

Beam instrumentation and diagnostics – an overview

(= an introduction to an introduction)

I Polska Szkoła Akceleratorowa
IFJ, Kraków, 19.10.26

Marek Gąsior

Introduction to Beam Instrumentation and Diagnostics Lecture I

Michał Krupa – CERN BI Group
(based on previous lectures by Rhodri Jones)



Advanced CAS 24

Introduction to Beam Instrumentation and Diagnostics I

1

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[Introduction to BI+D, lecture I](#)

Introduction to Beam Instrumentation and Diagnostics Lecture II

Michał Krupa
(based on previous lectures by Rhodri Jones)



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[Introduction to BI+D, lecture II](#)

Intensity measurement

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Beam Instrumentation, 16 - 29
November 2025, Split, Croatia



[BI CAS 2025](#) [Intensity measurement](#)

[BI CAS 2018 Proceedings \(709 pages\)](#)

- Introduction
- Beam intensity measurement
- Beam loss monitoring
- Beam position measurement
- Transverse beam size measurement
- Tune measurement (a diagnostics example)



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

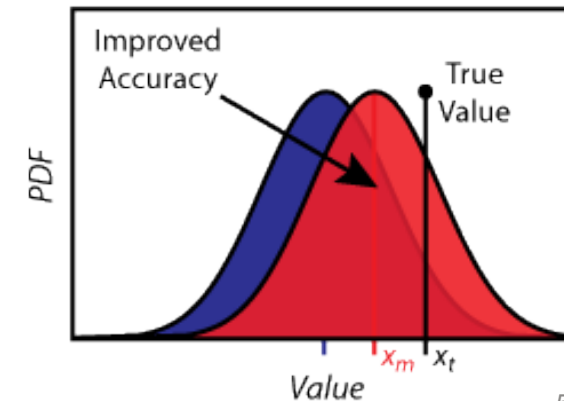
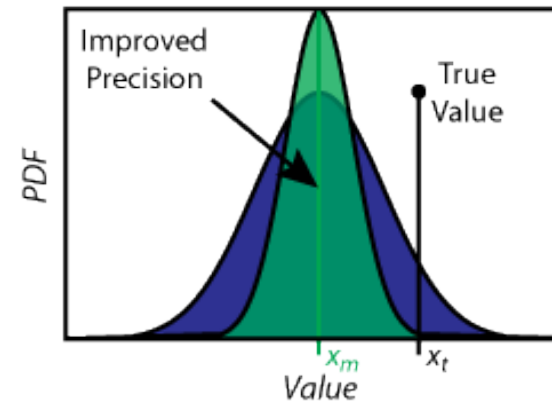
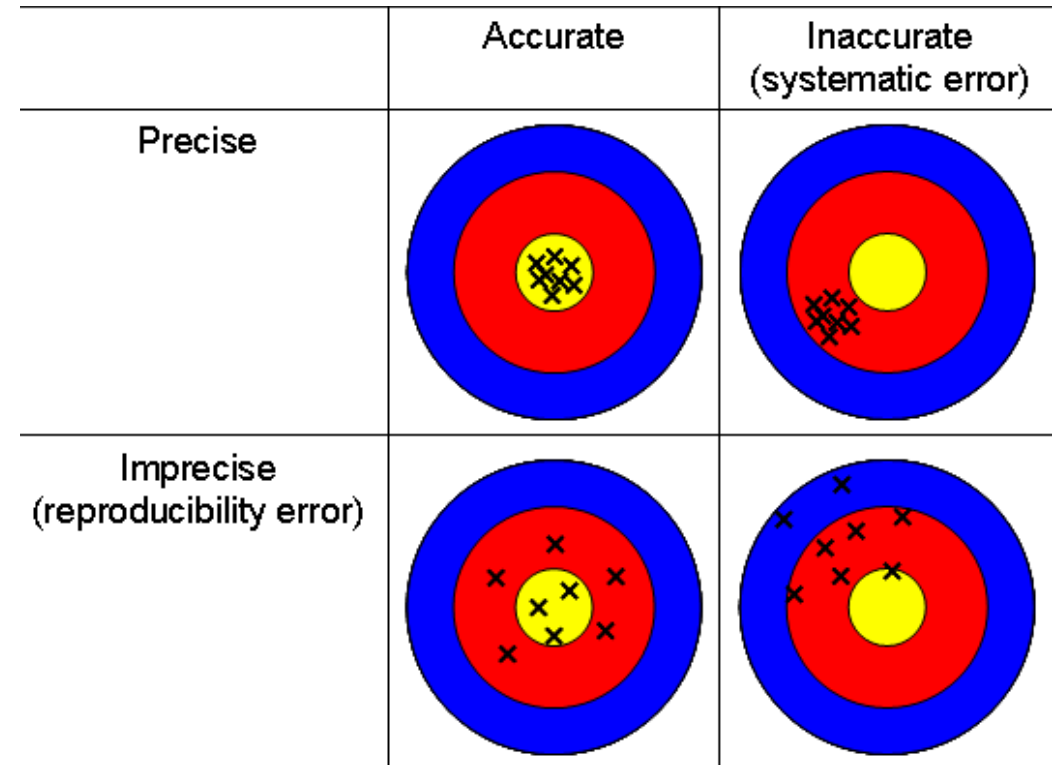
Beam diagnostics

- 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

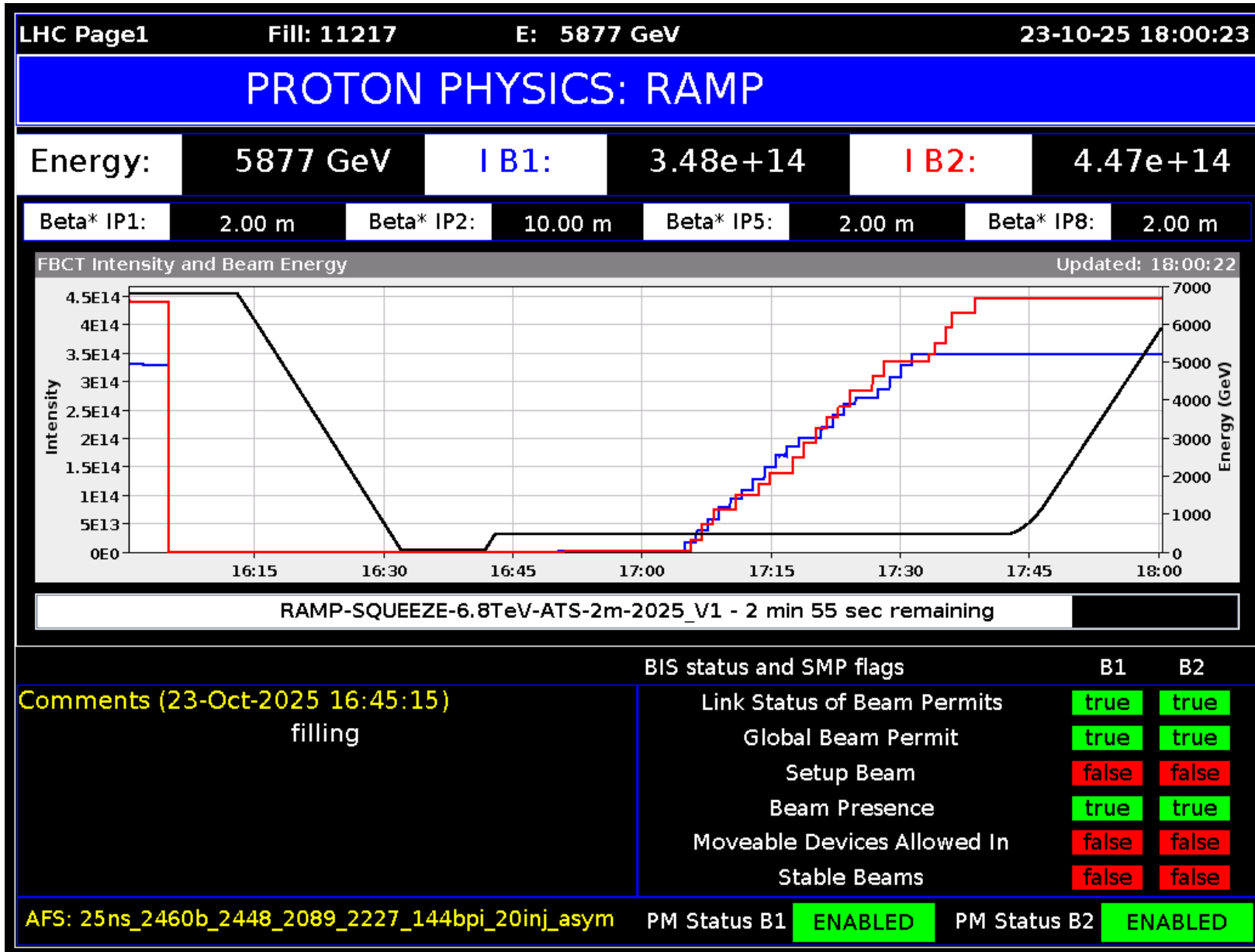
- **Accuracy** – trueness
- **Precision** – reproducibility
- **Resolution** – smallest measurable change
- **Dynamic range** – ratio of the largest and smallest measurable signal
- **Timescale** – multi-turn full beam, turn-by-turn, bunch-by-bunch
- **Availability** – continuous / on-demand



Beam intensity measurement



Intensity measurement



- Intensity is one of the most important beam parameters
- Derived quantity: beam lifetime
- Intensity measurement is essential for:
 - operating an accelerator
 - quantifying an optimizing accelerator performance
 - scaling physics data (accuracy)(performance most important)
- Intensity measurement can be critical for:
 - accelerator protection
 - equipment protection
 - human health (e.g. medical applications)(reliability most important)

Beam current, charge and intensity

N = beam intensity = number of particles

T = integration interval

I_M = maximal (peak) current

σ = RMS bunch length

current

charge

intensity

$$i_B(t) = \frac{dQ_B}{dt} = q_1 \frac{dN}{dt}$$

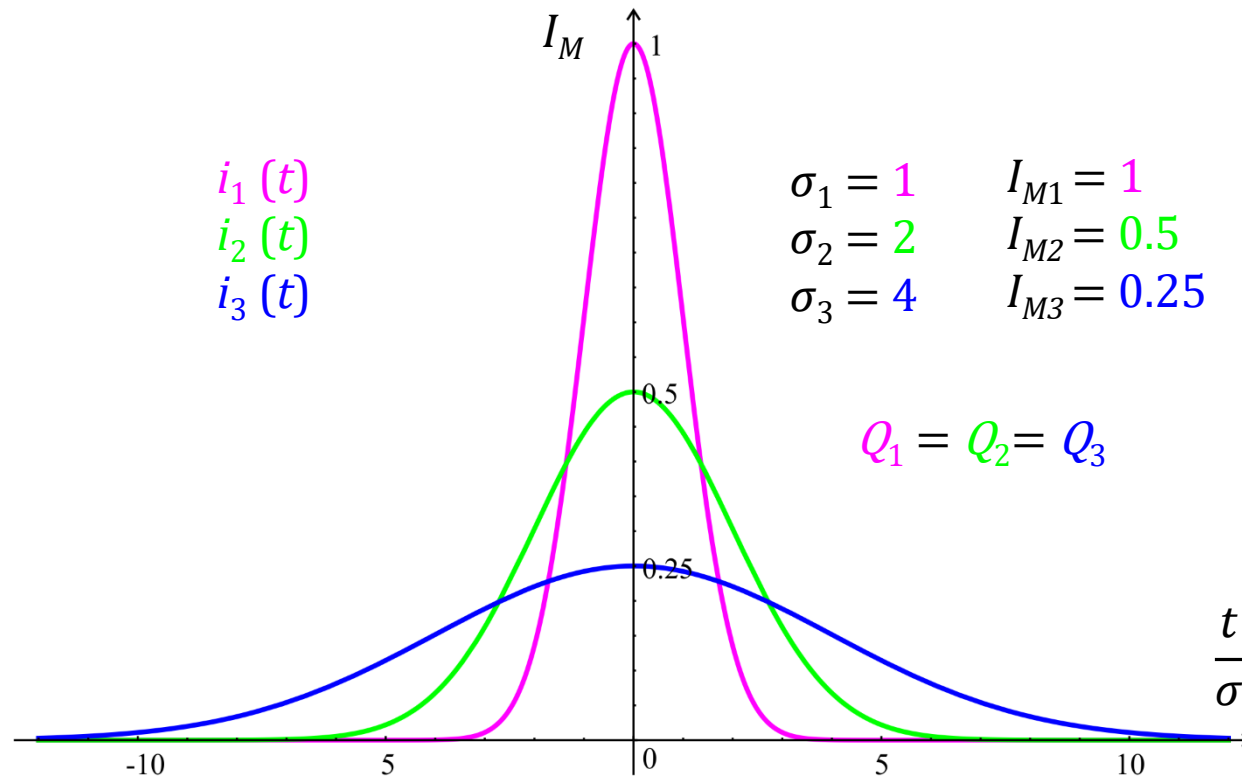
charge of one particle

$$N = \frac{Q_B}{q_1} = \frac{1}{q_1} \int_T i_B(t) dt$$

number of charges q_1 during time interval T

in BI world : often

beam intensity ↔ **beam charge**



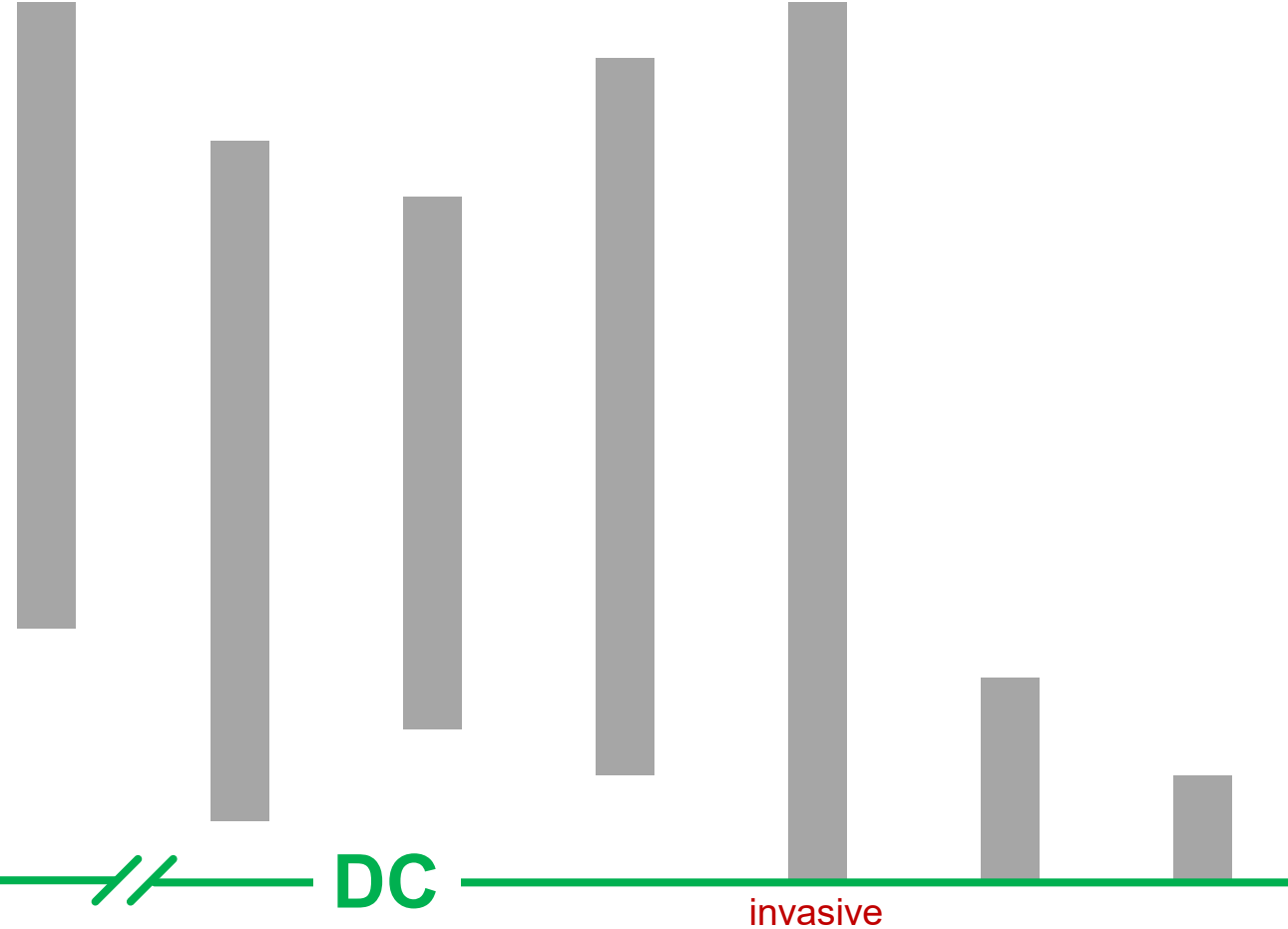
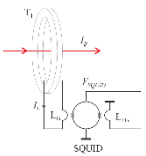
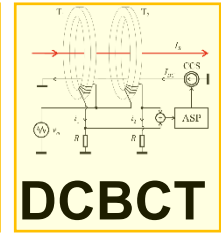
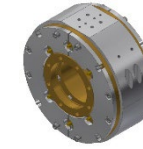
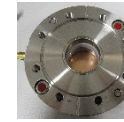
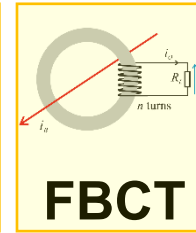
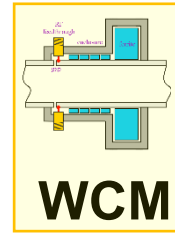
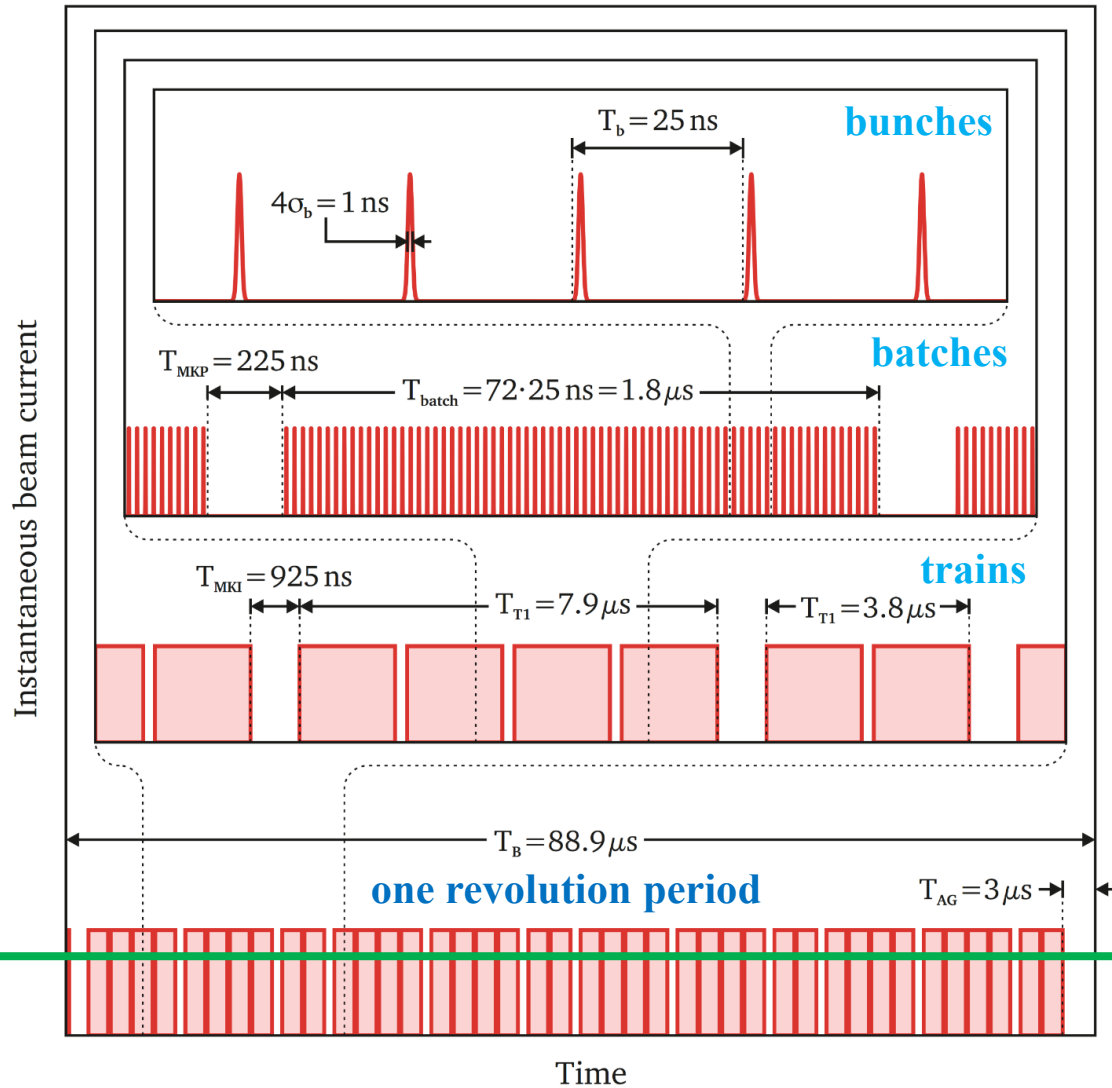
$$i_B(t) = I_M e^{-\frac{t^2}{2\sigma^2}}$$

current distribution in a Gaussian bunch

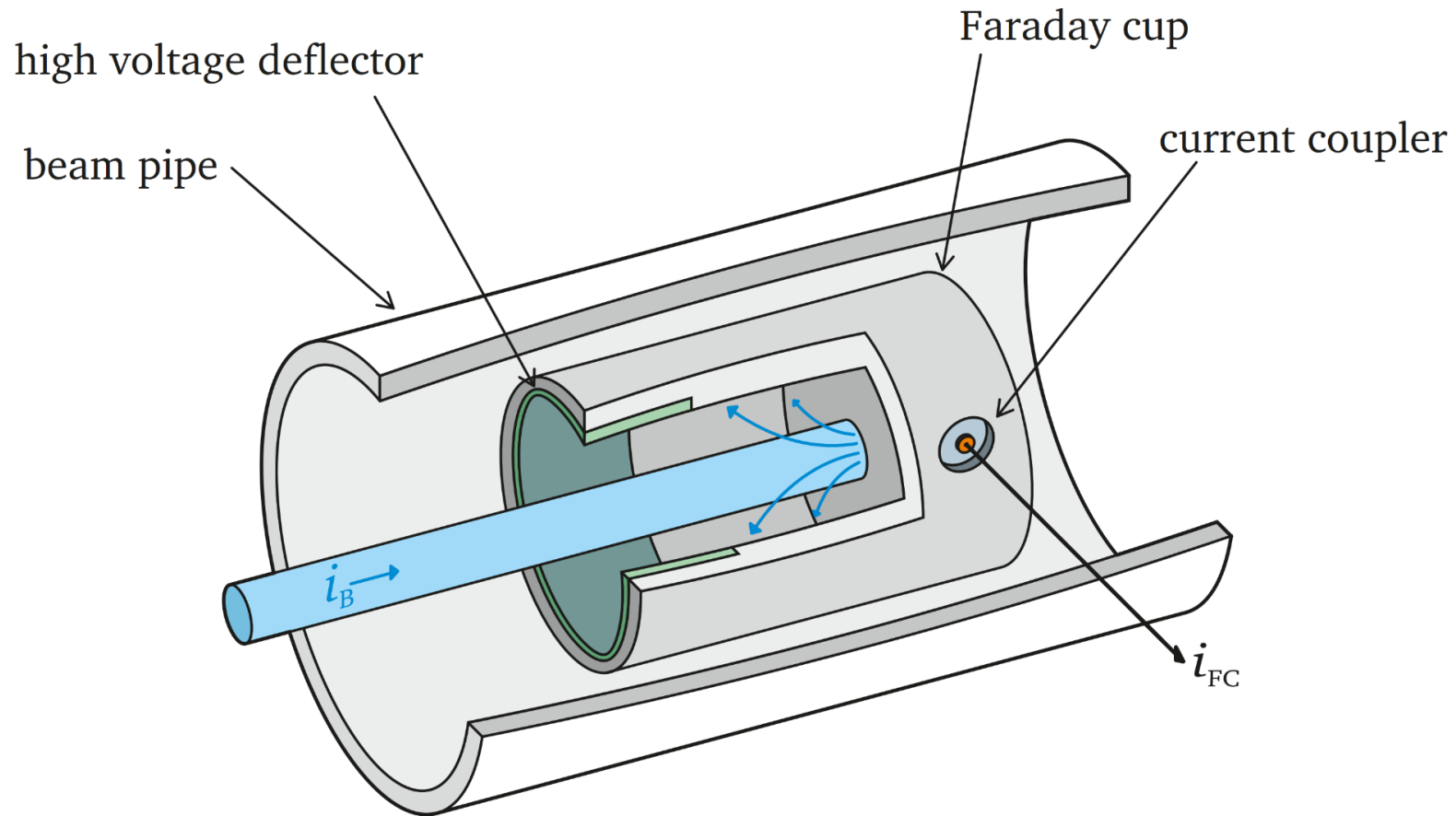
$$Q_B = \sqrt{2\pi} I_M \sigma \cong 2.5 I_M \sigma$$

charge of a Gaussian bunch

Intensity sensor bandwidth summary

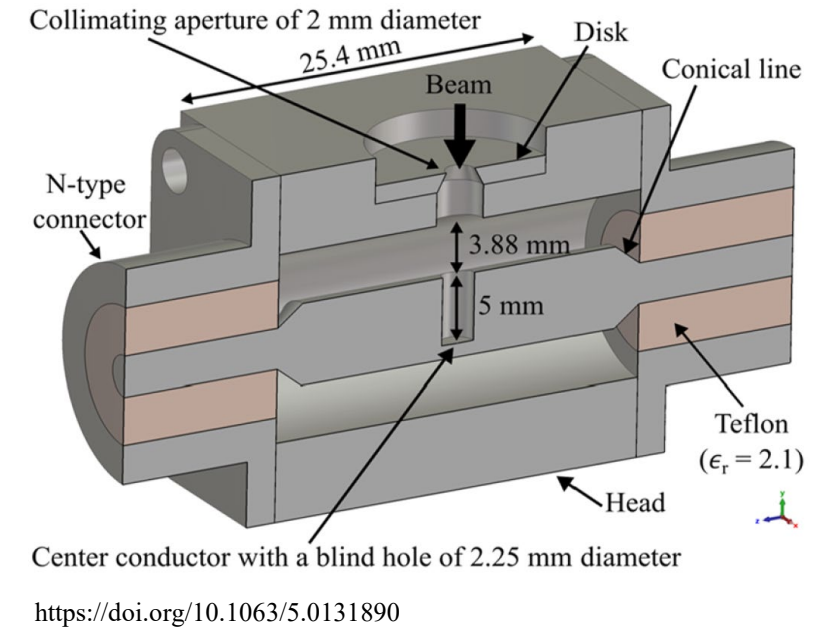
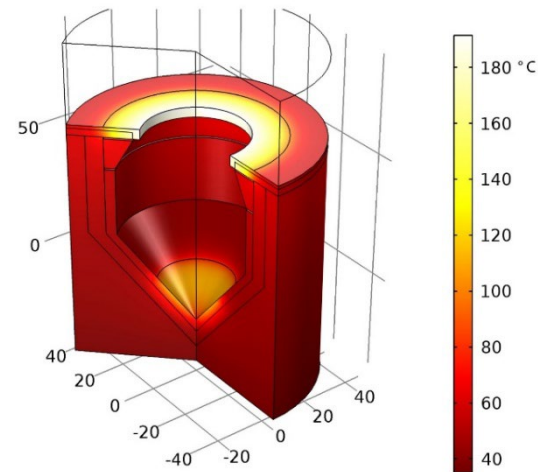
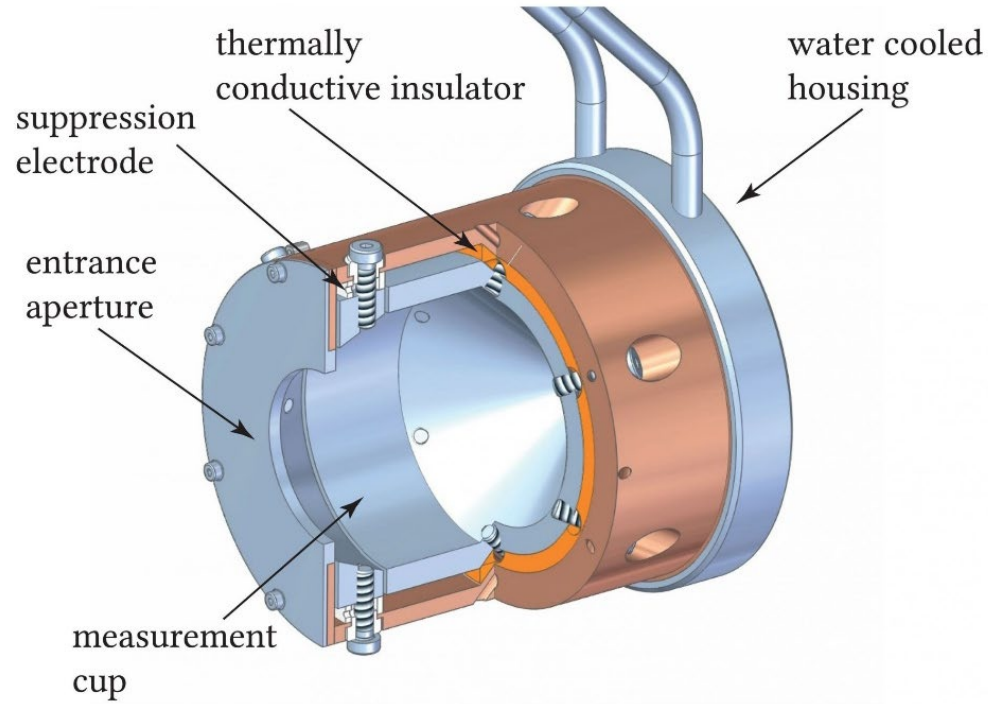


Faraday cup

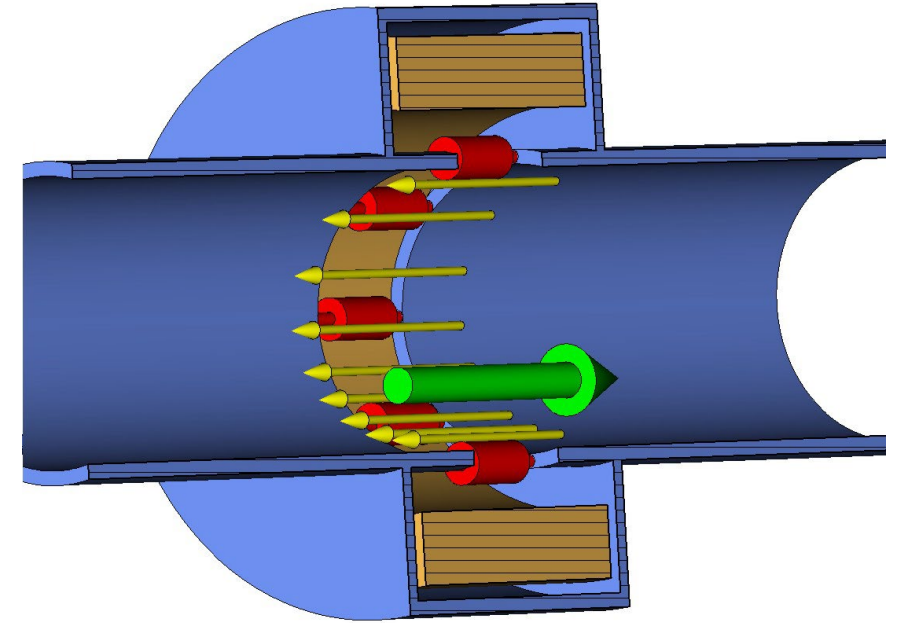
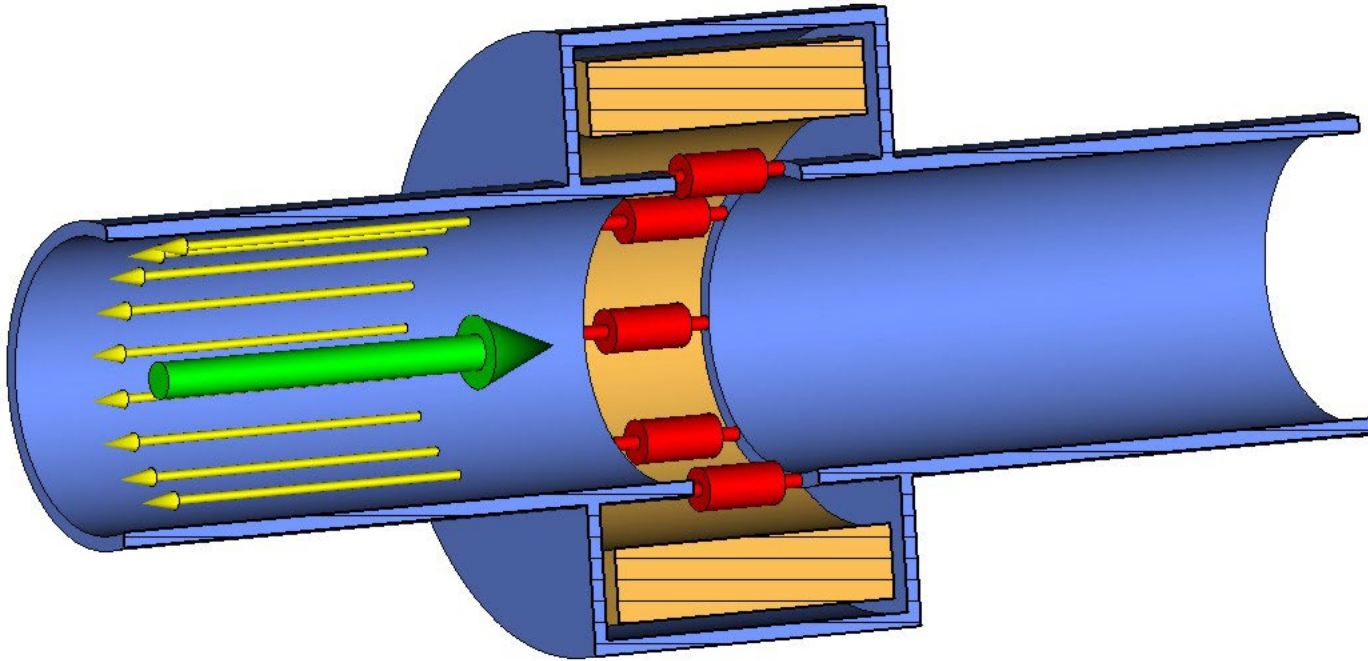


- Measurements from DC to GHz with special designs
- The only **destructive** sensor in the lecture
- “Natural” operation if combined with a beam dump (dissipated power may be a challenge)
- In any other location it requires some mechanics operating in the beam vacuum to put the sensor to/from the beam
- Can be designed to measure very small and very large currents
- The energy of the measured beam is very important for the design (low energy more difficult)
- Available commercially, along with dedicated acquisition
- Well described in the literature

Faraday cup



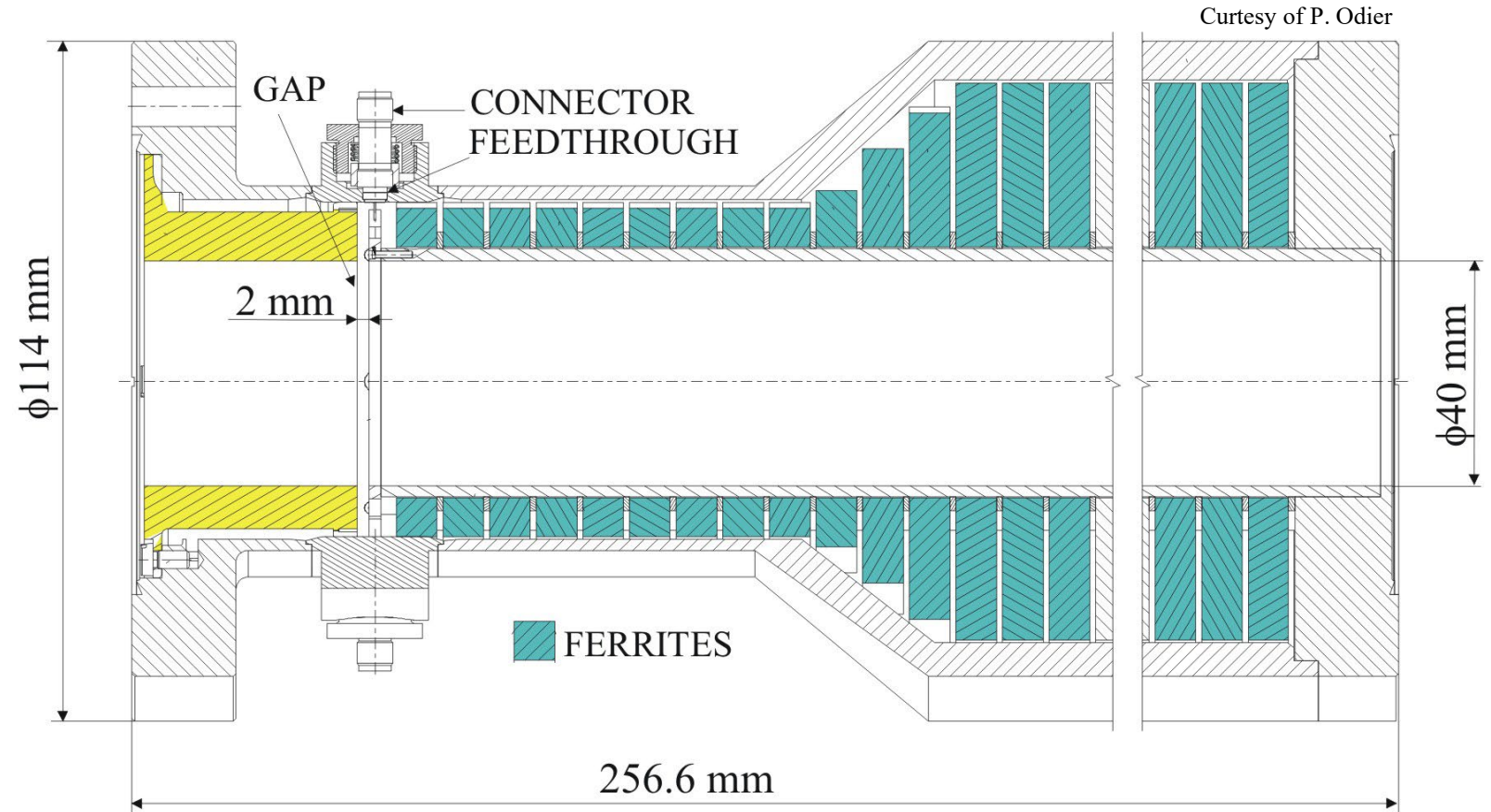
Wall Current Monitor (WCM)



Wall (image) current properties:

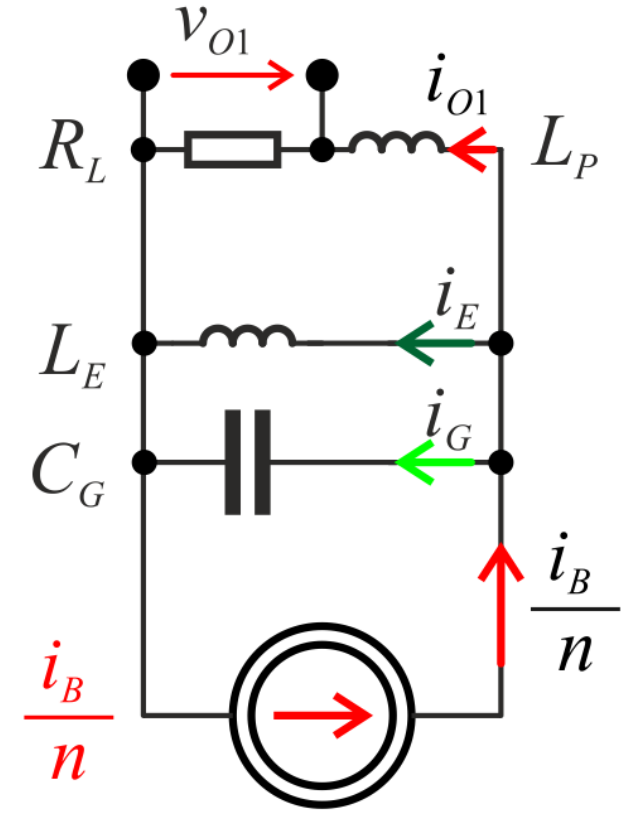
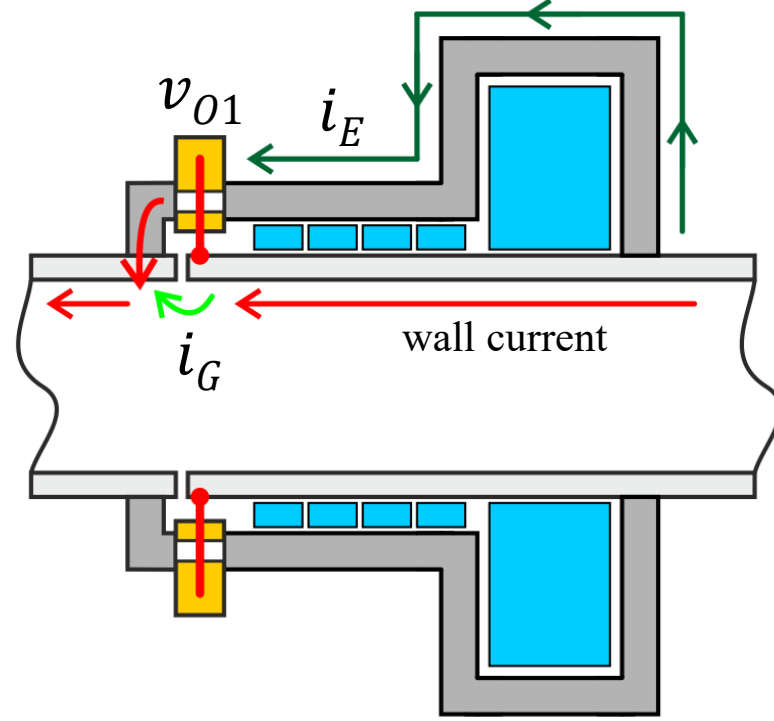
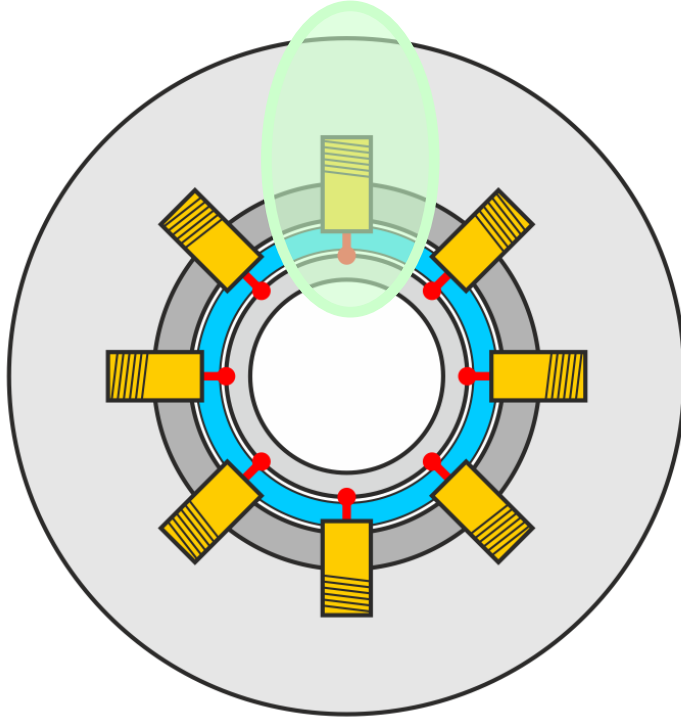
- Equal to the beam current (non-DC components) but with the opposite sign. Good proxy for beam/bunch intensity measurements
- Current density around the vacuum chamber correlated to the transverse beam position. Good proxy for beam/bunch position measurements
- Same longitudinal charge distribution as the beam for highly-relativistic beams. Good proxy for longitudinal measurements

WCM example (CTF)



- High frequency direct output bandwidth:
250 kHz – 10 GHz
- Low frequency output with an active compensation:
10 kHz – 300 MHz

Wall Current Monitor (WCM)



$$f_{CL} = \frac{R_L}{2\pi L_E}$$

≈ 400 kHz
@ $R_L=50\ \Omega$, $L_E=10\ \mu\text{H}$

$$f_{CH} = \frac{1}{2\pi R_L C_G}$$

≈ 3 GHz
@ $R_L=50\ \Omega$, $C_G=1\ \text{pF}$

1 pF $\approx 3 \times 3$ mm electrodes
with 1 mm distance

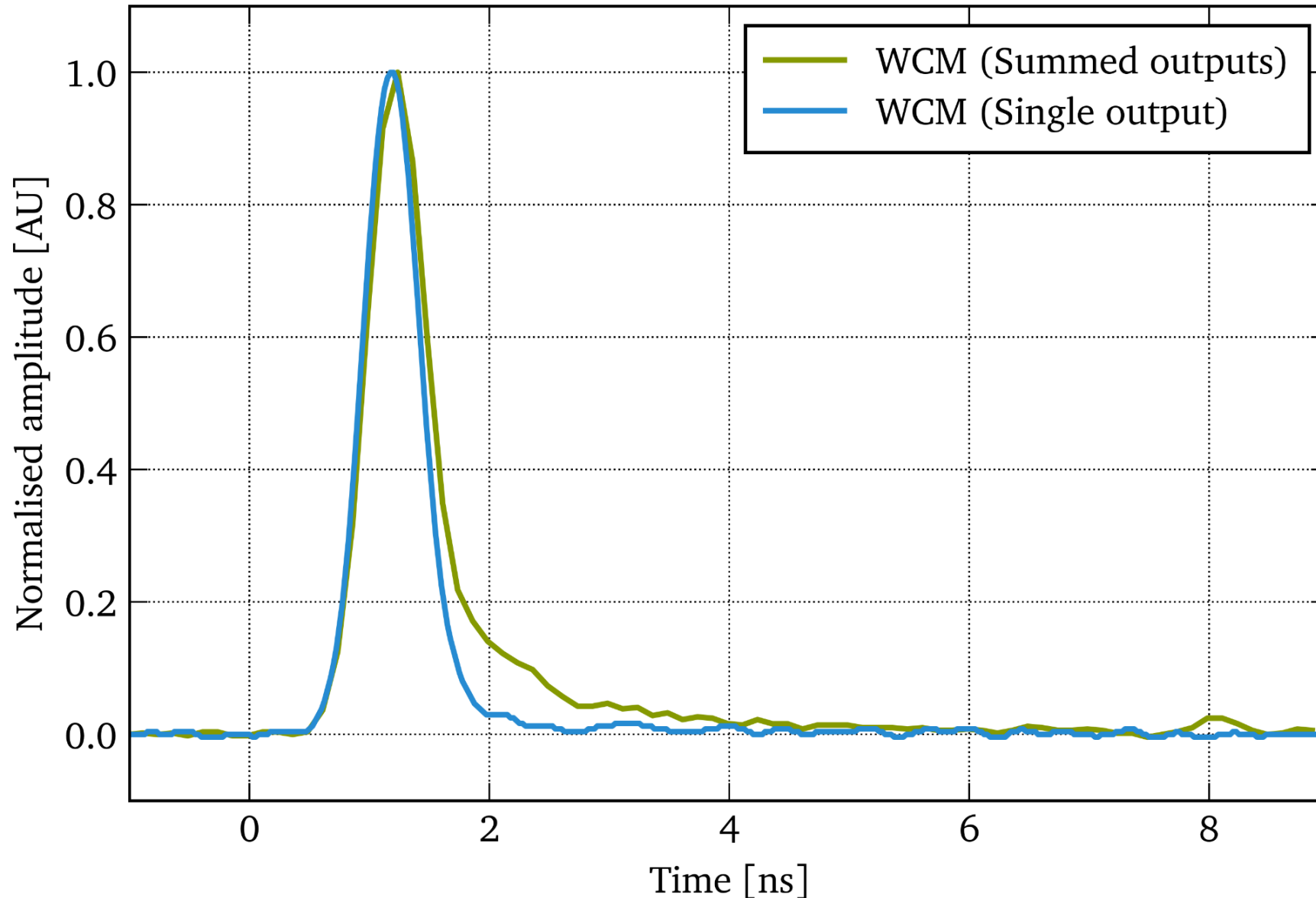
$$f'_{CH} = \frac{R_L}{2\pi L_P}$$

≈ 8 GHz
@ $R_L=50\ \Omega$, $L_P=1\ \text{nH}$

1 nH ≈ 1 mm piece of an
unmanaged wire

f_{CL} = cut-off low frequency
 f_{CH} = "gap" cut-off high frequency
 f'_{CH} = "series L" cut-off high frequency
 i_E = enclosure current
 L_E = enclosure inductance
 i_G = gap current
 C_G = gap capacitance
 L_P = parasitic series inductance

WCM bunch longitudinal profile measurement



To combine ...

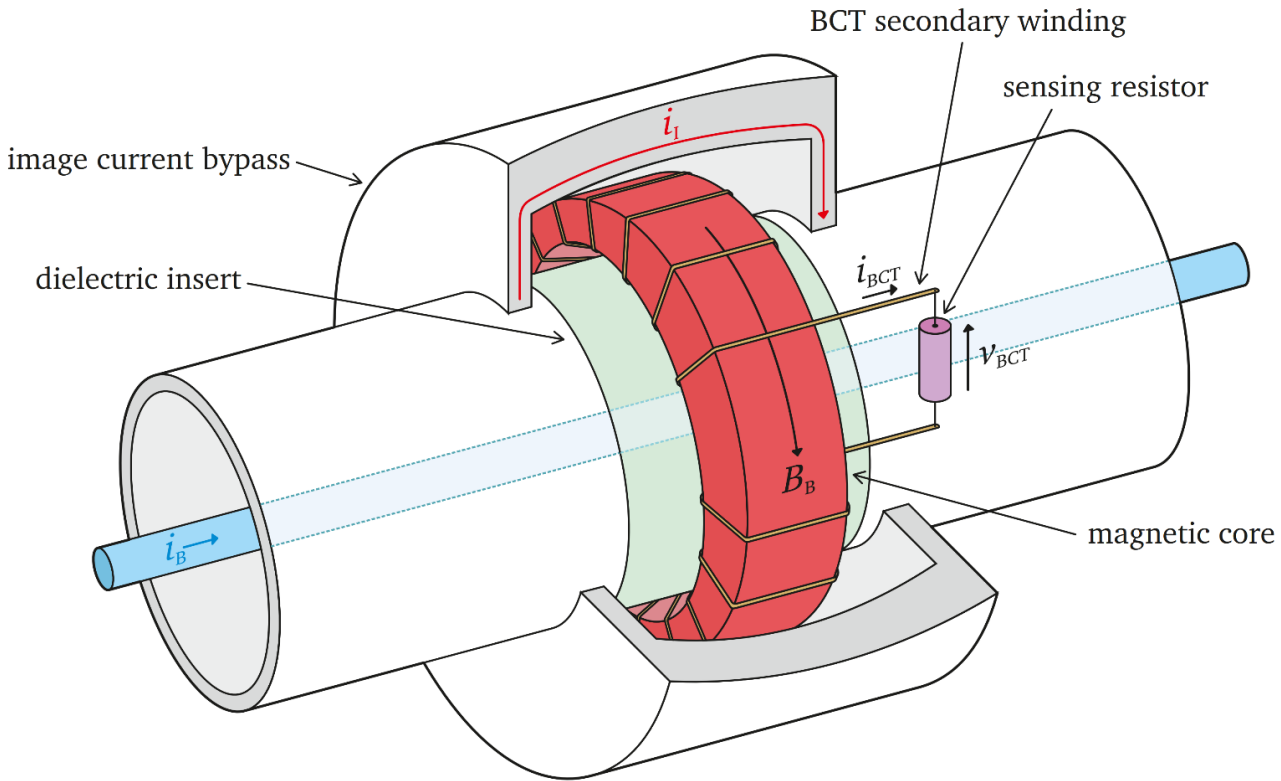
- Good signal position independency (only position dephasing)
- Signal deterioration by the combiner

... or not to combine

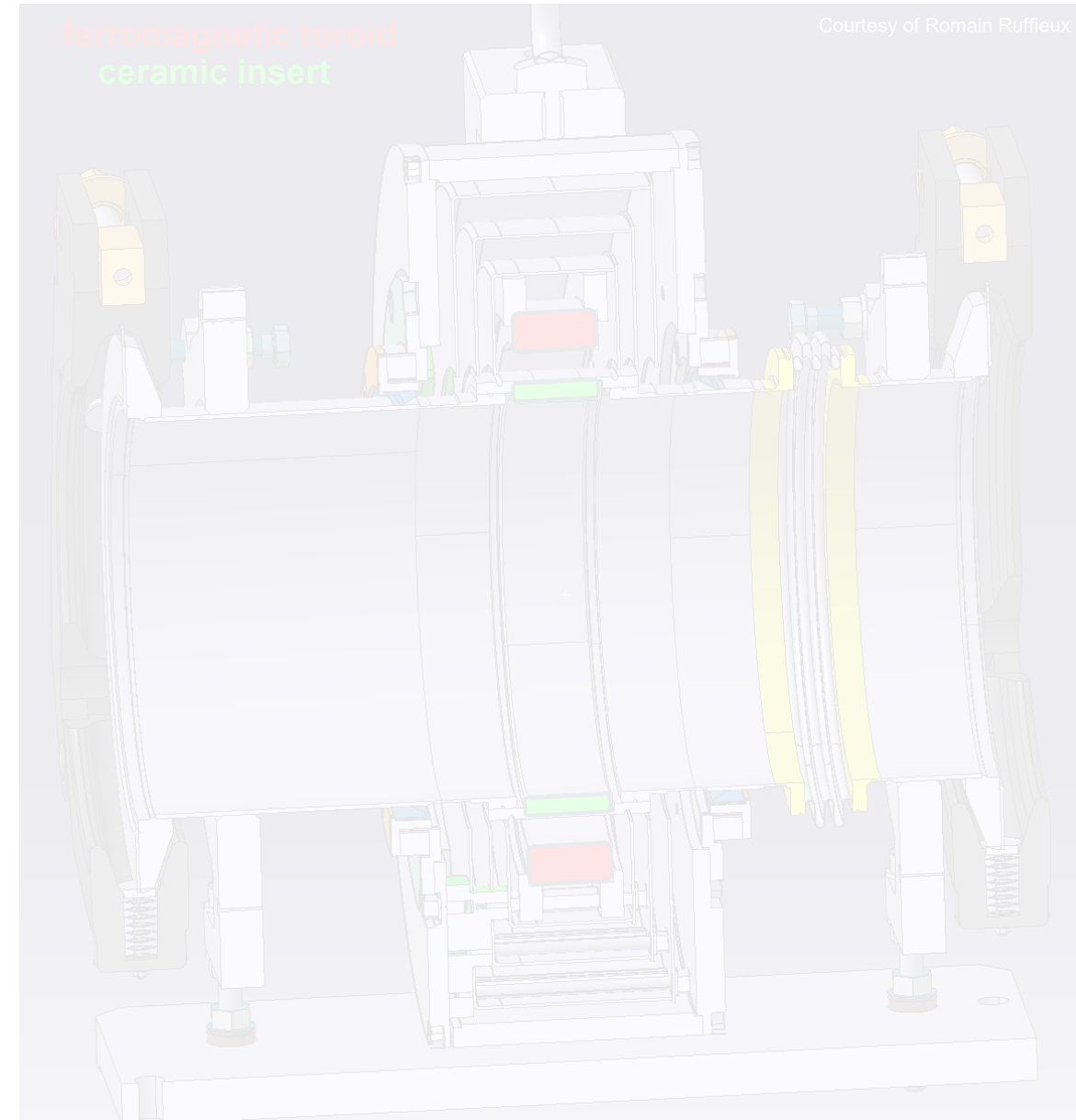
- Largest position dependency
- Best signal quality
- Some decoupling between respective outputs
- Saved money and thinking on the combiner

Fast Beam Current Transformer (FBCT)

16



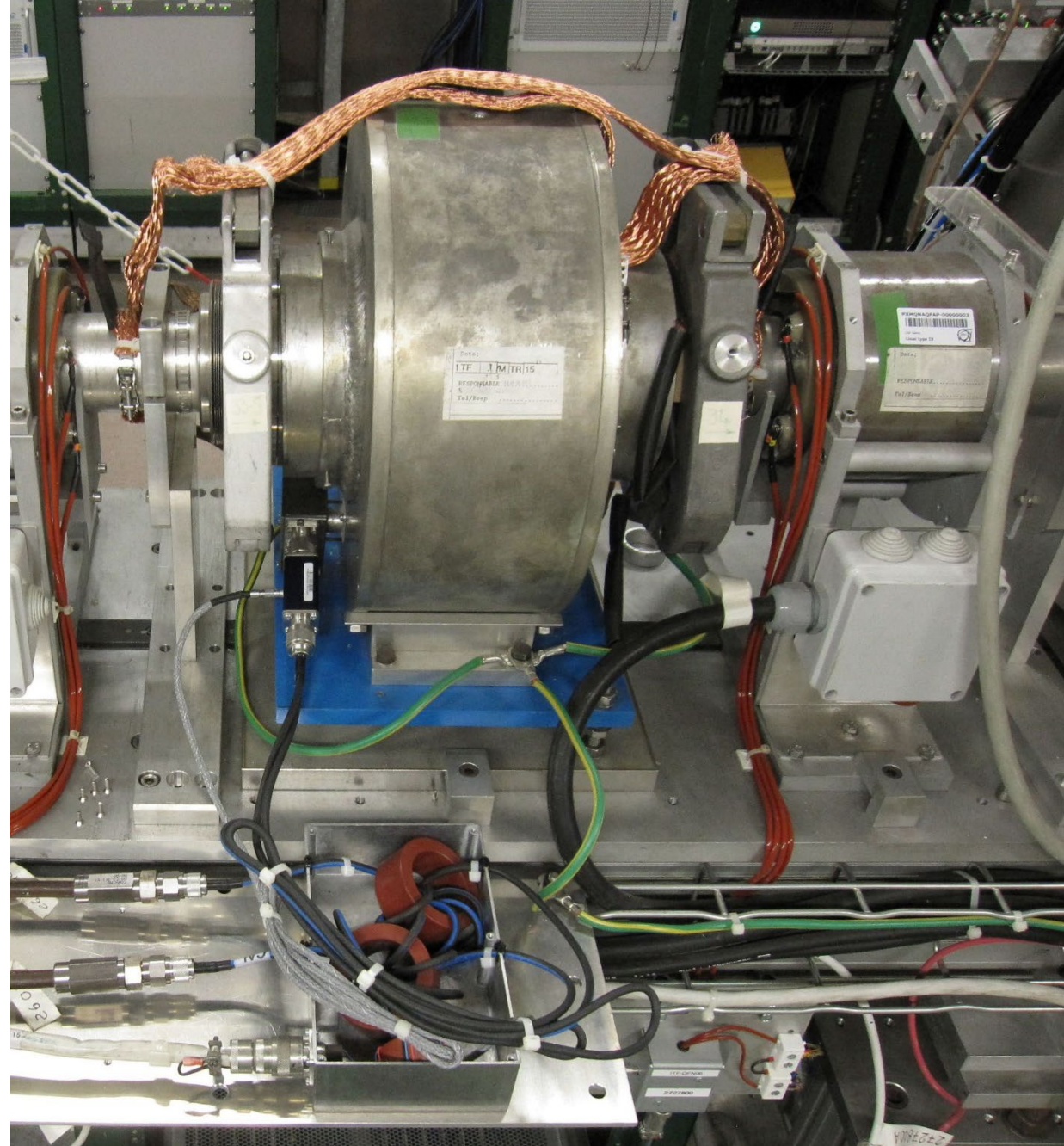
- Workhorse of intensity measurements in many accelerators
- In a circular machine one FBCT is enough, while linacs and transfer lines often require many of them
- It is a current transformer, with the beam forming the primary single turn winding
- Particular FBCT construction often determined (and sometimes limited) by the choice of commercially available ferromagnetic toroids
- FBCTs are available commercially, along with their dedicated electronics



Fast Beam Current Transformer

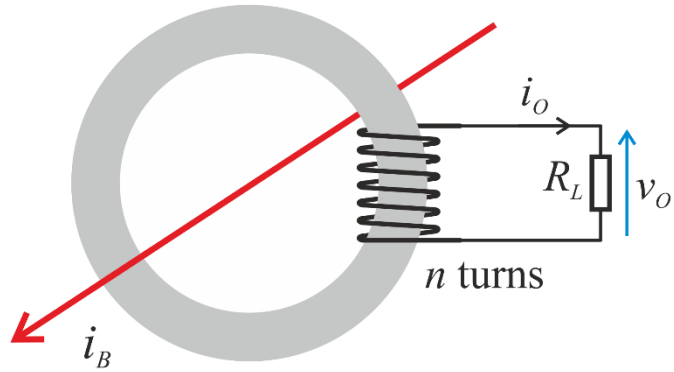


$i_B \sim 100 \text{ mA}$ (CERN L4 proton linac)



$i_B \sim 100 \text{ } \mu\text{A}$ (CERN L3 ion linac)

FBCT signal droop



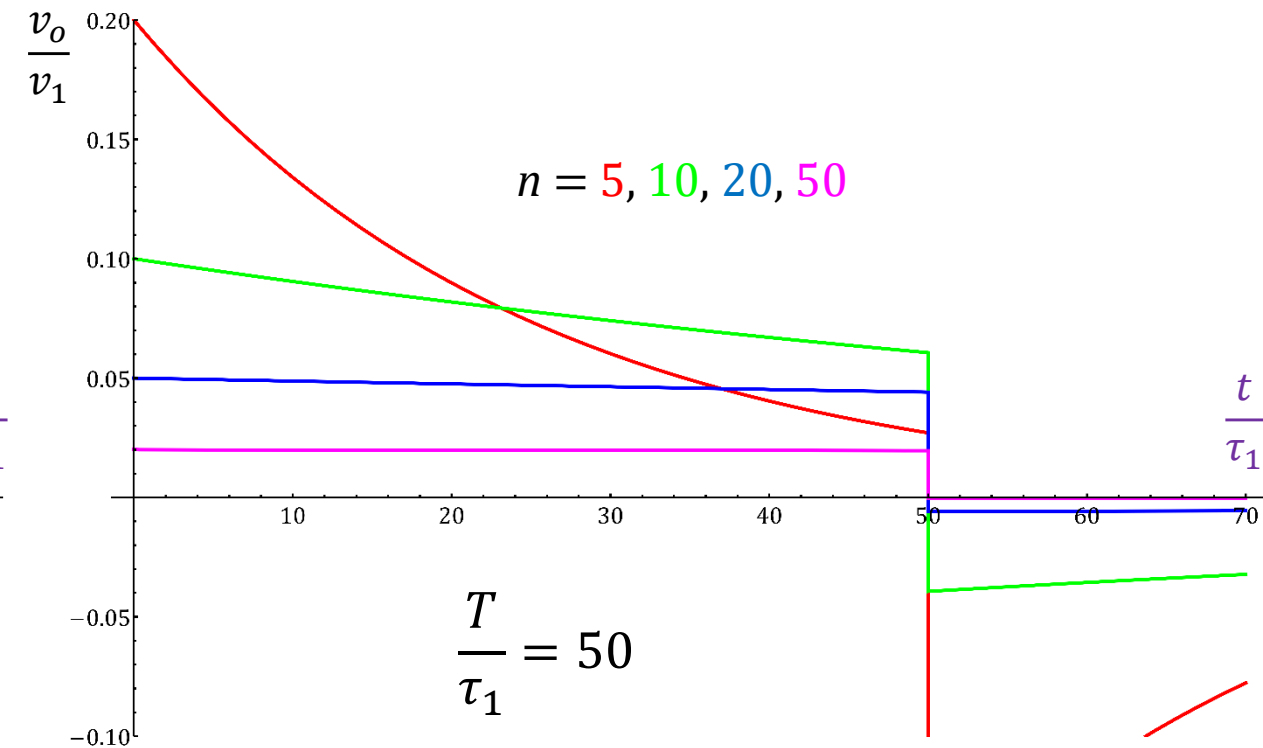
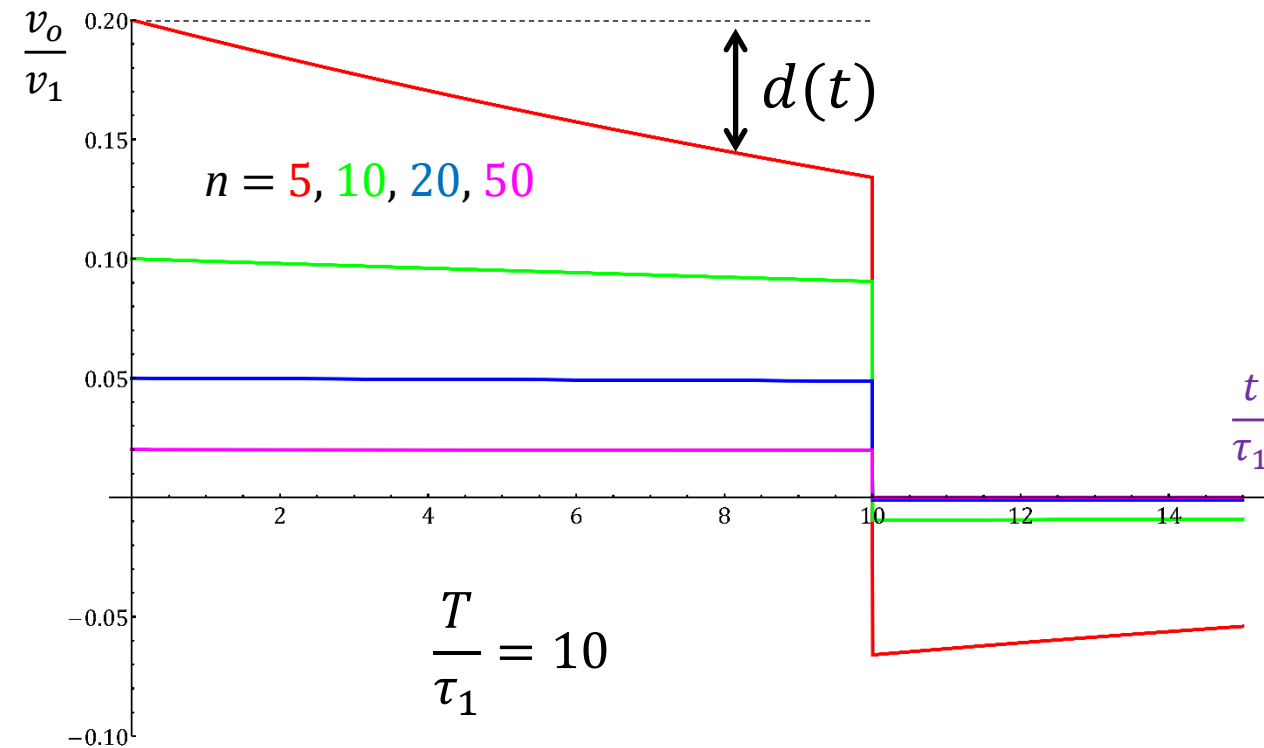
$$v_o(t) = \frac{i_B}{n} R_L \exp\left(-\frac{t}{\tau}\right)$$

$$d(t) = \exp\left(-\frac{1}{n^2} \frac{t}{\tau_1}\right)$$

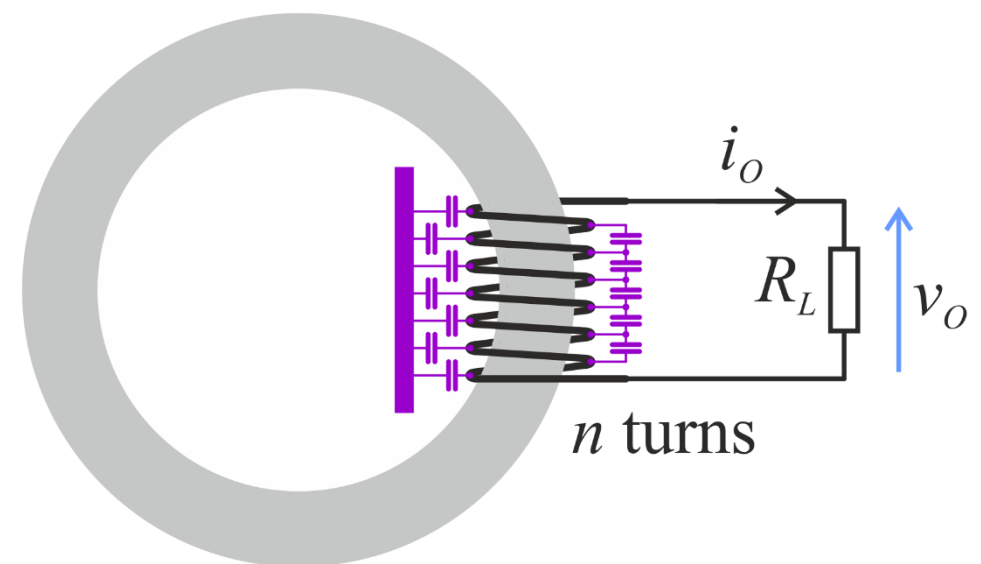
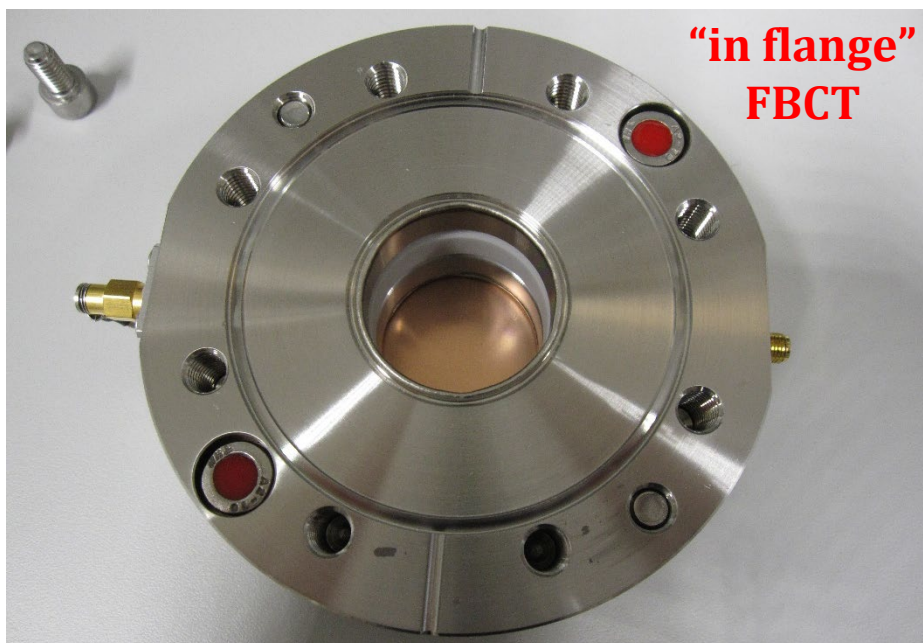
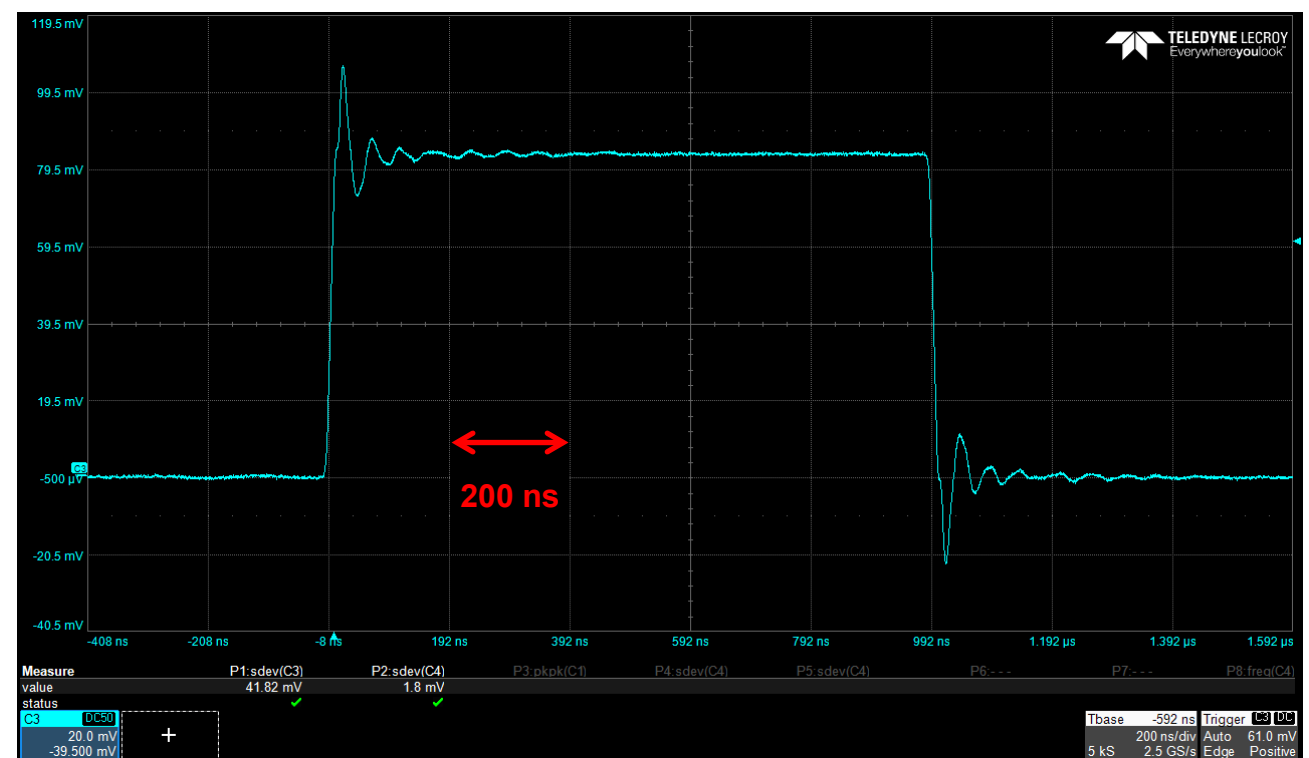
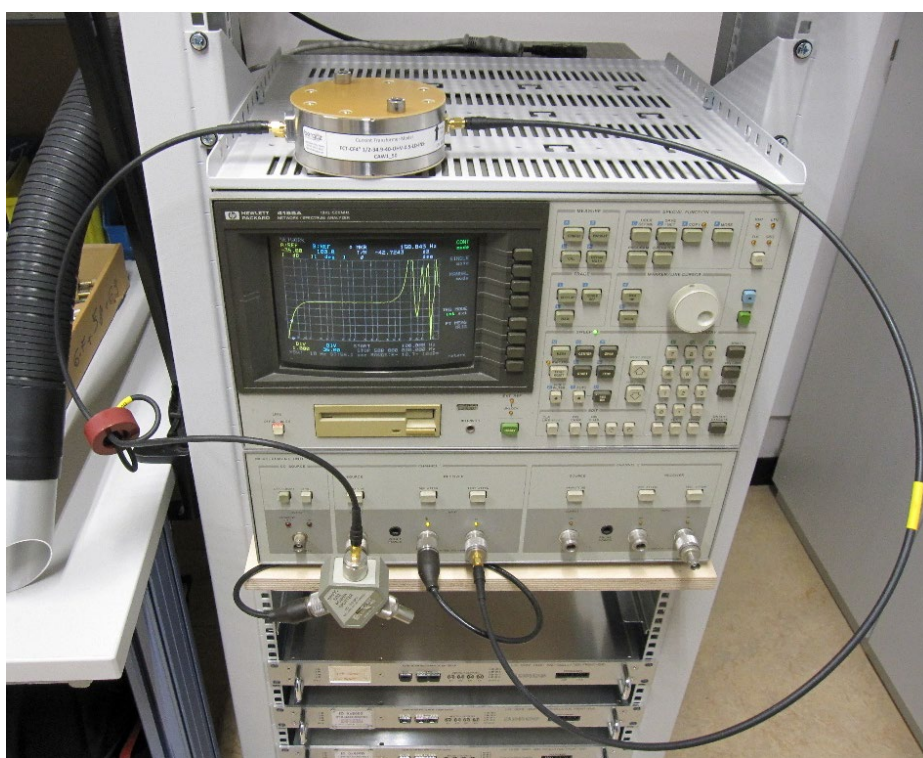
$$v_o(t) = \frac{V_1}{n} \exp\left(-\frac{1}{n^2} \frac{t}{\tau_1}\right)$$

v_1 – output voltage for $n=1$
 τ_1 – time constant for $n=1$

$$\tau_1 = \frac{A_L}{R_L}$$

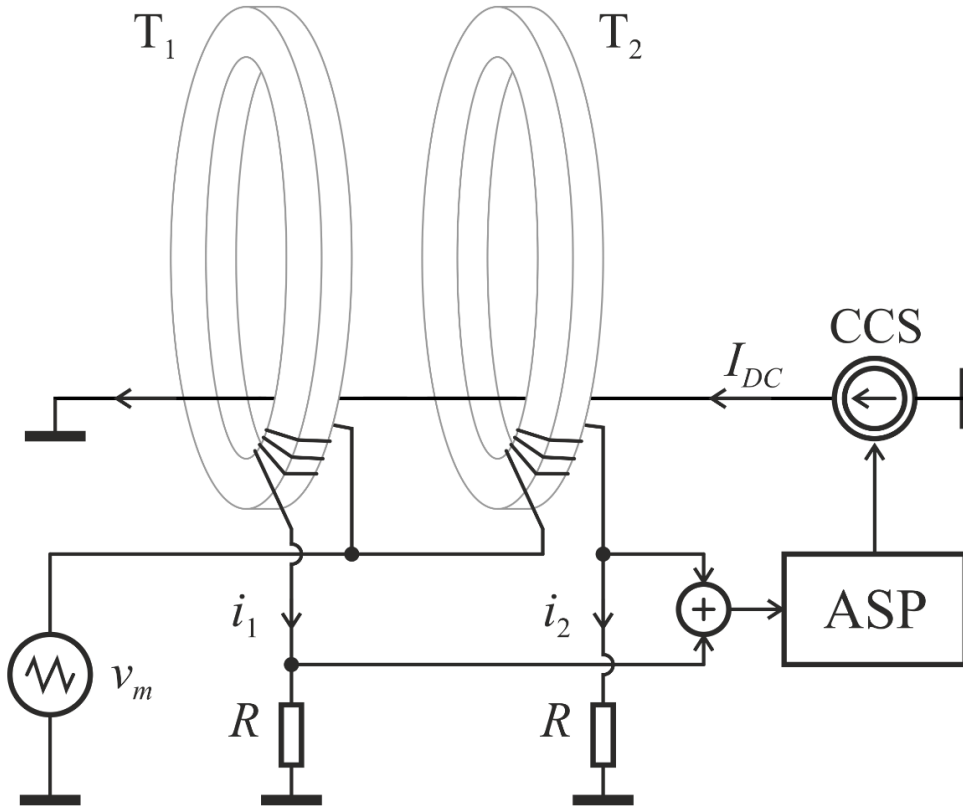


FBCT high frequency response

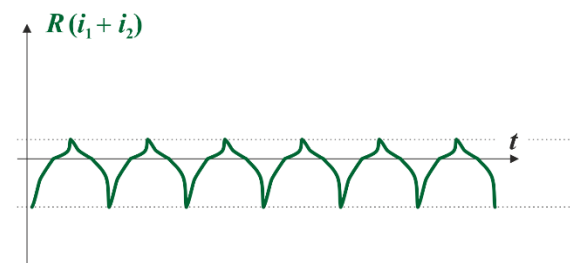
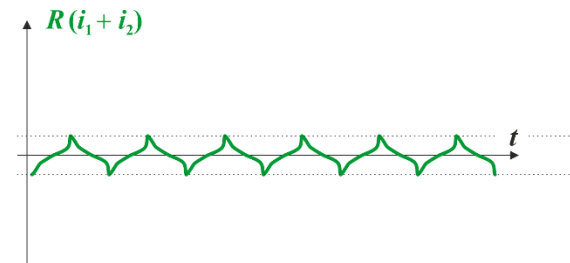
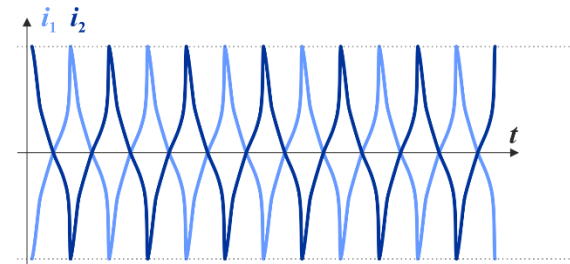
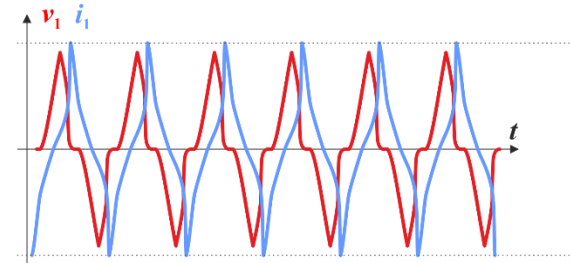
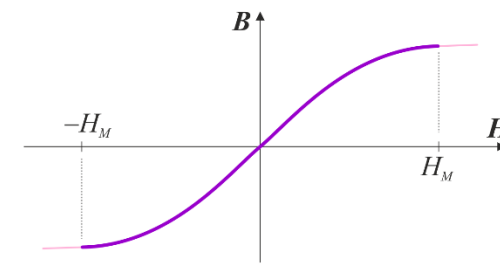


I_B = beam current
 I_{DC} = compensating DC current
 V_m = (triangular) modulation voltage
 i_1, i_2 = T_1, T_2 currents

T_1, T_2 = ferromagnetic toroids
 CCS = controllable current source
 ASP = analog signal processing



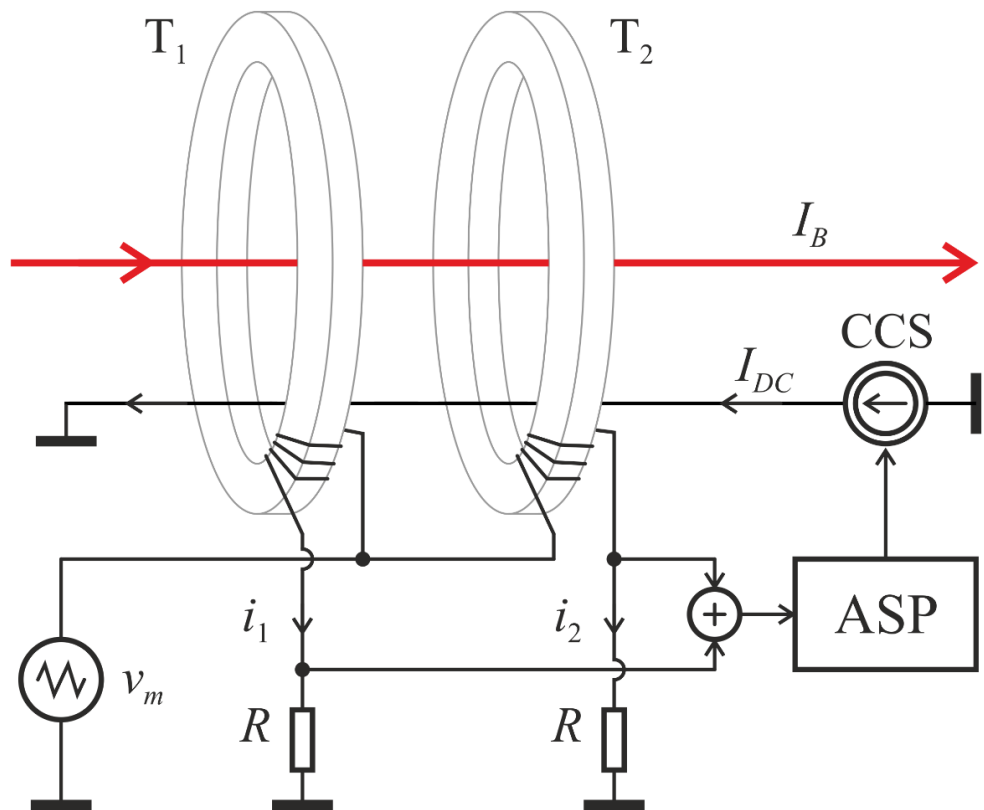
- Very small dynamic range of the sensitive detection circuitry addressed by using a compensation method
- “Zero flux” operation
- Excellent precision and dynamic range typical for DC measurements
- In many accelerators a golden standard used to calibrate other intensity measurement systems



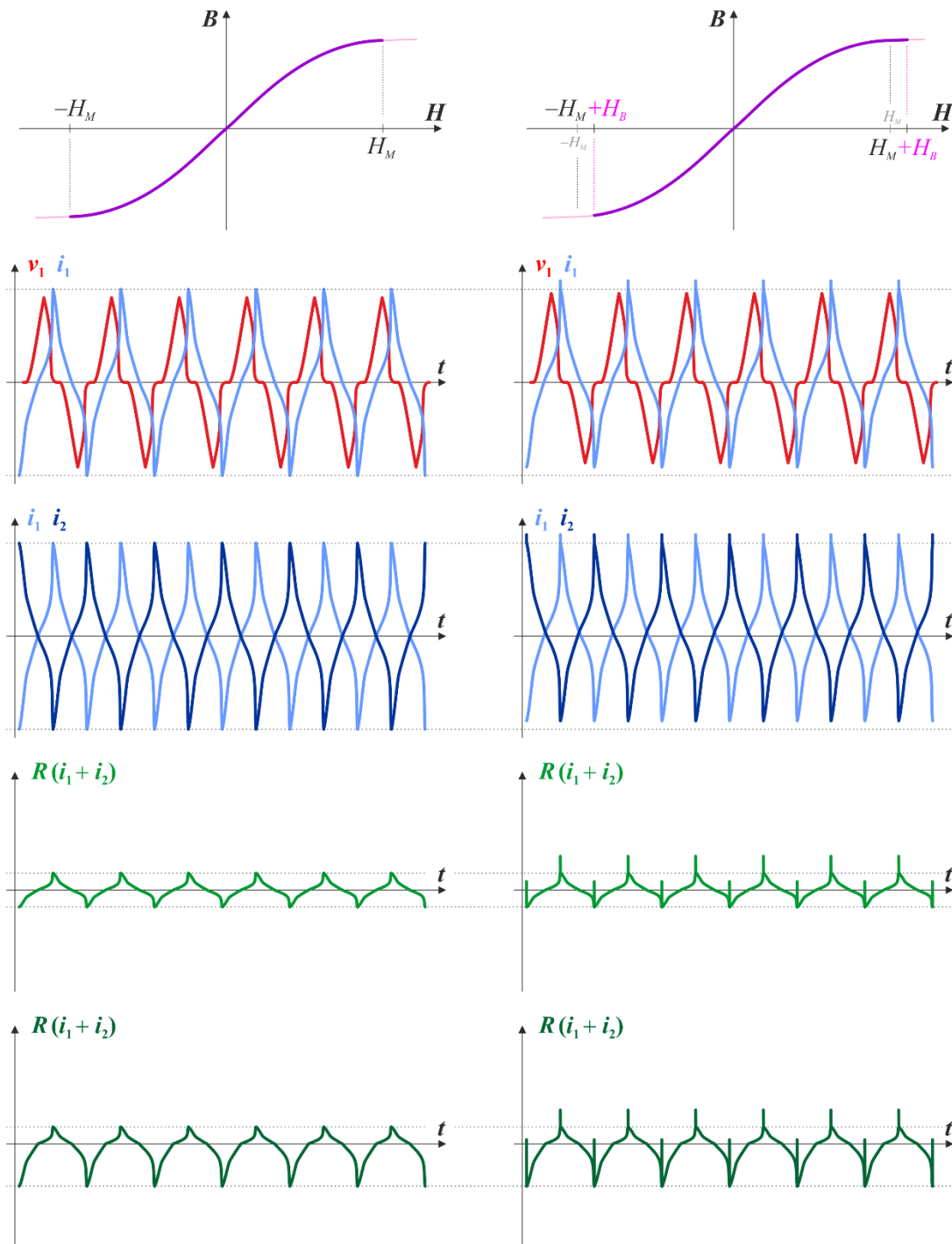
DC Beam Current Transformer

I_B = beam current
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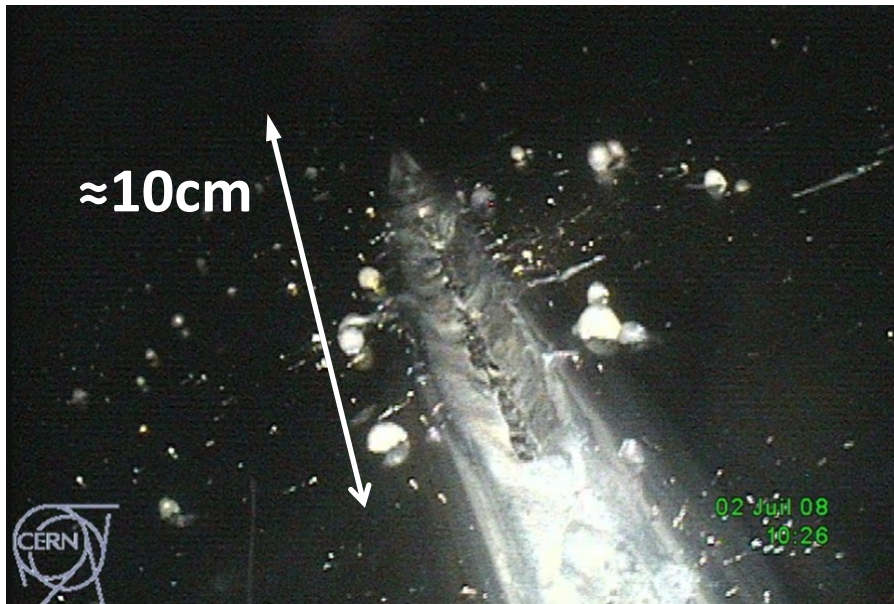
DC Beam Current Transformer (DC BCT)



Beam loss monitoring

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

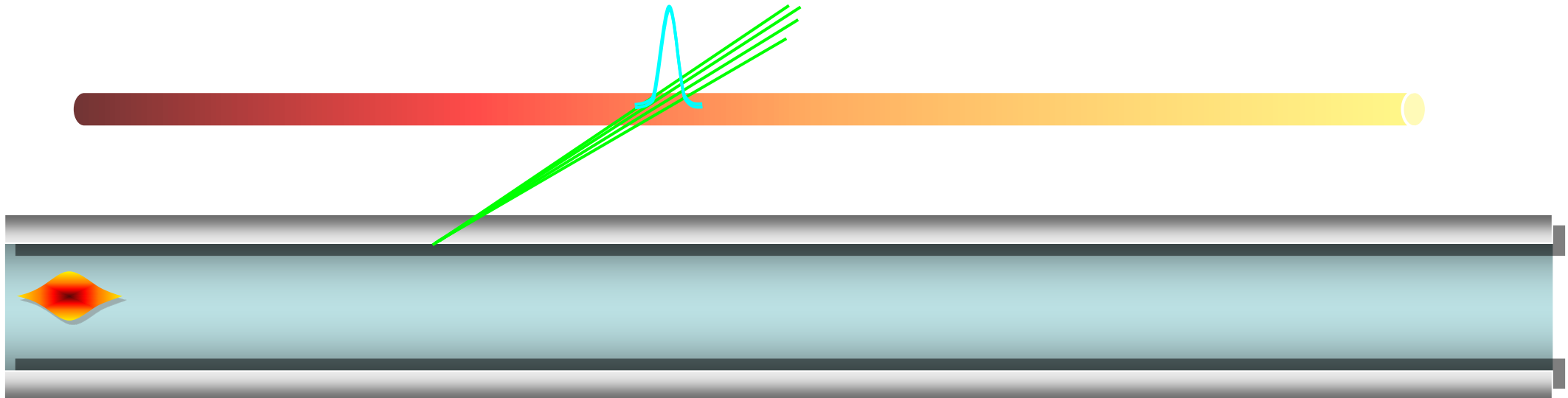
Beam 7 TeV	2 x 362 MJ
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Quench and Damage at 7 TeV

Quench level	$\approx 1 \text{ mJ/cm}^3$
Damage level	$\approx 1 \text{ J/cm}^3$

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

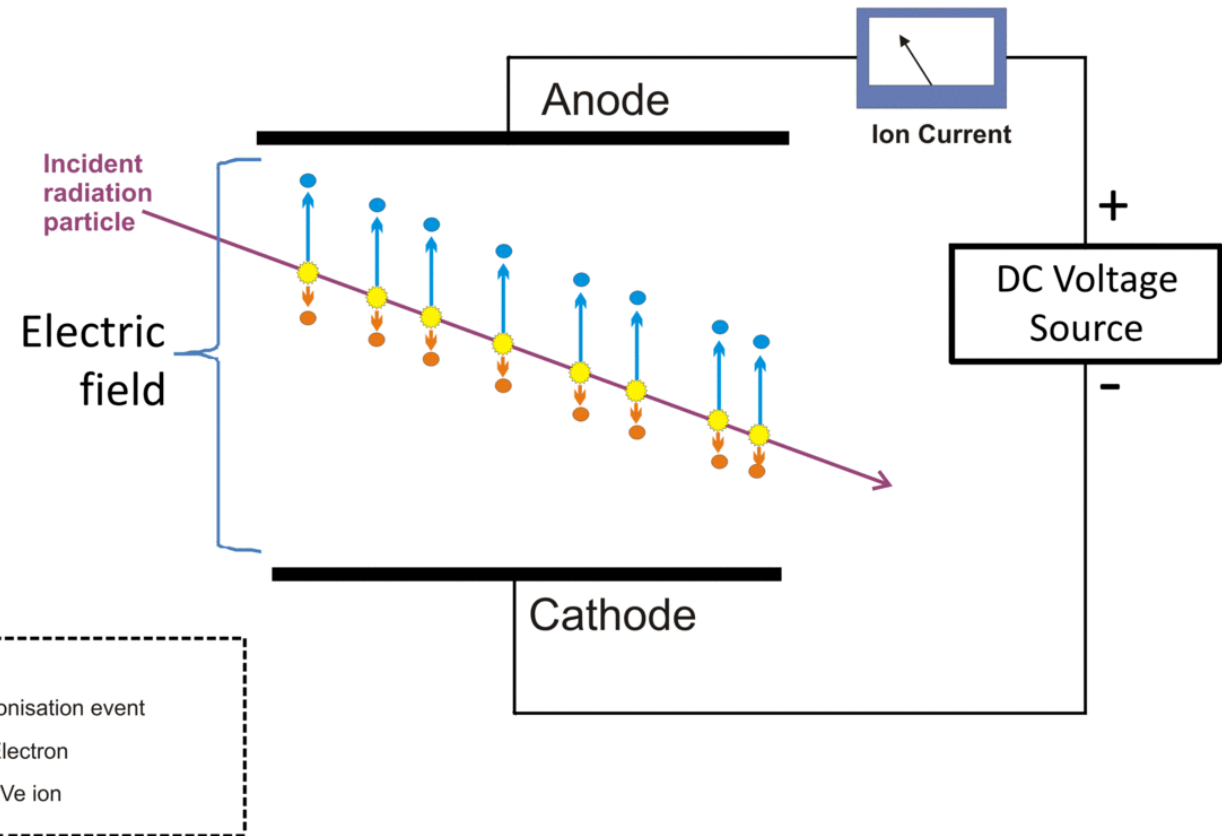


Ionisation chamber BLMs

- 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)

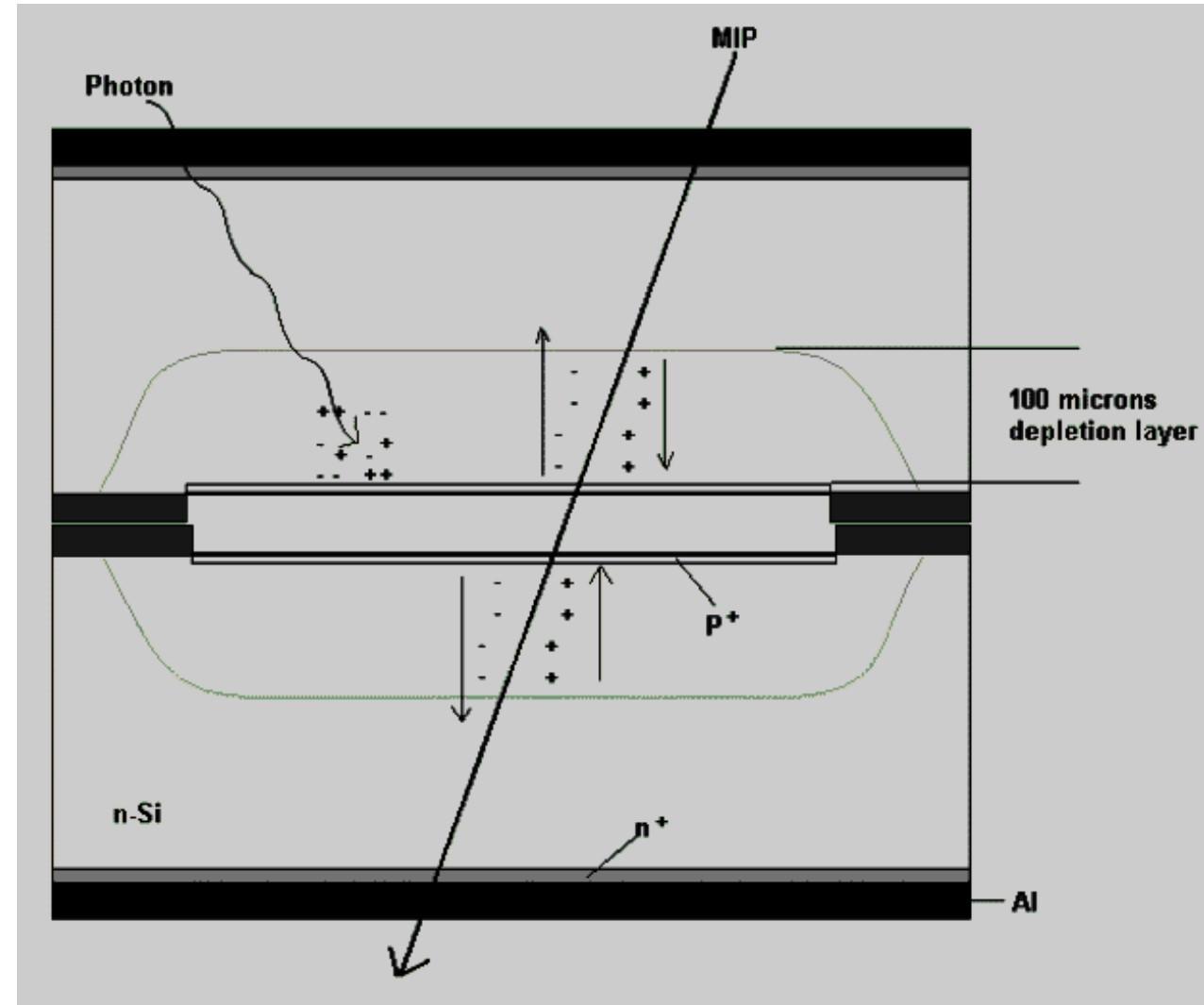


Visualisation of ion chamber operation



PIN photodiode BLMs

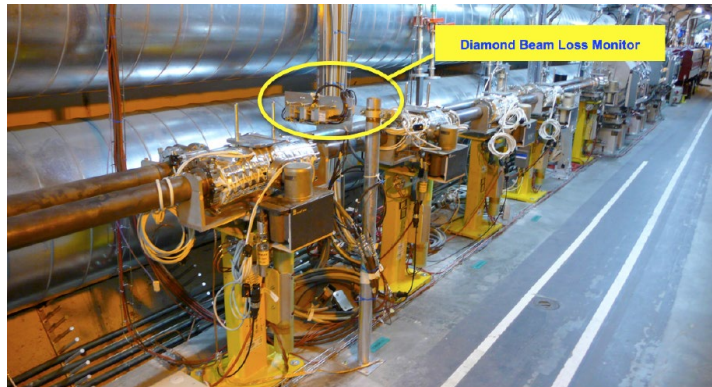
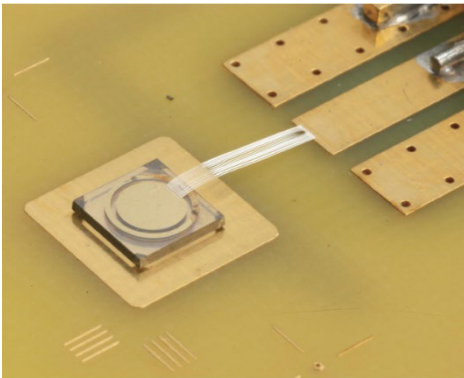
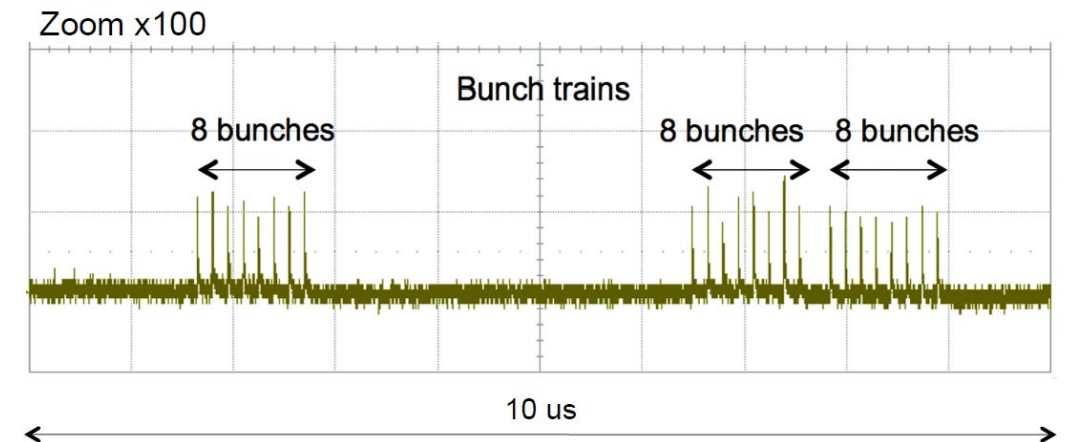
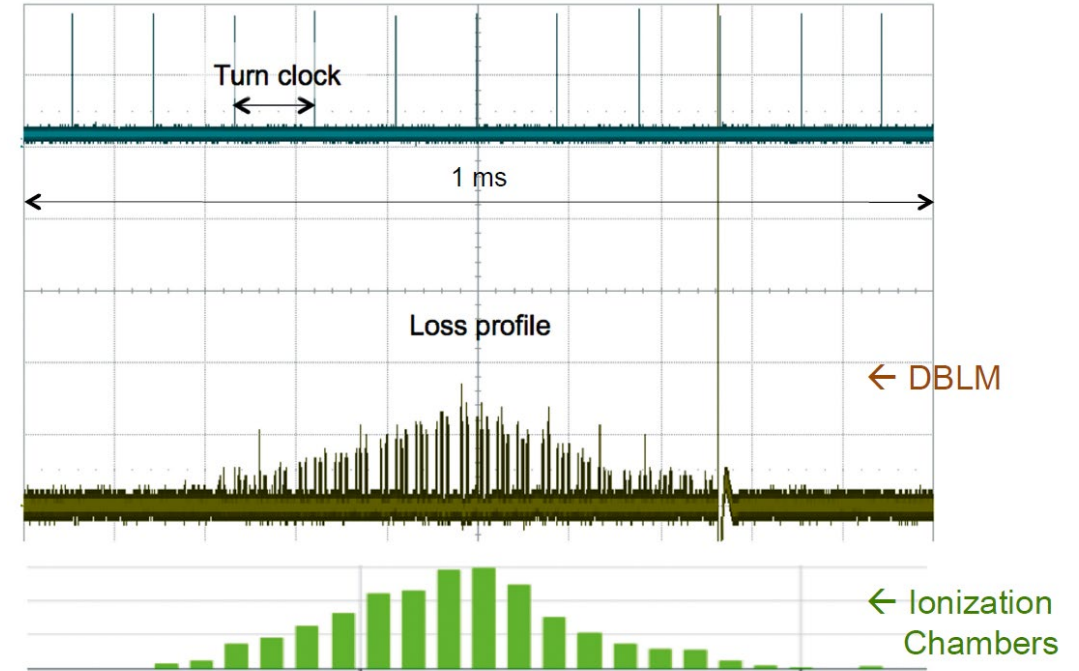
- Two reverse-biased PIN photodiodes mounted face-to-face
- Detect coincidence of ionising particles crossing both diodes
- Count rate proportional to beam loss – limited by integration time
- Can distinguish X-rays (low coincidence) and ionizing particles (high coincidence)
- Dynamic range up to 10^9



Diamond BLMs

28

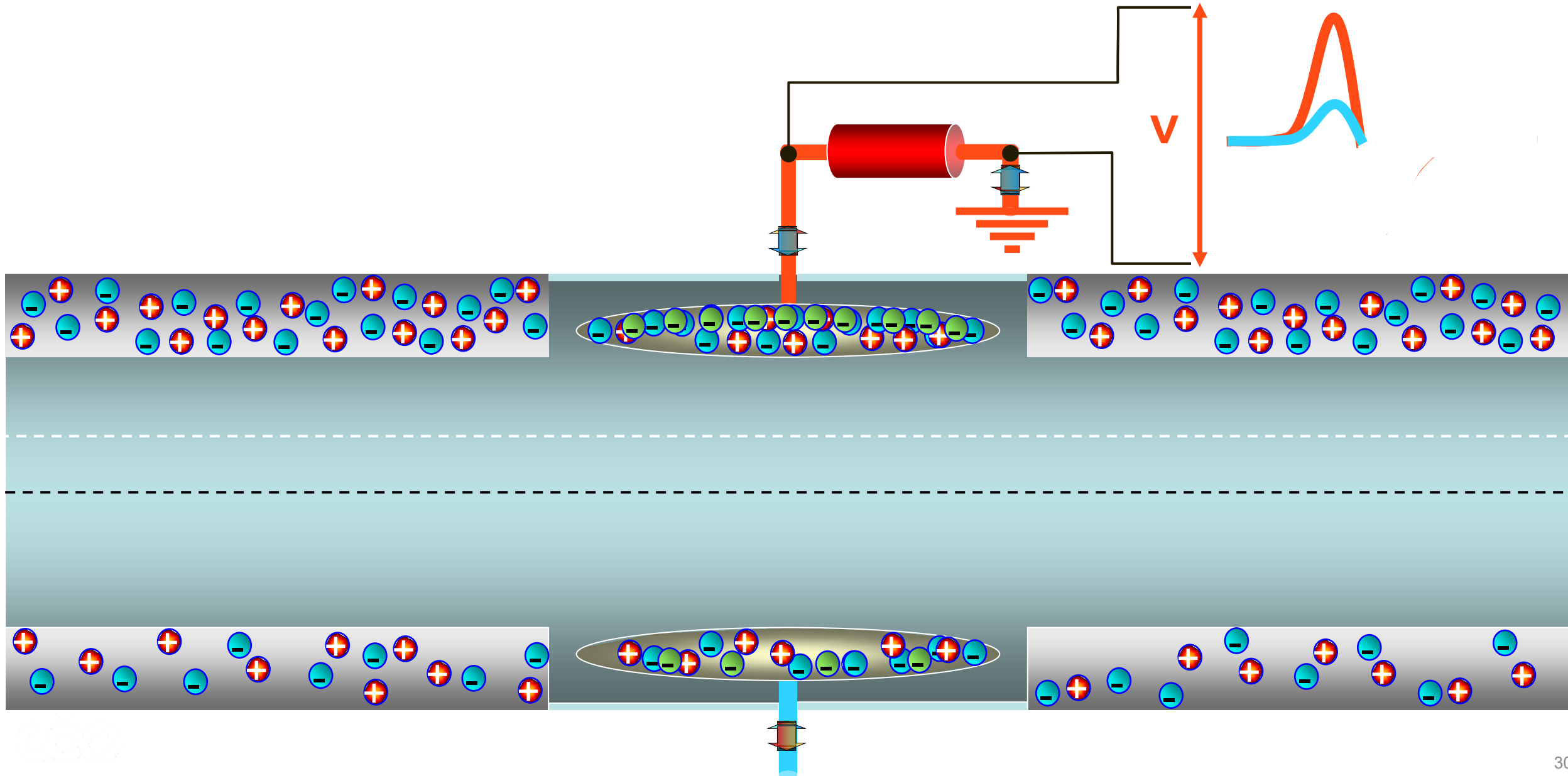
- Polycrystalline chemical vapor deposited diamond between two metal electrodes
- Ionizing particles crossing the diamond generate current flow between the electrodes
- Very fast response time (ns)
- Used in the LHC for bunch-by-bunch losses



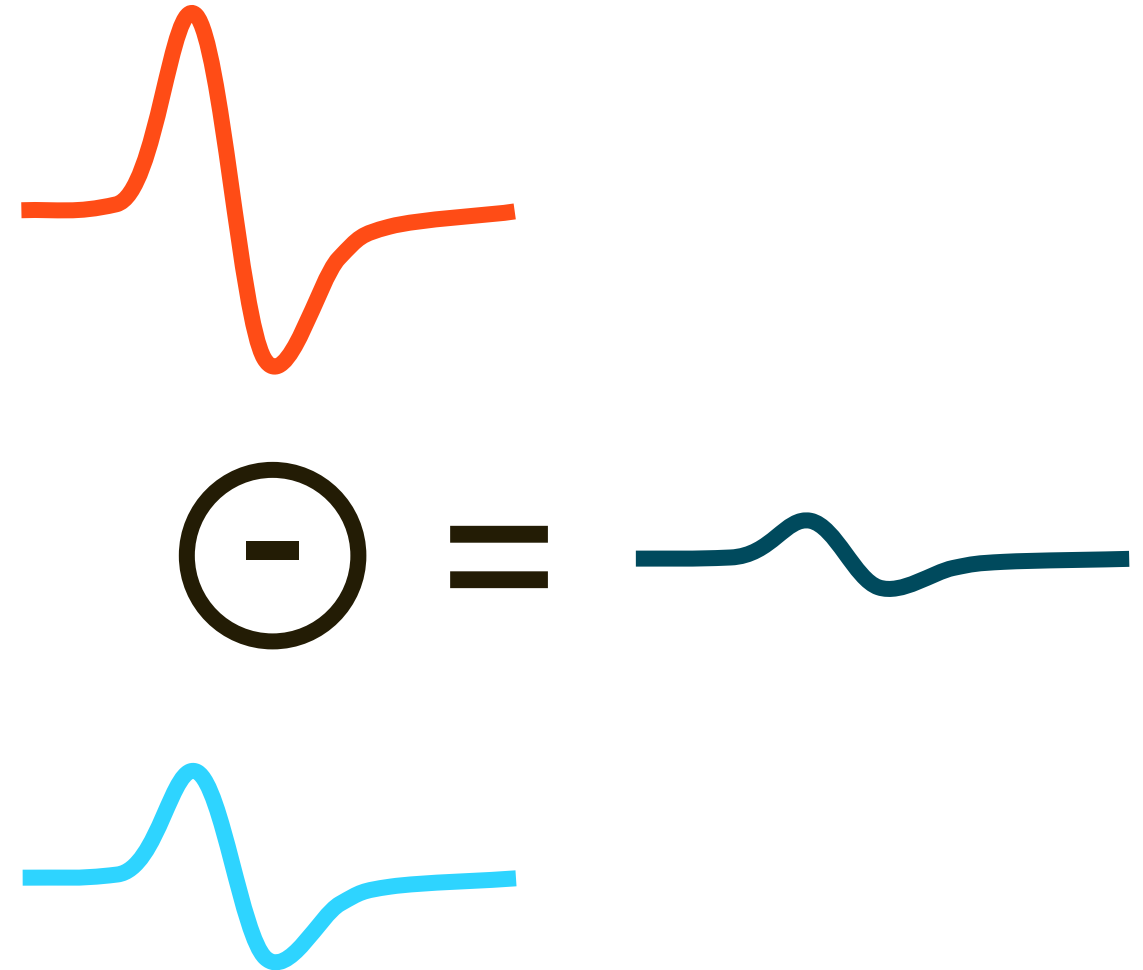
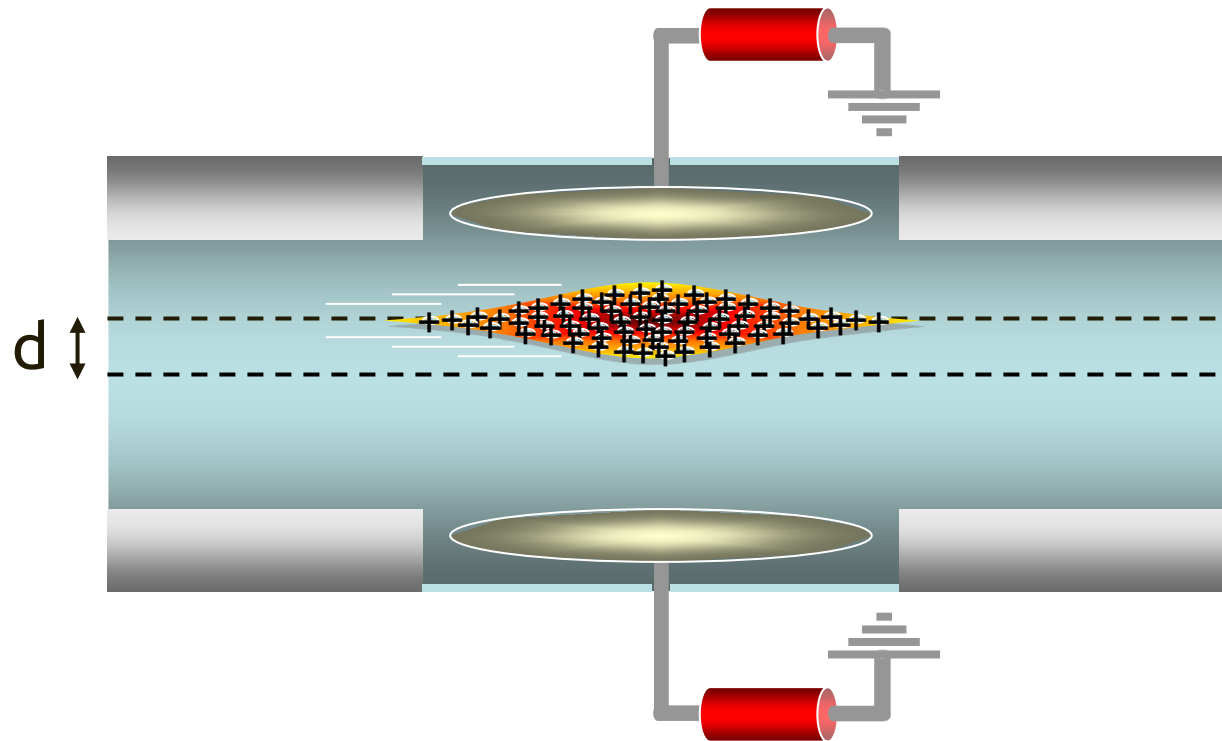
Courtesy of E. Griesmayer

Beam position measurement

Principle of operation of an electrostatic BPM



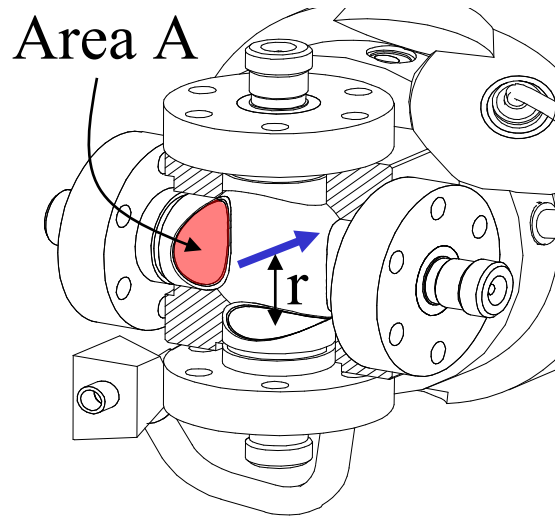
Electrostatic BPM – position sensing



Electrostatic BPM – button pick-up

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

$$V_{BPM} \propto I_{beam} \cdot \left(1 + 4 \frac{d}{A} + \text{higher-order terms}\right)$$



C_e – button capacitance

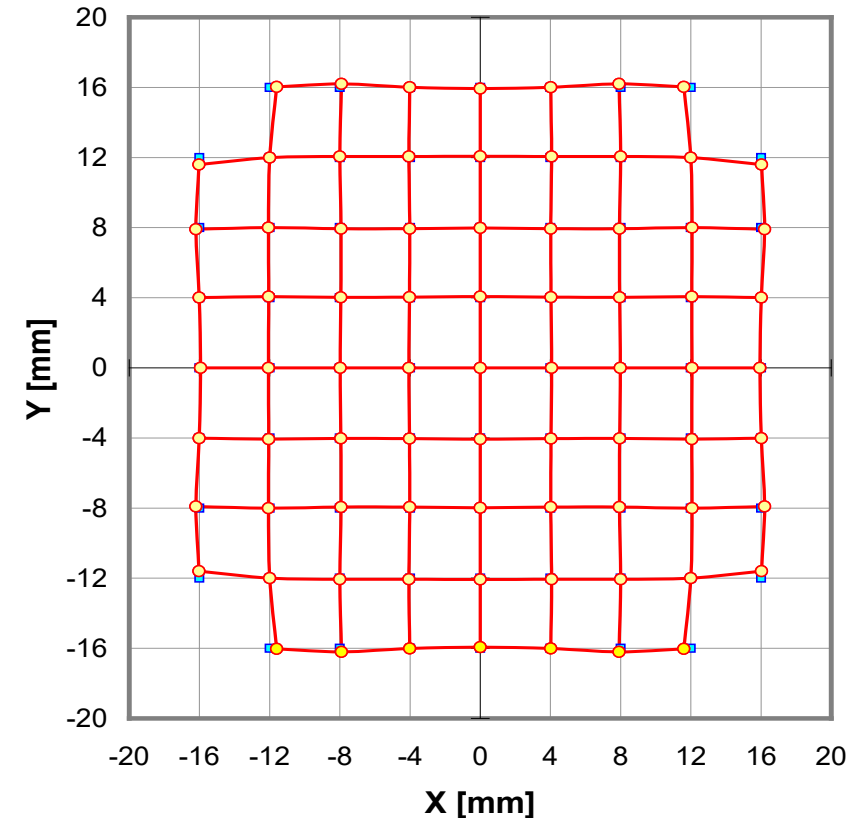
R_0 – load resistance

Transfer impedance

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

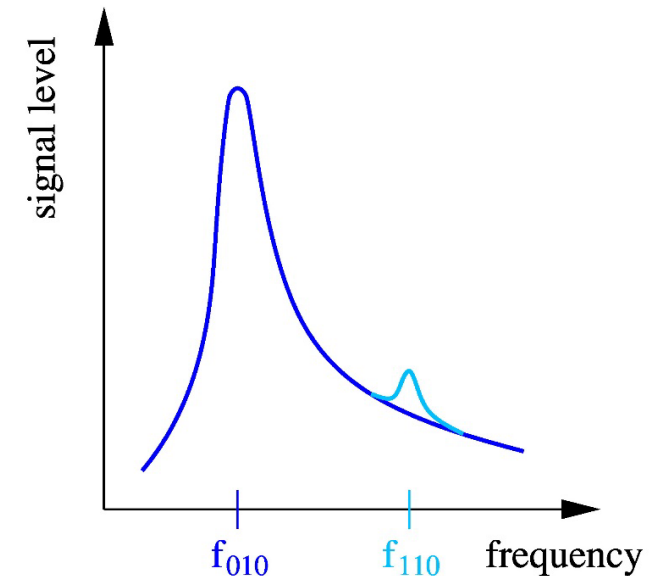
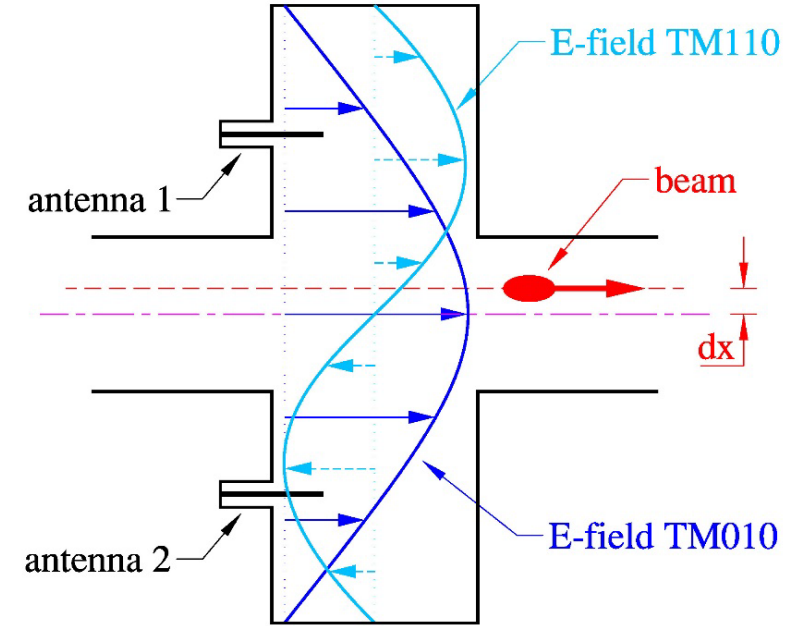
Low cut-off frequency

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



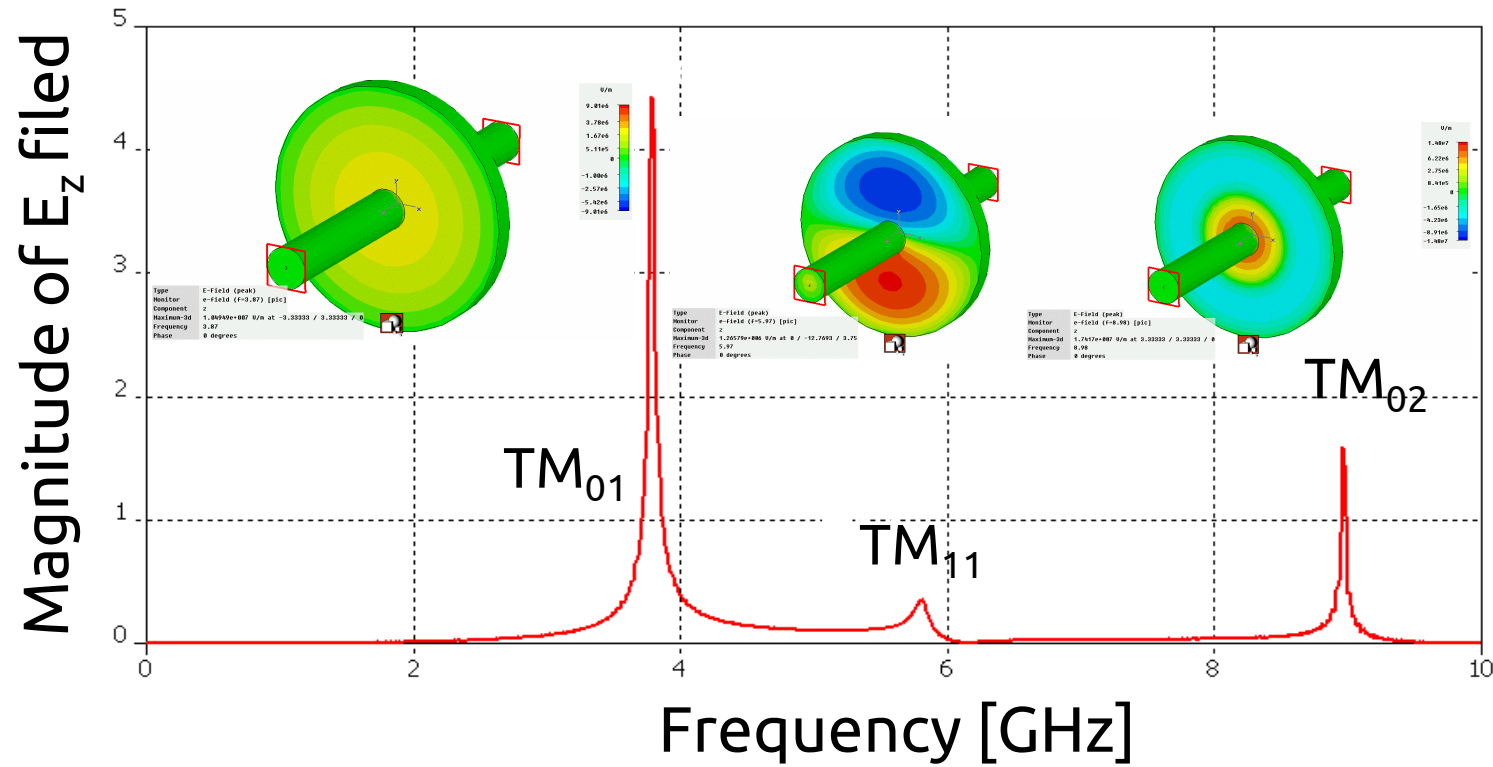
High-precision BPMs

- Standard BPM electrodes:
 $V_{BPM} \propto I_{beam} \cdot (1 + 4 \frac{d}{A} + \text{higher order terms})$
- Strong beam / bunch intensity component and therefore 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



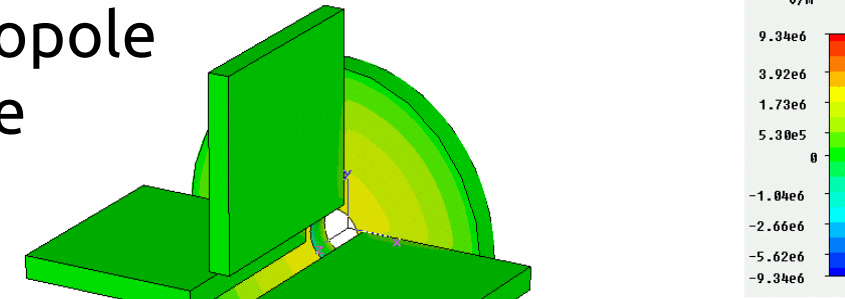
Cavity BPM

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



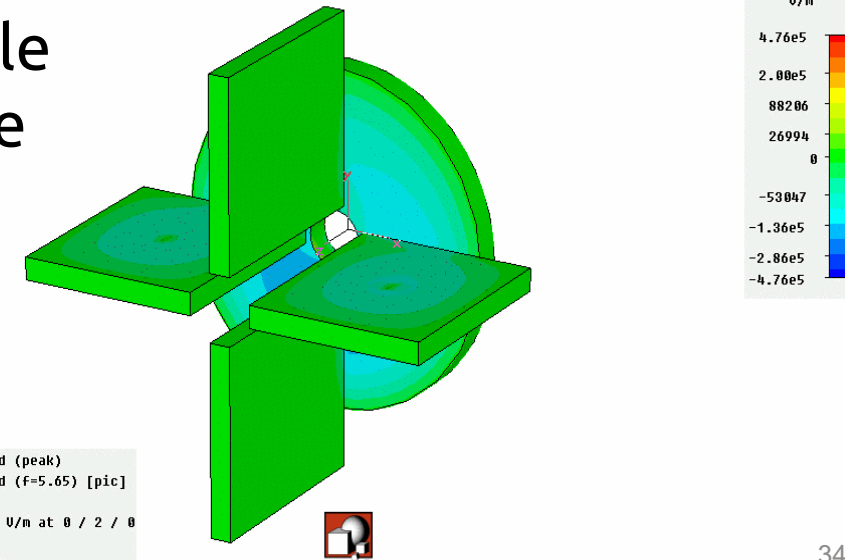
Courtesy of D. Lipka,
DESY, Hamburg

Monopole mode



Type E-Field (peak)
Monitor e-field (f=3.88) [pic]
Component Normal
Maximum-3d 1.17338e+007 U/m at -3.5 / 3.5 / 0
Frequency 3.88
Phase 0 degrees

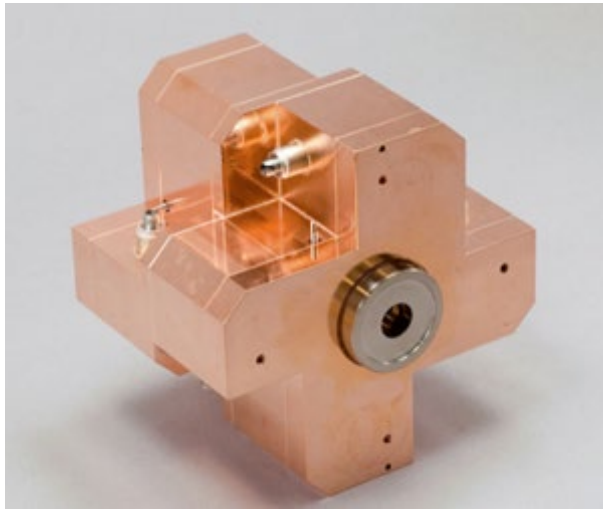
Dipole mode



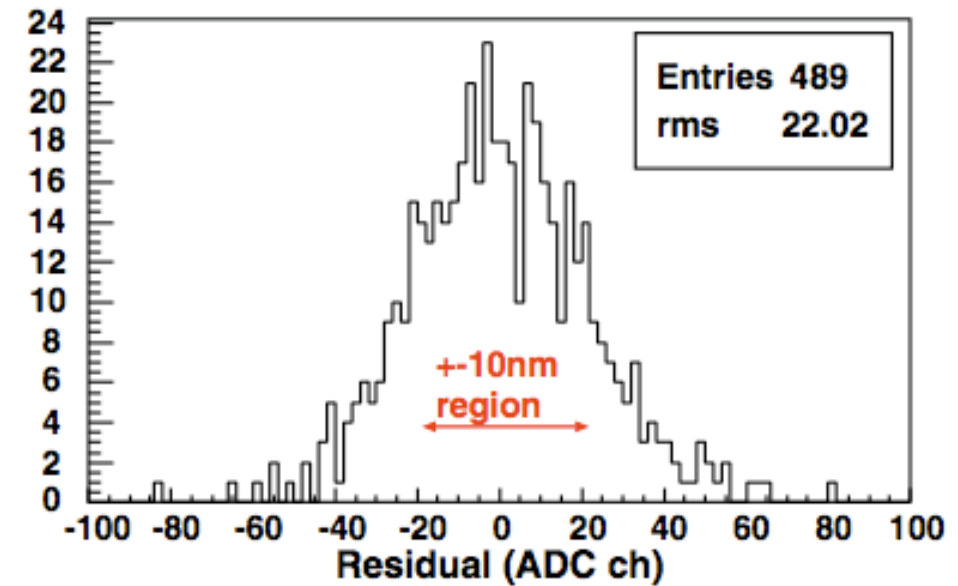
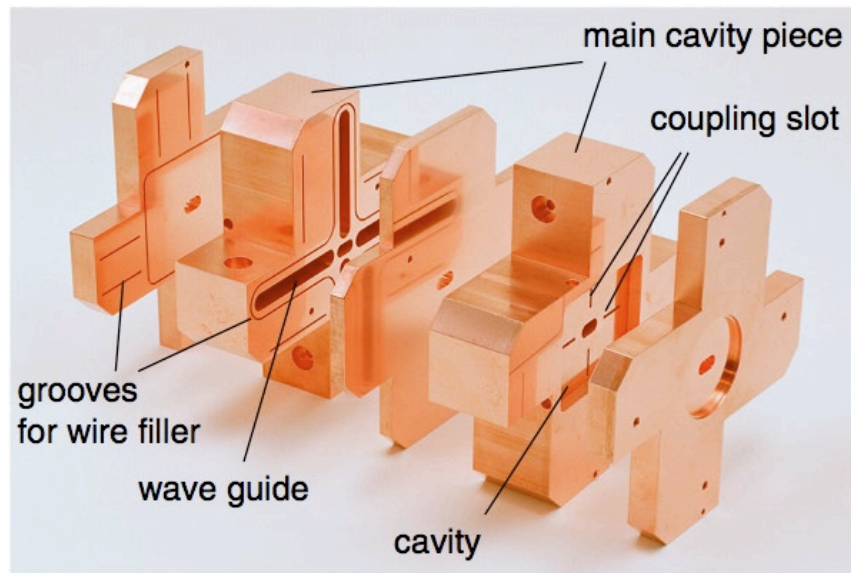
Type E-Field (peak)
Monitor e-field (f=5.65) [pic]
Component Normal
Maximum-3d 639869 U/m at 0 / 2 / 0
Frequency 5.65
Phase 0 degrees

Cavity BPM example: prototype for ILC Final Focus

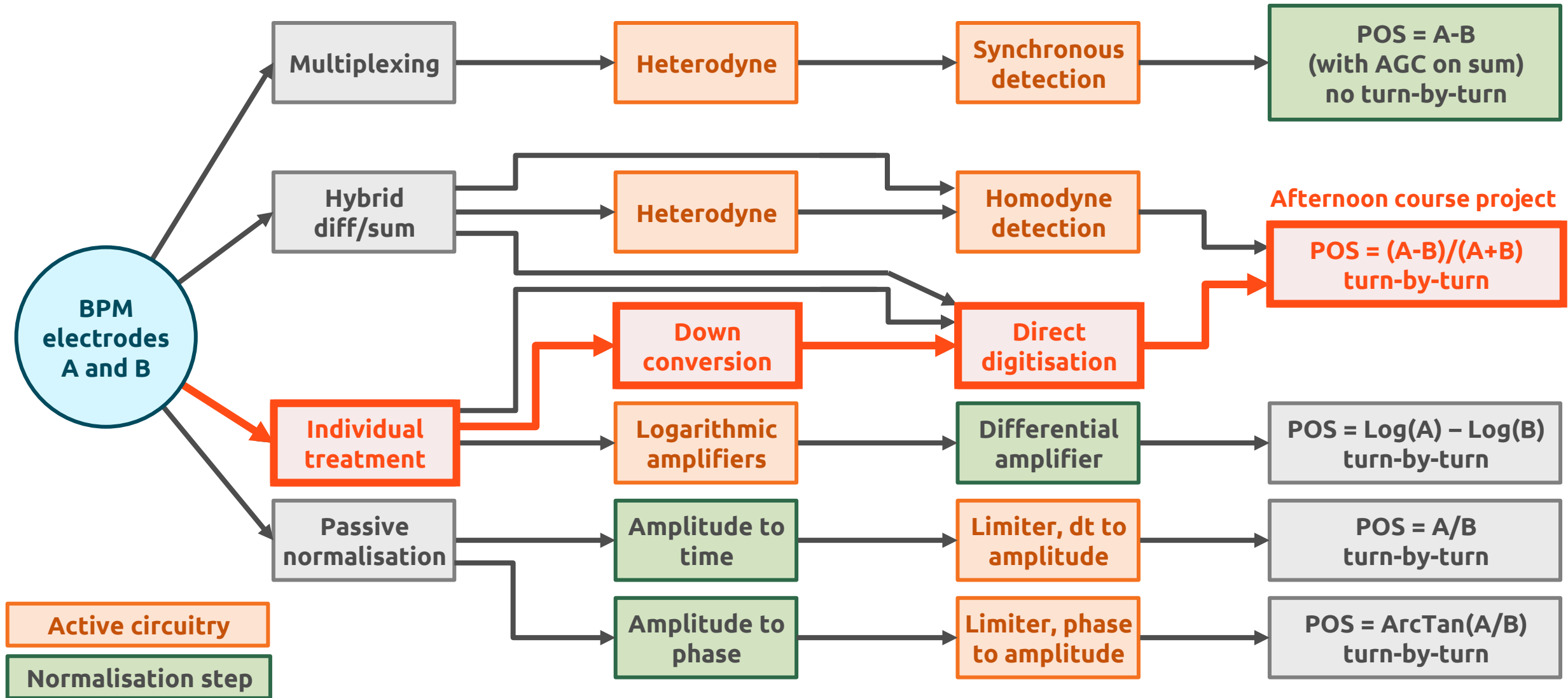
- Required resolution of 2 nm in a 6×12 mm oval beam pipe
- Demonstrated with beam: astonishing resolution of **8.7 nm** at ATF2 (KEK, Japan)



Courtesy of D. Lipka & Y. Honda

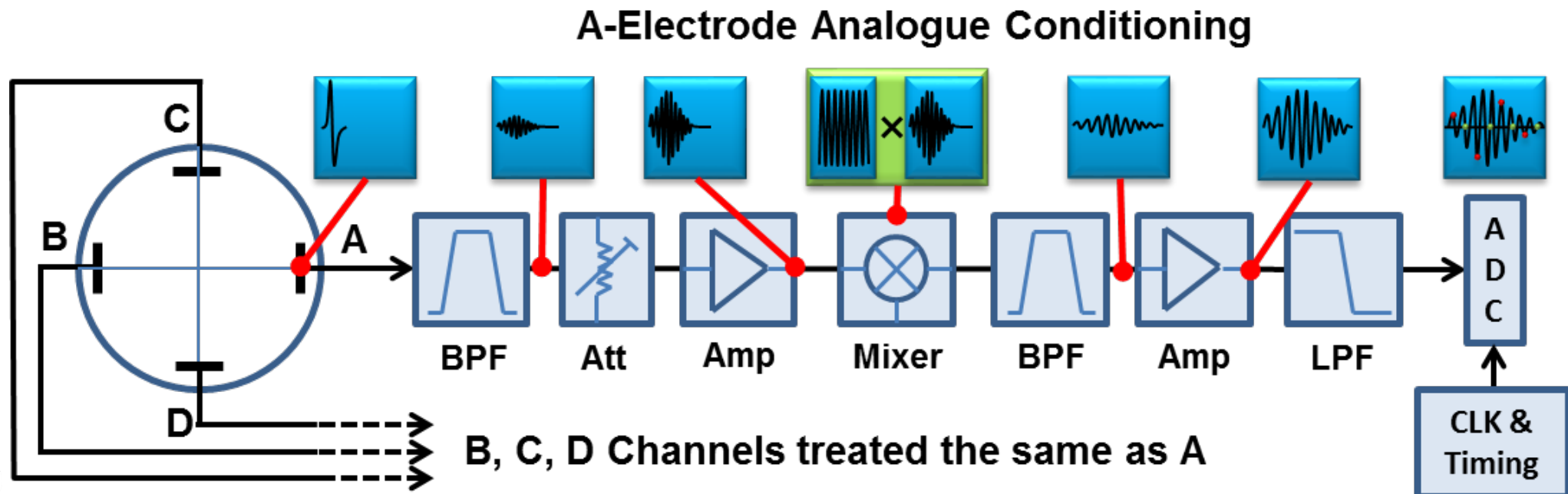


BPM data acquisition system families



An example of a modern BPM data acquisition system

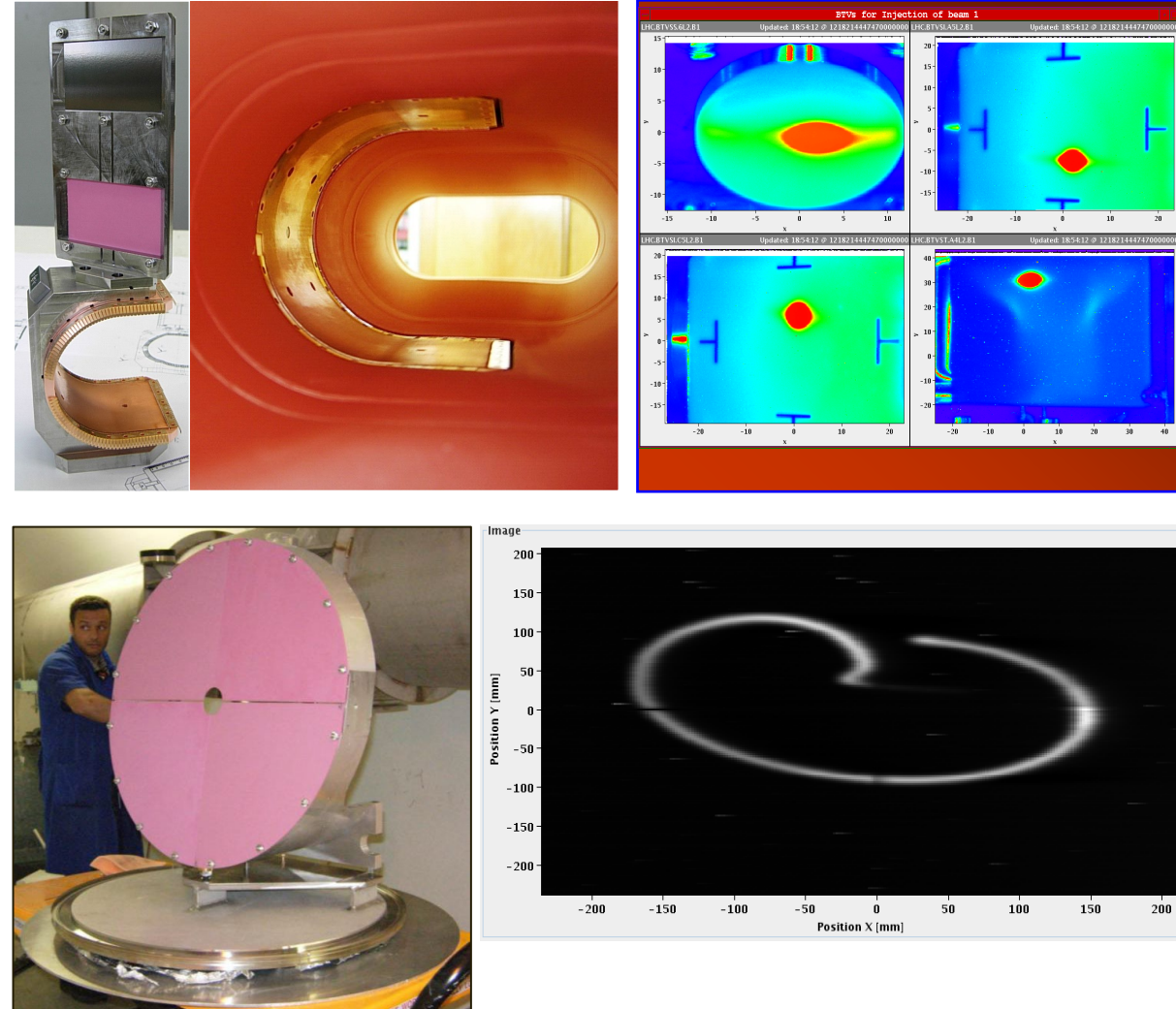
- Each electrode treated individually
- Frequency-domain processing – telecommunications industry approach
- Requires good-resolution and fast-sampling analogue-to-digital converters (ADCs)
 - BPM signal down-conversion to match the ADC characteristics
- Minimal analogue circuitry – most processing done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



Transverse beam size

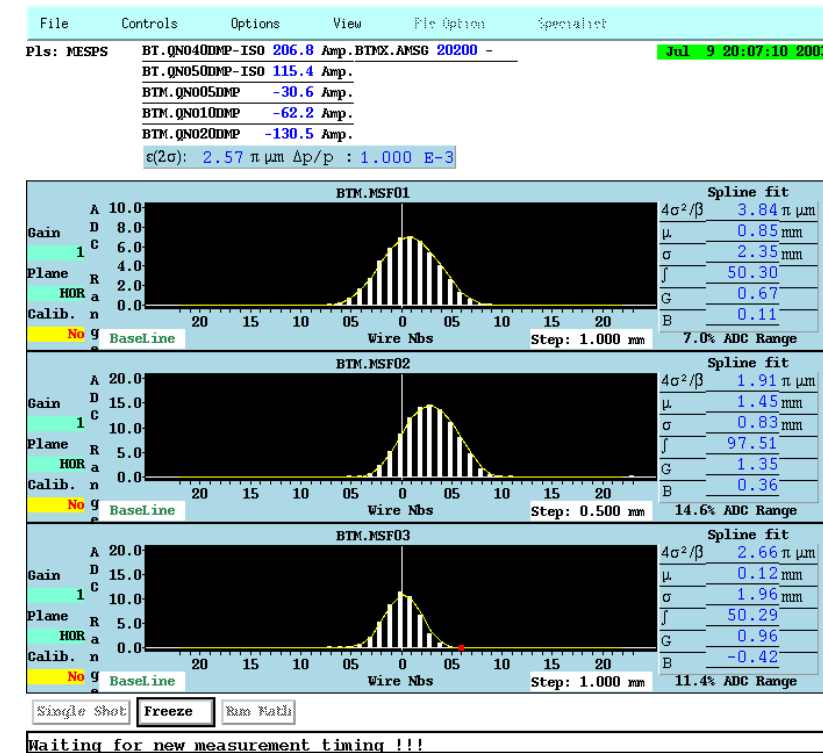
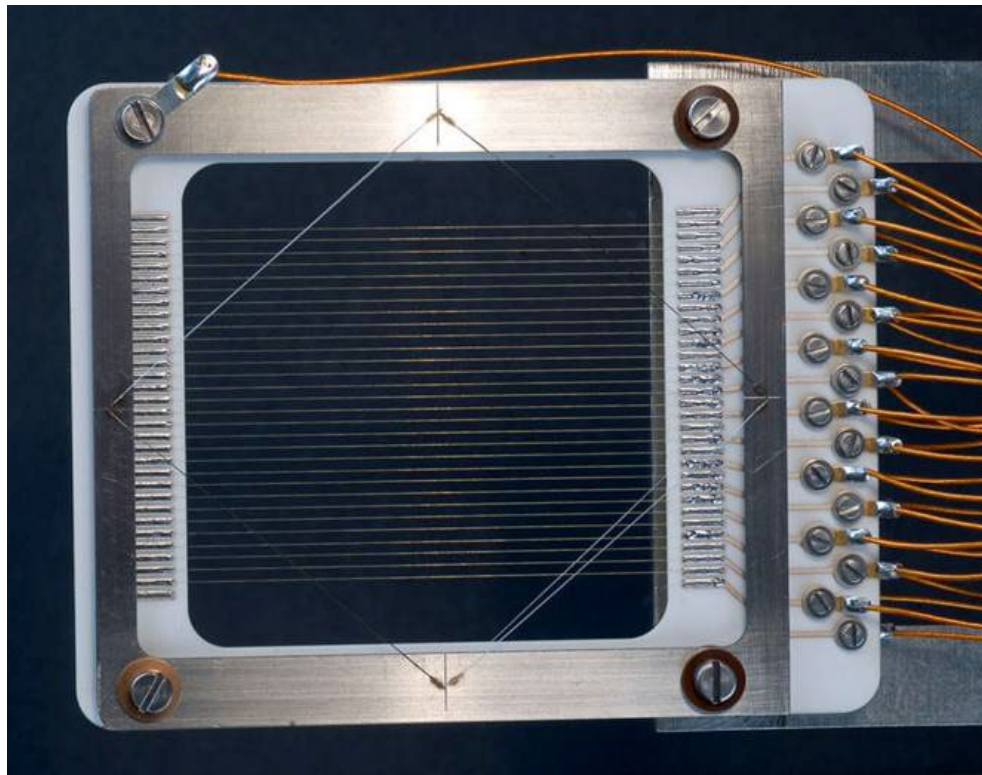
Luminescence / scintillating screens

- Light emission upon beam-screen interaction
- Straight-forward instrument for beam size and position monitoring
 - 2D information with CCD cameras
- Thick screens are destructive to the beam but work with low intensities



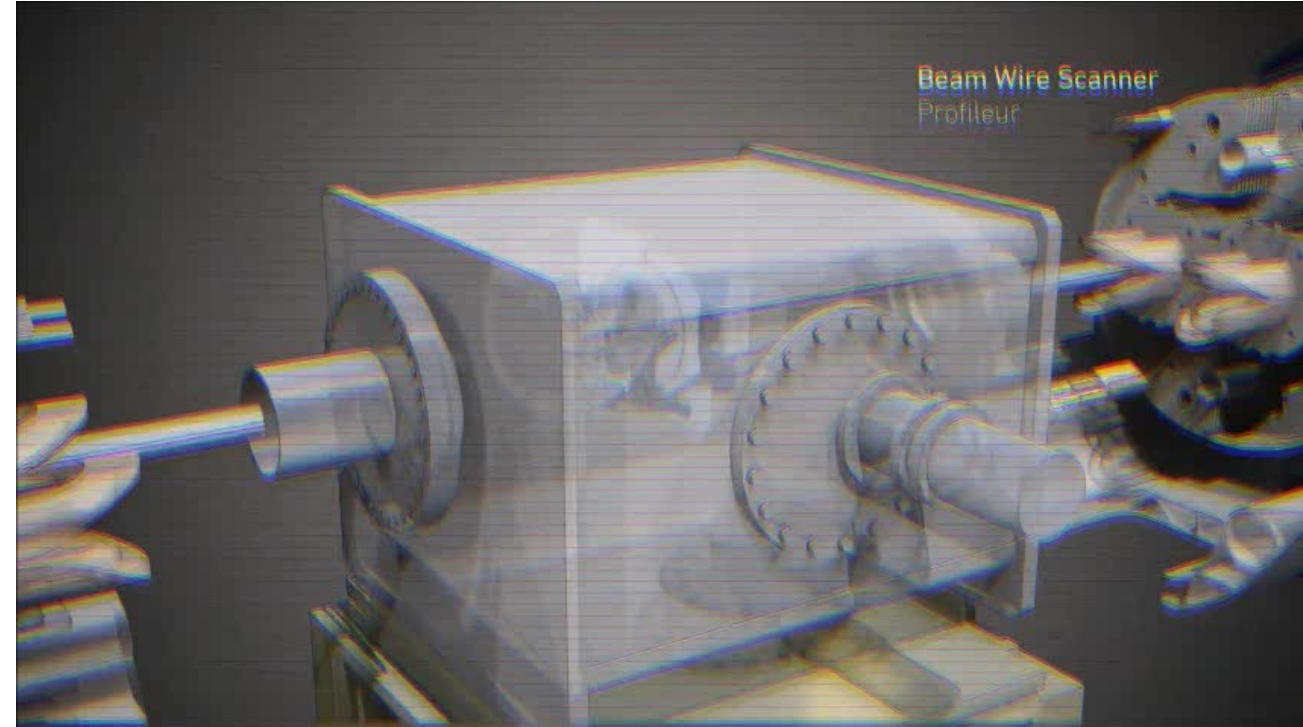
Secondary Emission Monitors (SEM, HARP)

- Secondary electrons emitted from beam-wire interaction resulting in an electric current in the wire
- Current in each wire read-out independently for beam profile reconstruction
- Wires can overheat = not ideal for circular machines



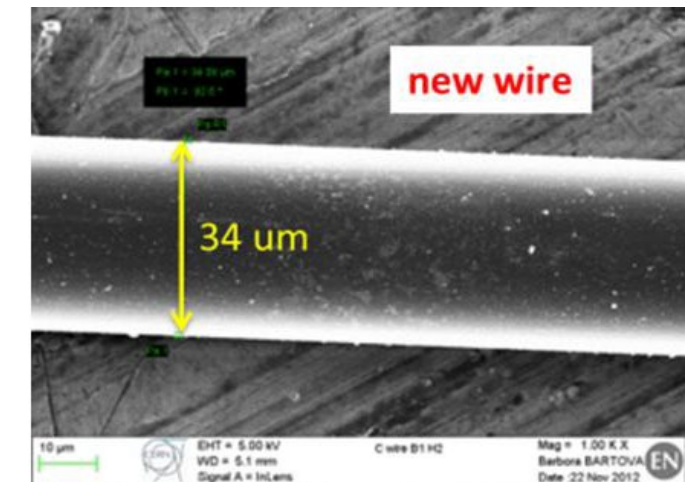
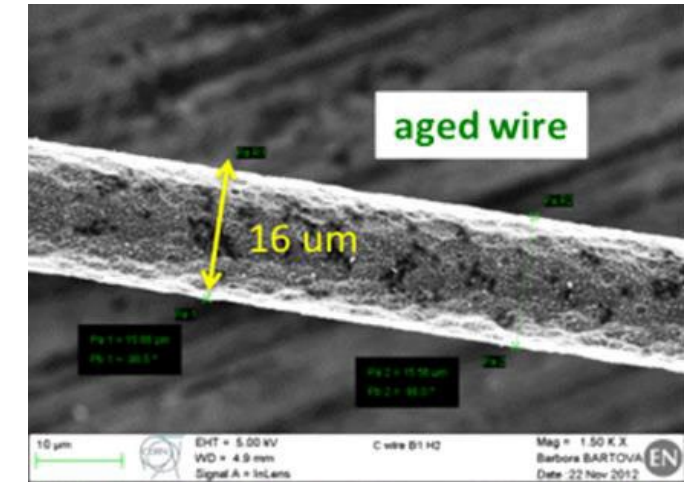
Wire scanners

- Single thin wire swept across the beam – correlate beam-wire interactions with the wire position
- Low-energy beams: current in the wire due to secondary emission
- High-energy beams: secondary shower measured outside of the vacuum (e.g. with scintillator)
- Absolute measurements that can be used for cross-calibration of other instruments



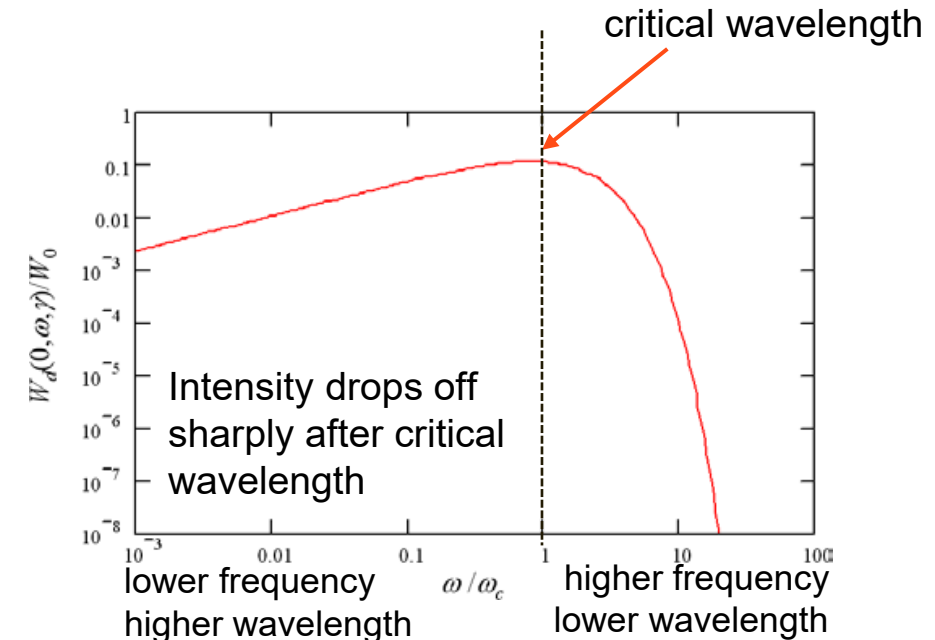
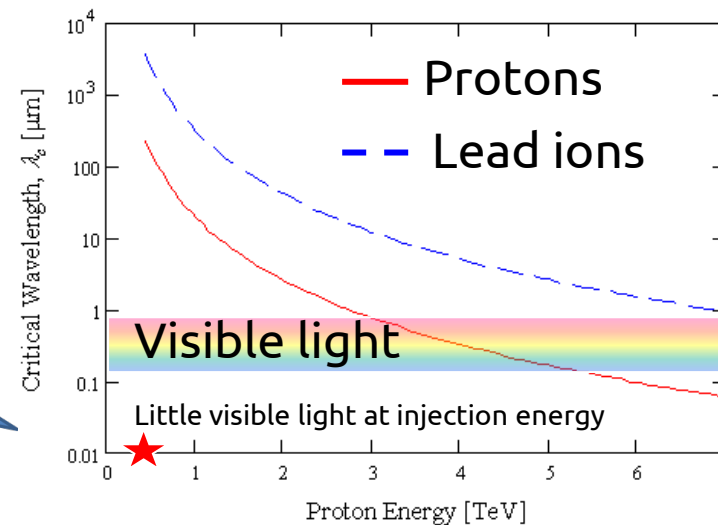
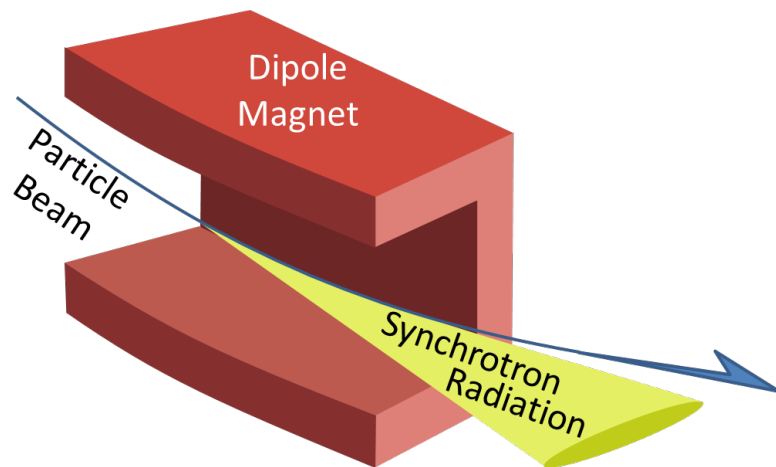
Wire scanners – limitations

- Wires can (and do!) get damaged
 - Mechanical failures – due to errors in motor controls
 - Melting / sublimation – energy deposition in the wire, large energy density for small beams
- Thermal behaviour of the wire depends on the heat capacity (increases with temperature!) and cooling (negligible during a ~ 1 ms scan time)
- Wire material: good mechanical properties, high heat capacity, high melting / sublimation point (e.g. 3915 K for carbon)



Synchrotron light monitors

- Light emission when the trajectory of a charged beam is bent (e.g. by a dipole, undulator, wiggler)
- Scientifically exploited in light sources
- Powerful diagnostic tool – non-invasive measurements
- Measurements in the visible range possible in some conditions

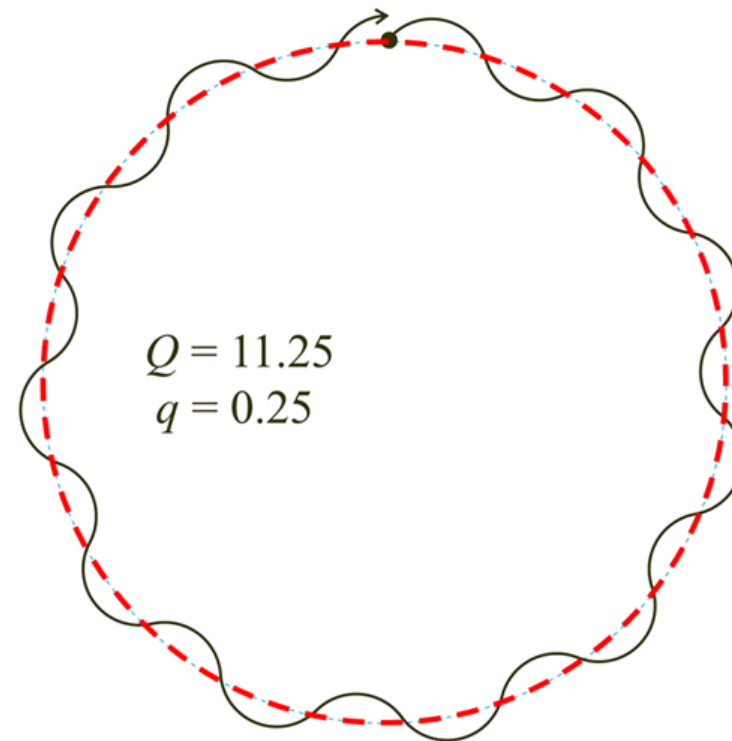
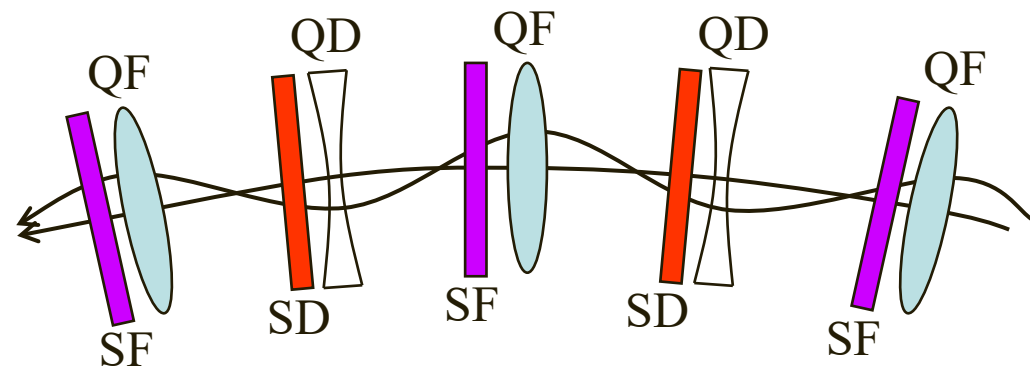


Tune measurement

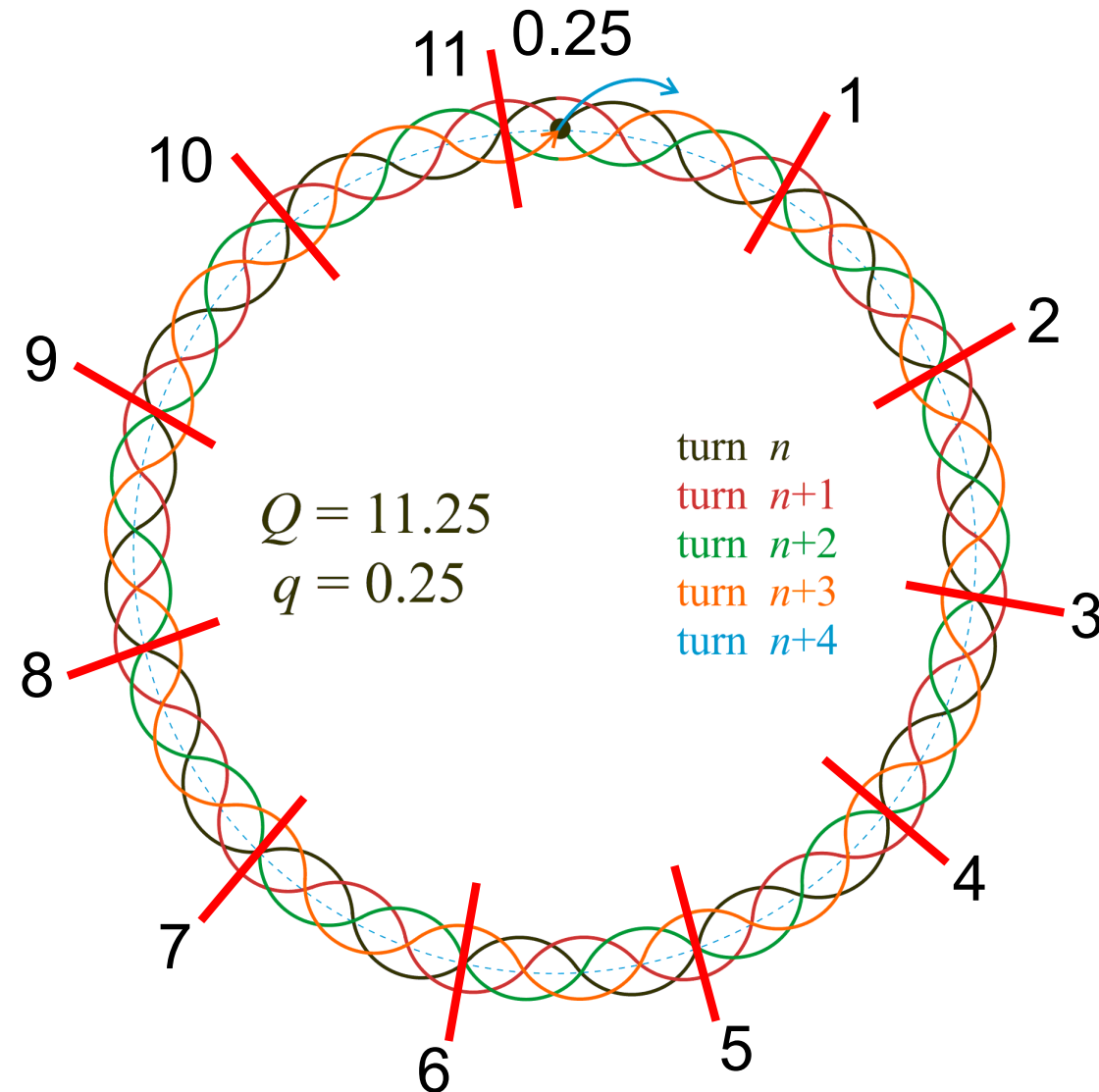


Accelerator tune

- Characteristic frequency of the magnetic lattice – betatron oscillation of off-axis beam particles
 - Set by the strength of quadrupoles
- For each transverse plane (H and V):
 - Q – full betatron tune
 - q – fractional tune (operating point)
- Real life is more complex
 - Oscillations in both planes are coupled
 - Betatron oscillations are non-linear at large amplitudes

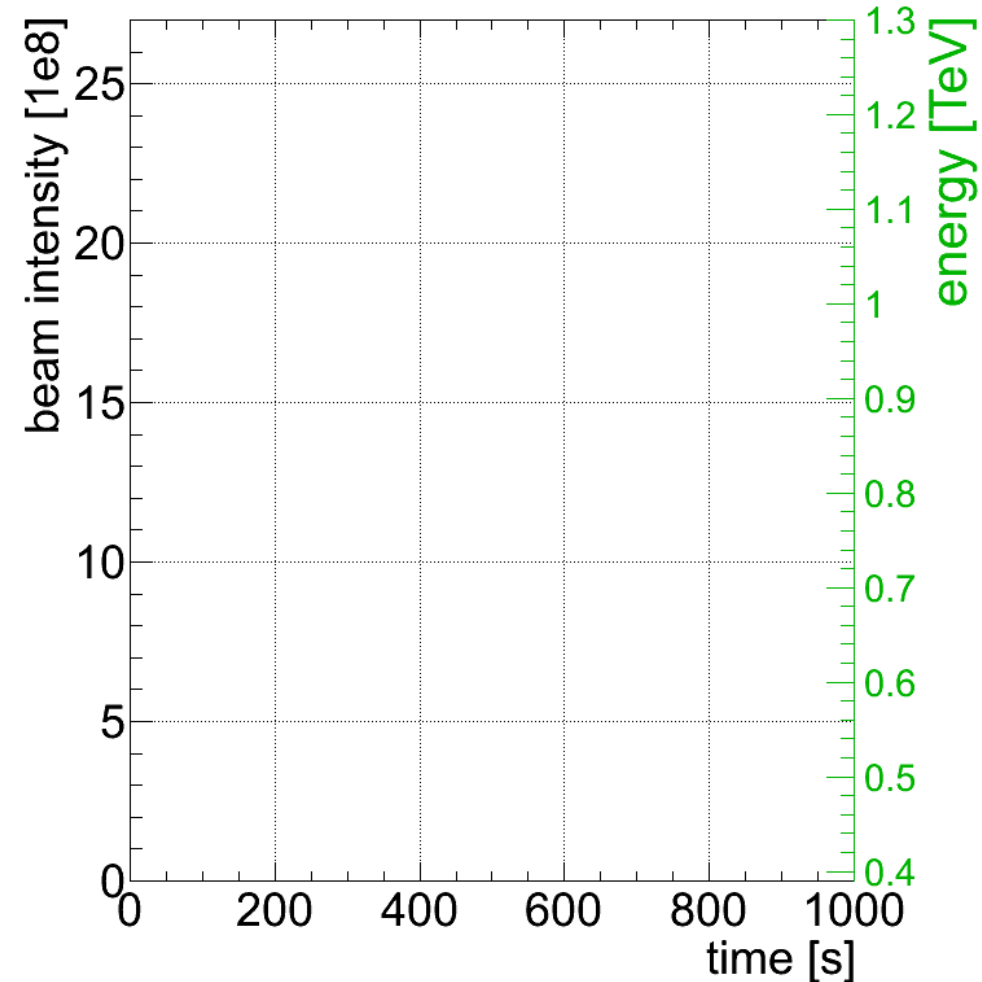
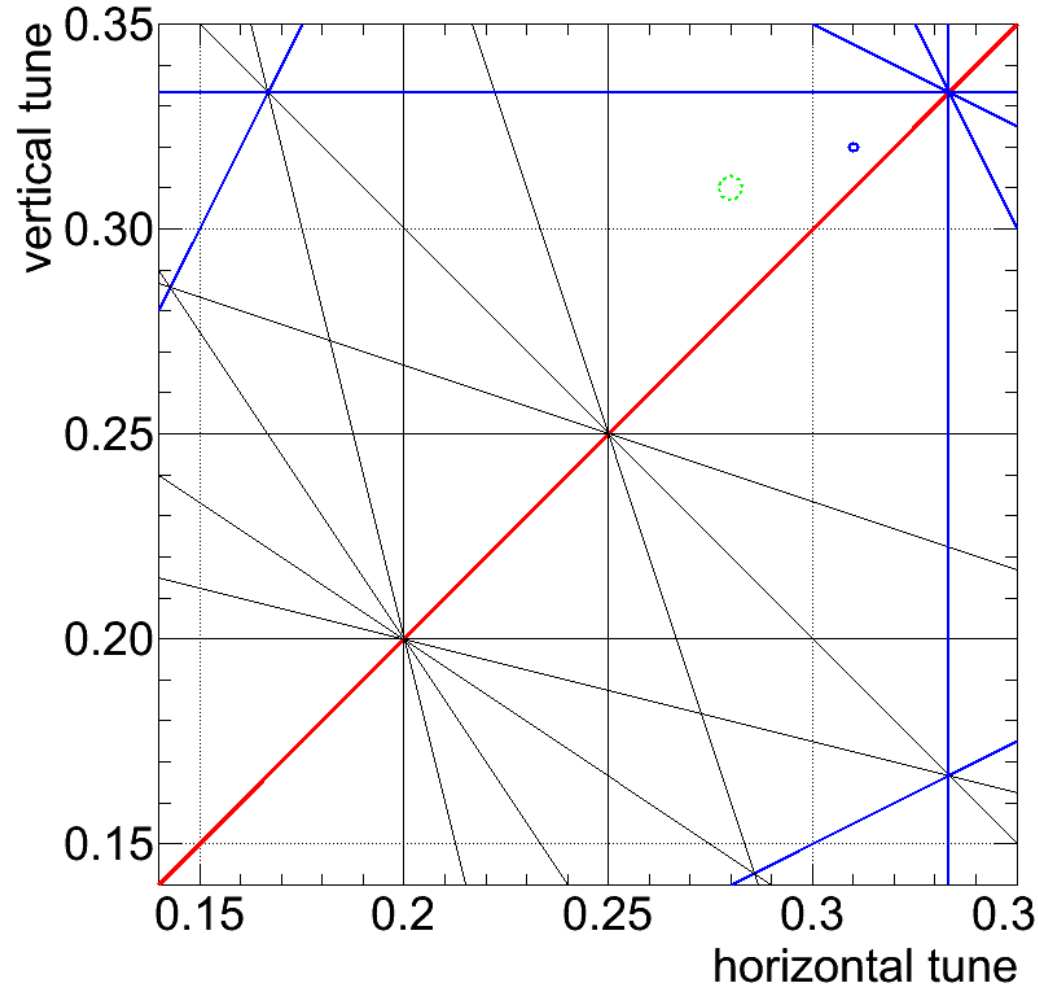


Betatron motion and accelerator tune



Importance of a good tune measurement and control

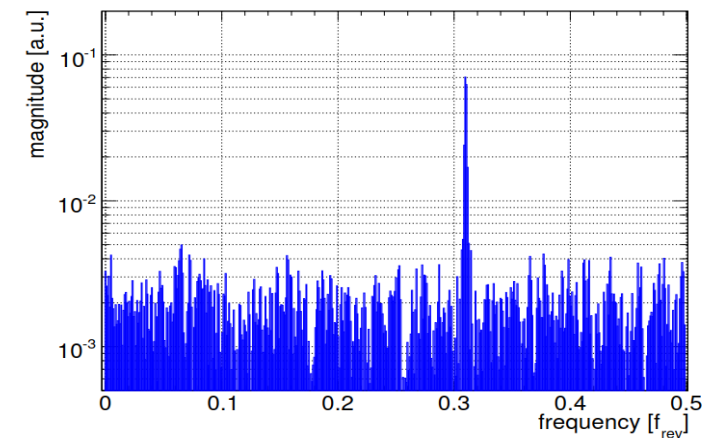
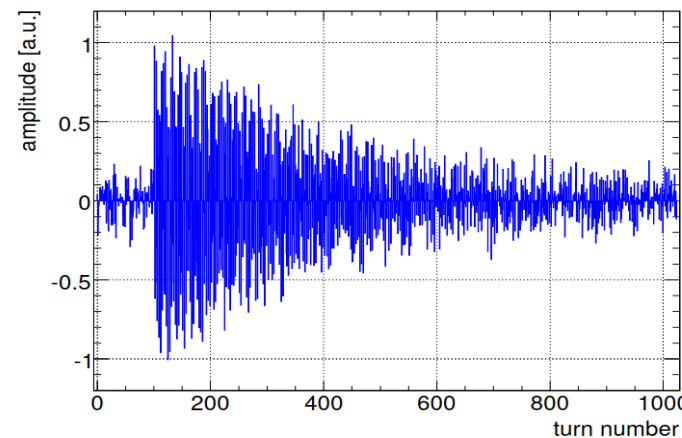
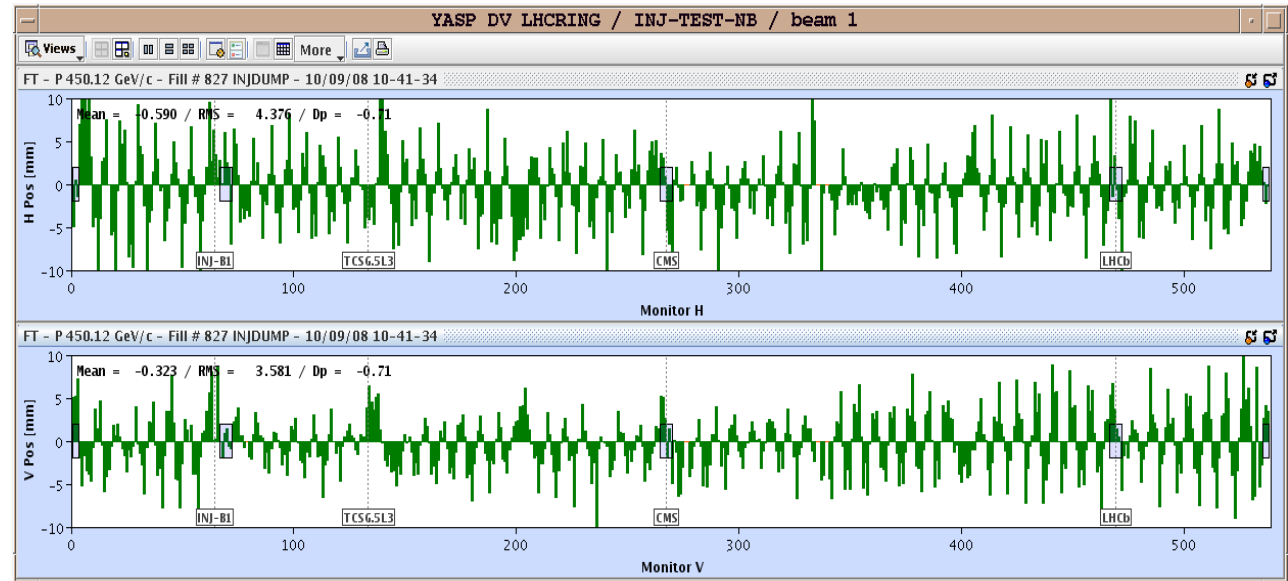
Early LHC - what happens during the energy ramp without good tune control



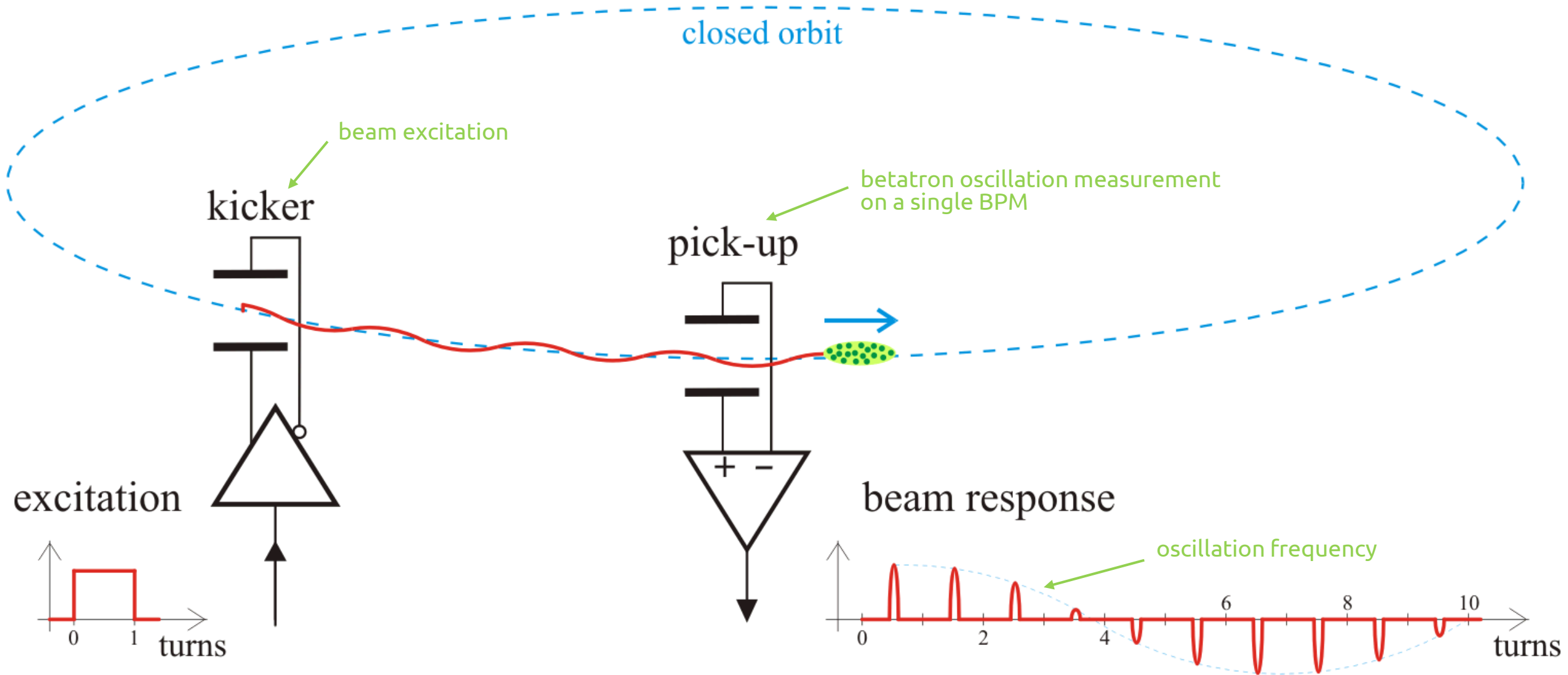
Tune measurements

- **Integer tune**
 - Seen in beam orbit measurements of all BPMs
- **Fractional tune (q)**
 - Seen in turn-by-turn measurements of a single BPM if a beam is kicked
 - Resonant frequency (q) identification in the frequency domain through the Fourier Transform of time domain beam position samples

LHC: ~ 550 BPMs per beam; Integer tunes: H: 59, V: 64

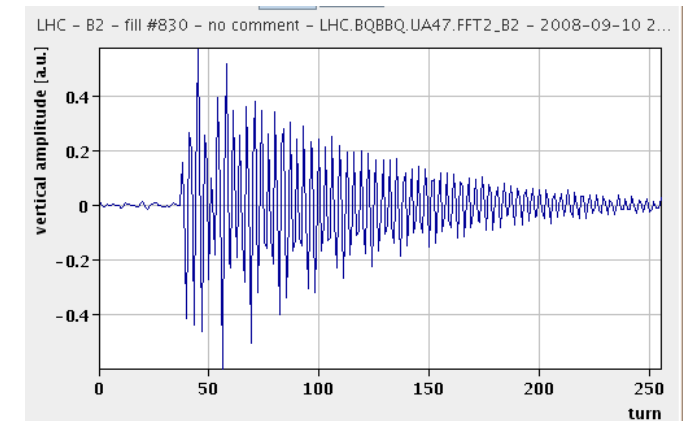
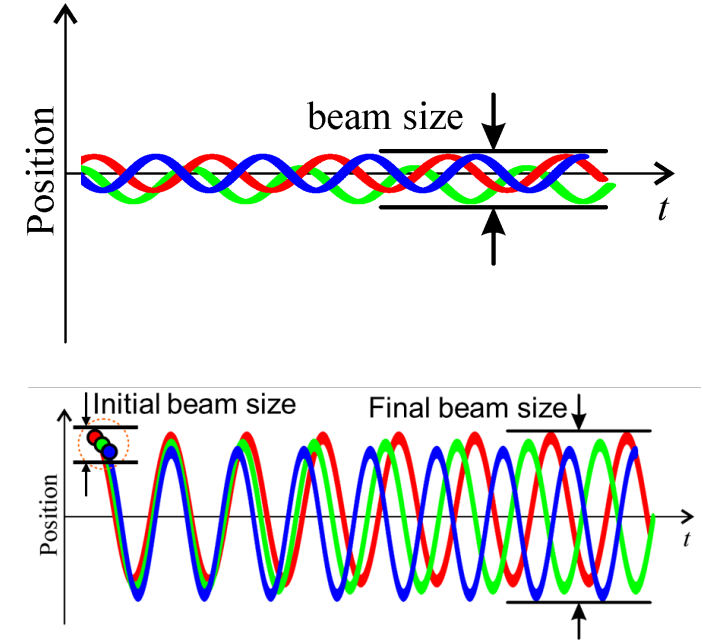


Tune measurements with an excitation



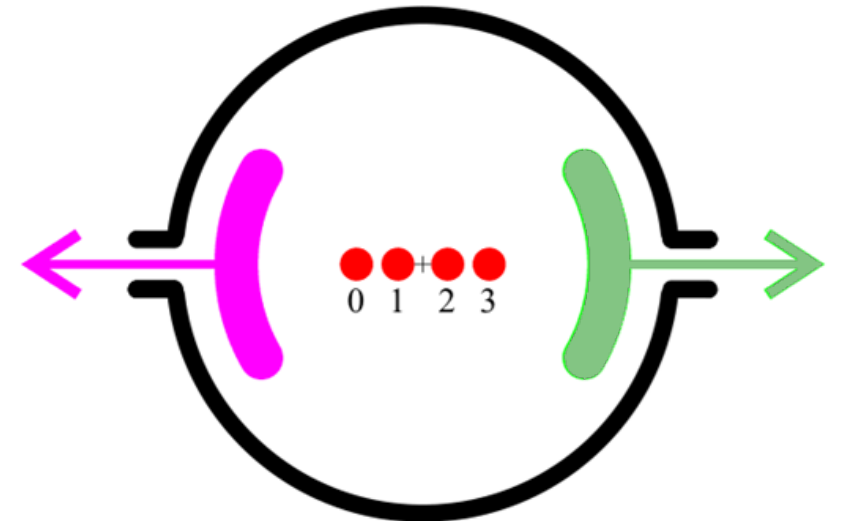
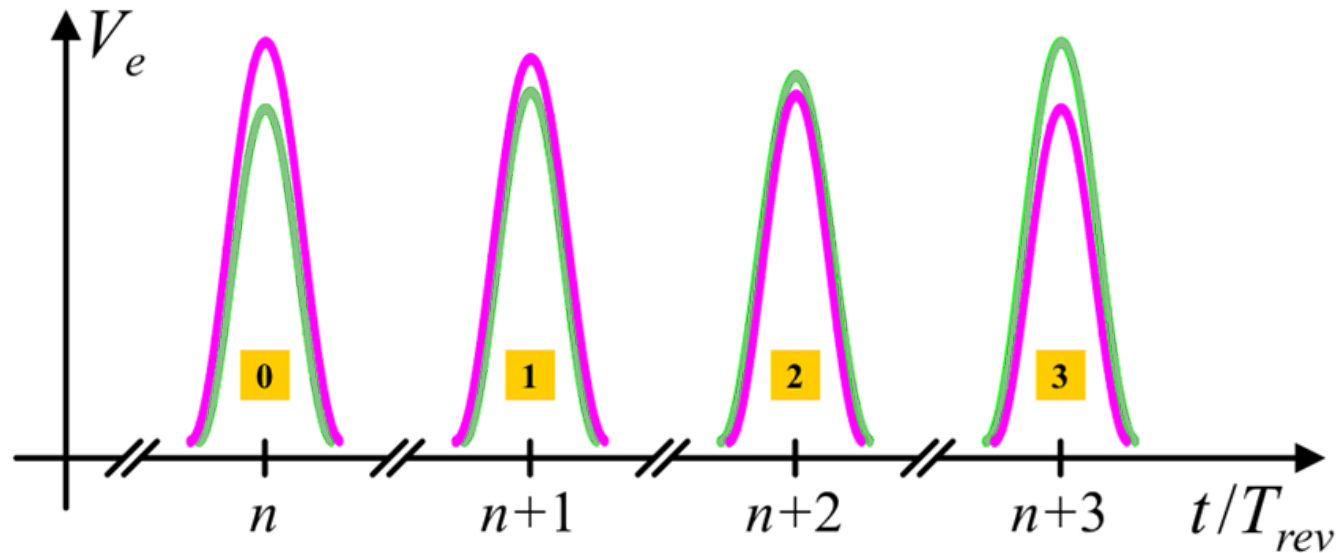
Betatron motion and accelerator tune

- Beam size is defined by the incoherent betatron motion of all particles
- Momentum spread of beam particles leads to a spread of focusing strength by the quadrupoles and to a spread in the frequency of the betatron oscillations (chromaticity)
- Coherent oscillations eventually de-cohere
 - Hadrons do not forget and once hit they keep oscillating, as there is no damping mechanism as for the electrons (synchrotron radiation)
 - For hadrons any excitation must be kept as low as possible



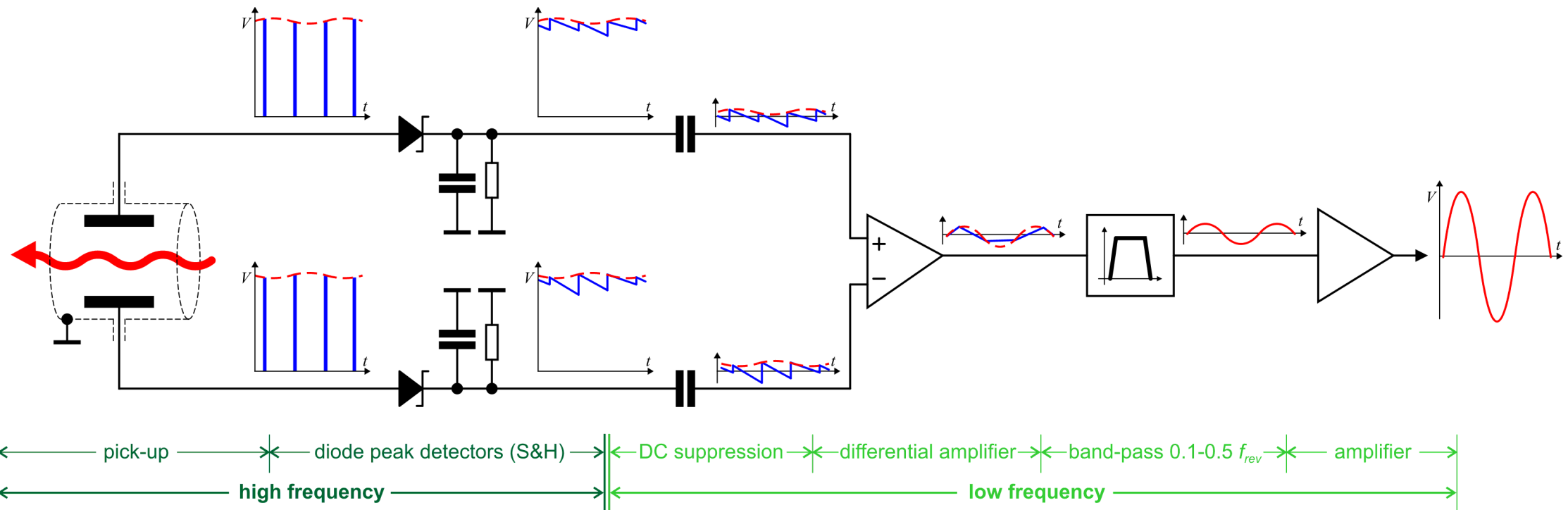
Tune measurements

- Pre-requisite: turn-by-turn position measurements from a BPM
- BPM electrode signal is proportional to the beam/bunch intensity and weakly modulated by the beam position (1-10% per mm of beam displacement)
 - Such signals are difficult to simulate in laboratory environment



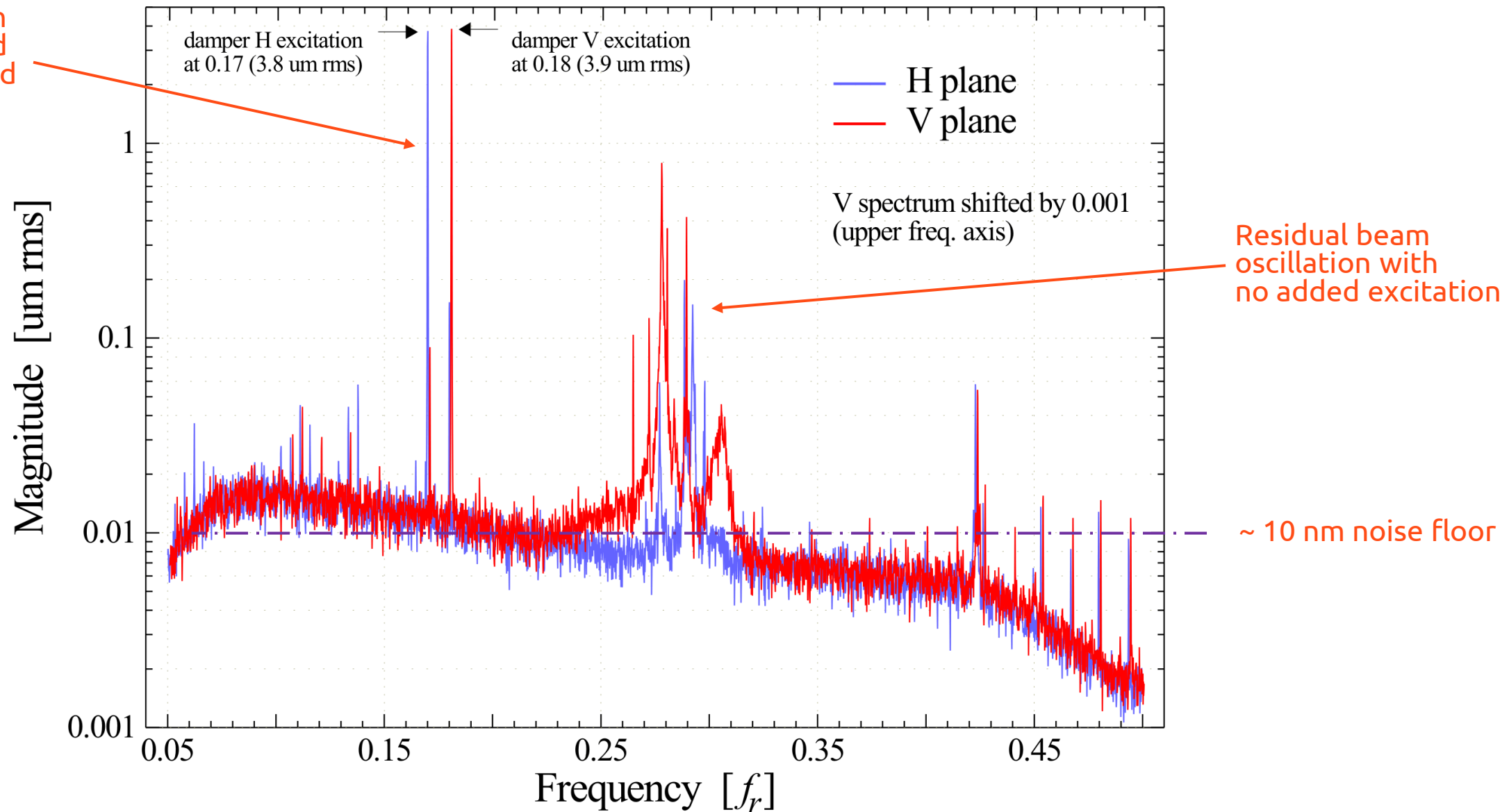
BaseBand Tune (BBQ) system (Direct Diode Detection)

- RF Schottky diodes: max peak voltage ~ 50 V per diode, several diodes in series possible (e.g. 6 for the LHC)
- Downmixing of the betatron modulation carried by nanosecond bunches to below the revolution frequency, allowing digital signal processing with inexpensive high-performance audio ADCs
- Similar to an AM radio receiver but with extremely low noise, very slow discharge and with brutal filtering of the carrier (revolution) frequency and the out-of-band signals



LHC BBQ performance with a single pilot bunch

Intentional beam excitations which can be measured by BPMs operated in an averaging mode



An SPS example of a real-time tune measurement

