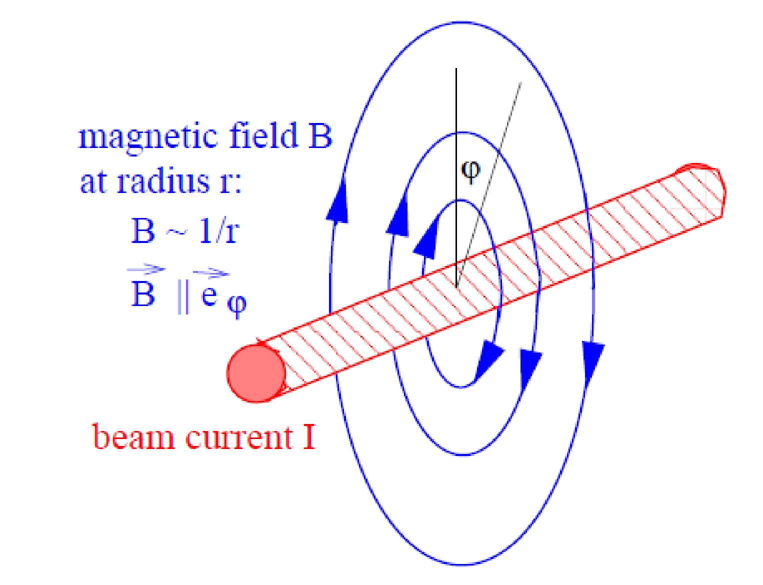
Beam Position Systems

Beam Intensity Monitors

Beam Profile Monitors

Beam Loss Monitors

Beam Intensity measurement



Moving charges = BEAM CURRENT

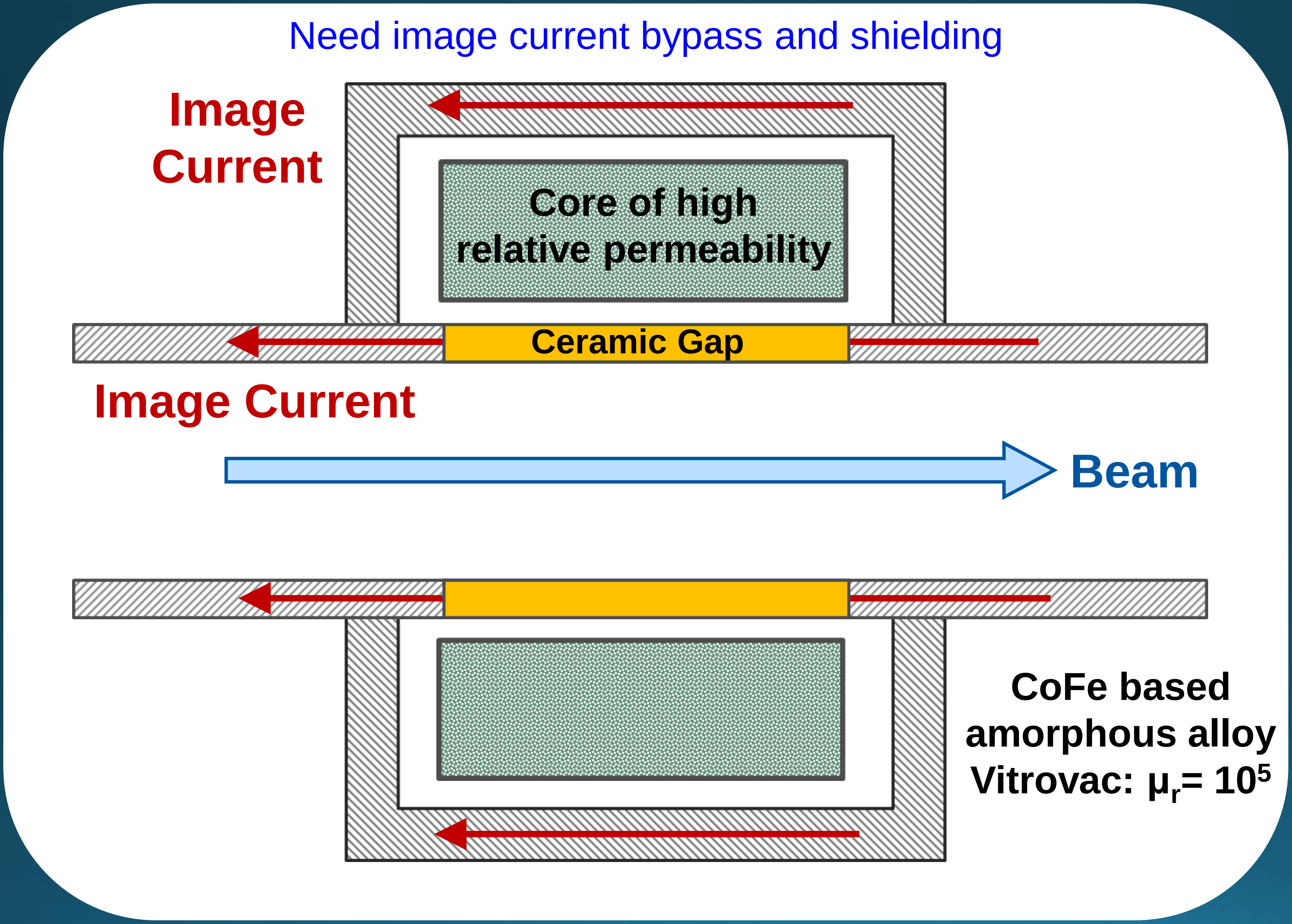
$$I_{beam} = \frac{dq}{dt} = \frac{q \cdot N}{t} = \frac{q \cdot N}{l} \cdot v$$

AZIMUTHAL B-FIELD COMPONENT

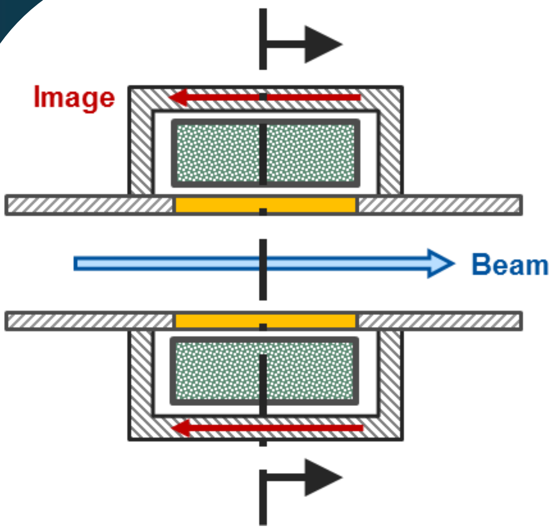
$$\boldsymbol{B} = \mu_0 \frac{I_{beam}}{2\pi r} \cdot \boldsymbol{e_\varphi}$$

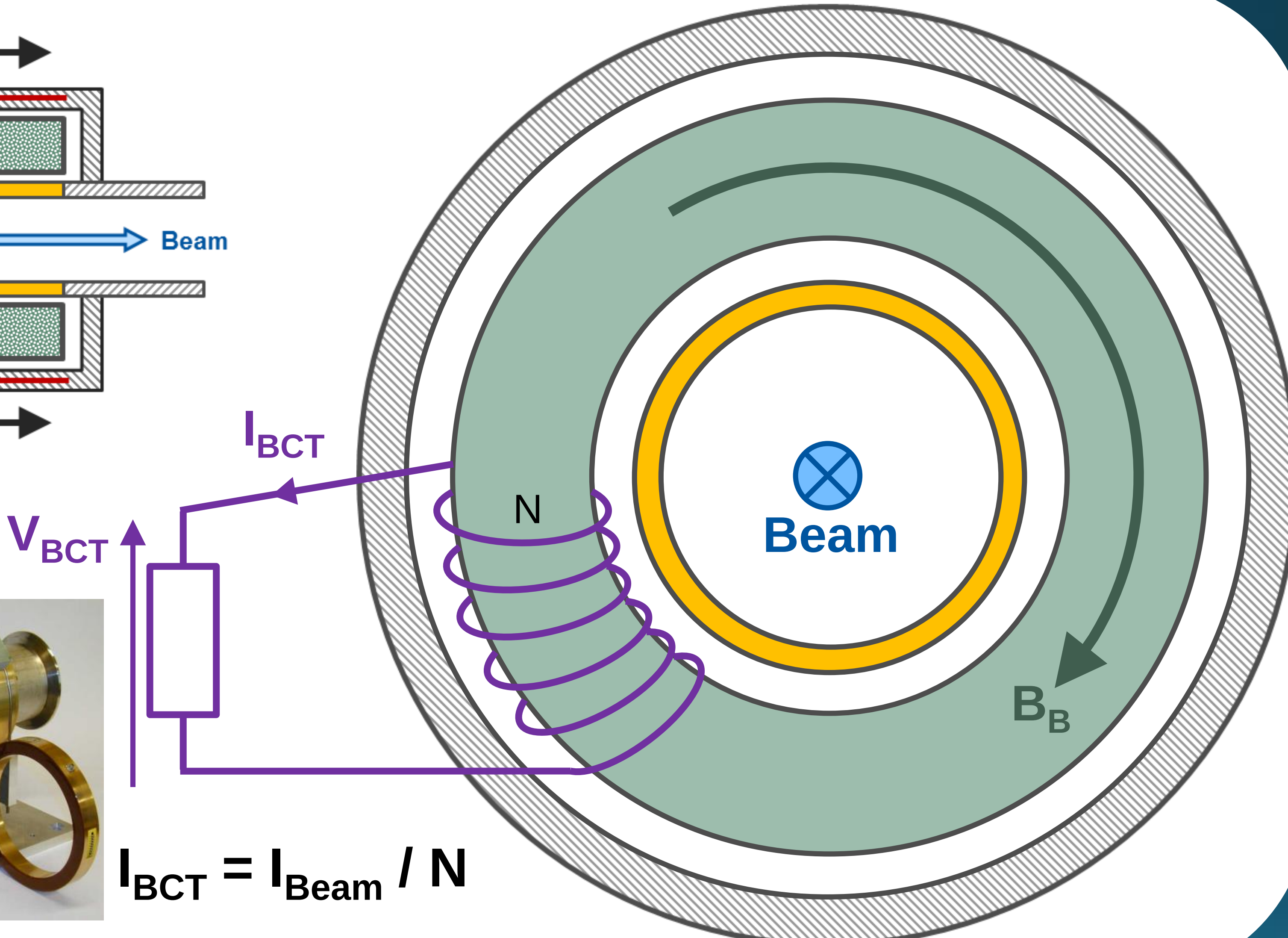
- Fields are very low ($I=1\mu A$; $r=10cm$ → $B=2pT$)
  Earth magnetic field ~ $30\mu T$
- Using a torus of very high relative permeability ($\mu_R=10^5$) allow to measure azimuthal component and have little position dependency

Fast Current Transformers



Fast Current Transformers

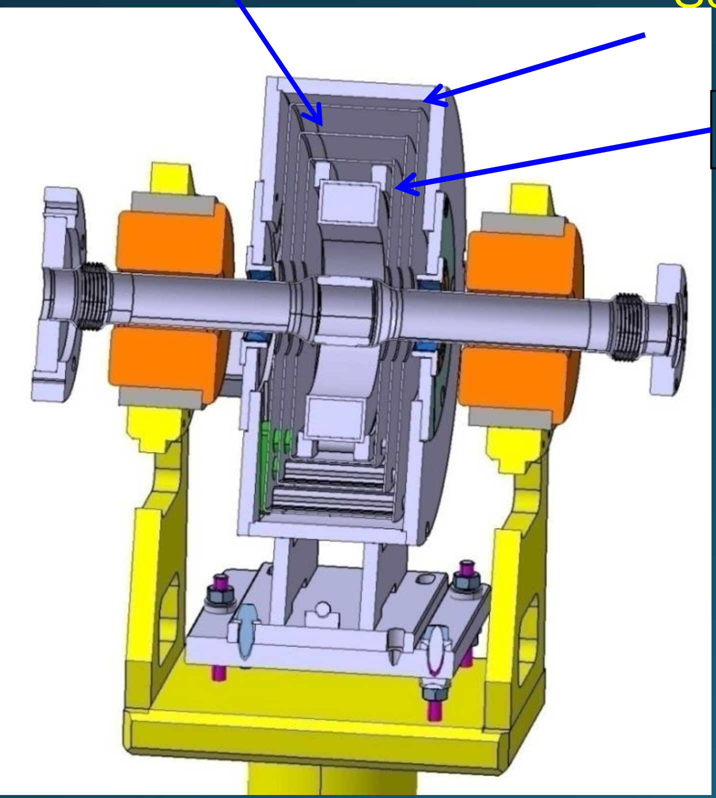


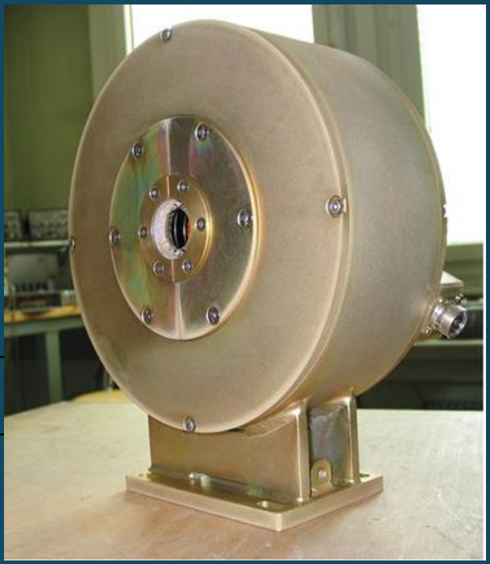


$$I_{BCT} = I_{Beam} / N$$

Magnetic shielding

Several layers of magnetic shielding

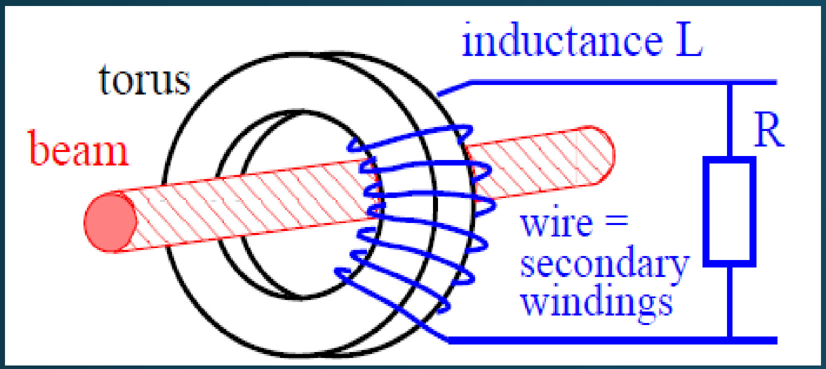




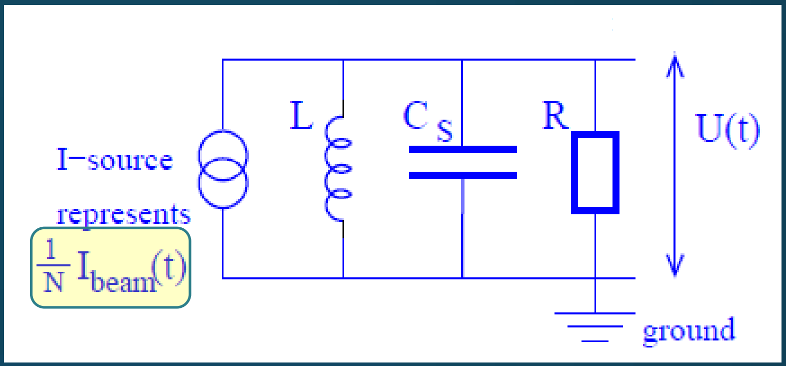
- Outer shielding thick and has lower mu in order to avoid saturation
- Tight design to avoid magnetic interference from e.g. magnets
- Shield should have highest μ possible but should not saturate

Fast Current Transformer

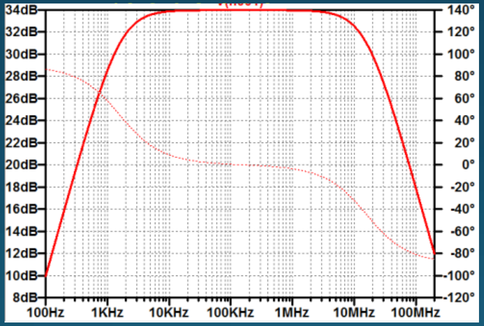
Actual configuration



Simplified equivalent circuit



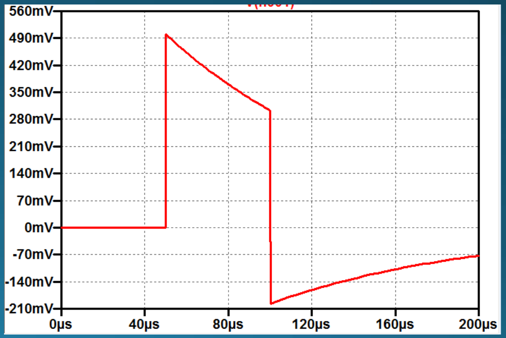
Frequency



Transformer Inductance

$$L = \frac{\mu_0 \mu_r}{2\pi} \cdot l N^2 \cdot \ln \frac{r_o}{r_i}$$

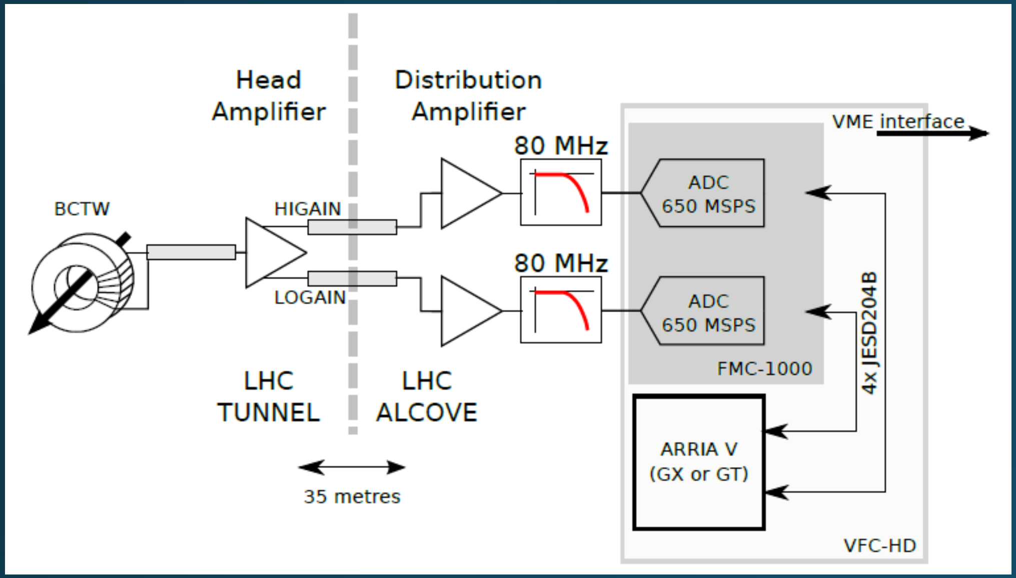
Square pulse

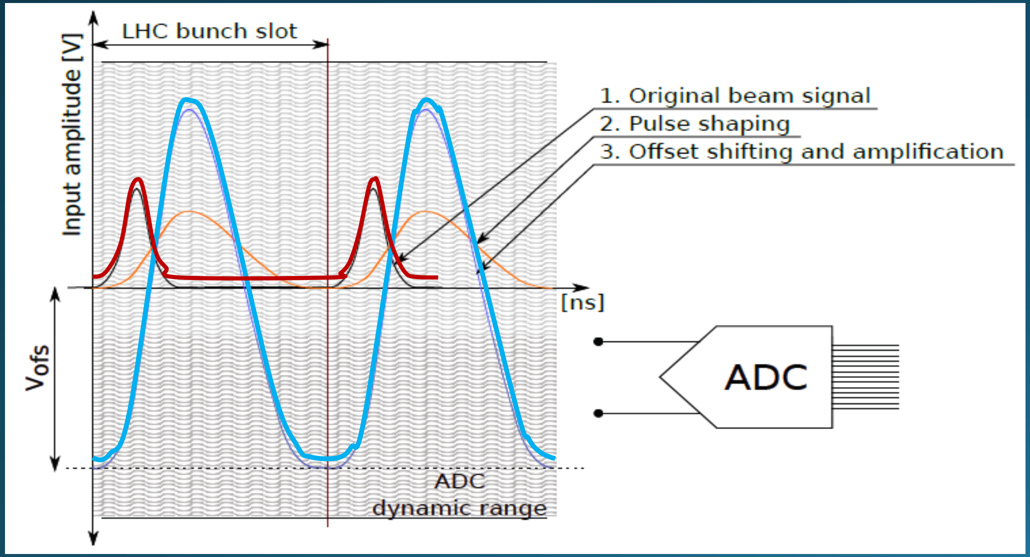


- Beam is primary winding with = 1 turn
- N= number of turns on secondary
- Current ratio is 1/N
- C_s is the stray capacitance. Limits high frequency
- τ_{DROOP}= L / R

FBCT Digital Acquisition system

Block diagram





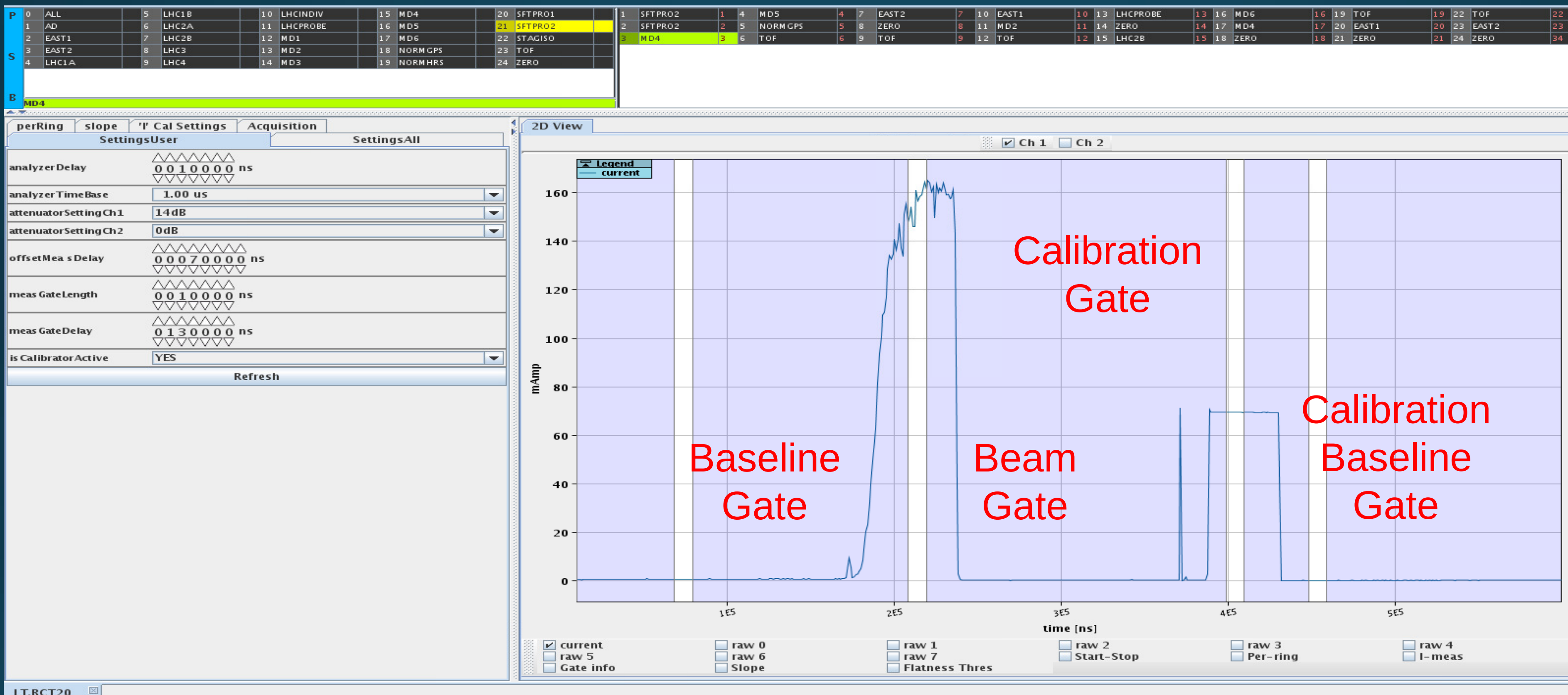
ADC

- Sampling rate >500Msps
- ENOB 10bit
- 80MHz low pass filter with both antialiasing and pulse stretching fuctions

DSP

- Integration of pulses done by summation of samples.
- Bunch shape independant
- Scaling factor gives number of charges per bunch
- Offset shif to better use the ADC dynamic range

Calibration and acquisition of fast BCTs

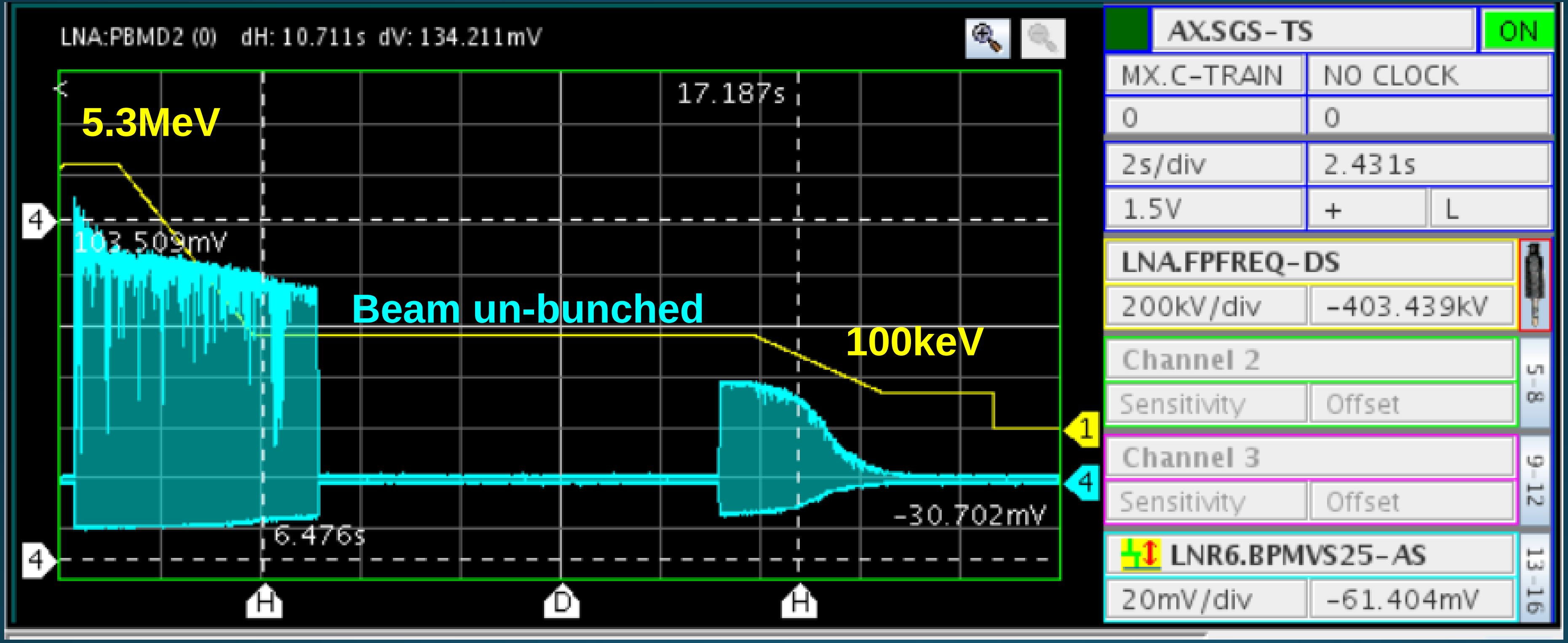


- The transformer is calibrated with a very precise current source
- The calibration signal is injected into a separate 1 turn calibration winding

Diagnostics using Beam Intensity Monitors:

Provide the general visual diagnostics
for most accelerators

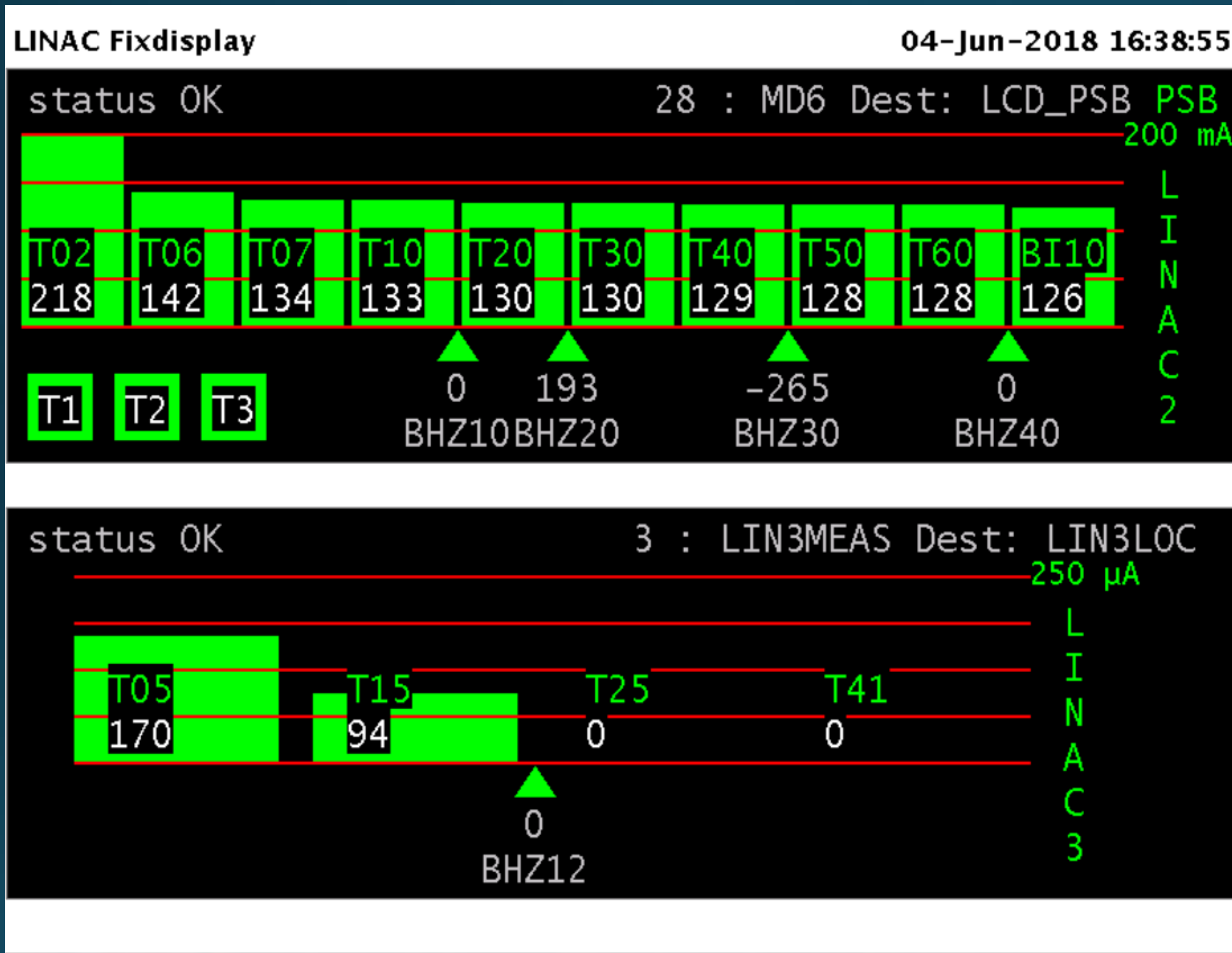
ELENA Fast BCT



Blue trace: Intensity

Yellow trace: Magnetic field

L2 and L3 Fast BCTs

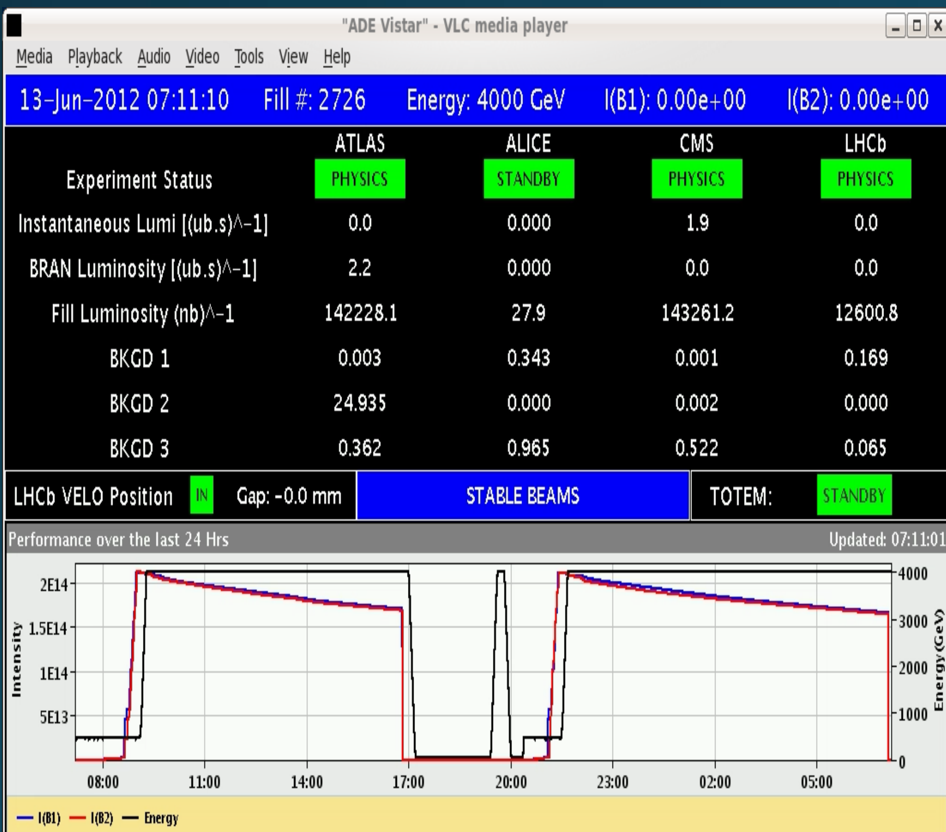


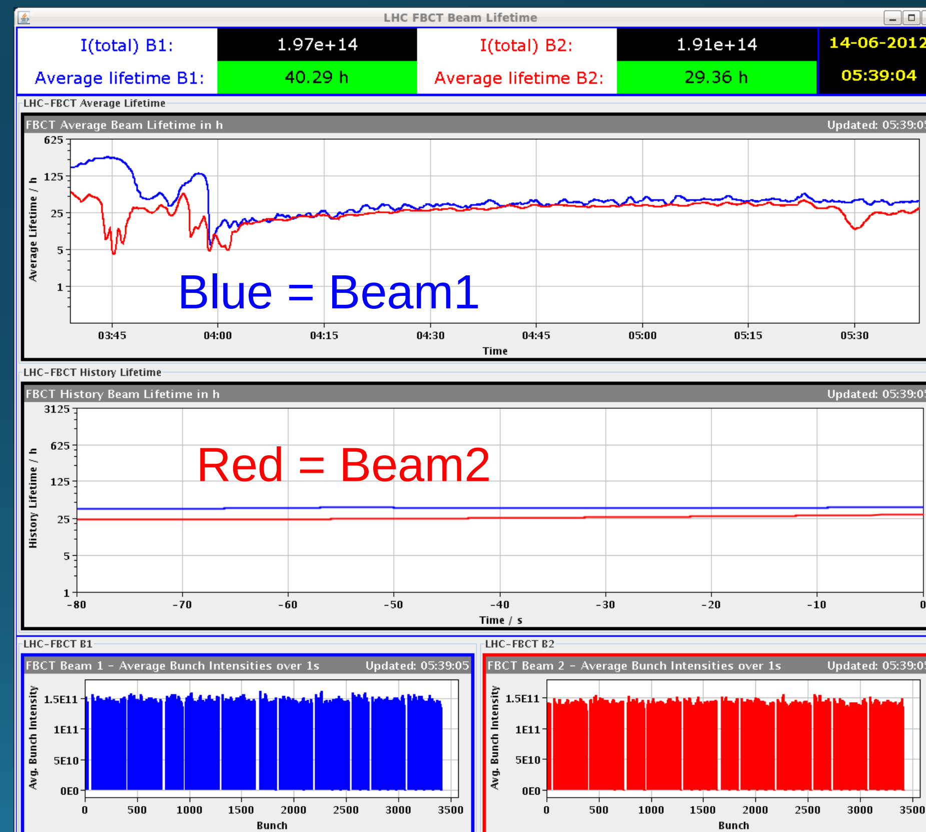
Pulse length 100us

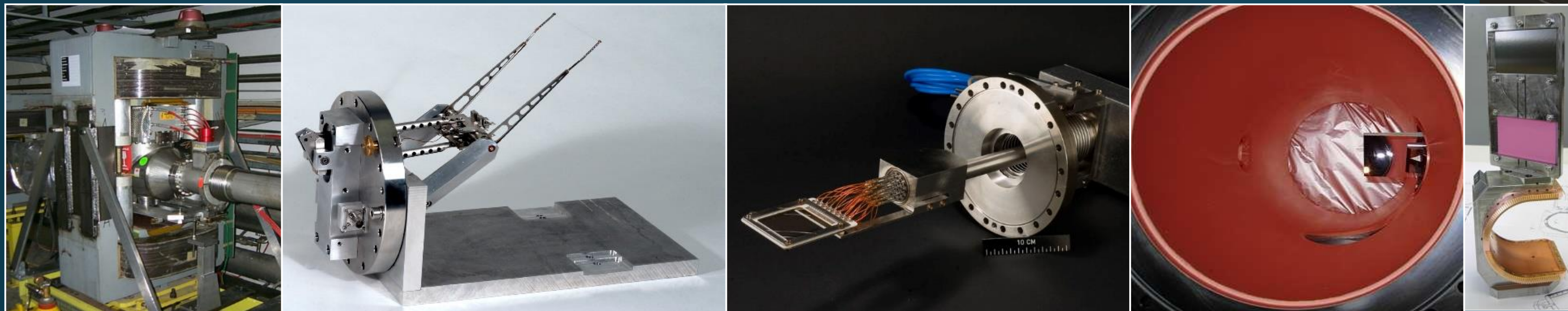
L3 ion current factor 1000 lover than L2

LHC Fast BCTs

- LHC Operation Pages
  - Bunch intensity of every bunch spaced by 25ns (σ=0.25ns)
  - Total intensity measurement, adding intensity of up to 2808 bunches
  - Lifetime calculation







Beam Position Systems

Beam Intensity Monitors

Beam Profile Monitors

Beam Loss Monitors

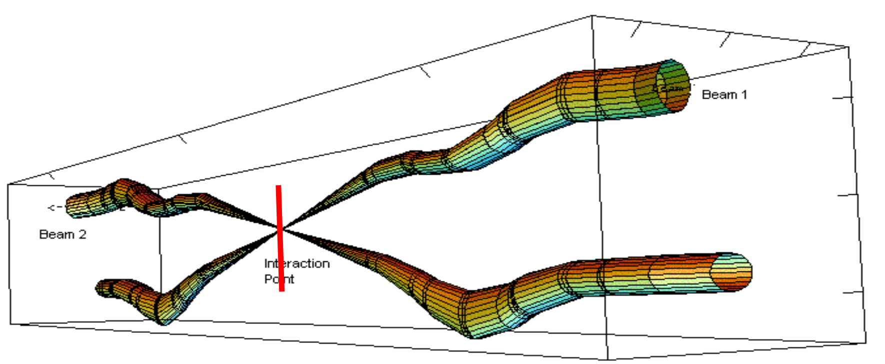
Why Measure the Beam Profile?

- All accelerators
  - The **transverse emittance** tells if a beam fits in the vacuum chamber or not
- For LHC experiments
  - The more closely packed the particles the higher the luminosity.
  - We aim to squeeze the **beam size** down as much as possible at the collision point to increase the chances of a collision

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

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

emittance, beta function

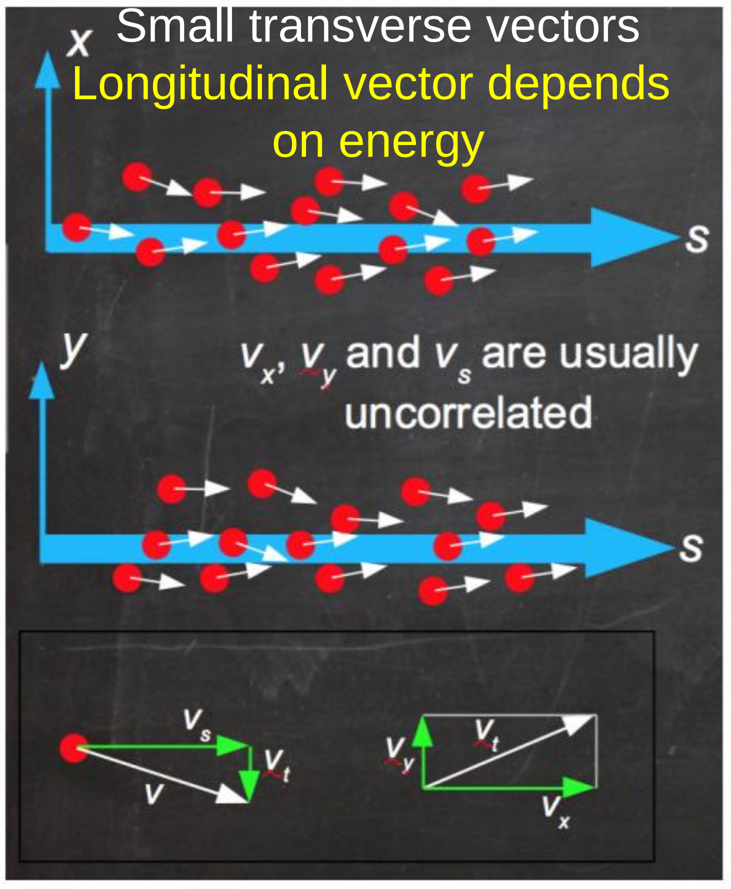


Relative beam sizes around IP1 (Atlas) in collision

– Cannot directly measure the beam size at the experimental interaction points

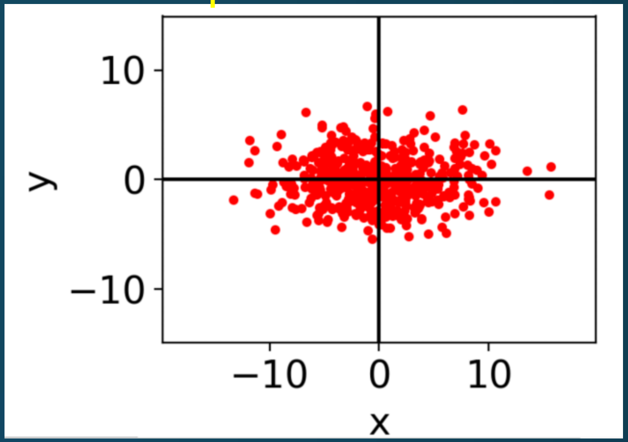
– Need to measure the beam size at another location to calculate the **emittance to "transport" the beam to the collision point**

Emittance what is it?



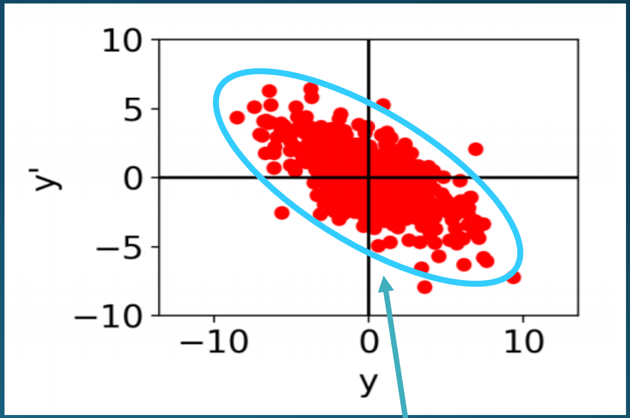
This we can easily measure

Real space distribution



This is what the accelerator physicist needs

Transverse phase space



- Emittance – the spatial and angular spread of particles = Area of ellipse (mRad)
- Understanding emittance growth essential to optimise performance but is mainly determined by emittance in the first accelerator: Linac

How to measure the Beam emittance?

- In a Synchrotron the lattice functions are "fixed"
- Beam width and emittance are related
- The β function and the Dispersion function D are known or measured with other means. Often measured where D is zero.

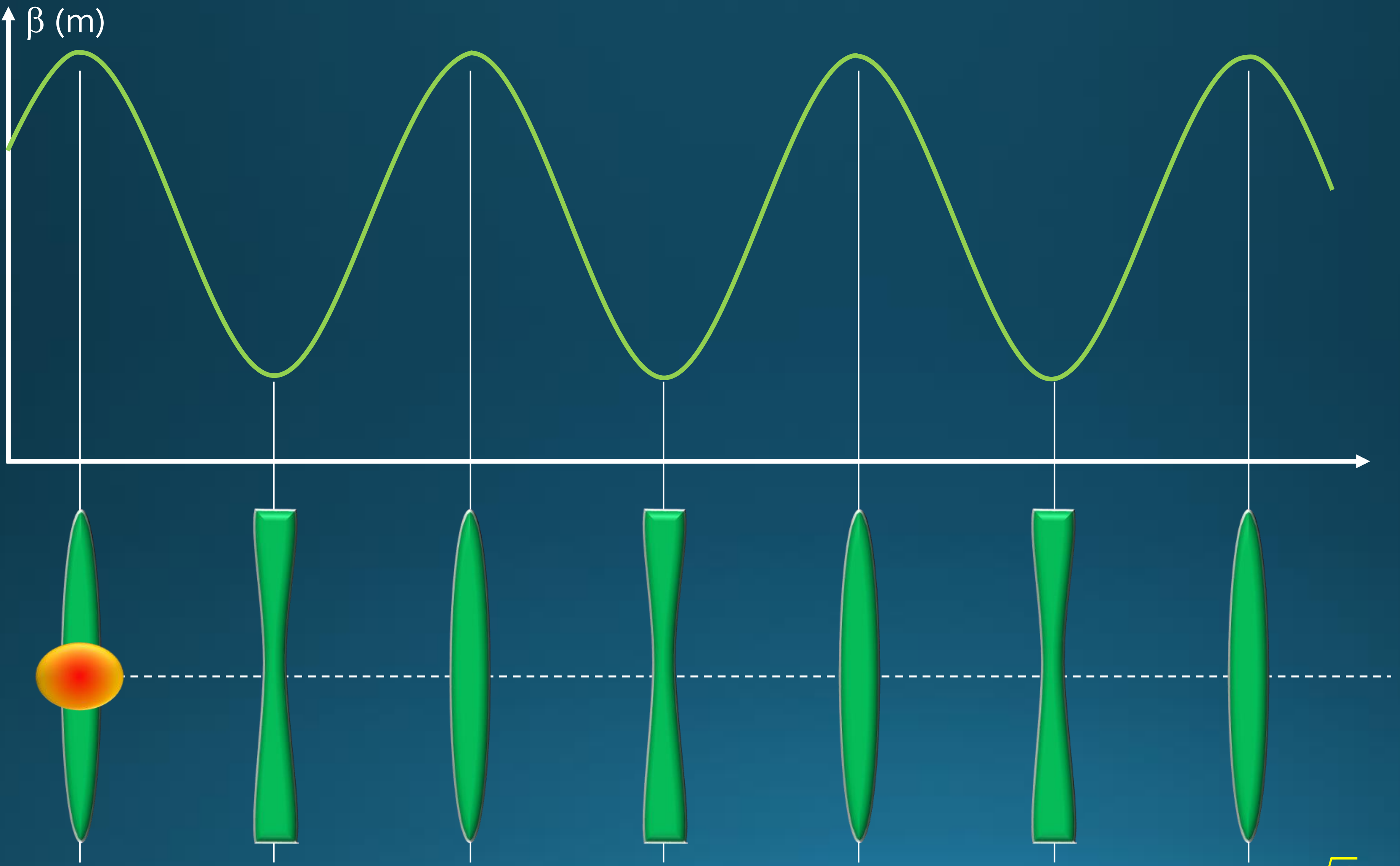
$$\varepsilon_{n_{x,y}} = \frac{\gamma\beta}{\beta_{x,y}}\left[{\sigma_{x,y}}^2 - \left[D_{x,y} \cdot \left(\frac{\Delta p}{p}\right)\right]^2\right]$$

measured

□ Machine Parameter: Beta Function, Dispersion Function

○ Beam Parameter: Relativistic factor, Momentum spread

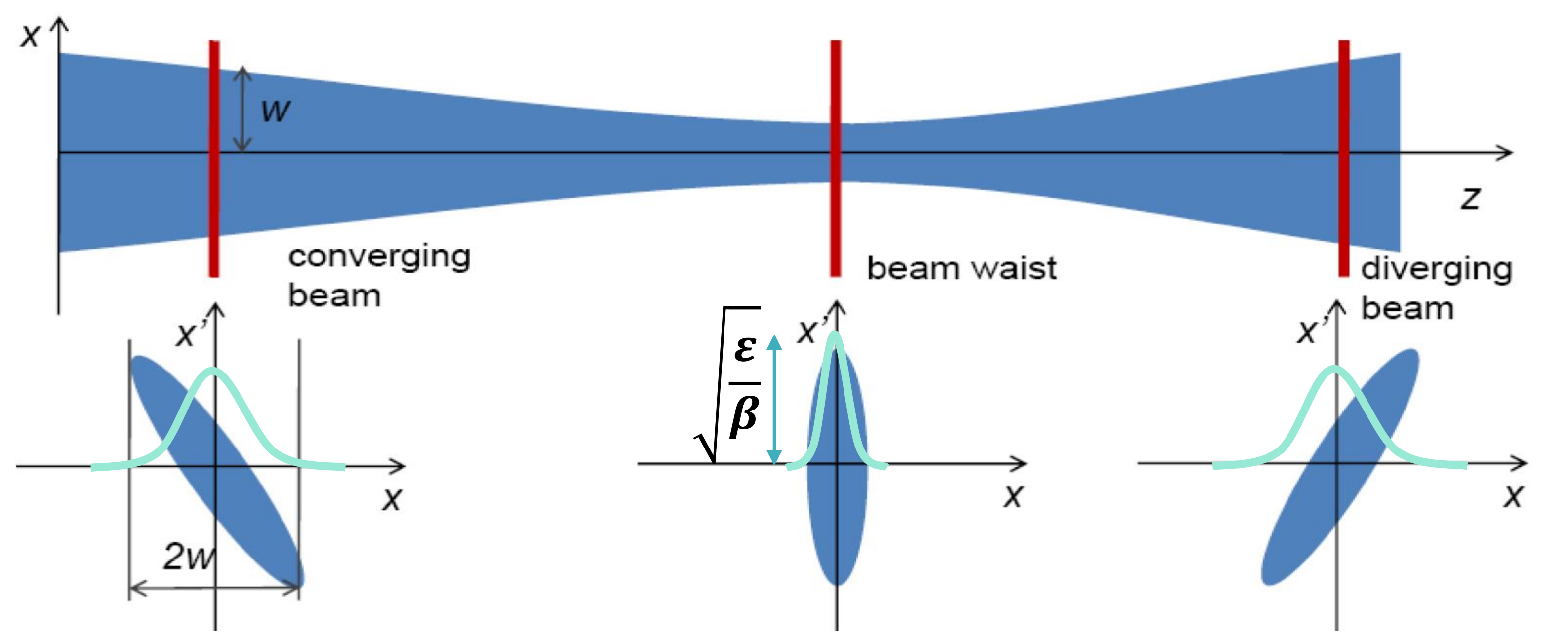
The Machine β-Function



$Beam\ Size \propto \sqrt{\beta}$

Variation of the ellipse along the transport line

- Emittance measurement
  - Calculated from beam profile at 3 screens (or by changing the magnet current)
    - 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

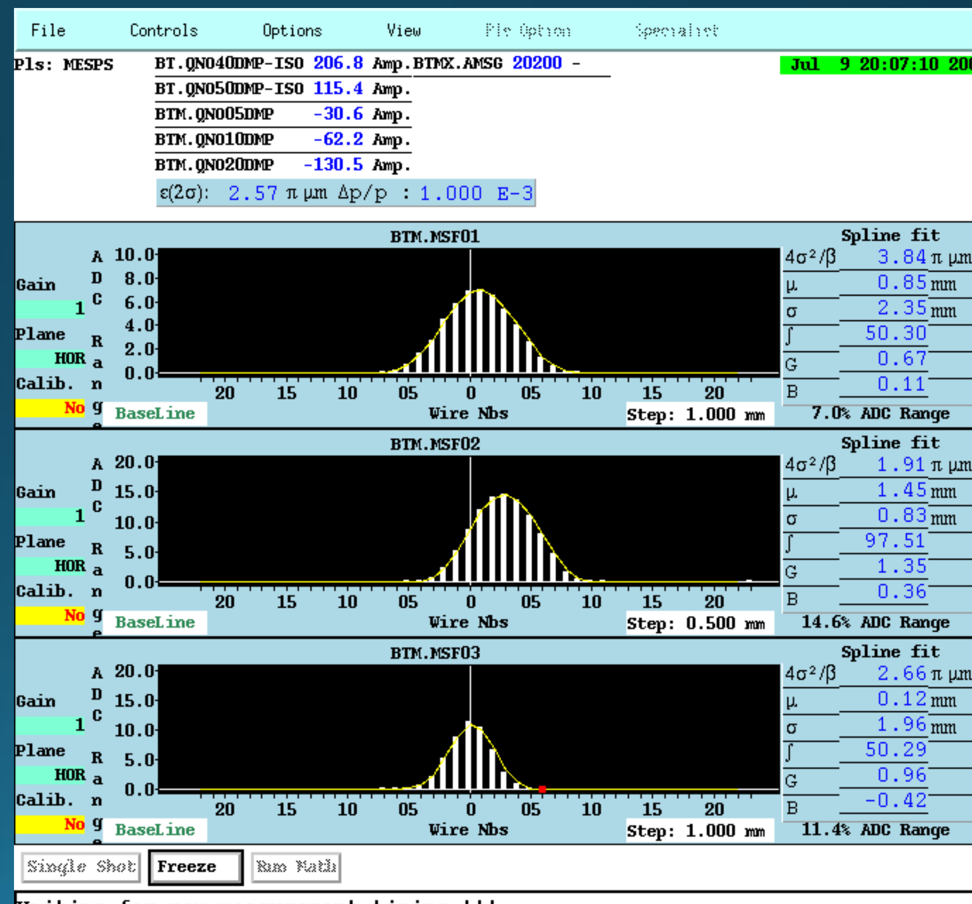


Along a beamline the orientation and aspect ratio of beam ellipse in x, x' plane varies, but area $\pi\varepsilon$ remains constant

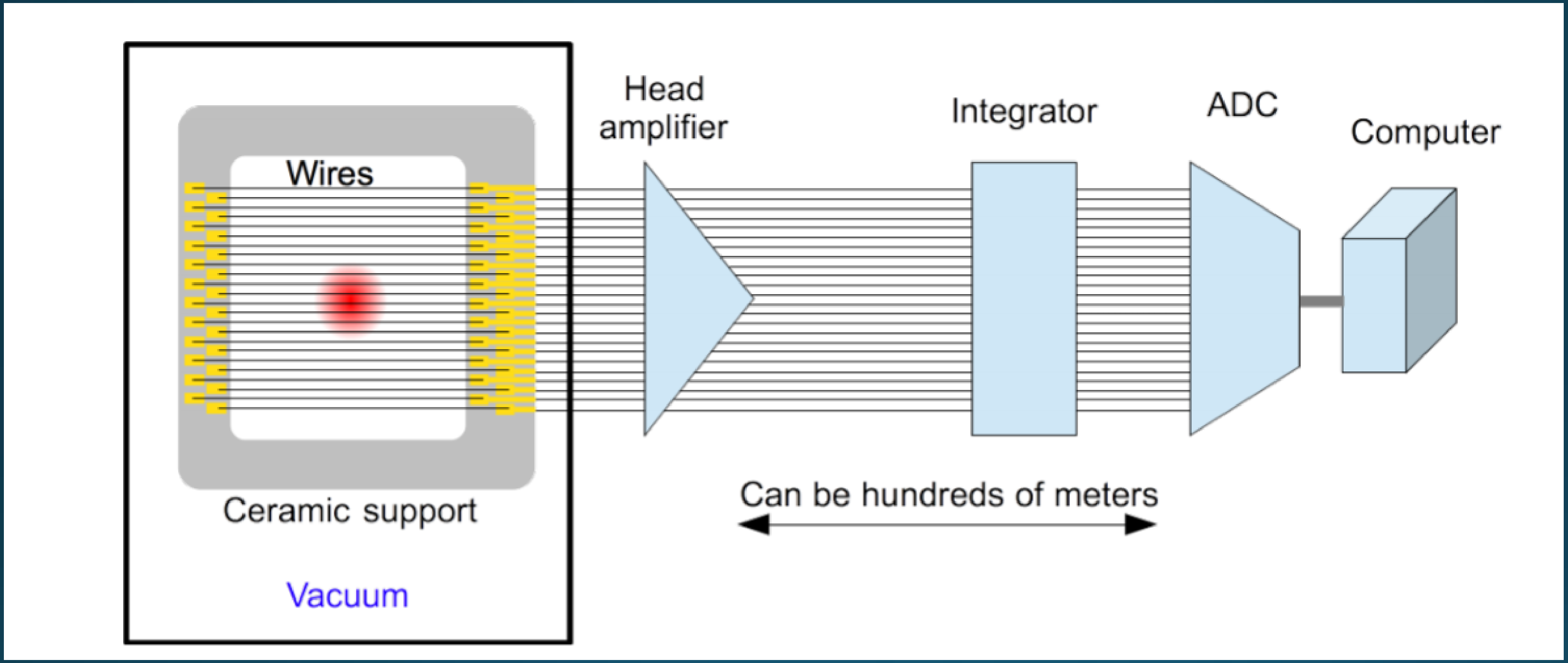
Beam width along z is described with $w(z) = \sqrt{\beta(z)\,\varepsilon}$

Profile Monitoring using Wires

- Secondary Emission Monitors (SEM or HARP)
  - Beam profile from secondary electrons emitted from wire grid on beam impact
  - Current in wire proportional to particle density
  - Require many electronic channels for readout

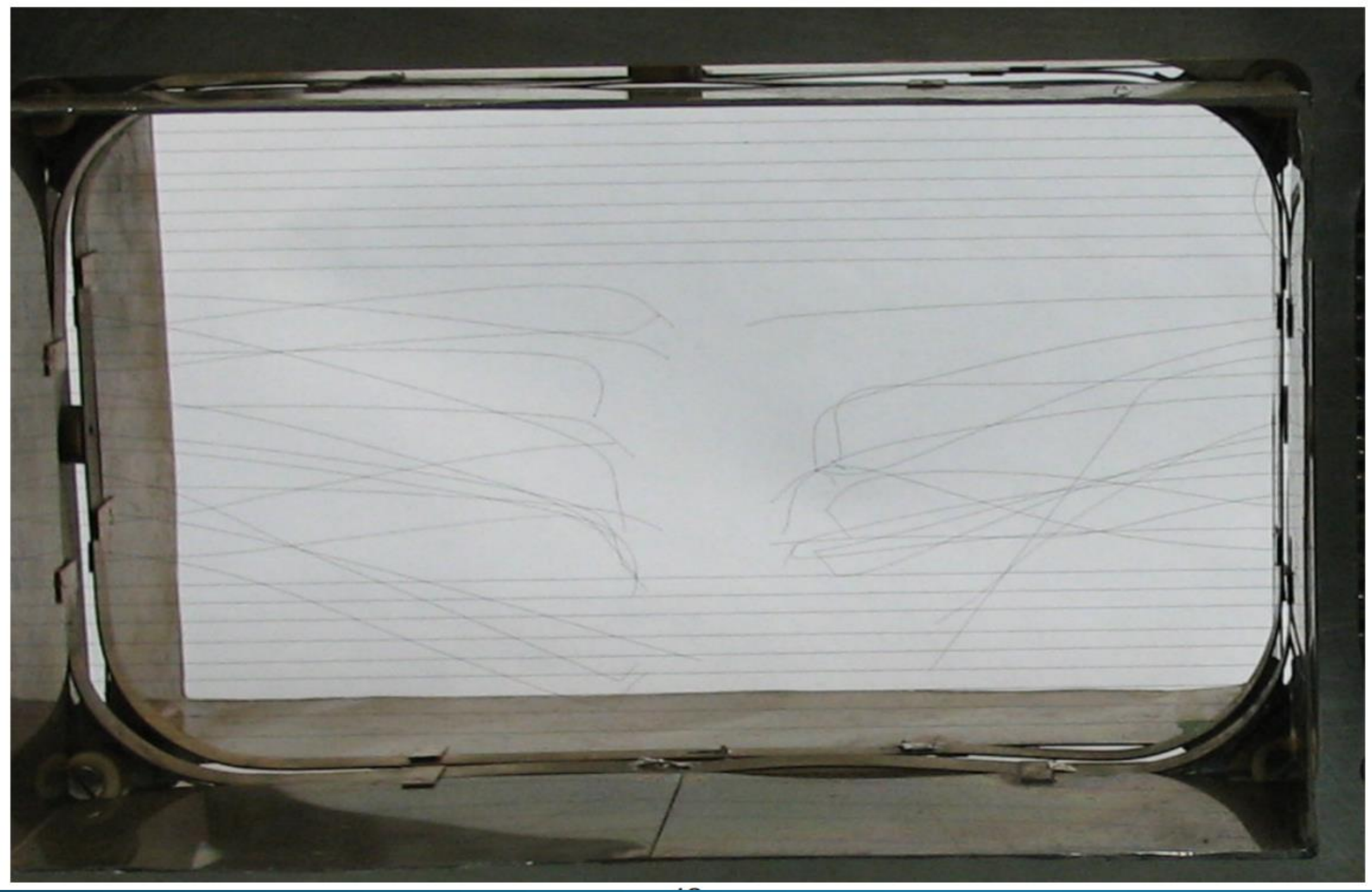


SEM grid acquisition system



- The SE current from each wire or strip is acquired independently
- Complex cabling and electronics
- Wire spacing down to a few hundred microns

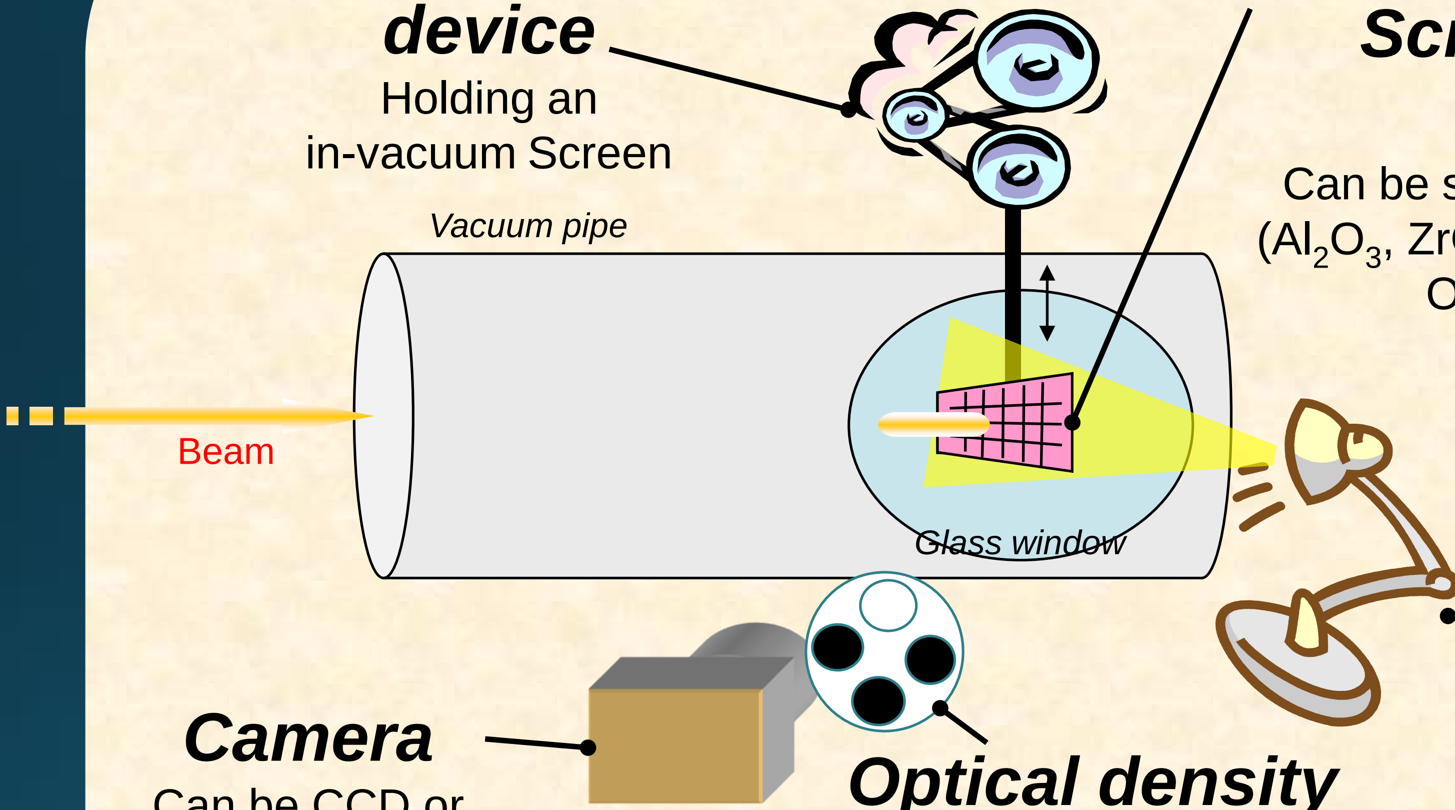
SEM- Grid



Profile Monitoring using Screens

Insertion device
Holding an in-vacuum Screen

Radiator / Screen
Can be scintillating (Al_2O_3, ZrO_2 etc…) or OTR



Camera
Can be CCD or special Rad hard (CMOS, CID, Vidicon tube)

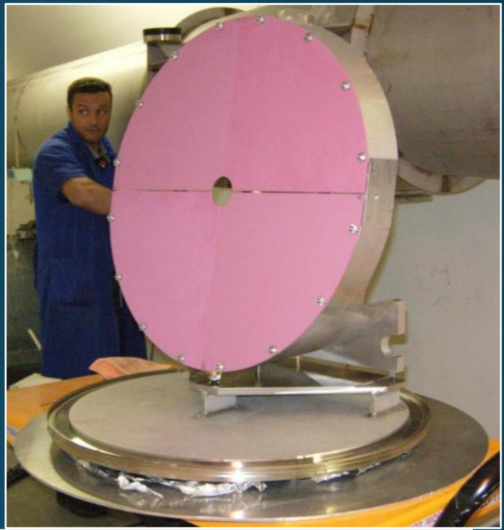
Optical density filters
Increase the dynamics of the system

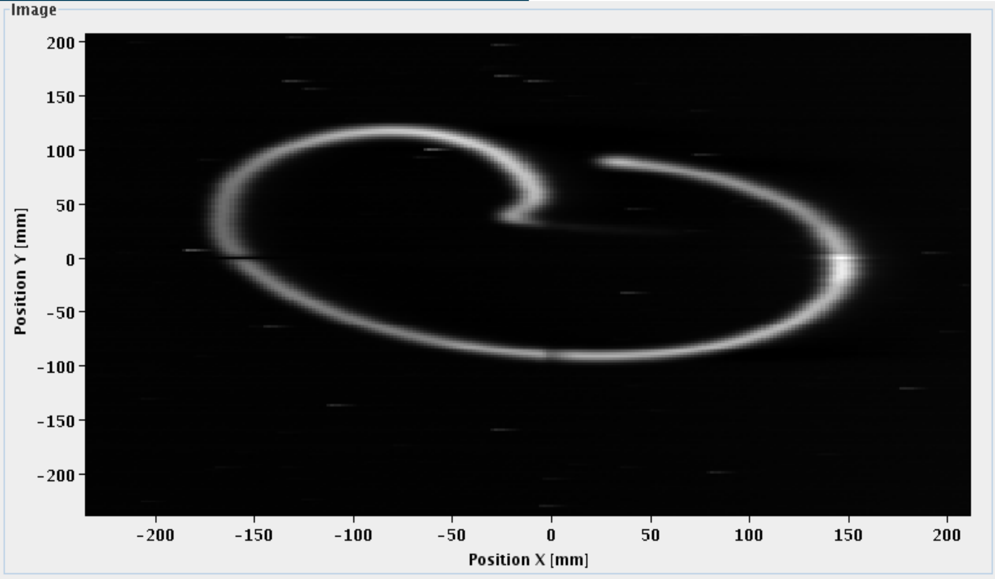
Lights
Mainly used for system calibration and beam steering

Profile Monitoring using Screens

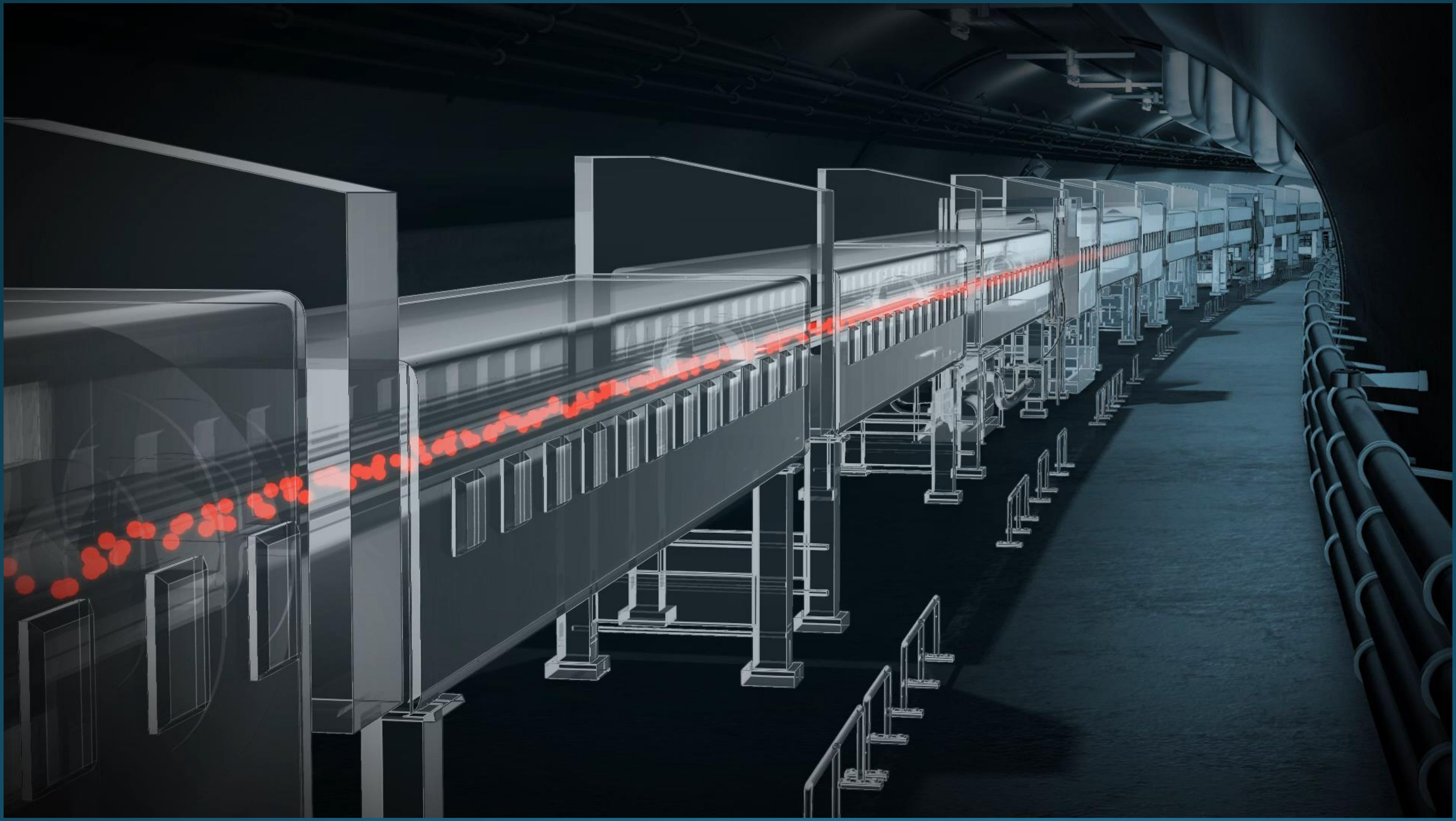
- Early Diagnostics
  - Luminescence / Scintillating Screens
  - Destructive (thick) but work with low intensities
- Advantages
  - Allows use of CCD camera
  - Gives 2D information
- Photons are emitted by the de-excitation of atomic states populated by the passage of the particle
- Ceramics, glasses and crystals are common choices in high energy accelerators :
  - Chromox: $Al_2O_3:CrO_2$
  - YAG: $Y_3Al_5O_{12}$

LHC dump screen



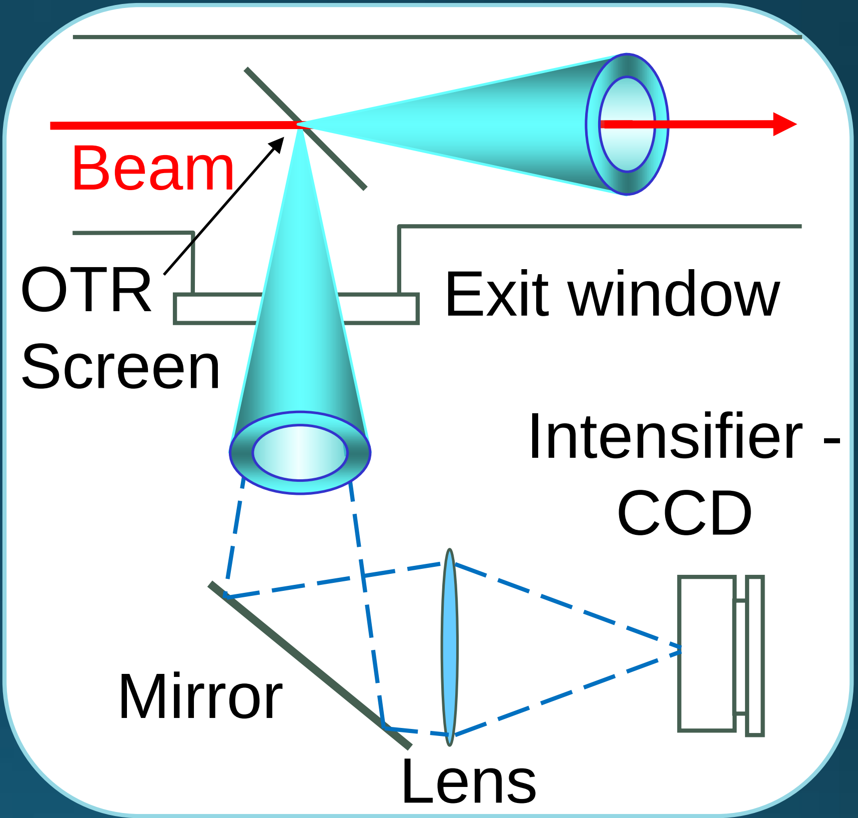


Video showing scintillating screen

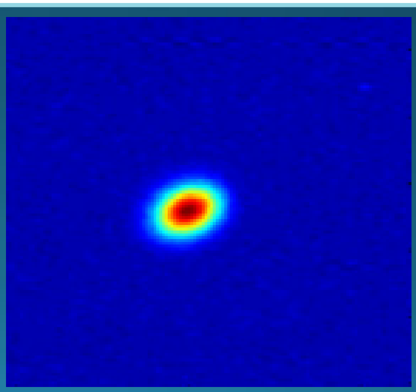


Profile Monitoring using Screens

- Optical Transition Radiation
  - Radiation emitted when a charged particle goes through an interface with different dielectric constants
  - Surface phenomenon allows use of very thin screens (~10μm)
    - Can use multiple screens with single pass in transfer lines
    - Can leave it in for hundreds of turns e.g. for injection matching

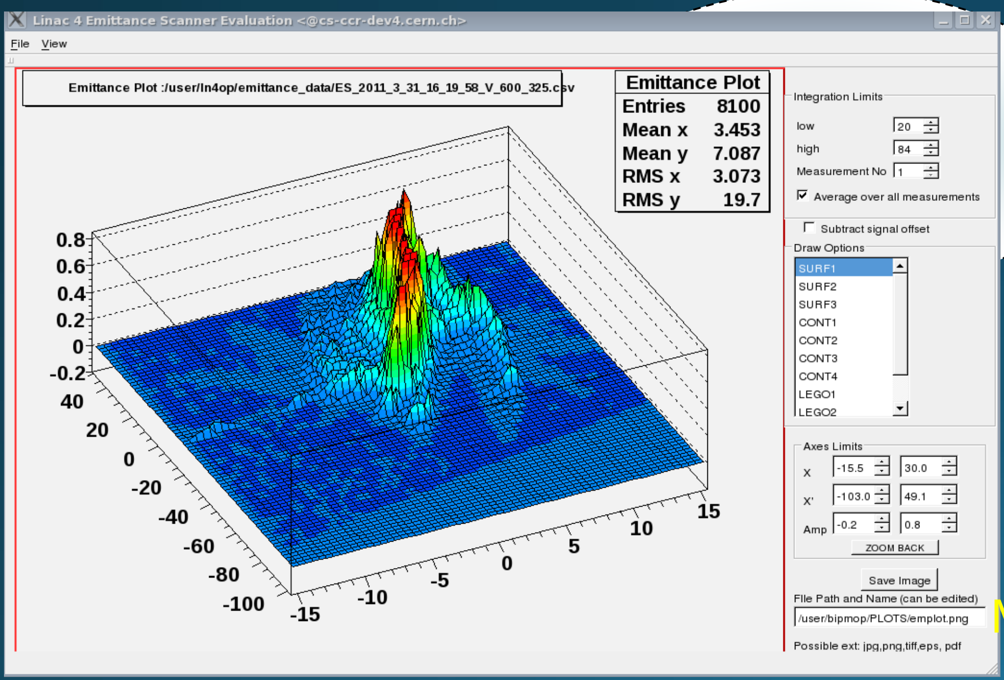


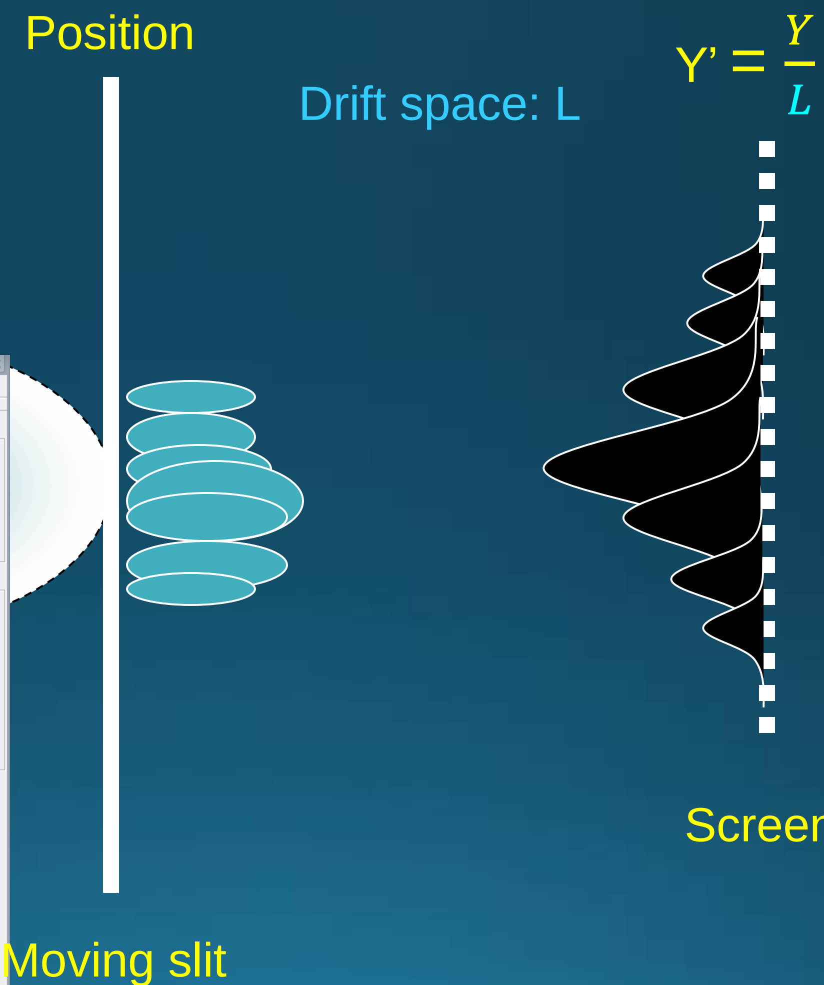
- OTR screens
  - Less destructive than scintillation but requires higher energy / intensity beam
  - Can be used for extremely high resolution measurements



The Slit Method for direct emittance measurement

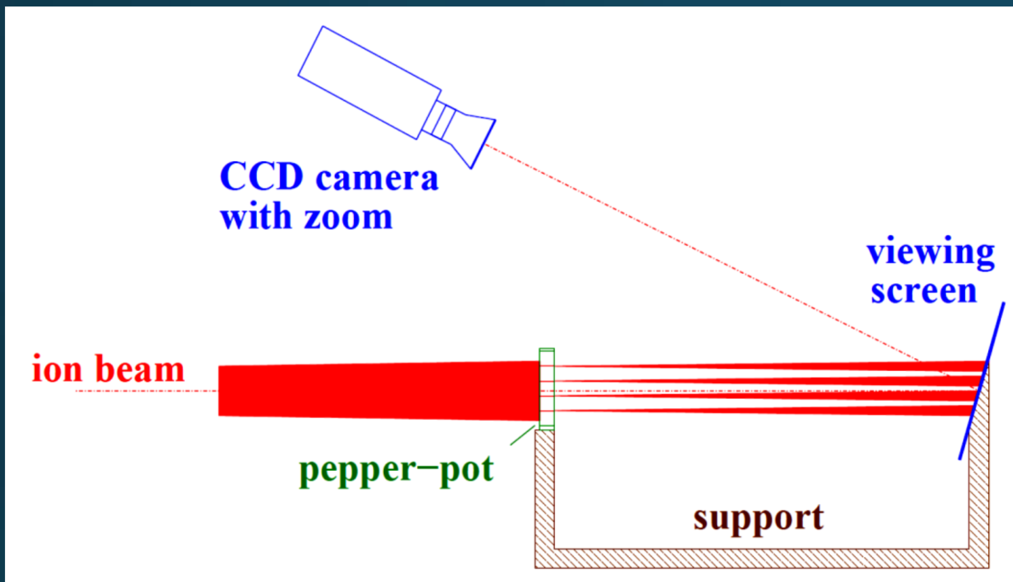
- If we place a slit into the beam we cut out a small vertical slice of phase space
- Converting the angles into position through a drift space allows to reconstruct the angular distribution at the position defined by the slit

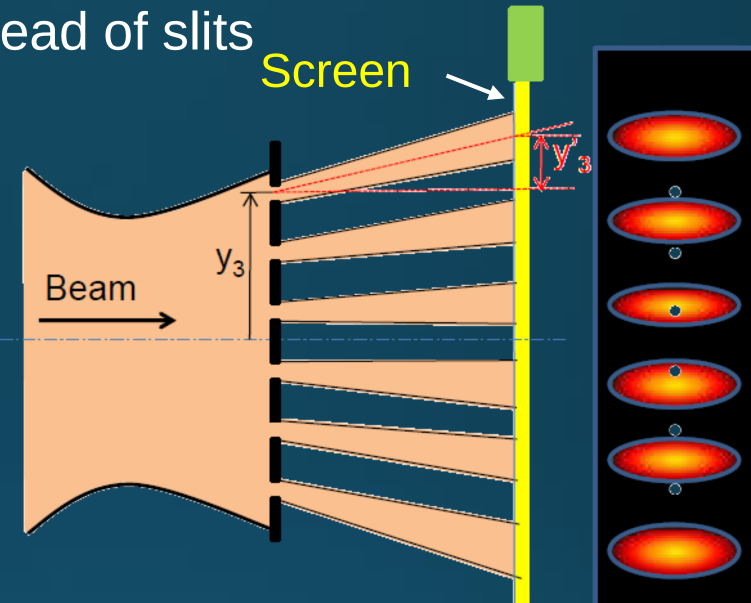




The Pepper pot emittance device

For pulsed LINACs: Uses small holes instead of slits

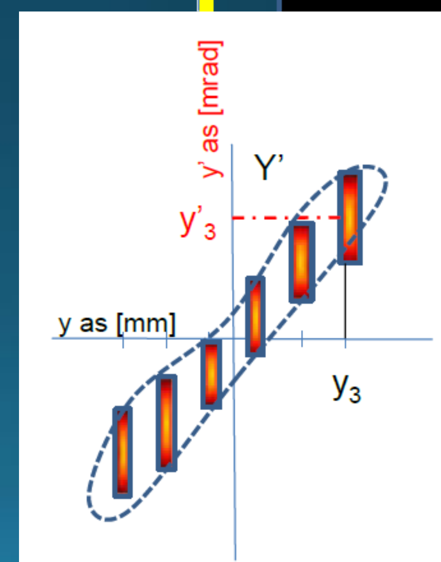




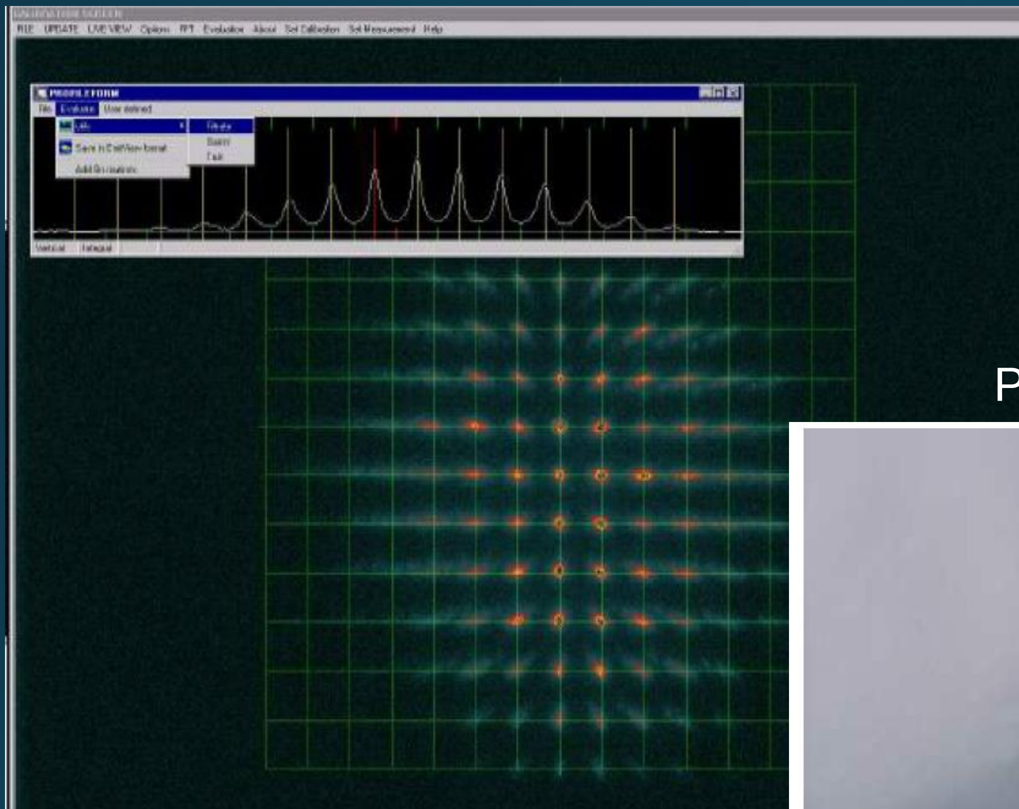
- Measures horizontal and vertical emittance in a single shot

Good **spatial** resolution if many holes are illuminated.

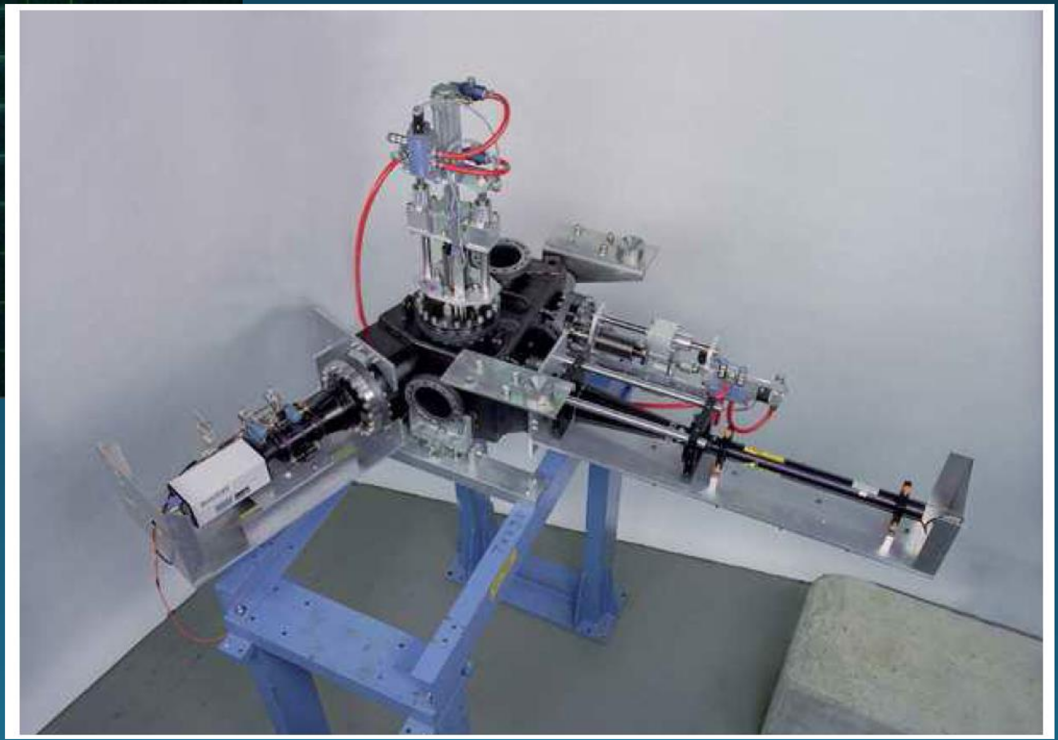
Good **angle** resolution ***only*** if spots do not overlap.



The Pepper pot emittance device

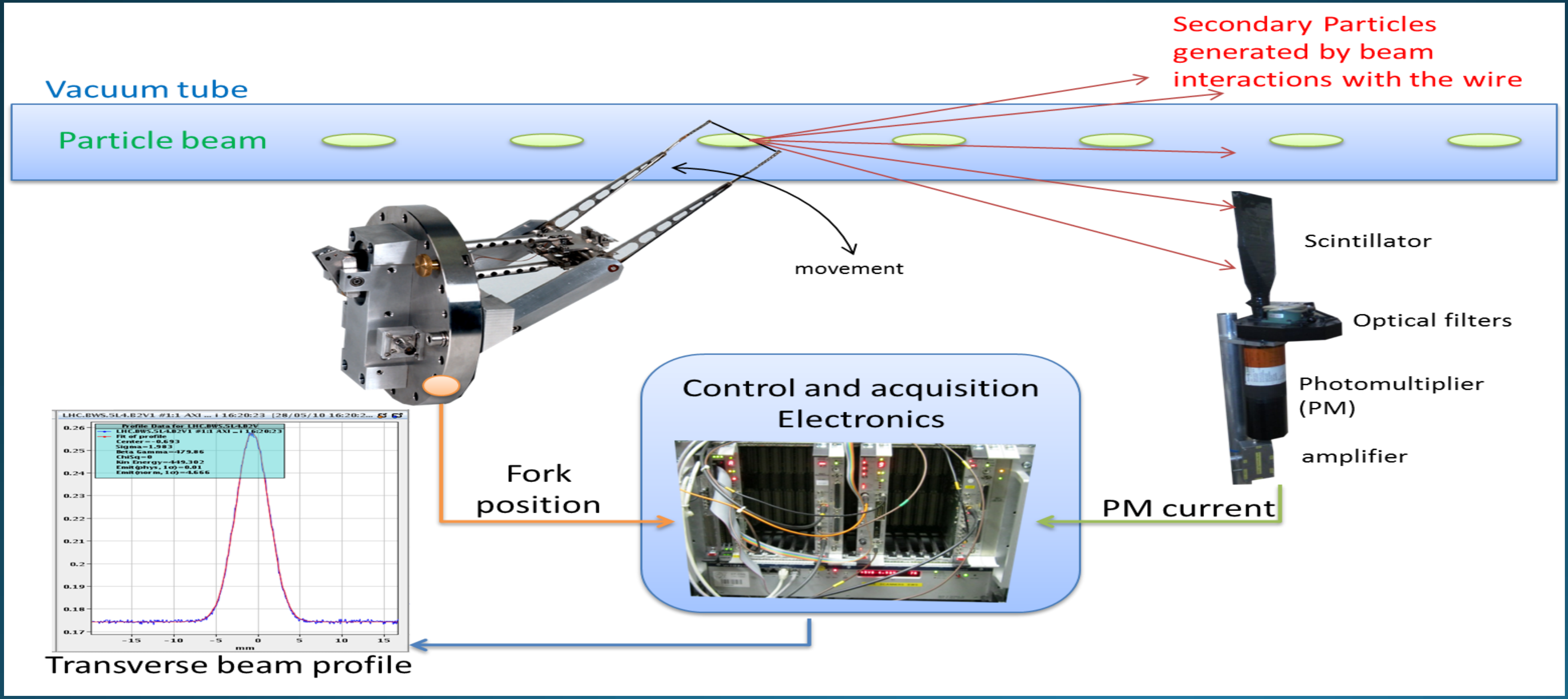


Pepper pot from GSI, Germany



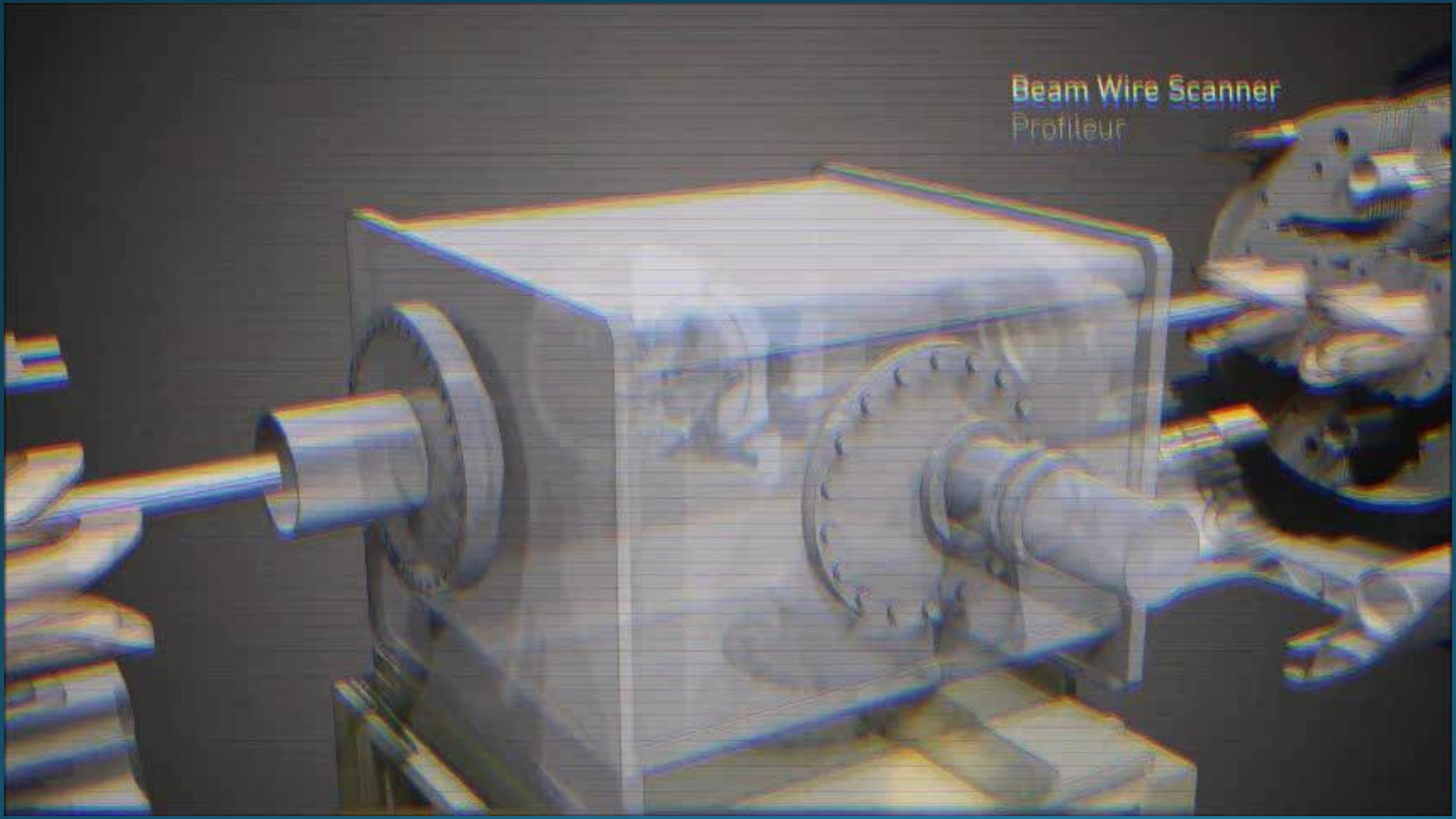
Beam Profile Monitoring using Wire-Scanners

- A thin wire is moved across the beam
  Has to move fast to avoid excessive heating of the wire in case of high intensities.
- Detection
  - High energy:
    - Secondary particle shower detected outside the vacuum chamber using a scintillator / photo-multiplier assembly
  - Low energy: Secondary emission current in wire
- Correlating wire position with detected signal gives the beam profile



Profile Monitoring using Wires

- Wire-scanners
  - Fragile: Wire can break due to error in motor control or excessive heating
  - Wire material: Carbon or tungsten
  - Scan duration : Typical 1ms and it takes around 10-15ms for the wire to cool down



Beam Position Systems

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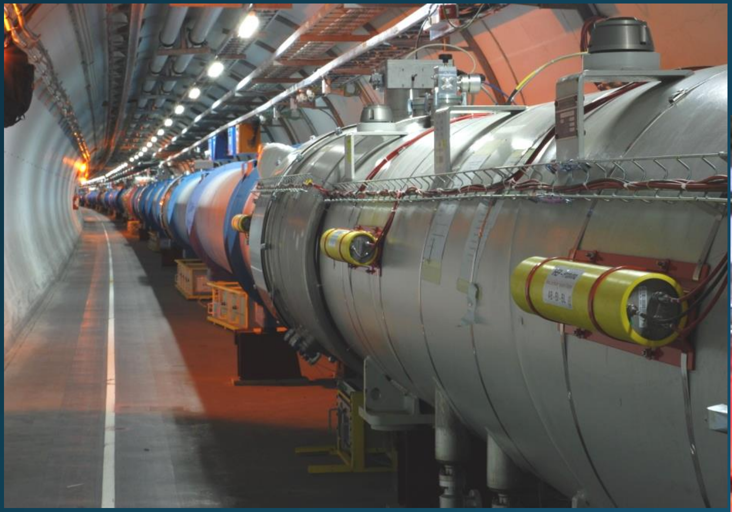
Beam Profile Monitors

Beam Loss Monitors

Beam Loss Detection

- Role of a Beam Loss Monitor (BLM) system:
  - Protect the machine from damage
  - Dump the beam to avoid magnet quenches (for SC magnets)
  - Diagnostic tool to improve the performance of the accelerator



LHC Machine Protection

- Failure in protection
  - loss of complete LHC is possible
- Magnet damage
  - months of downtime & significant cost
- Magnet quench
  - hours of downtime

Stored Energy	
Beam 7 TeV	2 x 362 MJ
2011 Beam 3.5 TeV	above 2 x 100 MJ
Magnets 7 TeV	10 GJ

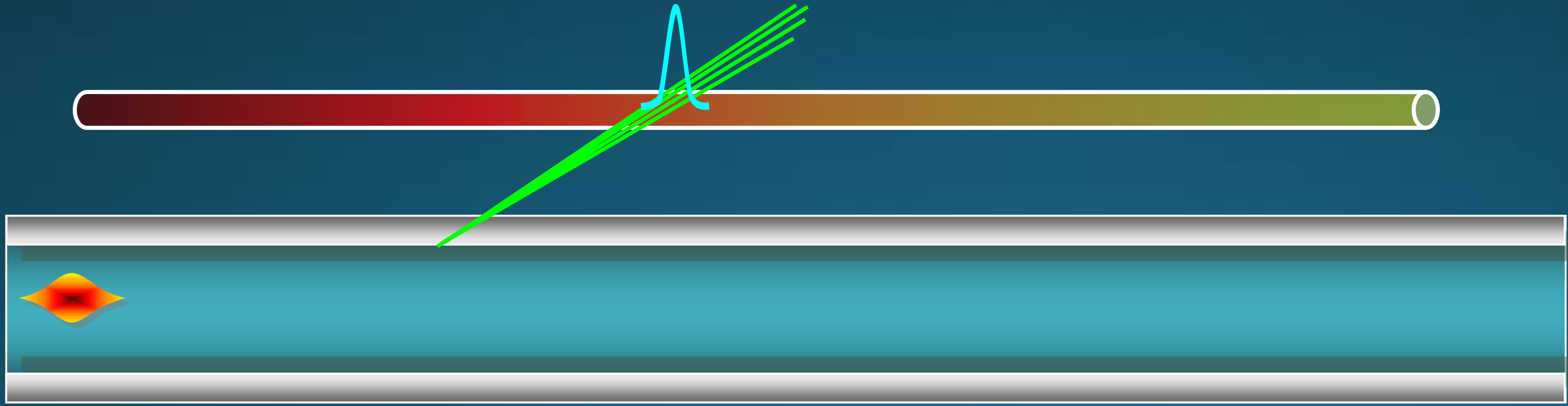
Quench and Damage at 7 TeV	
Quench level	≈ 1mJ/cm^3
Damage level	≈ 1 J/cm^3

LHC BLM System Challenges

- Design Specifications
  - Reliability
    - Tolerable failure rate 10^{-7} per hour per channel $\Rightarrow$ 10^{-3} magnets lost per year (assuming 100 dangerous losses per year)
    - Implies
    - Reliable components, radiation tolerant electronics
    - Redundancy, voting (FPGA)
    - Monitoring of availability and drift of channels
  - Less than 2 false dumps per month (operation efficiency)
  - High dynamic range 10^{13}
  - Fast (1 turn, 89 μs) trigger generation for dump signal

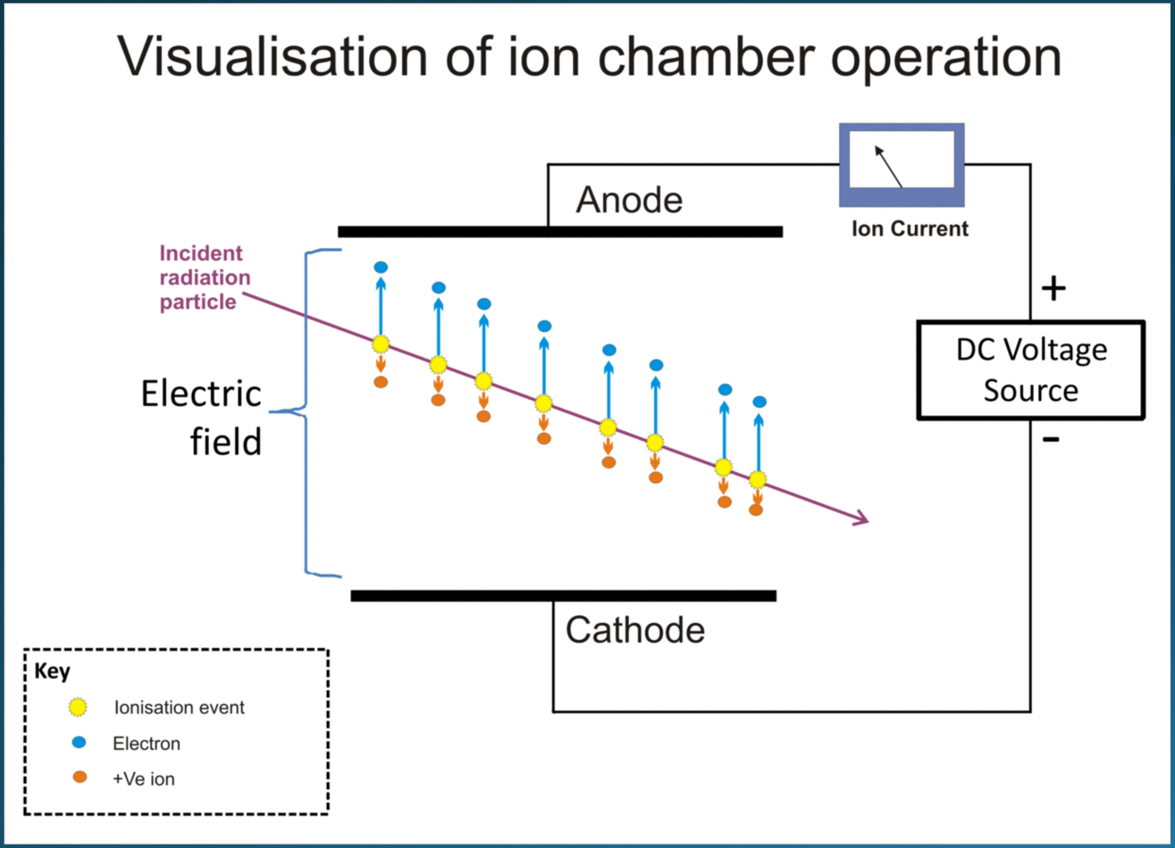
Beam Loss Detectors

- Common types of monitor
  - Long ionisation chamber (charge detection)
    - Up to several km of gas filled hollow coaxial cables
    - Localisation of loss achieved by comparing direct & reflected pulse
      - e.g. SLAC – 8m position resolution (30ns) over 3.5km cable length
    - Dynamic range of up to 10^4
  - Fibre optic monitors
    - Electrical signals replaced by light produced through Cerenkov effect



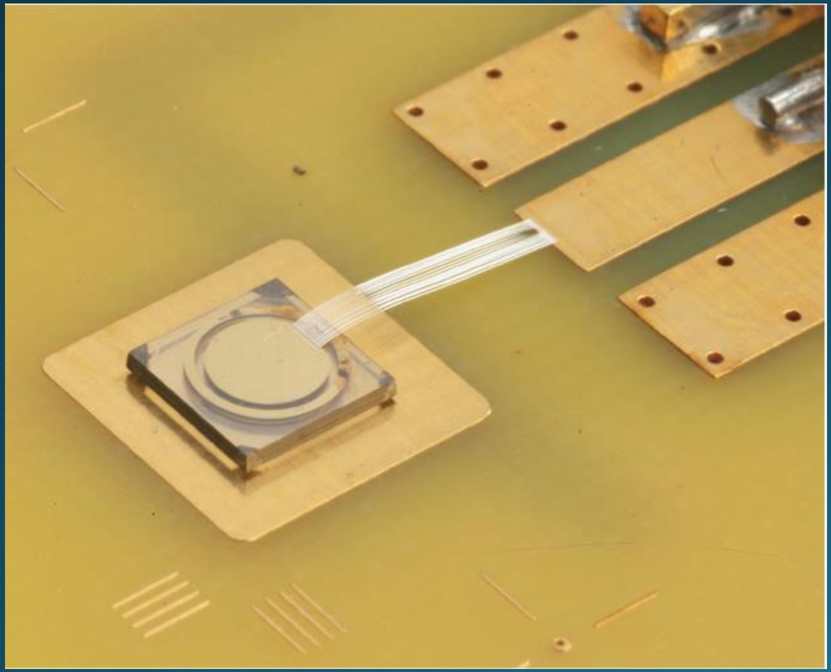
Beam Loss Detectors

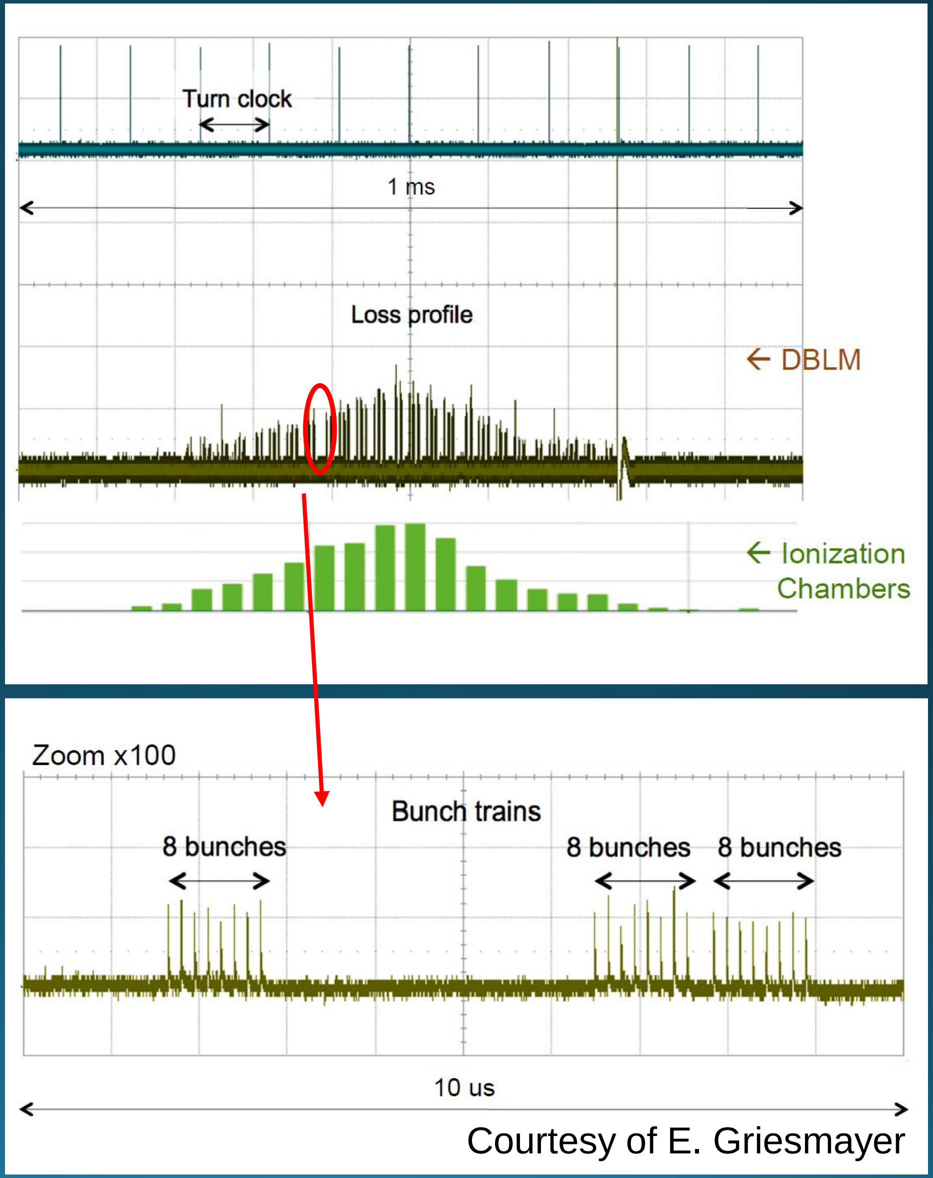
- Common types of monitor
  - Ionisation chambers
  - Dynamic range of < 10^8
  - Slow response (μs) due to ion drift time in large volume



Beam Loss Detectors – New Materials

- Diamond Detectors
  - Fast & sensitive (small and low drift times)
  - Used in LHC to distinguish bunch by bunch losses
  - High dynamic range 10^8
  - Small and easy to integrate and can work in cryogenic conditions
  - Linear response to particle flux
  - Same working principle as ionization chambers

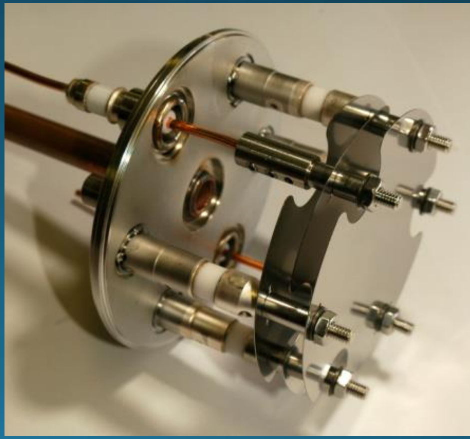




The LHC BLM System

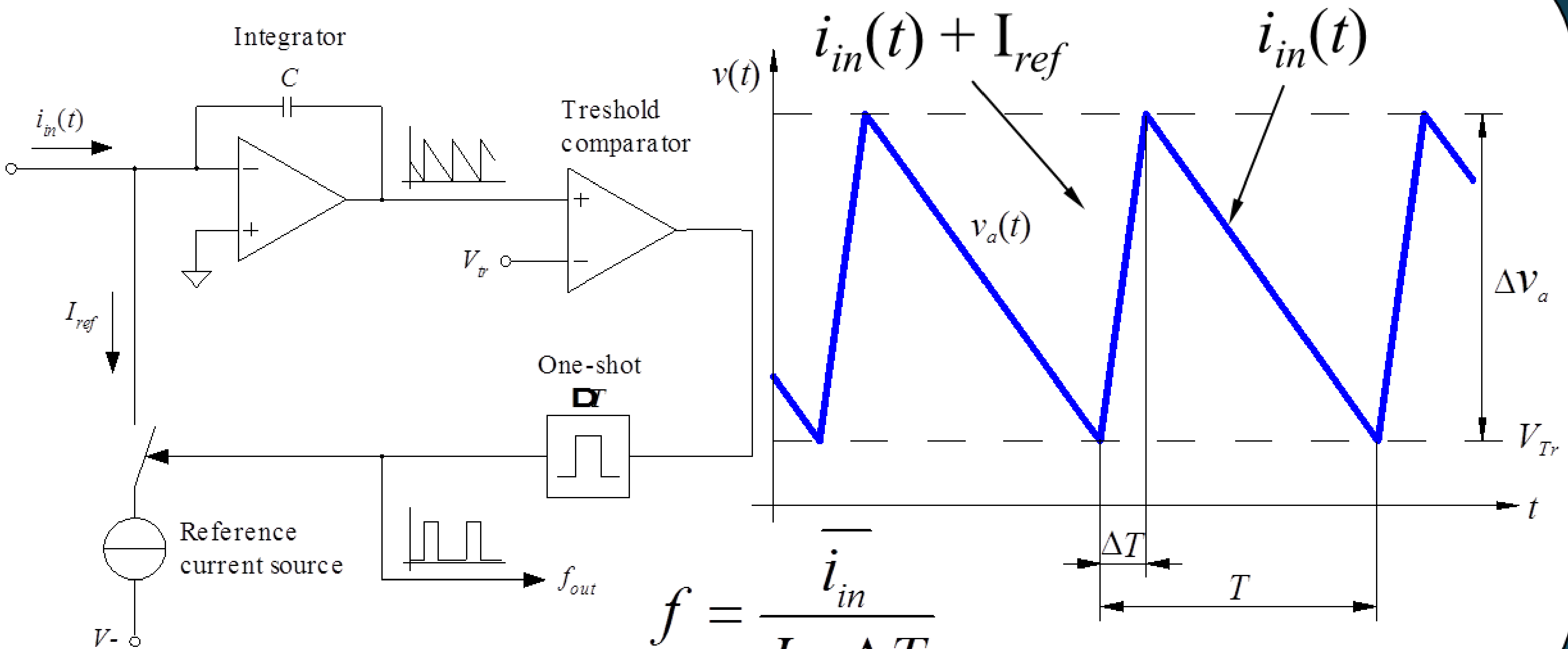
- Ionisation chamber
  - ~3600 installed
  - Nitrogen gas filled with many metallic electrodes & kV bias
    - Length 50 cm
    - Sensitive volume 1.5 litre N_2 gas filled at 1.1 bar
  - Speed limited by ion collection time
  - Dynamic range of up to 10^9 : 1pA to 1mA
    - Limited by leakage current through ceramic & saturation

- Secondary emission monitor
  - ~300 installed
  - Vacuum filled, few electrodes & kV bias
    - Length 10 cm
    - pressure < 10^{-7} bar
  - Measures secondary emission current
  - Complements ionisation chamber
    - ~70,000 times smaller gain
    - For high losses



BLM System Electronics

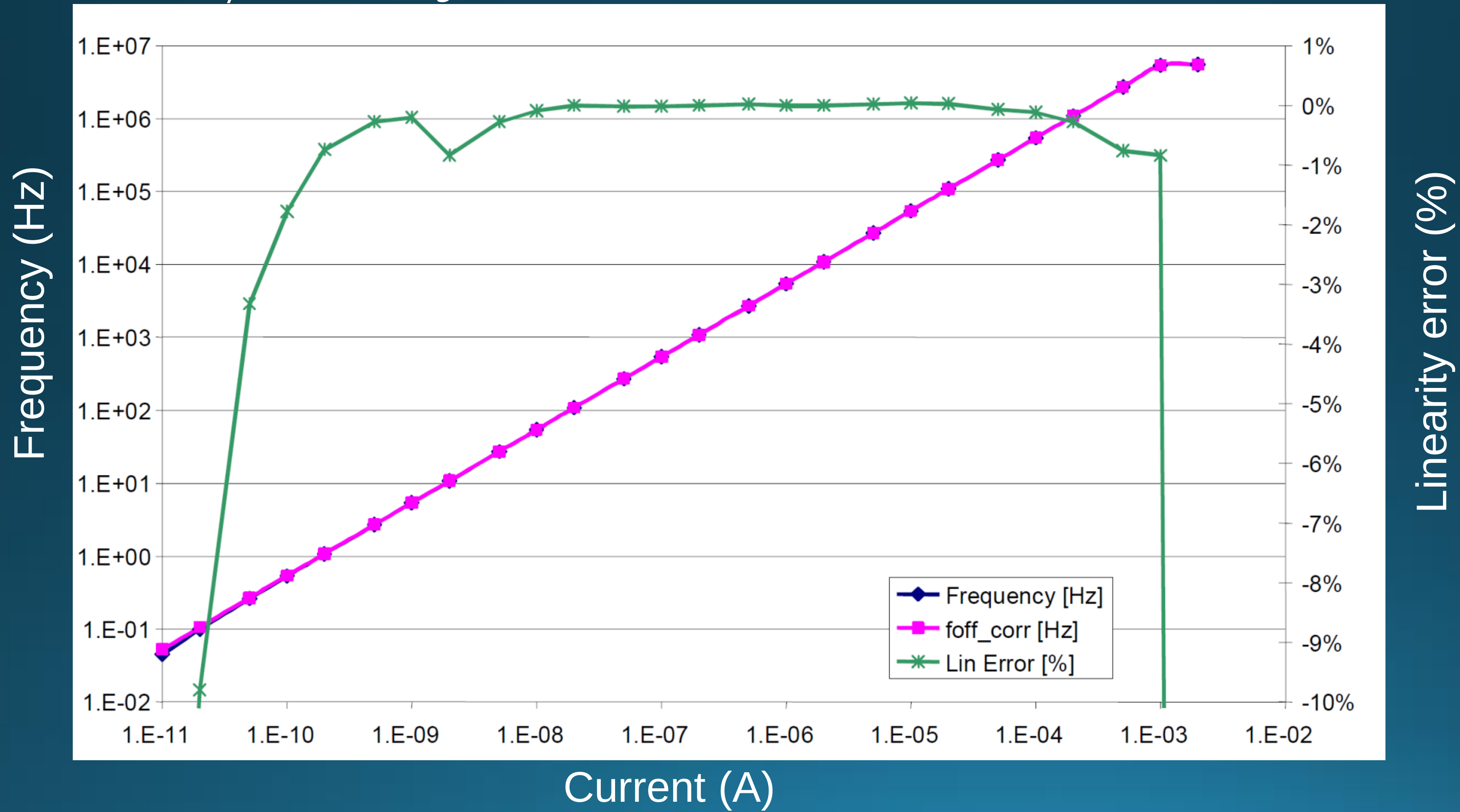
- Based on Current to Frequency Conversion



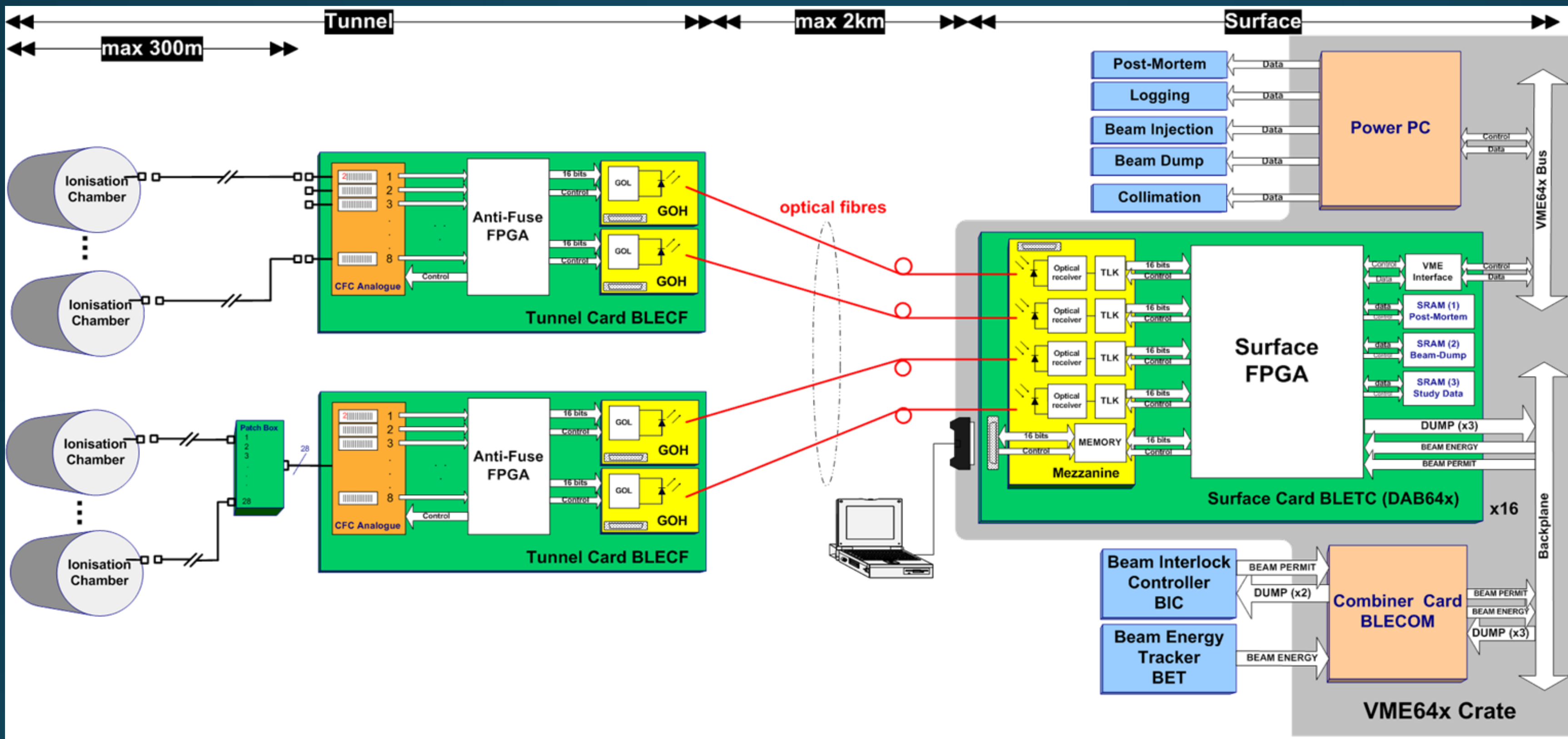
$$f = \frac{\overline{i_{in}}}{I_{ref}\Delta T}$$

BLM System Electronics

- Linearity
  - Measures currents from tens of pA to 1mA
    - Corresponding frequency from few tenths of a Hz to a few MHz
    - Linearity better than 5%



The BLM Acquisition System



Tunnel electronics (Radiation Hard)

- Current to Frequency Converters (CFCs)
- Analogue to Digital Converters (ADCs)
- Gigabit Optical Links

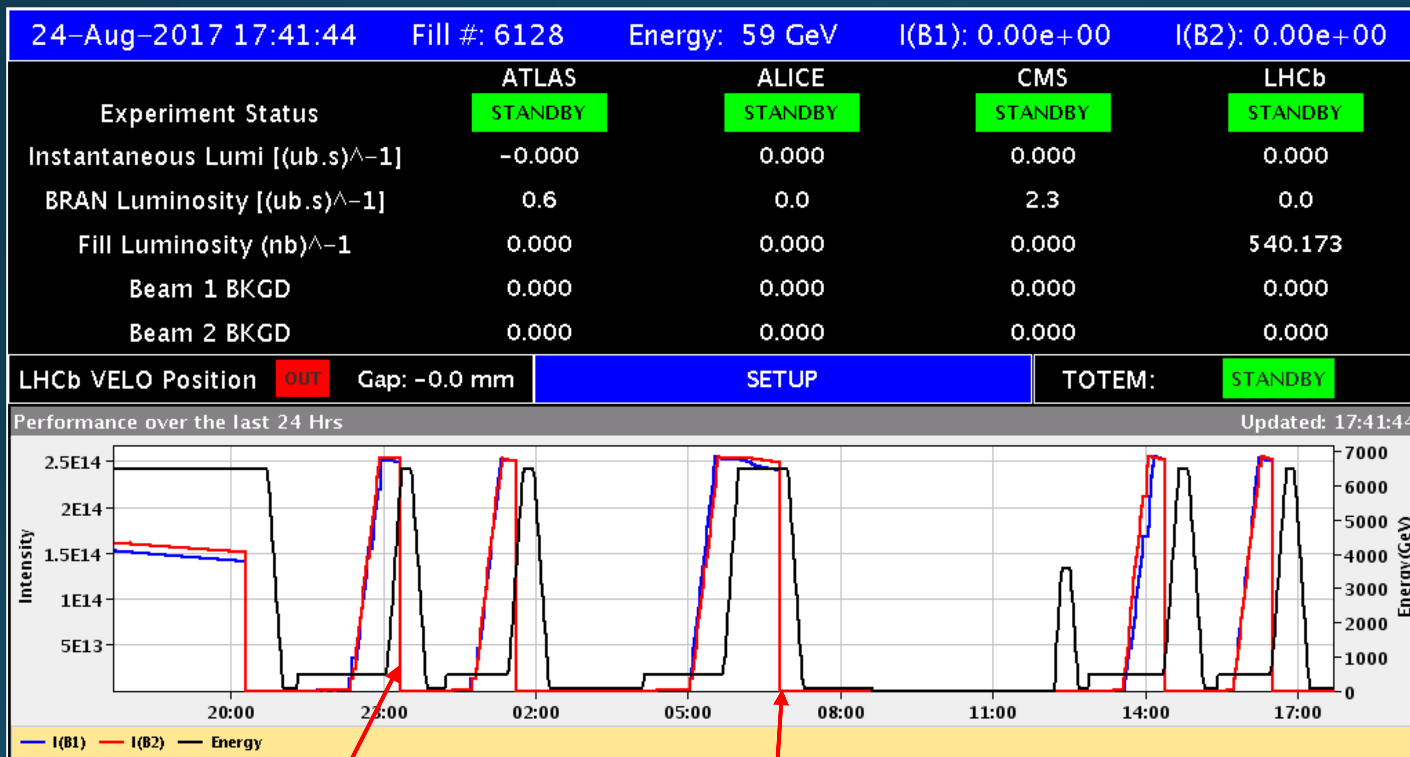
Surface electronics

- Gigabit Optical Receiver
- FPGA for data processing
- SRAM memory for temporary storage
- Non volatile RAM for system settings

Diagnostics using Beam Loss Monitors

Recent Example from LHC

- Beam continually lost due to losses
  - What is going on?



Dump #1 5.9TeV

RF issue

Dump #2 7TeV

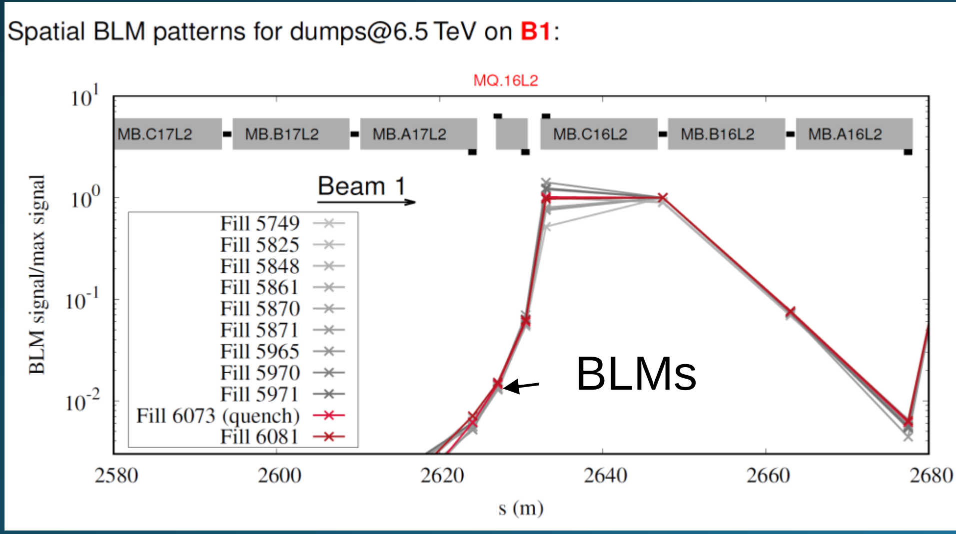
Dump #3 0.9TeV

Dump #4 0.8TeV

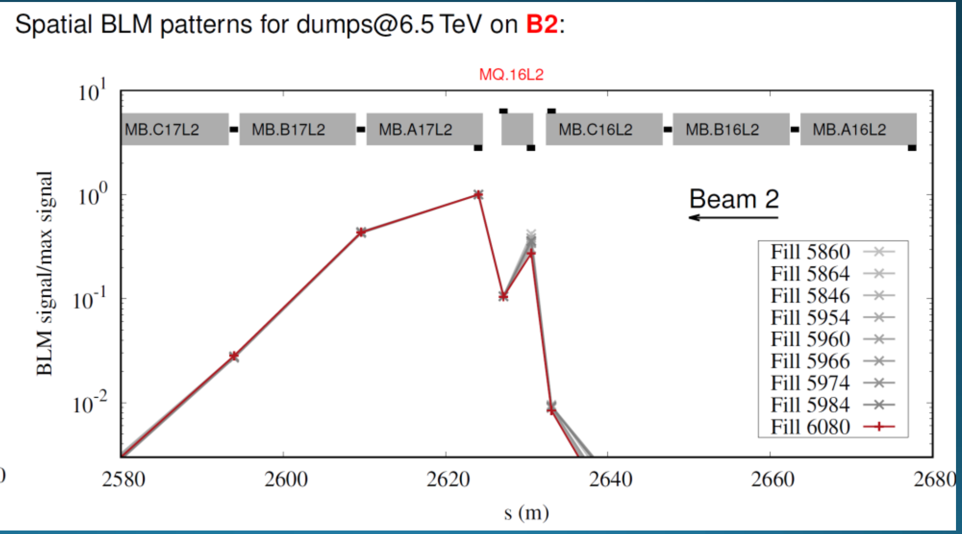
BLM Diagnostics

- Localization
  - BLM Spatial patterns clearly show losses originate from one specific interconnection
    - MQ16L2 (Cell 16 left of LHC Point 2)
    - Localization possible to within 1m by comparing with simulation
  - Losses can be on either beam

Beam 1

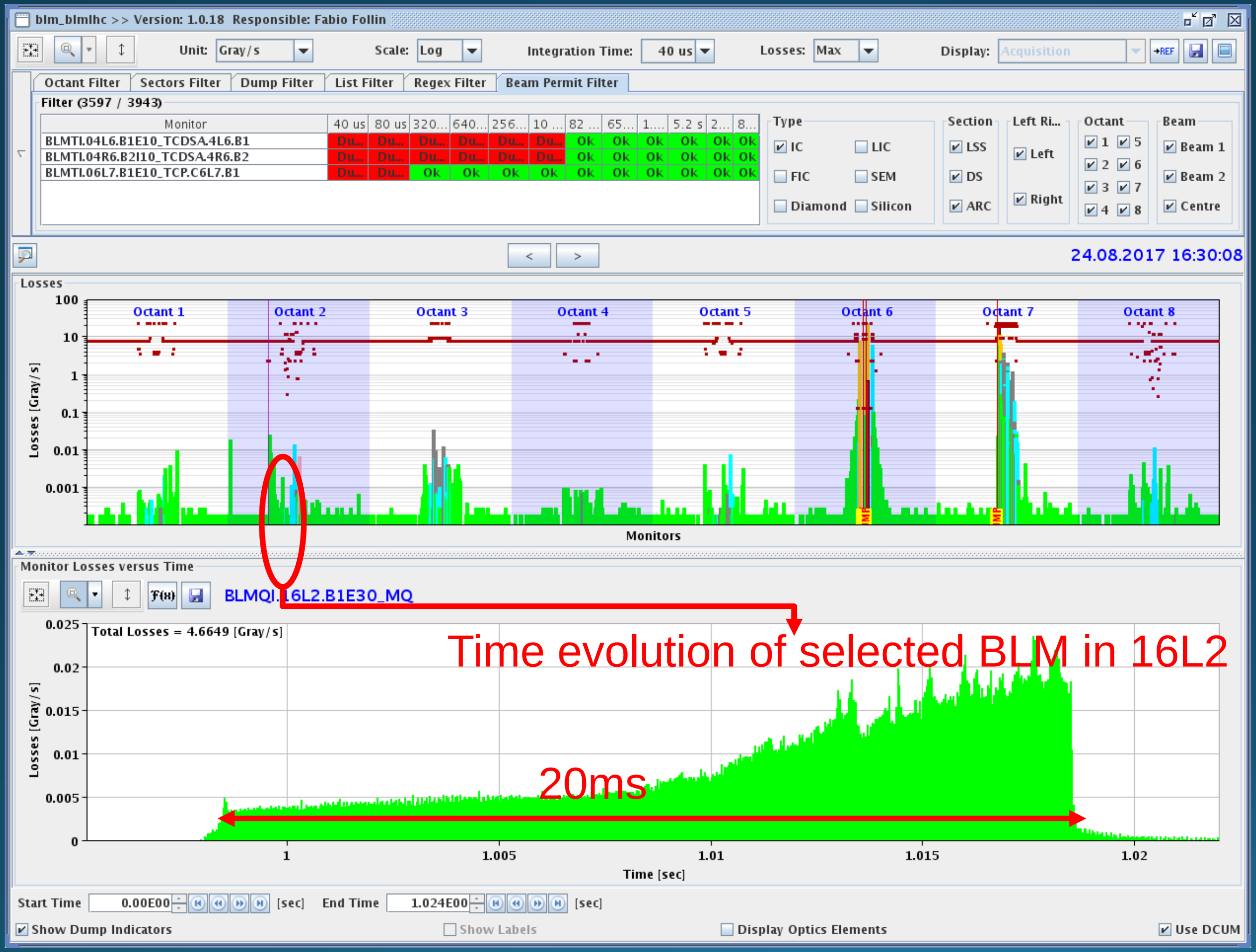


Beam 2



BLM Diagnostics

- Time evolution



Summary

- Brief overview of most important beam diagnostics devices.
- Mainly used by operations and beam accelerator physicists to improve accelerator performance
- Close collaboration with the beam diagnostics experts
- Many disciplines involved
  - Applied physics
  - Software engineering
  - Mechanical engineering
  - Electronics engineering
  - Vacuum technologies
- Often working with BSC, Master and PhD studentds

Thank you for your attention !

Questions ?

Friday morning we will try to simulate and measure a BPM ☺