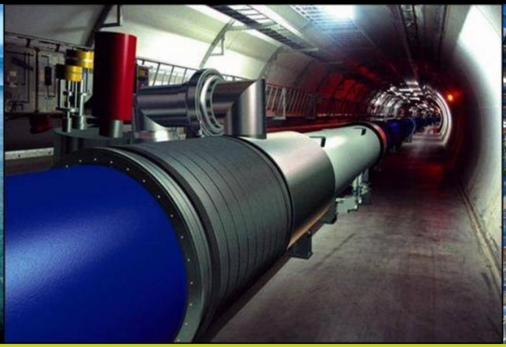
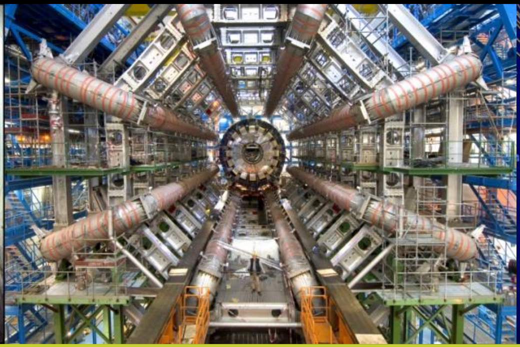
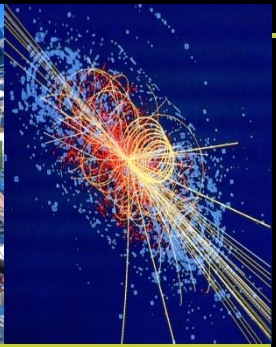





Introduction to LHC Beam Instrumentation

Beam Profile Measurement

CERN Academic Lectures 2014

12th – 14th November, 2014

Dr. Rhodri Jones

Head of the CERN Beam Instrumentation Group

The Typical LHC Instruments

Yesterday

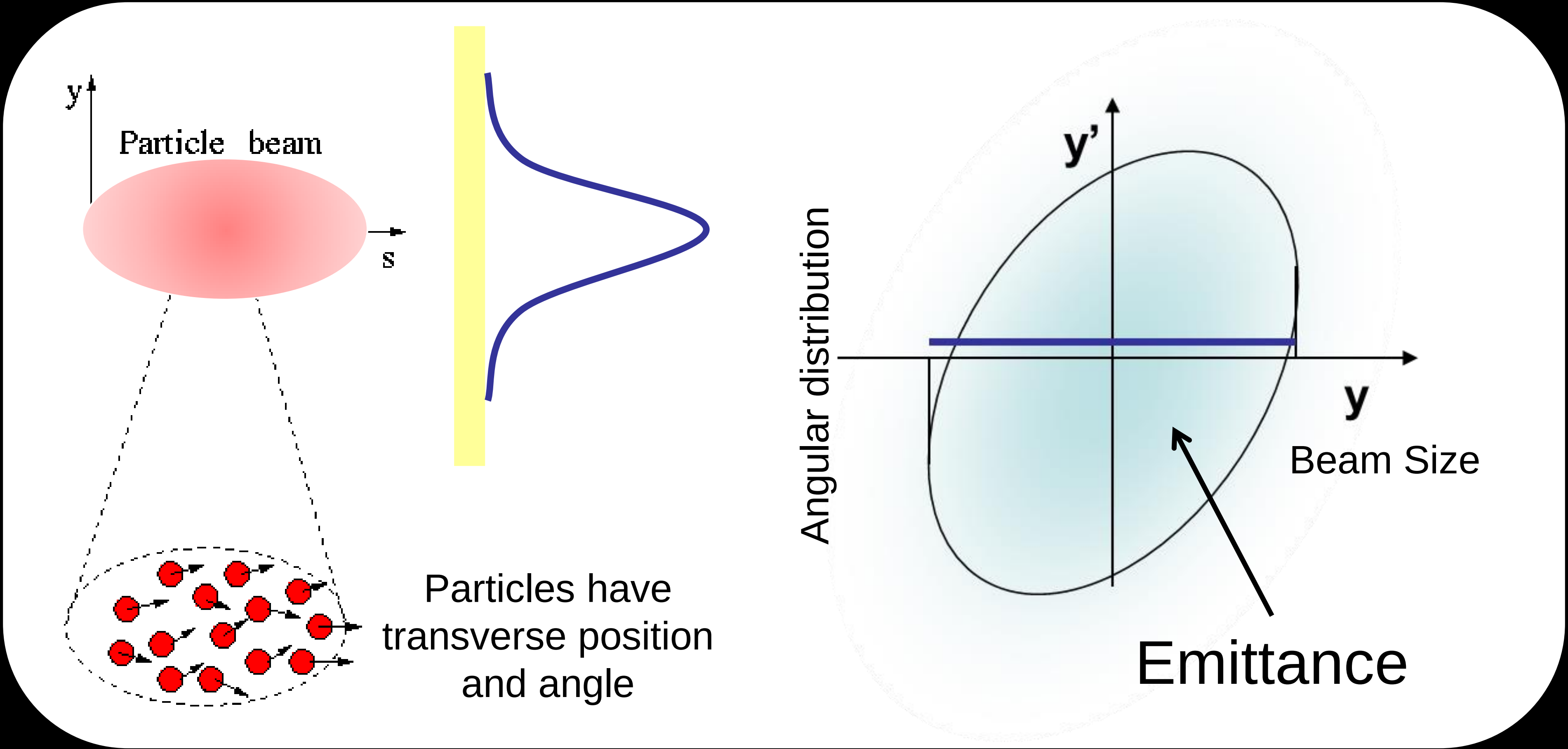
Today

Tomorrow

- Beam Position
  - electrostatic or electromagnetic pick-ups and related electronics
- Beam Intensity
  - beam current transformers
- Beam Profile
  - screens
  - wire scanners
  - synchrotron light monitors
  - rest gas monitors
- Beam Loss
  - ionisation chambers and solid-state detectors
- Machine Tune and Chromaticity
  - base band tune measurement system
- Other Monitors
  - Luminosity, schottky, abort gap, instability

Why Measure the Beam Profile?

- Beam Size
  - A beam is made of many, many particles each moving with given velocity
  - Most of the velocity vector is parallel to the direction of the beam (s)
  - Small transverse component



Why Measure the Beam Profile?

- For LHC
  - The more closely packed the particles the denser the collisions & the higher the luminosity
  - Emittance – the spatial and angular spread of particles
  - Understanding emittance growth essential to optimise performance

Luminosity L: $$L = \frac{N_1 N_2}{4\pi\,\sigma^2} f_{rev}$$

Beam size σ: $$\sigma^2 = \epsilon\,\beta^*$$

emittance, beta function

Why Measure the Beam Profile?

- For LHC
  - Cannot directly measure the beam size at the experimental interaction points
  - Need to measure the beam size at another location to calculate emittance

$$\varepsilon_{n_{x,y}} = \frac{\gamma\beta}{\beta_{x,y}}\left[\sigma_{x,y}{}^2 - \left[D_{x,y}\cdot\left(\frac{\Delta p}{p}\right)\right]^2\right]$$

measured

Machine Parameter: Beta Function, Dispersion Function

Beam Parameter: Relativistic factor, Momentum spread

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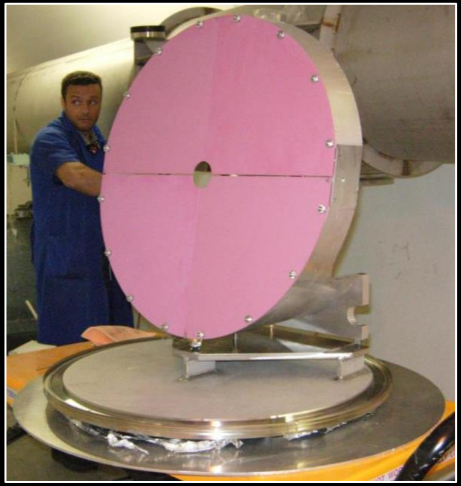
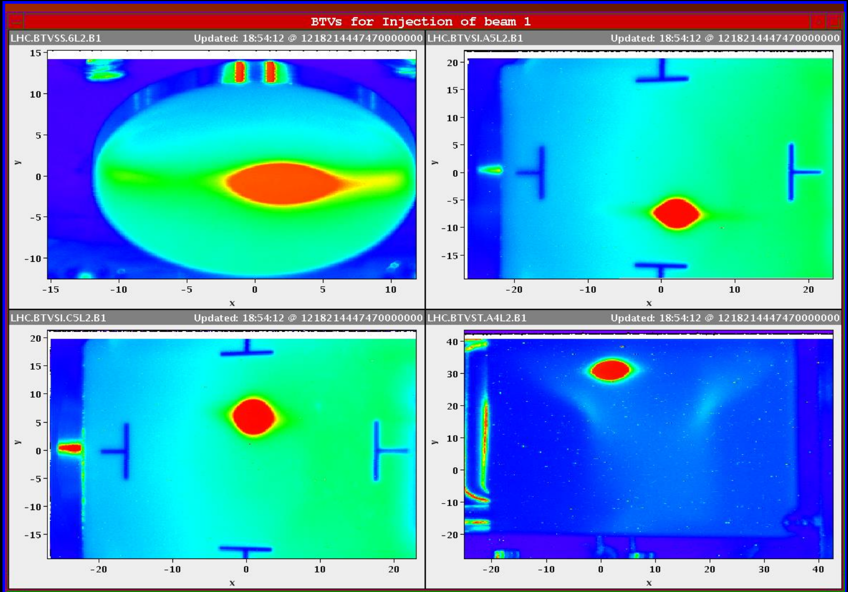
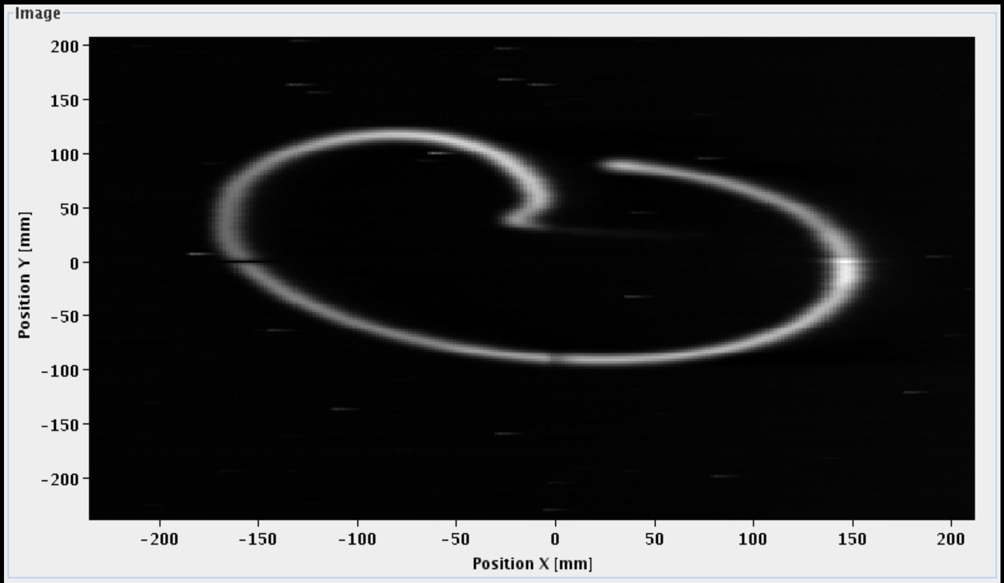
Beam Profile Monitoring using Screens

- Early Diagnostics
  - Injecting into the LHC
  - Extracting from the LHC
- Advantages
  - allows use of CCD camera
    - gives 2D information
    - high resolution



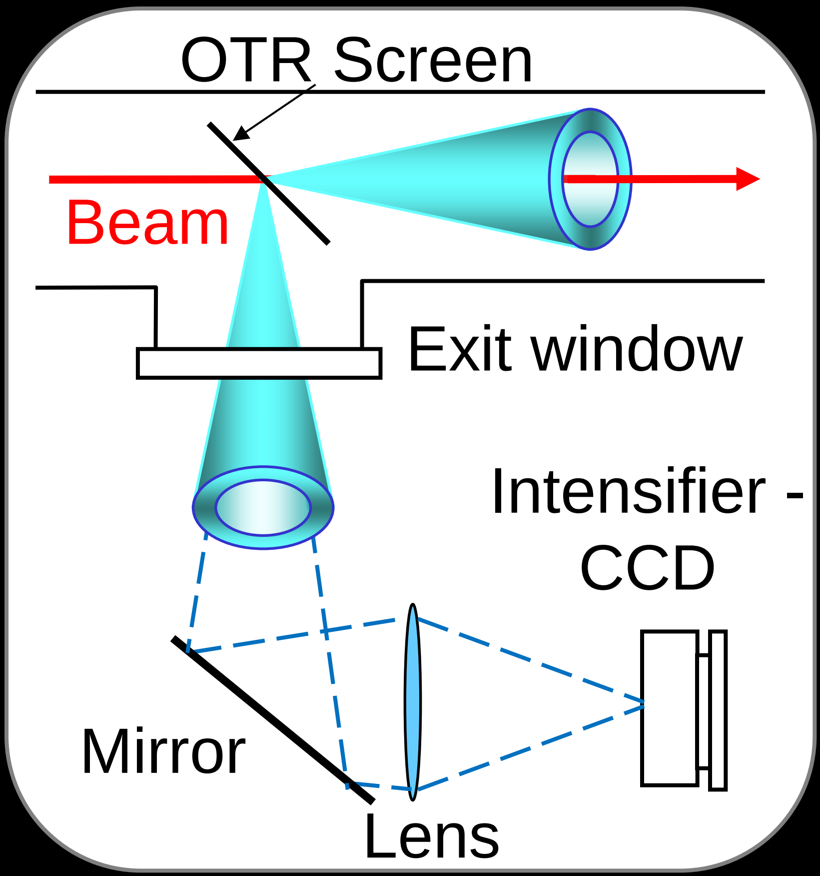


First Beam in the LHC 8/8/2008



Beam Profile Monitoring using Screens

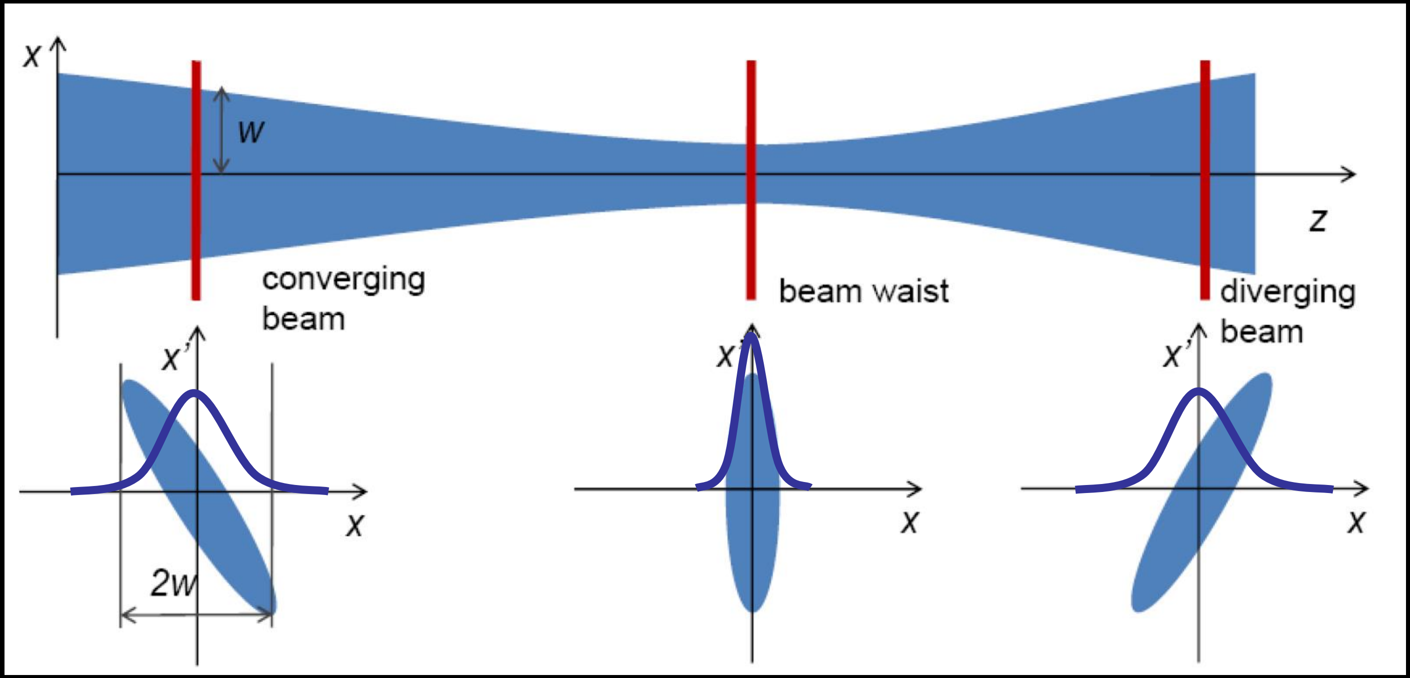
- Screen Types
  - Luminescence Screens - destructive (thick) but work with low intensities
  - Optical Transition Radiation (OTR) screens
    - Much less destructive (thin) but require higher intensity



- OTR
  - Radiation emitted when charged particle beam goes through interface of media with different dielectric constants
  - Surface phenomenon allows the use of very thin screens (~10µm)
    - Can use multiple screens with single pass in transfer lines
    - Can leave it in with a pilot bunch for hundreds of turns for injection matching

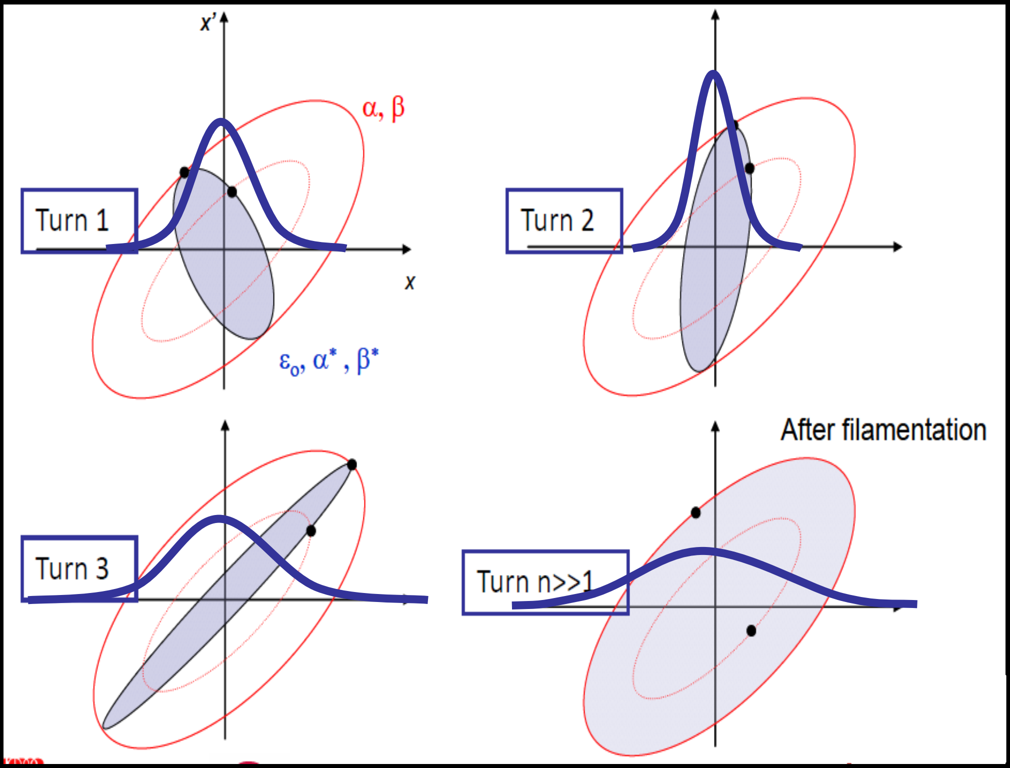
Measurements with Screens

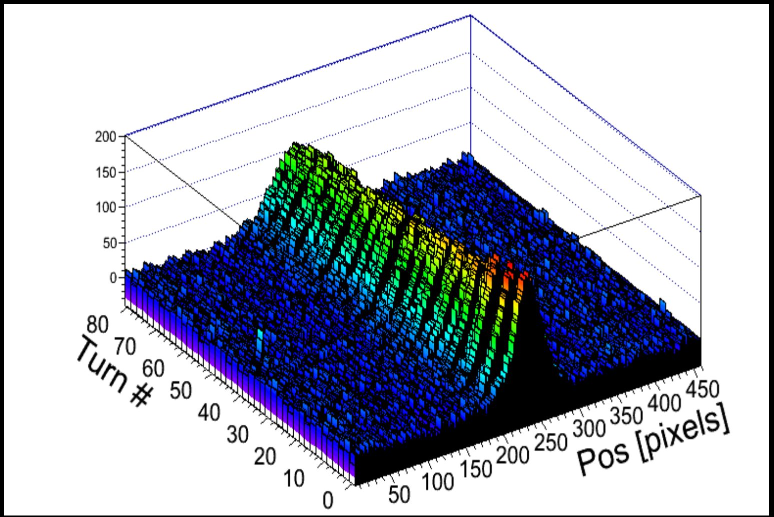
- Emittance measurement
  - Calculated from beam profile at 3 screens
    - Knowing the optical transport functions
    - Set of simultaneous equations that can be solved for emittance with no knowledge of the actual optical function values at the locations
  - Used with OTR monitors in transfer lines

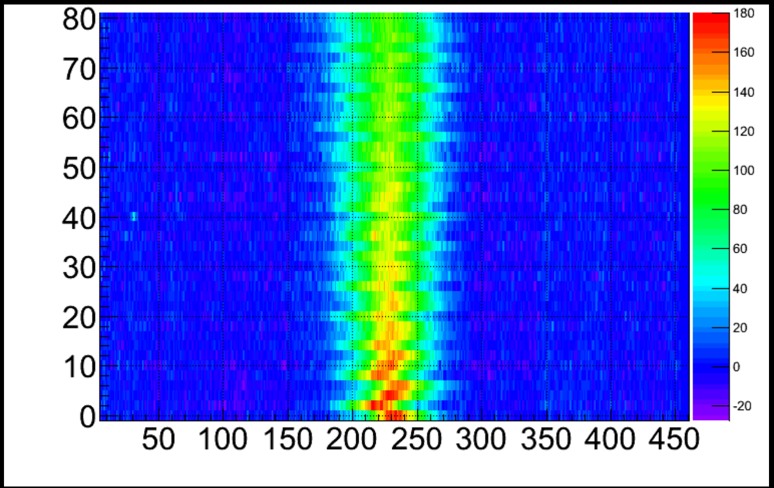


Measurements with Screens

- Injection matching measurements with OTR
  - Filamentation
  - Optical Mismatch







The Typical LHC Instruments

- Beam Position
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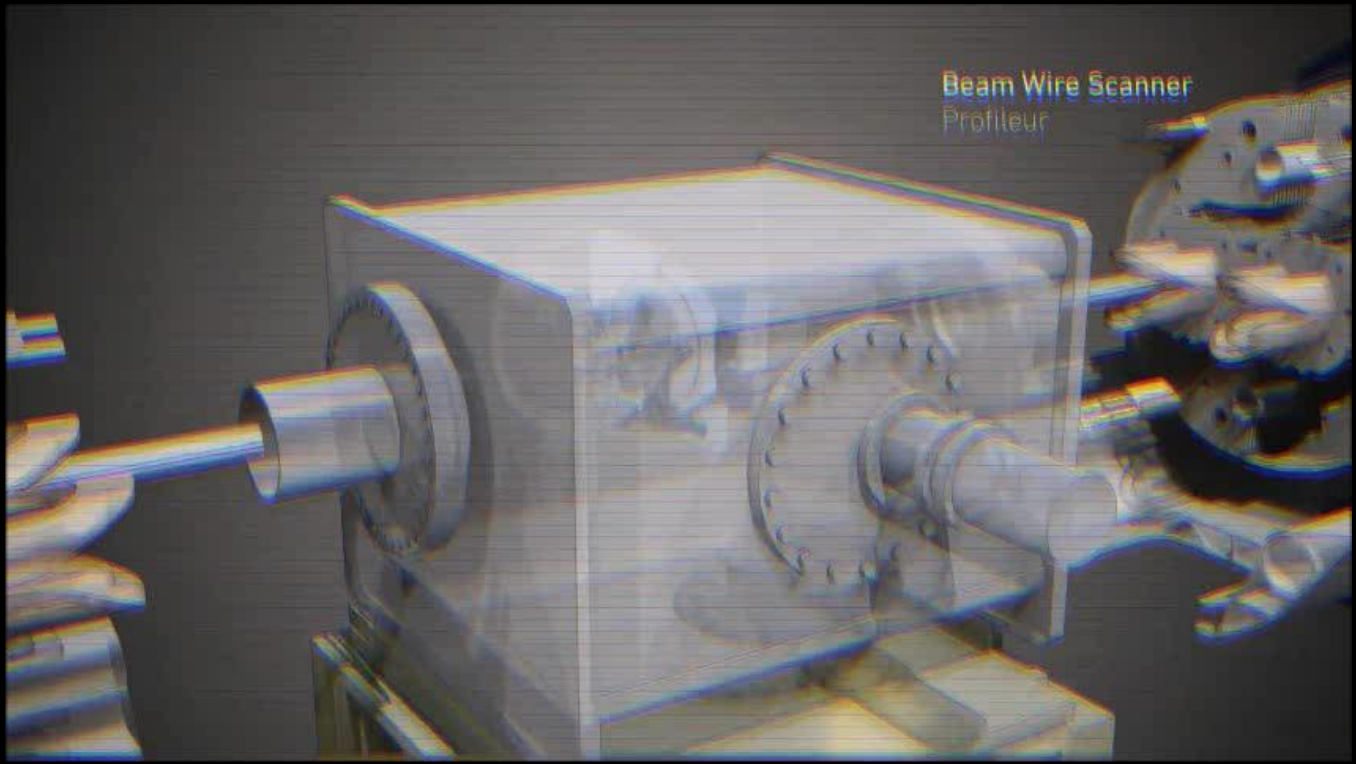
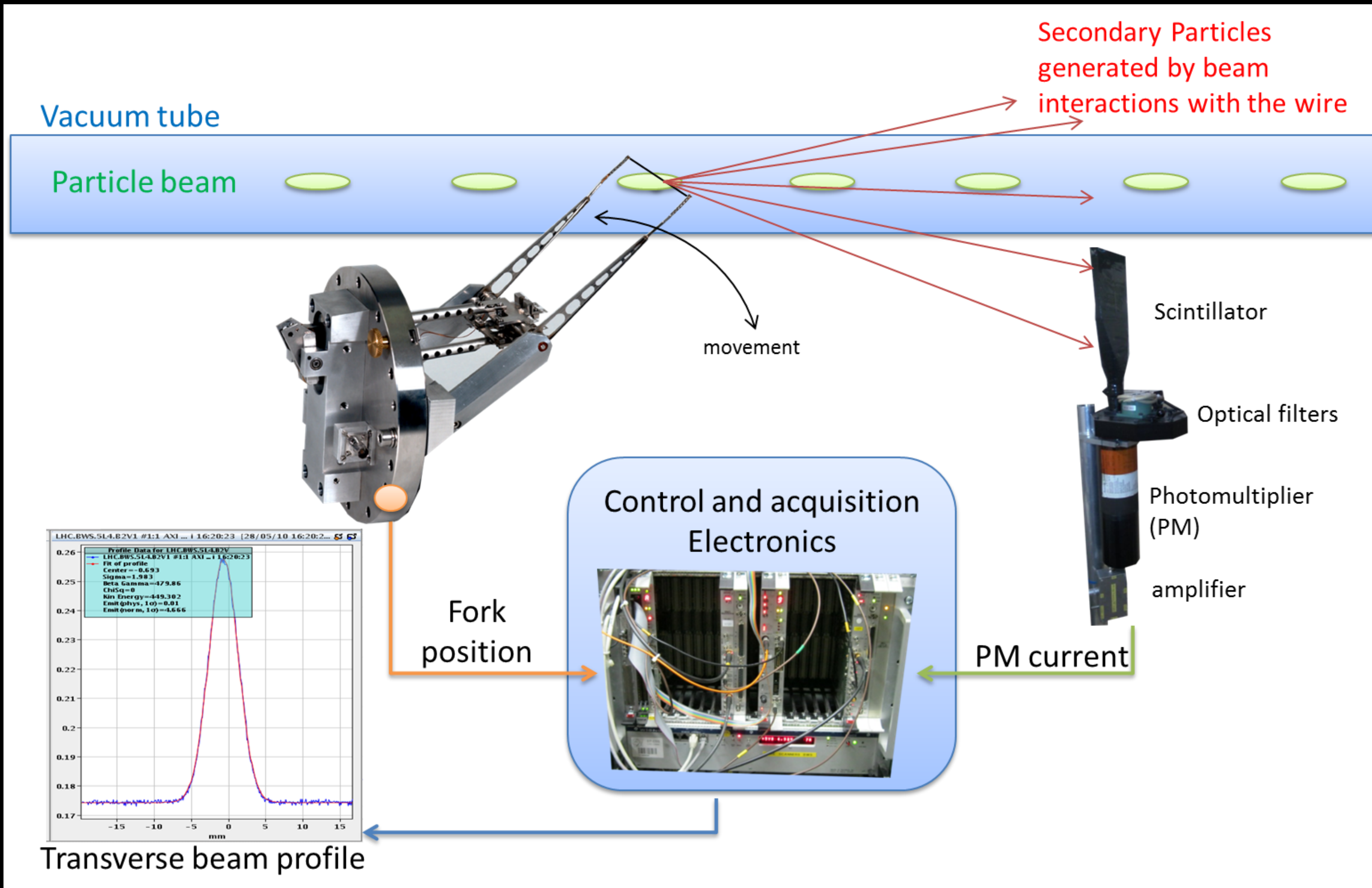
Beam Profile Monitoring using Wire-Scanners

- A thin wire is moved across the beam
  - Has to move fast to avoid excessive heating of the wire
- Detection
  - Secondary particle shower detected outside vacuum chamber using scintillator/photo-multiplier
- Correlating wire position with detected signal gives the beam profile
  - LHC scanner is a linear scanner operating at a speed of 1 ms^{-1}
  - The only device to give absolute measurements & provides cross calibration to all others

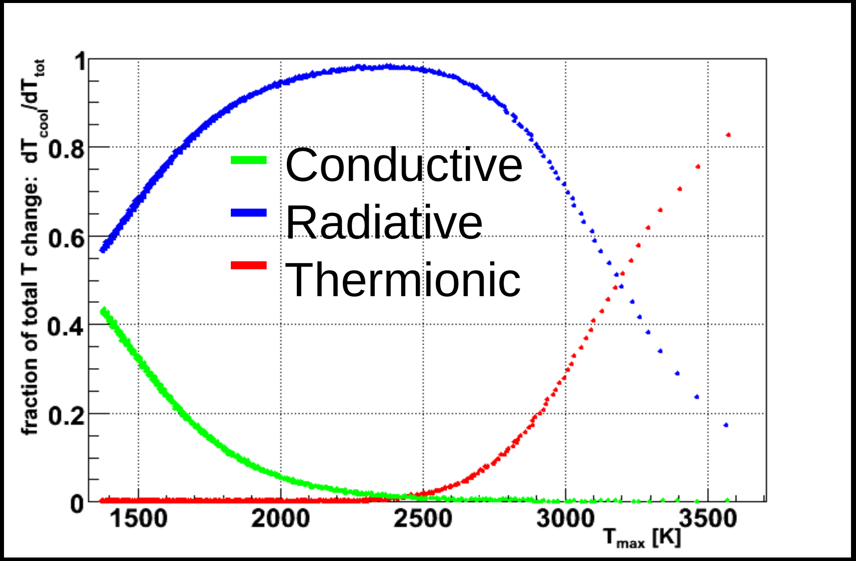


Beam Profile Monitoring using Wire-Scanners



Limitation of WireScanners

- Wire Breakage – why?
  - Brittle or Plastic failure (error in motor control)
  - Melting/Sublimation (main intensity limit)
    - Due to energy deposition in wire by proton beam
- Temperature evolution depends on
  - Heat capacity, which increases with temperature!
  - Cooling
    - Radiative
    - Conductive
    - Thermionic
    - Sublimation
- Wire Choice
  - 33μm Carbon
    - Good mechanical properties
    - Sublimates at 3915K

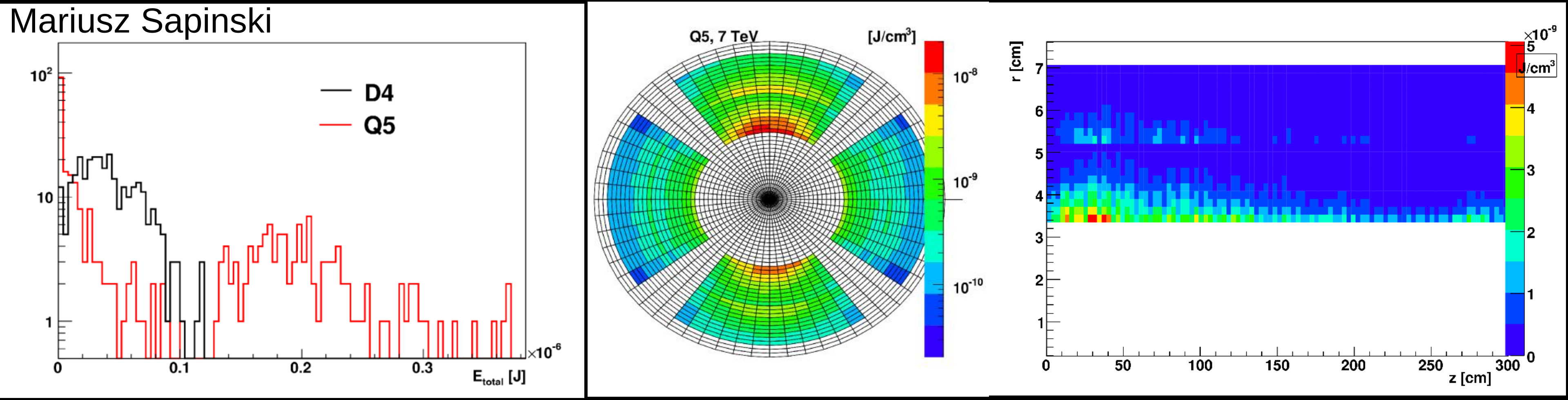


  - Typical scan lasts 1 ms & total cooling time constant ~10-15 ms
    - Cooling during measurement negligible

Limitation of WireScanners

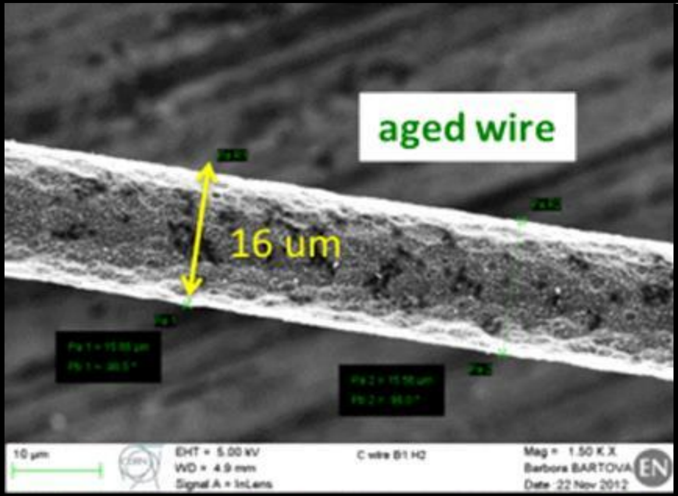
- Quench of downstream magnets?
  - Simulations & experiments show that:
    - Number of events with large energy deposition higher in Q5 than D4
    - The wire scanner can work to ~ 6 x 10^{12} protons at 7 TeV
- What can be done to increase this margin?
  - Scan faster
  - Reduce the wire diameter

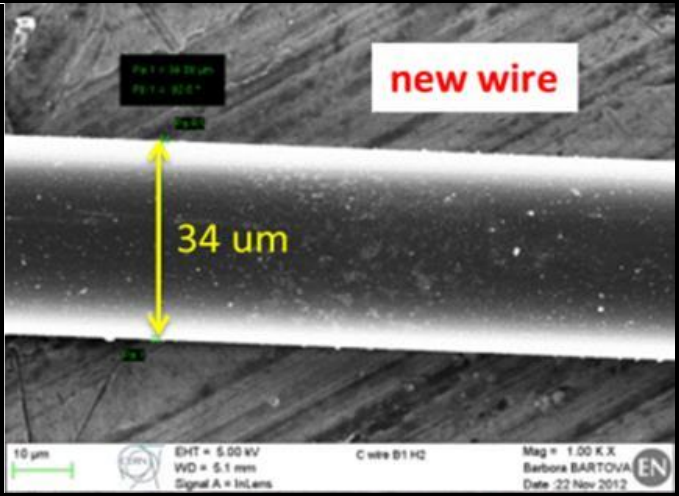
Mariusz Sapinski



Wire Scanners - Operational limits after LS1

- Limit defined by wire sublimation process (not quench)





- 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 calibrating other beam size measurement devices
- New fast wirescanner (20 ms^{-1} being developed for HL-LHC)
  - Would allow scanning all bunches at injection

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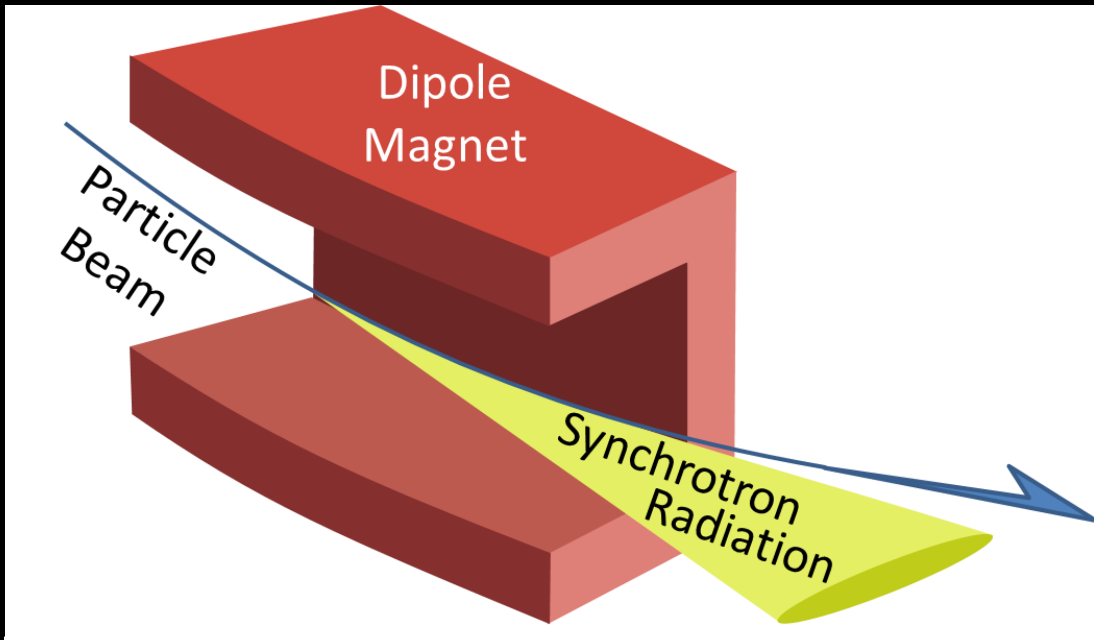
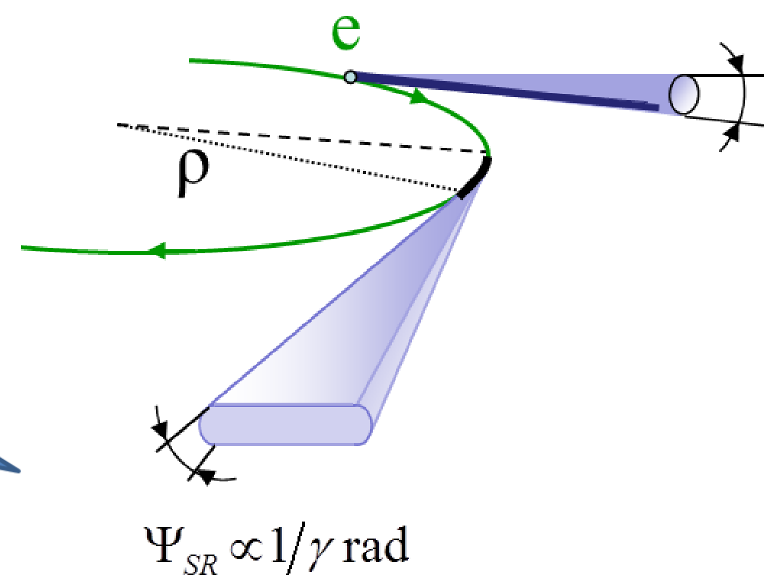
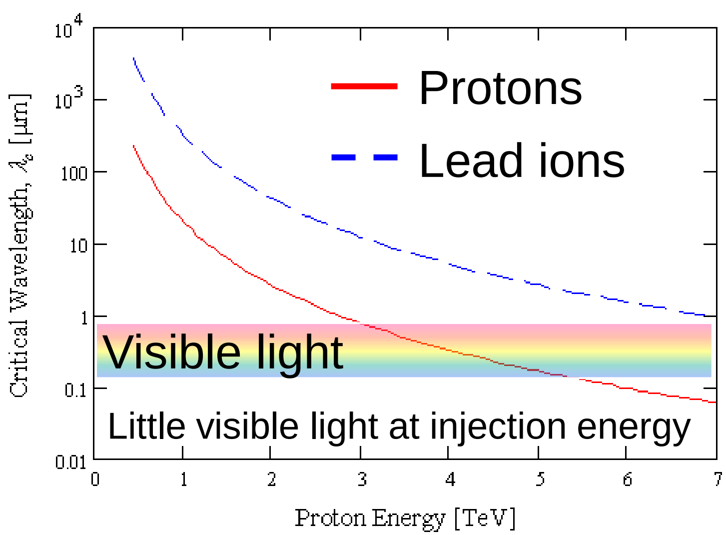
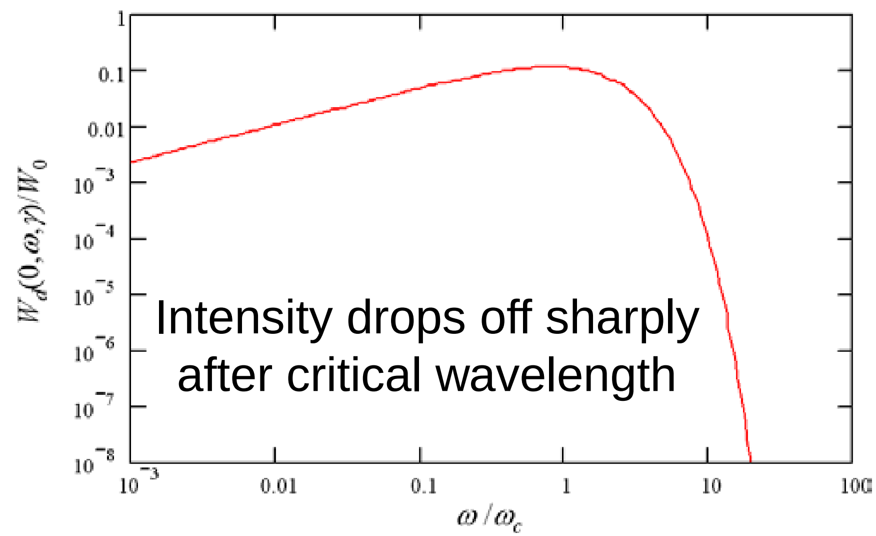
Synchrotron Light in the LHC



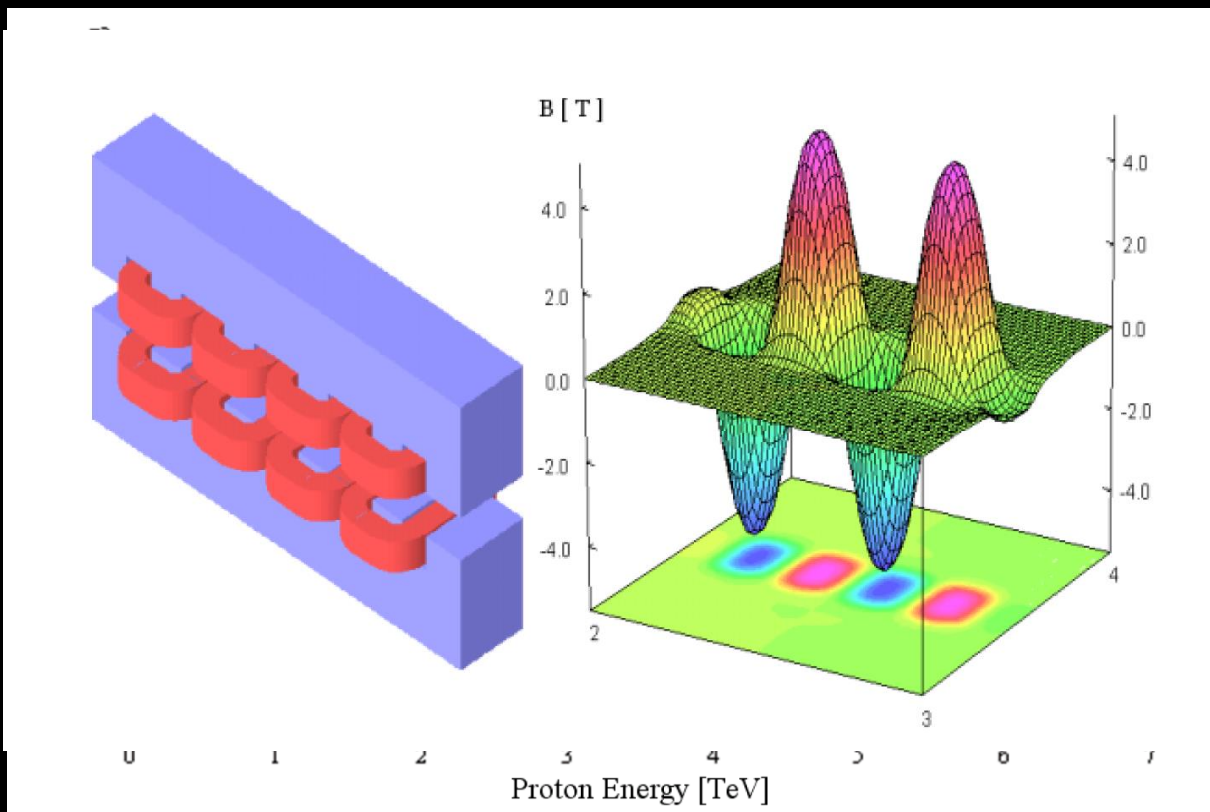


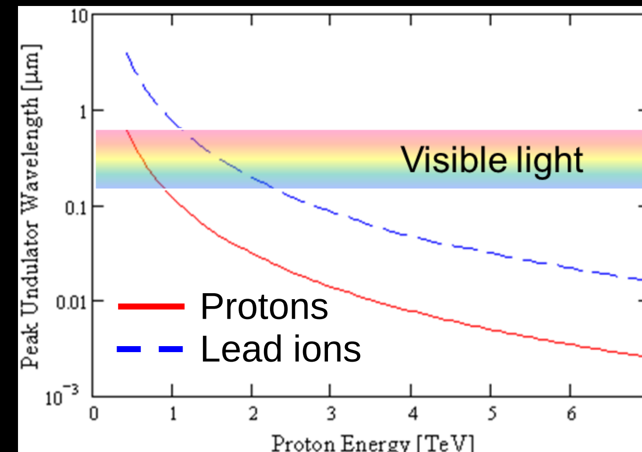


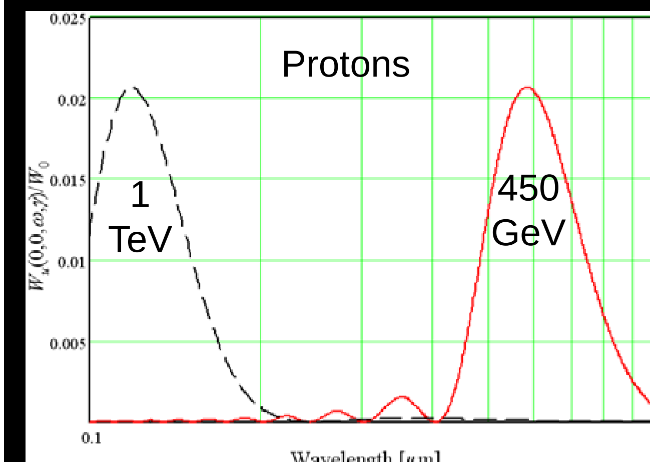


Synchrotron Light in the LHC

- At LHC injection energy
  - Visible emission from D3 dipole very low
  - Short superconducting undulator added
  - 2 periods of length 28cm with B field of 5 T

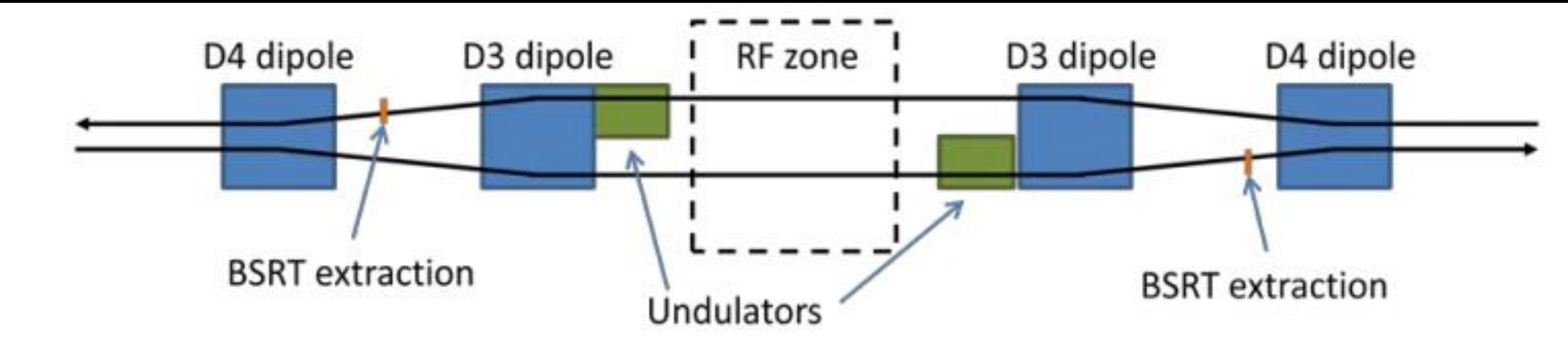






Synchrotron Light in the LHC

- Beam Synchrotron Radiation Telescope
  - BSRT located in Point 4 of the LHC



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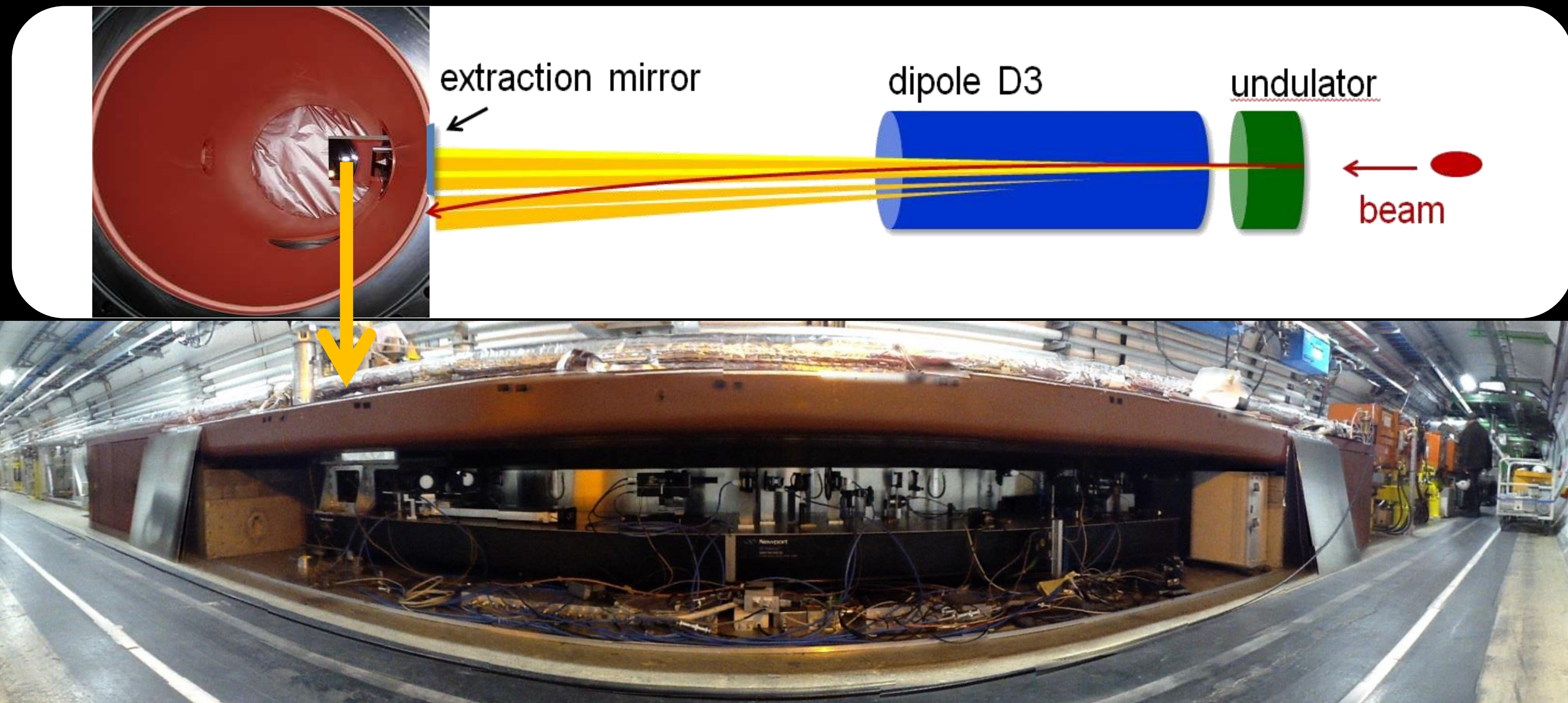


Image Acquisition in the LHC

- Using a gated intensified camera

Image Acquisition in the LHC

- Using a gated intensified camera

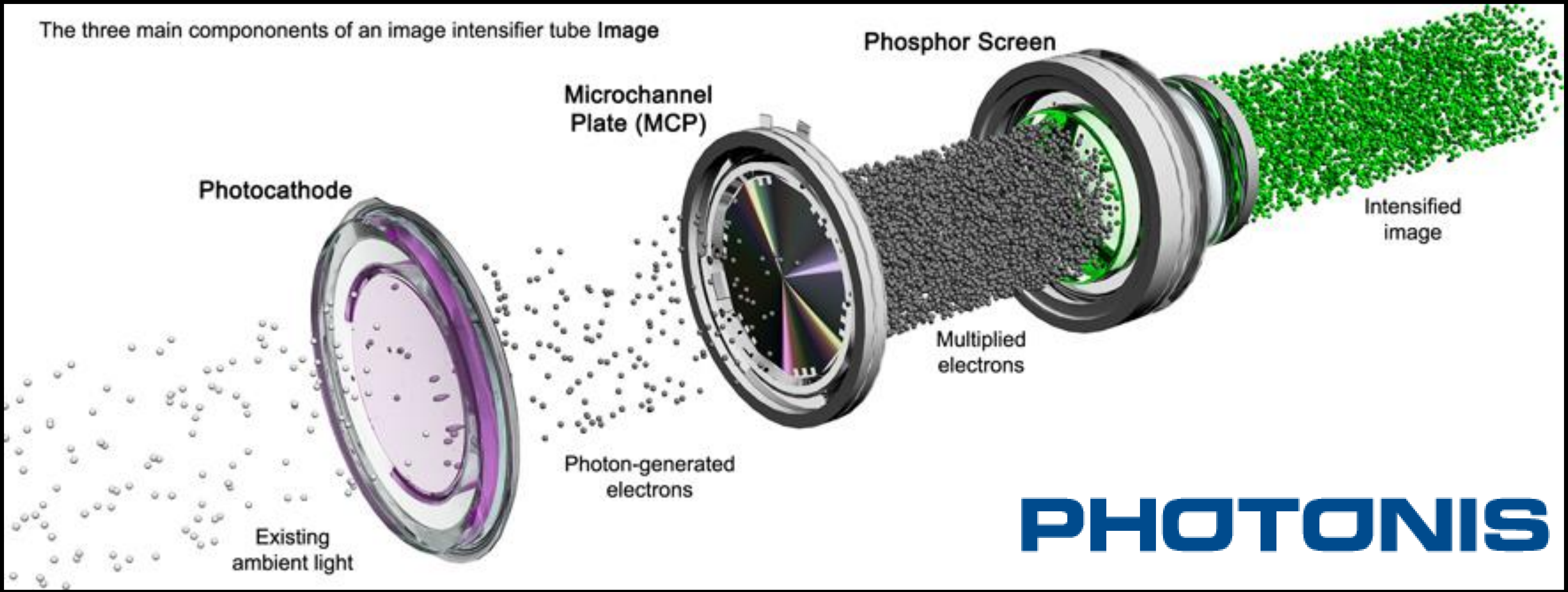
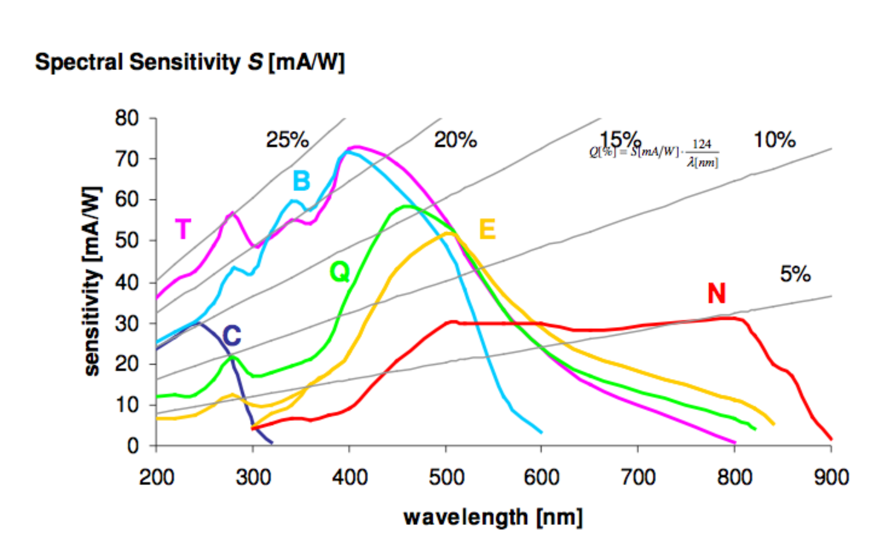


Image Acquisition in the LHC

- Proxitronic gated intensified camera
  - Intensifier max trigger rate : 200 Hz (~55 LHC turns)
  - Intensifier min gating : 25ns (1 LHC bucket)
- Present max acquisition rate is 10Hz
  - On paper 10 bunches per second but slower to get statistics

Photocathode response

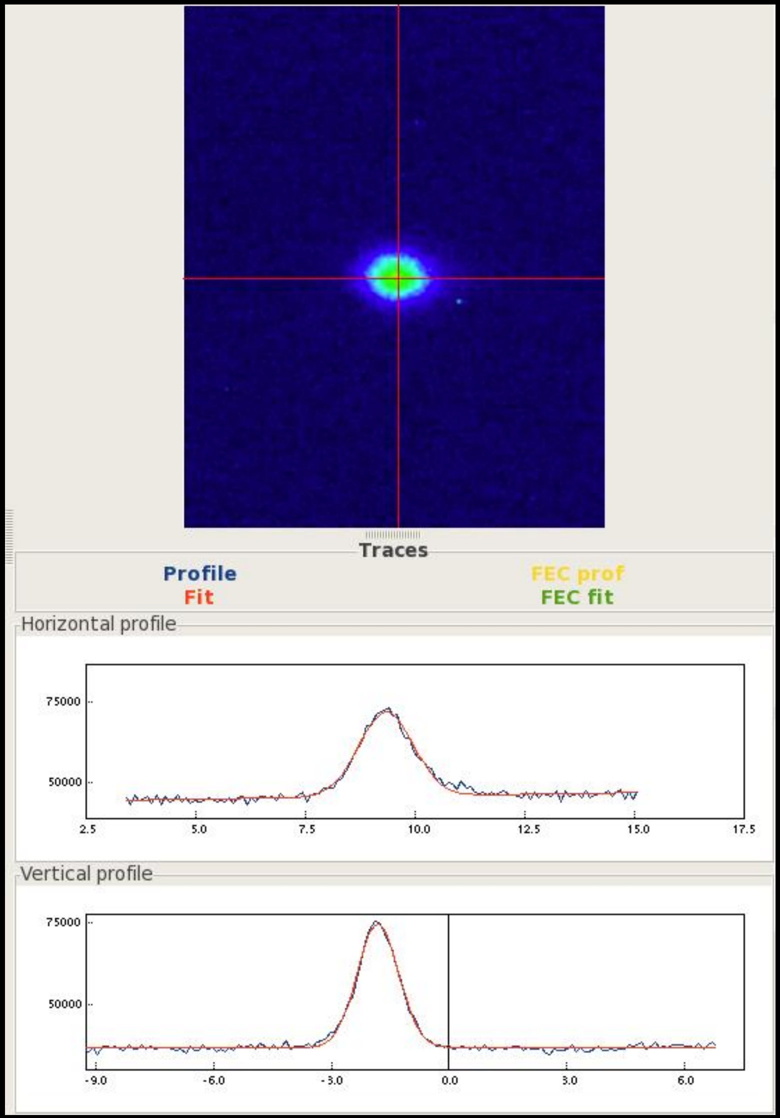
- cameras equipped with **N type** during Run I
- Will be equipped with **T type** for Run II



- Overall system sensitivity
  - Enough light to see
    - single proton pilot bunch (5e9p) on a single turn at injection (450GeV)
    - ~20 Ion Pb bunches at injection, averaged over 4 turns

Proton Image Example

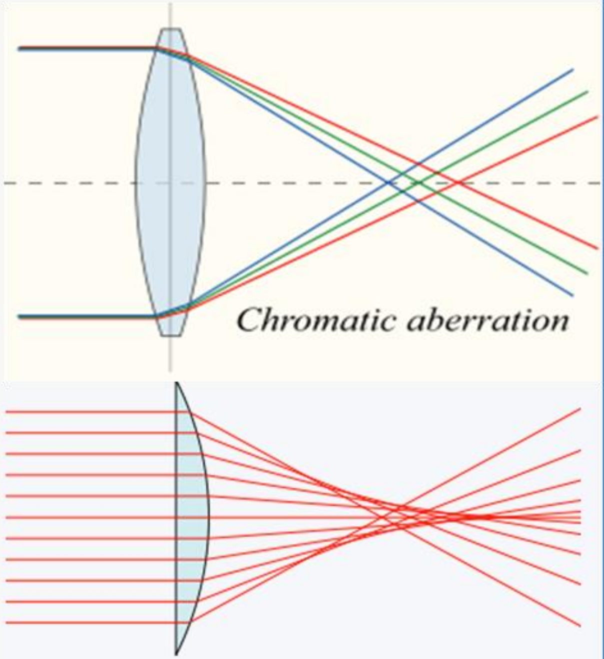
- Beam
  - Single bunch ~1.1e11p @ 3.5 TeV
- Acquistion
  - Accumulated over 4 turns at 200Hz



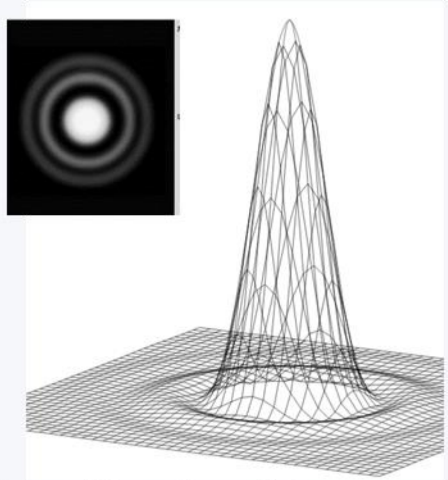
Beam Size Measurement with Synchrotron Light

- Imaging Resolution

Aberrations (spherical, chromatic, surface irregularity...) $\rightarrow \sigma_{aberr}$

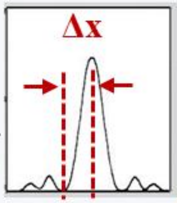


fundamental resolution limit (diffraction) $\rightarrow \sigma_{diff}$

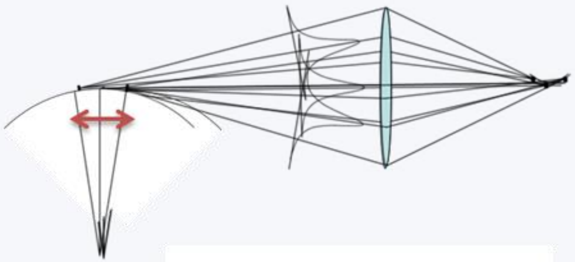


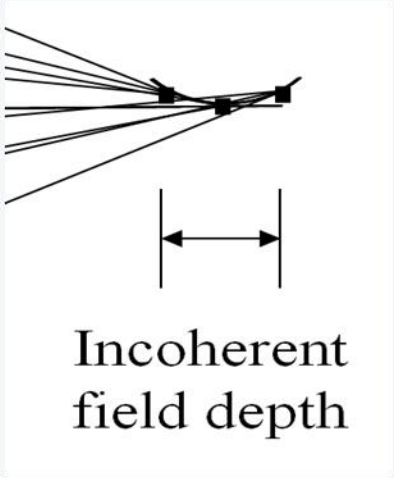
Magnification M

$$\Delta x = 0.61 \frac{M\lambda}{\sin\vartheta}$$



extended object (depth of field) moving object $\rightarrow \sigma_{dof}$



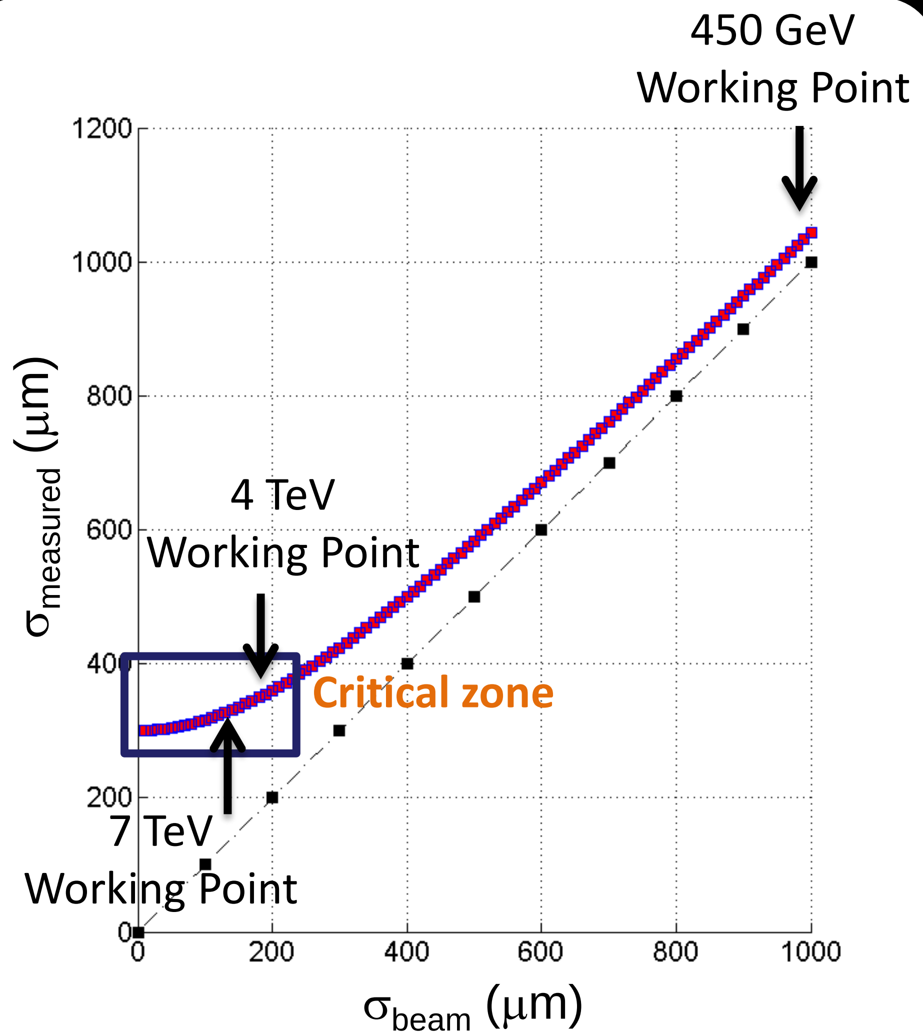


$$\sigma_{corr} = \sqrt{\sigma_{dof}^2 + \sigma_{diff}^2 + \sigma_{aberr}^2}$$

Synchrotron light limitations in the LHC

- $\sigma_{correction}$
  - Difficult to model accurately & simulate
  - Therefore experimentally measured ,knowing the real beams size
    - WireScanner cross calibration

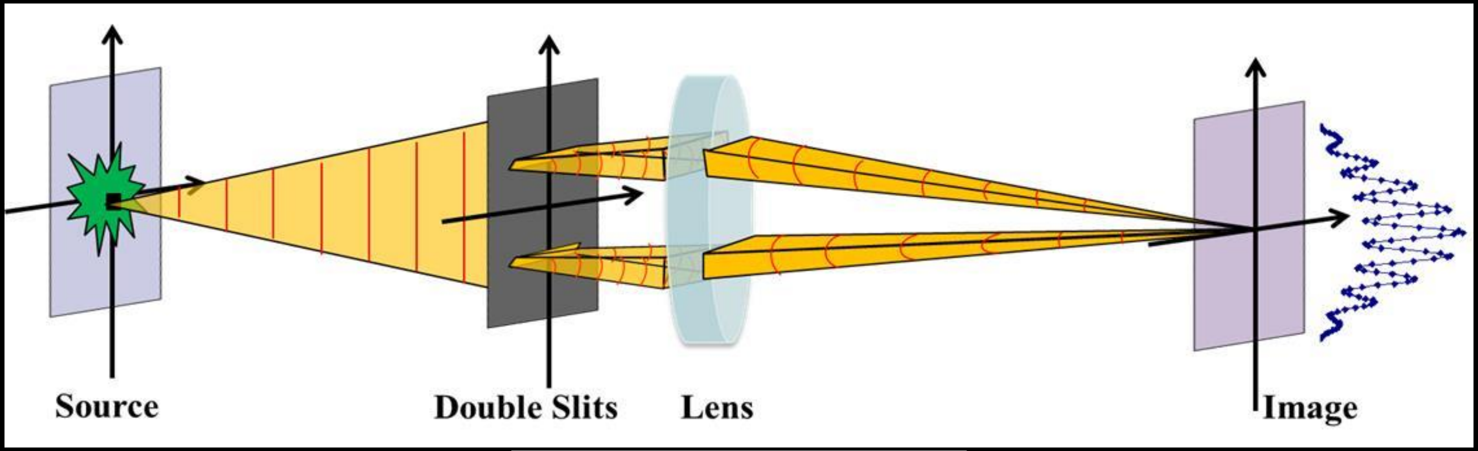
- Size measured has to be de-covoluted by a correction factor to obtain the real size
  - For LHC correction factor is of same order as real beam size

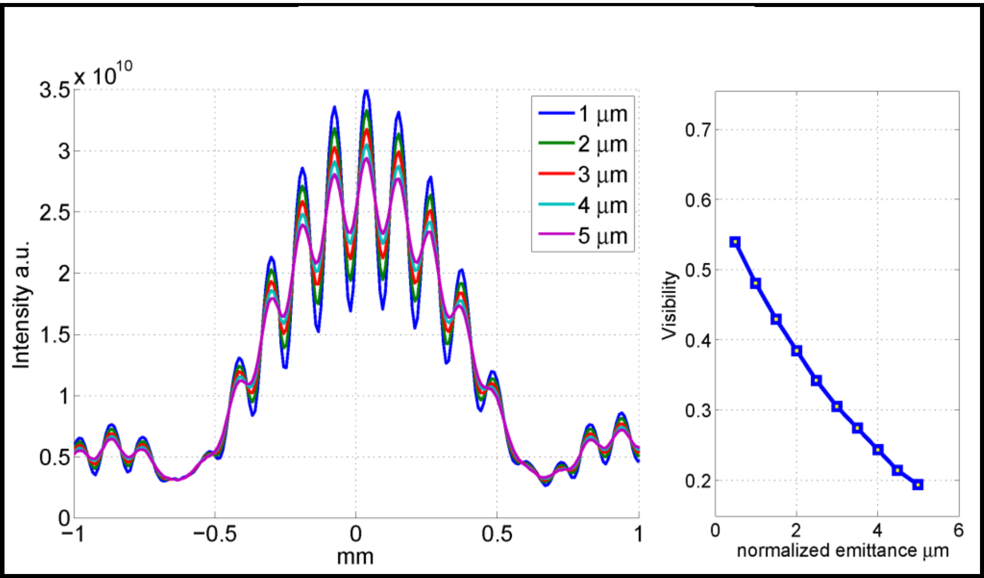


$$\sigma_{beam}{}^2 = \sigma_{measured}{}^2 - \sigma_{correction}{}^2$$

Overcoming this limitation

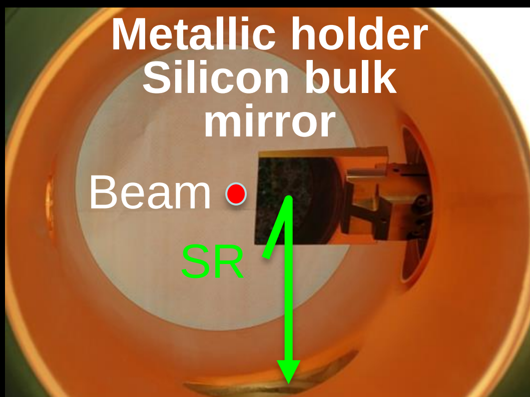
- Using Interferometry?
  - Will be tested after LS1





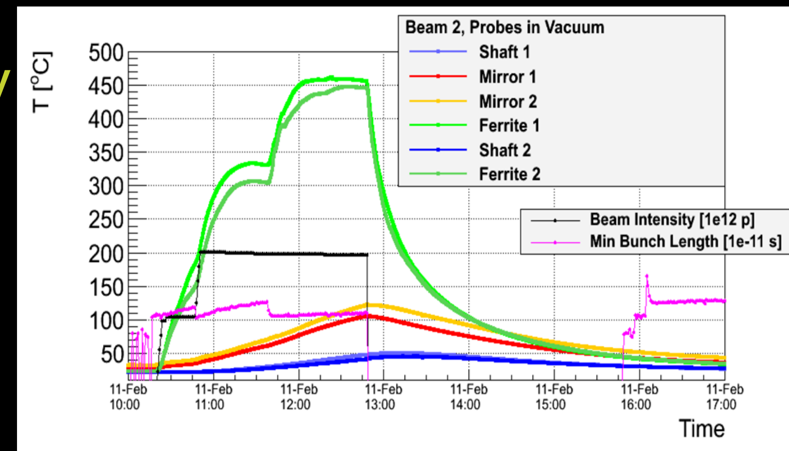
Other issues with the BSRT

- RF Heating due to the Beam

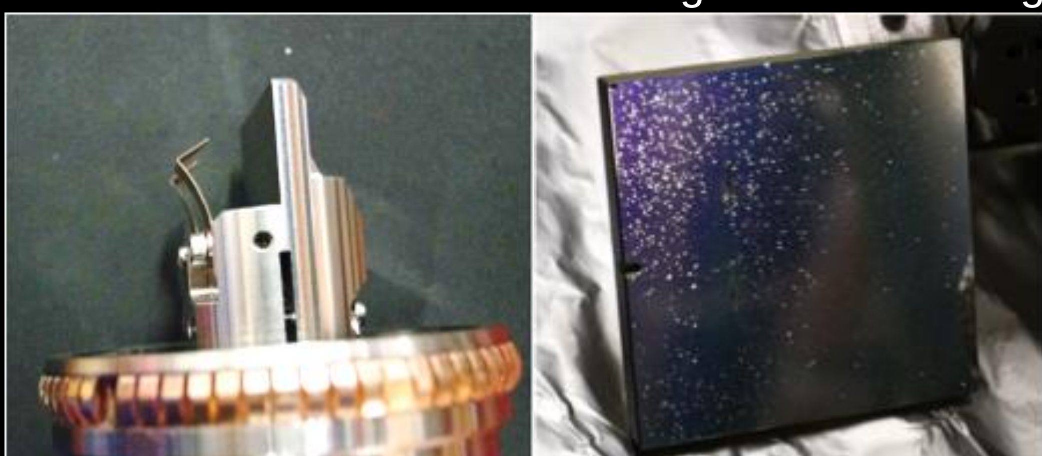


Mirror heating clearly correlated to

- beam intensity
- beam spectrum
- bunch length



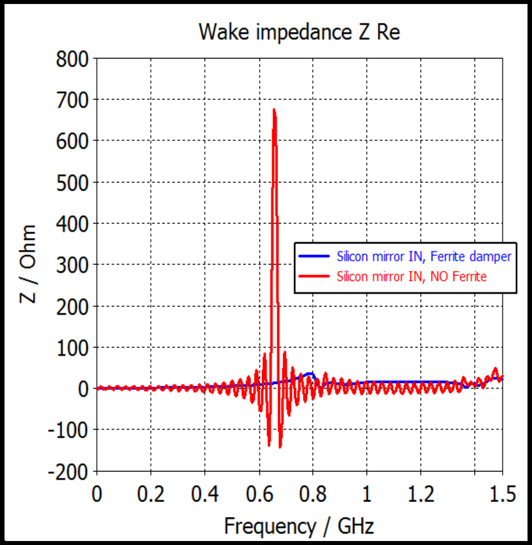
Failure of mirror holder + blistering of mirror coating



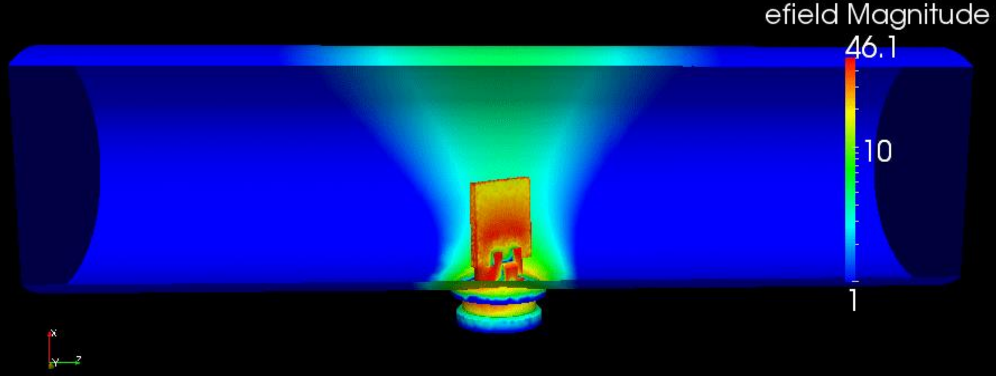
Complete Re-design

- EM Simulations
- Lab Measurements

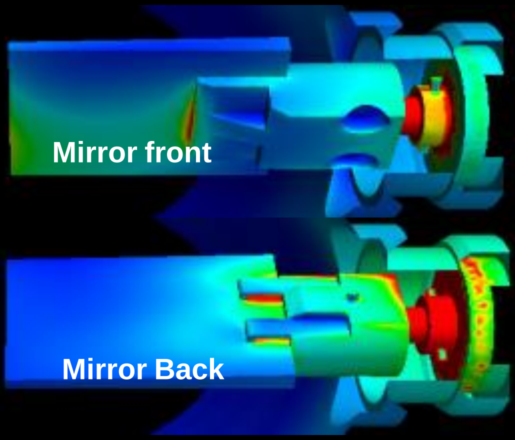
Extraction Mirror Heating



Longitudinal wake impedance of BSRT with and without Ferrite damping



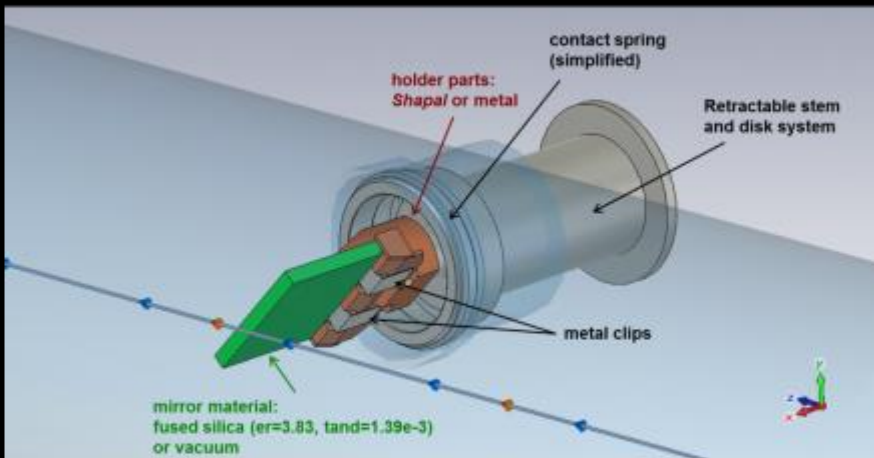
E-field of a dominant resonating mode at 650 MHz. (Q = 1263 / Rsh = 25841 Ohm)



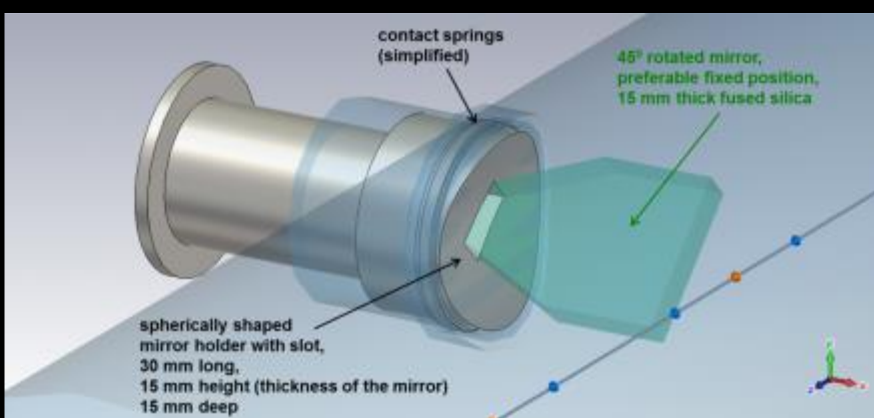
B-field of the beam in Time Domain.
Red = Hot (bigger current density) :
Blue = Cold

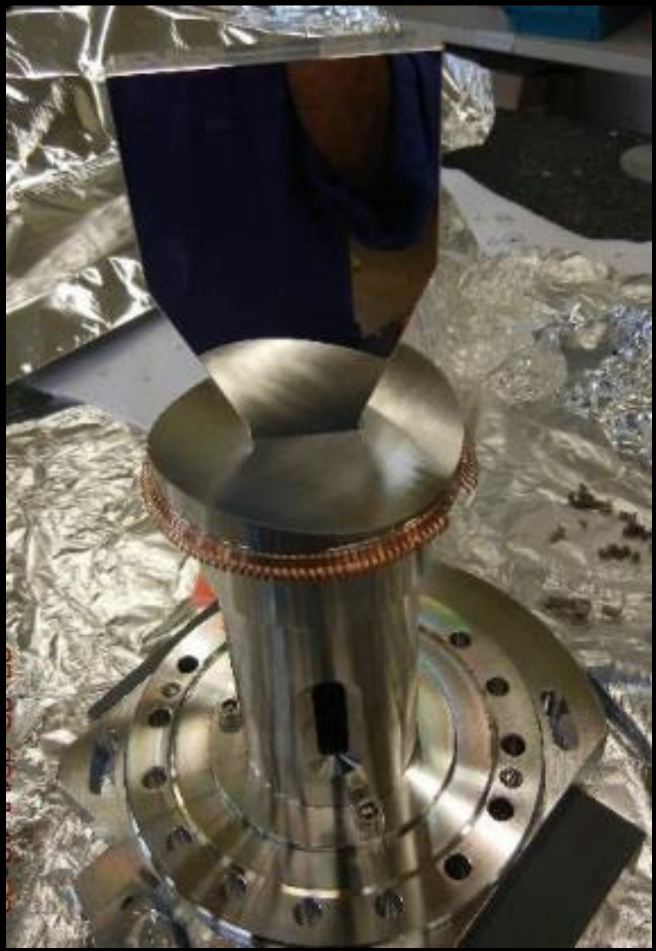
New Extraction Mirror for Run II

OLD Extraction Mirror



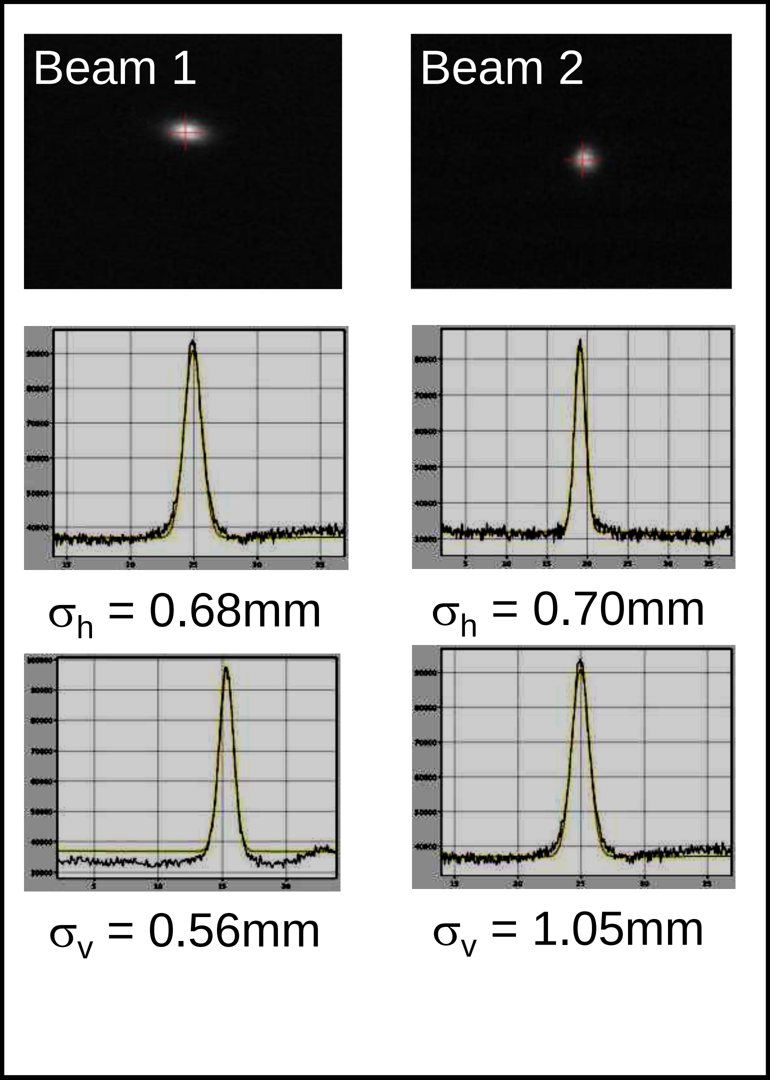
NEW Extraction Mirror



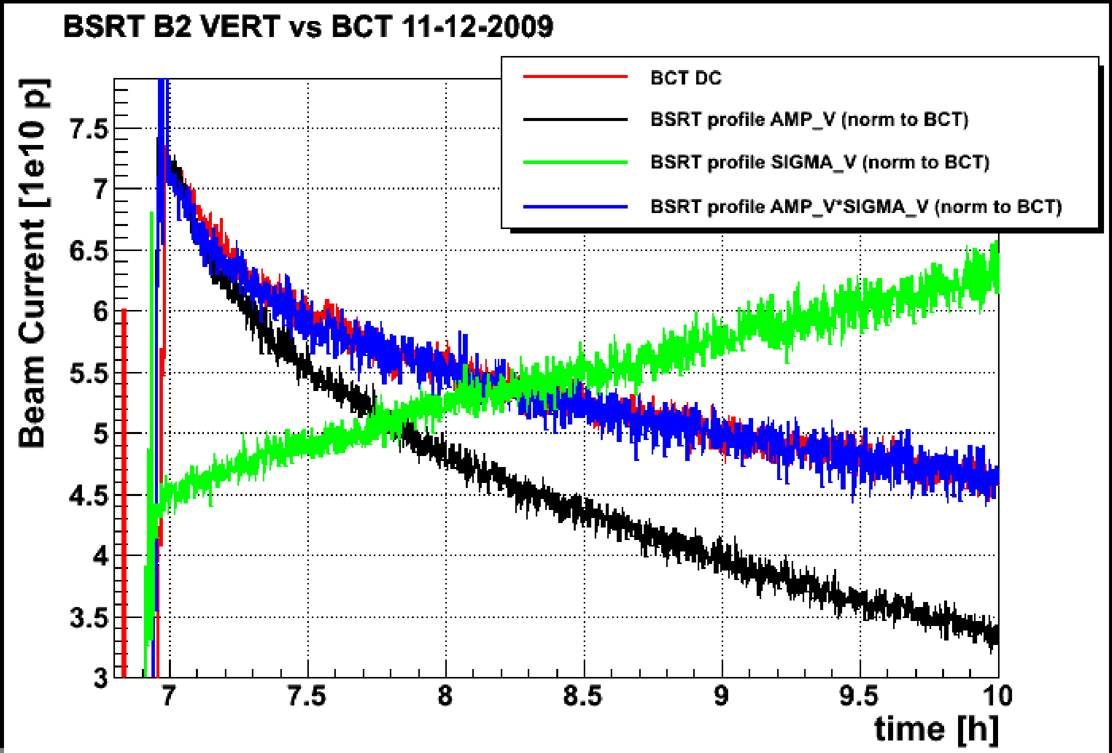


Solution for Run II with low RF ‘footprint’ and shielded cavities

Using the BSRT in the LHC



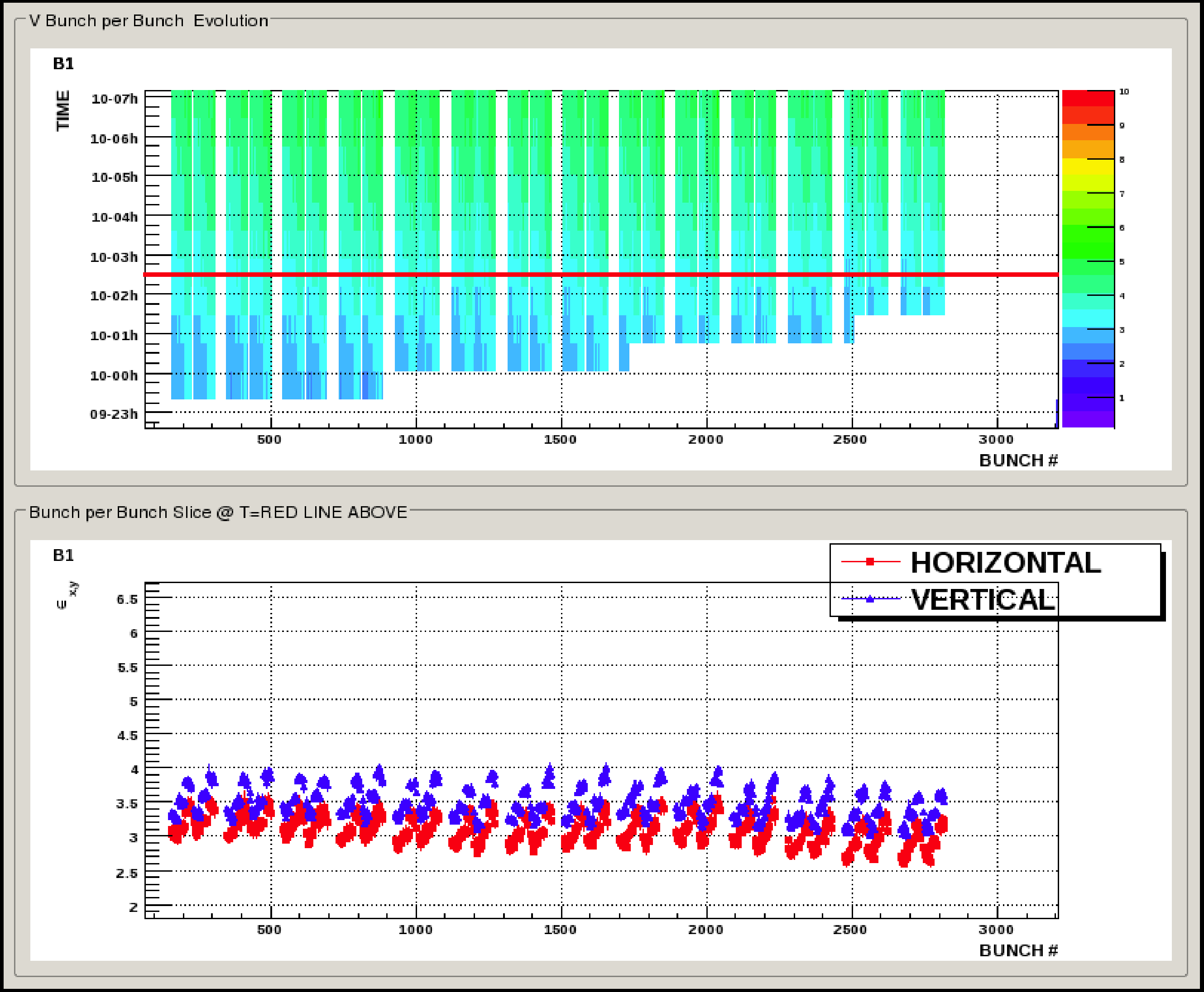
- CCD camera fitted with gated intensifier
  - Used from very early stage to investigate emittance growth



Bunch by Bunch Profile Measurement

Diagnostics

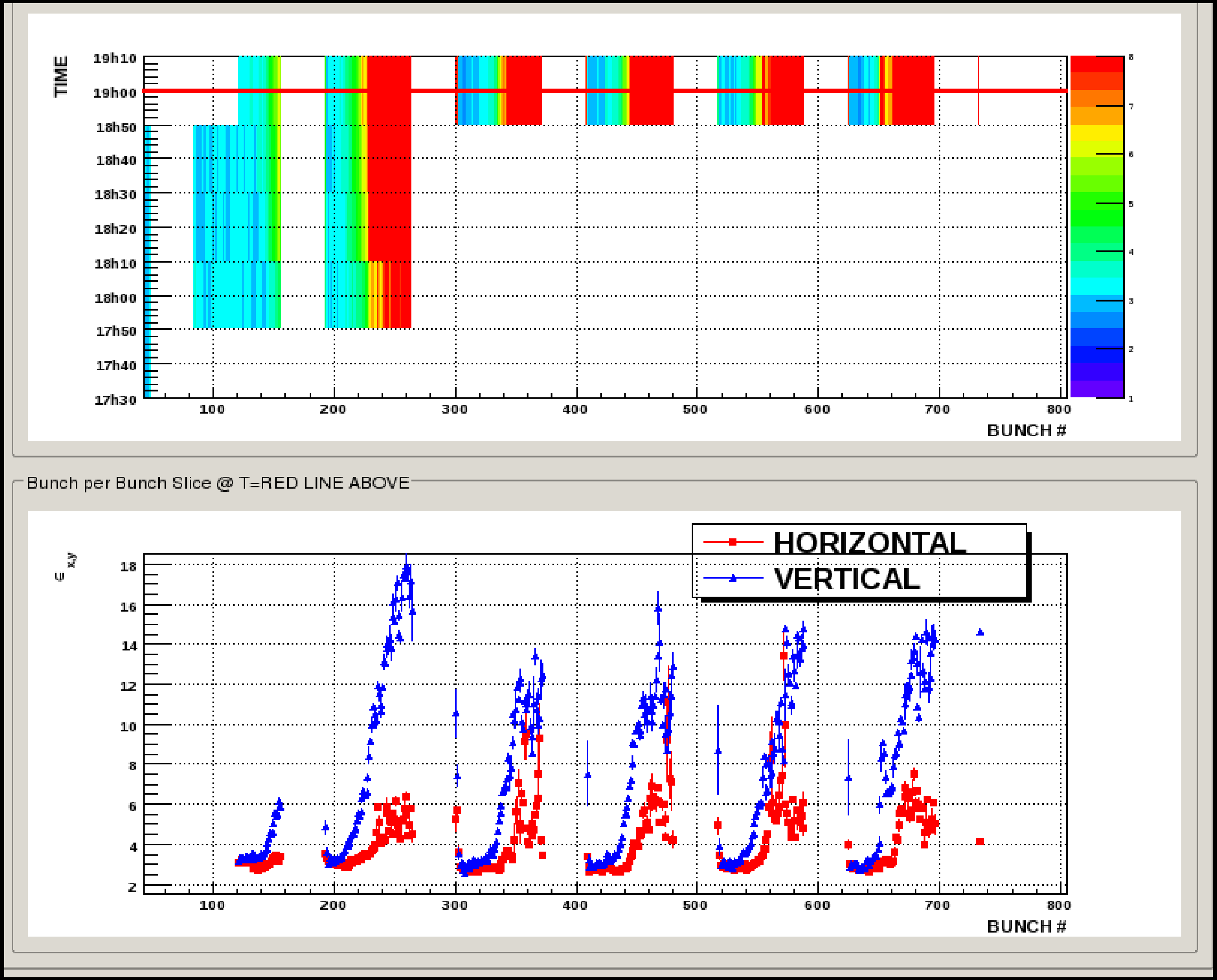
- Allowed diagnosis of systematic emittance patterns from the LHC injectors
  - In this case variations in the emittance from the different PSB rings



Bunch by Bunch Profile Measurement

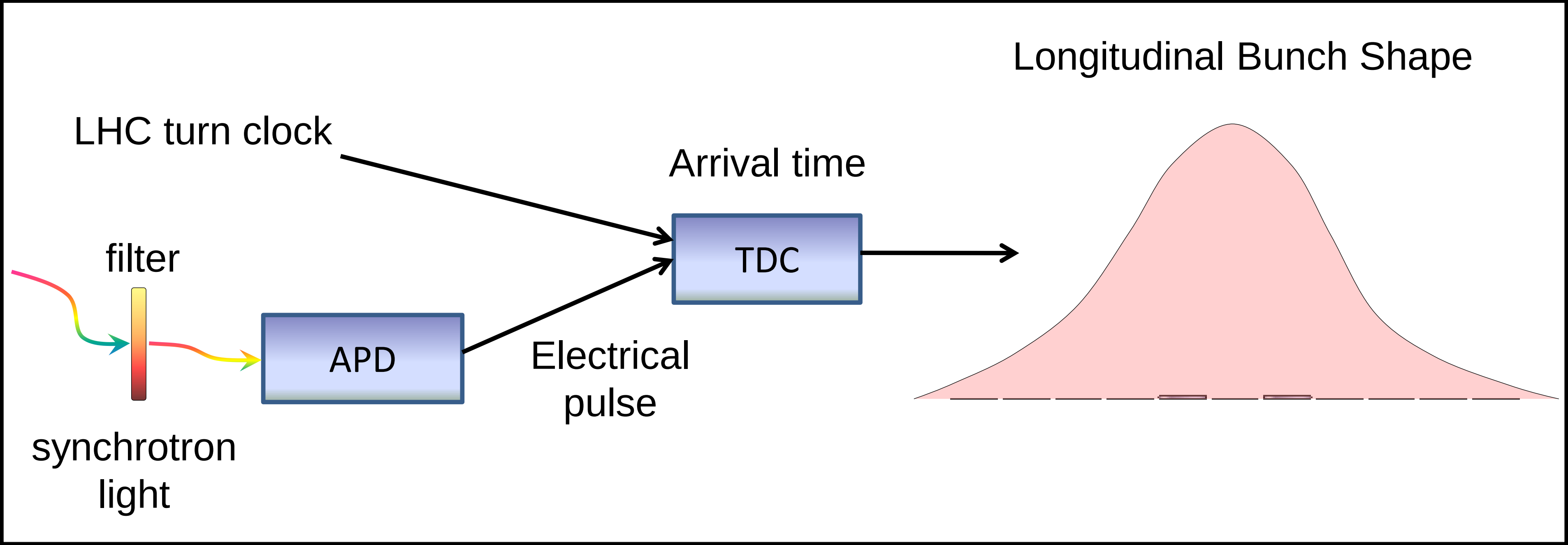
Diagnostics

- During 25ns bunch spacing scrubbing run
  - Electron cloud increases the size of the bunches in the second part of each train

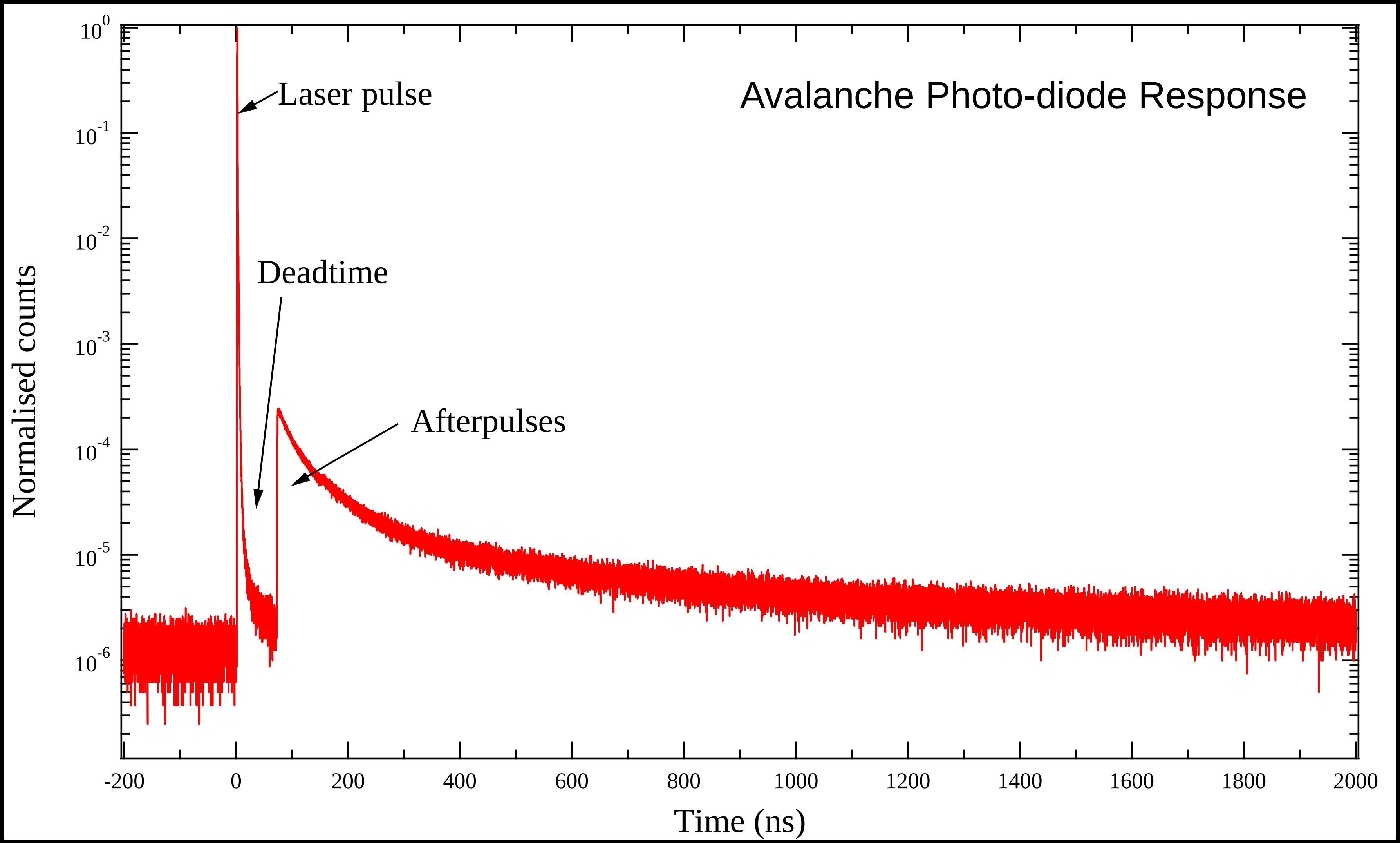


Longitudinal Density Monitor (LDM)

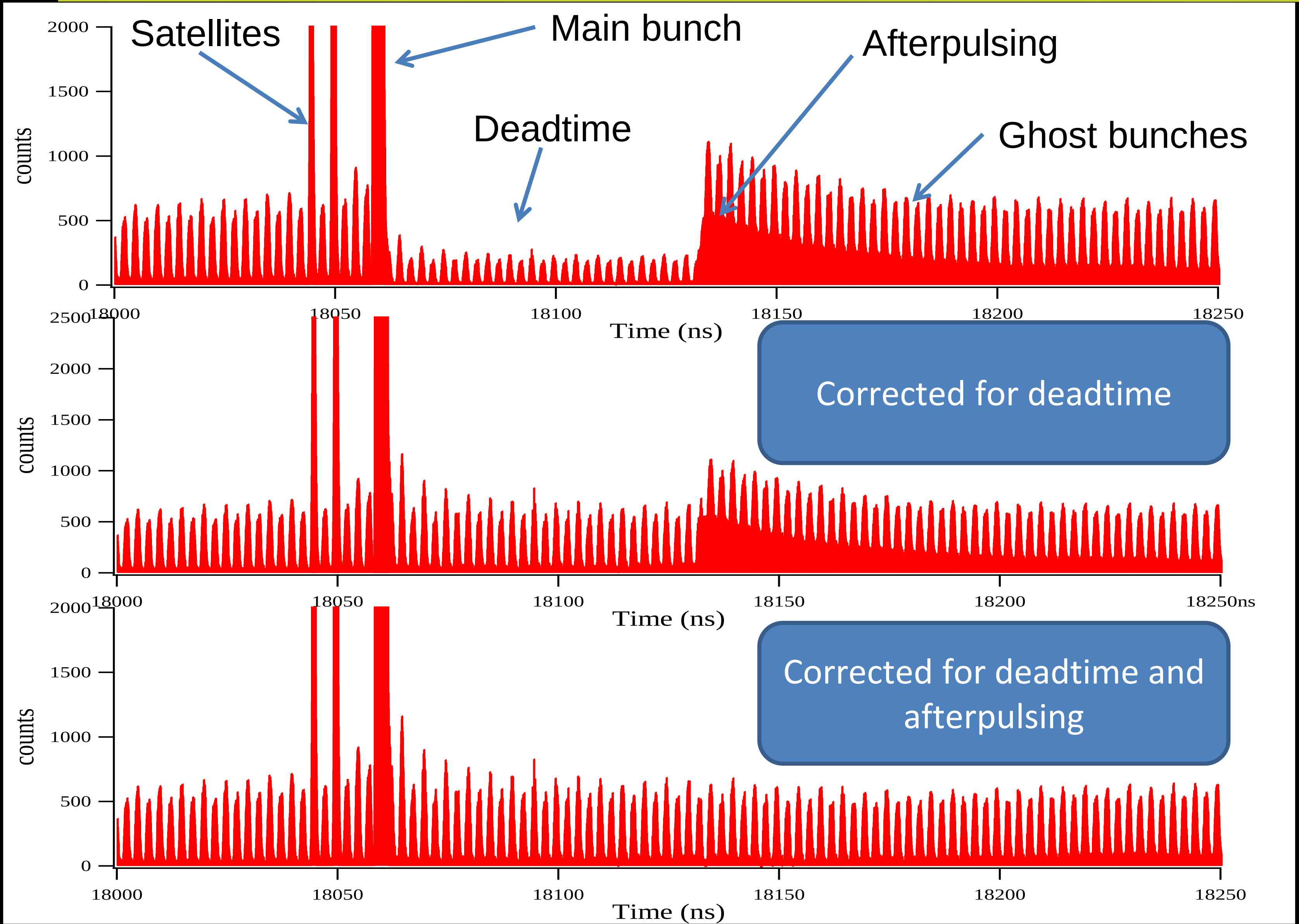
- Longitudinal Profile Measurement using Synchrotron Light
  - Single photon counting with Synchrotron light
    - Avalanche photodiode detector
    - 60ps resolution TDC
  - Profiles the whole LHC ring with high time resolution
  - High dynamic range for ghost charge measurement



LDM Instrument Response

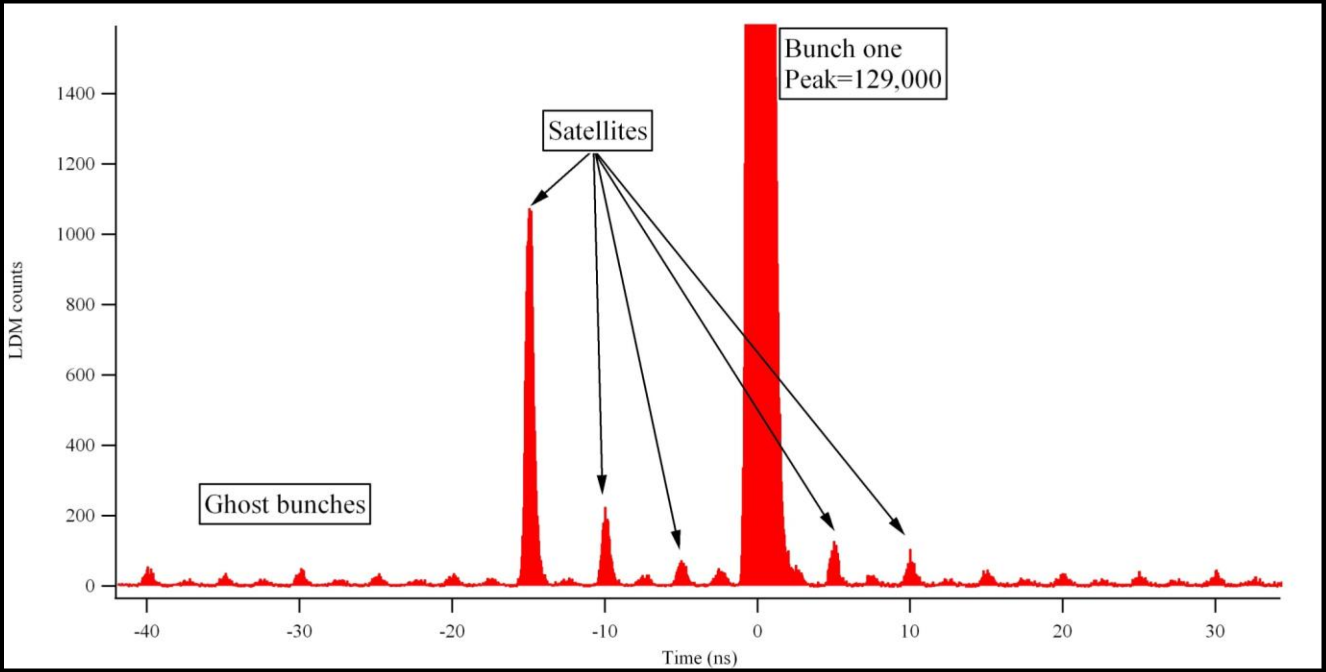


LDM On-line Correction



LHC Optimisation with the LDM

- Achievements:
  - Dynamic range of up to 10^5 with integration time of a few minutes
- Used for:
  - Detection of ghost & satellite populations
    - Injector optimisation
    - Important to qualify bunch by bunch BCT data for absolute luminosity calibration



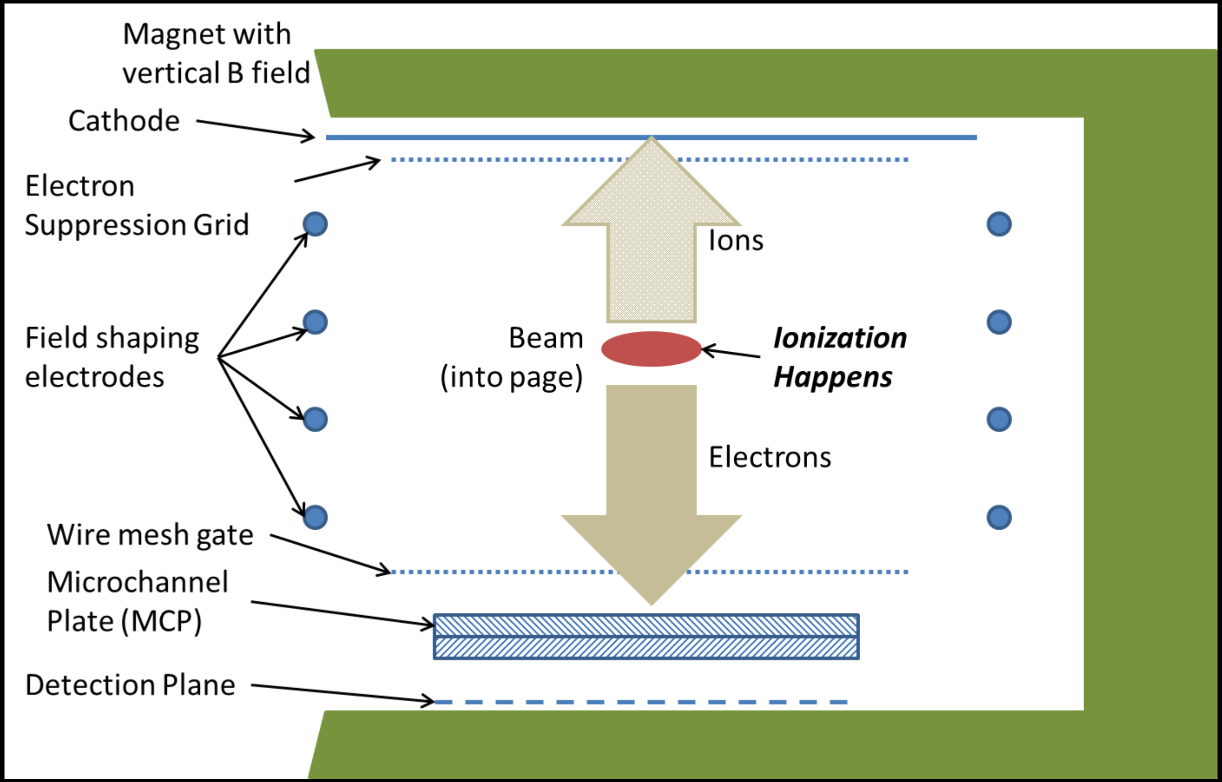
Lead ions at 3.5 Z TeV
10 min integration

The Typical LHC Instruments

- Beam Position
  - electrostatic or electromagnetic pick-ups and related electronics
- Beam Intensity
  - beam current transformers
- Beam Profile
  - screens
  - wire scanners
  - synchrotron light monitors
  - rest gas monitors
- Beam Loss
  - ionisation chambers and solid-state detectors
- Machine Tune and Chromaticity
  - base band tune measurement system
- Other Monitors
  - luminosity, schottky, abort gap, instability

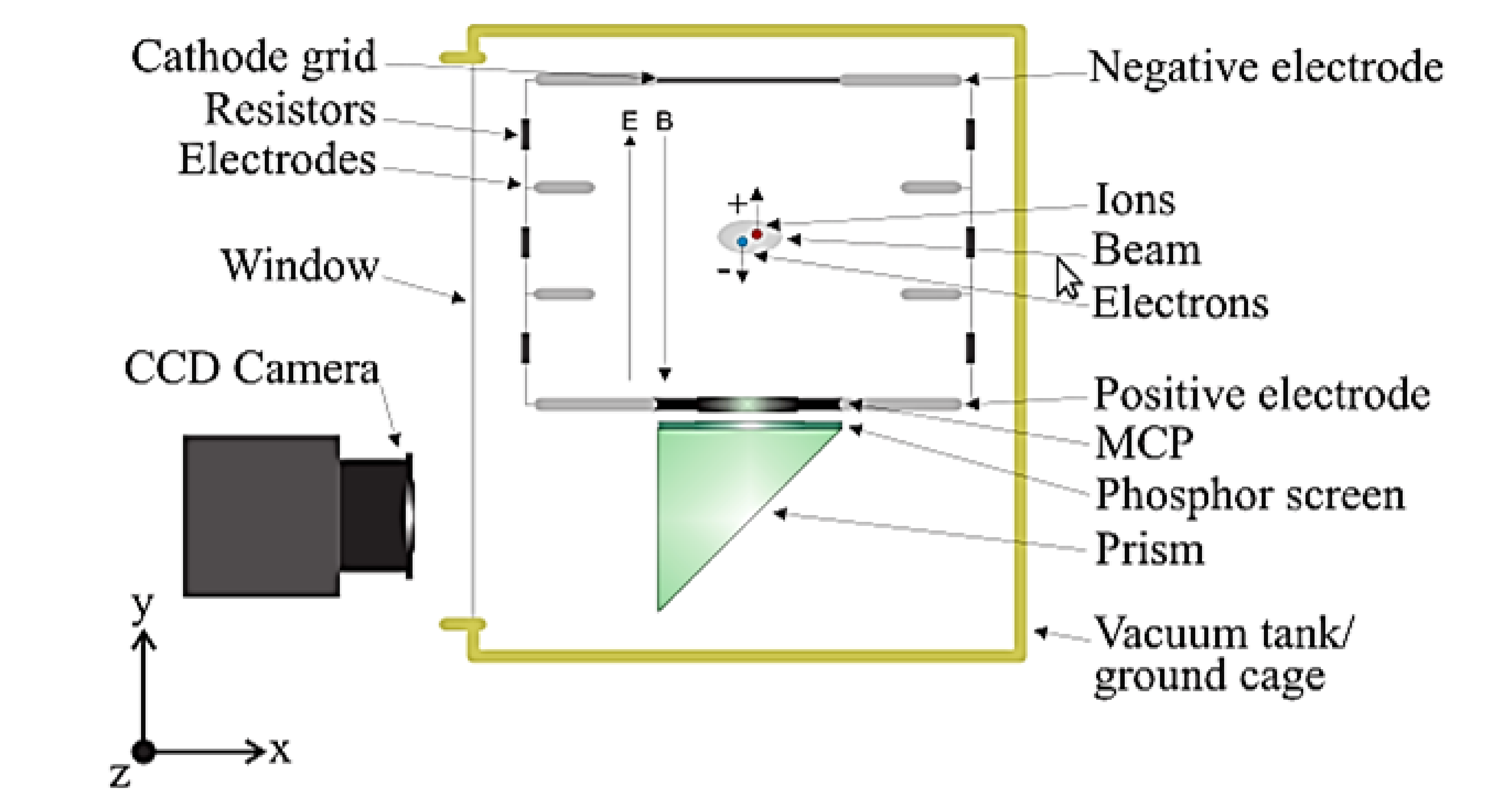
Rest Gas Monitors

- Ionisation Profile Monitor (BGI)
  - Beam ionises residual gas
  - E-field accelerates gas-ions or released electrons
  - B-field keeps transverse position of ionisation product
    - Used with electron detection
    - Ideally cyclotron radius along field line is comparable to resolution of MCP



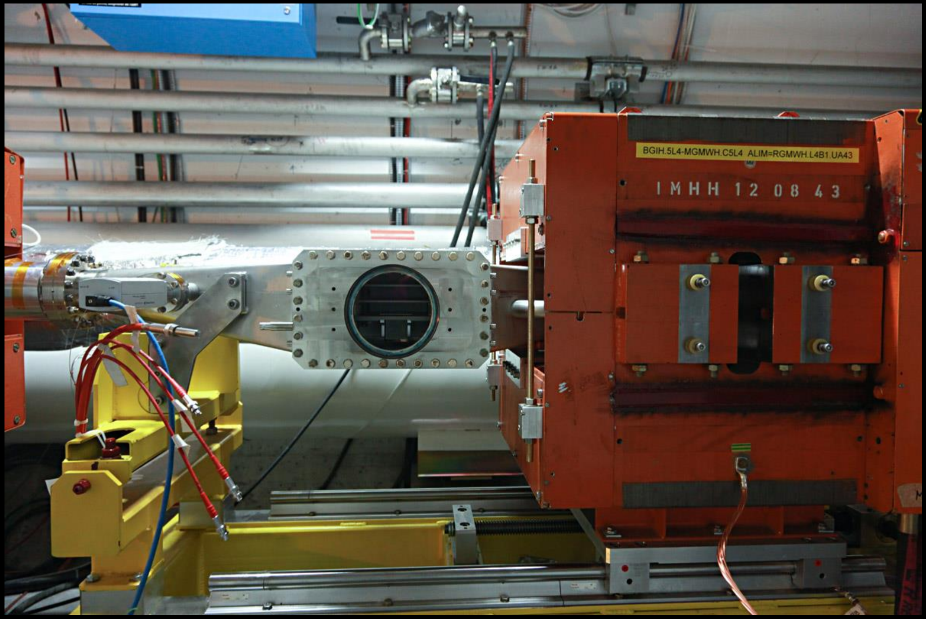
LHC Ionisation Profile Monitor

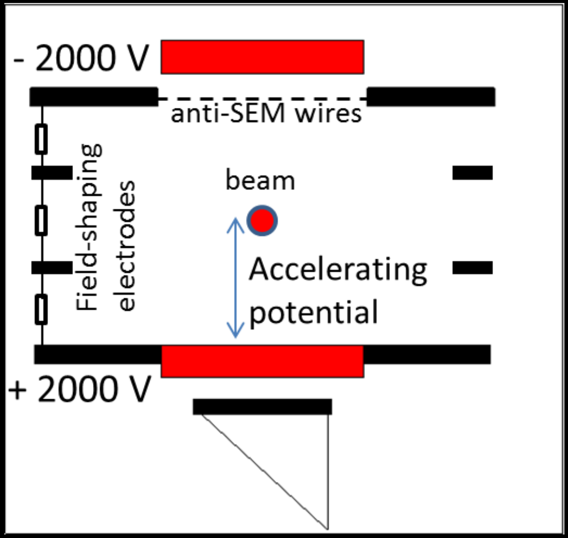
- Optical Detection
  - Micro channel plate amplifies incident electrons
  - Electron avalanche hits phosphor screen
  - Screen scintillation observed using a radiation hard CCD camera

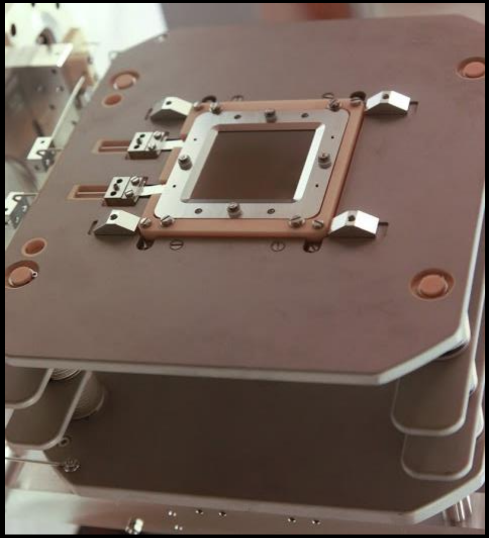


LHC Ionisation Profile Monitor

- Magnetic field
  - 0.2 T magnets originally from ISR with yoke modified to allow extraction of light
  - Magnetic field compensated by 2 neigbouring magnets
    - Maintains original beam orbit
- Electric Field
  - Anode at up to -2 kV
  - Cathode at up to +2 kV
  - Field shaping electrodes to obtain a uniform field

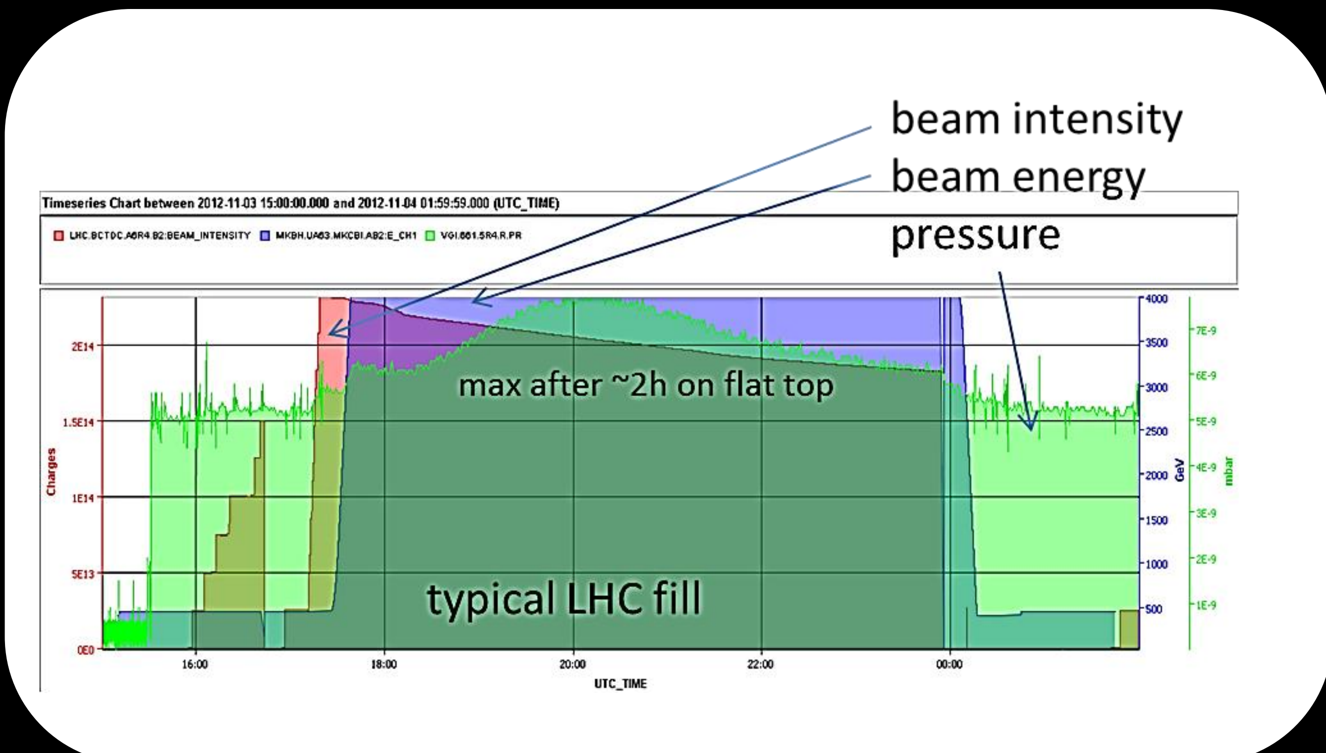


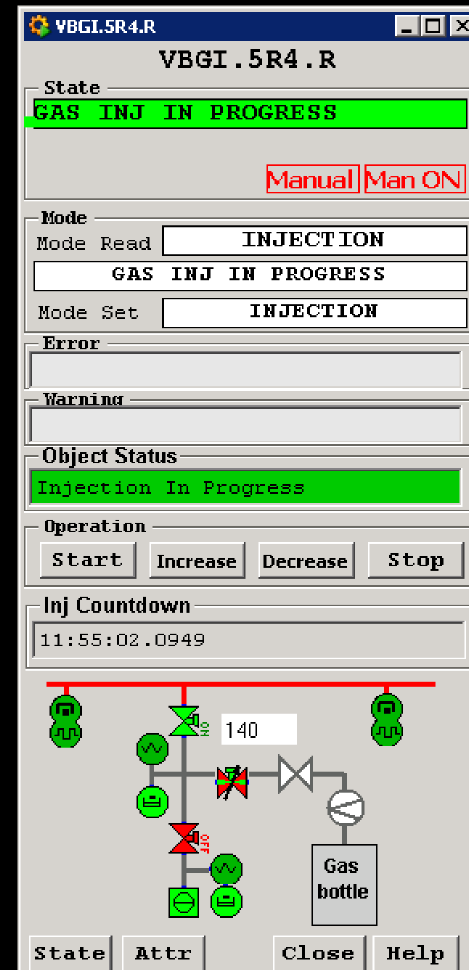




LHC Ionisation Profile Monitor

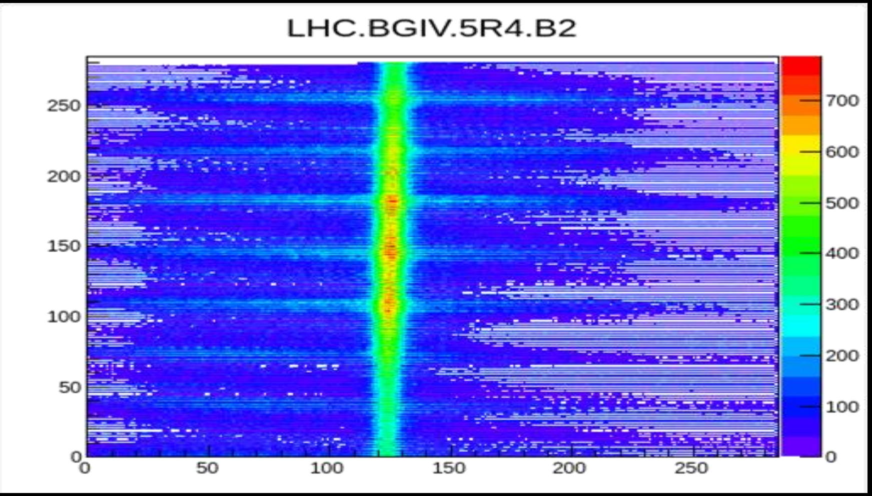
- Gas injection
  - needed to see something in LHC
    - normal vacuum 10^{-11} mbar
  - gas injection up to 10^{-8} mbar

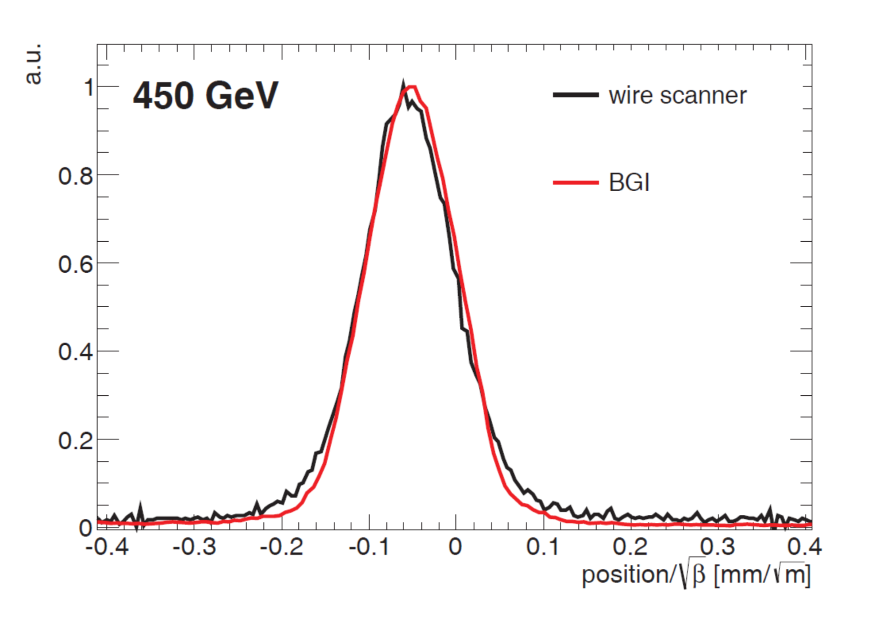


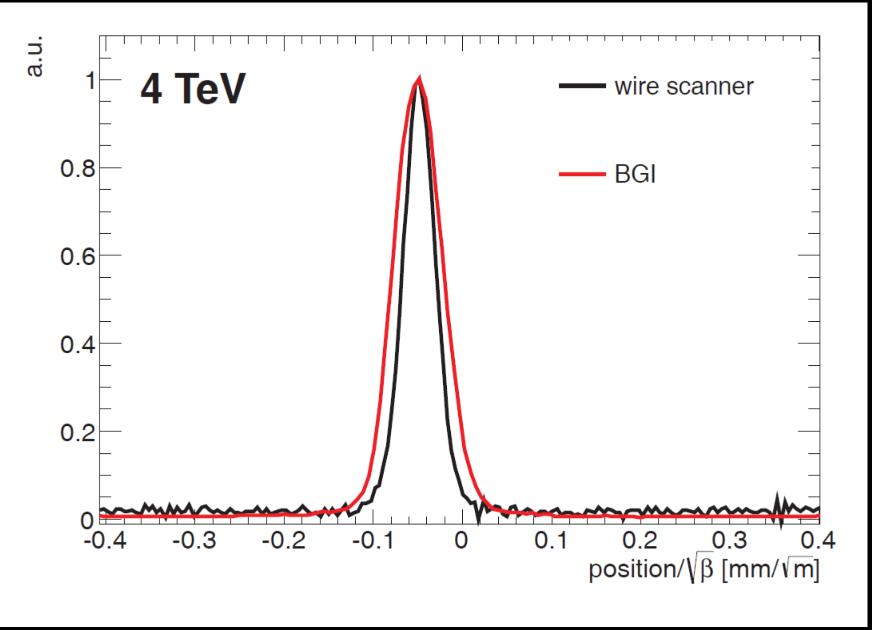


LHC Ionisation Profile Monitor

- Results with Pb^{54+}
  - Worked well at injection
  - Broadening observed at 4TeV but could be corrected for
  - Algorithms to clean-up the camera signal being introduced

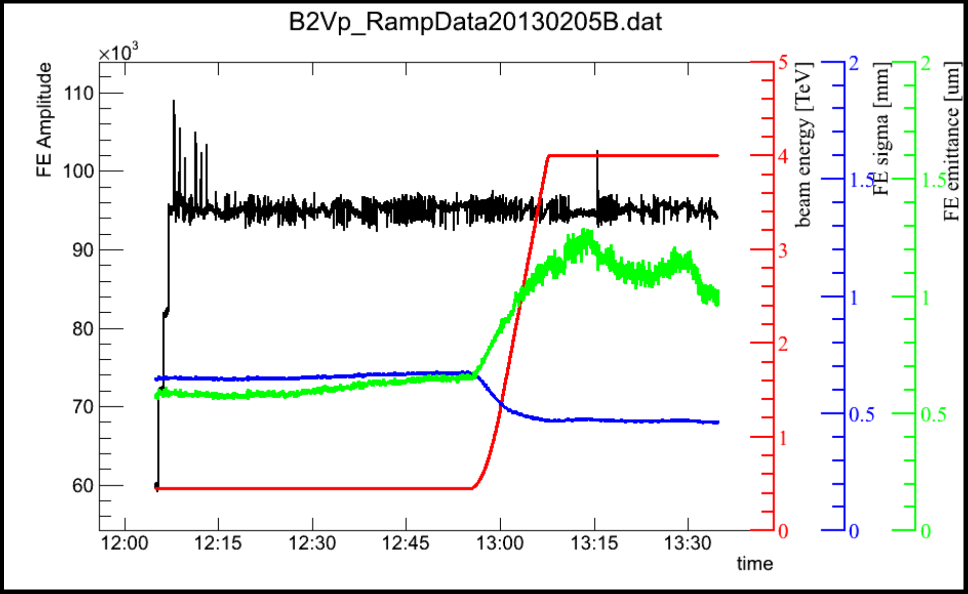


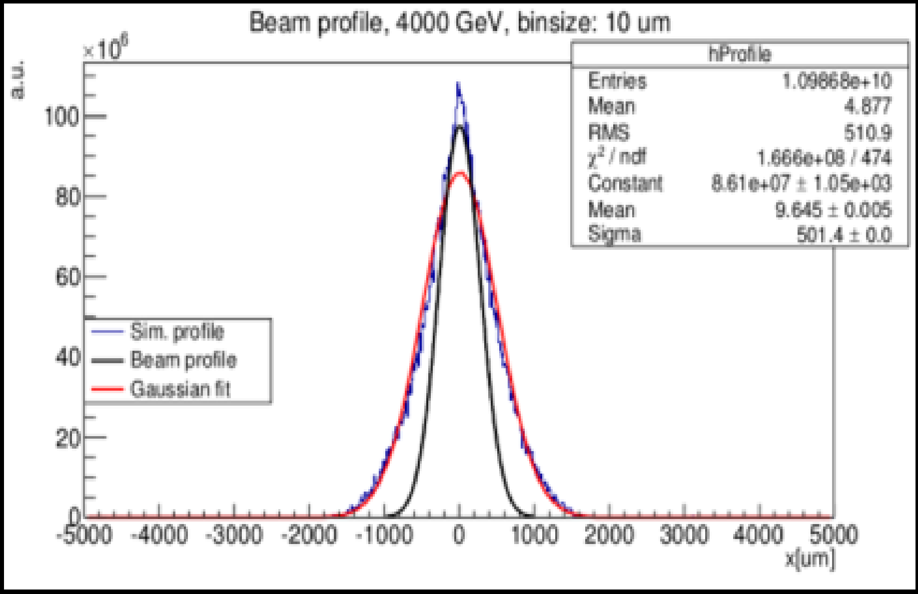




LHC Ionisation Profile Monitor

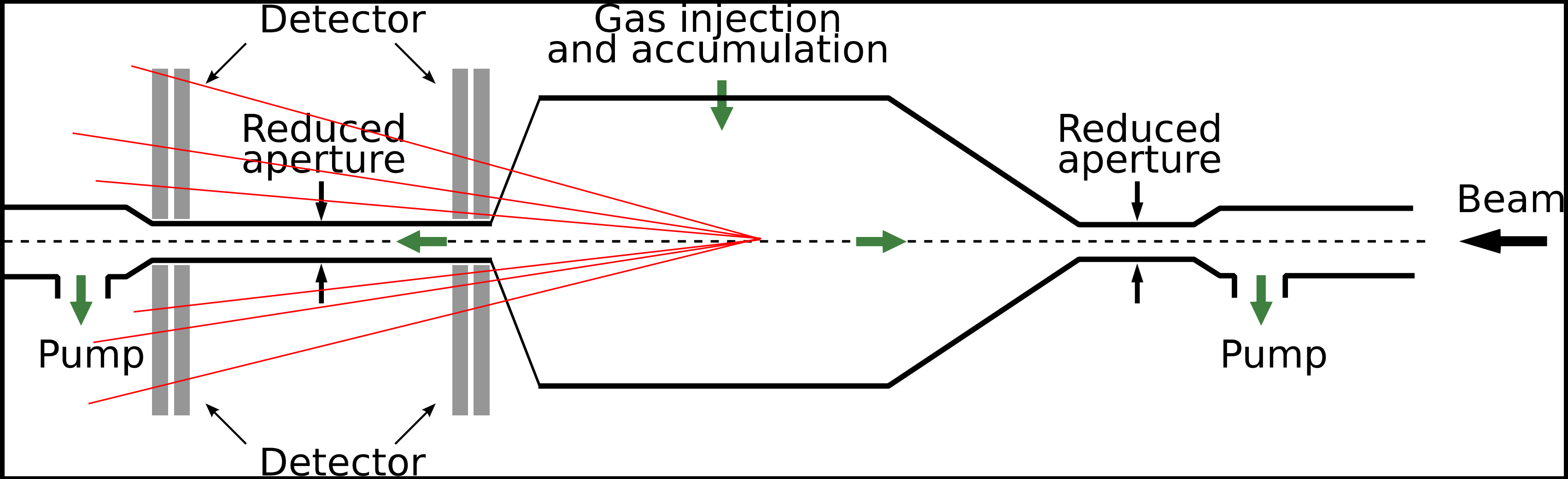
- Results with Protons
  - At injection:
    - Beam size OK - agreement with wire scanner
  - Unphysical behaviour during ramp and squeeze
    - Explanation: profile distortion due to beam space-charge
    - Confirmed by simulations
  - Distorted profile cannot easily be fitted
    - Solution: increase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





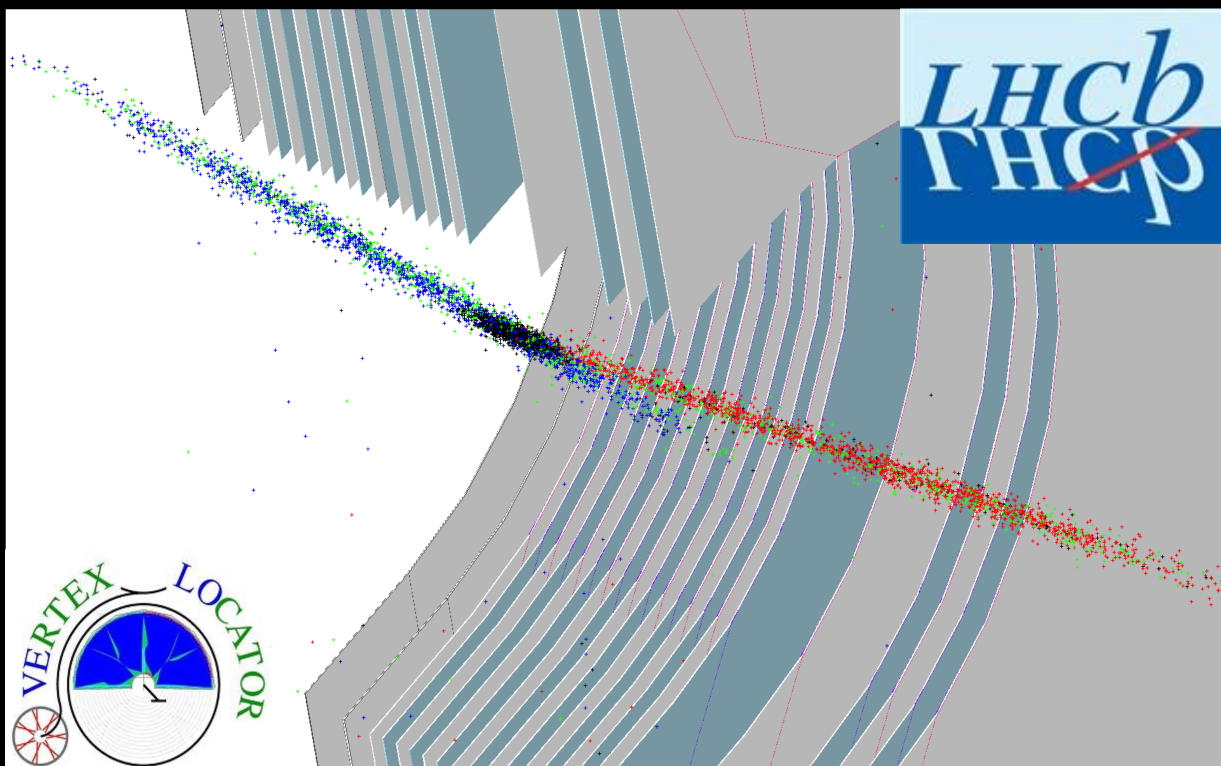
Rest Gas Monitors

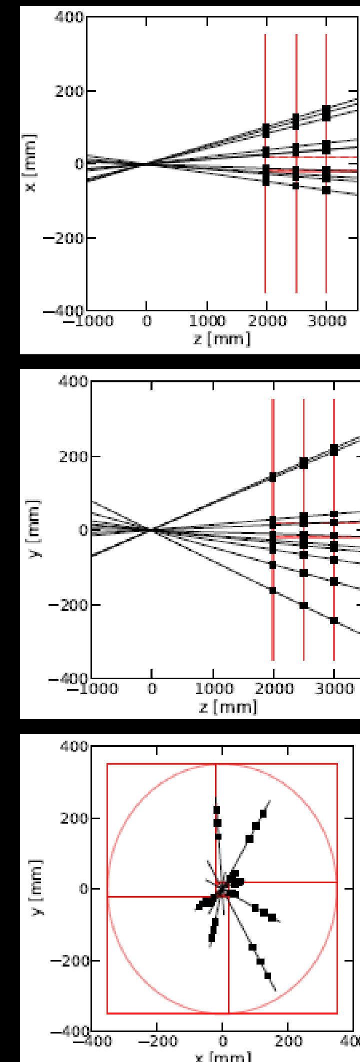
- Beam imaging with vertex reconstruction of beam gas interactions
  - Reconstruct tracks coming from inelastic beam-gas interactions
  - Determine position of the interaction (vertex)
  - Accumulate vertices to measure profile
- Main requirements
  - Sufficient beam-gas rate → controlled pressure bump
  - Good vertex resolution → precise detectors and optimized geometry



Beam Gas Vertex (BGV) Detector

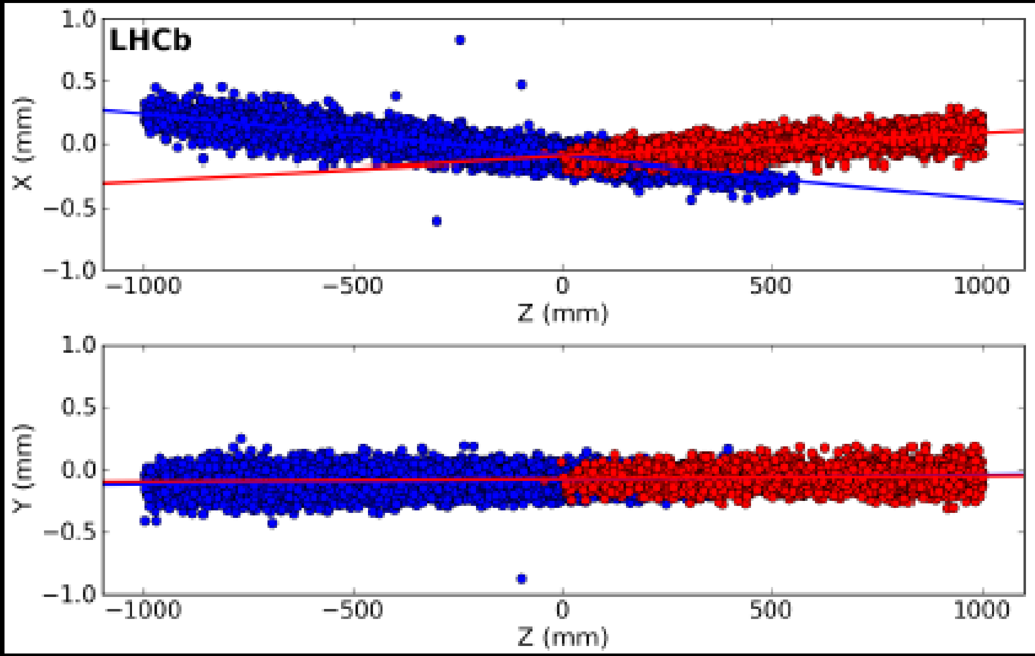
- As small physics experiment to measure beam size!
  - Based on method used by LHCb VELO detection
    - Used mostly for luminosity calibration
  - Needs minimum of 2 or 3 measurement planes

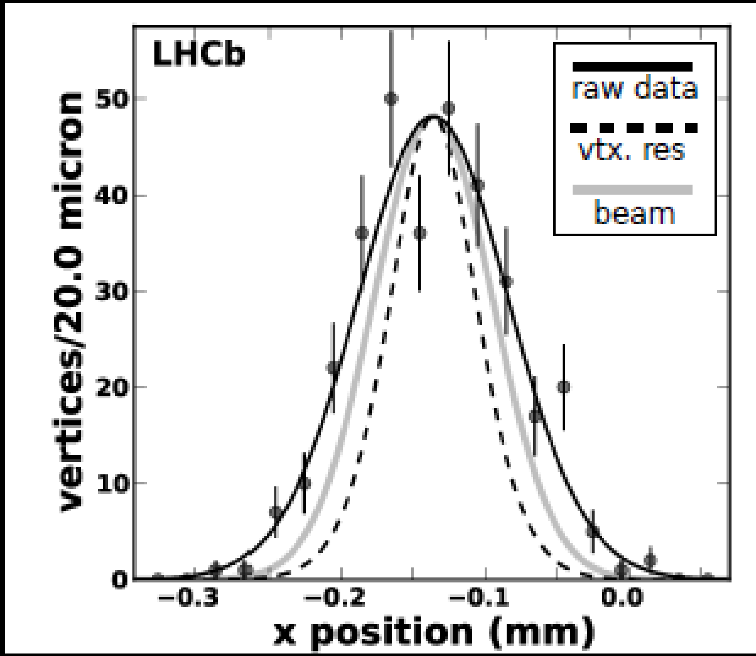




Beam Gas Vertex (BGV) Detector

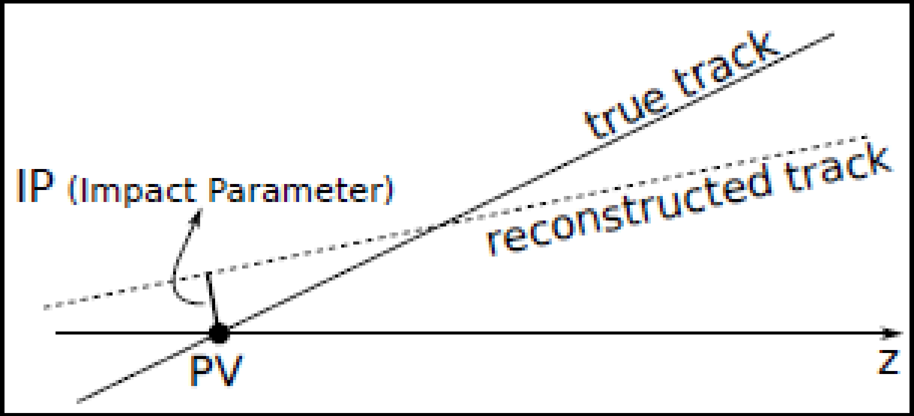
- Measurement Method
  - Reconstruct the tracks from beam-gas interactions
  - Accumulate vertices ⇔ statistical precision
  - Fit to a line ⇒ determine position and angle
  - Project ⇒ determine width

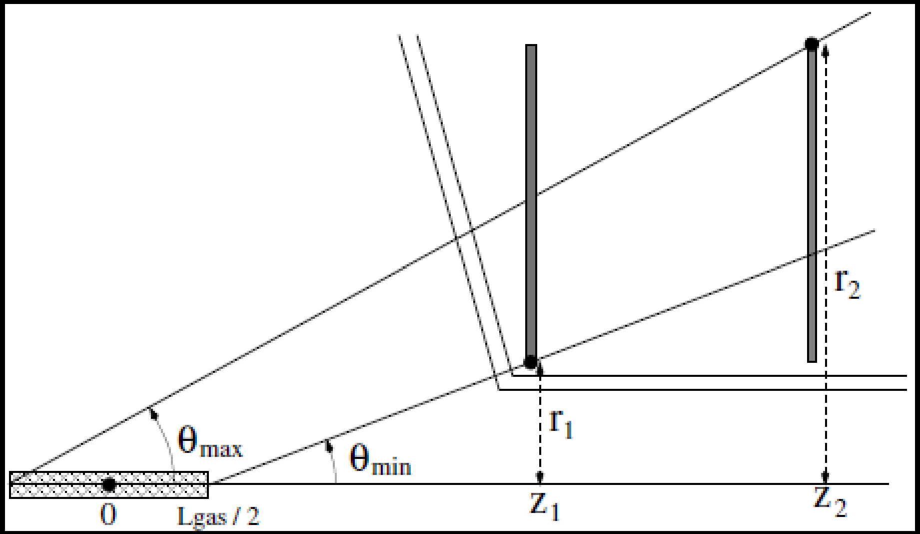




Beam Gas Vertex (BGV) Detector

- Tracking Precision
  - Defined by Impact Parameter (IP)





- Where

σ_{MS} = IP induced by multiple scattering

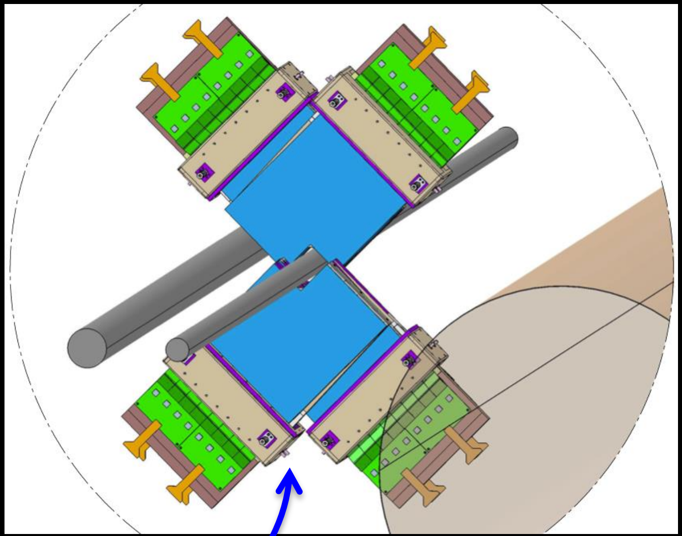
σ_{extrap} = IP induced by detector hit resolution

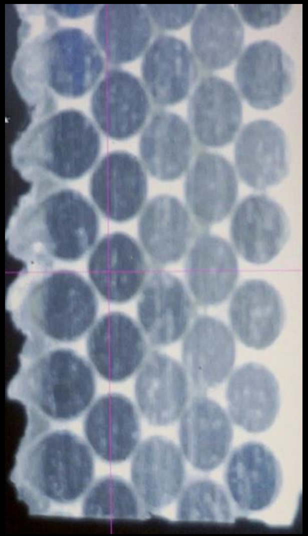
$$\sigma_{\mathrm{MS}} \approx r_1 \frac{13.6\ \mathrm{MeV}}{p_T} \sqrt{\frac{x}{X_0}}$$

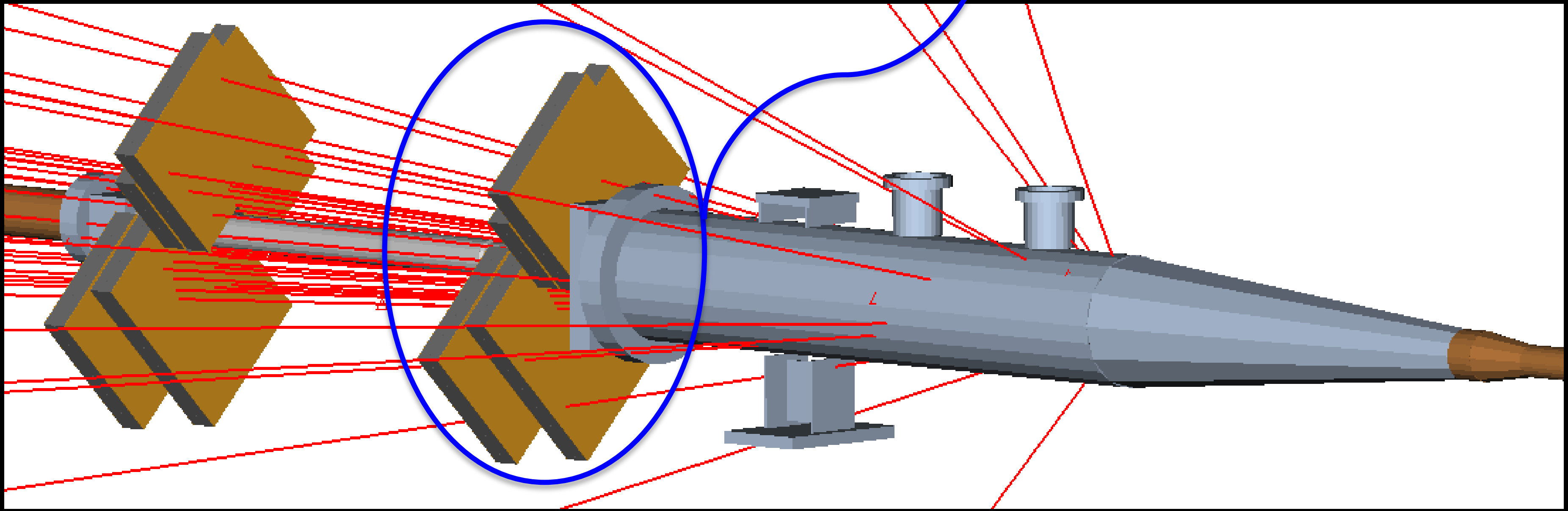
$$\sigma_{\mathrm{extrap}} \approx \sqrt{\frac{z_1^2 + z_2^2}{(z_2 - z_1)^2}} \cdot \sigma_{\mathrm{hit}}$$

Beam Gas Vertex (BGV) Detector

- Design of Prototype
  - 8 Scintillating fibre modules in 2 tracking stations
  - Each module has 2 mattresses of SciFi
  - 250 μm fibres with $\sigma_{hit} \approx 60$ μm
- Synergy with LHCb fibre tracker upgrade

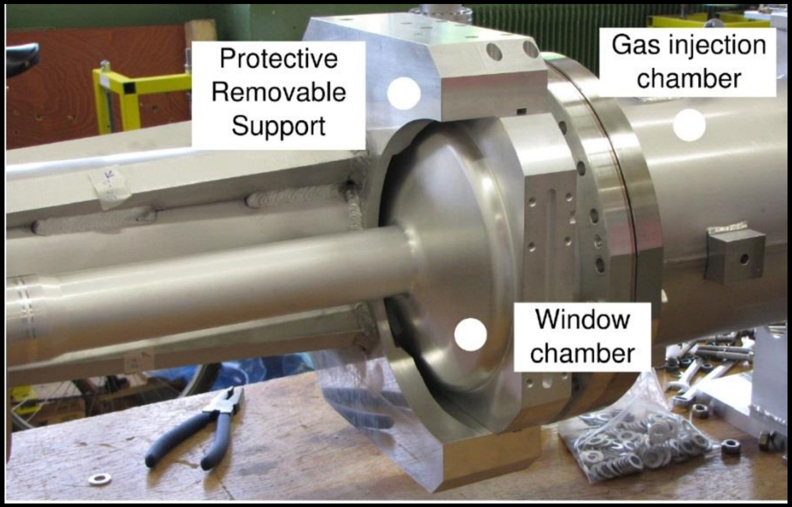






Beam Gas Vertex (BGV) Detector

- Status
  - BGV demonstrator installed in LHC on Beam 2 during LS1
  - Beam pipe components, gas injection system & detector infrastructure in place
  - Detectors and electronics to be installed in 2015
  - First tests foreseen for 2016
- Aim for demonstrator
  - Bunch-by-bunch profile measurements with a resolution of 5 % within 5 minutes
  - Absolute average beam width measurement to 10 % within 1 minute



Summary

- Several systems installed in LHC to measure beam profile
  - None are yet capable of providing what is ultimately required
    - Fast, non-invasive, bunch by bunch, absolute beam size measurements throughout the LHC acceleration cycle
    - One of the big challenges for all high brightness hadron machines
- Each developed to compliment the others
  - Screens: seeing is believing!
  - WireScanners: the reference for absolute measurement
    - Cannot withstand full beam power
  - Synchrotron light monitor: fast, non invasive
    - requires significant corrections at 7TeV
  - Beam gas ionisation monitor: non invasive
    - Can only be used for ions
  - Beam gas vertex detector: non invasive, absolute measurement
    - Requires significant integration times

- Tomorrow - how beam loss & tune are measured in the LHC

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