

Beam Instrumentation

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CAS

**Introductory level course on
Accelerator Physics**

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

Introduction, cont'd

- Aim: assist in commissioning, tuning and operating the accelerator and to improve performance → see tomorrow

- 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

Classification of Selected Devices

- 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 | Effect on beam | | | |
|-------------------------------|------------------|--------------|----------------|---------------|----------------|---|---|---|
| | | | | | N | - | + | D |
| Current transformers | ● | | | | x | | | |
| Pick-ups | ● | ● | | | x | | | |
| Faraday cup | ● | | | | | | | x |
| Secondary emission monitors | ● | ● | ● | ● | x | x | | |
| Wire scanners | | ● | ● | ● | x | | | |
| Scintillator screens | | ● | ● | | x | x | | |
| OTR screen | | ● | ● | | x | x | | |
| Residual-gas profile monitors | | ● | ● | ● | x | | | |
| Beam loss monitors | | | | | x | | | |

Effect on beam depends on circumstances (e.g. on beam energy)

N none
 - slight
 + perturbing
 D destructive

- Different Labs have different names for the same device!

Introduction, cont'd

- Some instrument classifications:
 - **LINAC and transport lines**: Single pass, can have separate measurement lines \leftrightarrow **Synchrotron**: multi pass
 - **Total Beam Energy** (beam particles x particle energy) low \leftrightarrow high

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

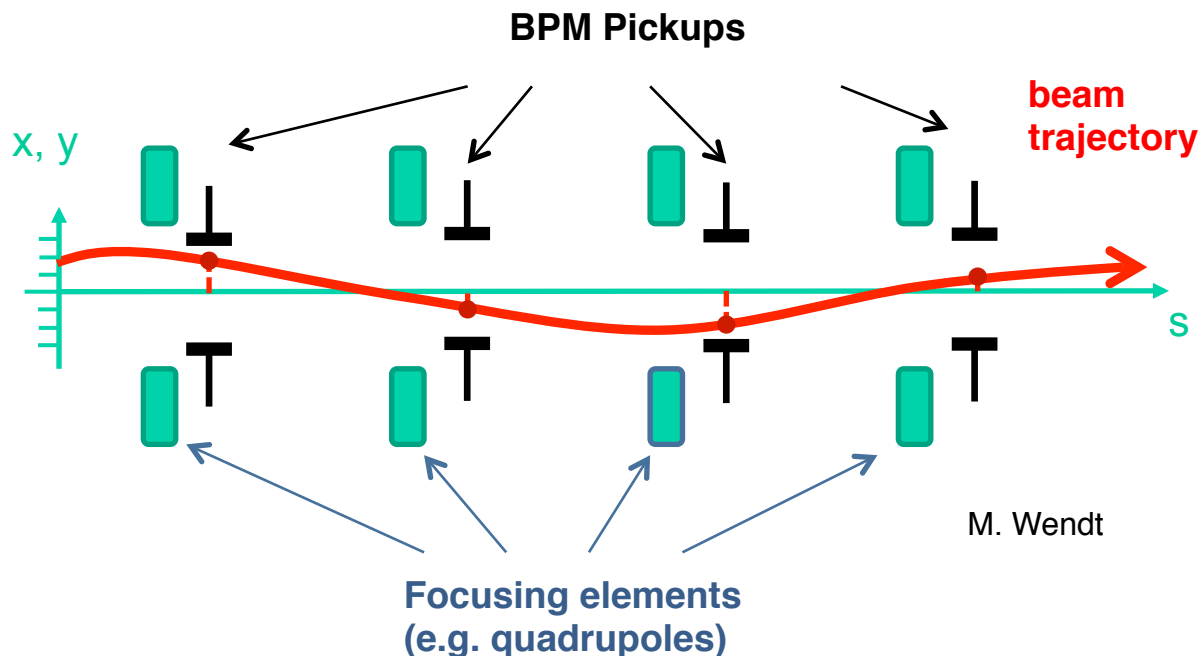
Resources and References

- 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>
- 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 and Hermann Schmickler: *Introduction to Beam Instrumentation and Diagnostics*, CERN-2006-002.
 - Daniel Brandt (Ed.), 2008 CAS on *Beam Diagnostics for Accelerators*, Dourdan, CERN-2009-005 (2009).
 - Heribert Koziol, *Beam Diagnostic for Accelerators*, Loutraki, Greece (2000), CERN/PS 2001-012 (DR), see also extended Bibliography.
- Jacques Bosser (Ed.), *Beam Instrumentation*, CERN-PE-ED 001-92, Rev. 1994

Beam Position Monitors

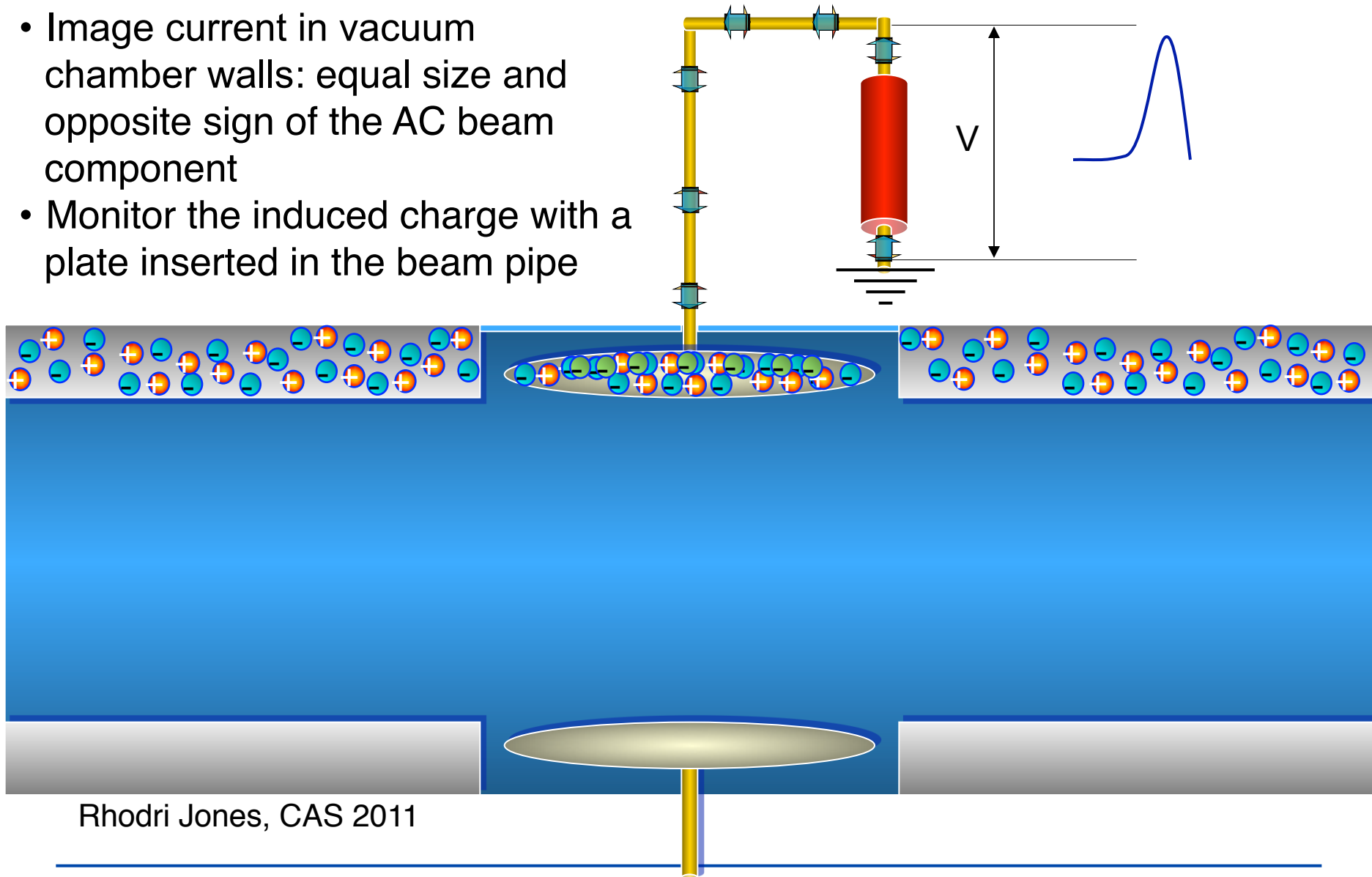
Capacitive Pick-Ups for Bunched Beams

- 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

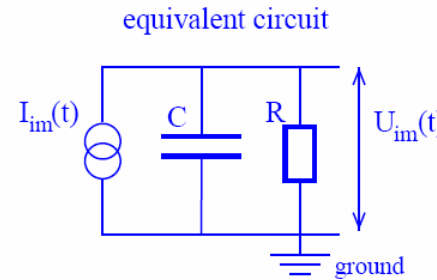
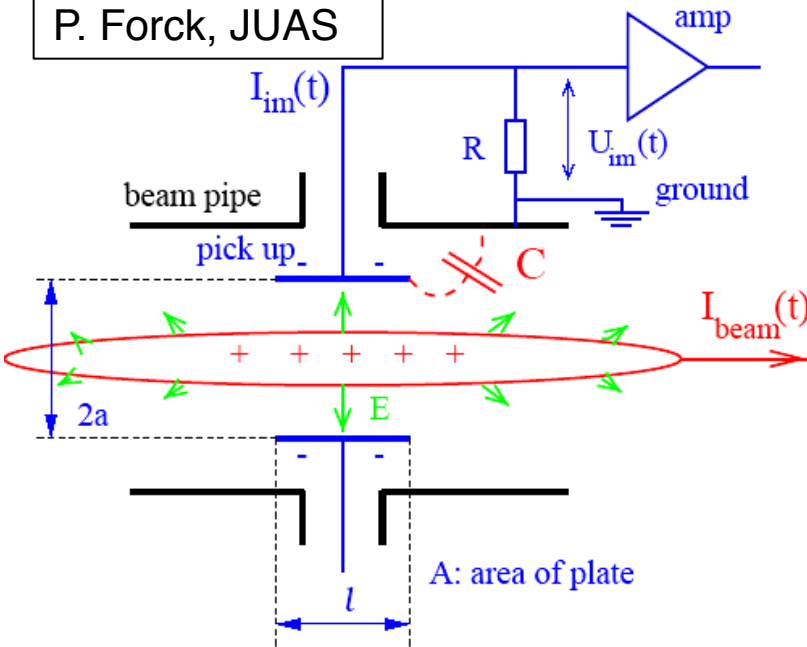
- Image current in vacuum chamber walls: equal size and opposite sign of the AC beam component
- Monitor the induced charge with a plate inserted in the beam pipe



Rhodri Jones, CAS 2011

Schematics and Simplified Equivalent Circuit

P. Forck, JUAS



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

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

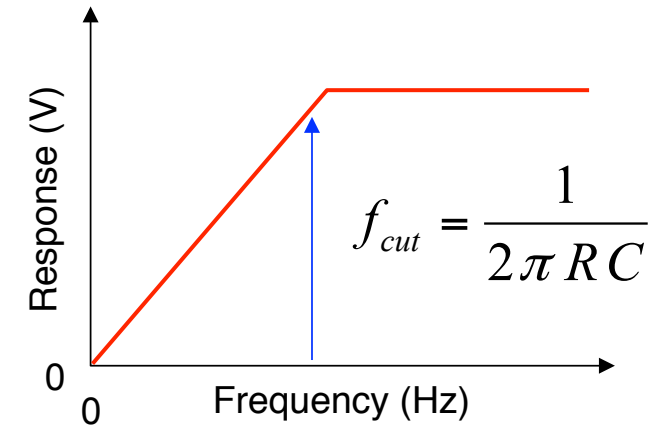
$$\equiv Z_t(\omega, \beta) \cdot I_{beam}(\omega)$$

Z_t ... longitudinal transfer impedance
 \Rightarrow High pass characteristics with a cut-off frequency, f_{cut}

$$I_{im} = A/2\pi a l (-l/\beta c dI_{beam}/dt) = A/2\pi a l 1/\beta c i\omega I_{beam}(\omega)$$

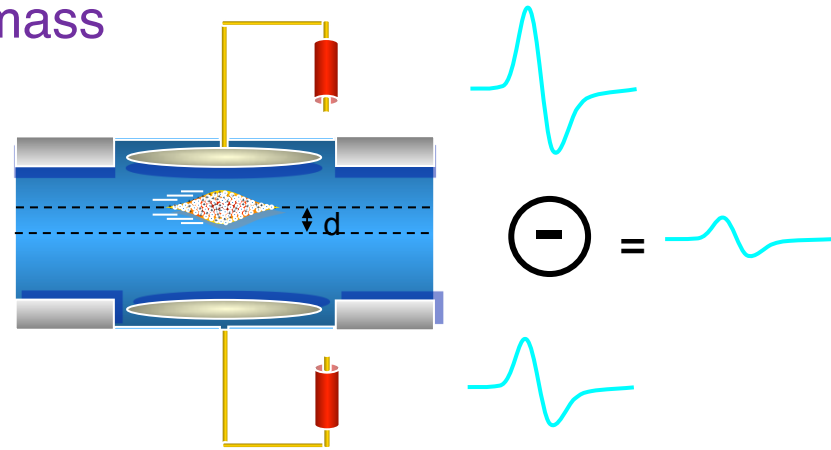
frequency domain: $I_{im} = I_{im0} e^{i\omega t}$

- U_{im} ... voltage measured due to image current
- R ... amplifier input resistor
- ω ... frequency
- βc ... beam velocity



Beam Position

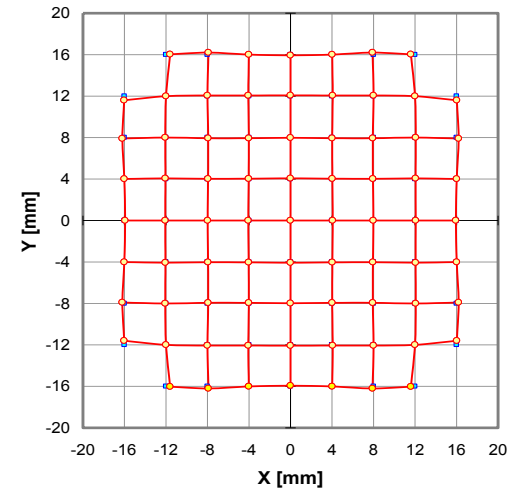
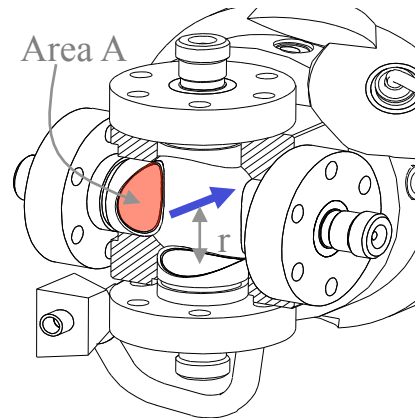
- Signal on each plate is proportional to the beam intensity
- The **difference signal** (ΔU), top - bottom, or left – right, is proportional to the **position of the beam center of mass**
- Normalization to the **sum signal** (ΣU) gives the **position**:
 - $x = \frac{1}{S} \frac{\Delta U}{\Sigma U} \cdot \text{position sensitivity}$
- 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



Example: Button Pick-up

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

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

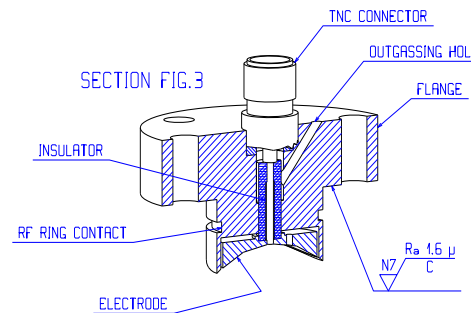


R. Jones, CAS

LHC buttons

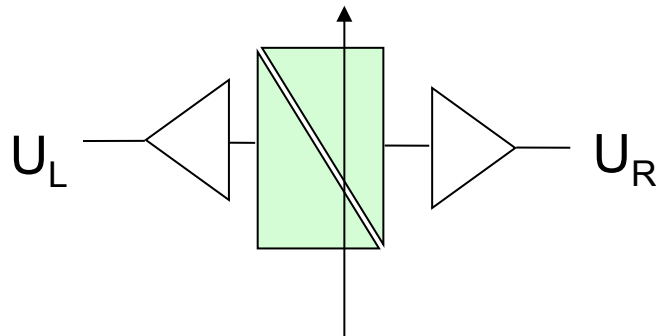
$$f_{cut} = \frac{1}{2\pi RC} = \frac{1}{2\pi \times 50\Omega \times 8pF} = 400MHz$$

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

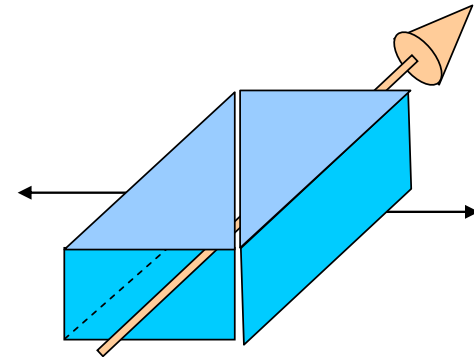


Shoebox Pick-up

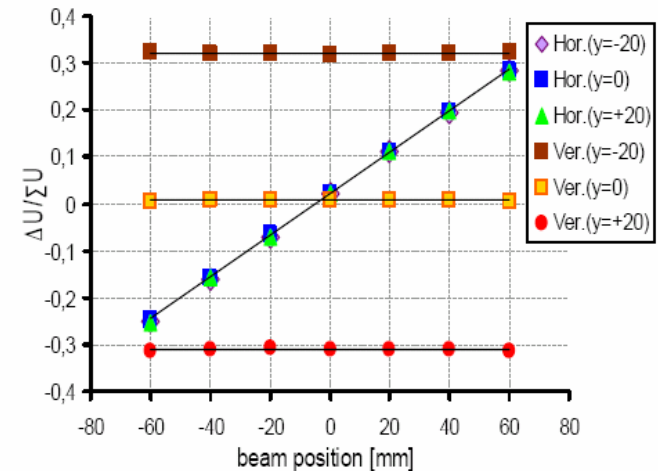
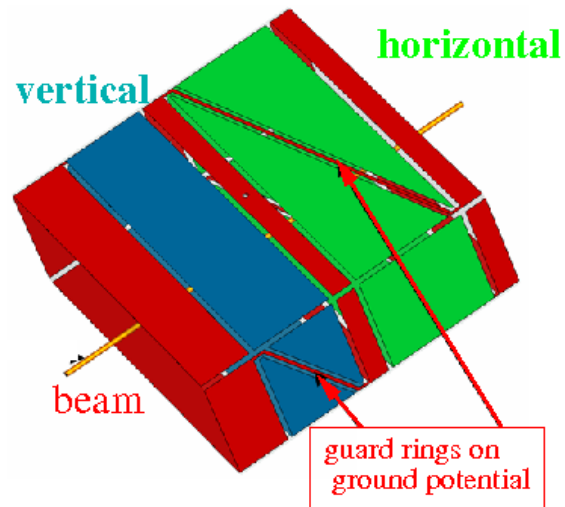
- ΔU gives linear position reading (no geometric correction)
- Condition: Linear cut: projection on the measurement plane must be linear:



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

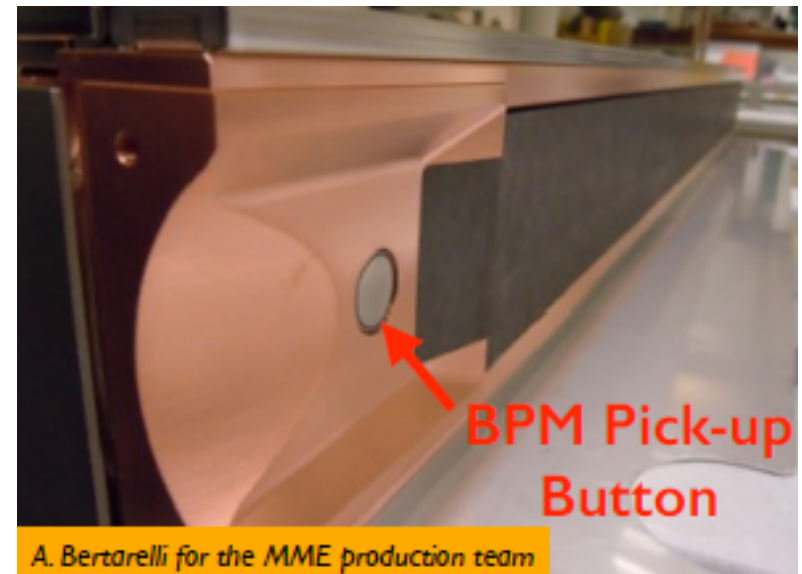


- Various geometries have been built, example from GSI optimization study (P.Kowina et al., DIPAC 2005)



New LHC Collimators with Integrated BPMs

- Beam-based setup currently with BLM signal → time consuming
- Tighter tolerances will be required for future LHC operation
- BPM integrated in the tapered end of the collimator jaws (10.6mm retraction from jaw surface)
 - Drastically reduce set-up time
 - Allow constant monitoring of beam position to jaw position
- **Successfully tested in the SPS** (D. Wollmann, HB2012)
 - $<25\ \mu\text{m}$ difference to BLM setup - believed to be dominated by the BLM setup method
 - single pass (transfer line): $<90\ \mu\text{m}$ rms
 - no disturbance observed from protons hitting the jaws or from shower particles

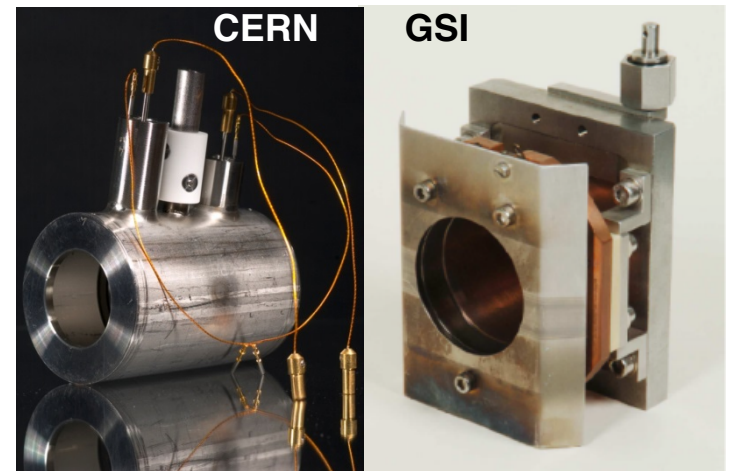
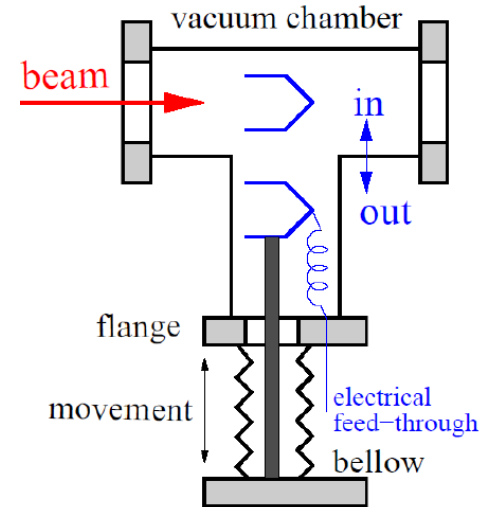


Beam Current

Faraday Cup

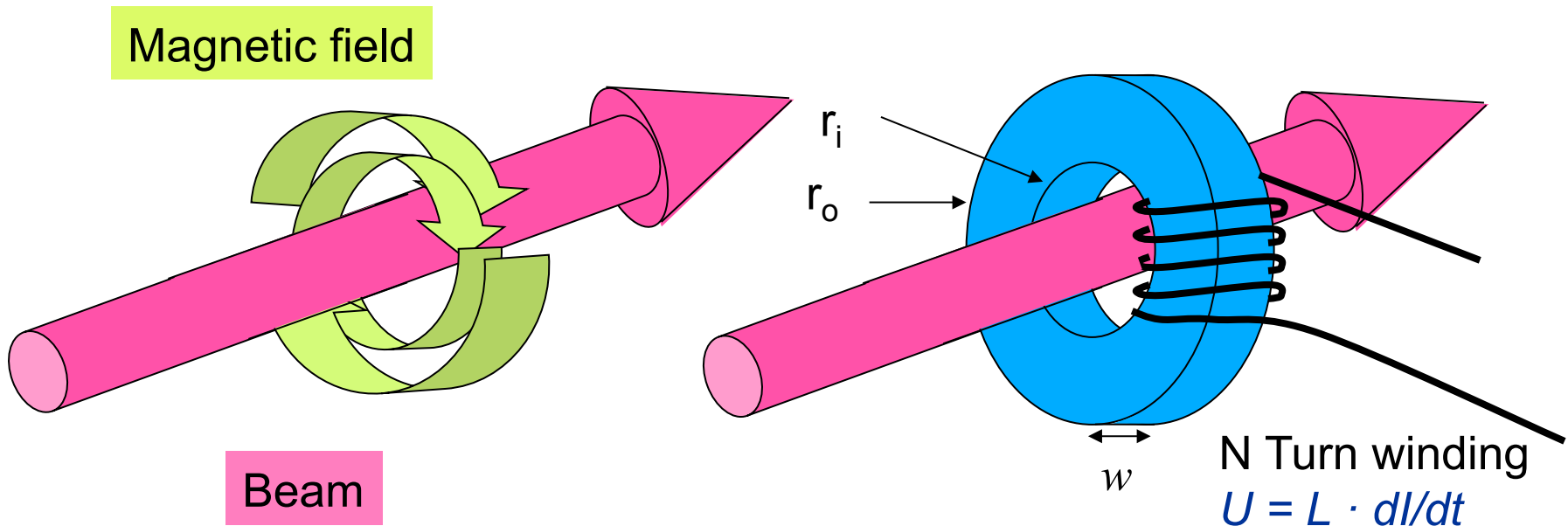
- Measurement of the beam's **electrical charges**
 - Low energies only
 - Particles are stopped in the device
→ **Destructive**
 - Sensitive to low currents:
down to 1 pA can be measured
 - Creation of secondary electrons of low energy (below 20 eV)
 - Repelling electrode with some 100 V polarization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

Faraday Cup at GSI LINAC, P. Forck, JUAS



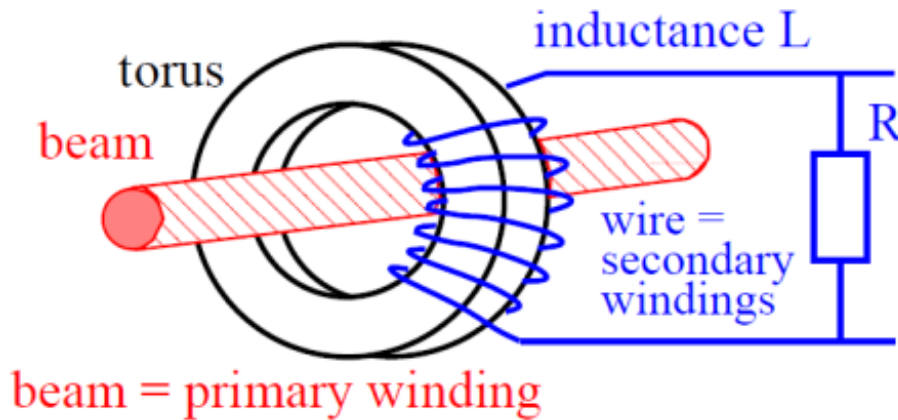
Beam Current Transformer (BCT)

- Measurement of the **magnetic field** of the beam
- **Non-interceptive**
- Independent on beam energy
- Beam as primary winding of a transformer



U. Raich, CAS

Current Transformers



P. Forck, JUAS

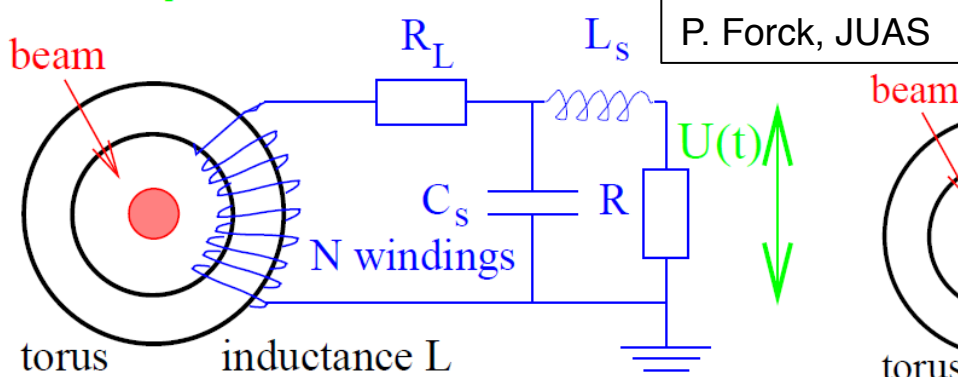
Transformer Inductance

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

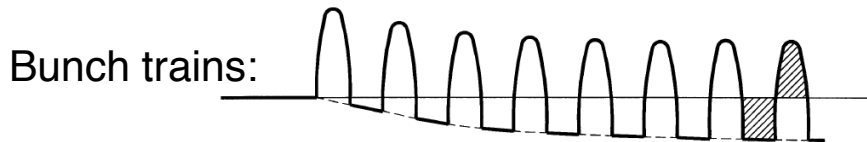
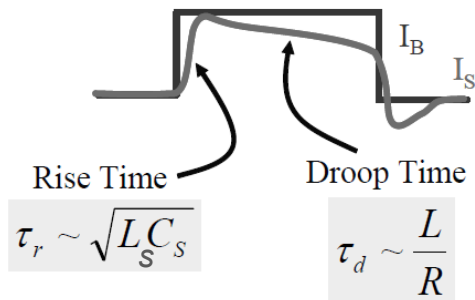
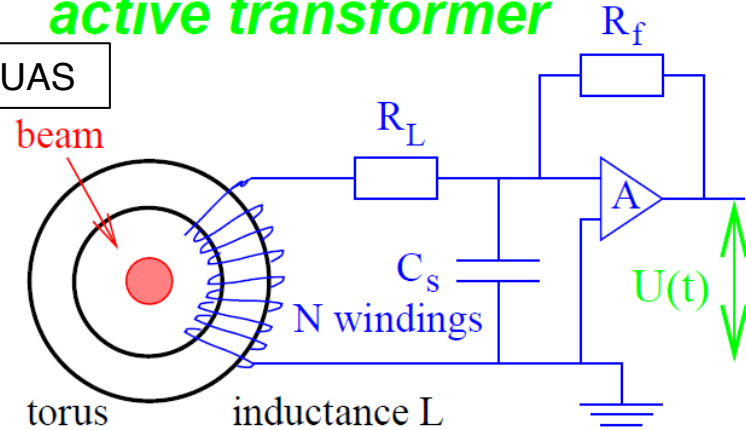
- Magnetic field of the beam is very low (Example: 1 μA , $r = 10\text{cm} \Rightarrow 2 \text{ pT}$; compared to earth magnetic field of $\approx 50 \mu\text{T}$)
- Aim of the Torus:
 - Capture magnetic field lines with cores of high relative permeability
 - Signal strength nearly independent of beam position.
 - CoFe based amorphous alloy Vitrovac: $\mu_r = 10^5$

Adapt Droop Time with Active Transformer

passive transformer



active transformer



- Equal areas
- Baseline shift proportional to intensity

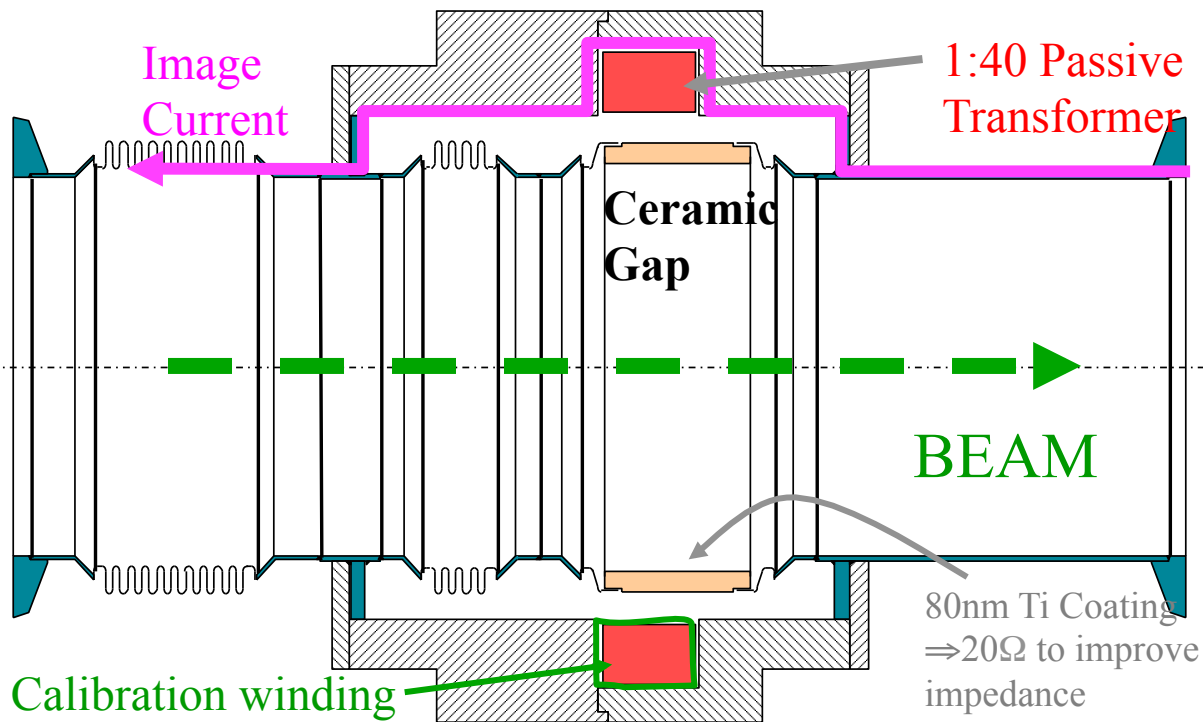
H. Koziol, CAS

- 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)

$$\tau \downarrow d = L/R \downarrow f / A + R \downarrow L \approx L/R \downarrow L$$

Transformer Housing

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



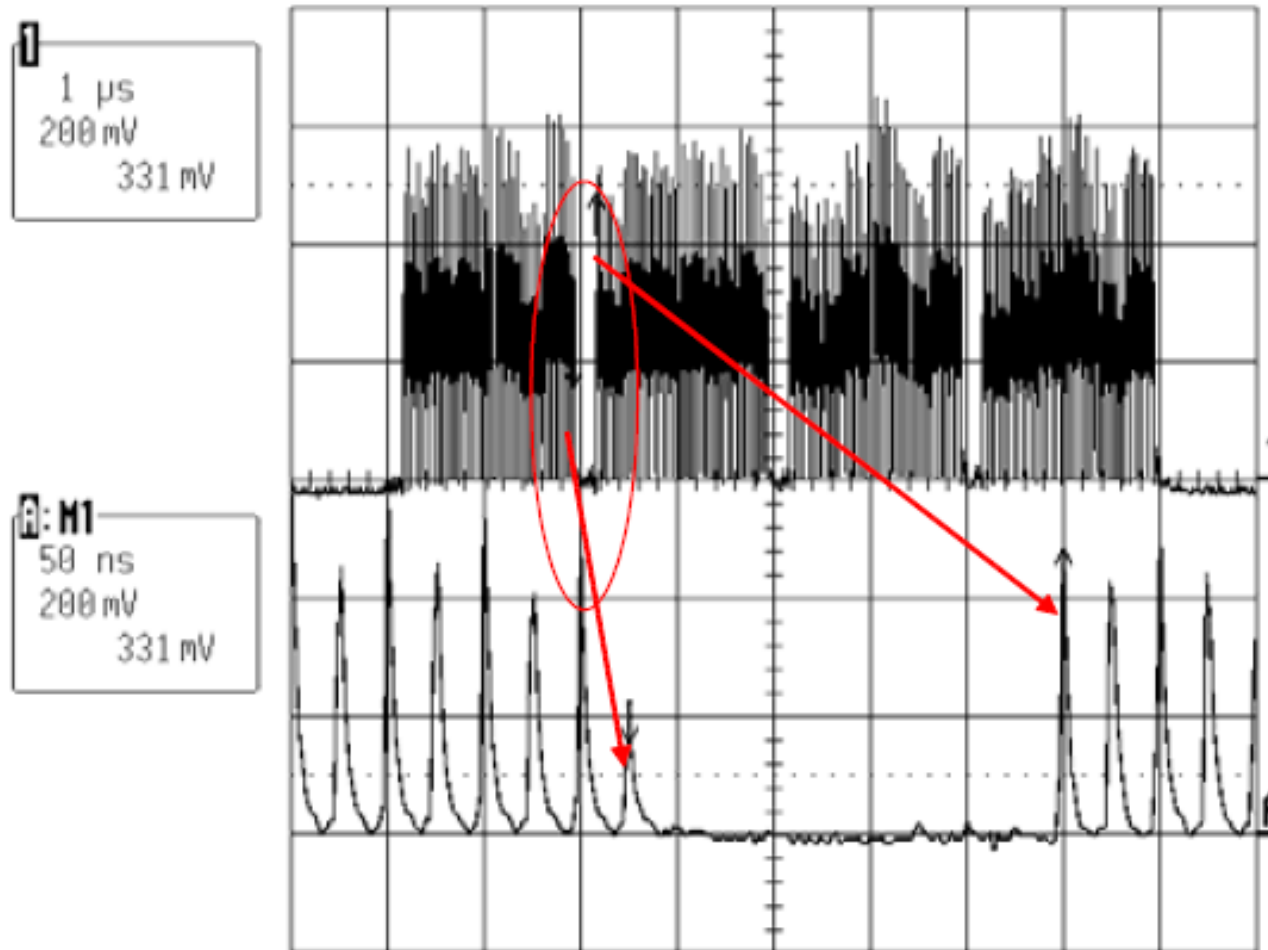
CERN SPS Fast Beam
Current Transformer
(FBCT)

Diagram by
H. Jakob

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

CERN FBCT Readings of LHC Type Beams in the SPS

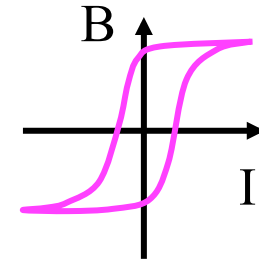
- 4 batches each containing 72 bunches separated by 25 ns



R. Jones,
DIPAC'03

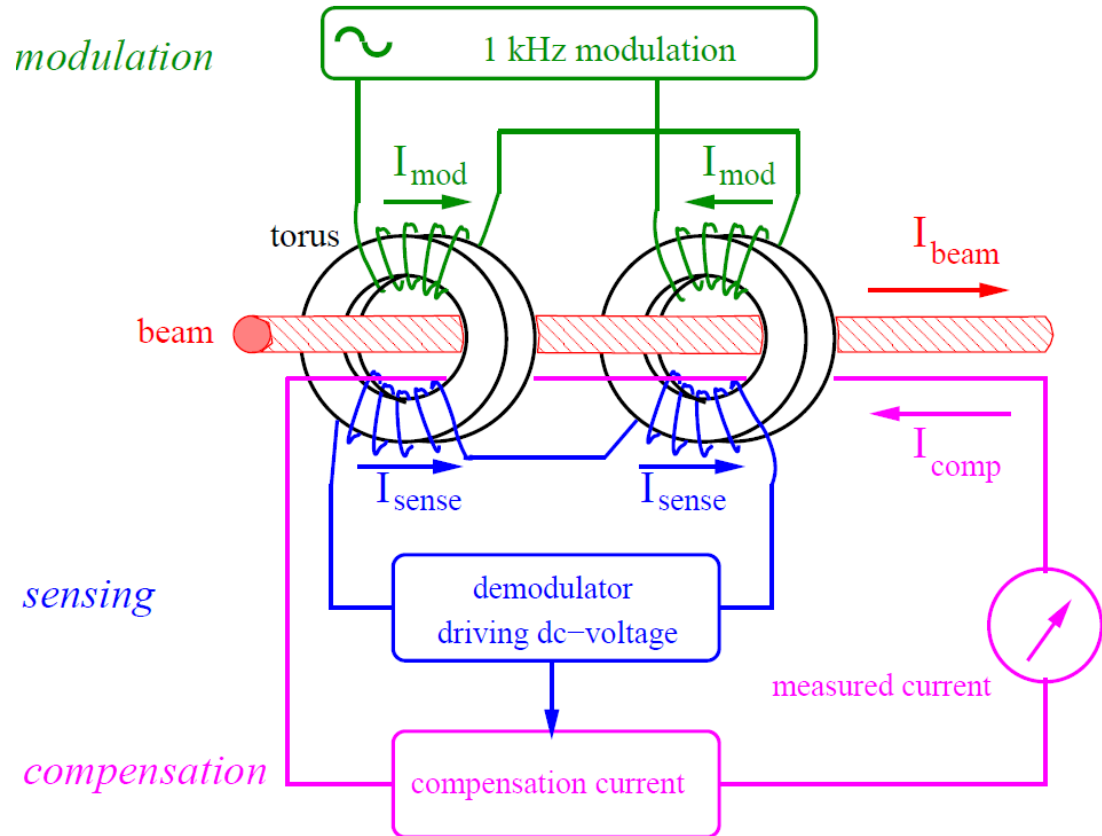
DCCT: DC Beam Current Transformer

- 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

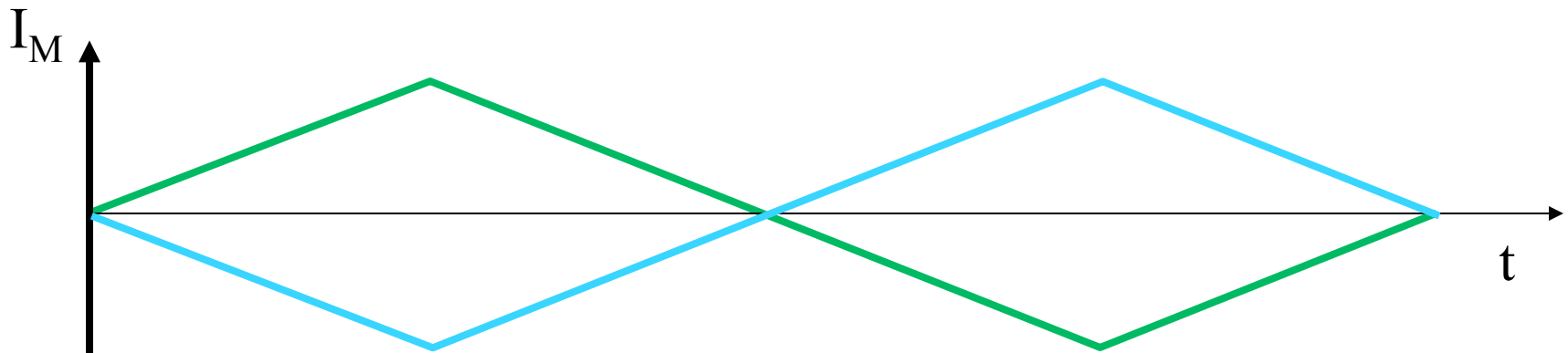
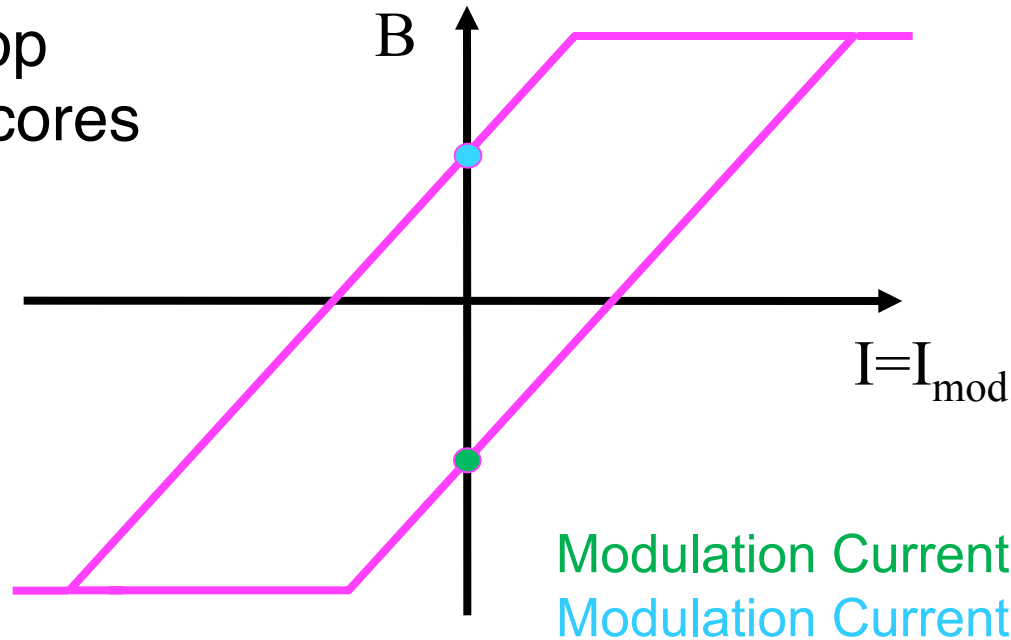
P. Forck, JUAS



DCCT Principle – Case 1: No Beam

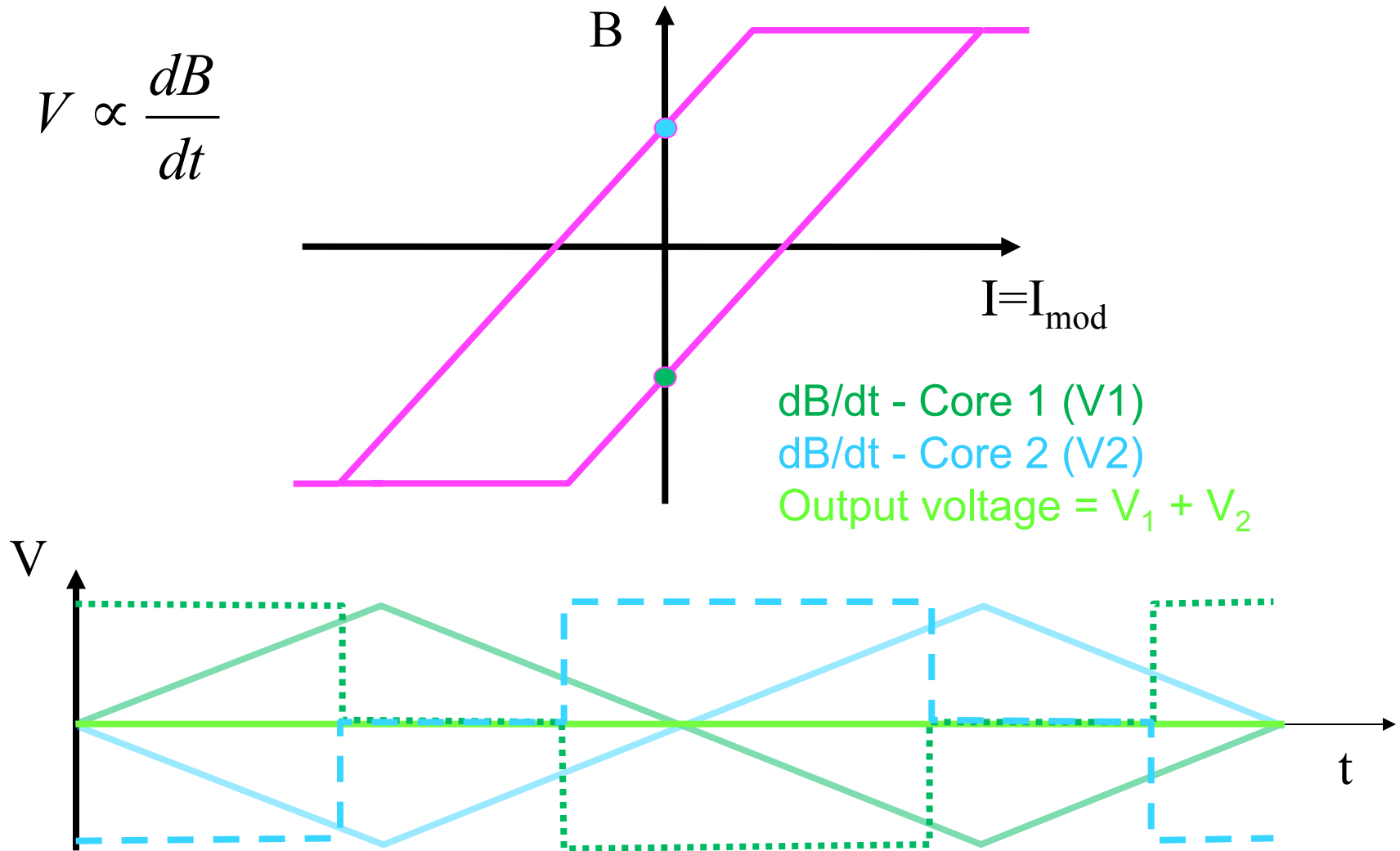
R. Jones, CAS

Hysteresis loop
of modulator cores



DCCT Principle – Case 1: No Beam

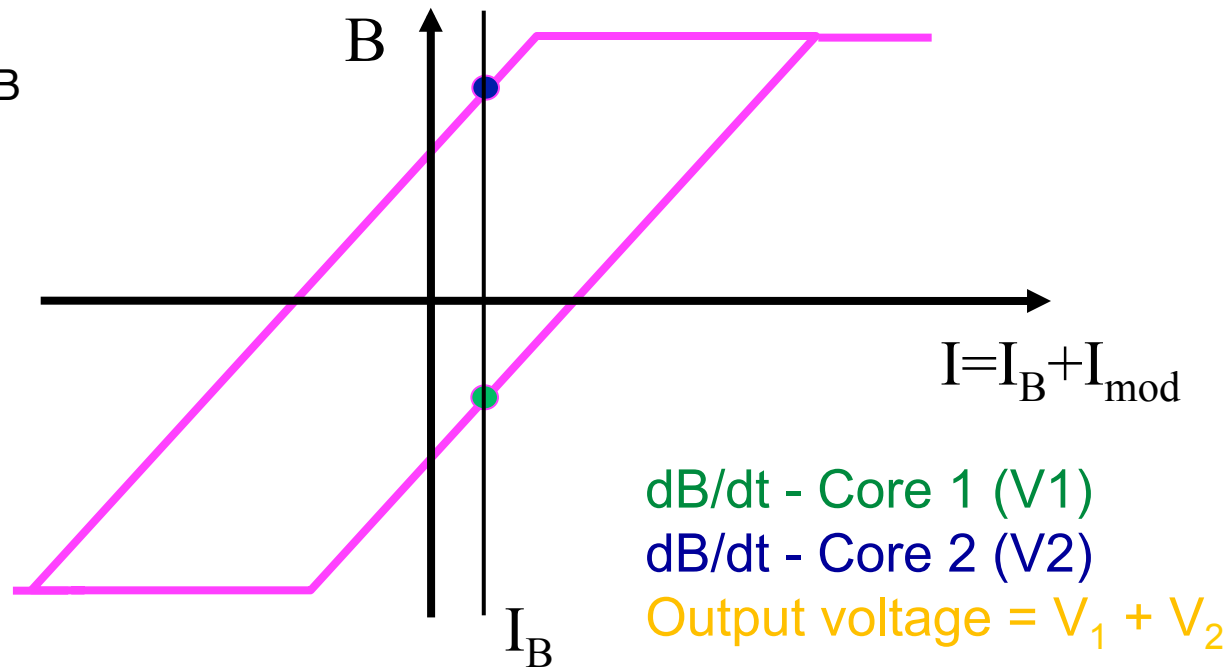
R. Jones, CAS



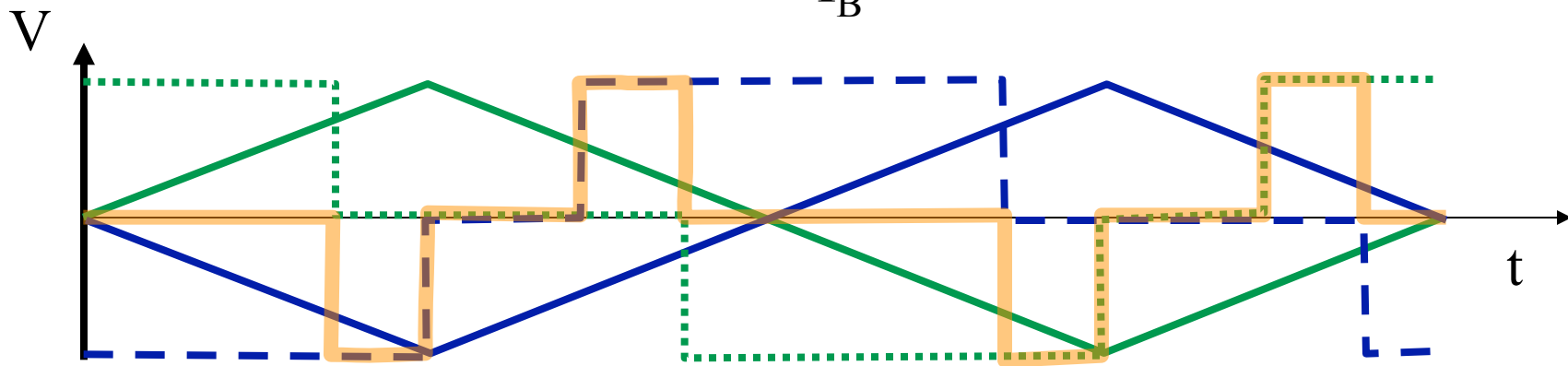
DCCT Principle – Case 2: With Beam

Beam Current I_B

Output signal is at twice the modulation frequency

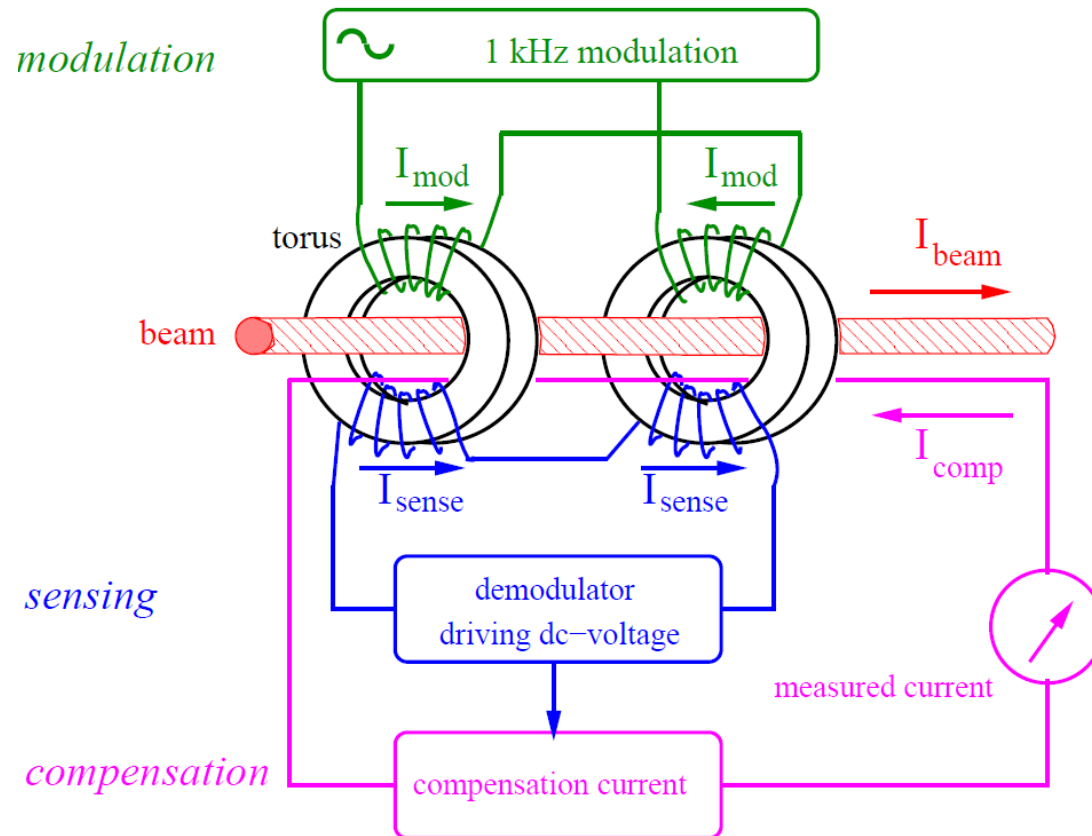


$\frac{dB}{dt}$ - Core 1 (V_1)
 $\frac{dB}{dt}$ - Core 2 (V_2)
Output voltage = $V_1 + V_2$



DCCT in the “Zero Flux” Scheme

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

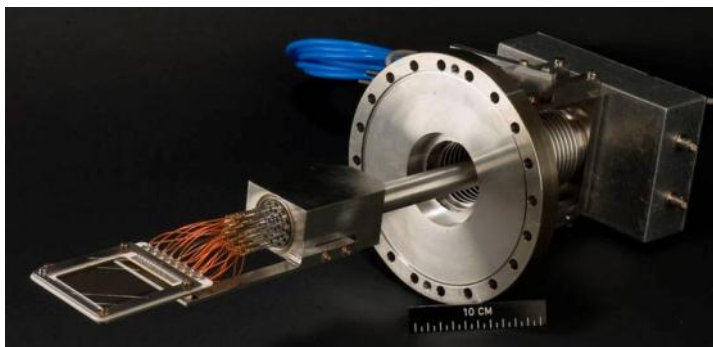
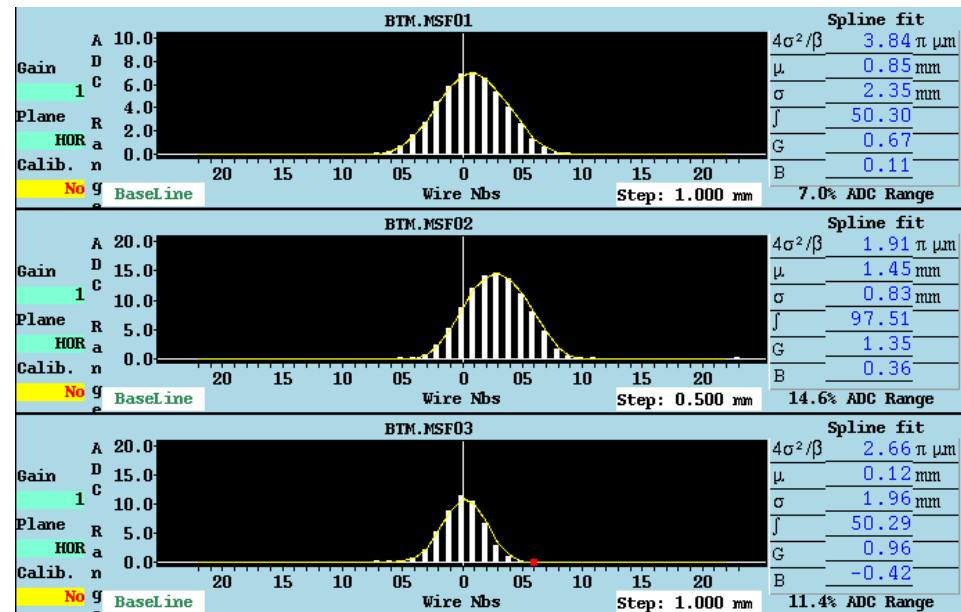
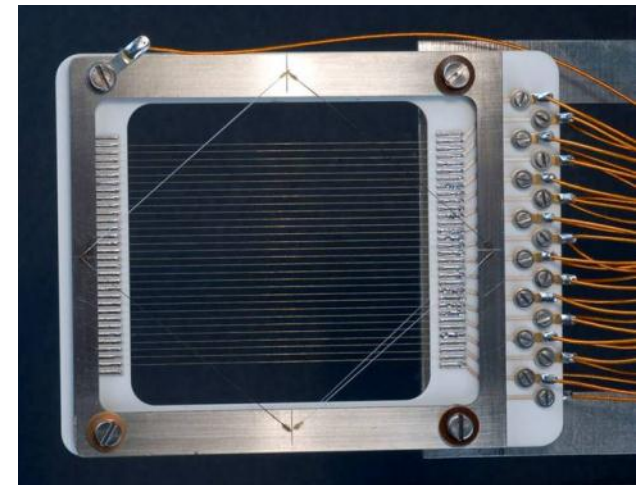
Overview - Beam Profile measurement

- 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

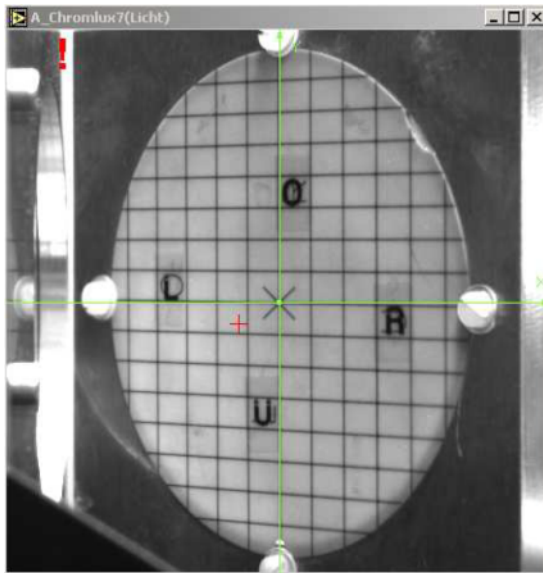
Secondary Emission (SEM) Grids

- 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 $\lesssim 0.25\text{mm}$
- 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



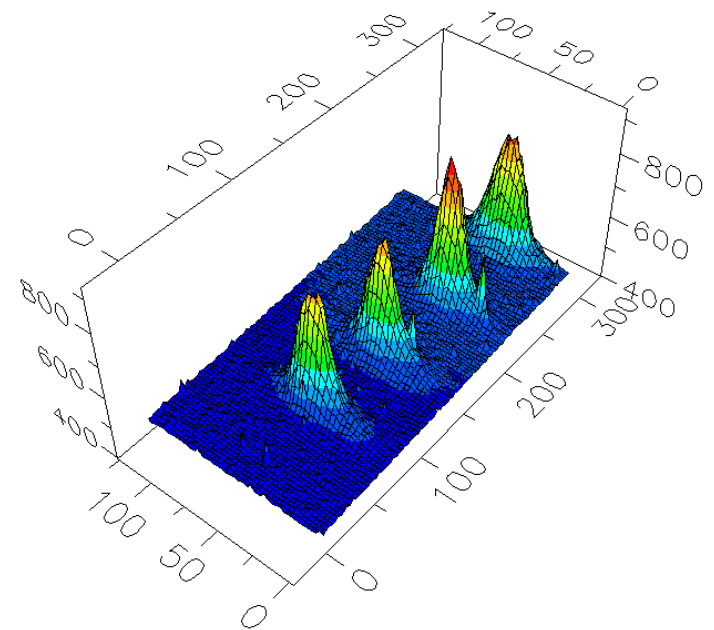
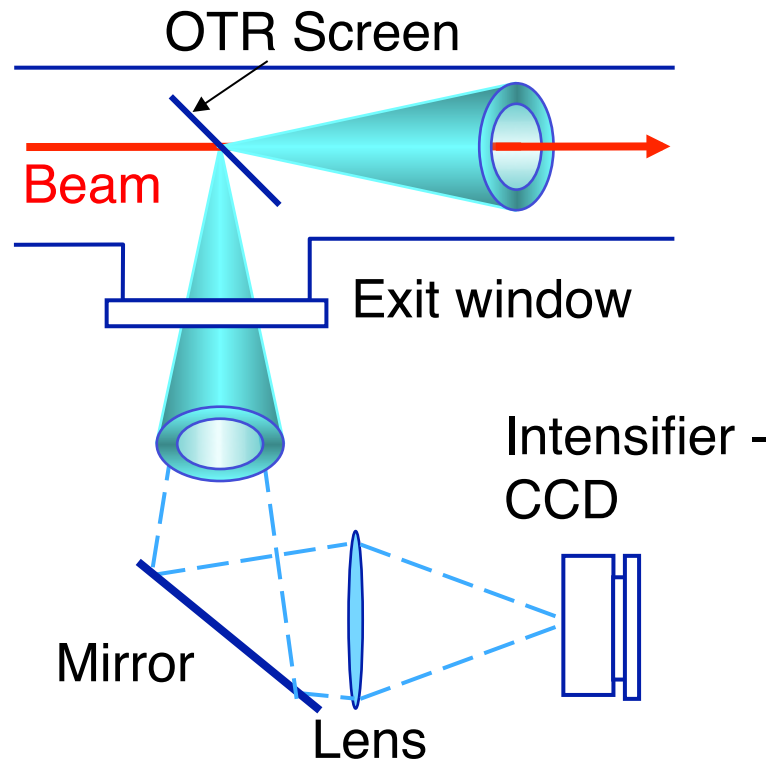
| Abbreviation | Material | Activator | max. emission | decay time |
|--------------|--|-----------|---------------|------------|
| Quartz | SiO ₂ | none | 470 nm | < 10 ns |
| | CsI | Tl | 550 nm | 1 μs |
| Chromolux | Al ₂ O ₃ | Cr | 700 nm | 100 ms |
| YAG | Y ₃ Al ₅ O ₁₂ | Ce | 550 nm | 0.2 μs |
| | 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

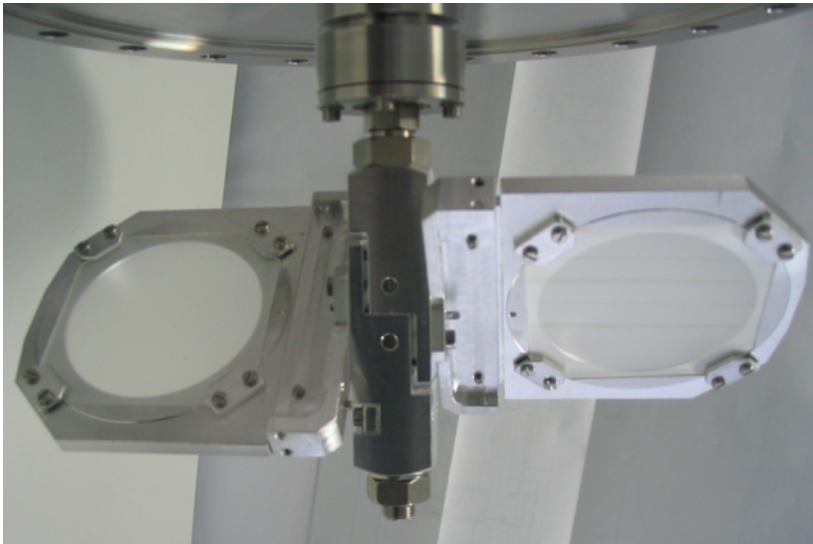
- Radiation emitted when a charged particle beam goes through the interface of two media with different dielectric constants
- Surface phenomenon allows the use of very thin screens ($\geq 0.25 \mu\text{m}$)
- Much less intercepting, but requires higher intensity



CERN SPS at injection

Beam Profile Monitoring Using Screens

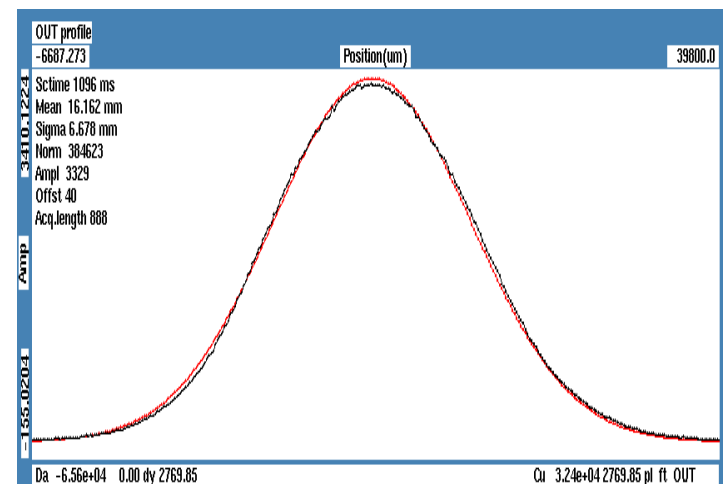
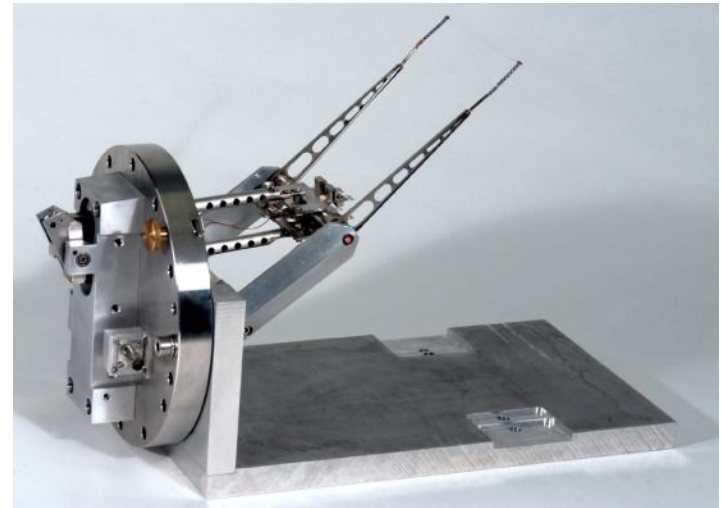
- Combine several screens in one housing e.g.
 - Al_2O_3 scintillation screen for setting-up with low intensity
 - Thin ($\approx 10\mu\text{m}$) Ti OTR screen for high intensity measurements
 - Carbon OTR screen for very high intensity operation



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

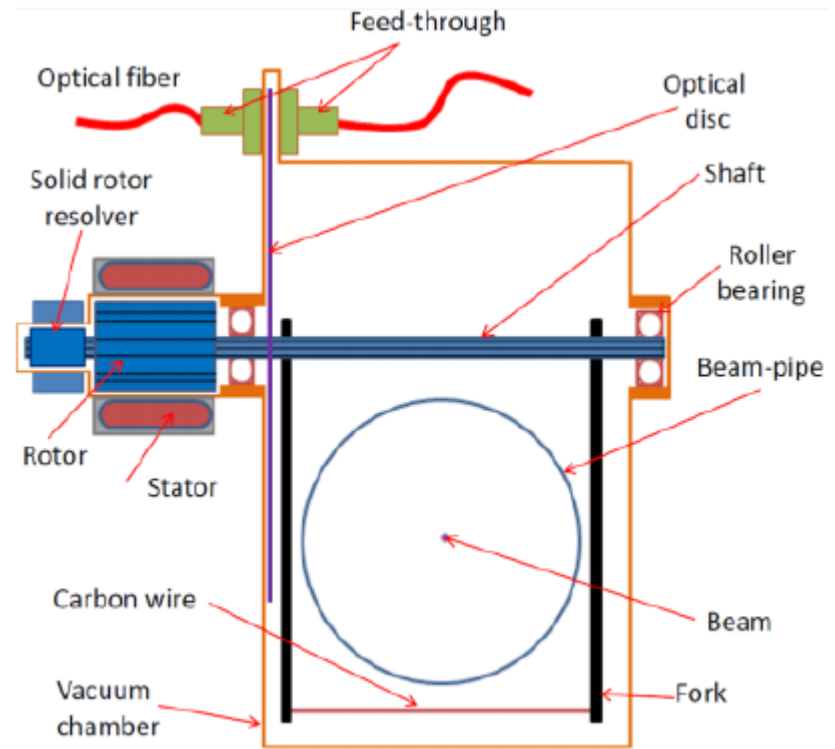
Wire Scanners

- A thin wire (down to $10\ \mu\text{m}$) is moved across the beam
 - Has to move fast to avoid excessive heating of the wire
 - Rotational scanner up to 10 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 goals:
 - Spatial resolution of few μm (using high resolution angular position sensor)
 - Dynamic range: 10^4
 - Usage of sensor with large dynamic (diamond)
 - Automatic electronic switching of gain ranges
 - Minimize fork and wire deformations
 - Study of dynamic behavior of fork/wire system
 - Vibration mode optimized acceleration profile
- 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

**Beam Loss Measurement
for Protection and Diagnostics**

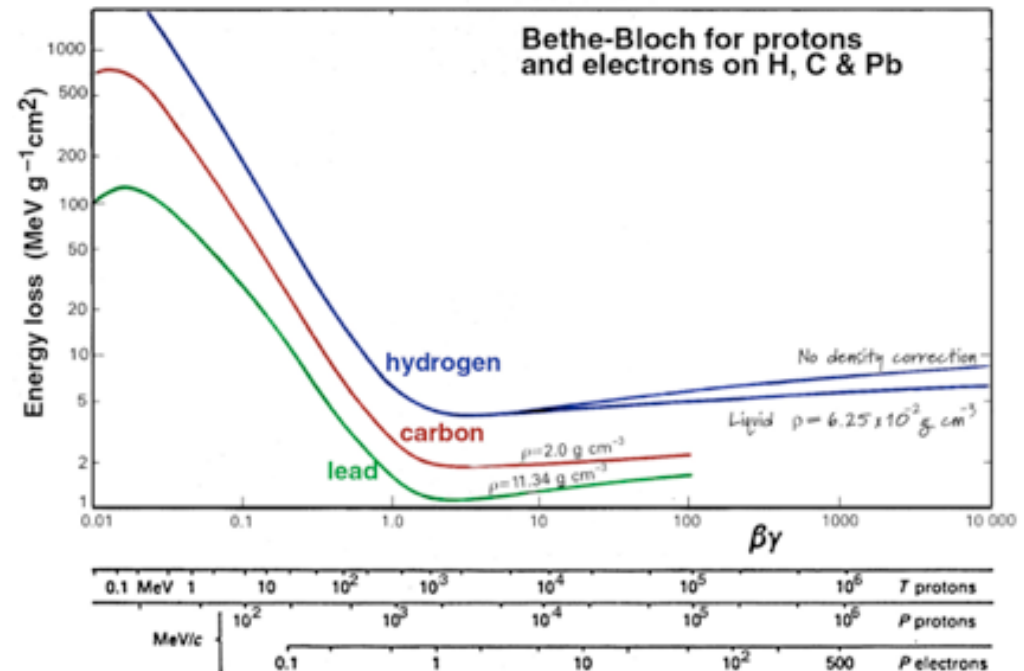
Detection Principles

- See *Review of Particle Physics*, J. Beringer et al. (Particle Data Group), Phys. Rev. D 86, 010001 (2012) for reference.

Ionization

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

- $$\frac{dE}{dx}_{MIP} = (1-5) \text{ MeV cm}^2 \text{ g}^{-1}$$

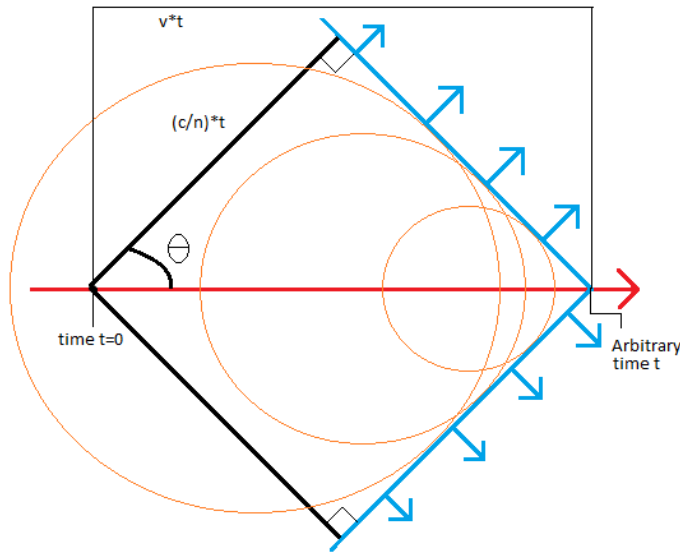


Scintillation

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

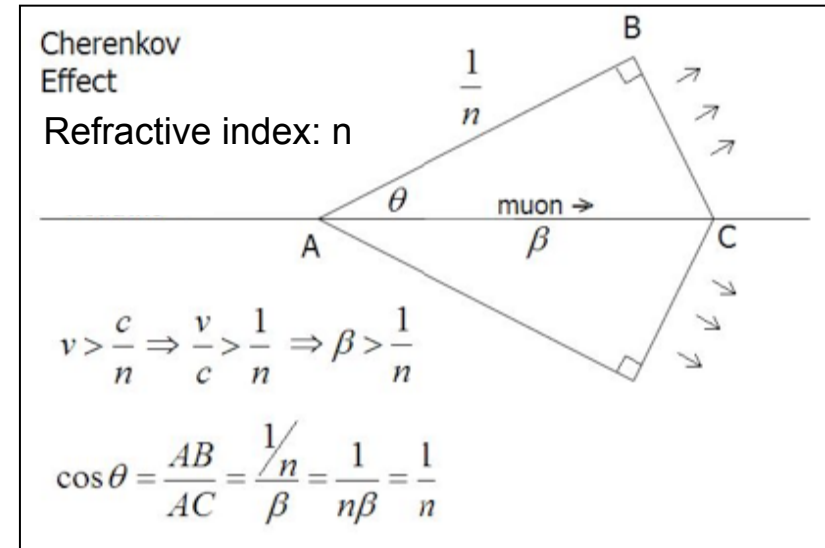
Detection Principles cont'd

Cherenkov light



- Trajectory of Particle
- Cherenkov Light
- Shock Waves

Drawing: Bock and Vasilescu 1999

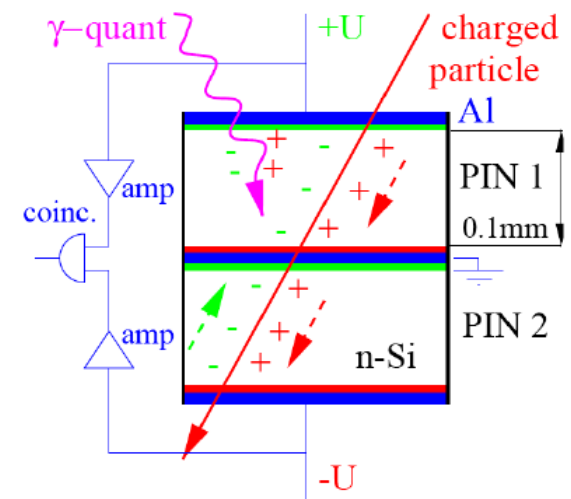
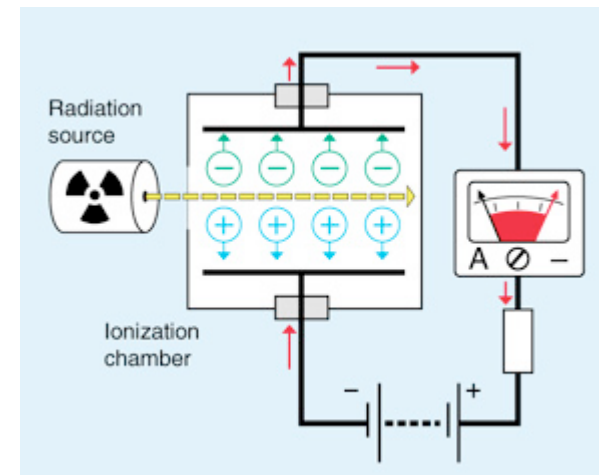


$$\text{photon yield: } \frac{dN}{dx} = 2 \cdot \pi \cdot \alpha \cdot \sin^2 \Theta \cdot \left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2} \right)$$

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

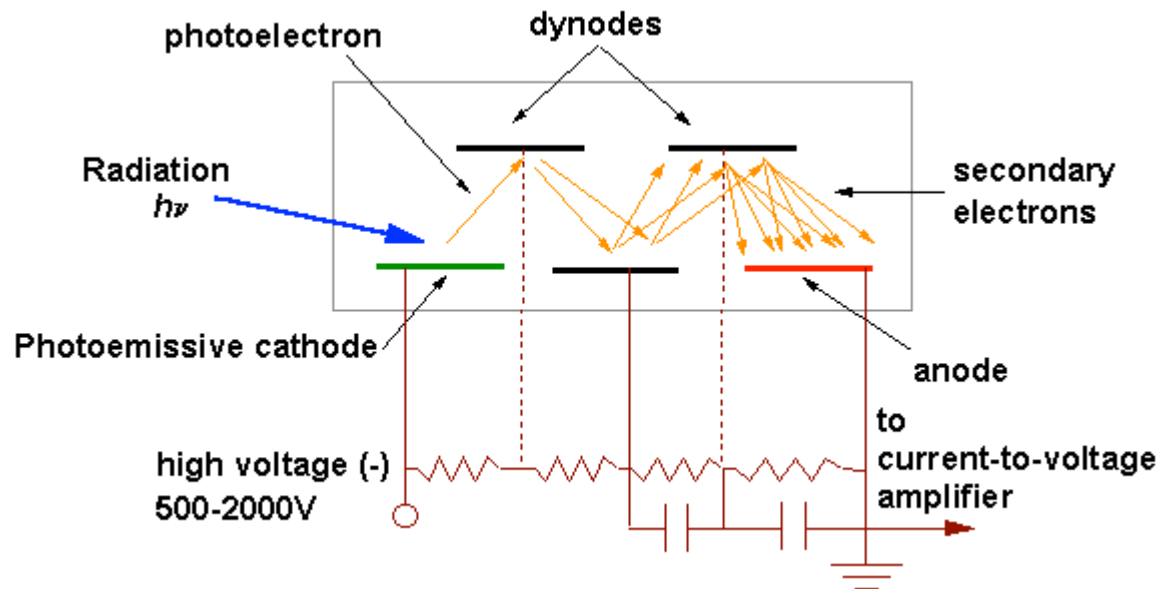
Common types of monitors

- **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)



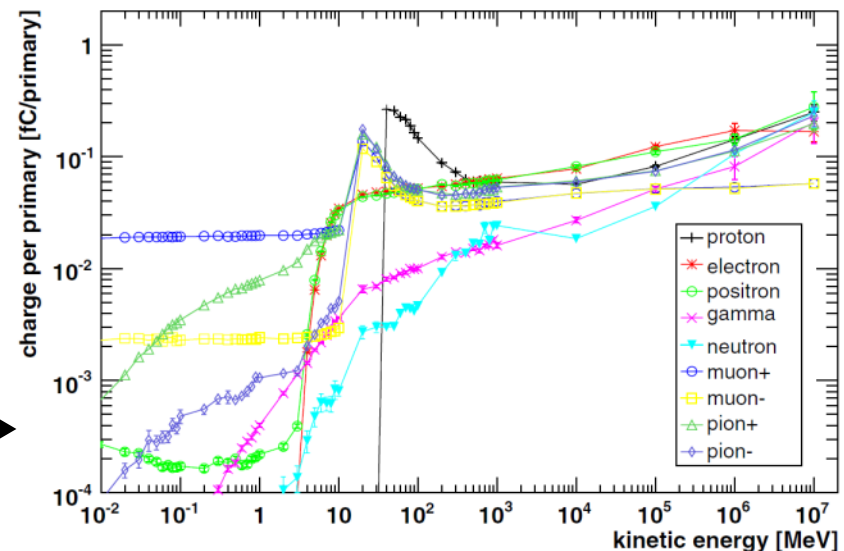
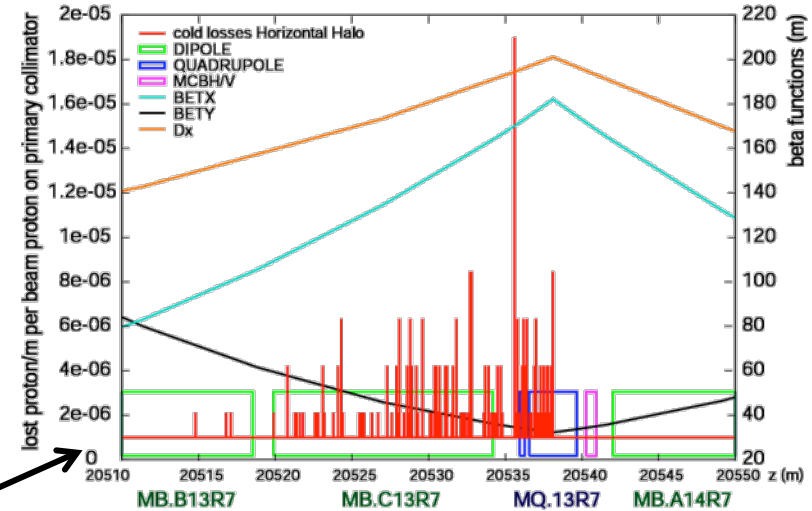
→ 1.5 Million threshold values

- 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**



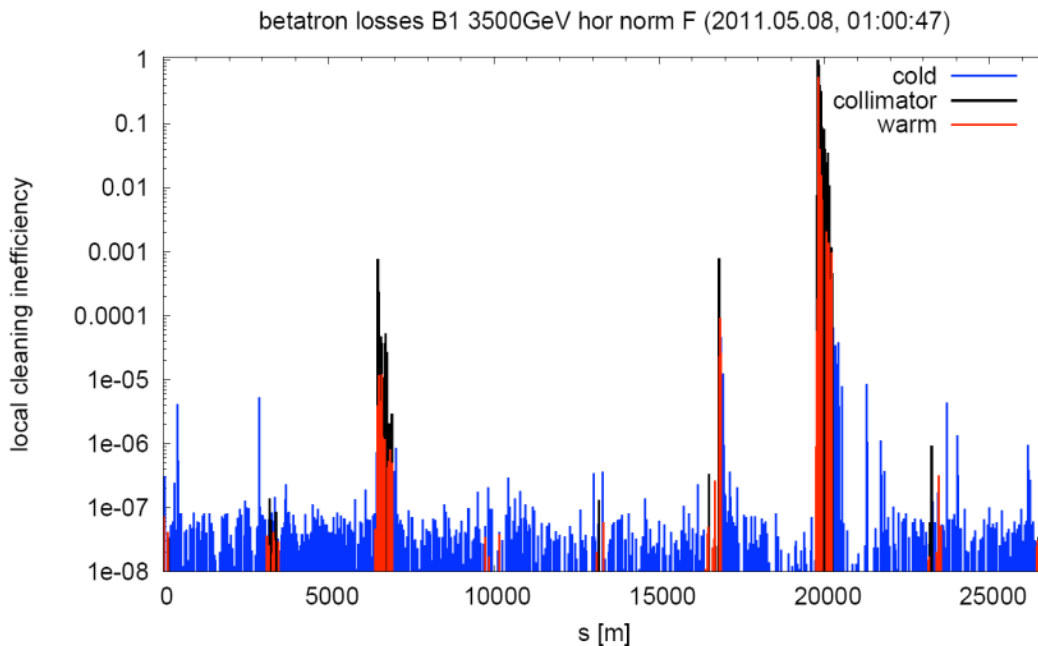
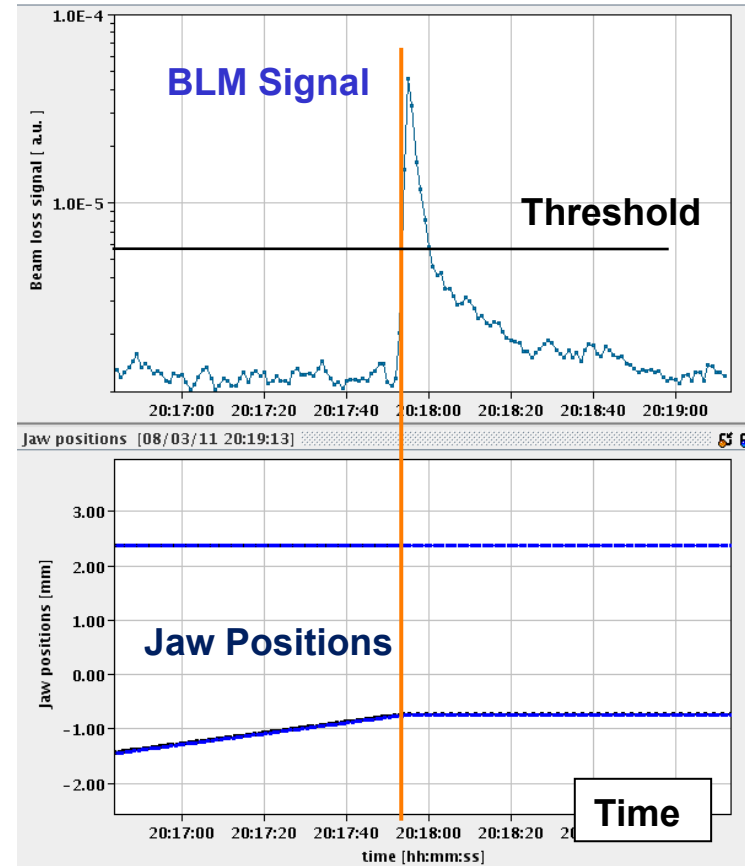
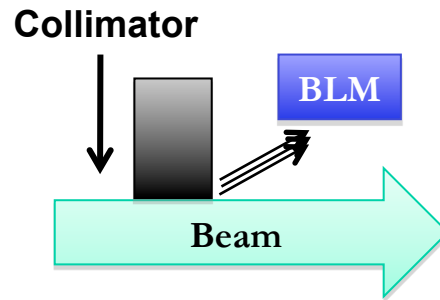
Beam Abort Threshold Determination

- 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 (GEANT, FLUKA, GARFIELD)



Set-up and validation of collimation performance

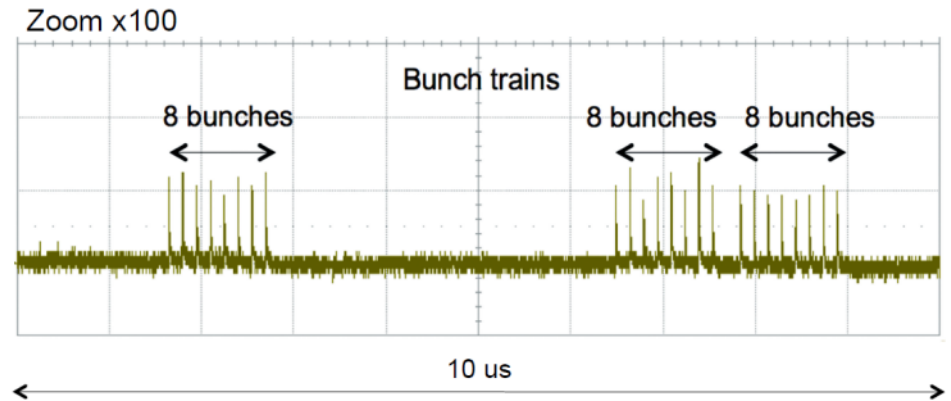
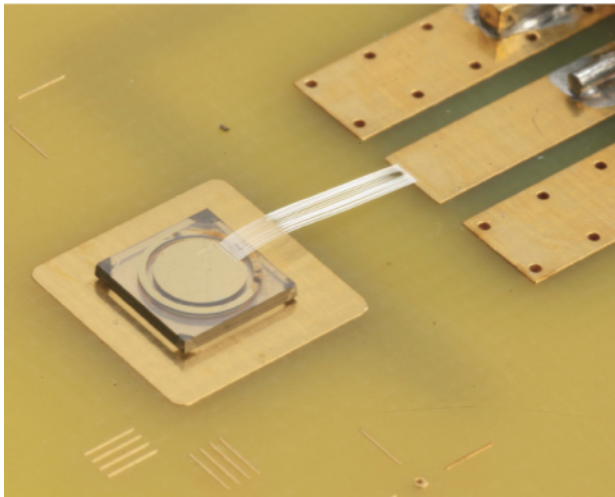
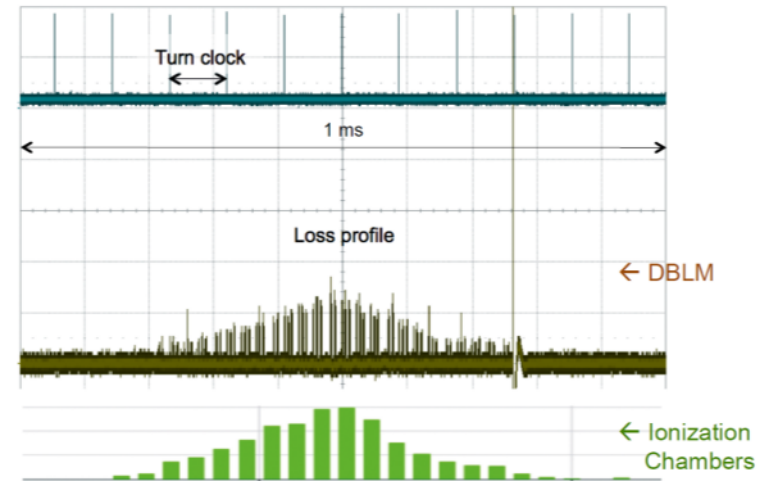
- Find the beam center with each collimator jaw by stepping the jaw towards the beam and observing the BLM signal



‘loss map’: losses along the ring normalized to the losses at the primary collimator: performance verification

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

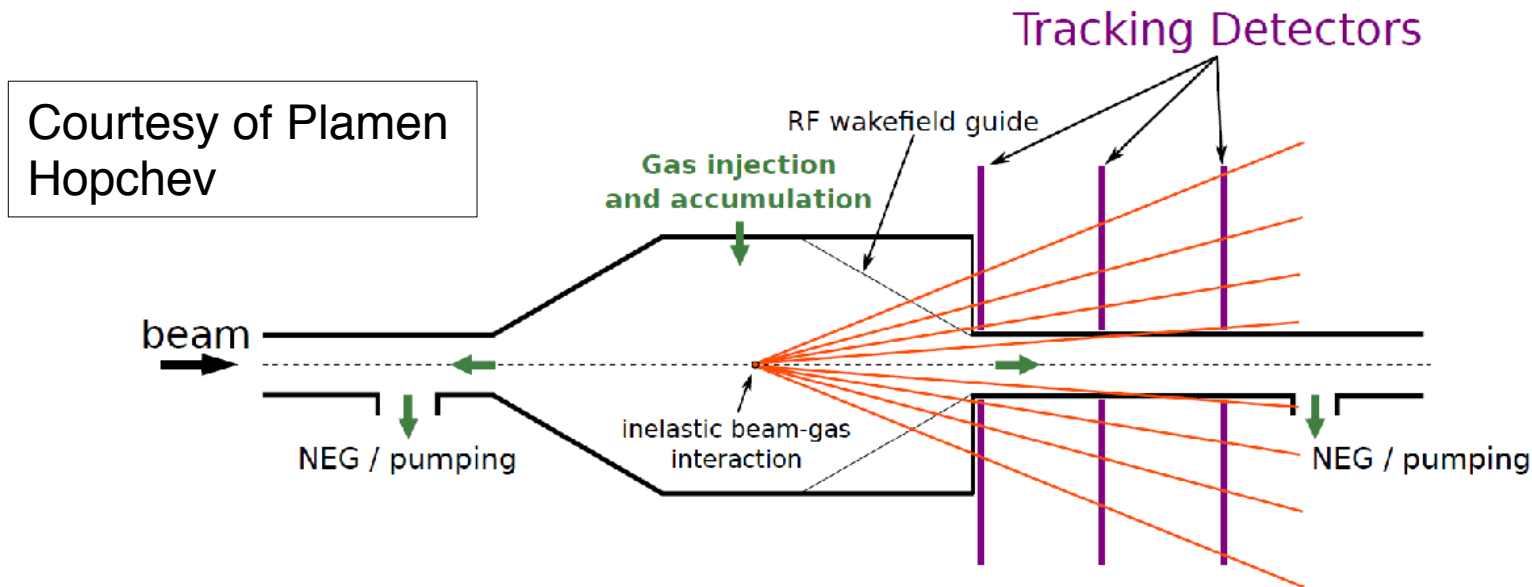


Thank you for your Attention

(Quasi) Non-Invasive Beam Size Measurement

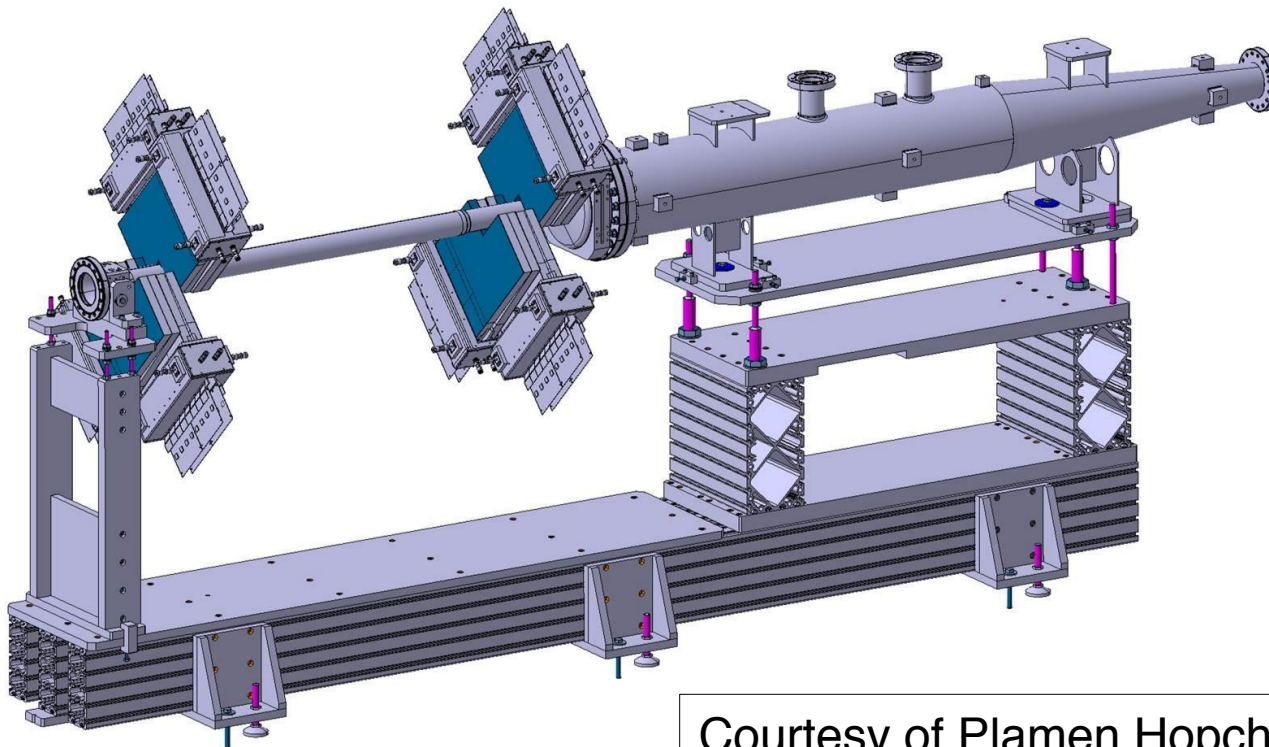
Beam Gas Vertex monitor

- Beam imaging with vertex reconstruction of beam gas interactions
 - Reconstruct the tracks coming from inelastic beam-gas interactions
 - Determine the position of the interaction (vertex)
 - Accumulate vertices to measure beam position, angle, width and relative bunch populations
- Main requirements
 - Sufficient beam-gas rate → controlled pressure bump
 - Good vertex resolution → precise detectors and optimized geometry



BGV Demonstrator

- Goal: develop a transverse profile monitor for (HL) LHC
 - Overcome the limitations and complement the existing devices
- Demonstrate the potential of this technique by installing a prototype BGV system on one beam at the LHC
 - Commissioning planned for 2015



Detector

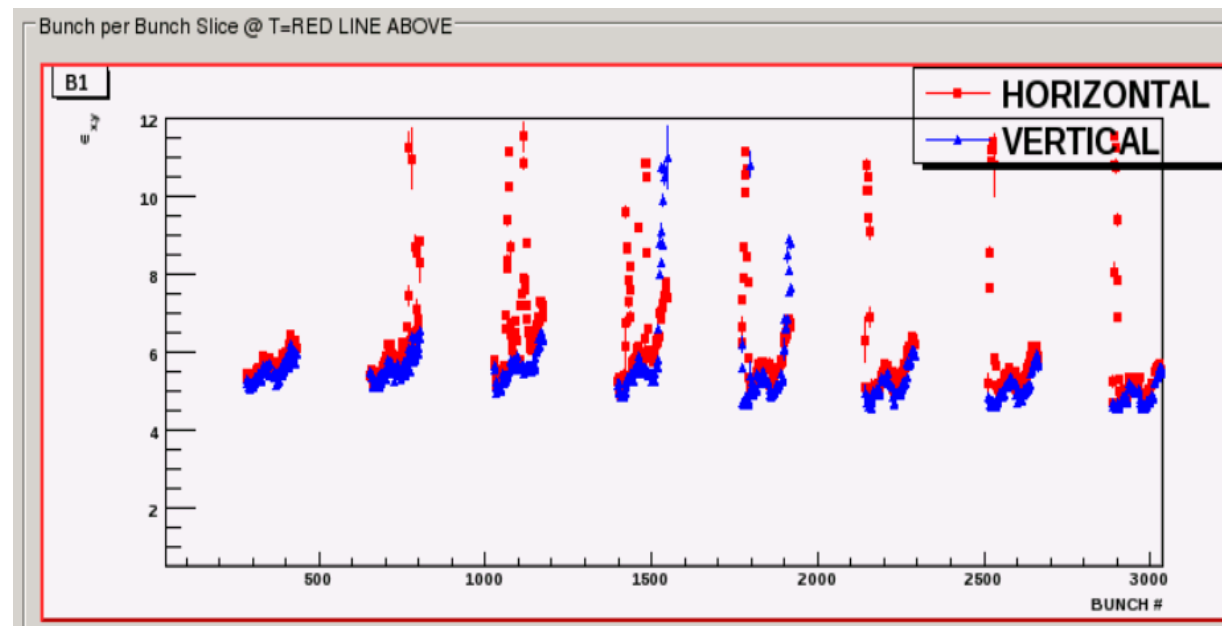
- Scintillating fibres read out with SiPMs
- Same technology as for the LHCb upgrade

Courtesy of Plamen Hopchev

Synchrotron Light Monitor

- Only for electrons & very high energy protons/ions (LHC)
- For linear machine: difficult to separate the light from the beam
- Difficult to get absolute calibration:
Image correction factors typically bigger than the beam size
- Dynamic range 200 (10^5 by changing the attenuation)
- Accuracy 30%
- Spatial resolution $50\mu\text{m}$

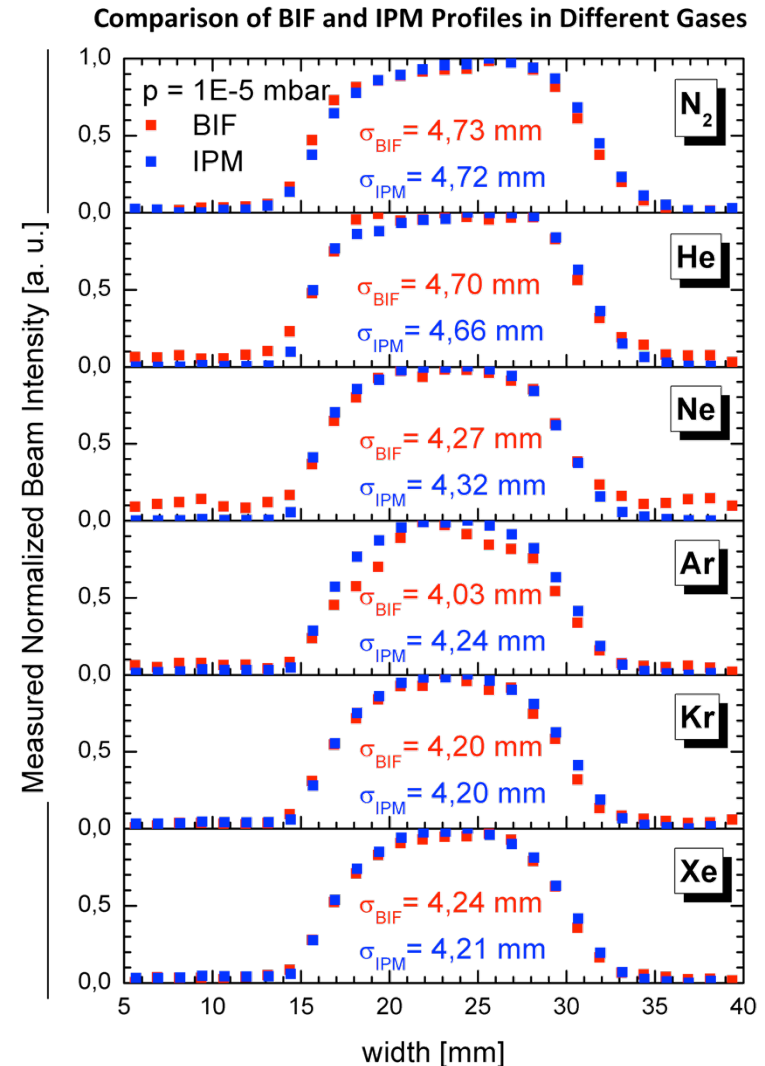
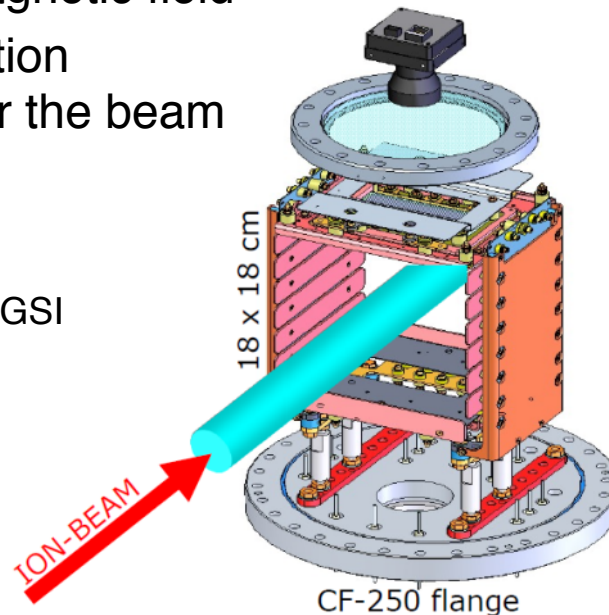
LHC: transverse blow-up of individual bunches



IPM (Ionization Profile Monitors)

- Residual Gas Ionisation
- dynamic range: up to 10^3
- ≈ 10 times more sensitive than Luminescence
- Image broadening due to space charge
- More complicated to build
 - High voltage
 - Guiding magnetic field
 - Compensation magnets for the beam

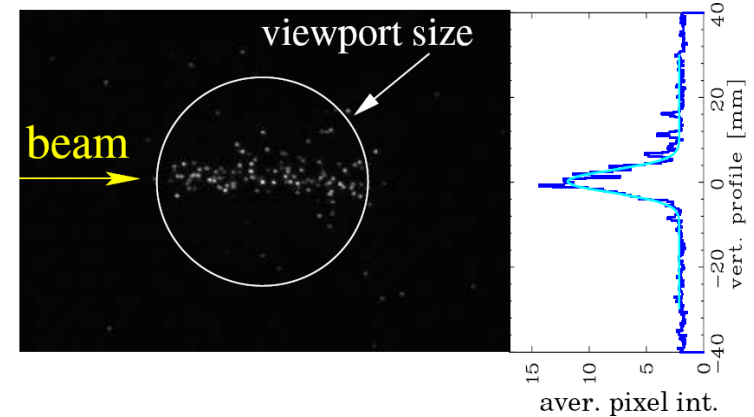
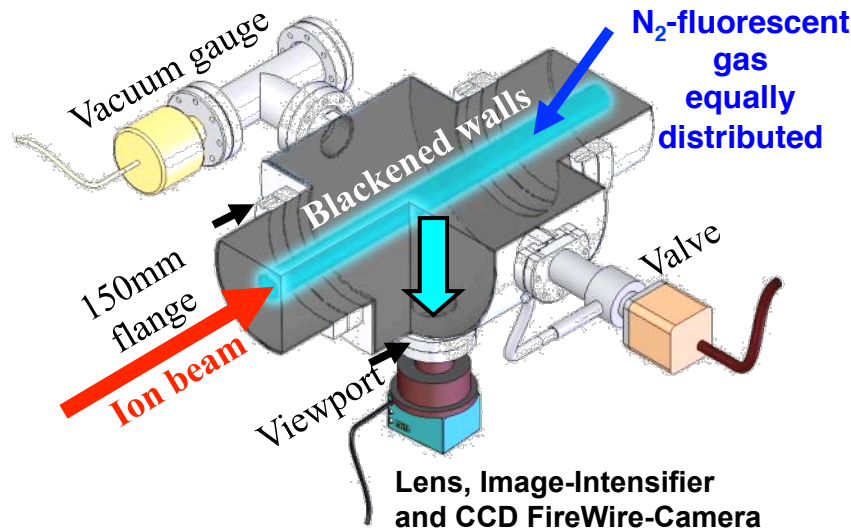
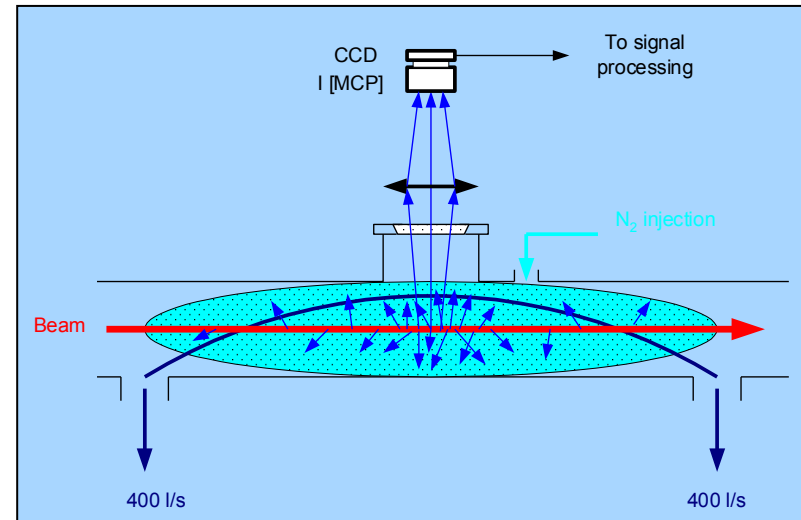
T. Giacomini et al., GSI



M.Schwickert, P.Forck, F.Becker, GSI

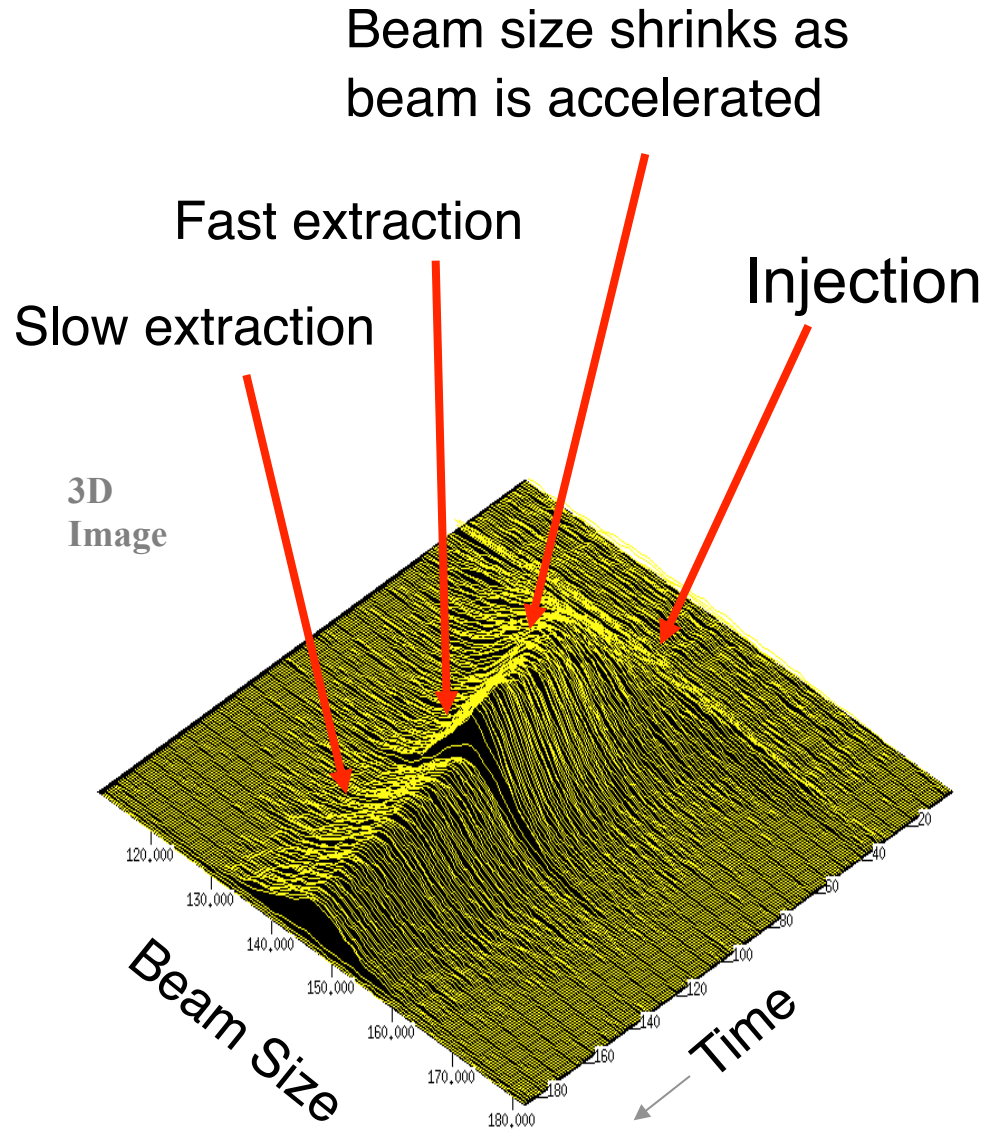
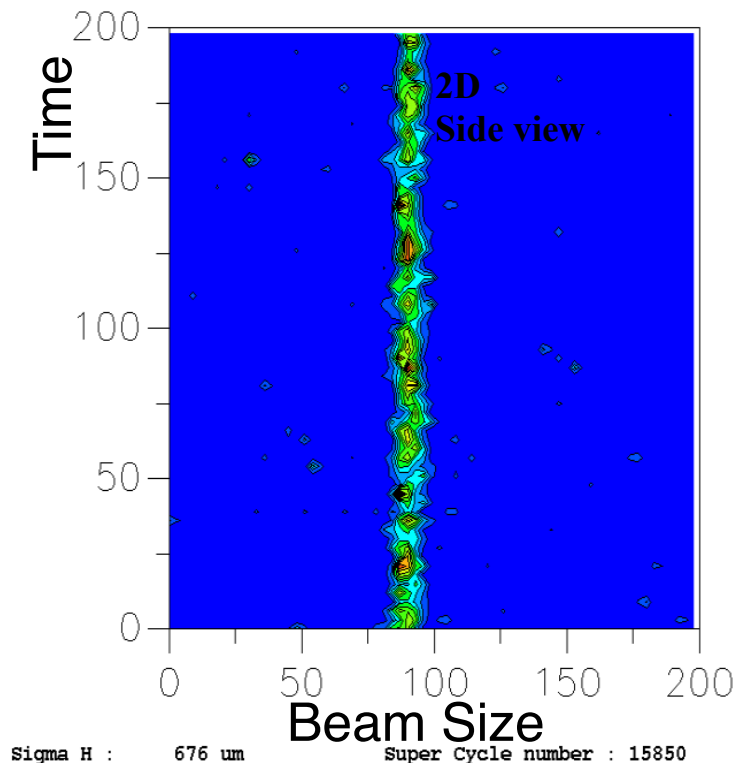
Luminescence Profile Monitor

- Beam Induced Fluorescence (BIF)
- Insensitive to electric and magnetic fields (e.g. beam space charge)
- Sensitive to radiation → leading to background
- Low signal yield → gas injection (e.g. $N\downarrow 2$, $H\downarrow 2$)
- Dynamic range: $\approx 10^3$



M.Schwickert, P.Forck, F.Becker, GSI

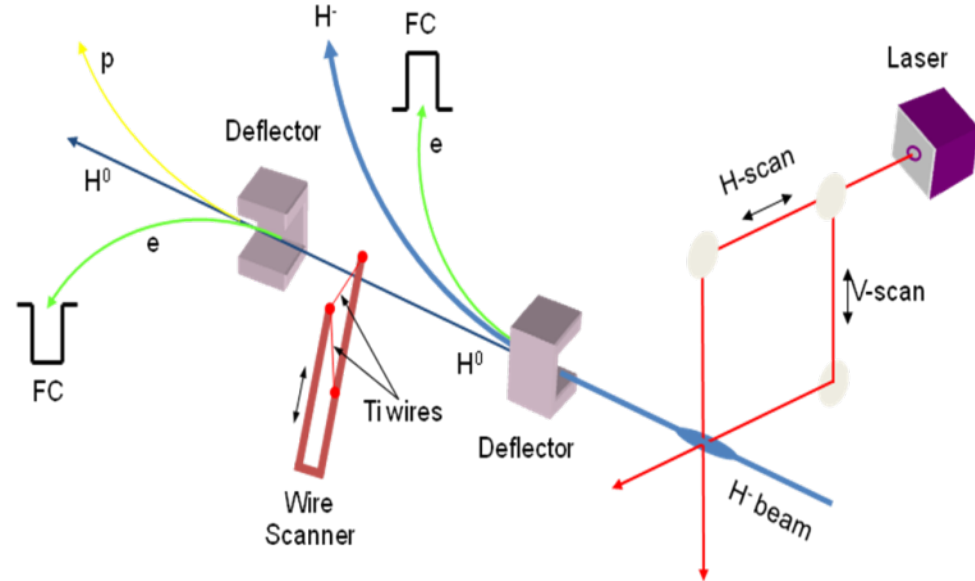
Luminescence Profile Monitor – Example CERN SPS



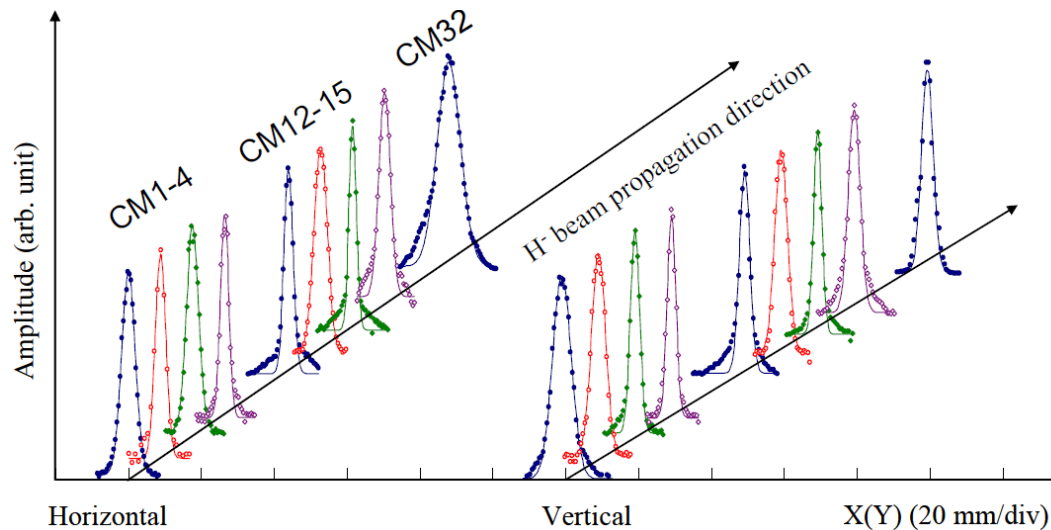
- Profile Collected every 20ms
- Local Pressure at $\approx 5 \times 10^{-7}$ Torr

Laser wire scanner

- Good candidate for H^- (and electrons)
- Electron is stripped from the H^- , deflected and measured (e.g. Faraday cup)
- Can measure down to μm level
- dynamic range: up to 10^3



Courtesy of A. Alexandrov



1 MW beam power
Y. Liu, SNS, PAC'11

Electron Beam Scanner

- Electron beam scanner (SNS, PAC'11, HB2012, W. Blokland)
 - Electrons are deflected by proton beam and measured on a fluorescent screen

