Introduction to Beam Instrumentation and Diagnostics Lecture I

Michal Krupa – CERN BI Group

(based on previous lectures by Rhodri Jones)

Outline

- **Lecture I - today**
  - **Introduction**
  - **Beam position monitoring**
  - **Beam intensity monitoring**
  - **Beam loss monitoring**
- Lecture II - tomorrow
  - Transverse beam profile monitoring
  - Tune measurements
  - Coupling measurements
  - Chromaticity measurements
  - Diagnosing accelerator issues

Introduction

Beam instrumentation

- Instruments that observe the beam and its behaviour – “eyes” of the operators
  - Ultimate limit to quantify the performance of an accelerator
- Typical BI system architecture:

sensor → processing electronics → digitizer → processing software

discussed in these lectures

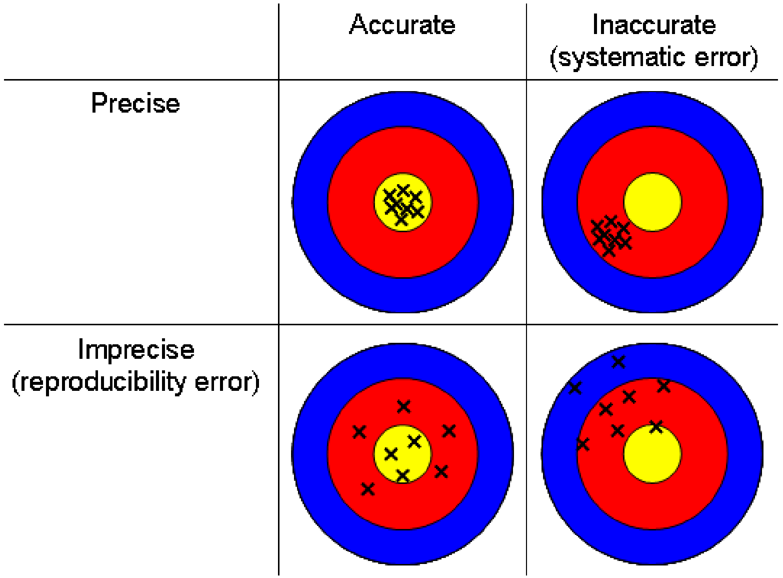
- BI expertise: applied and accelerator physics; mechanical, electronics, and software engineering
- BI system size: from 1 sensor / accelerator to 1000’s sensors / accelerator
- Commonly measured beam parameters:
  - **Transverse beam position**: horizontal and vertical, all along and in specific places
  - **Beam intensity (and lifetime)**: bunch-by-bunch charge and total current
  - **Beam loss**: for protection and optimization
  - **Beam profiles**: transverse and longitudinal distribution of beam particles

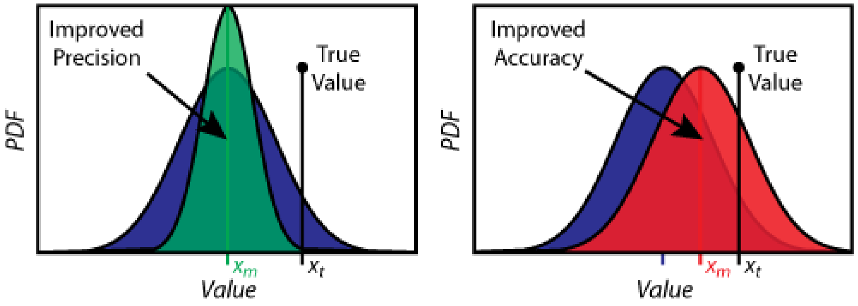
Beam diagnostics

- Making use of beam instrumentation – extracting useful information from (a combination of) beam observables
- Examples of beam diagnostics:
  - **Daily operation of accelerators**: measurements and correction of beam orbit, tune, chromaticity…
  - **Understanding of accelerator limitations**: beam losses, instabilities, emittance growth…
  - **Improvement of accelerator performance**: luminosity, brilliance, feedbacks
  - **Detection of equipment faults**: aperture restrictions, magnet polarity inversion, wrong setting

Measurement quality

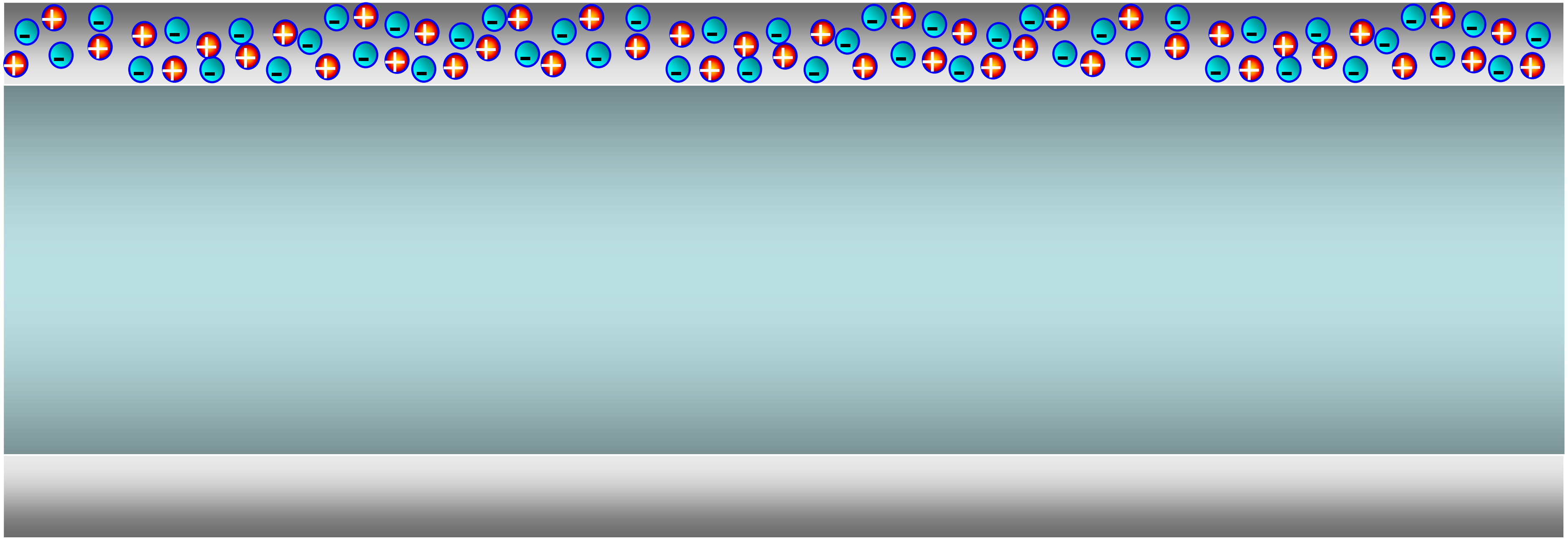
- **Accuracy** – trueness
- **Precision** – reproducibility
- **Resolution** – smallest measurable change
- **Dynamic range** – ratio of the largest and smallest measurable signal
- **Timescale** – multi-turn full beam / turn-by-turn / bunch-by-bunch
- **Availability** – continuous / on-demand





Beam Position Monitors (BPMs)

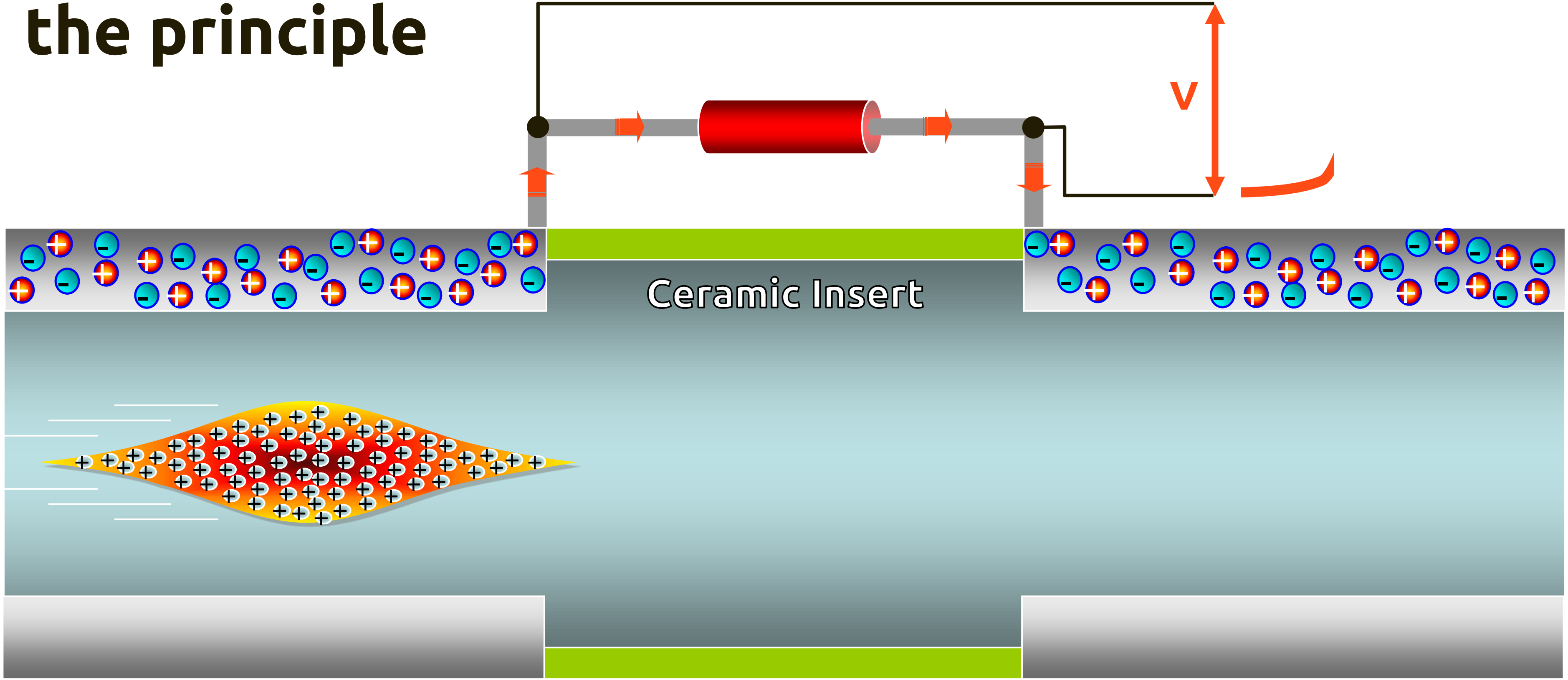
Beam image current



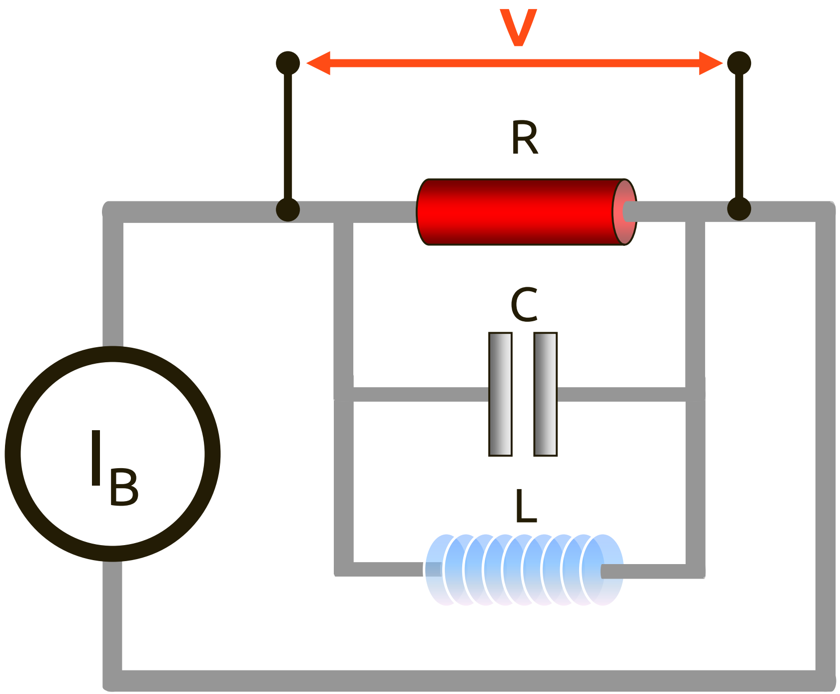
Beam image current properties

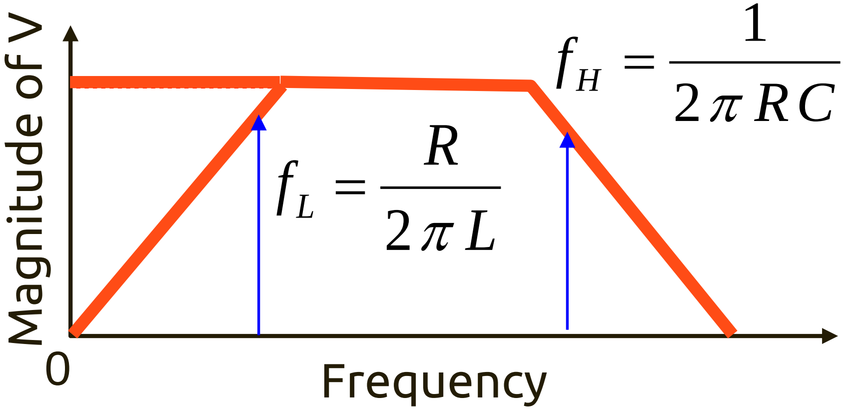
- Equal to the beam current (non-DC components) but with the opposite sign: $I_{Image} = -I_{beam}$
  - Good proxy for beam/bunch intensity measurements
- Current density around the vacuum chamber correlated to the transverse beam position
  - Good proxy for beam/bunch position measurements
- Same longitudinal charge distribution as the beam for highly-relativistic beams
  - Good proxy for longitudinal measurements
- Often referred to as the “wall current”

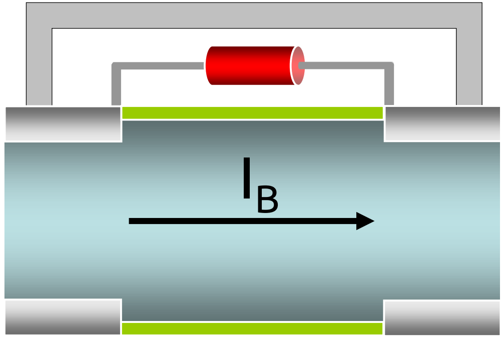
Wall Current Monitor
the principle



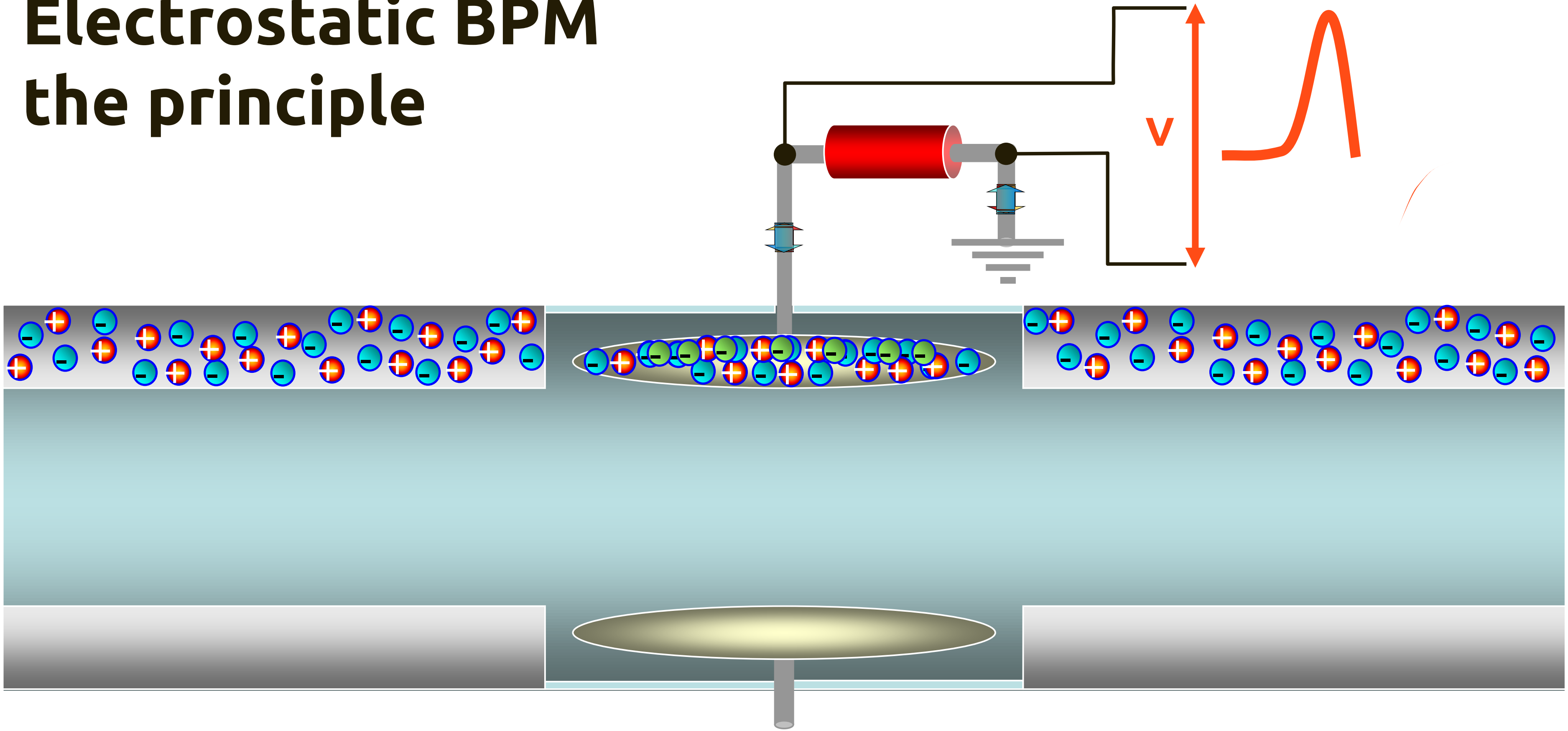
Wall Current Monitor – beam response



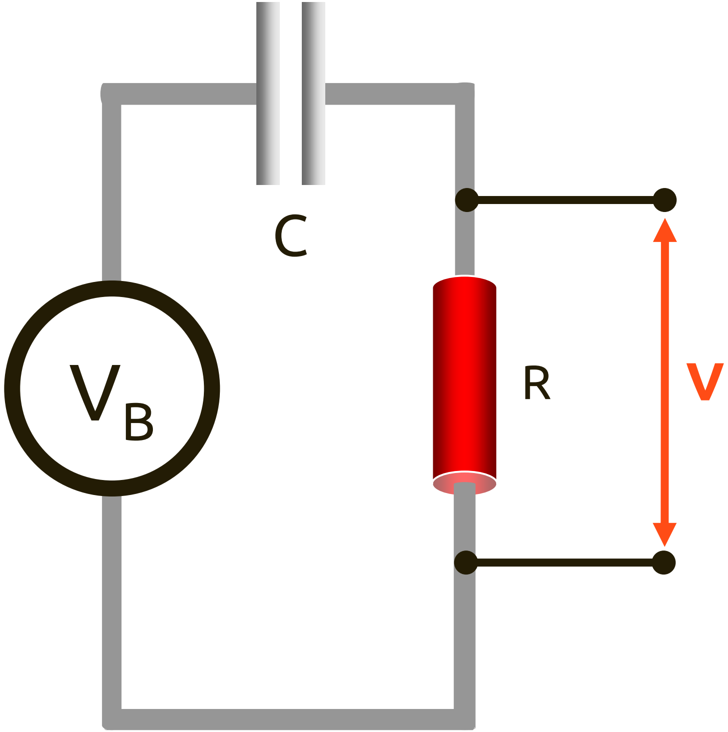


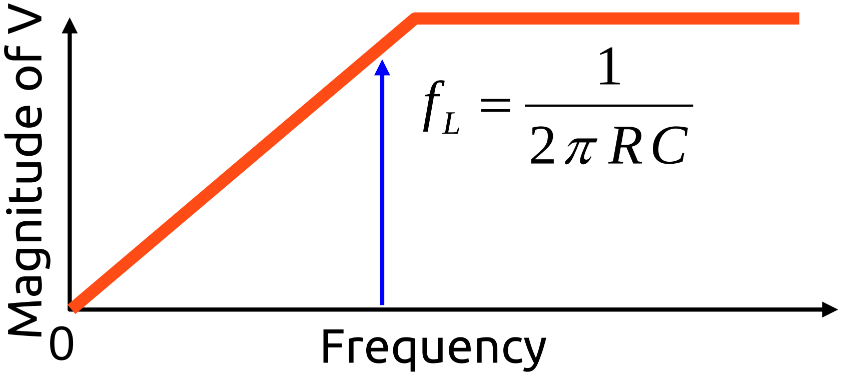


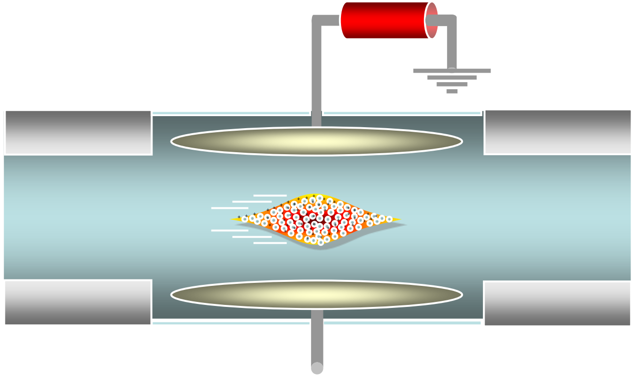
Electrostatic BPM
the principle



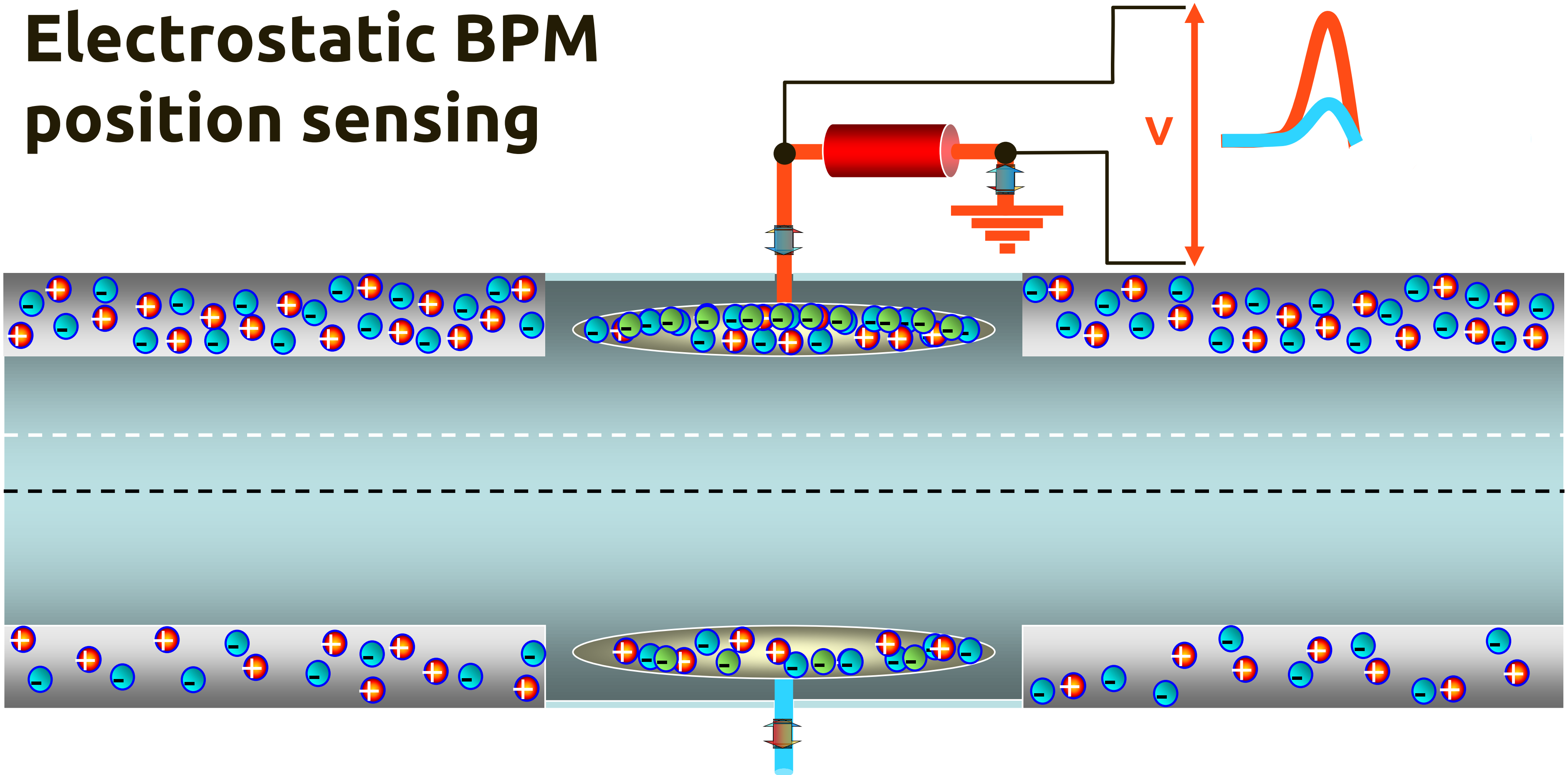
Electrostatic BPM – beam response



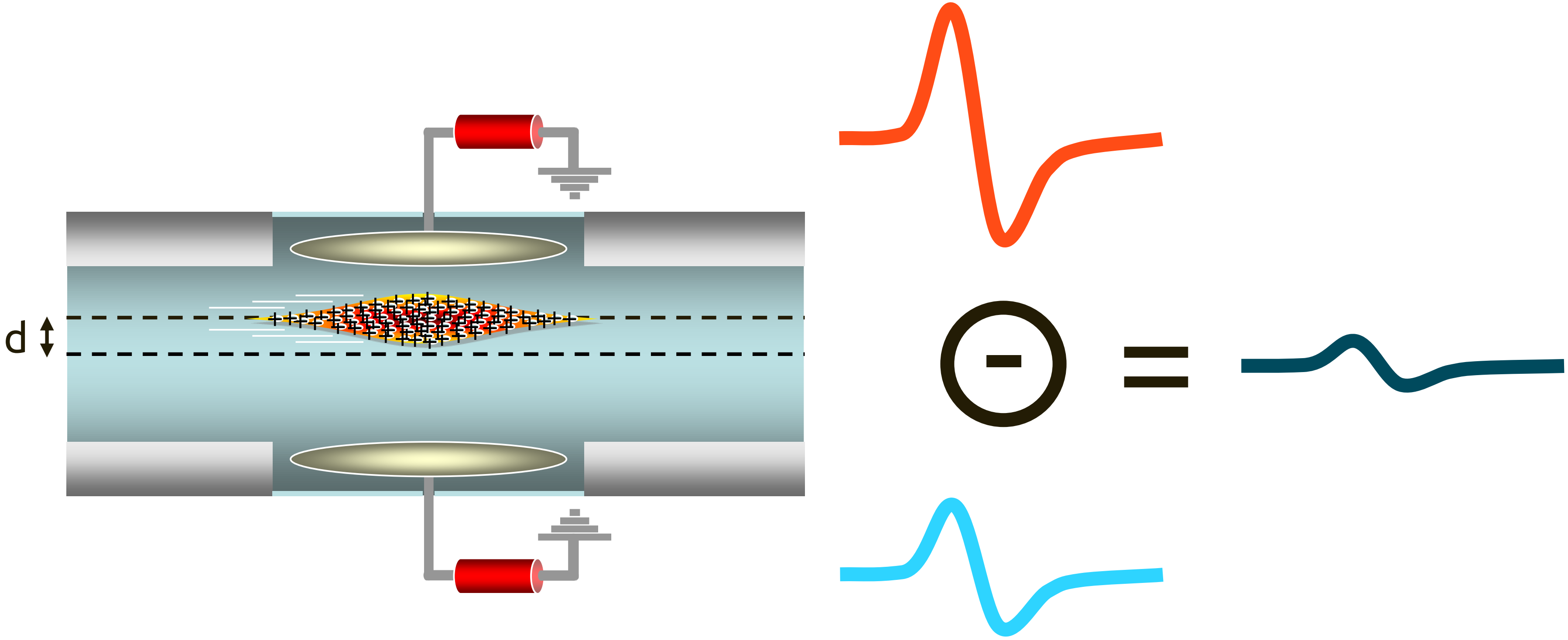




Electrostatic BPM position sensing

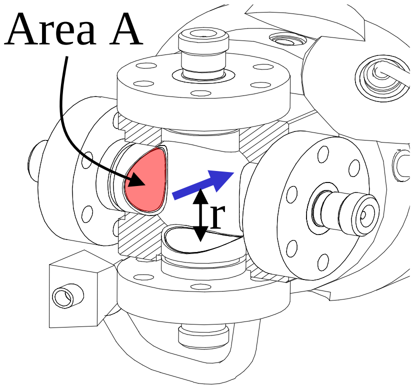


Electrostatic BPM – position sensing



Electrostatic BPM – button pick-up

- **Low cost** – most popular electrode type
- **Non-linear** – requires corrections for large beam displacements



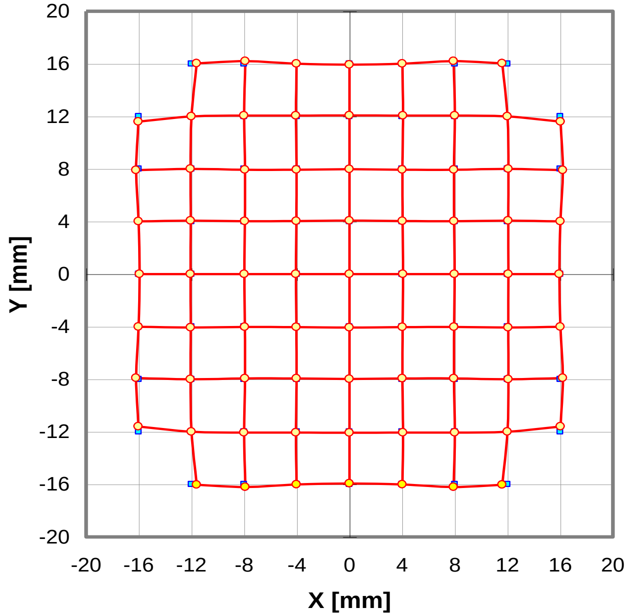
C_e – button capacitance
R_0 – load resistance

Transfer impedance

$$Z_{T(f>>f_c)} = \frac{A}{(2\pi r)\times c\times C_e}$$

Low cut-off frequency

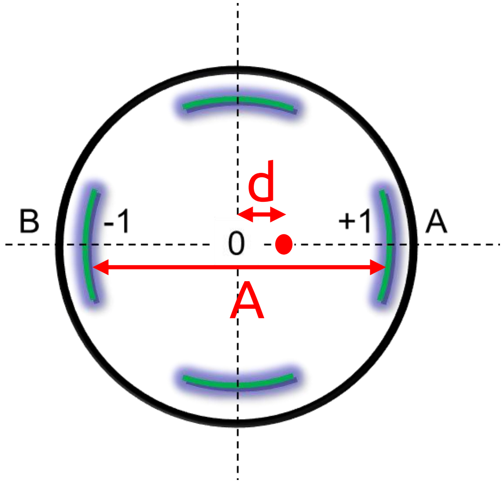
$$f_L = \frac{1}{2\pi R_0 C_e}$$



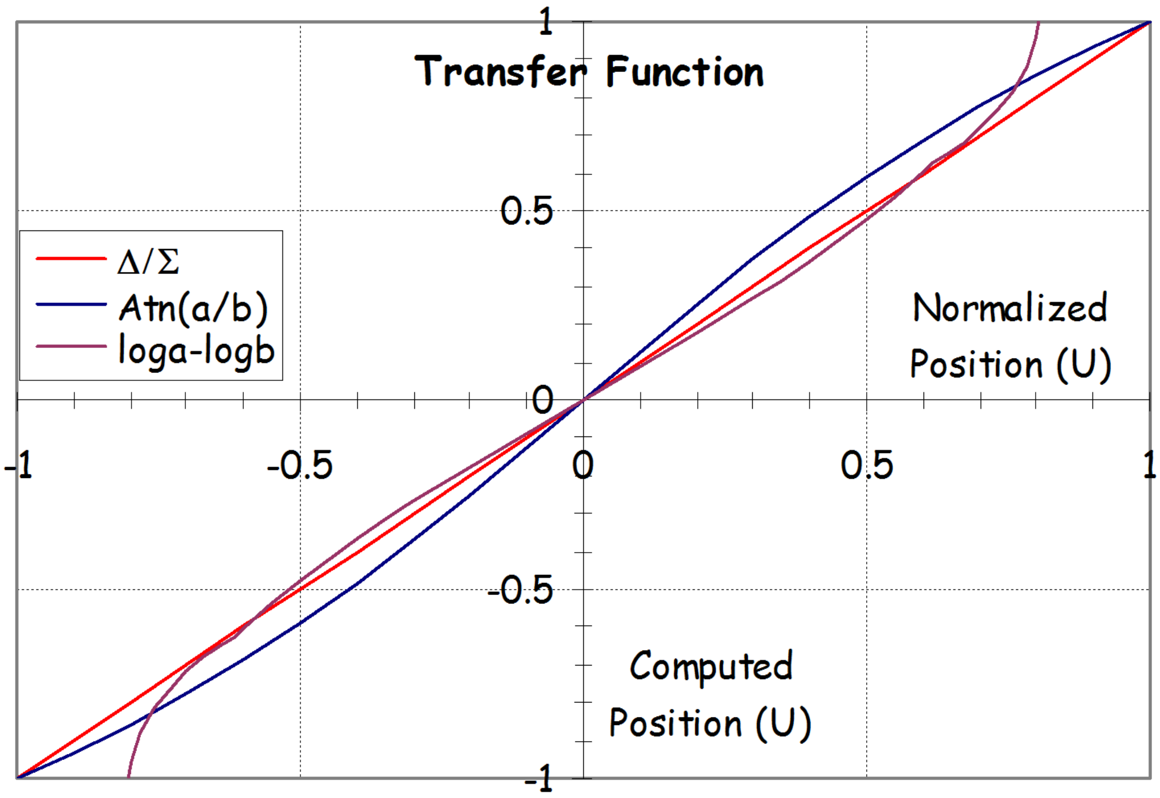
$$X = 2.30\cdot10^{-5} X_1^{\,5} + 3.70\cdot10^{-5} X_1^{\,3} + 1.035\, X_1 + 7.53\cdot10^{-6} X_1^{\,3} Y_1^{\,2} + 1.53\cdot10^{-5} X_1 Y_1^{\,4}$$

Normalisation of BPM measurements

- Required to make measurement independent of beam / bunch intensity
- $V_{BPM} \propto I_{beam} \cdot (1 + 4\frac{d}{A} + \text{higher-order terms})$
- Three main methods:
  - **Phase:** $\text{ArcTan}\left(\frac{V_A}{V_B}\right) \approx \text{ArcTan}\left(2\frac{d}{A}\right)$
  - **Logarithm:** $\text{Log}\left(\frac{V_A}{V_B}\right) = \text{Log}(V_A) - \text{Log}(V_B) \approx \text{Log}\left(2\frac{d}{A}\right)$
  - **Difference / Sum:** $\frac{(V_A - V_B)}{(V_A + V_B)} = \frac{\Delta}{\Sigma} \approx 4\frac{d}{A}$

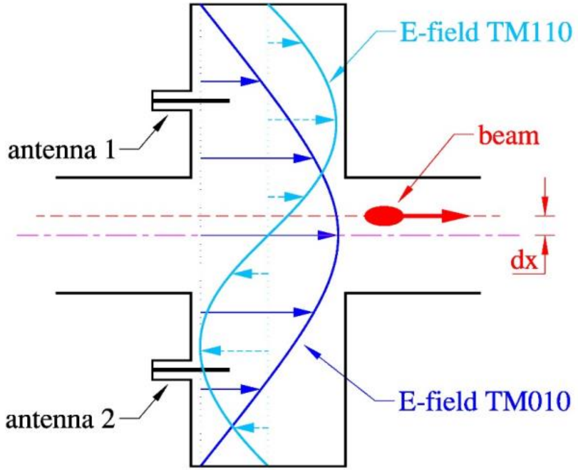


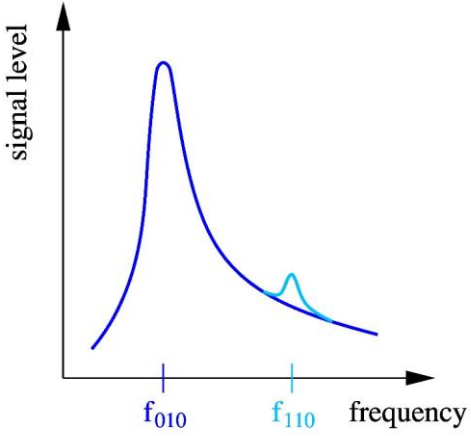
Normalisation of BPM measurements



High-precision BPMs

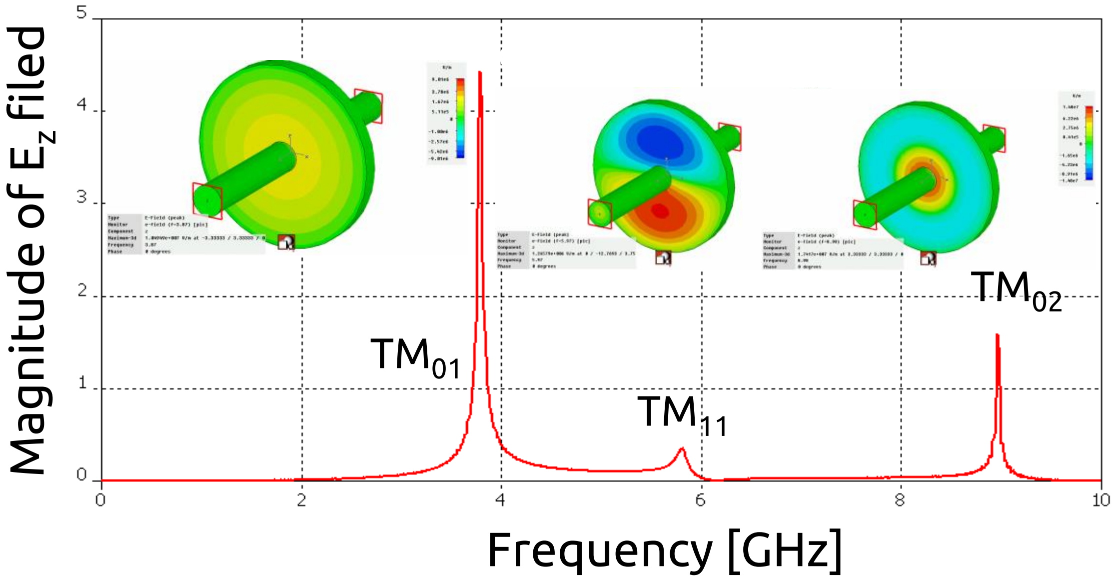
- Standard BPM electrodes:
  $V_{BPM} \propto I_{beam} \cdot (1 + 4\frac{d}{A} + \text{H.O.T.})$
  - Strong beam / bunch intensity component – difficult to suppress
  - Rather weak dependence on the beam position
- Another approach: **Cavity BPMs**
  - Separate the intensity component (TM010) and the position component (TM110) in the frequency domain
  - Intensity component still needed for normalisation
  - Not suitable for circular accelerators



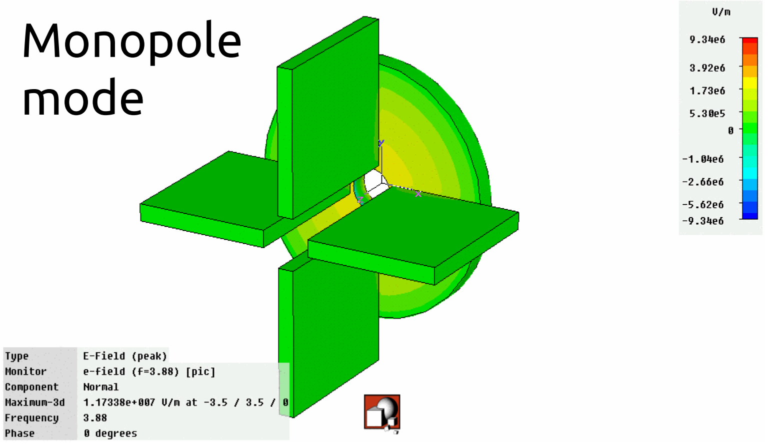


Cavity BPM

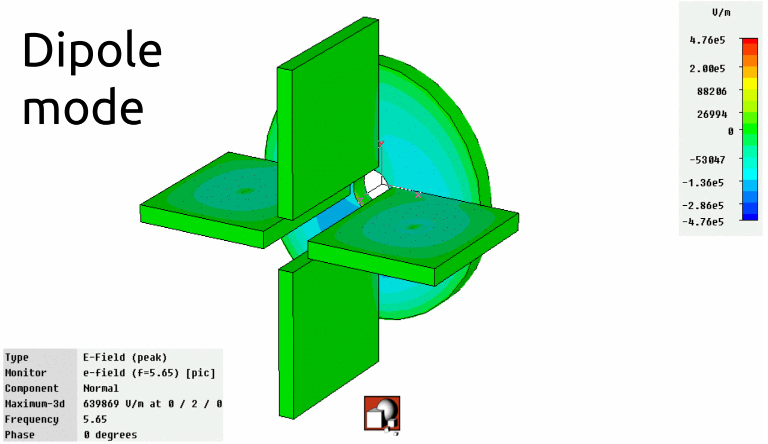
Use waveguides to couple out only the dipole mode and suppress the monopole mode



Monopole mode



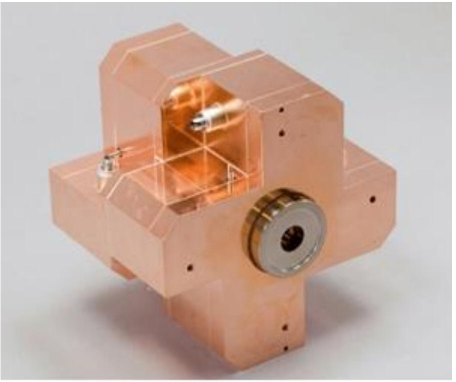
Dipole mode



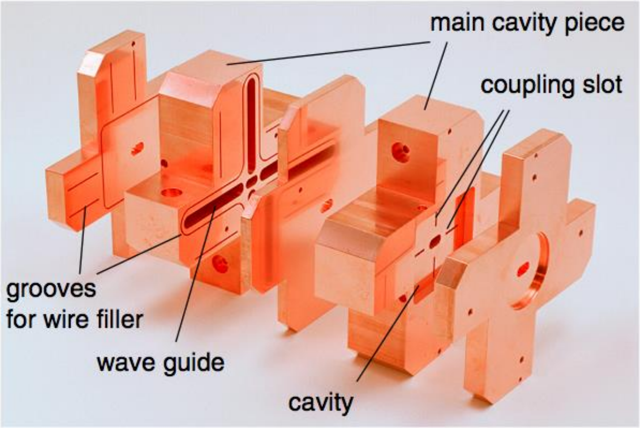
Courtesy of D. Lipka, DESY, Hamburg

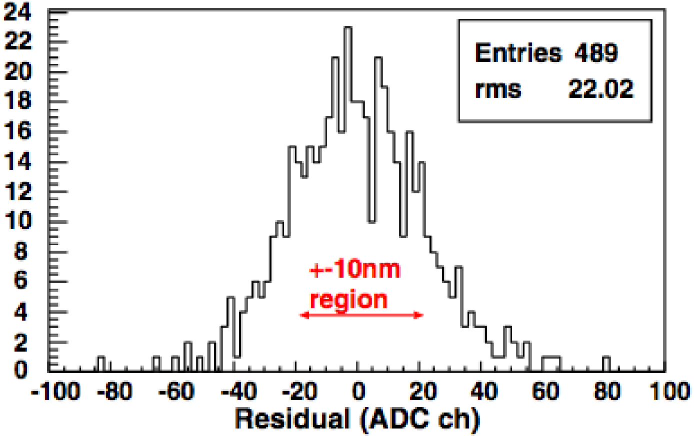
Prototype Cavity BPM for ILC Final Focus

- Required resolution of 2 nm in a 6 × 12 mm oval beam pipe
- Demonstrated with beam: astonishing resolution of **8.7 nm** at ATF2 (KEK, Japan)



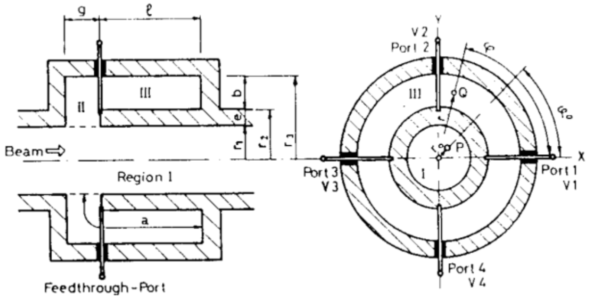
Courtesy of D. Lipka & Y. Honda

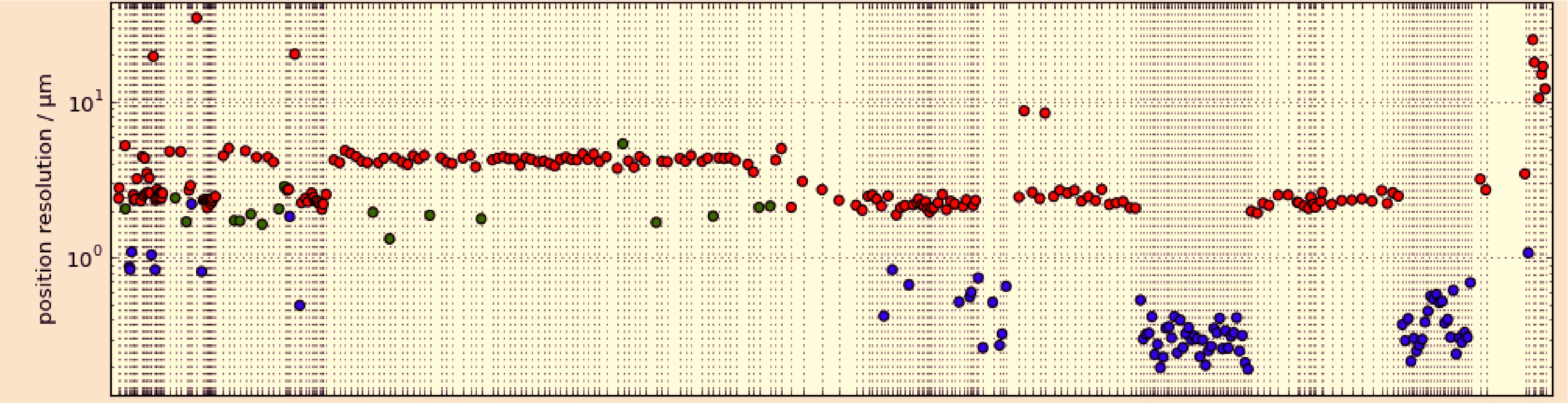




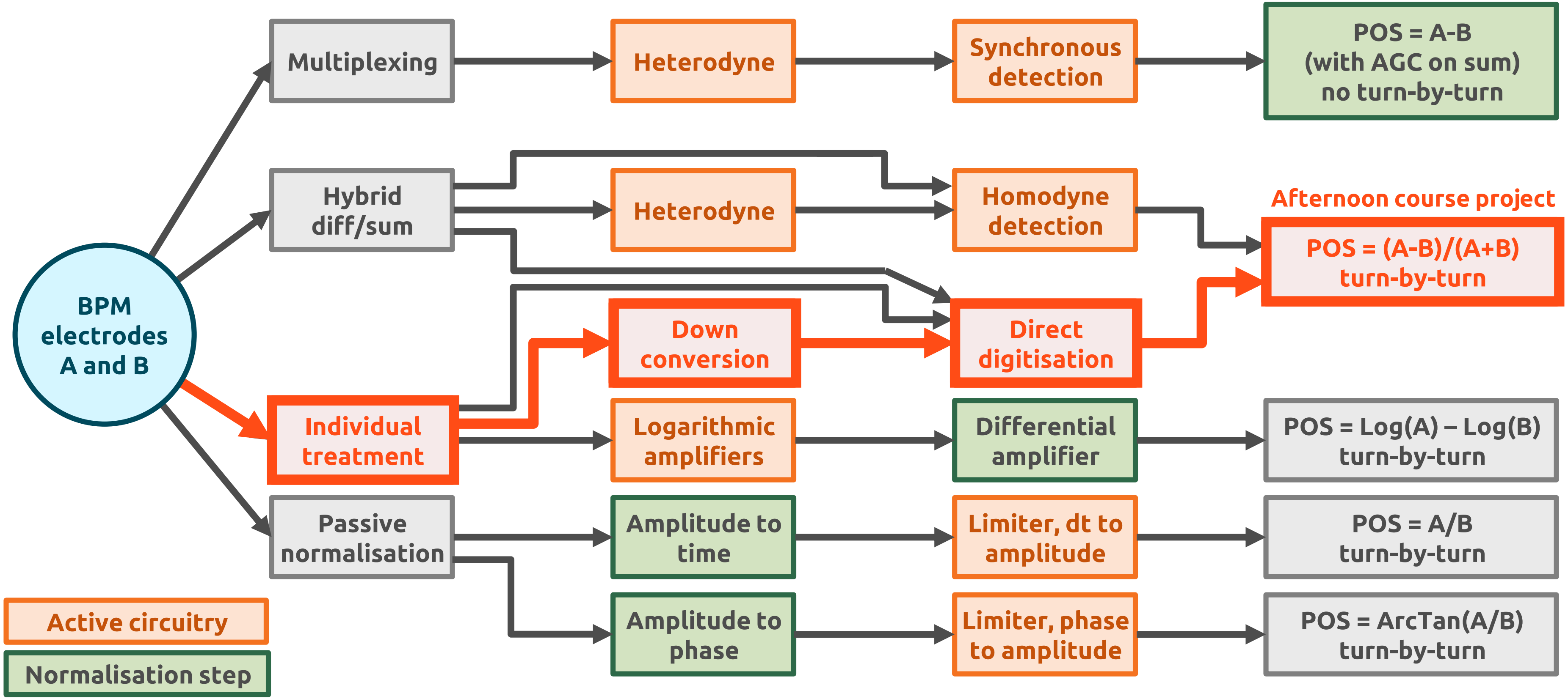
Electrostatic and cavity BPM – resolution comparison

- XFEL (Germany) results from 2017 beam commissioning:
  - **Red dots**: button BPMs (78 mm and 40.5 mm aperture)
  - **Green dots**: re-entrant cavity BPMs (78 mm aperture)
  - **Blue dots**: cavity BPMs (40.5 and 10 mm aperture)



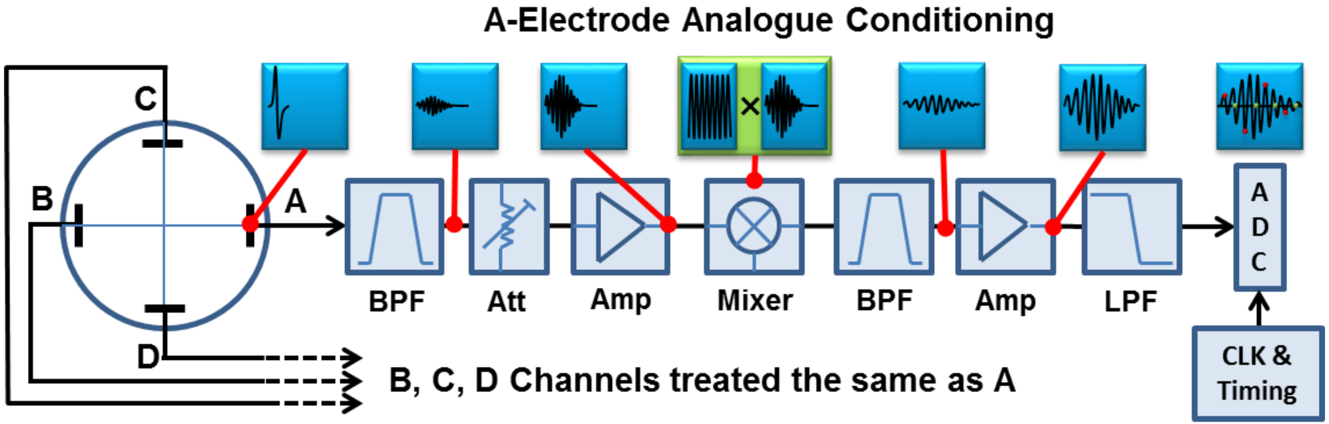


BPM data acquisition system families



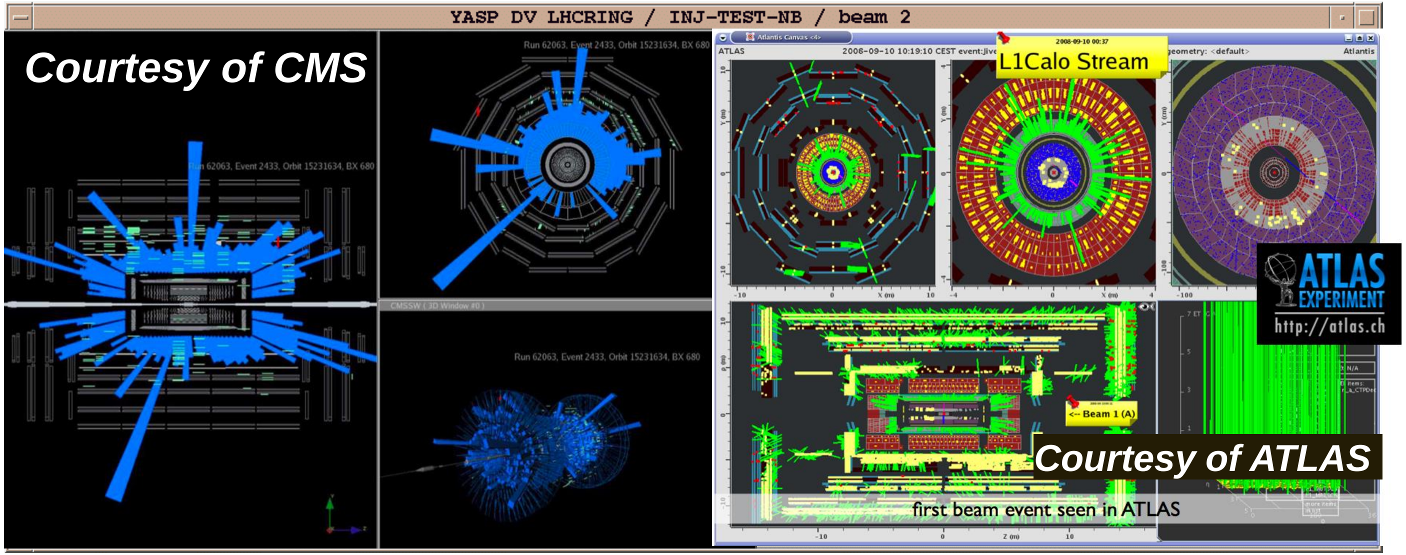
Modern BPM data acquisition system

- Each electrode treated individually
- Frequency-domain processing – telecommunications industry approach
- Requires good-resolution and fast-sampling analogue-to-digital converters
  - BPM signal down-conversion to match the ADC characteristics
- Minimal analogue circuitry – most processing done digitally

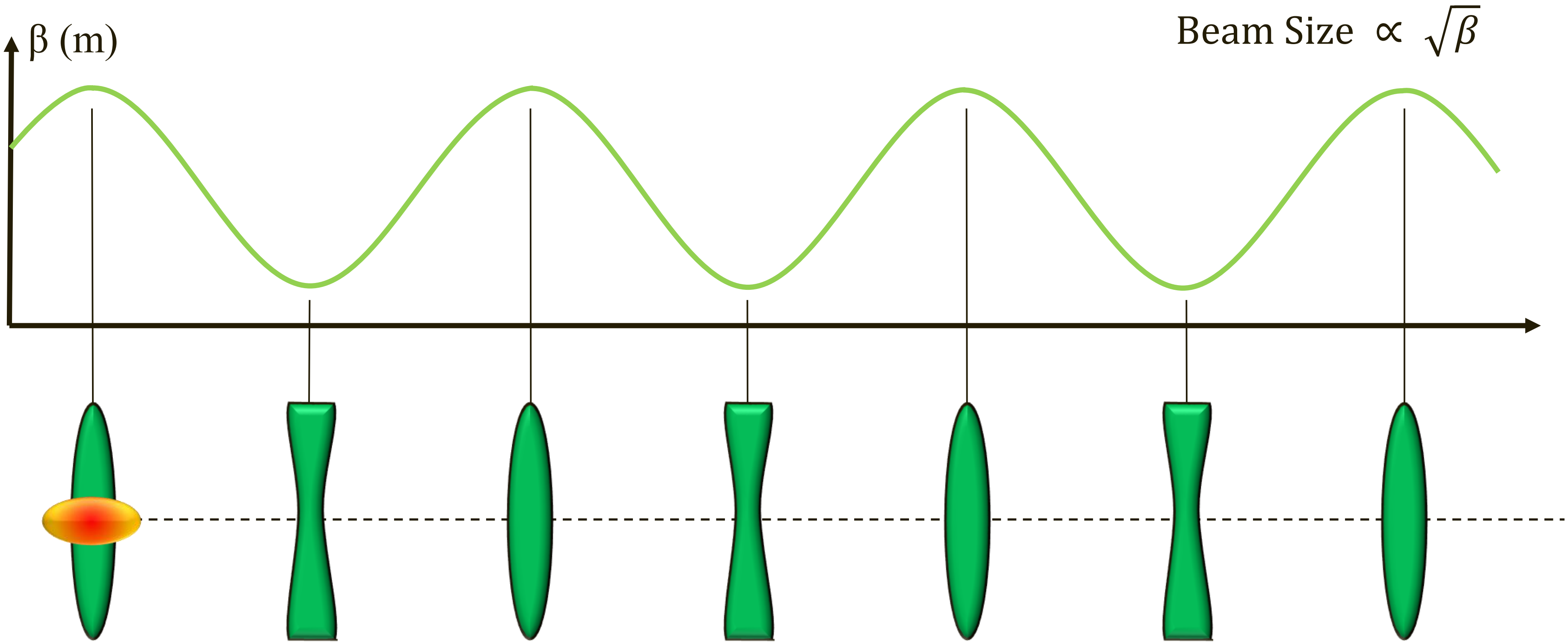


Initial accelerator commissioning using BPMs

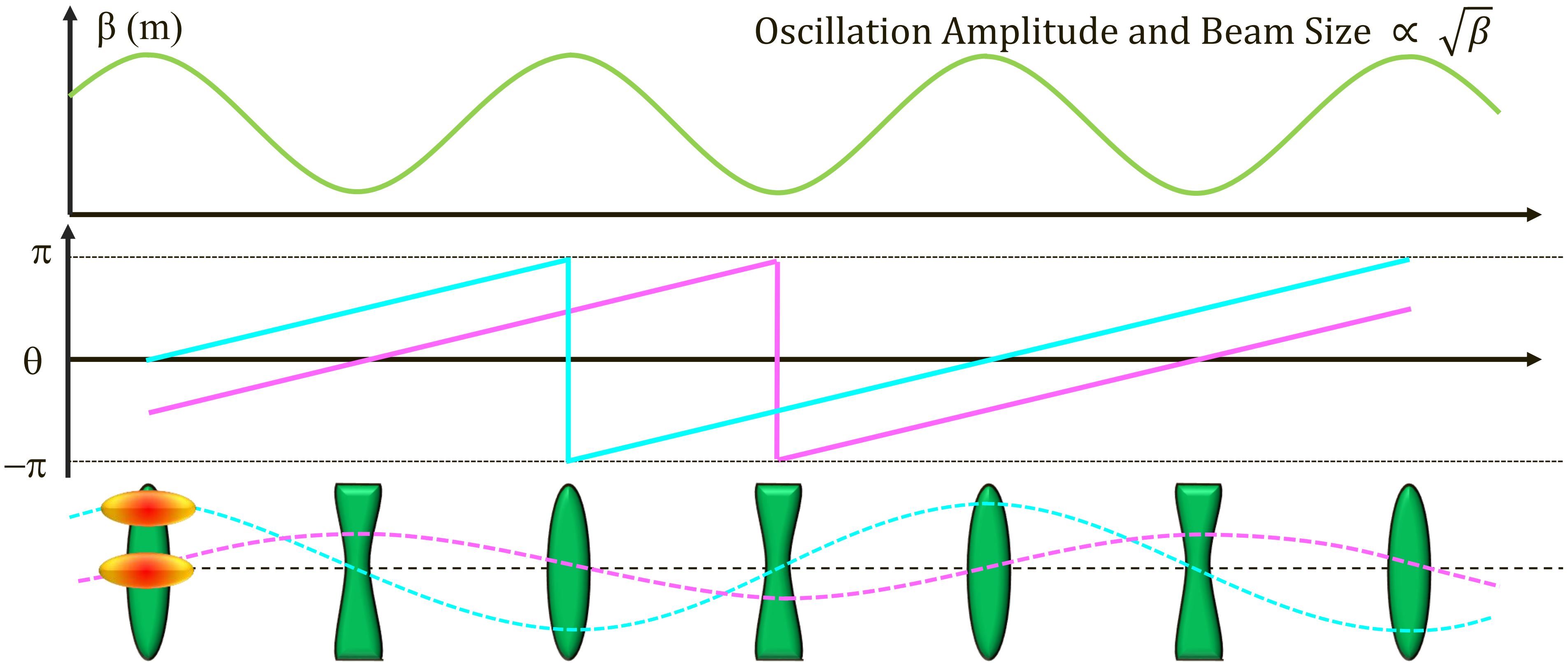
- Beam threading in the LHC
  - One beam at a time, ~1 hour per beam
  - Beam intercepted by the closest downstream collimator
  - Correct trajectory, open collimator, carry on



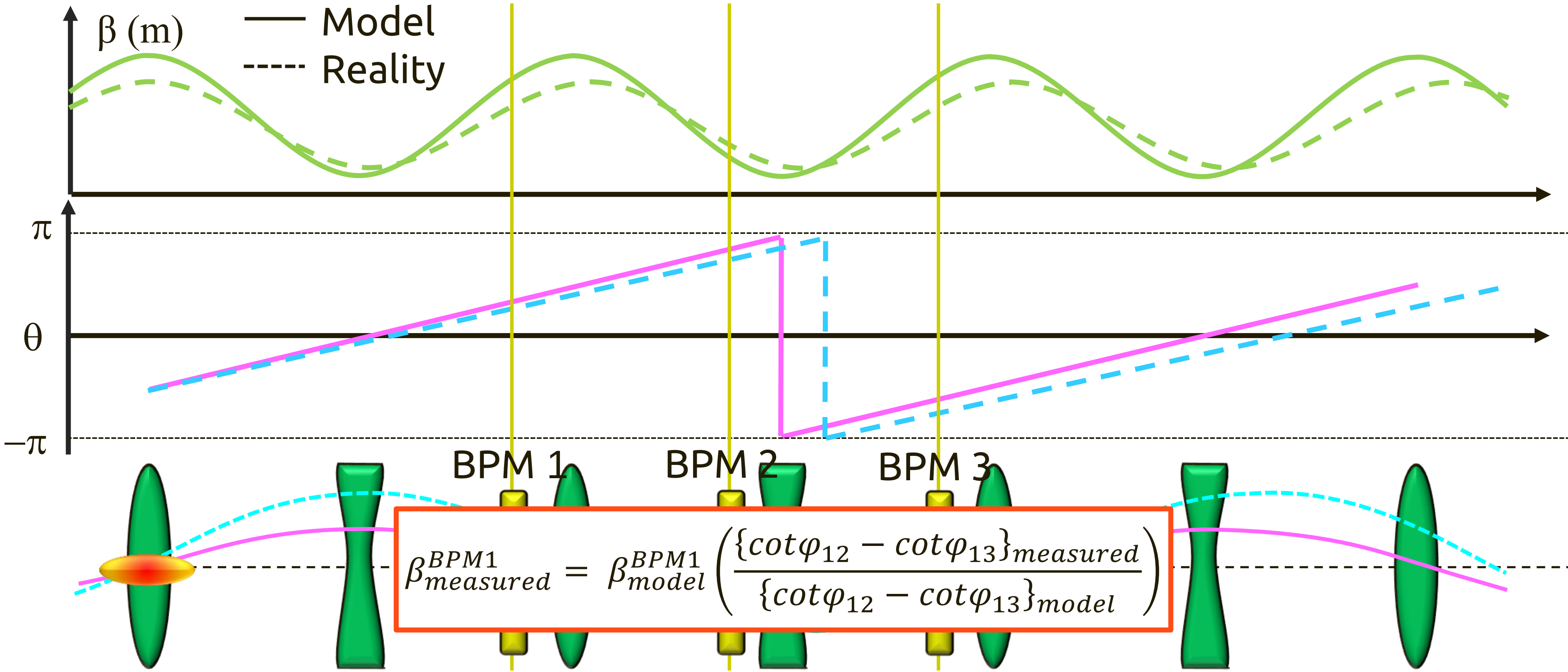
Accelerator beta function measurement with BPMs



Accelerator beta function measurement with BPMs



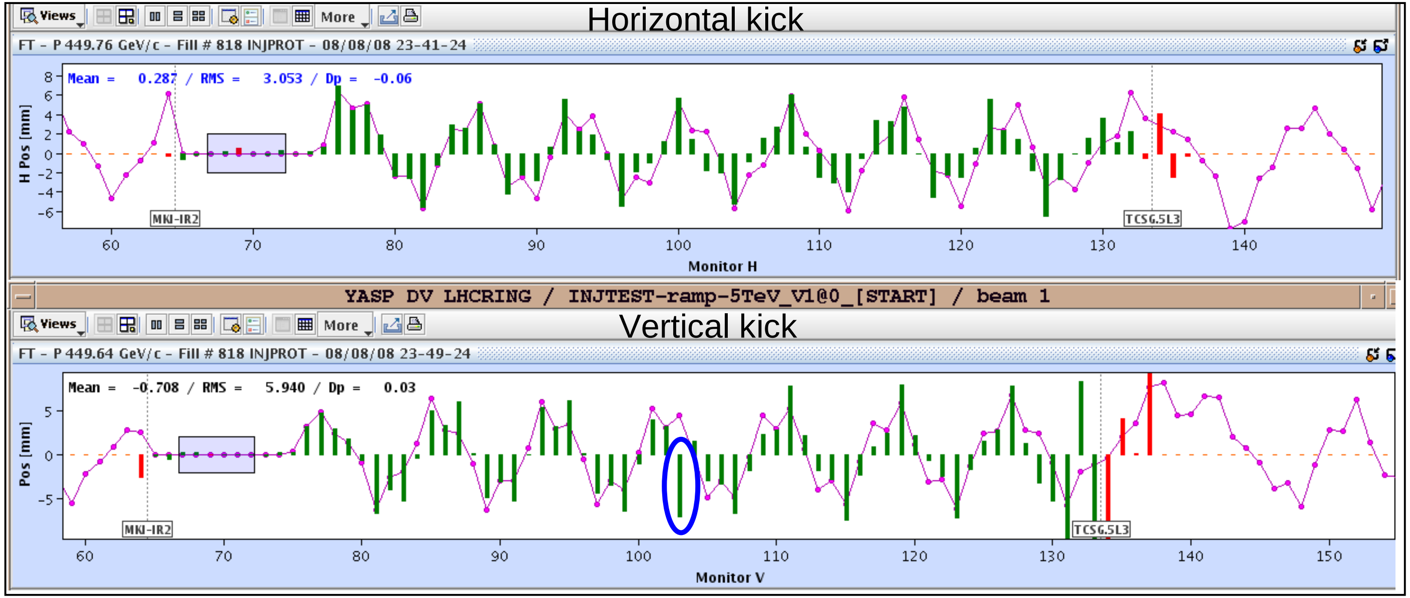
Accelerator beta function measurement with BPMs



$$\beta^{BPM1}_{measured} = \beta^{BPM1}_{model}\left(\frac{\{cot\varphi_{12} - cot\varphi_{13}\}_{measured}}{\{cot\varphi_{12} - cot\varphi_{13}\}_{model}}\right)$$

Online analysis of BPM data

- Easy identification of polarity errors with 45° BPM sampling
- Quick indication of phase advance errors
- Verification of optics functions (e.g. injection matching)

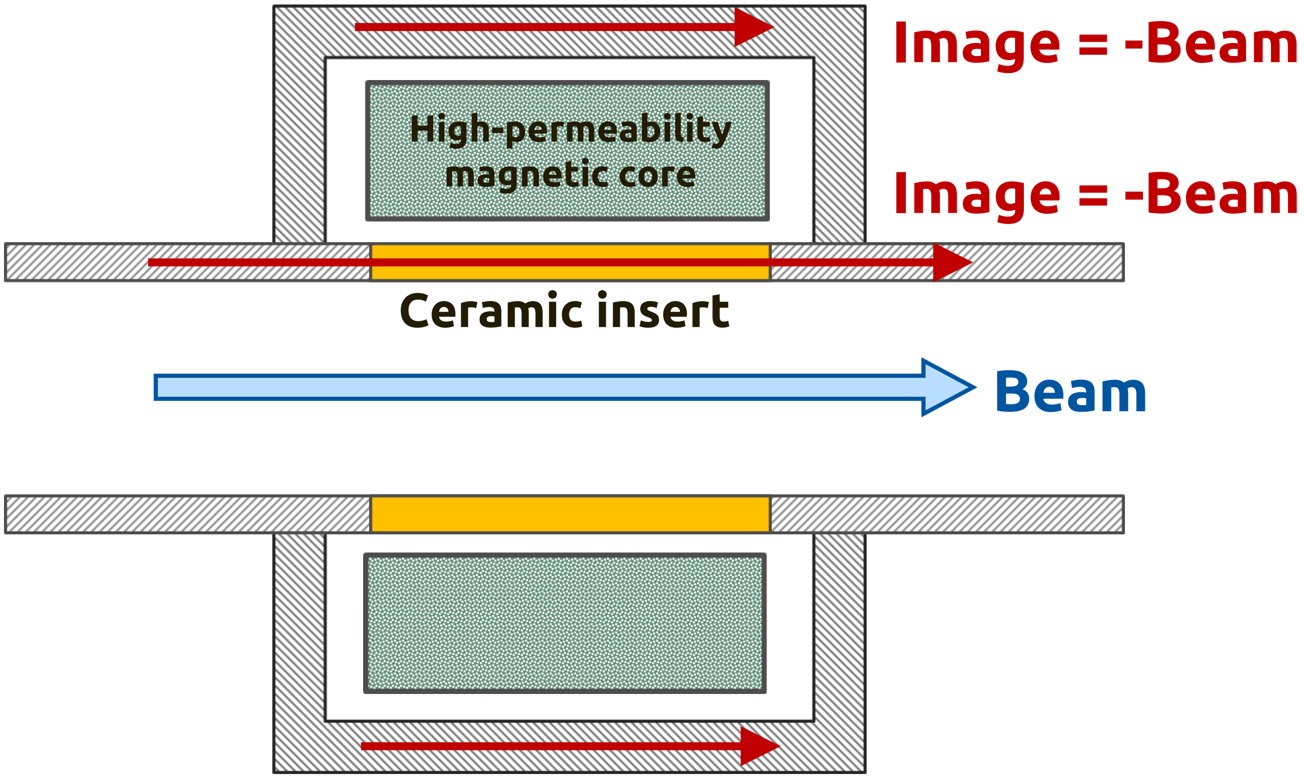


Optics phase error

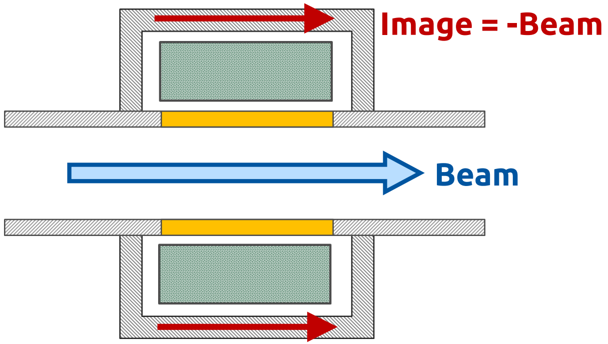
BPM polarity error

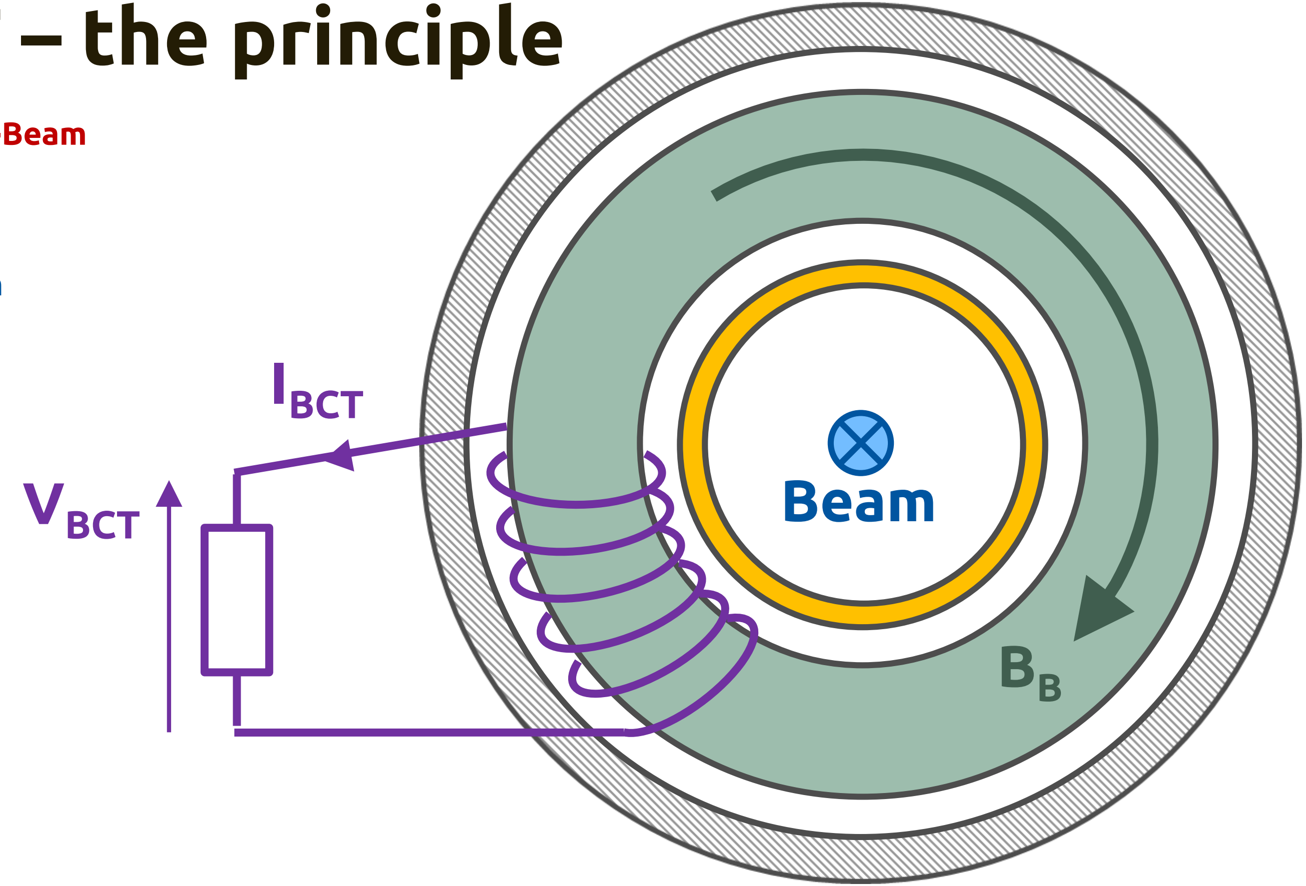
Beam Intensity Measurements with Beam Current Transformers (BCTs)

AC / Fast BCT – the principle



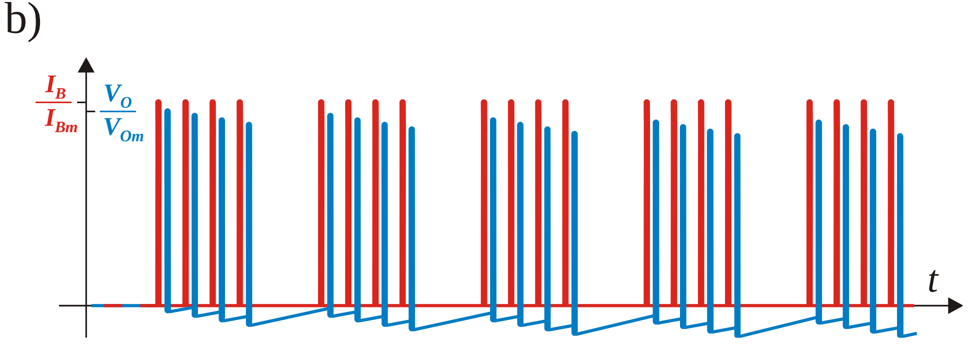
AC / Fast BCT – the principle

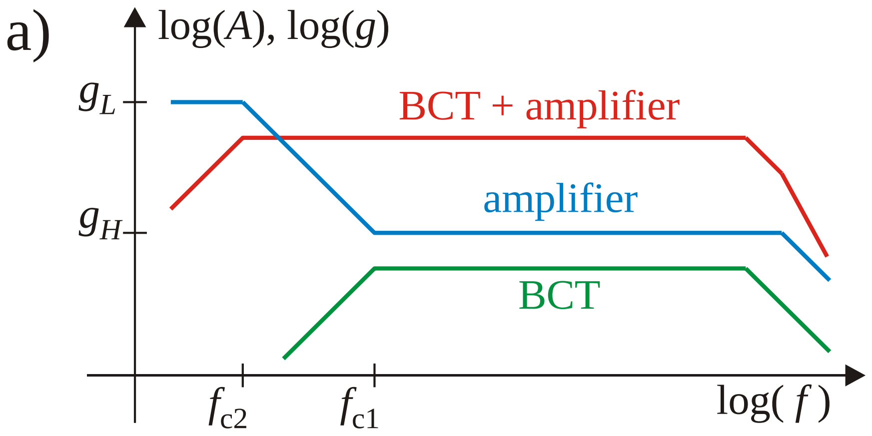


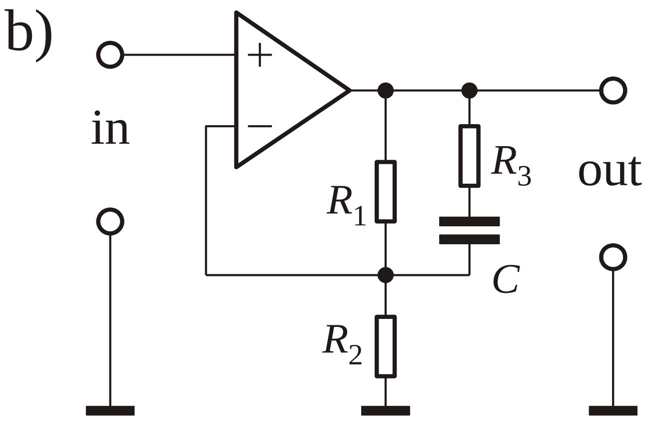


AC / Fast BCT – beam response

- **High-pass characteristics** – no low frequency signal components
  - Impedance of secondary winding ∝ frequency
  - Baseline droop – analogue or digital restoration

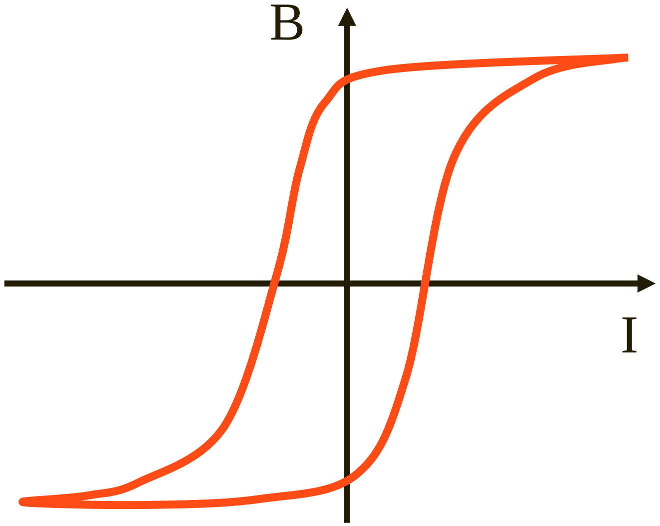






DC BCT

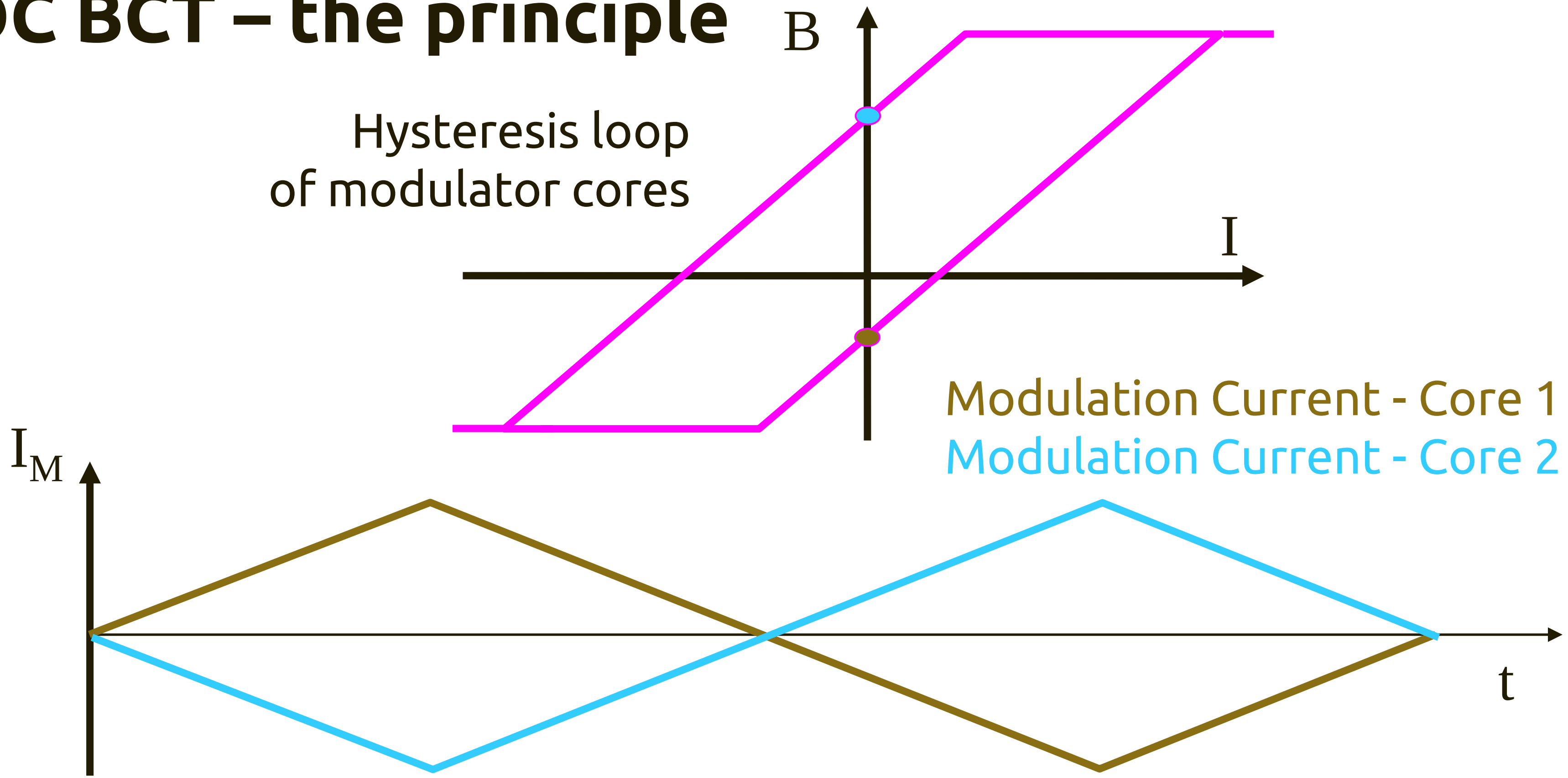
- AC BCTs cannot measure DC beam current (no dI/dt)
- DC beam current measurement needed in storage rings
- **DC BCTs** – take advantage of non-linear magnetisation curve and use two identical cores magnetized in the opposite way



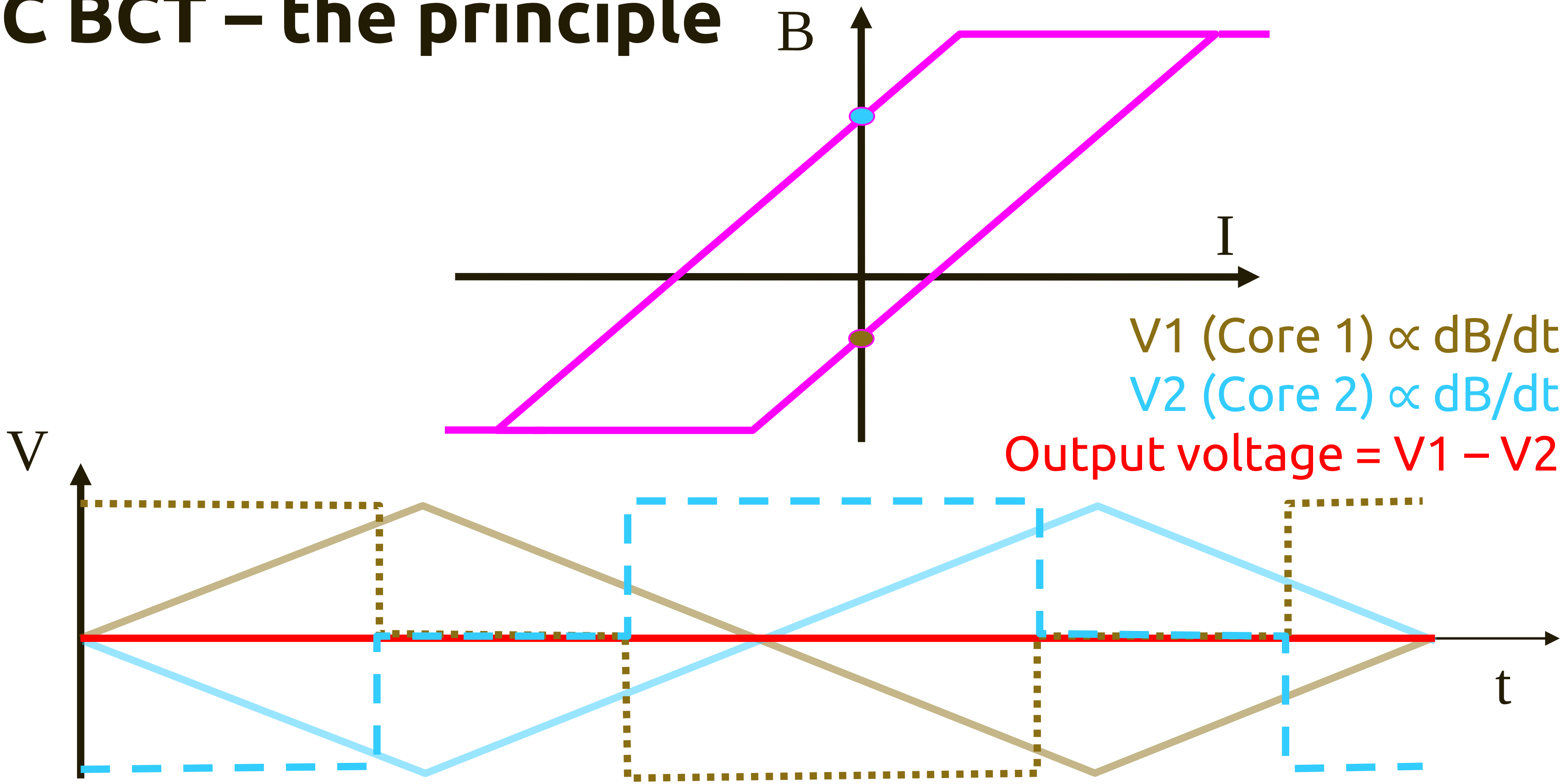
I – magnetizing current (i.e. beam current)

B – magnetic filed in the core

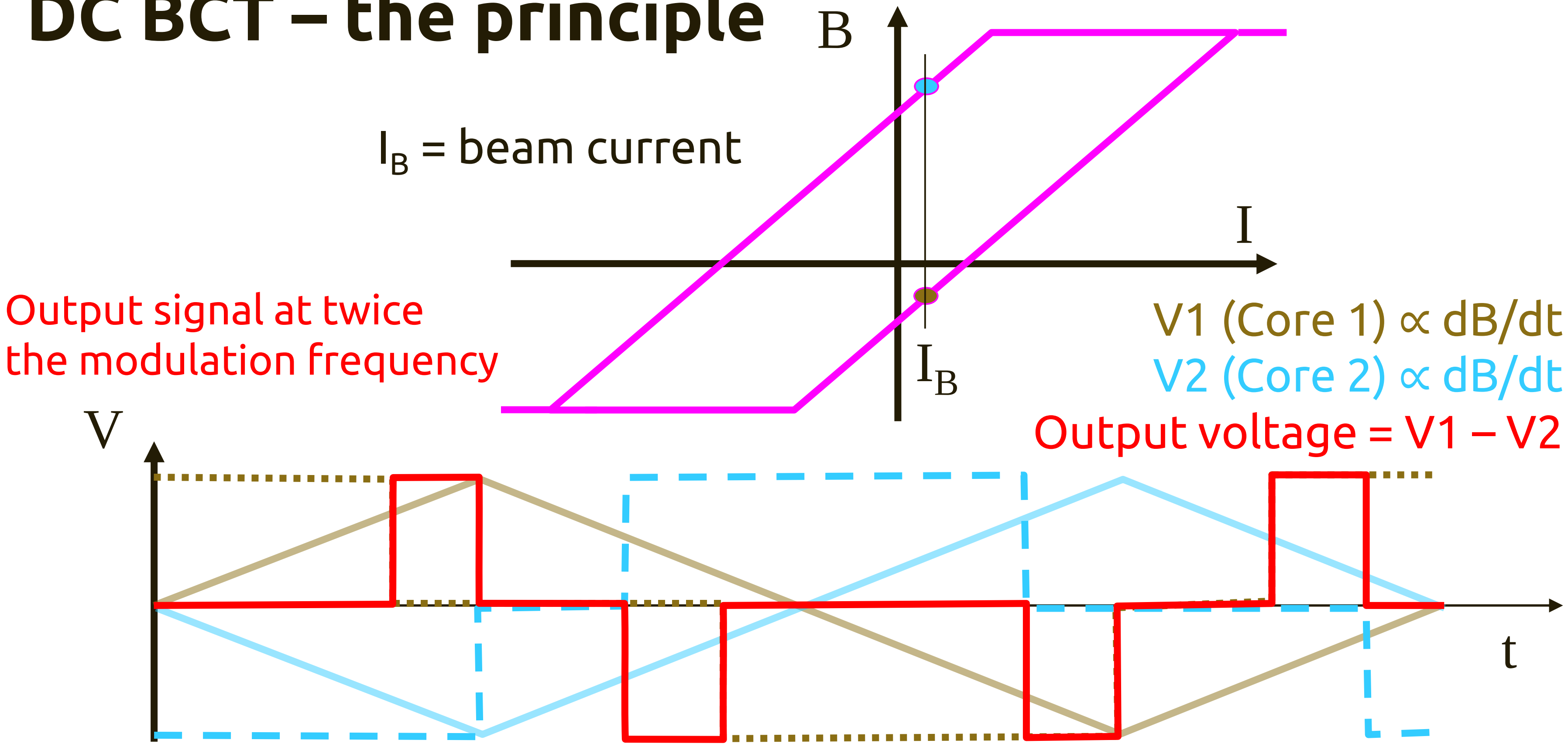
DC BCT – the principle



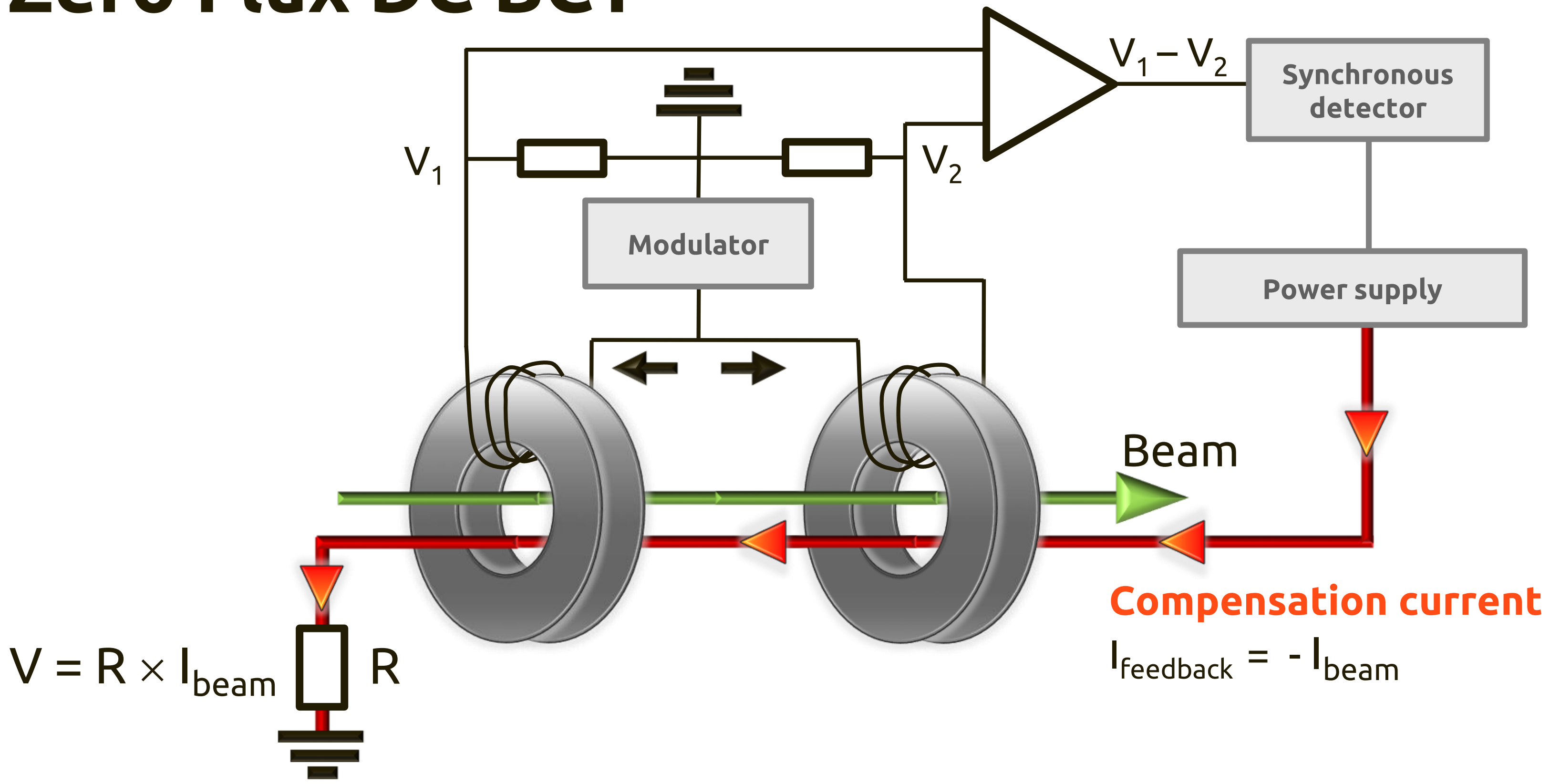
DC BCT – the principle



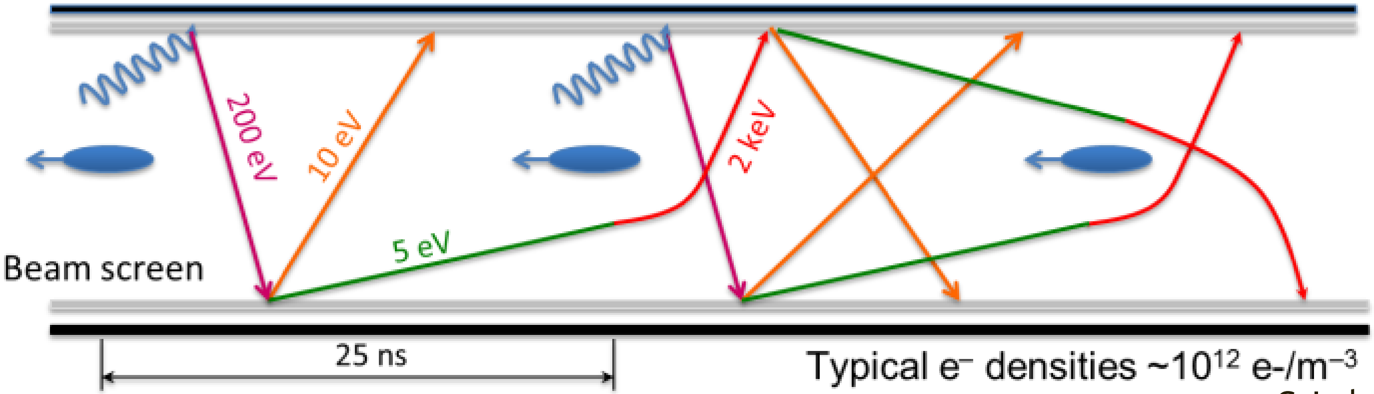
DC BCT – the principle

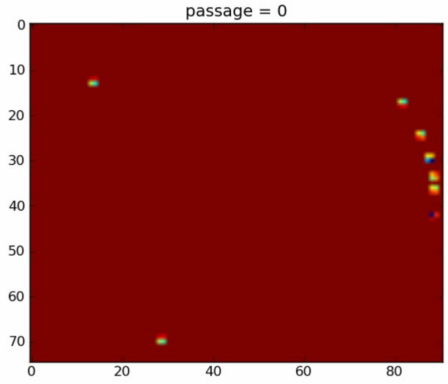


Zero Flux DC BCT



LHC electron cloud diagnostics with BCTs



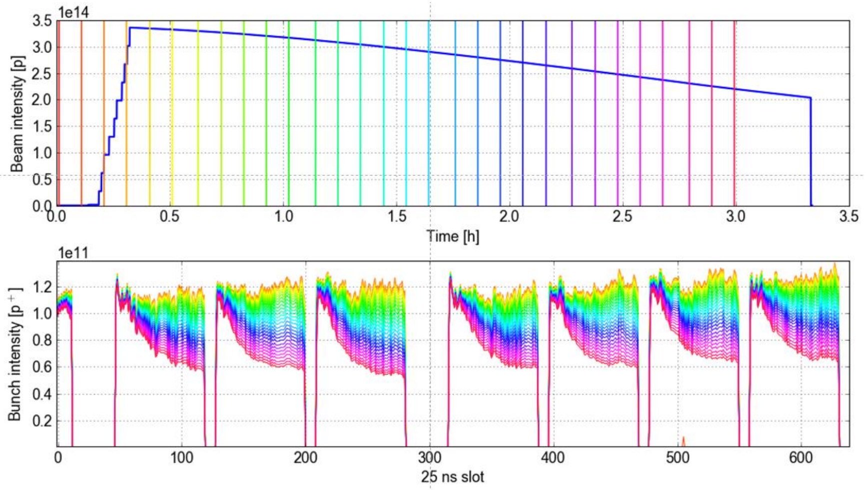


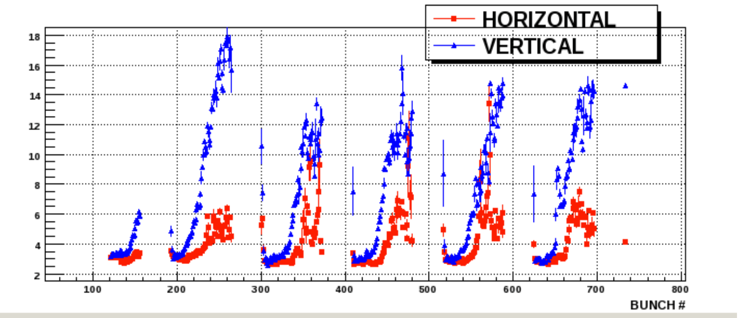
G. Iadarola, G. Rumolo, G. Arduini (CERN)

- Secondary Emission Yield (SEY) – emitted / impacting electrons
  - When SEY > threshold → multipacting (avalanche effect)
- Possible detrimental consequences:
  - Beam quality degradation: instabilities, emittance growth
  - Impact on the machine: vacuum degradation, background, heat load
- SEY can be reduced through electron bombardment (scrubbing)

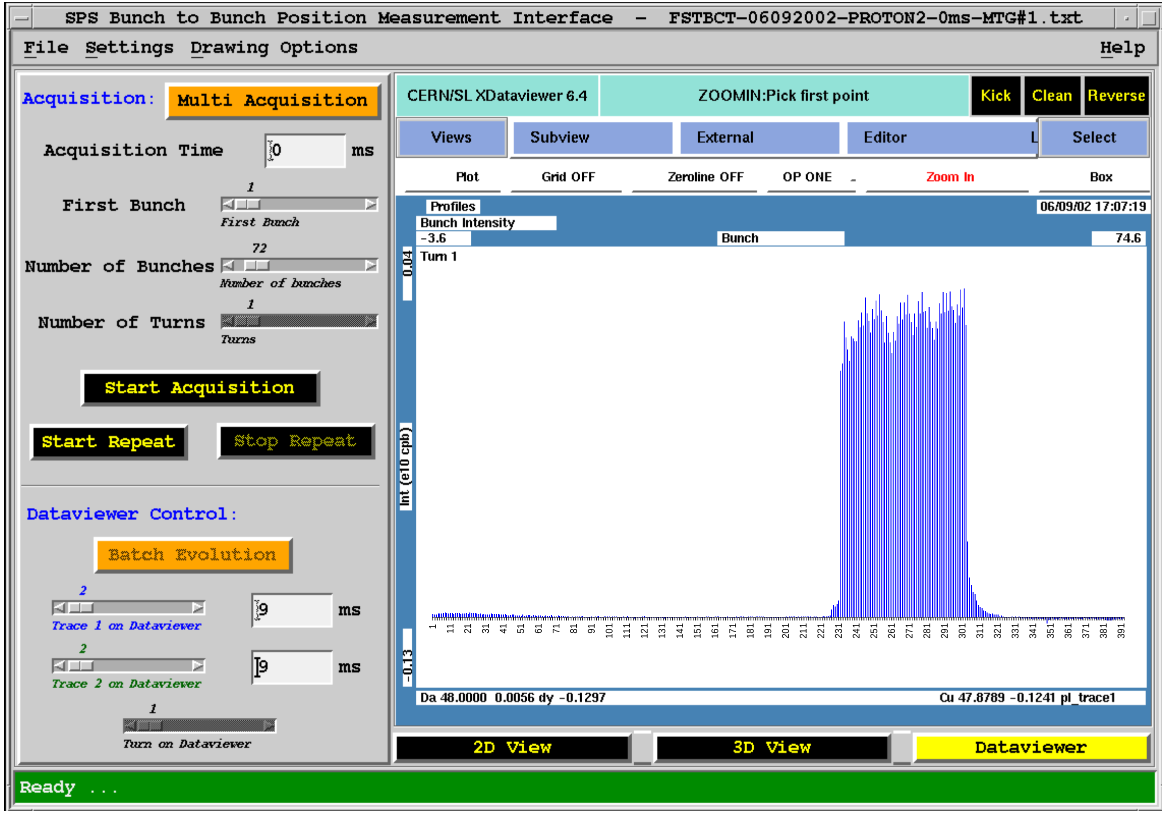
LHC electron cloud diagnostics with BCTs

- Instabilities in tails of bunch trains → increasing beam size → beam losses
- Countermeasures:
  - Chromaticity
  - Transverse feedback
  - Beam scrubbing
- Diagnostics:
  - **Fast BCTs** – bunch-by-bunch intensity measurements
  - **Synchrotron Light Monitor** – bunch-by-bunch profile measurements





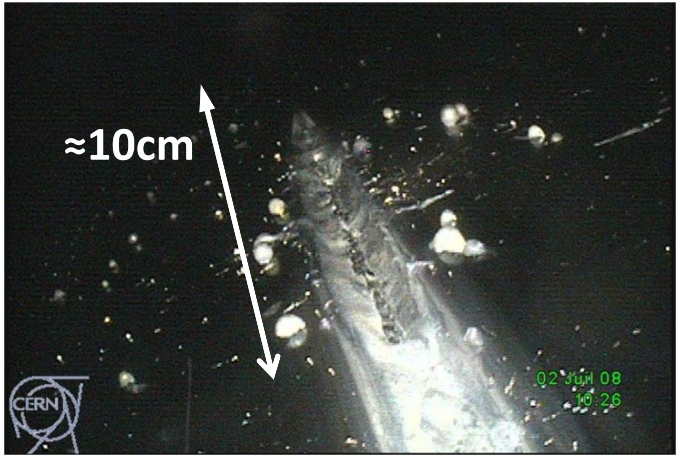
RF capture diagnostics with BCTs



Beam Loss Monitors (BLMs)

Beam Loss Monitoring

- Main functions of a BLM system:
  - Protect the accelerator from damage
  - Safely extract the beam to avoid superconducting magnet quenches
  - Provide diagnostics data to improve accelerator performance



2008 SPS incident: 2 MJ beam lost at 400 GeV

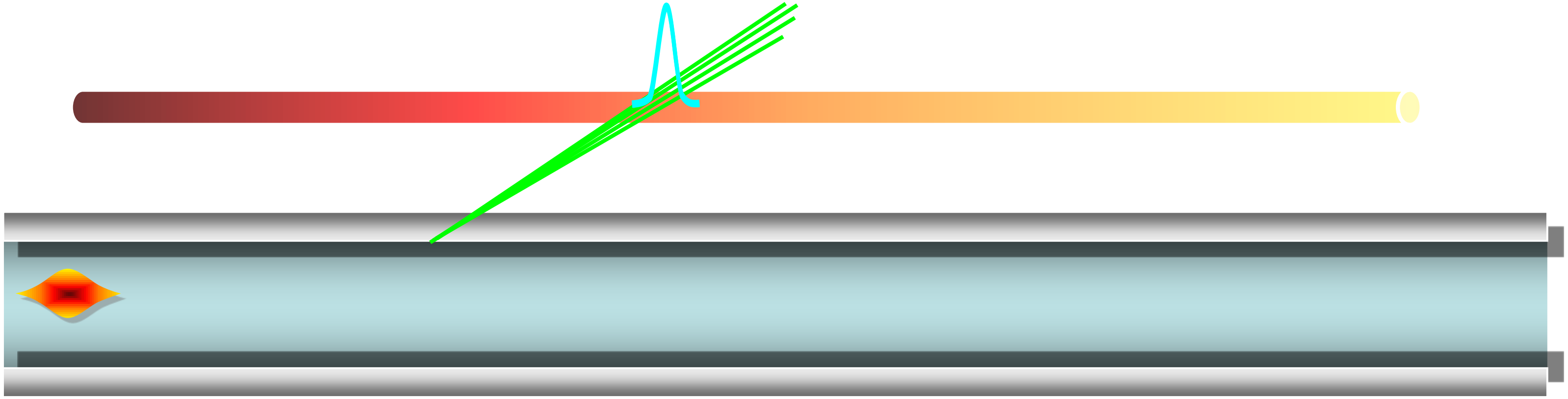
LHC beams and loss limits

Stored Energy	
Beam 7 TeV	2 x 362 MJ

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

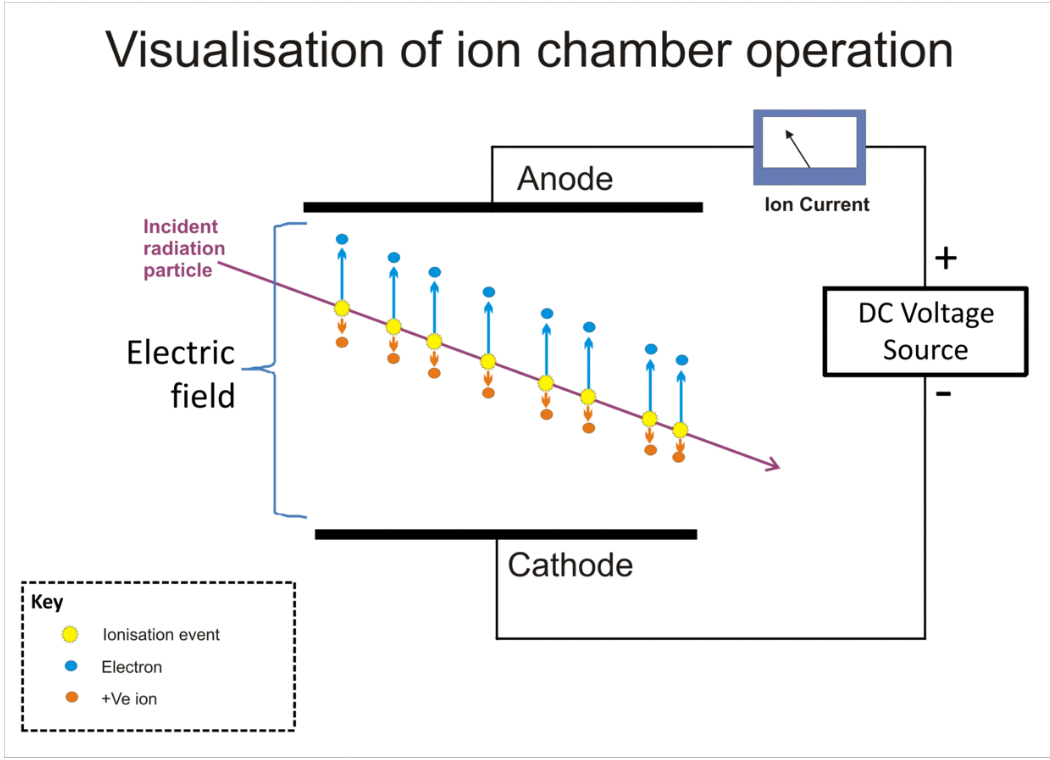
Long BLMs

- **Long ionisation chambers**
  - Several km long coaxial cables filled with gas
  - Detection of direct and reflected pulse – spacial resolution of several meters
  - Dynamic range of up to 10^4
- **Fibre optic BLMs**
  - Electric signals replaced by light generated via Cherenkov radiation



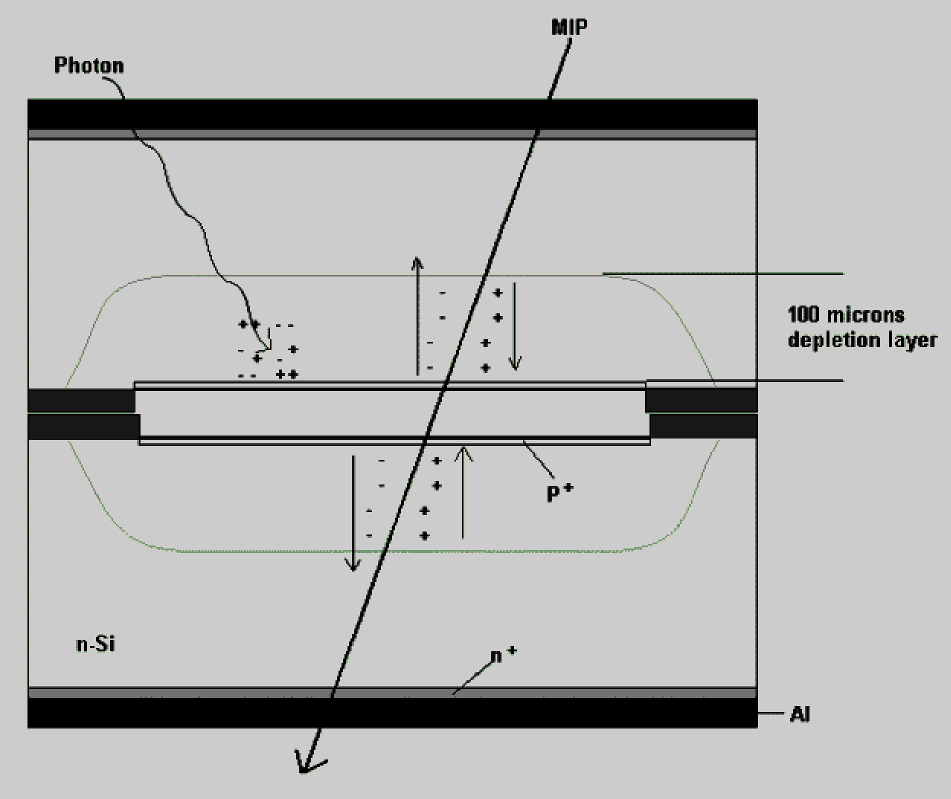
Ionisation chamber BLMs

- Formed by metal plates, filled with inert gas, high potential across the plates
- Electron-ion pair creation by high-energy particles = current on electrodes
- Dynamic range of < 10^8
- Slow response (µs) due to ion drift time
- Very radiation tolerant, long lifetime (20+ years)



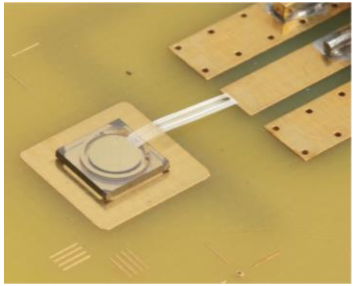
PIN photodiode BLMs

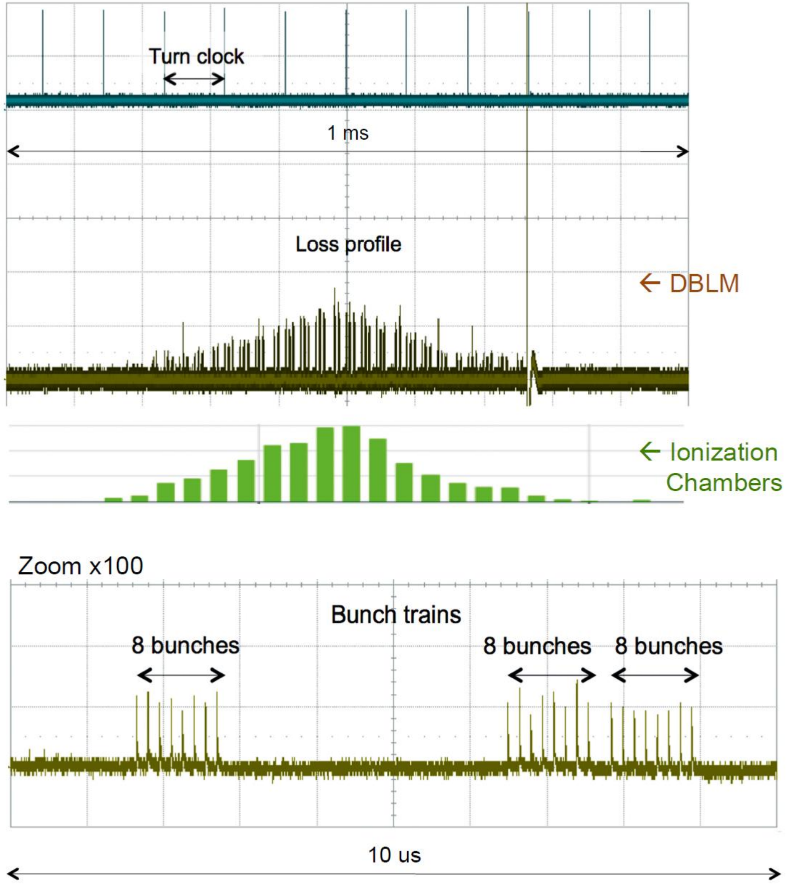
- Two reverse-biased PIN photodiodes mounted face-to-face
- Detect coincidence of ionising particles crossing both diodes
- Count rate proportional to beam loss – limited by integration time
- Can distinguish X-rays (low coincidence) and ionizing particles (high coincidence)
- Dynamic range up to 10^9



Diamond BLMs

- pCVD diamond between two metal electrodes
- Ionizing particles crossing the diamond generate current flow between the electrodes
- Very fast response time (ns)
- Used in the LHC for bunch-by-bunch losses

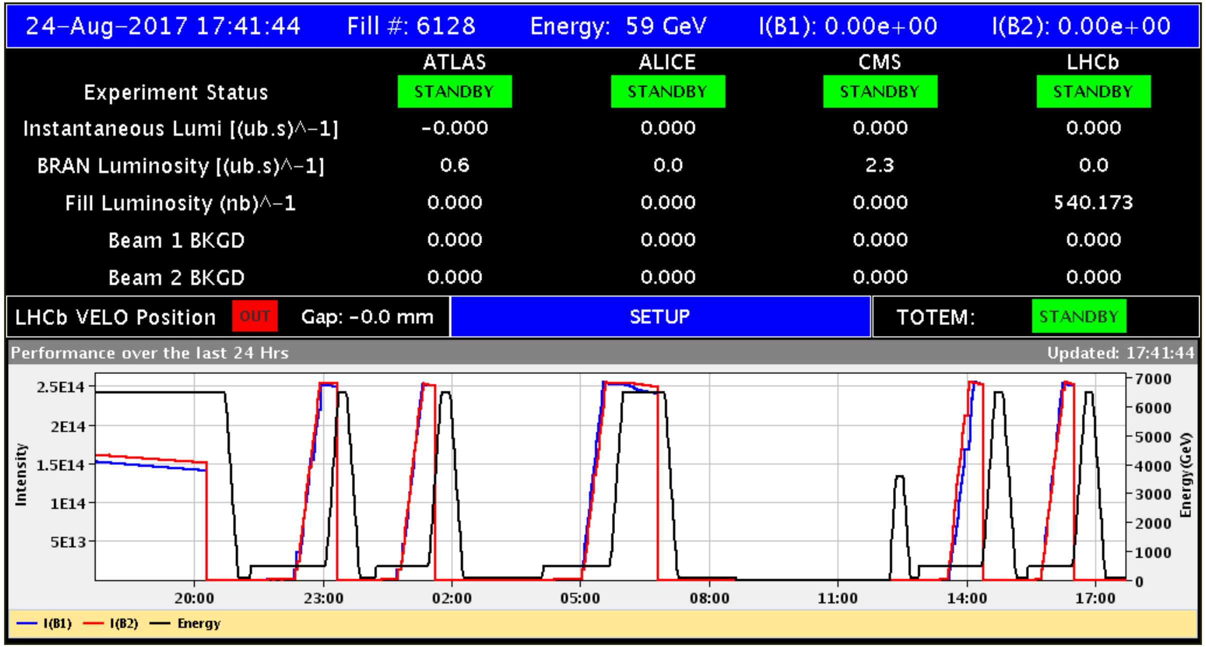




Courtesy of E. Griesmayer

"LHC 16L2" diagnostics with BLMs – motive

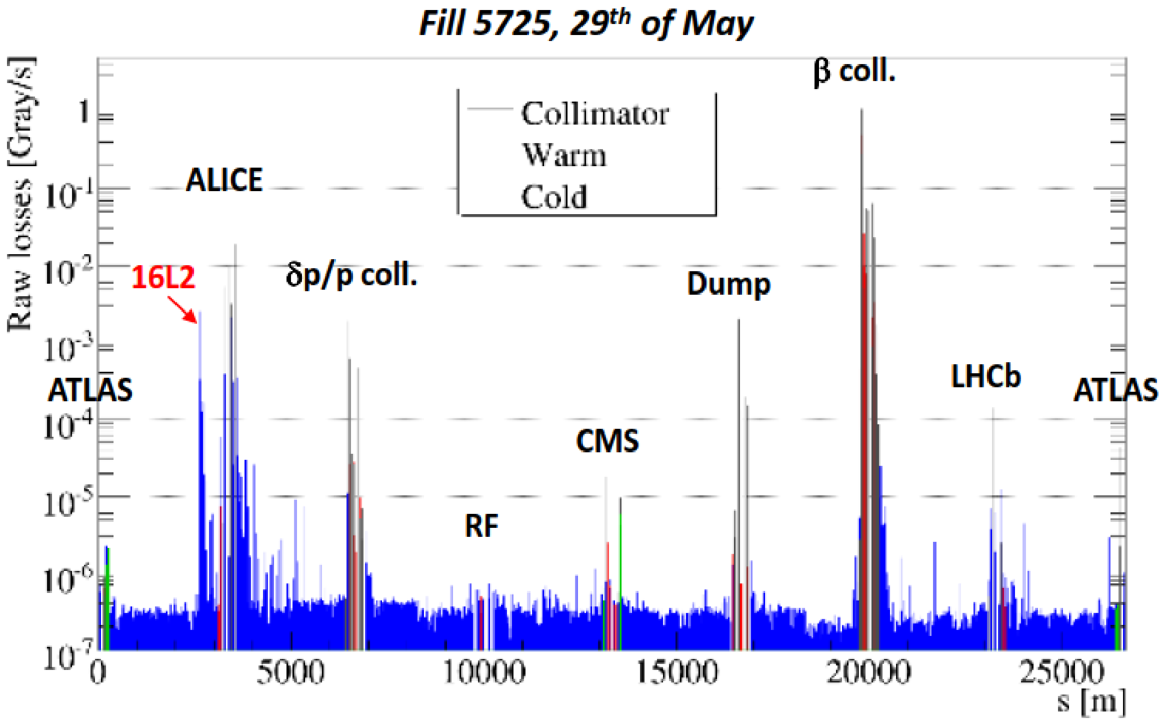
- Beam lost over and over again due to excessive losses
- Significant impact on the LHC availability in 2017



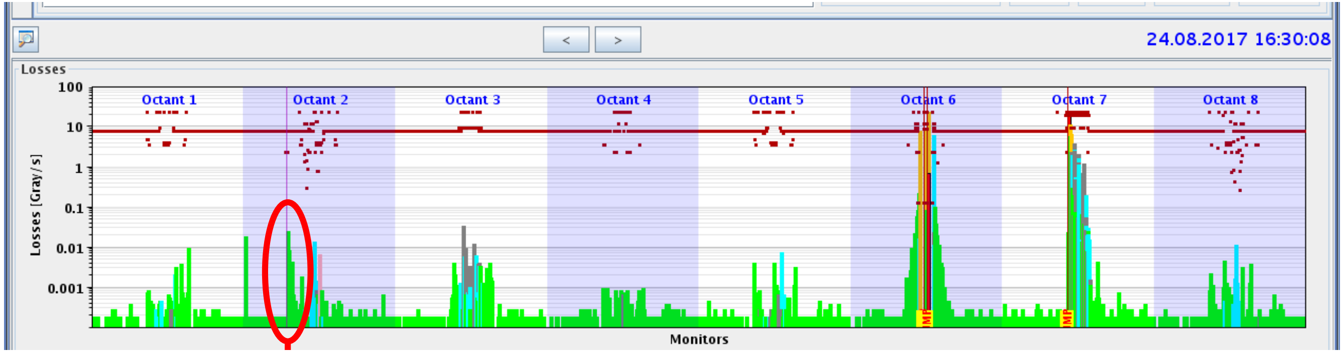
Dump #1 5.9TeV | RF issue | Dump #2 7TeV | Dump #3 0.9TeV | Dump #4 0.8TeV

"LHC 16L2" diagnostics with BLMs – first event

- No aperture restriction seen after local measurements
- Clear signature of losses from both beams

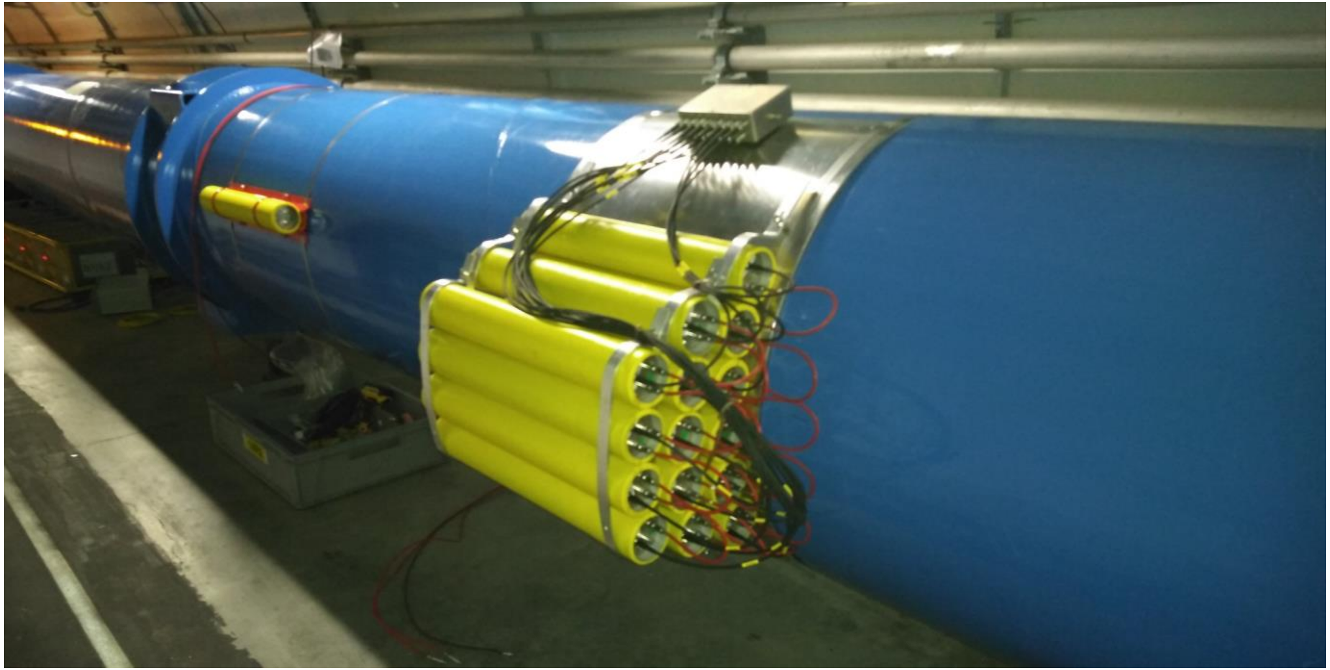


“LHC 16L2” diagnostics with BLMs – loss evolution



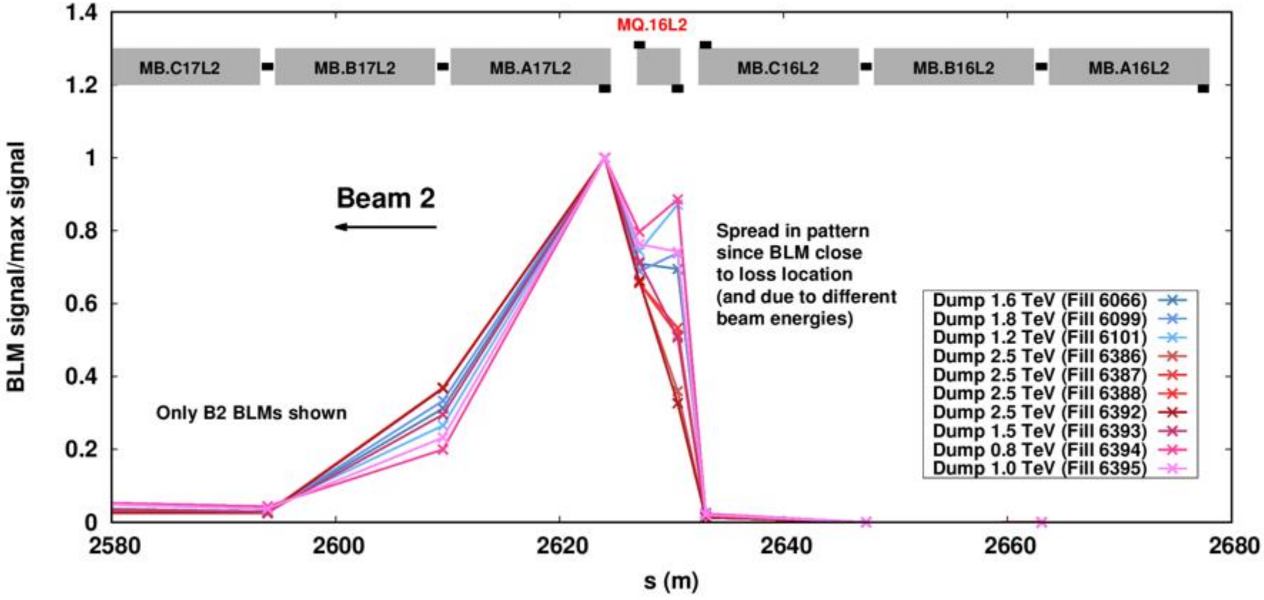
“LHC 16L2” diagnostics with BLMs – extra sensitivity

- How to quickly improve BLM sensitivity by a factor of 15



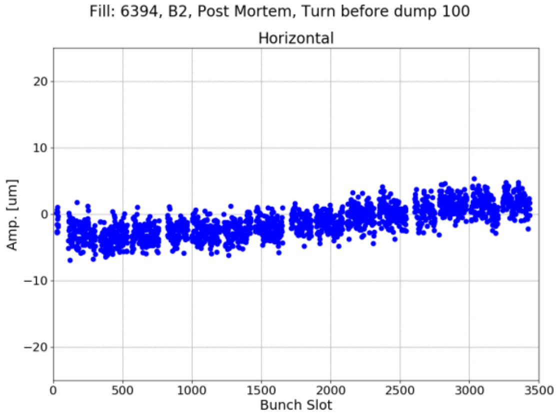
“LHC 16L2” diagnostics with BLMs – exact location

- BLM spatial patterns clearly indicate losses from one specific interconnection: quadrupole 16L2 (within 1 m)

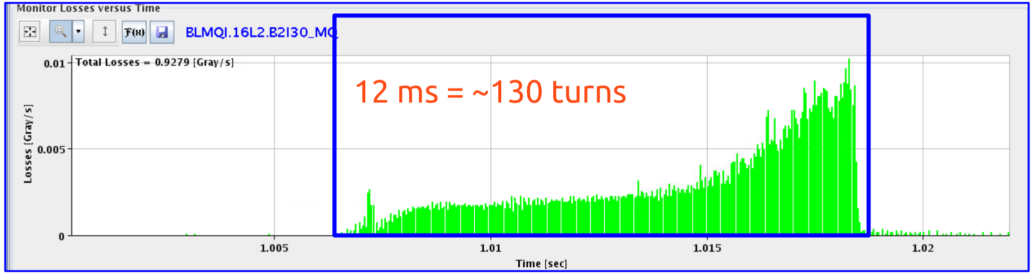


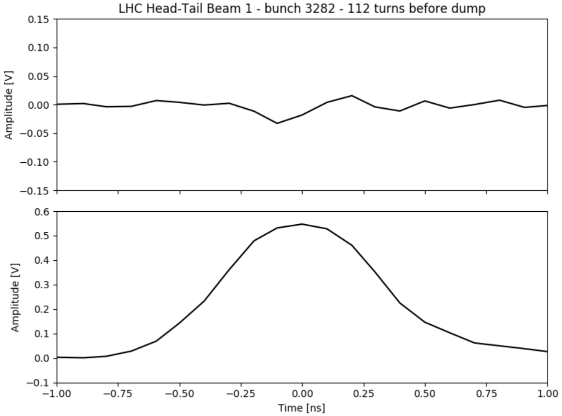
"LHC 16L2" diagnostics with BLMs – additional data

- Many dumps triggered by BLMs near primary collimators (far away from 16L2)
  - Indication of a growing transverse instability



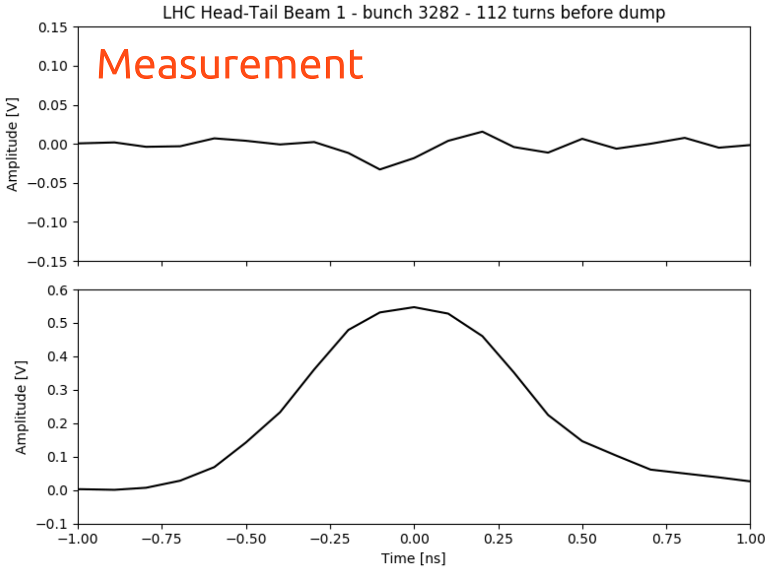
Losses at BLM

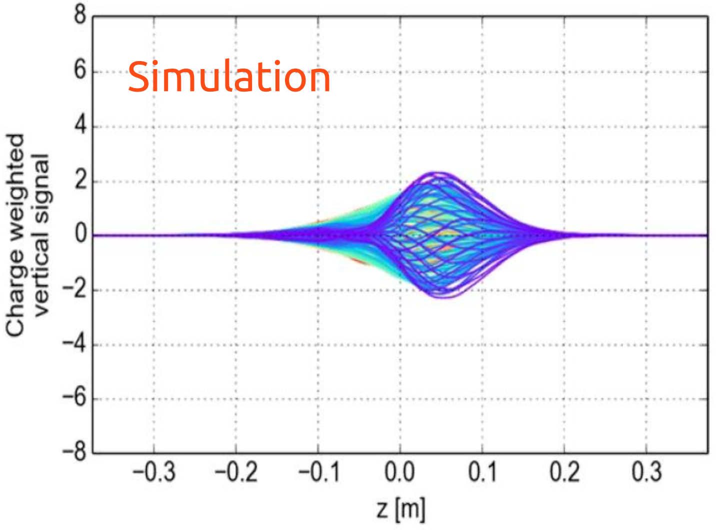




"LHC 16L2" diagnostics with BLMs – additional data

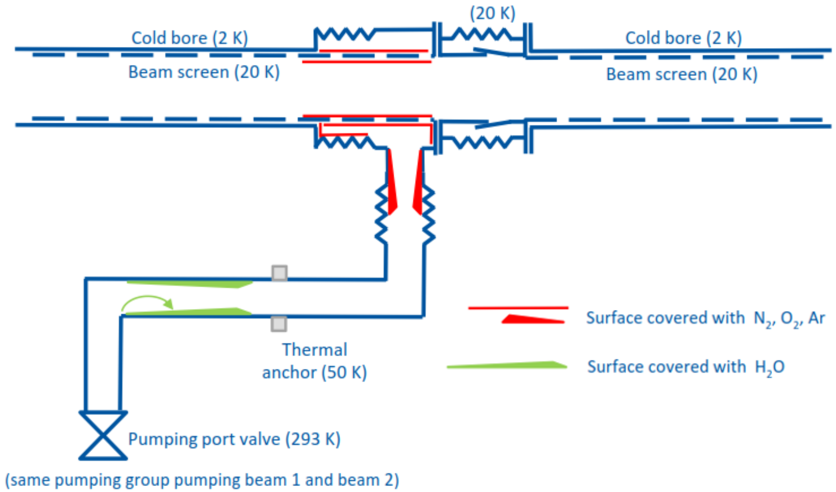
- Clear instability in the tail of the bunches
  - Simulations performed to recreate a similar instability
  - Required conditions: large density of electrons over a short distance – ionised gas cloud

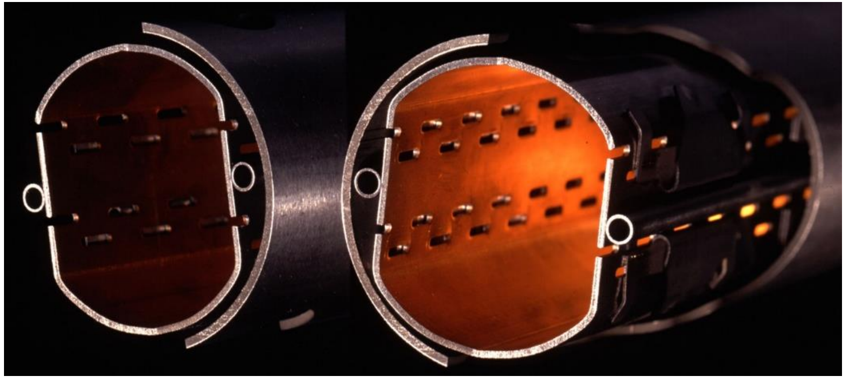




"LHC 16L2" - conclusion

- Some air was trapped on beam screen and cold bore during vacuum pump down
  - Solid nitrogen and oxygen formed inside the beam vacuum
  - Particles fall into the beam and immediately vaporise locally rising pressure
  - Beam interactions produce an ionised gas cloud leading to losses and instabilities





Summary

- Focus of today: general introduction, BPMs, BCTs and BLMs
  - Principle of operation
  - Diagnostics use
- Tomorrow's subjects:
  - Transvers profile monitoring
  - Tune, coupling and chromaticity measurements and feedback

- For those following the BI afternoon course:
  - 3 sessions on beam signals and BPM design: 2 x simulation software + 1 x practical hands-on exercises
    - **Please install the BI simulation software on your laptop today!**
  - 3 sessions on profile measurements (transverse and longitudinal): hands-on experiments