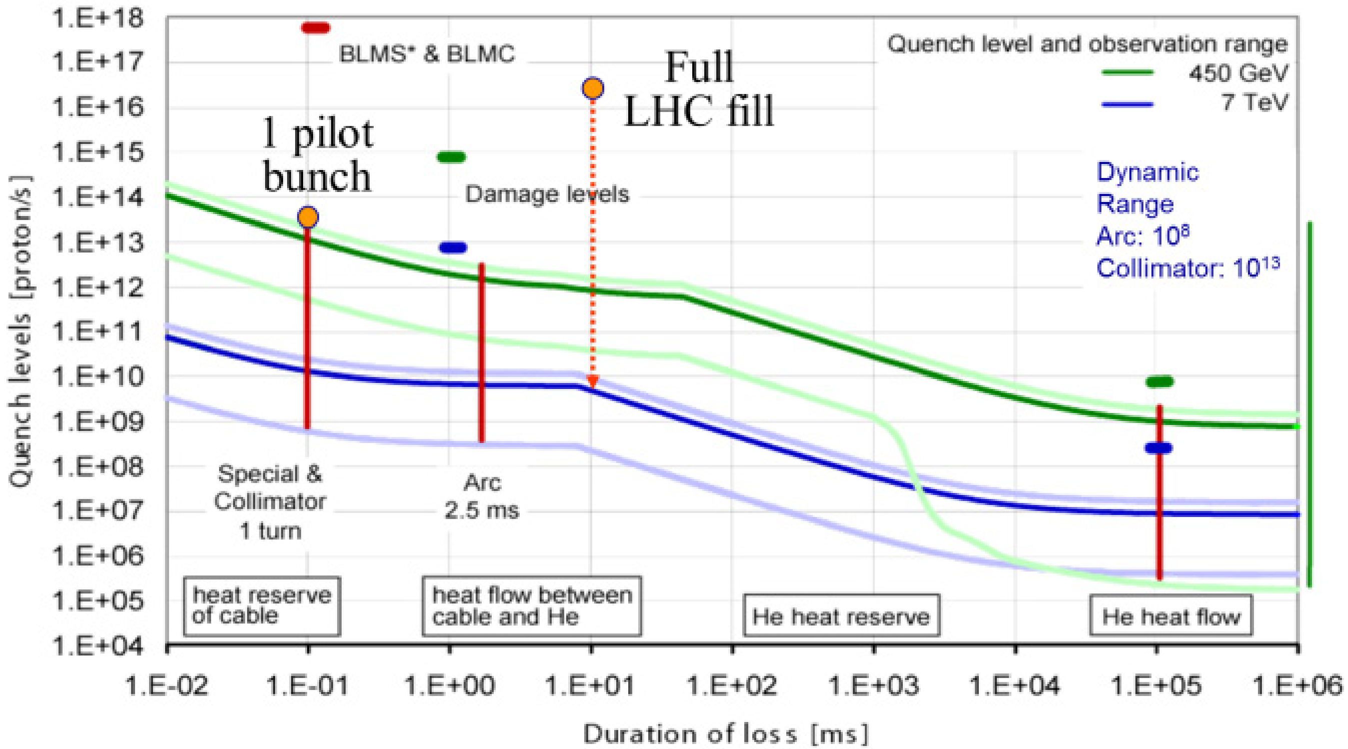
Testing & Facilities

The Challenges for Run II

- Running at higher energy
  - Significantly reduced quench thresholds
    - Maintaining collimation hierarchy
    - Dealing with Unidentified Falling Objects (UFOs)
- Running with 25ns bunch spacing
  - Dealing with electron cloud
  - RF heating issues
  - Understanding & curing instabilities
- Coping with high brightness beams
  - Measurement of small beam sizes

Running at Higher Energy

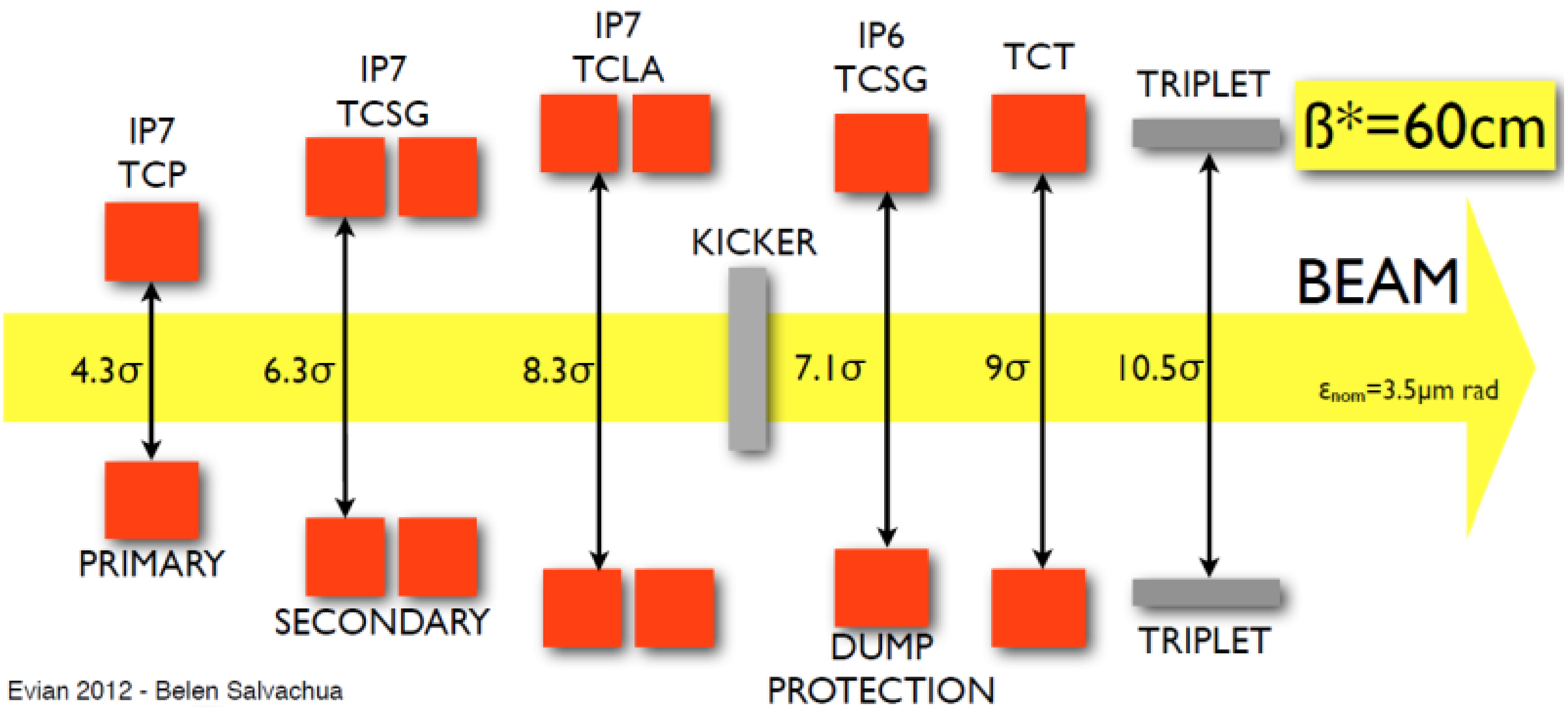
- Significantly reduced quench and damage thresholds



- Pilot bunch of 5×10^{9} close to damage level at 7TeV
- Loss of 3×10^{-7} of nominal beam over 10ms can create a quench at 7TeV

Collimation @ LHC

- Multi-stage collimation system with ~100 moveable devices
- Hierarchy between cleaning stages must be preserved
- To date - no quench with stored beam energies up to 140 MJ



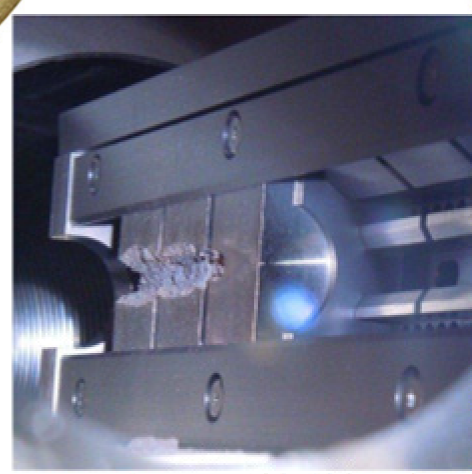
Evian 2012 - Belen Salvachua

How Tight is Tight?

Norway

Iberian
peninsula

Intermediate settings (2011):
~3.1 mm gap
at primary collimator



Inermet 180, 72 bunches

Tight settings (2012):
~2.2 mm gap at
primary collimator

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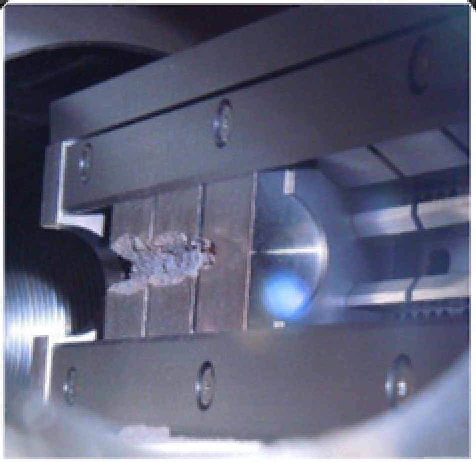

Inermet 180, 72 bunches

Tight settings (2012):
~2.2 mm gap at
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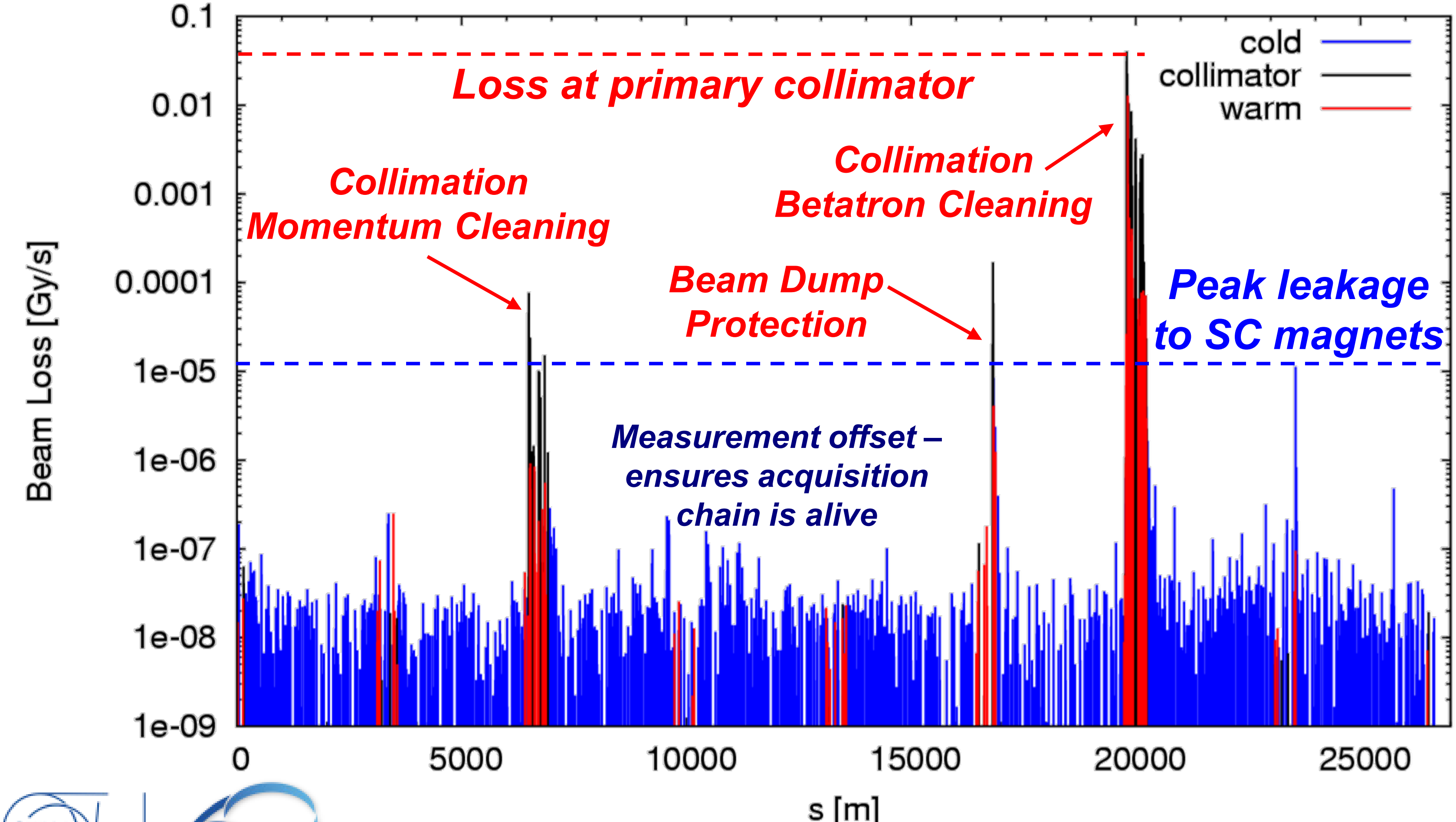
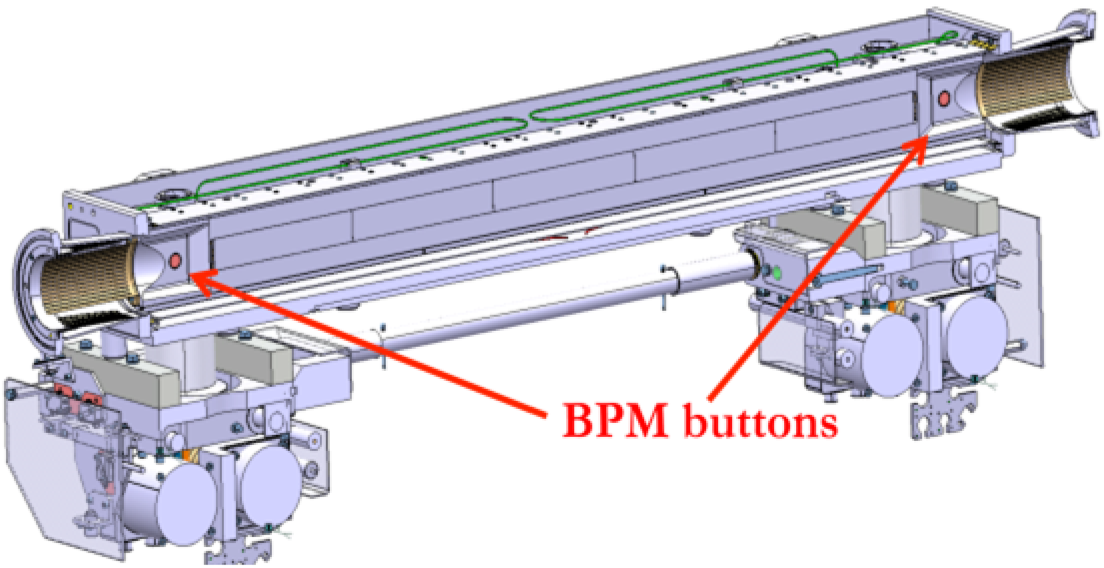
Collimation Verification

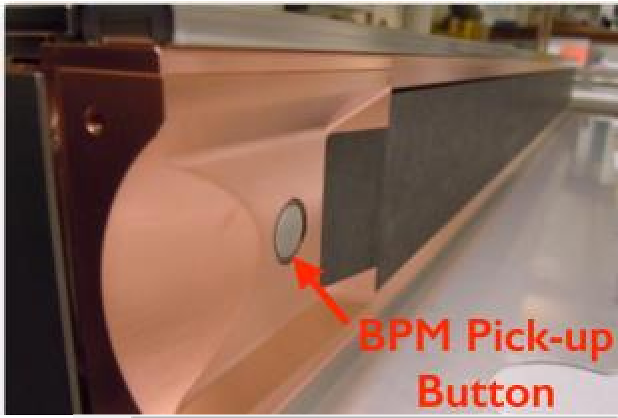
- BLM system used both for setting-up and qualifying
- Beam cleaning efficiencies ≥ 99.98% ~ as designed

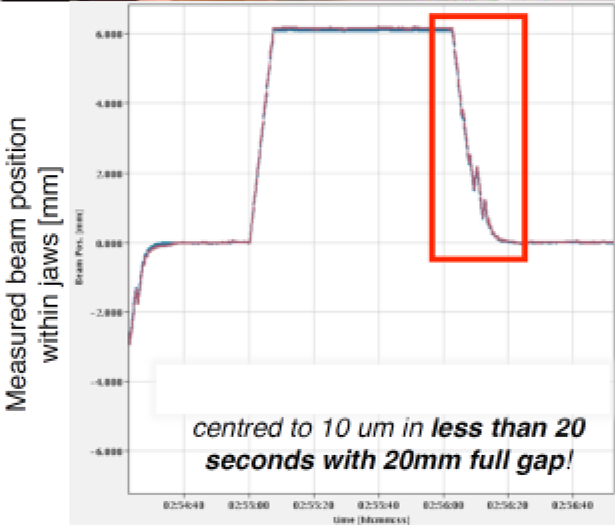


Collimators with Embedded BPMs

- 18 tertiary collimators now equipped with BPM buttons
- Readout via high resolution Diode Orbit electronics
    - Compensated diode peak detectors - resolution <100nm for centred beams
- Allows fast, parallel alignment
    - < 20 s for all BPM collimators without touching the beam
    - 2 orders of magnitude faster than BLM method

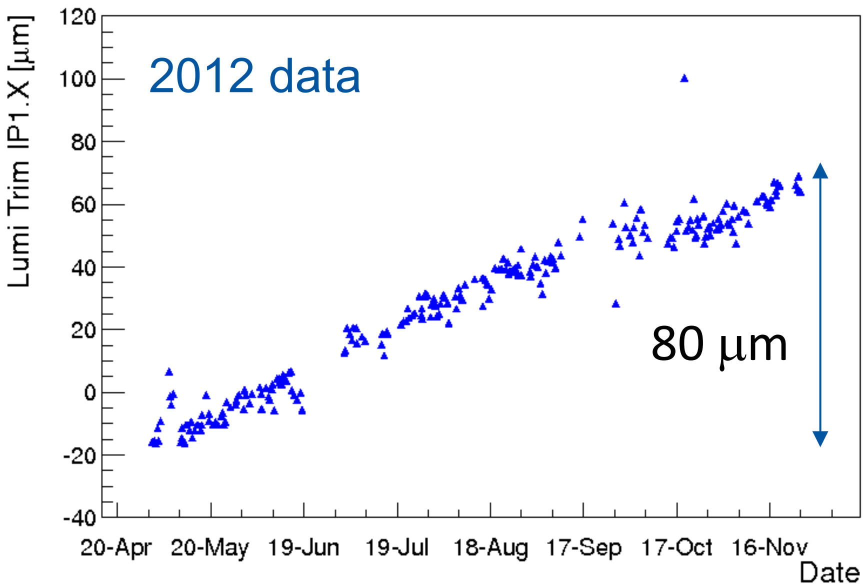






Orbit Stability

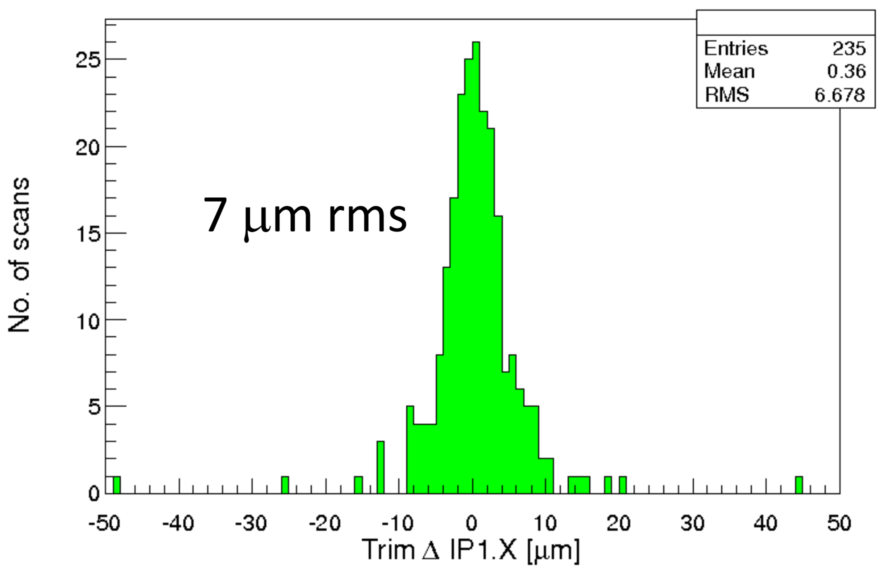
- Important for collimation and collision process
- LHC does not work without orbit feedback
- Main limitations
  - Temperature dependence of electronics
  - Linearity and directivity of stripline couplers near the interaction points



Fill to fill difference is very small

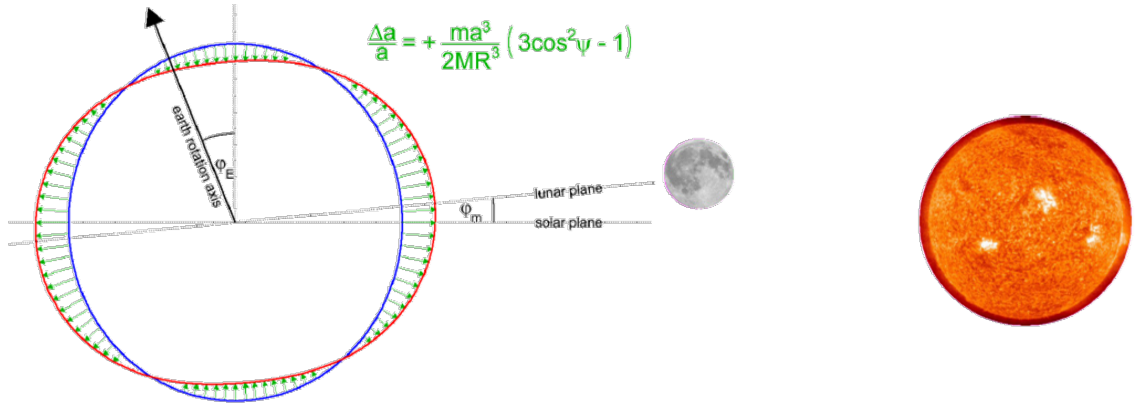
Orbit correction at IP to bring beams head-on

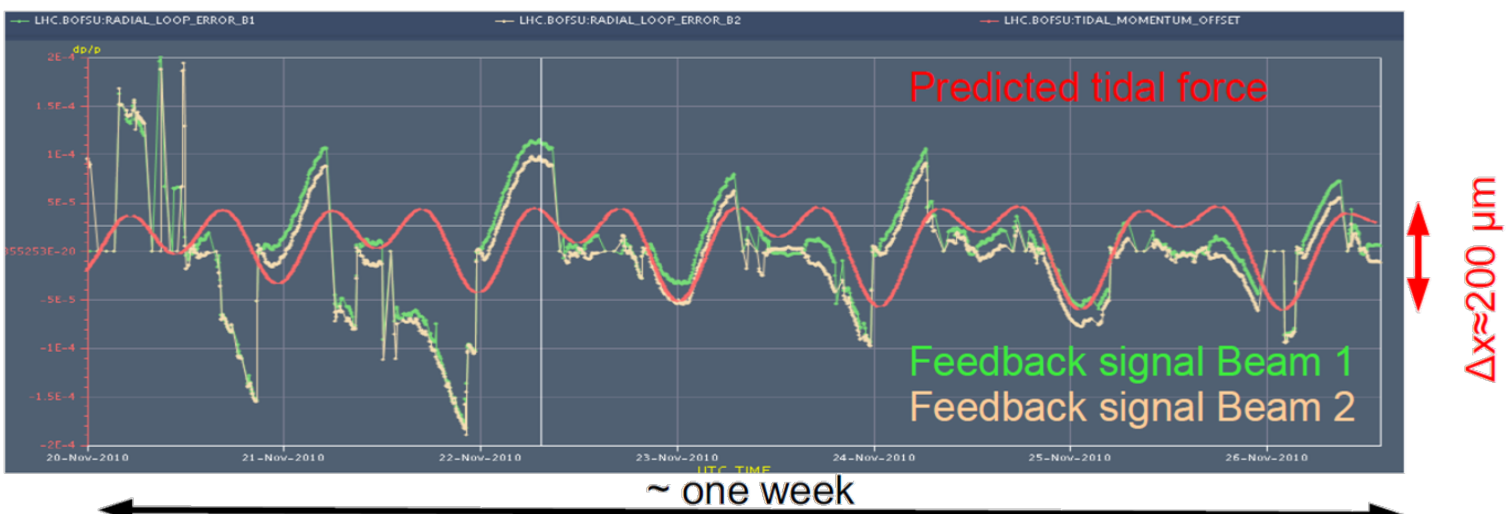
Slow drift over the year → not corrected by feedback



Orbit Stability

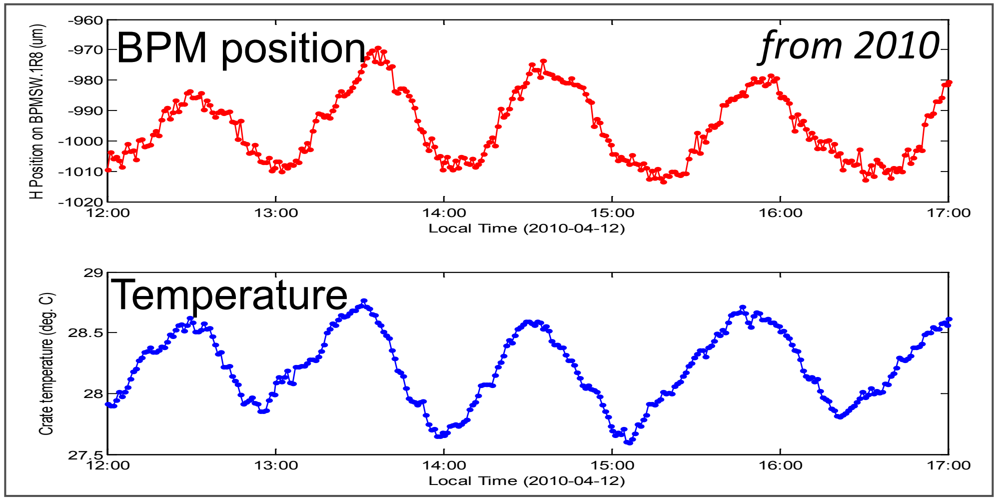
- Earth Tides dominate during Physics

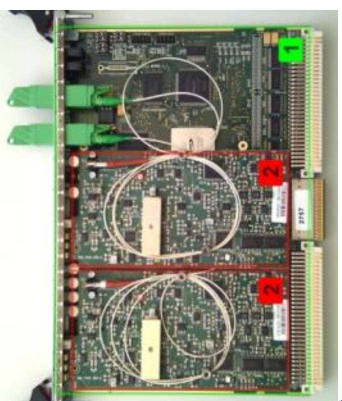


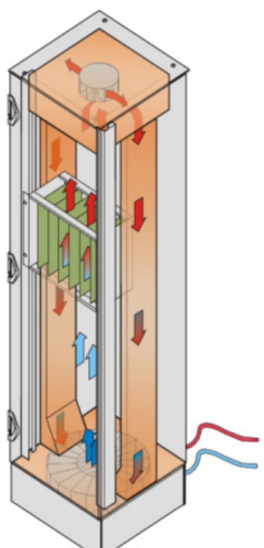


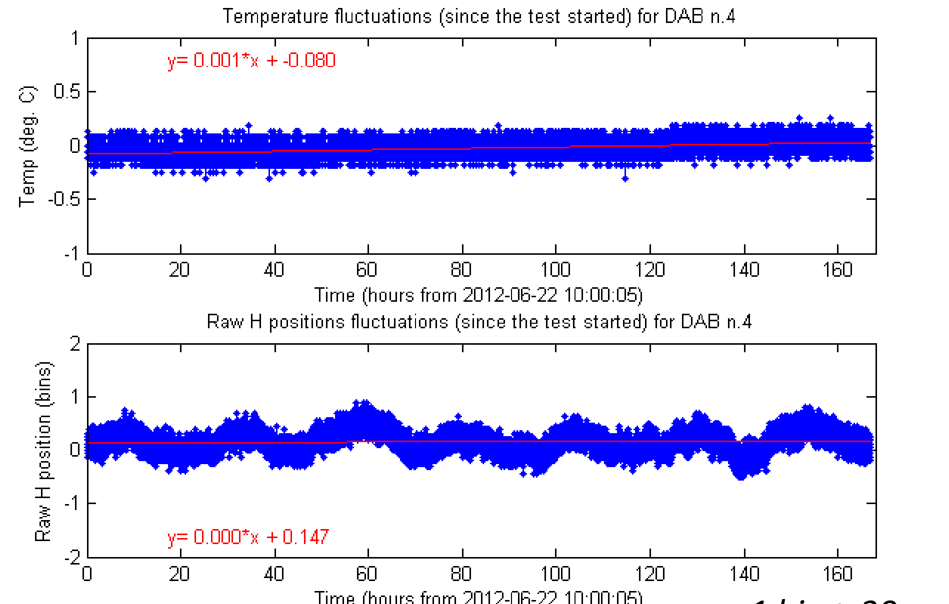
Orbit Stability

- Improvements Foreseen
  - Thermalised racks
  - Maintains temperature within ±0.2°C
  - Prototype successfully tested in 2012





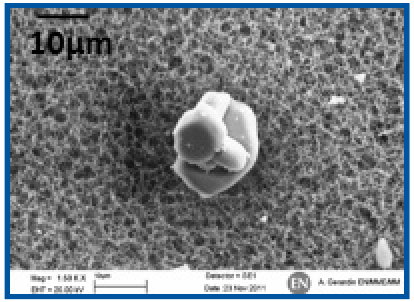


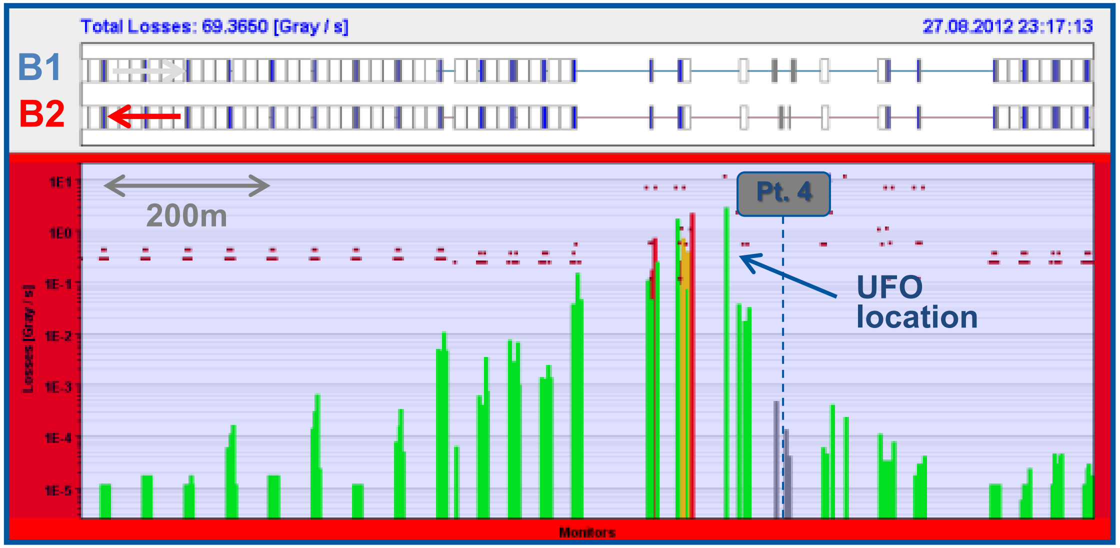


1 bin ~ 30um

Running at Higher Energy

- Dealing with Unidentified Falling Objects (UFOs)
- In 2012:
  - 20 beam dumps due to (Un)identified Falling Objects
    - 14 dumps at 4TeV, 3 during ramp, 3 at 450GeV
  - ~17,000 candidate UFOs below BLM thresholds
- At 6.5 – 7 TeV quench thresholds are significantly lower hence many more dumps expected





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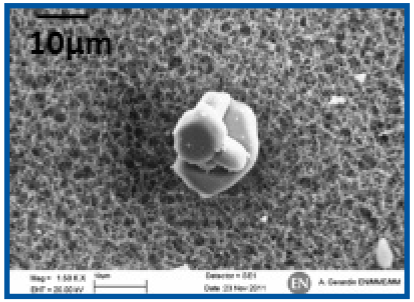
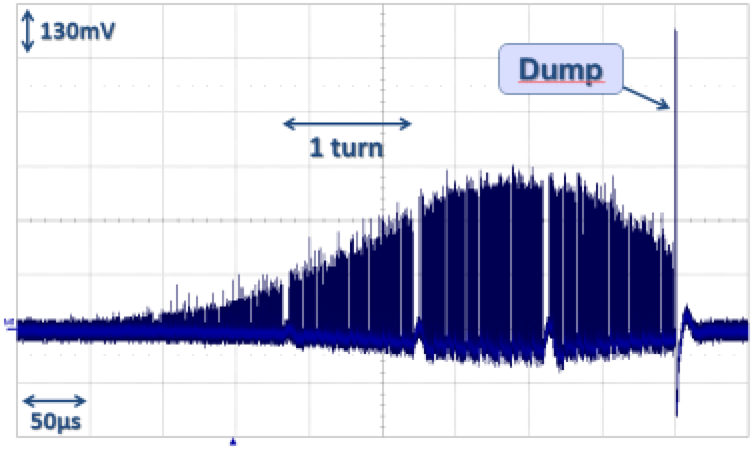
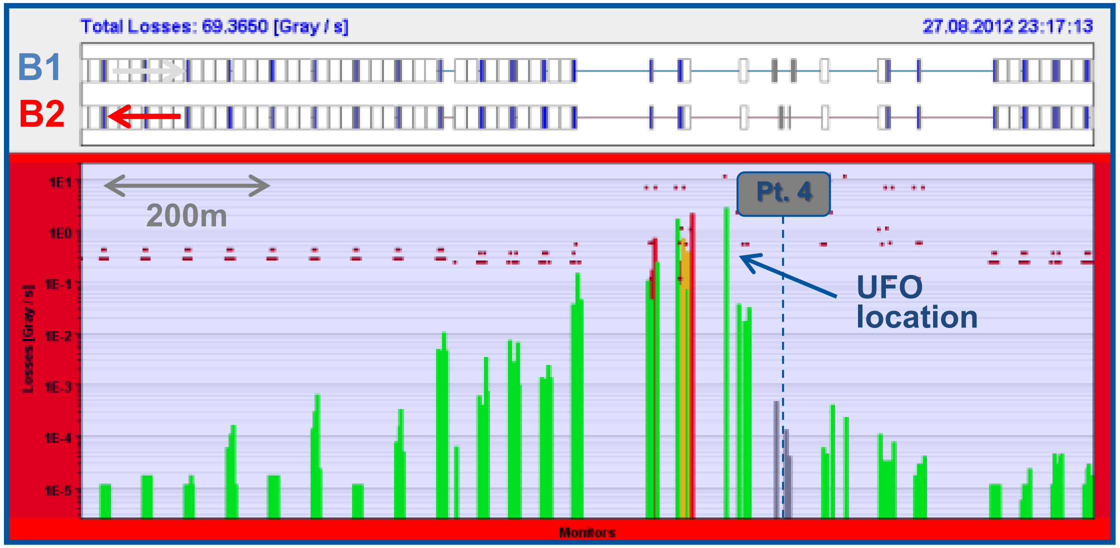


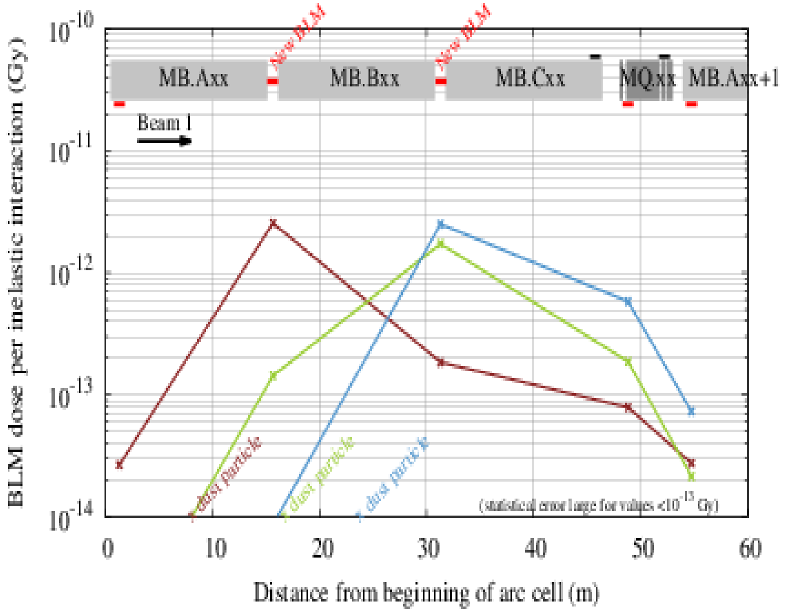


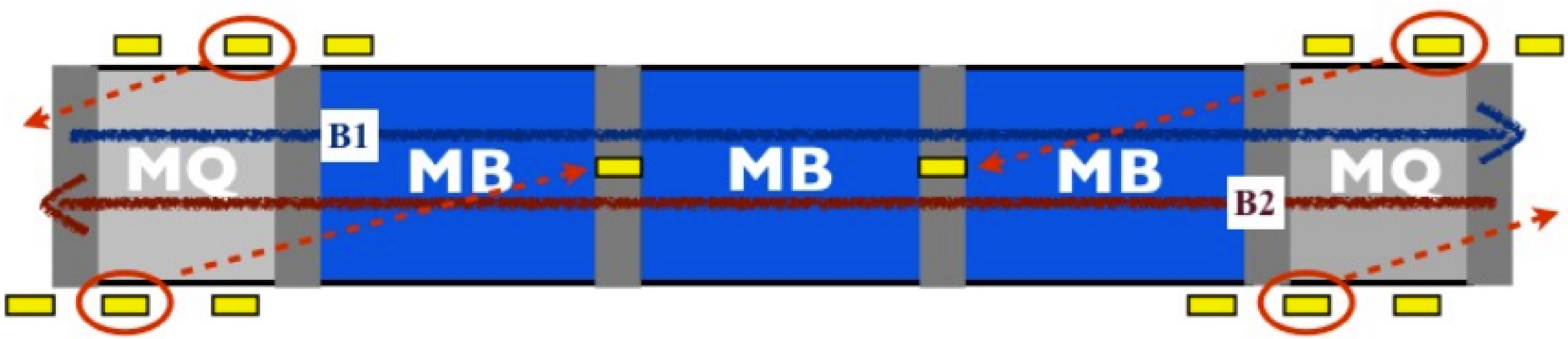
Diamond BLM in IR7



BLM Relocation for UFO Detection

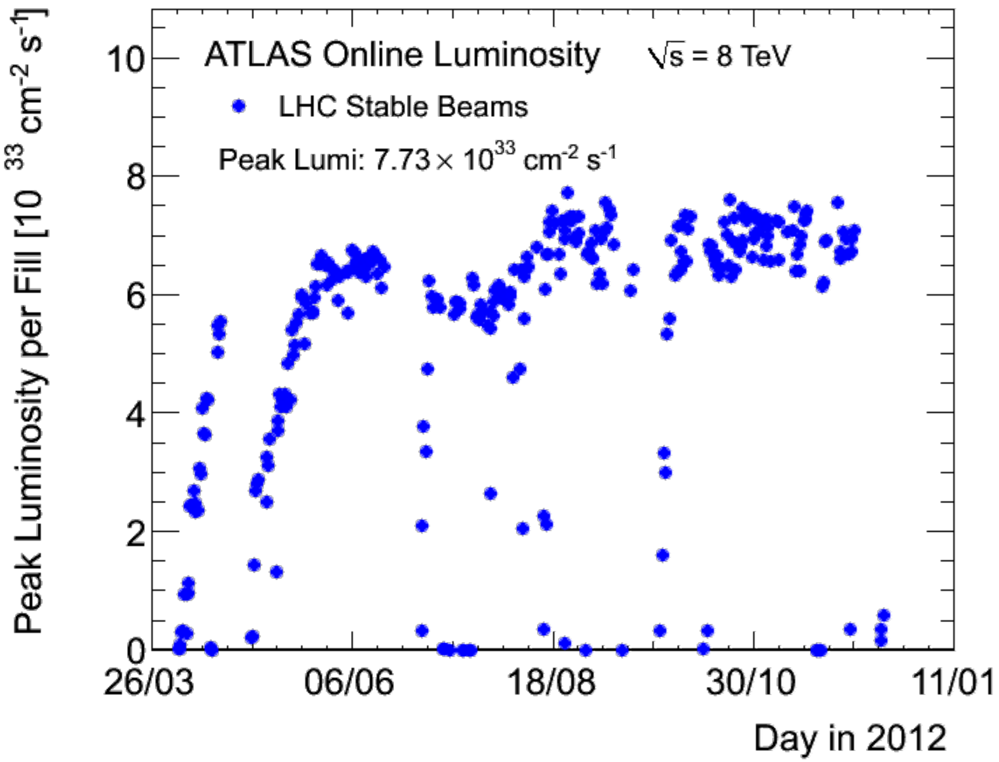
- BLM system designed to protect from beam losses at maximum-beta locations (quadrupoles)
- During Run1 there were 3 BLMs per beam per Quadrupole
- Middle BLM moved to main dipole interconnect in order to protect efficiently from UFO losses
  - Gain a factor 30 in sensitivity





Running at 25ns Bunch Spacing

- During Run I ran at 50ns bunch spacing with near ultimate bunch intensities and small emittances
  - Achieved a peak luminosity of nearly 8×10^{33} $cm^{-2}s^{-1}$
- Close to design luminosity of 10^{34} $cm^{-2}s^{-1}$
- Why change?



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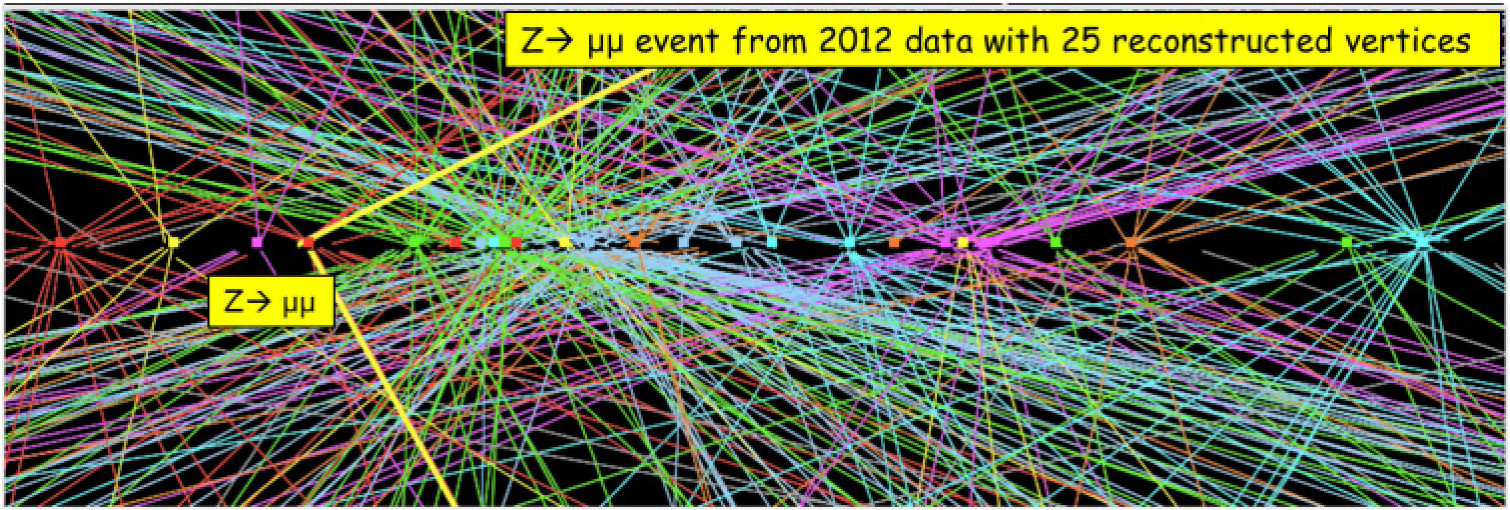
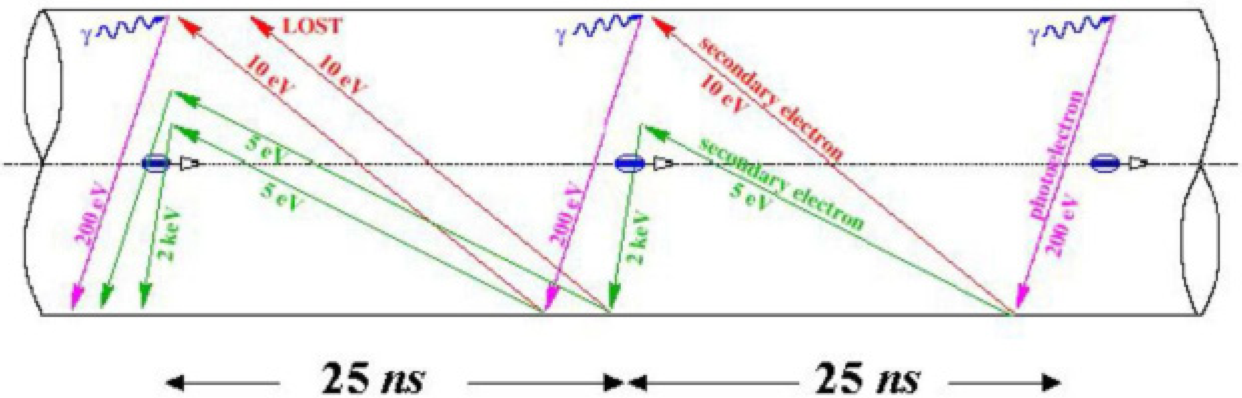


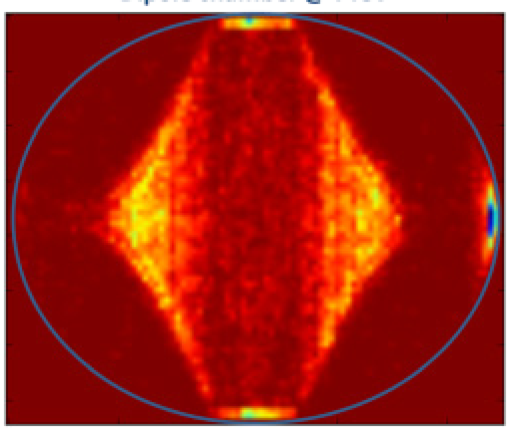
- Experiments inefficient with large number of collisions per crossing
- Moving to 25ns spacing
  - increases total intensity while significantly lowering pile-up

25ns and Electron Cloud

- When an accelerator is operated with close bunch spacing an Electron Cloud can develop in the beam chamber due to Secondary Emission from the chamber wall

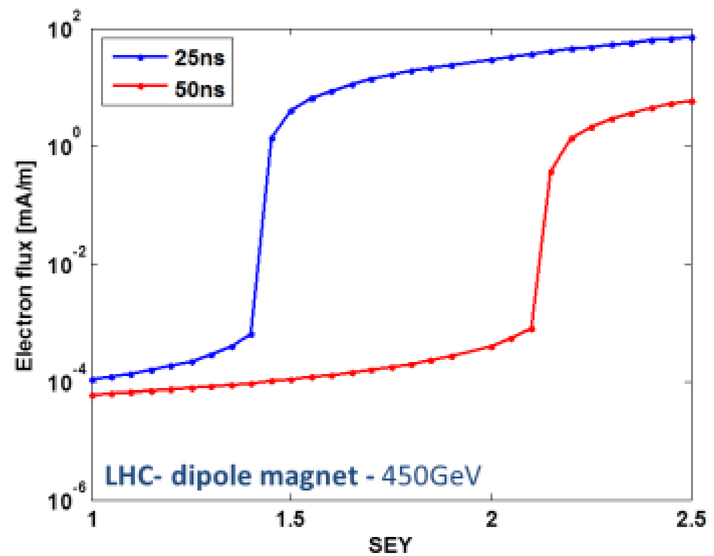


Dipole chamber @ 7TeV



<u>Consequences</u>

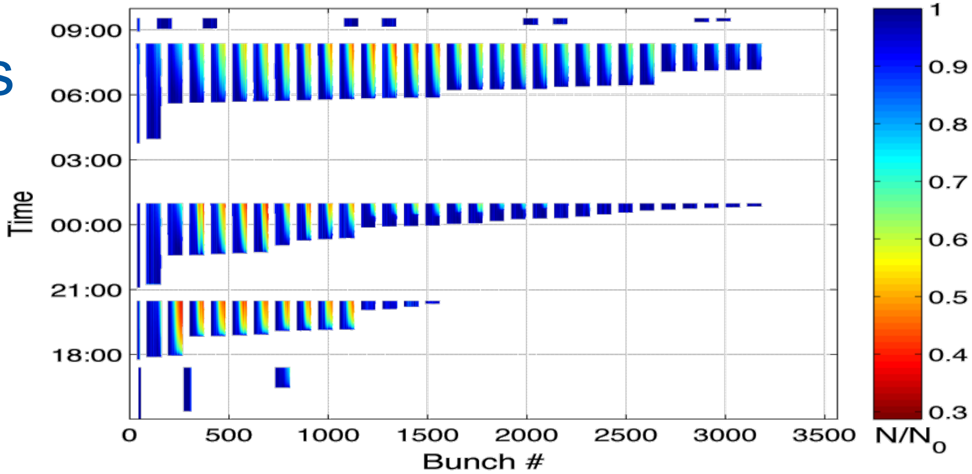
- Impact on beam quality
  - induced instabilities, particle loss, emittance growth
  - Dynamic pressure rise
  - Heat load (for cryogenic sections)
- For LHC these are much worse for 25ns beams



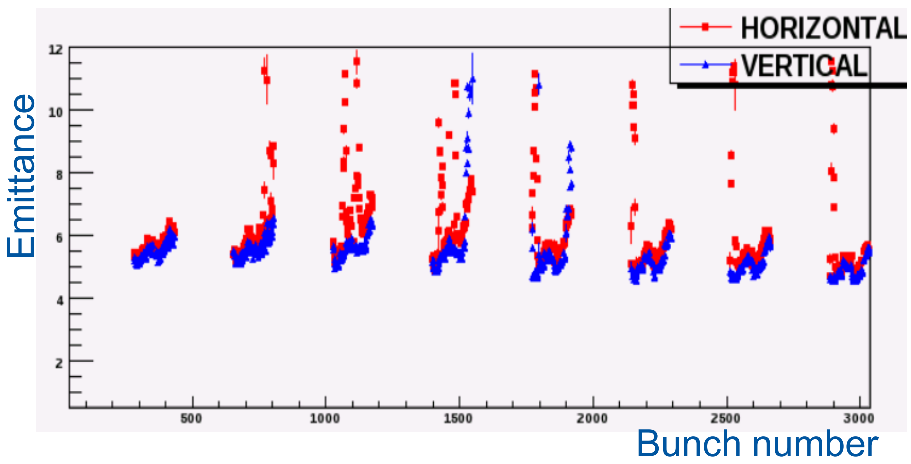
25ns – Measuring Instabilities

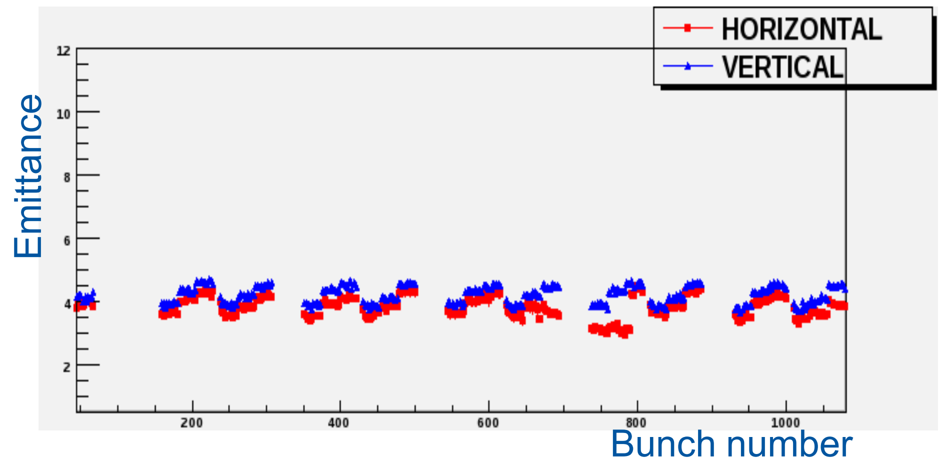
Bunch-by-bunch measurements

- Fast Beam Current Transformer
  - Relative bunch intensities



- Synchrotron Light Monitor
  - Relative bunch size
  - Gated camera allows profile of all bunches to be captured in a few minutes



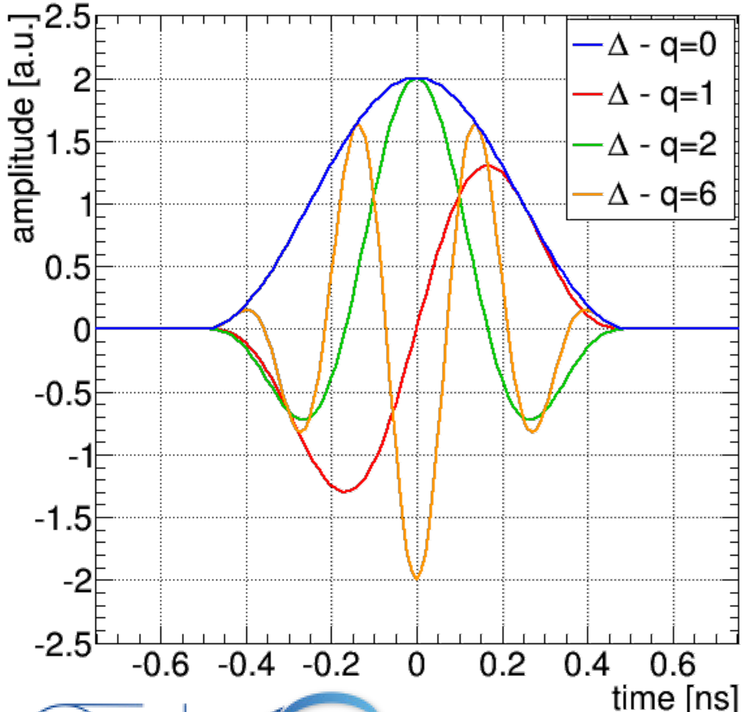


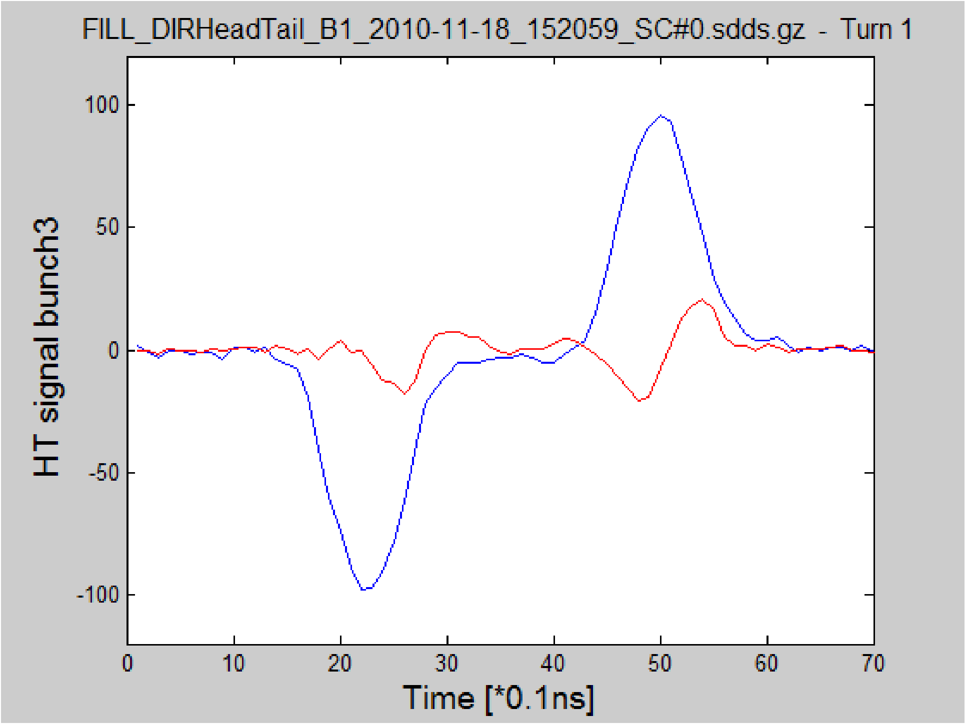
Emittance blow-up before & after scrubbing

25ns – Measuring Instabilities

Intra-bunch measurements

- Head-Tail monitor
  - Resolution limited to ~100μm due to orbit offsets & limited ADC resolution
- Multiband Instability Monitor – currently being developed
  - 16 bands @ Δf_b = 400 MHz
  - Use filter bank followed by direct diode detection for high sensitivity
  - Can infer mode of oscillation and be used to trigger other systems





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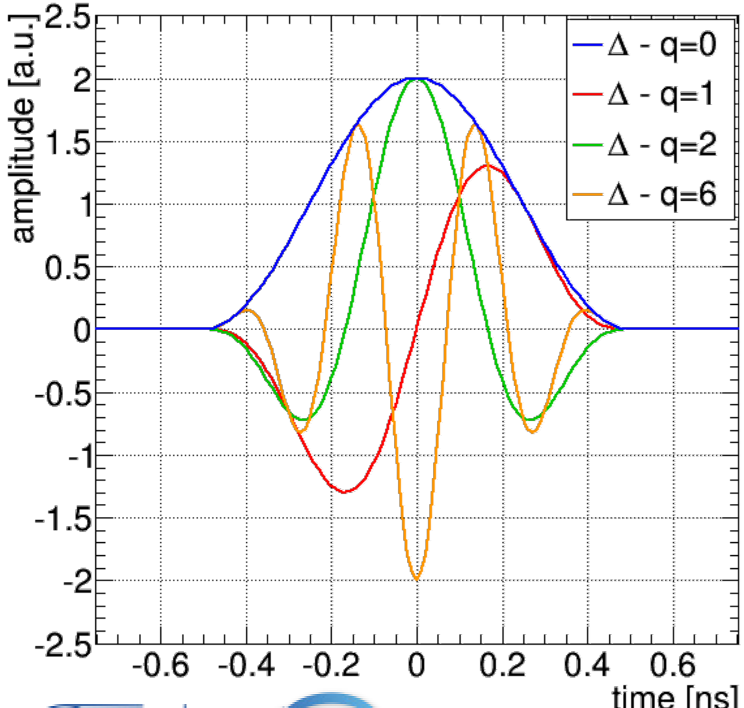

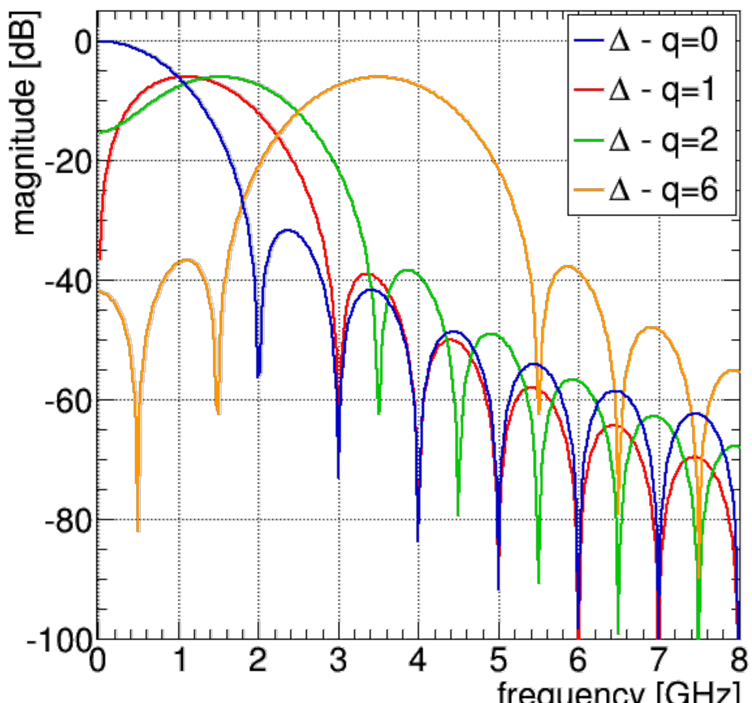

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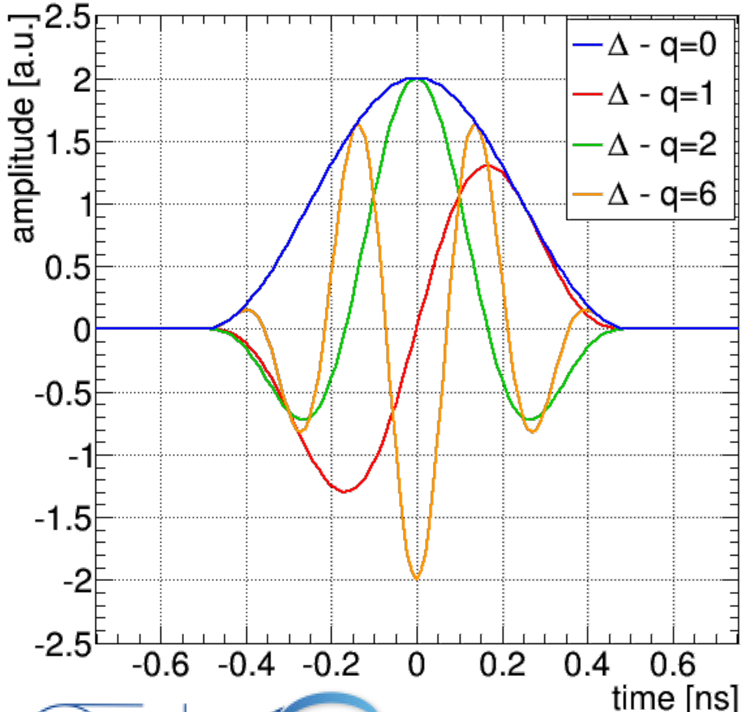
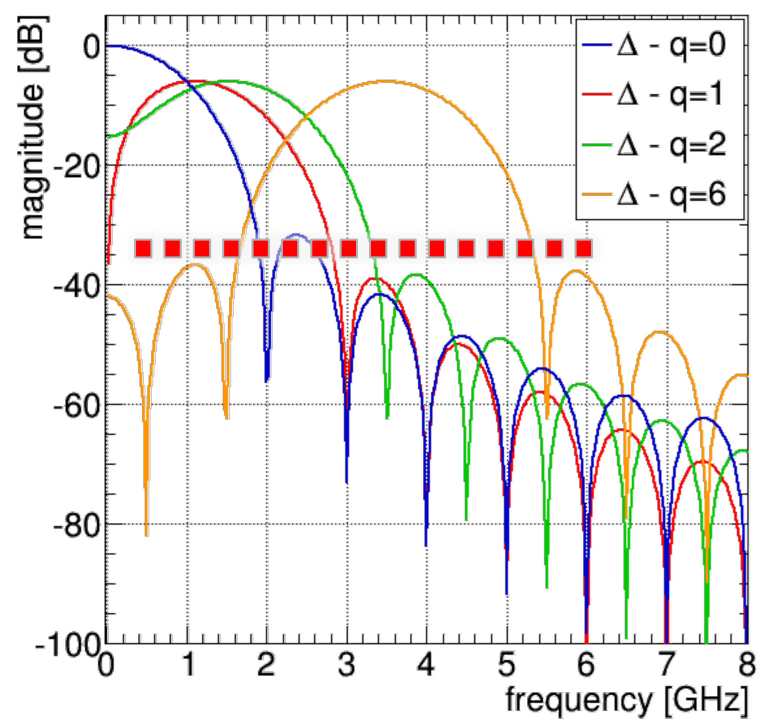
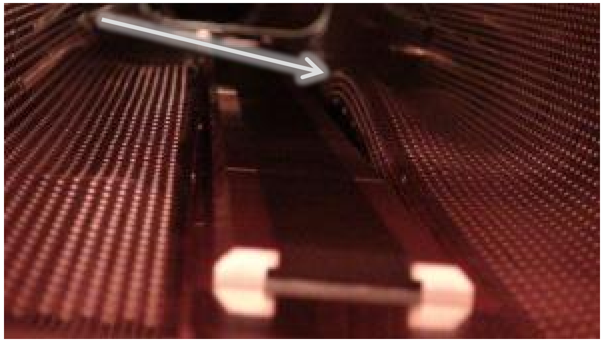




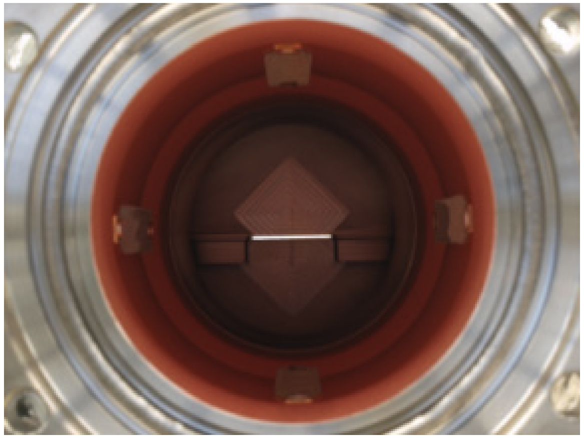
Coping with High Brightness Beams

Beam induced RF Heating

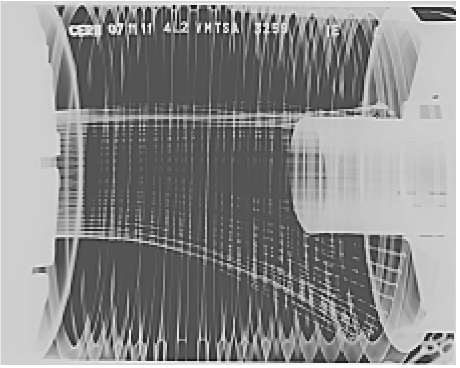
- Observed on many systems in Run I
- 25ns running could give further surprises



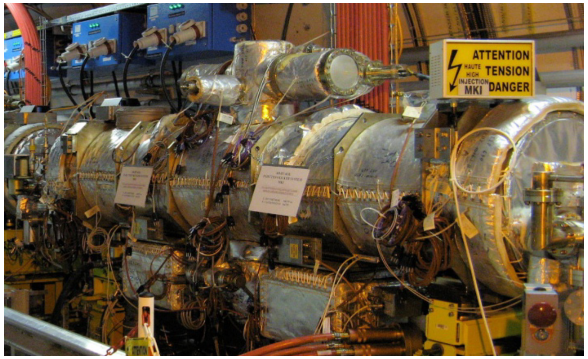
Deformation of Beam screen around injection protection jaw



Heating of ATLAS ALFA Detector

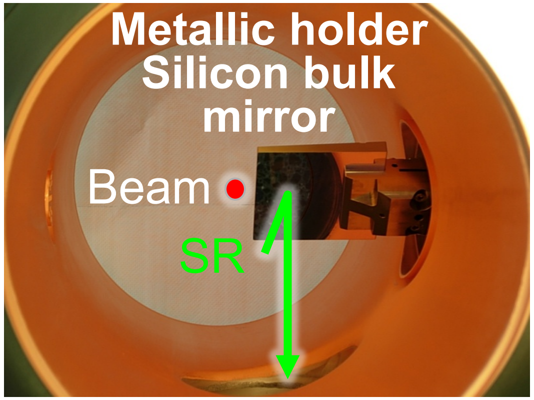


Deformation of bellow support spring



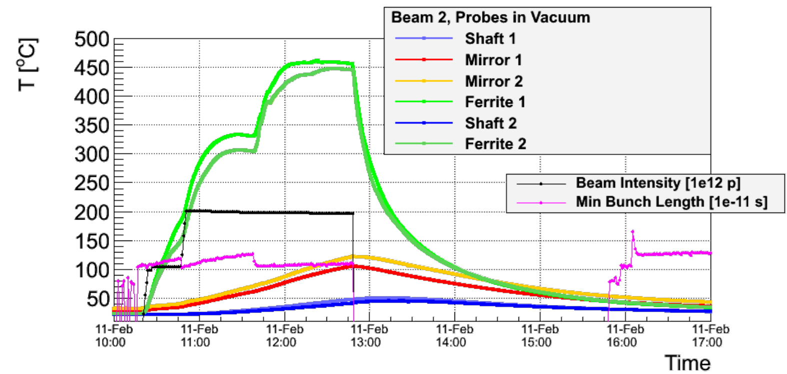
Injection Kicker heating

Synchrotron Light Extraction Mirror

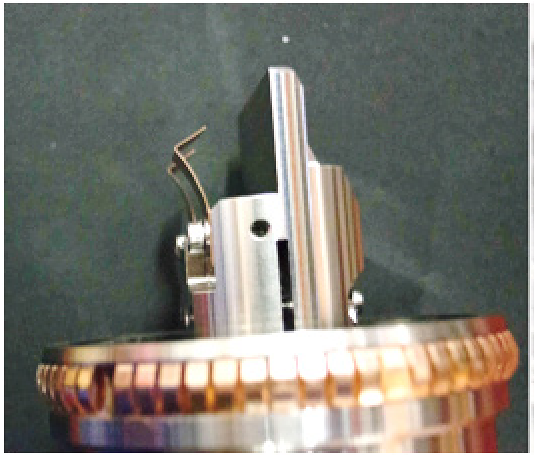


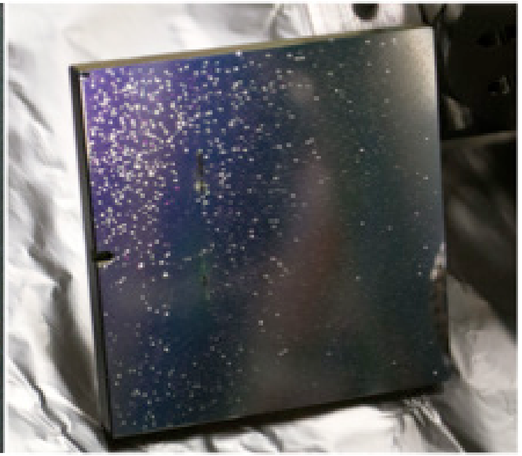
Mirror heating clearly correlated to

- beam intensity
- beam spectrum
- bunch length



Failure of mirror holder + blistering of mirror coating

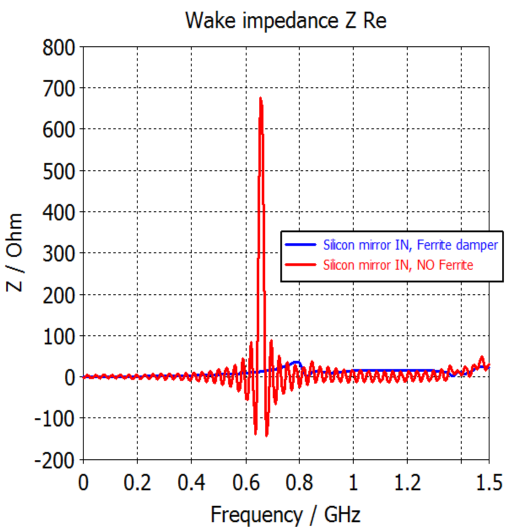




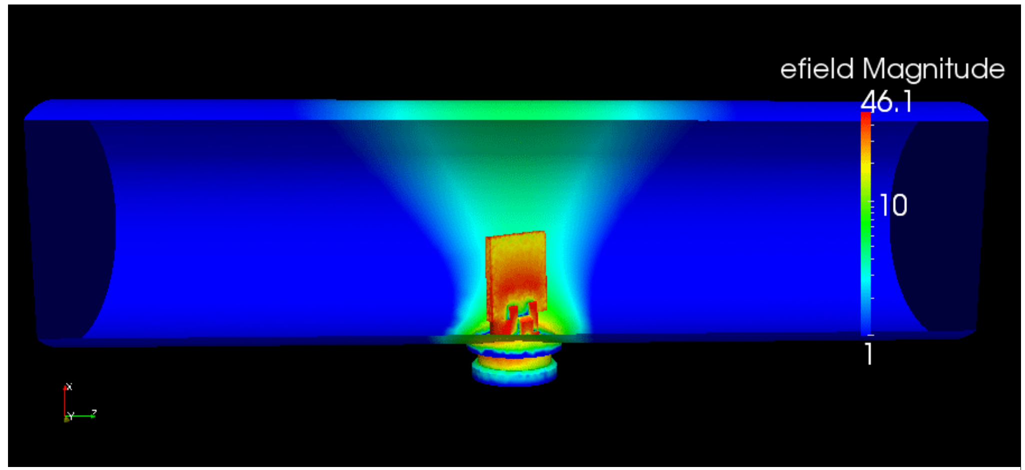
Complete Re-design

- EM Simulations
- Lab Measurements

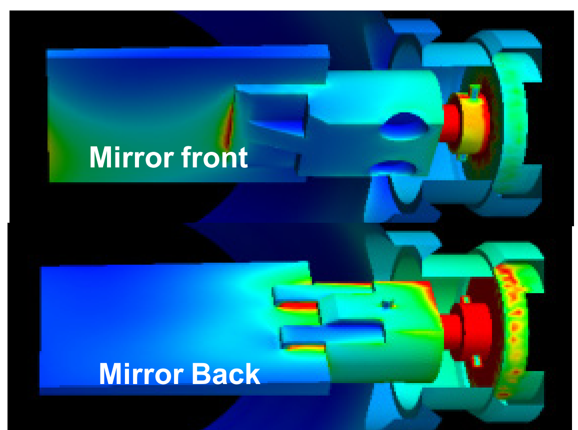
Synchrotron Light Extraction Mirror



Longitudinal wake impedance of BSRT with and without Ferrite damping



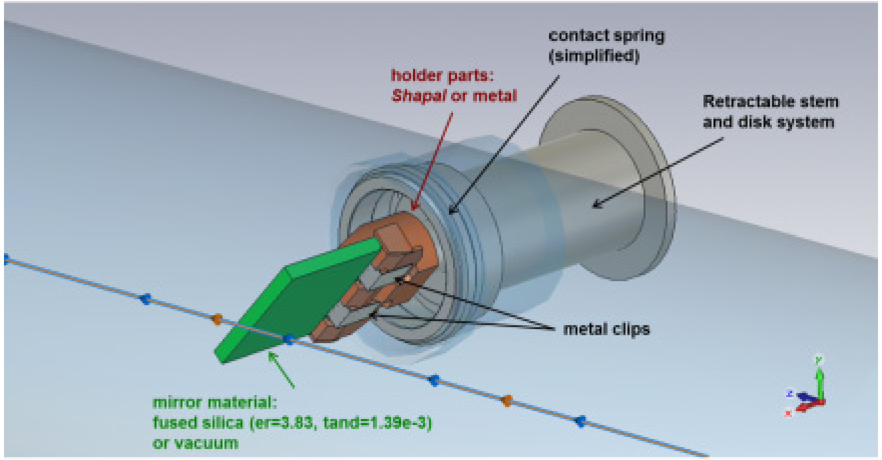
E-field of a dominant resonating mode at 650 MHz. (Q = 1263 / Rsh = 25841 Ohm)



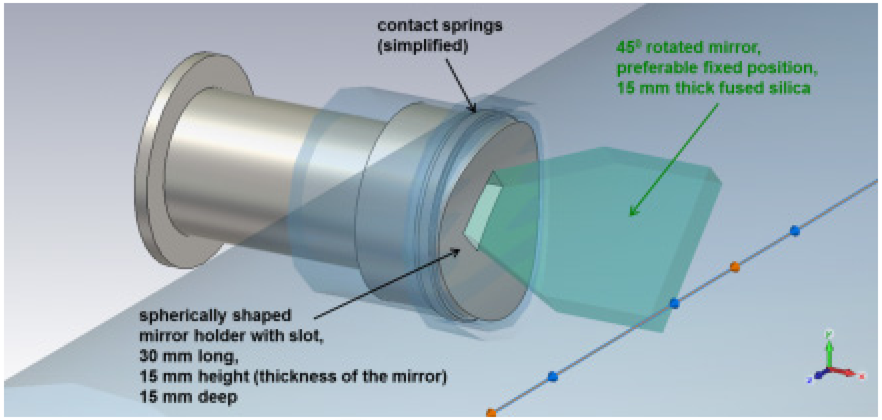
B-field of the beam in Time Domain.
Red = Hot (bigger current density) :
Blue = Cold

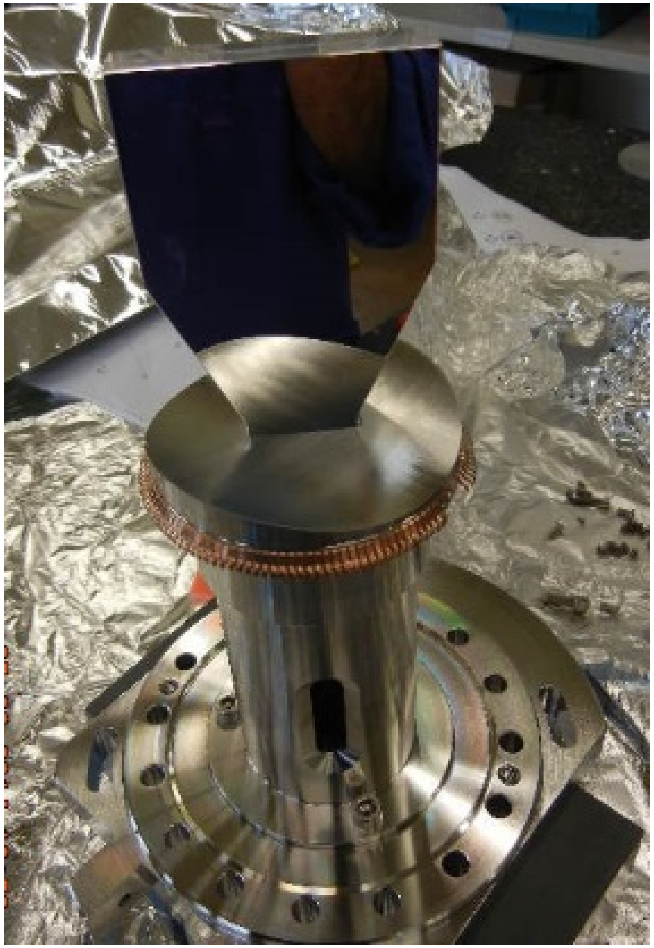
Synchrotron Light Extraction Mirror

OLD Extraction Mirror



NEW Extraction Mirror



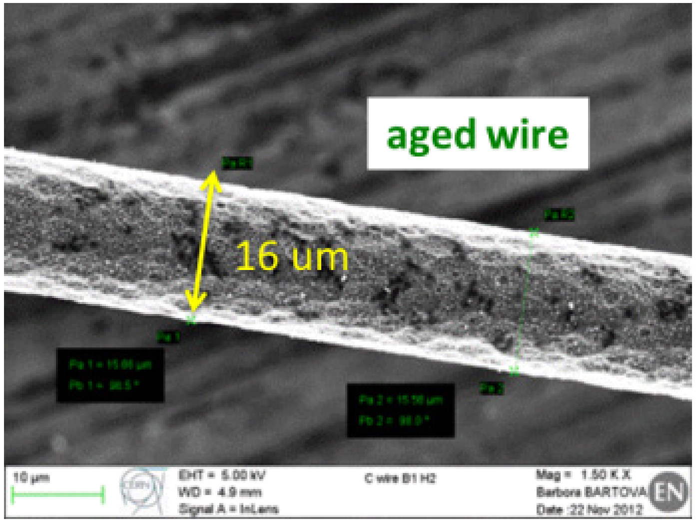


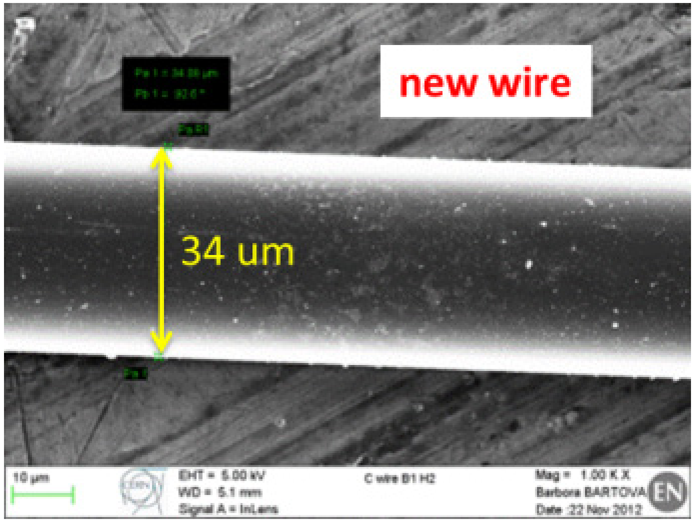
Solution for Run II with low RF 'footprint' and shielded cavities

Coping with High Brightness Beams
The measurement of small beam sizes

Wire Scanners - Operational limits after LS1

- Limit defined by wire sublimation process





- At 450 GeV limit at 2.7×10^{13} protons
  - One injected SPS batch of 144 bunches @ 50ns OK
  - One injected SPS batch of 288 bunches @ 25ns NOT OK
- At 6.5 TeV limit at 2.7×10^{12} protons
  - ~20 bunches
- Issue for calibration of all other beam size measurement devices

Measurement of small beam sizes using the synchrotron light monitor

Problem

During Run1 :

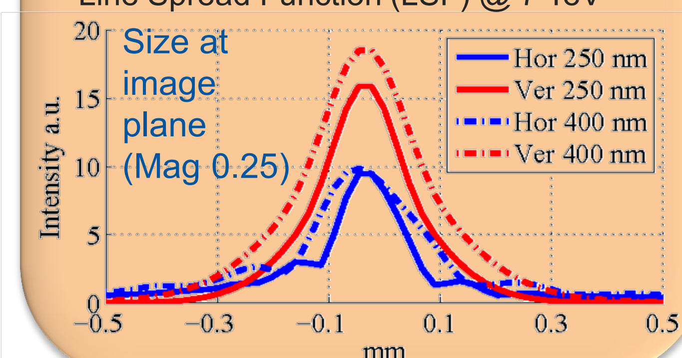
imaging accuracy compromised by extraction mirror heating and coating blistering

→light scattering, image blurring

@ 6.5-7 TeV when imaging in the UV (e.g. 250nm):

contribution from diffraction (~250μm) > beam size (180μm)

Line Spread Function (LSF) @ 7 TeV



Proposed Solution

New extraction mirror design

Wave-front distortion measurements (Shack-Hartman mask method) with and without beam

Imaging a narrow band in the near UV to reduce diffraction

250nm focusing lenses

UV sensitive CCD camera photocathode

Interferometry (not diffraction limited)

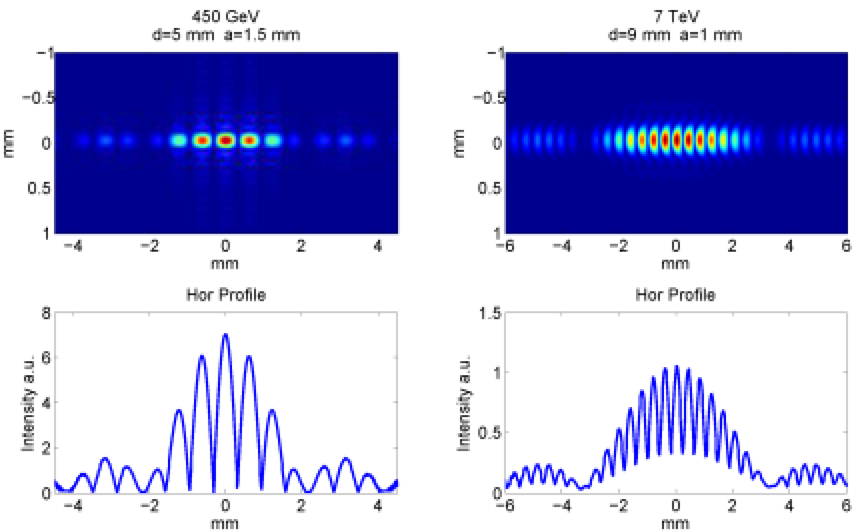
New optical line (in parallel to imaging, after splitting)

Measurement of small beam sizes using the synchrotron light monitor

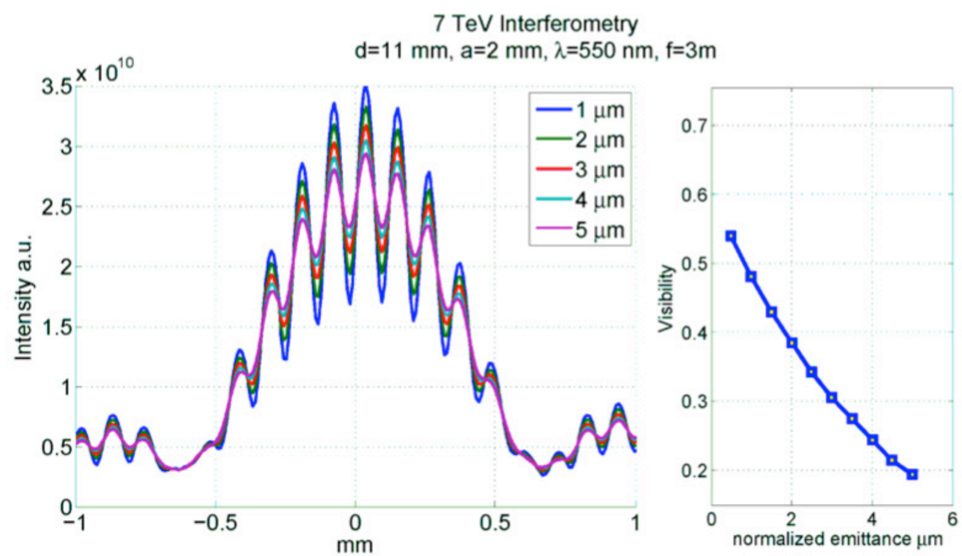
Interferometry

- Non-diffraction limited & widely used in e^- machines for very small beam sizes
- New project in collaboration with KEK, SLAC & CELLS-ALBA

Injection 7 TeV



Simulated interference fringes & resulting Line Spread Function



Interference fringes for different emittances & predicted visibility as function of emittance

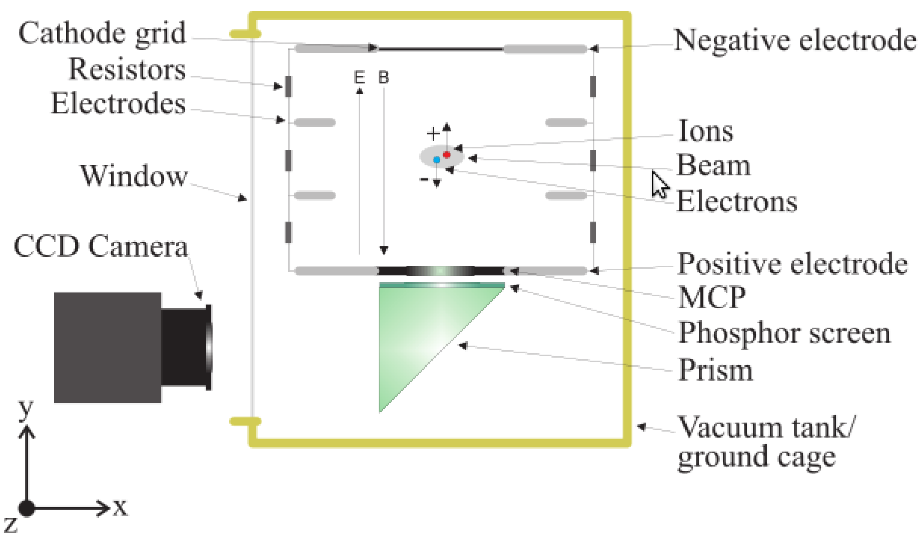
Measurement of small beam sizes using the ionization profile monitor

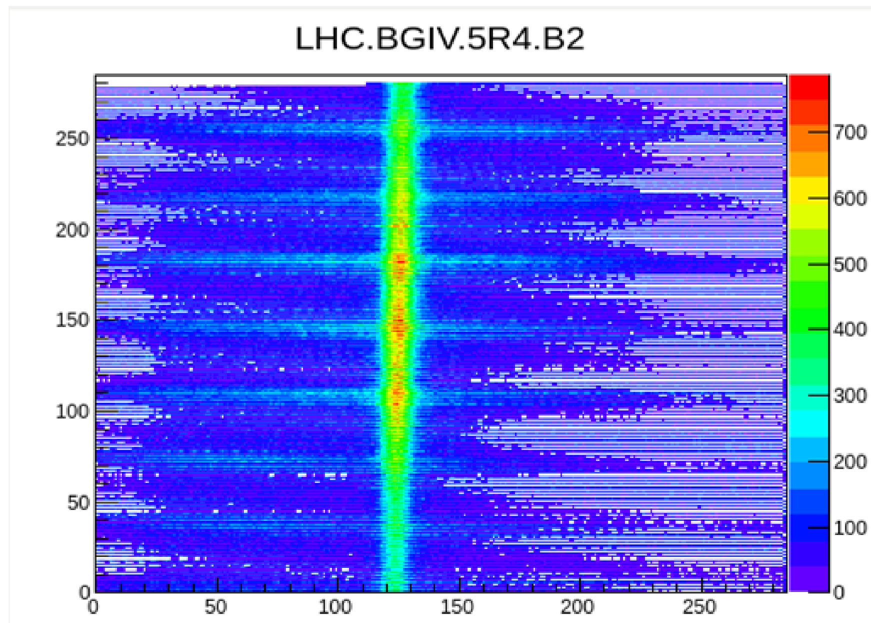
Layout

- Gas injection (Ne)
- Electron collection with 0.2 T guide magnets and MCP signal amplification
- Optical readout from phosphor screen with Rad-hard camera

Results

- Worked well for Pb ions (what it was designed for)
- Gave distorted images for protons at high energy

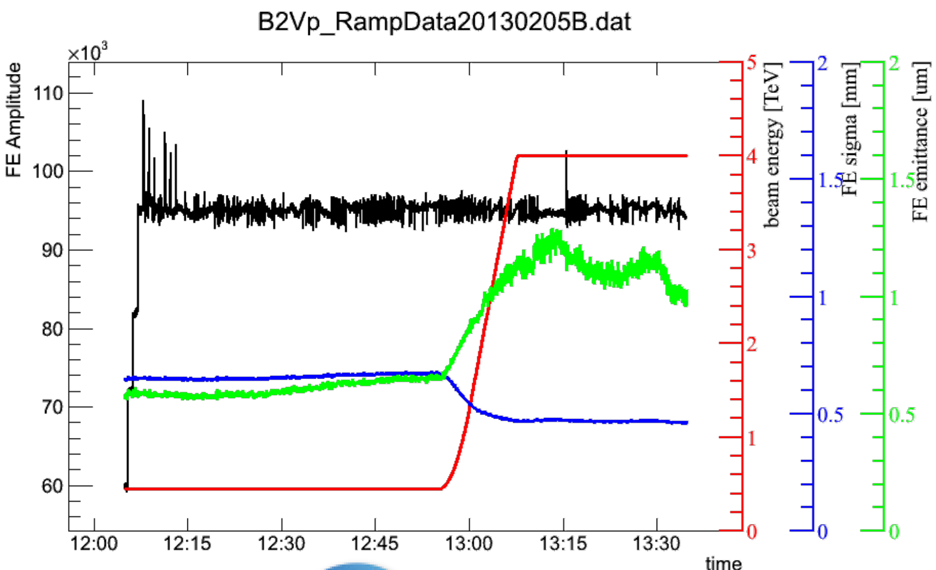


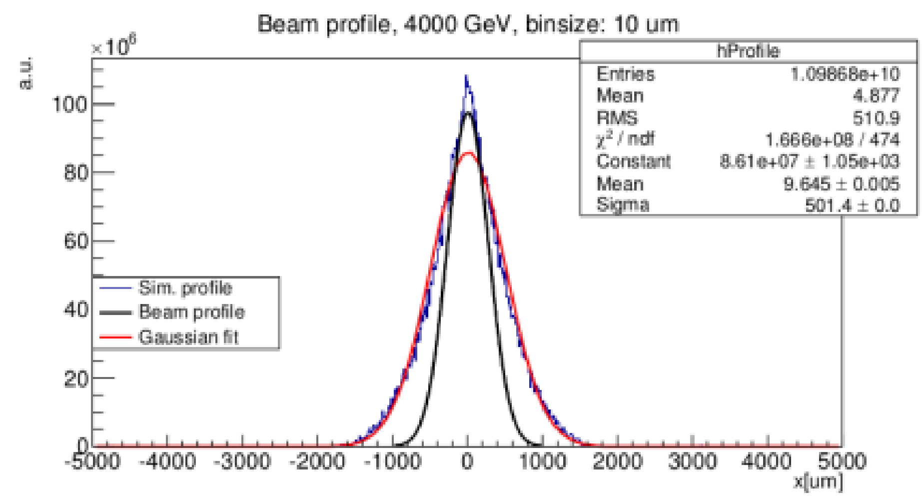


Measurement of small beam sizes using the ionization profile monitor

Outlook for proton beam size measurements

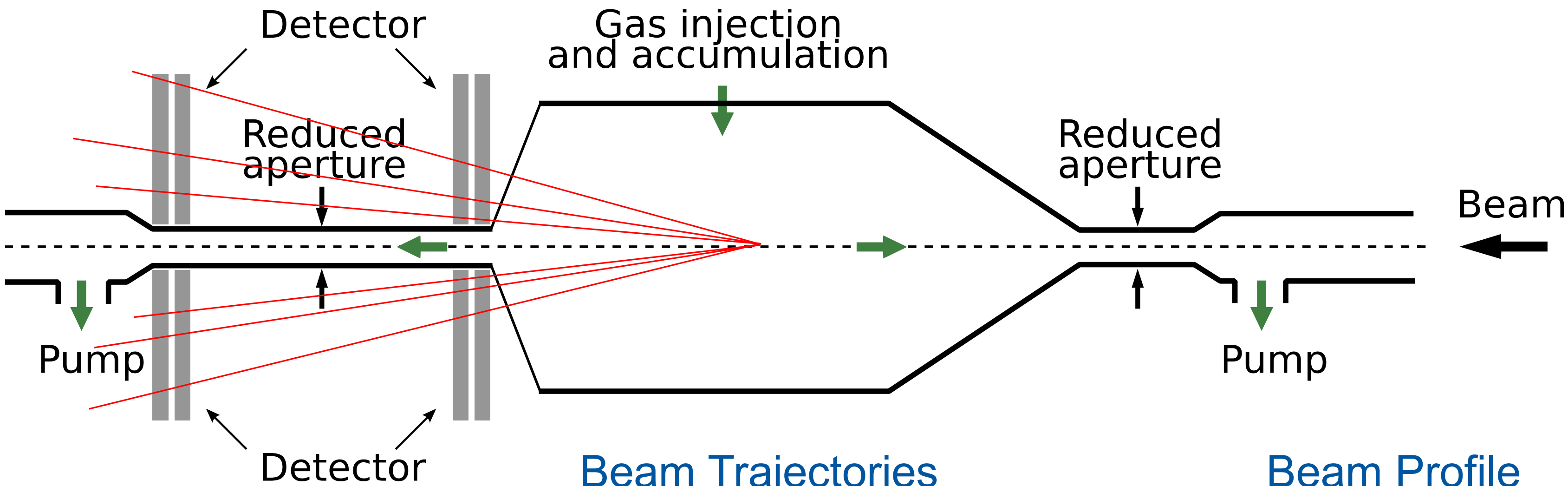
- At injection: emittance OK - agreement with wire scanner
- Unphysical behavior during ramp and squeeze.
  - Explanation: profile distortion due to beam space-charge
  - Confirmed by simulations.
- Distorted profile cannot easily be fitted
- Solution: increase of magnetic field to 1 T (not foreseen for the moment)



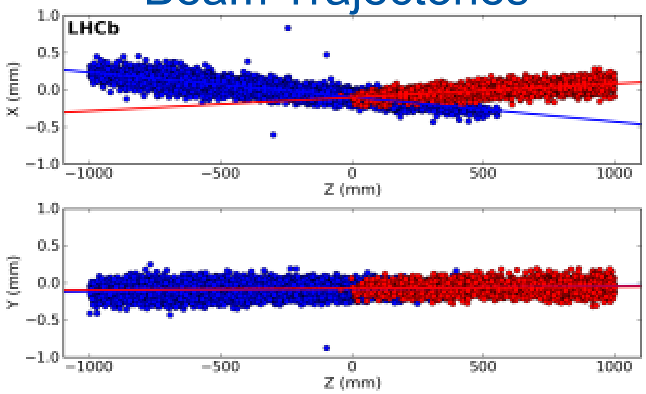


New non-invasive beam size measurement method

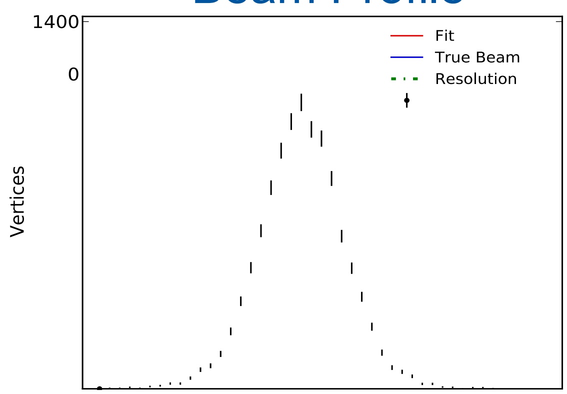
- The Beam Gas Vertex Detector



Beam Trajectories



Beam Profile

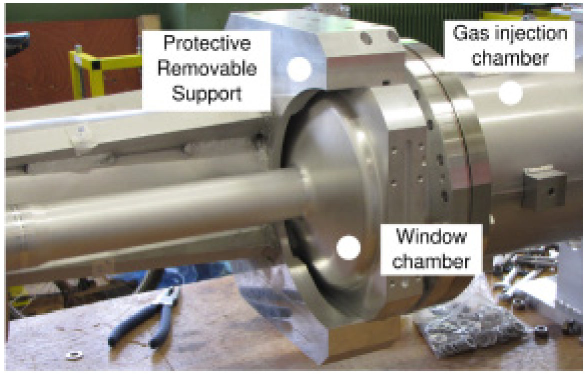


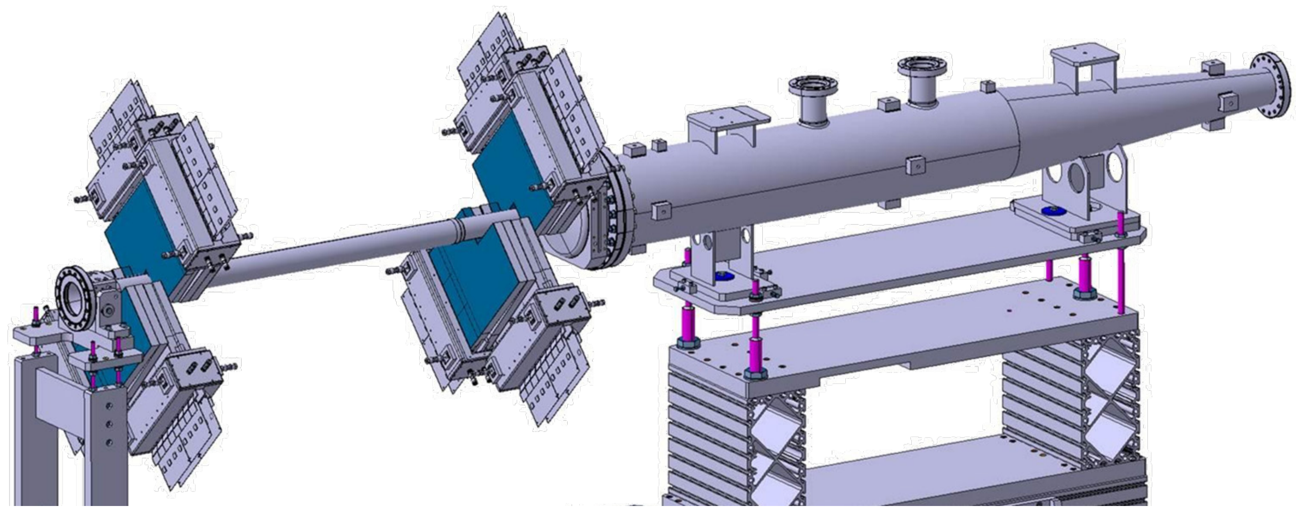
Based on concept used by LHCb vertex detector

The Beam Gas Vertex Detector

- Prototype installed on one beam during LS1
  - Detectors based on scintillating fibres read out with SiPMs
    - LHCb (CERN)
    - EPFL (CH)
    - Aachen (DE)

Quantity	Accuracy	Time interval	Key factors
Relative bunch width	$5\ \%$	< 1 min	vertex resolution stability
Absolute average beam width	$2\ \%$	< 1 min	$\sigma_{\text{beam}}, \sigma_{\text{MS}}, \sigma_{\text{extrap}}\ (\sigma_{\text{hit}})$

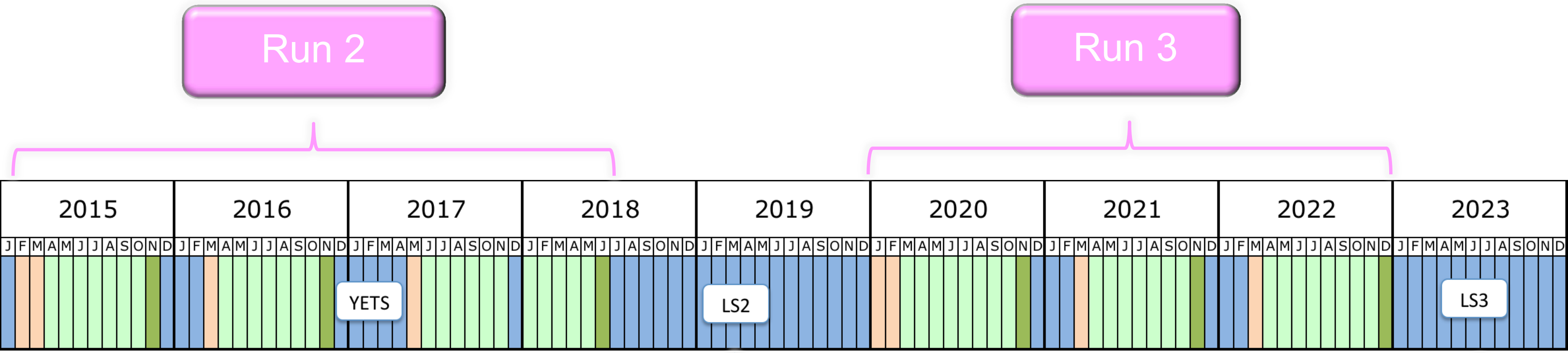




Summary of Beam Instrumentation Consolidation and Upgrades

- BLM
    - Re-distribution of monitors to counter threat from UFOs
    - Test of cryogenic BLMs for the High Luminosity LHC
- BPM system
    - Addition of temperature controlled racks
    - Test of new, high resolution diode orbit system
    - Addition of BPMs embedded in collimator jaws
- Synchrotron Light Monitor
    - New extraction mirror
    - Test of interferometry
    - New algorithms for correcting single photon counting longitudinal density monitoring
- Tune & Instability Monitoring
    - Test of new multi-band instability monitor
    - Revamped Schottky system for on-line chromaticity & bunch by bunch tune
- Others
    - Installation of new fast current transformers
    - Installation of beam gas vertex detector prototype

The Next 10 Years



6.5 to 7 TeV
Peak luminosity **$1.7x10^{34}cm^{-2}s^{-1}$**

7 TeV
Peak luminosity **$2.0x10^{34}cm^{-2}s^{-1}$**

LHC Injector Upgrade:
- Connection of new LINAC4
- Major upgrades to many systems
  - RF, BI, injection/extraction,…

Experimental Upgrade:
- ALICE & LHCb

High Luminosity LHC Upgrade:
- Peak luminosity **$5×10^{34}$ $cm^{-2}s^{-1}$**
- **3000 fb^{-1}** in ~10 years
- Replacement of Triplet Quads
- Addition of crab cavities
- Cryogenic upgrade
- Major Experimental Upgrade