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 ↔ **Synchrotron:** multi pass
  - **Total Beam Energy** (beam particles x particle energy) low ↔ high

- 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
  - Accessibility and maintenance
  - Sometimes: cryogenic temperatures
  - Mostly: must operate in vacuum and be UHV compatible

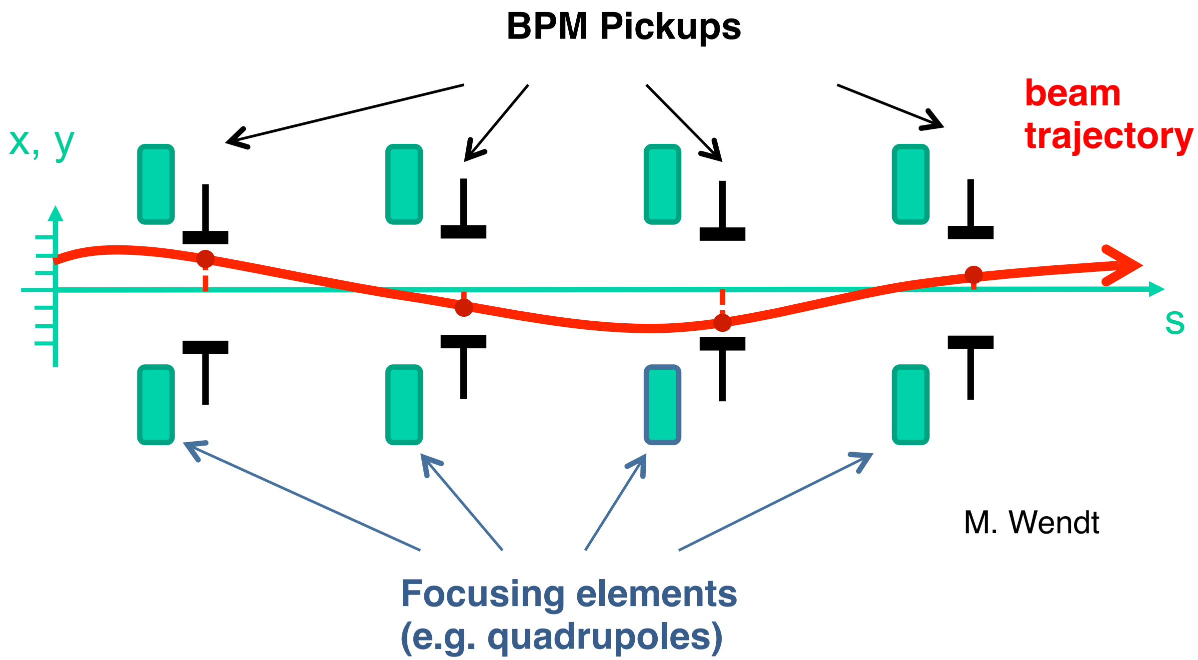
Resources and References

- 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

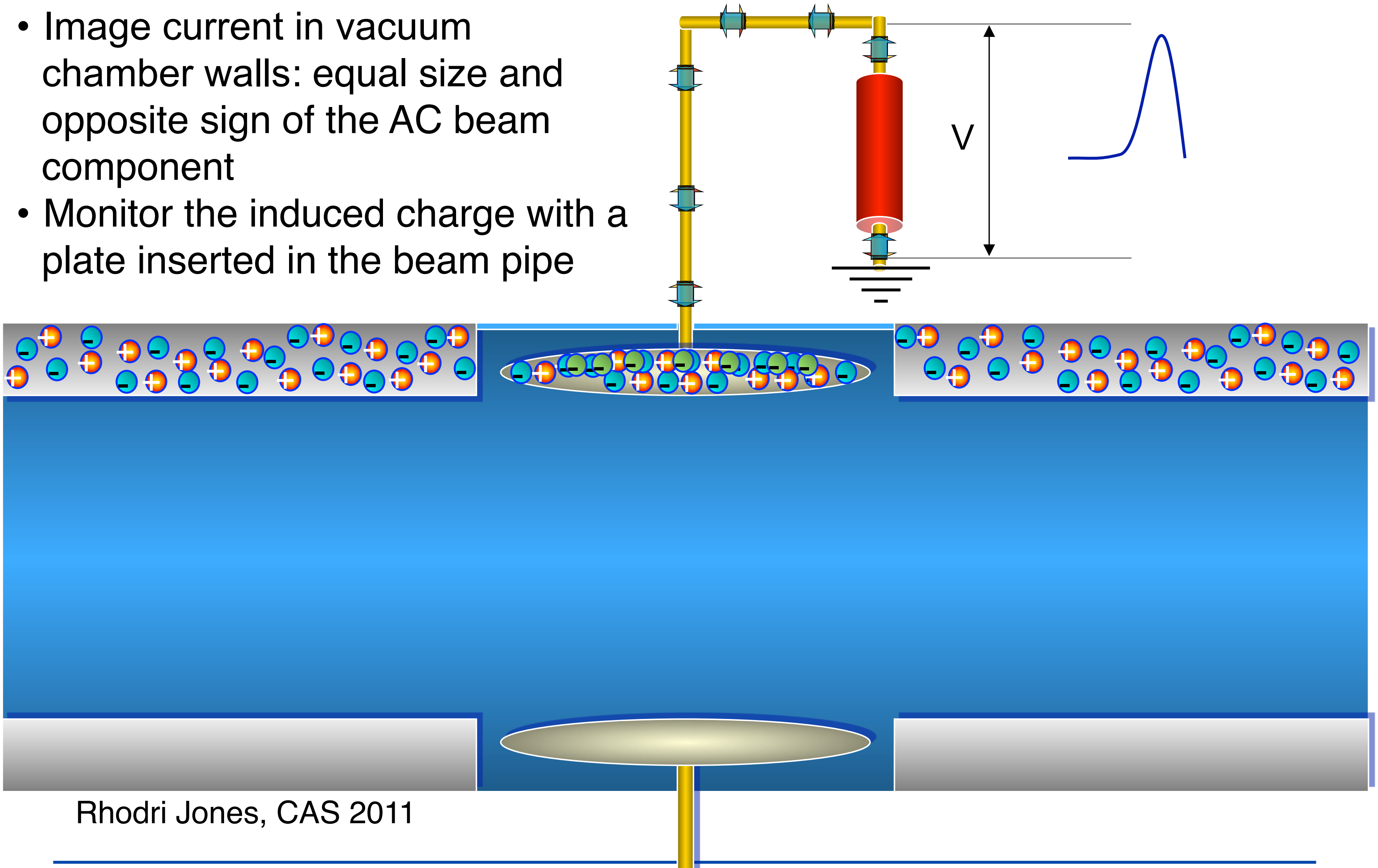
Capacitive Pick-Ups for Bunched Beams

- 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

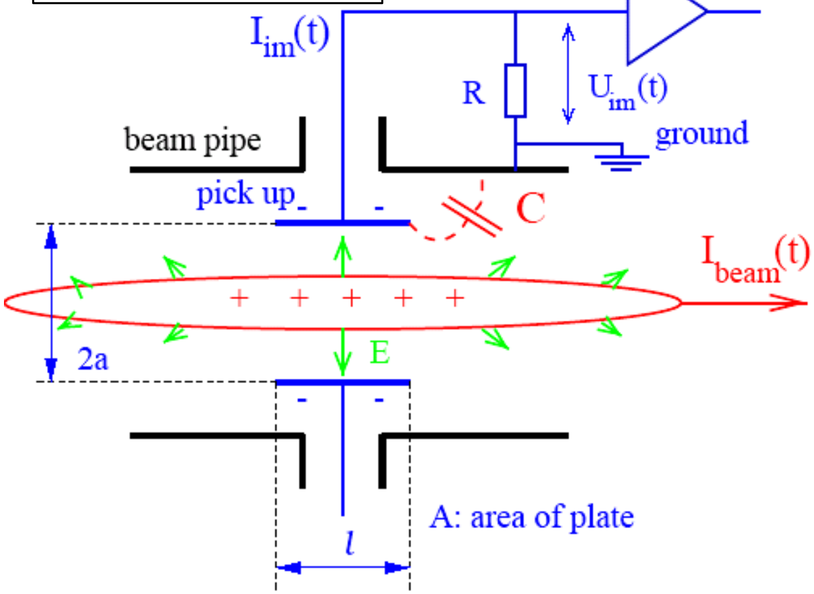
- Image current in vacuum chamber walls: equal size and opposite sign of the AC beam component
- Monitor the induced charge with a plate inserted in the beam pipe

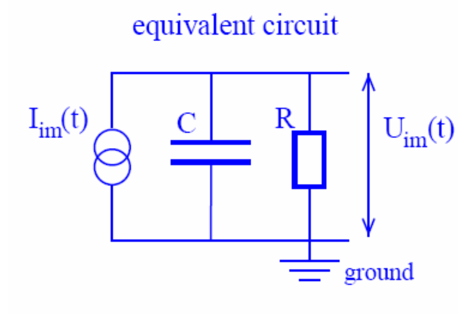


Rhodri Jones, CAS 2011

Schematics and Simplified Equivalent Circuit

P. Forck, JUAS





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

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

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

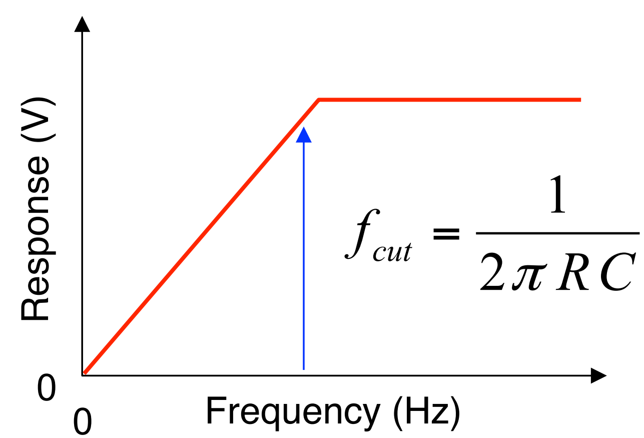
U_{im} … voltage measured due to image current
R … amplifier input resistor
ω … frequency
βc … beam velocity

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

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

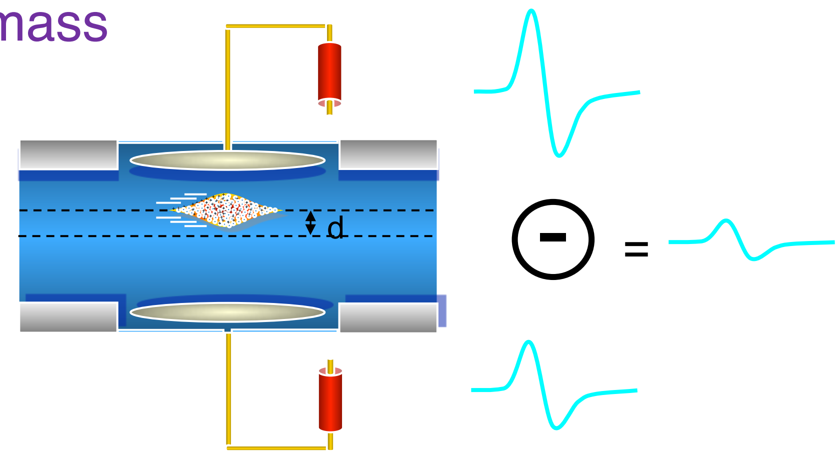
Z_t … longitudinal transfer impedance

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



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:**
  - $x = \frac{1}{S_x(\omega,x,y)} \cdot \frac{\Delta U}{\Sigma U}$ *(S_x ... position sensitivity)*
- The difference signal (ΔU) is normally at least a factor 10 lower than the sum signal (ΣU)

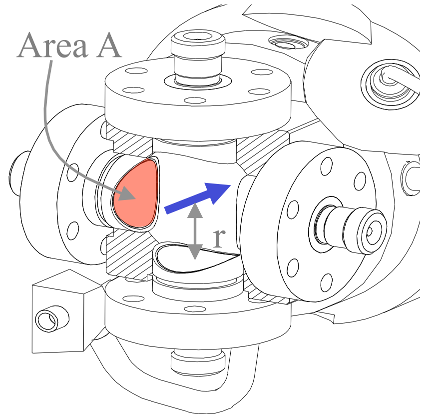


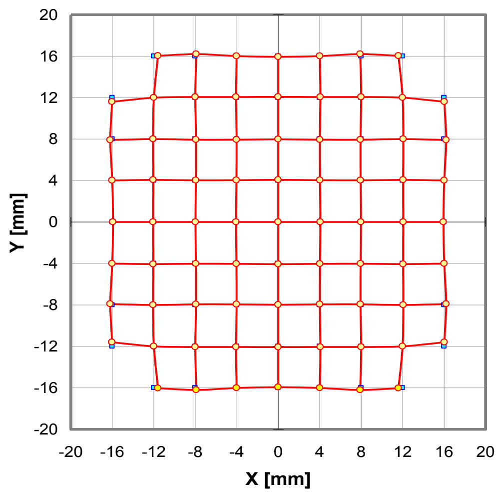
- Difficult to do electronically without some of the intensity information leaking through
- When looking for small differences this leakage can dominate the measurement
- **Resolution** for typical apertures:
  - ≈ tens µm turn-by-turn
  - ≈ µm multi-turn resolution

Example: Button Pick-up

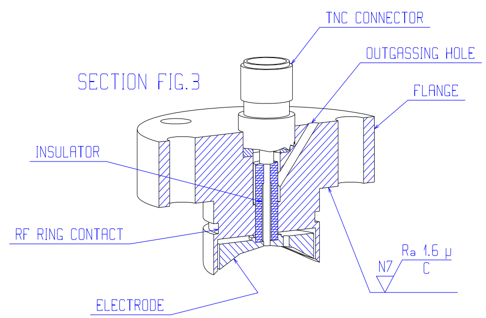
- ✓ Low cost ⇒ most popular
- × Non-linear
  - requires correction algorithm when beam is off-centre

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





R. Jones, CAS



LHC buttons

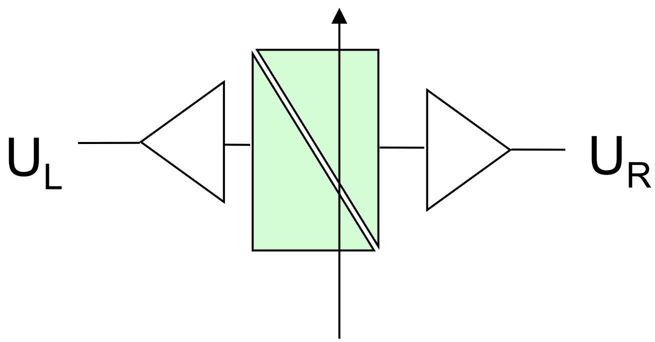
$$f_{cut} = \frac{1}{2\pi RC} = \frac{1}{2\pi \times 50\Omega \times 8pF} = 400MHz$$

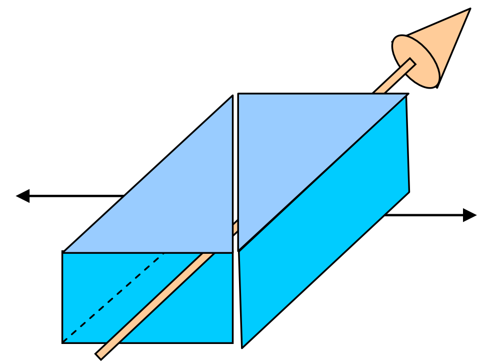
$$Z_{t\infty} = \frac{A}{(2\pi a)\times c \times C_e} = \frac{\pi \times (12mm)^2}{(2\pi \times 24.5mm)\times c \times (8pF)} = 1.2\,\Omega$$

Shoebox Pick-up

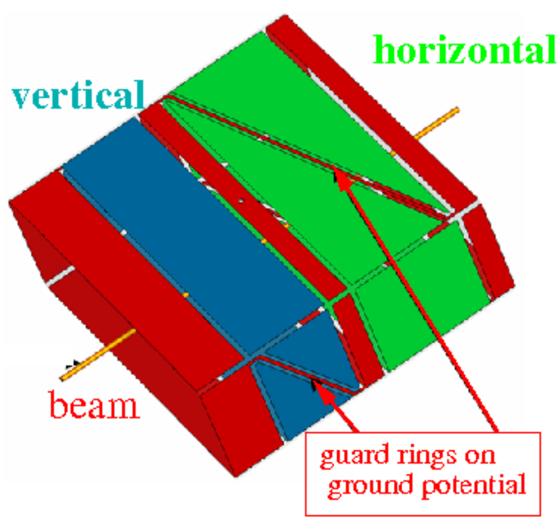
- ΔU gives linear position reading (no geometric correction)
- Condition: Linear cut: projection on the measurement plane must be linear:

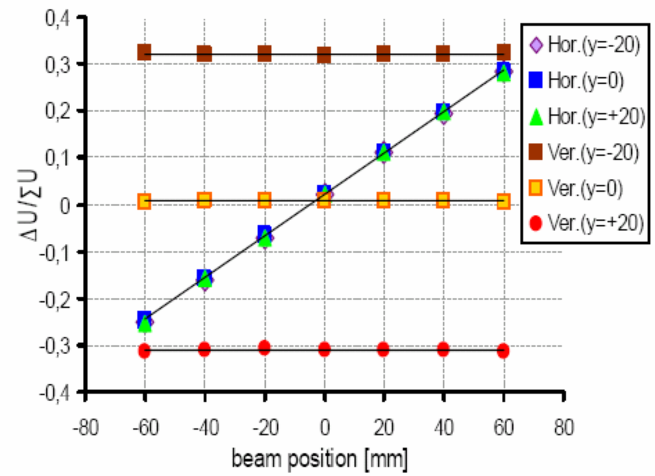
$$x \propto \frac{U_L - U_R}{U_L + U_R} = \frac{\Delta U}{\Sigma U}$$





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

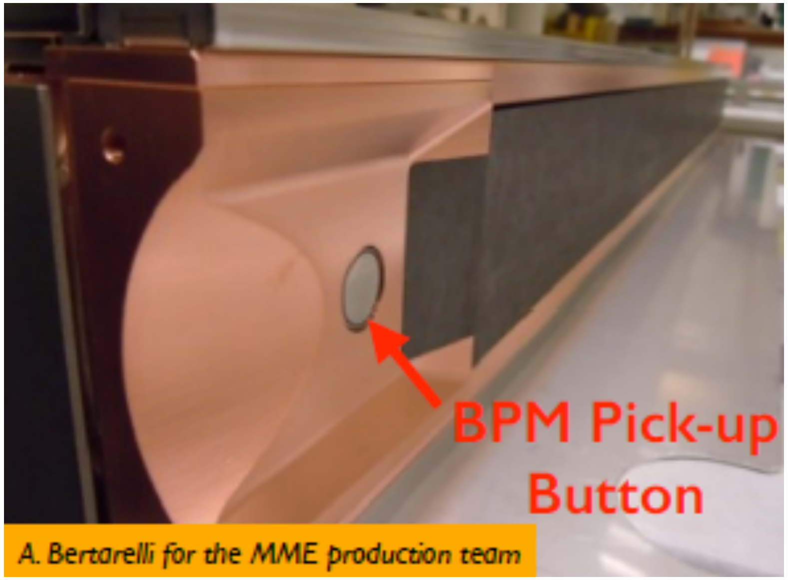




New LHC Collimators with Integrated BPMs

- 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 μm difference to BLM setup - believed to be dominated by the BLM setup method
  - single pass (transfer line): <90μm rms
  - no disturbance observed from protons hitting the jaws or from shower particles

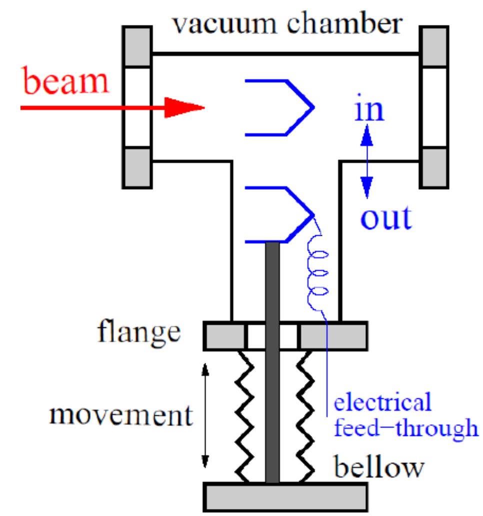


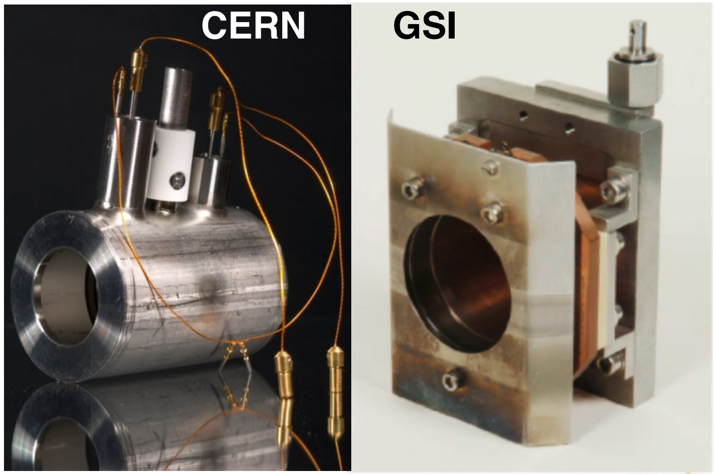
Beam Current

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:
    - ≈ 1% (some monitors reach 0.1%)

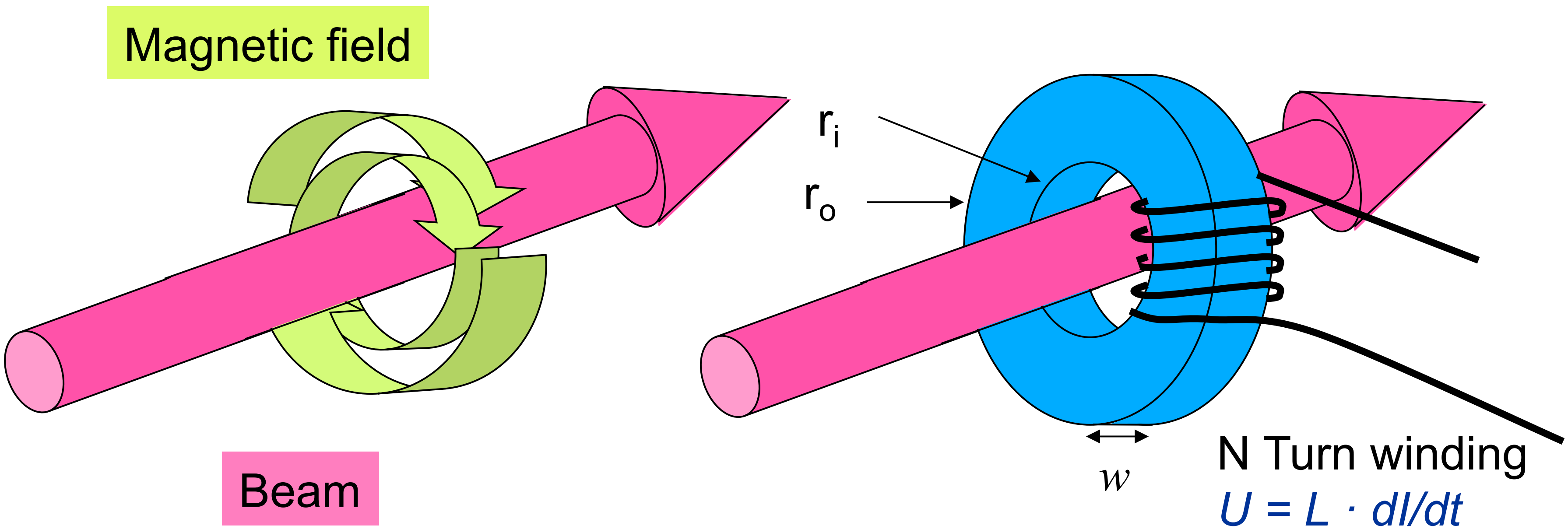
Faraday Cup at GSI LINAC, P. Forck, JUAS





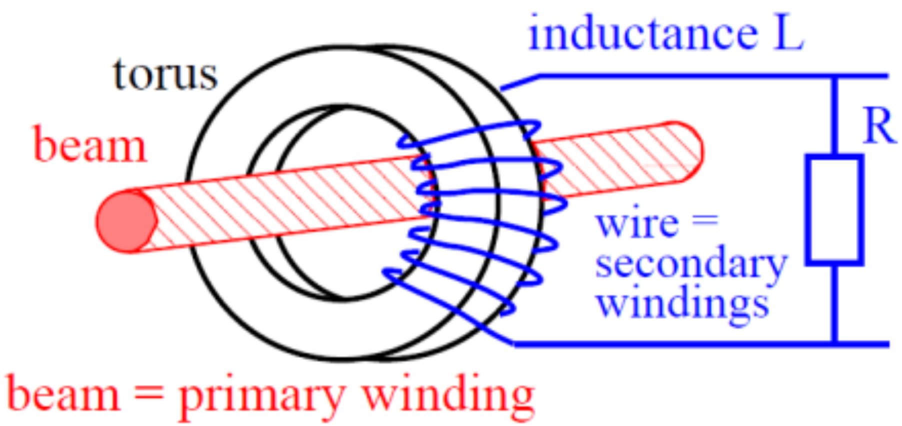
Beam Current Transformer (BCT)

- 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

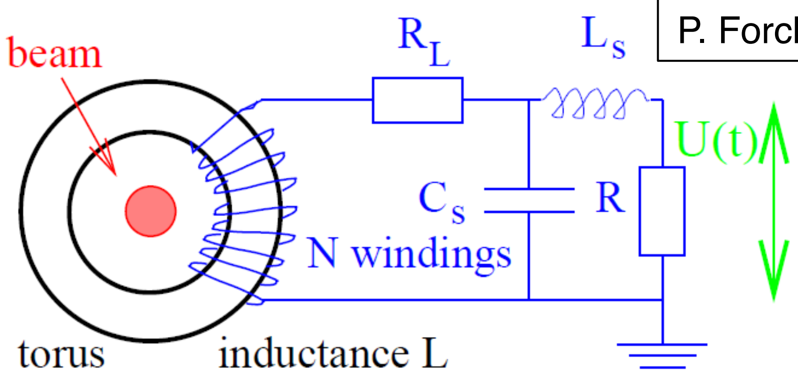
$$L = \frac{\mu_0 \mu_r}{2\pi} w N^2 \ln \frac{r_0}{r_i}$$

- Magnetic field of the beam is very low (Example: 1 µA, r = 10cm ⇒ 2 pT; compared to earth magnetic field of ≈50 µT)

- 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: $\mu_r = 10^5$

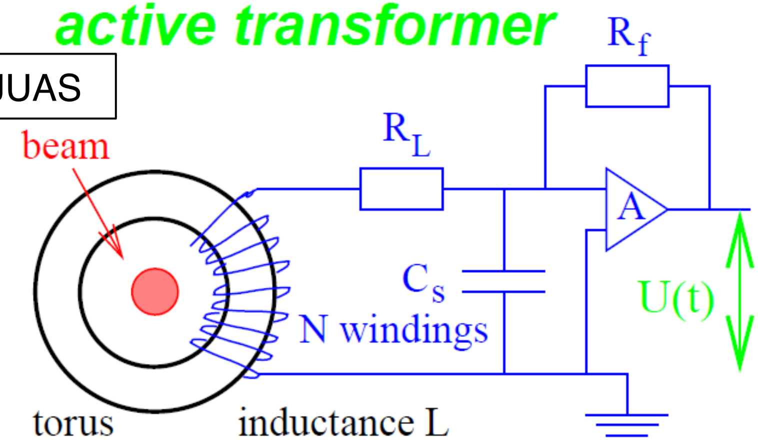
Adapt Droop Time with Active Transformer

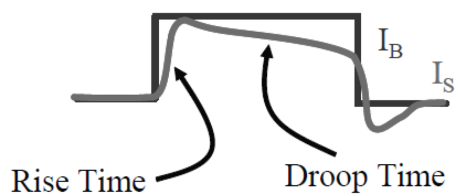
passive transformer



P. Forck, JUAS

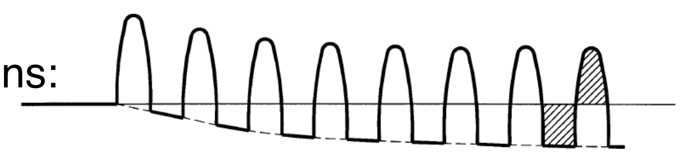
active transformer





$\tau_r \sim \sqrt{L_S C_S}$ $\qquad$ $\tau_d \sim \frac{L}{R}$

Bunch trains:



- Equal areas
- Baseline shift proportional to intensity

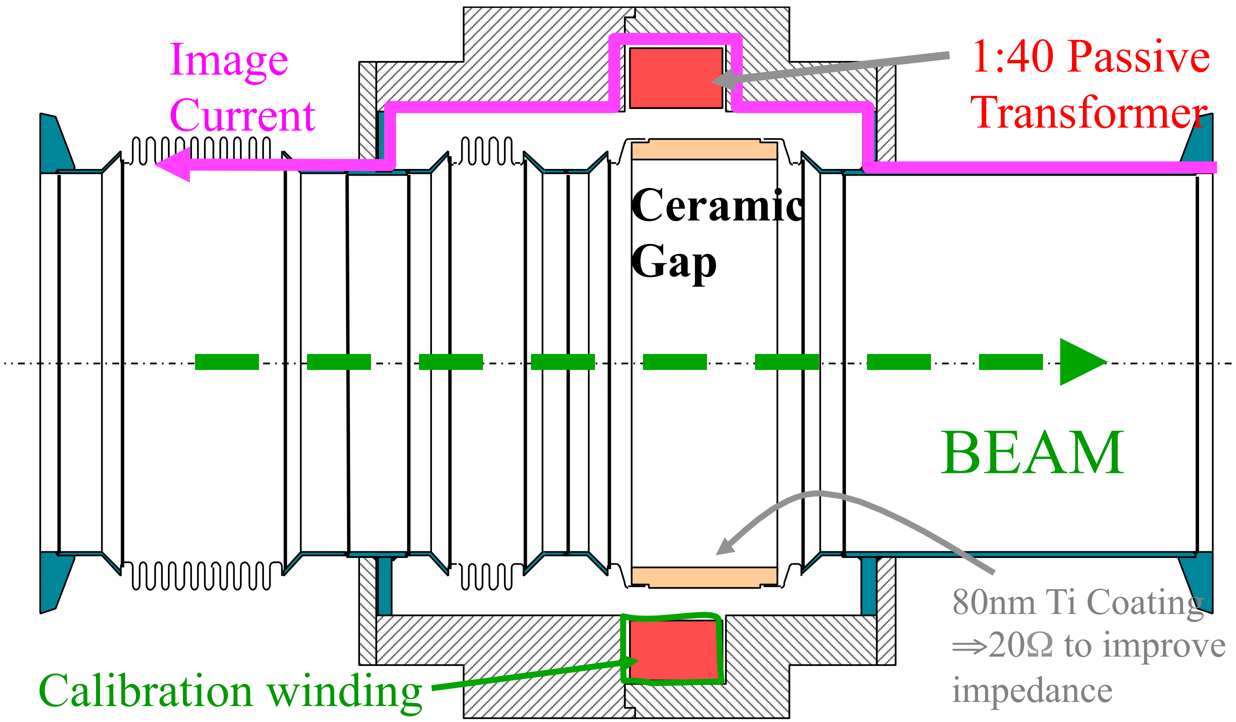
H. Koziol, CAS

- Use a trans-impedance amplifier (current-to-voltage converter) for observation of beam pulses > 10 µs, 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

$$\tau_d = L/(R_f/A + R_L) \approx L/R_L$$

Transformer Housing

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



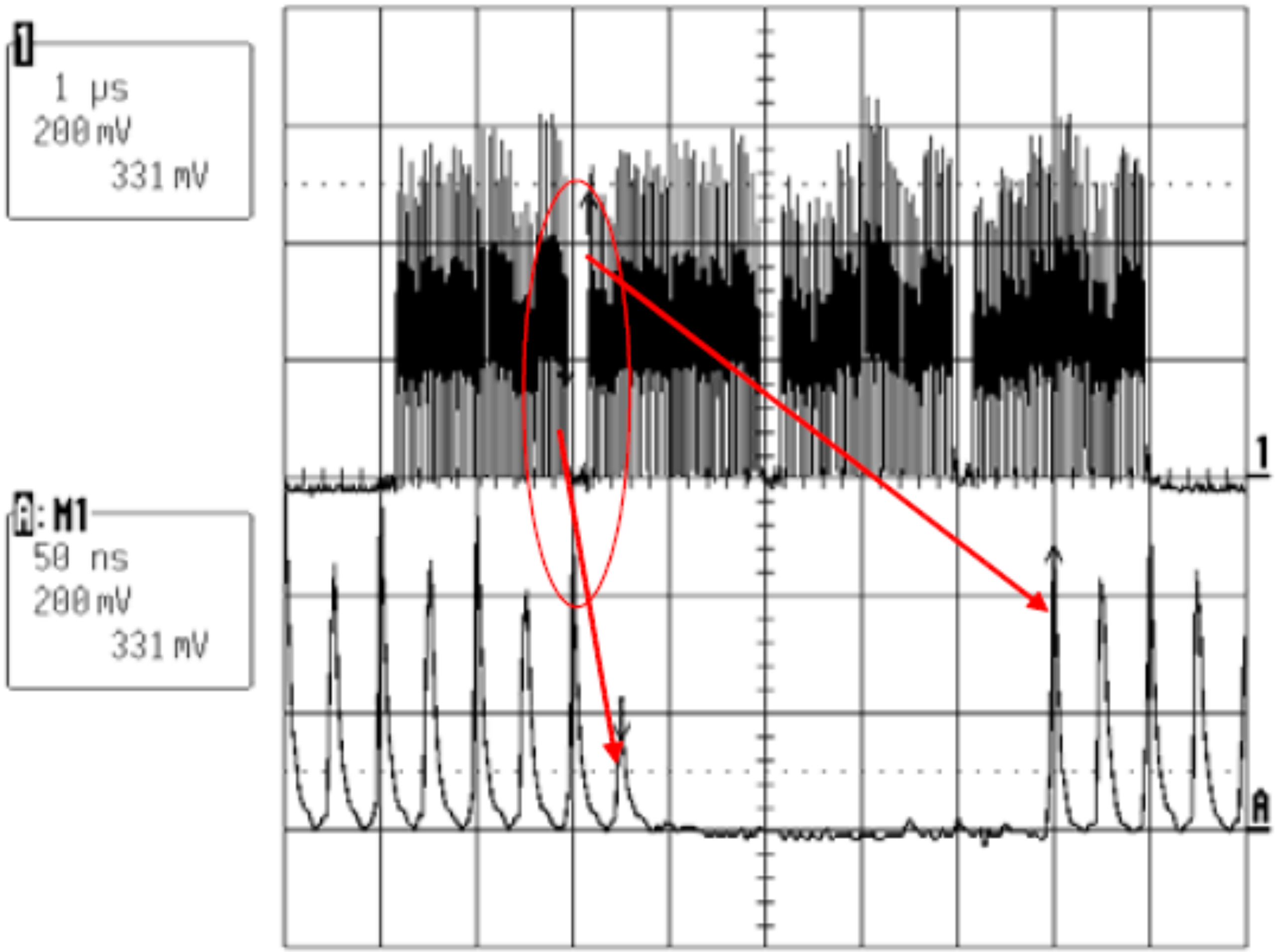
CERN SPS Fast Beam Current Transformer (FBCT)

Diagram by H. Jakob

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

CERN FBCT Readings of LHC Type Beams in the SPS

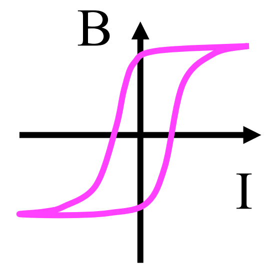
- 4 batches each containing 72 bunches separated by 25 ns



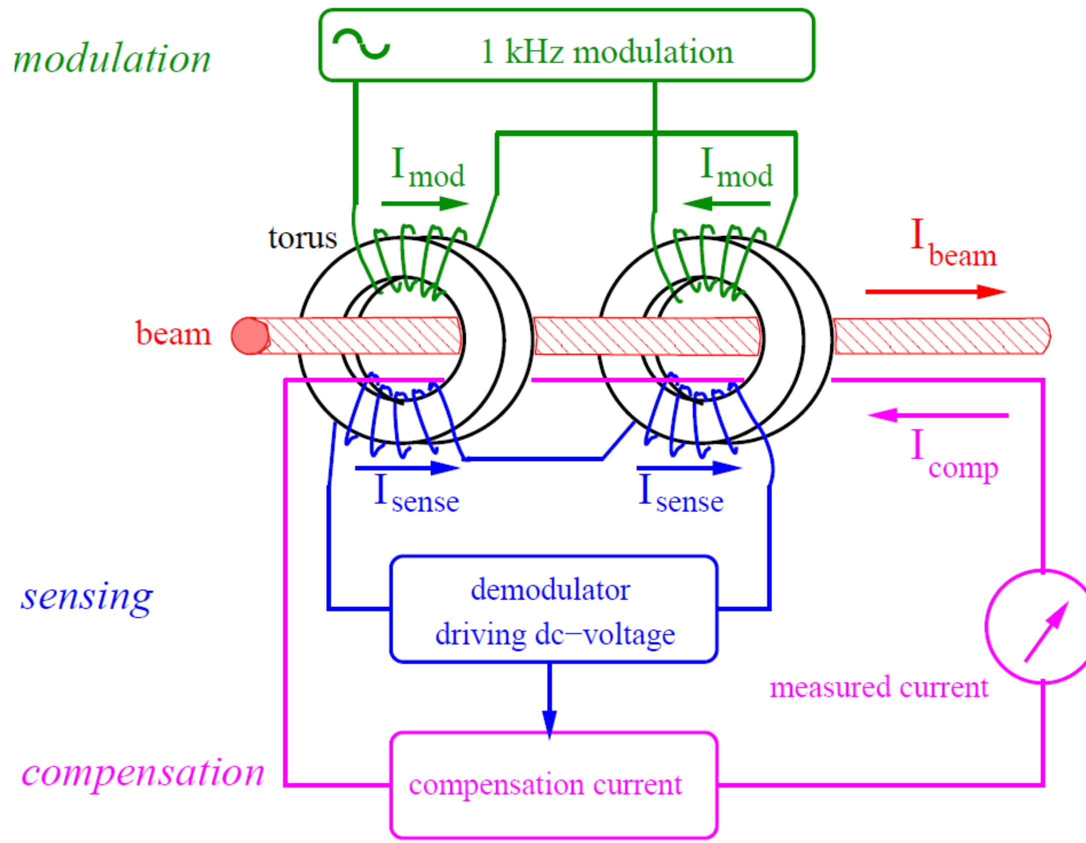
R. Jones, DIPAC'03

DCCT: DC Beam Current Transformer

- DC current dB/dt = 0 ⇒ 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

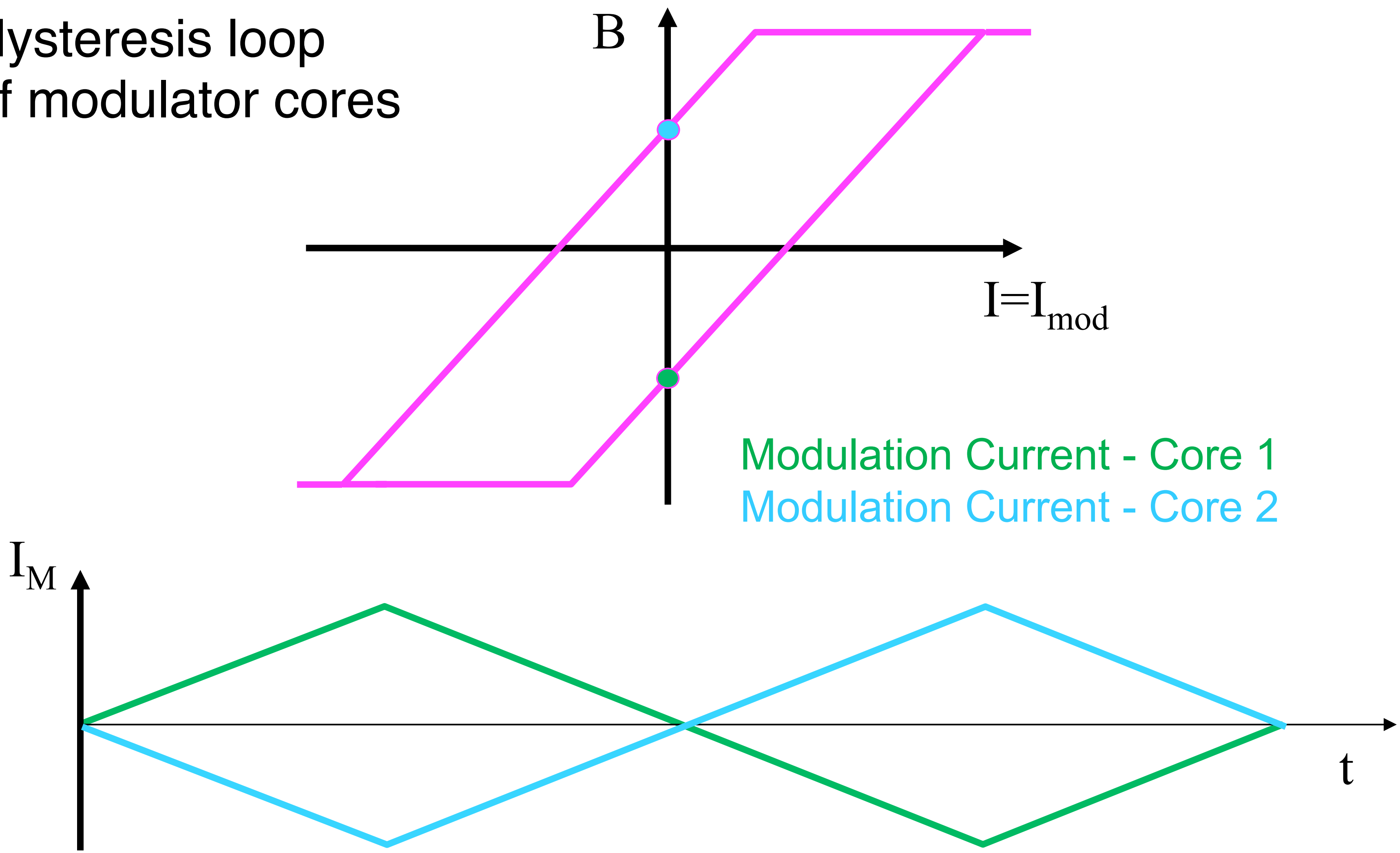


P. Forck, JUAS

DCCT Principle – Case 1: No Beam

R. Jones, CAS

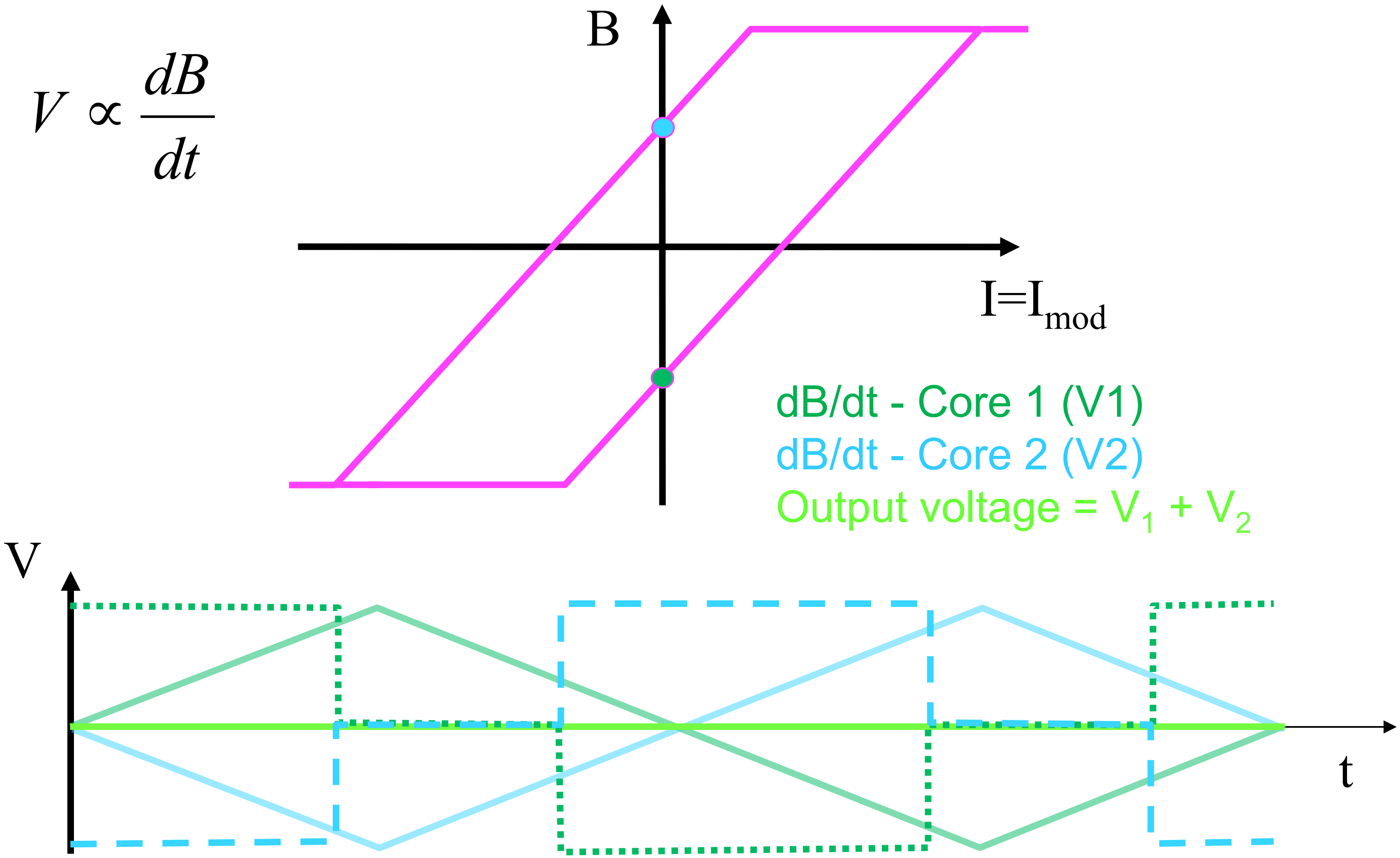
Hysteresis loop
of modulator cores



DCCT Principle – Case 1: No Beam

R. Jones, CAS

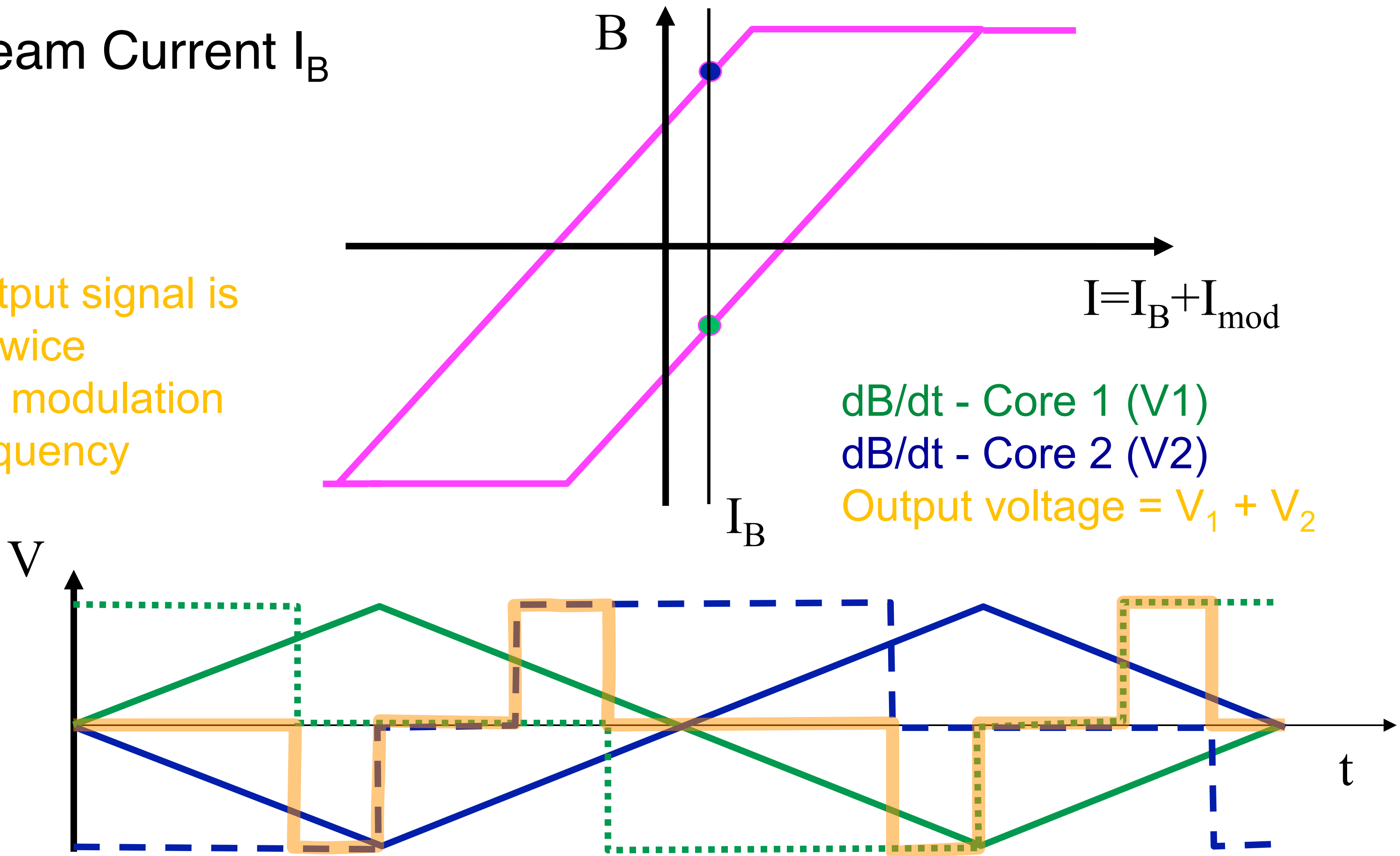
$$V \propto \frac{dB}{dt}$$



DCCT Principle – Case 2: With Beam

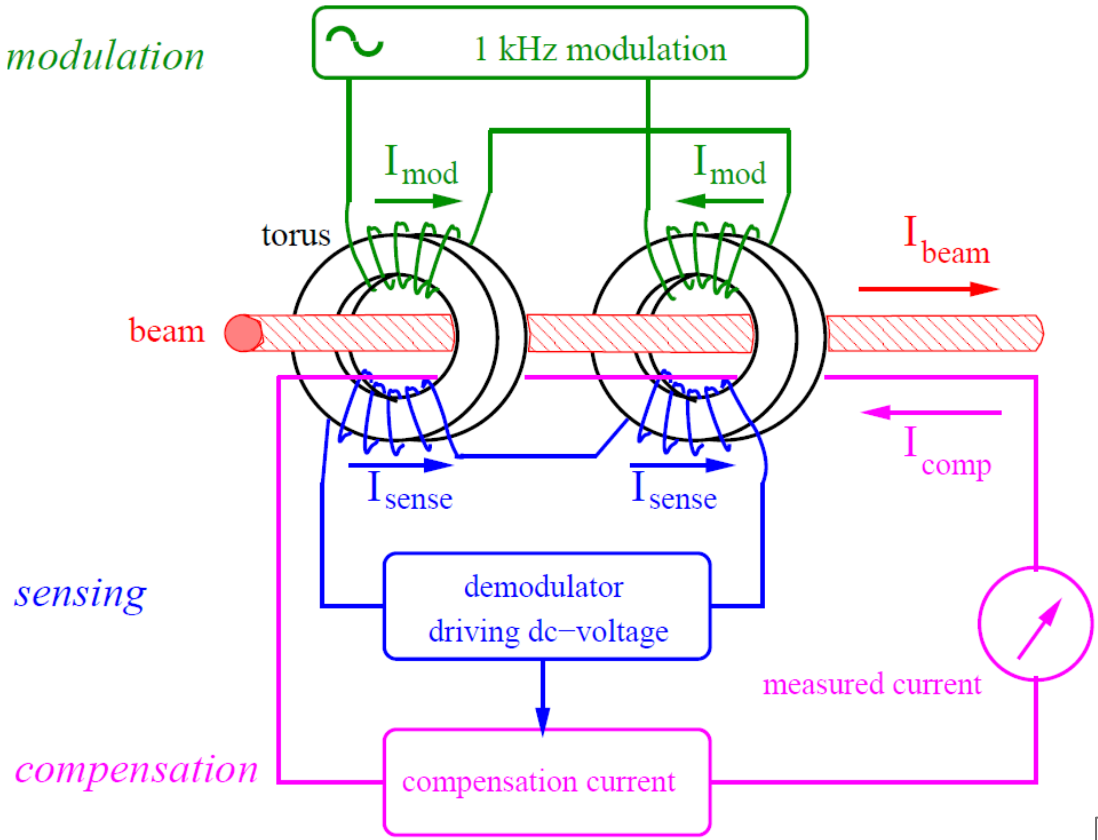
Beam Current I_B

Output signal is
at twice
the modulation
frequency



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 μA
  - Dynamic range 10^6 (μA – 1A)

Transverse Profile

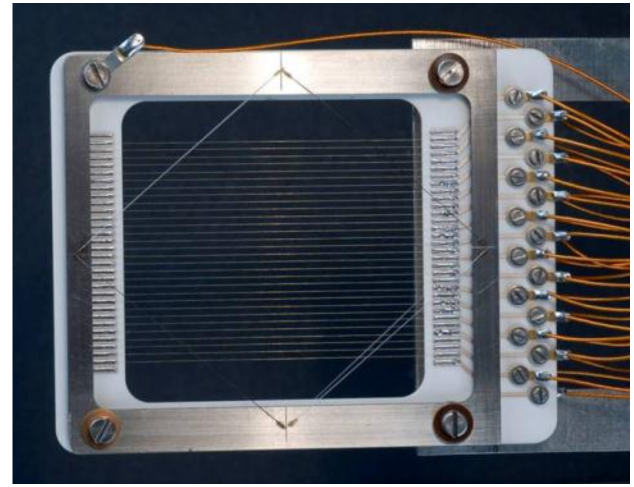
Overview - Beam Profile measurement

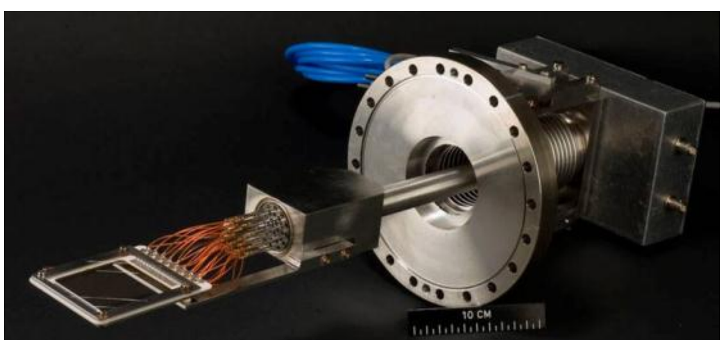
- Methods which intercept the beam with matter:
    - Secondary emission (SEM) grids
    - Screens
    - Wire scanners
  - more or less perturbing to the beam
  - Energies/intensity threshold for safe operation
    - Material damage (e.g. wire sublimation, breakage)
    - Radiation to other machine components (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

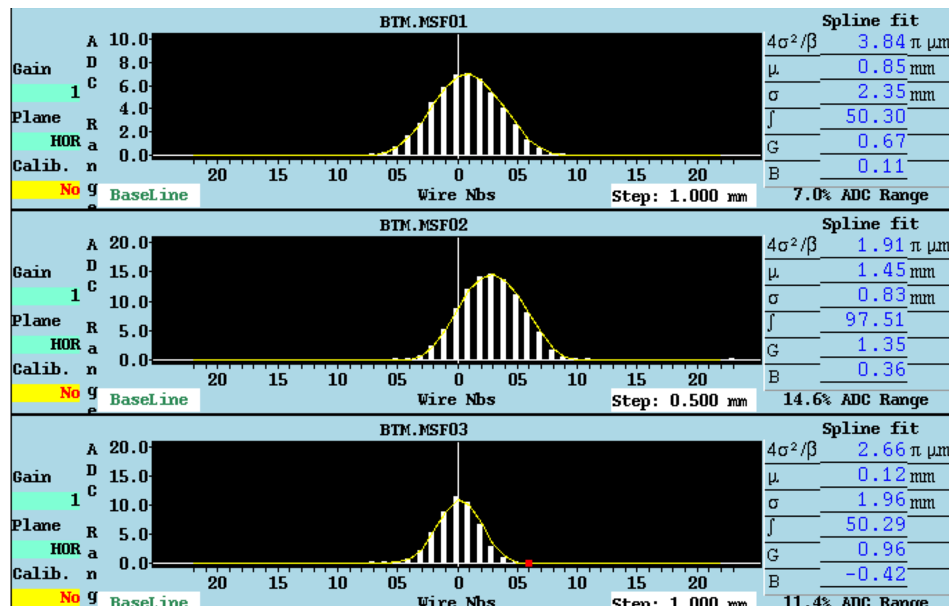
SEM grids and wire scanners:
Used as reference measurement for the other methods

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 <≈ 0.25mm
- Dynamic range: ≈ 10^6

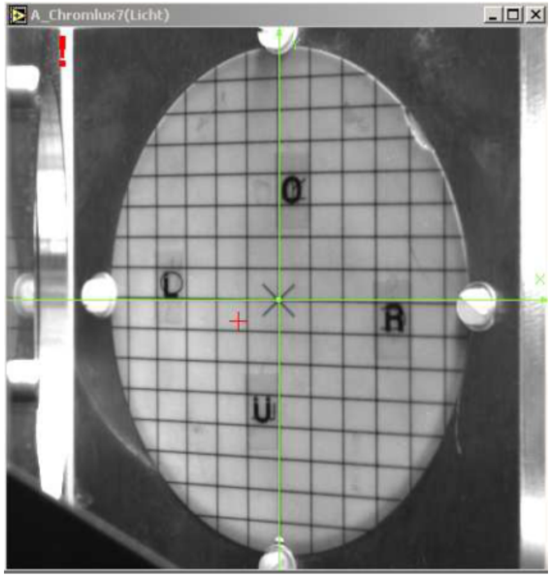






Scintillation Screens

- 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



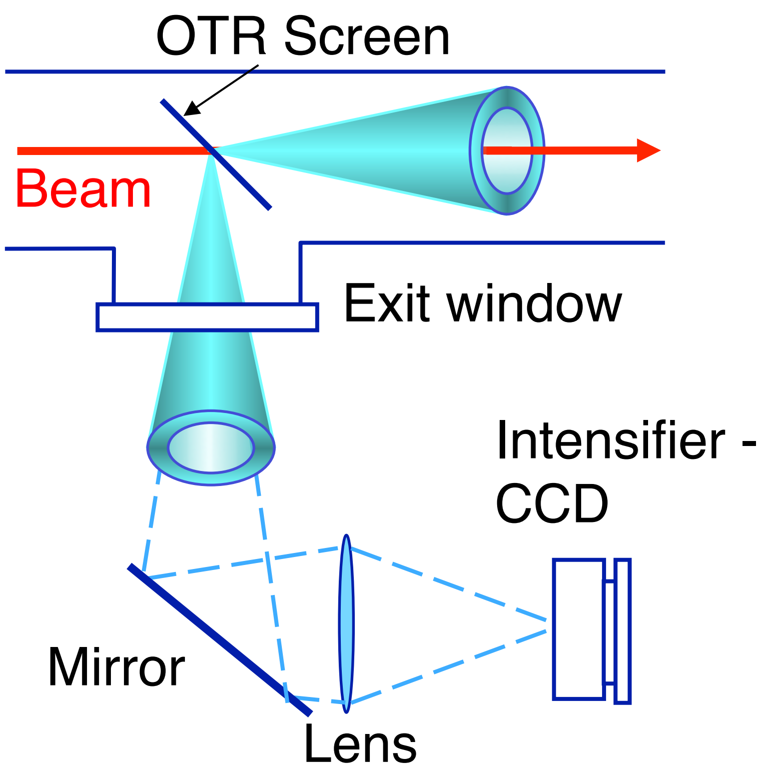
Abbreviation	Material	Activator	max. emission	decay time
Quartz	SiO_2	none	470 nm	< 10 ns
	CsI	Tl	550 nm	1 μs
Chromolux	Al_2O_3	Cr	700 nm	100 ms
YAG	$Y_3Al_5O_{12}$	Ce	550 nm	0.2 μs
	Li glass	Ce	400 nm	0.1 μs
P11	ZnS	Ag	450 nm	3 ms
P43	Gd_2O_2S	Tb	545 nm	1 ms
P46	$Y_3Al_5O_{12}$	Ce	530 nm	0.3 μs
P47	$Y_2Si_5O_5$	Ce&Tb	400 nm	100 ns

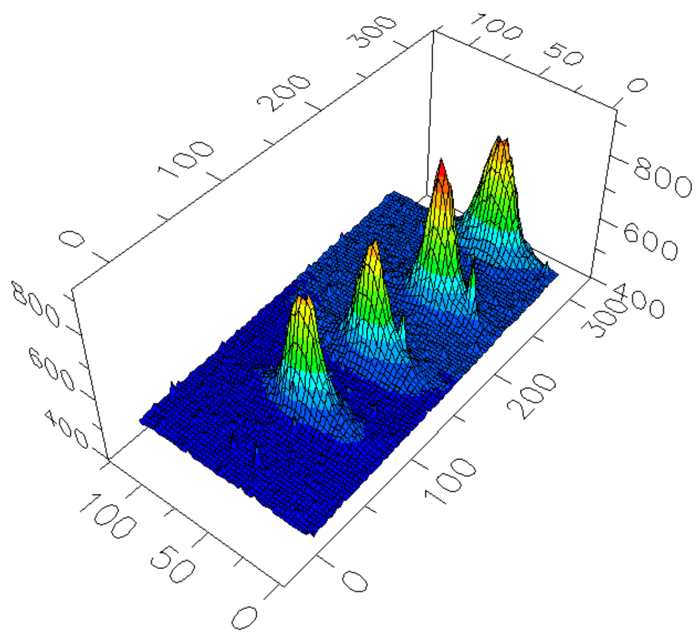
Approximate values for inorganic scintillators

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 (≥ 0.25 µm)
- Much less intercepting, but requires higher intensity

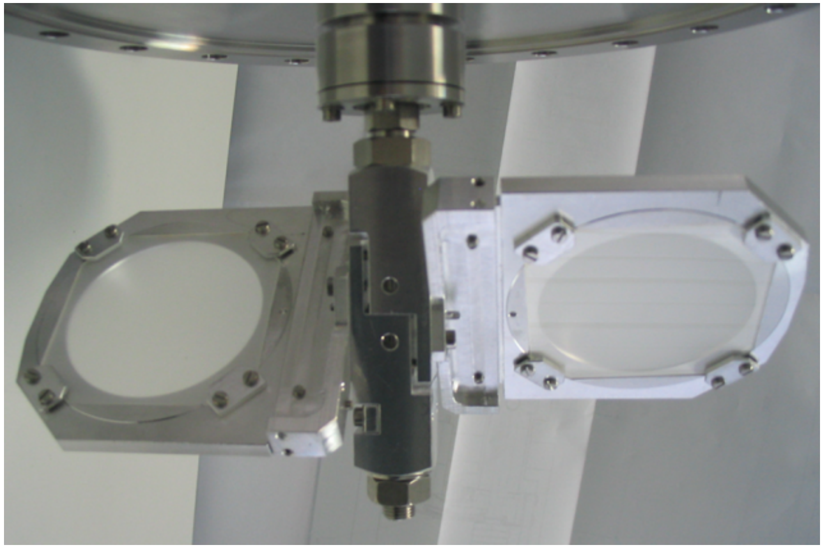


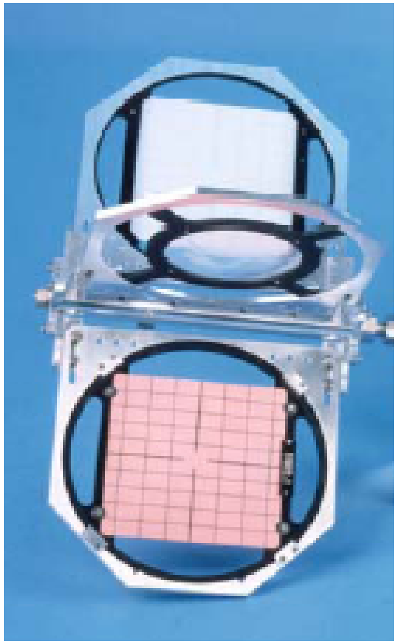


CERN SPS at injection

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 (≈10µm) Ti OTR screen for high intensity measurements
  - Carbon OTR screen for very high intensity operation

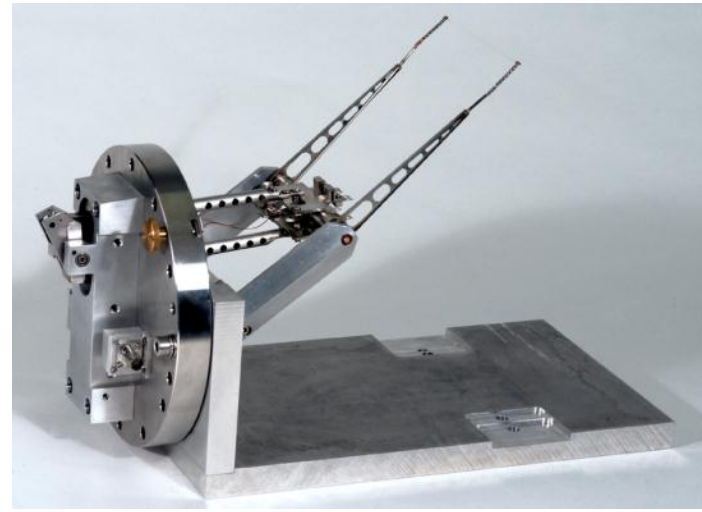


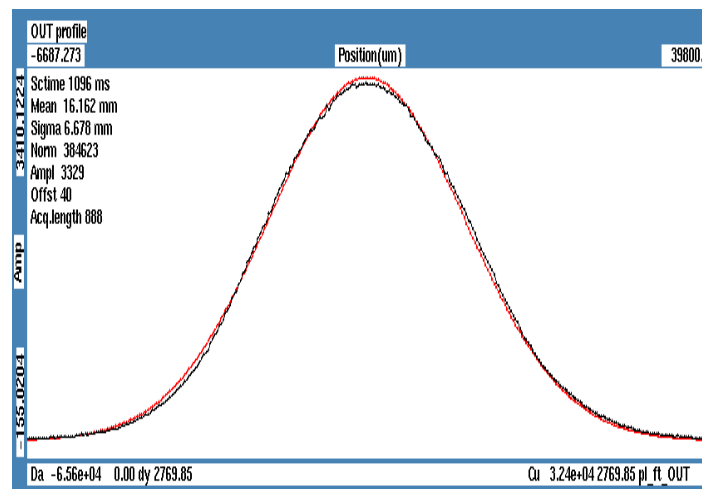


- Cameras:
  - CCD cameras are radiation sensitive
  - Analogue VIDICON camera can be used with high radiation

Wire Scanners

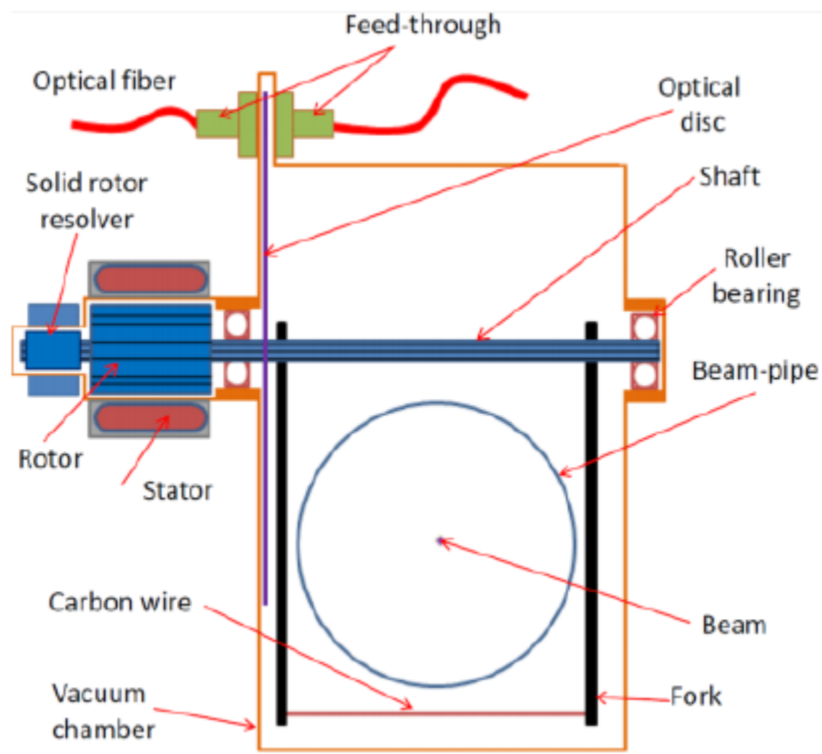
- A thin wire (down to 10 μm) is moved across the beam
  - Has to move fast to avoid excessive heating of the wire
  - Rotational scanner up to 10 m/s with special pneumatic mechanism (linear scanners slower)
- Detection
  - Secondary particle shower detected outside the vacuum chamber e.g. using a scintillator/photo-multiplier 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



B. Dehning

- Current Wire Scanners at CERN:
  - Dynamic range 100; accuracy 5-10%; spatial resolution 50 μm (linear type) and 200 μm (rotational)

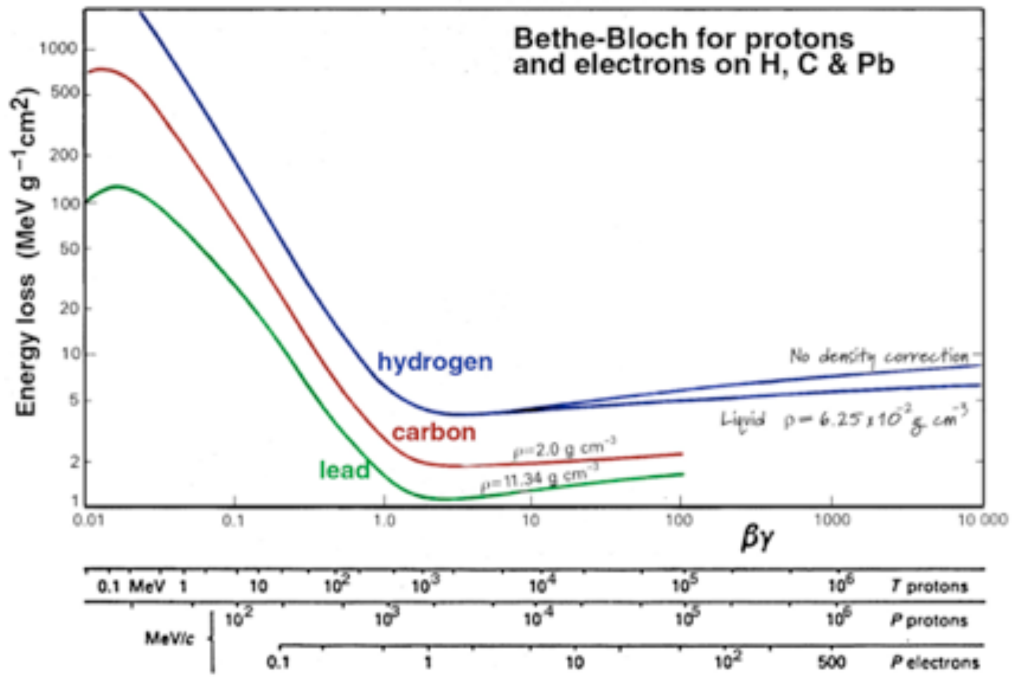
Beam Loss Measurement

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
    - **dE/dx_{MIP} =**

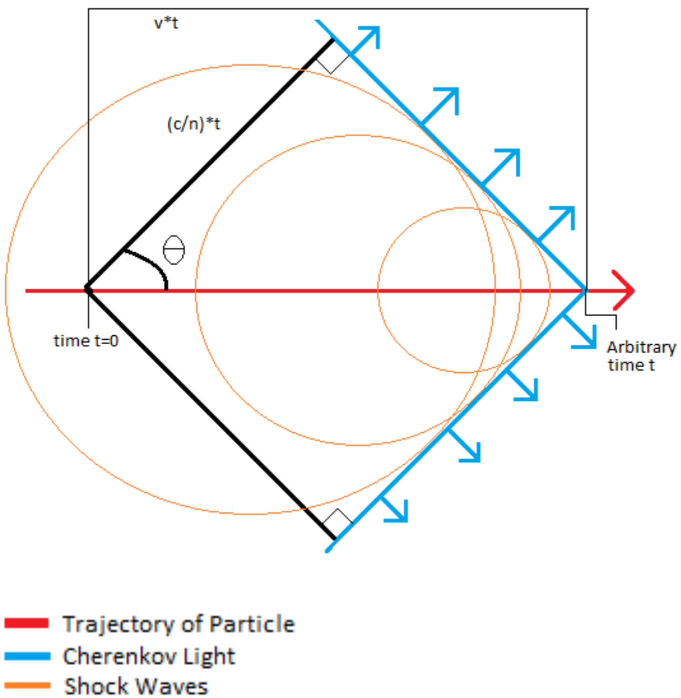
      (1-5) MeV cm^2 g^{-1}



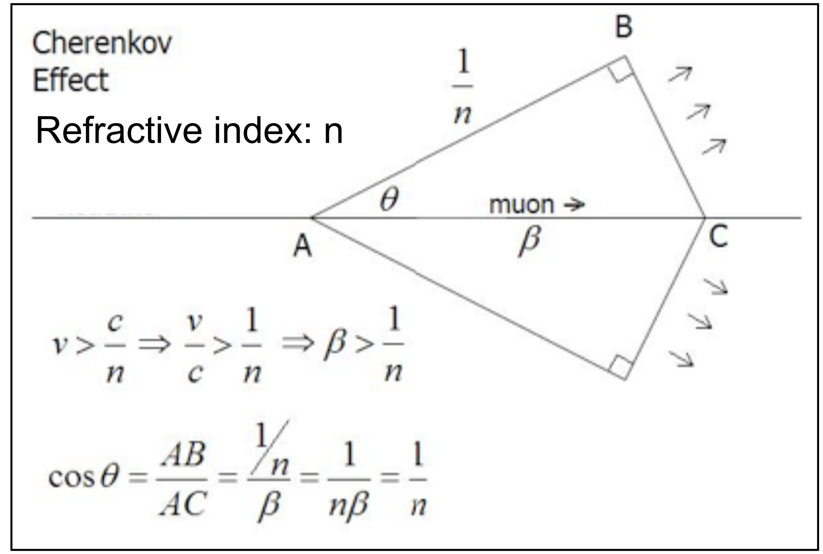
- **Scintillation**
  - Light produced by de-excitation of atom / molecule
  - Yield is proportional to the energy loss
    - **Y = dL/dx = R dE/dx**

Detection Principles cont'd

- **Cherenkov light**



Drawing: Bock and Vasilescu 1999

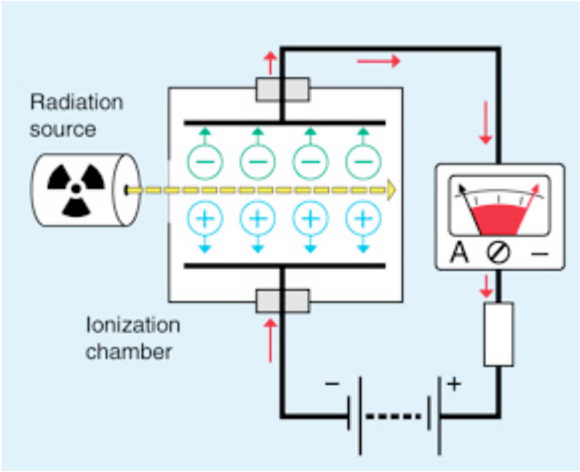


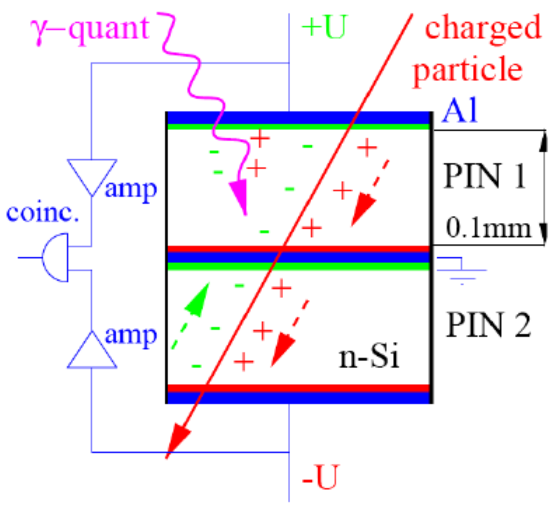
$$\textit{photon yield}: \frac{dN}{dx} = 2 \cdot \pi \cdot \alpha \cdot \sin^2\Theta \cdot \left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2}\right)$$

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

Common types of monitors

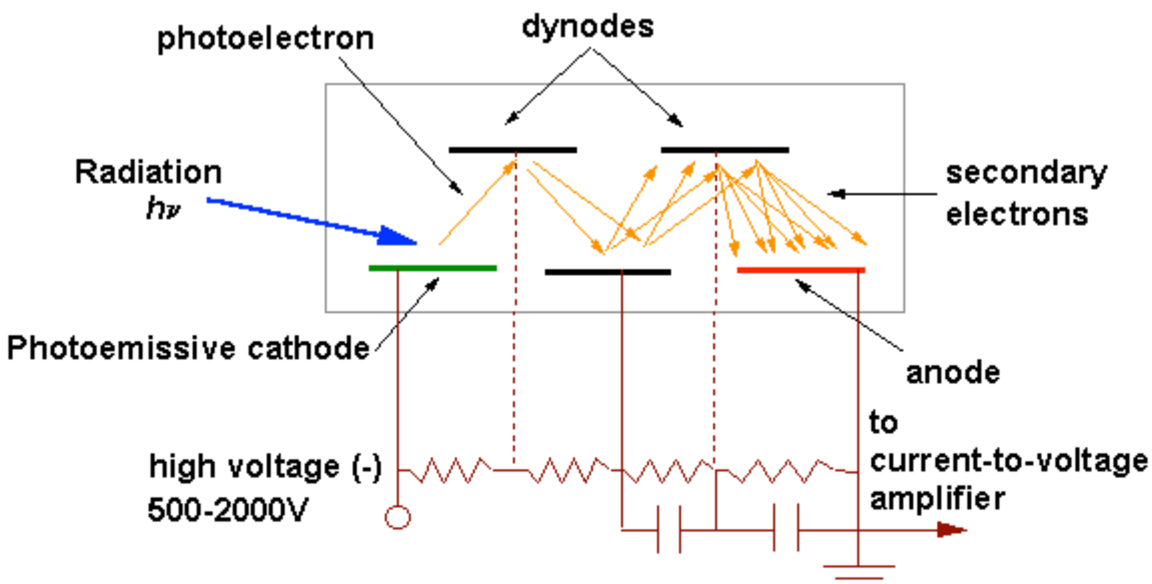
- Short ionisation chamber (charge detection)
  - Typically gas filled with many metallic electrodes and kV bias
  - Speed limited by ion collection time – tens of microseconds
  - Dynamic range of up to 10^8
- PIN photodiode (count detection)
  - Detect charged particle
  - Insensitive to photons from 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

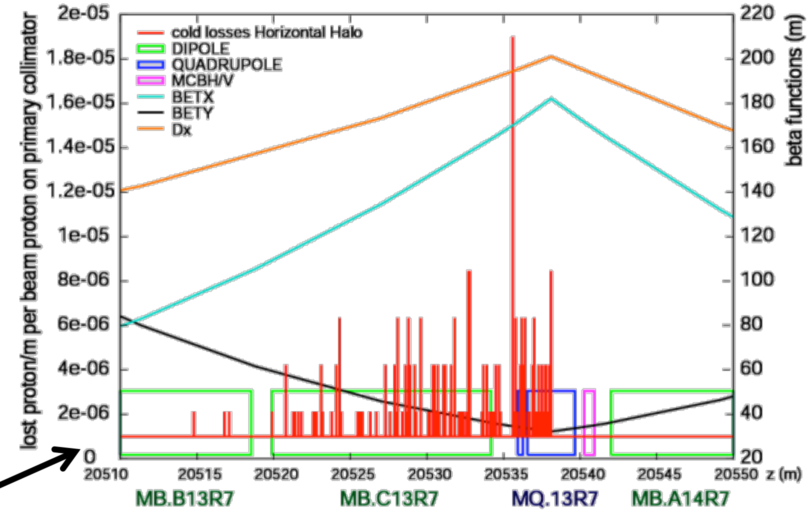
- Main purpose: **prevent damage and quench**
- 3600 Ionization chambers
- Beam abort thresholds:
  - 12 integration intervals: 40µs to 84s (32 energy levels)

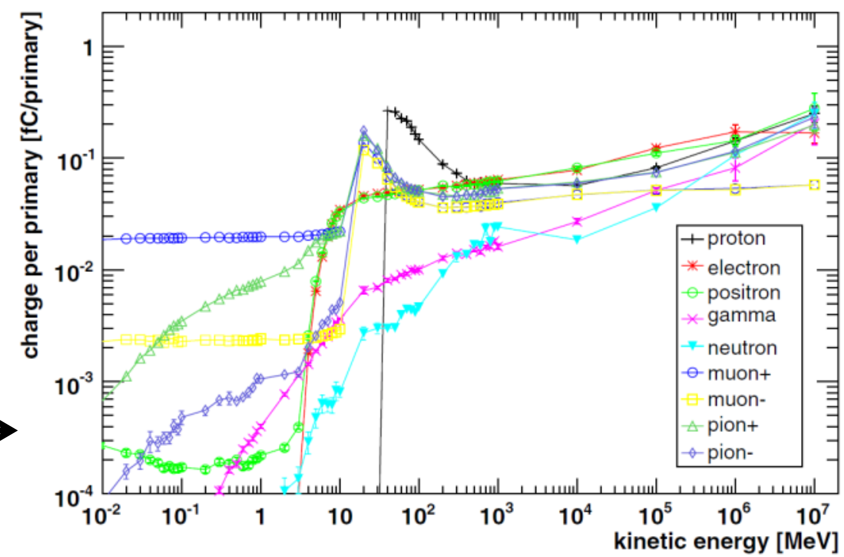
→ 1.5 Million threshold values

- 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 µs)
  - Dynamic range: 10^8 (at 40μs 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

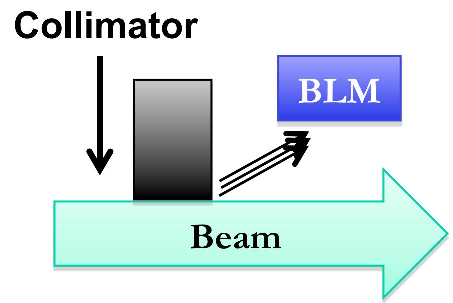
- Relate the BLM signal to the:
  - Number of locally lost beam particles
  - Deposited energy in the machine
  - Quench and damage levels
- Extensive simulations and experiments during system design and beam tests in the LHC
  - Proton loss locations (tracking codes: MAD-X, SIXTRACK)
  - Hadronic showers 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)

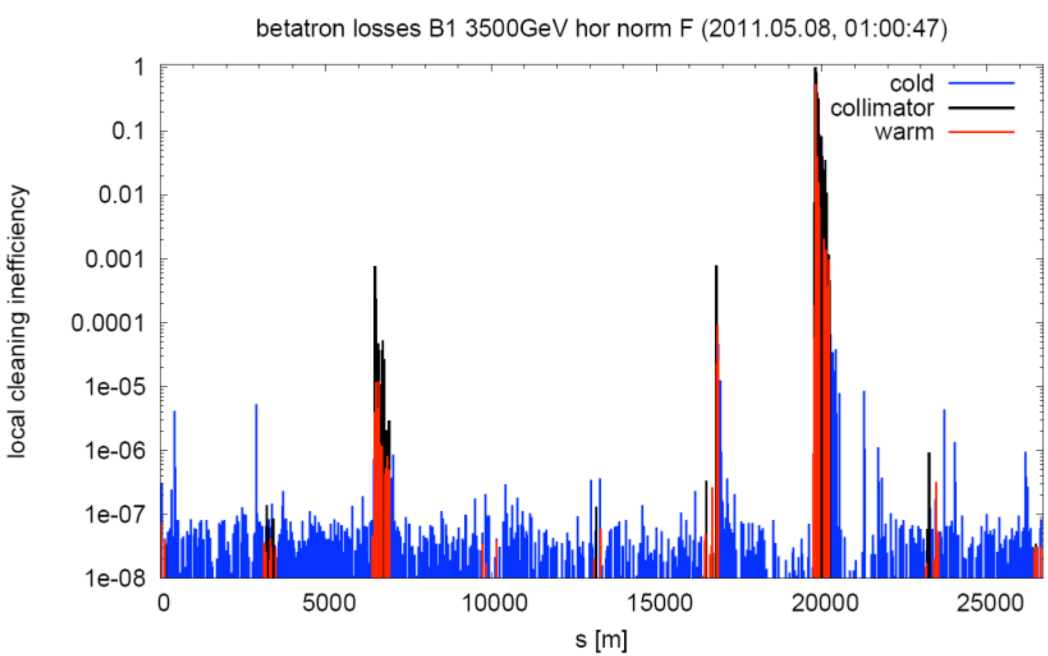


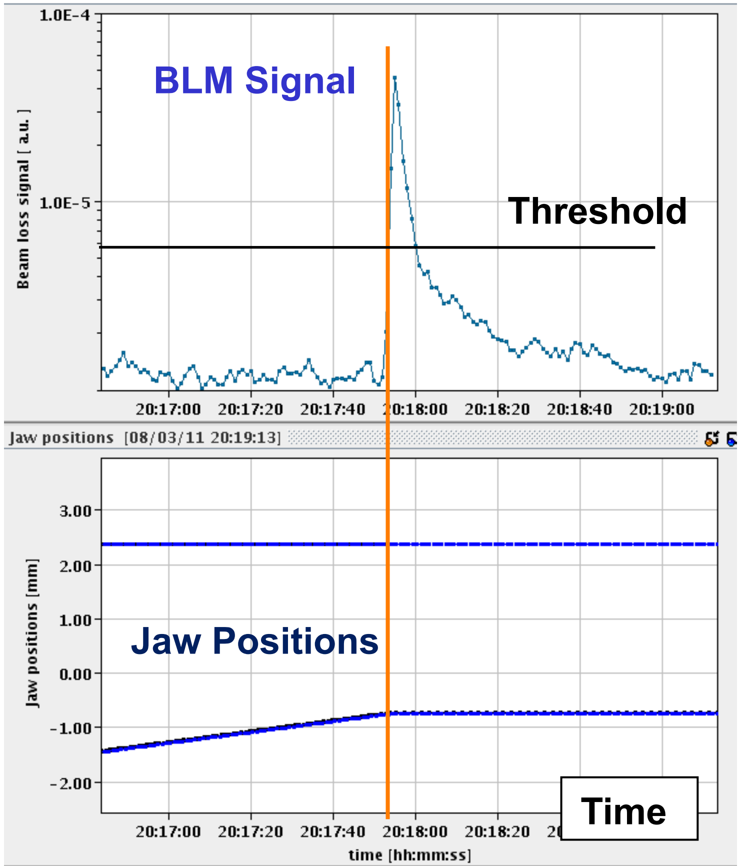


Set-up and validation of collimation performance

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



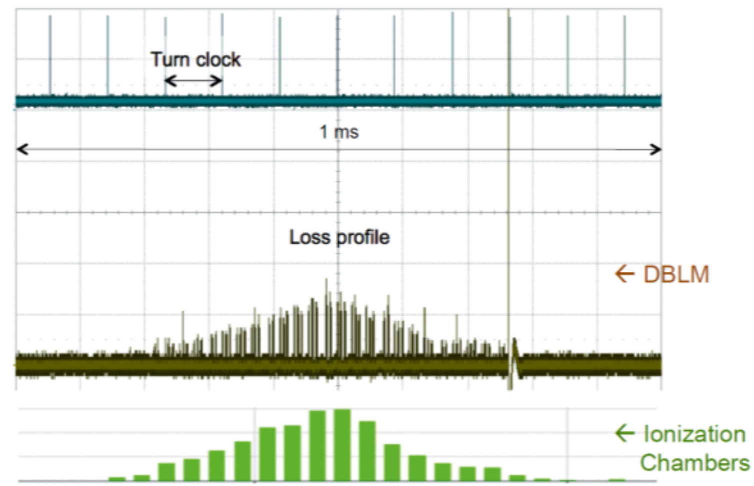


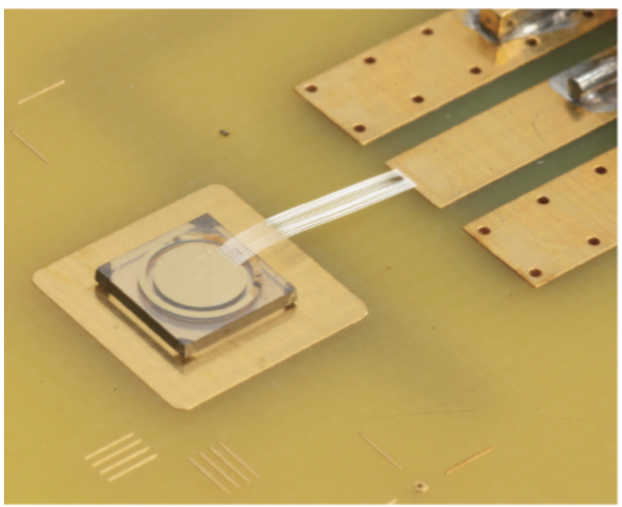


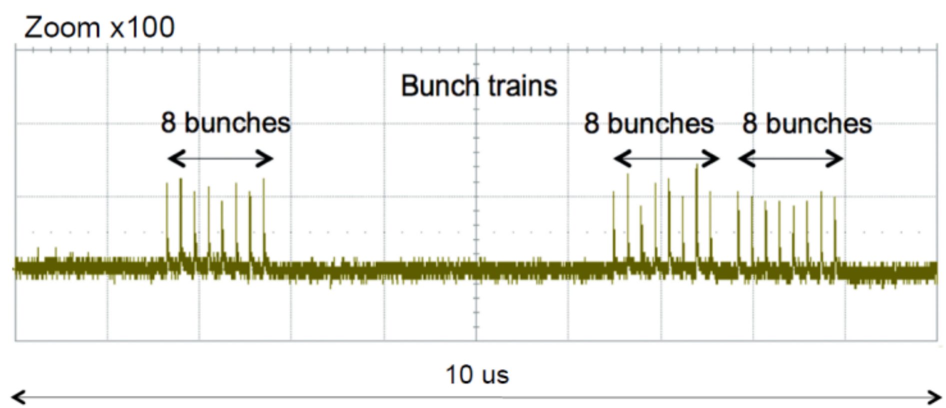
'loss map': losses along the ring normalized to the losses at the primary collimator: performance verification

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







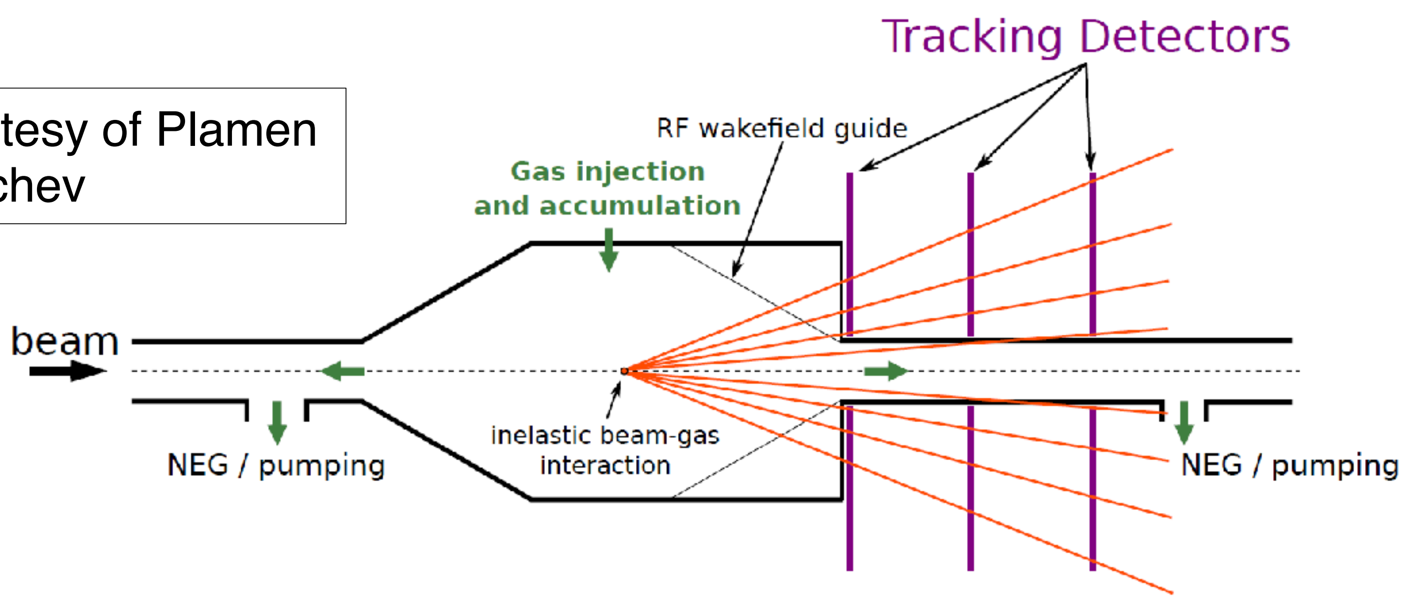
Thank you for your Attention

(Quasi) Non-Invasive Beam Size Measurement

Beam Gas Vertex monitor

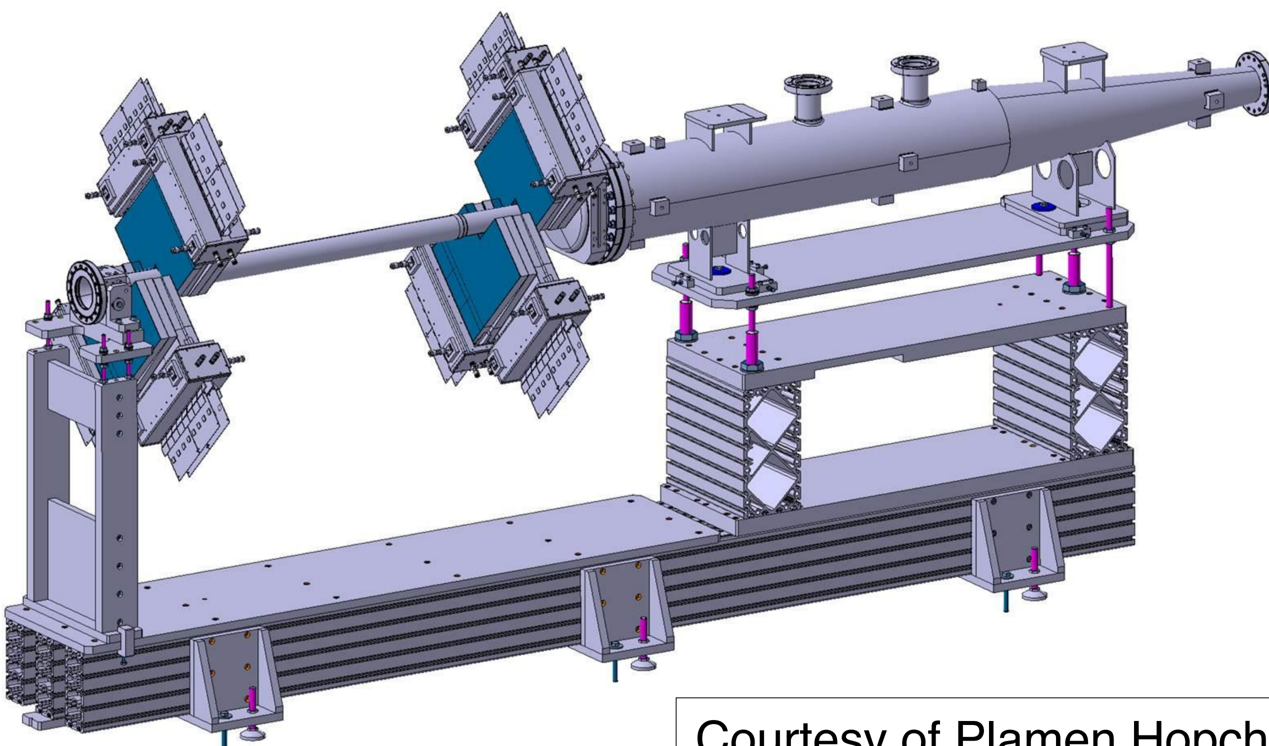
- Beam imaging with vertex reconstruction of beam gas interactions
  - Reconstruct the tracks coming from inelastic beam-gas interactions
  - Determine the position of the interaction (vertex)
  - Accumulate vertices to measure beam position, angle, width and relative bunch populations
- Main requirements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

Courtesy of Plamen Hopchev



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



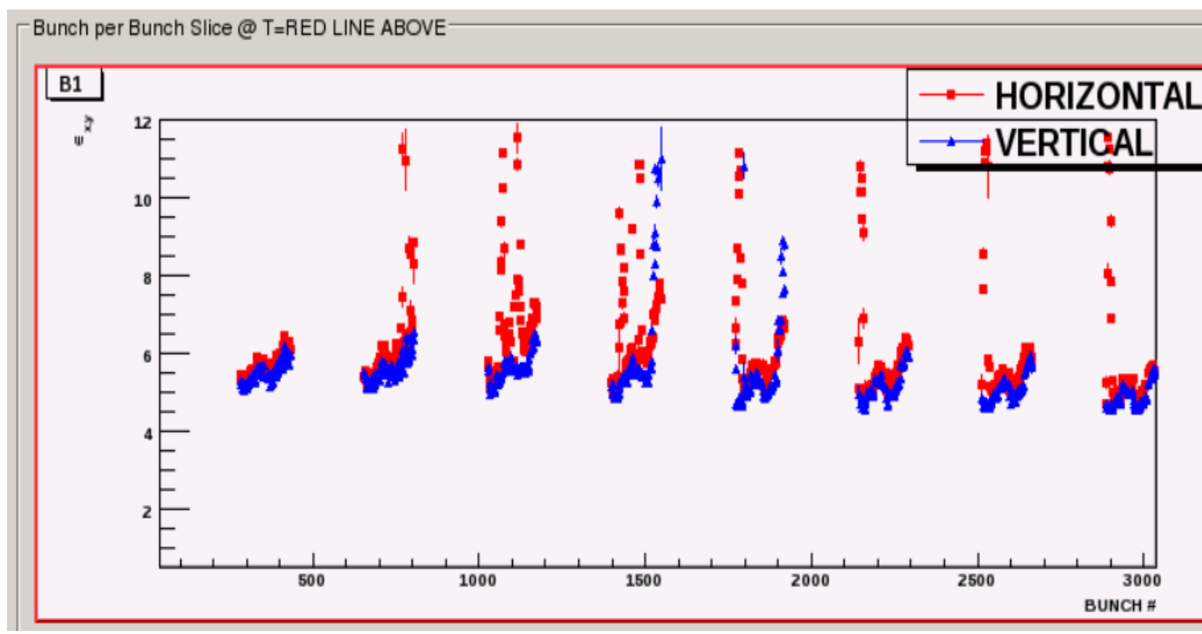
Detector
- Scintillating fibres read out with SiPMs
- Same technology as for the LHCb upgrade

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 50µm

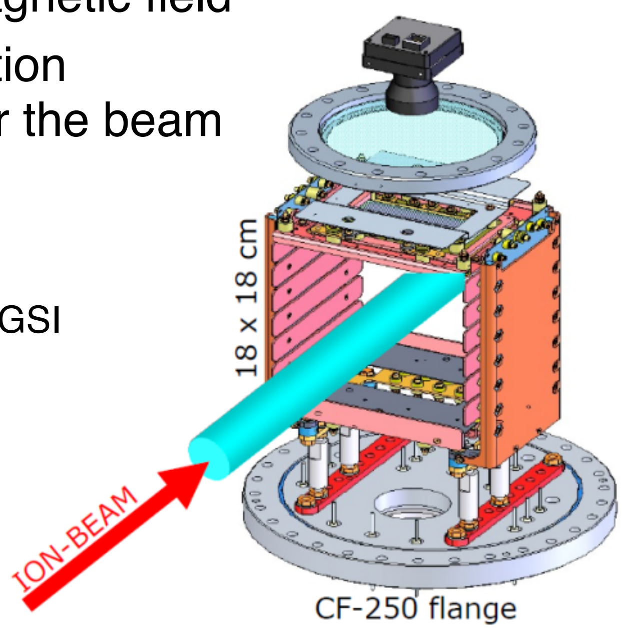
LHC: transverse blow-up of individual bunches

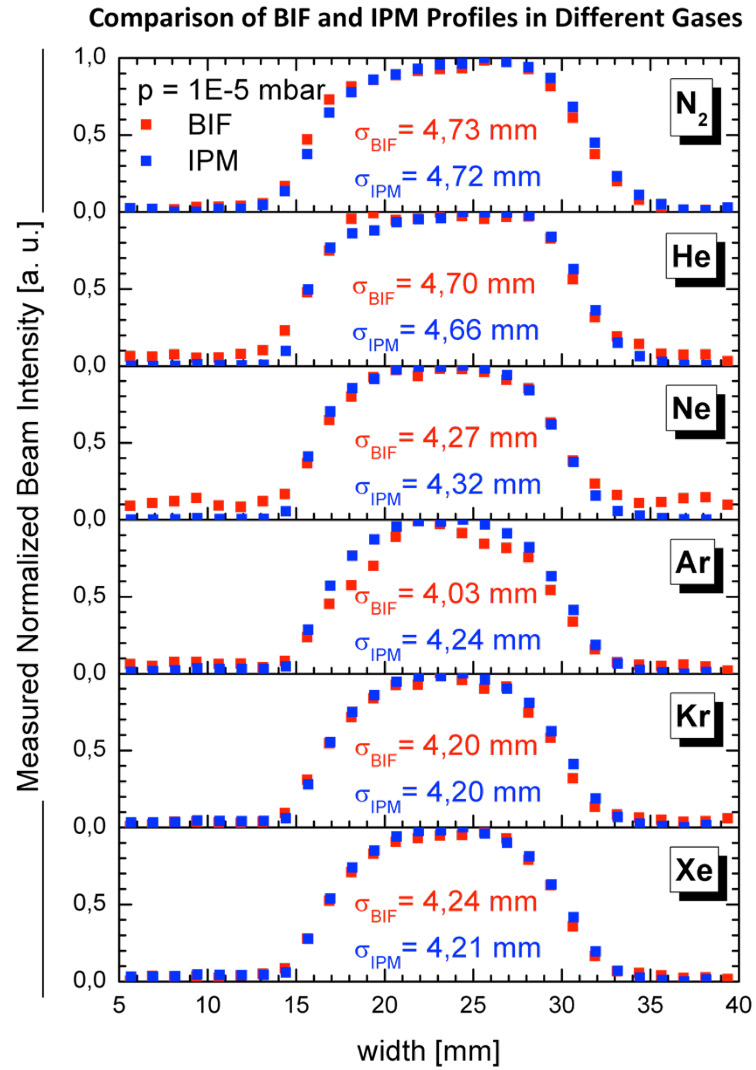


IPM (Ionization Profile Monitors)

- 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

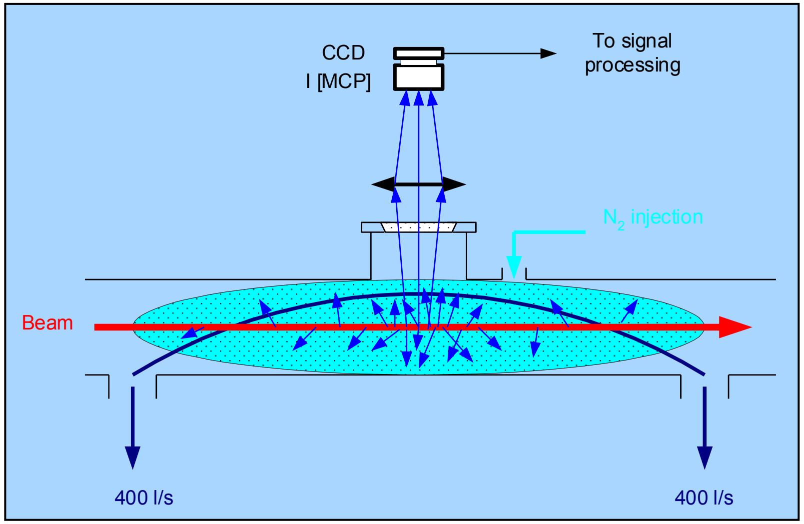


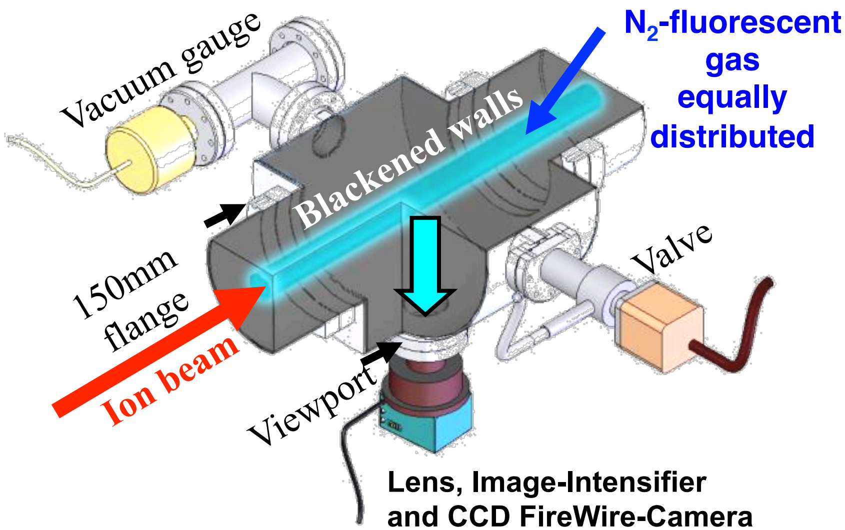


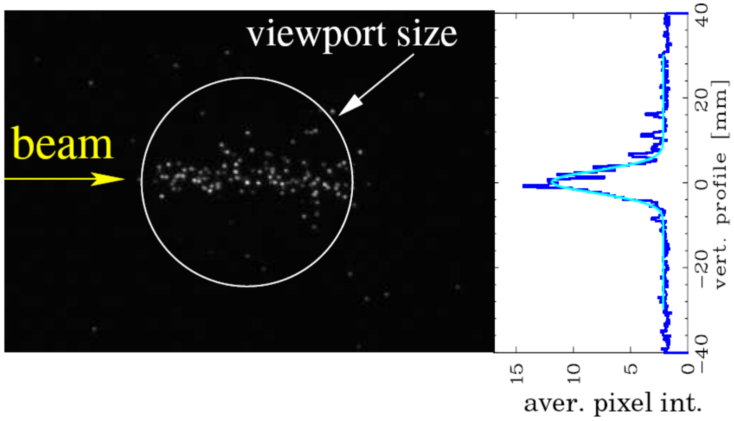
M.Schwickert, P.Forck, F.Becker, GSI

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_2, H_2)
- Dynamic range: ≈ 10^3

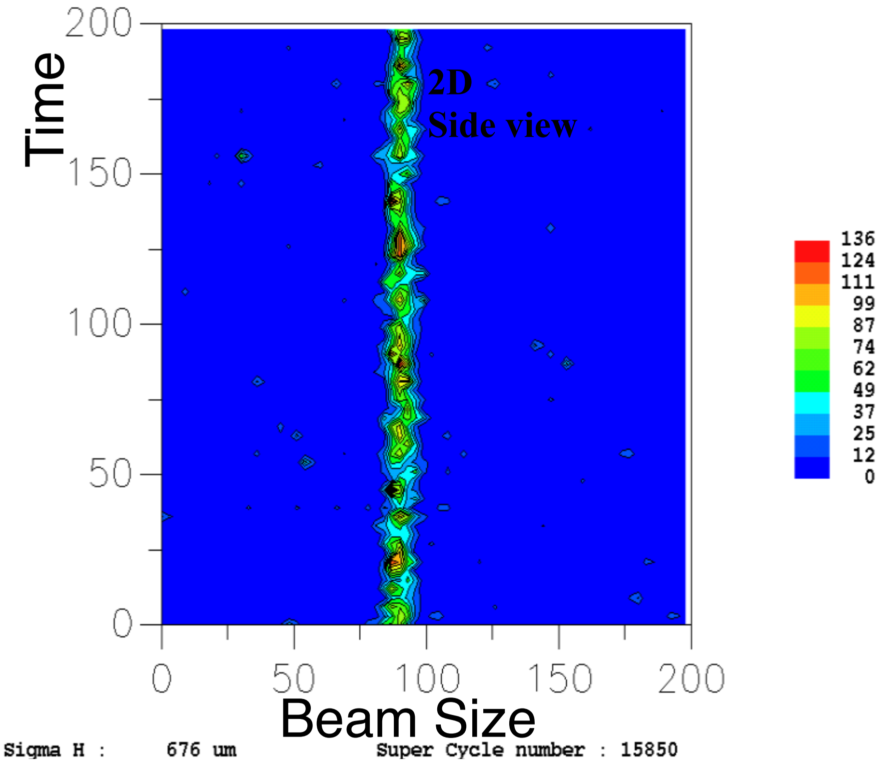


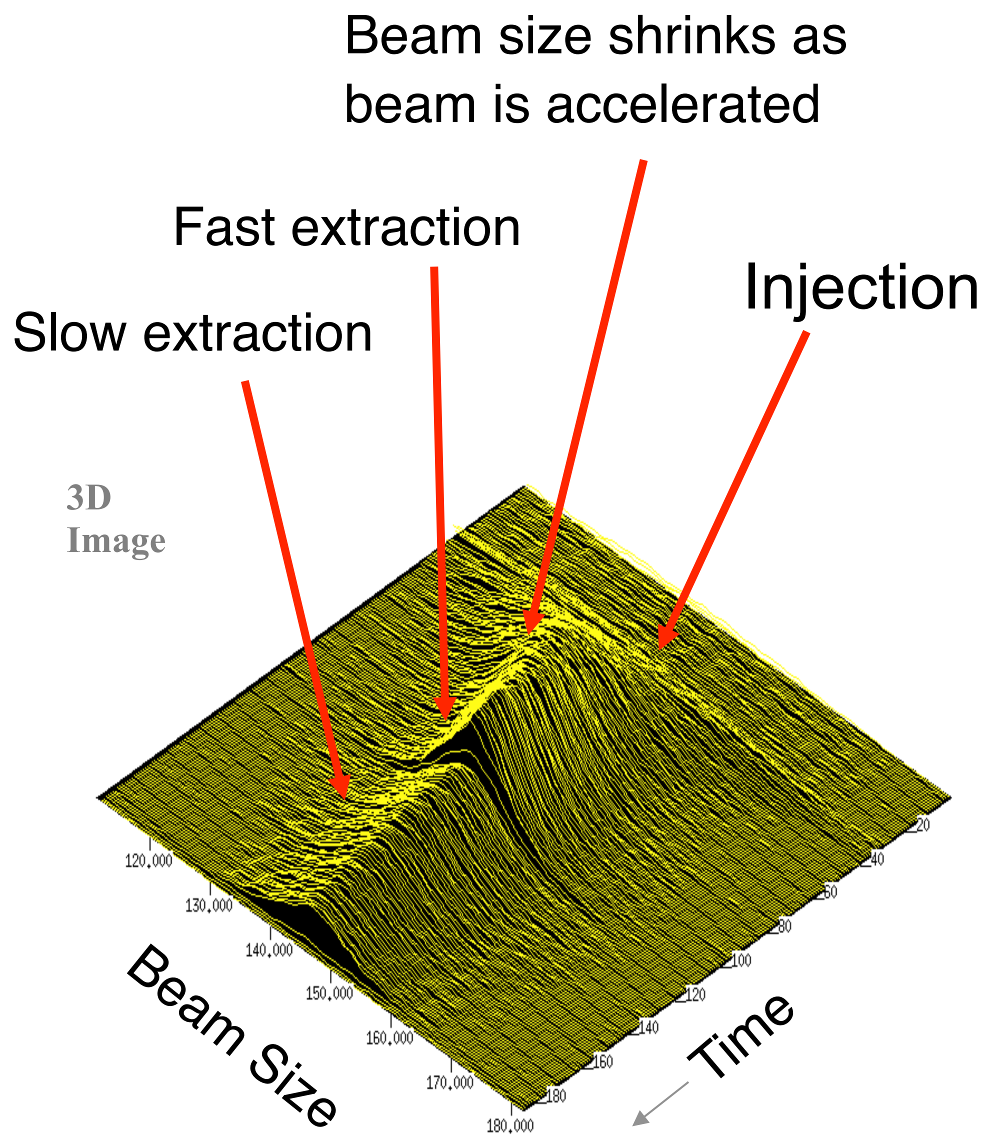




M.Schwickert, P.Forck, F.Becker, GSI

Luminescence Profile Monitor – Example CERN SPS

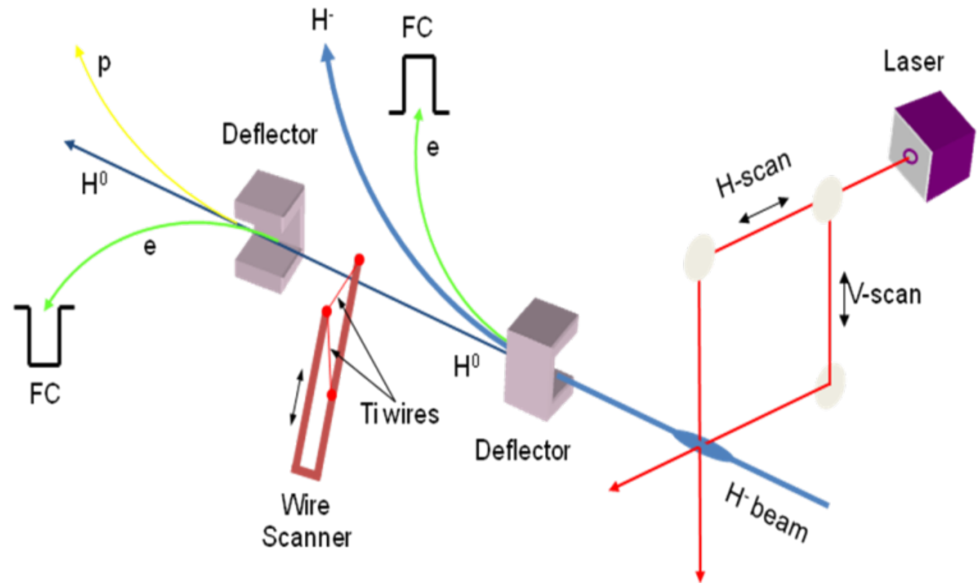




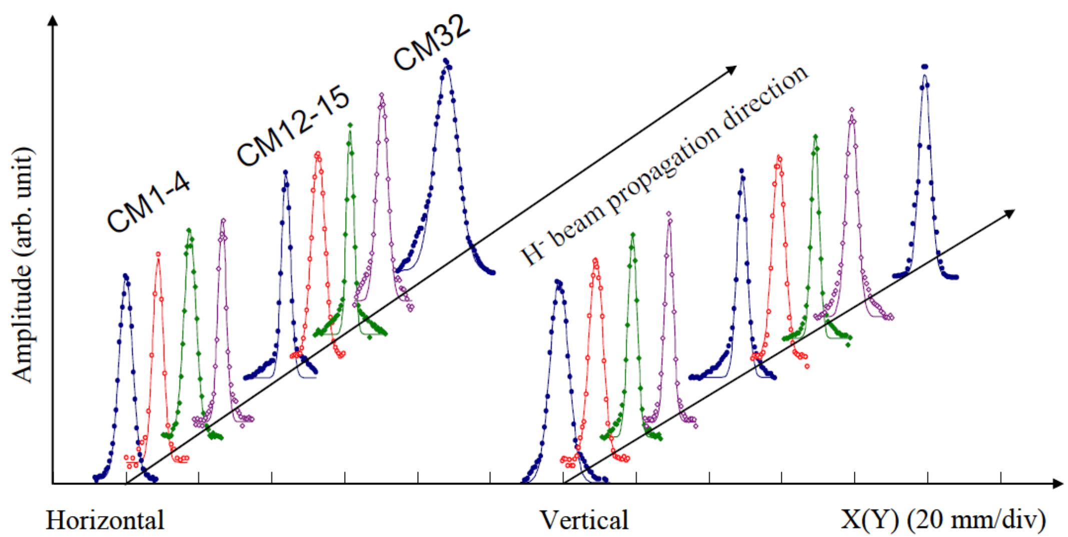
- Profile Collected every 20ms
- Local Pressure at ≈5×10^{-7} Torr

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