Beam Instrumentation and Diagnostics (Lecture 1)

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Introduction

- What do we mean by beam instrumentation?
  - The "eyes" of the machine operators
    - i.e. the instruments that observe beam behaviour
    - An accelerator can never be better than the instruments measuring its performance!
- What does work in beam instrumentation entail?
  - Design, construction & operation of instruments to observe particle beams
  - R&D to find new or improve existing techniques to fulfill new requirements
  - A combination of the following disciplines
    - Applied & Accelerator Physics; Mechanical, Electronic & Software Engineering
- What beam parameters do we measure?
  - Beam Position
    - Horizontal and vertical throughout the accelerator
    - At a specific location for tune, coupling & chromaticity measurements
  - Beam Intensity (& lifetime measurement for a storage ring/collider)
    - Bunch-by-bunch charge and total circulating current
  - Beam Loss
    - Especially important for high brightness and superconducting machines
  - Beam profiles
    - Transverse and longitudinal distribution

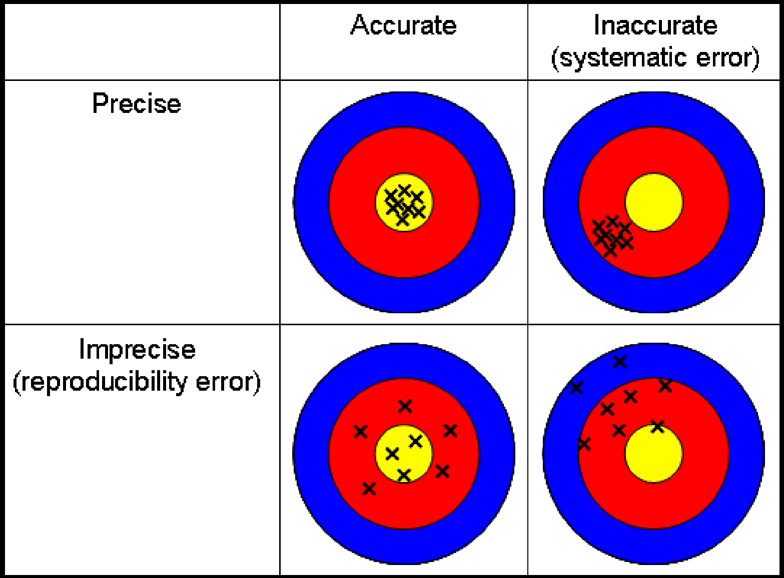
What is meant by Beam Diagnostics?

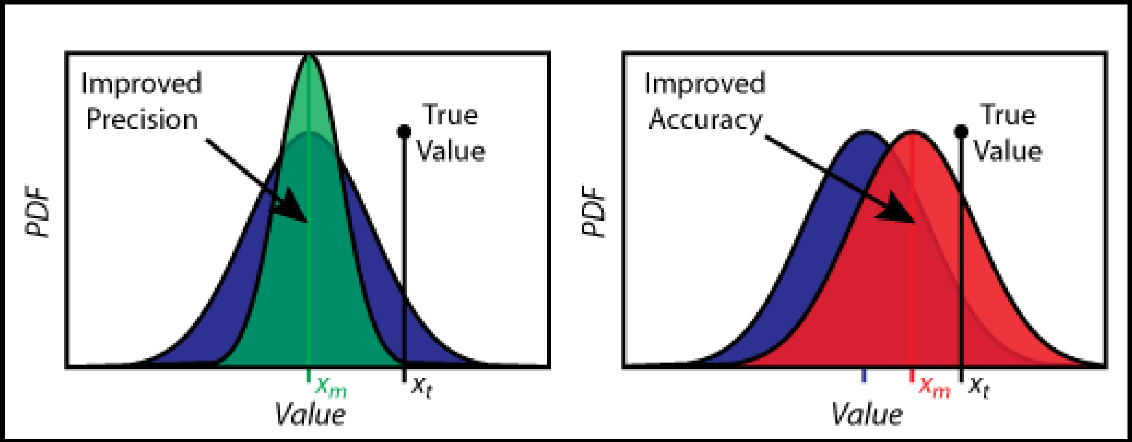
- Beam Diagnostics
  - Making use of beam instrumentation

- What do we consider as beam diagnostics?
  - Operating the accelerators
    - Using instrumentation to measure and correct standard parameters
      - Orbit, tune, chromaticity control etc.
  - Improving the performance of the accelerators
    - Understanding current performance to allow future improvements
    - Requires the measurement of performance indicators
      - Luminosity, brilliance (intensity and size) etc.
  - Understanding accelerator limitations
    - Beam loss, instabilities, emittance growth etc.
  - Detecting equipment faults
    - Aperture restrictions, polarity inversions, wrong settings etc.

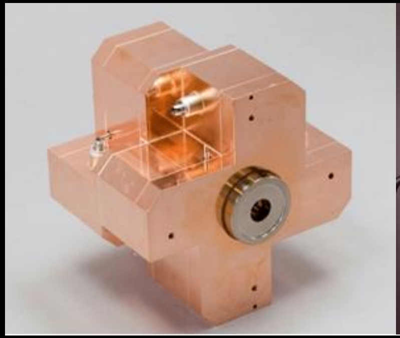
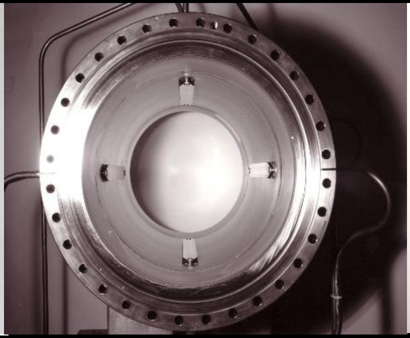
How do we Qualify Beam Measurements?

- Accuracy, Precision, Resolution
  - Very often confused in day-to-day language
    - Accuracy – also known as the trueness of a measurement
    - Precision – how well a measurement can be reproduced
    - Resolution – the smallest possible difference measureable



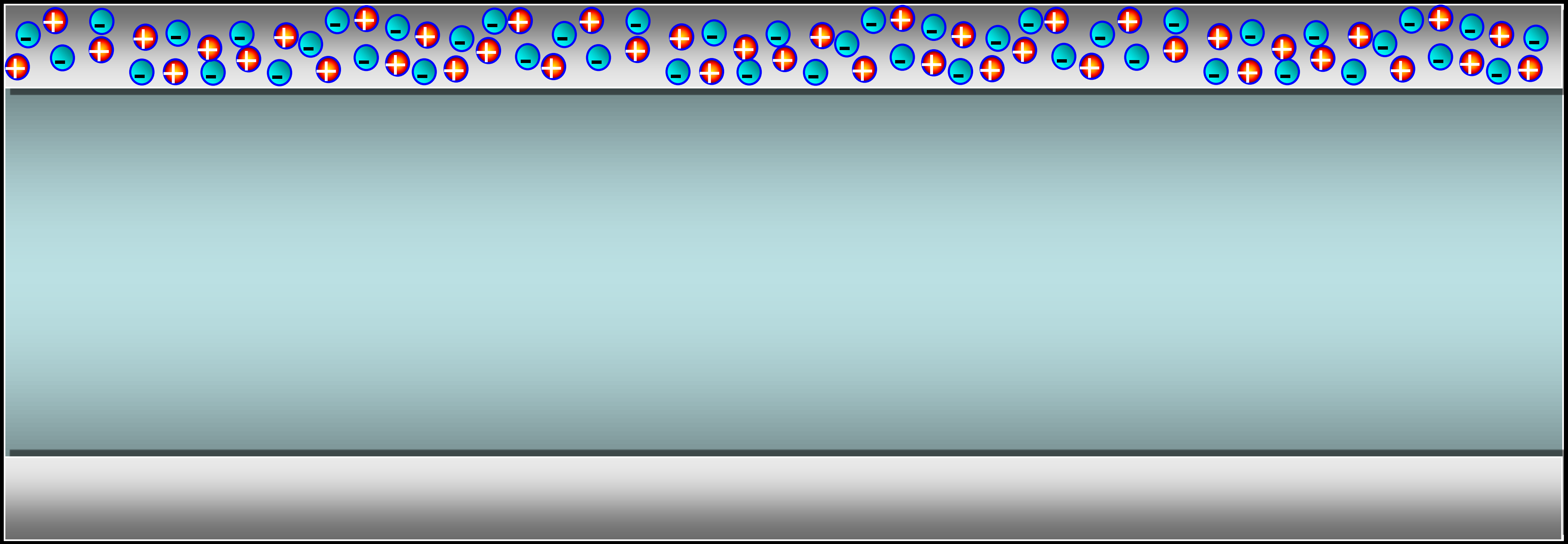


- Example for a BPM
  - Mechanical & electrical offsets and gain factors influence accuracy
  - Various noise sources or timing jitter influence the precision
  - Number of bits in the ADC will limit the resolution

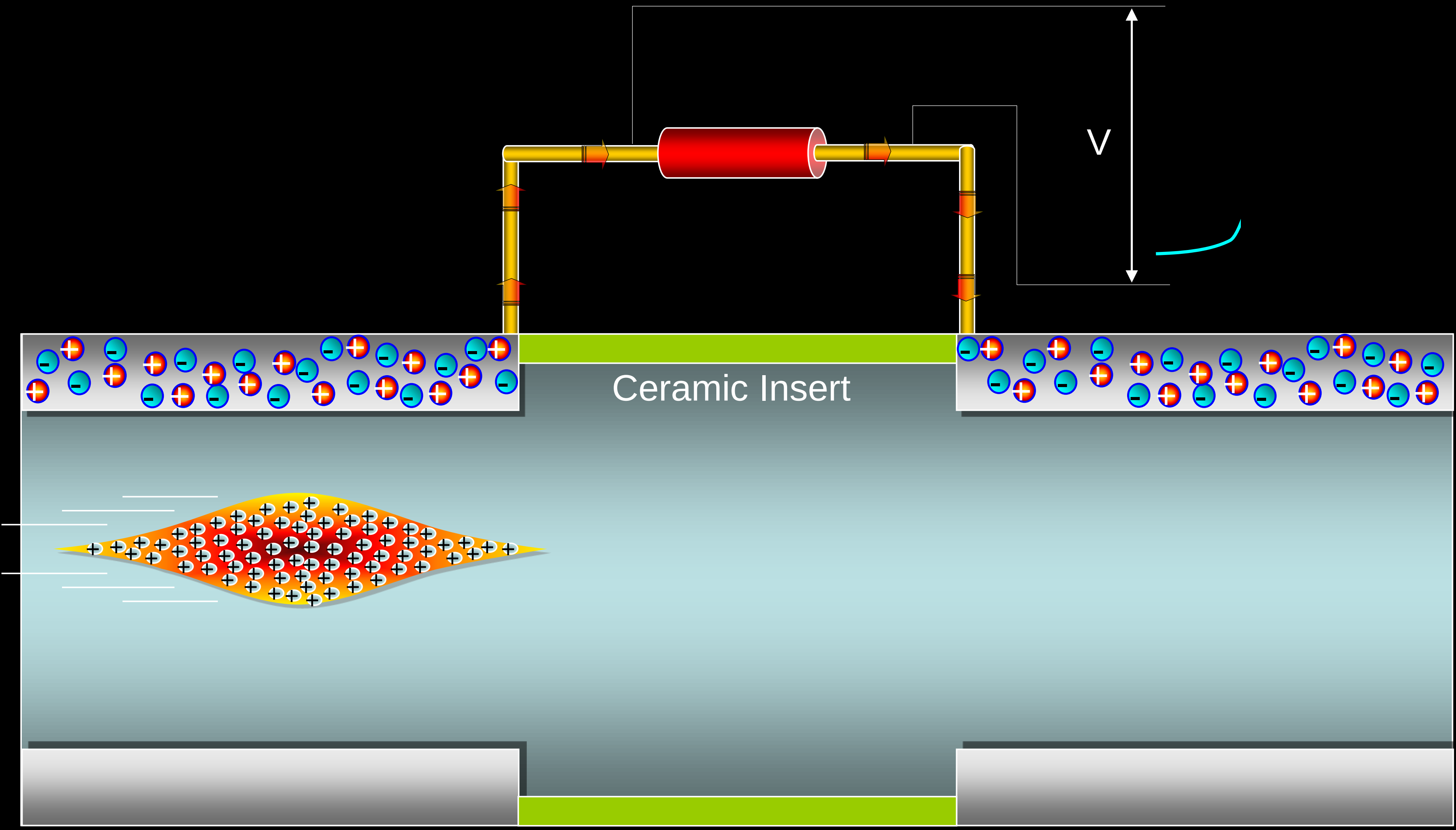




Beam Position Systems

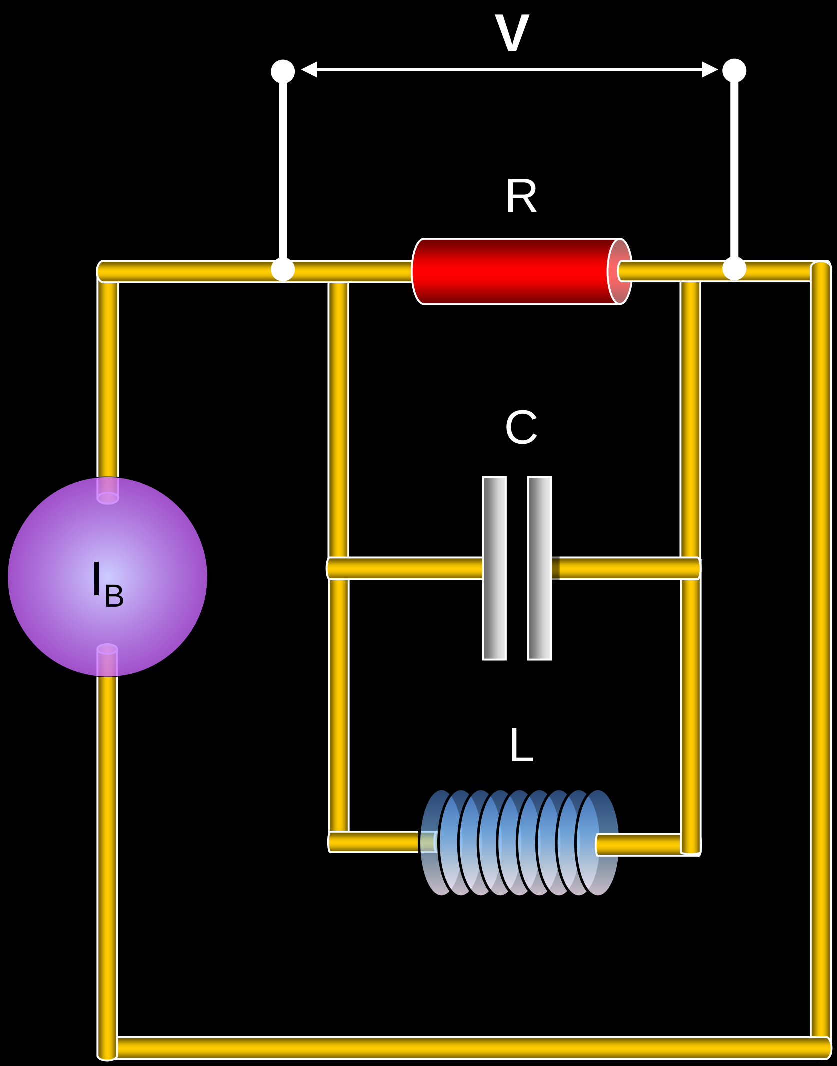
Measuring Beam Position – The Principle

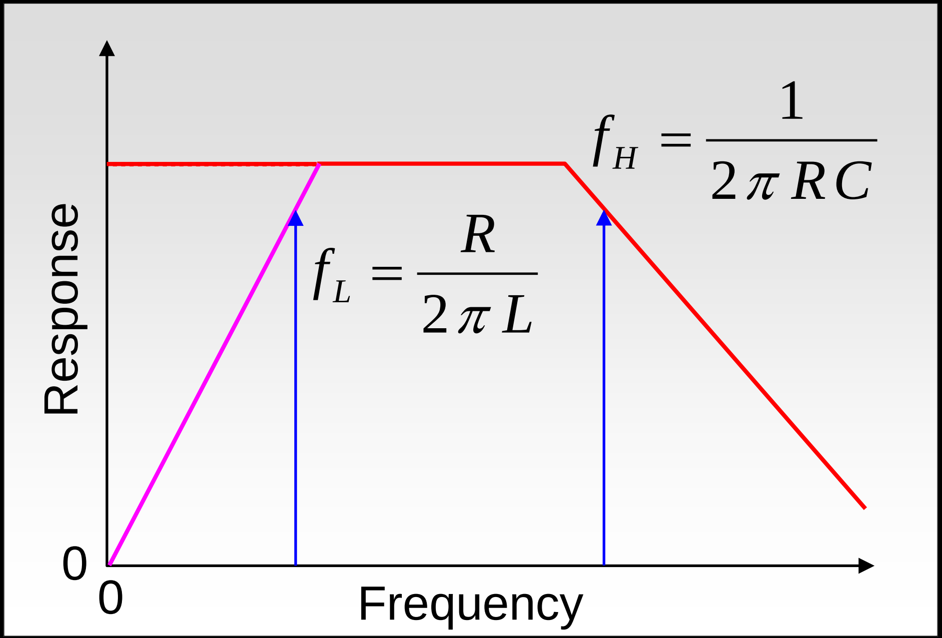


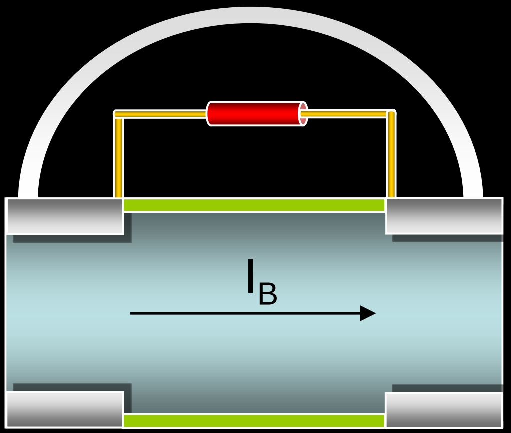
Wall Current Monitor – The Principle



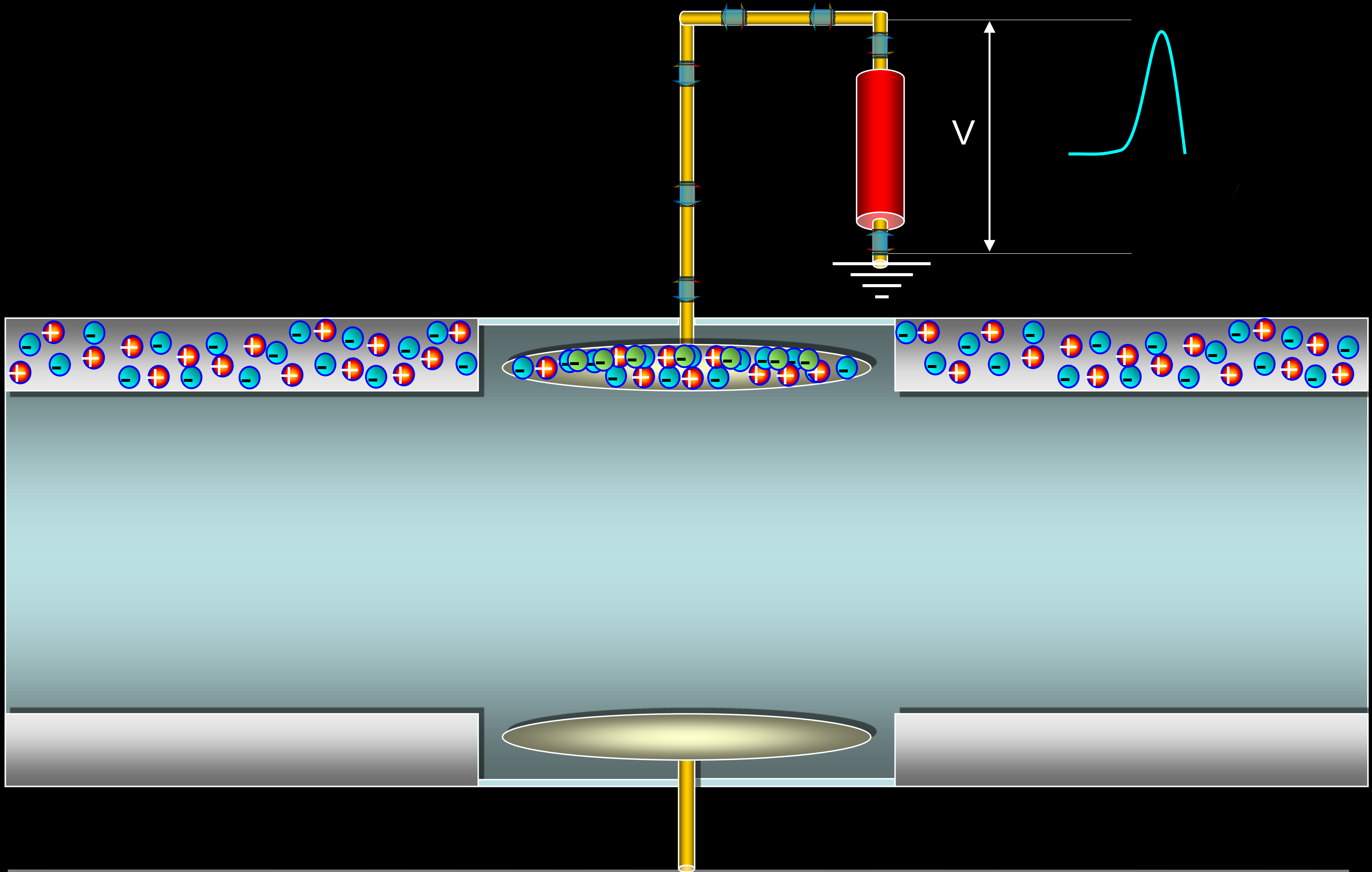
Wall Current Monitor – Beam Response



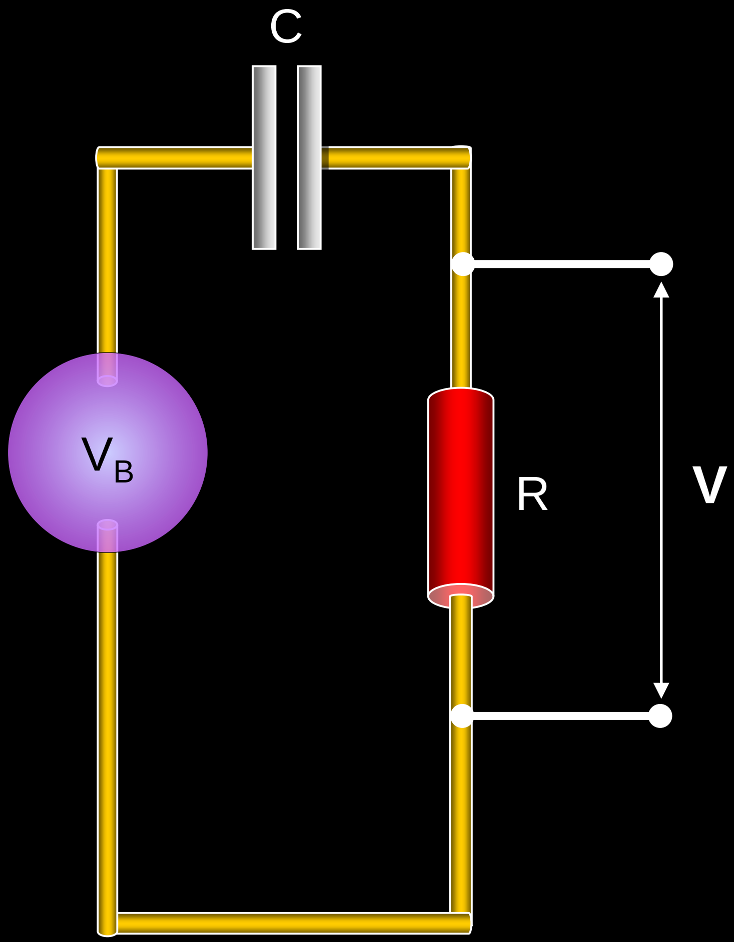


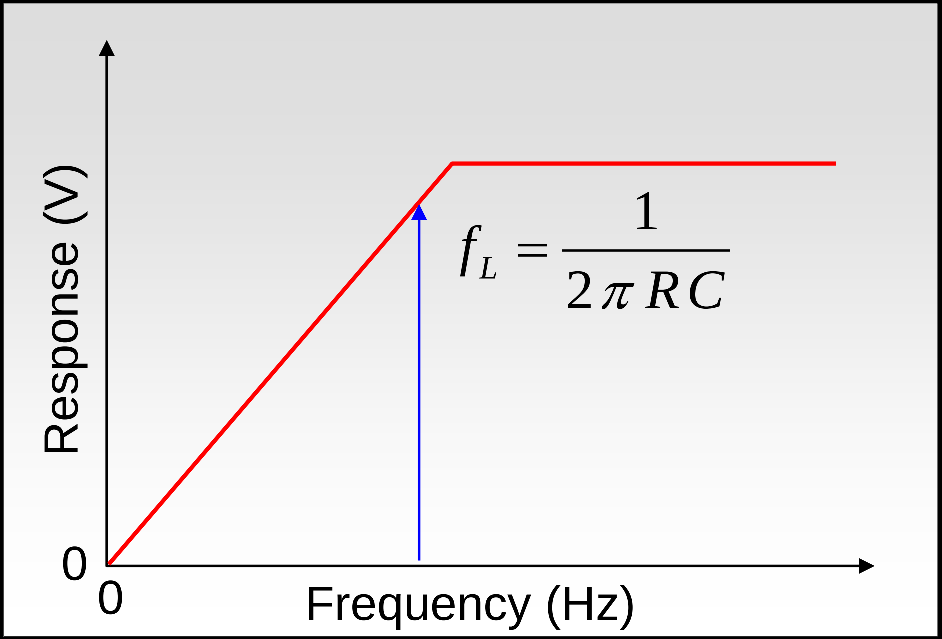


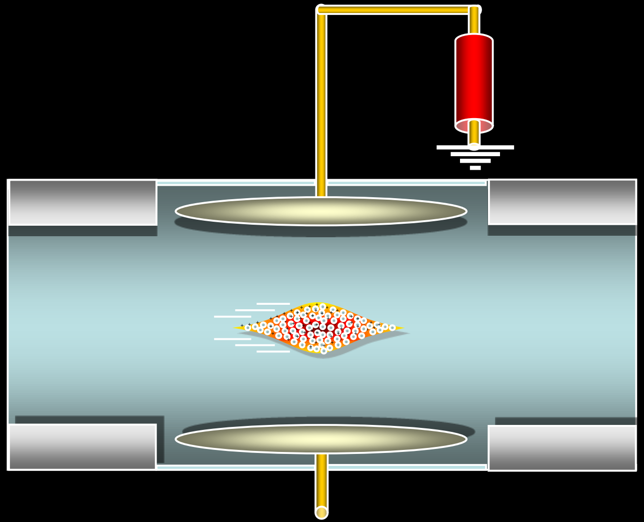
Electrostatic Monitor – The Principle



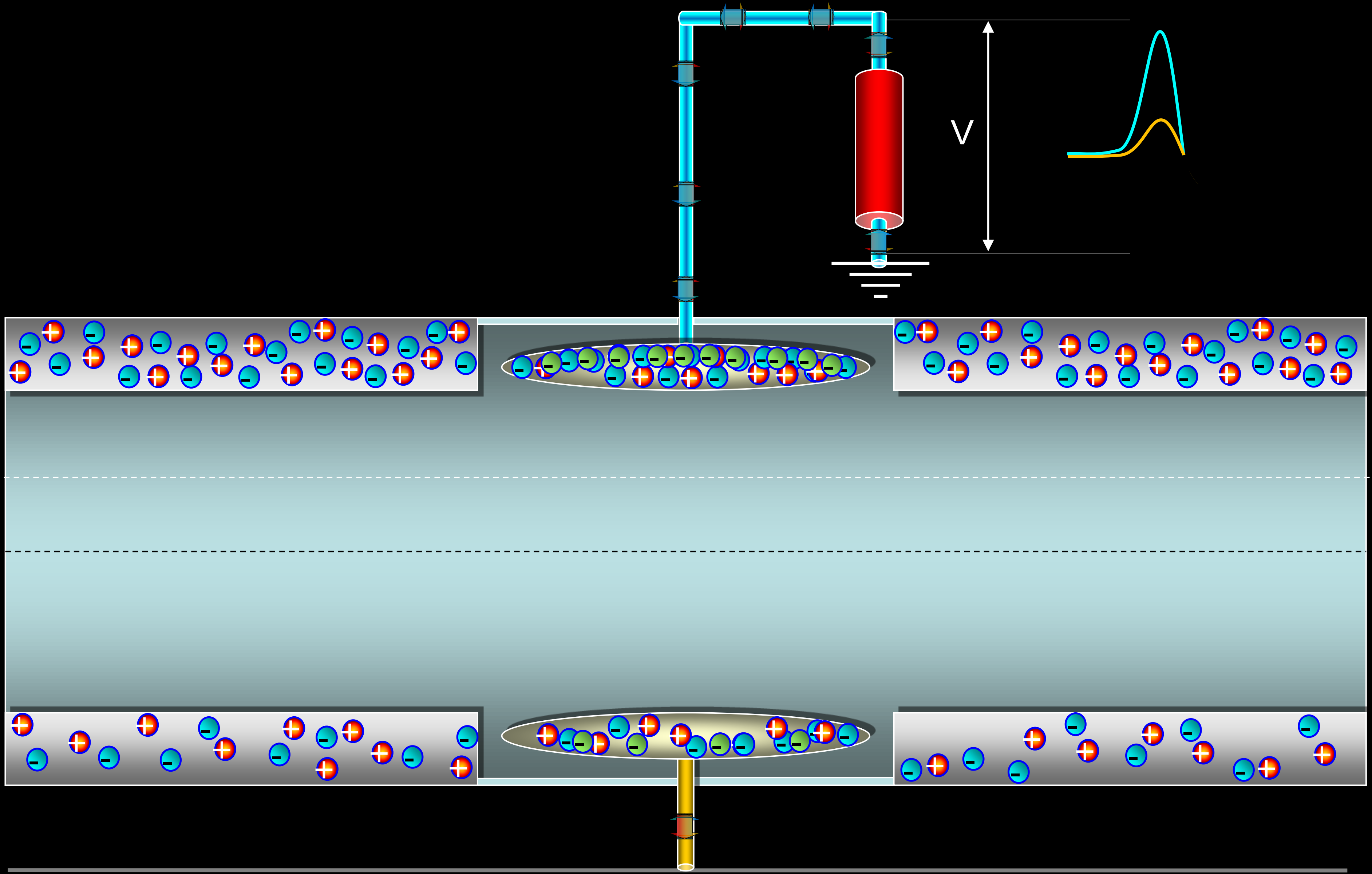
Electrostatic Monitor – Beam Response



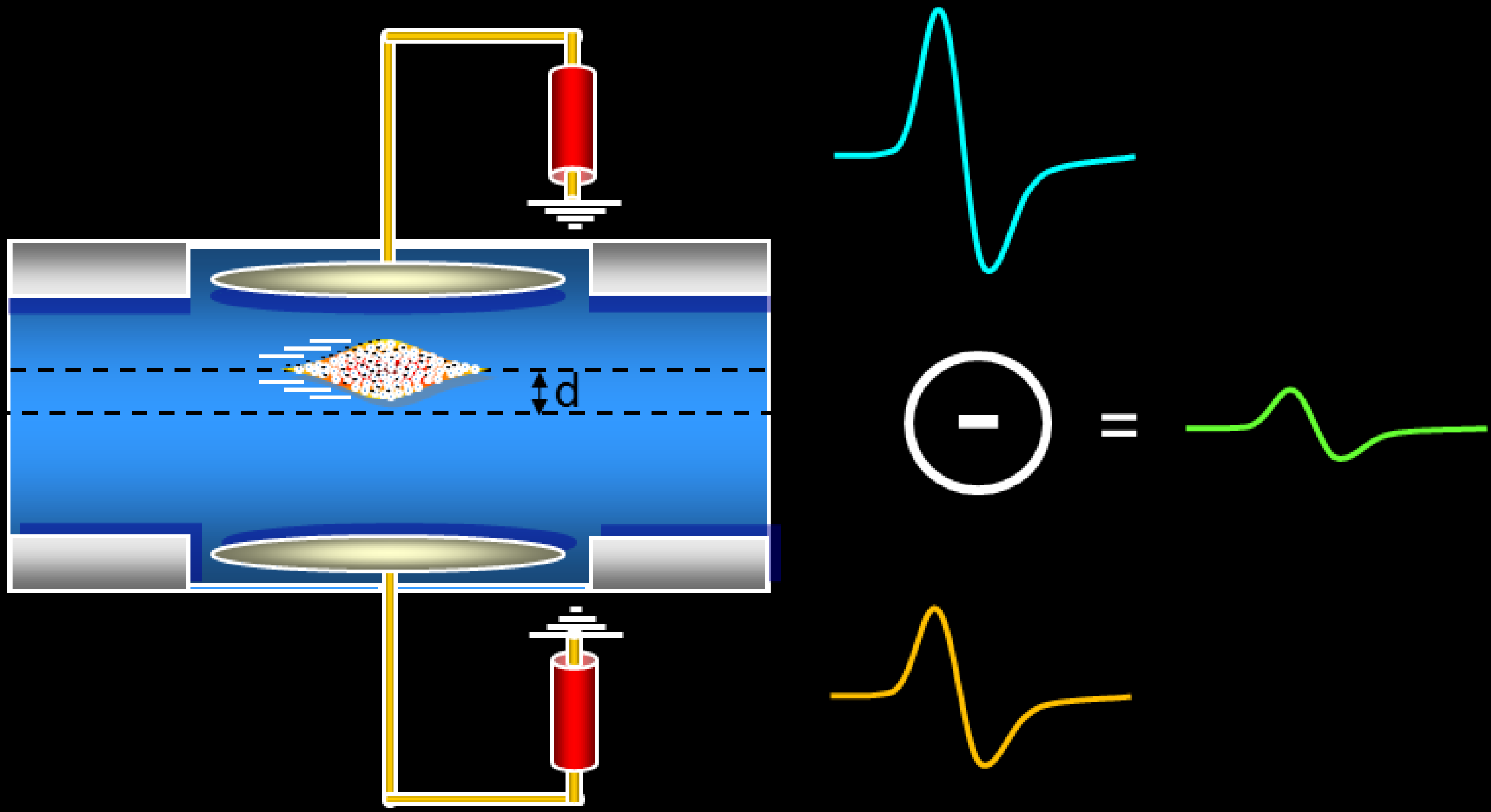




Electrostatic Beam Position Monitor



Electrostatic Monitor – The Principle



Electrostatic Pick-up – Button

- ✓ Low cost ⇒ most popular
- ✗ Non-linear
  - requires correction algorithm when beam is off-centre

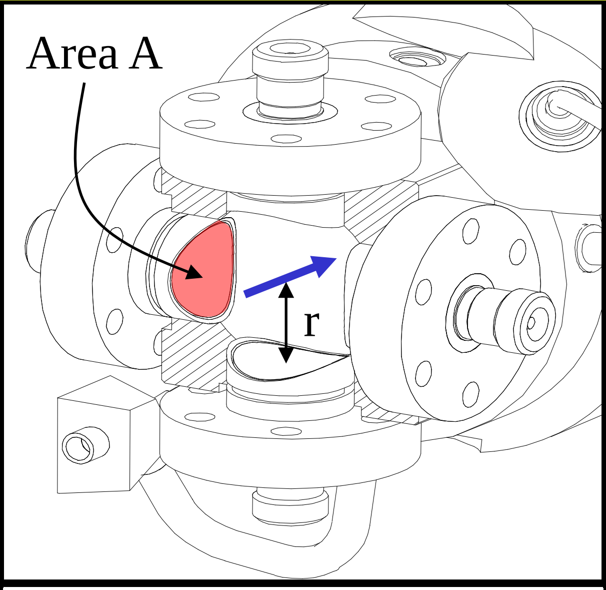
For Button with Capacitance C_e & Characteristic Impedance R_0

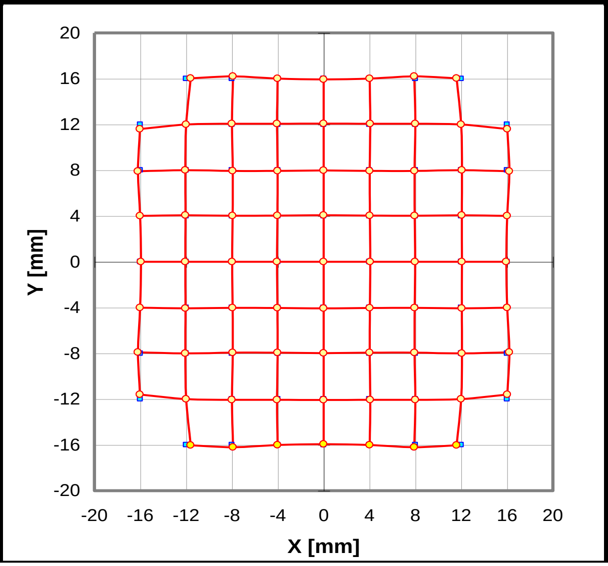
Transfer Impedance:

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

Lower Corner Frequency:

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

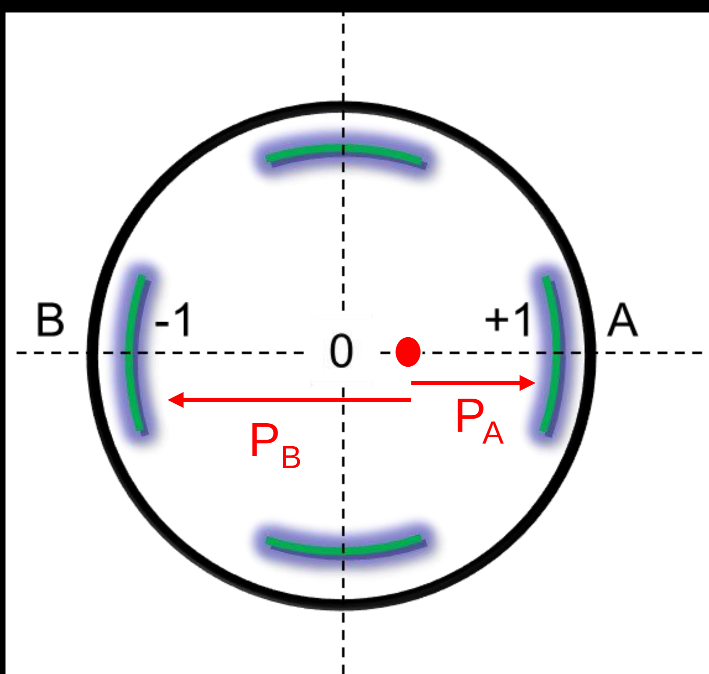


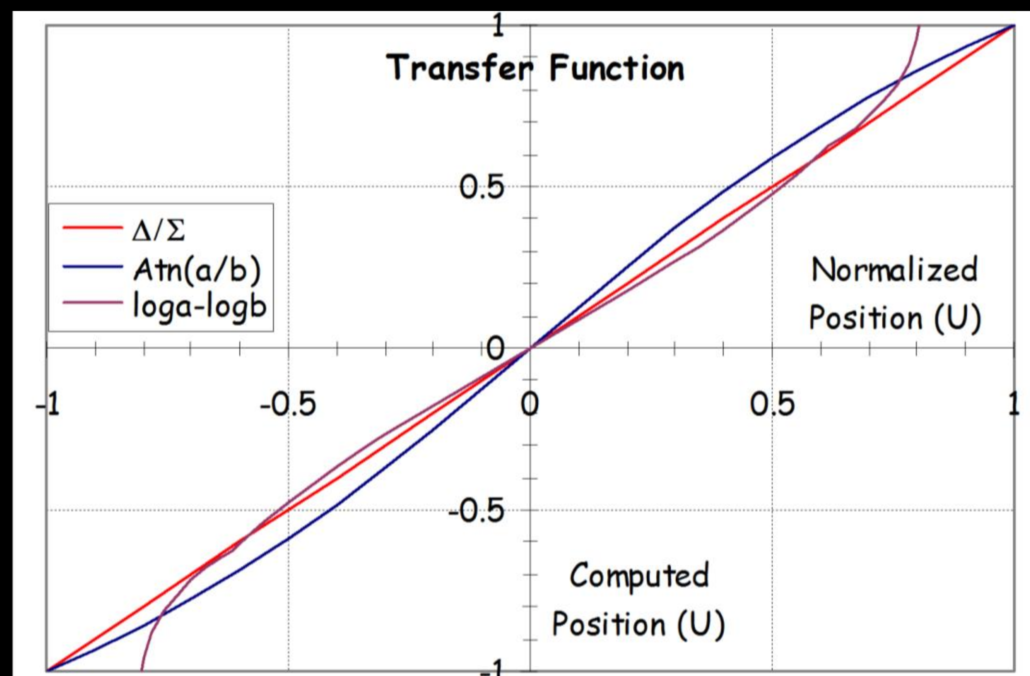


$$X = 2.30\cdot10^{-5} X_1^{\,5} + 3.70\cdot10^{-5} X_1^{\,3} + 1.035\,X_1 + 7.53\cdot10^{-6} X_1^{\,3} Y_1^{\,2} + 1.53\cdot10^{-5} X_1 Y_1^{\,4}$$

Normalising the Position Reading

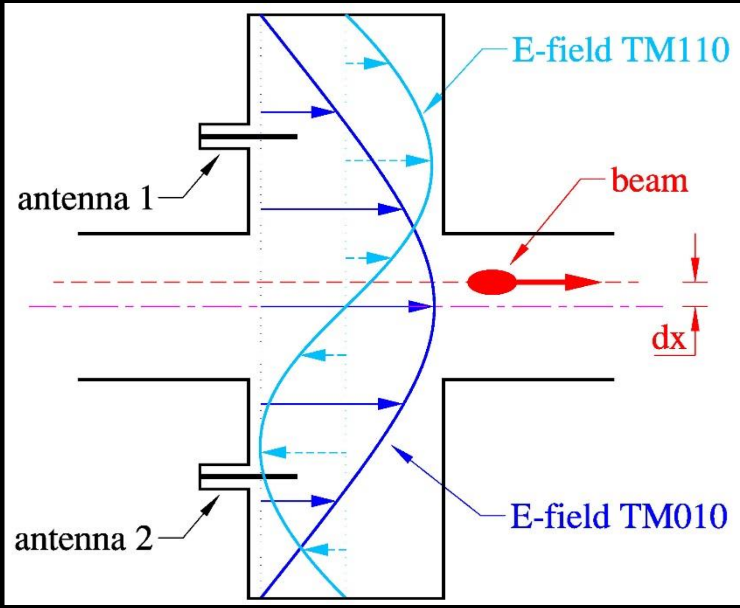
- To make it independent of intensity
- 3 main methods: ($V_A \propto I \times P_A$ and $V_B \propto I \times P_B$)
  - Difference/Sum : $\frac{(V_A - V_B)}{(V_A + V_B)} = \frac{\Delta}{\Sigma} = \frac{(P_A - P_B)}{(P_A + P_B)} = \frac{\Delta P}{Aperture}$
  - Phase : $ArcTan\left(\frac{V_A}{V_B}\right) = ArcTan\left(\frac{P_A}{P_B}\right)$
  - Logarithm : $\mathrm{Log}\left(\frac{V_A}{V_B}\right) = Log\left(\frac{P_A}{P_B}\right) = Log(V_A) - Log(V_B)$

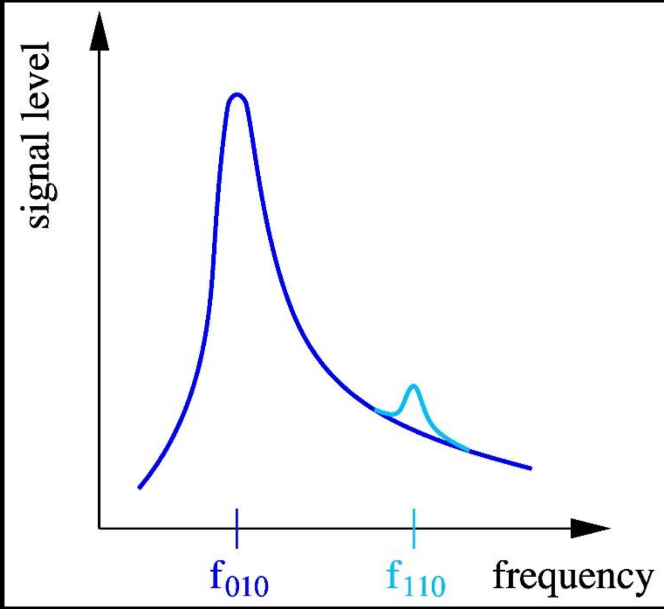




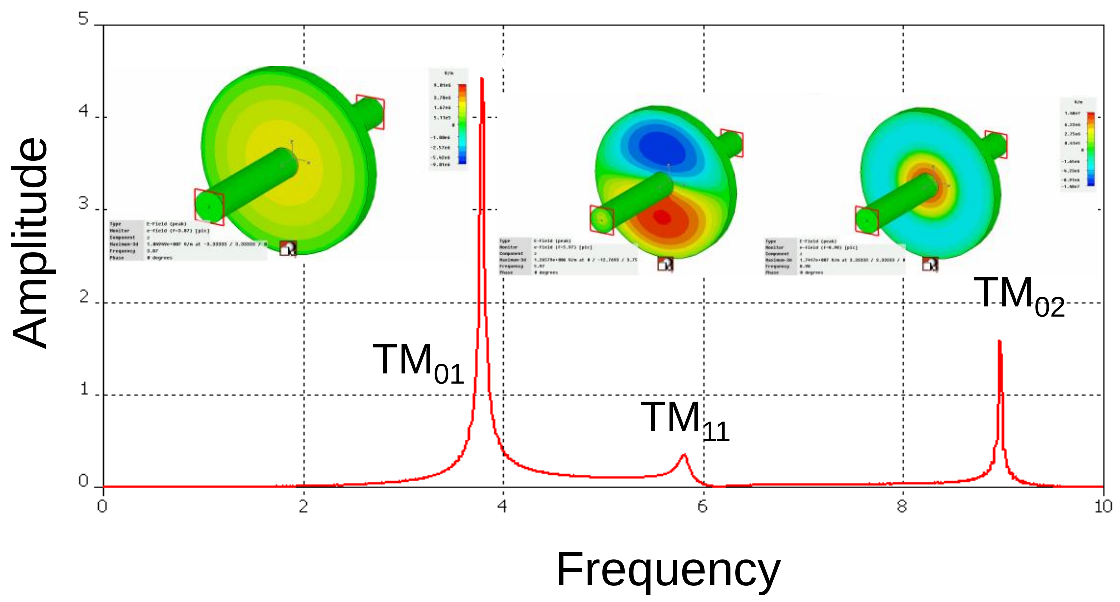
Improving Precision for Next Generation Accelerators

- BPM electrodes typically give “intensity signals” with some position dependence!
  - Need to remove intensity content to get to the position
  - Difficult to do electronically without some intensity information leaking through
    - When looking for small differences this leakage can dominate the measurement
- Solution – cavity BPM allowing sub micron resolution
  - Design the detector to collect only the difference signal
    - Dipole Mode TM_{11} proportional to POSITION OFFSET (& intensity)
    - Shifted in frequency with respect to intensity dependent Monopole Mode TM_{01}



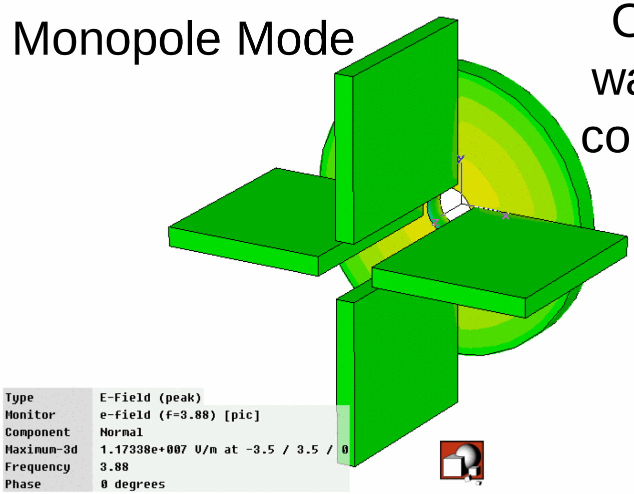


Cavity Beam Position Monitors



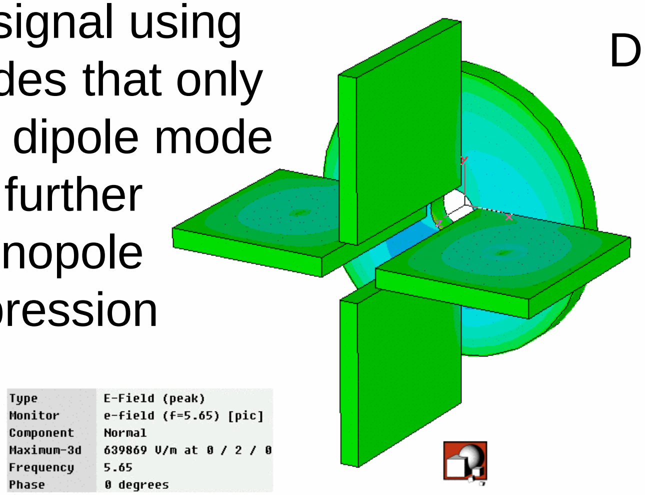
Courtesy of D. Lipka, DESY, Hamburg

Monopole Mode



Obtain signal using waveguides that only couple to dipole mode for further Monopole Supression

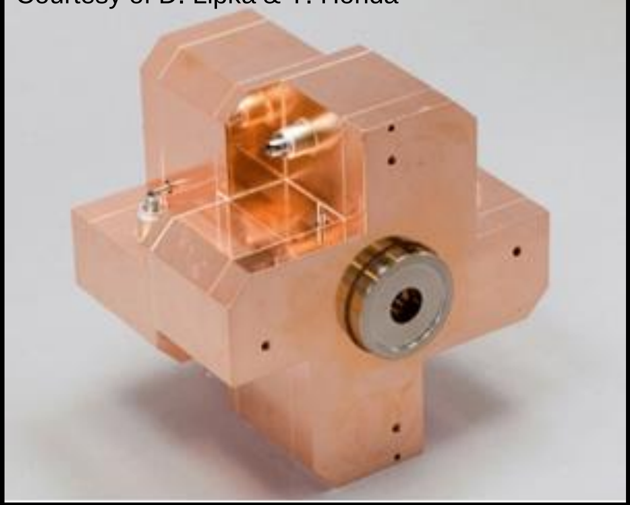
Dipole Mode

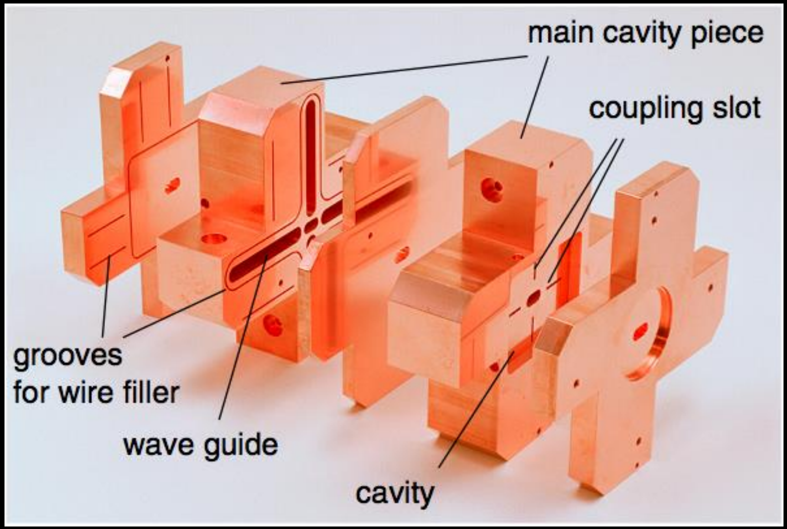


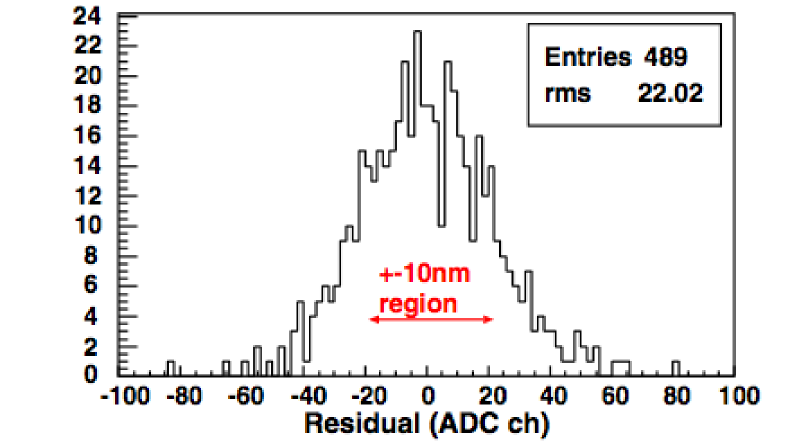
Today's State of the Art BPMs

- Prototype BPM for ILC Final Focus
  - Required resolution of 2nm (yes nano!) in a 6 × 12mm diameter beam pipe
  - Achieved World Record (so far!) resolution of 8.7nm at ATF2 (KEK, Japan)

Courtesy of D. Lipka & Y. Honda

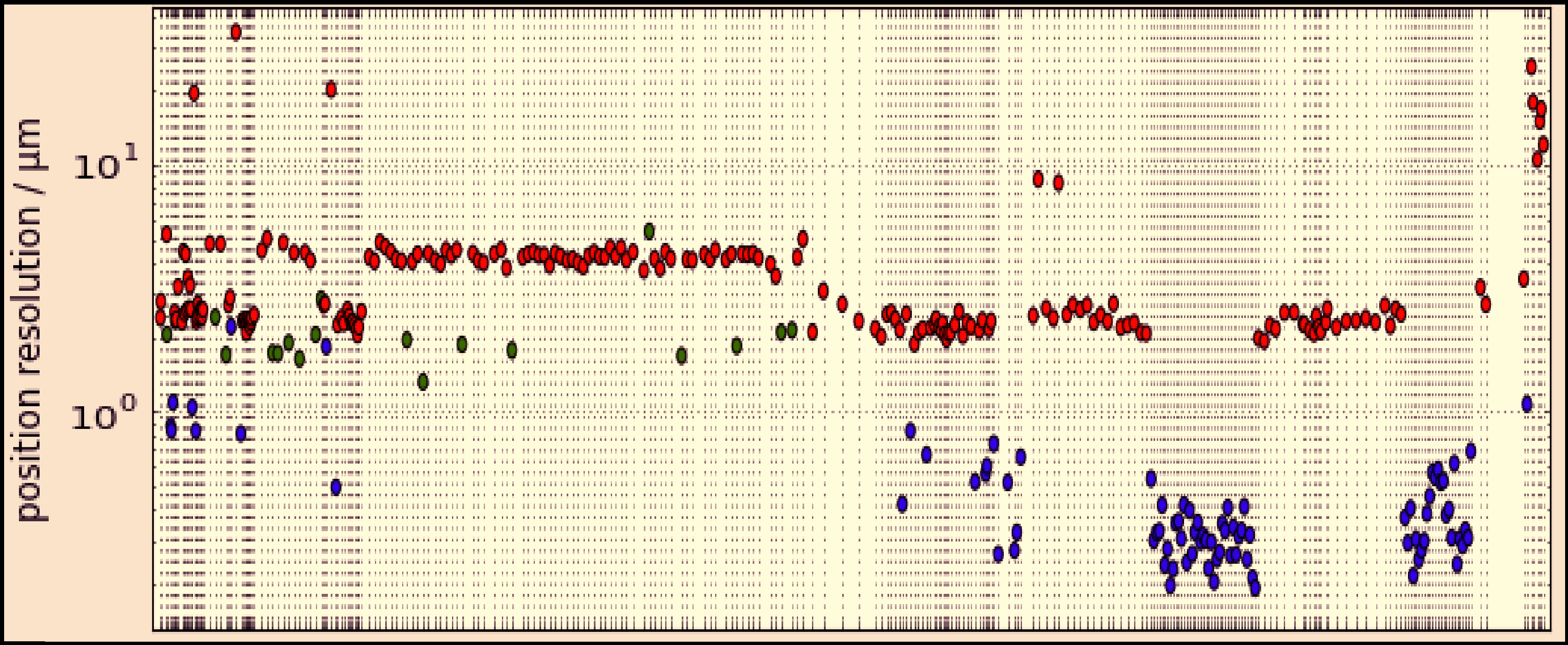




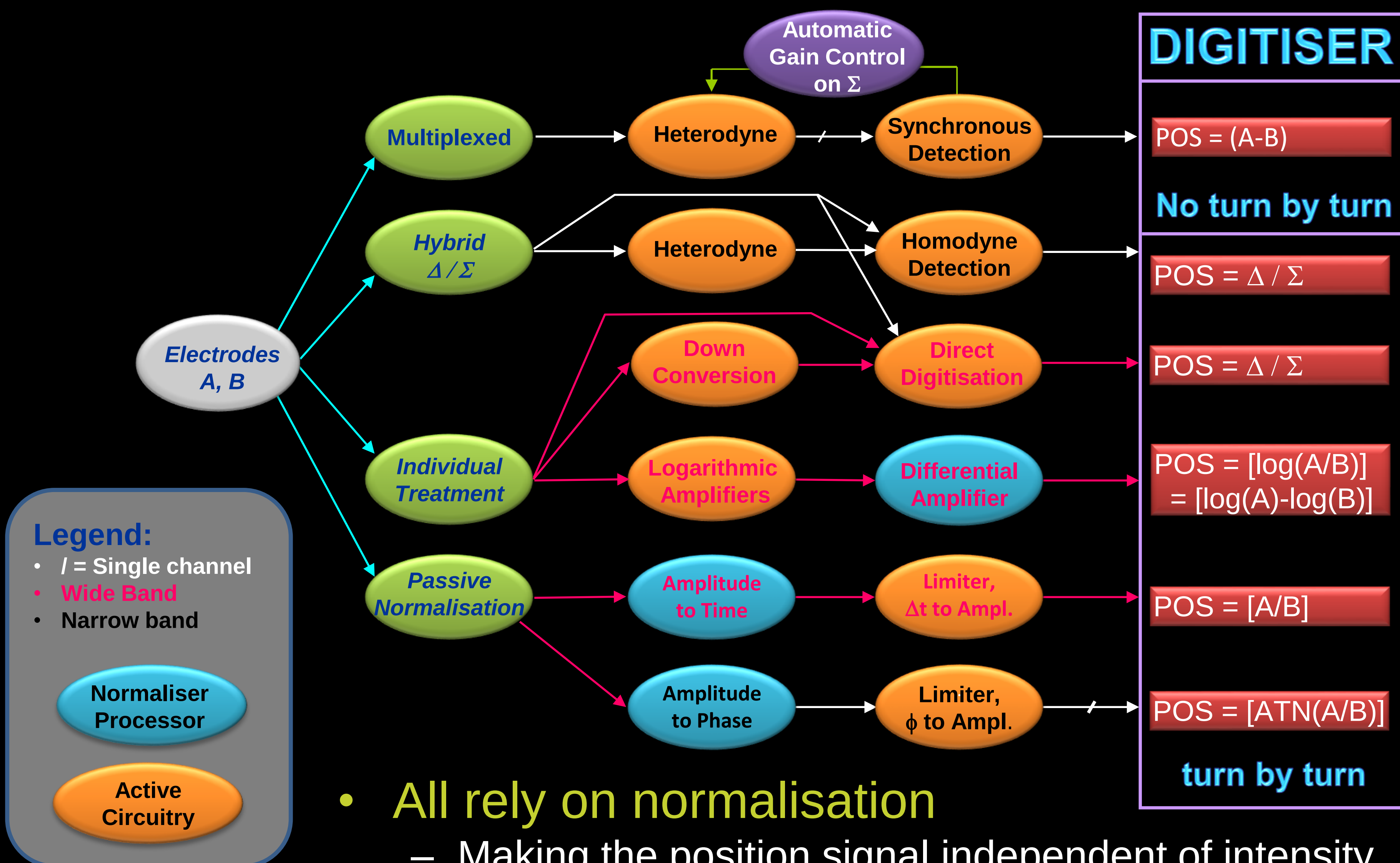


Comparison of BPM Resolution

- XFEL Data from 2017 Commissioning
  - Standard Button BPMs : 78 mm & 40.5 mm aperture (RED)
  - Re-entrant cavity BPMs : 78 mm aperture (GREEN)
  - Cavity BPMs : 40.5 mm and 10 mm aperture (BLUE)



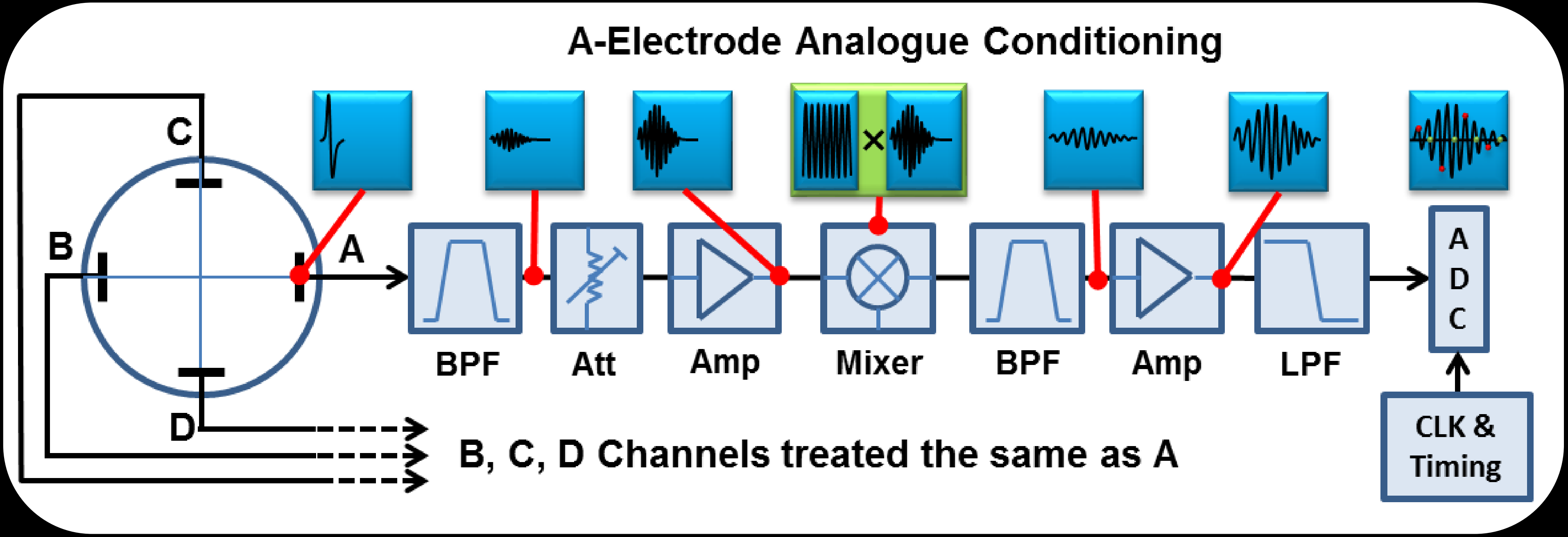
Processing System Families

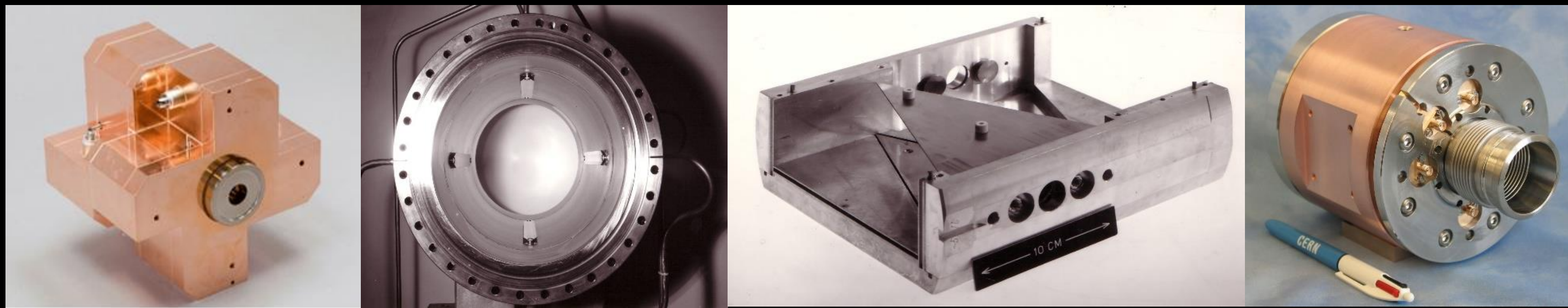


- All rely on normalisation
  - Making the position signal independent of intensity

Modern BPM Read-out Electronics

- Based on the individual treatment of the electrode signals
  - Use of frequency domain signal processing techniques
    - Developed for telecommunications market
  - Rely on high frequency & high resolution analogue to digital converters
    - Minimising analogue circuitry
    - Frequency down-conversion used if necessary to adapt to ADC sampling rate
    - All further processing carried out in the subsequent digital electronics

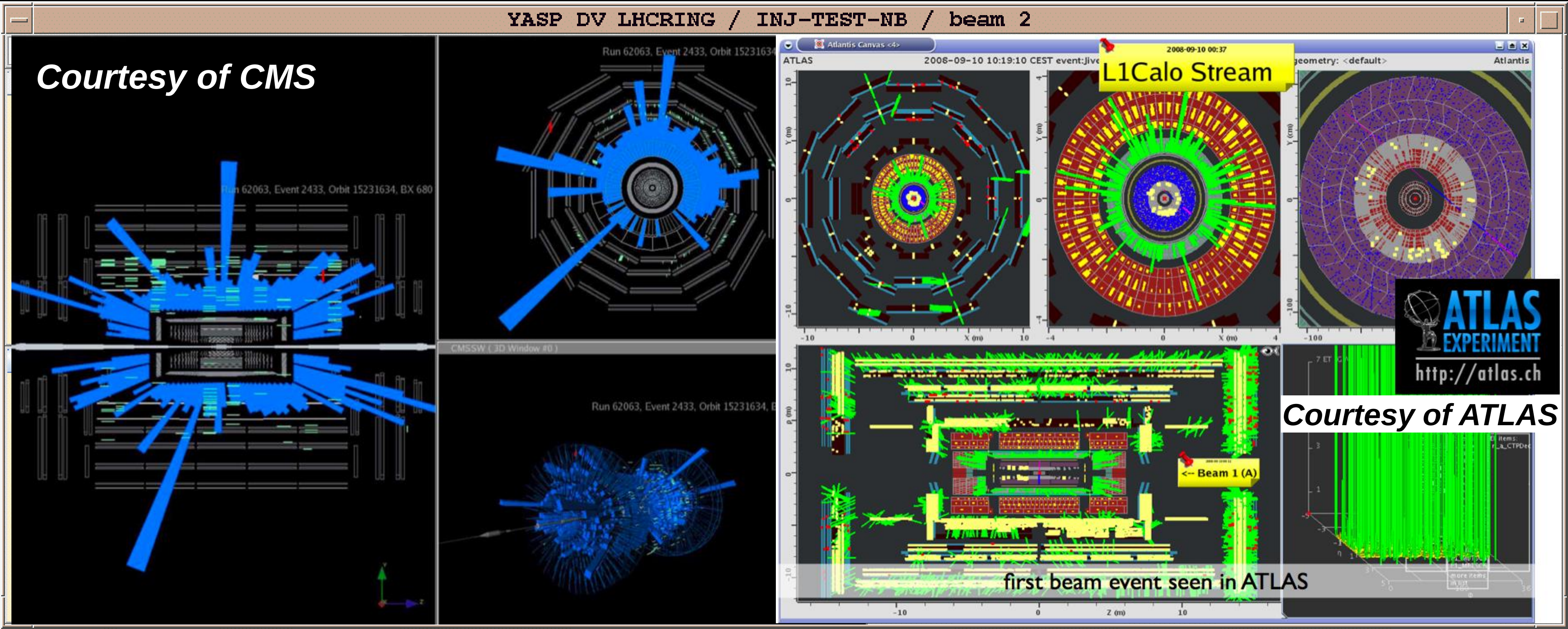




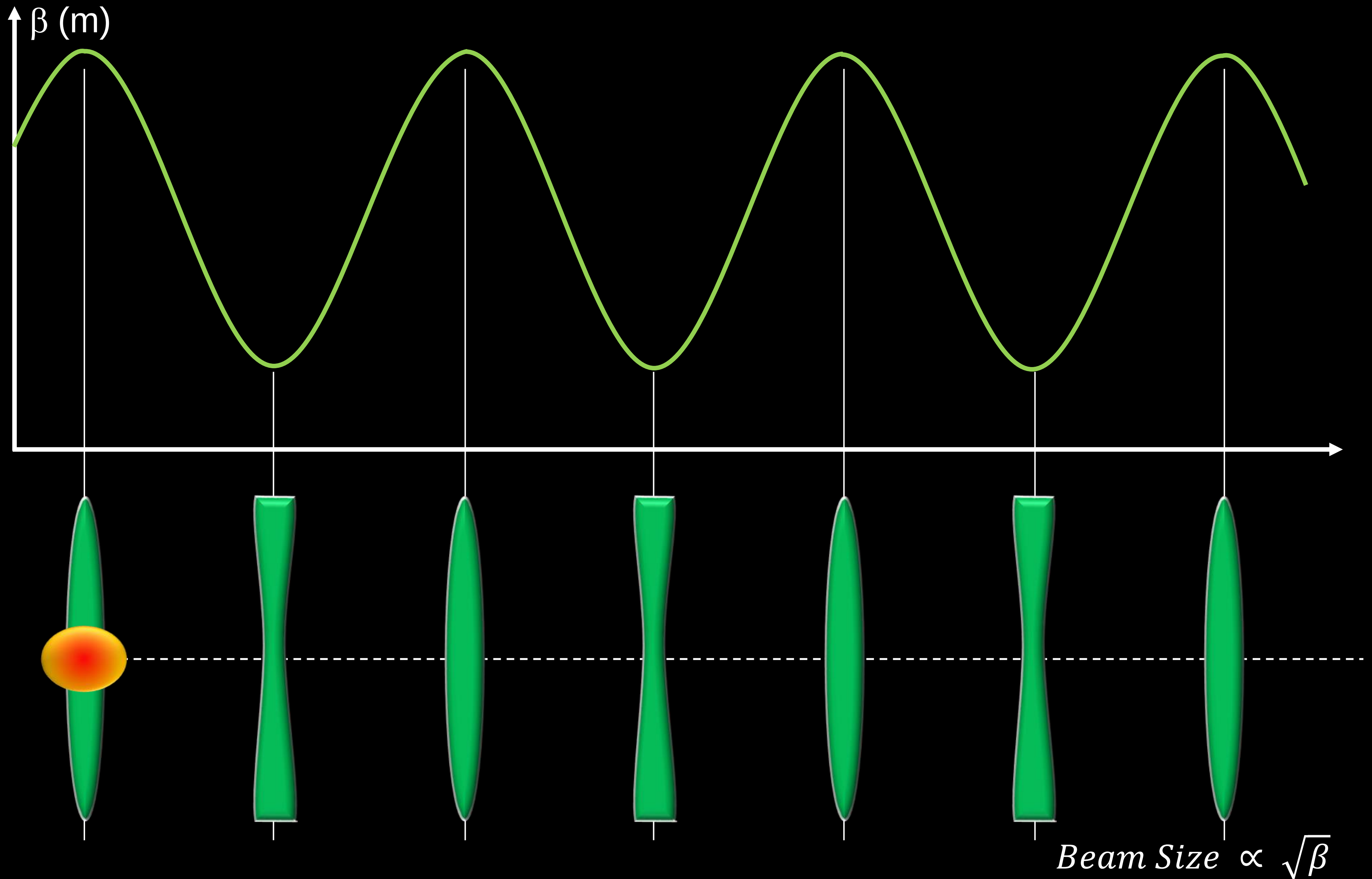
Diagnostics using Beam Position Systems

Initial Commissioning

- Threading the first pilot bunch round the LHC
  - One beam at a time, one hour per beam
  - Collimators used to intercept the beam
  - Correct trajectory, open collimator and move on



The Machine β-Function



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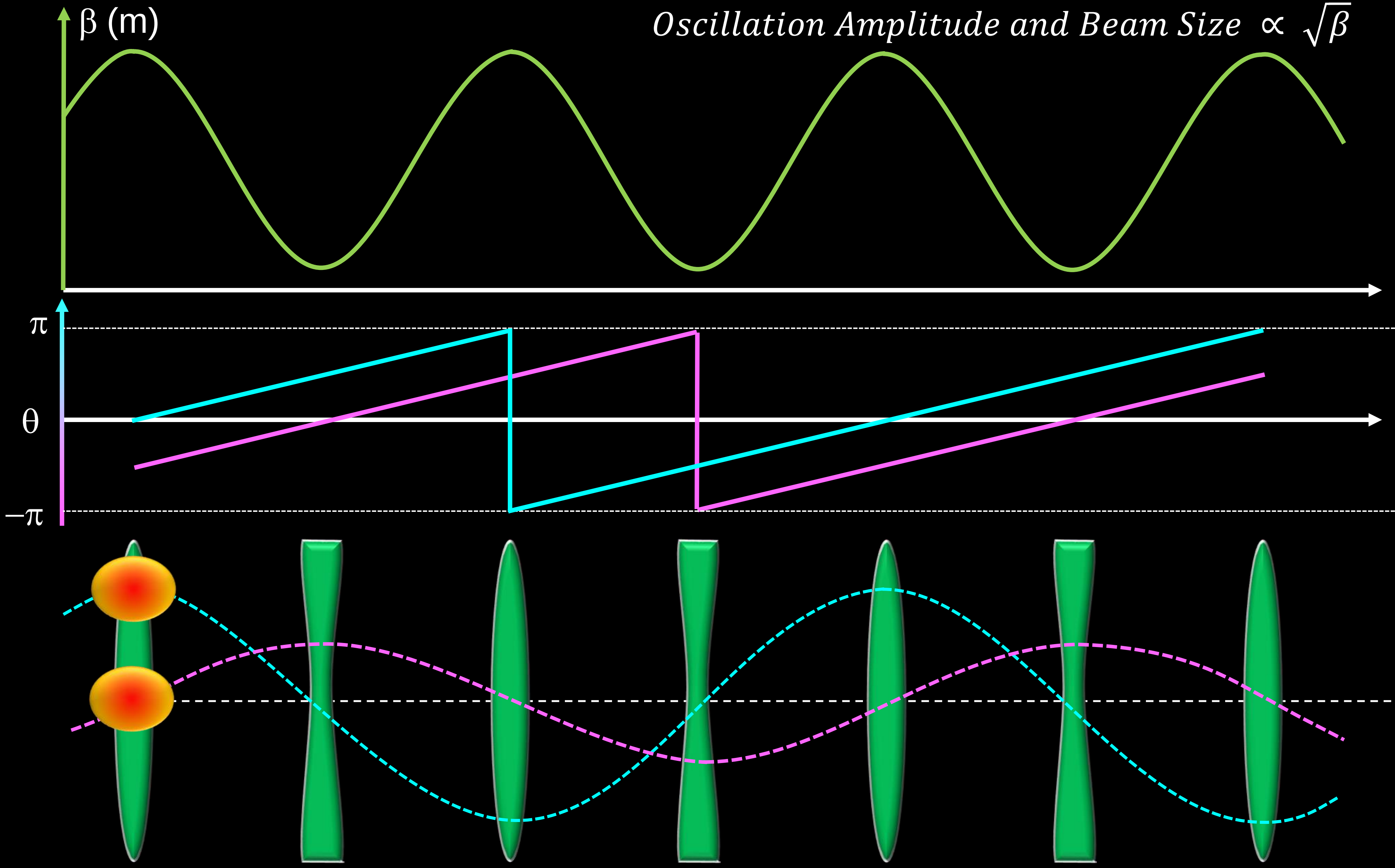
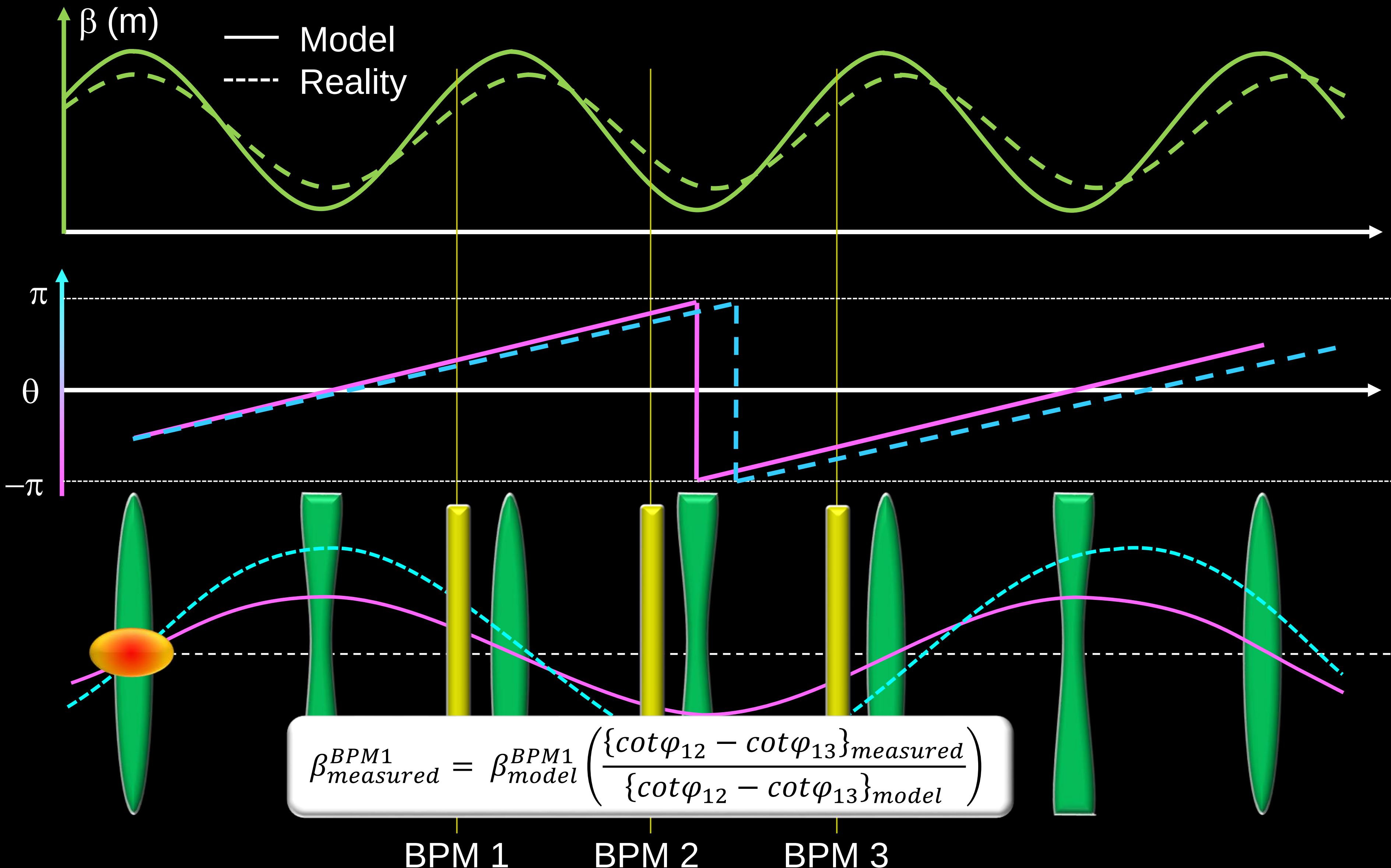


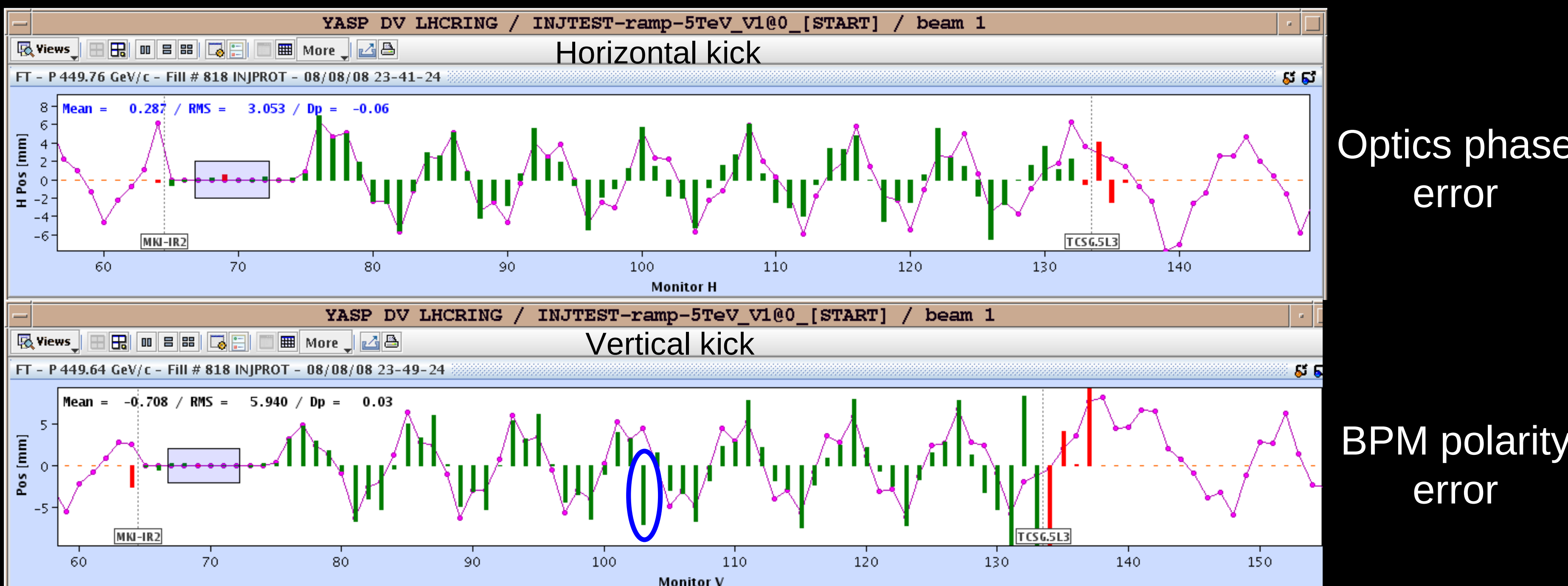
The Machine β-Function



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

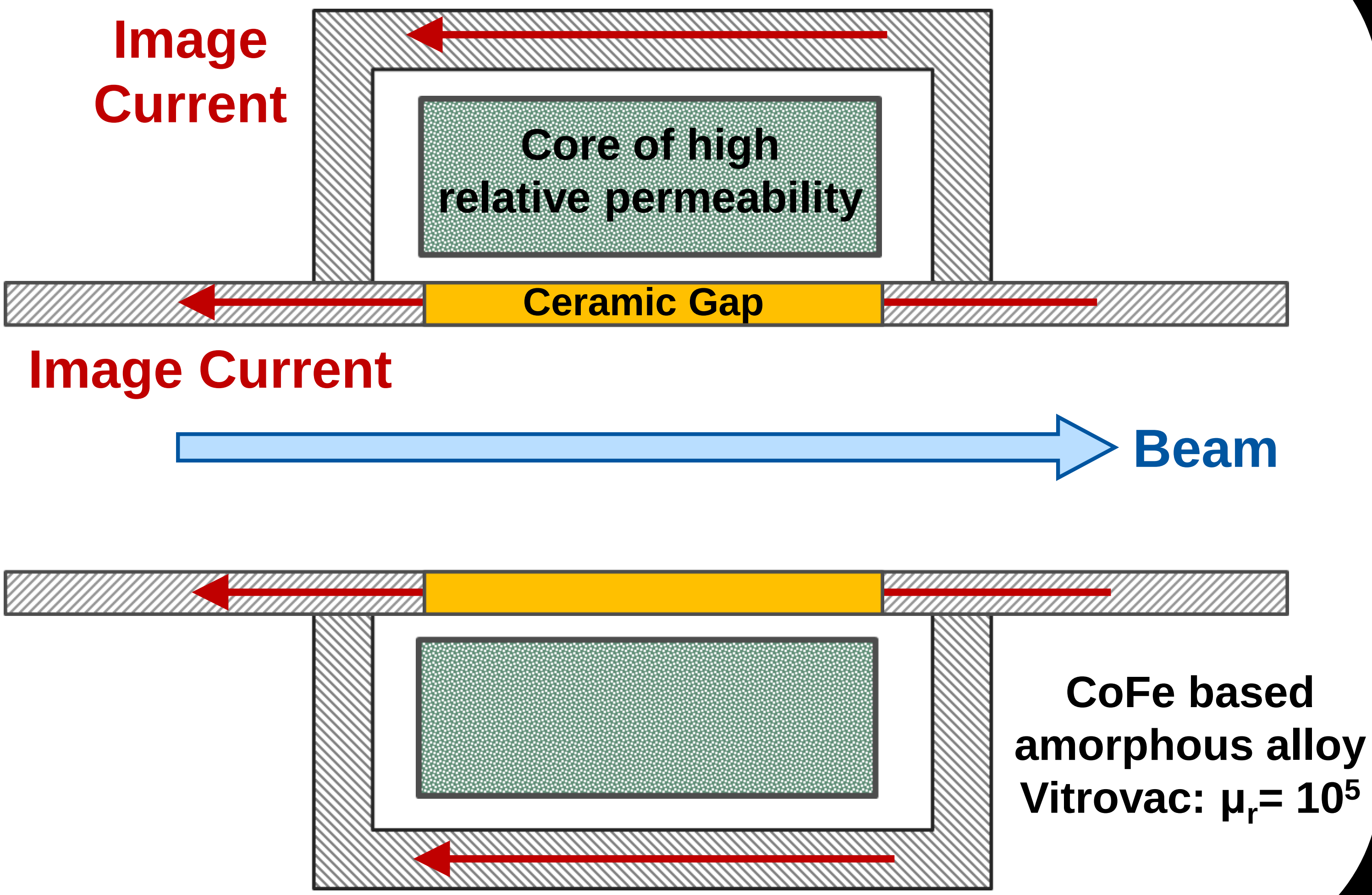
Analysis of BPM Data

- On line analysis of BPM Data
  - Polarity errors easily identified with 45° BPM sampling
  - Quick indication of phase advance errors
  - Used to verify optics functions
    - e.g. matching from transfer lines into ring



Beam Intensity Monitors

AC (Fast) Current Transformers



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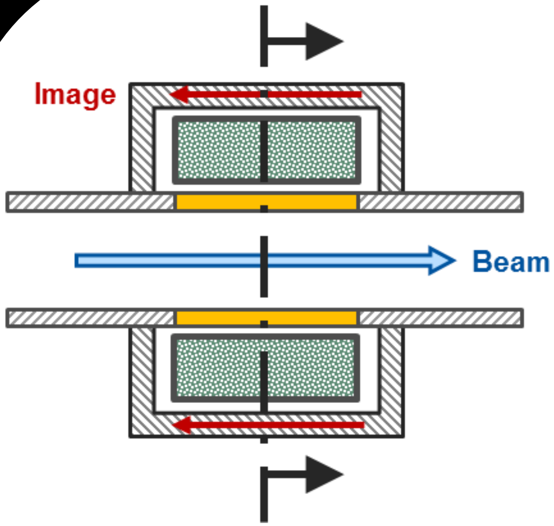
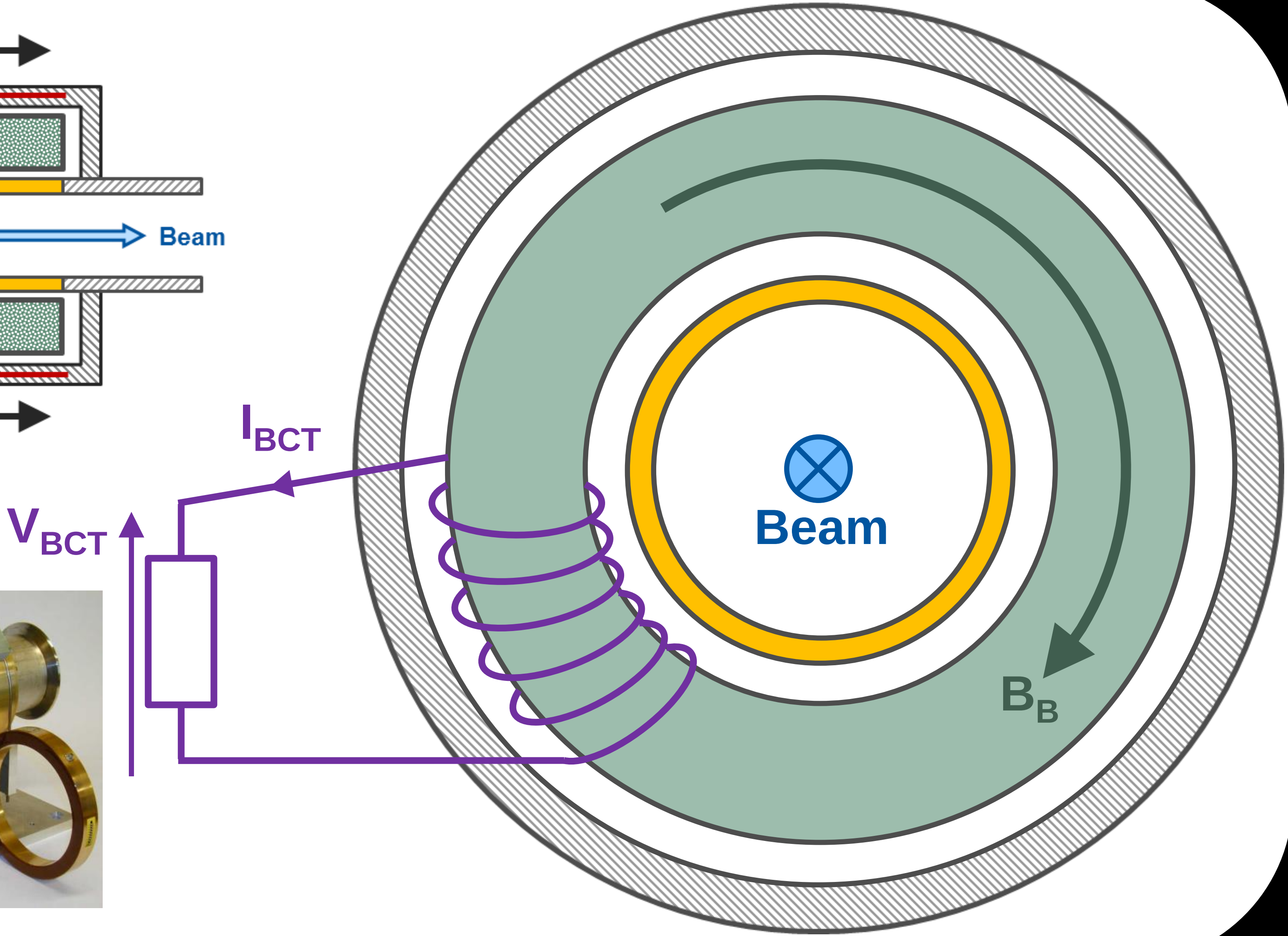
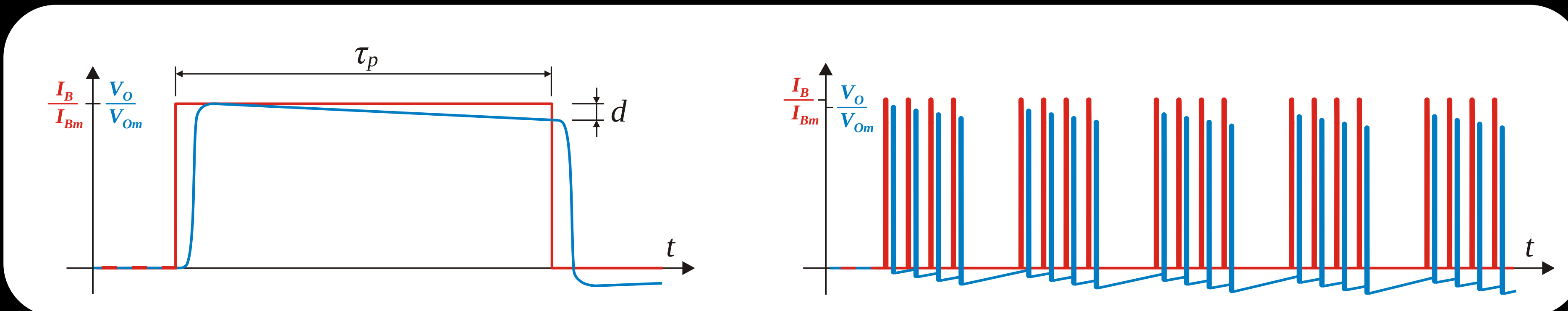
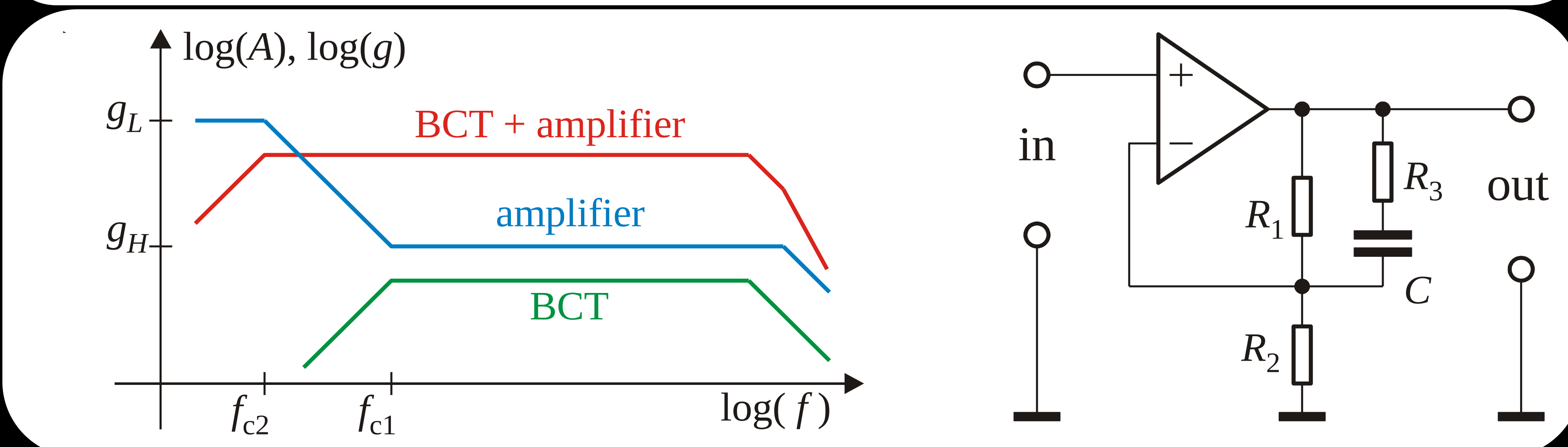




AC (Fast) Transformer Response

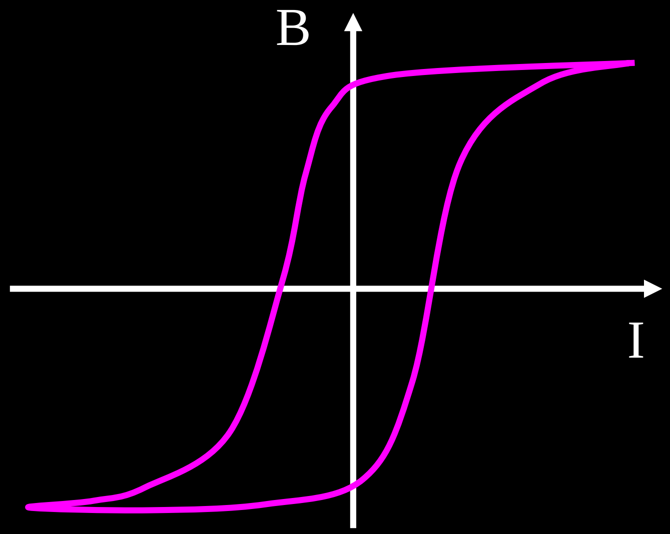
- Low cut-off
  - Impedance of secondary winding decreases at low frequency
  - Results in signal droop and baseline shift
  - Mitigated by baseline restoration techniques (analogue or digital)





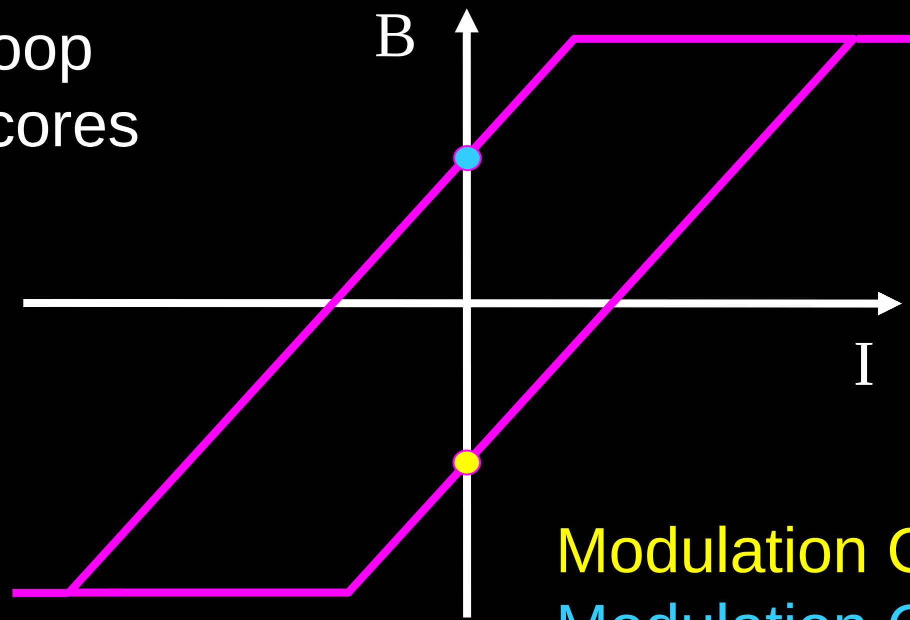
The DC transformer

- AC transformers can be extended to very low frequency but not to DC (no dI/dt !)
- DC measurement is required in storage rings
- To do this:
  - Take advantage of non-linear magnetisation curve
  - Use 2 identical cores modulated with opposite polarities

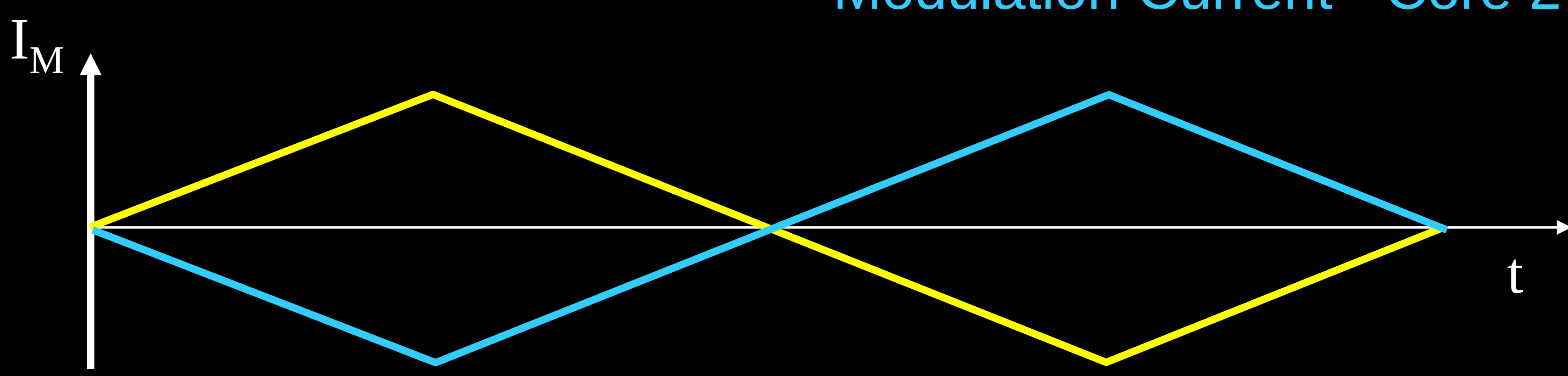


DCCT Principle – Case 1: no beam

Hysteresis loop
of modulator cores

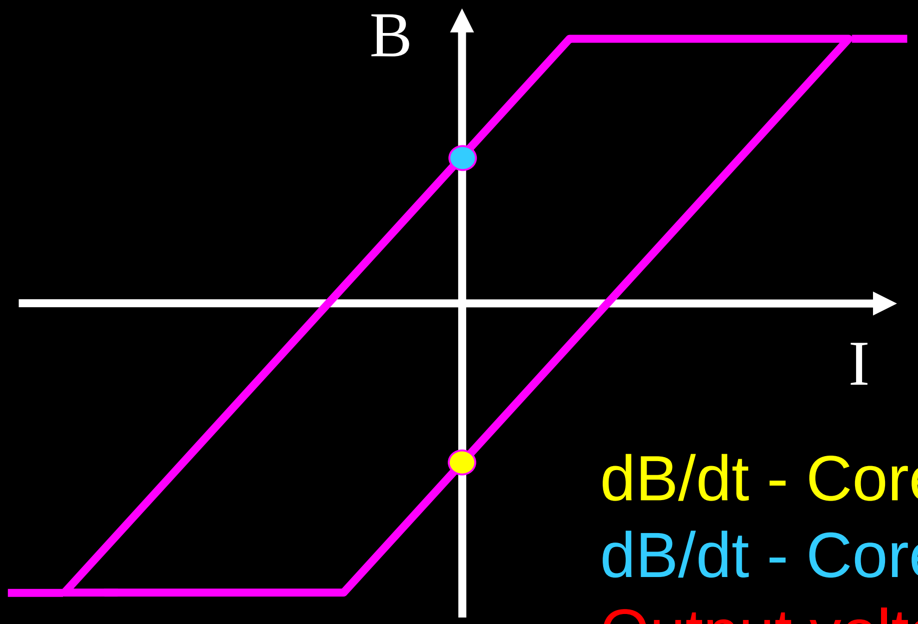


Modulation Current - Core 1
Modulation Current - Core 2



DCCT Principle – Case 1: no beam

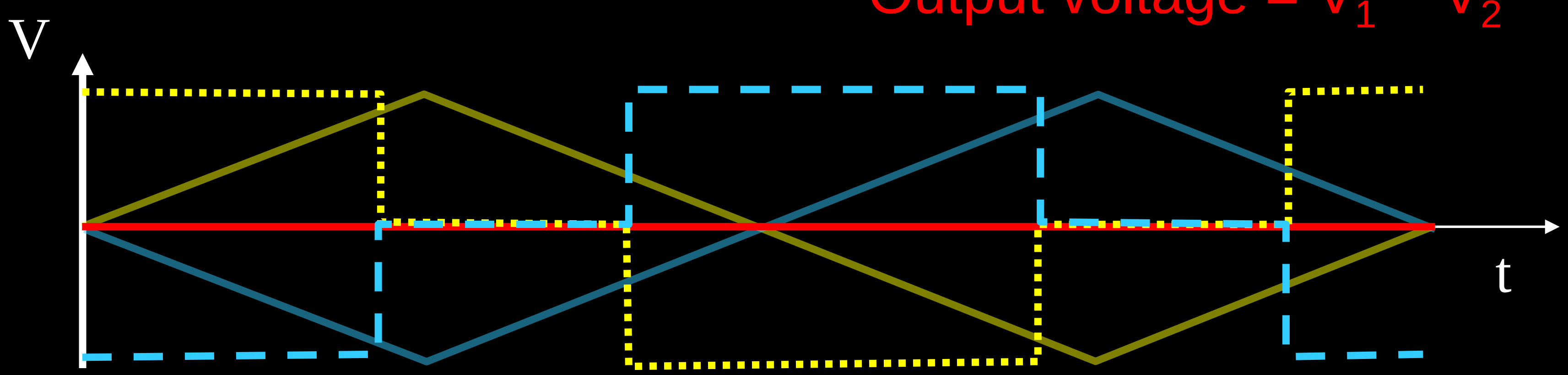
$$V \propto \frac{dB}{dt}$$



dB/dt - Core 1 (V1)

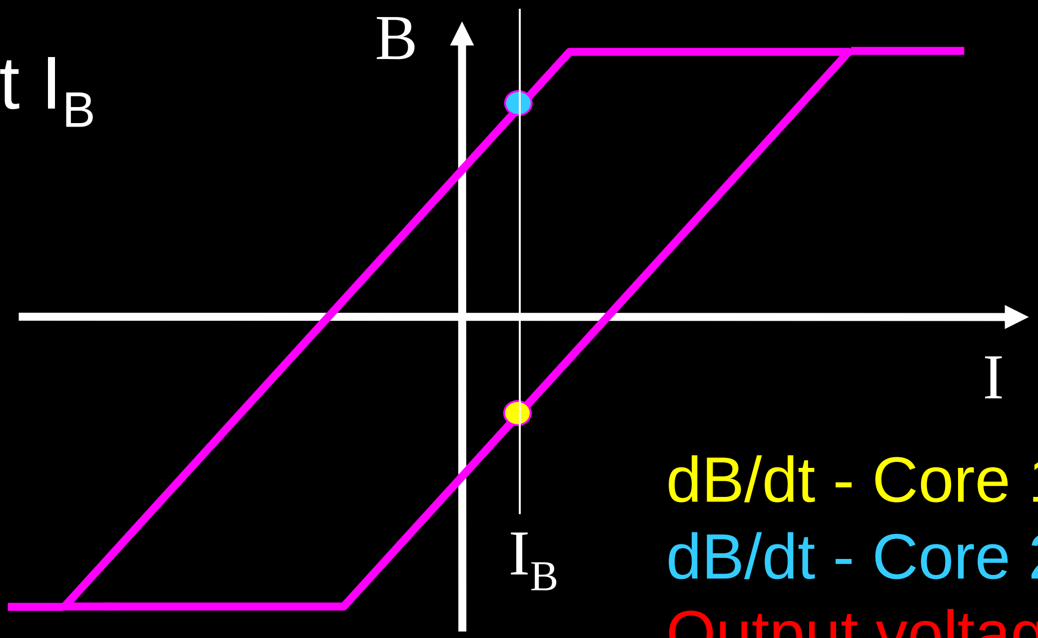
dB/dt - Core 2 (V2)

Output voltage = $V_1 – V_2$



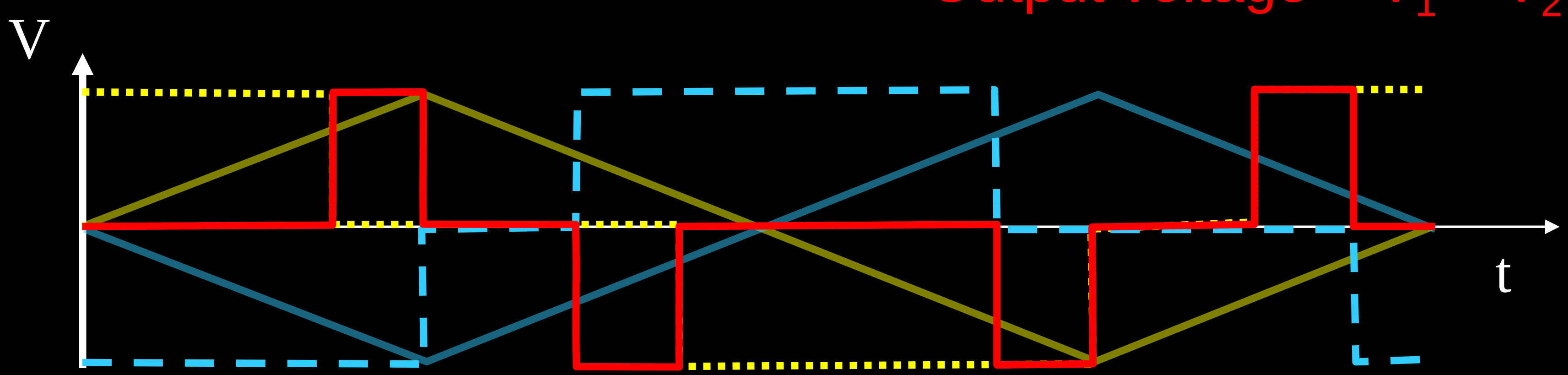
DCCT Principle – Case 2: with beam

Beam Current I_B

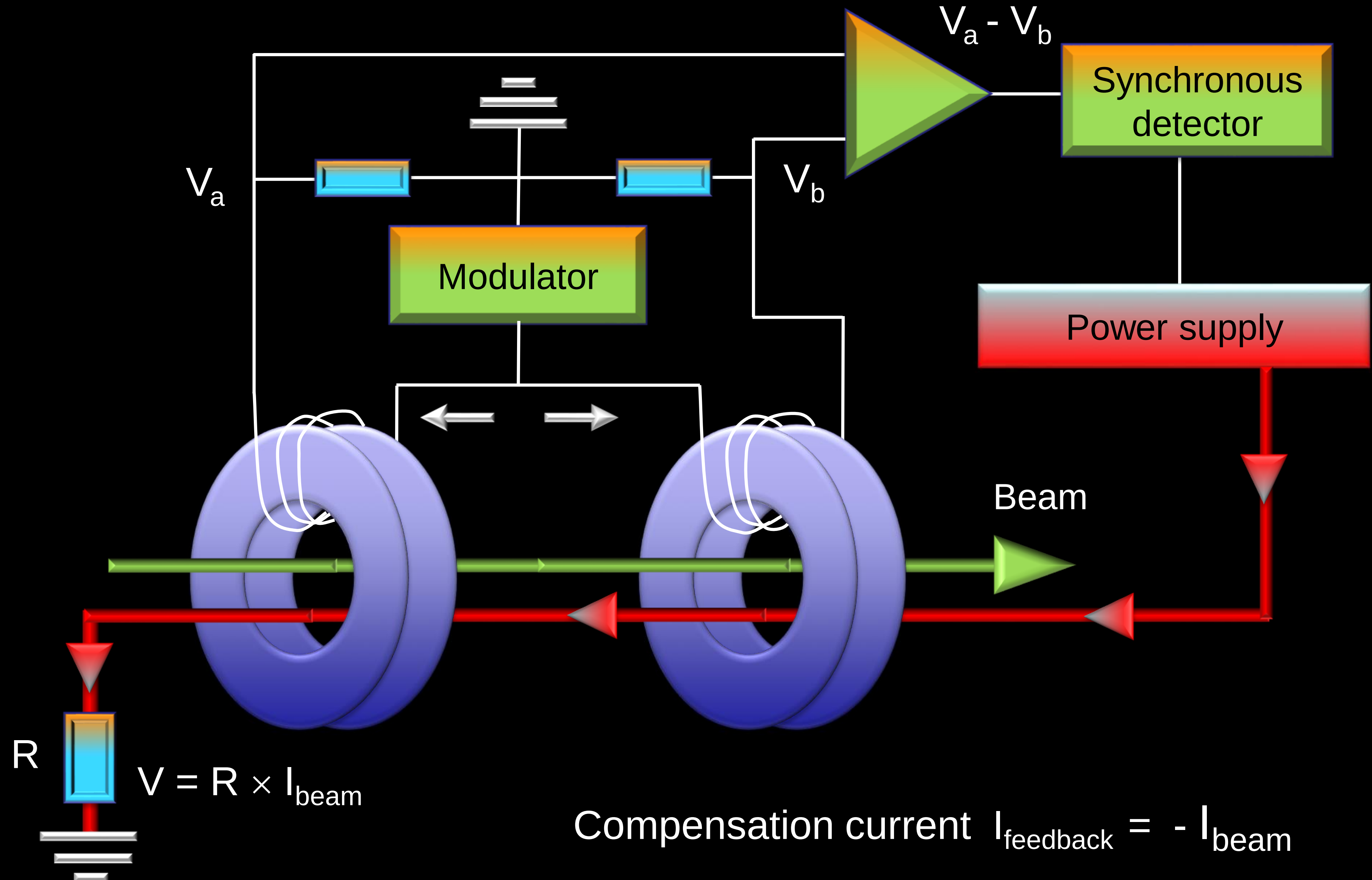


Output signal is at TWICE the modulation frequency

dB/dt - Core 1 (V1)
dB/dt - Core 2 (V2)
Output voltage = $V_1 - V_2$



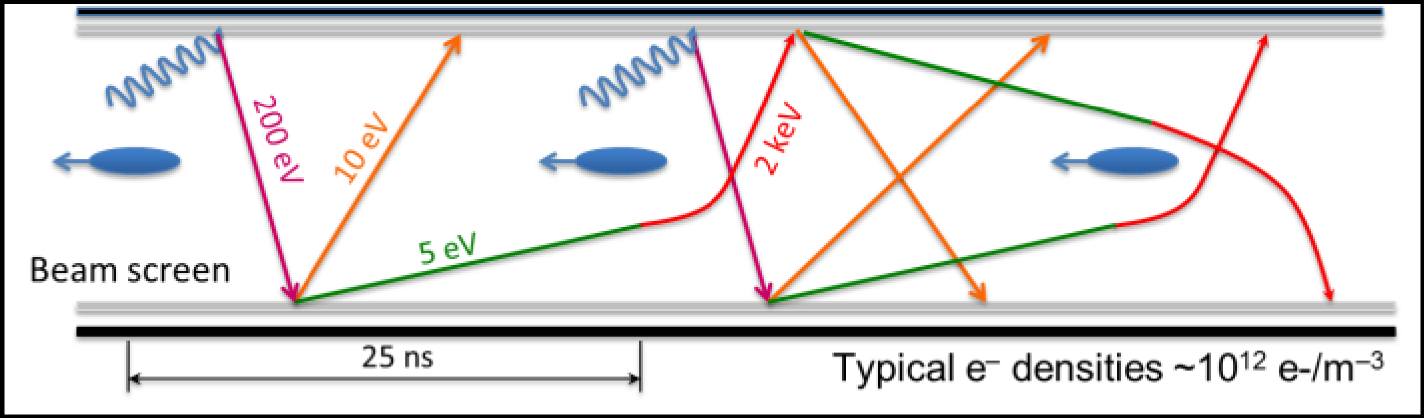
Zero Flux DCCT Schematic

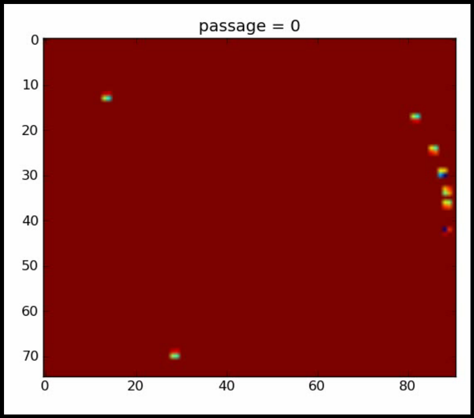


Compensation current $I_{feedback} = - I_{beam}$

Diagnostics using Beam Intensity Monitors

Monitoring Electron Cloud Activity





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

- Secondary Emission Yield [SEY]
  - SEY > Threshold ⇒ avalanche effect (multipacting)
- Possible consequences:
  - Instabilities, emittance growth, vacuum degradation, background
  - Energy deposition in cryogenic surfaces
- Electron bombardment can reduce SEY of a material
  - A function of the delivered electron dose
  - This technique of “scrubbing” can suppress electron cloud build-up

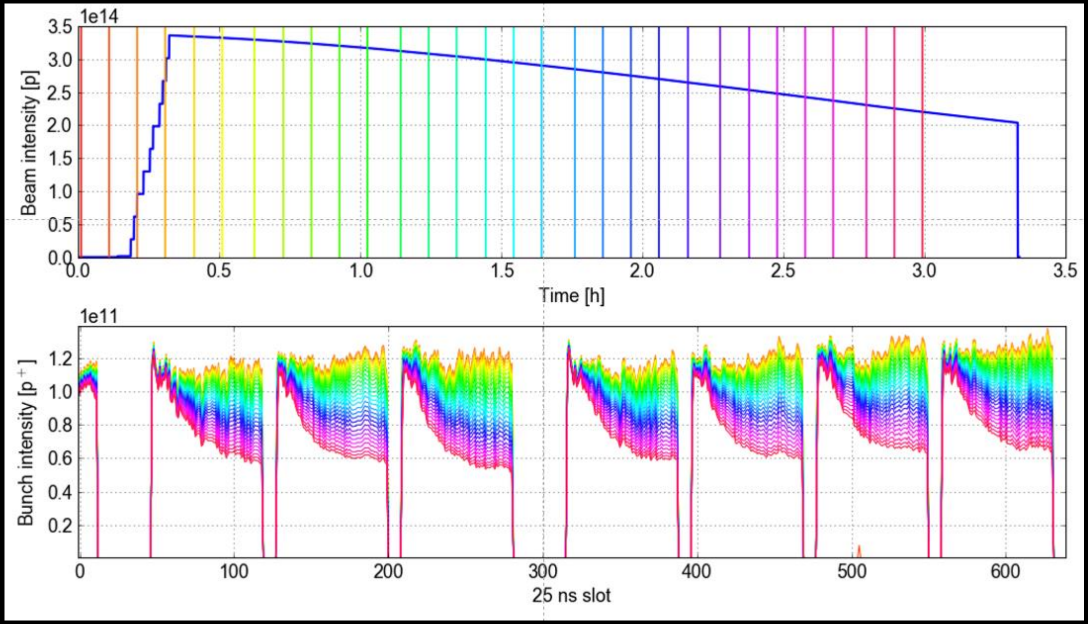
Bunch by Bunch Diagnostics

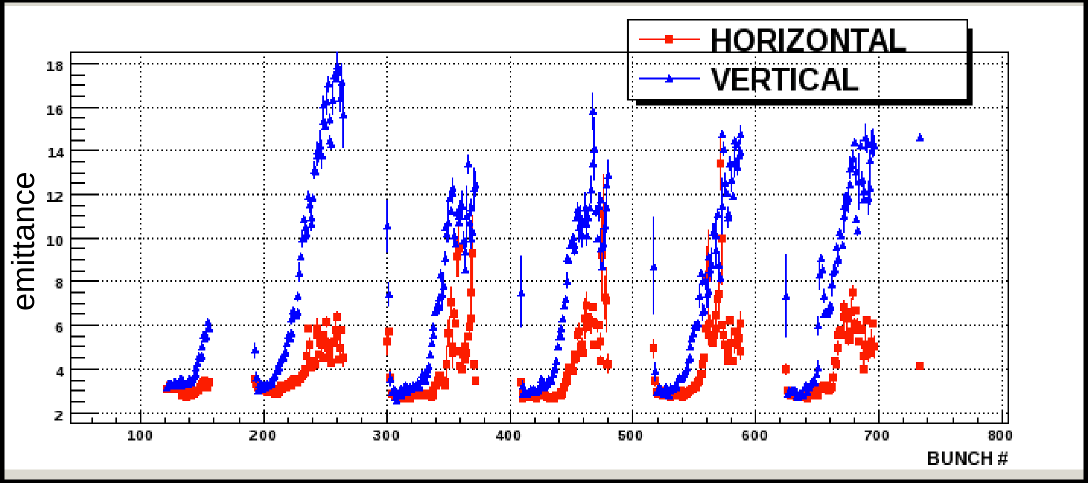
Electron Cloud in the LHC

- Electron cloud creates instability in tail of bunch trains
- Increases the size of the bunches towards the end of each bunch train
- Leads to losses for these bunches
- Adjustments made to counter this effect
  - Chromaticity
  - Transverse feedback
  - Beam scrubbing

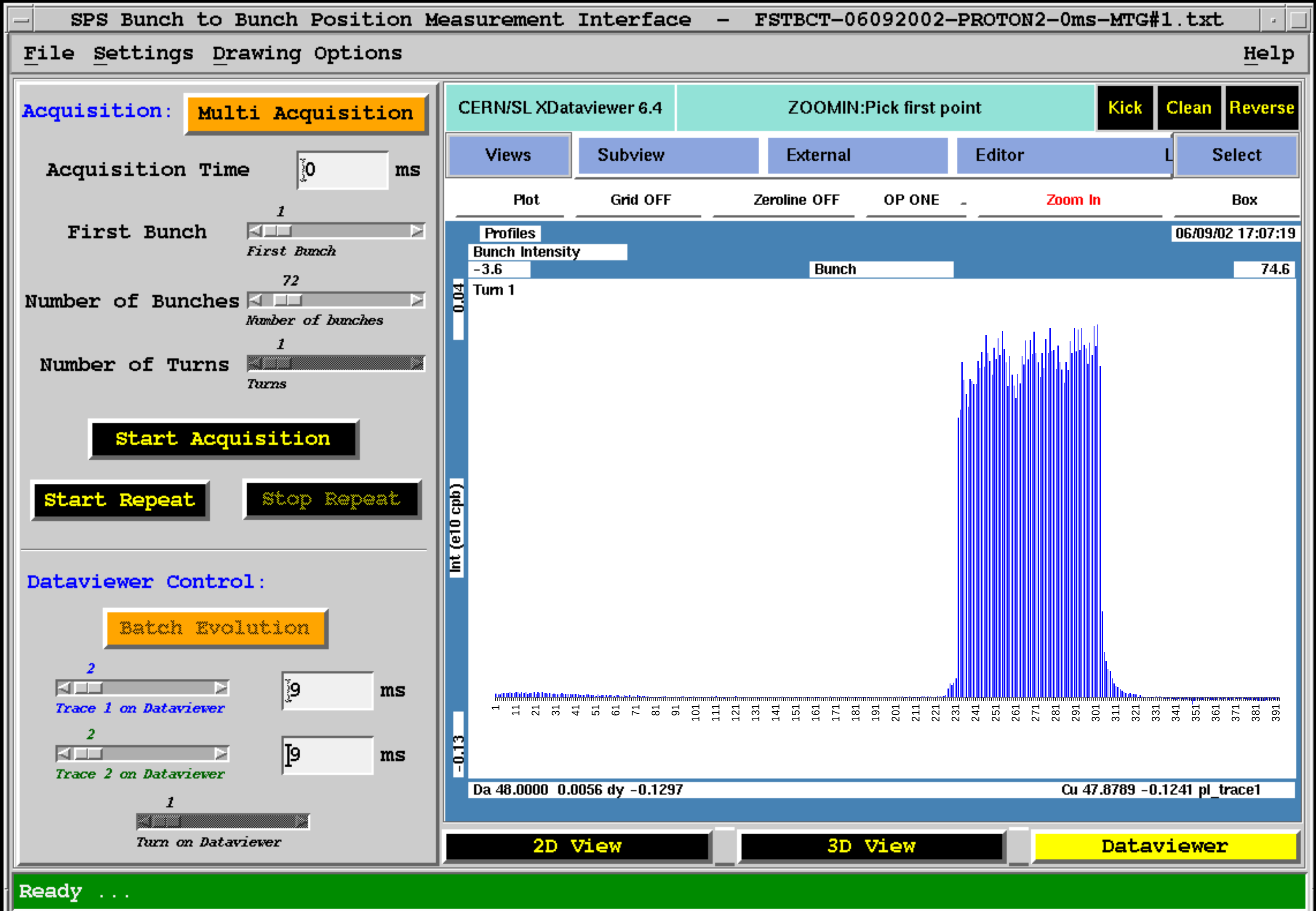
Diagnostics

- LHC fast BCT
  - Allows bunch by bunch intensity measurement
- LHC Synchrotron Light Monitor
  - Gated intensified Camera
  - Allows bunch by bunch profile measurement





Diagnostics using Fact BCTs



Bad RF Capture of a single LHC Batch in the SPS (72 bunches)

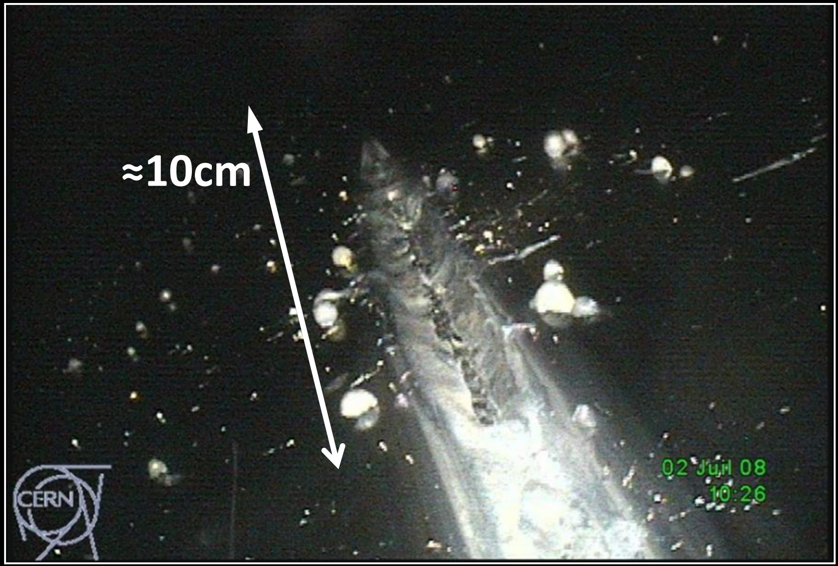
Beam Loss Monitors

Beam Loss Detectors

- Role of a BLM system:
  - Protect the machine from damage
  - Dump the beam to avoid magnet quenches (for superconducting magnets)
  - Diagnostic tool to improve the performance of the accelerator
- E.g. LHC

Stored Energy	
Beam 7 TeV	2 x 362 MJ

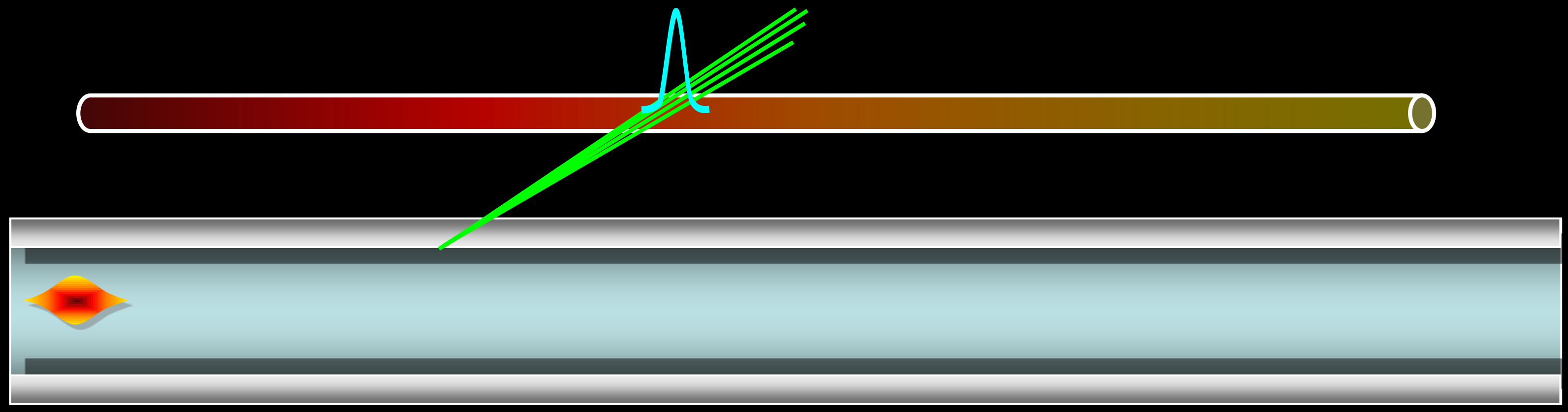
Quench and Damage at 7 TeV	
Quench level	≈ 1mJ/cm^3
Damage level	≈ 1 J/cm^3



- SPS incident
  - June 2008
  - 2 MJ beam lost at 400GeV

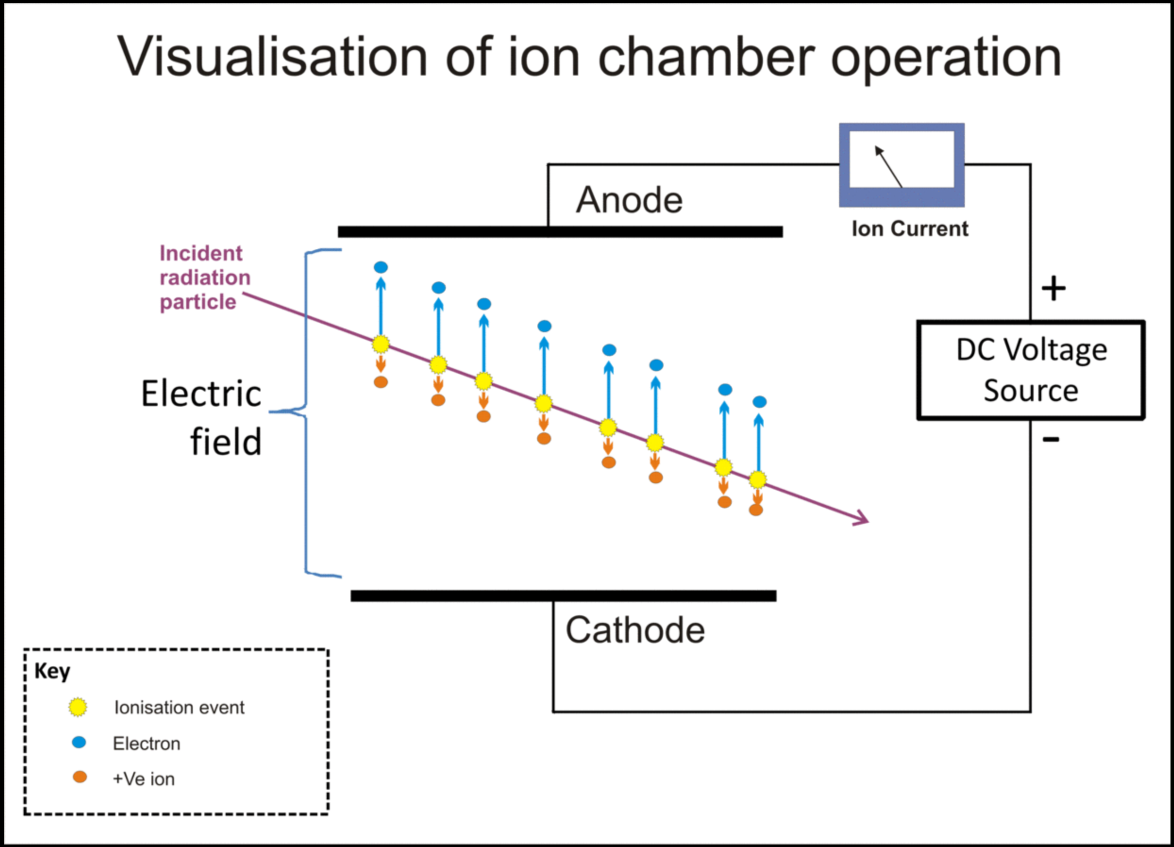
Beam Loss Detectors

- Common types of monitor
  - Long ionisation chamber (charge detection)
    - Up to several km of gas filled hollow coaxial cables
    - Position sensitivity 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



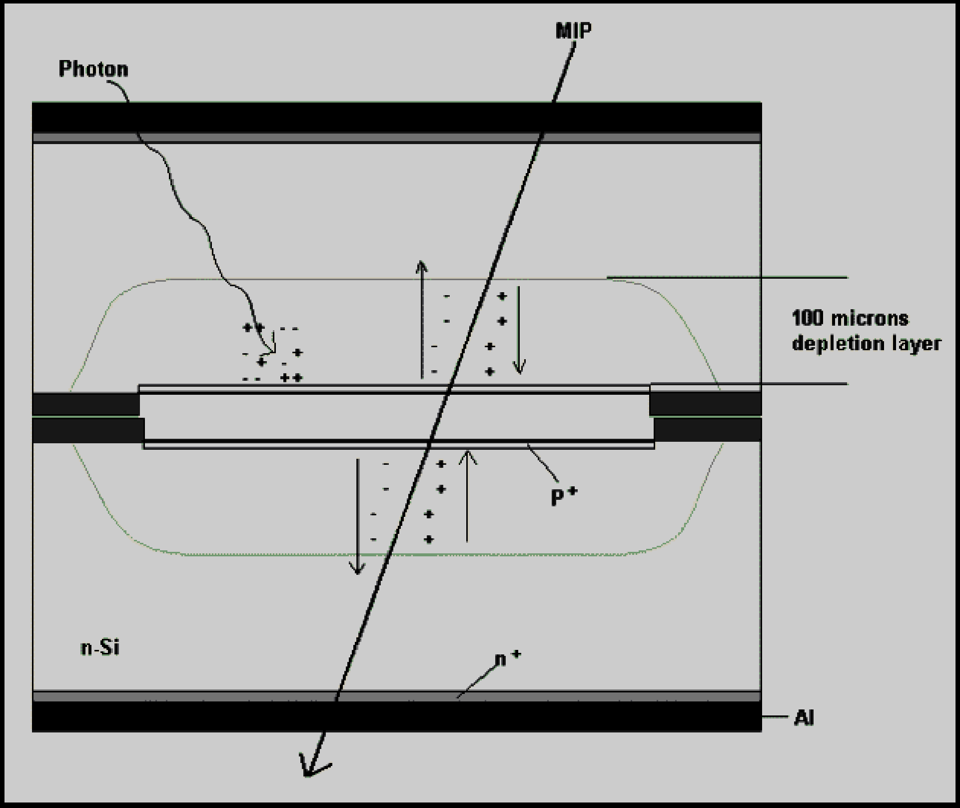
Beam Loss Detectors

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



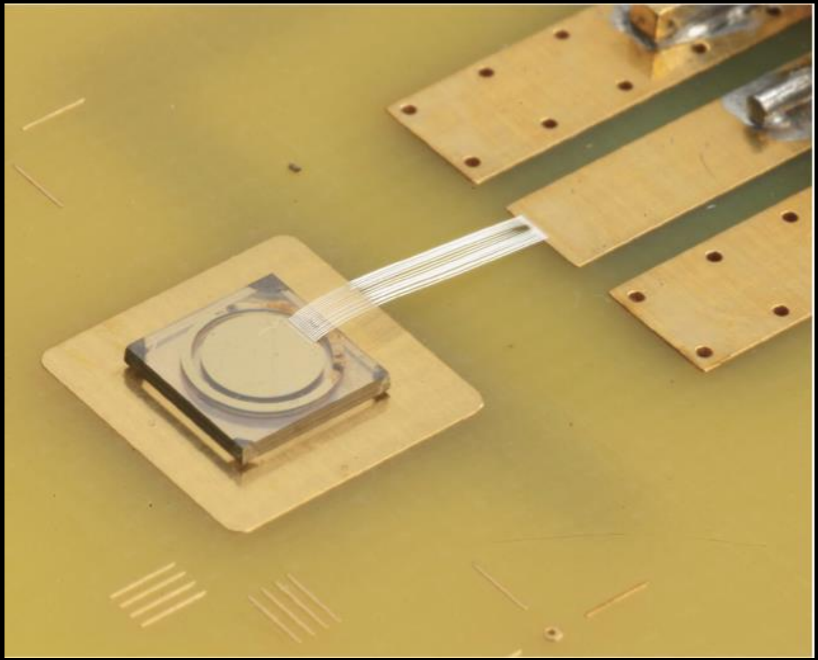
Beam Loss Detectors

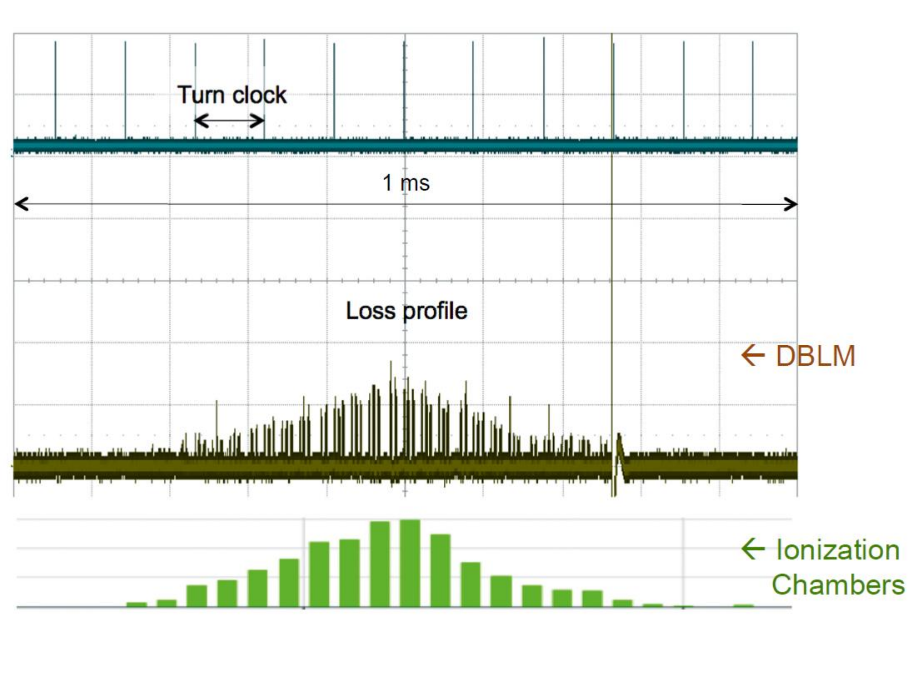
- Common types of monitor
  - PIN photodiode (solid state ionisation chamber)
    - Detect coincidence of ionising particle crossing photodiodes
    - Count rate proportional to beam loss with speed limited by integration time
    - Can distinguish between X-rays & ionising particles
    - Dynamic range of up to 10^9

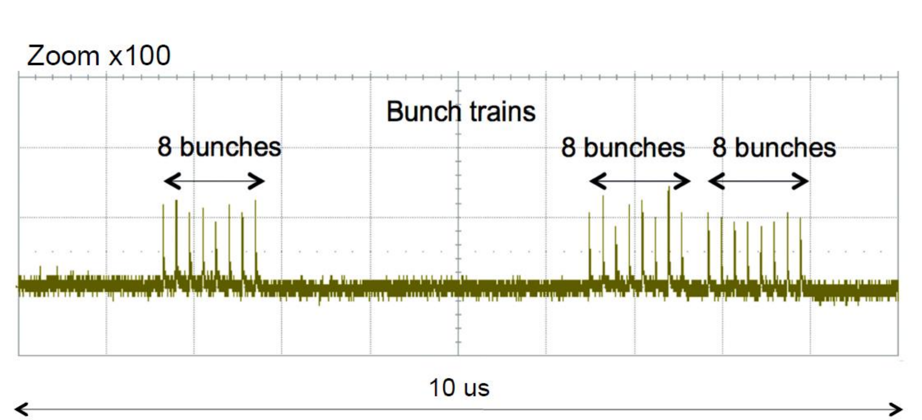


Beam Loss Detectors – New Materials

- Diamond Detectors
  - Fast & sensitive
  - Used in LHC to distinguish bunch by bunch losses





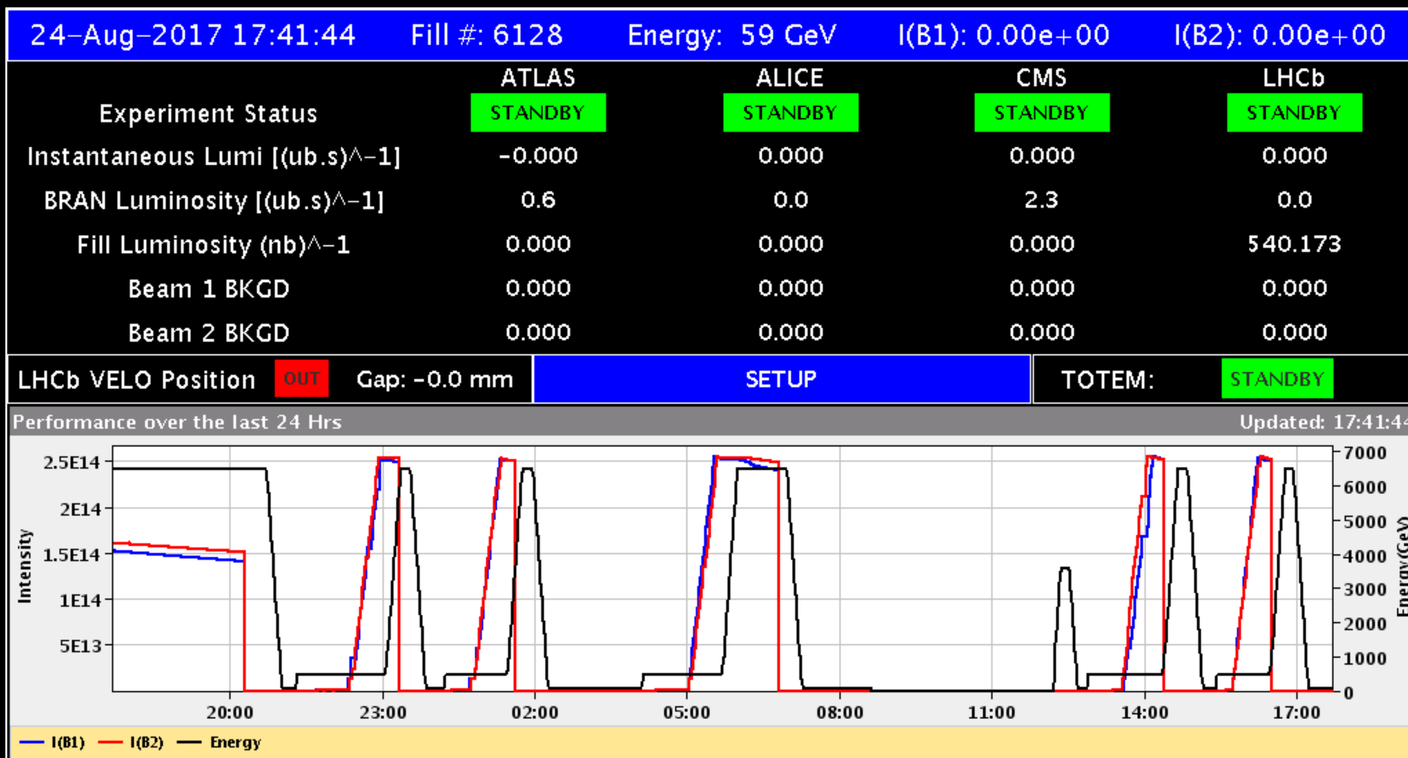


Courtesy of E. Griesmayer

Diagnostics using Beam Loss Monitors

Example from Last LHC Run

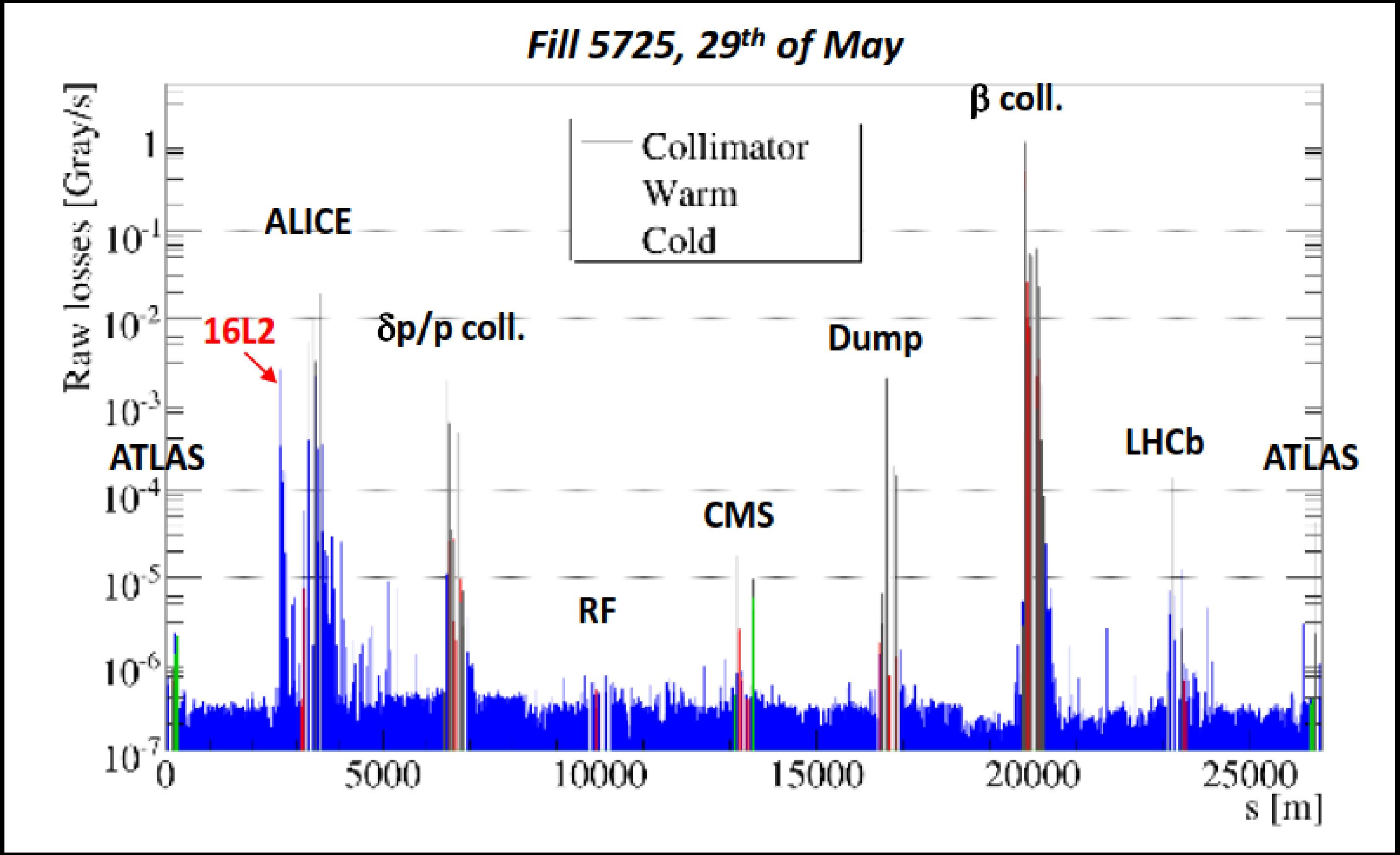
- Beam continually lost due to excessive losses
  - What is going on?



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

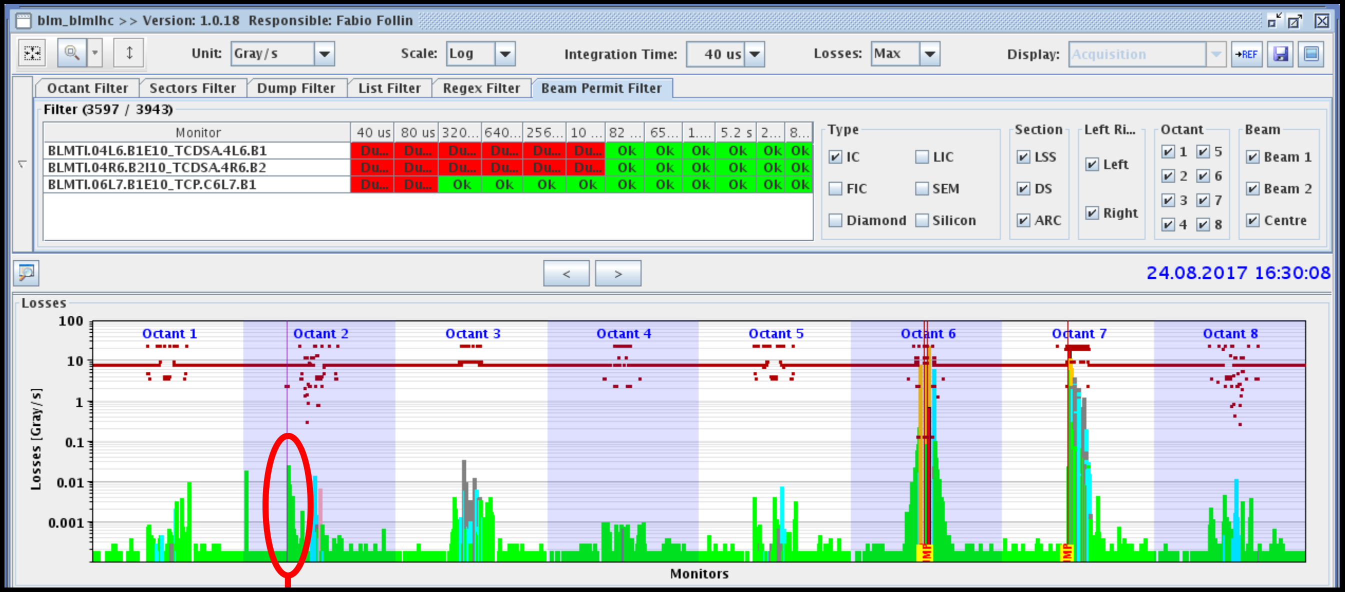
16L2 – First Event

- First beam dump event – as seen by the BLMs
  - Local aperture measurements did not reveal evident aperture restriction
  - Clear signature of losses from both beams
    - Both beams interacting with nuclei



BLM Diagnostics

- Time evolution of Losses

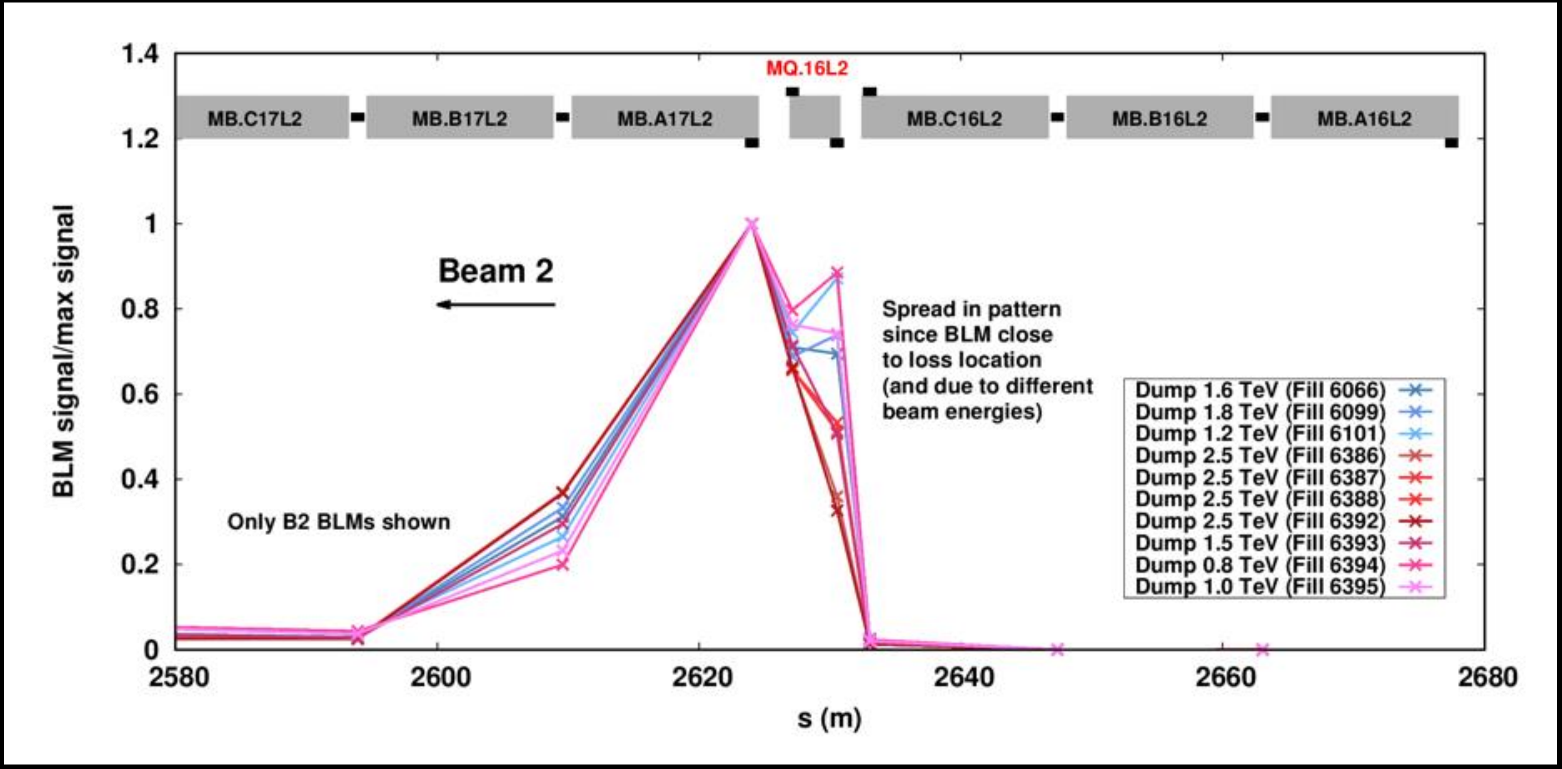


Looking for constant losses

- Installation of additional BLMs!
  - Factor 15 improvement in sensitivity

BLM Diagnostics

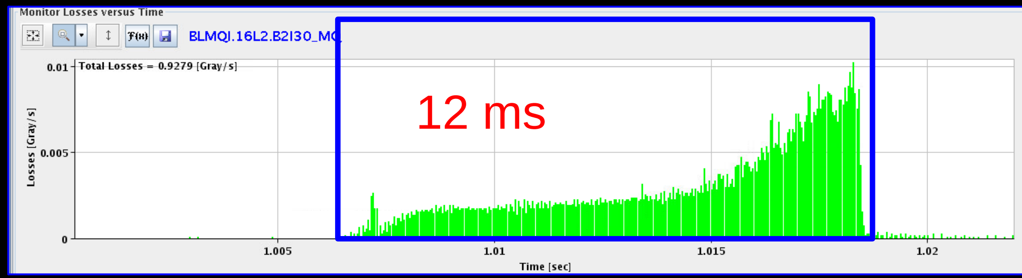
- Localisation
  - BLM Spatial patterns clearly show losses originate from one specific interconnection
    - MQ16L2 (Cell 16 left of LHC Point 2)
    - Localisation possible to within 1m comparing with simulation
  - Losses can be on either beam

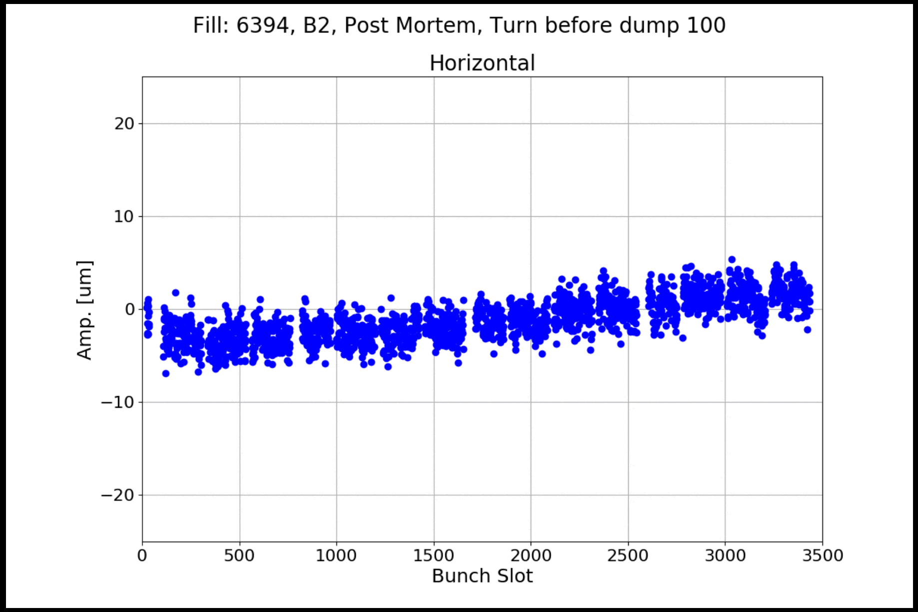


Additional Observations

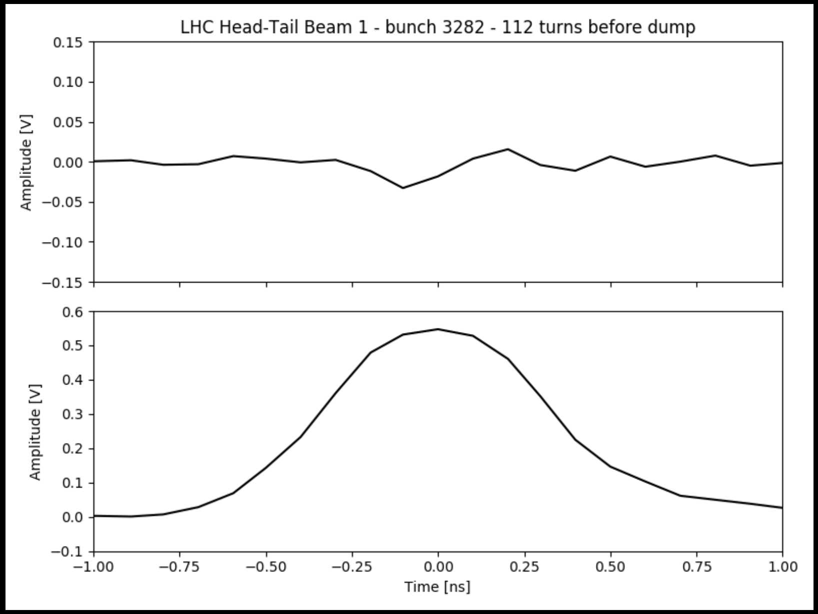
- Beam not always dumped by BLMs in 16L2
  - Often dumped by BLMs near primary collimators
    - Indicating development of transverse instability

Losses at BLM





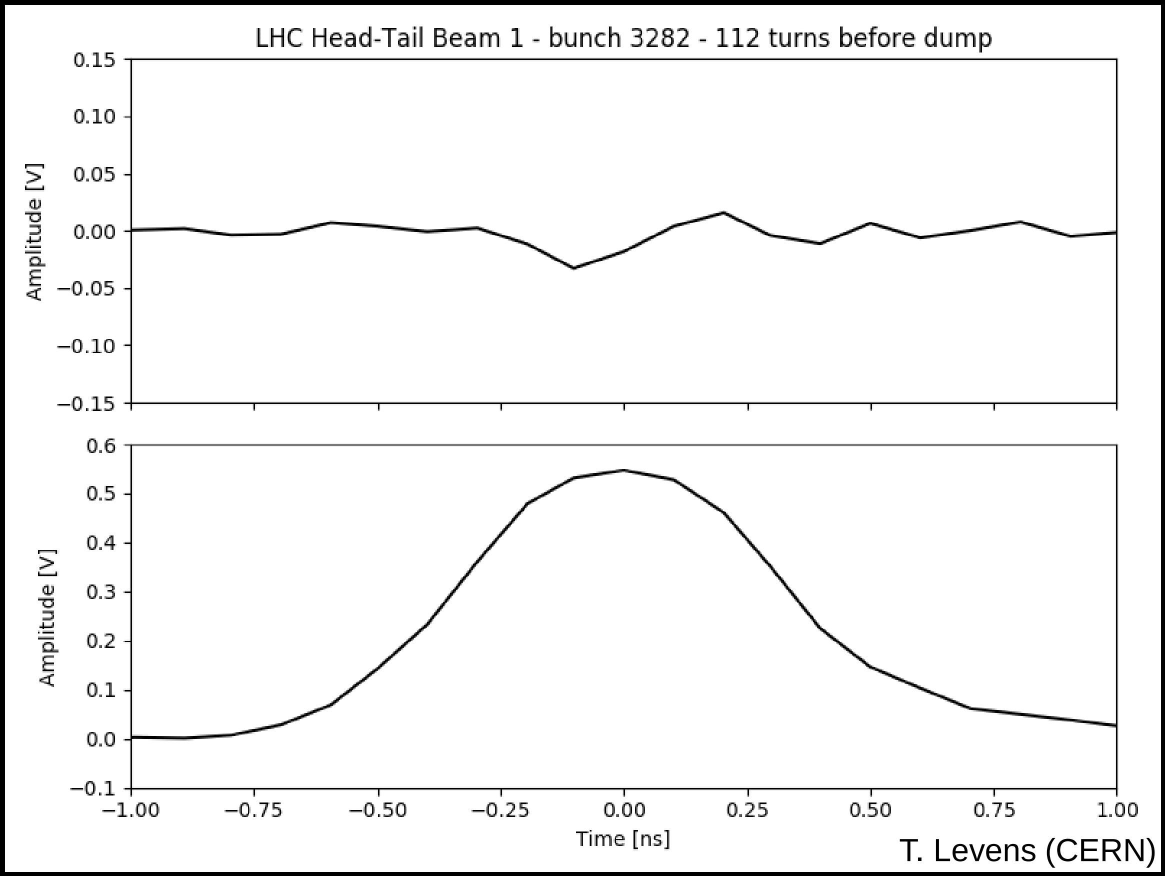
Bunch by bunch position



Intra-bunch position

Head-Tail Instability Monitor

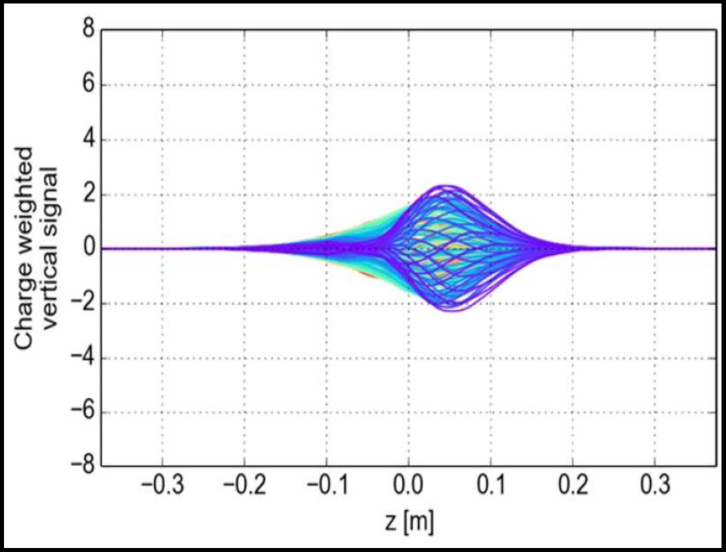
- Clearly shows instability in tail of bunch
  - Allowed simulations to try and re-create similar instability
  - Achieved when considering a large density of electrons over a short distance
    - Compatible with an ionised gas cloud



T. Levens (CERN)

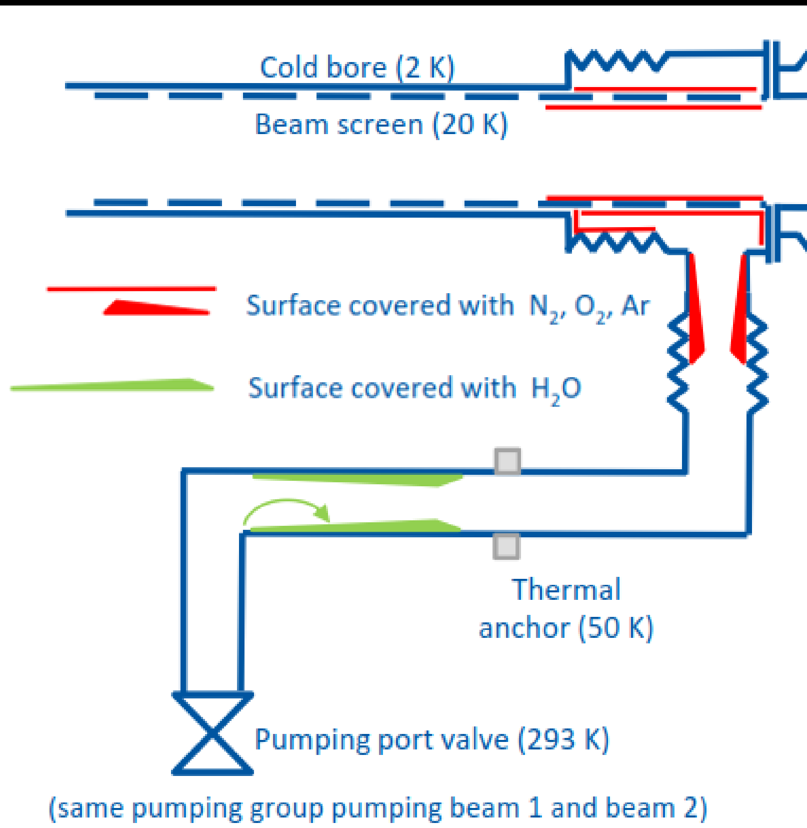
Measurement from head-tail monitor

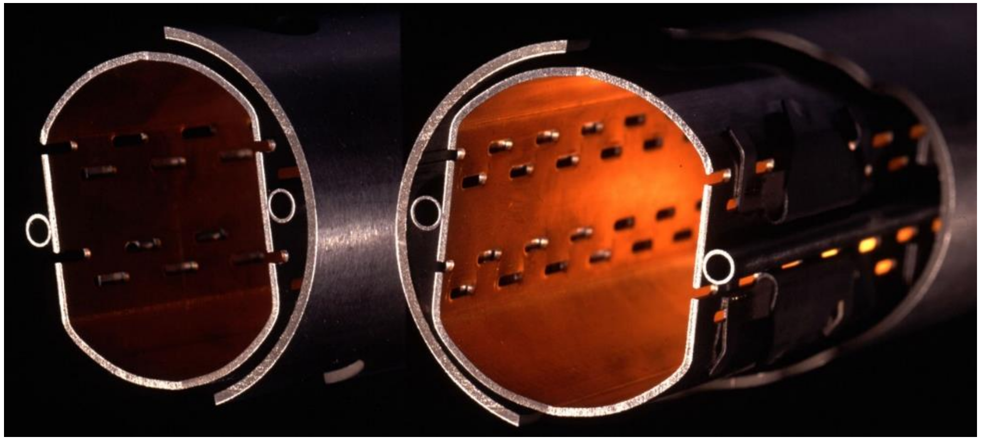
Simulation



16L2 - Hypothesis

- Something went wrong during vacuum pumpdown
  - Air trapped on beam screen & cold bore of both beams
    - Solid nitrogen & oxygen formed
  - Falls into the beam & immediately vaporised
    - Creates local pressure rise with beam interaction producing ionized gas cloud
    - Leads to losses & beam instability





Summary of Lecture 1

- Today concentrated on beam position, intensity & loss monitors
  - Went into details of how they worked
  - Gave examples of their use as diagnostic tools
- Tomorrow we'll continue with a look at
  - Beam profile monitoring & diagnostics
  - Tune, Coupling & Chromaticity measurement & feedback

For those that want to know more then I hope you'll join the Beam Instrumentation Afternoon Course!

- 3 Sessions on Beam Signals and BPM design
  - 2 afternoons using dedicated simulation software
  - 1 afternoon "hands-on" doing laboratory measurements
- 3 Sessions on Profile Measurements
  - "Hands-on" laboratory experiments looking at different ways of measuring the transverse & longitudinal profile of the beam