

Beam Instrumentation and Diagnostics

Part 1

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CAS

**Introductory level course on
Accelerator Physics**

Resources and References

- Peter Forck: *Lecture on Beam Instrumentation and Diagnostics* at the Joint University Accelerator School (JUAS), see also the extended Bibliography <http://www-bd.gsi.de/conf/juas/juas.html>
- M.G. Minty and F. Zimmermann: *Measurement and Control of Charged Particle Beams*, Springer Verlag 2003, (book).
- Conference series: **IBIC** (International Beam Instrumentation Conference), **IPAC** (International Particle Accelerator Conference), historic: **DIPAC** (Workshop on Beam Diagnostics and Instrumentation for Particle Accelerators), **BIW** (Beam Instrumentation Workshop)
- CERN Accelerator Schools (CAS):
<http://cas.web.cern.ch/cas/CAS%20Welcome/Previous%20Schools.htm> and http://cas.web.cern.ch/cas/CAS_Proceedings.html
 - Rhodri Jones et al.: *Introduction to Beam Instrumentation and Diagnostics*, CERN-2014-009.
 - Daniel Brandt (Ed.), 2008 CAS on *Beam Diagnostics for Accelerators*, Dourdan, CERN-2009-005 (2009).
 - Heribert Koziol, *Beam Diagnostic for Accelerators*, Univ. Jyväskylä, Finland, 1992, CERN 94-01, <http://cas.web.cern.ch/cas/CAS%20Welcome/Previous%20Schools.htm>
- Jacques Bosser (Ed.), *Beam Instrumentation*, CERN-PE-ED 001-92, Rev. 1994

Introduction

- Beam Instrumentation is a very wide subject; with a large range of technologies and fields involved, including:
 - Accelerator physics
 - understand the beam parameters to be measured
 - distinguish beam effects from sensor effects
 - Particle physics and detector physics
 - understand the interaction of the beam with the sensor
 - RF technology
 - Optics
 - Mechanics
 - Electronics
 - Analogue signal treatment
 - Low noise amplifiers
 - High frequency analogue electronics
 - Digital signal processing
 - Digital electronics for data readout
 - Software engineering
 - Front-end and Application Software

- Aim: assist in commissioning, tuning and operating the accelerator and to improve performance
- In this presentation:
 - Explain working principles of some of the most important instruments
 - Give indication on achievable performance
 - Give selected examples from operating machines and current developments

Measured Quantities

- Beam intensity
- Ideally: 6D phase space of the beam
- Real measurements: mean values and 1D-projection, some 2D-projections
 - Transverse position (mean x , y) → trajectory and orbit
 - Transverse profile
 - Bunch length, bunch shape
 - Mean momentum and momentum spread
 - Emittance and 2D phase space reconstruction (transverse and longitudinal)
 - Beam halo measurements
- Tune, chromaticity, coupling, beta function, dispersion
- Beam Losses
- Polarisation
- Luminosity

Classifications and Selected Devices

- **Singe pass machine** (LINAC and transport lines, also dedicated measurement lines) ↔ **multi pass machine** (synchrotron)
- **Total Beam Energy** (beam particles x particle energy) low ↔ high
- **Non-intercepting** ↔ **Intercepting / Perturbing** ↔ **Destructive**. Often depending on:
 - Beam quantitates (intensity, energy, particle type)
 - Single pass or multi pass
- Different devices (techniques) to measure the same quantity ↔ Same device to measure different quantities

PROPERTY MEASURED →	Intensity/charge	tr. Position	tr. Size/shape	tr. Emittance	Beam Halo	Beam Loss
	Current transformers	●				
Faraday cup	●					
Pick-ups	●	●				
Secondary emission monitors	●	●	●	●		
Wire scanners		●	●	●	●	
Scintillator screens		●	●	●		
OTR screen		●	●			
Residual-gas profile monitors		●	●	●		
Beam loss monitors						●

- Different Accelerator Laboratories have different names for the same type of device!

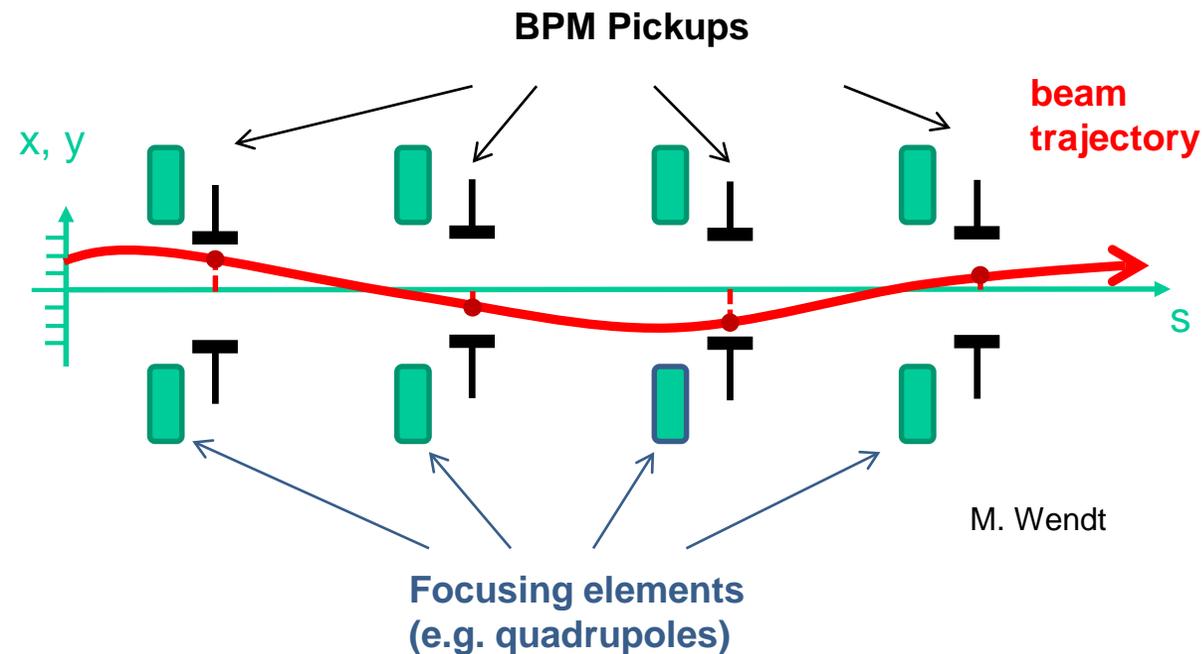
Harsh Environment

- Radiation (single event effects, radiation ageing, activation)
- Many sources of measurement noise and background
 - Place readout close to detector, but → radiation
- RF heating by the beam
- Sometimes: cryogenic temperatures
- Mostly: must operate in vacuum and be UHV compatible
- Accessibility and maintenance

Beam Position Monitors

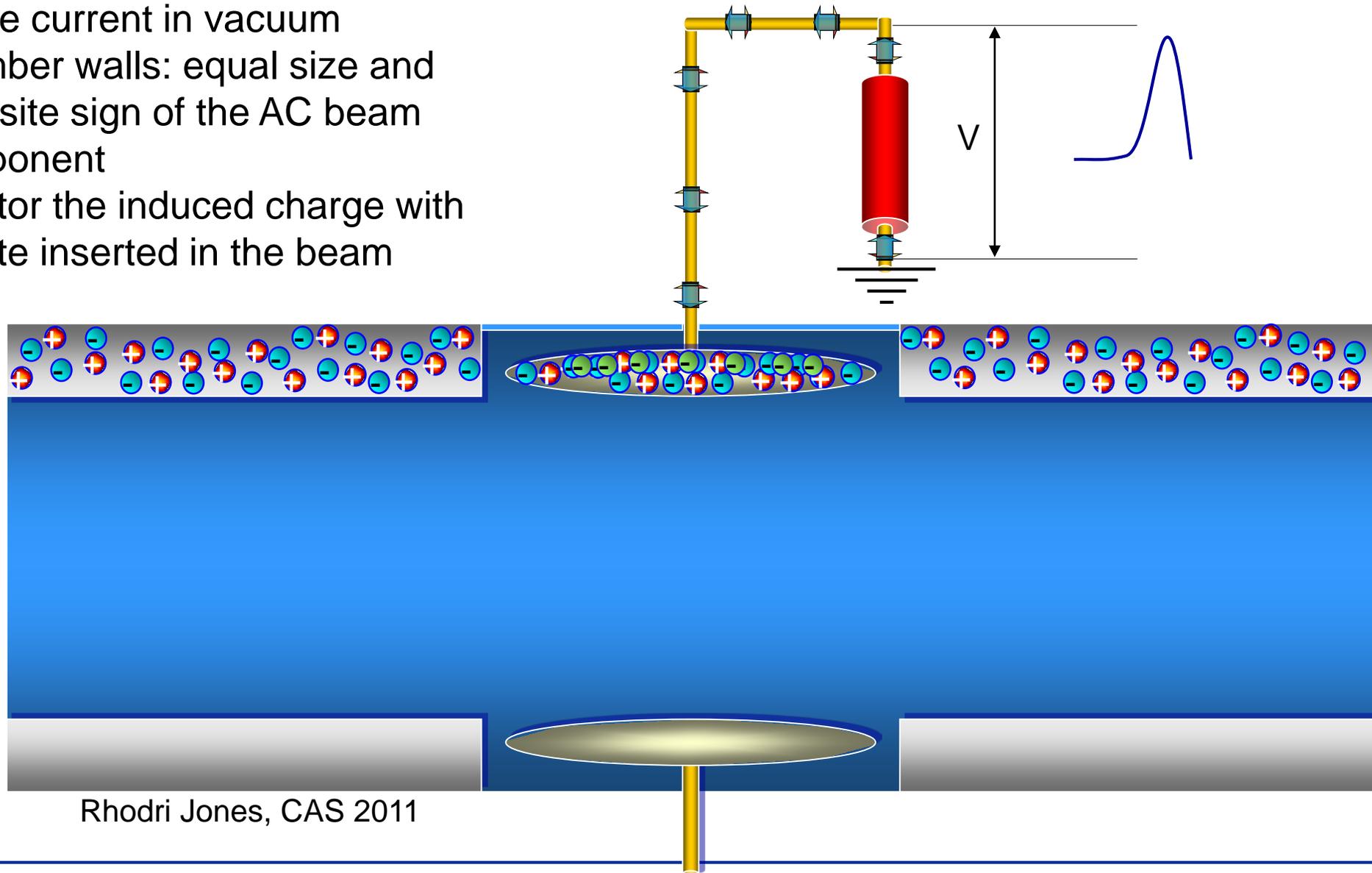
Capacitive Pick-Ups for Bunched Beams

- Among the most numerous instruments
- Measurements:
 - Transverse beam position (typically next to focusing elements)
 - Beam trajectory or closed orbit
 - injection oscillations
 - Tune and lattice function in synchrotrons



Capacitive Pick-Up – The Principle

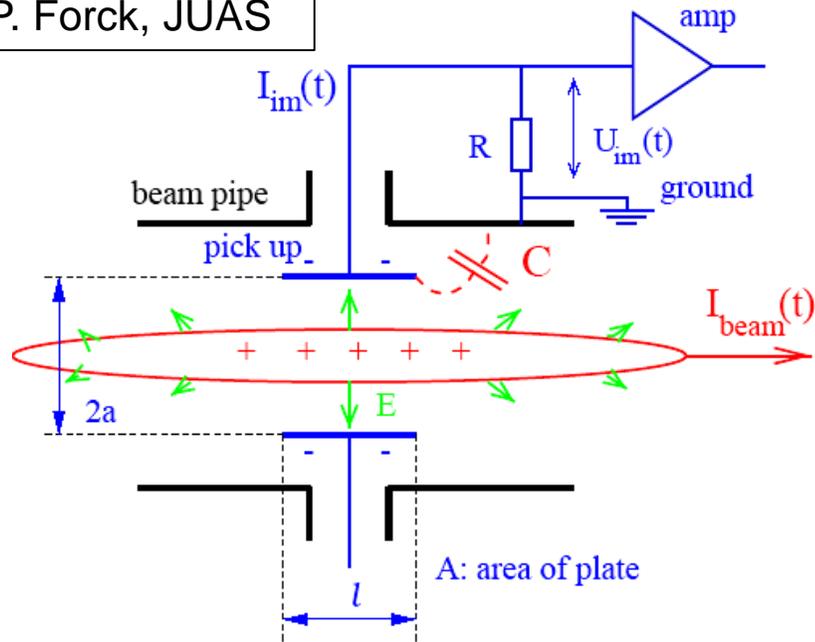
- Image current in vacuum chamber walls: equal size and opposite sign of the AC beam component
- Monitor the induced charge with a plate inserted in the beam pipe



Rhodri Jones, CAS 2011

Schematics and Simplified Equivalent Circuit

P. Forck, JUAS



$$I_{im} = \frac{A}{2\pi a l} \left(-\frac{l}{\beta c} \frac{dI_{beam}}{dt} \right) = \frac{A}{2\pi a l \beta c} i\omega I_{beam}(\omega)$$

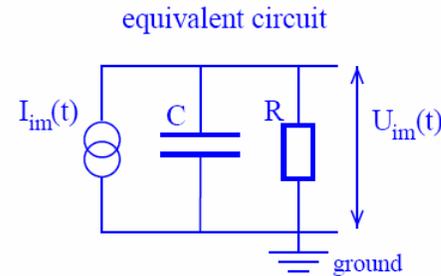
frequency domain: $I_{beam} = I_0 e^{-i\omega t}$

U_{im} ... voltage measured due to image current

R ... amplifier input resistor

ω ... frequency

βc ... beam velocity



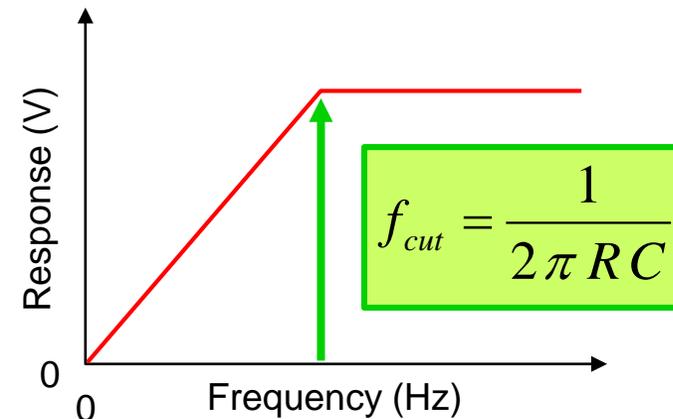
$$U_{im}(\omega) = \frac{R}{1 + i\omega RC} \cdot I_{im}(\omega)$$

$$U_{im}(\omega) = \frac{A}{2\pi a} \cdot \frac{1}{\beta c} \cdot \frac{1}{C} \cdot \frac{i\omega RC}{1 + i\omega RC} \cdot I_{beam}(\omega)$$

$$U_{im}(\omega) \equiv Z_t(\omega, \beta) \cdot I_{beam}(\omega)$$

Z_t ... longitudinal transfer impedance

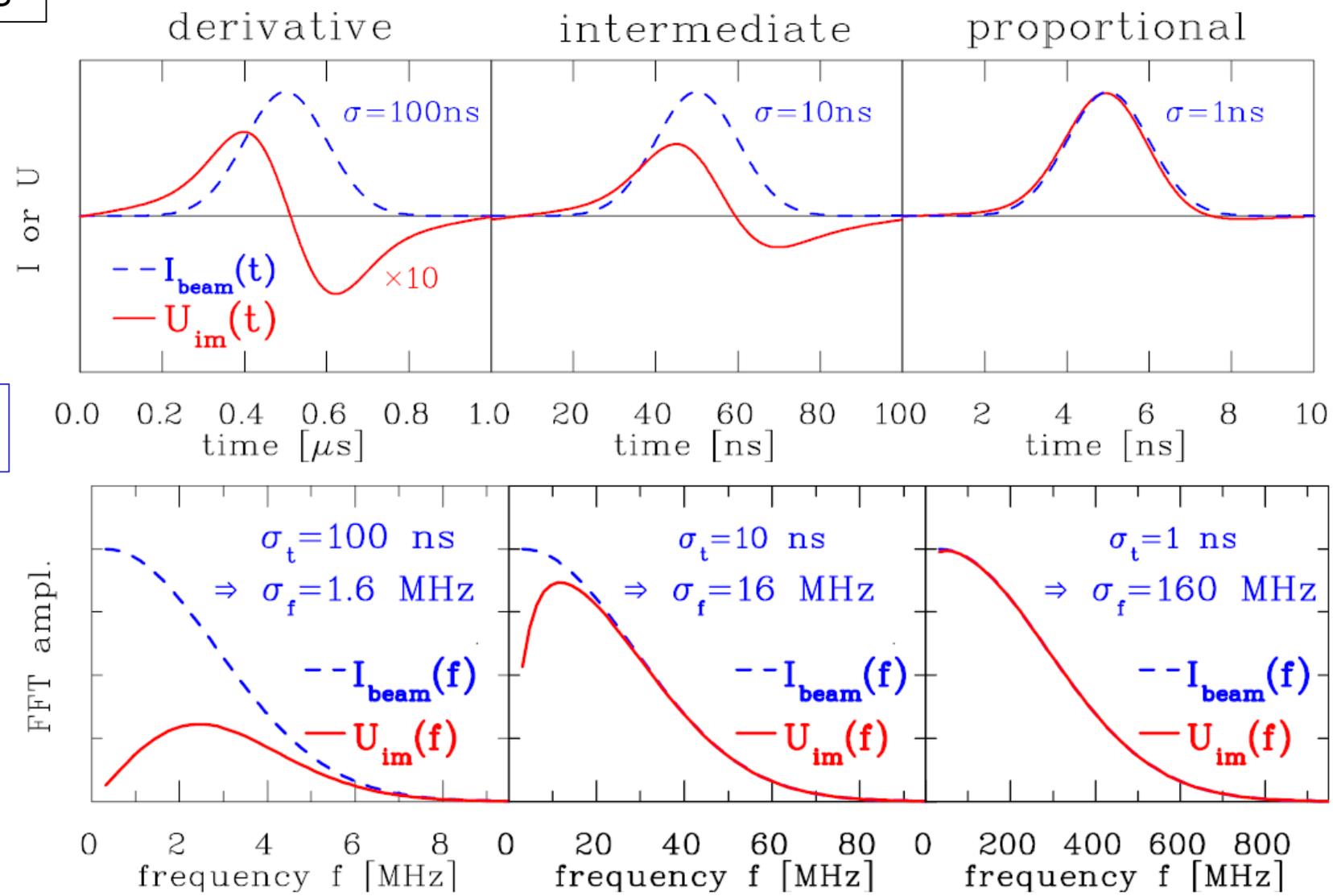
⇒ High pass characteristics with a cut-off frequency, f_{cut}



Example: Pick-up with Cut-off Frequency of 32 MHz

$$f_{cut} = \frac{1}{2\pi RC}$$

P. Forck, JUAS

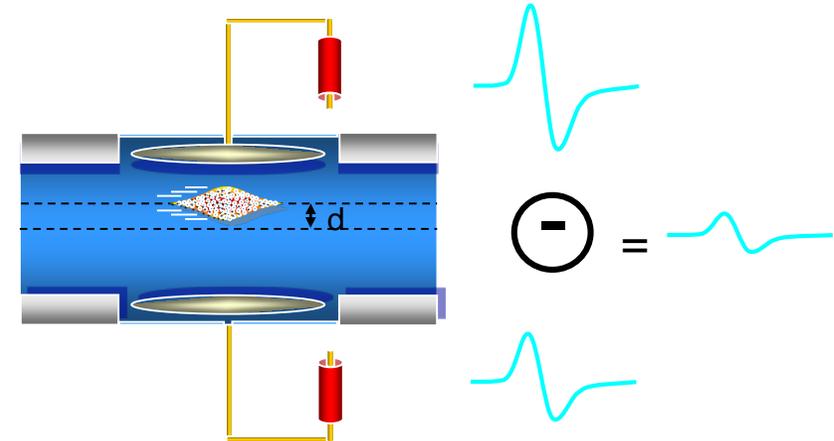


Fourier Transformation

Inverse Fourier Transformation

Beam Position

- Signal on each plate is proportional to the beam intensity
- The **difference signal** (ΔU), top - bottom, or left – right, is a measure of the **position of the beam center of mass**
- Normalization to the **sum signal** (ΣU) gives the **position**:
 - $x = \frac{1}{S_x(\omega, x, y)} \cdot \frac{\Delta U}{\Sigma U}$ ($S_x \dots$ position sensitivity)
- The **difference signal** (ΔU) is normally at least a factor 10 lower than the **sum signal** (ΣU)
- Difficult to do electronically without some of the intensity information leaking through
- When looking for small differences this leakage can dominate the measurement
- **Resolution** for typical apertures:
 - \approx tens μm turn-by-turn
 - \approx μm multi-turn resolution

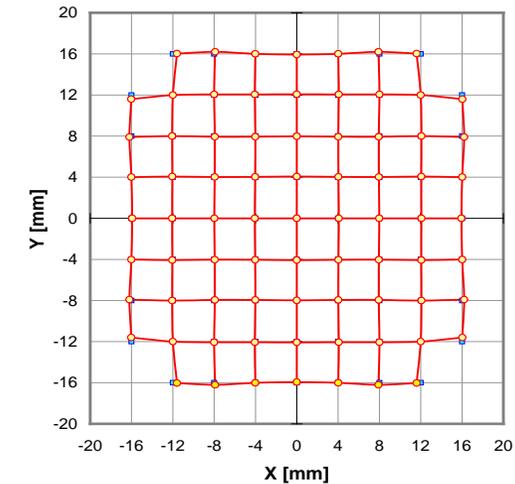
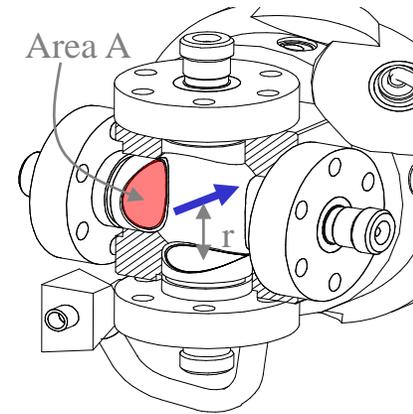


Measurement resolution: smallest change in the underlying physical quantity that produces a change in the measurement

Example: Button Pick-up

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

$$X = 2.30 \cdot 10^{-5} X_1^5 + 3.70 \cdot 10^{-5} X_1^3 + 1.035 X_1 + 7.53 \cdot 10^{-6} X_1^3 Y_1^2 + 1.53 \cdot 10^{-5} X_1 Y_1^4$$

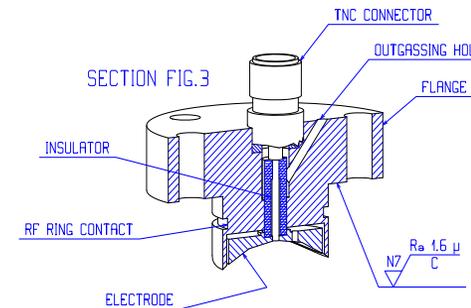


R. Jones, CAS

LHC buttons

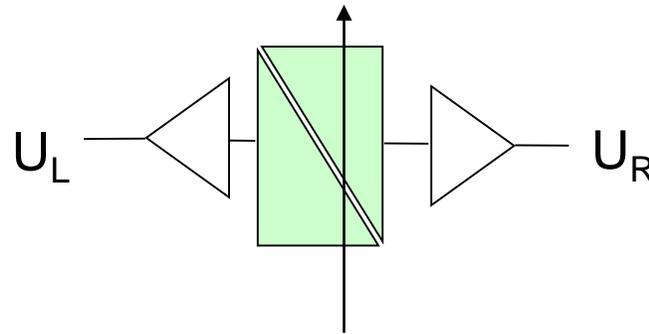
$$f_{cut} = \frac{1}{2\pi RC} = \frac{1}{2\pi \times 50\Omega \times 8pF} = 400MHz$$

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

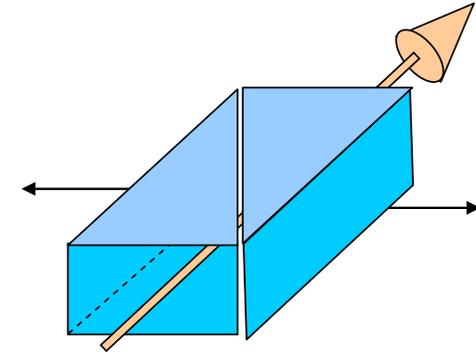


Shoebox Pick-up

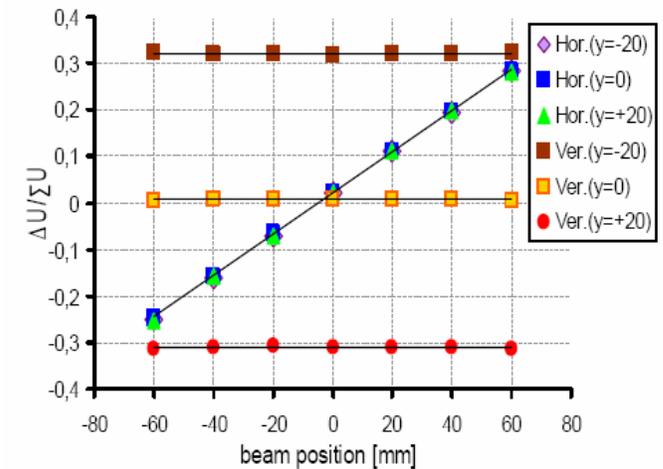
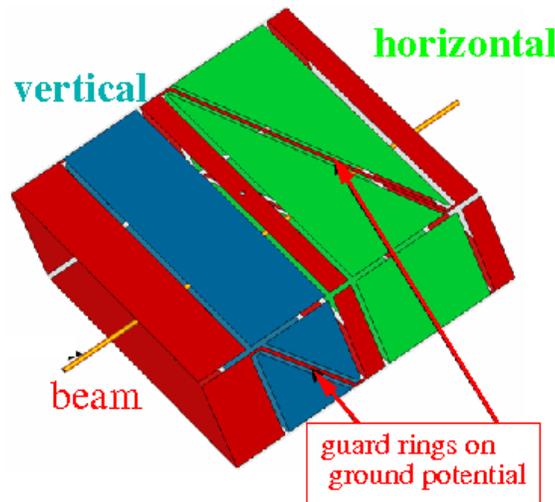
- ΔU gives linear position reading (no geometric correction)
- Condition: Linear cut: projection on the measurement plane must be linear:



$$X \propto \frac{U_L - U_R}{U_L + U_R} = \frac{\Delta U}{\Sigma U}$$



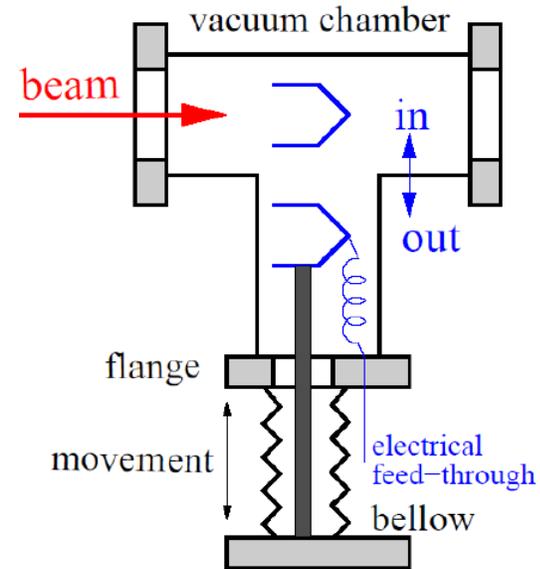
- Various geometries have been built, example from GSI optimization study (P.Kowina et al., DIPAC 2005)



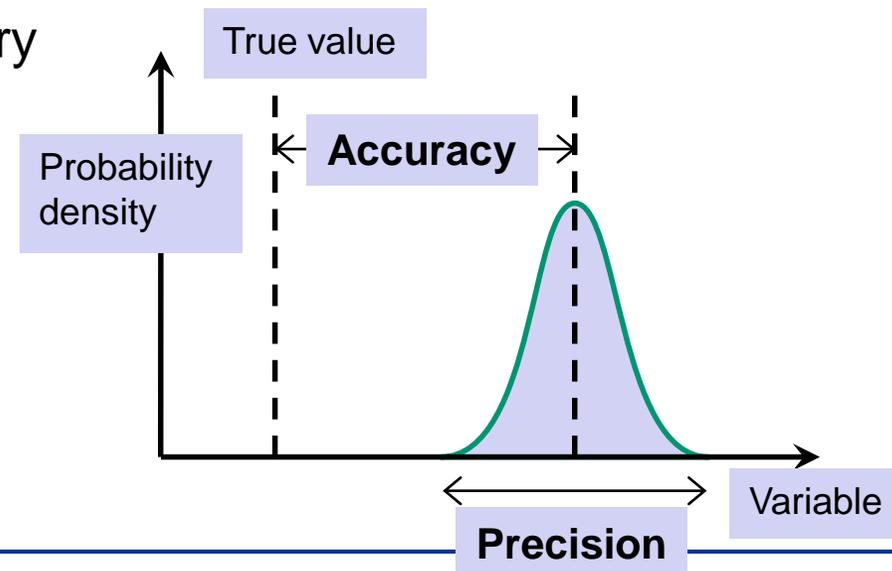
Beam Current

Faraday Cup

- Measurement of the beam's **electrical charges**
 - Low energies only
 - Particles are stopped in the device
→ **Destructive**
 - Sensitive to low currents: down to 1 pA can be measured
 - Creation of secondary electrons of low energy (below 20 eV)
 - Repelling electrode with some 100 V polarization voltage pushes secondary electrons back onto the electrode
 - Absolute accuracy:
 - ≈ 1% (some monitors reach 0.1%)

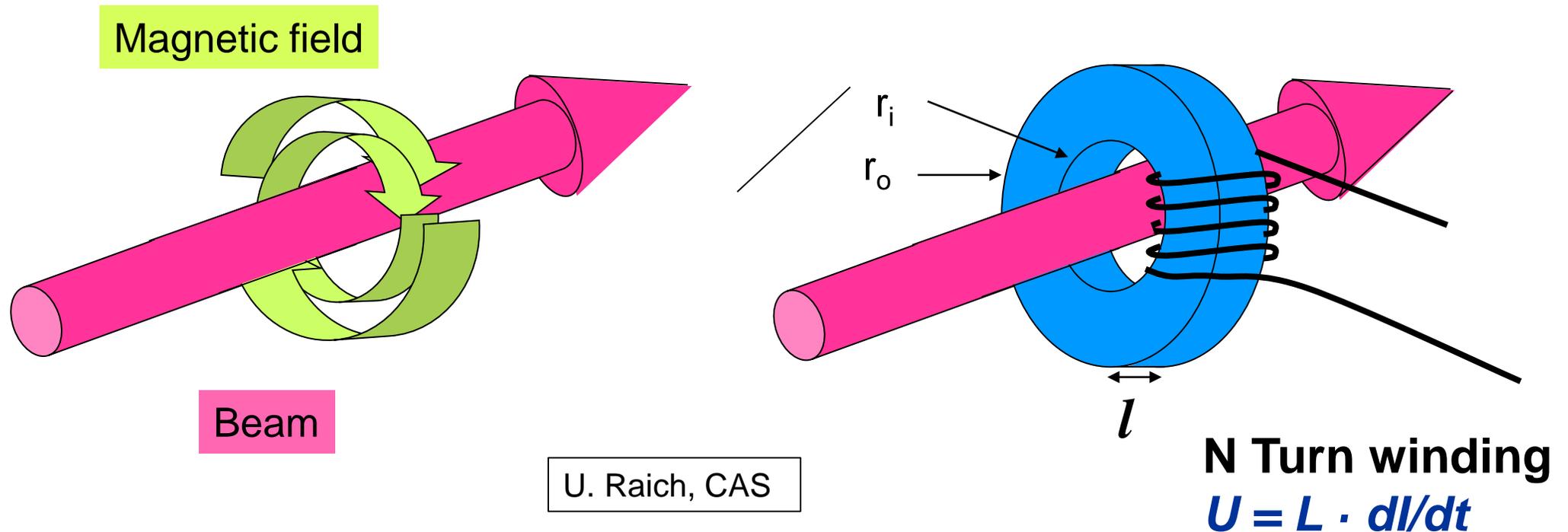


Faraday Cup at GSI LINAC, P. Forck, JUAS



Beam Current Transformer (BCT)

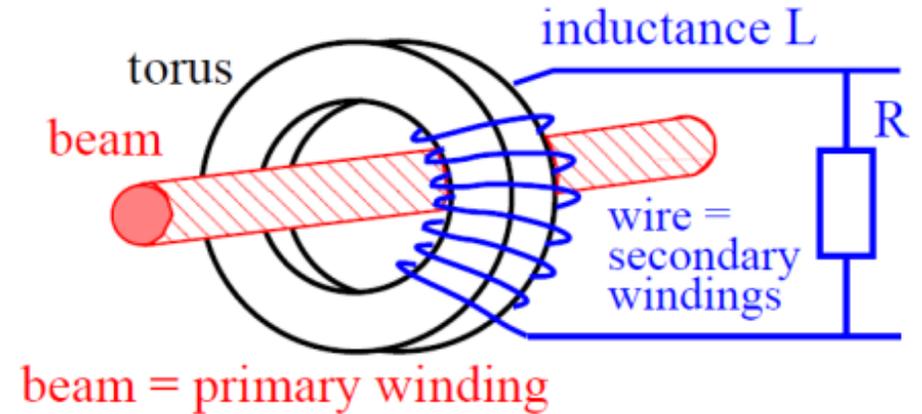
- Measurement of the **magnetic field** of the beam
- **Non-interceptive**
- Independent on beam energy
- Beam as primary winding of a transformer
- Cannot measure DC ($I = \text{const.}$) beams



Current Transformers

- Magnetic field of the beam is very low
(Example: $1 \mu\text{A}$, $r = 10\text{cm} \Rightarrow 2 \text{pT}$;
compared to earth magnetic field of
 $\approx 50 \mu\text{T}$)

 \rightarrow 7 orders of magnitude!



P. Forck, JUAS

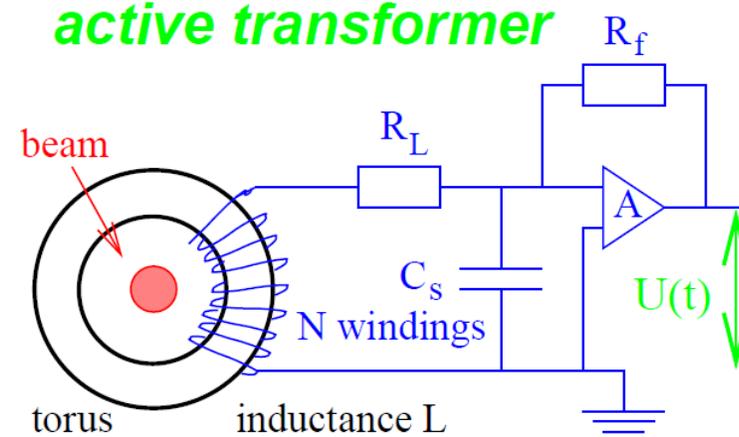
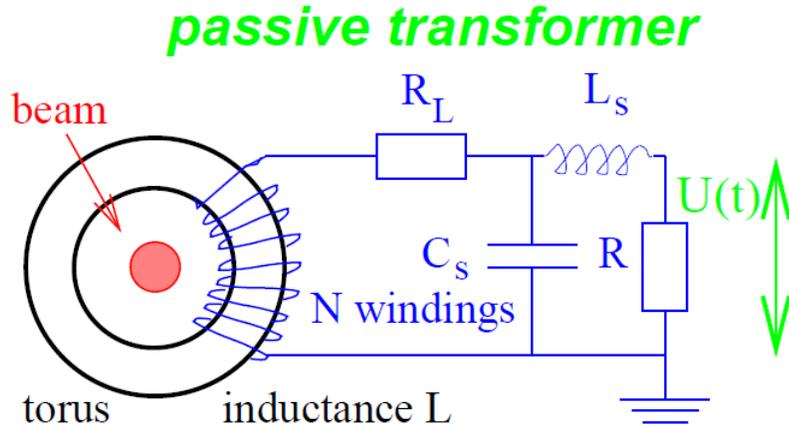
Transformer Inductance

$$L = \frac{\mu_0 \mu_r l N^2}{2\pi} \ln \frac{r_0}{r_i}$$

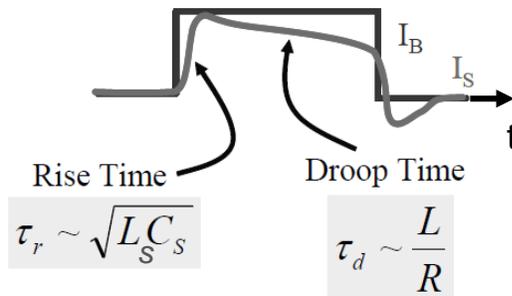
N ... number of windings
 l ... length of the toroid

- Aim of the Torus:
 - Confine and guide magnetic field lines with cores of high relative permeability
 - Signal strength nearly independent of beam position.
 - CoFe based amorphous alloy Vitrovac:
 $\mu_r = 10^5$

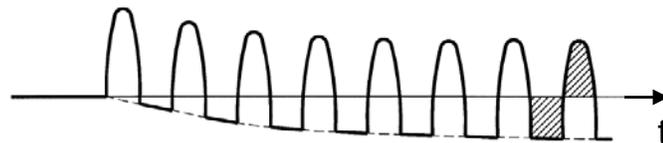
Adapt Droop Time with Active Transformer



P. Forck, JUAS



Bunch trains:



- Equal areas
- Baseline shift proportional to intensity

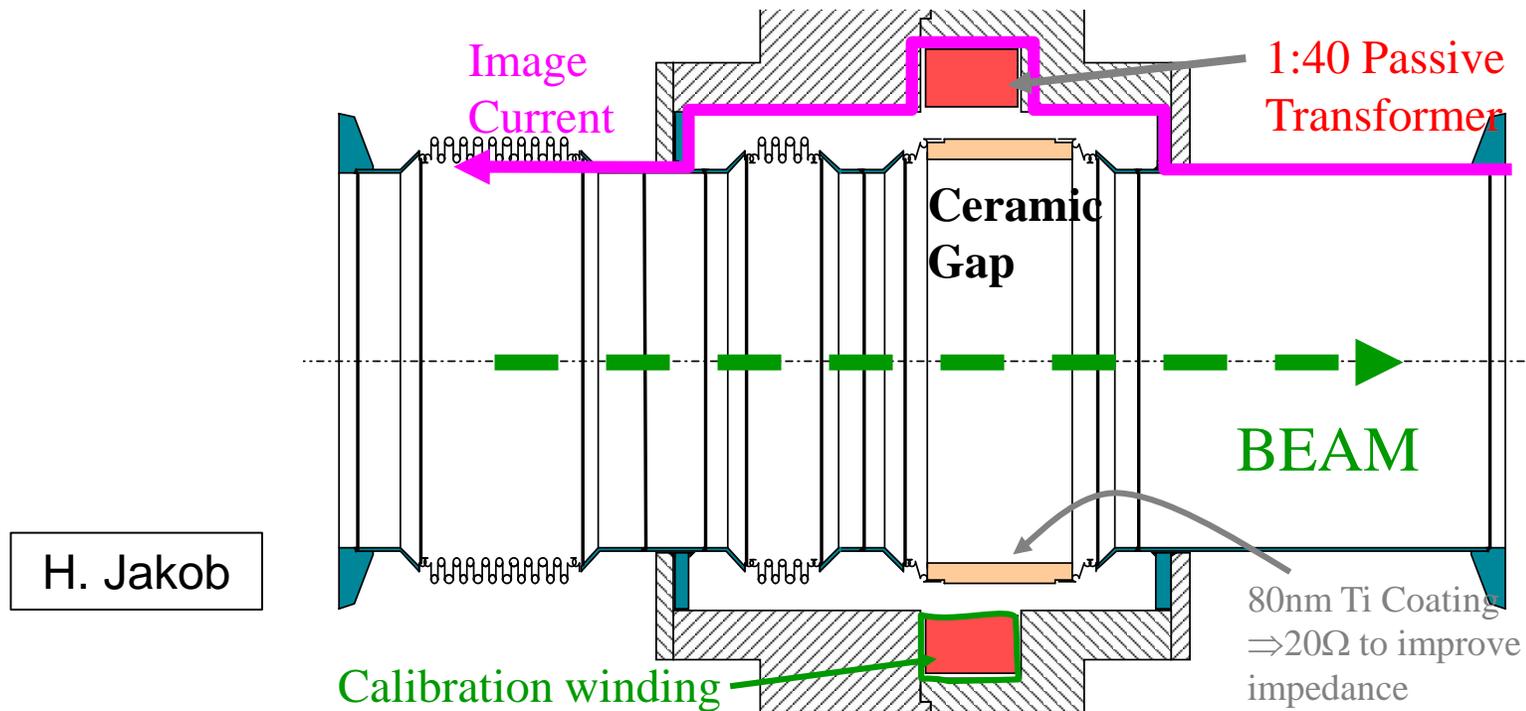
H. Koziol, CAS

- Use a trans-impedance amplifier (current-to-voltage converter) for observation of beam pulses $> 10 \mu\text{s}$, e.g. at pulsed LINAC
- Droop time constants of up to 1s
- Longer rise times as well (to reduce high frequency noise of the amplifier)

$$\tau_d = \frac{L}{R_f/A + R_L} \approx \frac{L}{R_L}$$

Transformer Housing

- Image current passing outside of the transformer torus
- High permeability material shields the transformer against external magnetic fields



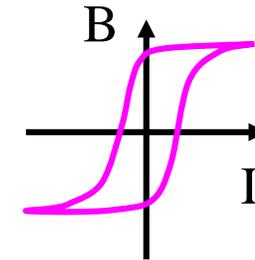
500 MHz Bandwidth; Low droop ($< 0.2\%/ms$)



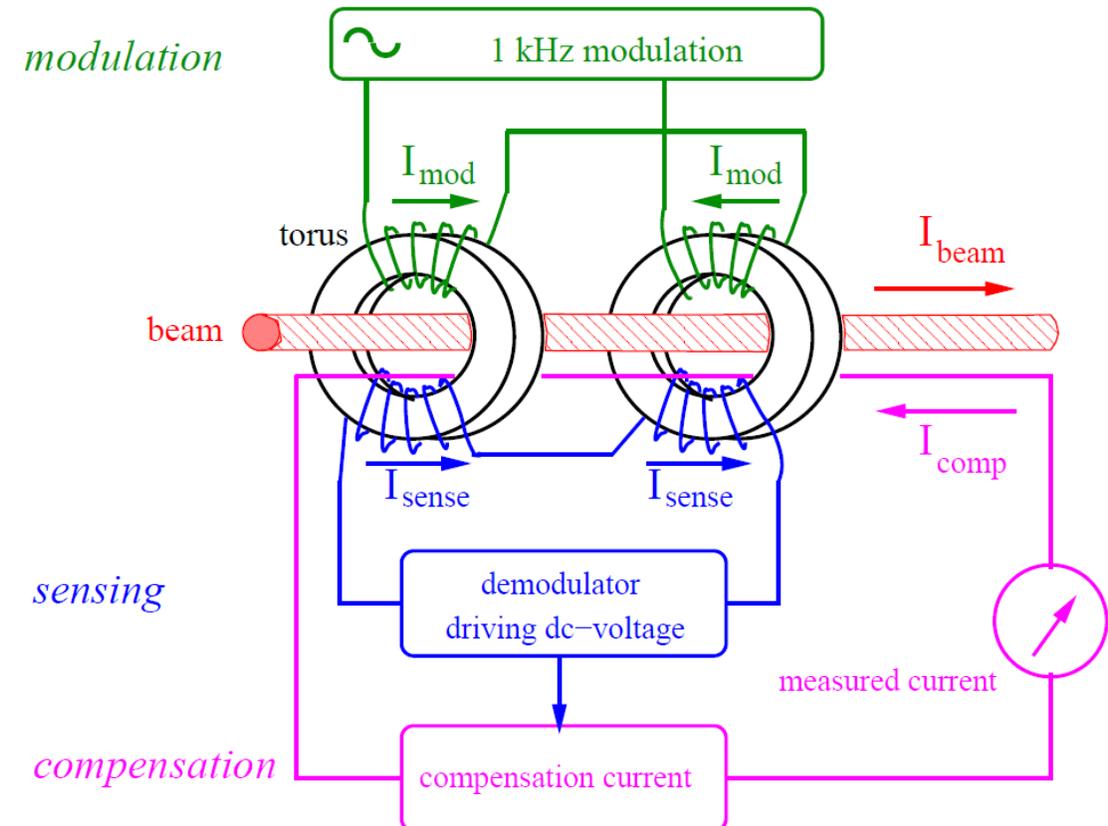
CERN SPS Fast Beam
Current Transformer
(FBCT)

DCCT: DC Beam Current Transformer

- DC current $dB/dt = 0 \Rightarrow$ no voltage induced
- Use two **identical** toroids
- Take advantage of non-linear magnetisation curve



- **Modulation** of opposite sign drives toroids into saturation
- **Sense windings** measure the modulation signal
 - Signals from the two toroids cancel each other as long as there is no beam

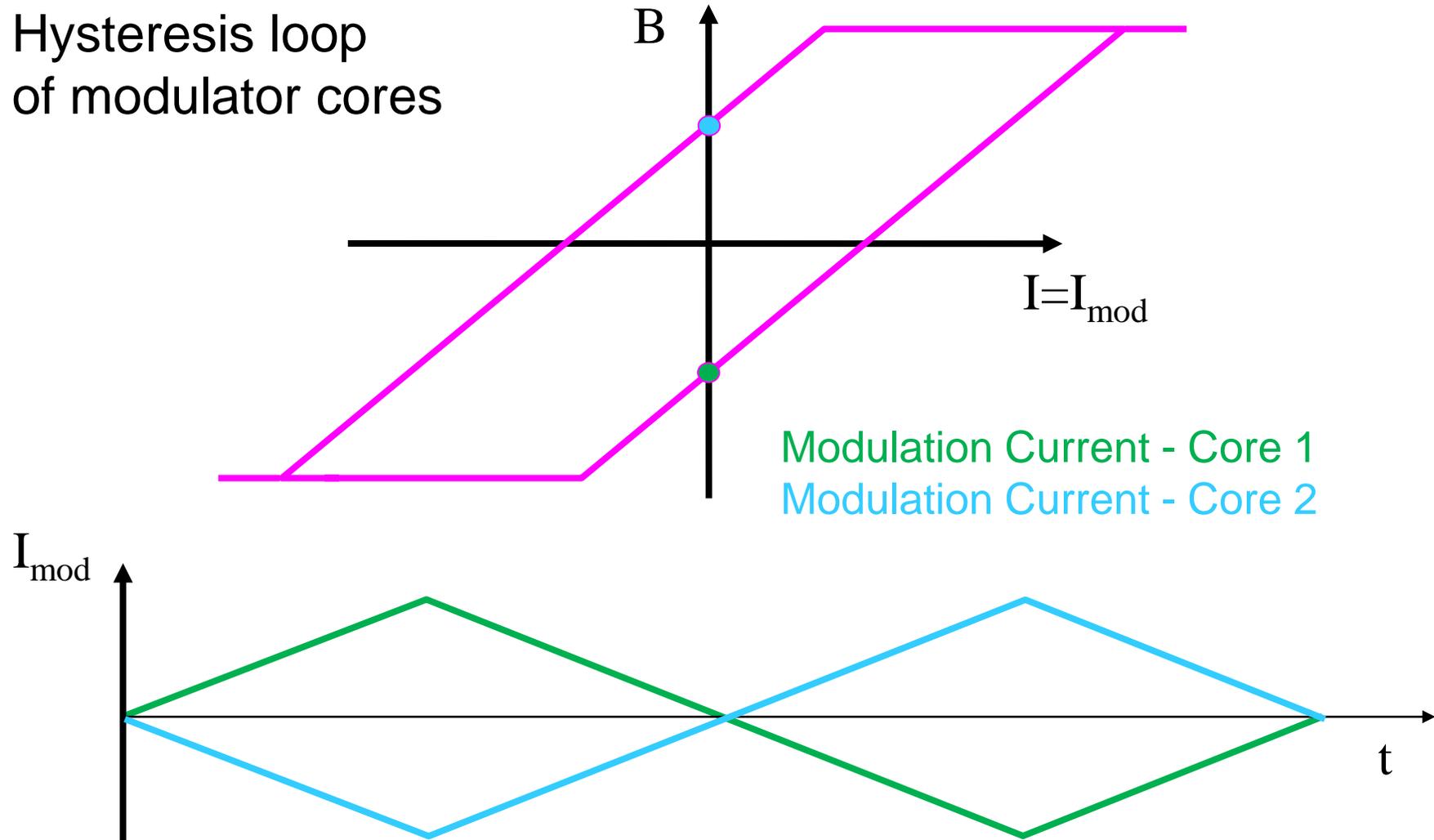


P. Forck, JUAS

DCCT Principle – Case 1: No Beam

R. Jones, CAS

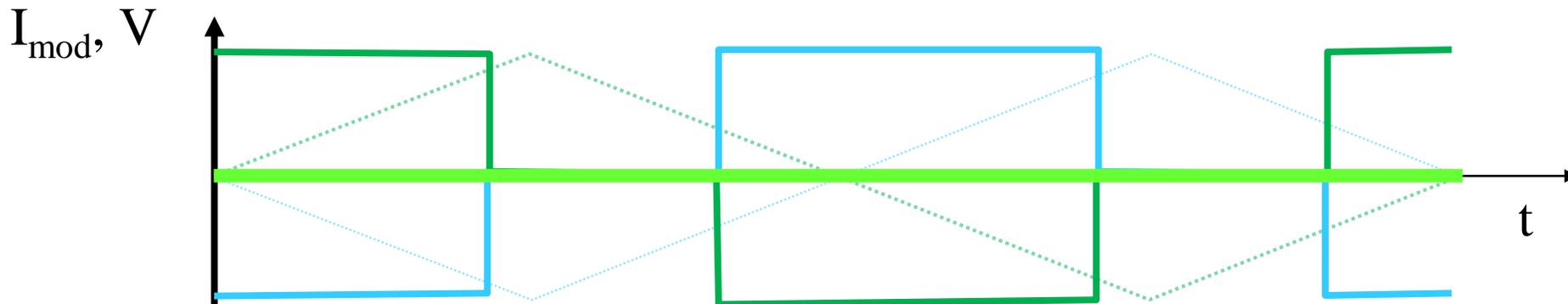
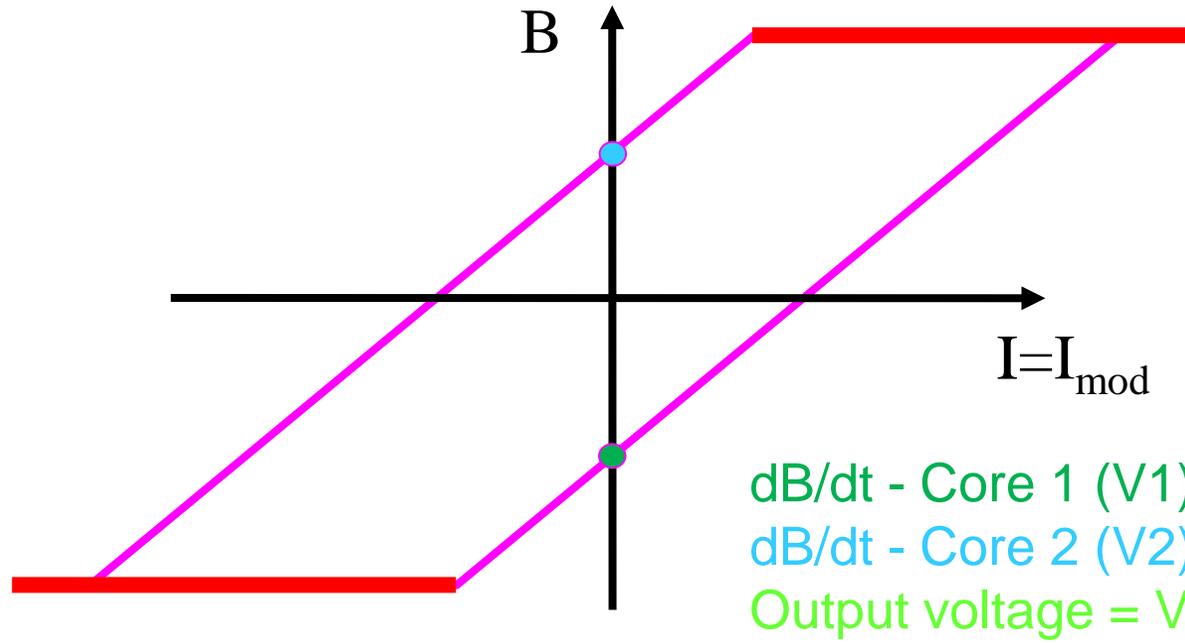
Hysteresis loop
of modulator cores



DCCT Principle – Case 1: No Beam

R. Jones, CAS

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



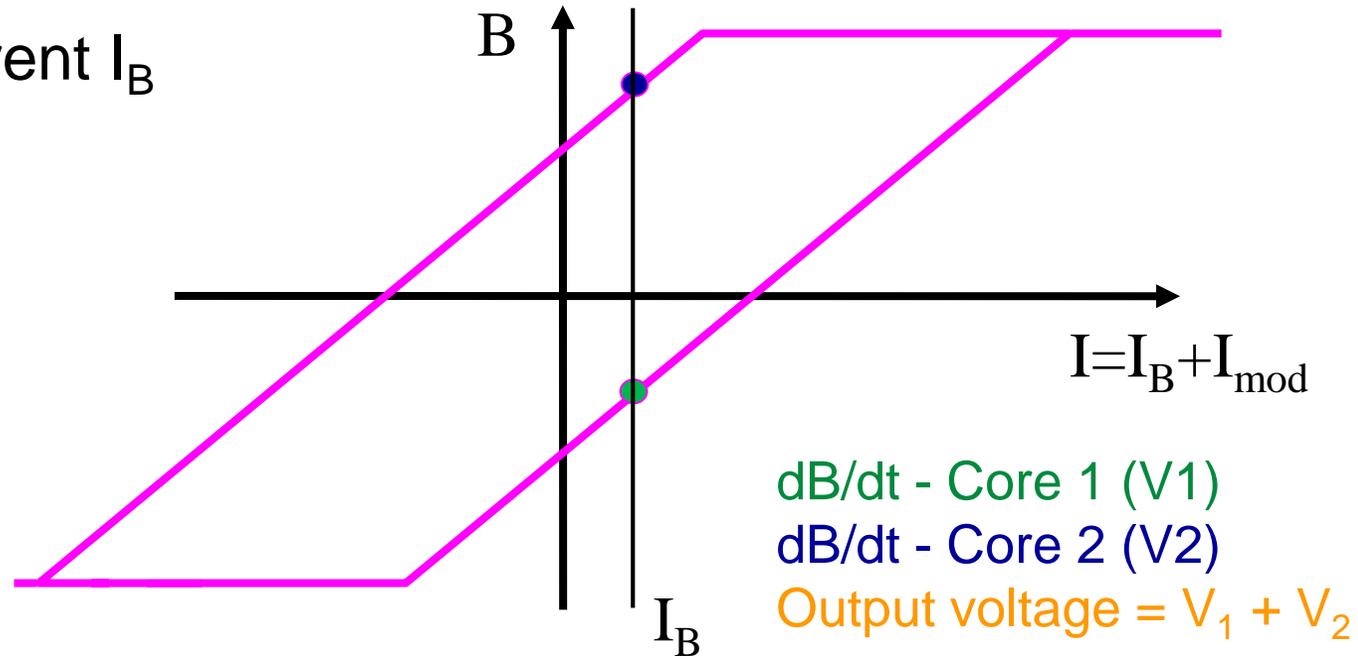
DCCT Principle – Case 2: With Beam

R. Jones, CAS

Beam Current I_B

Output signal is at twice the modulation frequency

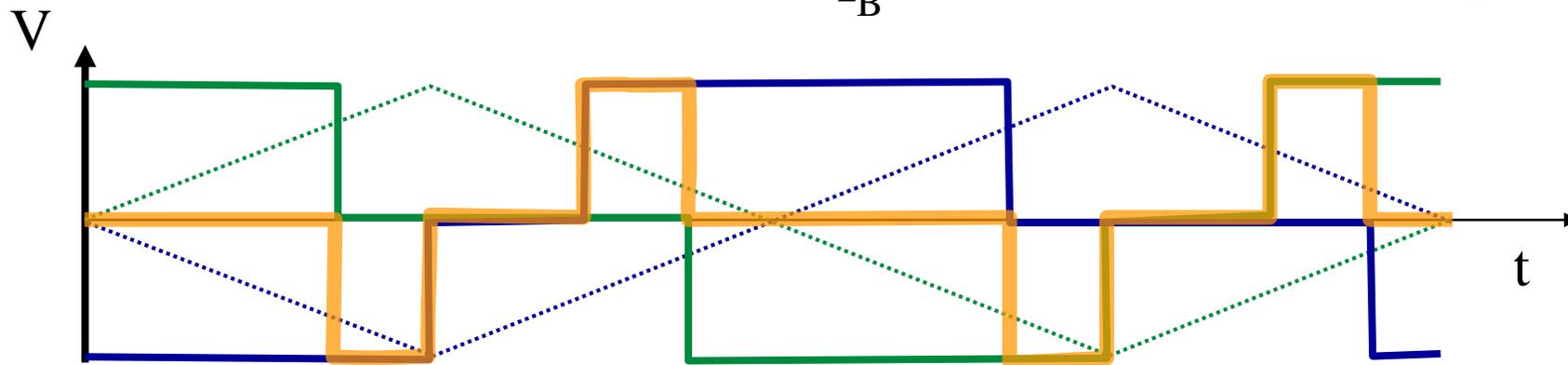
The length of the pulses is a measure for the beam current



$\frac{dB}{dt}$ - Core 1 (V_1)

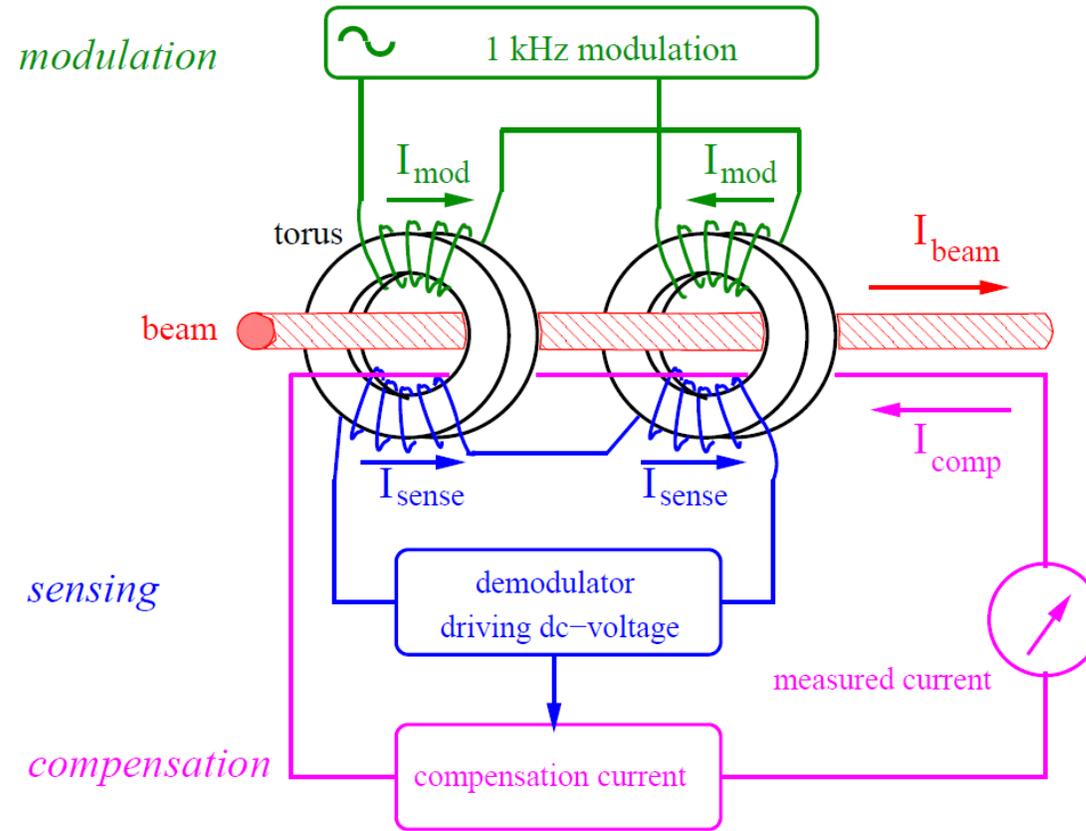
$\frac{dB}{dt}$ - Core 2 (V_2)

Output voltage = $V_1 + V_2$



DCCT in the “Zero Flux” Scheme

- Zero-flux scheme: compensate for the beam current and measure the magnitude of the compensation current



P. Forck, JUAS

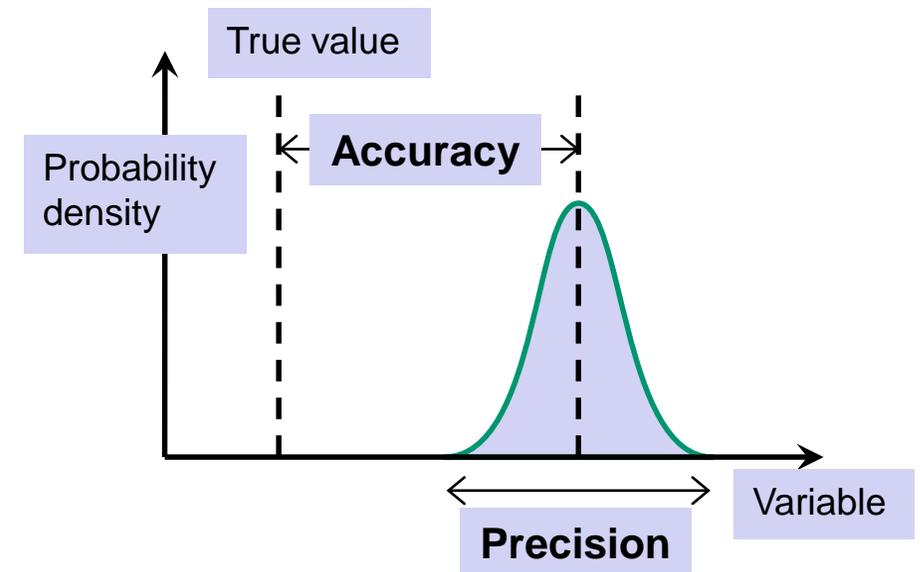
Performance

- Achievable performance Fast Beam Current Transformers (FBCT):

- Absolute accuracy: 1%
- Reproducibility / relative precision: 0.1%
- Dynamic range: 10^3 (10^4)

- Performance LHC DC Beam Current Transformers (DCCT):

- Absolute accuracy: 0.2%
- Noise floor: $2 \mu\text{A}$
- Dynamic range: 10^6 ($\mu\text{A} - 1\text{A}$)



Transverse Profile

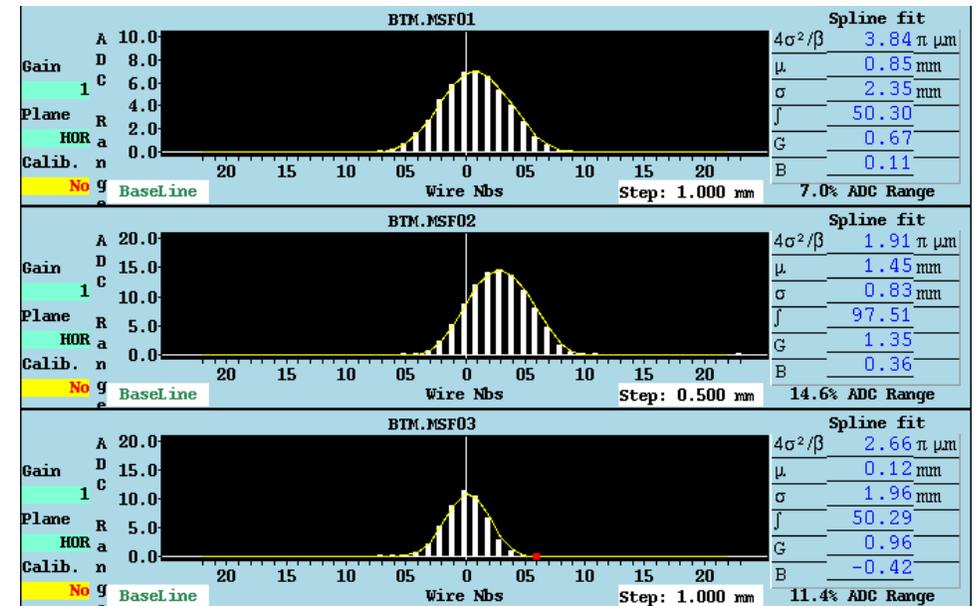
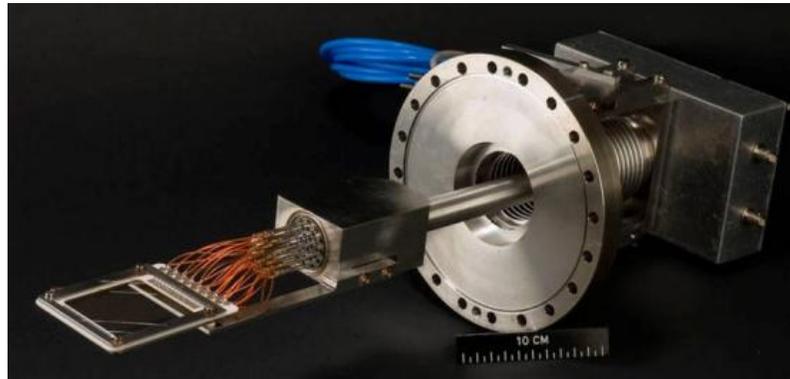
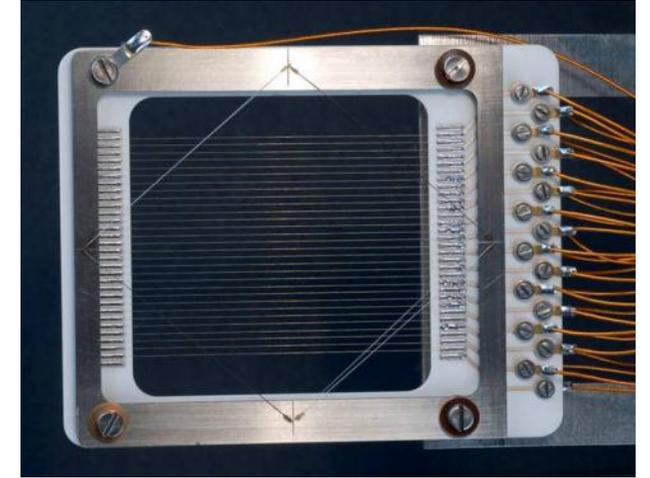
Overview - Beam Profile measurement

- Methods which intercept the beam with matter:
 - Secondary emission (SEM) grids
 - Screens
 - Wire scanners
- more or less perturbing to the beam
- Energies/intensity threshold for safe operation
 - Material damage (e.g. wire sublimation, breakage)
 - Radiation to other machine components (e.g. quenching of superconducting magnets)
- (Quasi) Non-Invasive Methods:
 - Synchrotron light monitors
 - Rest Gas Ionisation monitors
 - Luminescence monitors
 - Laser wire scanner
 - Electron beam scanner
 - Gas screen, gas pencil beams
 - Beam Gas Vertex Detector – designed for absolute measurement

SEM grids and wire scanners:
Used as reference measurement for the other methods

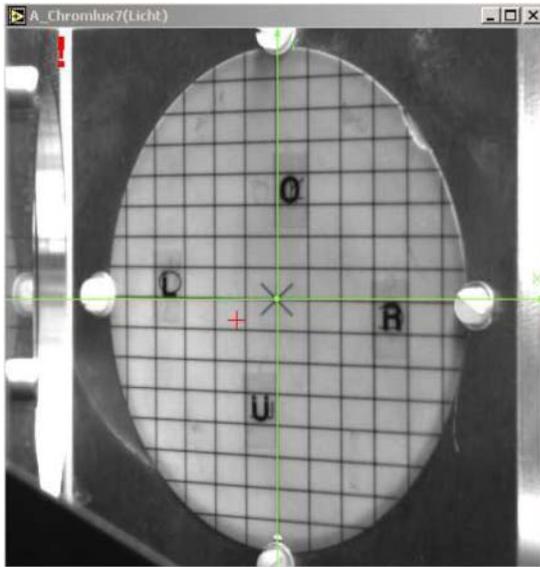
Secondary Emission (SEM) Grids

- When the beam passes through a wire, secondary electrons are emitted, proportional to beam intensity
- The current flowing back onto the wires is measured using one amplifier/ADC chain for each wire
- Clearing field removes liberated electrons
- Problem: thermal emission
- Very high sensitivity, semi-transparent
- Good absolute measurement
- Spatial resolution limited by wire spacing to $\approx 0.25\text{mm}$
- Dynamic range: $\approx 10^6$



Scintillation Screens

- Typically for setting-up with low intensities, thick screens (mm)
→ emittance blow-up
- Workshop in 2011 at GSI to look at resolution possible with various screen materials:
<http://www-bd.gsi.de/ssabd/home.htm>
- Sensitivities of different materials vary by orders of magnitudes



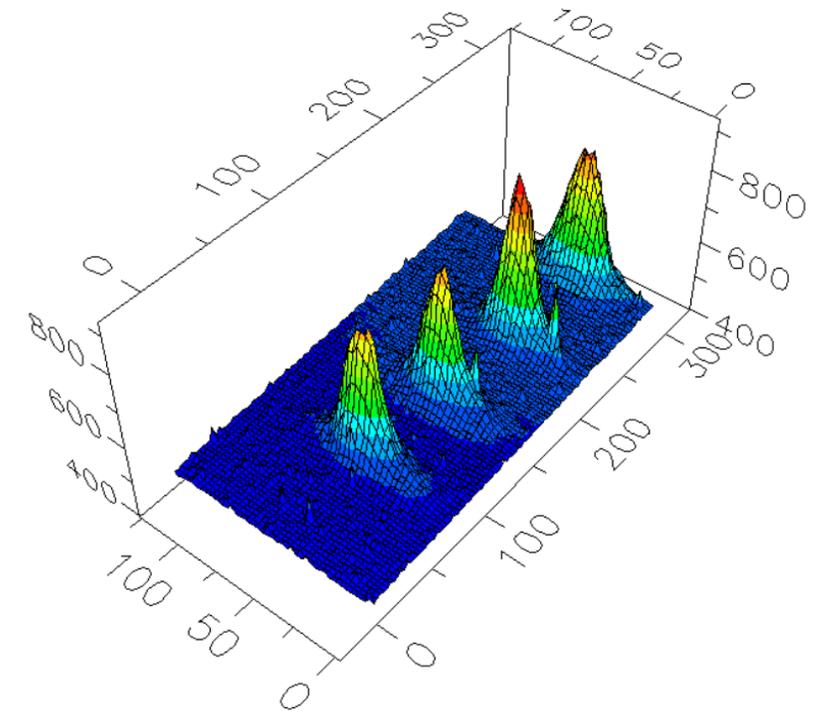
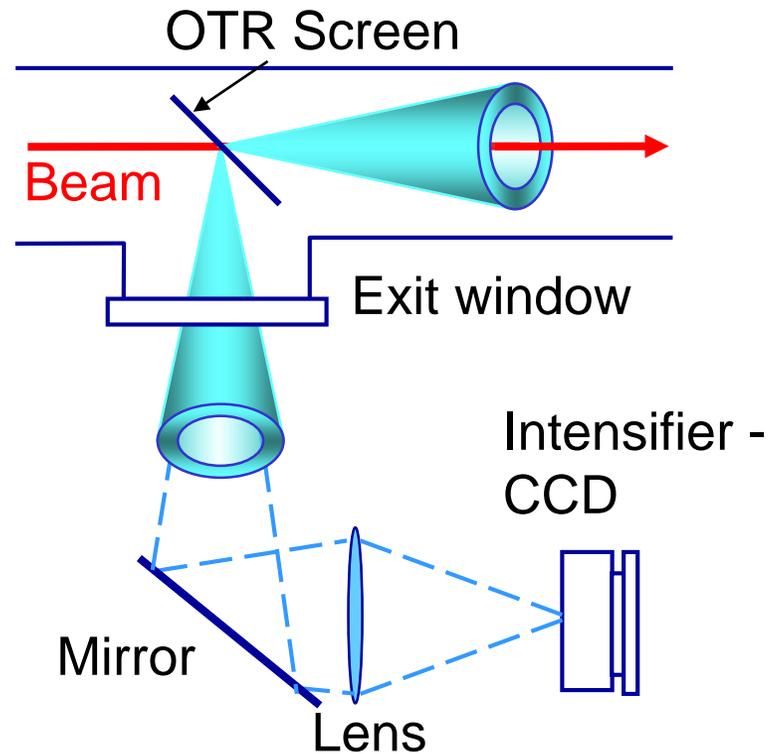
Abbreviation	Material	Activator	max. emission	decay time
Quartz	SiO ₂	none	470 nm	< 10 ns
	CsI	Tl	550 nm	1 μs
Chromolux	Al ₂ O ₃	Cr	700 nm	100 ms
YAG	Y ₃ Al ₅ O ₁₂	Ce	550 nm	0.2 μs
	Li glass	Ce	400 nm	0.1 μs
P11	ZnS	Ag	450 nm	3 ms
P43	Gd ₂ O ₂ S	Tb	545 nm	1 ms
P46	Y ₃ Al ₅ O ₁₂	Ce	530 nm	0.3 μs
P47	Y ₂ Si ₅ O ₅	Ce&Tb	400 nm	100 ns

Approximate values for inorganic scintillators

P. Forck, JUAS

Optical Transition Radiation (OTR) Screens

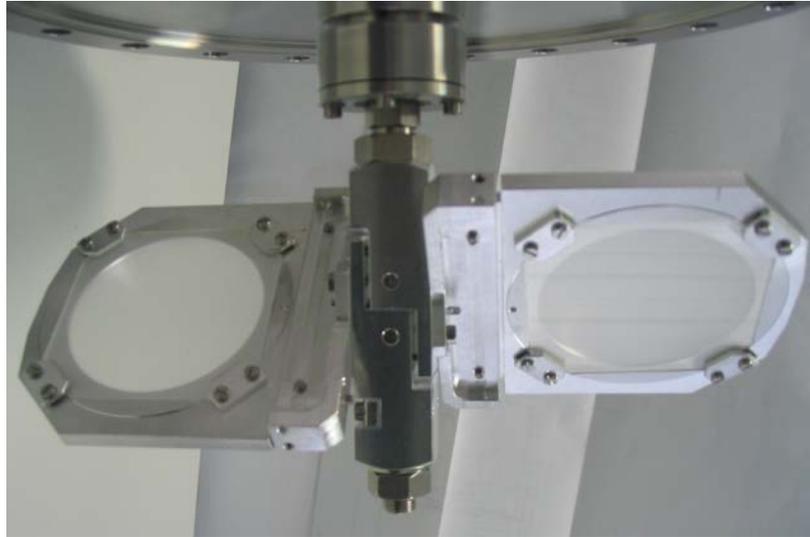
- Radiation emitted when a charged particle beam goes through the interface of two media with different dielectric constants
- Surface phenomenon allows the use of very thin screens ($\geq 0.25 \mu\text{m}$)
- Much less intercepting, but requires higher intensity



CERN SPS 4 turns at injection

Beam Profile Monitoring Using Screens

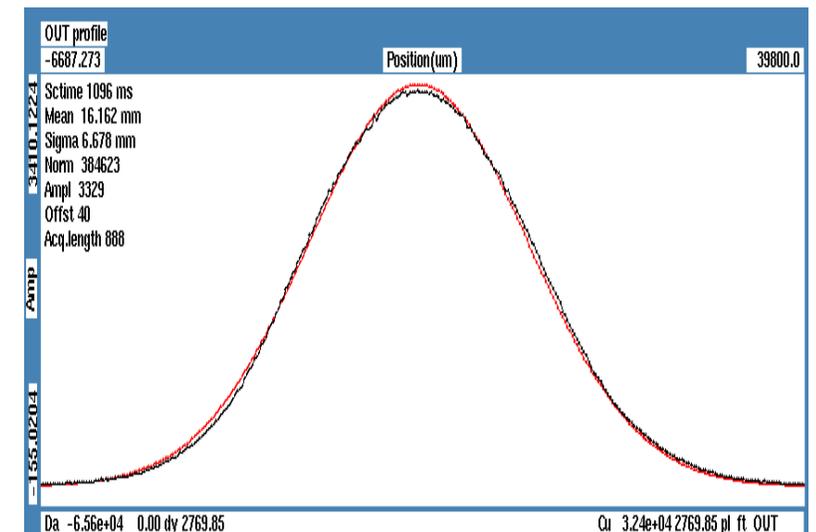
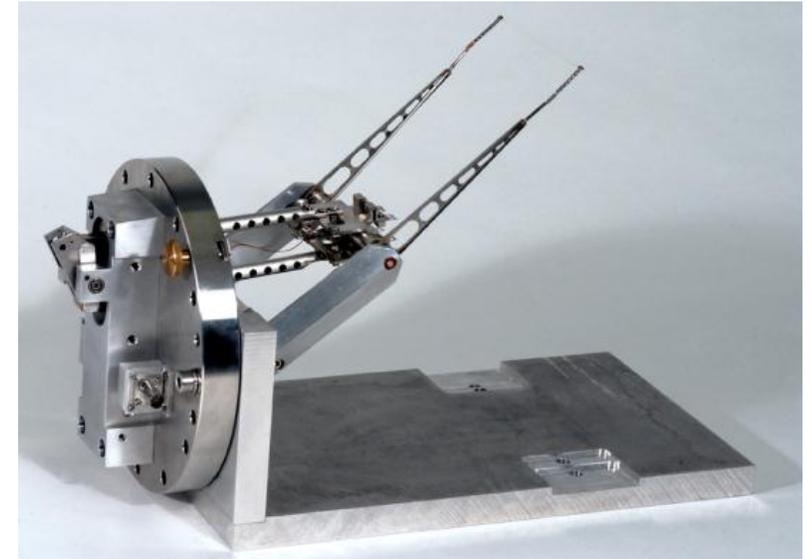
- Combine several screens in one housing e.g.
 - Al_2O_3 scintillation screen for setting-up with low intensity
 - Thin ($\approx 10\mu\text{m}$) Ti OTR screen for high intensity measurements
 - Carbon OTR screen for very high intensity operation



- Cameras:
 - CCD cameras are radiation sensitive
 - Analogue VIDICON camera can be used with high radiation

Wire Scanners

- A thin wire (down to $10\ \mu\text{m}$) is moved across the beam
 - Rings: has to move fast to avoid excessive heating of the wire
 - Rotational scanner up to $10\ \text{m/s}$ with special pneumatic mechanism (linear scanners slower)
- Detection
 - Secondary particle shower detected outside the vacuum chamber e.g. using a scintillator/photo-multiplier assembly
 - Secondary emission current detected as for SEM grids
- Correlating wire position with detected signal gives the beam profile
 - Wire vibrations limit position resolution
- Less invasive than screen or SEM grids

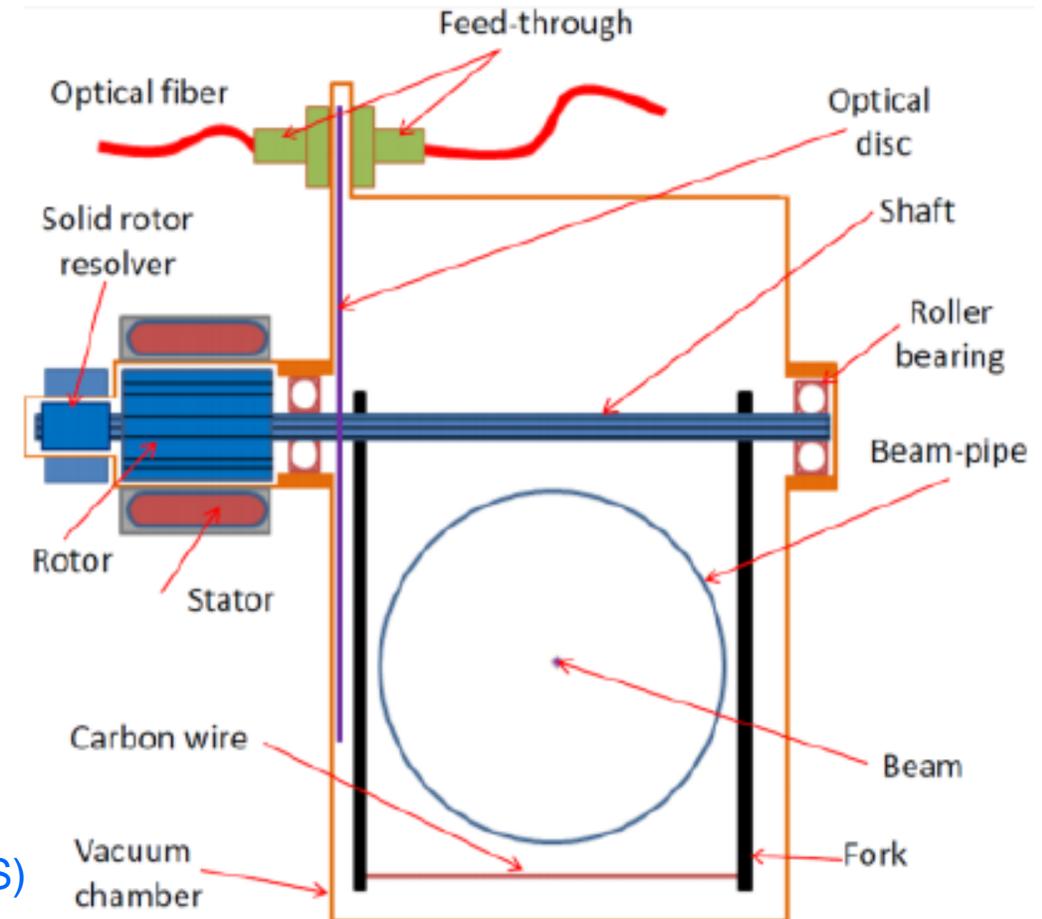


New Wire Scanner being developed at CERN

Design specifications:

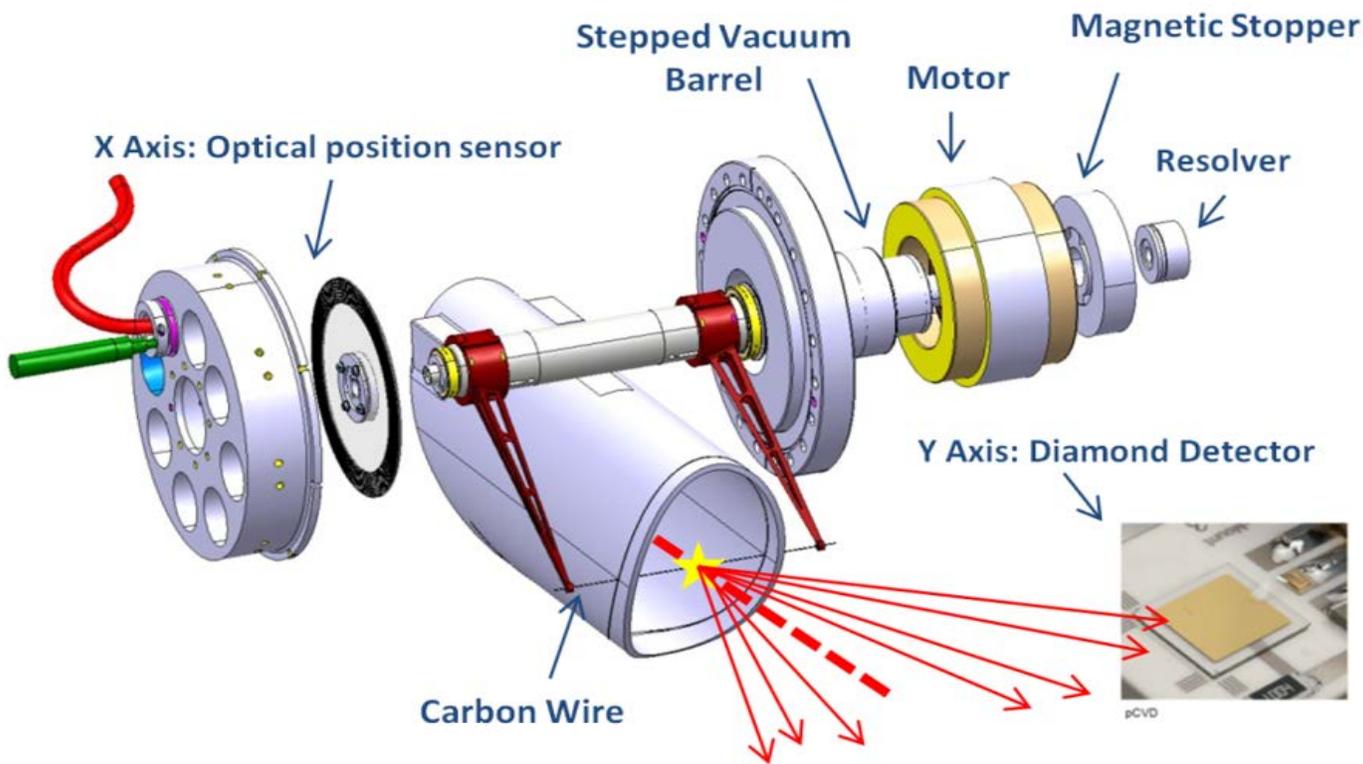
Wire speed	Wire position resolution
20 m/s	$< 50 \mu\text{m} \pm 2.5 \mu\text{m}$

- Using high resolution angular position sensor
- Dynamic range: $10^5 - 10^6$
 - Usage of sensor with large dynamic (e.g. diamond)
 - Automatic selection of gain range by the electronic
- Minimize fork and wire deformations
 - Mechanical design (Study of dynamic behavior of fork/wire system)
 - Vibration mode optimized acceleration profile
- Bunch by bunch measurements
 - 40 MHz digitalization of 25 ns integrated signal
 - Measurements synchronous with bunch clock (LHC and SPS)
- 20 kGy over 20 years
- Current Wire Scanners at CERN:
 - Dynamic range 100; accuracy 5-10%; spatial resolution $50 \mu\text{m}$ (linear type) and $200 \mu\text{m}$ (rotational)

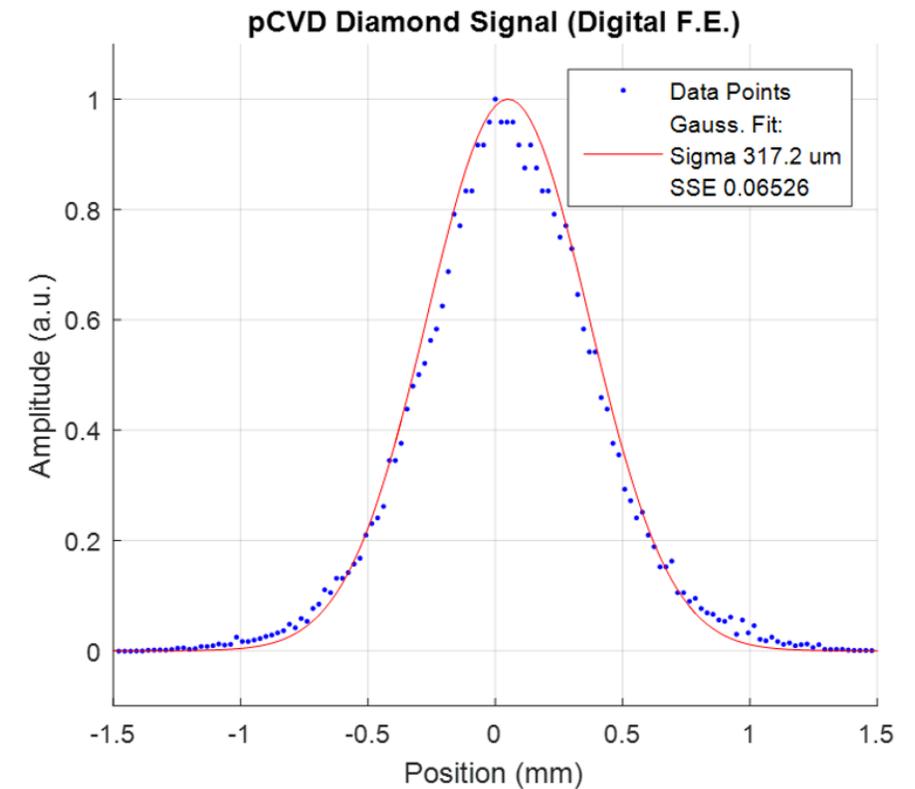


B. Dehning

Mechanical Design and Profile Reconstruction



Beam profile measured with pCVD Diamond detector and upgraded acquisition electronics

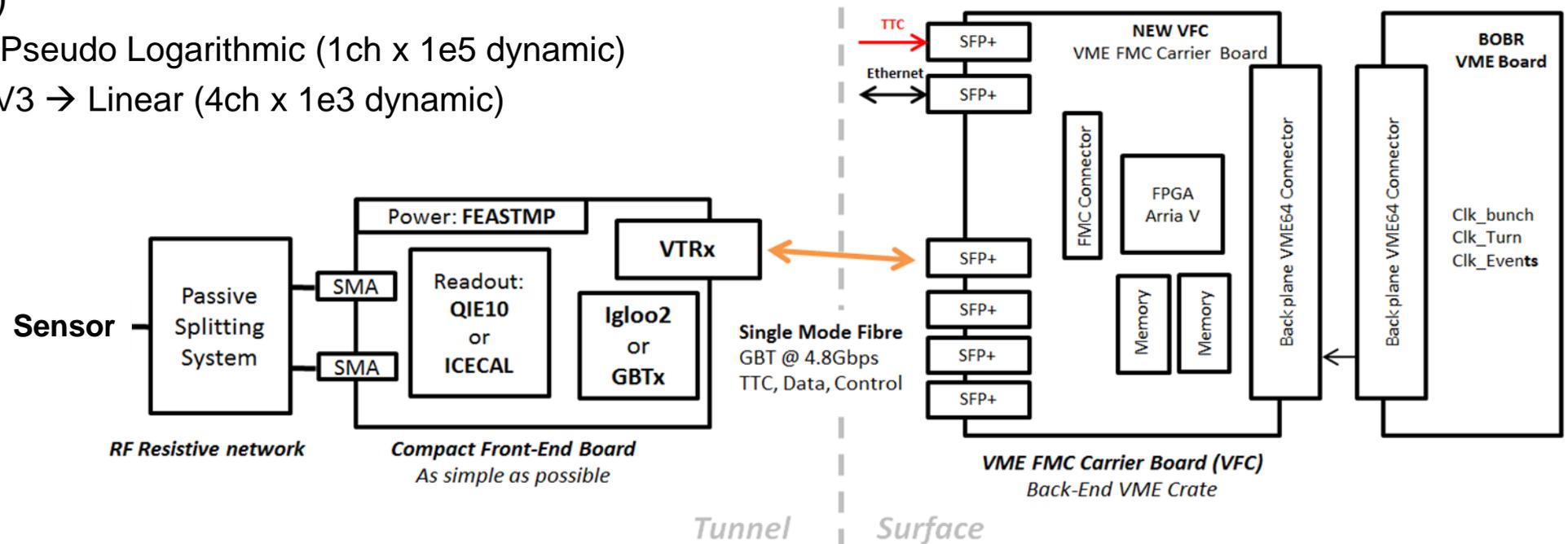


Jose Luis Sirvent Blasco

<https://twiki.cern.ch/twiki/bin/view/BWSUpgrade/SecondariesAcquisitionSystem>

X axis: Optical position sensors ($50 \pm 2.5 \mu\text{m}$)
Y axis: signal from diamond detector

- Radiation hard front-end close to wire scanner
- Optical transmission to surface back-end electronics (VME bus and crate standard)
- CERN/BI standard components as much as possible (front-end motherboard (GEFE), Gigabit optical link with 4.8Gbps, back-end VME card (VFC), timing card (BOBR))
- Wire scanner specific components:
 - Front-end FPGA mezzanine card (FMC) holding radiation hard ASIC for Integration & Digitalization (two options investigated, developed at Fermilab for CMS/Atlas and University of Barcelona for LHCb respectively)
 - QIE10 → Pseudo Logarithmic (1ch x 1e5 dynamic)
 - ICECAL_V3 → Linear (4ch x 1e3 dynamic)



Glossary:

- **GEFE : GBT Expandable Front-End**
 - CERN/BI general purpose FPGA-based radiation tolerant front-end motherboard with optical signal transmission
 - Target Total Ionizing Dose (TID): up to 75 krad
- **Igloo2 UMd Board**
 - Another option for the front-end motherboard, equipped with a flash-based FPGA Igloo2, radiation tolerant components and a versatile link transceiver (VTRx) to drive the optical link with the GBT protocol.
- **VFC board: VME FMC Carrier Board**
 - CERN/BI general purpose FPGA-based back-end VME board
- **FMC: FPGA Mezzanine Card**
 - https://en.wikipedia.org/wiki/FPGA_Mezzanine_Card
 - Here: application specific Mezzanine card for the VFC board
- **GBT: Gigabit Transceiver Link (4.8Gbps)**
- **QIE: Charge Integrator & Encoder**
- **SMA: connector standard**
- **ASIC: Application-specific integrated circuit**
 - https://en.wikipedia.org/wiki/Application-specific_integrated_circuit

**Beam Loss Measurement
for Machine Protection and Diagnostics**

Detection Principles

- See *The Review of Particle Physics*, C. Patrignani et al. (Particle Data Group), Chin. Phys. C, 40, 100001 (2016) for reference, <http://pdg.lbl.gov/>.

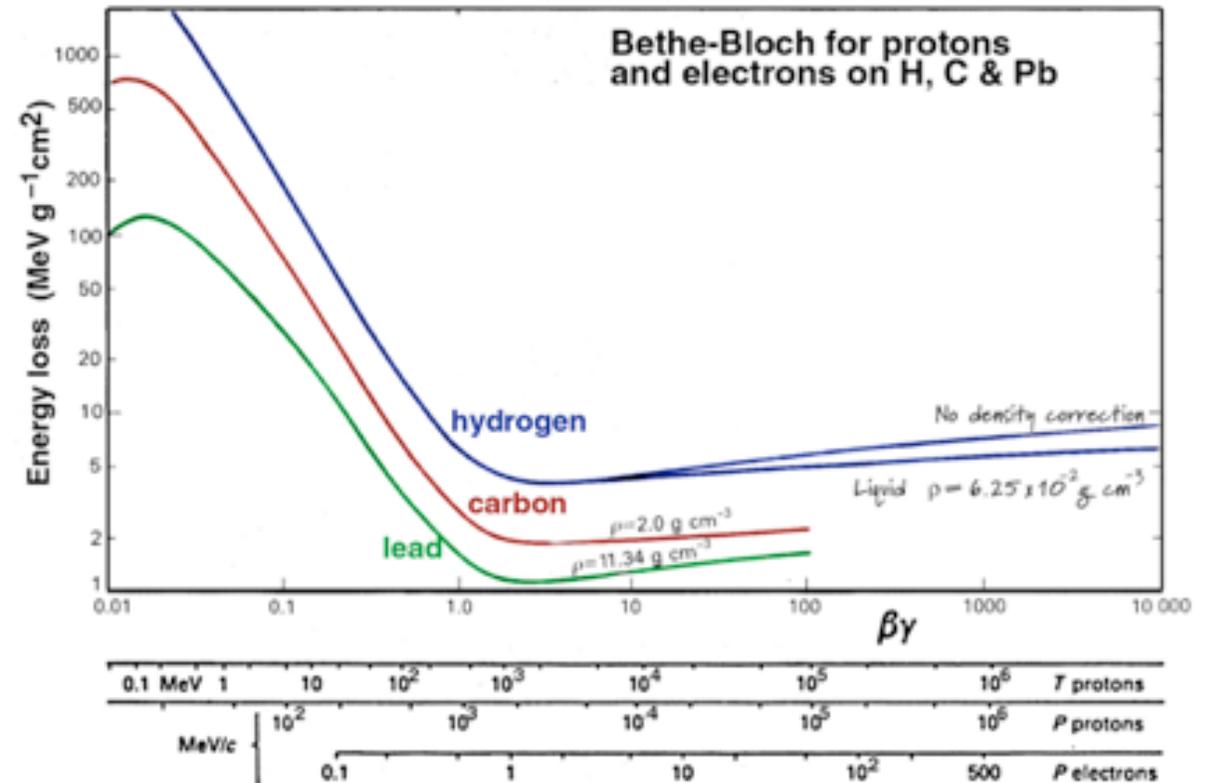
Ionization

- Energy loss by Ionization described by the Bethe-Bloch formula
- Concept of Minimum Ionizing Particle

- $dE/dx_{MIP} =$
(1-5) MeV cm² g⁻¹

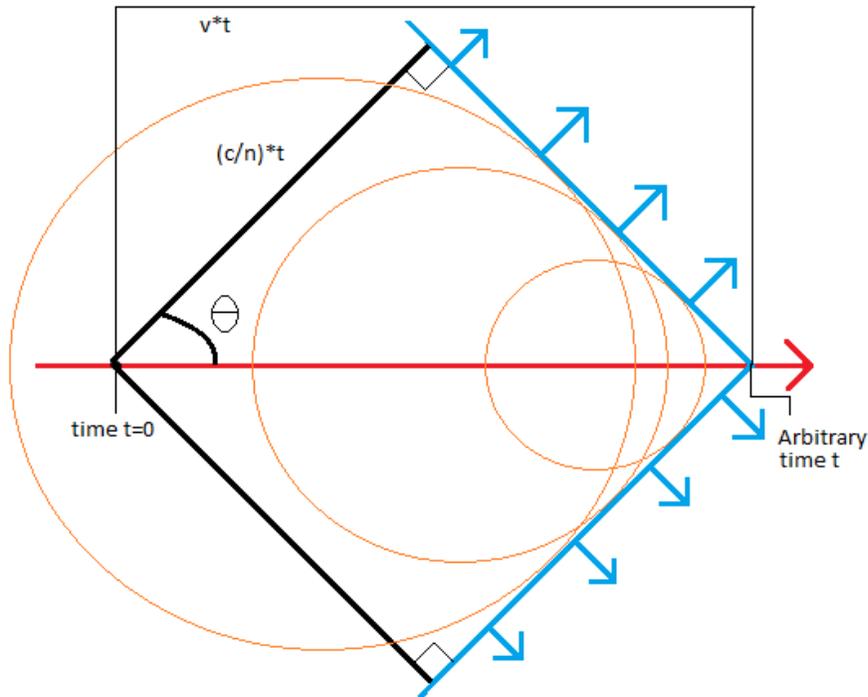
Scintillation

- Light produced by de-excitation of atom / molecule
- Yield is proportional to the energy loss
 - $Y = dL/dx = R dE/dx$

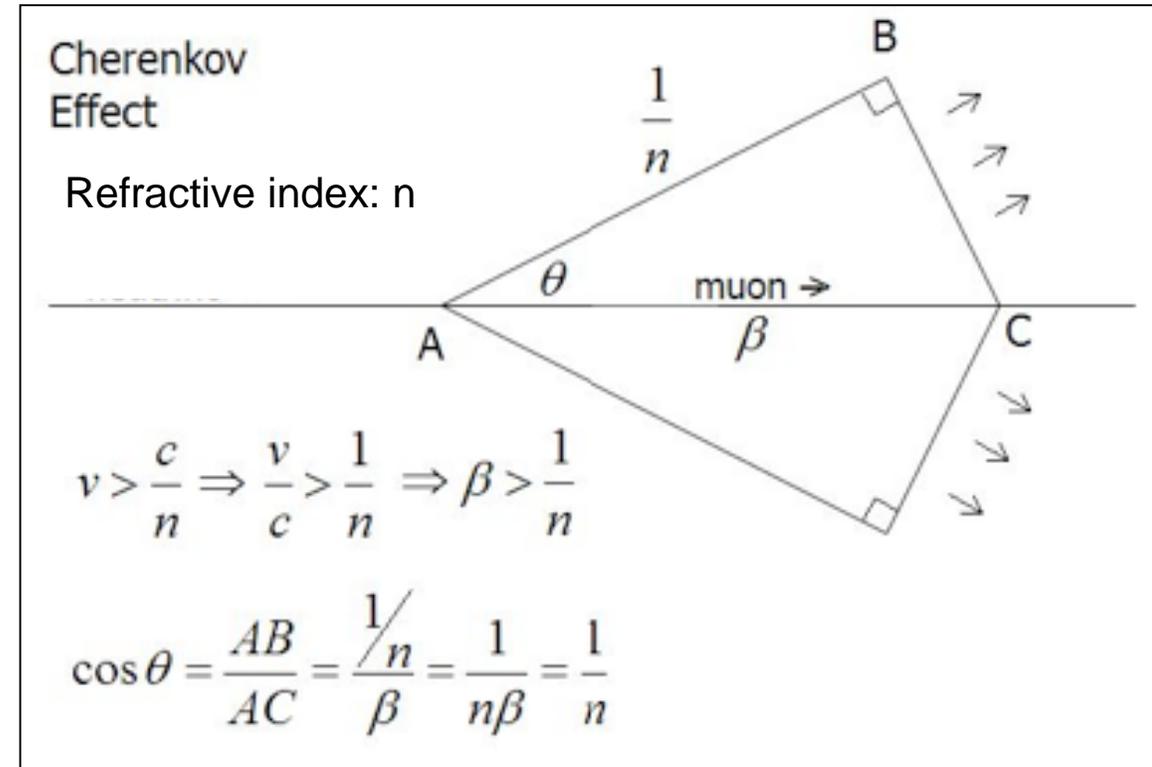


Detection Principles cont'd

Cherenkov light



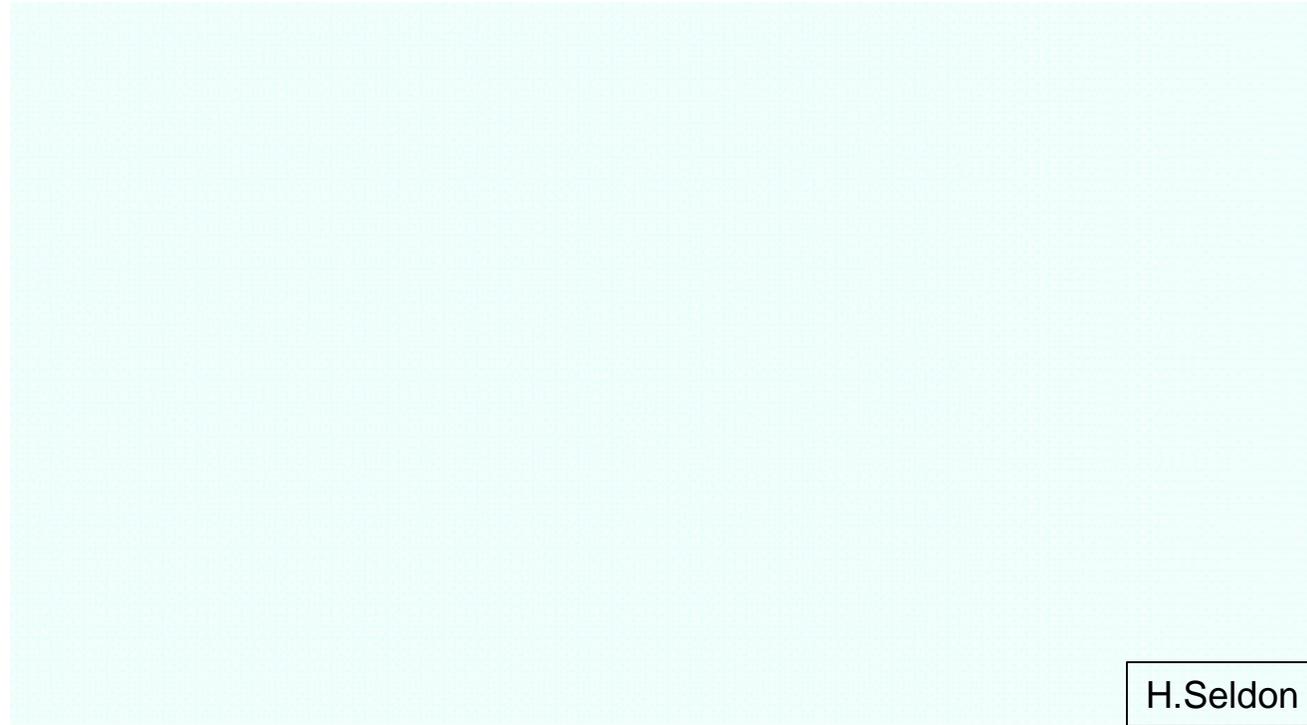
- █ Trajectory of Particle
 - █ Cherenkov Light
 - █ Shock Waves
- Drawing: Bock and Vasilescu 1999



$$\text{photon yield} : \frac{dN}{dx} = 2 \cdot \pi \cdot \alpha \cdot \sin^2 \Theta \cdot \left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2} \right)$$

$$\cos \Theta = \frac{1}{\beta \cdot n} \text{ with } \beta > 1/n; \alpha = 1/137.036 \text{ and } \lambda_{1,2} = \text{wavelength interval}$$

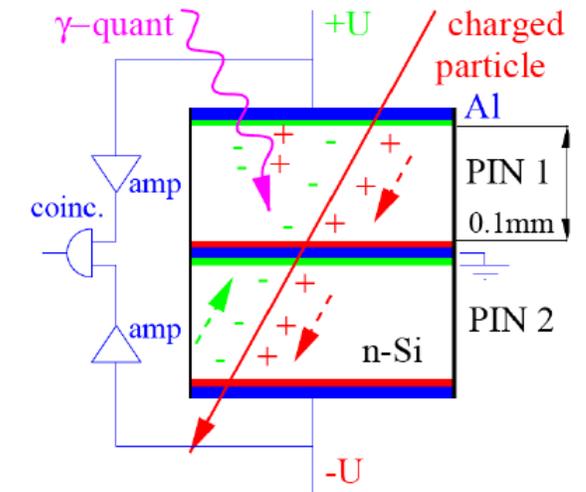
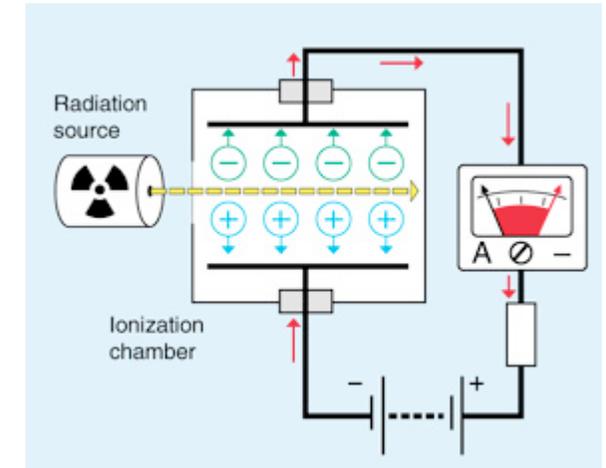
Cherenkov light



H.Seldon

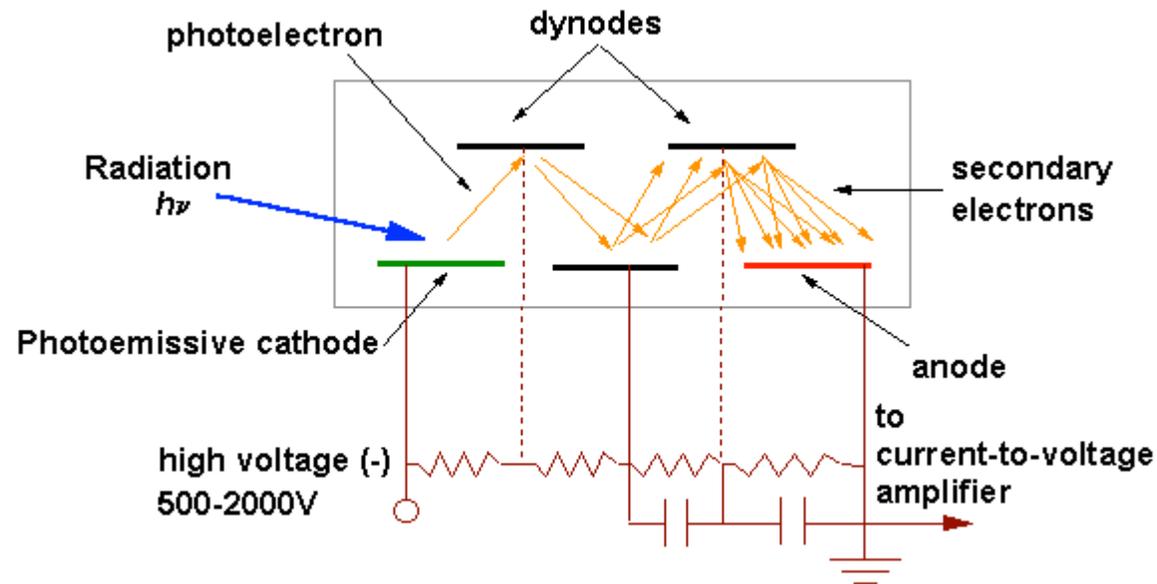
Common types of monitors

- **Short ionisation chamber** (charge detection)
 - Typically gas filled with many metallic electrodes and kV bias
 - Speed limited by ion collection time – tens of microseconds
 - Dynamic range of up to 10^8
- **PIN photodiode** (count detection)
 - Detect charged particle
 - Insensitive to photons from synchrotron radiation due to coincidence counting in two back-to-back mounted PIN diodes (K. Wittenburg, DESY)
 - Count rate proportional to beam loss
 - Speed limited by integration time
 - Dynamic range of up to 10^9



Common types of monitors cont'd

- Scintillator plus photo-multiplier
 - Types of scintillators
 - Inorganic crystals: NaI, CsI,
 - Organic (plastic, liquid)
 - Light directed (via waveguides) to **photomultiplier tube**



Common types of monitors cont'd

- **Long ionisation chamber** (charge detection)
 - Up to several km of gas filled hollow coaxial cables
 - Longitudinal position information by arrival time measurement
 - e.g. SLAC – 8m position resolution (30ns) over 3.5km cable length
 - Dynamic range of up to 10^4

- **Cherenkov fibres**
 - Time resolution 1 ns
 - Minimal space requirement
 - Insensitive to gamma background, E and B fields
 - Radiation hard (depending on type)
 - Combination fiber / readout can adapt to a wide dose range
 - Dynamic range 10^4 seems feasible

LHC BLM System

- Main purpose: **prevent damage and quench**

- 3600 Ionization chambers

- Beam abort thresholds:

- 12 integration intervals:
40 μ s to 84s (32 energy levels)

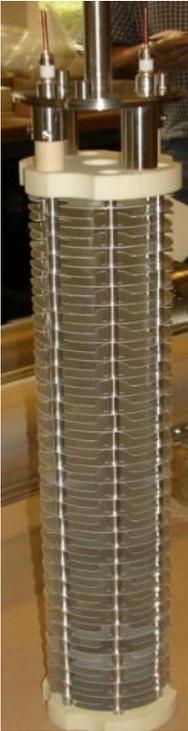
→ 1.5 Million threshold values

- Each monitor aborts beam

- One of 12 integration intervals over threshold
- Internal test failed

- **Requirements and Challenges**

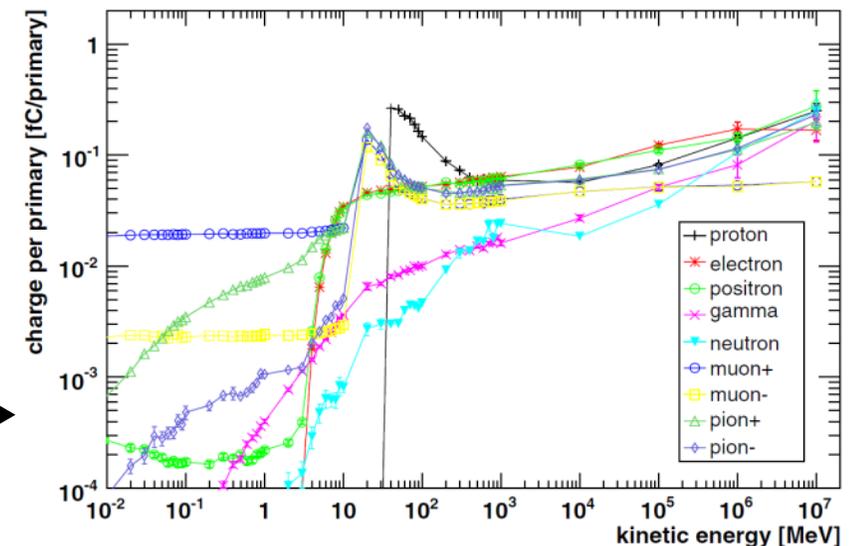
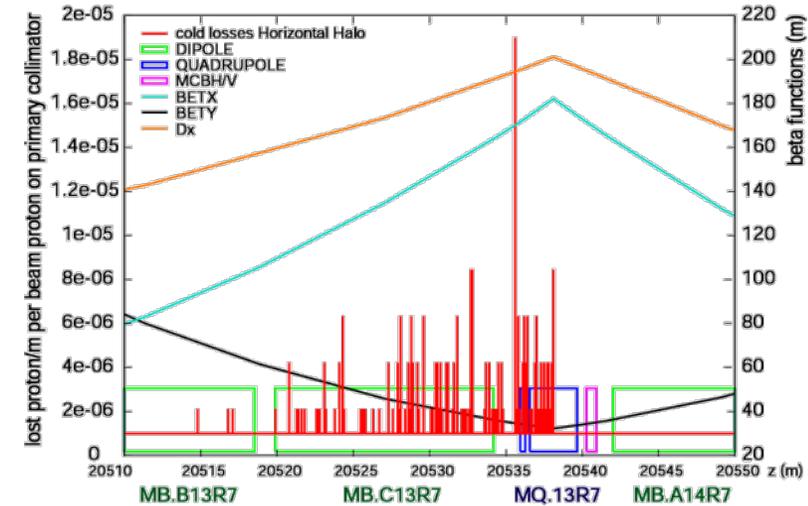
- High Dependability (Reliability, Availability, Safety)
- Threshold precision (factor 2)
- Reaction time 1-2 turns (100 – 200 μ s)
- Dynamic range: 10^8 (at 40 μ s 10^5 achieved – 10^6 planned)
- **Radiation hard: currently at CERN development of kGy radiation hard readout to avoid noise from long cables**



Beam Abort Threshold Determination

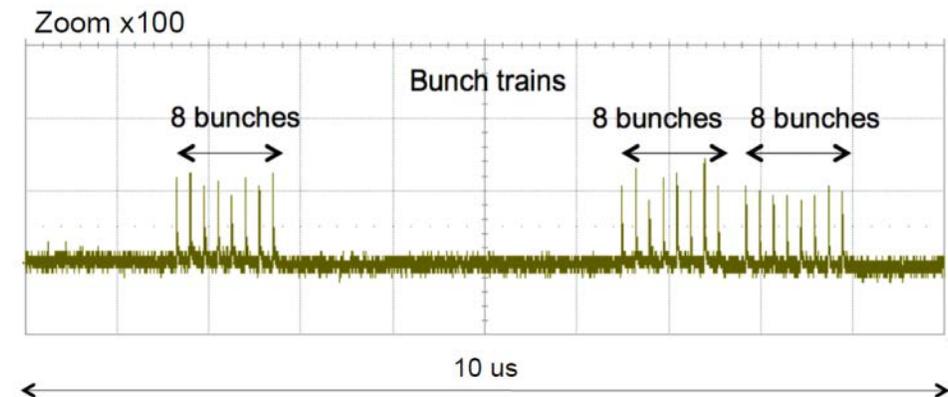
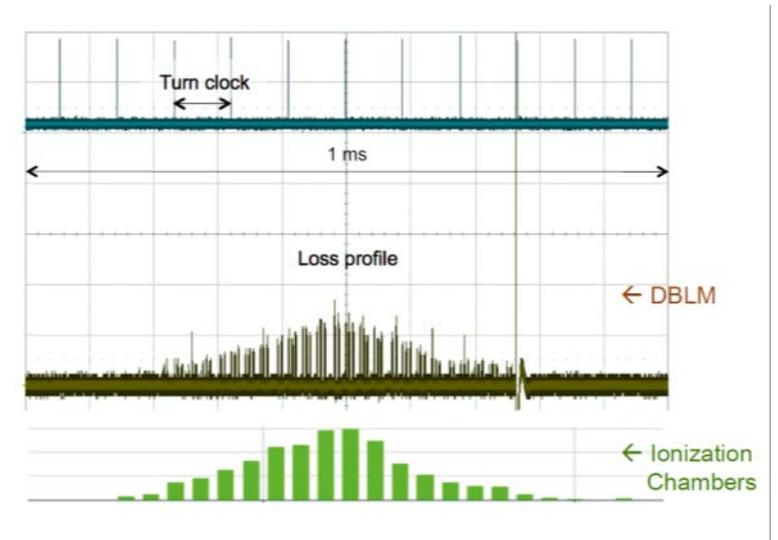
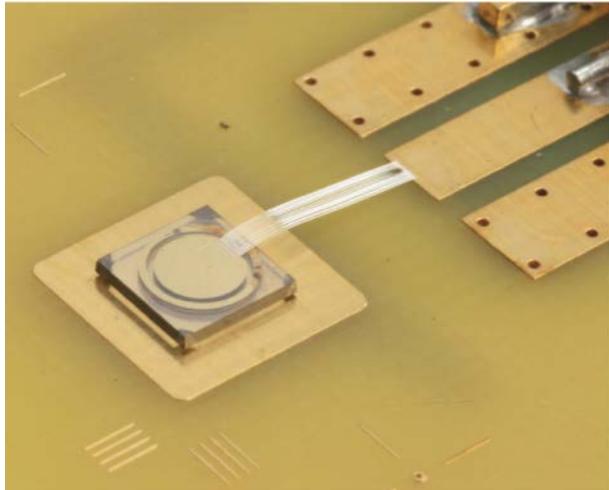
- Relate the BLM signal to the:
 - Number of locally lost beam particles
 - Deposited energy in the machine
 - Quench and damage levels

- Extensive simulations and experiments during system design and beam tests in the LHC
 - Proton loss locations (tracking codes: MAD-X, SIXTRACK)
 - Hadronic showers through magnets (GEANT, FLUKA)
 - Magnet quench levels as function of beam energy and loss duration
 - Chamber response to the mixed radiation field



Diamond Detectors

- Fast and sensitive
- Small and radiation hard
- Used in LHC to distinguish bunch by bunch losses
- Dynamic range of monitor: 10^9
- Temporal resolution: few ns
- Test system installed in cryo magnet at LHC



Thank you for your Attention

Overview of the most commonly used diagnostics devices for for the different beam parameters.

From: Peter Forck: *Lecture on Beam Instrumentation and Diagnostics* at the Joint University Accelerator School (JUAS)

<http://www-bd.gsi.de/conf/juas/juas.html>

Beam quantity		LINAC, transfer line	Synchrotron
current I	<i>general</i>	transformer (dc, pulsed) Faraday cup	transformer (dc)
	<i>special</i>	particle detector (Scint. IC, SEM)	normalized pick-up signal
position \bar{x}	<i>general</i>	pick-up	pick-up
	<i>special</i>	using profile measurement	cavity excitation (e^-)
profile x_{width}	<i>general</i>	SEM-grid, wire scanner viewing screen, OTR-screen	residual gas monitor synch. radiation (e^-) wire scanner
	<i>special</i>	grid with ampl. (MWPC)	
trans. emittance ϵ_{trans}	<i>general</i>	slit grid quadrupole scan	residual gas monitor wire scanner
	<i>special</i>	pepper-pot	transverse Schottky pick-up wire scanner
momentum p and $\Delta p/p$	<i>general</i>	pick-up (TOF) magn. spectrometer	pick-up
	<i>special</i>		Schottky noise pick-up
bunch width $\Delta\varphi$	<i>general</i>	pick-up	pick-up wall current monitor
	<i>special</i>	particle detector secondary electrons	streak camera (e^-)
long. emittance ϵ_{long}	<i>general</i>	magn. spectrometer buncher scan	
	<i>special</i>	TOF application	pick-up + tomography
tune, chromaticity Q, ξ	<i>general</i>	—	exciter + pick-up (BTF)
	<i>special</i>	—	transverse Schottky pick-up
beam loss r_{loss}	<i>general</i>		particle detector
polarization P	<i>general</i>		particle detector
	<i>special</i>		Compton scattering with laser
luminosity \mathcal{L}	<i>general</i>		particle detector