# Beam Instrumentation & Beam Diagnostics

CAS 2003

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(CERN)

# Write-up and Hand-Outs

- The two lectures on beam instrumentation and diagnostics contain a lot of visual information (movies etc) which are not easy to reproduce in hand-outs.
- On the internet a similar lecture from CAS2002 can be downloaded from the url:

  http://sl-div.web.cern.ch/sl-div-bi/CAS%20/lecture/

- In about 2 weeks the lectures of 2003 will be available from the same url.

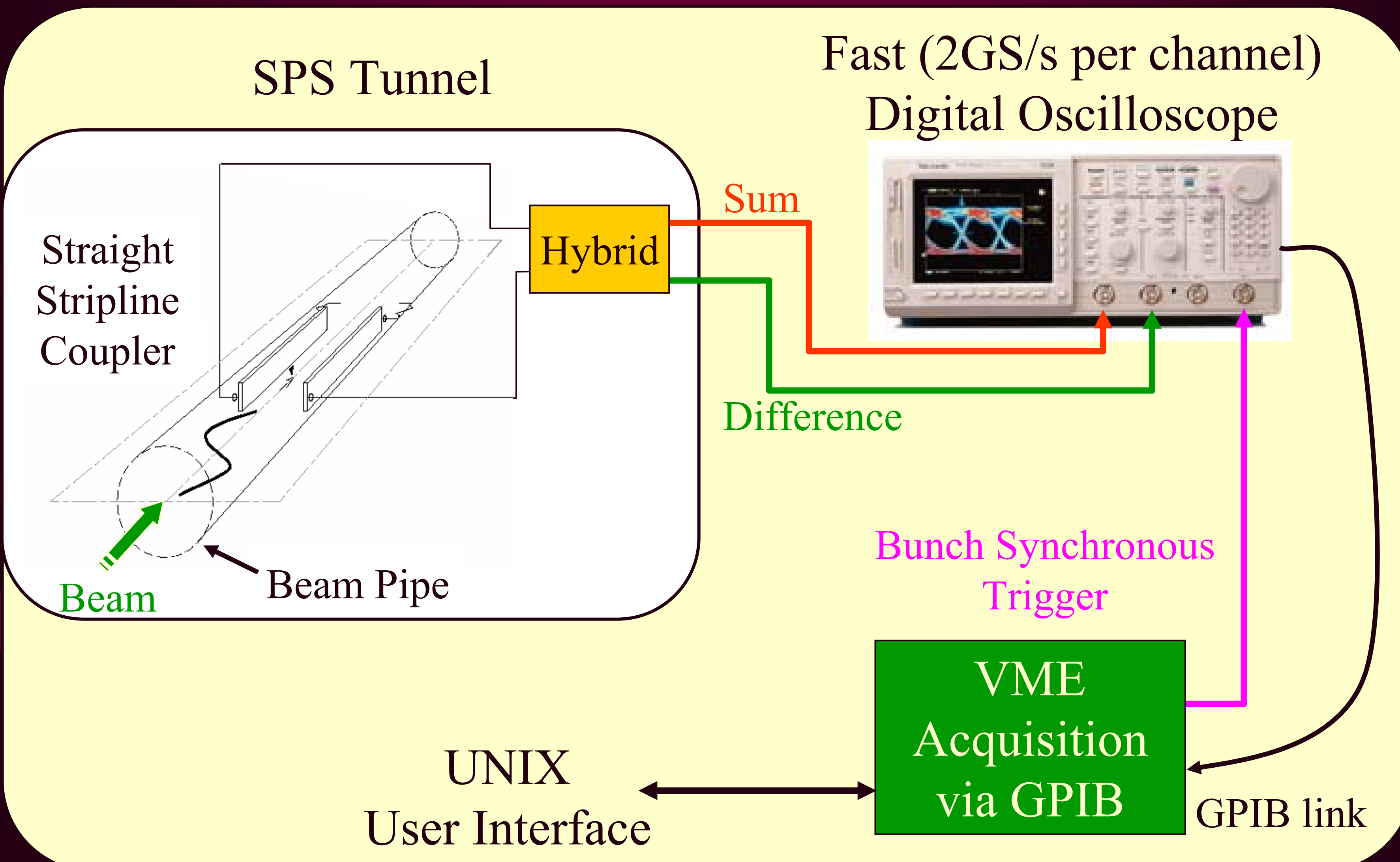
# A Starter

A Beam Diagnostics and Instrumentation activity shall design, build, maintain and improve the diagnostic instruments that allow the observation of particle beams with the precision required to diagnose, tune, operate and improve the accelerators and associated transfer lines.

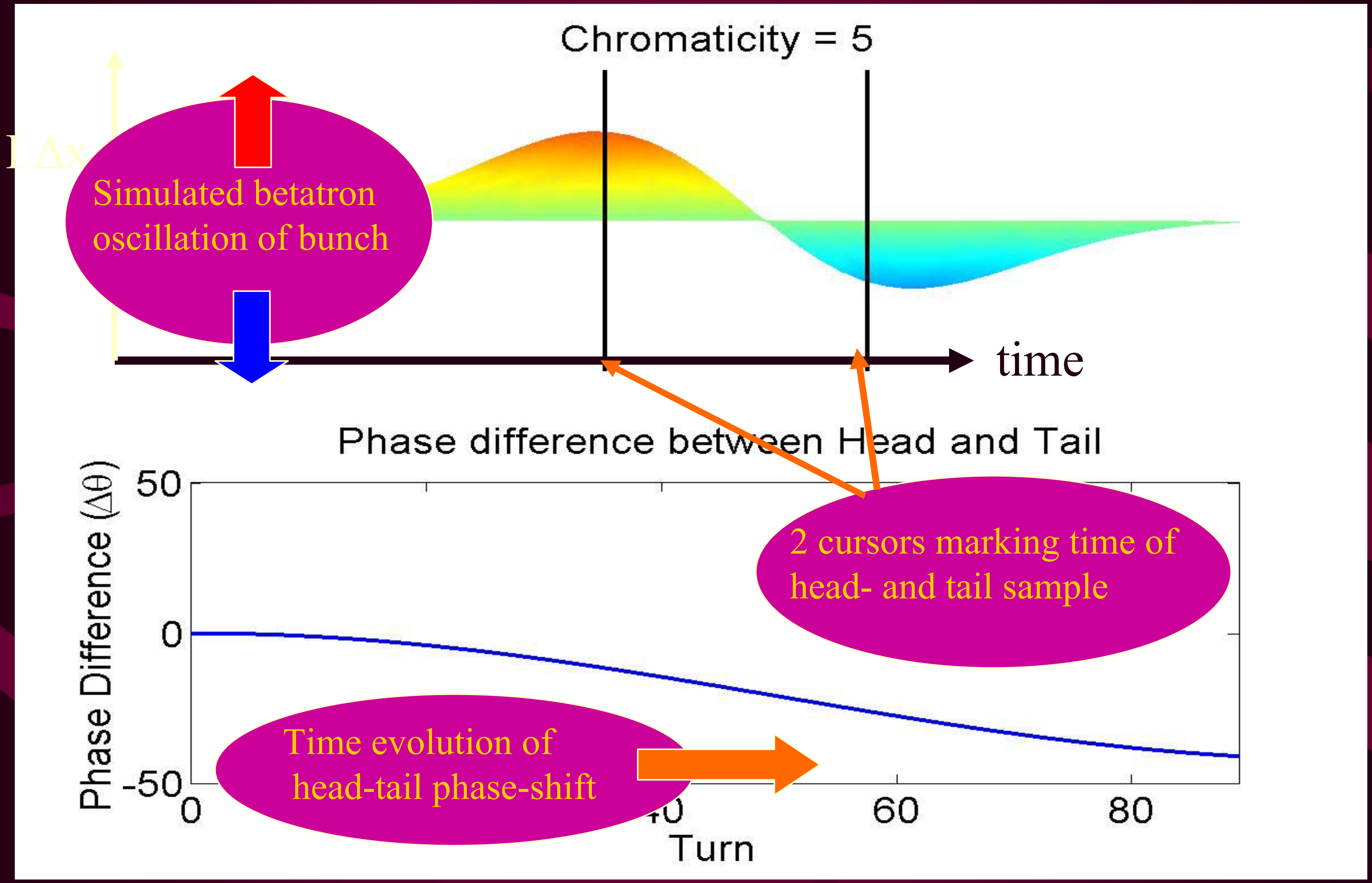
This means that Beam Instrumentation combines the disciplines of accelerator physics, mechanical engineering, electronic engineering and software engineering.

In Short: One of the most fascinating fields of work I can imagine

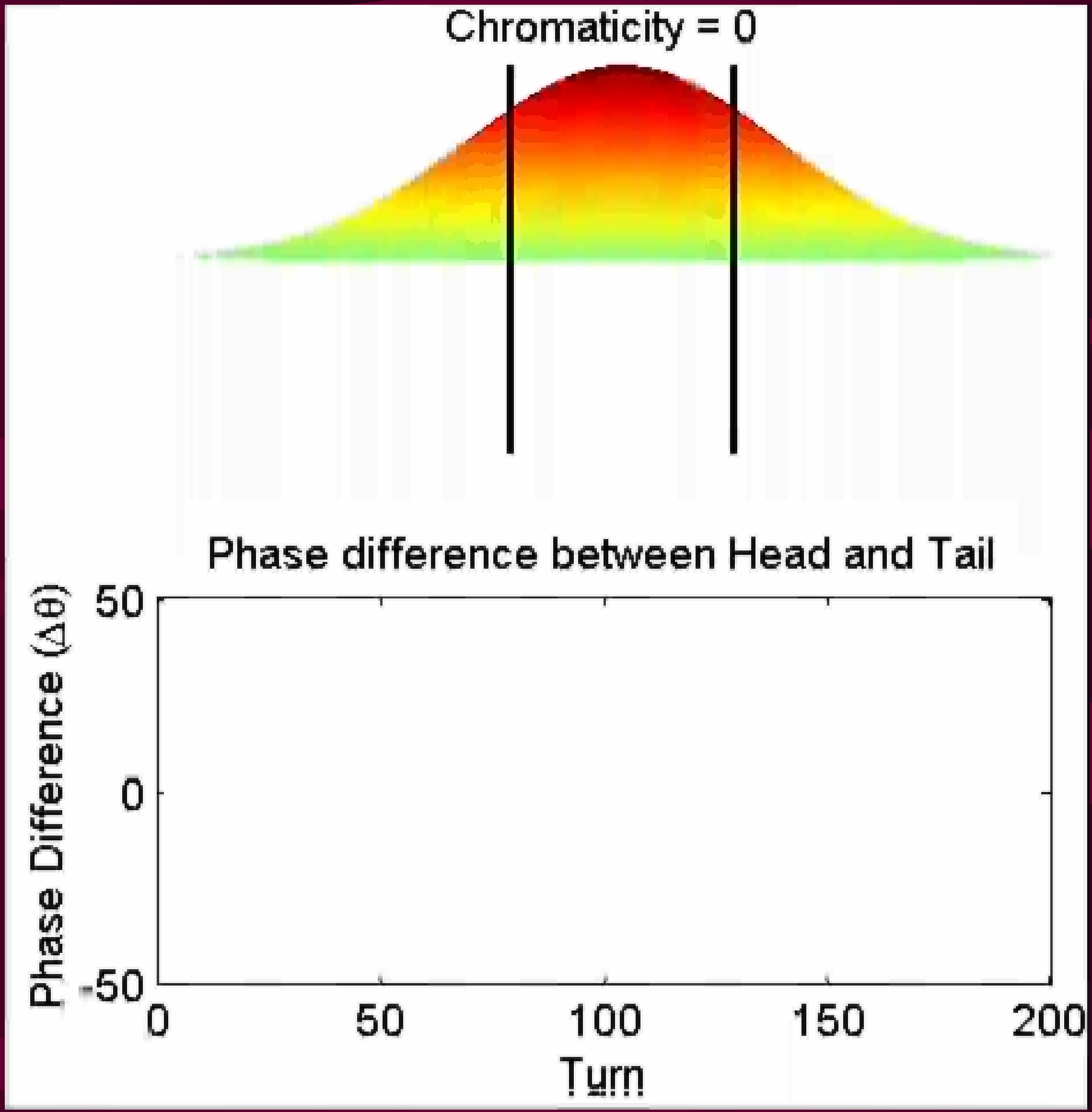
# Starter Example:
## Setup for Head-tail observations



# …snapshot of movies to follow...



# The Head-Tail Principle



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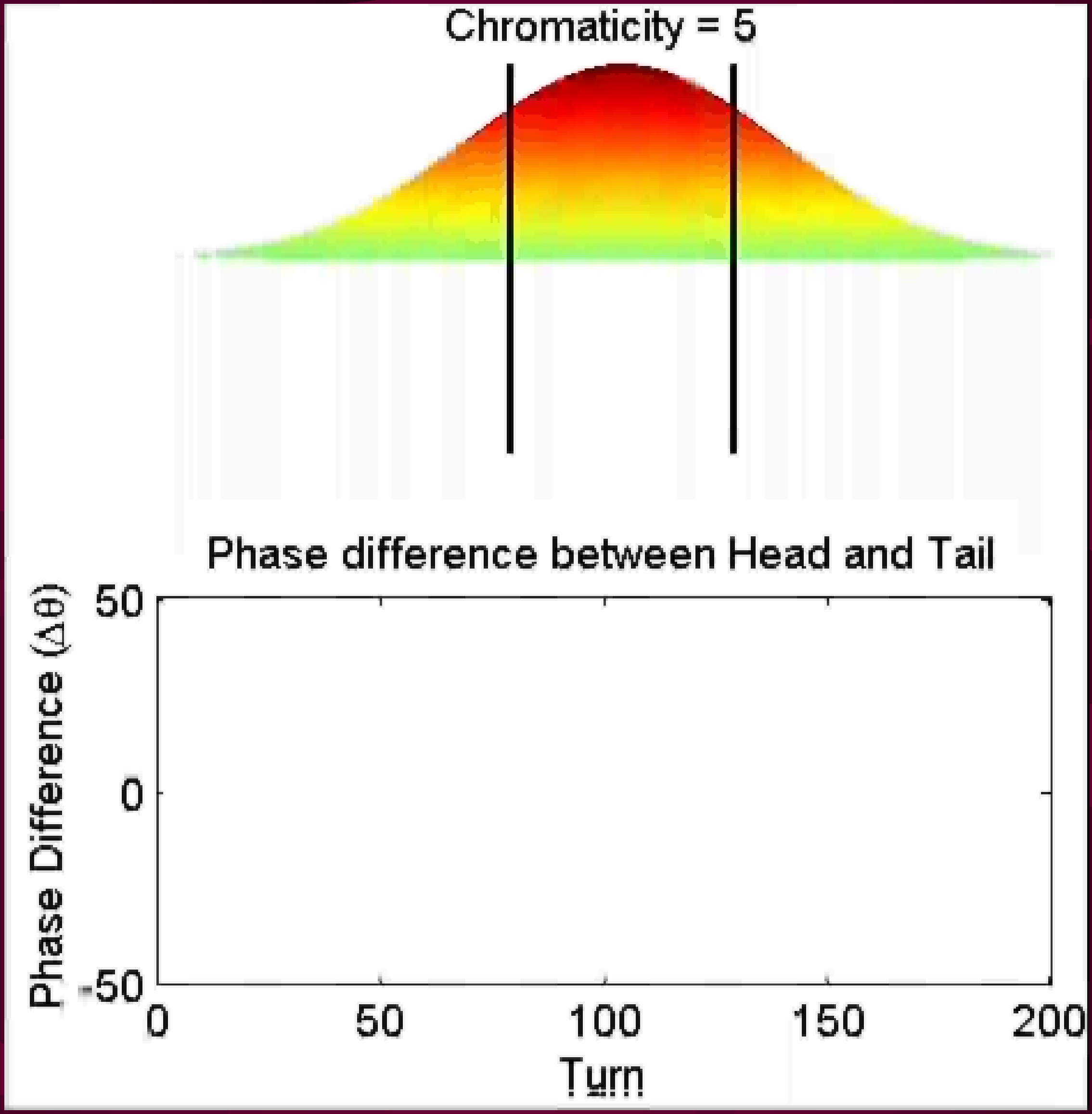
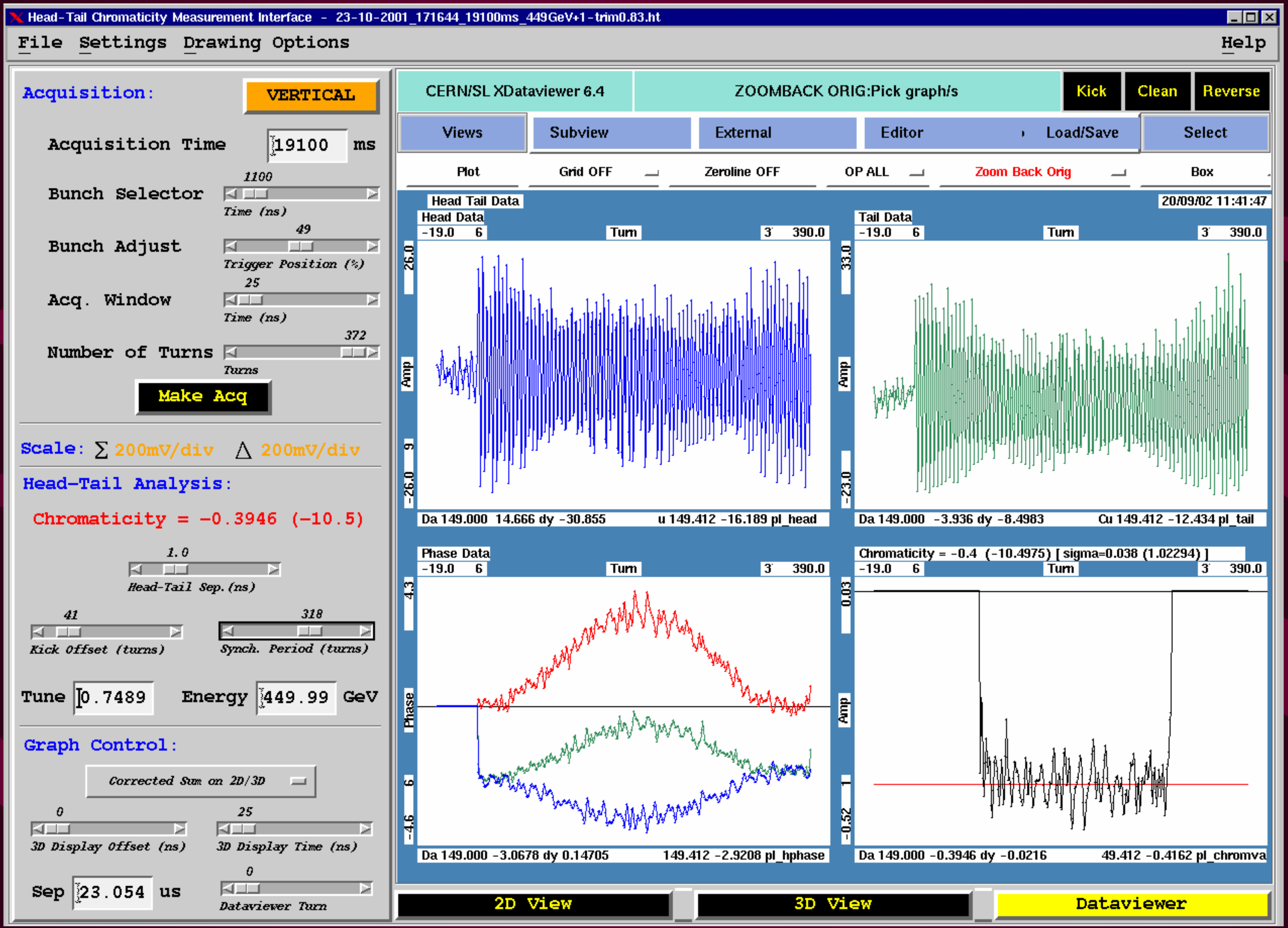


# Deducible Beam Parameter: Chromaticity
## (…more of this tomorrow in the diagnostics part)



# Outline for Today

- Focus on “What and How we Measure”

  & the technologies involved

- Introduction
  - → What do we mean by “Beam Instrumentation”
  - → What instruments are involved

- Beam Instrumentation Selection
  - → Beam Position Measurement
  - → Beam Loss Measurement
  - → Beam Intensity Measurement
  - → Luminosity Measurement

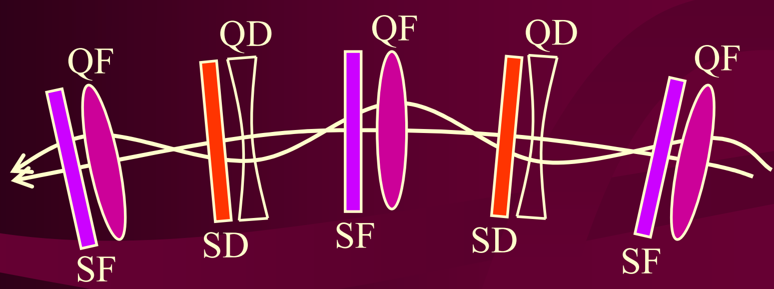
# Introduction

- What do we mean by beam instrumentation?
  - → The "eyes" of the machine operators
    - i.e the instruments that observe beam behaviour

- What beam parameters do we measure?
  - → Beam Position
    - Horizontal and vertical all around the ring
    - Corrected using orbit corrector magnets (dipoles)
  - → Beam Loss all around the ring
    - Especially important for superconducting machines
  - → Beam Intensity (& lifetime measurement for a collider)
    - Circulating current and bunch-by-bunch charge
  - → Beam size
    - Transverse and longitudinal distribution
  - → Collision rate / Luminosity (for colliders)

# More Measurements

- Machine Tunes



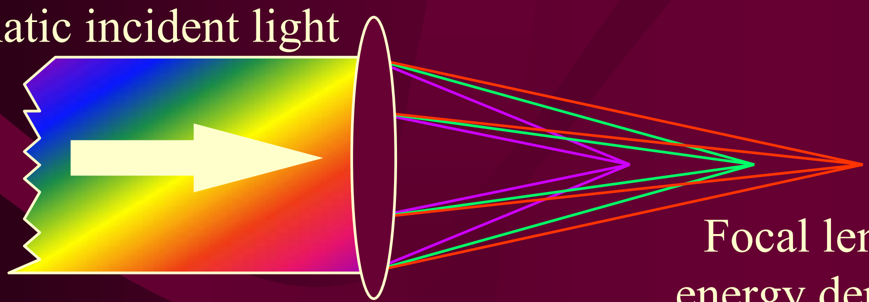

Characteristic Frequency of the Magnet Lattice

Produced by the strength of the Quadrupole magnets

- Machine Chromaticities

**Optics Analogy:**

Achromatic incident light



Lens

Focal length is energy dependent

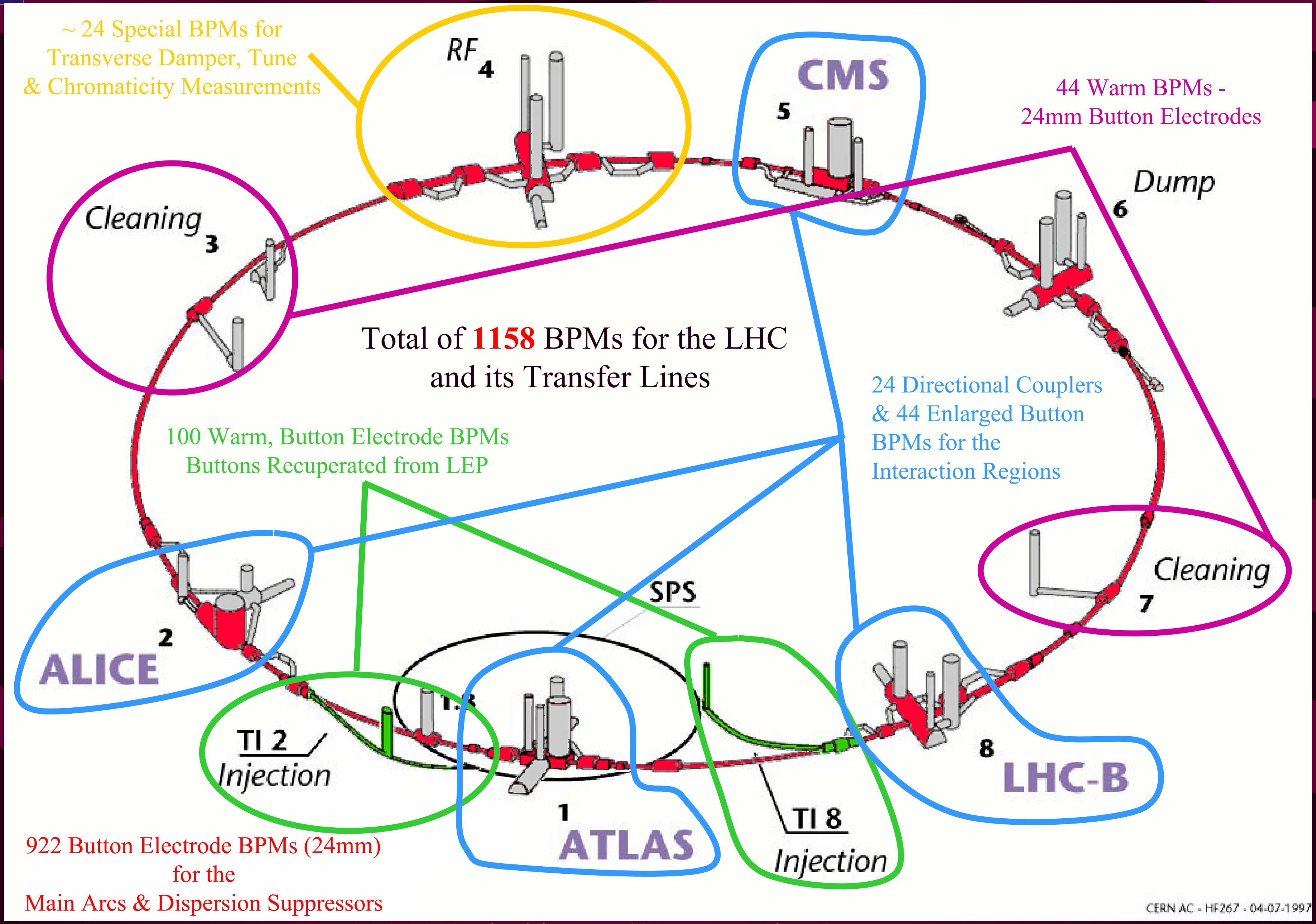
Spread in the Machine Tune due to Particle Energy Spread

Controlled by Sextupole magnets

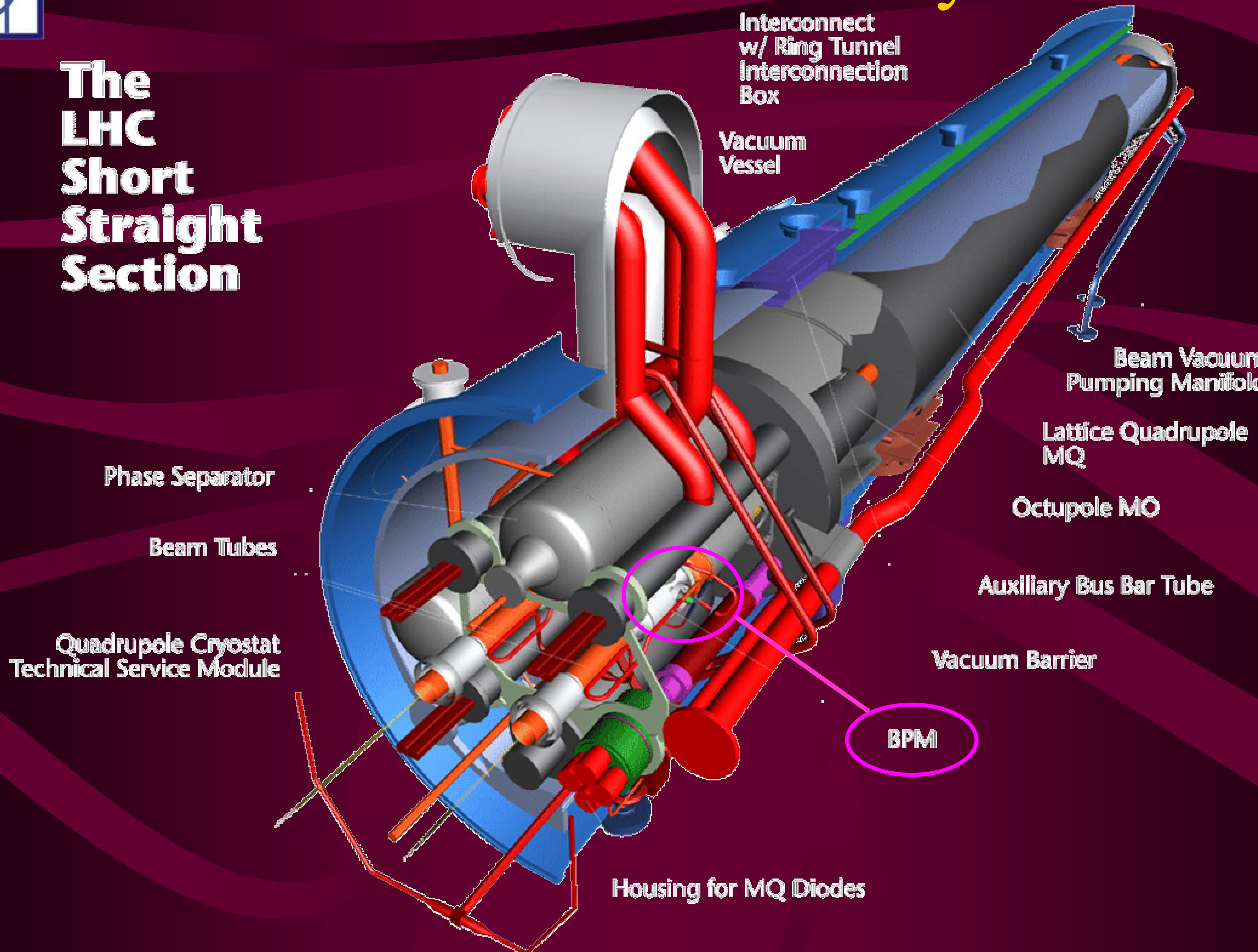
# The Typical Instruments

- Beam Position
  → electrostatic or electromagnetic pick-ups and related electronics
- Beam Loss
  → ionisation chambers or pin diodes
- Beam Intensity
  → beam current transformers
- Beam Size (transverse)
  → in diagnostics section of tomorrow
- Beam Size (longitudinal)
  → RF pick-ups or synchrotron light
- Luminosity
  → ionisation chambers or semiconductors
- Machine Tunes and Chromacitities
  → in diagnostics section of tomorrow

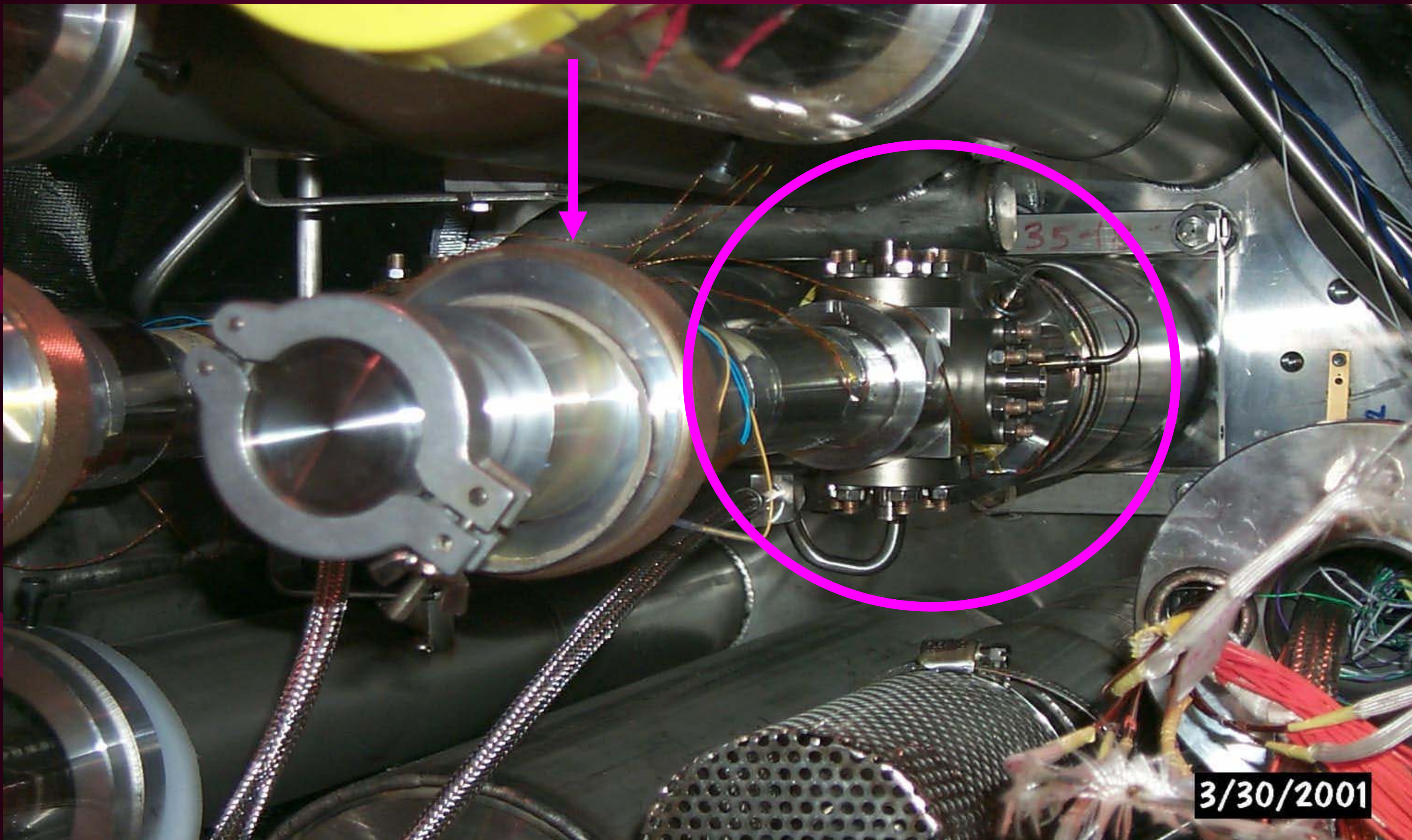
# LHC BPM System - General Layout



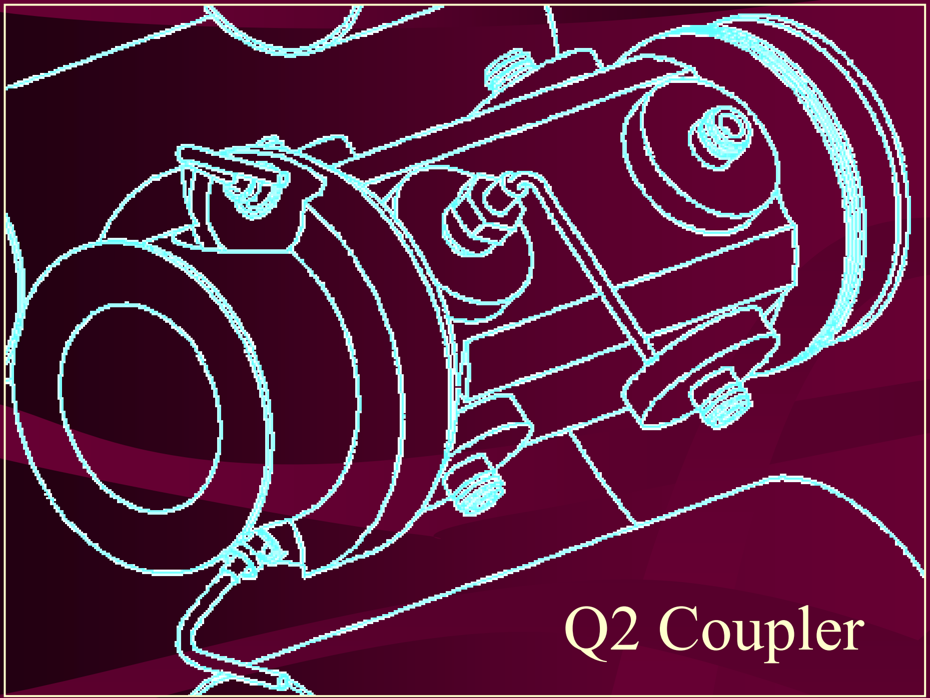
# The Arc BPM - SSS Layout

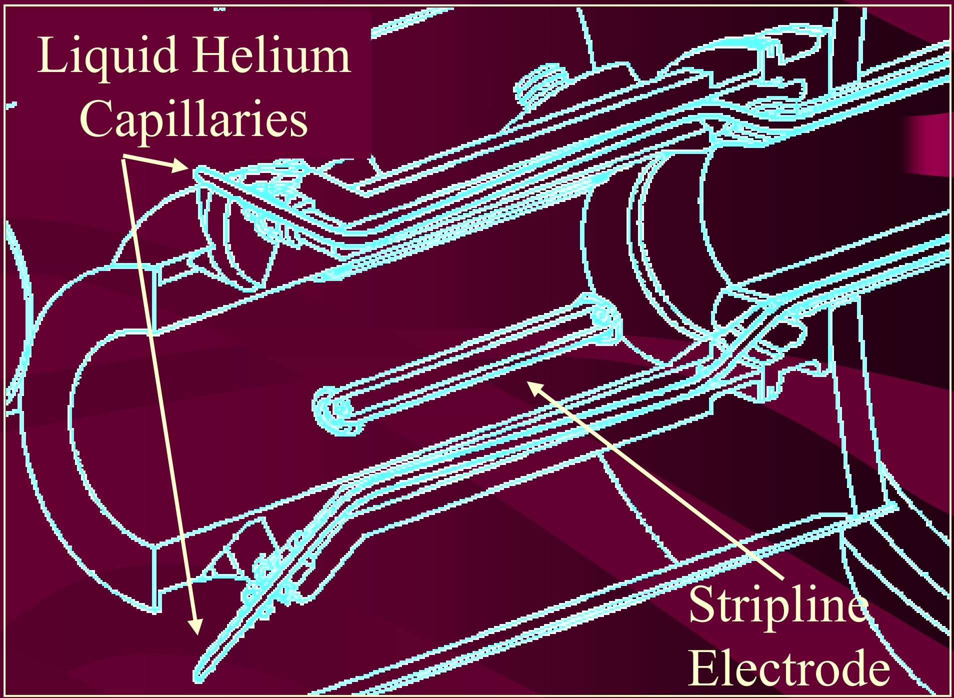


# LHC Arc Type BPM (String 2)



# Interaction Region BPMs



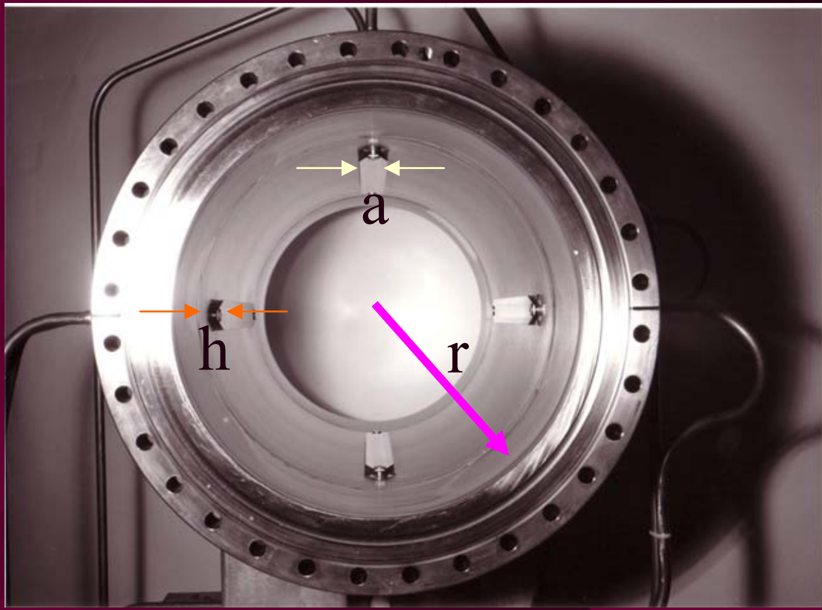

- Directional stripline couplers
  - → Outputs signals only from the upstream port
  - → Can distinguish between counter-rotating beams

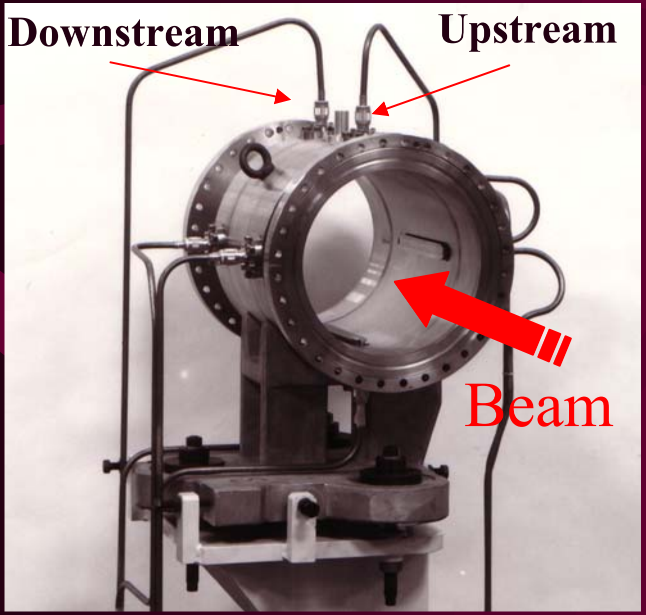
# Electromagnetic (Directional) coupler

- **Is a transmission line (strip line) which couples to the transverse electromagnetic (TEM) beam field**

$$Z_{t\,\infty} = 60 \ln[(r+h)/r] \equiv Z_0 * [a/2\pi(r+h)]$$

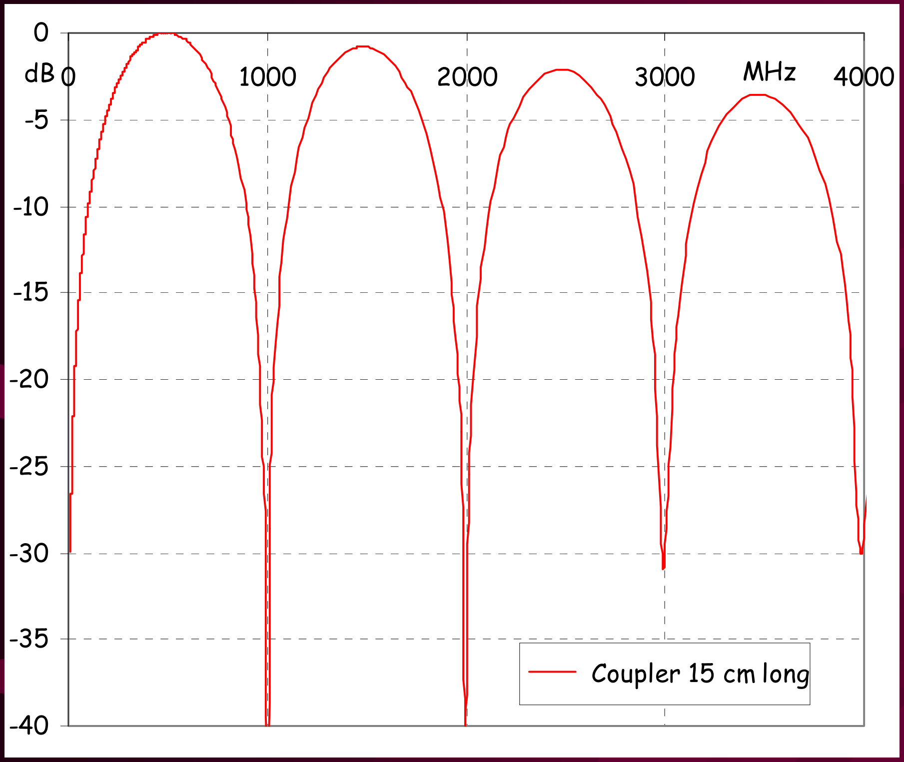
  - $Z_0$ is the characteristic impedance
  - a, r, h, l are the mechanical dimensions
  - t = l/c is the propagation time in the coupler

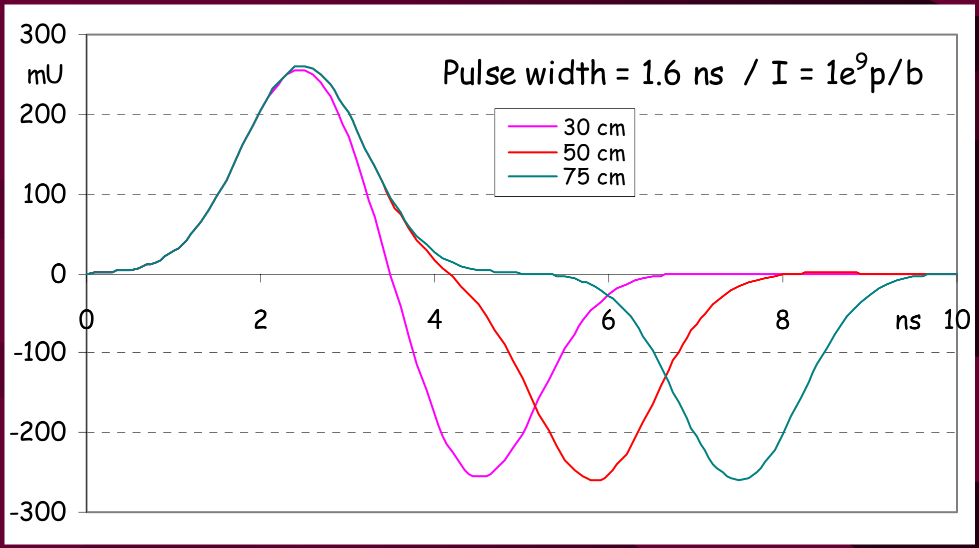


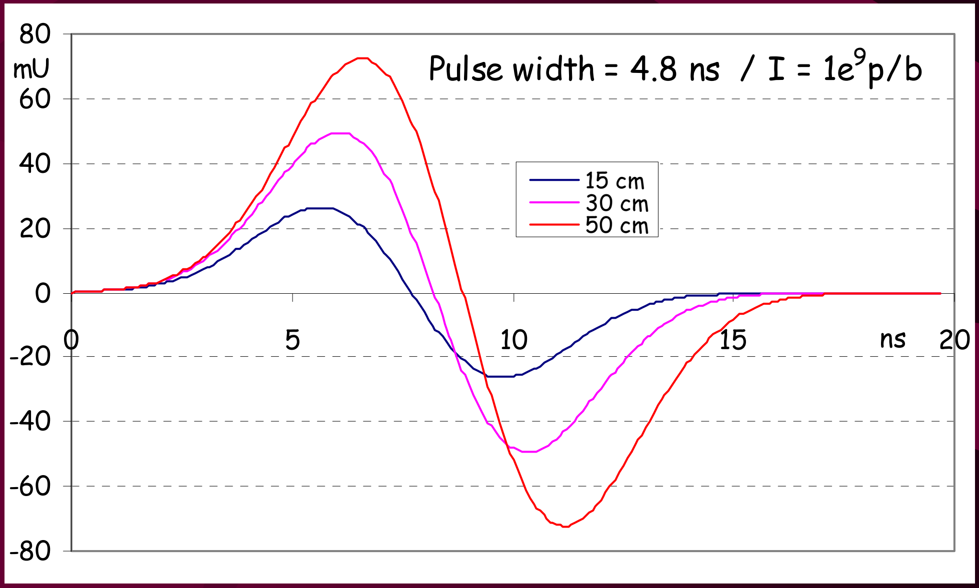




- **Two termination ports**
  - → Upstream: usually used to acquire signal.
    - Same signal seen whether Downstream port is open, shorted or terminated on $Z_0$
  - → Downstream: 3 cases
    - Upstream terminated on $Z_0 \Rightarrow$ no signal
    - Downstream open $\Rightarrow$ delayed signal
    - Upstream short circuit $\Rightarrow$ delayed & reversed signal

# Coupler frequency & time response




→ Sinusodal amplitude response

- Maximum signal for f = 1/4*t
- Zero signal for f = 1/2*t

→ Time domain:

- Bipolar pulse

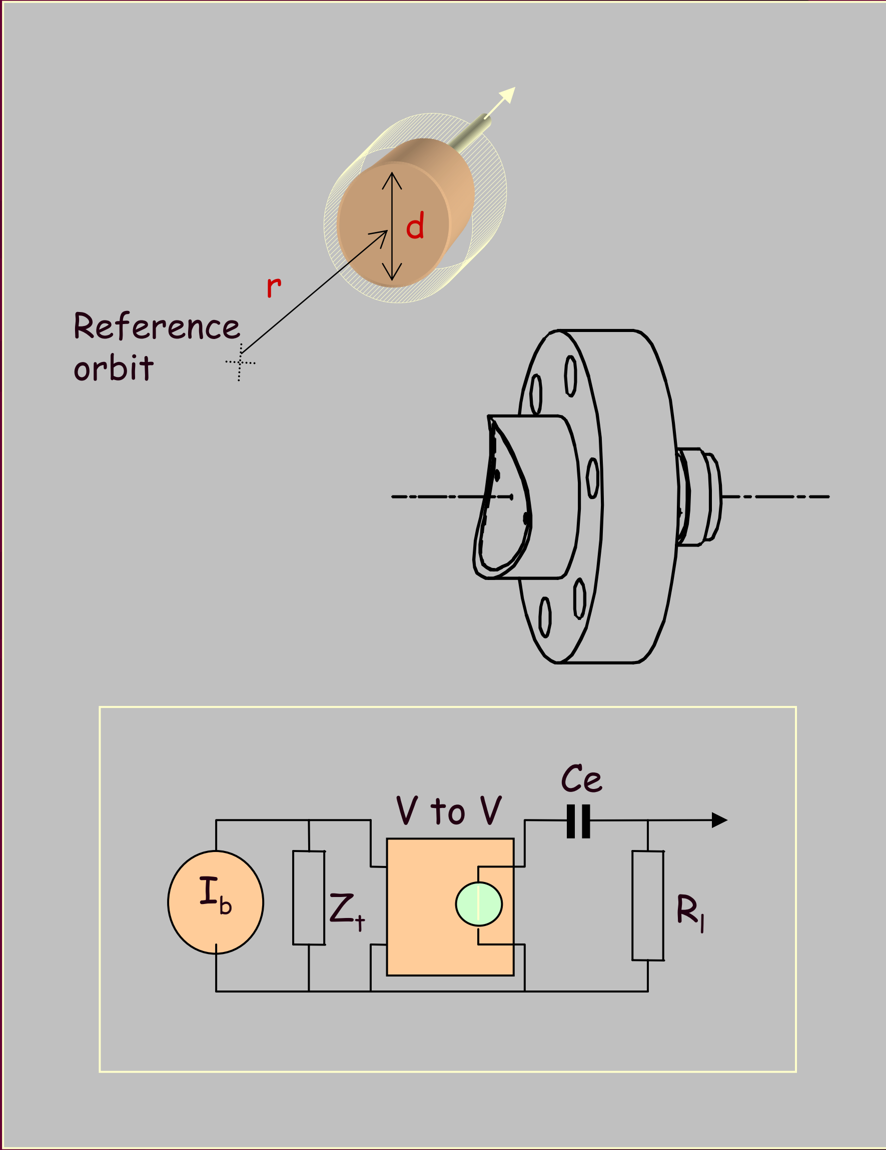
# Electrostatic PU (Button)

- Variant of electrostatic PU
- Low cost ⇒ most popular

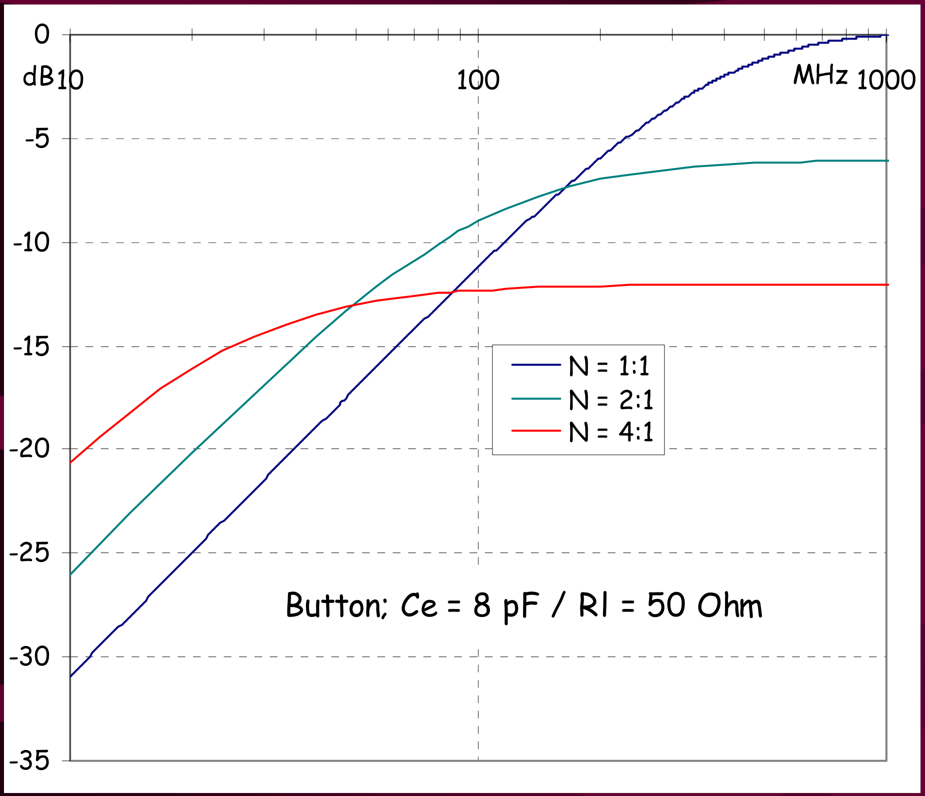
$$Z_{t\infty} \equiv d / 2\pi r C_e$$

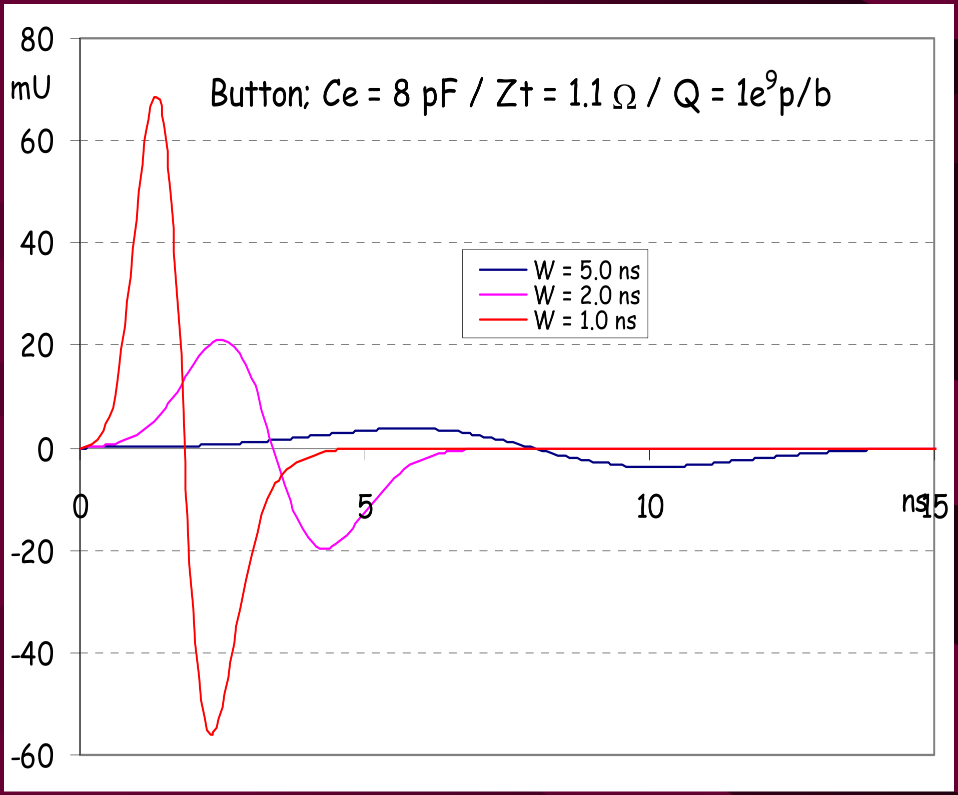
Low frequency cut-off

$T = R_l C_e$ (few hundreds MHz)



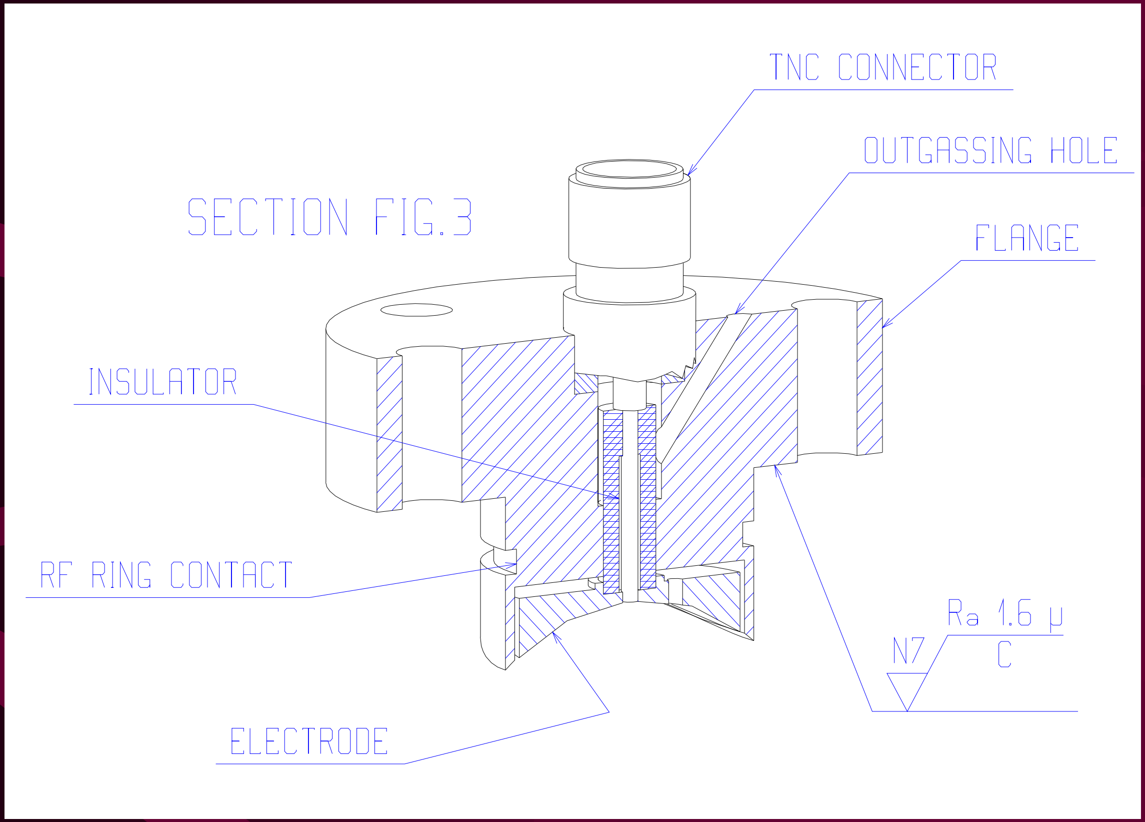
# Button Frequency & Time Response



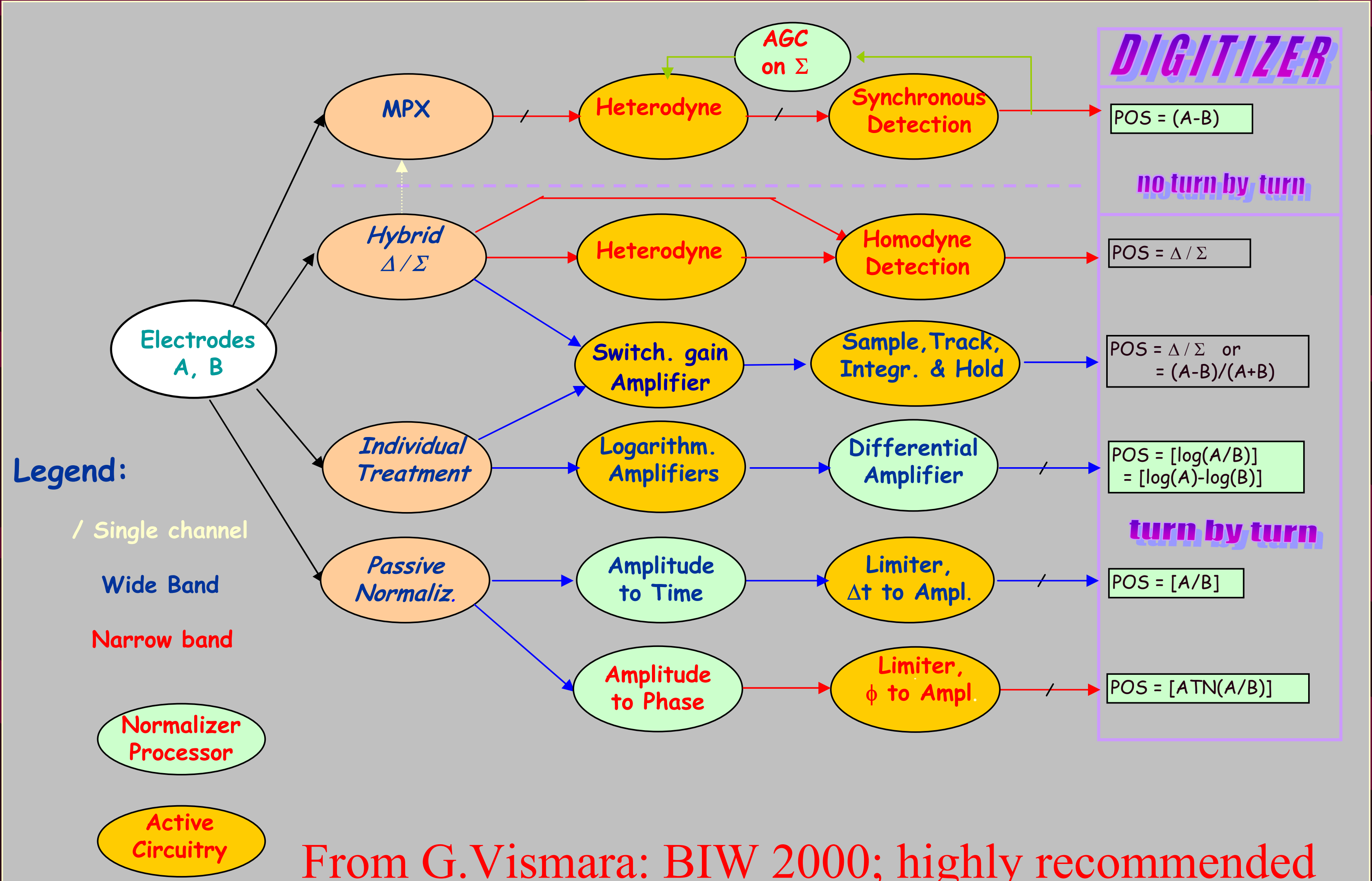




- Frequency domain:
  - → Impedance transformers improve the low frequency levels at the expense of the high frequency
- Time domain:
  - → Differentiated pulse
  - → Amplitude is exponentially bunch length dependent

# What does a real (LHC) electrostatic button monitor look like?




# Processing system families

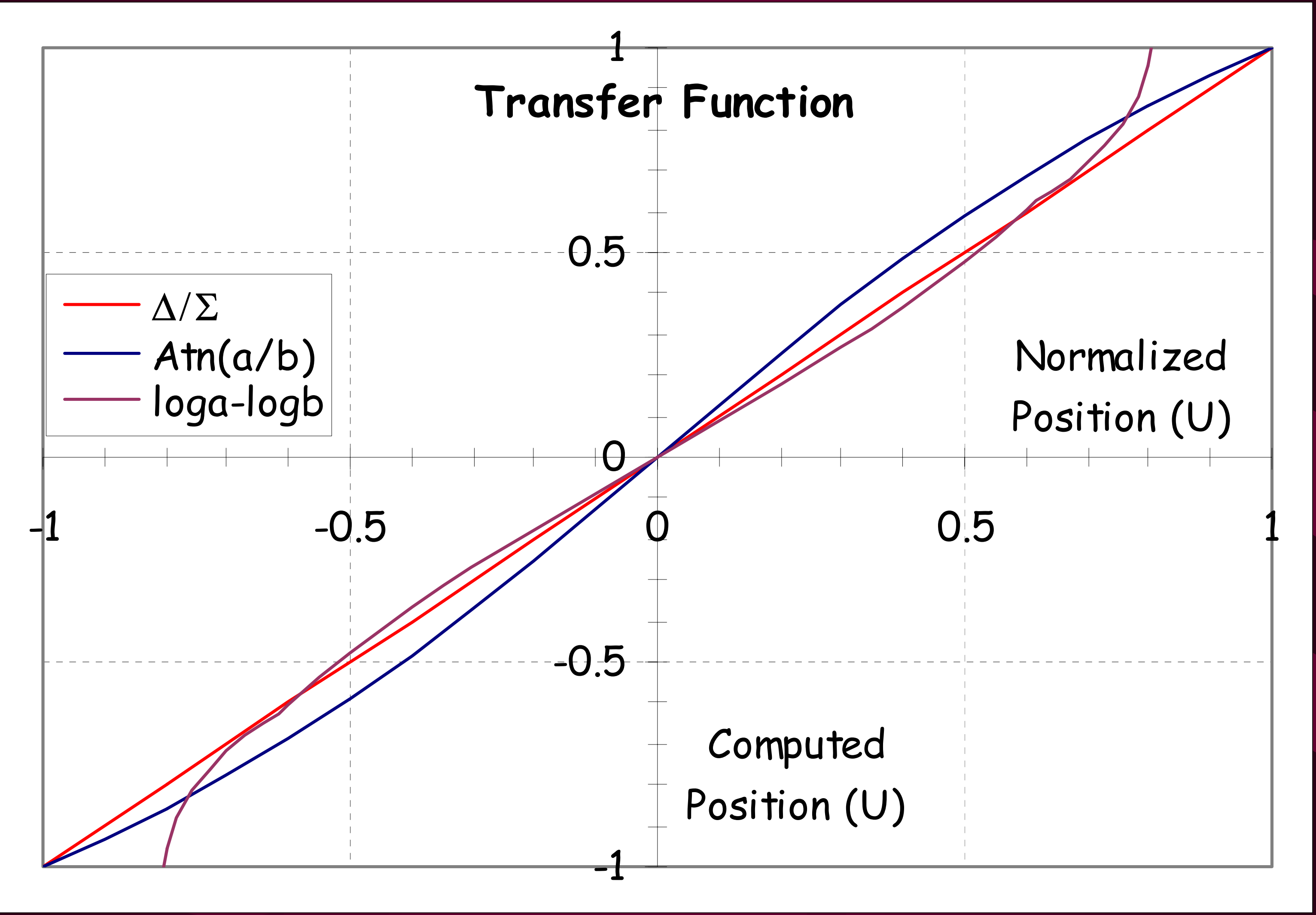



From G.Vismara: BIW 2000; highly recommended

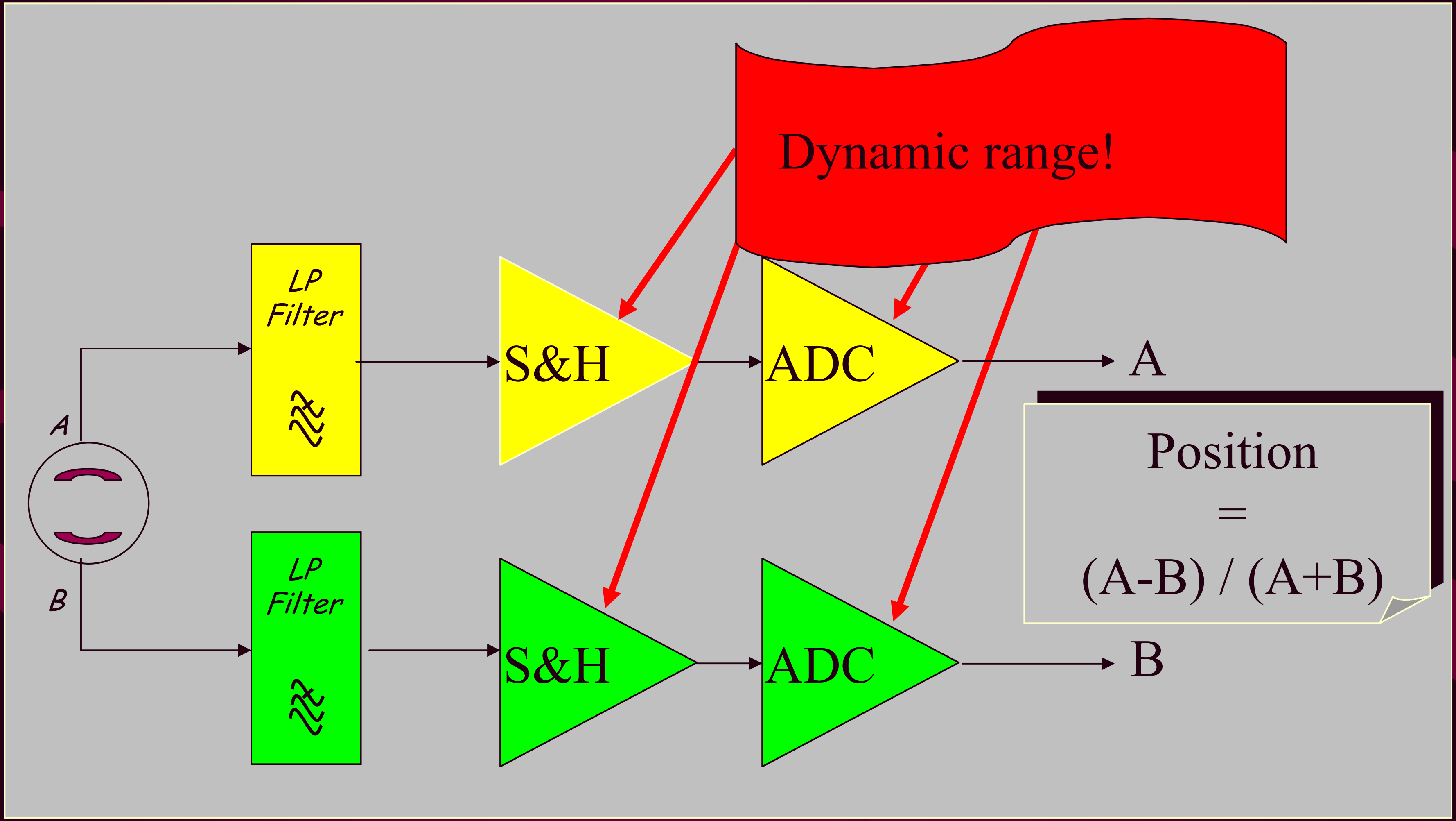
# Criteria for Electronics Choice so called "Processor Electronics"

- Accuracy: mechanical and electromagnetic errors, electronic components
- Resolution
- Stability over time
- Sensitivity and Dynamic Range
- Acquisition (Measurement) Time
- Linearity (over aperture & intensity)
- Radiation tolerance

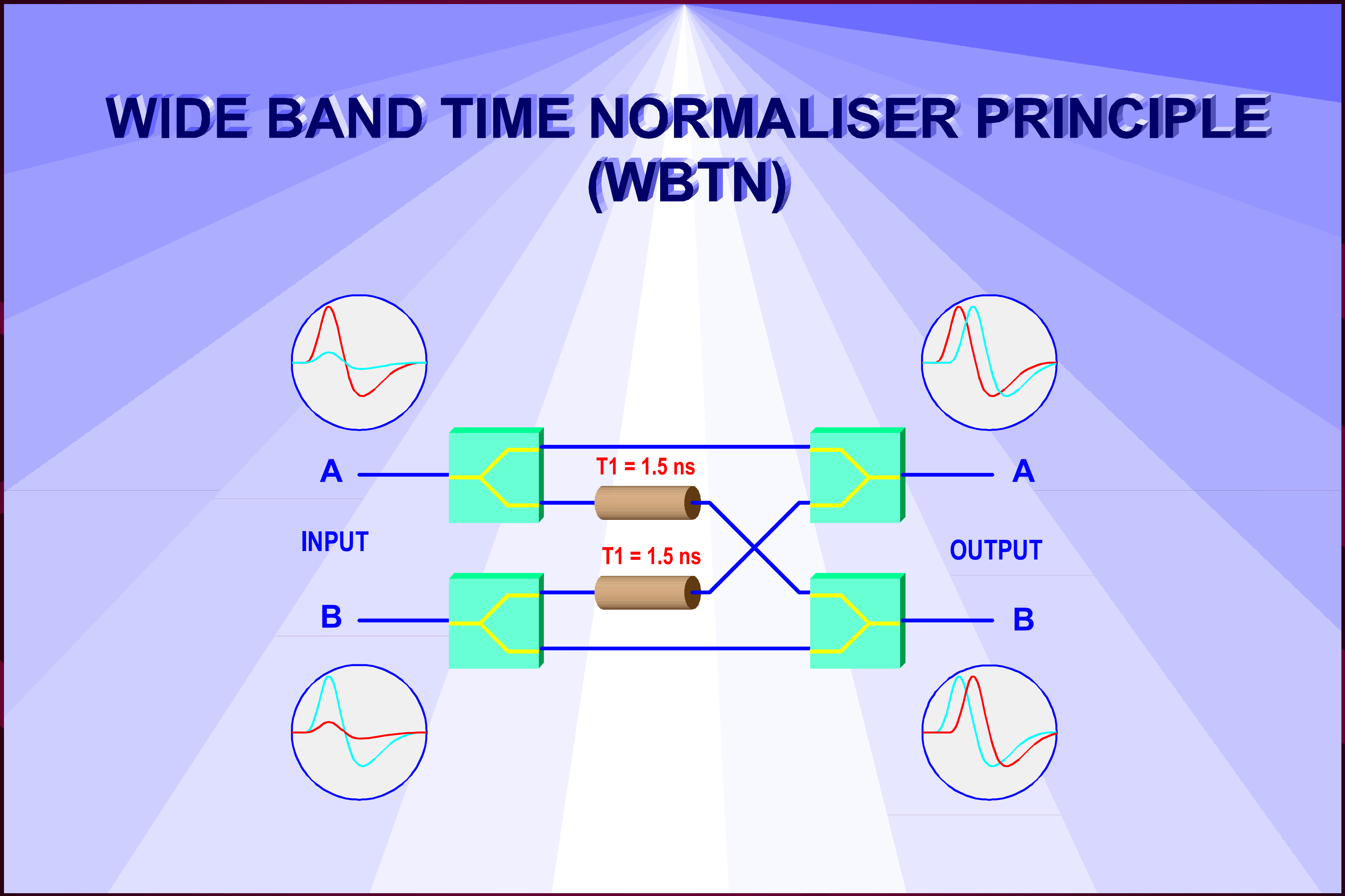
# LINEARITY Comparison



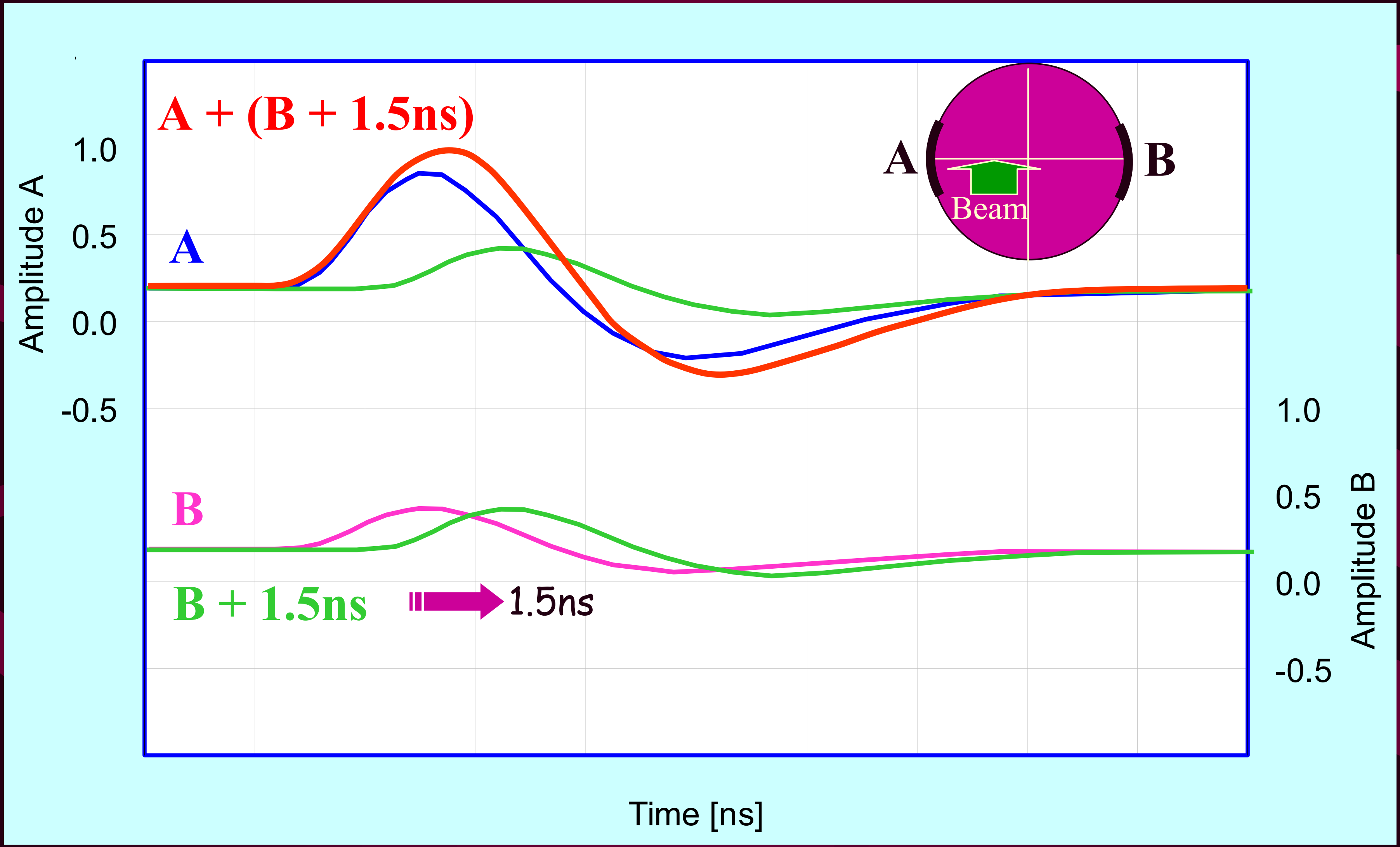
# Simple Example: Sampling of Individual Detector Signals



# A Real System:
## LHC Amplitude to Time Normaliser Schematics



# The Wide Band Time Normaliser



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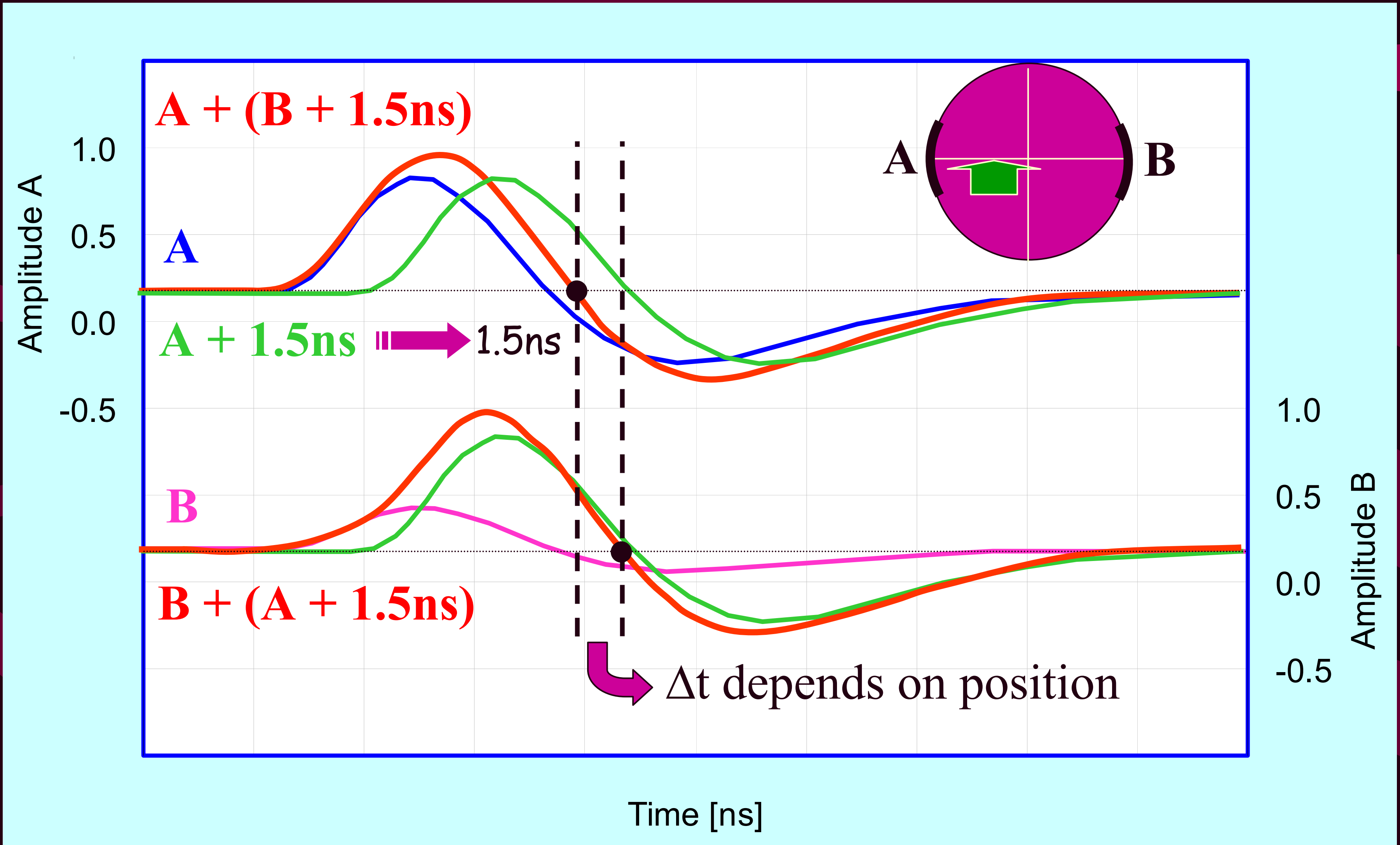

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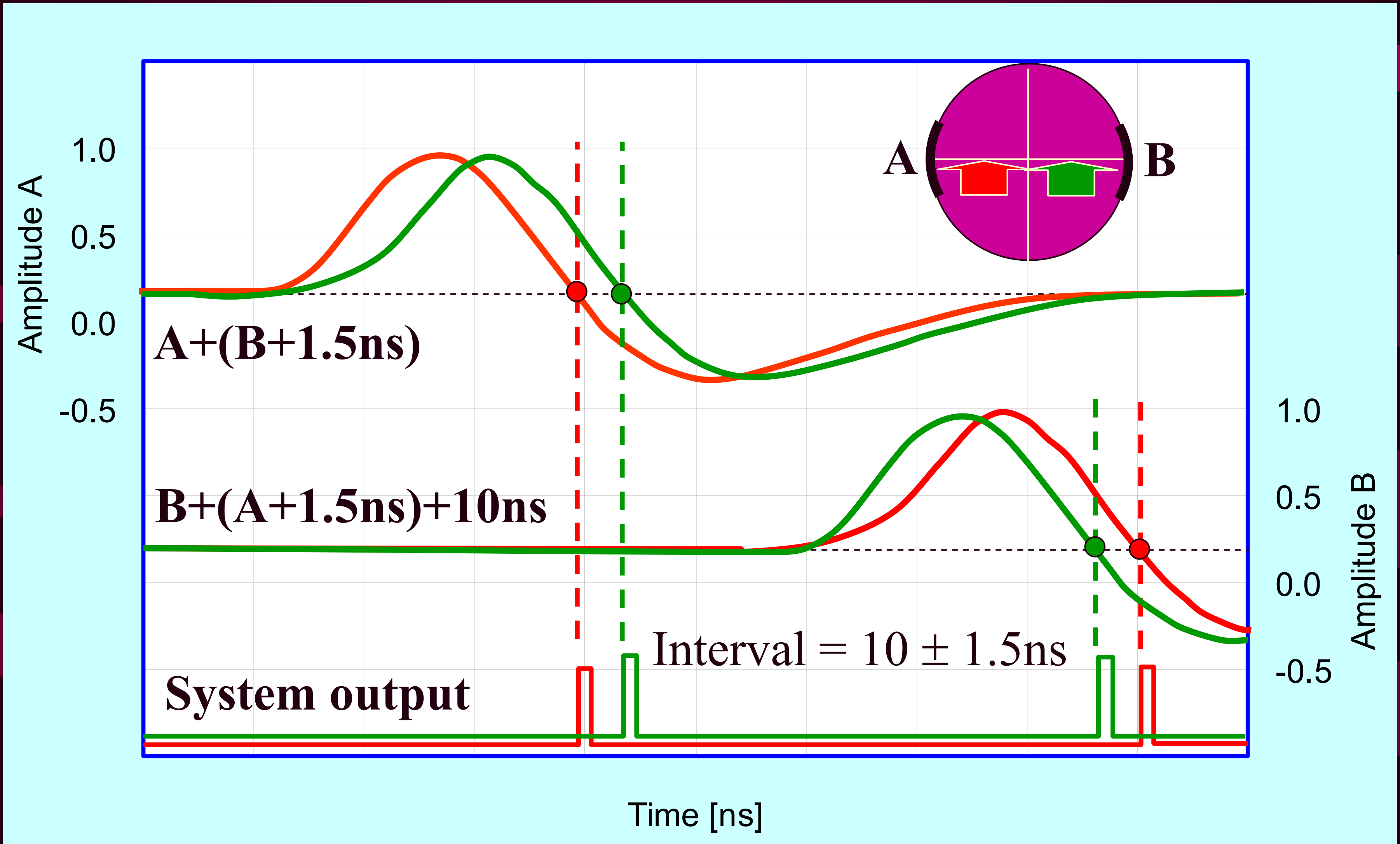


# Amplitude to Time Normaliser Evaluation

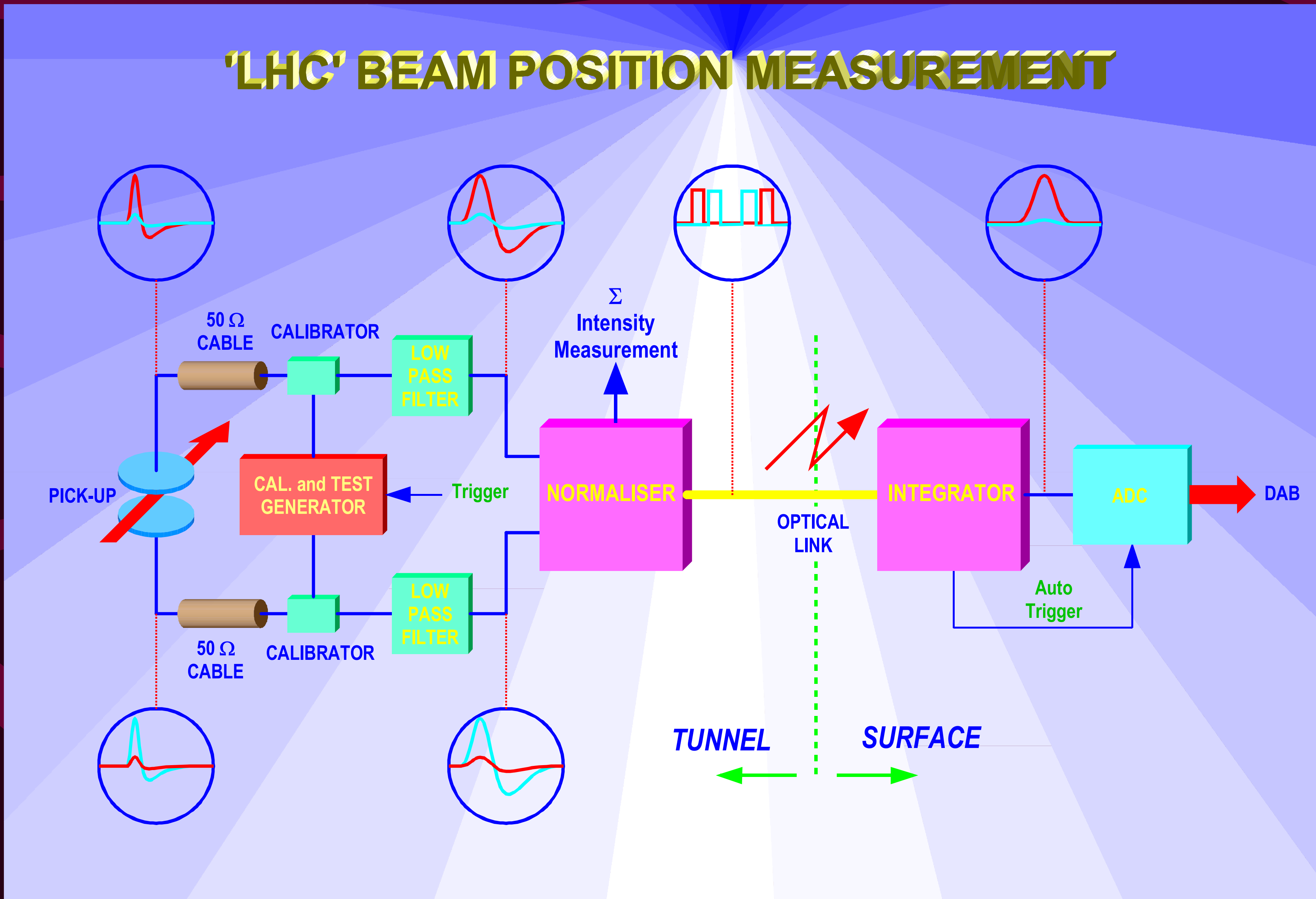
## Advantages

- Reduced number of channels (x2)
- No need for gain selection
- Input dynamic > 50 dB
- Signal dynamic independent on the number of bunches
- ~10 dB compression of the position dynamic (recombination)
- Auto-trigger
- Reduced N° of bits at equivalent resolution (Normalisation)

## Limitations

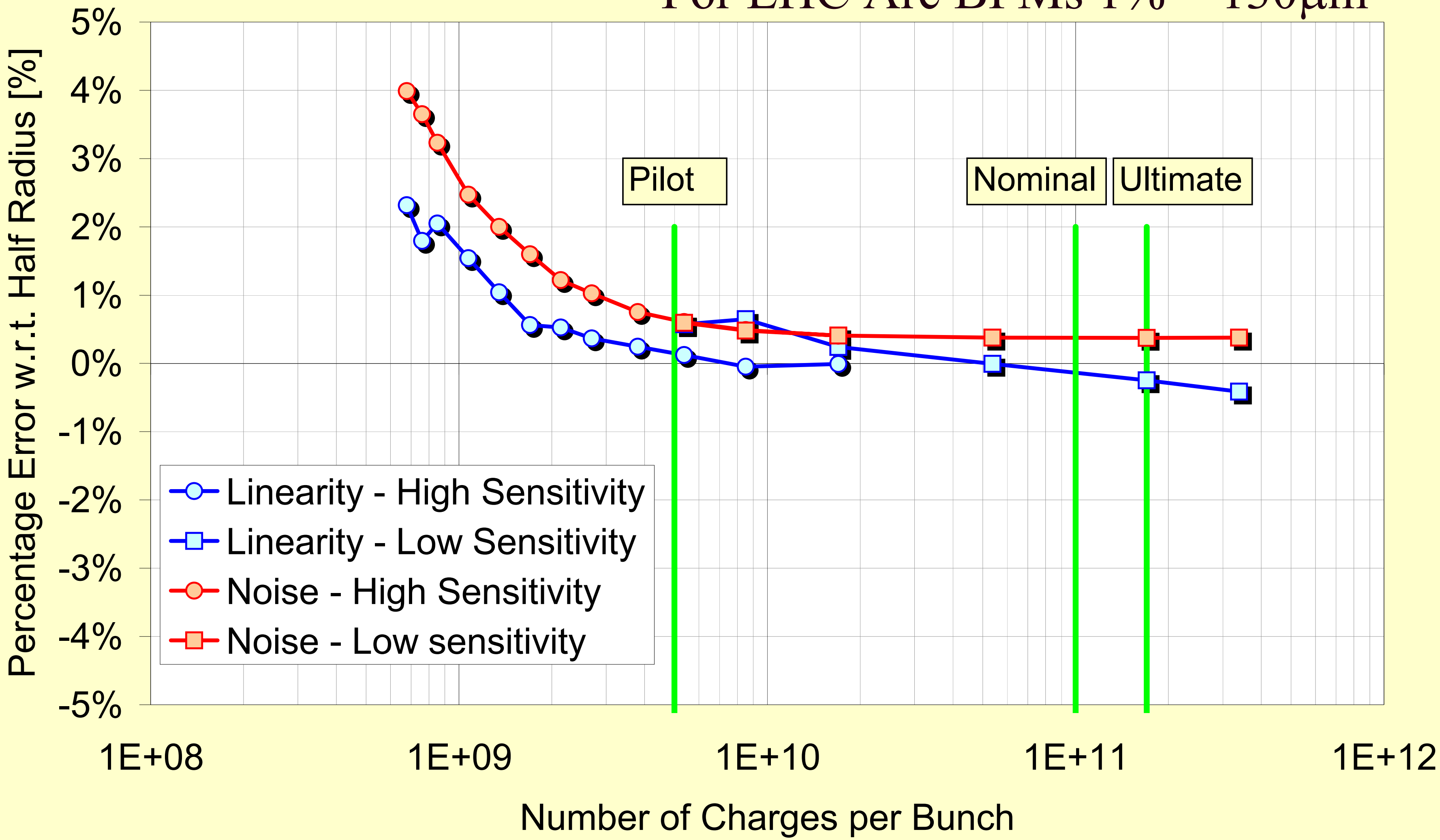
- Mainly reserved for bunched beams
- Tight time adjustment
- Propagation delay stability and switching time uncertainty are the limiting performance factors
- No Intensity information

# LHC Beam Position System Layout

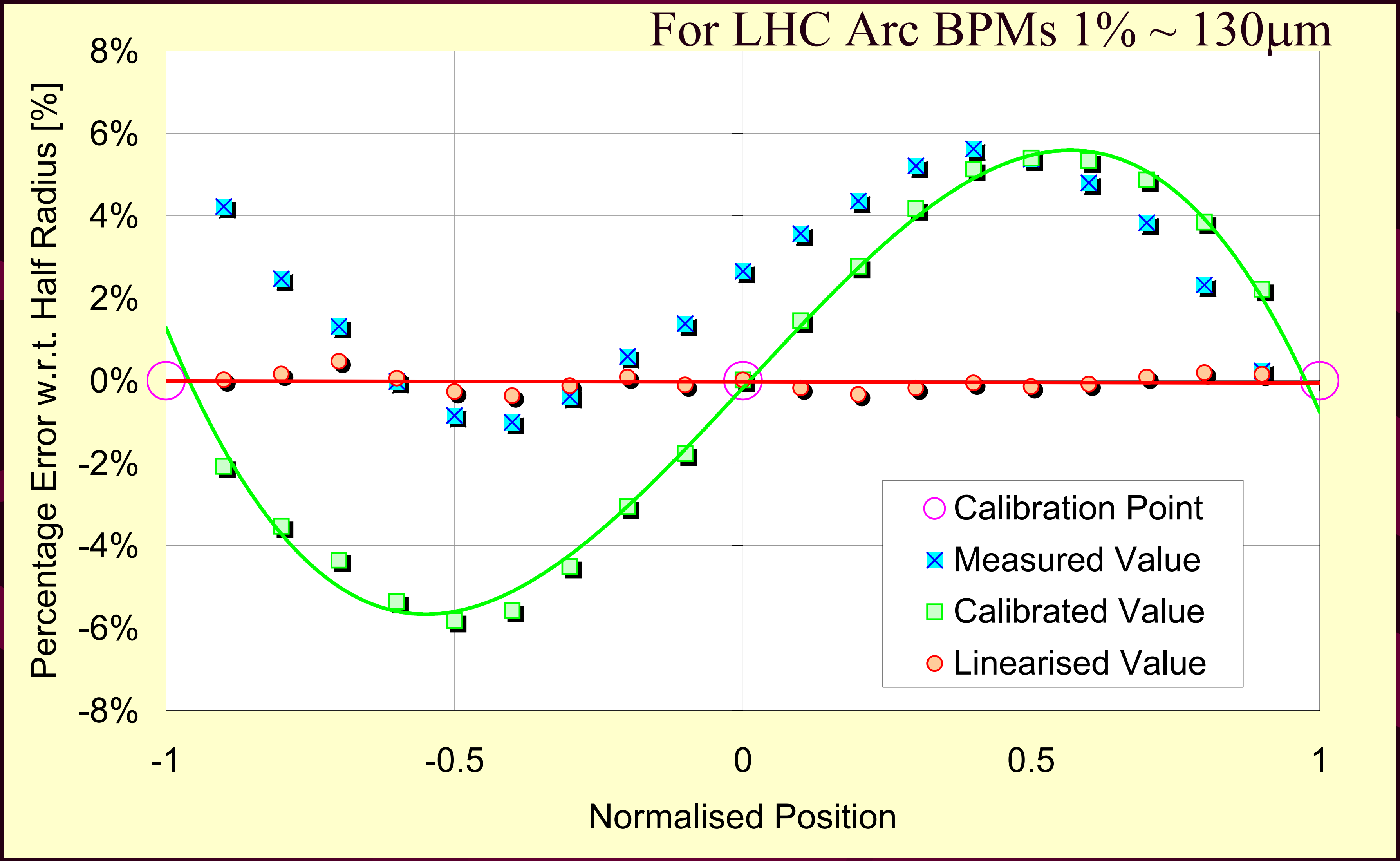


# WBTN - Linearity v Intensity

For LHC Arc BPMs 1% ~ 130μm



# WBTN - Linearity v Position



# WBTN - Radiation Issues

- The Front-end Electronics for the Arc BPMs will be located under the main quadrupoles
  - → can expect to see a dose of some 12Gy/year

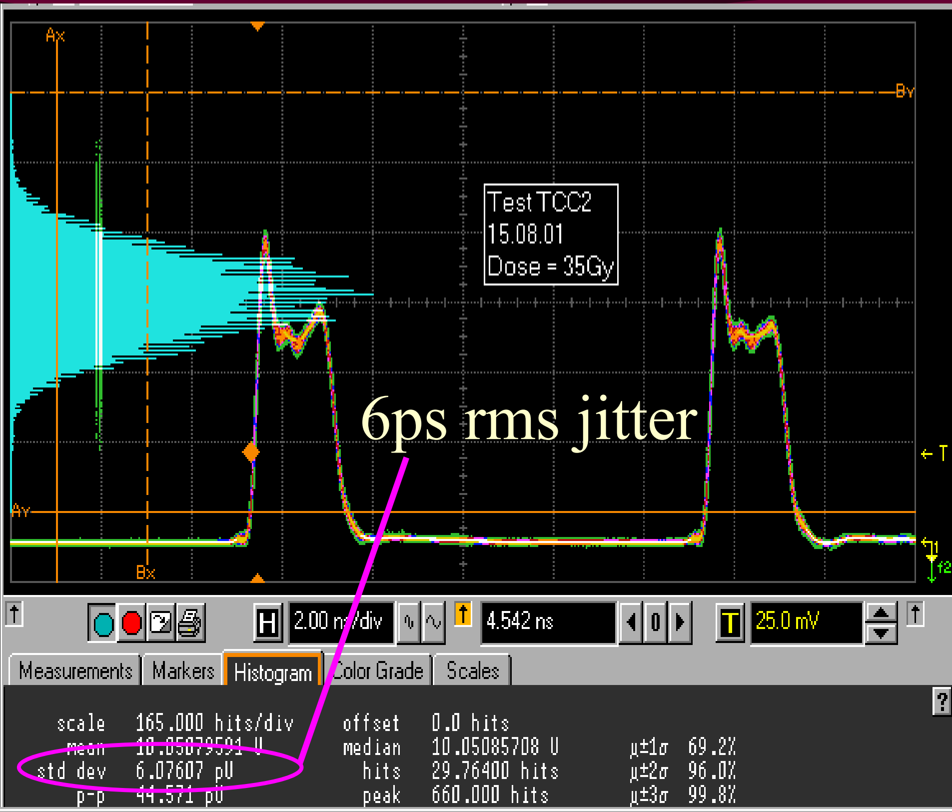
- Tests in the SPS-TCC2 area during 2000 showed that use of DIGITAL components in the tunnel should be avoided
  - → Most memories and FPGA's too easily corrupted
  - → Qualification of components long & difficult

# WBTN - Radiation Issues

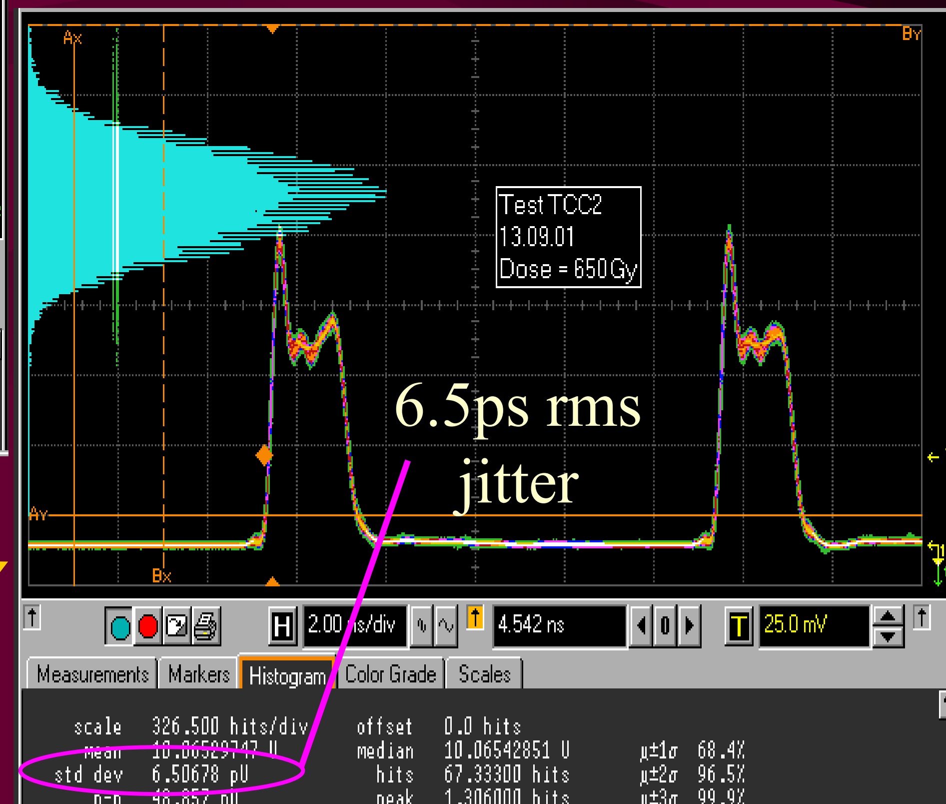
- In 2001 : Fibre-Optic Link added to LHC BPM system
  - → only the minimum of analogue electronics kept in tunnel
  - → all sensitive digital electronics located on the surface
  - → allows easy access to most of the acquisition system
- Cost of large scale fibre-optic installation compensated by
  - → elimination of 13km of expensive low loss coaxial cable
  - → reduction in number of acquisition crates
  - → no bunch synchronous timing required in the tunnel

# WBTN - Radiation Test Results

2001 Test results of the very front-end WBTN card with Fibre-Optic Link

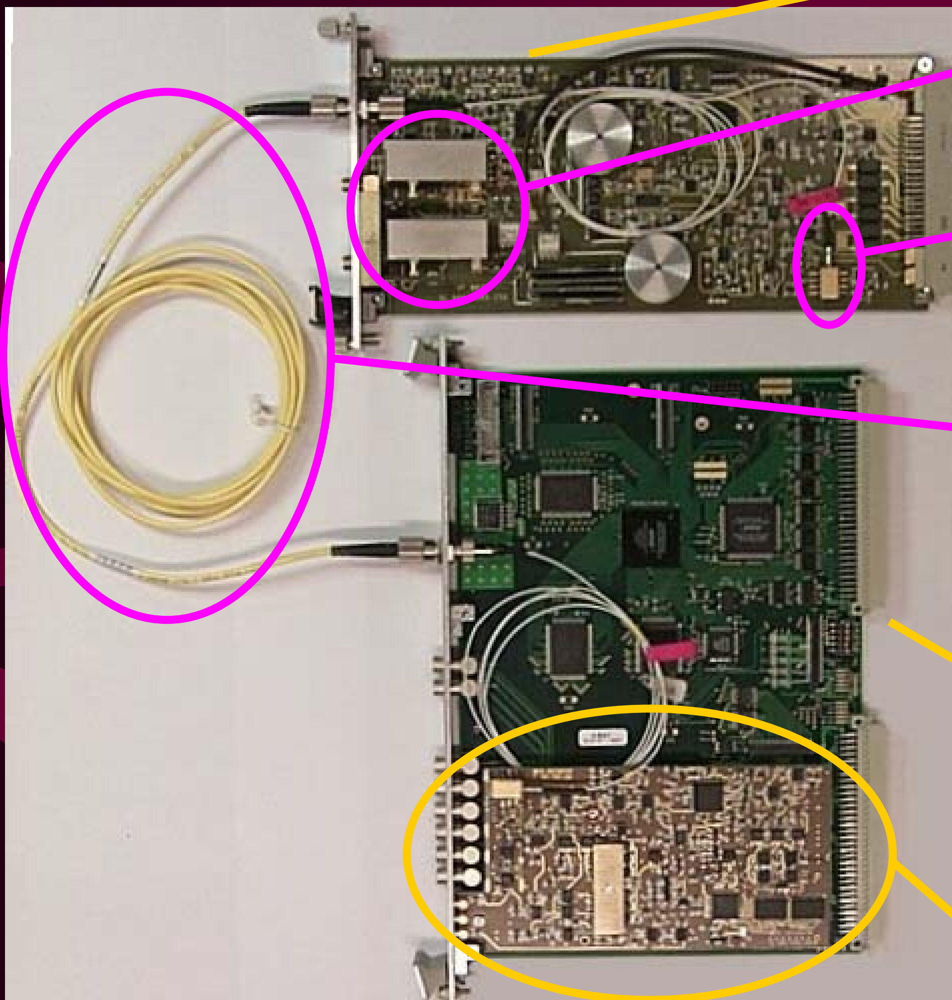



Initial performance




After 650Gy no significant deterioration in the performance is visible

# 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

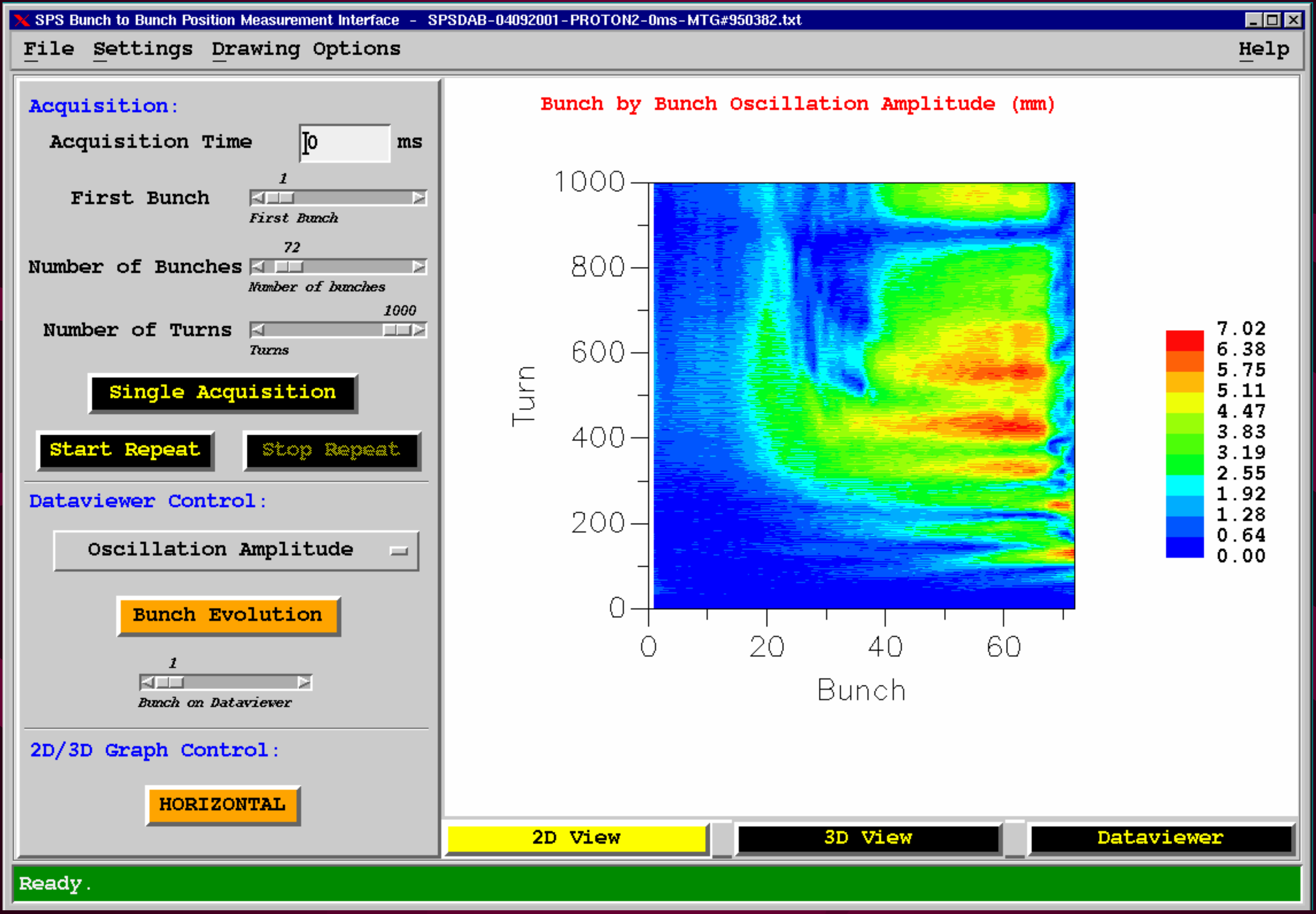
Surface

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

WBTN Mezzanine Card
(10bit digitisation at 40MHz)

# Operational Prototype Results in 2001

System extensively used in SPS for electron cloud & instability studies.



# The Typical Instruments

- Beam Position
  - → electrostatic or electromagnetic pick-ups and related electronics
- Beam Loss
  - → ionisation chambers or pin diodes
- Beam Intensity
  - → beam current transformers
- Beam Size (transverse)
  - → in diagnostics section of tomorrow
- Beam Size (longitudinal)
  - → RF pick-ups or synchrotron light
- Luminosity
  - → ionisation chambers or semiconductors
- Machine Tunes and Chromacitities
  - → in diagnostics section of tomorrow

# The LHC Beam Loss System

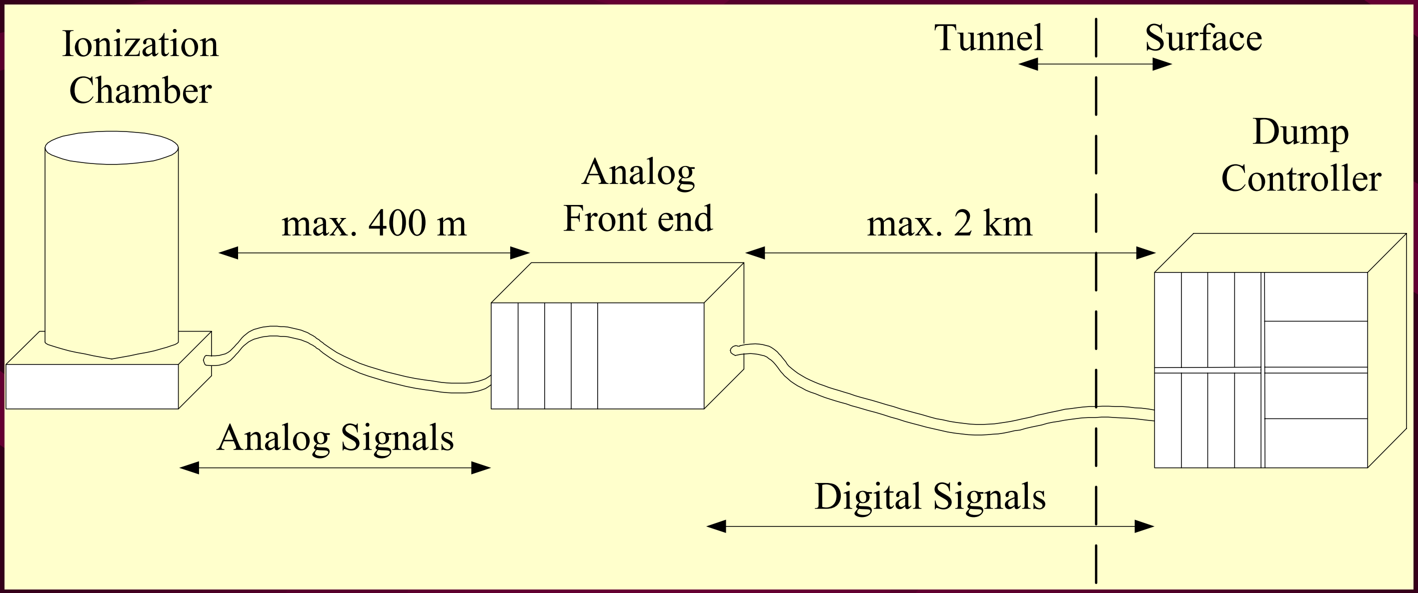
Role of the BLM system:

1. Protect the LHC from damage
2. Dump the beam to avoid magnet quenches
3. Diagnostic tool to improve the performance of the LHC

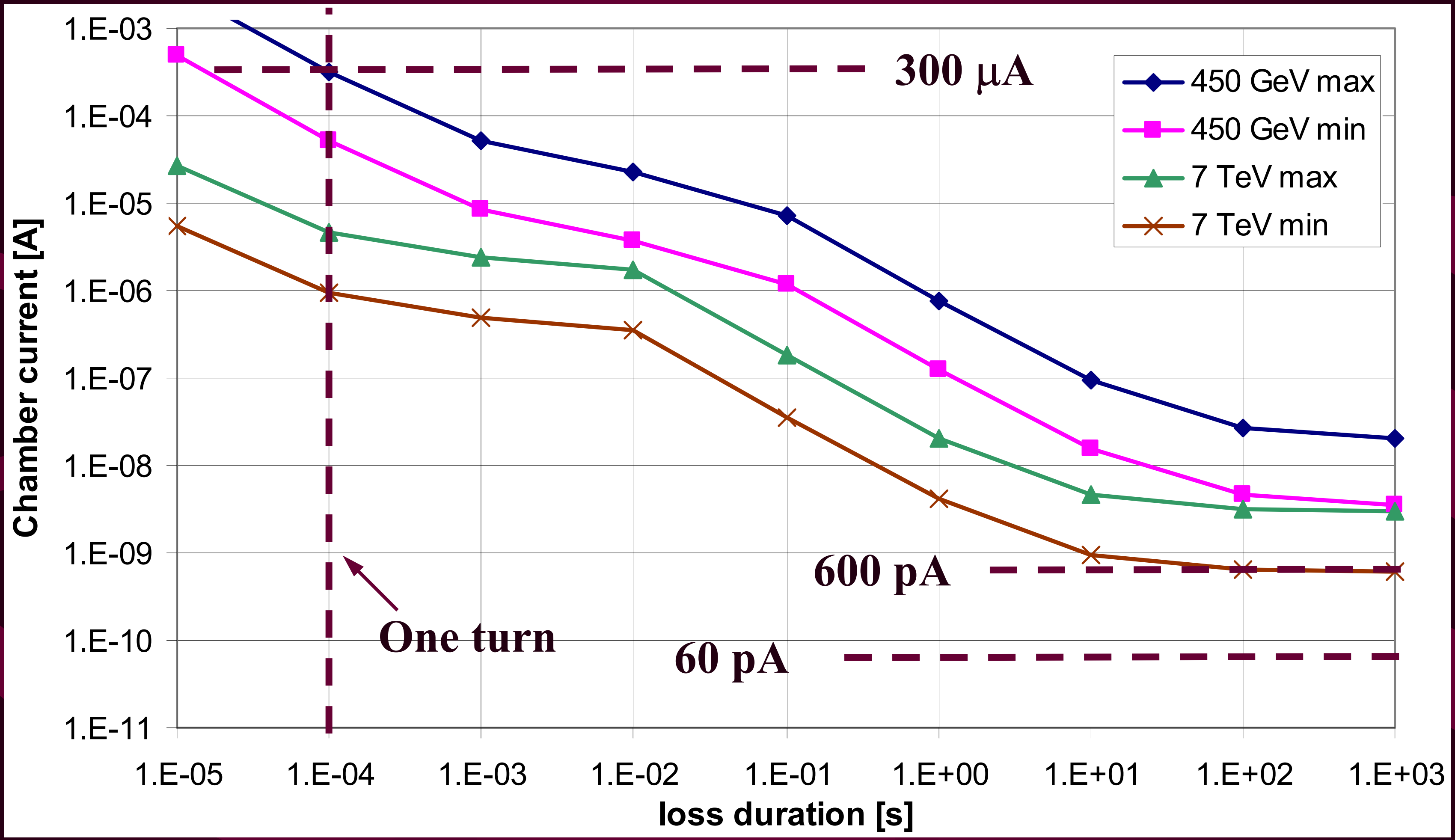
- Acquisition requirements:
  - → Calculation of quench level equivalent chamber signal
    - – Electric currents from 600 pA to 300 μA
  - → A dump should be requested at 50% of the quench level
    - – i.e. from 300 pA to 150 μA
  - → Extend dynamic range for sufficient sensitivity at low losses
    - – Measuring current from 60 pA to 300 μA
  - → Arc BLM acquisition rate not faster than one turn (89 μs)
    - – Fastest total loss is ~ 6 turns & will be detected by special BLMs.

# Structure of the BLM Readout Chain

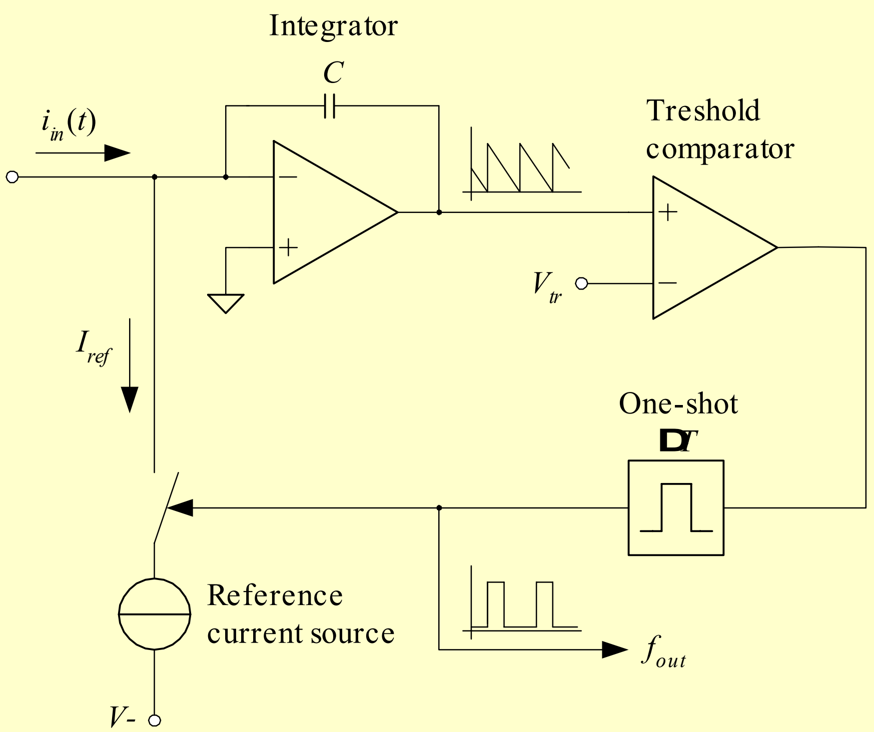
- Ionisation Chamber
  - → transforms particle losses into an electric current
  - → 6 per quadrupole (3 for each LHC ring) ⇒ ~3000 monitors
- Analogue Front-End
  - → measures current and transmits data from Tunnel ⇒ Surface
- Dump Controller
  - → processes data and interfaces to the beam interlock system

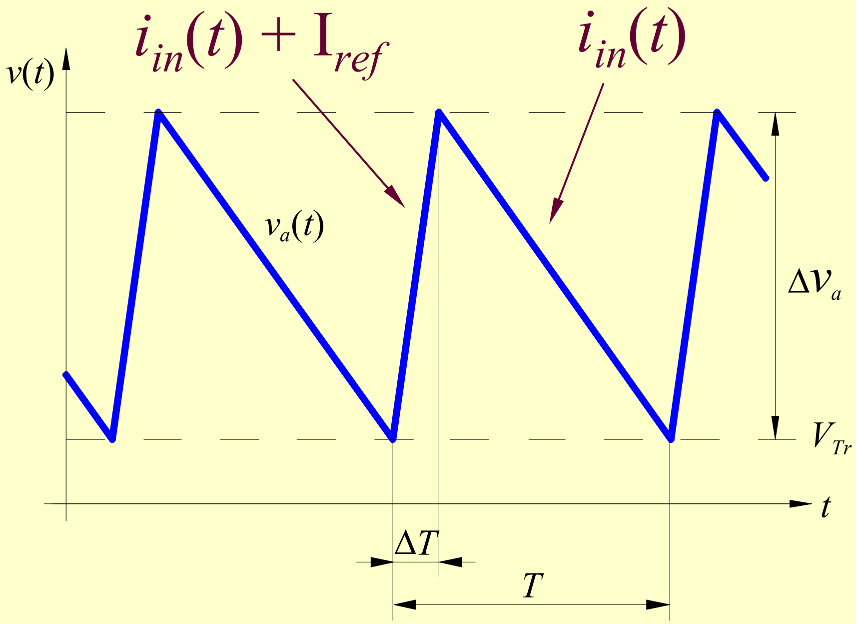


# Quench Level Equivalent Chamber Current



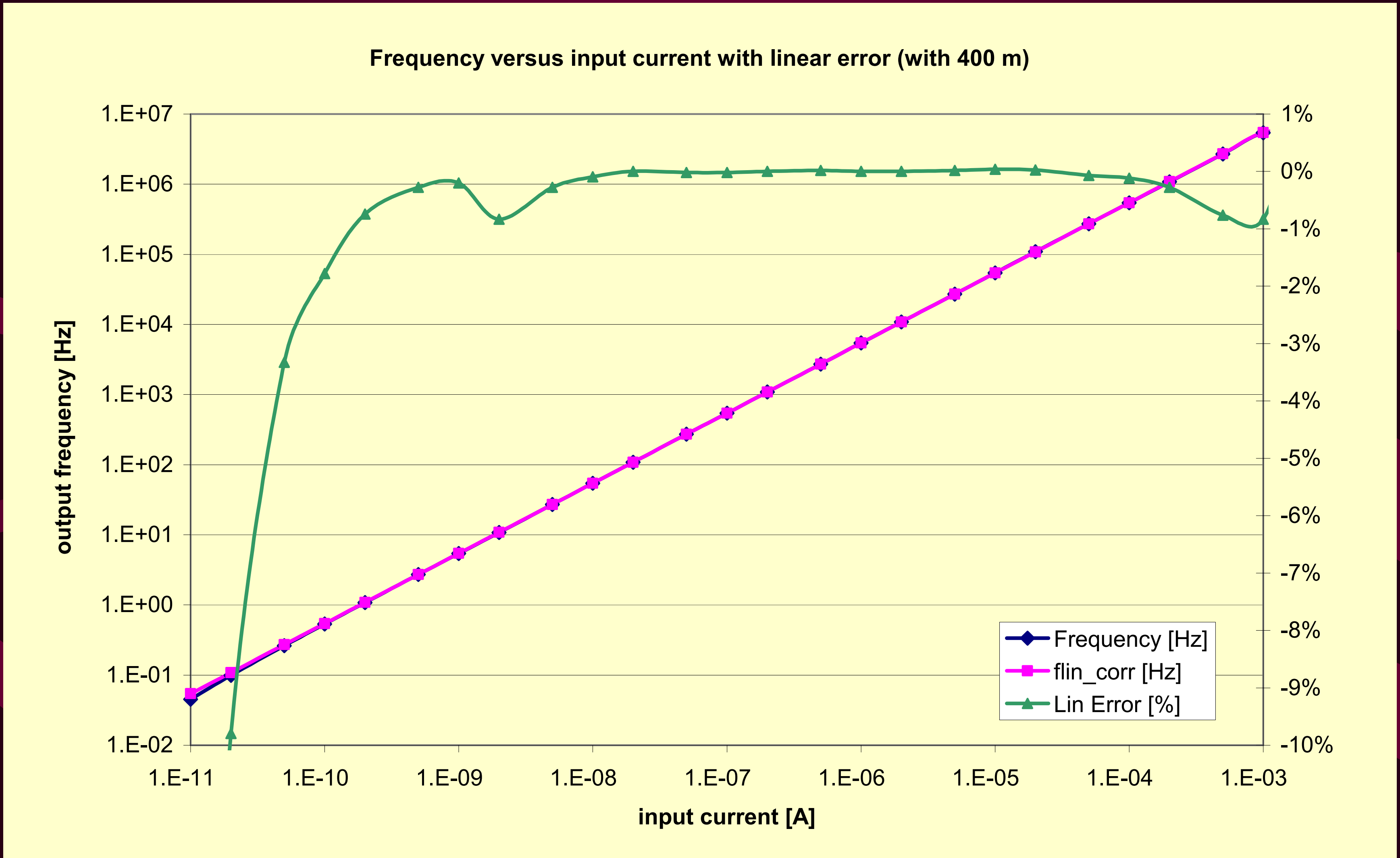
# Charge-Balanced Converter




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

# Current-Frequency Characteristics



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  → RF pick-ups or synchrotron light
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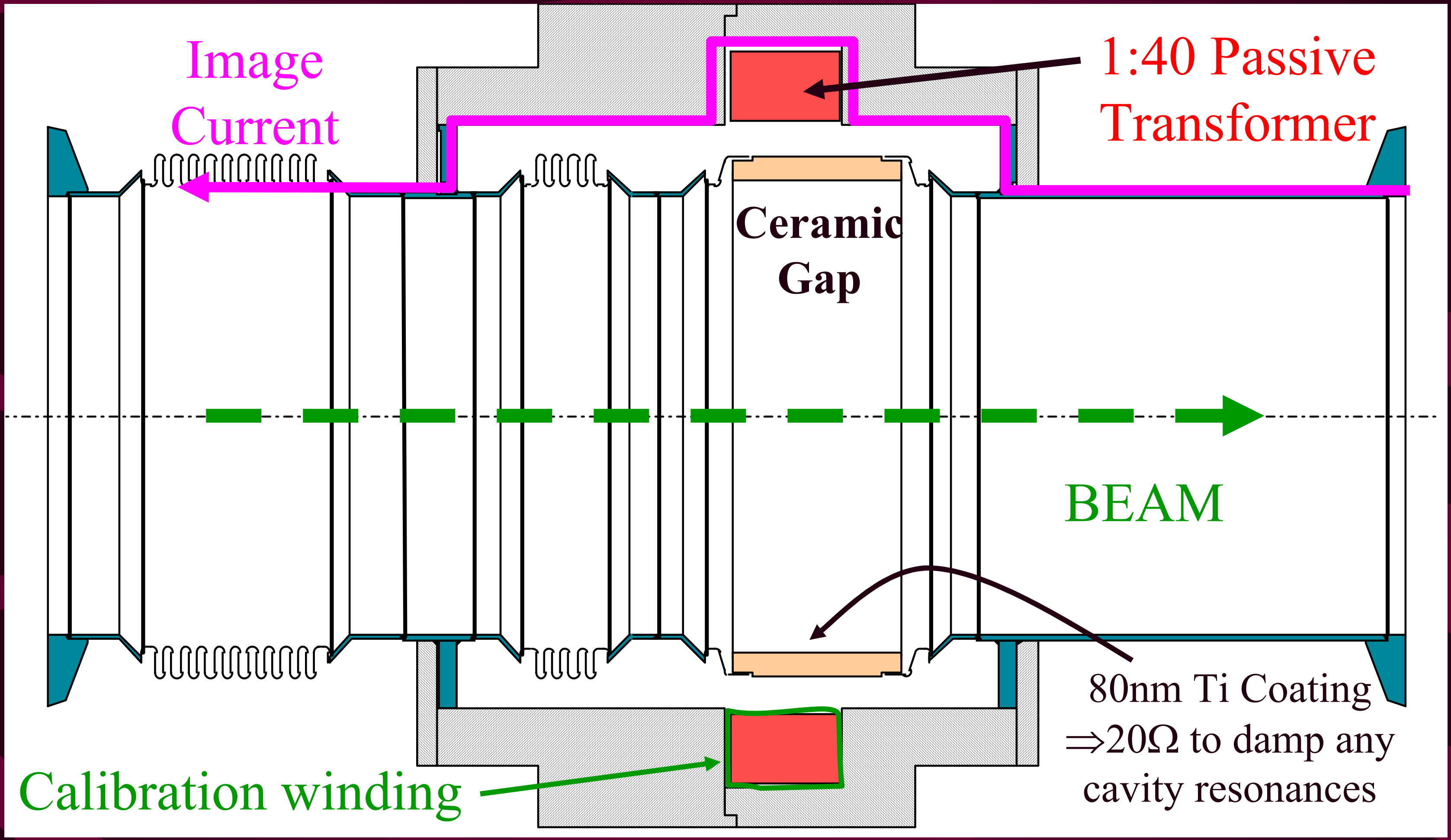
  → in diagnostics section of tomorrow

# Fast Beam Current Transformer


- Installed in the SPS and LHC transfer lines
- LHC fast BCT will be a scaled version
- Capable of 40MHz bunch by bunch measurement
- Dynamic range to cover $5\times10^{9}$ to $1.7 \times 10^{11}$ cpb

# Fast Beam Current Transformer



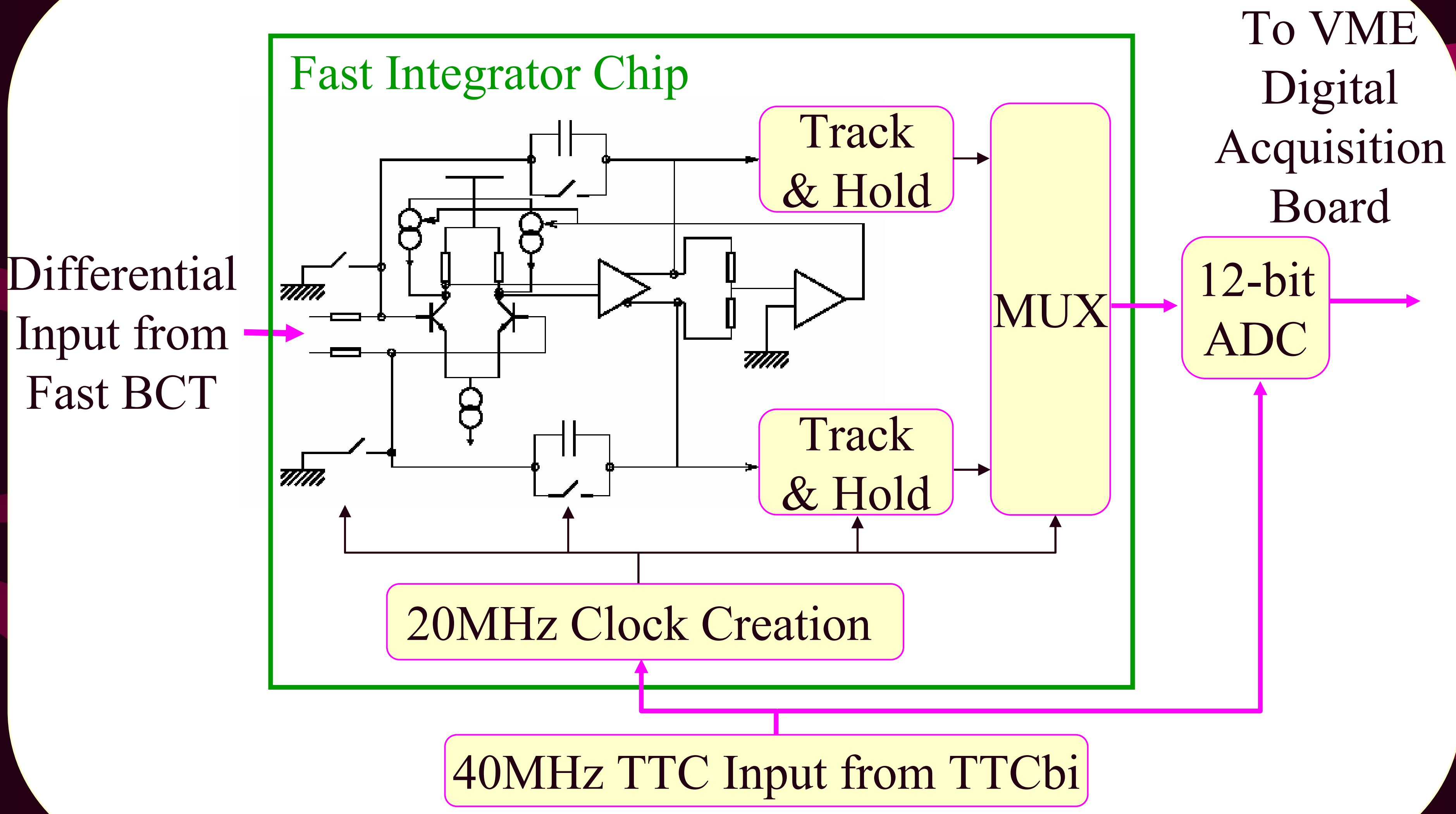

- 500MHz Bandwidth
- Low droop (< 0.2%/μs)

# Acquisition Electronics

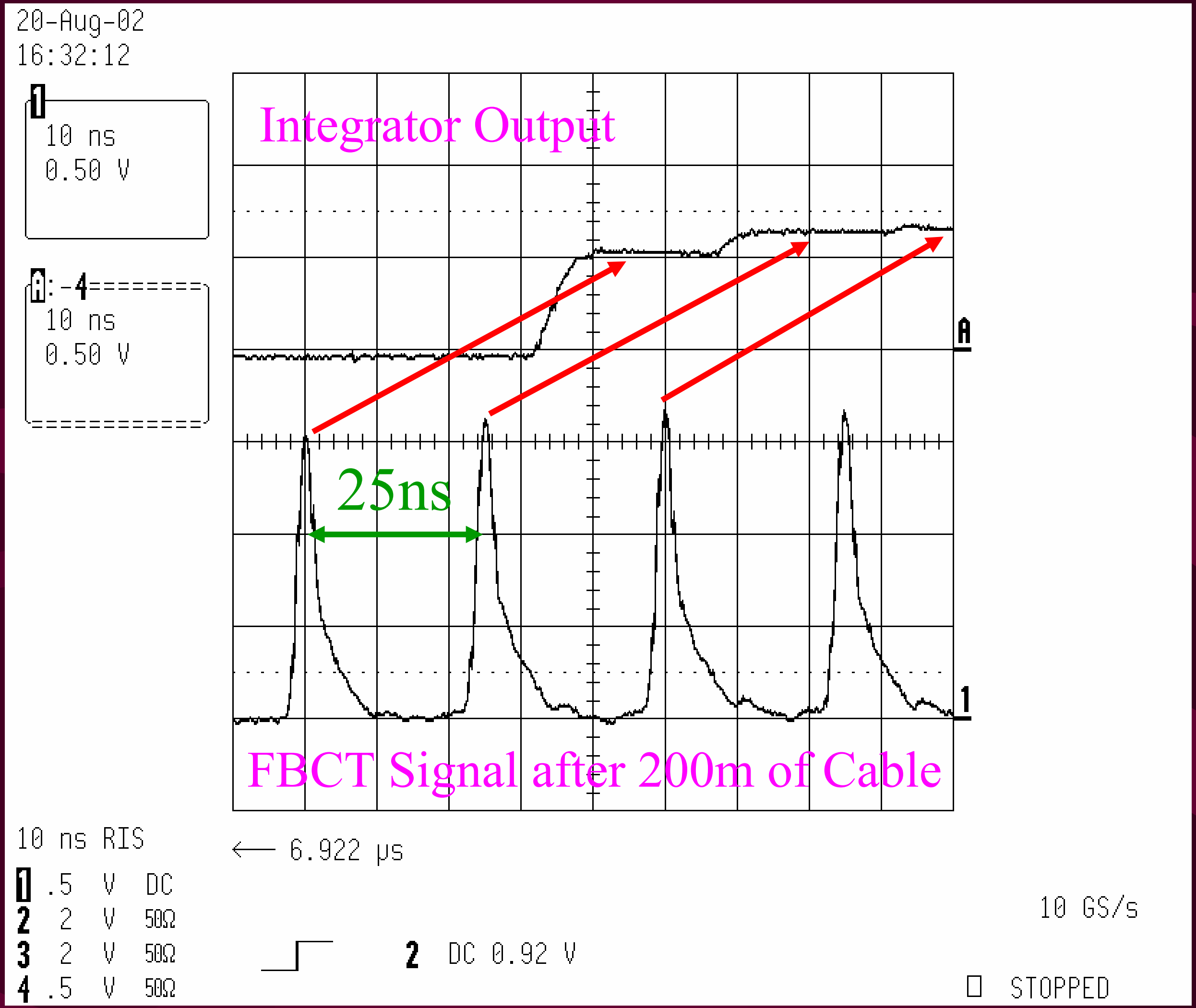
- Analogue Acquisition based on a fast integrator chip
  - → Designed by the Laboratoire de Physique Corpusculaire, Clermont-Ferrand for use in the LHCb Preshower Detector.
  - → Uses interleaved, 20MHz integrators and sample & hold circuitry to give 40MHz data.
- Digital Acquisition
  - → PMC size Mezzanine card developed by CERN & contains
    - Fast integrator chip
    - 12bit, 40MHz ADC
    - Timing provided by the TTCbi module, part of the Timing, Trigger & Control system developed for the LHC experiments

    Mezzanine sits on the same VME 40MHz Data Acquisition Board developed for the LHC Beam Position System (TRIUMF, Canada)

# Acquisition Electronics

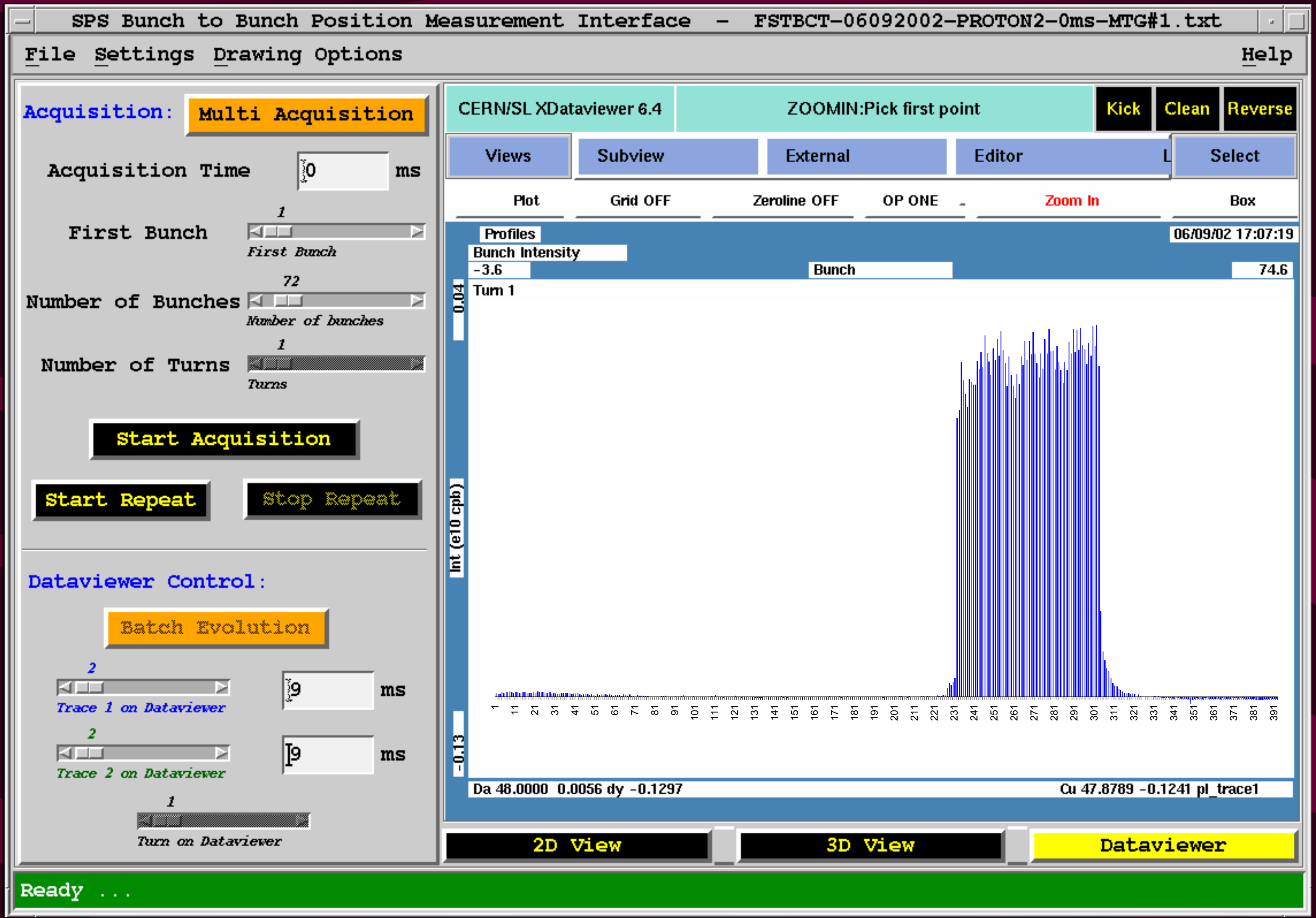


# Acquisition Electronics




Data taken on LHC type beams at the CERN-SPS (2002)

# Results from the CERN-SPS (2002)




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

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  → in diagnostics section of tomorrow

# Luminosity & Beam-Beam Tune Shift

- Luminosity
- Normalized emittance
- Beam-beam tune shift

$$L = f_{rev} \frac{MN^2}{4\pi\sigma_*^2}$$

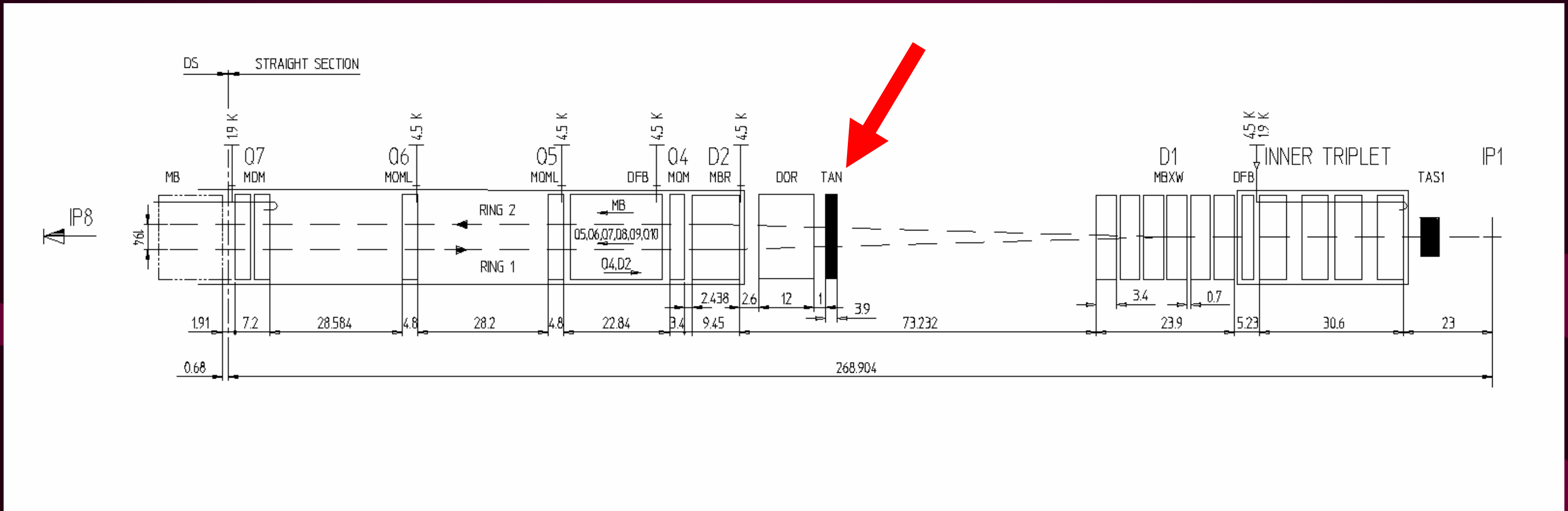
$$\varepsilon_N = \gamma \frac{\sigma_*^2}{\beta_*}$$

$$\Delta\nu_{bb} = \frac{Nr_p}{4\pi\varepsilon_N} \leq 0.006 \text{ (LHC)}$$

$$\therefore \qquad L = f_{rev} \frac{MN\gamma\Delta\nu_{bb}}{\beta_*}$$

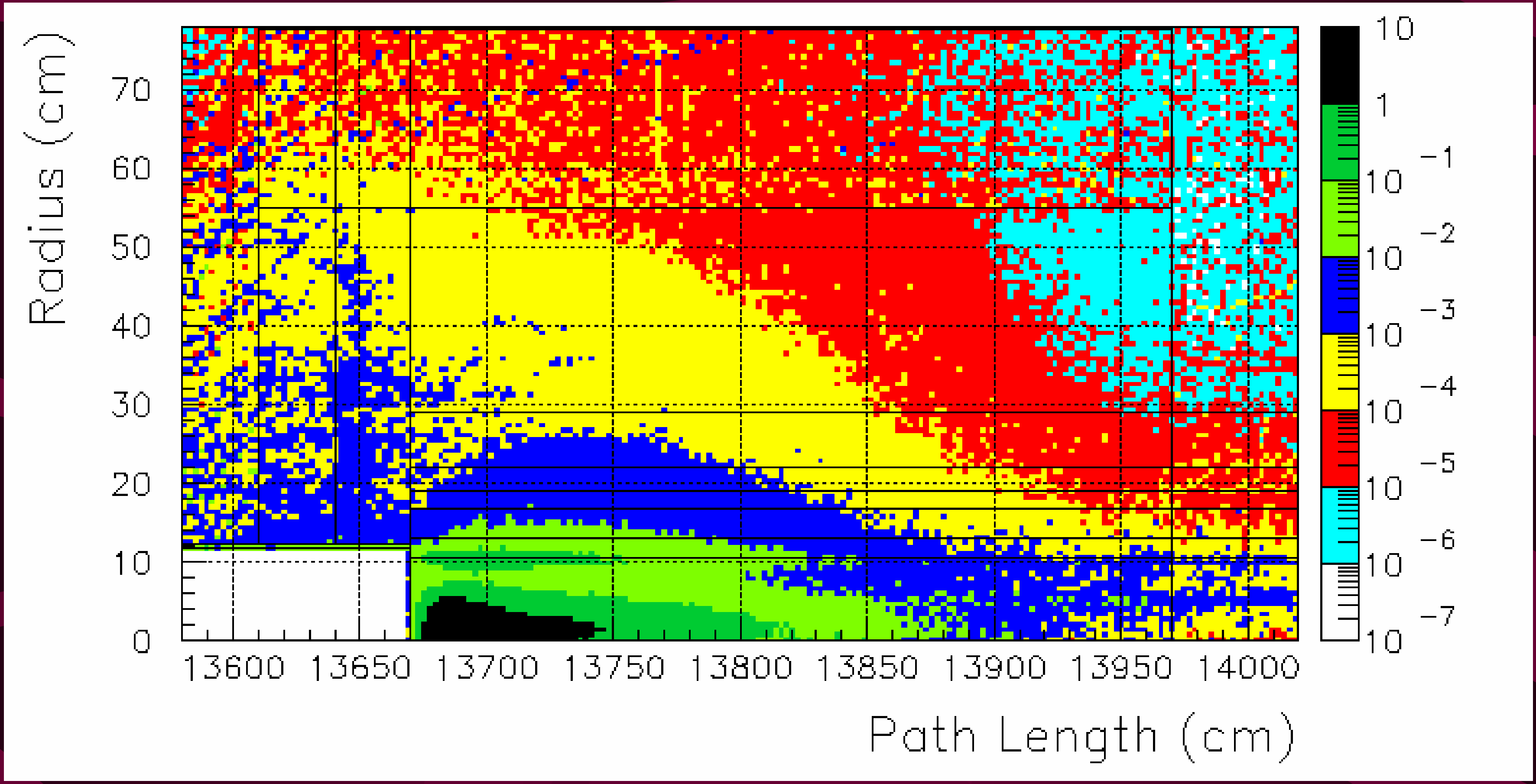
- To maximize L and minimize the stored energy, increase N to the tune shift limit, choose large M and small $\beta_*$

# Nominal locations of the front quadrupole (TAS) and neutral (TAN) absorbers




- The TAS absorbs forward collision products that have escaped the beam tube in front of Q1 (mostly charged pions and photons)
- The TAN absorbs forward neutral collision products (mostly neutrons and photons) and is placed in front of the outer beam separation dipole D2

# TAN Power Deposition (W/kgm)




- Peak power density of 1-10 $W.kg^{-1}.m^{-1}$ (location of ionization chamber)
- A 3m radiation hard cable will allow electronics to be located in a region with power density < $10^{-5}$ $W.kg^{-1}.m^{-1}$ (100 Gy/year for nominal operation)

# LHC Luminosity Measurement

## Requirements:

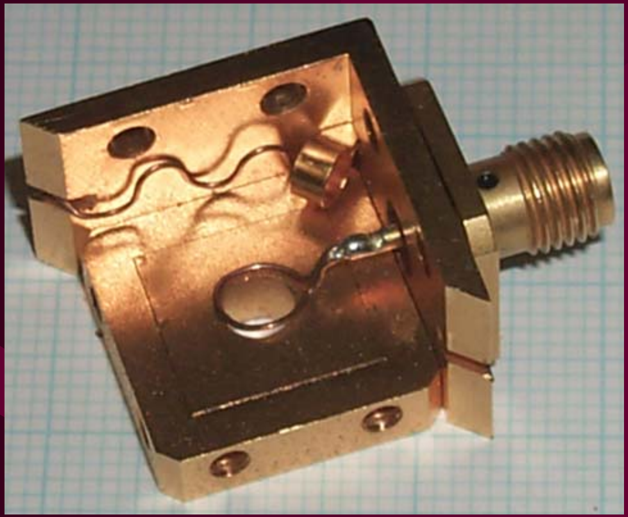
- Capable of 40MHz acquisition
- Has to withstand high radiation dose: ~$10^8$ Gy/year
  - → estimated $10^{18}$ Neutrons/cm$^2$ over its lifetime (20yrs LHC operation)
  - → estimated $10^{16}$ Protons/cm$^2$ over its lifetime (20yrs LHC operation)
- No maintenance

## Candidates:

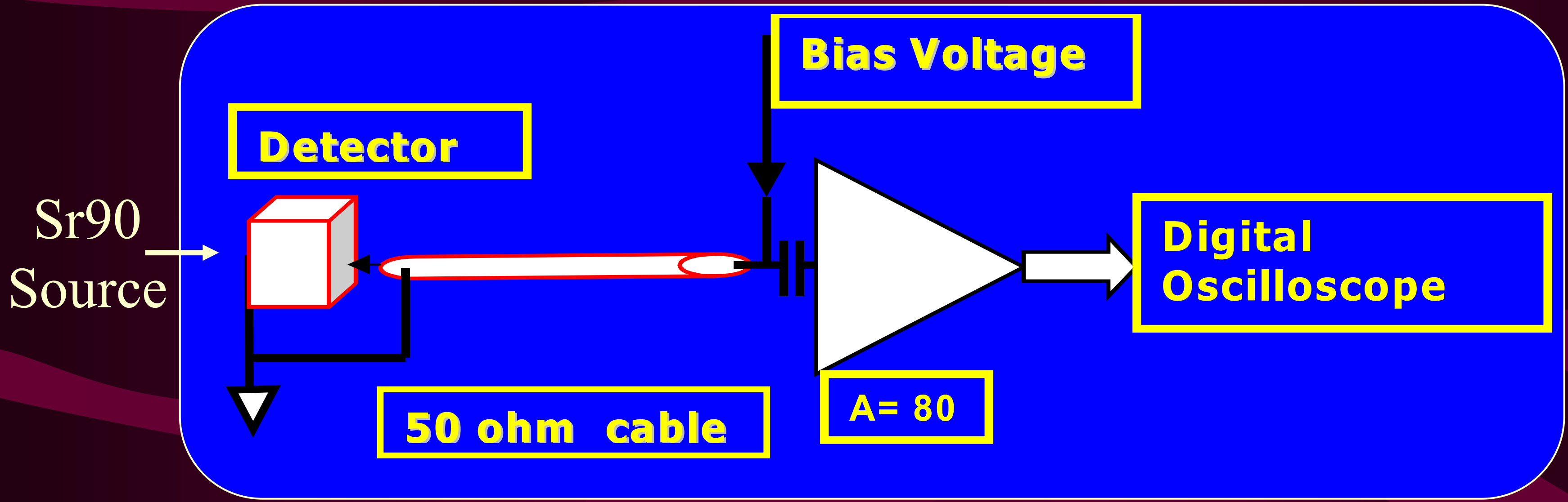
- Ionisation Chambers
  - → developed by LBL
    - Good radiation hardness
    - Difficult to get working at 40MHz
- CdTe detectors
  - → developed by CERN in collaboration with LETI (Grenoble)
    - Fulfills 40MHz requirement
    - Not yet proven for the highest levels of radiation

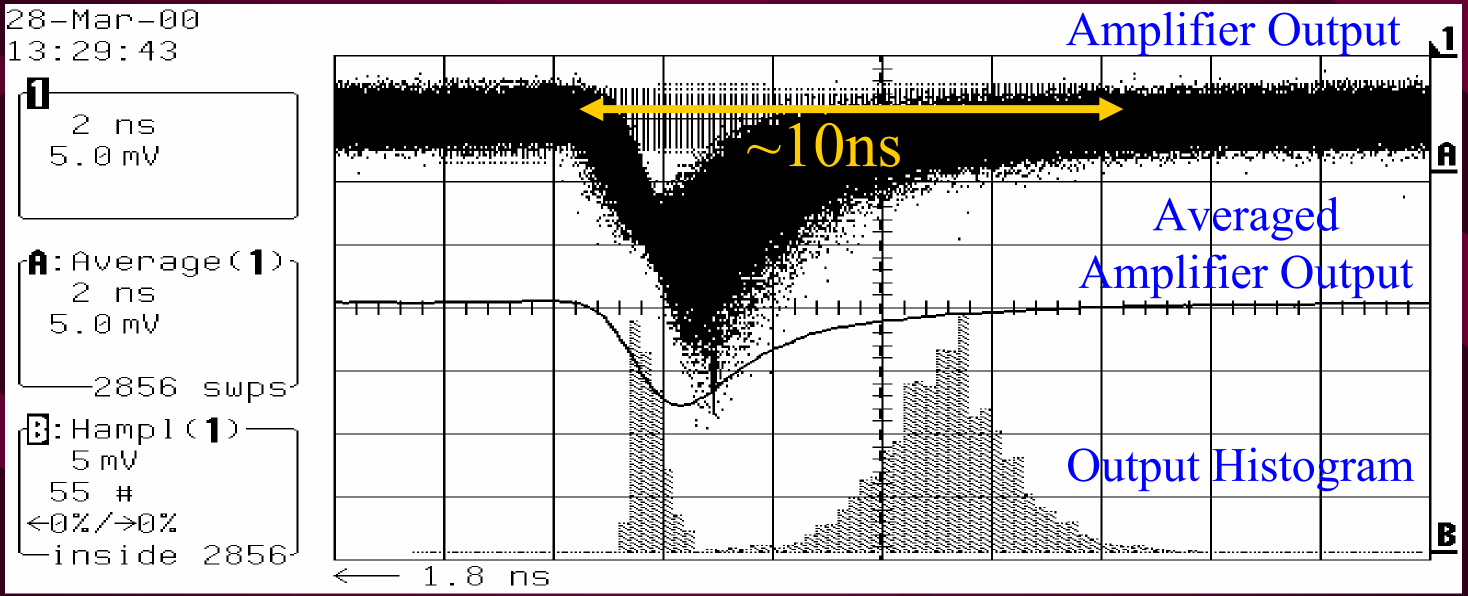
# Polycrystalline CdTe Detectors

- Experience at CERN with CdTe X-RAY detector
  - → running in LEP for beam emittance measurement
  - → was used up to the end with total dose $10^{14}$ Gray
- Advantages
  - → large number of e- created per MIP (~5 × Diamond)
  - → very fast response time
  - → simple construction

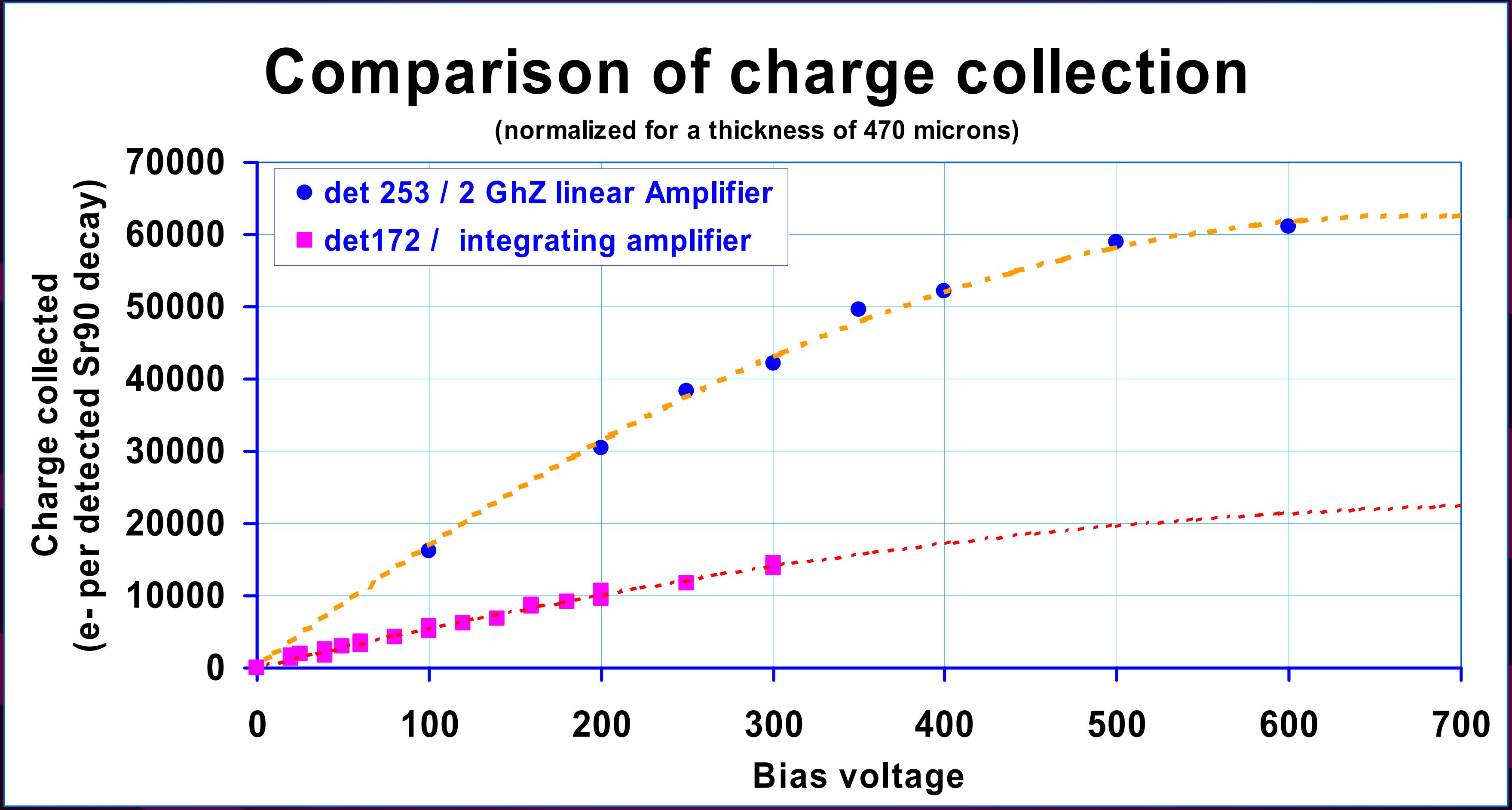


# CdTe Detectors – Test Set-up



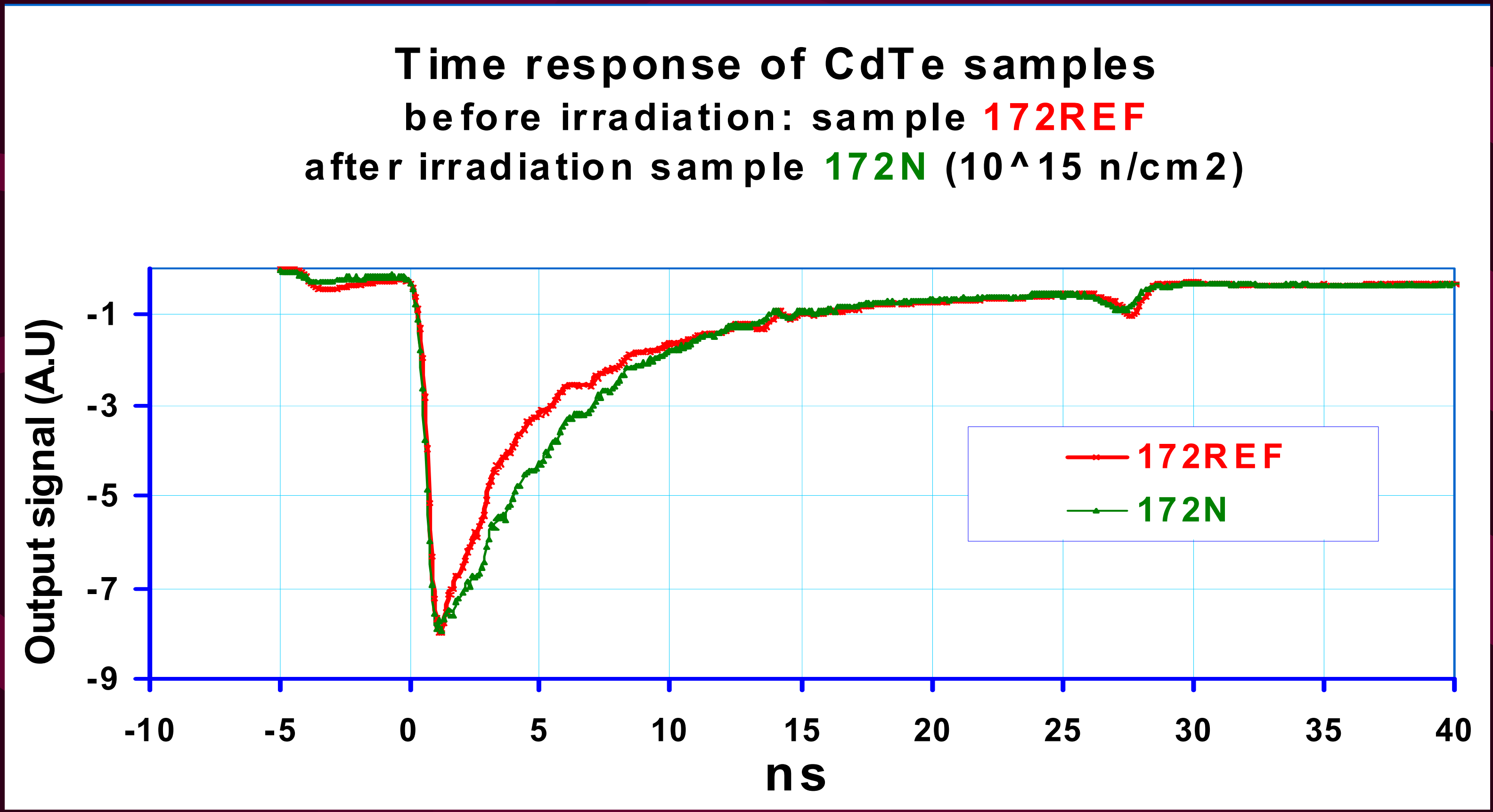



# Polycrystalline CdTe Detectors



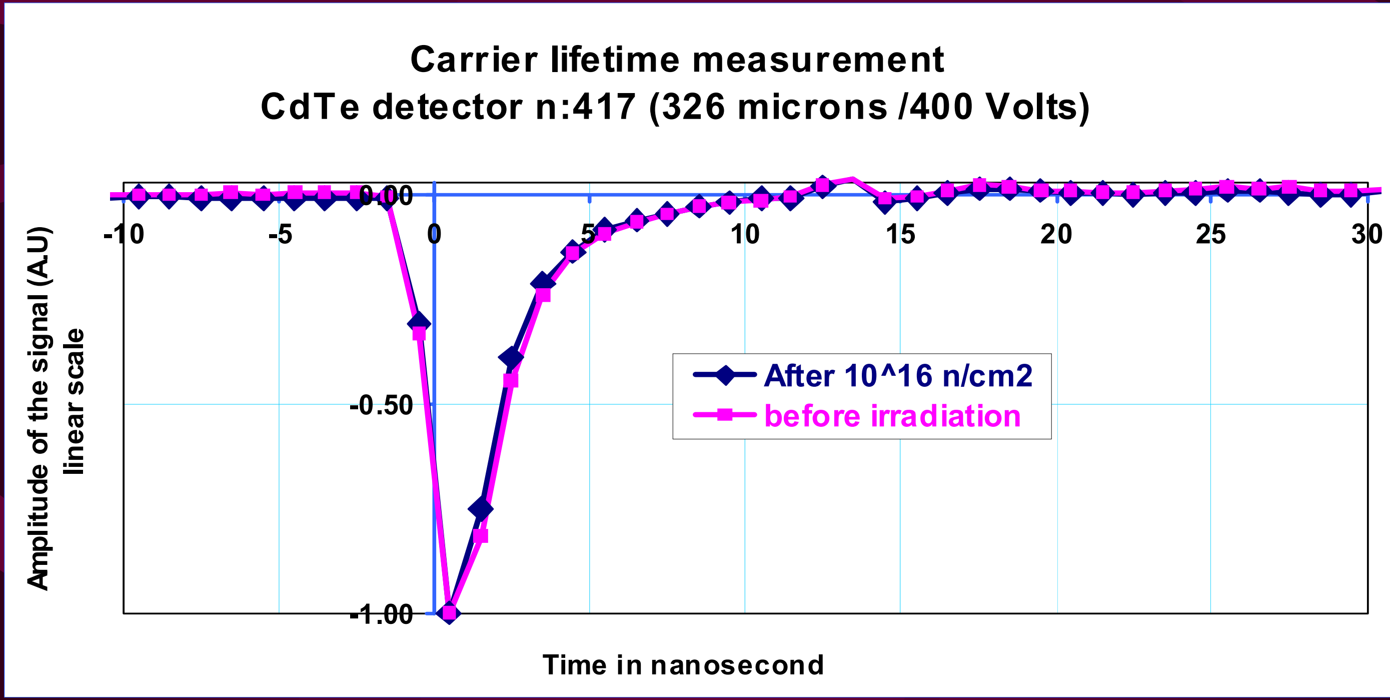
# Irradiation Test Results

- CERN-SPS (2001)
  - → Irradiation test up to $10^{15}$ neutrons/cm$^2$



# Irradiation Test Results

- Triga type reactor (Ljubljana,Slovenia - 2002)
  - → Irradiation steps
    - $10^{13}$ neutrons/cm$^2$
    - $10^{15}$ neutrons/cm$^2$
    - $10^{16}$ neutrons/cm$^2$ activation of all set-up
      - – next step $10^{18}$ neutrons/cm$^2$ (2003)



We have seen a wide variety of technologies and applications

Tomorrow we will see how to use the instruments to run and optimize accelerators

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Accelerator Diagnostics

http://sl-div.web.cern.ch/sl-div-bi/CAS%20/lecture/