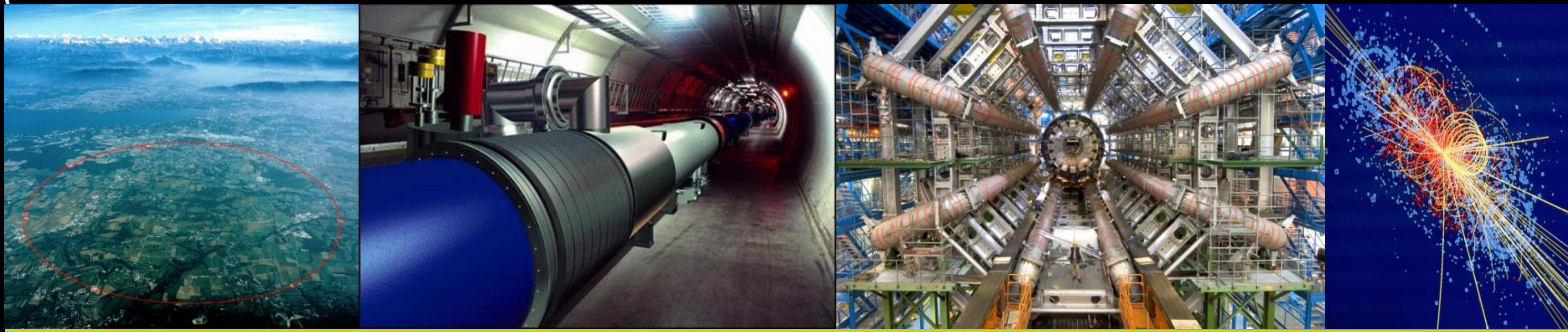


Introduction to LHC Beam Instrumentation

Beam Position and Beam Intensity

CERN Academic Lectures 2014

10th – 14th November, 2014

Dr. Rhodri Jones

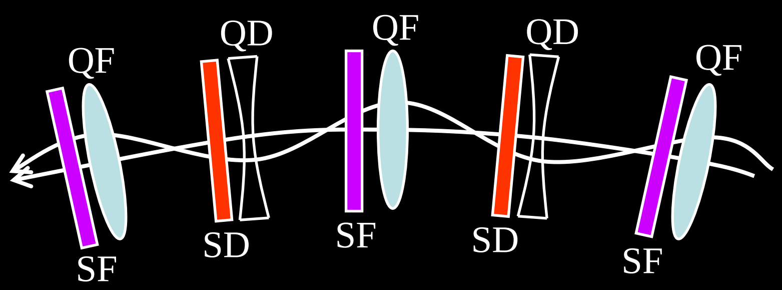
Head of the CERN Beam Instrumentation Group

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
  - A fascinating field of work!
- What beam parameters do we measure?
  - Beam Position
    - Horizontal and vertical throughout the accelerator
  - Beam Intensity (& lifetime measurement for a storage ring/collider)
    - Bunch-by-bunch charge and total circulating current
  - Beam Loss
    - Especially important for superconducting machines
  - Beam profiles
    - Transverse and longitudinal distribution
  - Collision rate / Luminosity (for colliders)
    - Measure of how well the beams are overlapped at the collision point

More Measurements

- Machine Tune

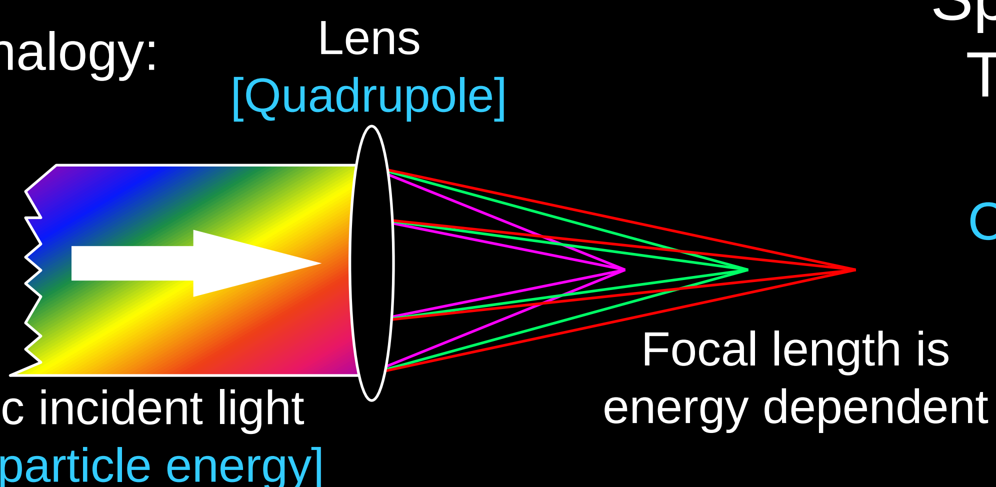


Characteristic Frequency of the Magnetic Lattice

Given by the strength of the Quadrupole magnets

- Machine Chromaticity

Optics Analogy:



Spread in the Machine Tune due to Particle Energy Spread

Controlled by Sextupole magnets

The Typical LHC Instruments

Today

- Beam Position
  - electrostatic or electromagnetic pick-ups and related electronics
- Beam Intensity
  - beam current transformers

Tomorrow

- Beam Profile
  - screens
  - wire scanners
  - synchrotron light monitors
  - ionisation monitors

Friday

- Beam Loss
  - ionisation chambers and solid-state detectors
- Machine Tune and Chromaticity
  - base band tune measurement system
- Other Monitors
  - Luminosity, schottky, abort gap, instability

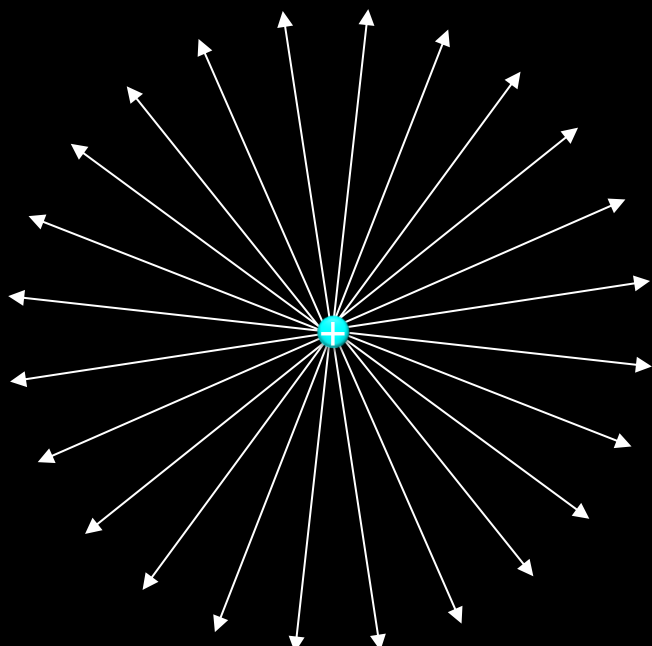
Position Measurement

- Main functionalities
  - – Orbit measurements and single turn trajectories
  - – Feedback to align and stabilize beams
  - – Position interlock to dump the beam if deviating

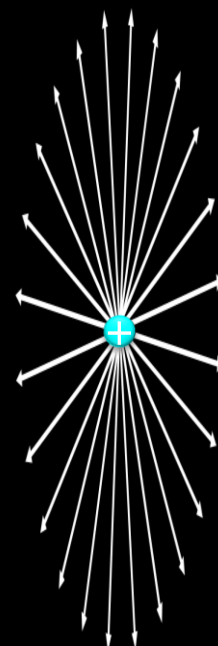
- Secondary functionalities
  - – Measurements of lattice parameters:
    - Turn-by-turn on a single monitor:
      - – Betatron oscillation, beam response, transfer function
    - Turn-by-turn on the whole monitors:
      - – Phase advance, phase change, optics checks, local chromaticity
    - Averaged read out:
      - – Energy calibration, Machine impedance

Electromagnetic Fields & Relativity

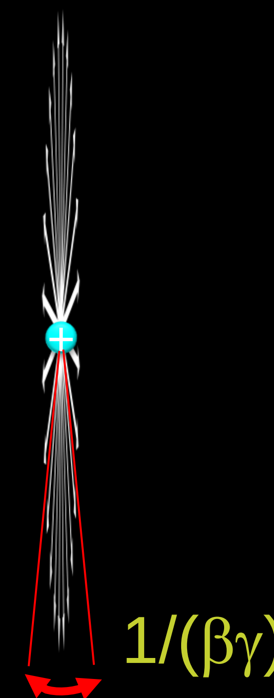
Static Point Charge



Moving Point Charge

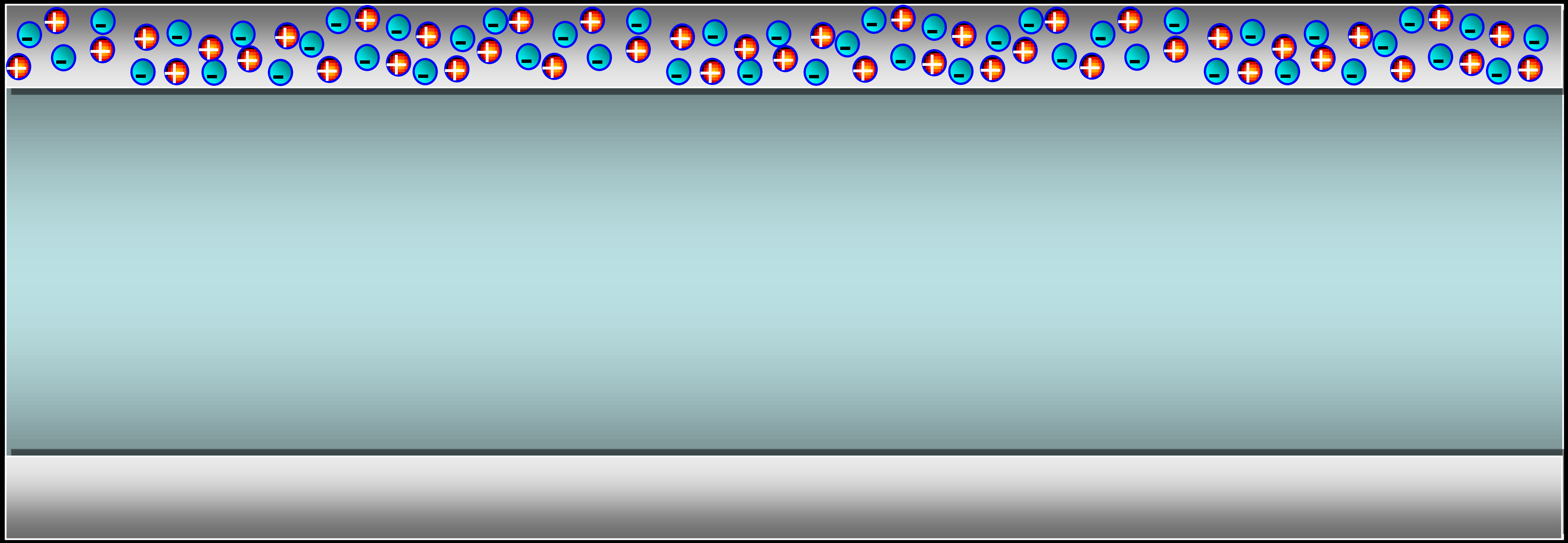


Relativistic Point Charge

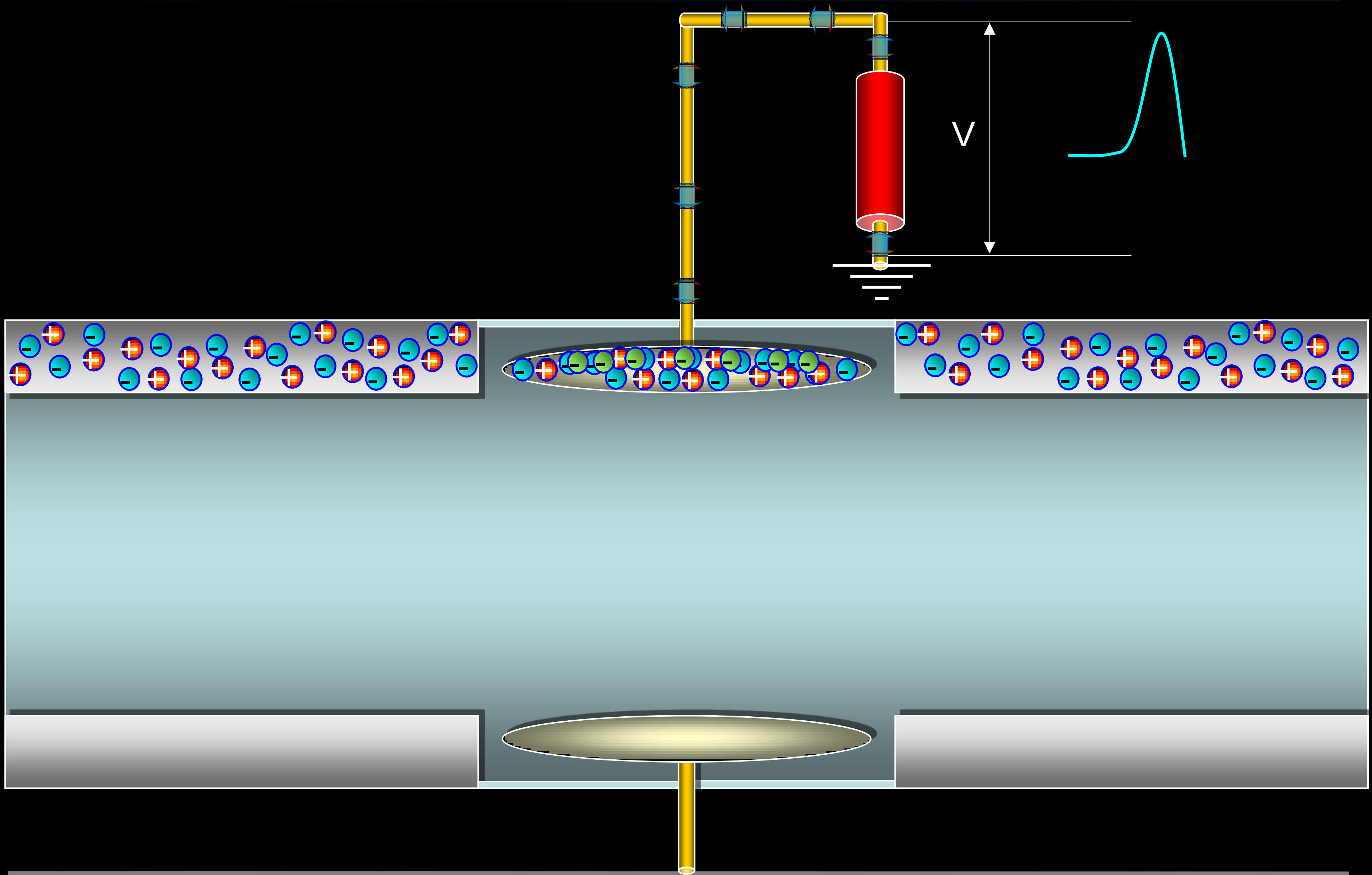


- LHC Case – relativistic protons
  - Electric & magnetic fields transverse to the direction of motion
  - Can be considered as a TEM wave

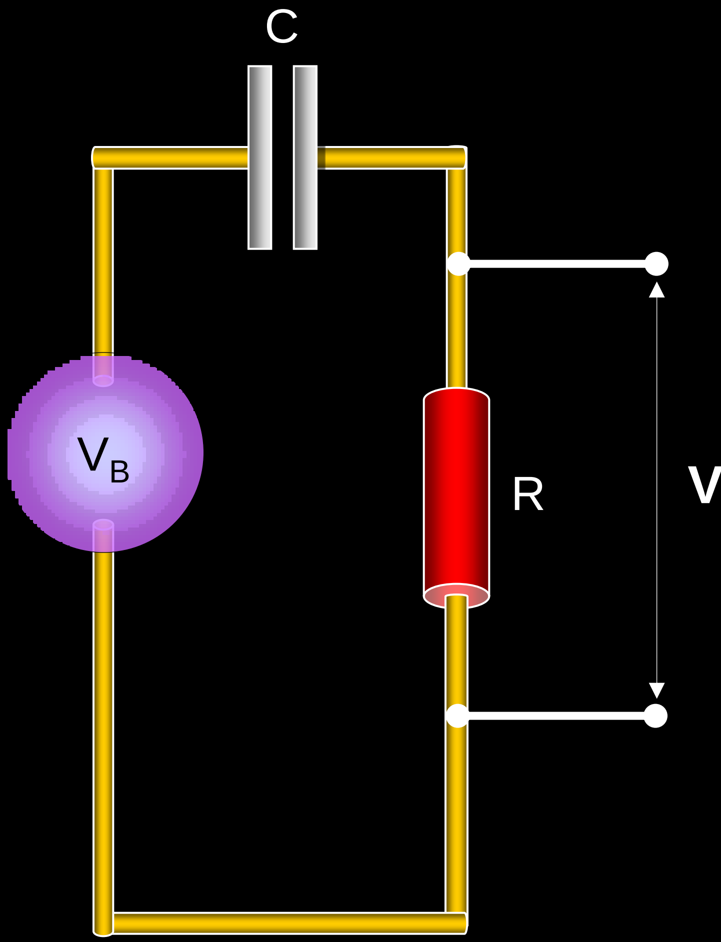
Measuring Beam Position – The Principle

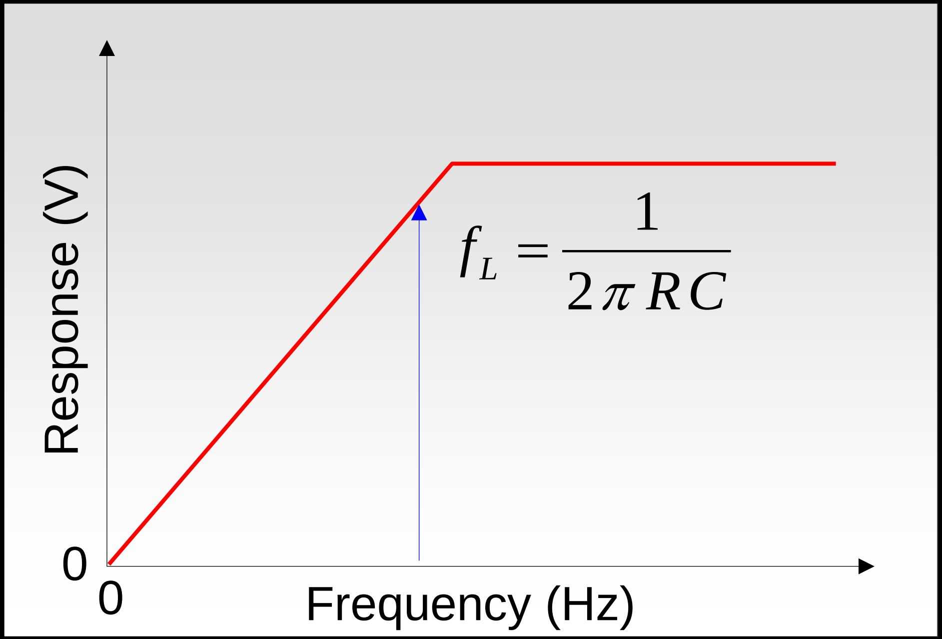


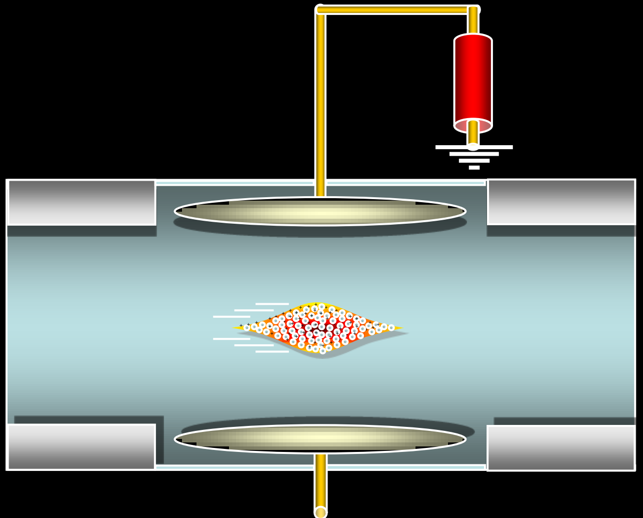
Electrostatic Monitor – The Principle



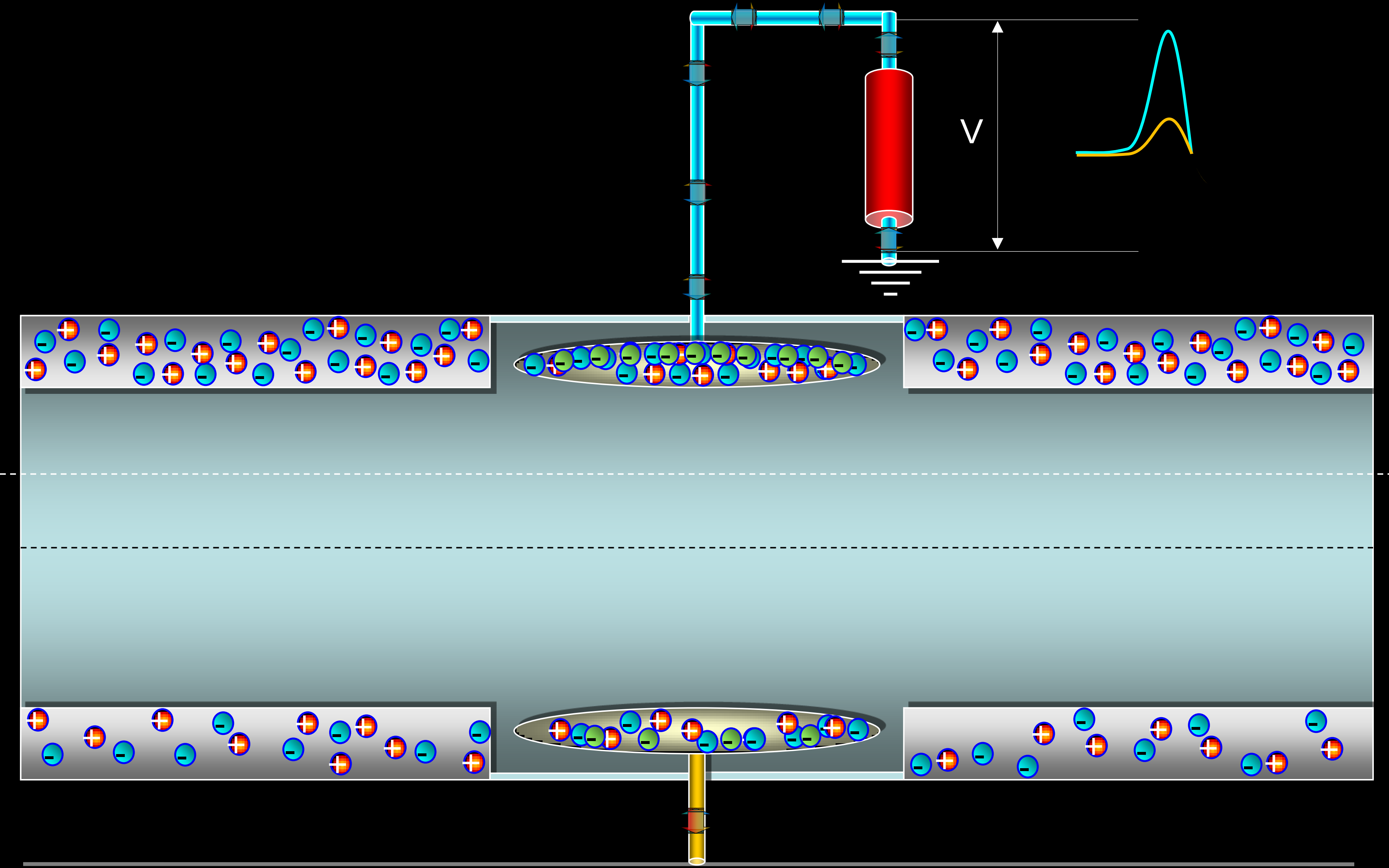
Electrostatic Monitor – Beam Response



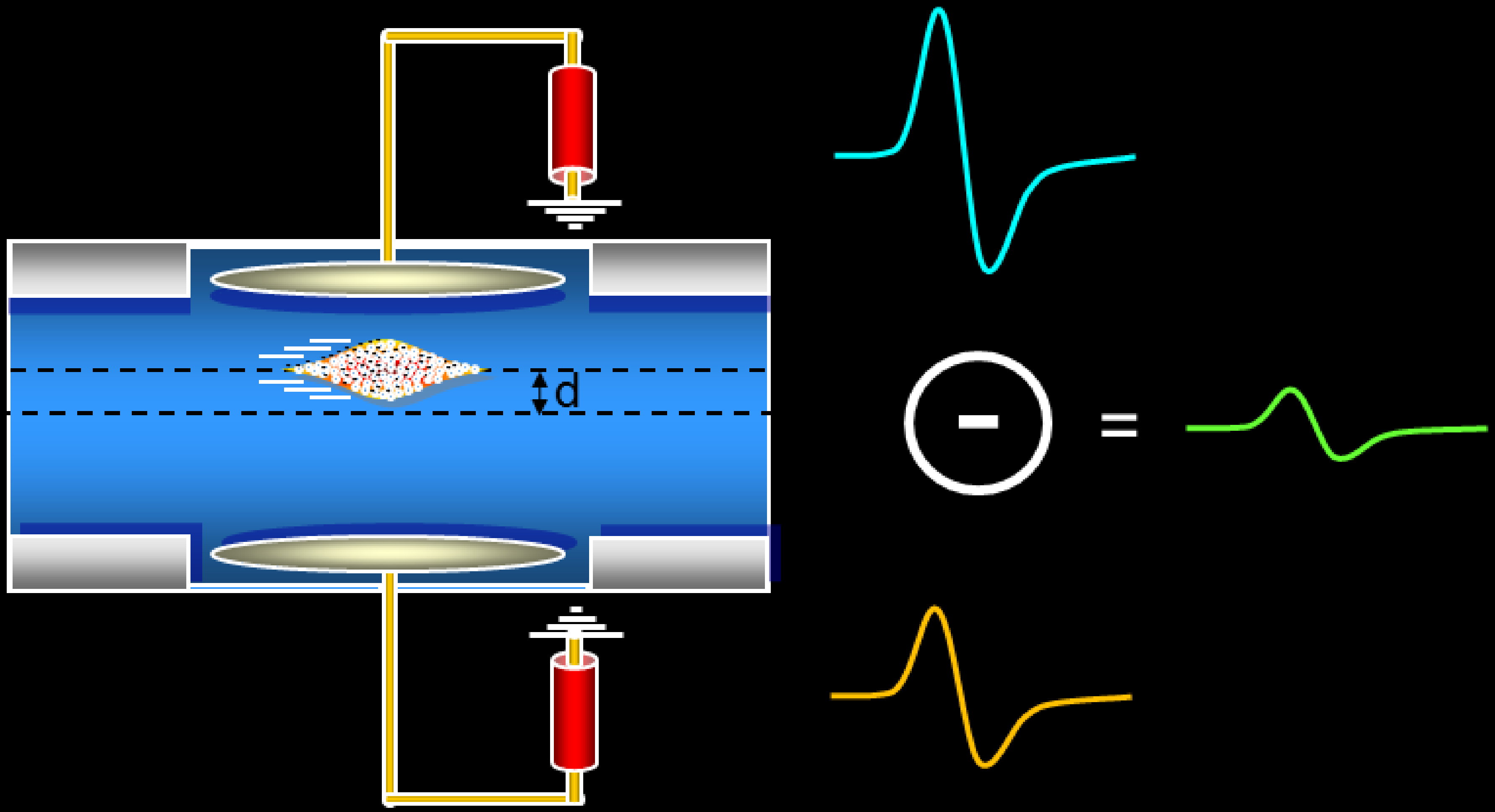




Electrostatic Monitor – The Principle



Electrostatic Monitor – The Principle



Electrostatic Pick-up – Button

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

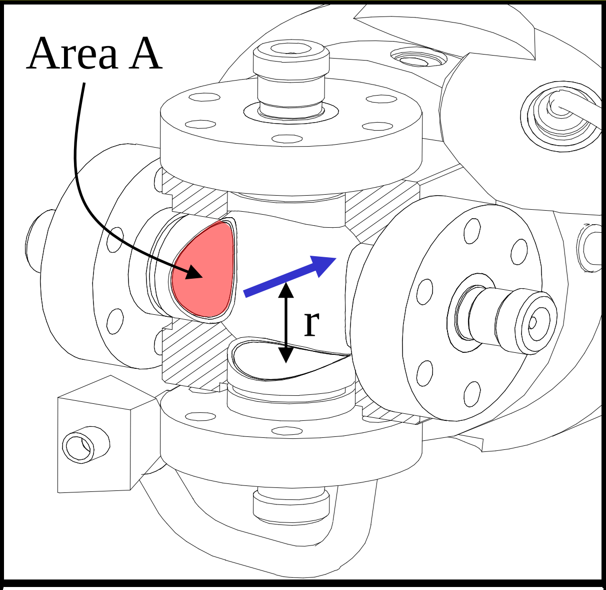
For Button with Capacitance C_e & Characteristic Impedance R_0

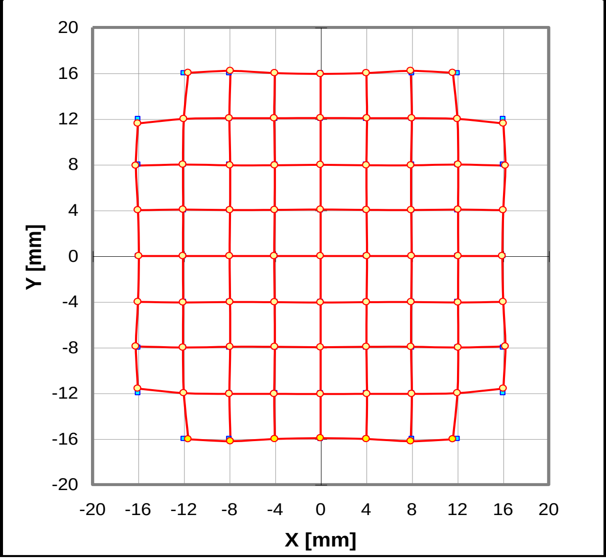
Transfer Impedance:

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

Lower Corner Frequency:

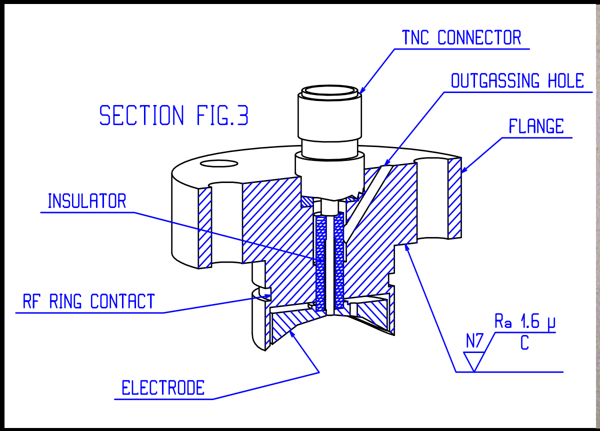
$$f_L = \frac{1}{2\pi R_0 C_e}$$

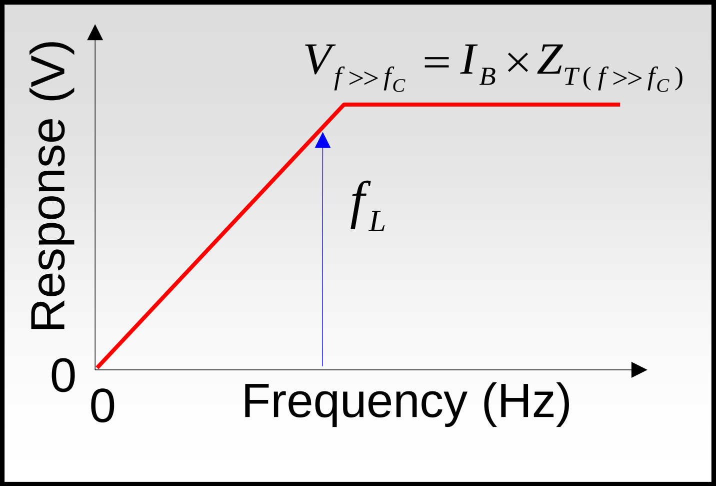




$$X = 2.30\cdot10^{-5}X_1^{\,5} + 3.70\cdot10^{-5}X_1^{\,3} + 1.035X_1 + 7.53\cdot10^{-6}X_1^{\,3}Y_1^{\,2} + 1.53\cdot10^{-5}X_1Y_1^{\,4}$$

A Real Example – The LHC Button





$$f_L = \frac{1}{2\pi RC} = \frac{1}{2\pi \times 50\Omega \times 8pF} = 400MHz$$

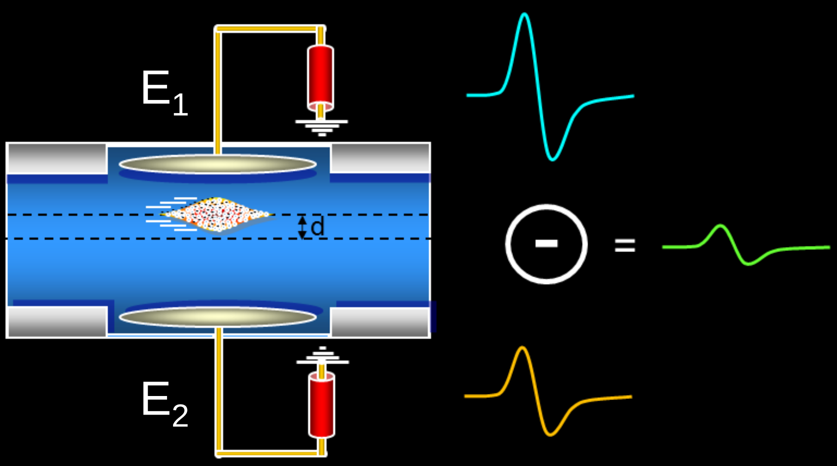
$$Z_{T\infty} = \frac{A}{(2\pi r)\times c \times C_e} = \frac{\pi \times (12mm)^2}{(2\pi \times 24.5mm)\times c \times (8pF)} = 1.2\Omega$$

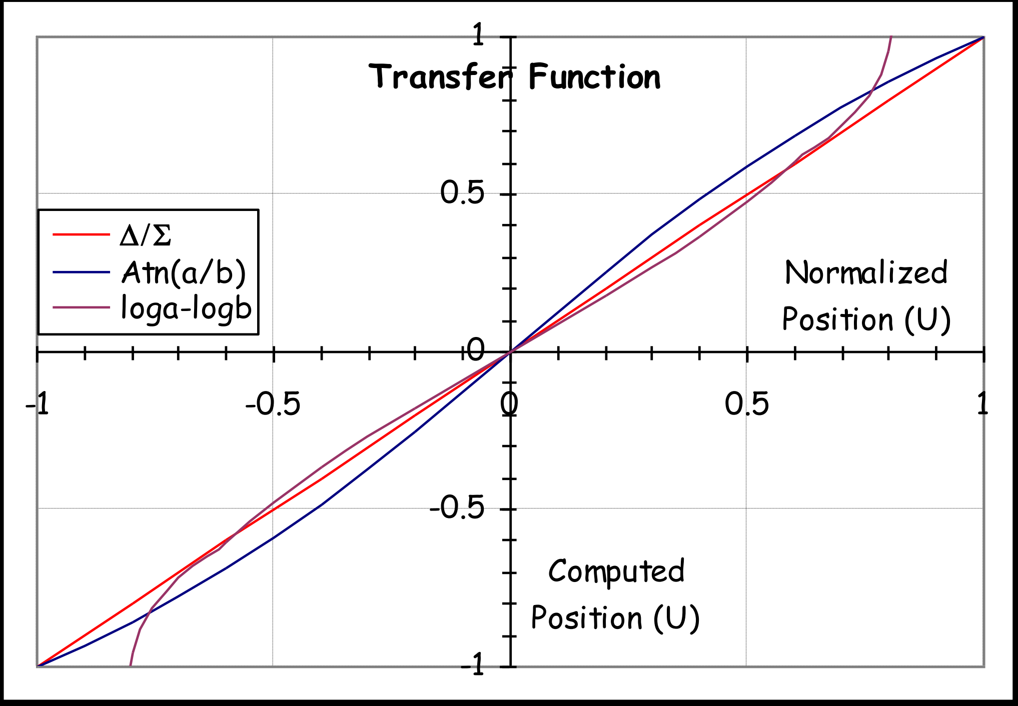
$$I_B = \frac{N_{pilot}e}{t} = \frac{5\times10^9 \times 1.6\times10^{-19}}{0.75\times10^{-9}} = 1.1A_{peak} \Rightarrow V_{f=\infty} = 1.1\times1.2 = 1.3V_{peak}$$

$$= \frac{N_{nom}e}{t} = \frac{1\times10^{11} \times 1.6\times10^{-19}}{0.75\times10^{-9}} = 21A_{peak} \Rightarrow V_{f=\infty} = 21\times1.2 = 25V_{peak}$$

Normalising the Position Reading

- To make it independent of intensity
- 3 main methods:
  - $(E_1 - E_2) / (E_1 + E_2) = \Delta / \Sigma$
  - $\text{Arctan}(E_1 / E_2)$
  - $\text{Log}(E_1) - \text{Log}(E_2)$
- LHC uses equivalent of 2nd method as we'll see in a moment





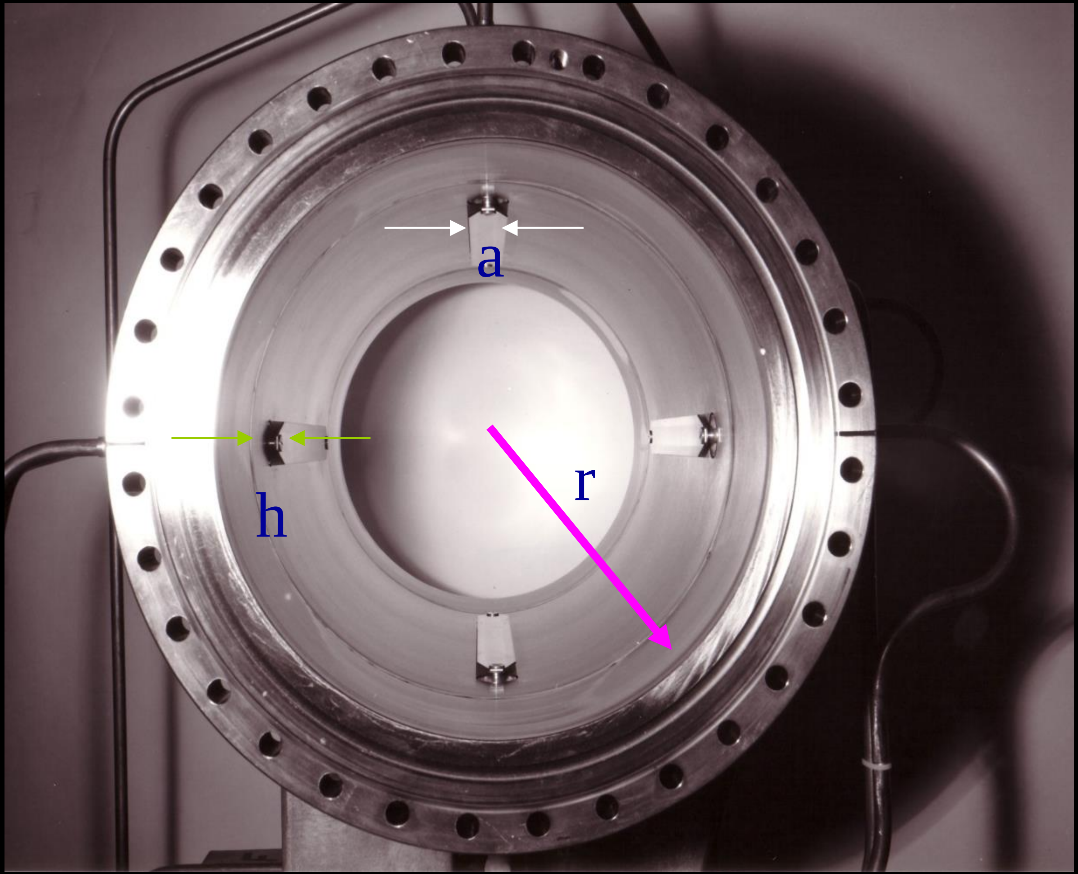
Electromagnetic (Directional) coupler

- A transmission line (stripline) which couples to the transverse electromagnetic (TEM) beam field

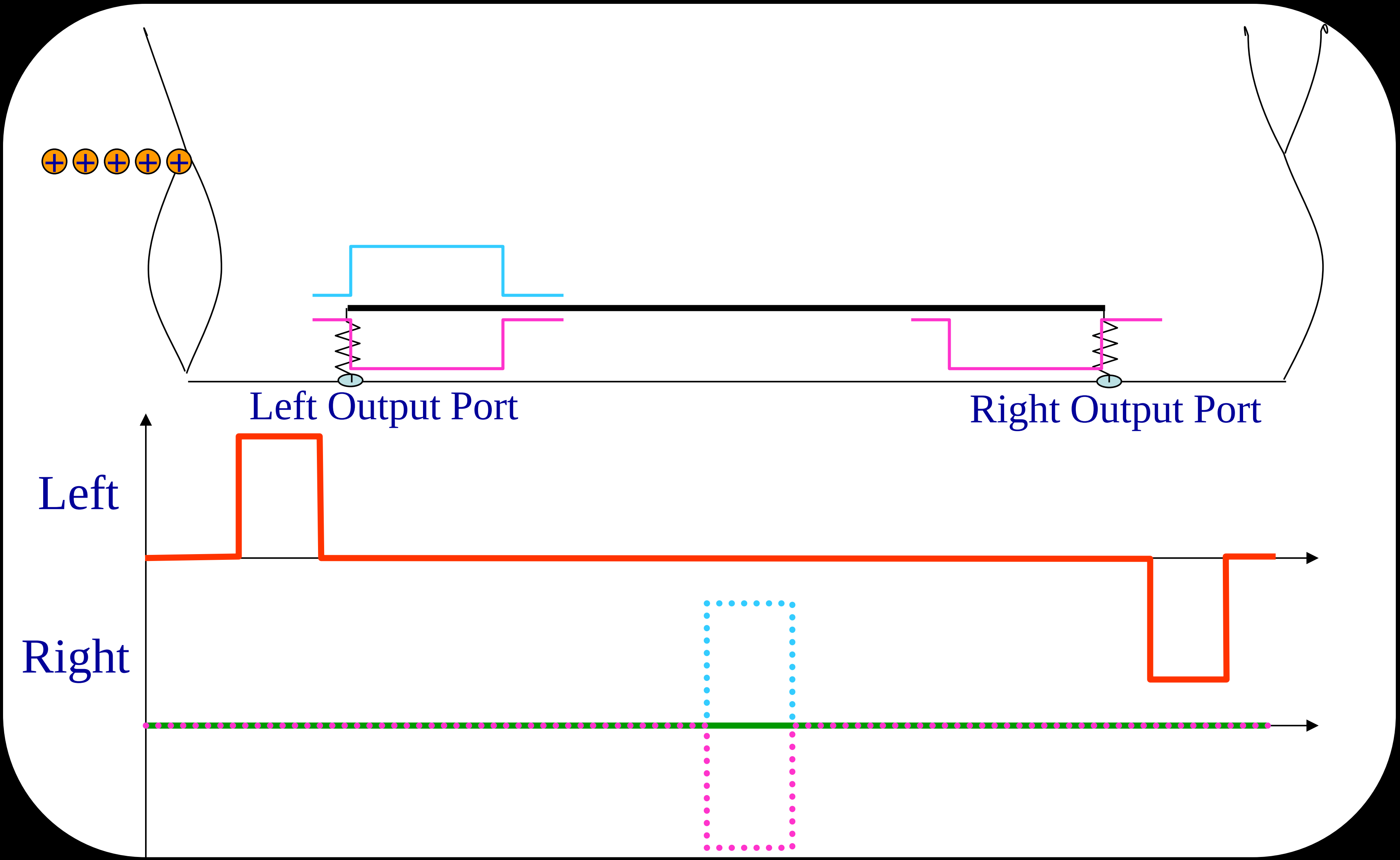
$$Z_{t\,\infty} = 60 \ln[(r+h)/r]$$

$$\equiv Z_0 * [a/2\pi(r+h)]$$

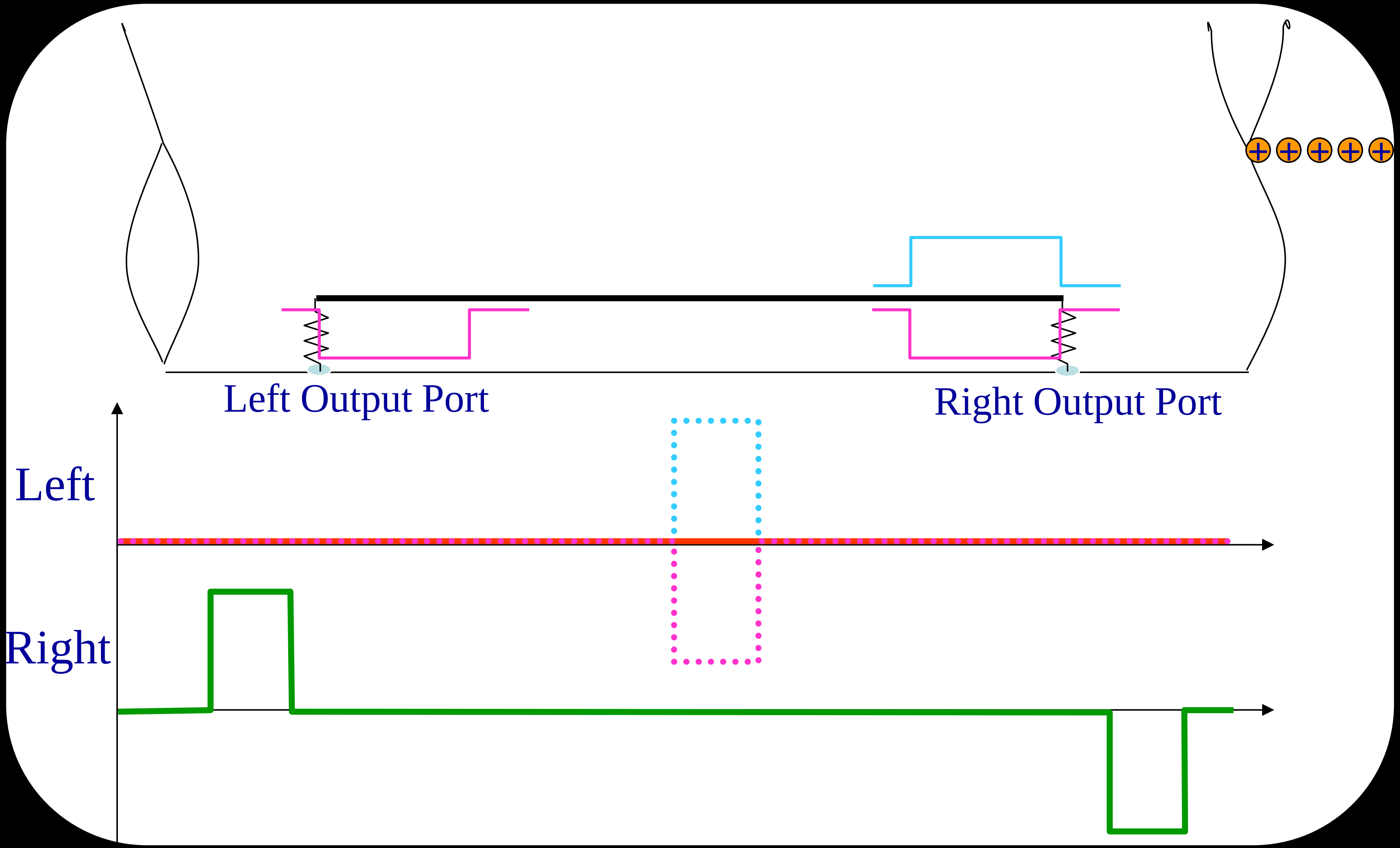
- Z_0 is the characteristic impedance
- a, r, h, l are the mechanical dimensions
- t = l/c is the propagation time in the coupler



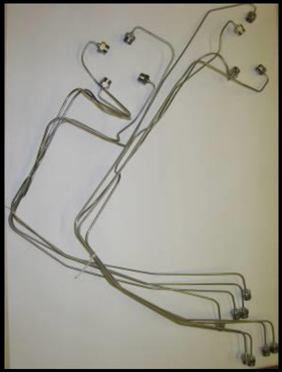
EM Stripline Coupler – right travelling beam



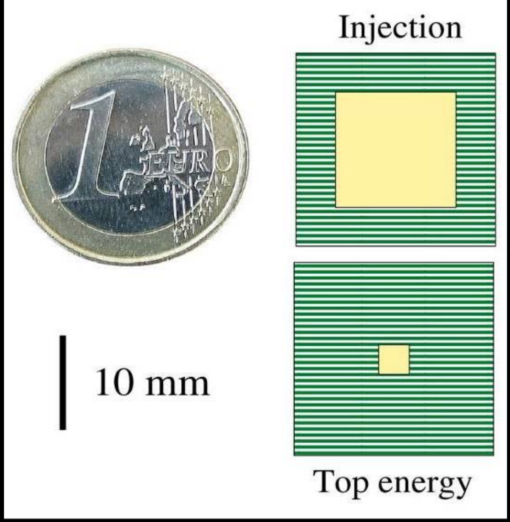
EM Stripline Coupler – left travelling beam



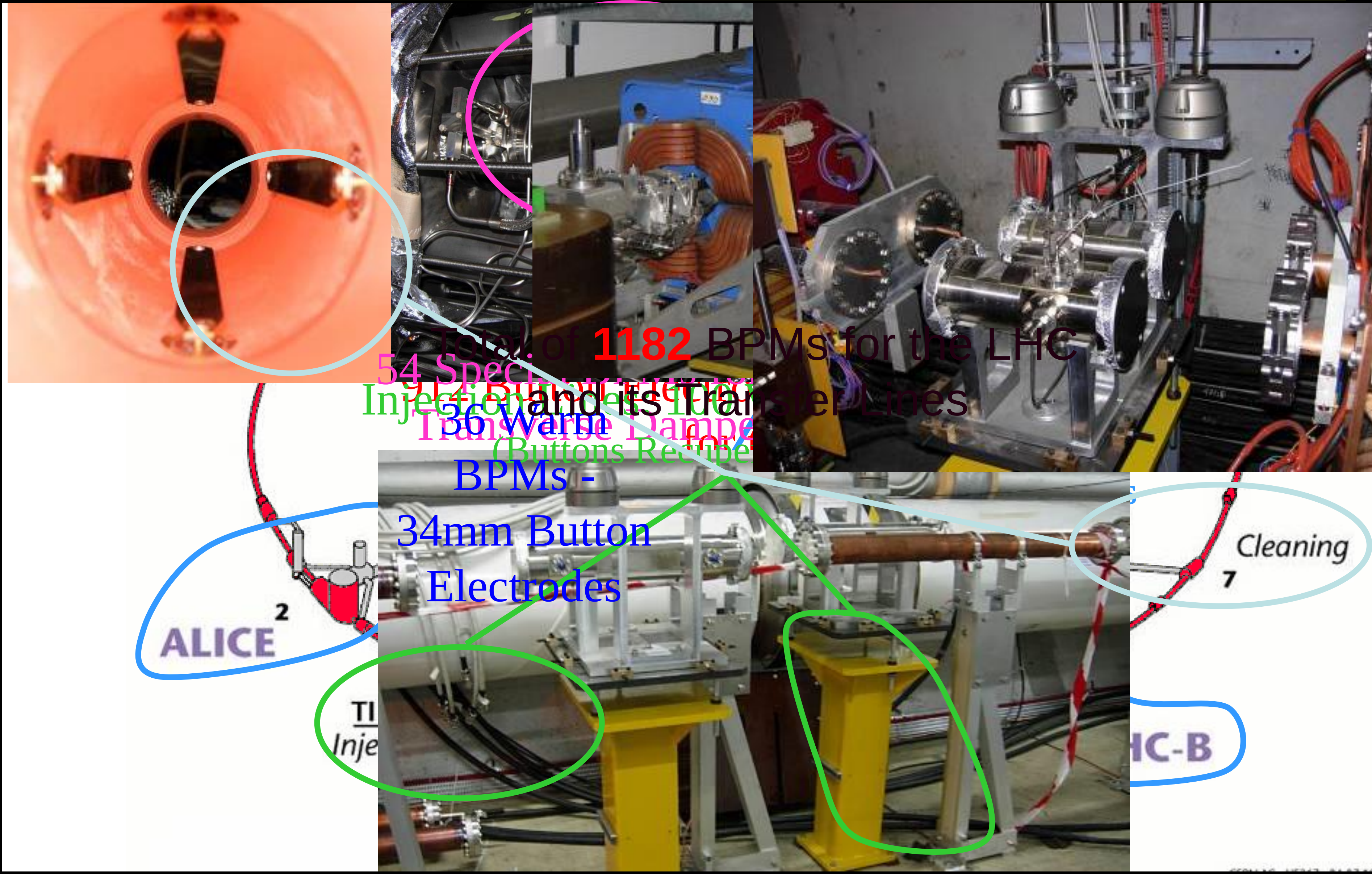
Beam Position System Challenges



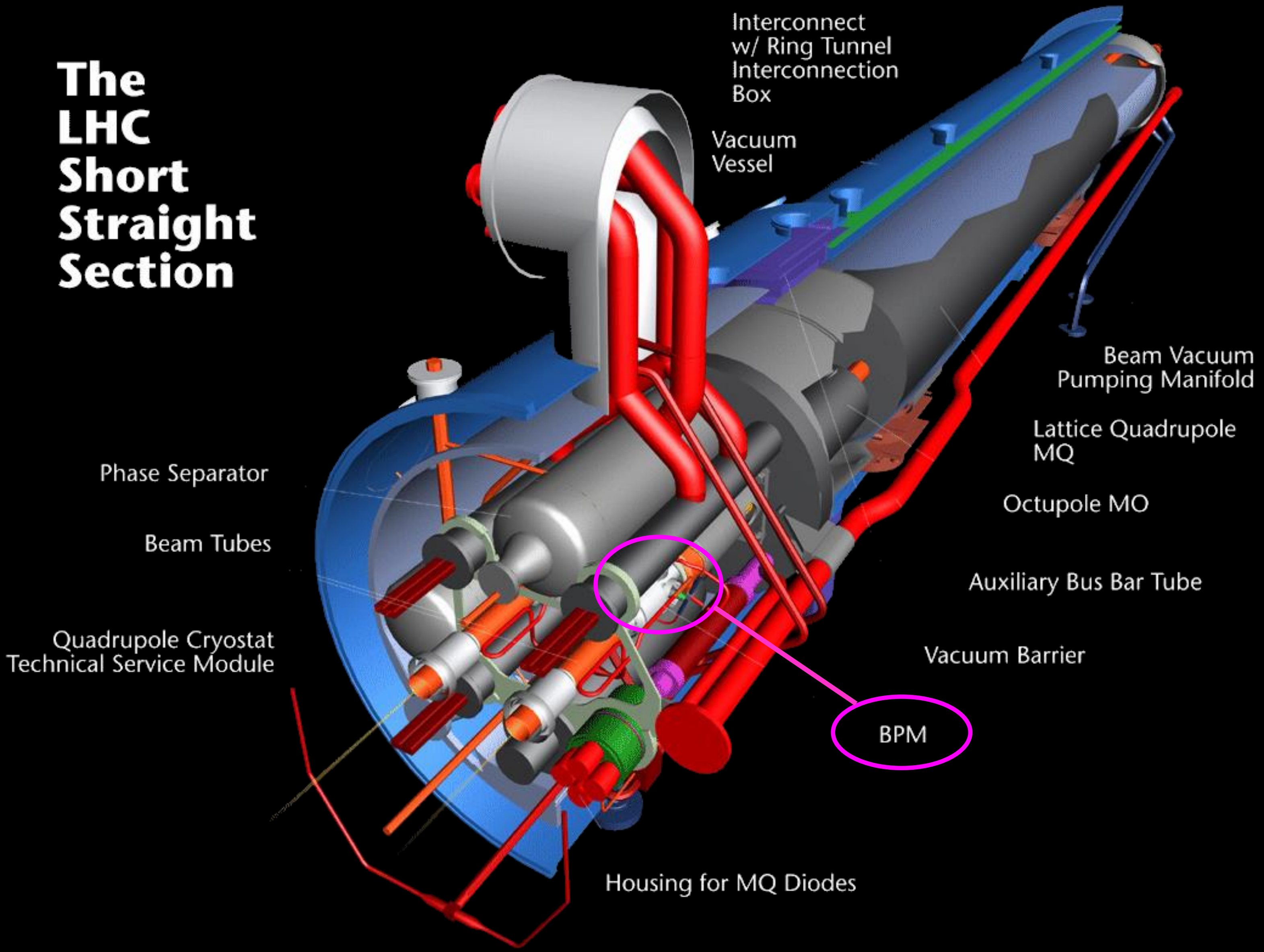
- Pick-up requirements
  - Mechanics that can operate at ~4K
  - Maximise aperture & signal strength
  - Minimise transverse impedance
- Dynamic Range
  - From 1 bunch of 1×10^9 charges to 2808 bunches of 1.7×10^{11} charges
- Linearity
  - Better than 1% of half radius, ~130μm for arc BPMs
    - Over whole intensity range
    - Over large fraction of the aperture
- Resolution
  - In the micron range for accurate global orbit control
    - Driven by collimation requirements
    - Over 120 collimator jaws in the LHC



LHC BPM System - General Layout



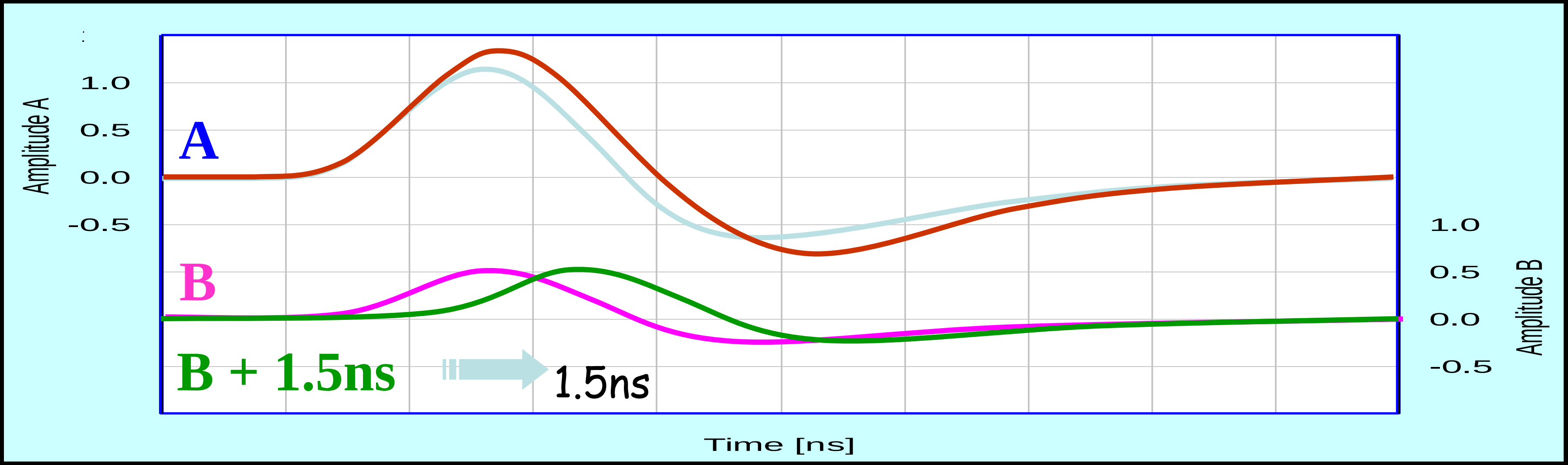
The Arc BPM - SSS Layout

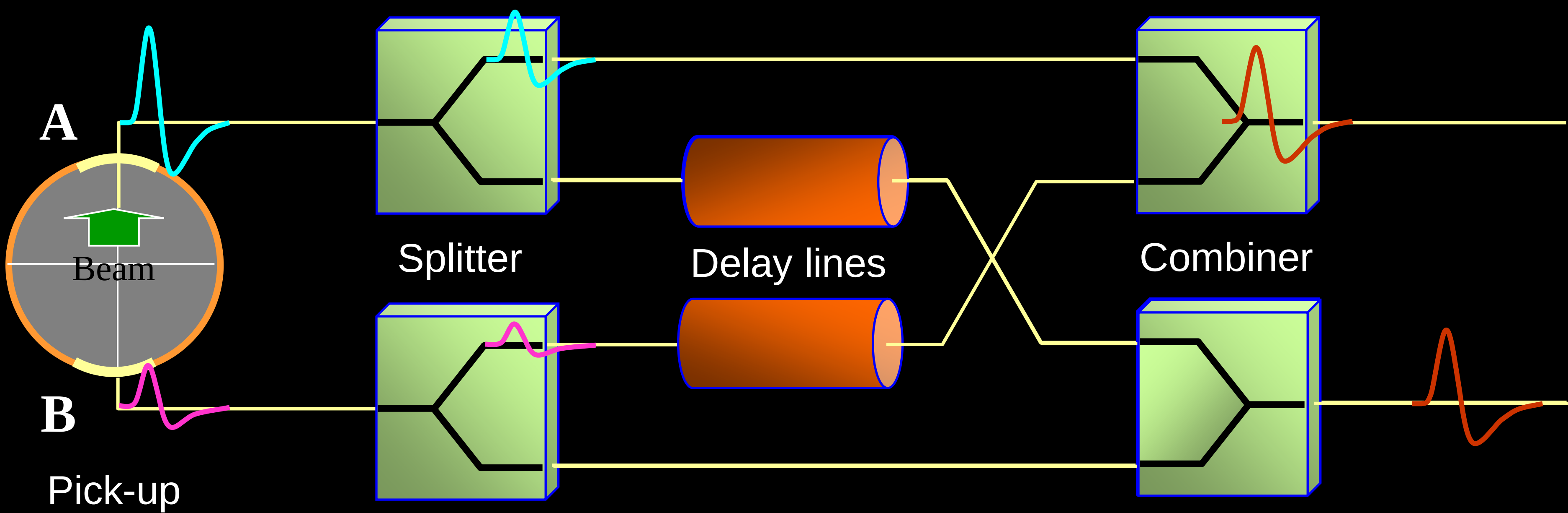


BPM electronics

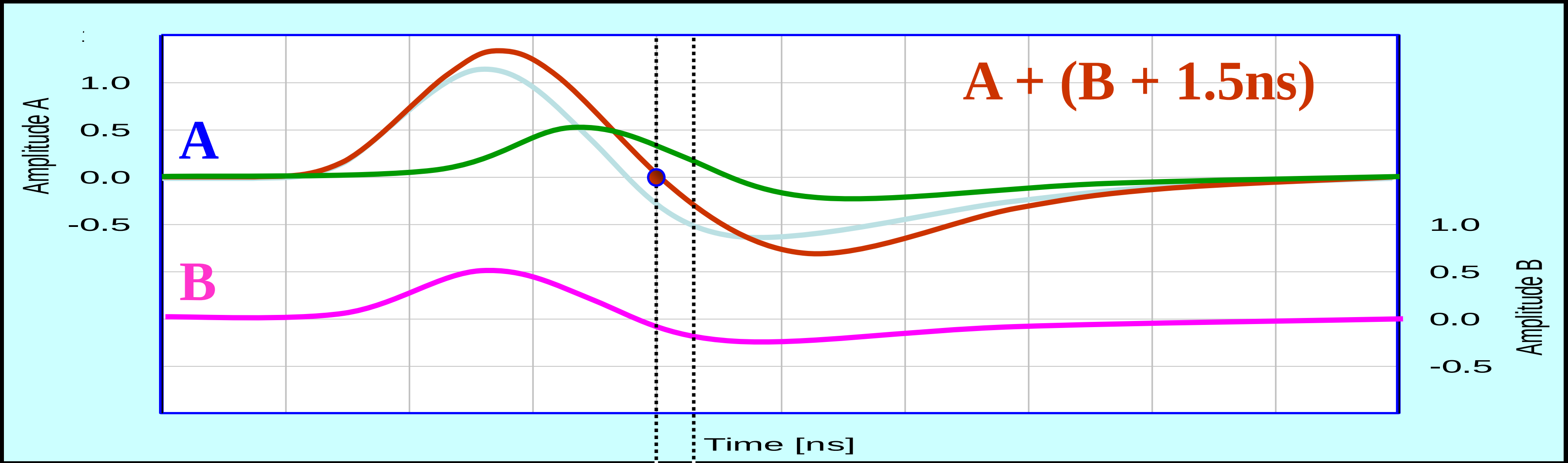
- Distributed System
  - Front-ends located under each arc quadrupole
    - Minimises cable length
    - Radiation tolerant (12Gy/year expected dose)
  - Amplitude to time normalisation in tunnel
    - Position converted into time difference
  - Fibre-optic transmission to surface

Amplitude to Time Normalisation

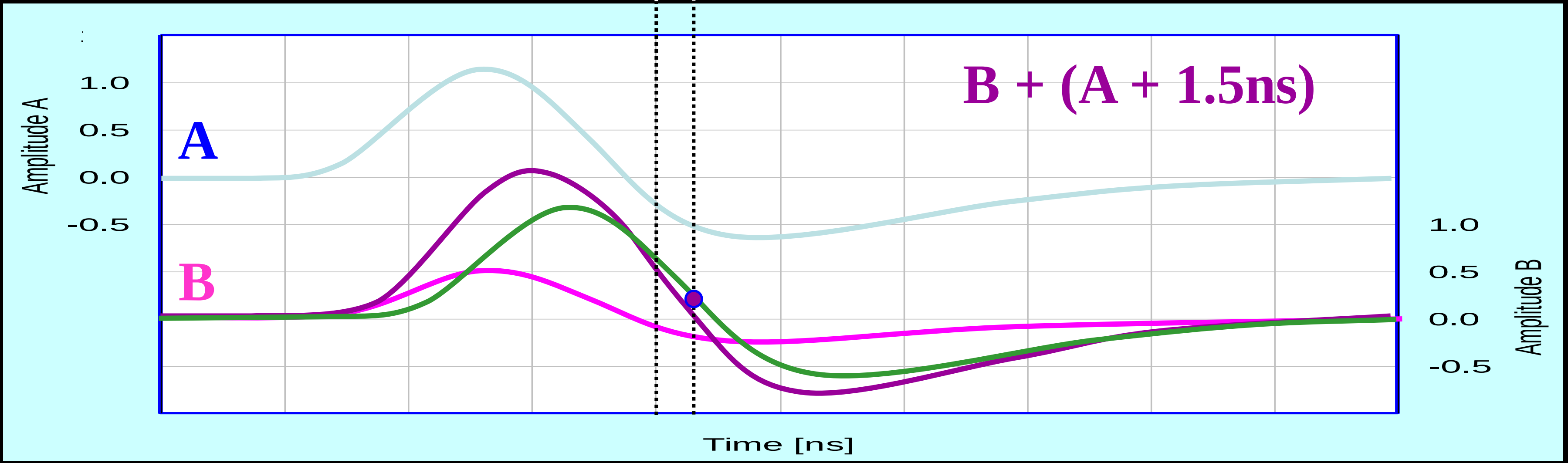




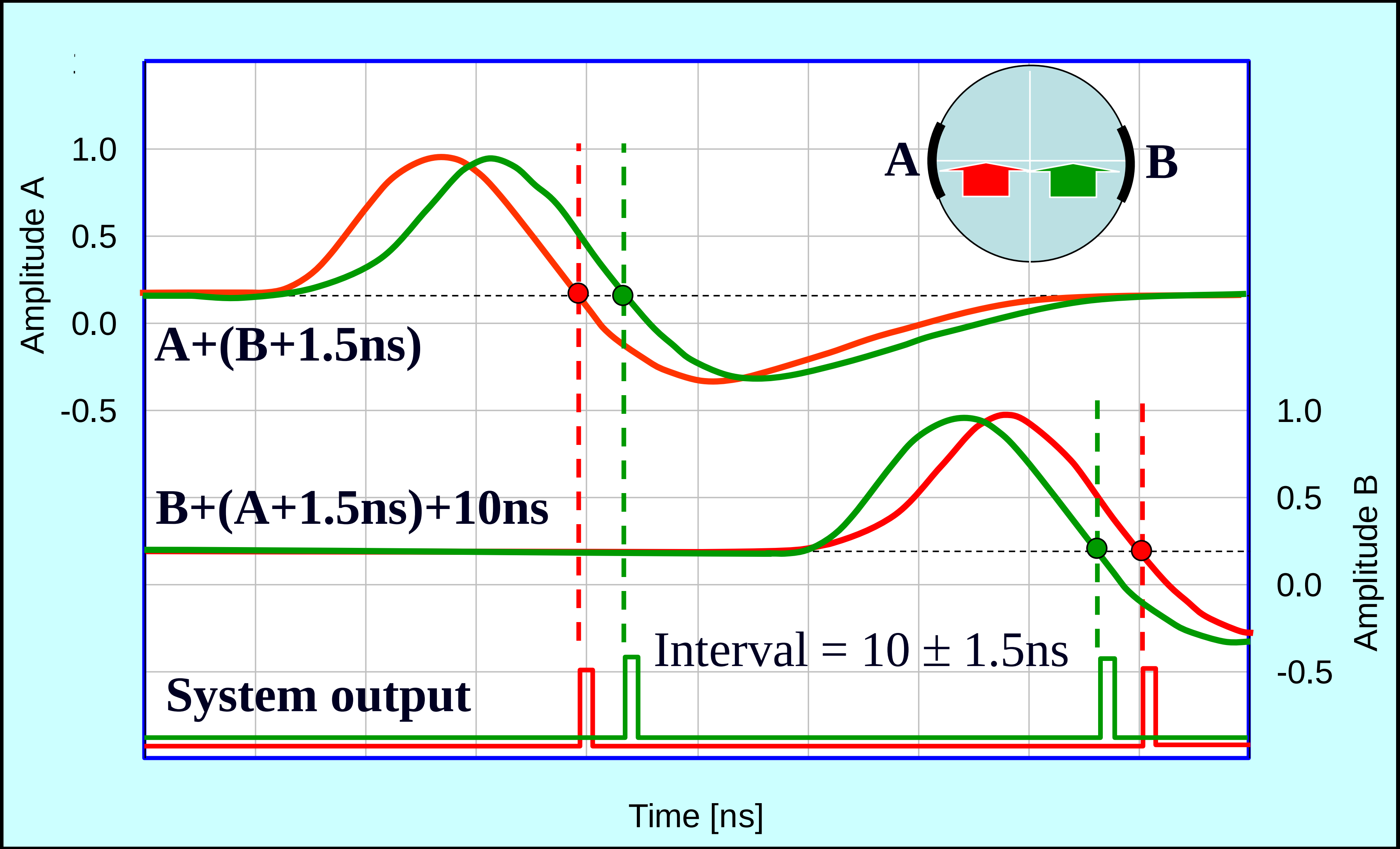
Amplitude to Time Normalisation



Δt depends on position



The Wide Band Time Normaliser



LHC BPM Acquisition Electronics

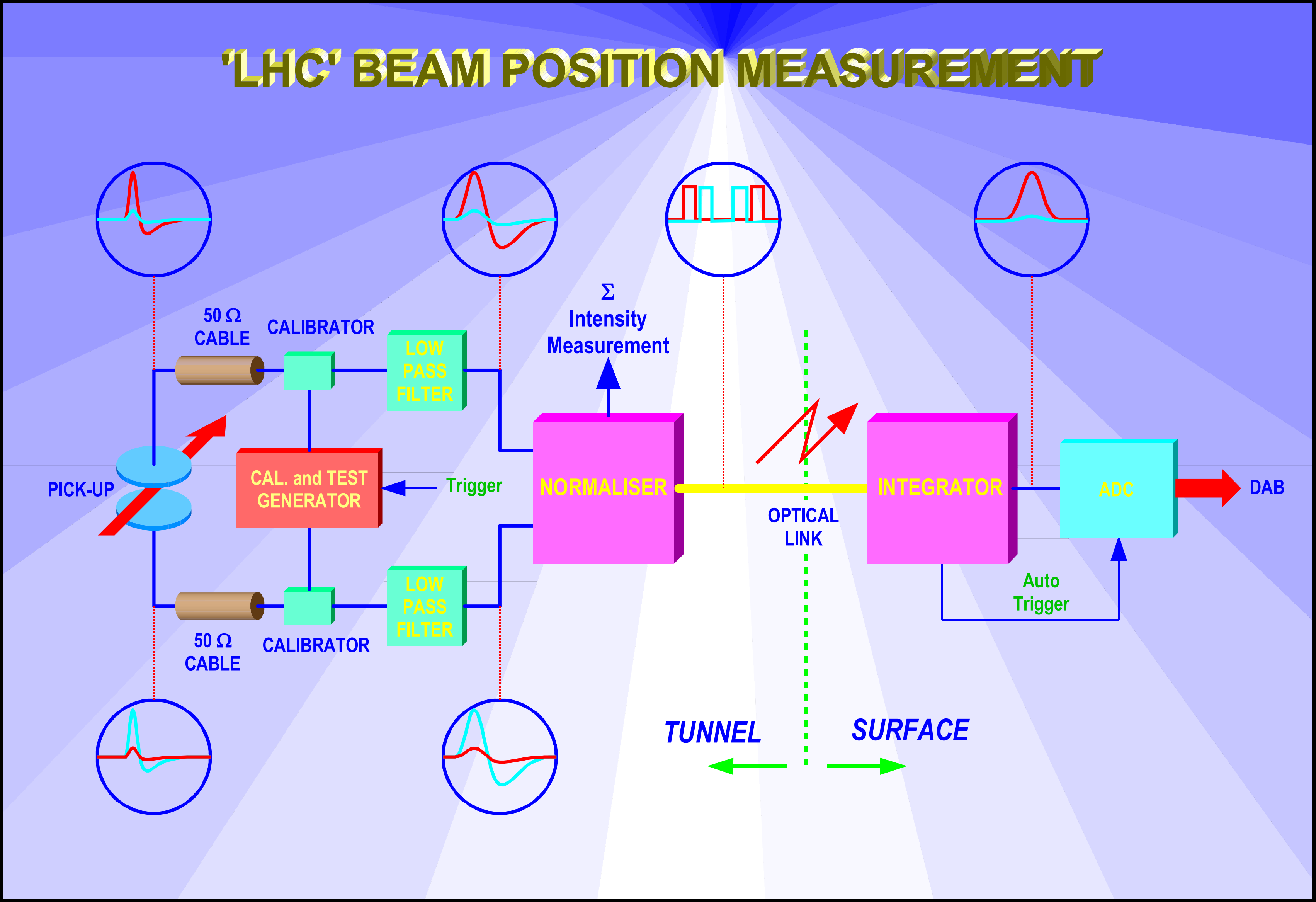
Advantages

- Fast normalisation (< 25ns)
  - bunch to bunch measurement
- Signal dynamic independent of the number of bunches
  - Input dynamic range ~45 dB
  - No need for gain selection
- Reduced number of channels
  - normalisation at the front-end
- ~10 dB compression of the position dynamic due to the recombination of signals
- Independent of external timing
- Time encoding allows fibre optic transmission to be used

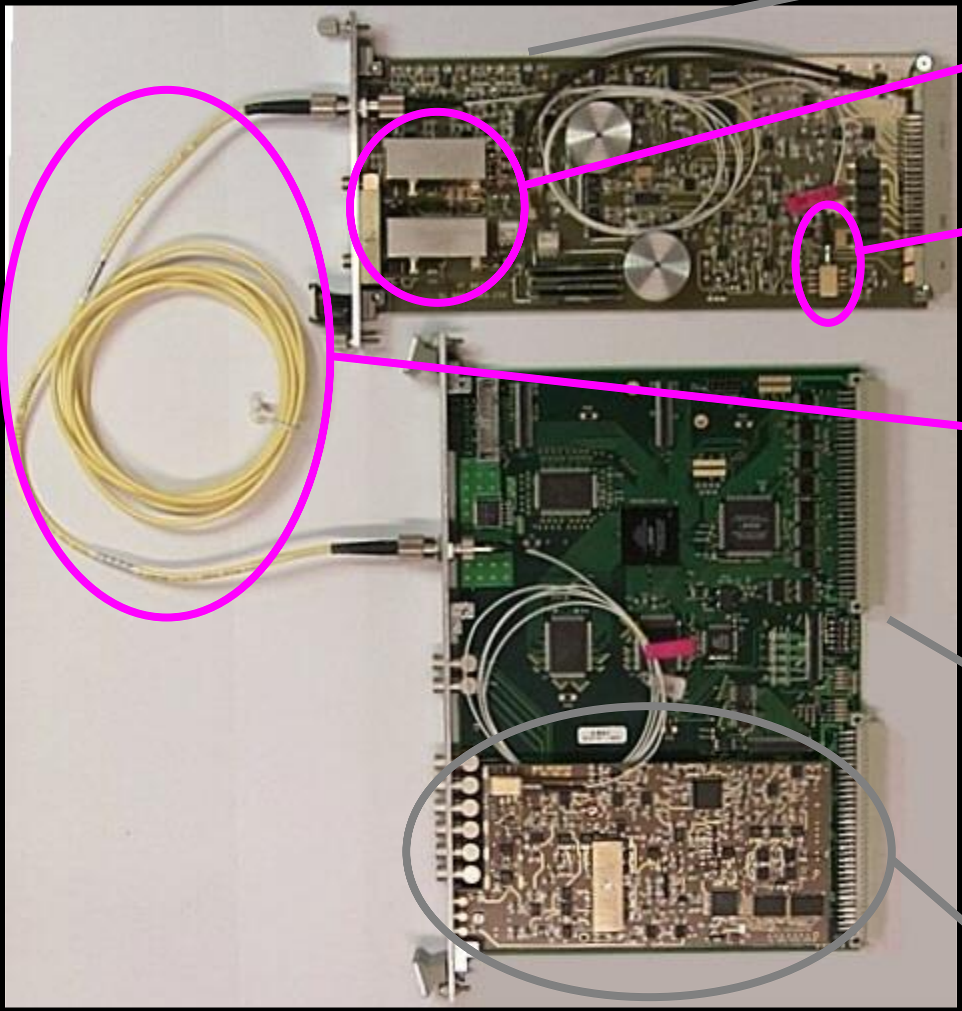
Limitations

- Reserved for beams with empty RF buckets between bunches e.g.
  - LHC 400MHz RF but 25ns spacing
  - 1 bunch every 10 buckets filled
- Tight time adjustment required
- No Intensity information
- Needs two sensitivity threshold settings to avoid spurious triggers
- Propagation delay stability and switching time uncertainty are the limiting performance factors

LHC Beam Position System Layout



The LHC BPM Acquisition System



Very Front-End WBTN Card

70MHz Low Pass Filters
Supplied by TRIUMF (Canada)

1310nm Diode Laser
Transmitter ⬆ Tunnel

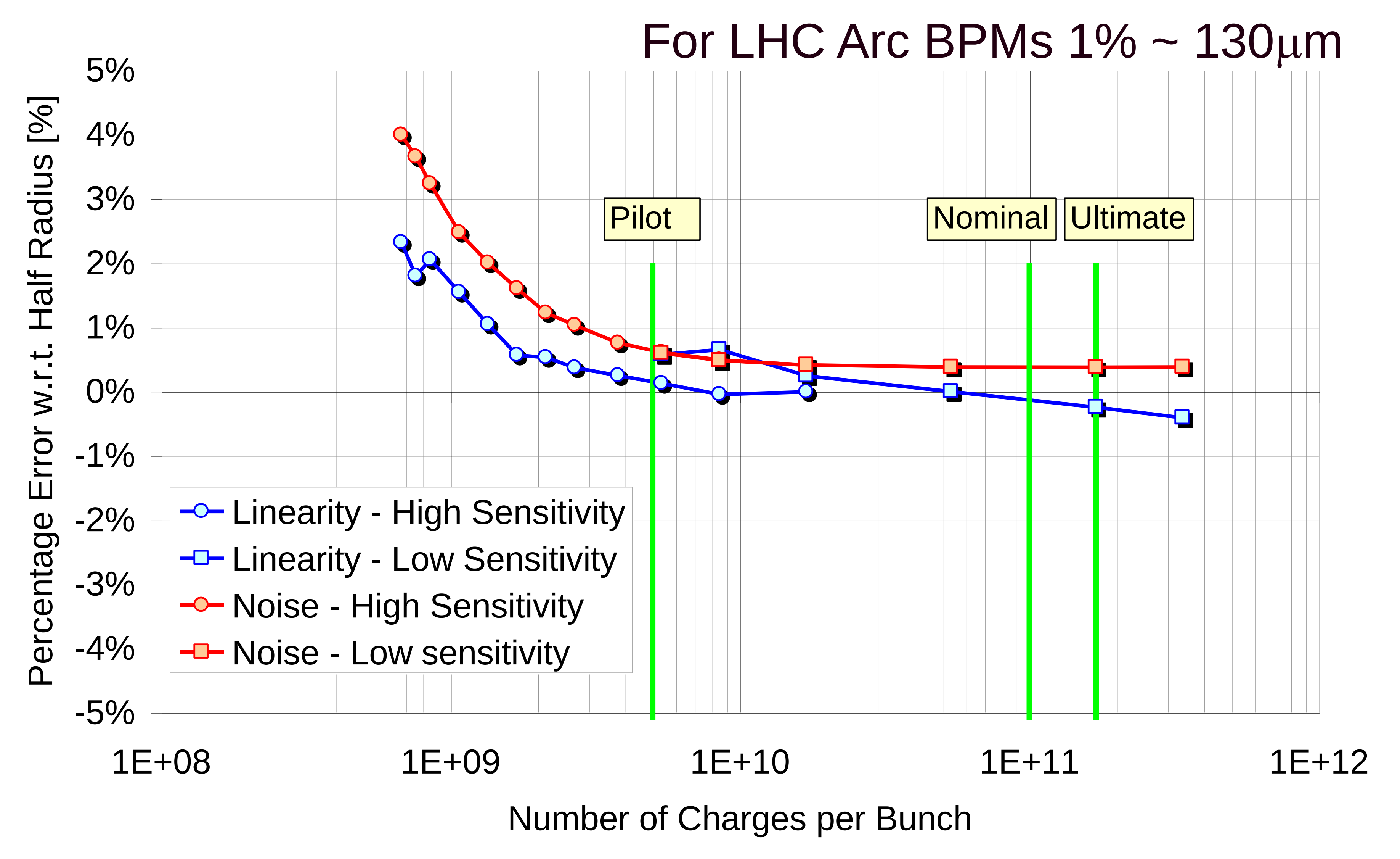
Single-Mode Fibre-Optic Link

⬇ Surface

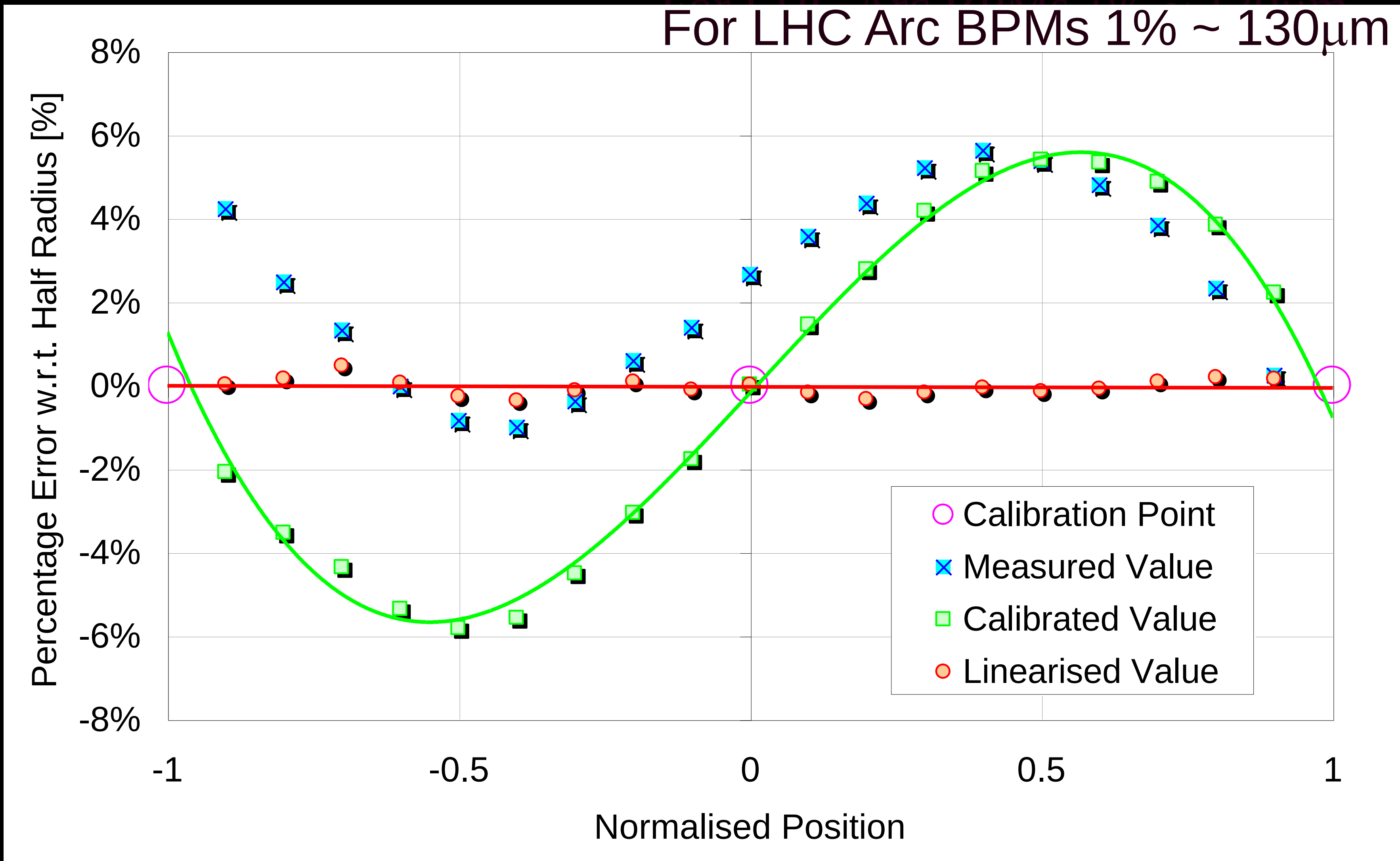
VME based
Digital Acquisition Board
TRIUMF (Canada)
(2 x 12bit 40MHz Acq)

WBTN Mezzanine Card
(10bit digitisation at 40MHz)

WBTN - Linearity v Intensity

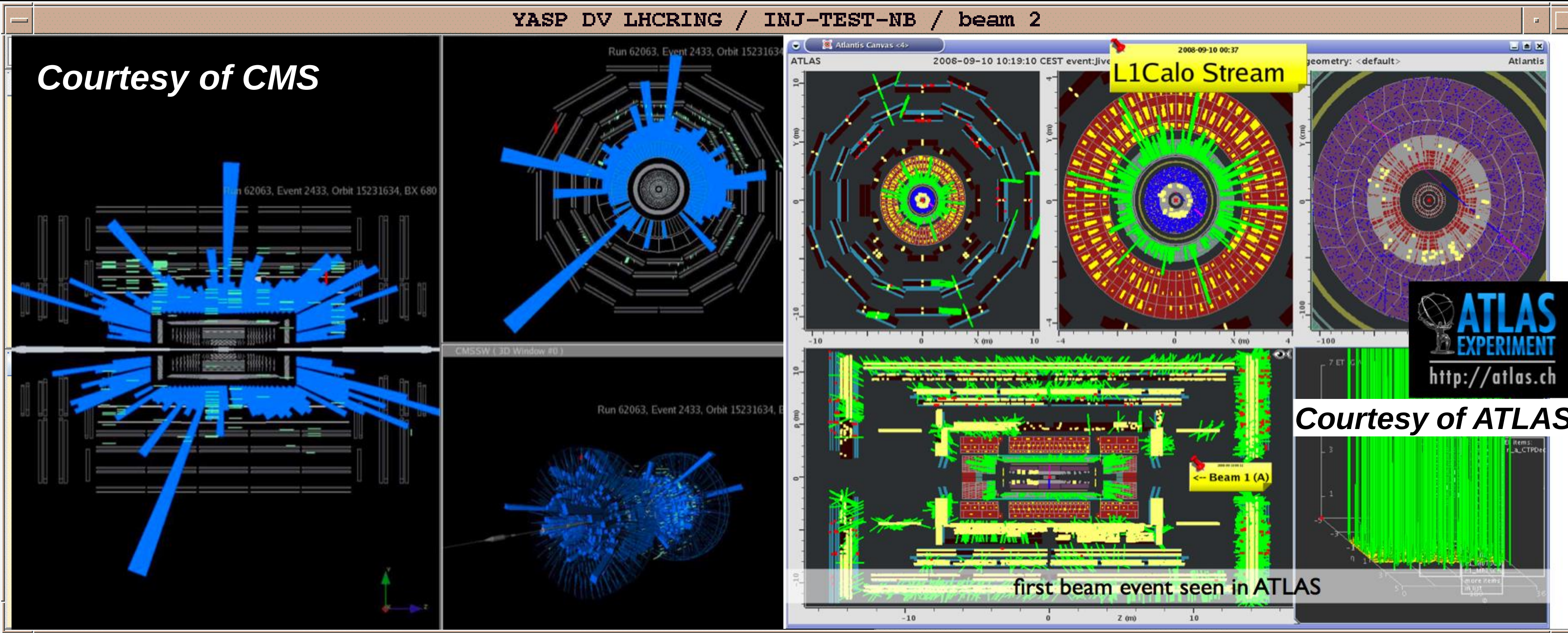


WBTN - Linearity v Position



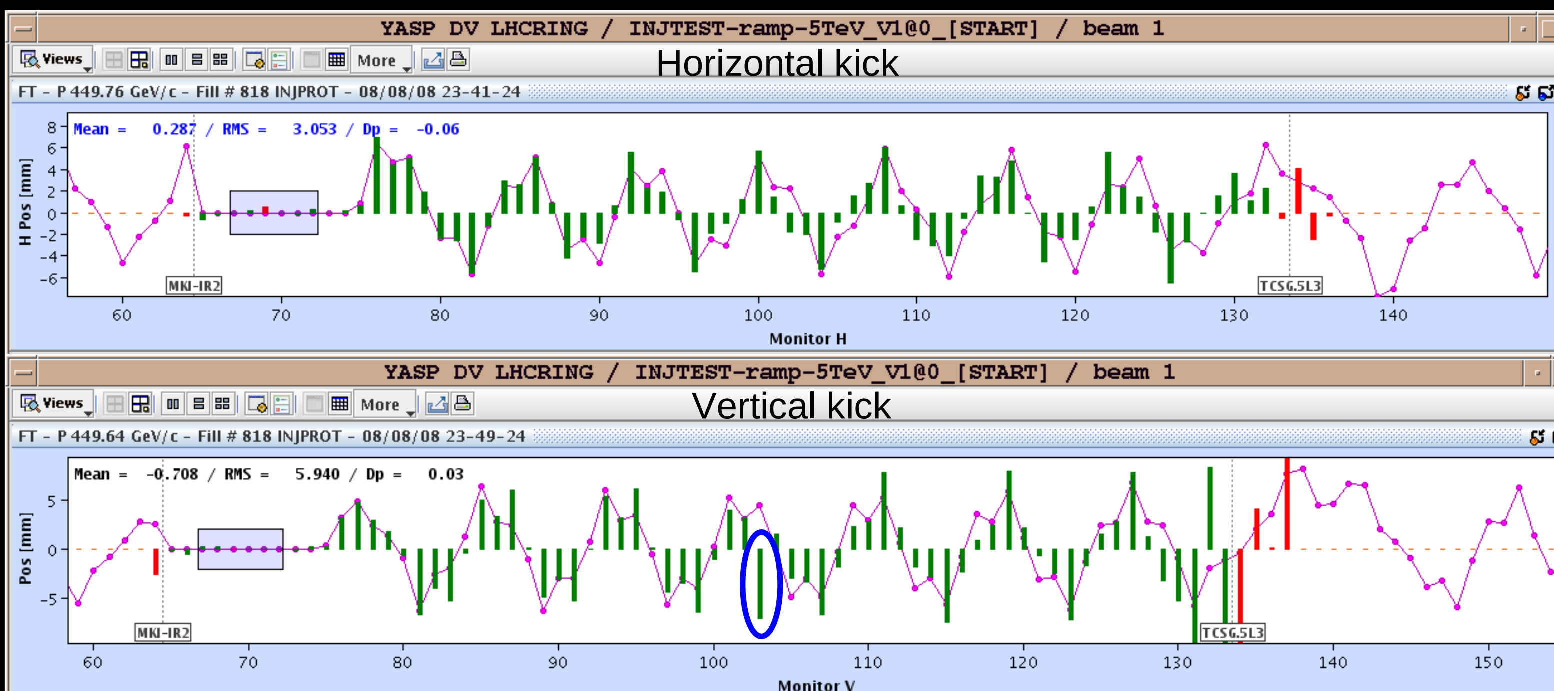
LHC BPM System Performance

- Threading the first pilot bunch round the LHC
  - Trajectory
    - using BPMs one beam at a time, one hour per beam
    - each bar represents one BPM horizontal or vertical channel
    - dipole corrector magnets used to optimise trajectory



LHC BPM System Performance

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

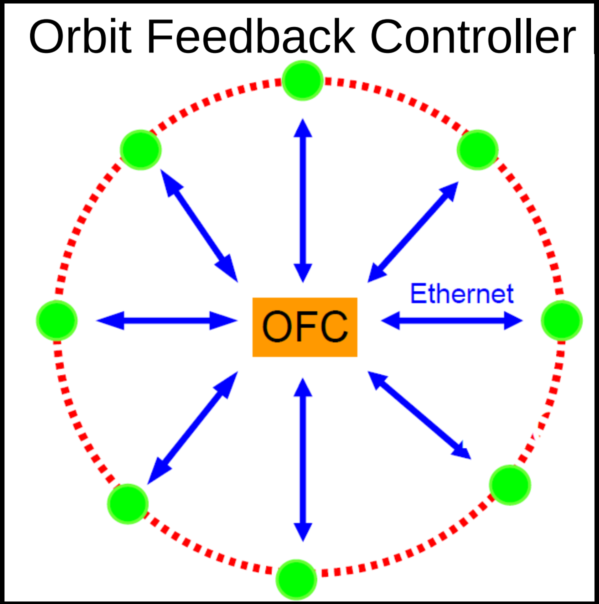


Optics phase error

BPM polarity error

Machine Optimisation - Feedbacks

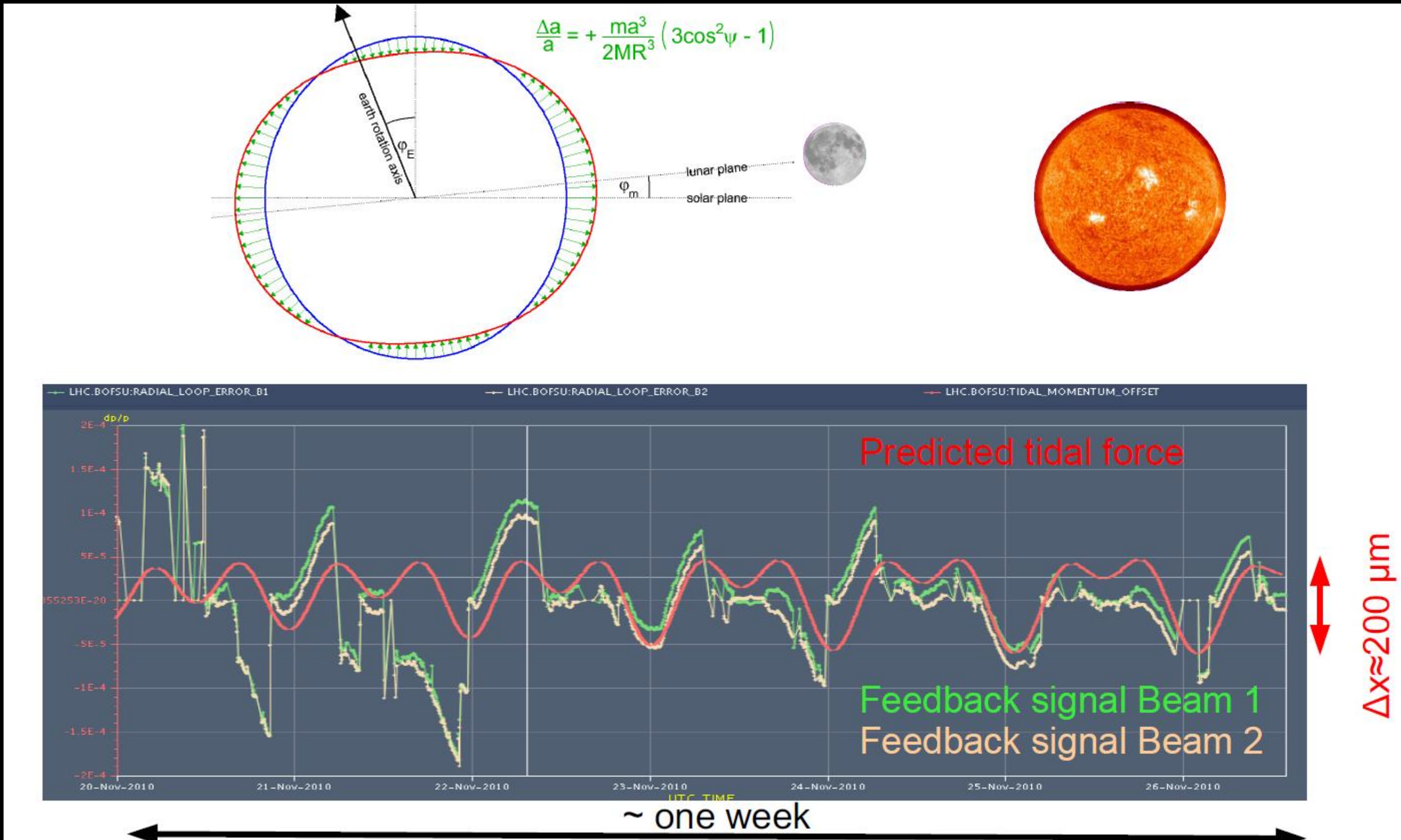
- Opted for central global feedback system regrouping:
  - Orbit, energy, tune (operational)
  - Chromaticity, coupling (tested)
- Initial requirements:
  - Chromaticity expected to be most critical parameter for real-time control
  - BUT
    - Large losses during early ramps changed focus to tune followed by orbit feedback



- Orbit-Feedback is largest & most complex LHC feedback:
  - 1088 BPMs → 2176+ readings @ 25 Hz from 68 front-ends
  - 530 correction dipole magnets/plane, distributed over ~50 front-ends
  - Closed Loop Bandwidth of 1Hz
- Total >3500 devices involved
  - more than half the LHC is controlled by beam based feedbacks!

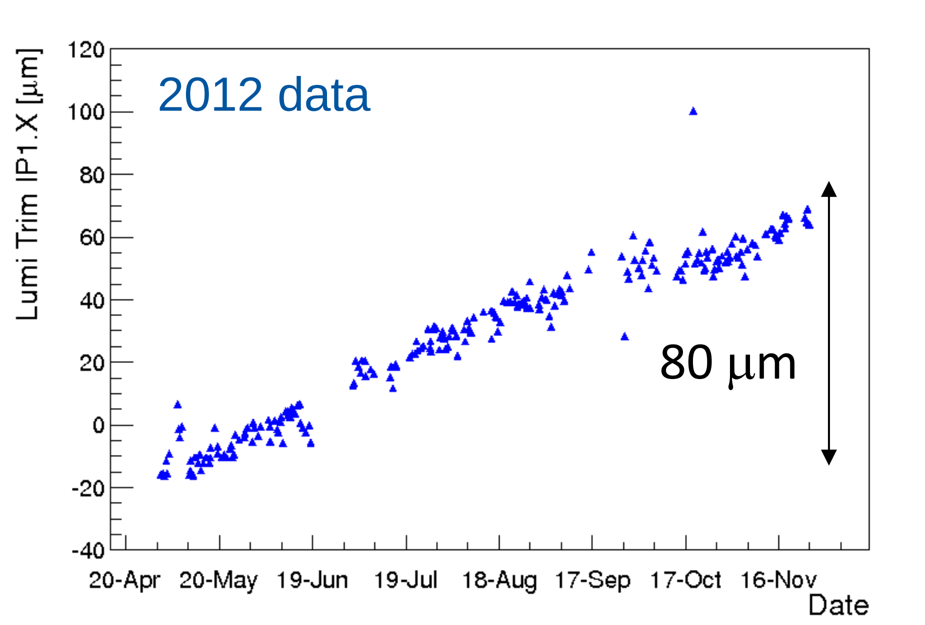
Orbit Stability

- Earth Tides dominate during Physics



Orbit Stability

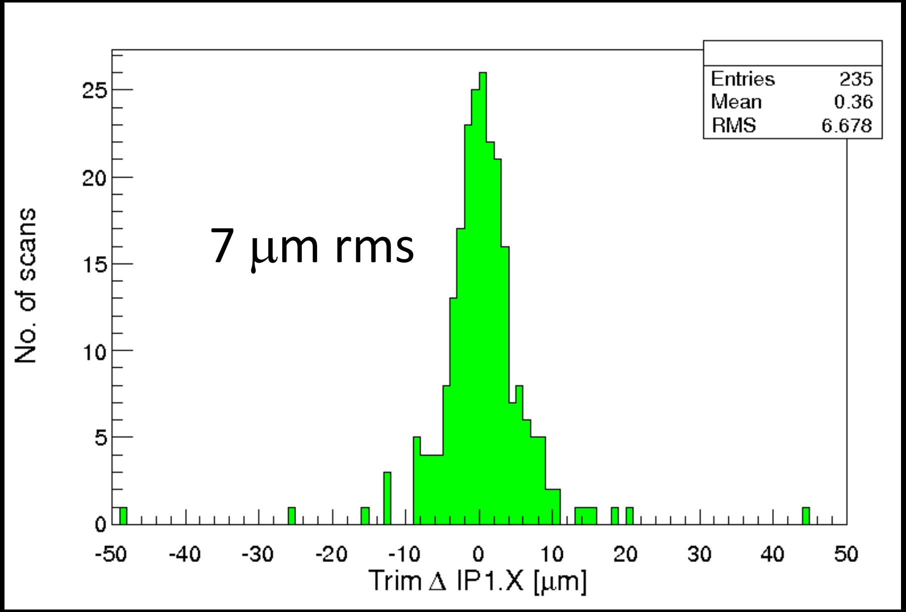
- Important for collimation and collision process
- LHC does not work without orbit feedback
- Main limitations
  - Temperature dependence of electronics
  - Linearity and directivity of stripline couplers near the interaction points



Orbit correction at IP to bring beams head-on

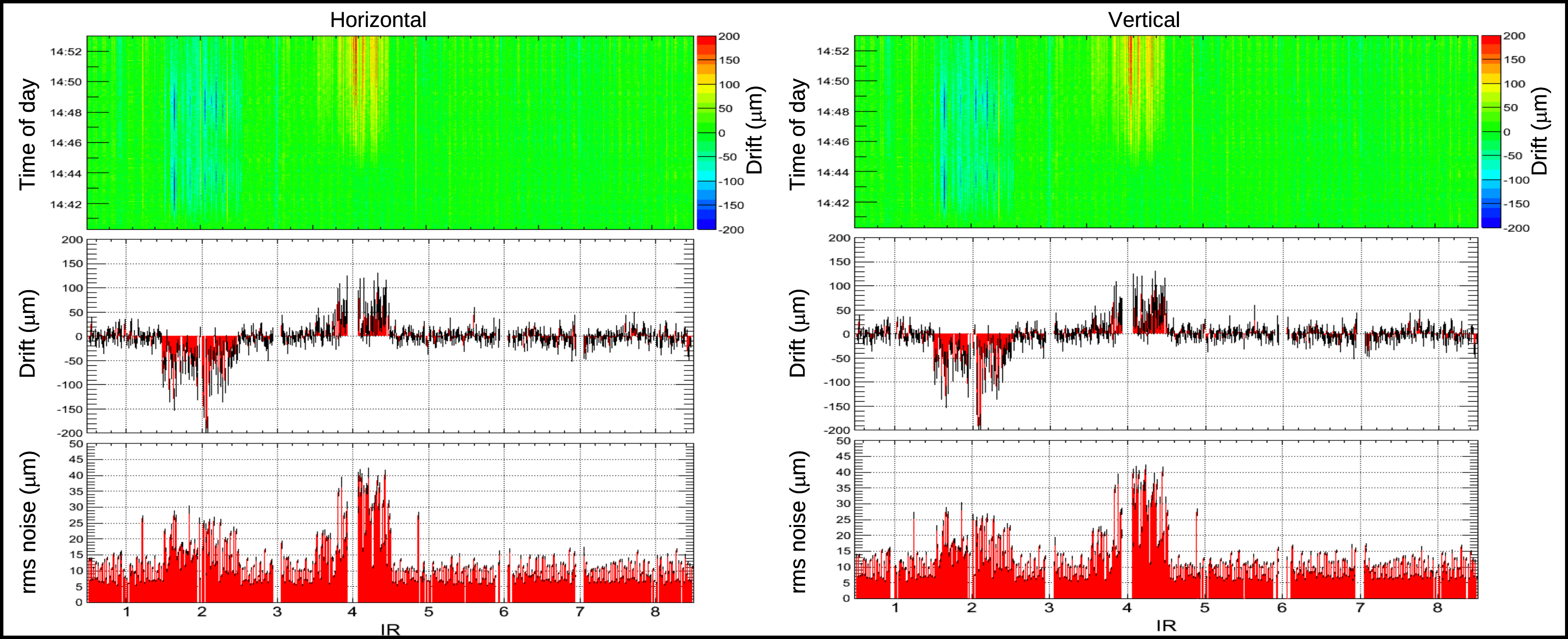
Slow drift over year not corrected by feedforward

Fill to fill difference is very small



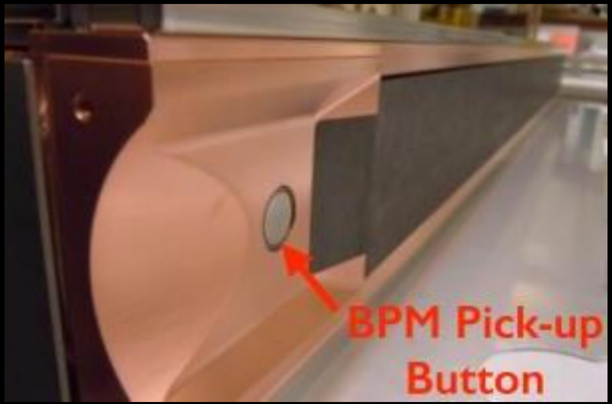
Orbit Stability Limitations

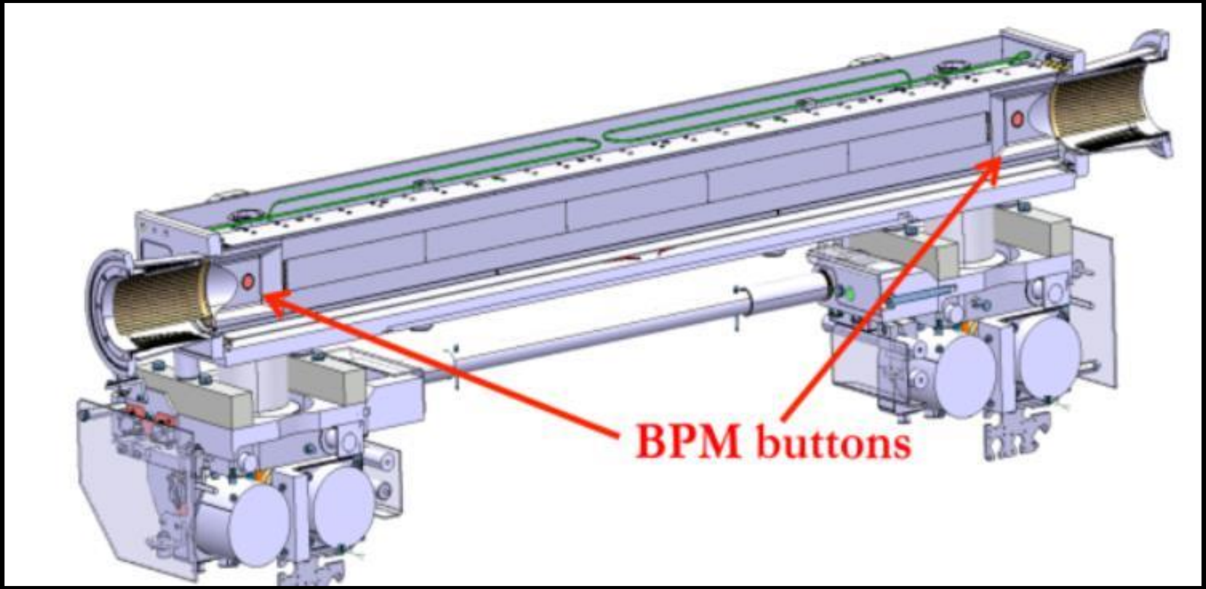
- Systematic BPM reading dependence on temperature
  - Initially caused drifts up to 300μm on long-term orbit
  - Suppressed to the order of 100μm by
    - Calibration before each fill
    - Temperature compensation of each individual BPM channel
  - During LS1 - placed electronics in temperature controlled racks

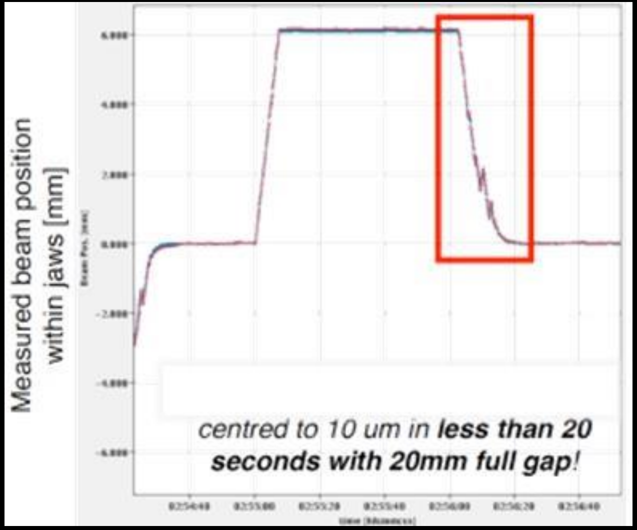


Improving the LHC BPM System

- Collimators with Embedded BPMs
  - 18 tertiary collimators now equipped with BPM buttons
  - Readout via high resolution Diode Orbit electronics
    - Compensated diode peak detectors
    - Resolution <100nm for centred beams
  - Allows fast, parallel alignment
    - < 20 s without touching beam
    - 2 orders of magnitude faster than BLM method



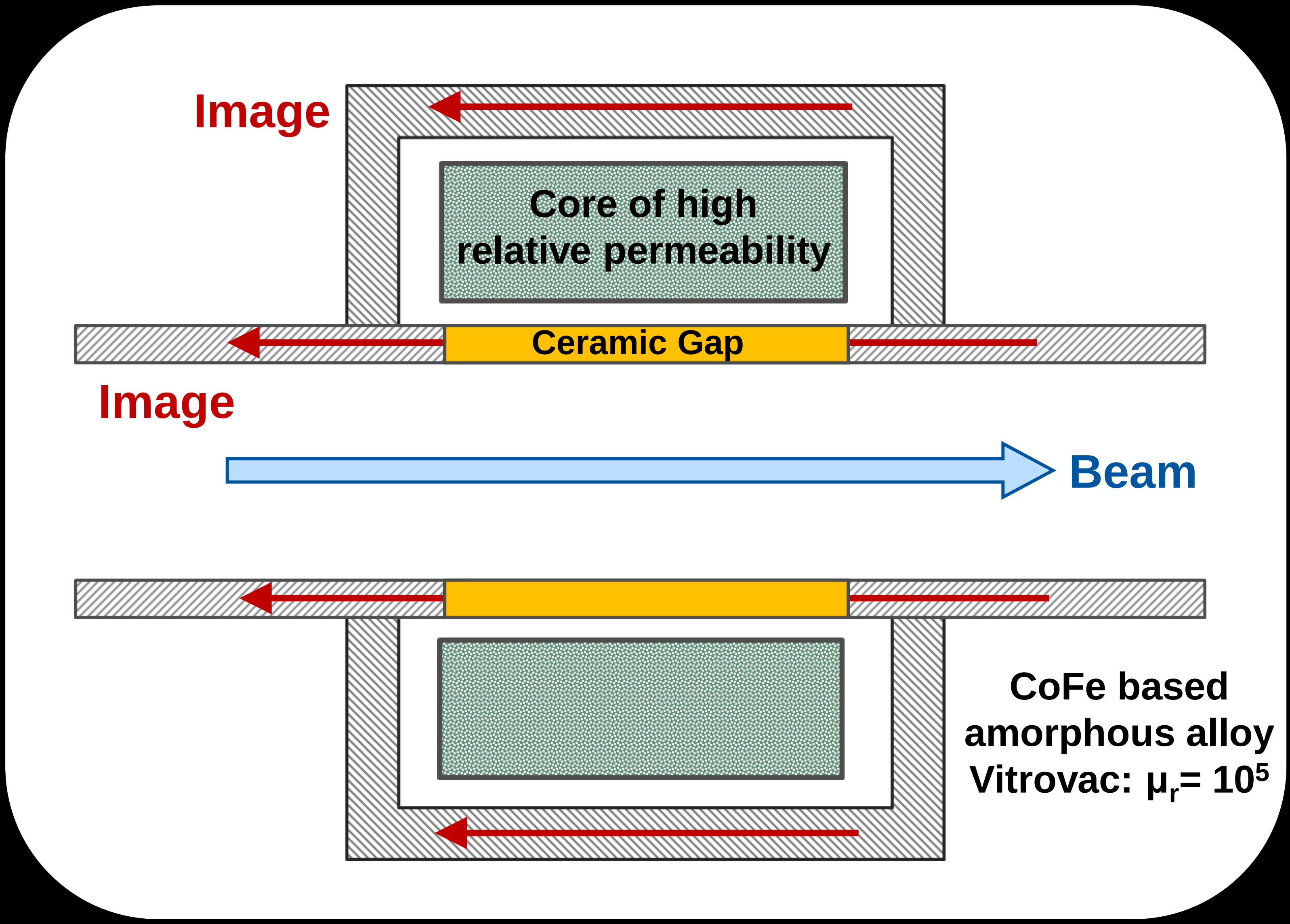




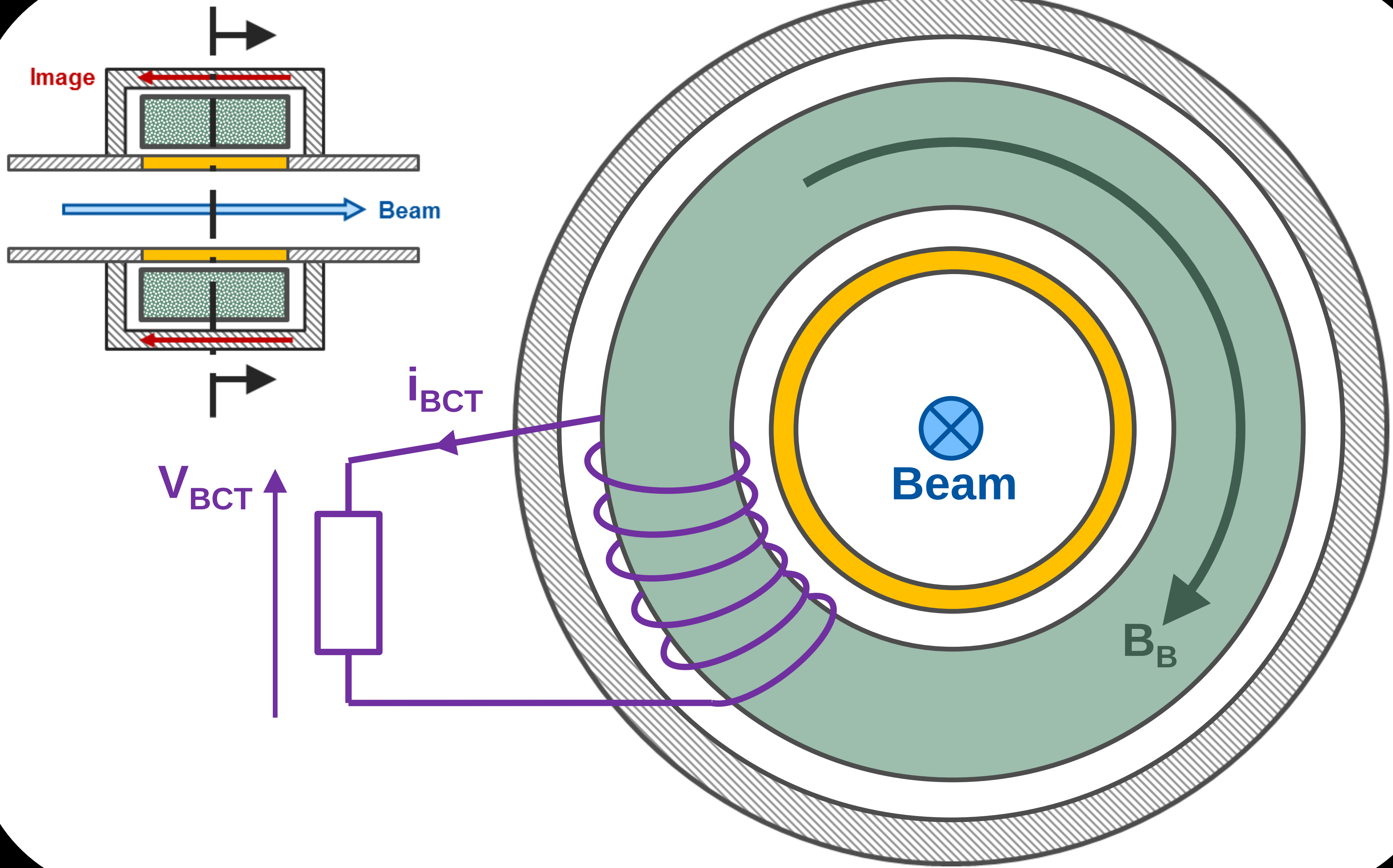
The Typical LHC Instruments

- Beam Position
  - electrostatic or electromagnetic pick-ups and related electronics
- Beam Intensity
  - beam current transformers
- Beam Profile
  - screens
  - wire scanners
  - synchrotron light monitors
  - ionisation 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

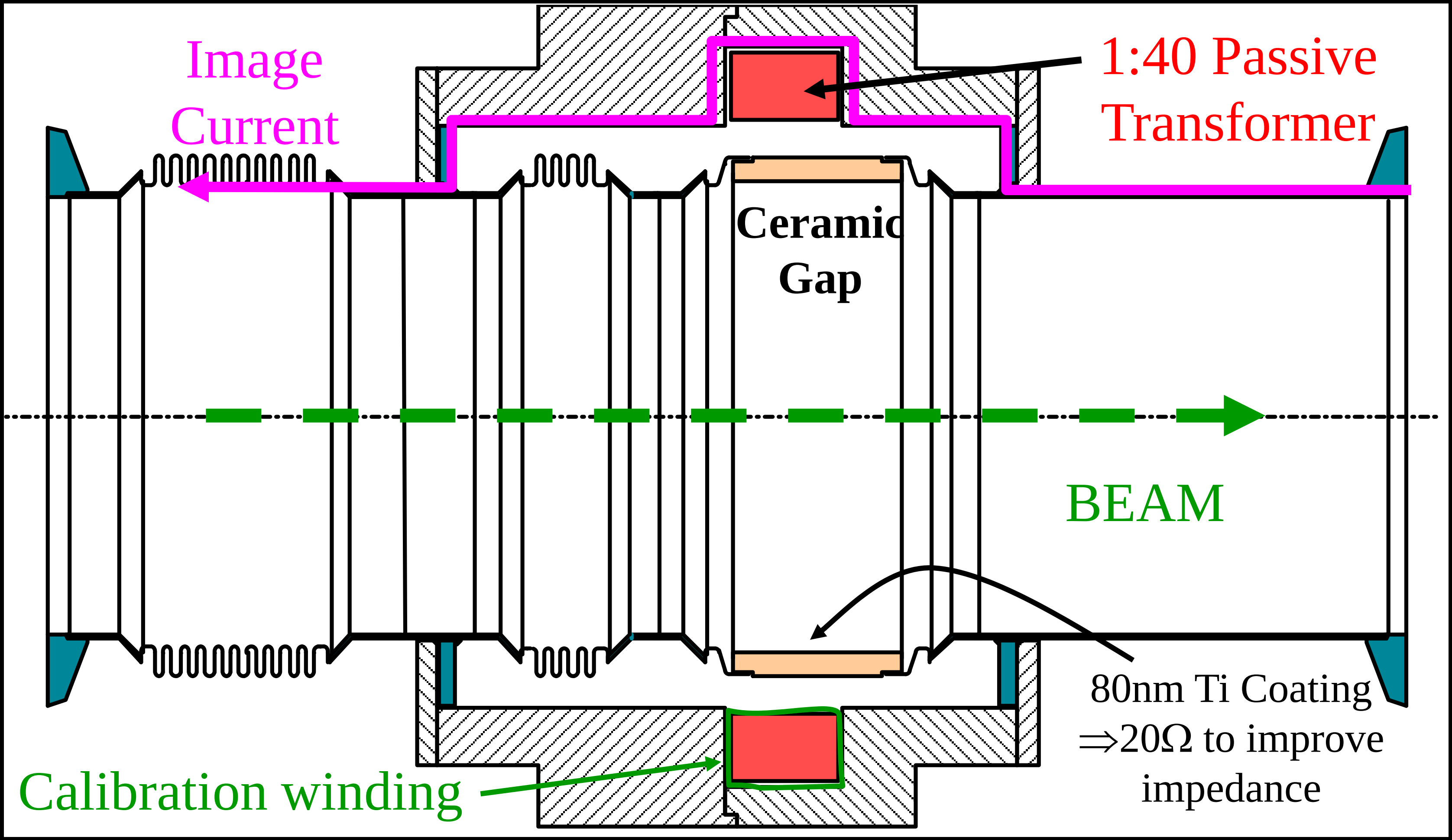
AC (Fast) Current Transformers



AC (Fast) Current Transformers

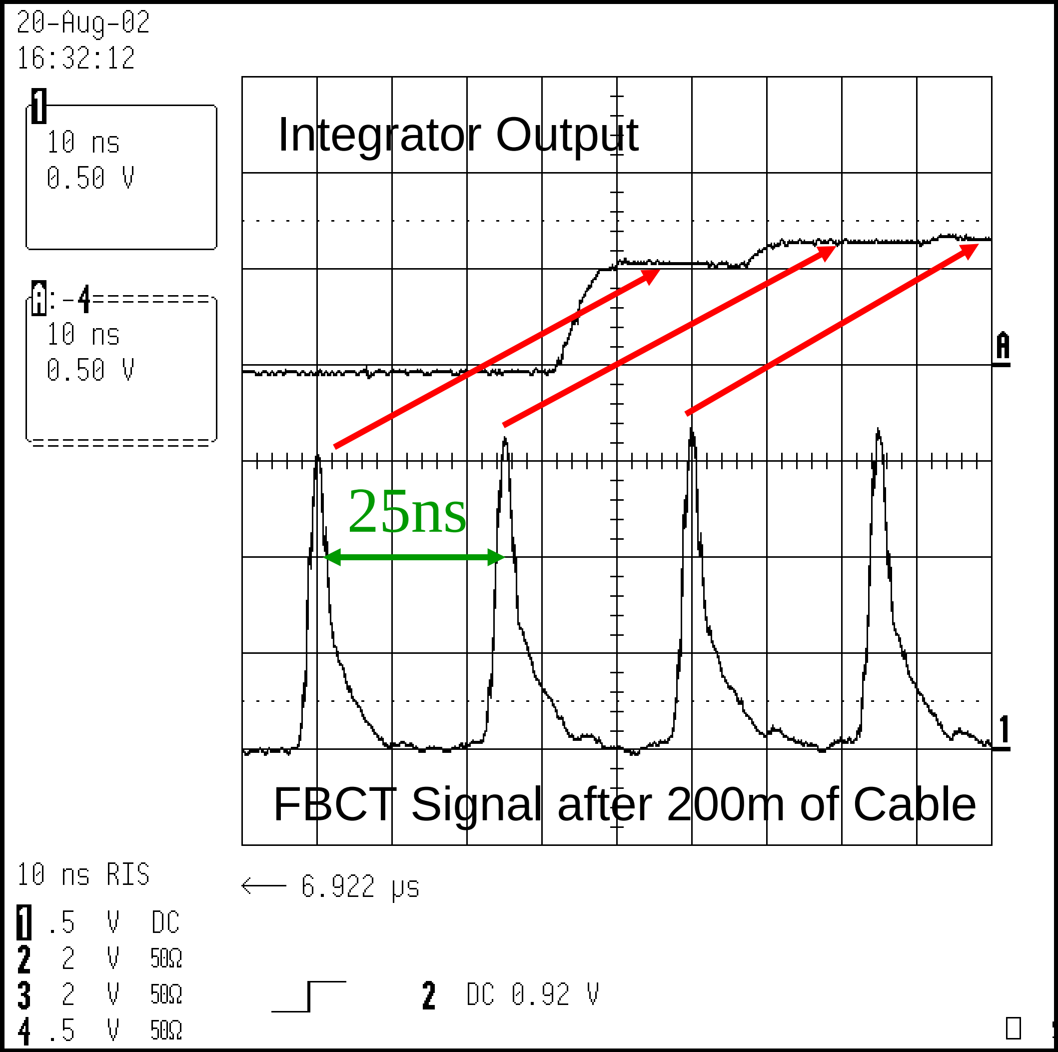


Fast Beam Current Transformer



- 500MHz Bandwidth
- Low droop (< 0.2%/μs)

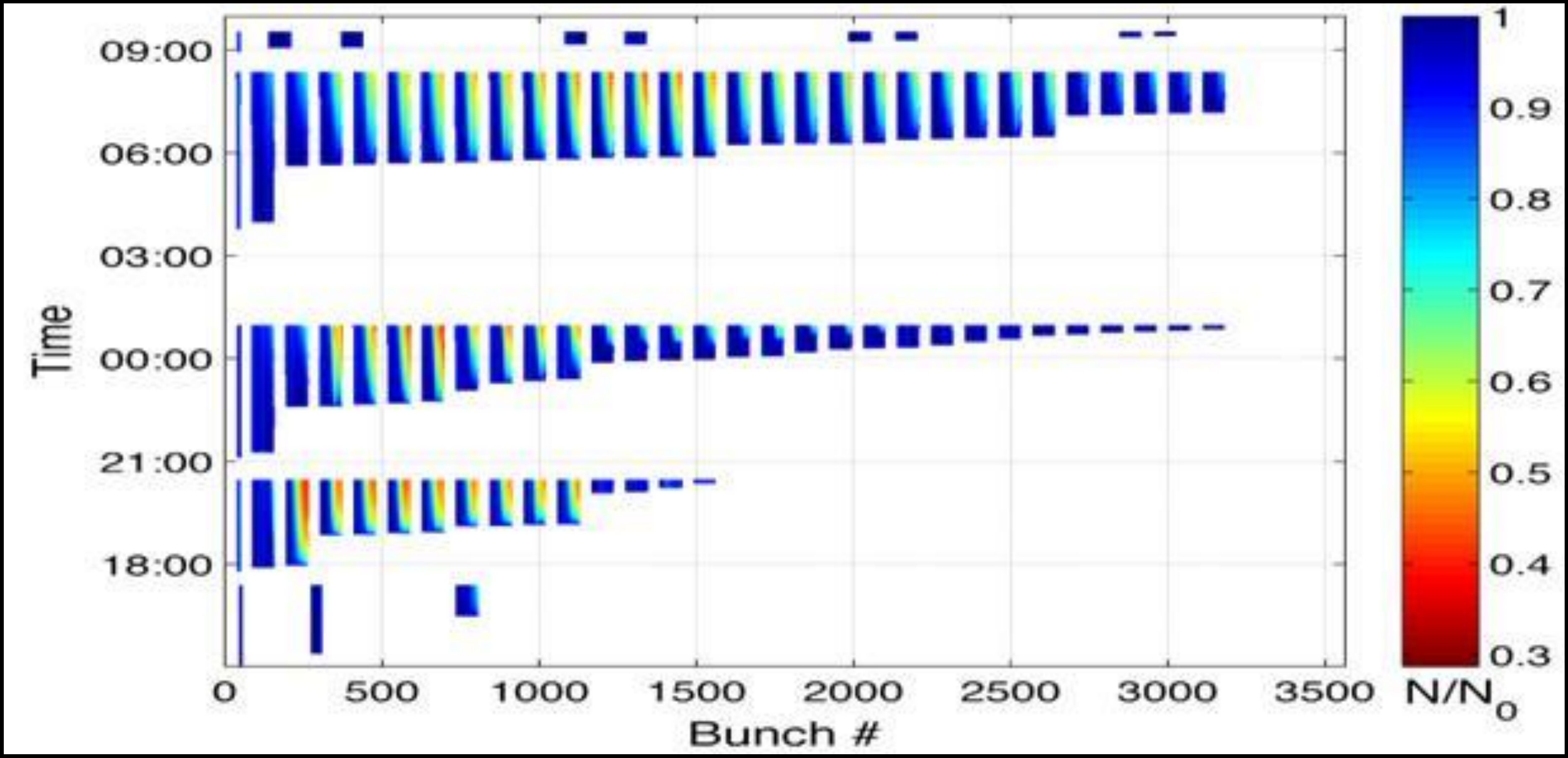
FBCT Acquisition Electronics



Data taken on LHC type beams at the CERN-SPS

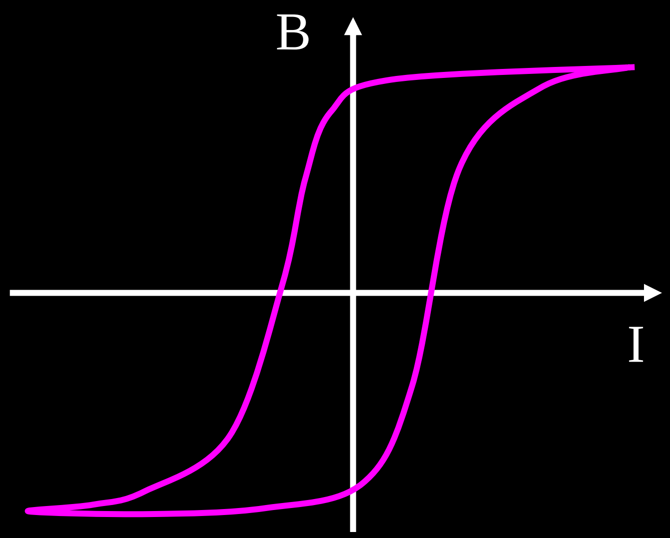
Bunch by bunch intensity measurement

- Extensively used to understand loss mechanisms
  - Example for intensity loss due to electron cloud instabilities
    - Effect of scrubbing in reducing the effect clearly visible

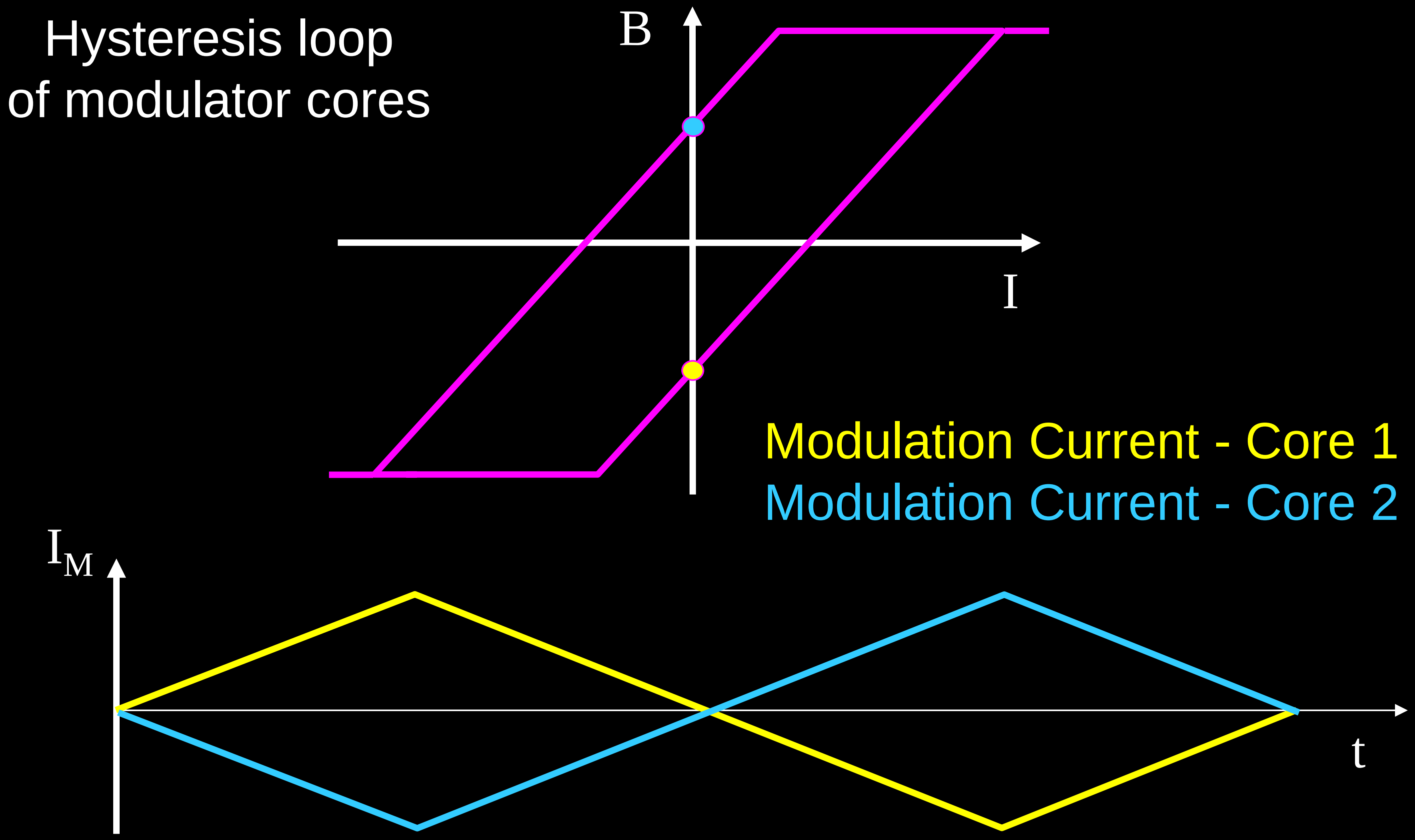


The DC transformer

- 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

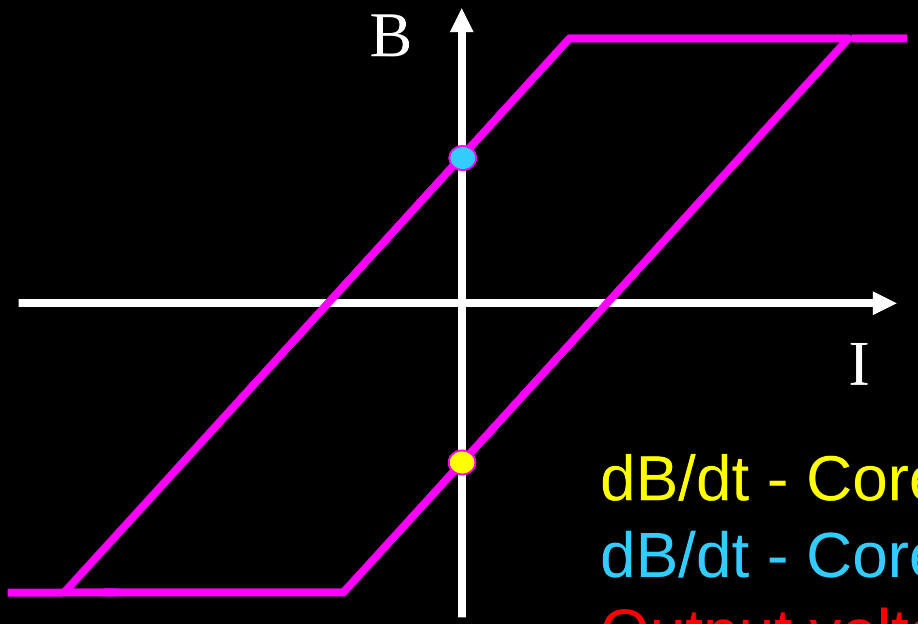


DCCT Principle – Case 1: no beam



DCCT Principle – Case 1: no beam

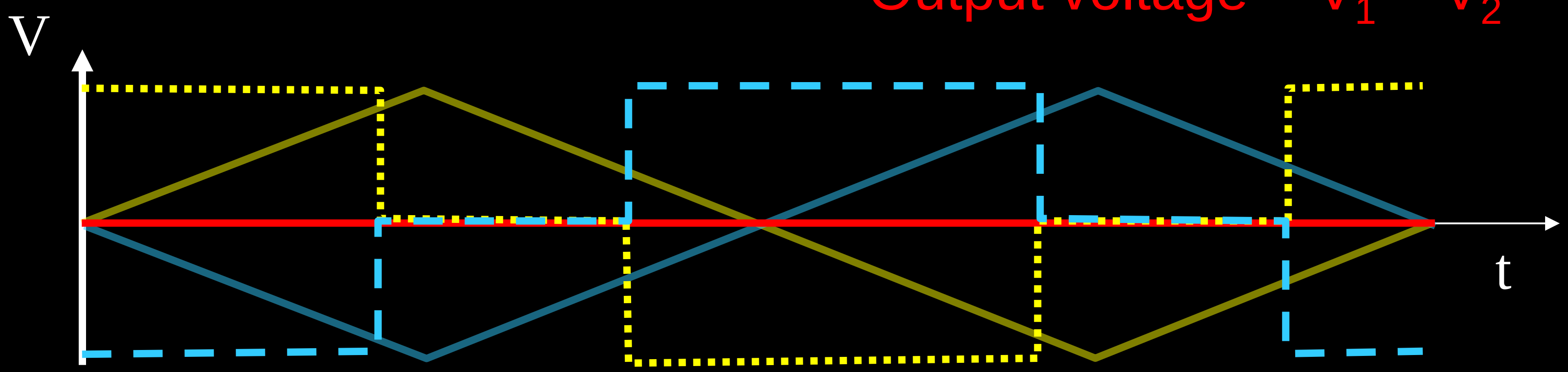
$$V \propto \frac{dB}{dt}$$



dB/dt - Core 1 (V1)

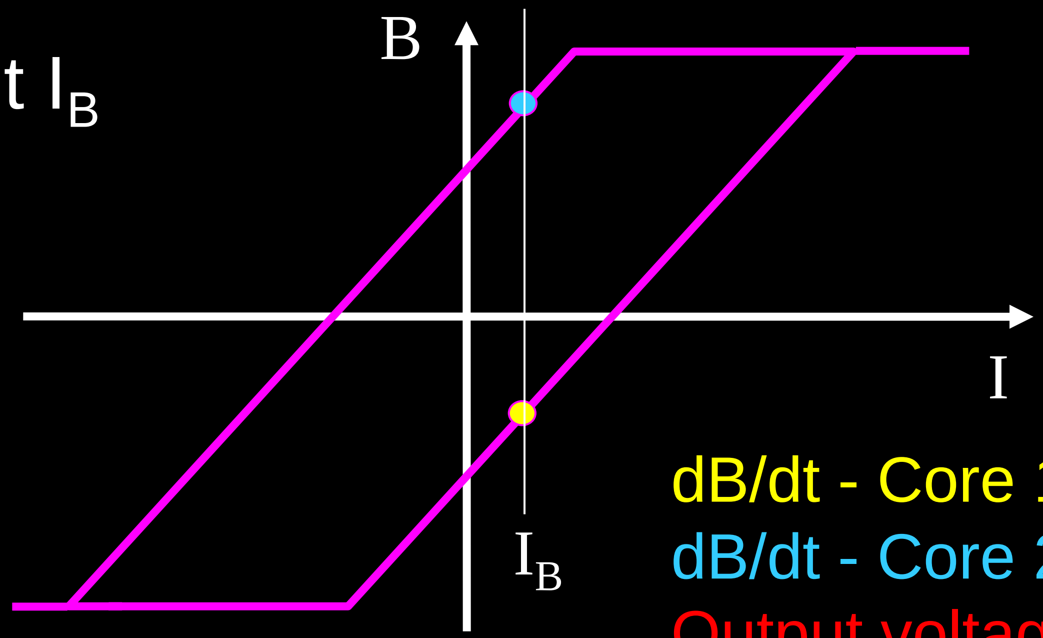
dB/dt - Core 2 (V2)

Output voltage = $V_1 - V_2$



DCCT Principle – Case 2: with beam

Beam Current I_B

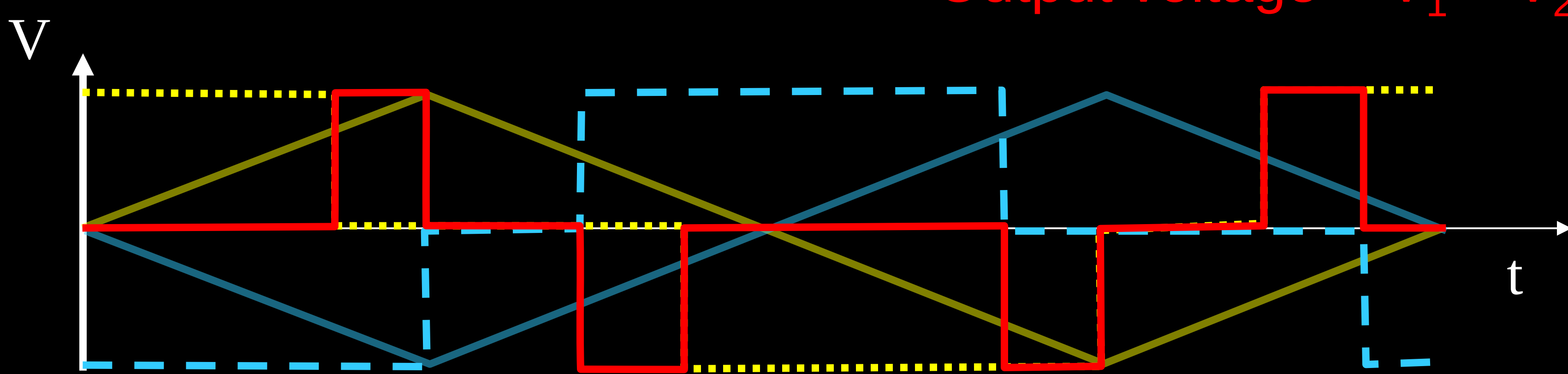


Output signal is at TWICE the modulation frequency

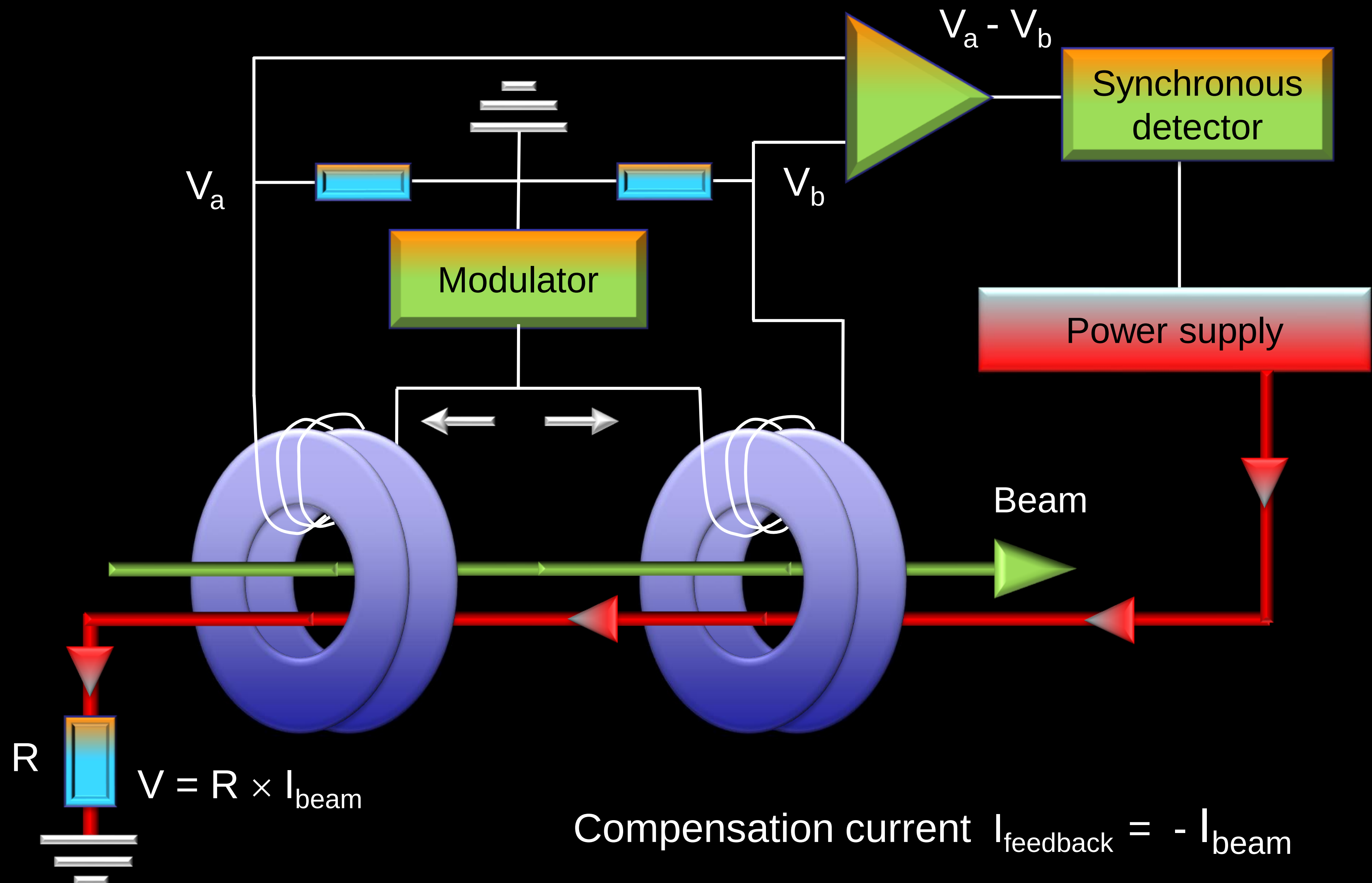
dB/dt - Core 1 (V1)

dB/dt - Core 2 (V2)

Output voltage = $V_1 - V_2$



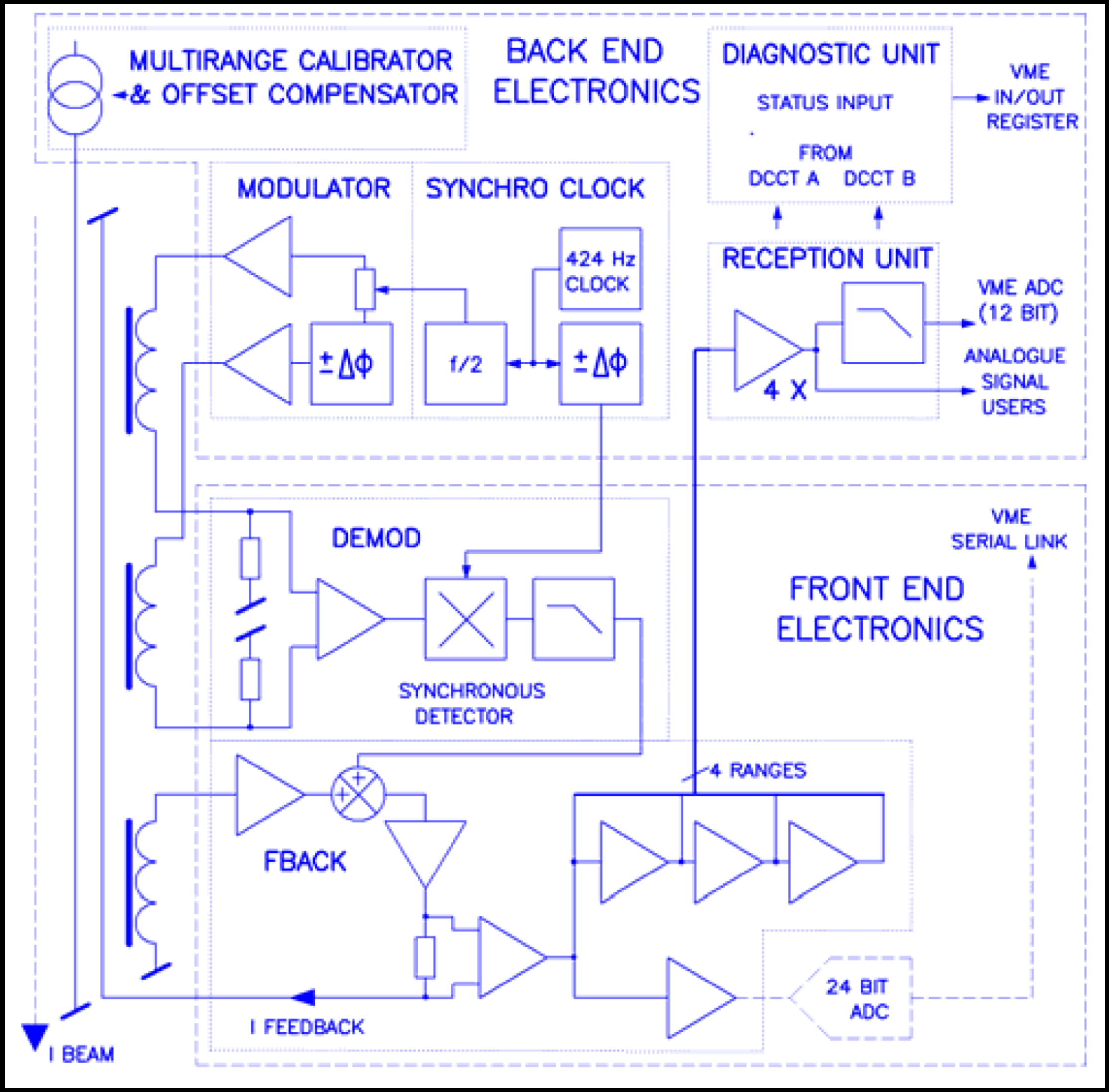
Zero Flux DCCT Schematic



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

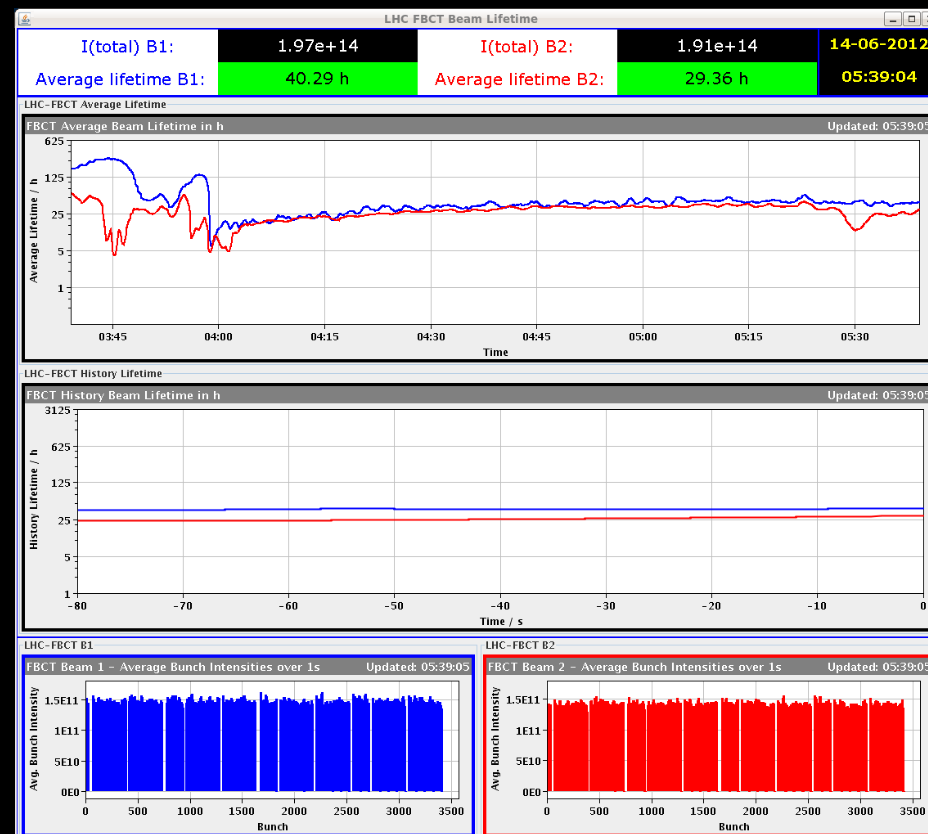
The LHC DCCT

- AC core added to extend bandwidth
  - Up to 1.5kHz
- Modulation frequency of 212Hz
  - Chosen to avoid beating with harmonics of mains
- Intensity range
  - From ~3µA to ~900mA
  - Now covered by single 24bit ADC



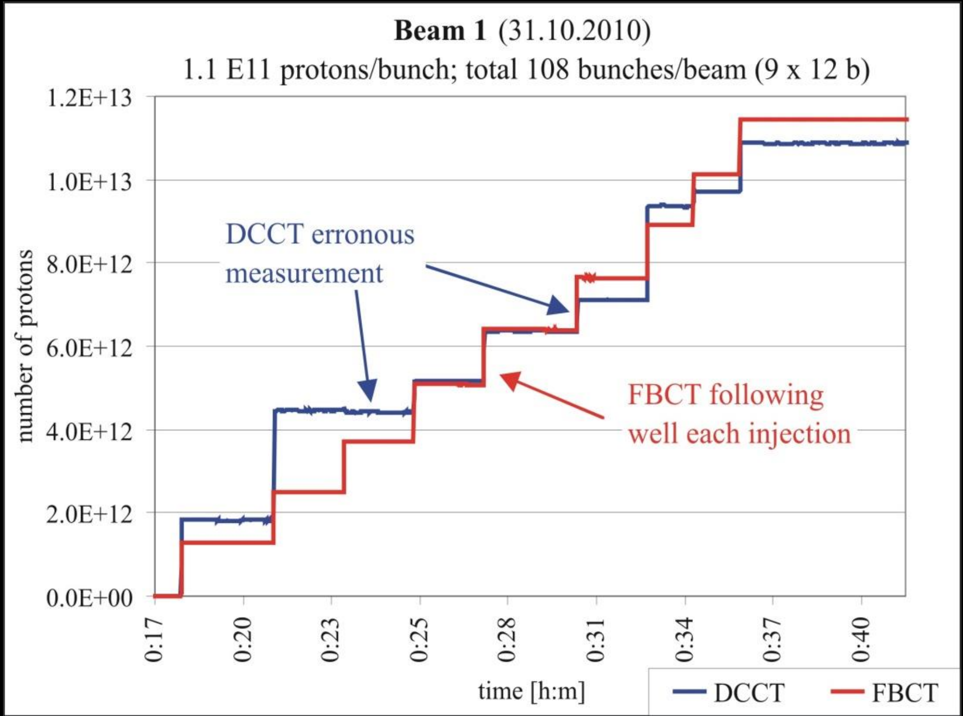
The LHC BCTs

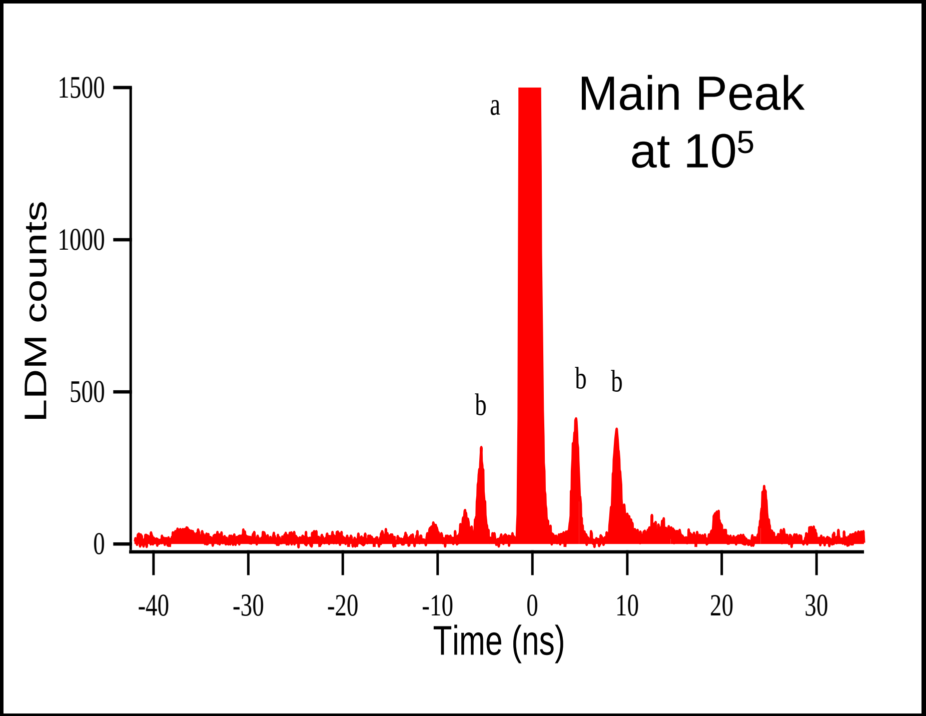
- Visual diagnostics for intensity & lifetime



BCT Error Sources & their Mitigation

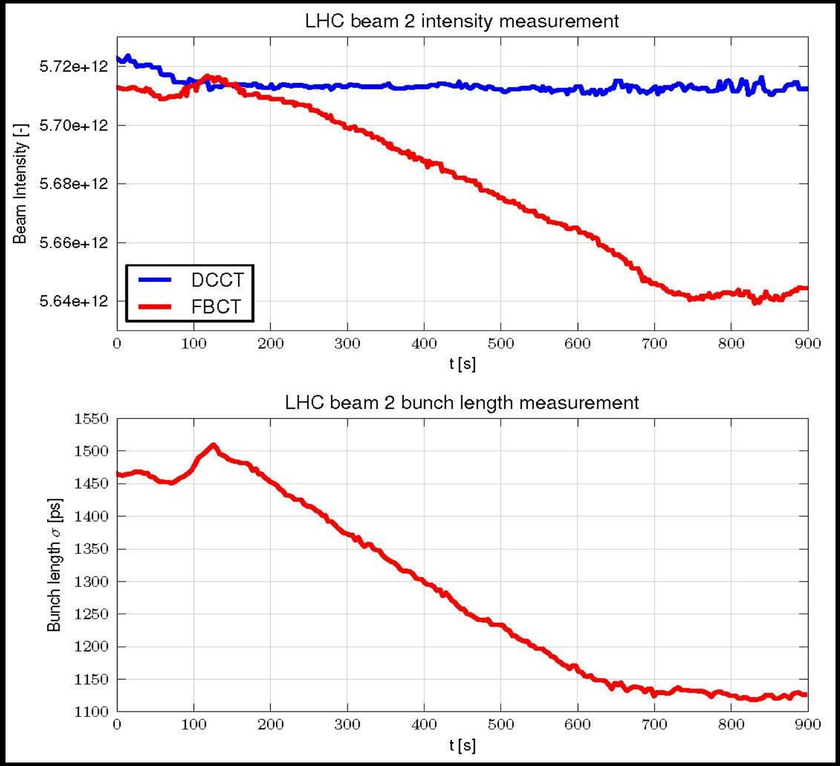
- Bunch pattern dependence & saturation of the DCCT
  - Modified DCCT feedback loop, wall-current bypass & front-end amplifiers
  - Uncertainty in the absolute DCCT calibration now at the 0.1% level
- Satellite bunches and unbunched beam
  - Produces uncertainty in cross-calibration of FBCT with DCCT
  - LDM & data from experiments used to ensure this is well below 1%

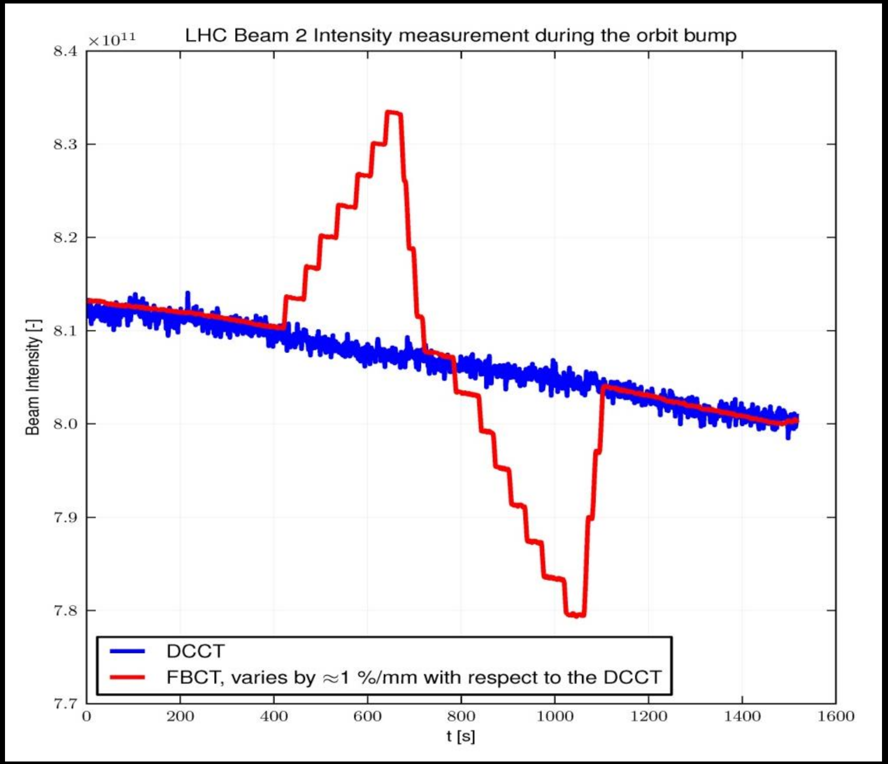




BCT Error Sources & their Mitigation

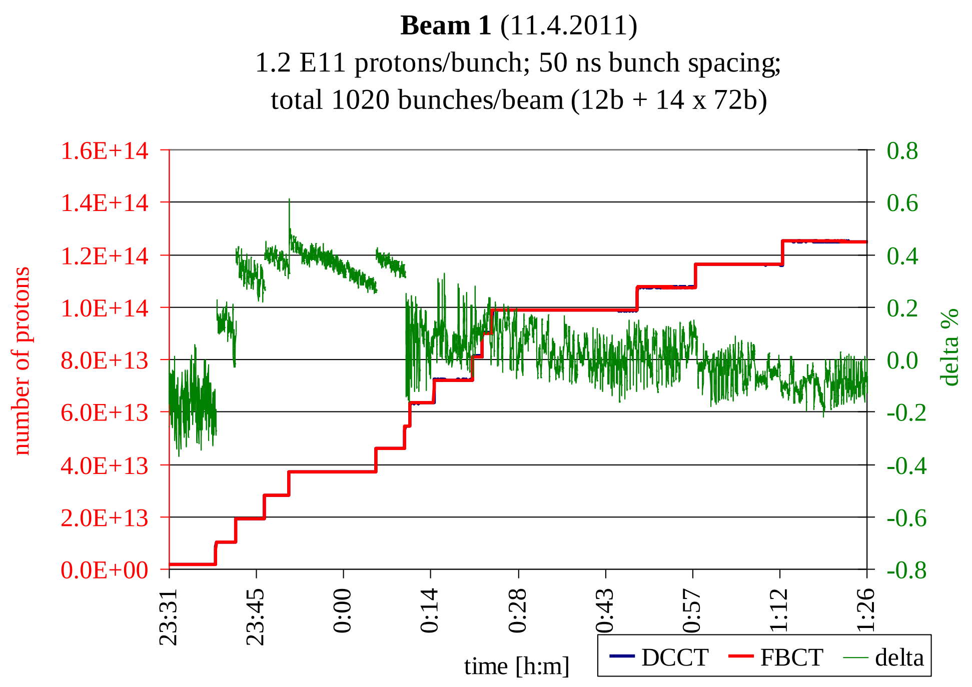
- Bunch length dependence of the fast BCT
  - Mitigated with 70MHz LP filters - still allows bunch-by-bunch measurement
- Bunch position dependence of the fast BCTs
  - At 1% per mm this effect was not at all expected
    - Found to come from commercial toroid used - new monitor under development
  - Fortunately orbit is kept sufficiently stable & limits effect to well below 1%

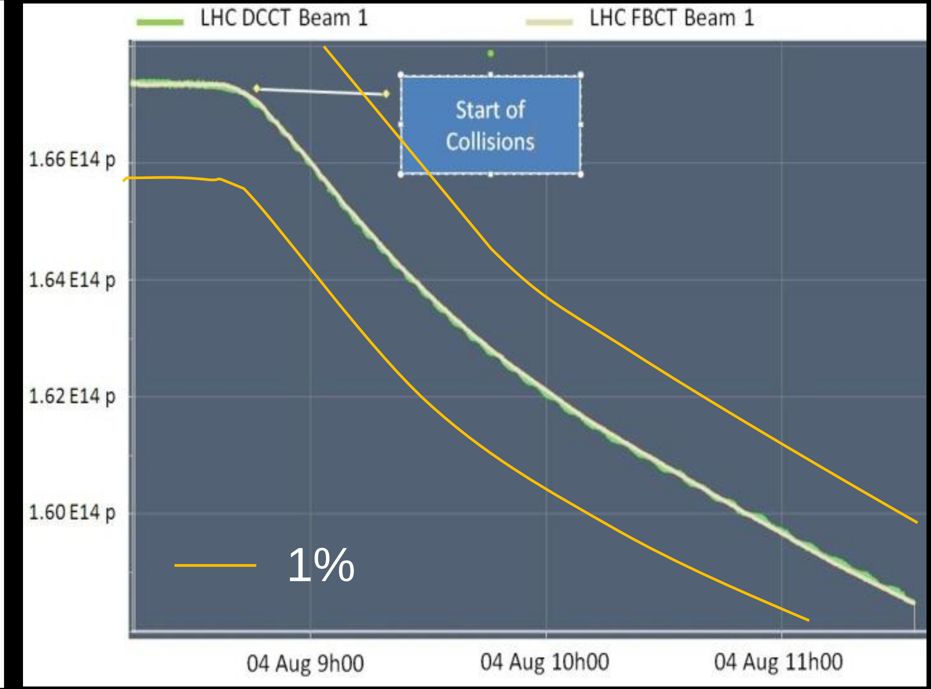




BCT Error Sources & their Mitigation

- Essential for Absolute Luminosity Determination
  - Important progress made in understanding many error sources
  - Bunch population uncertainties now in line with other experimental sources for absolute luminosity determination





Summary

- This was an overview of the LHC Beam Position and Beam Intensity Measurement systems
- Both systems have undergone upgrades during LS1
  - BPM system
    - Temperature controlled racks for electronics in all surface buildings
    - Addition of BPMs embedded in collimators with their own dedicated, high resolution acquisition system
  - Fast BCT system
    - 2 new types of toroid installed for testing to try and overcome bunch length and position dependency
- Tomorrow you will see how we measure the beam profile in the LHC
  - Essential to calculate the beam size & determine beam emittance

Acknowledgements

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