CERN

LHC Beam Instrumentation

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Outlook

- LHC beam characteristics
- Position/Orbit measurement
- Tune measurement
- Intensity measurement
- Emittance measurement
- Beam loss measurement

LHC beam characteristics

- Particle type: protons and ions (Pb82+)
- Energy: 0.45 – 7 ZTeV
- Bunch intensity: $5 \cdot 10^{8}$-$2 \cdot 10^{11}$ charges
- Number of bunches: 1-2808
- Bunch length: 5-12 cm
- Emittance: 0.5-3.5 μm (size 100 μm)
- Revolution frequency: 11.3 kHz
- Total stored energy: up to ~370 MJ

How to measure such object?

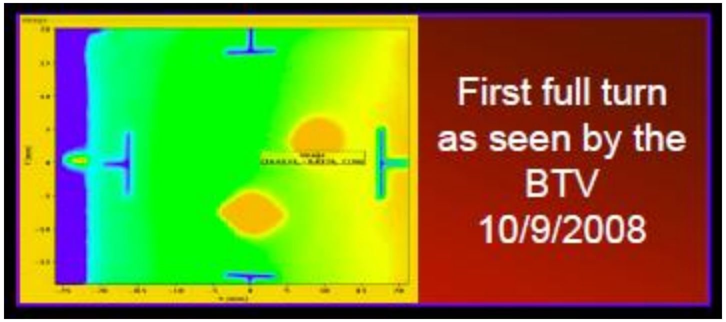
LHC - terminology

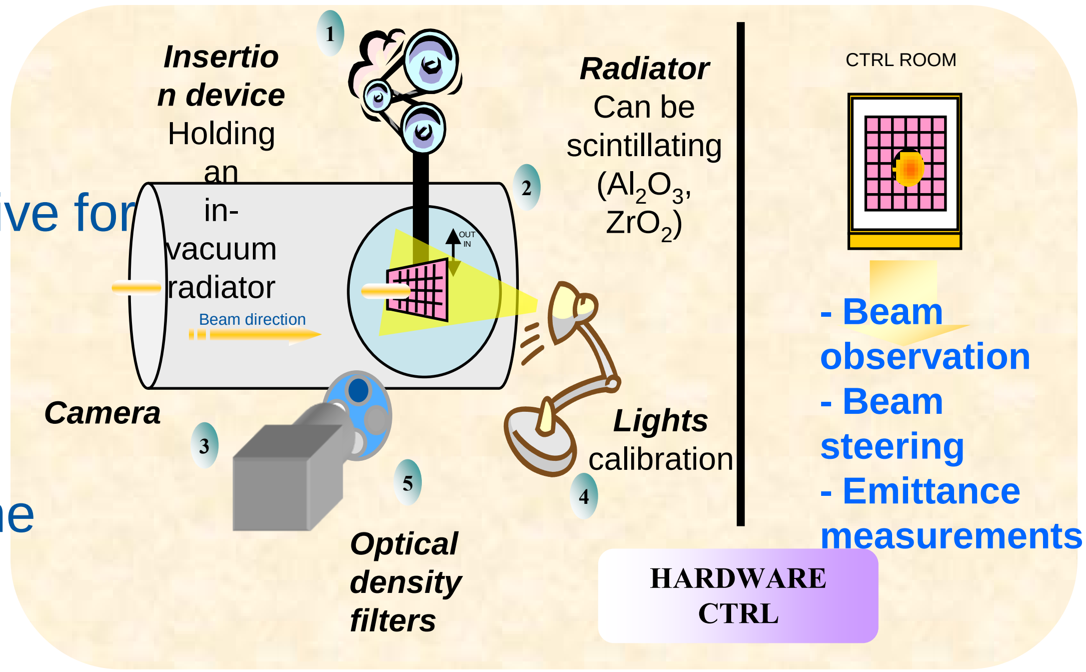
All beam measurement devices on LHC have names starting with B:

- BPM (Beam Position Monitors)
- BLM (Beam Loss Monitors)
- BWS (Beam Wire Scanner) - also WS
- BGI (Beam Gas Ionization) – also IPM
- BSRT (Beam SynchrotRron light Telescope)
- BGV (Beam Gas Vertexing)

Orbit – first turn

- Beam Screens (BTV)
- scintillating screens are doped alumina plates (Al_2O_3:Cr)
- Measurement destructive for the beam and for the equipment
- In LHC used only for the “first turn” beam setup

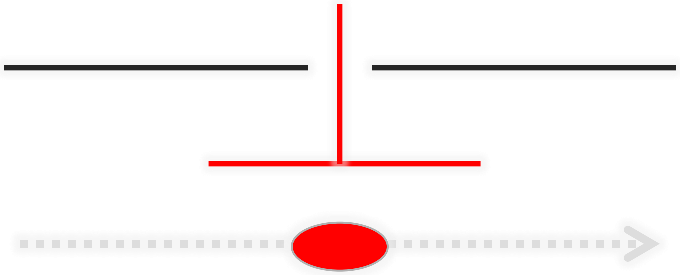




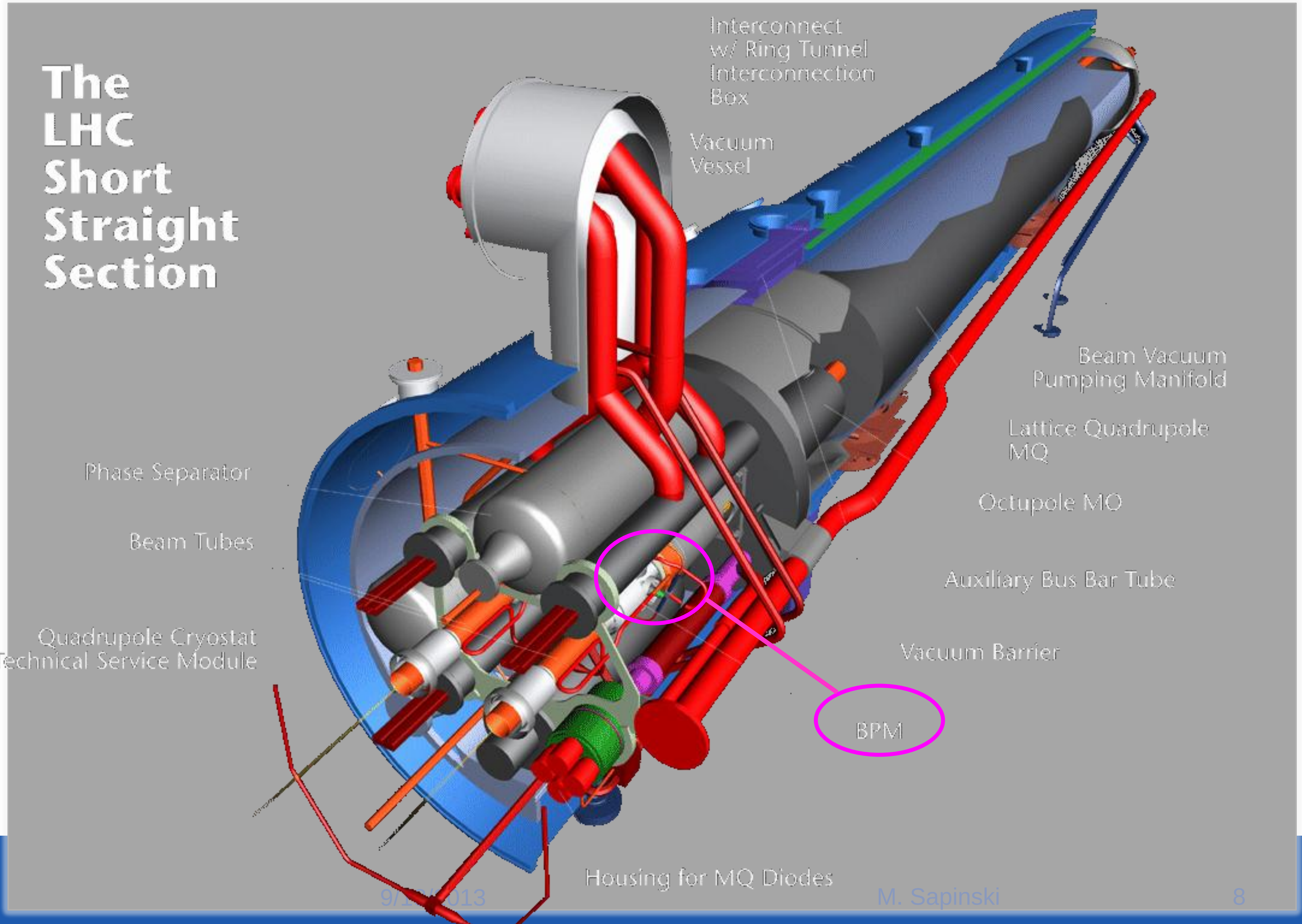
by Stephan Burger

Orbit – BPMs

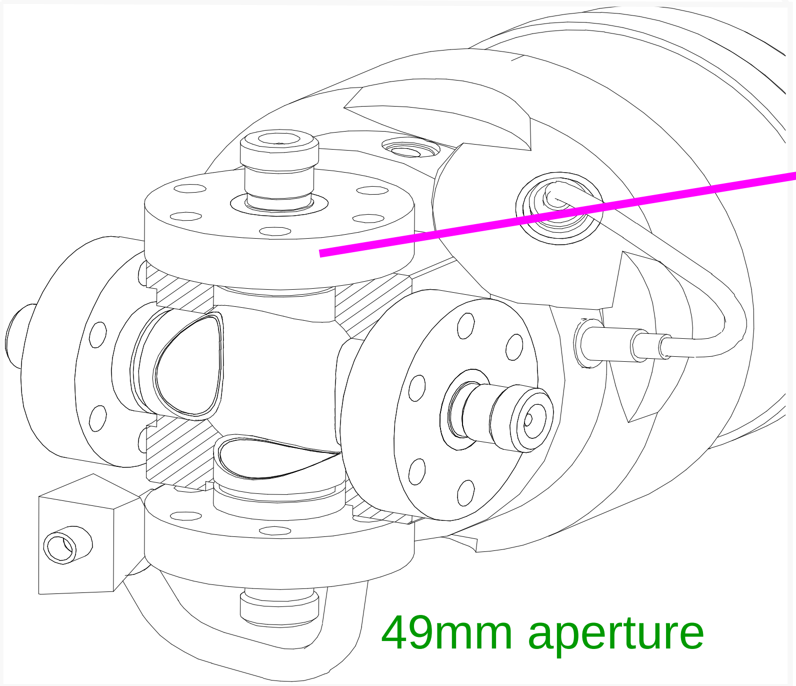
- Main measurement devices in every accelerator are little antennas which are listening to EM field generated by the beam
- They are called “pick-ups”



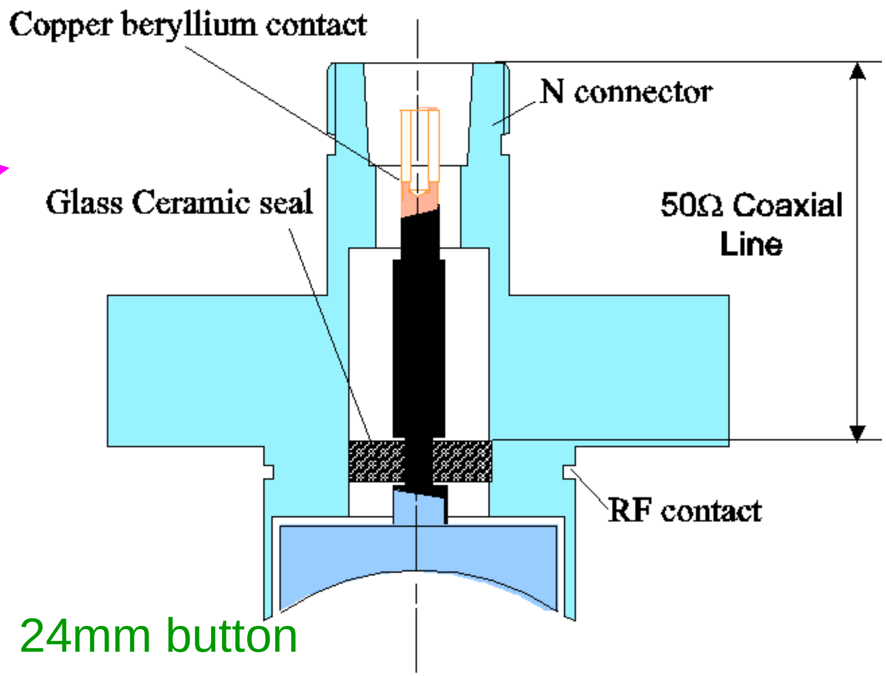
Orbit – BPMs


The LHC Short Straight Section
Interconnect w/ Ring Tunnel Interconnection Box
Vacuum Vessel
Beam Vacuum Pumping Manifold
Lattice Quadrupole MQ
Octupole MO
Auxiliary Bus Bar Tube
Vacuum Barrier
BPM
Phase Separator
Beam Tubes
Quadrupole Cryostat Technical Service Module
Housing for MQ Diodes

Orbit – BPMs

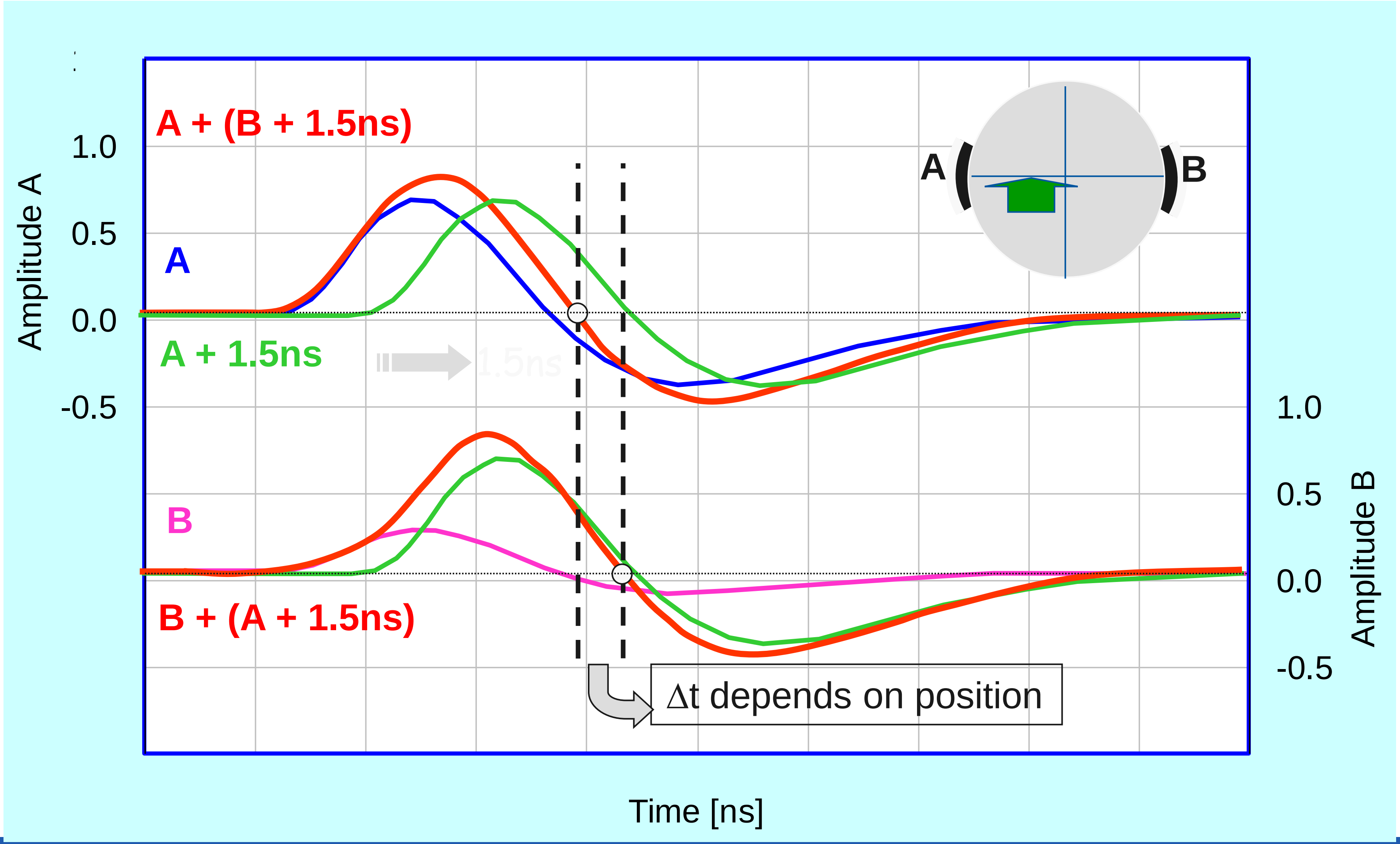


49mm aperture



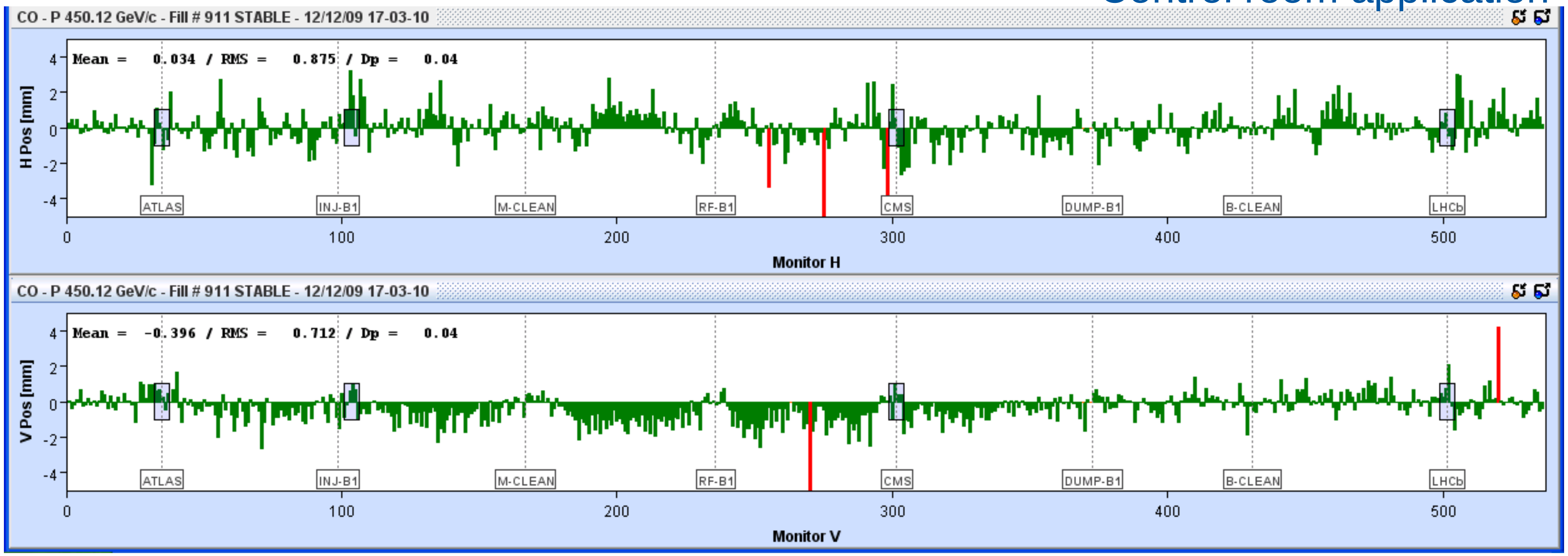
24mm button

The Wide Band Time Normaliser



Orbit – BPMs

Control room application



- LHC would not run without orbit feedback system
- Real time solver of a system of equations steering the corrector dipole magnets

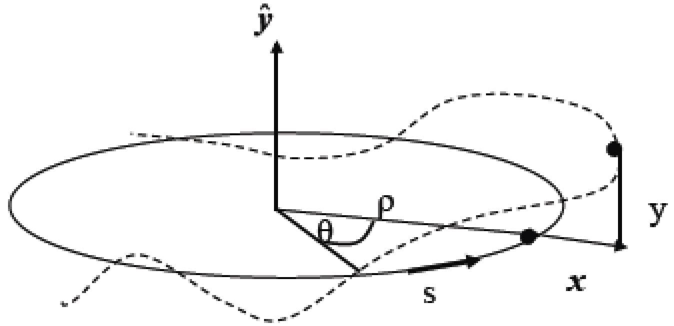
Tune

particles oscillate wrt ideal orbit following the "optics" (mainly quadrupoles)

The Equation of Motion:

Equation for the horizontal motion:

$$x'' + x\left(\frac{1}{\rho^2} - k\right) = 0$$



LHC tune

"working point" :

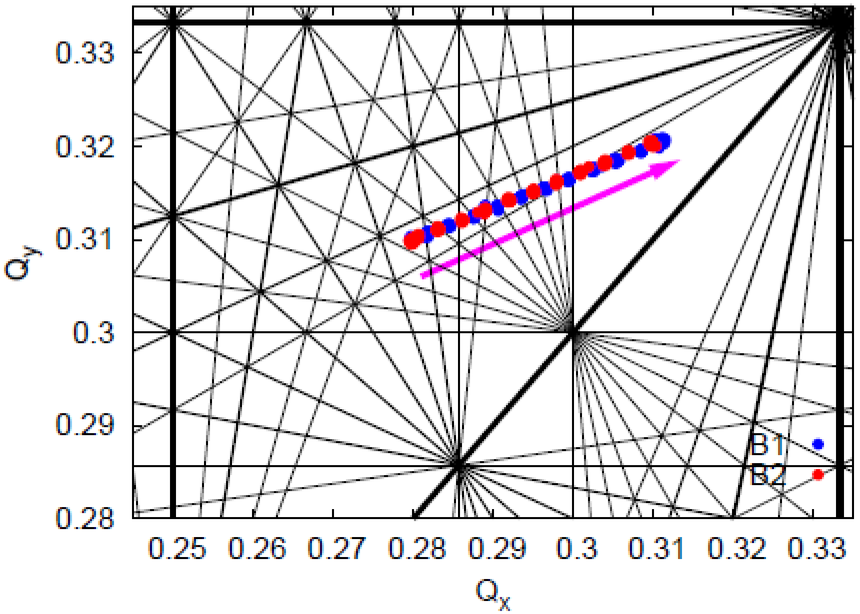
Q_H=64.31

Q_V=59.32

Important to keep tune

far from resonances

(feedback system)



Tune – BBQ (Beam-based Q)

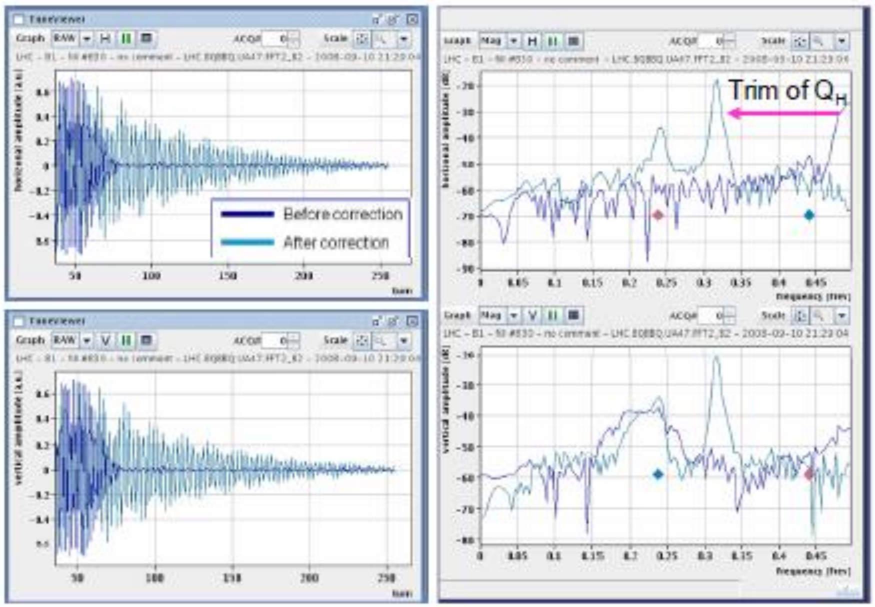


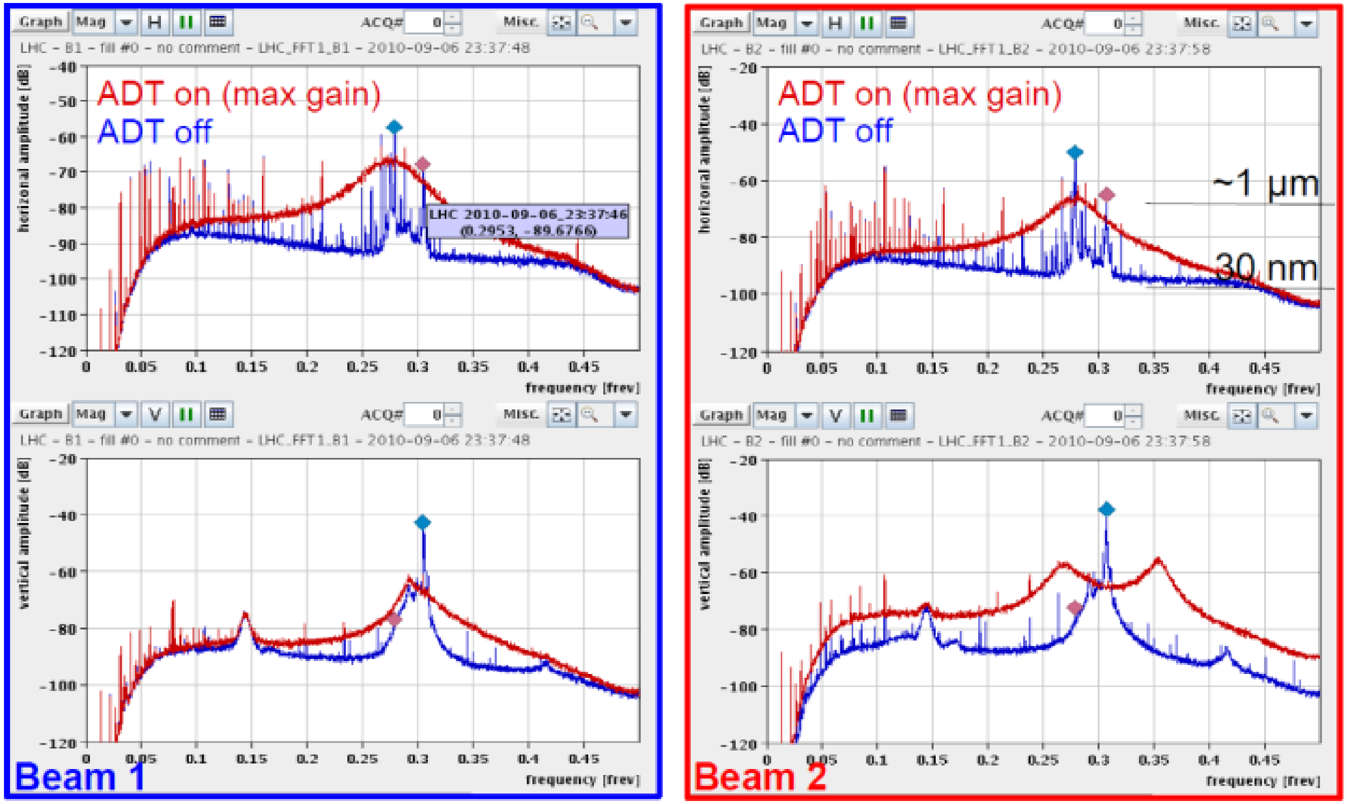
Figure 5 : First measurement and correction of tune using the LHC BBQ system.

Beam is excited, oscillations are naturally damped (Landau damping) and decay of the oscillation is measured (FFT).

Other detectors can measure tune as well, eg. Shottky monitor, it is visible even in FFT of beam losses.

Tune – BBQ (Control room appliaction)

Issue: transverse damper – crucial to keep beam stability, kills the tune signal…

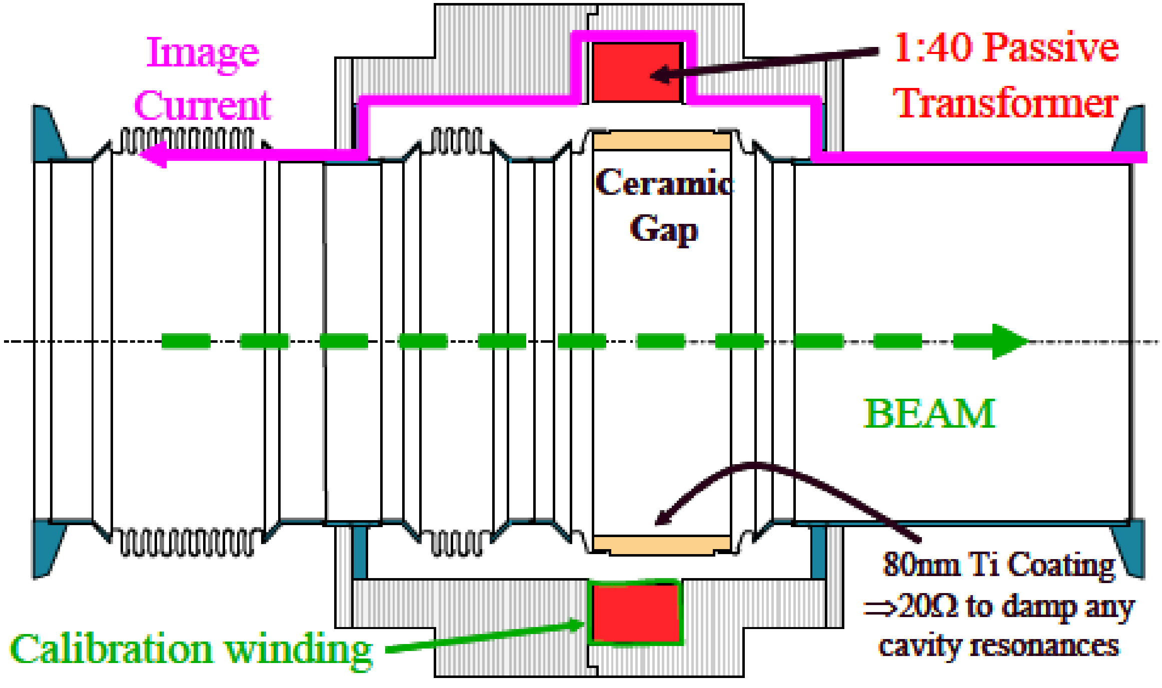


Beam Intensity – Beam Current Transformers

- Two systems, fast and precise:
- FBCT (bunch-by-bunch) and DCCT (total current also unbunched)
- Need to measure beam currents from 8 μA to 860 mA (DCCT)
- FBCT scheme:

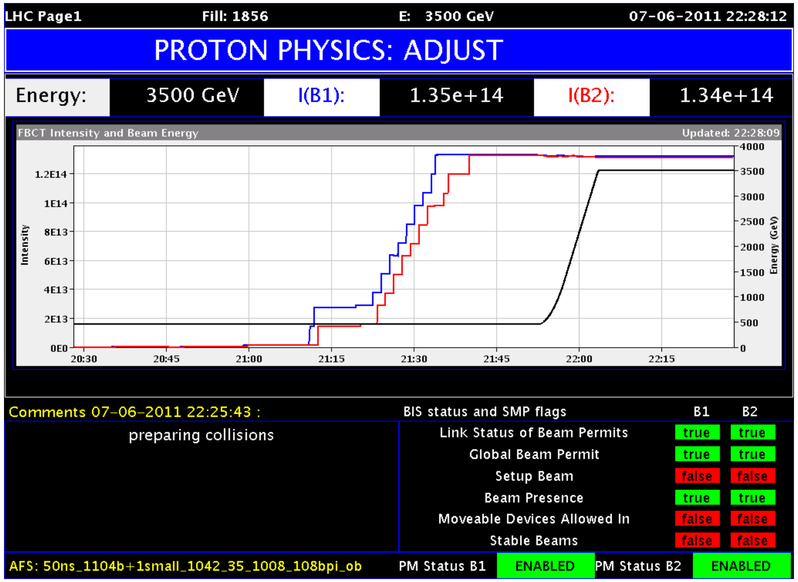
<u>Definition:</u>

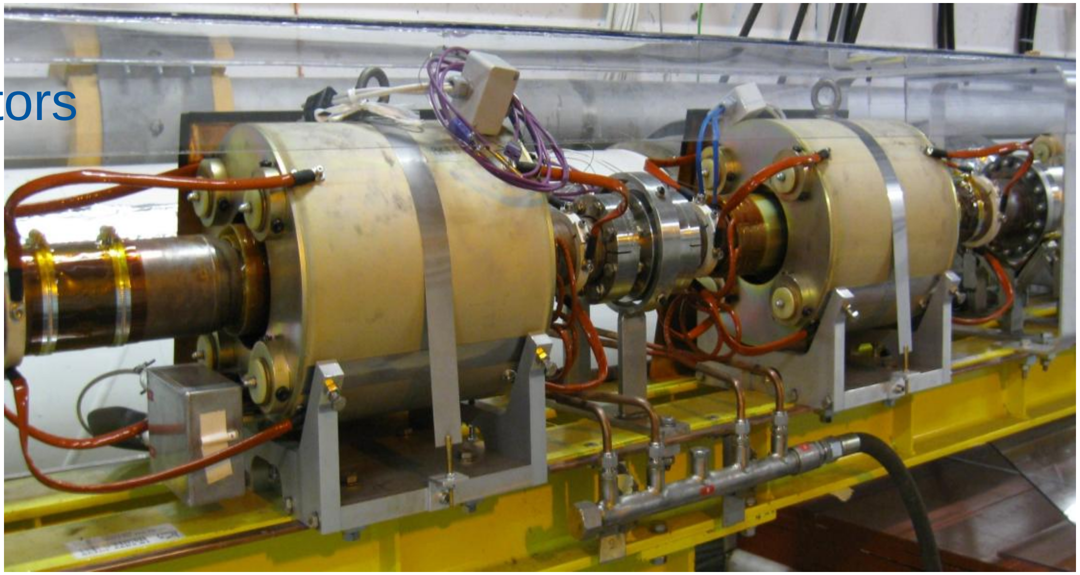
- **Ghost charge:** summed charge for all 25ns slots which are not visible by FBCT, (unbunched or below the threshold)
- **Satellite bunch:** captured charge in RF buckets within a few tens ns around the nominal buckets



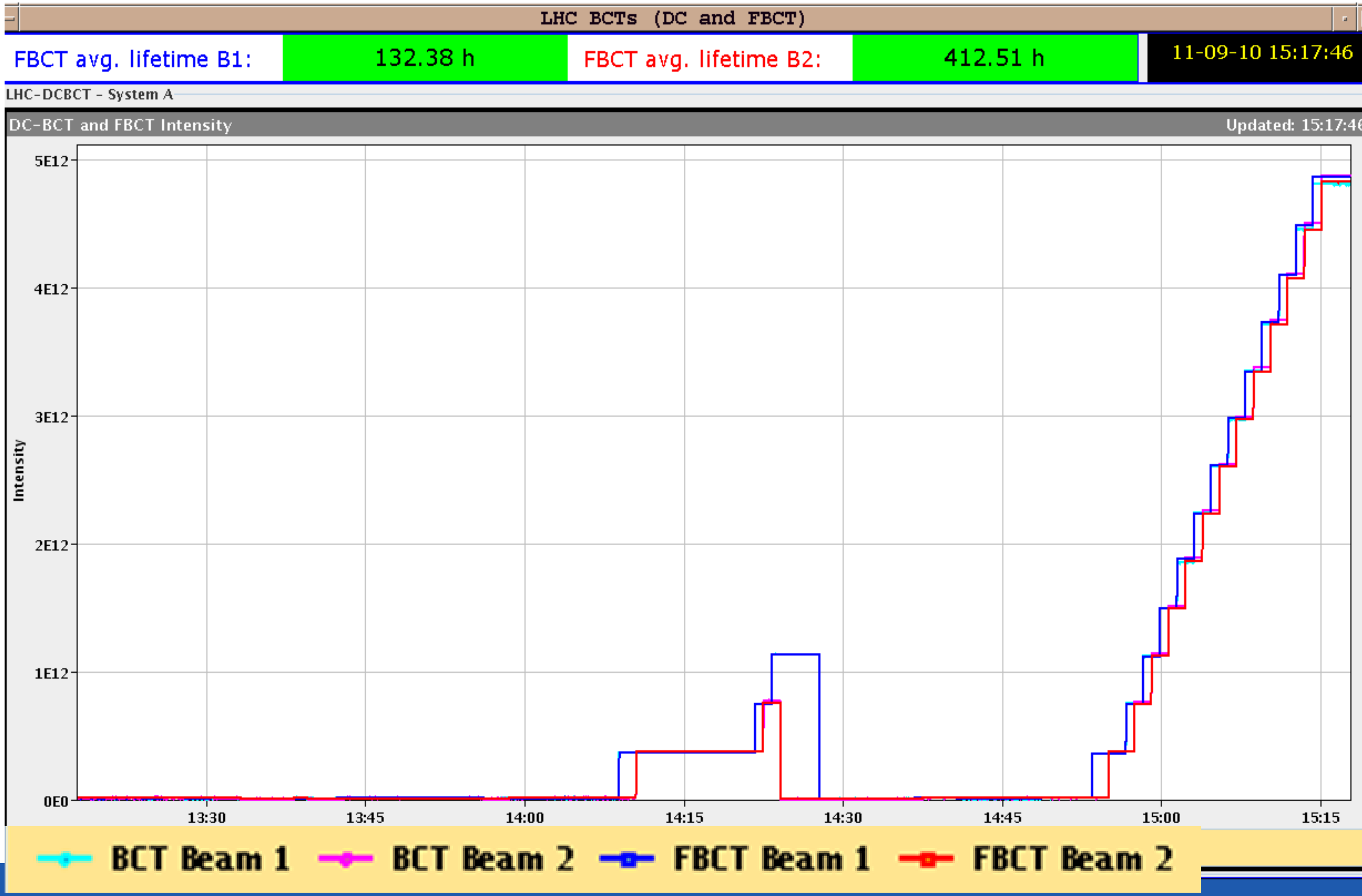
BCT

- Main information displayed on LHC page one (FBCT)
- DCCT in the tunnel:
- Issues, eg. beam position dependence (FBCT)
- Pick-ups, LHC detectors also used for intensity measurements

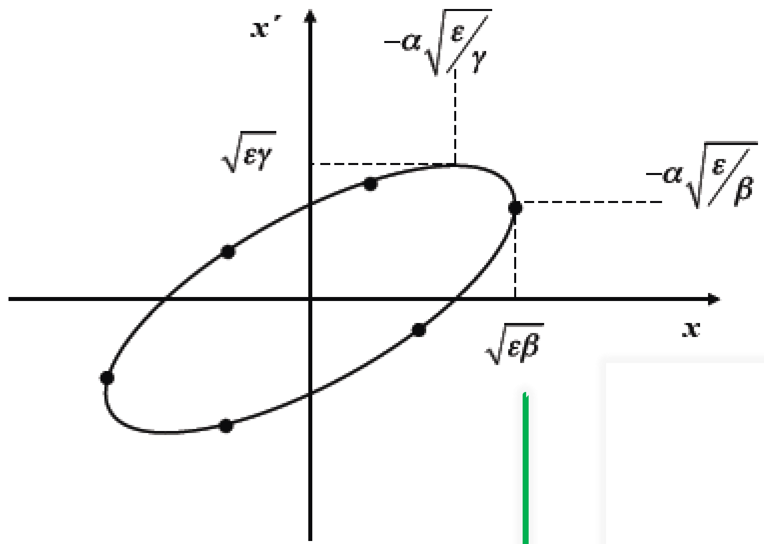




BCT - measurements



Emittance



Emittance – area in phase space.

Important because it is constant in reasonable hadron accelerator.

This looks complicated, but for circular machines one can approximate:

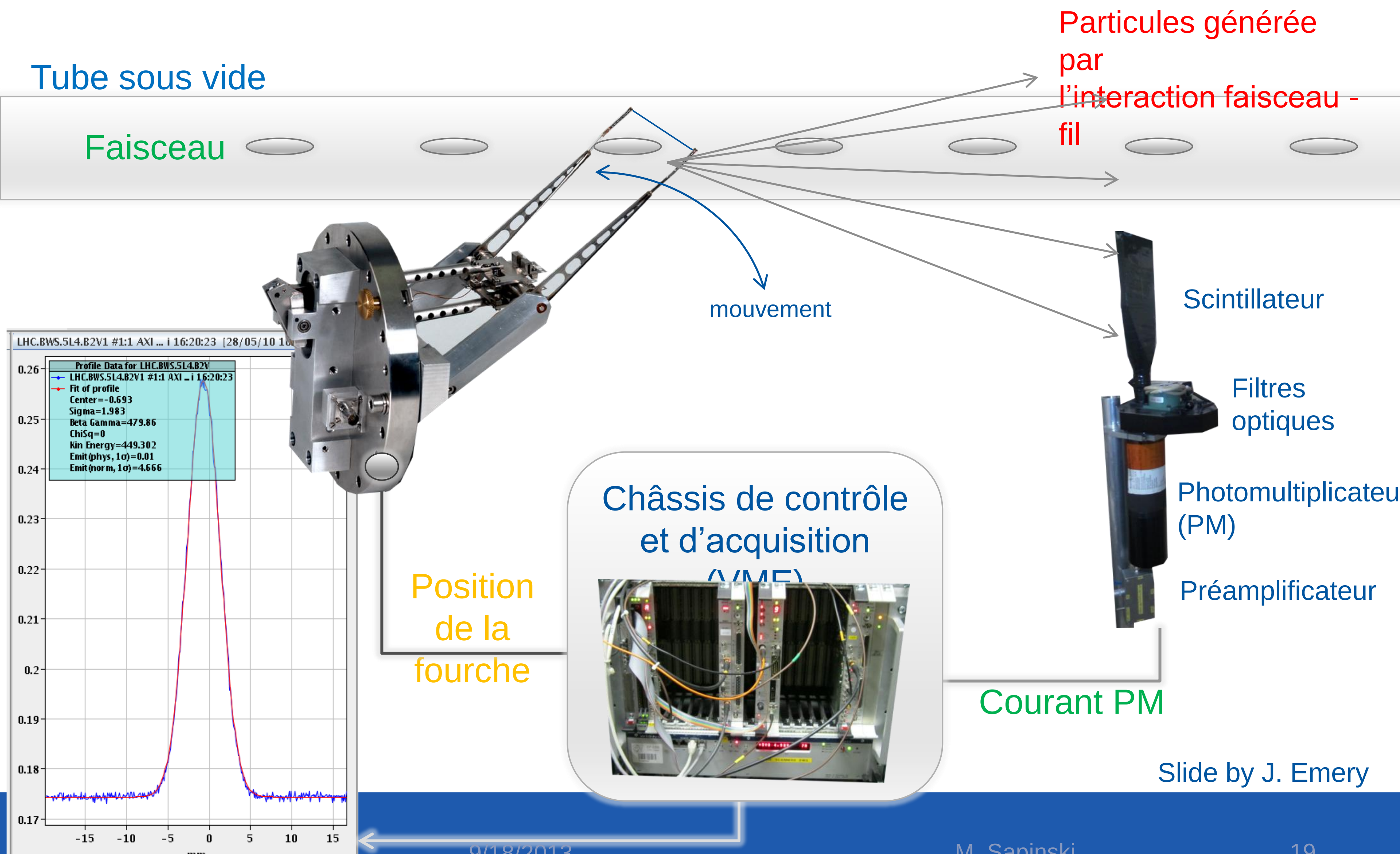
$$x_{\max} = \sqrt{\varepsilon\beta}$$

$$\varepsilon = \sigma^2 / \beta$$

So we need only to measure beam width σ

(and know optics function β)

Emittance – wire scanner

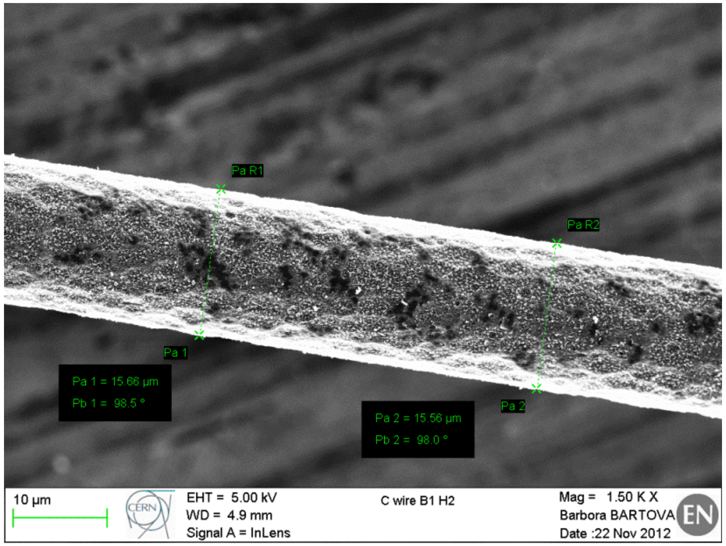


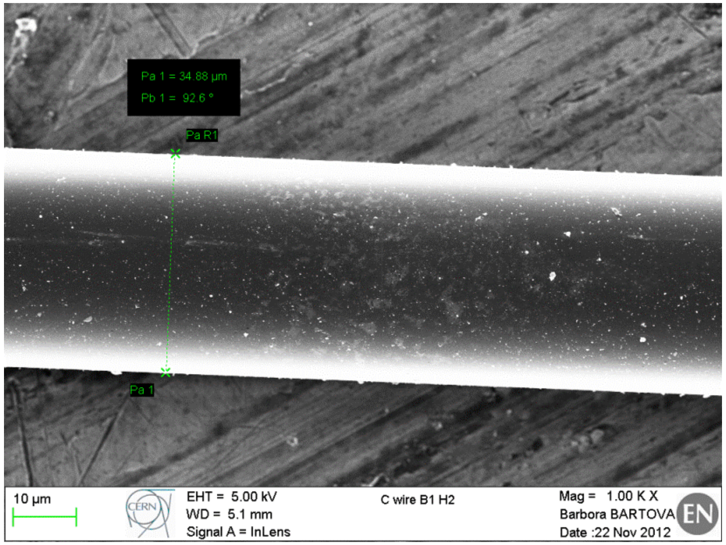
Slide by J. Emery

Profile transversal d'un faisceau LHC

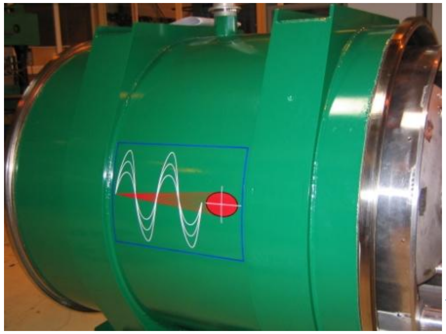
Emittance – wire scanner - limits

- In LHC 33 µm carbon fiber moves with 1 m/s.
- It is enough to scan 144 bunches at injection (out of 2808!) – wire damage
- And 20 bunches at 7 TeV (magnet quench)
- Wire sublimation is the main damage mechanism



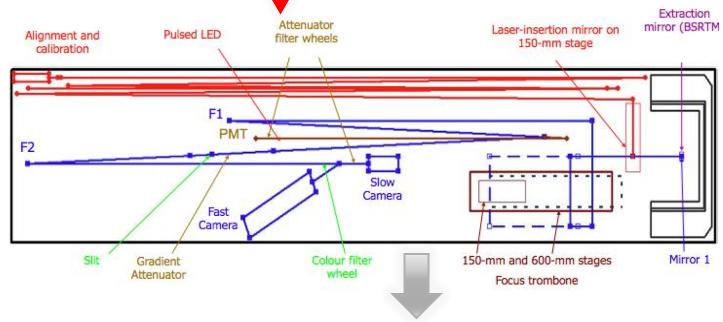


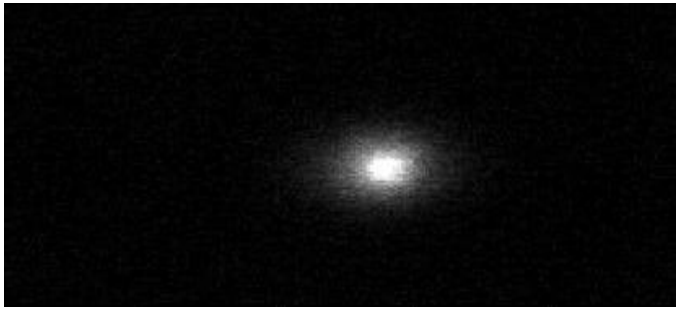
Emittance – synchrotron light telescope



Extraction mirror

Synchrotron light from undulator and dipole

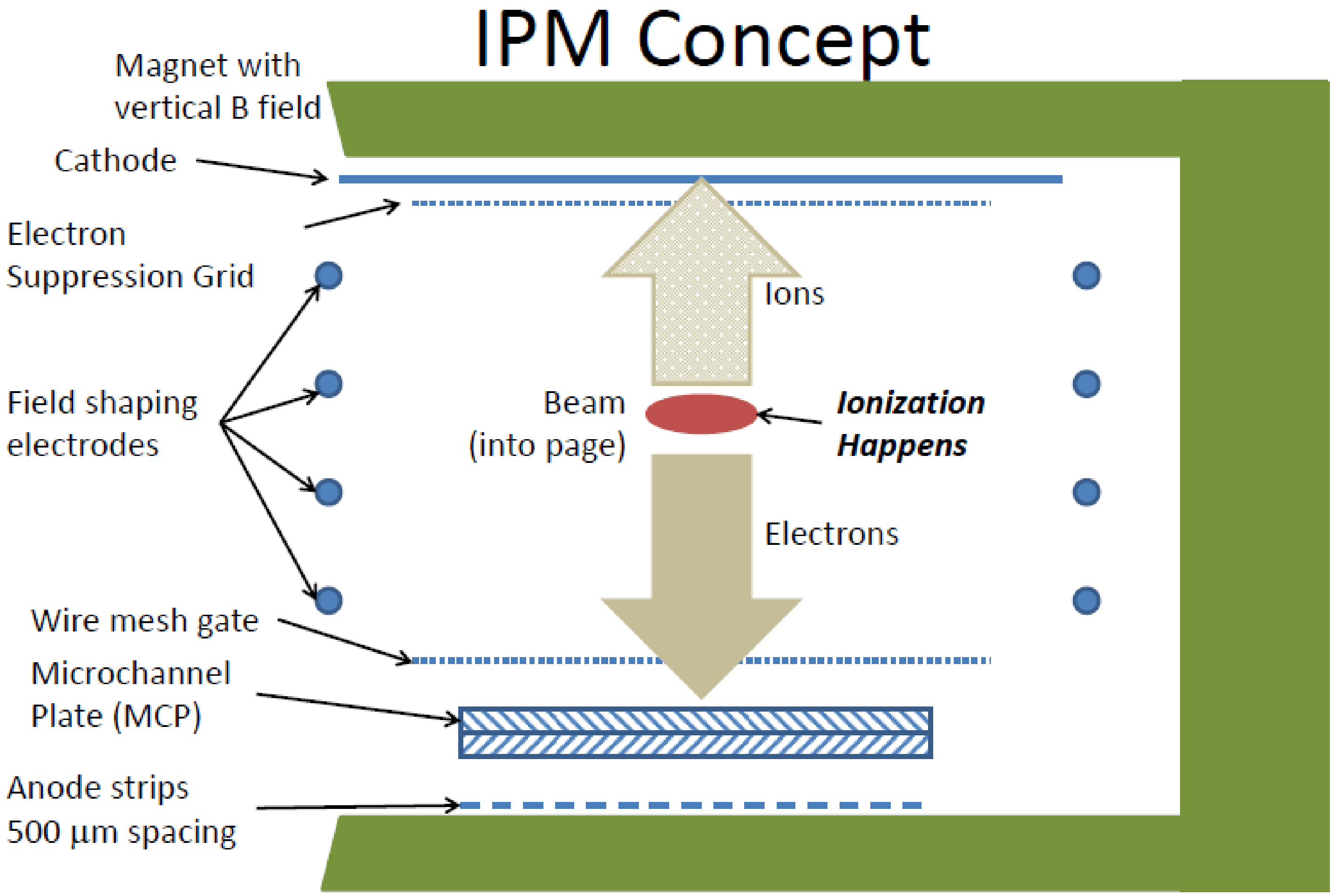




- OK for protons at 450 and 4000 GeV
- difficult during ramp because light source change from undulator to dipole
- ions at 4 ZTeV also visible

  (1st time in history)

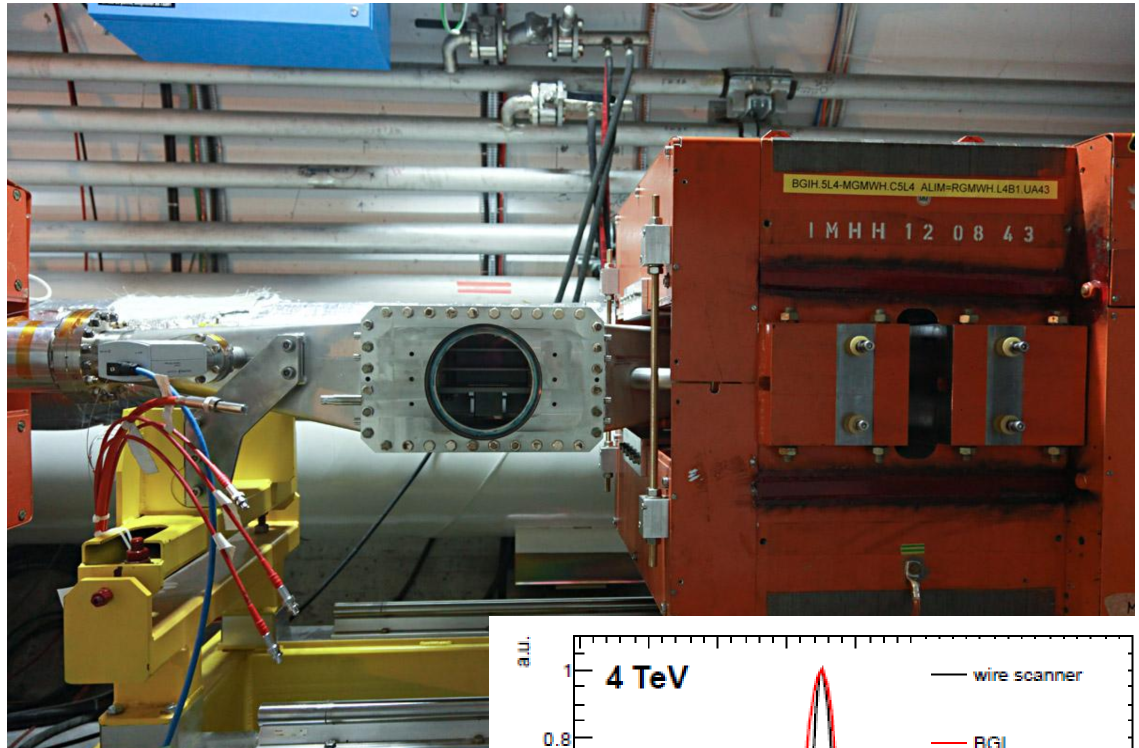
Emittance – ionization profile monitor



or optical readout (LHC)

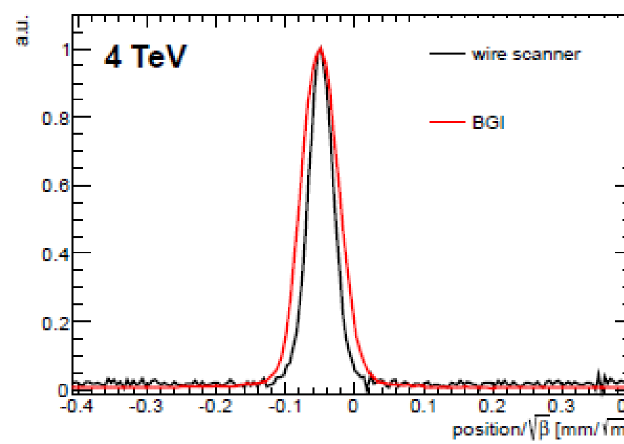
by Jim Zagel

Emittance – ionization profile monitor



In LHC most beams turned out to be too small and electrons were kicked out of their initial locations leading to profile distortion.

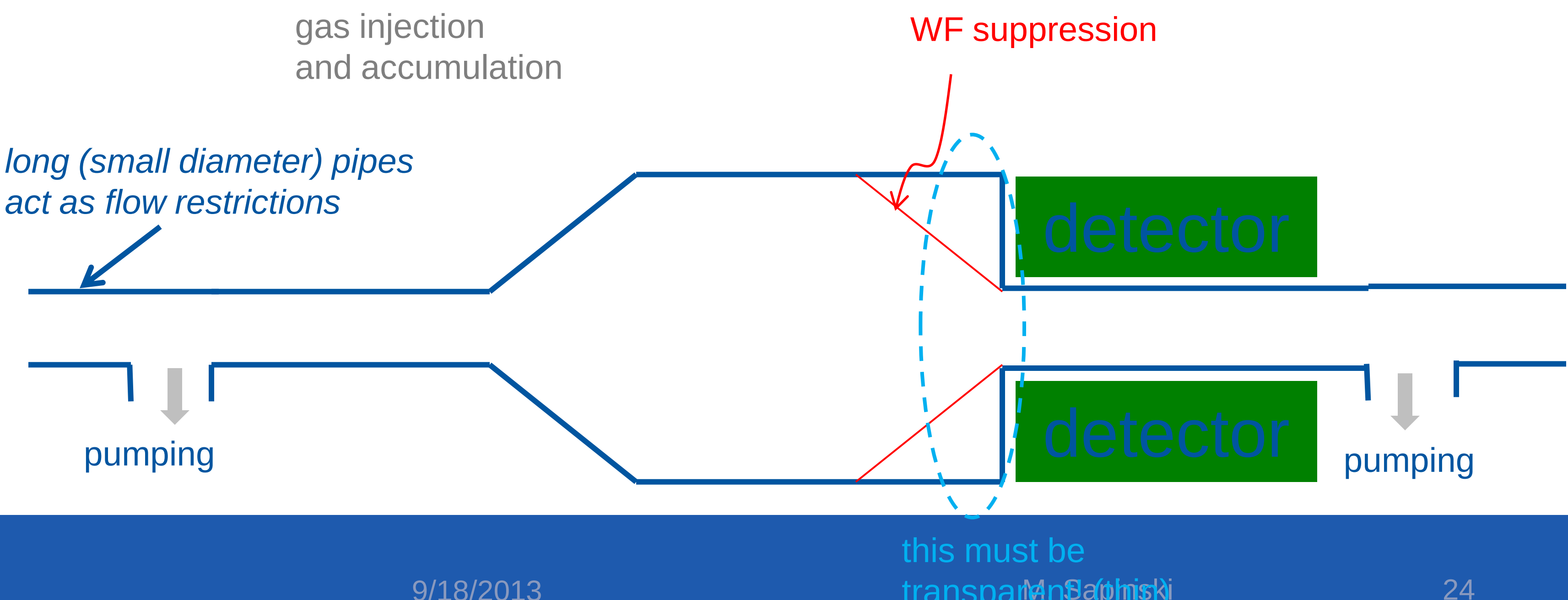
Profile broadening due to electron interaction with bunch charge



Emittance – Beam Gas Vertexing monitor

- In general emittance measurement on LHC found difficult
- Idea born to use interaction vertex reconstruction
- Detector configuration as in LHCb but with no magnetic field
- Tested in LHCb (SMOG)
- New development, started last year, approved

Similar to normal experiments, possible because tracking detectors technology available



Beam losses

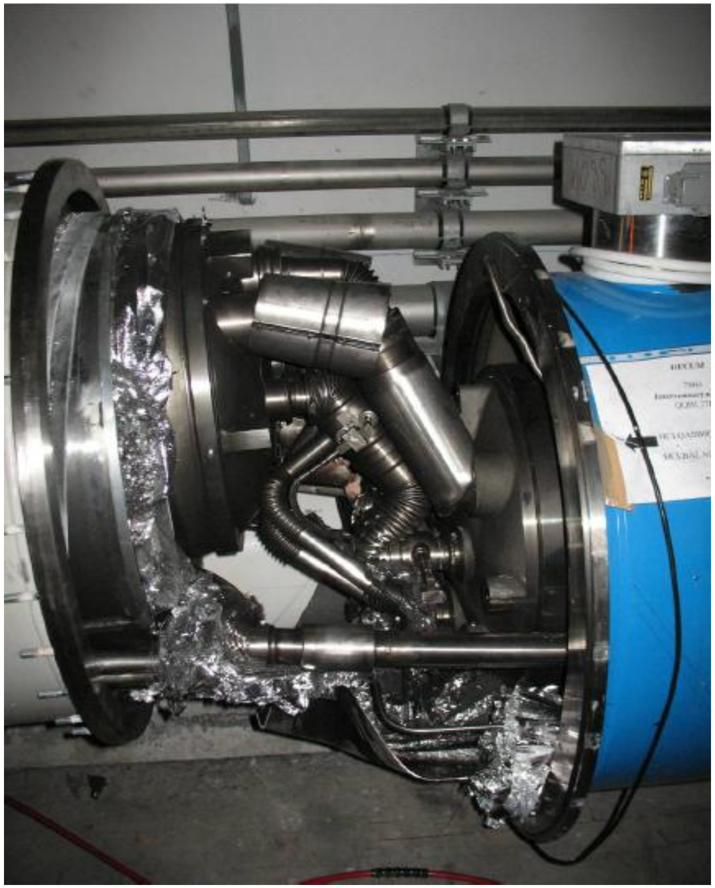
- Energy stored in LHC beam: 320-400 MJ (at 7 TeV)
- BTW: 1 MJ is when you drive a car on a motorway
- But here it is in 1 ng of protons
- Energy needed to quench a magnet: 10-100 mJ/cm^3
- Loss of ~10^{-9} fraction of the total beam intensity
- Why magnet quench is bad?
- Current is 11 kA, cable cross-section 30mm^2

- Total energy stored in magnet:

$$E_m = \int_V \frac{B^2}{2\mu_0} dv = \frac{1}{2} L I^2$$

Beam losses

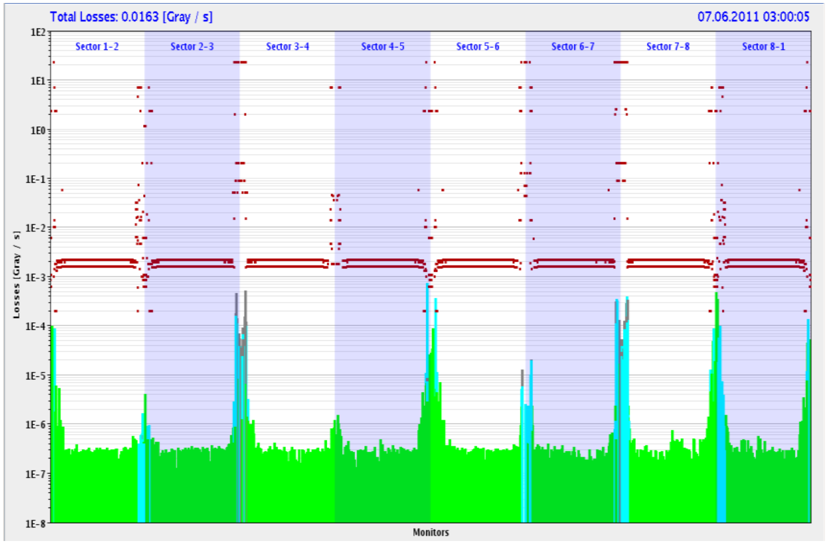
- Quench Protection System takes care about dissipation the energy stored in the magnet.
- If quench occurs it fires quench heaters and opens a diode dumping current to external resistor.
- Recovery after quench is up to 10 hours.
- Refilling the machine is only about 2-3 hours.
- Lepiej zapobiegac niz leczyc!



This is the result of a chain of events triggered by a quench in an LHC bus-bar

Beam losses

- About 4000 ionization chambers installed on LHC
- Most of them connected to beam interlock system
- They have multiple tasks:
  - Quench prevention
  - Damage prevention
  - Verification of the collimation system setup
  - Analysis of loss events
  - etc…



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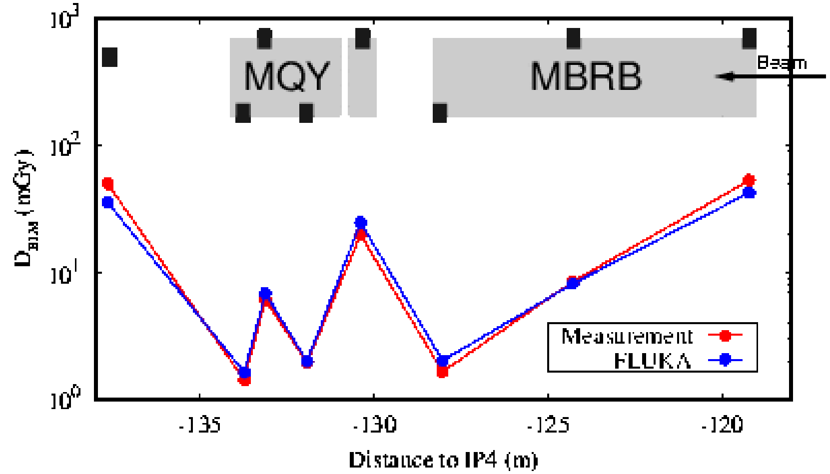
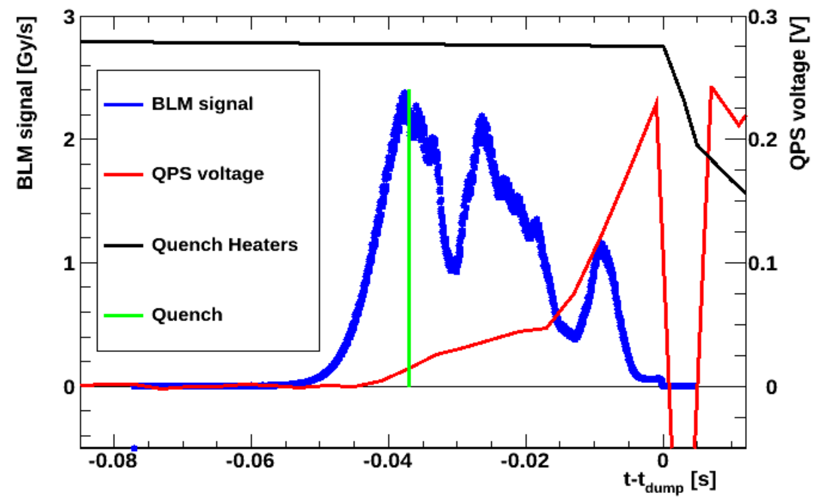
  - Quench tests, etc…





Cryogenic BLMs – new development

- Problem: current BLMs are far from coil to be protected (shielded by yoke)
- Solution: install radiation detectors close to the coils
- Challenges: large dose, no access for many years, operation temperature of 2 K
- Working on: special silicon and diamond detectors and LHe ionization chamber

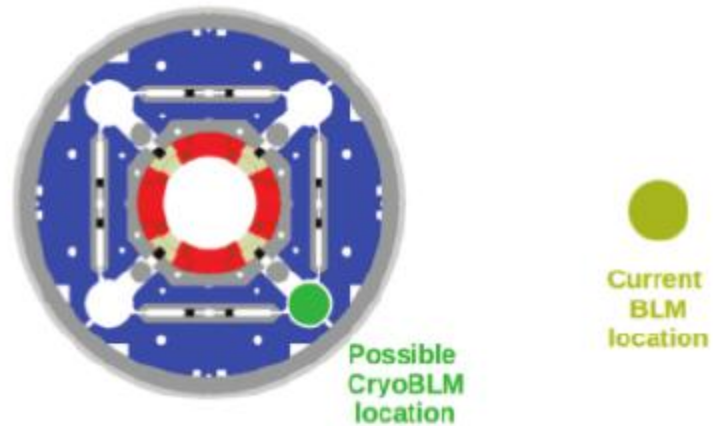


Figure 2: MQXF magnet cross section (courtesy of P. Ferracin) with the current BLM placement and the future possible Cryogenic BLM location.

Other measurements, not discussed here

- Intra-bunch instability measurements
- Luminosity measurements
- Longitudinal emittance measurements
- Satellite and ghost bunches measurements
- Beam tail measurements
- Combined beam quality measurement

Summary

- Beam Instruments are eyes and ears of LHC operators
- LHC turned out to be more demanding than expected (ε down to 1 μm instead of 3 μm)
- But orbit stability much better than expected
- Main observables: orbit, emittance, tune, beam losses
- New technologies being developed (BGV, Cryogenic BLM, new Wire Scanner, etc…)
- Beam Instrumentation for electron machines and low energy linacs – a lot of other interesting devices
- Very interdisciplinary field (physics, electronics, mechanics, materials, computing etc.)