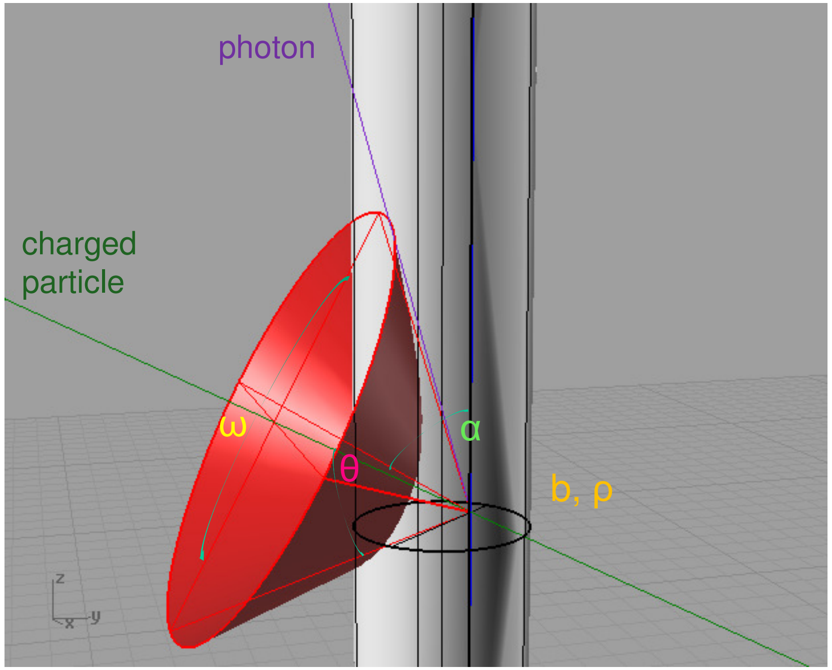
Beam Instrumentation and Beam Diagnostics



Eva Barbara Holzer
CERN, Geneva, Switzerland

517. WE-Heraeus-Seminar on
Accelerator Physics for Intense Ion Beams

Introduction

- Vast subject – large range of technologies

- Fields involved include:
  - Accelerator physics – particle physics – RF technology – optics – mechanics – electronics – software engineering – …

- Harsh environment:
  - Radiation (SEE, 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

Introduction, cont'd

- Aim: assist in commissioning, tuning and operating the accelerator and to improve performance
- Instrumentation varies:
  - **LINAC and transport lines**: Single pass, can have separate measurement lines ↔ **Synchrotron:** multi pass
  - **Protons/Ions:** non-relativistic for E_{kin} < 1 GeV/u
  - **Total Beam Energy** (beam particles x particle energy) low ↔ high
  - **Non-intercepting** ↔ **Intercepting** ↔ **Destructive** (often depending on beam energy)
- **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

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 Acclerators*, Univ. Jyväskylä, Finland, CERN 94-01,
    http://schools.web.cern.ch/Schools/CAS/CAS Proceedings.html (1993).
- Jacques Bosser (Ed.), *Beam Instrumentation*, CERN-PE-ED 001-92, Rev. 1994

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)
  - Transverse profile
  - Bunch length
  - 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

- Effect on beam depends on circumstances

  N none
  - slight, negligible
  + perturbing
  D destructive

- Different Labs (different machines) have different names for the same device!

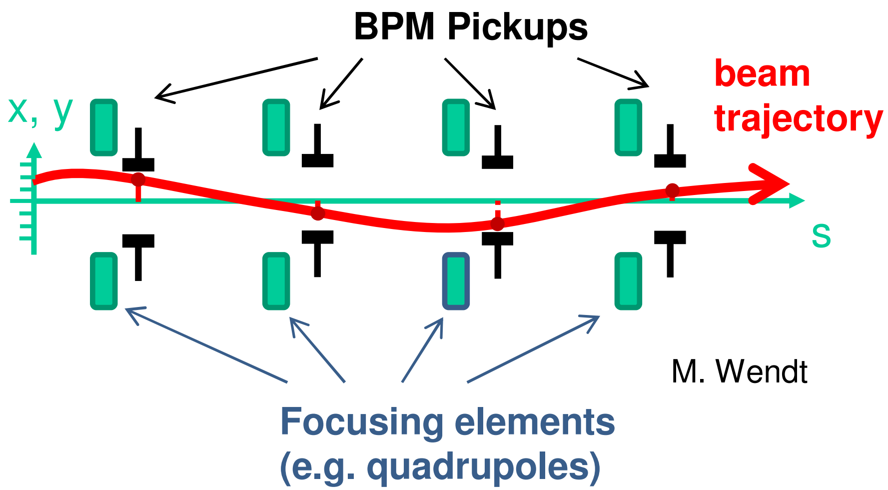
PROPERTY MEASURED →	Intensity/charge	tr. Position	tr. Size/shape	tr. Emittance	l. Size/shape	l. Emittance	Q-value + ΔQ	Energy + ΔE	Polarization	Effect on beam N	-	+	D
Beam transformers	●				●	●				x			
Wall-current monitors	●	●			●	●				x			
Pick-ups	●	●	●		●	●				x			
Faraday cup	●												x
Secondary emission monitors	●	●	●	●				•			x	x	
Wire scanners		●	●	●							x		
Wire chambers		●	●								x	x	
Beam loss monitors		•	•	•			•			x			
Residual-gas profile monitors		●	●	●						x			
Scintillator screens		●	●								x	x	x
Optical transition radiation		●	●	●							x		
Synchrotron radiation		●	●	●	●	●				x			
LASER-Compton scattering			●	●					●	x			
Scrapers and meas. targets		●	●	●									x
Schottky scans	●			●		•	●	●		x			

H. Koziol, CAS

Beam Position Monitors

Capacitive Pick-Ups for Bunched Beams

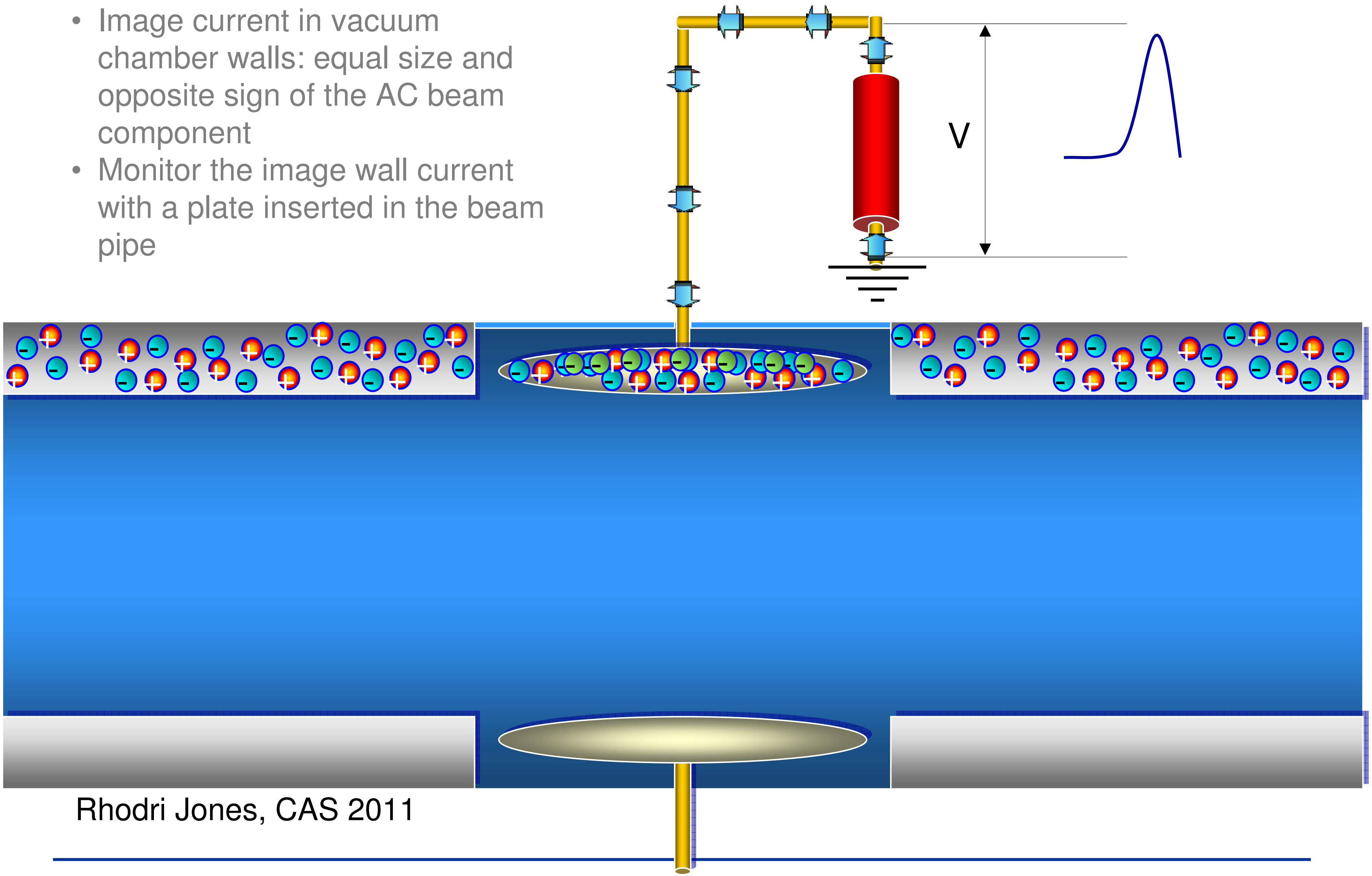
- Among the most numerous instruments
- Measurements:
  - Transverse beam position (typically next to focusing elements)
    - Beam trajectory or closed orbit
    - injection oscillations
  - Tune and lattice function in synchrotrons



- Working principle:
- Image current in vacuum chamber walls: equal size and opposite sign of the AC beam component
- Monitor the image wall current with a plate inserted in the beam pipe
- Adapt BPM electronics integration time
  - Single-bunch ↔ multi-bunch
  - turn-by-turn (single pass) ↔ multi-turn average

Capacitive Pick-Up – The Principle

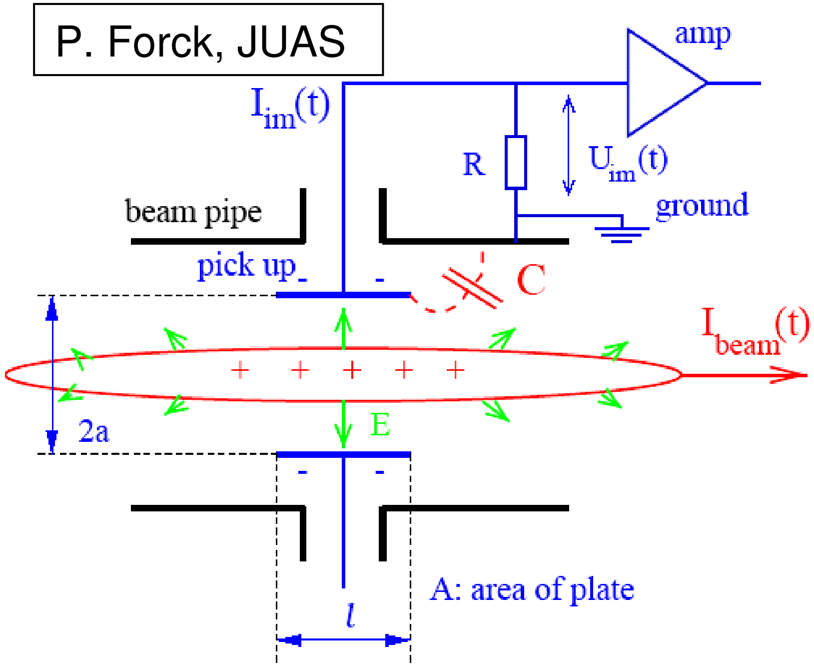
- Image current in vacuum chamber walls: equal size and opposite sign of the AC beam component
- Monitor the image wall current with a plate inserted in the beam pipe

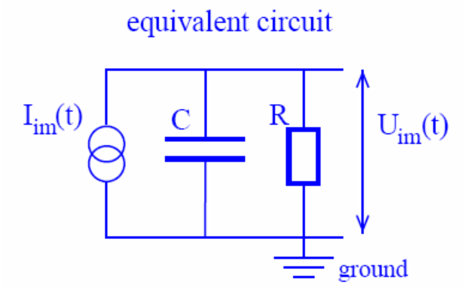


Rhodri Jones, CAS 2011

Schematics and Simplified Equivalent Circuit

P. Forck, JUAS





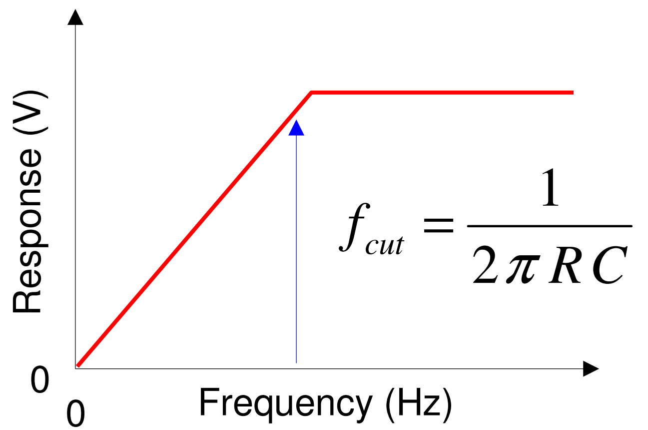
$$U_{im}(\omega) = \frac{R}{1 + i\omega RC} \cdot I_{im}(\omega)$$

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

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

Z_t … longitudinal transfer impedance

$\Rightarrow$ High pass characteristics with a cut-off frequency, f_{cut}



$$I_{im} = \frac{A}{2\pi al}\left(-\frac{l}{\beta c}\frac{dI_{beam}}{dt}\right) = \frac{A}{2\pi al}\frac{1}{\beta c} i\omega I_{beam}(\omega)$$

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

Transfer Impedance

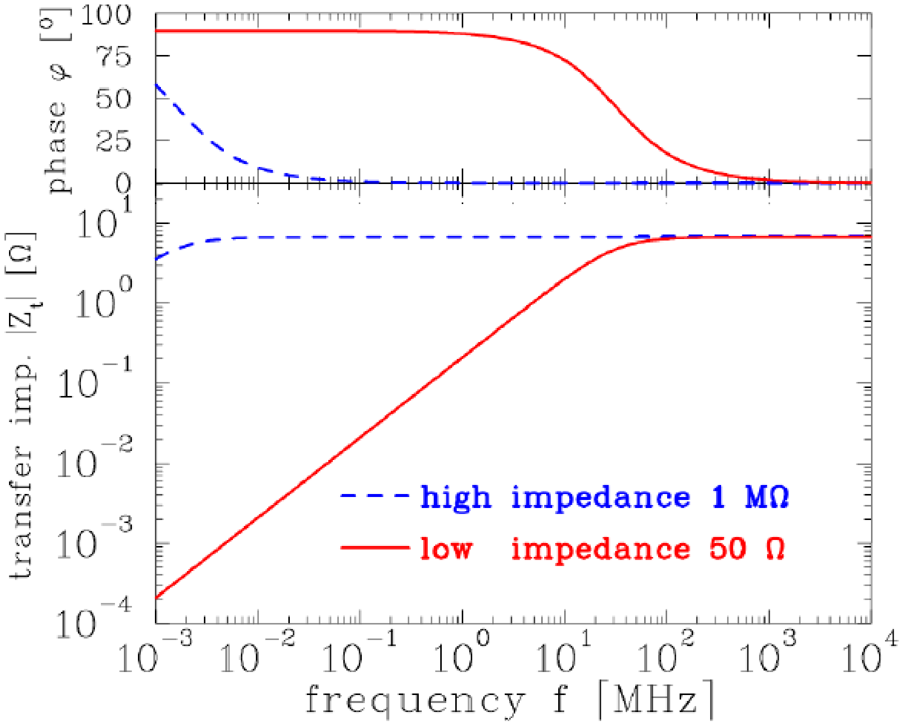
P. Forck, JUAS

$$|Z_t| = \frac{A}{2\pi a} \frac{1}{\beta c} \frac{1}{C} \frac{\omega/\omega_{cut}}{\sqrt{1+\omega^2/\omega_{cut}^2}}$$

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

R=50 Ω ⇒ f_{cut}= 32 MHz
R=1 MΩ ⇒ f_{cut}= 1.6 kHz

- large signal at lower frequencies
  ⇒ **high impedance**
- smooth signal transmission
  ⇒ **50 Ω**



l = 10 cm long cylindrical pick-up with a capacitance of C = 100 pF and an ion velocity of β = 50%

Operational Regime Determines Signal Shape

$$Z_t \propto \frac{i\omega/\omega_{cut}}{1 + i\omega/\omega_{cut}} \qquad \frac{dI_{beam}}{dt} = -\, i\omega\, I_{beam} \qquad U_{im}(\omega) = Z_t(\omega) I_{beam}(\omega)$$

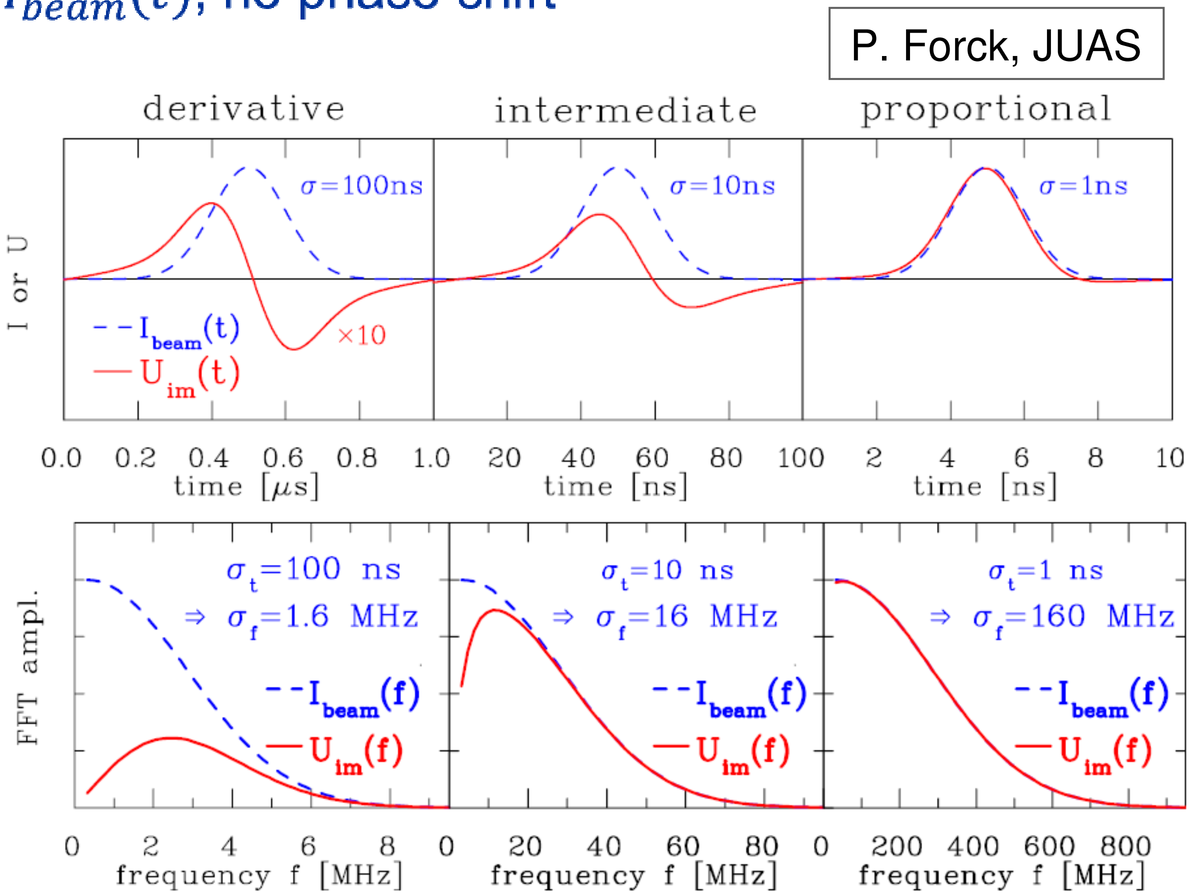
- $\omega \ll \omega_{cut}$: $U_{im}(t) \propto \frac{dI_{beam}}{dt}$, phase shift 90° → derivative signal
- $\omega \gg \omega_{cut}$: $U_{im}(t) \propto I_{beam}(t)$, no phase shift

l = 10 cm long cylindrical pick-up with a capacitance of C = 100 pF and an ion velocity of β = 0.5,

R=50 Ω

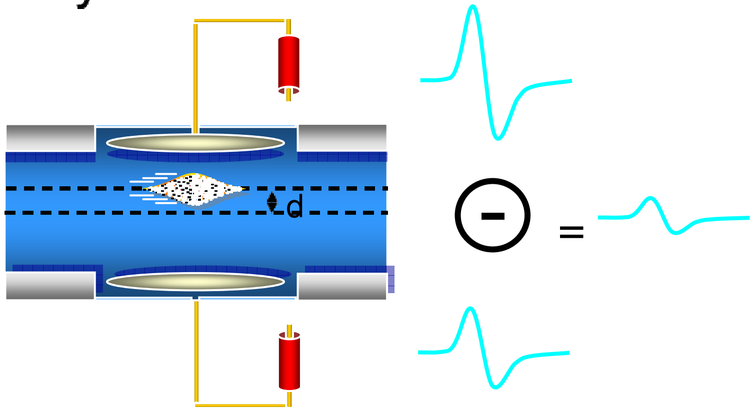
$f_{cut} = 32$ MHz

Operational regime depends on the bunch length!



Beam Position

- Standard BPMs give intensity signals which need to be subtracted (top - bottom, or left - right) to obtain a difference which is then proportional to position of the beam center of mass
- The difference signal (ΔU) is normally at least a factor 10 lower than the sum signal (ΣU)
  - Position: $x = \frac{1}{S_x(\omega,x,y)} \cdot \frac{\Delta U}{\Sigma U}$

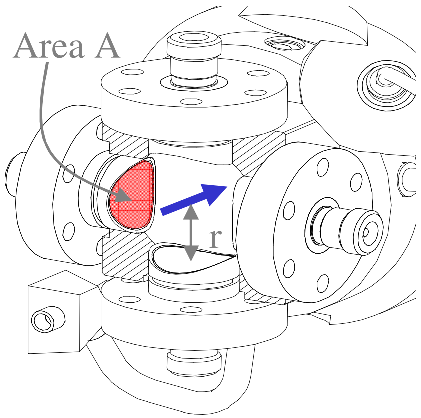


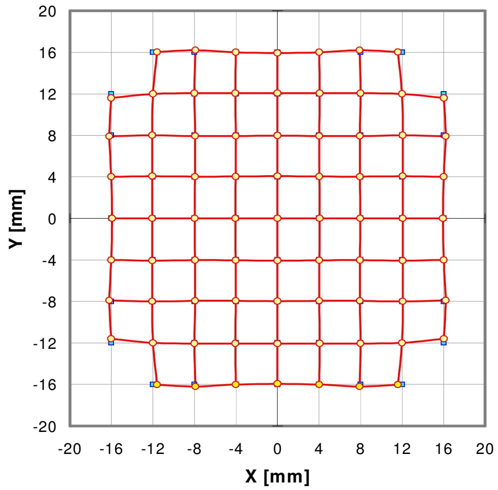
- Difficult to do electronically without some of the intensity information leaking through
- When looking for small differences this leakage can dominate the measurement
- **Resolution** for typical apertures:
  - ≈ tens µm turn-by-turn
  - ≈ µm multi-turn resolution

Example: Button Pick-up

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

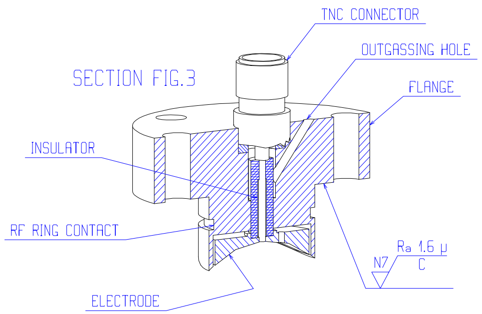
$$X = 2.30\cdot10^{-5}X_1^{\,5} + 3.70\cdot10^{-5}X_1^{\,3} + 1.035X_1 + 7.53\cdot10^{-6}X_1^{\,3}Y_1^{\,2} + 1.53\cdot10^{-5}X_1Y_1^{\,4}$$





R. Jones

LHC buttons



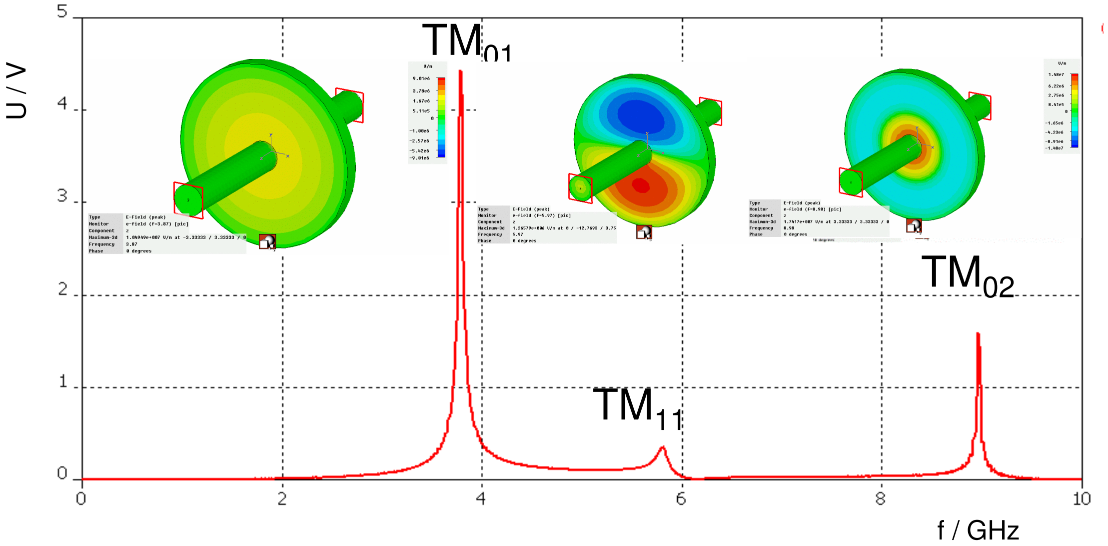
$$f_{cut} = \frac{1}{2\pi RC} = \frac{1}{2\pi\times50\Omega\times8\,pF} = 400MHz$$

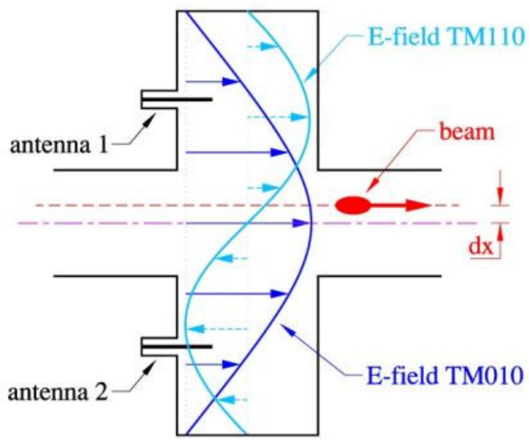
$$Z_{t\infty} = \frac{A}{(2\pi a)\times c\times C_e} = \frac{\pi\times(12mm)^2}{(2\pi\times24.5mm)\times c\times(8\,pF)} = 1.2\,\Omega$$

Improving Position Resolution

- Development driven by electron machines with very small beam sizes (FEL, linear collider final focus region, CLIC main linac)
- Cavity BPMs allow sub micron resolution
  - Design the detector to collect only the difference signal
  - Dipole Mode TM_{11} proportional to position & shifted in frequency with respect to monopole mode

Frequency Domain





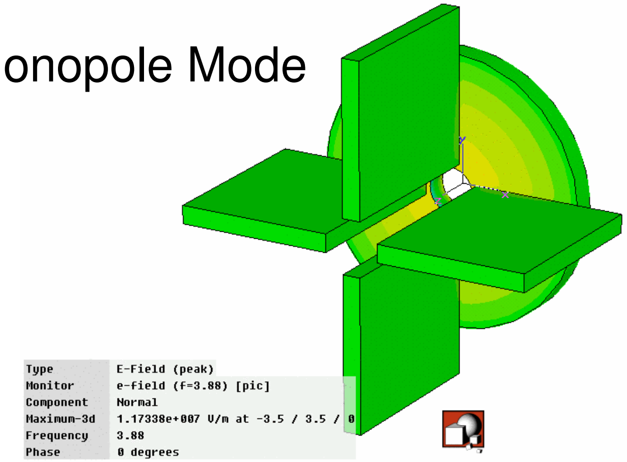
Courtesy of D. Lipka, DESY, Hamburg

U~Q *U~Qr* *U~Q*

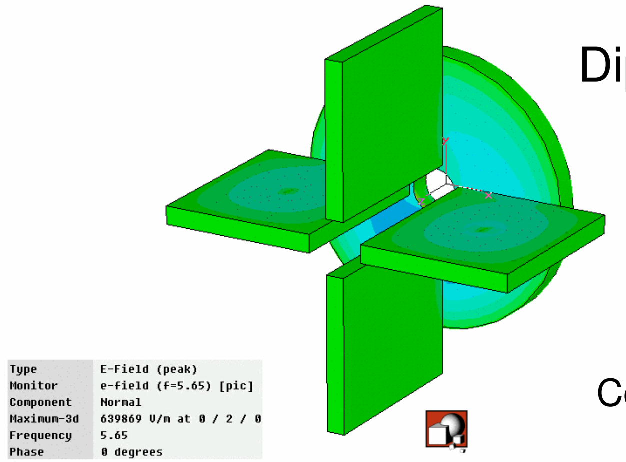
Today’s State of the Art BPMs

- Obtain signal using waveguides that only couple to dipole mode, further suppression of monopole mode

Monopole Mode

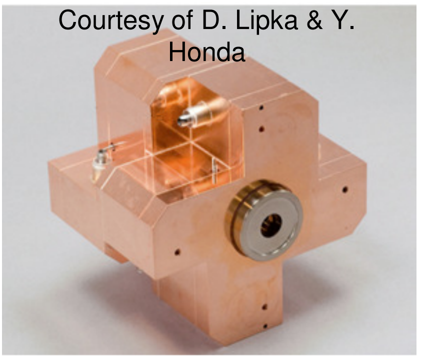


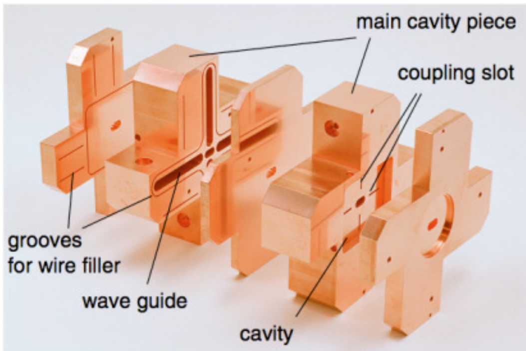
Dipole Mode

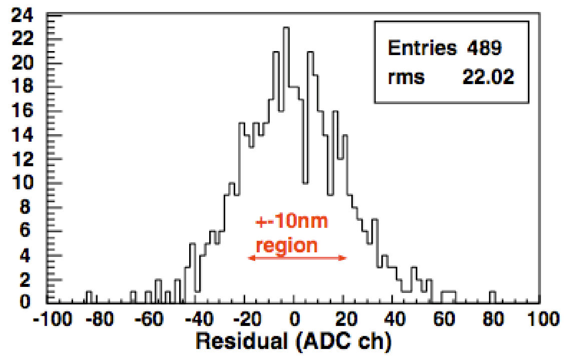


Courtesy of D. Lipka, DESY, Hamburg

- Prototype BPM for ILC Final Focus
  - Required resolution of 2nm (yes nano!) in a 6×12mm diameter beam pipe
  - Achieved World Record (so far!) res. of 8.7nm at ATF2 (KEK, Japan)



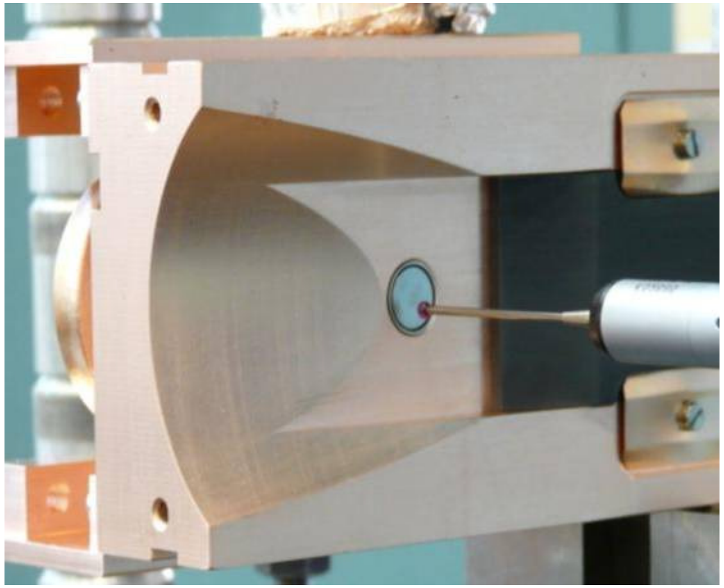




New LHC Collimators with Integrated BPMs

- 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

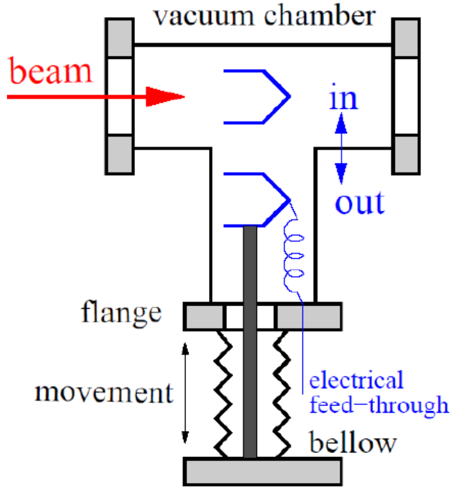
- Successfully tested in the SPS (D. Wollmann, HB2012)
  - <25 µm difference to BLM setup - believed to be dominated by the BLM setup method
  - single pass (transfer line): <90µm rms
  - no disturbance observed from protons hitting the jaws or from shower particles



Beam Current

Overview of Current Measurements

- Beam Current measurement is essential for all machines
- **Faraday cups:** Measurement of the beam's **electrical charges**
  - Low energies only
  - Particles are stopped in the device
    → Destructive
  - Sensitive to low currents
  - Absolute accuracy:
    - ≈ 1% (some monitors reach 0.1%)

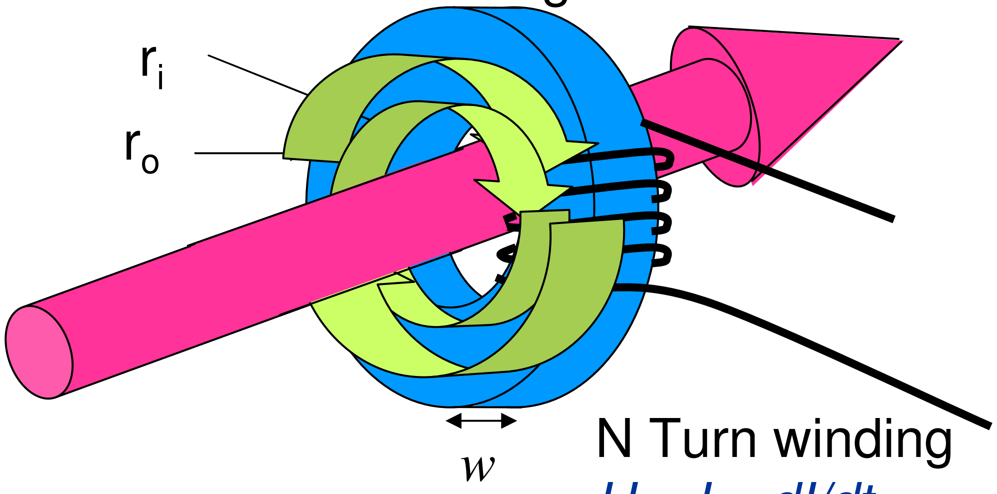


Faraday Cup at GSI LINAC, P. Forck, JUAS

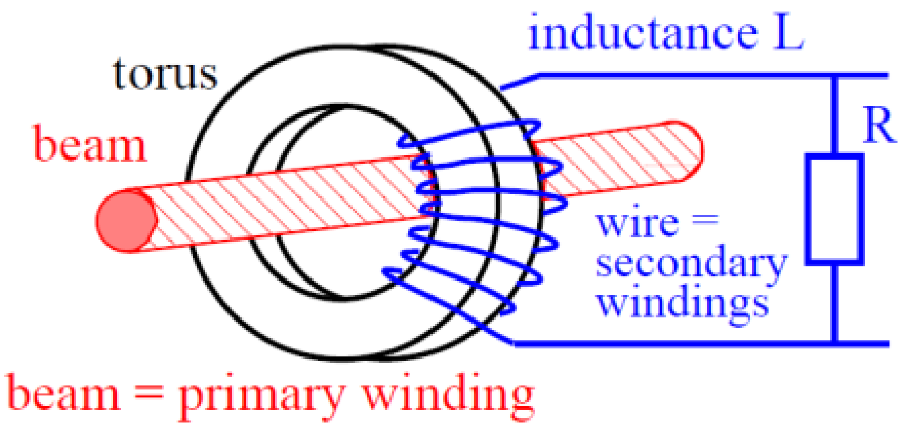
- **Particle detectors:** Measurement of the particle's **energy loss** in matter
  - Used for low currents at high energies e.g. for slow extraction
  - For example: scintillators, ionization chambers, secondary e– emission monitors
  - Interceptive

Overview of Current Measurements, cont'd

- Mostly: 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



Current Transformers



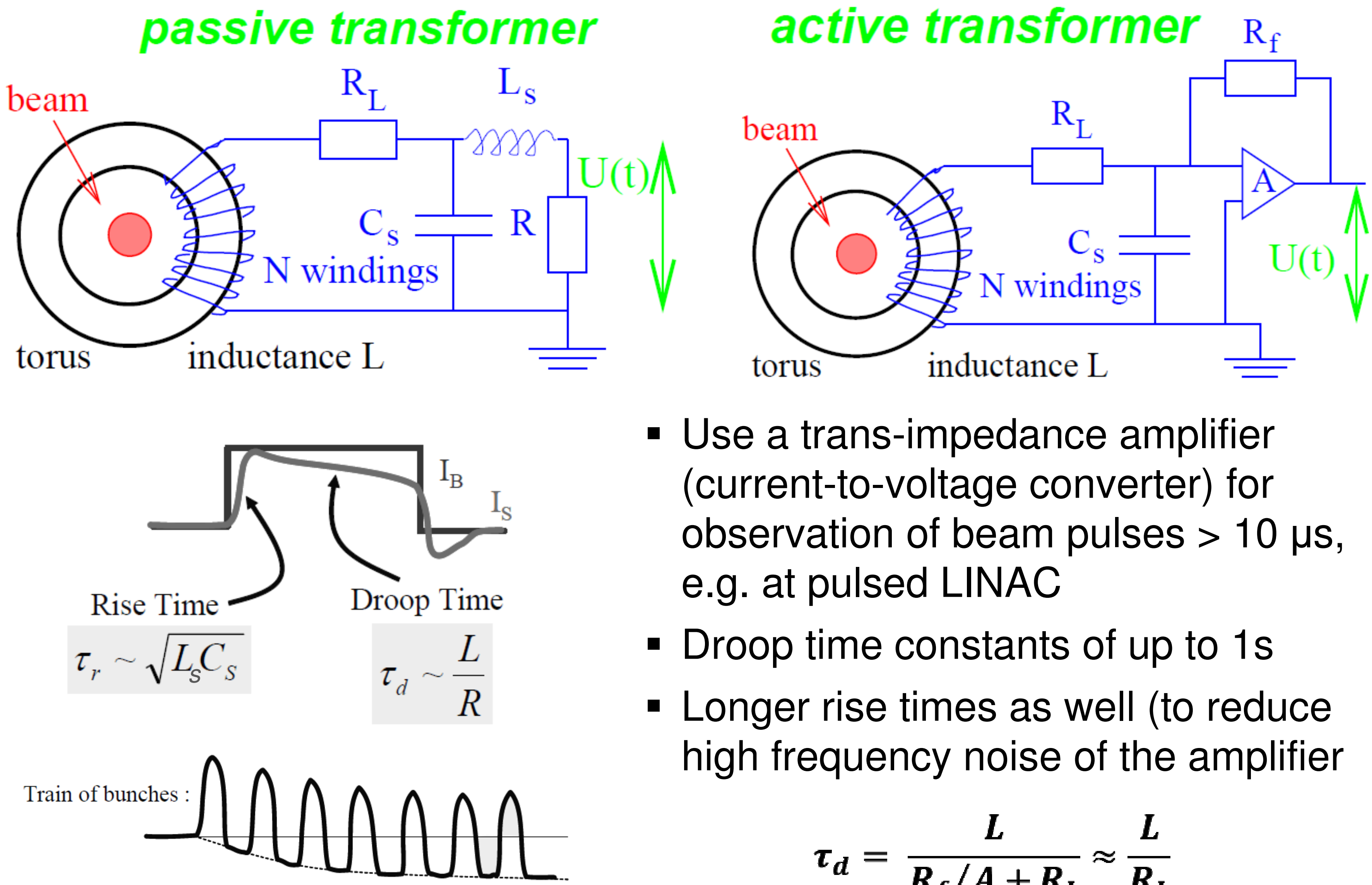
Beam current $I_{Beam} = \frac{e N_q}{t} = \frac{e N_q \beta c}{w}$

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

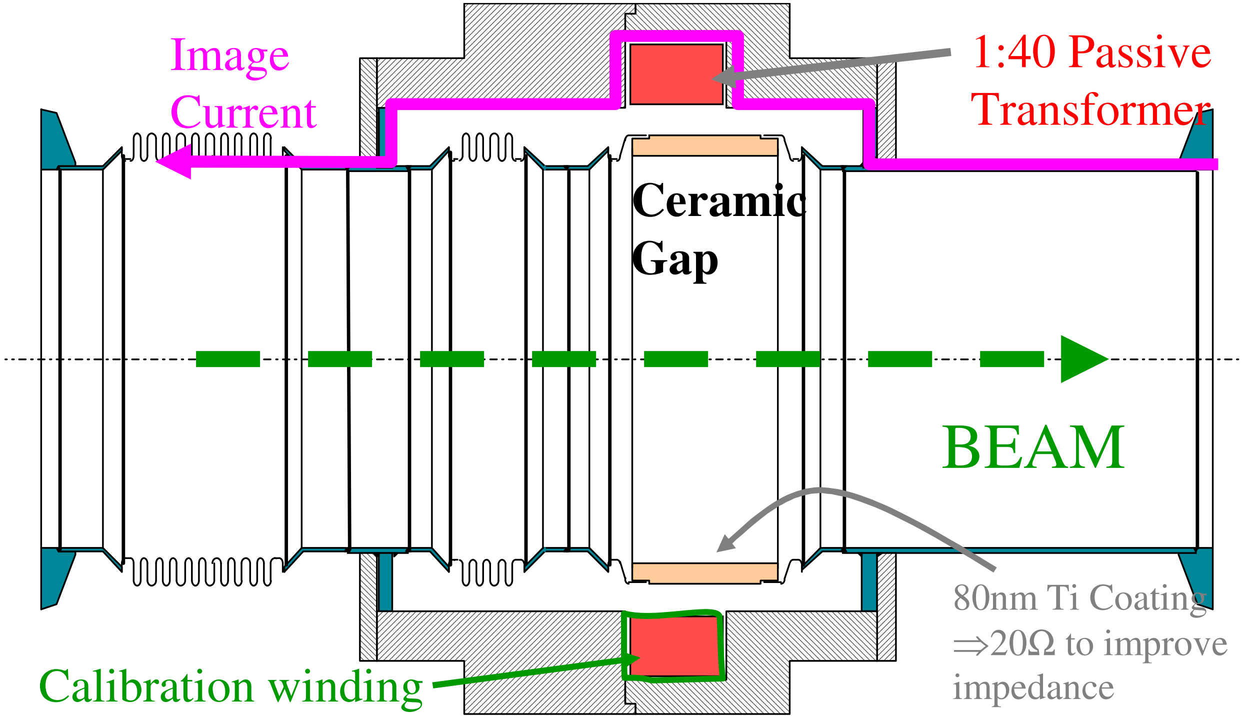


- Use a trans-impedance amplifier (current-to-voltage converter) for observation of beam pulses > 10 µs, e.g. at pulsed LINAC
- Droop time constants of up to 1s
- Longer rise times as well (to reduce high frequency noise of the amplifier

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

Transformer Housing

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

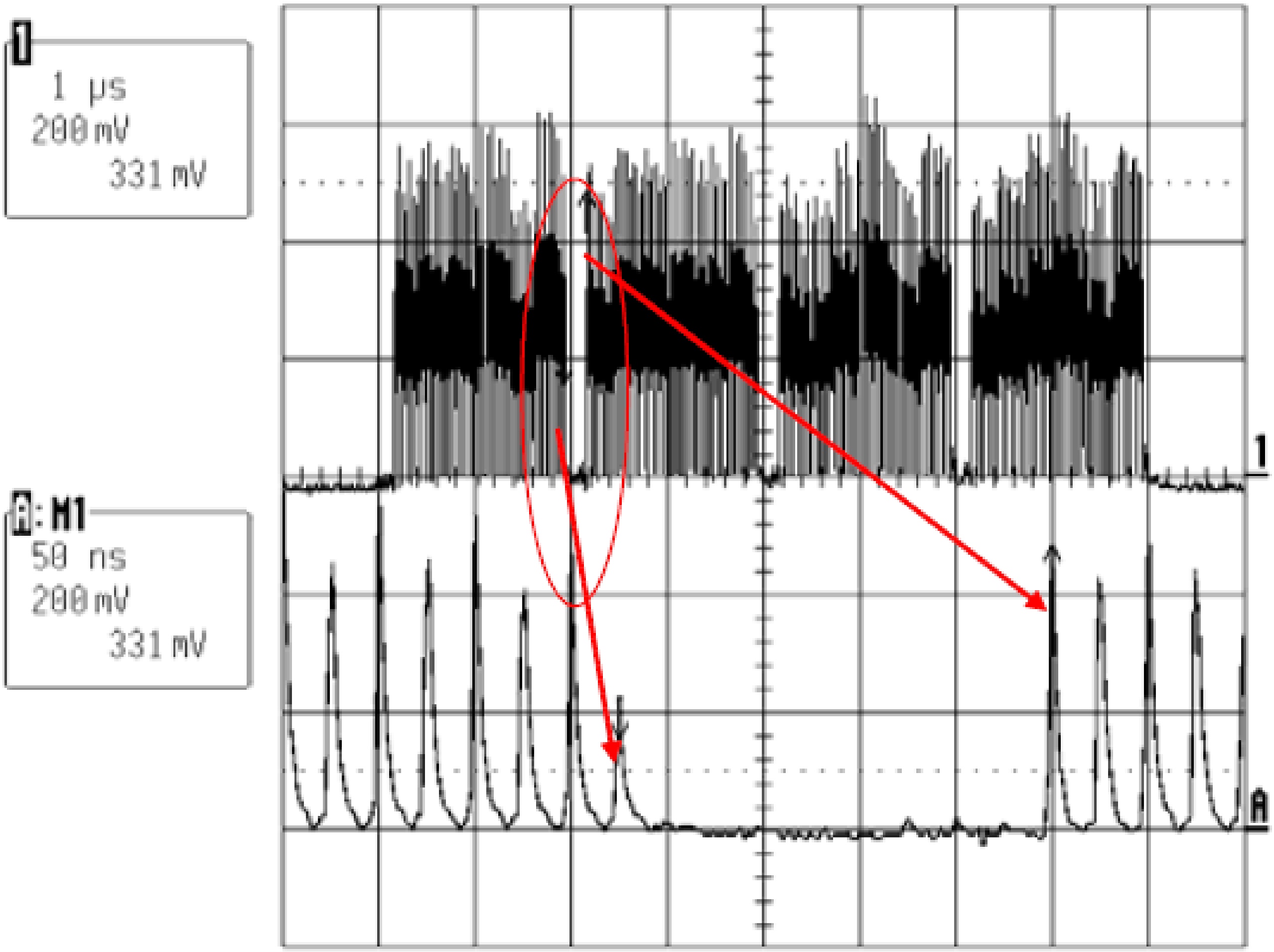


CERN SPS Fast Beam Current Transformer (FBCT)

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



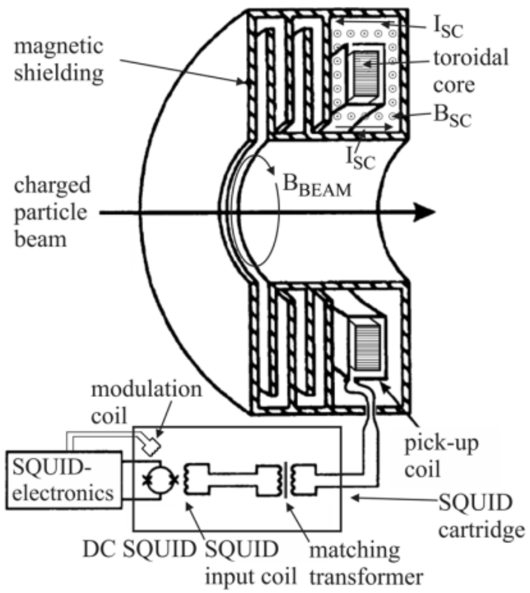
Performance

- 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)

Current Developments at CERN

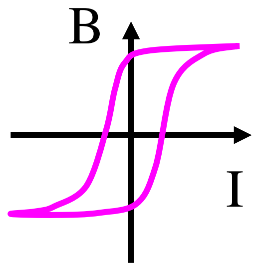
- DC: **Cryogenic Current Comparator, CCC** (A. Peters, GSI, BIW1998, T. Watanabe, RIKEN, BIW10)
  - For low current beams (AD and ELENA)
  - Uses **SQUID (Superconducting Quantum Interference Device)** as null detector for the magnetic field which can detect extremely small changes of the magnetic field.
  - Sub-nA resolution for 100 nA beams has been obtained.
  - Independent of beam position
  - Very delicate to implement



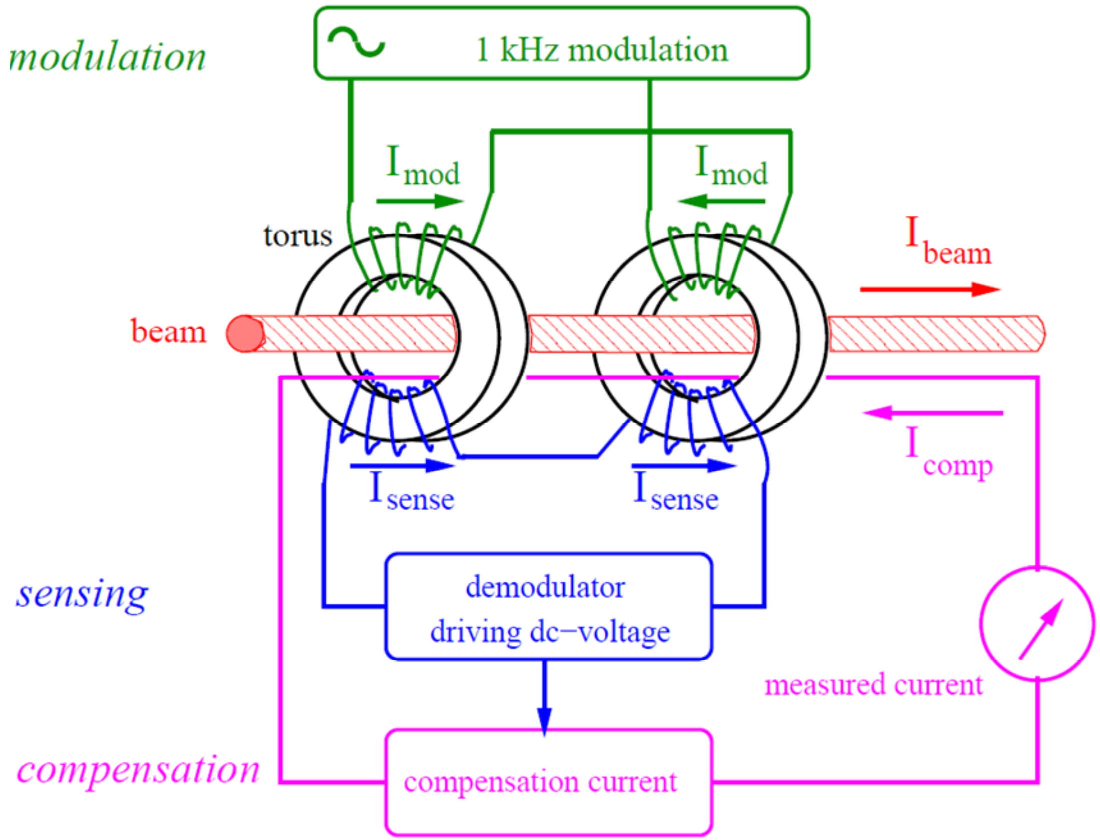
→ see poster F. Kurian

DCCT: DC Beam Current Transformer

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

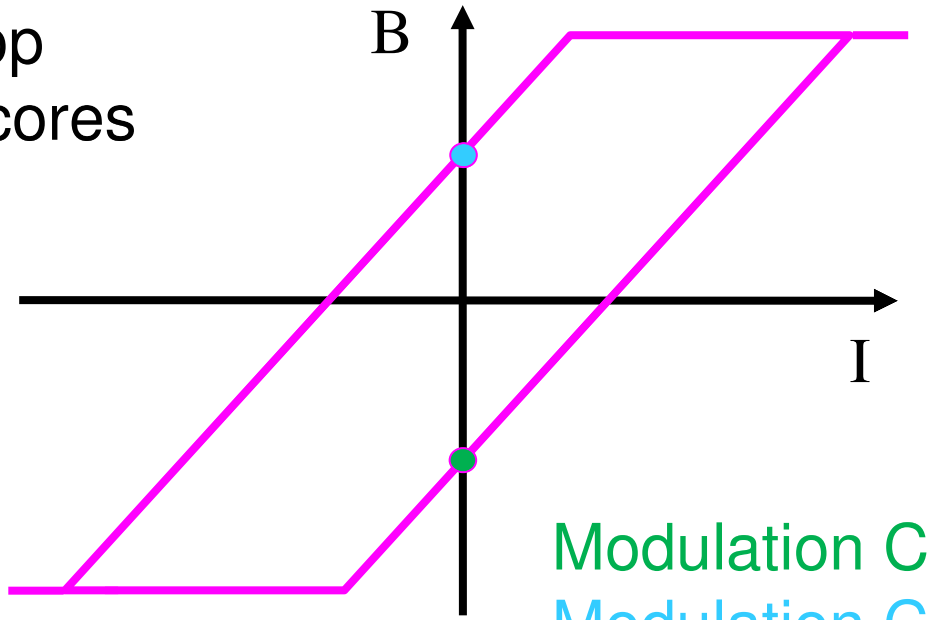


- Modulation of opposite sign drives toroids into saturation
- Sense windings measure the modulation signal
- Signals from the two toroids cancel each other as long as there is no beam

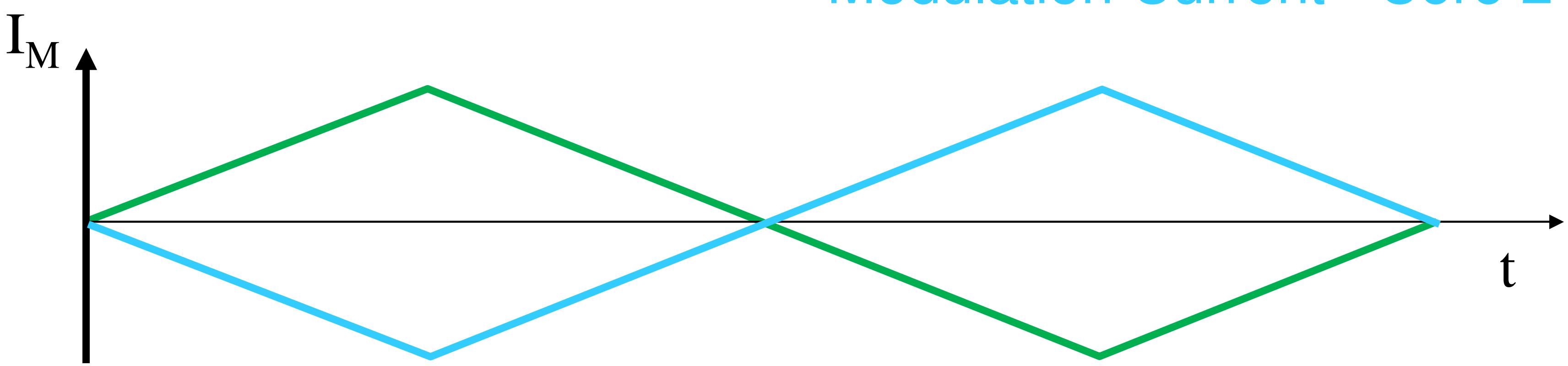


DCCT Principle – Case 1: No Beam

Hysteresis loop
of modulator cores

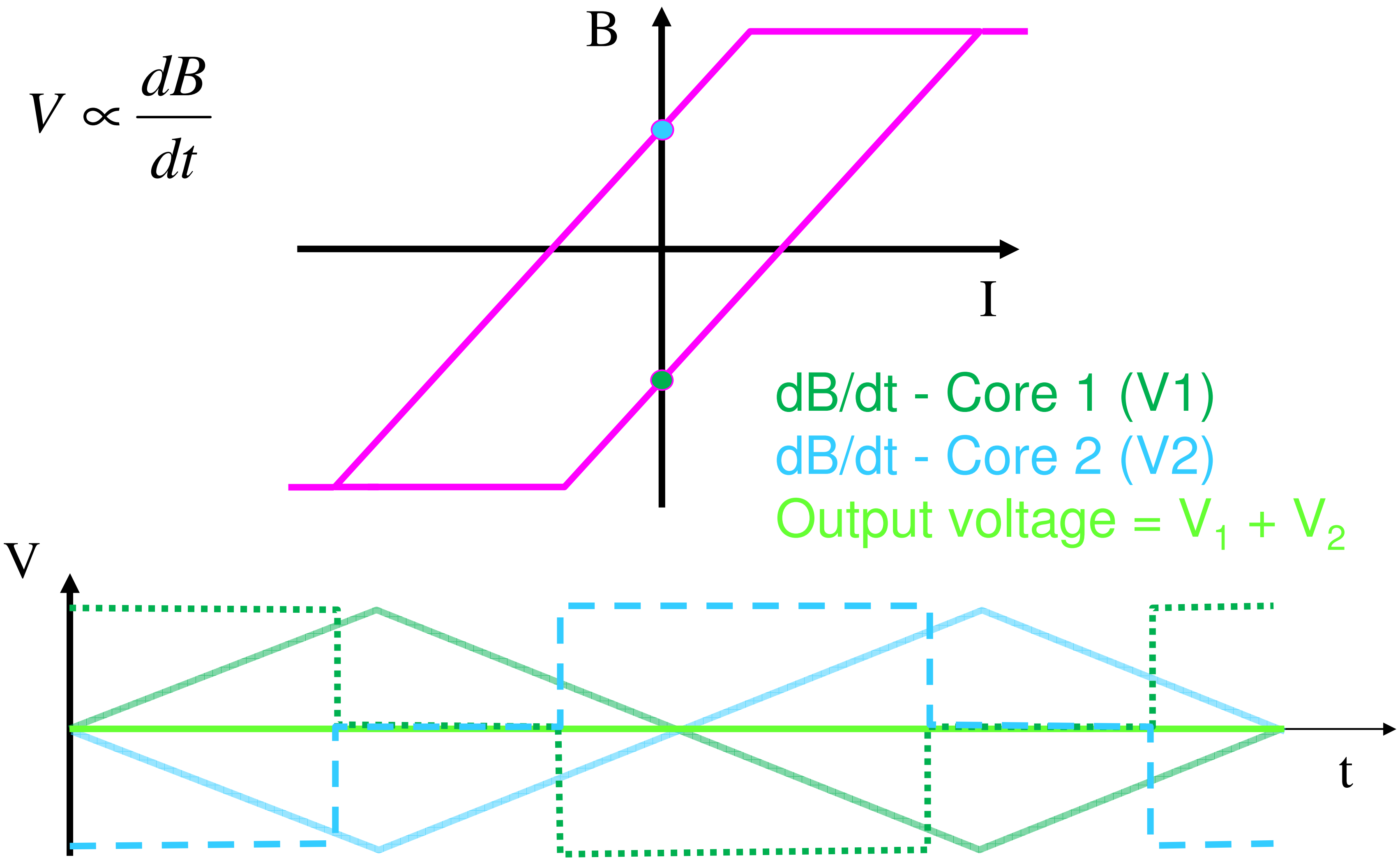


Modulation Current - Core 1
Modulation Current - Core 2



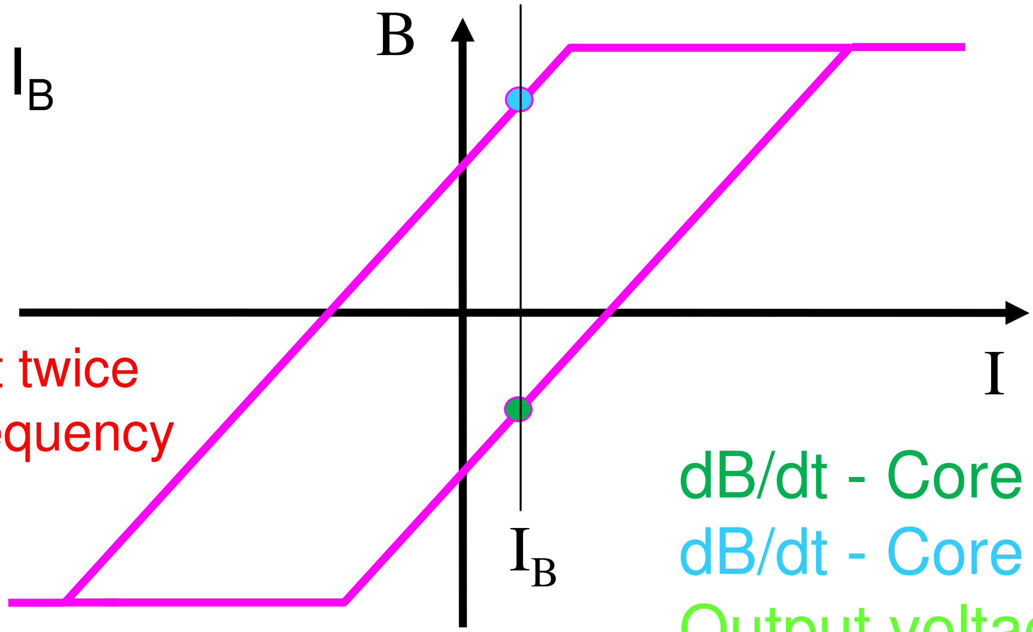
DCCT Principle – Case 1: No Beam

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



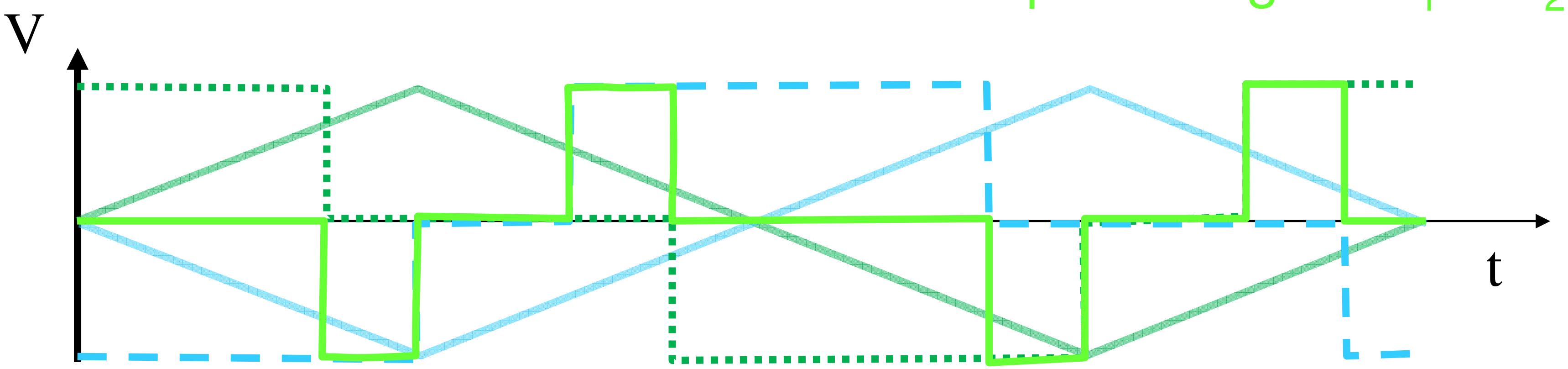
DCCT Principle – Case 2: With Beam

Beam Current I_B



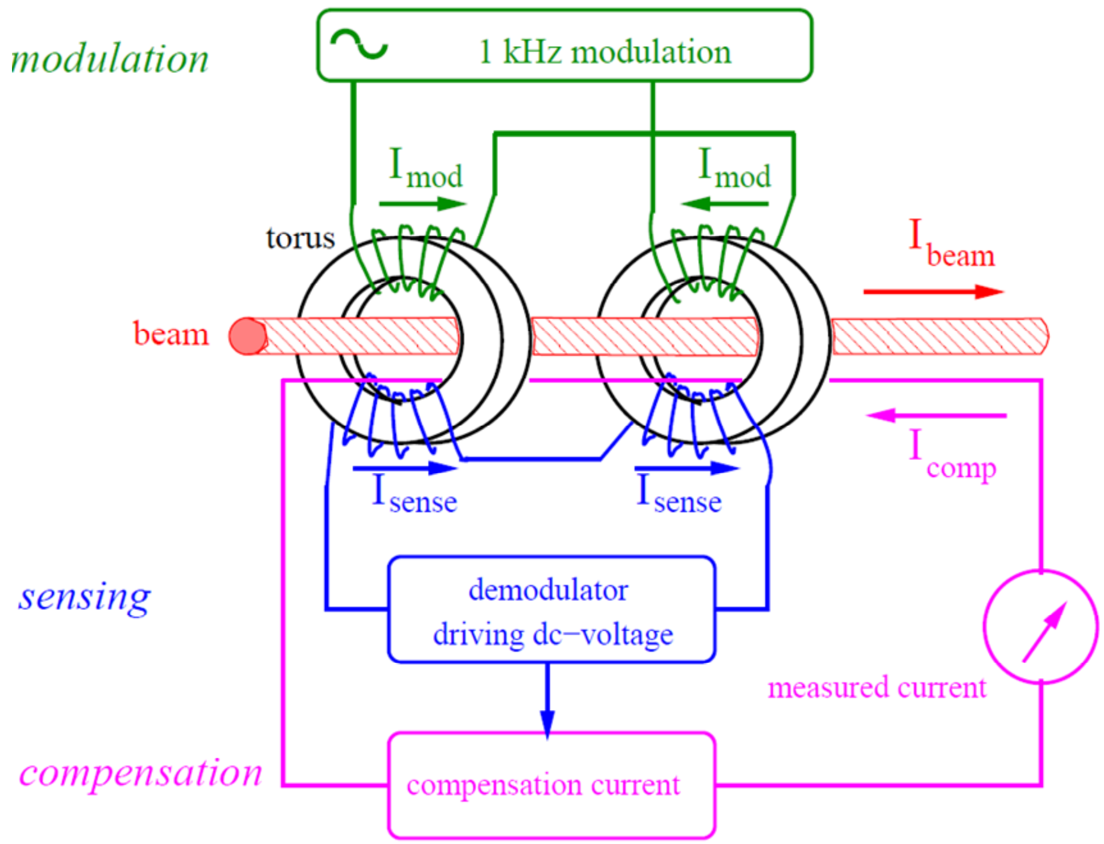
Output signal is at twice the modulation frequency

dB/dt - Core 1 (V1)
dB/dt - Core 2 (V2)
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



Transverse Profile and Emittance Measurement

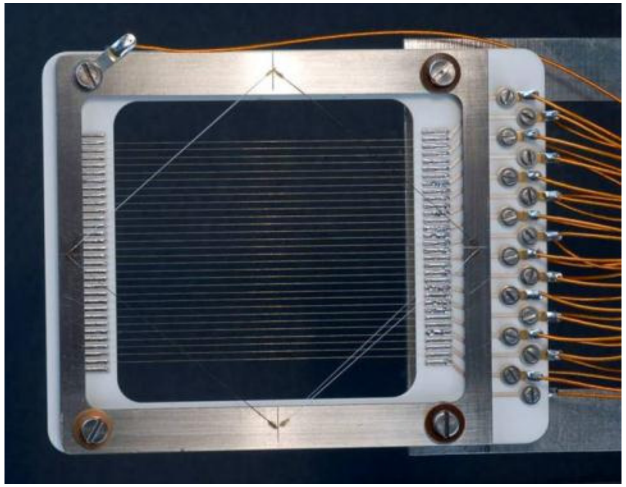
Overview

- Emittance Measurement:
  - Linear machine
    - Transverse profile (σ) and angular distribution at one location
      - Slit-grid device (1D) or Pepper pot (2D) (for E_{kin} < 100 MeV/u)
    - ‘Three grid’ method: transverse profile at different location and linear transformation
    - Quadrupole variation: transverse profile at one locations with different setting of quadrupole
  - Circular machine in a dispersion free region $\varepsilon = \frac{\sigma^2}{\beta}$
    - Accuracy ≈ 10% (because of uncertainties on optics parameters)

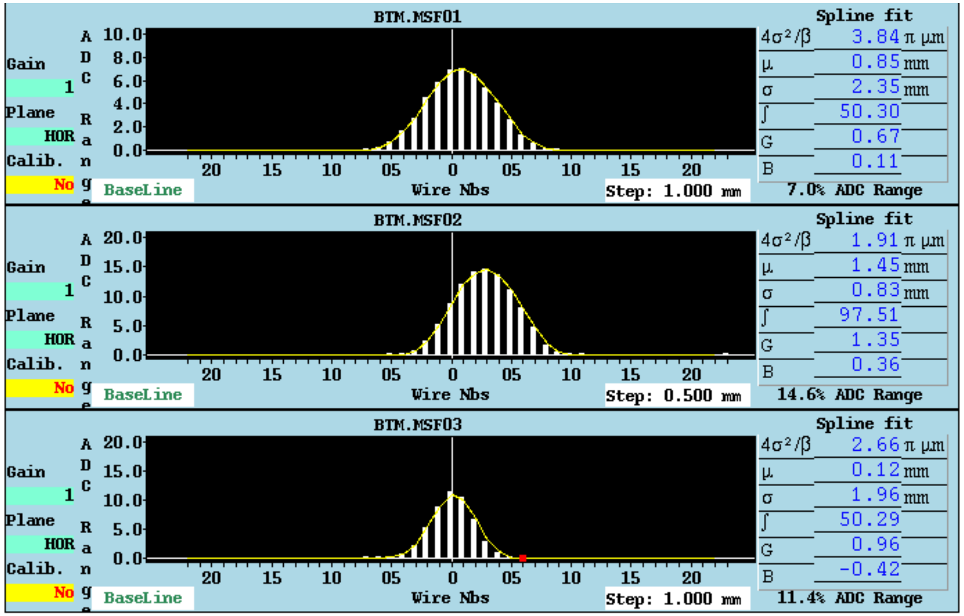
- Beam Profile measurement
  - Secondary emission grids and screens
  - Wire scanners
  - Synchrotron light monitors
  - Ionisation and luminescence monitors

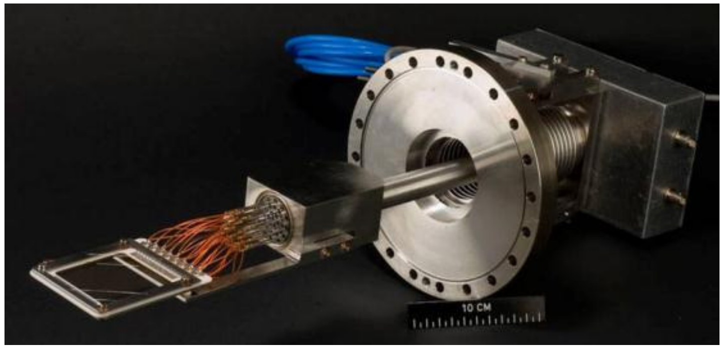
SEM grids and wire scanners:
Used as reference measurement for the other methods

Secondary Emission (SEM) Grids



- When the beam passes through, secondary electrons are emitted from a wire, proportional to beam intensity
- The current flowing back onto the wires is measured using one amplifier/ADC chain for each wire
- Very high sensitivity, semi-transparent
- Good absolute measurement
- Spatial resolution limited by wire spacing to <≈ 0.25mm
- Dynamic range: ≈ 10^6

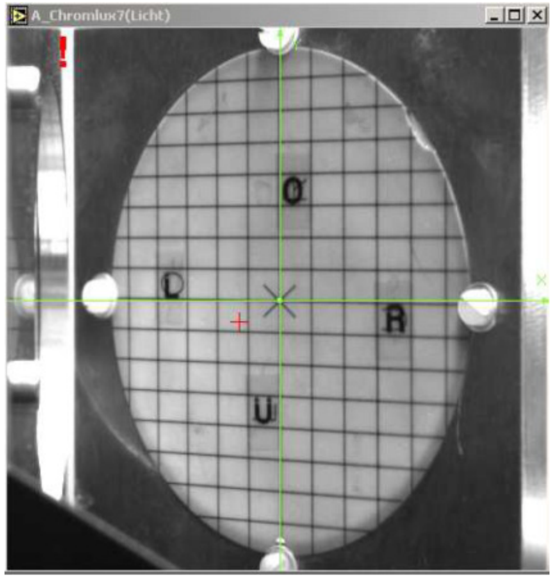




Scintillation Screens

- 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

  → see poster E. Guetlich



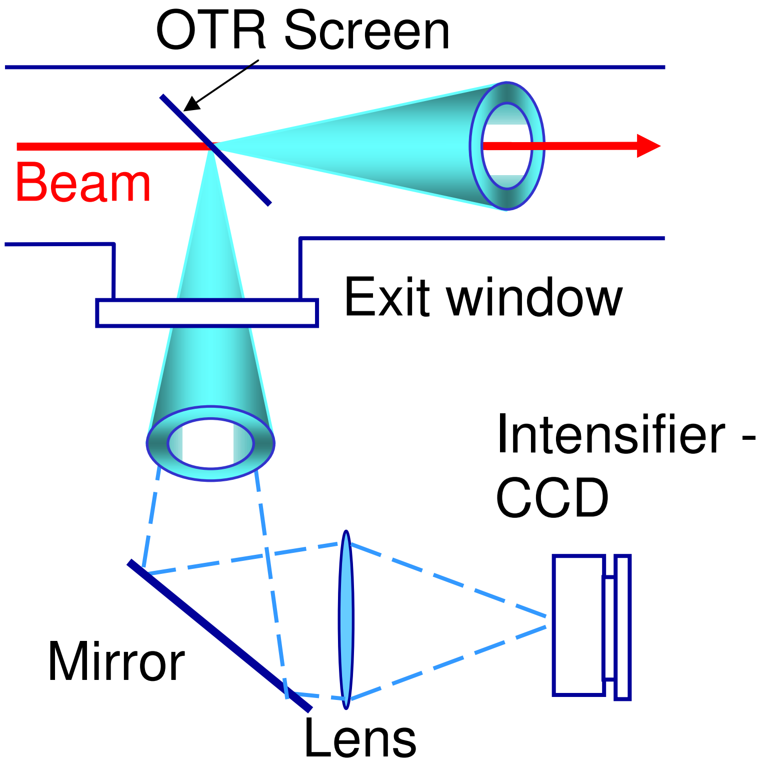
Abbreviation	Material	Activator	max. emission	decay time
Quartz	SiO_2	none	470 nm	< 10 ns
	CsI	Tl	550 nm	1 μs
Chromolux	Al_2O_3	Cr	700 nm	100 ms
YAG	$Y_3Al_5O_{12}$	Ce	550 nm	0.2 μs
	Li glass	Ce	400 nm	0.1 μs
P11	ZnS	Ag	450 nm	3 ms
P43	Gd_2O_2S	Tb	545 nm	1 ms
P46	$Y_3Al_5O_{12}$	Ce	530 nm	0.3 μs
P47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

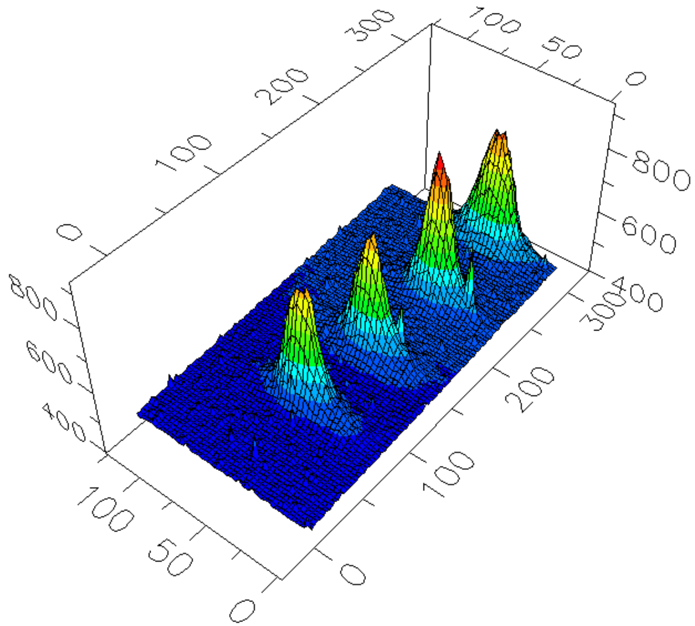
Approximate values for inorganic scintillators

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 (~10mm)
- much less intercepting, but requires higher intensity

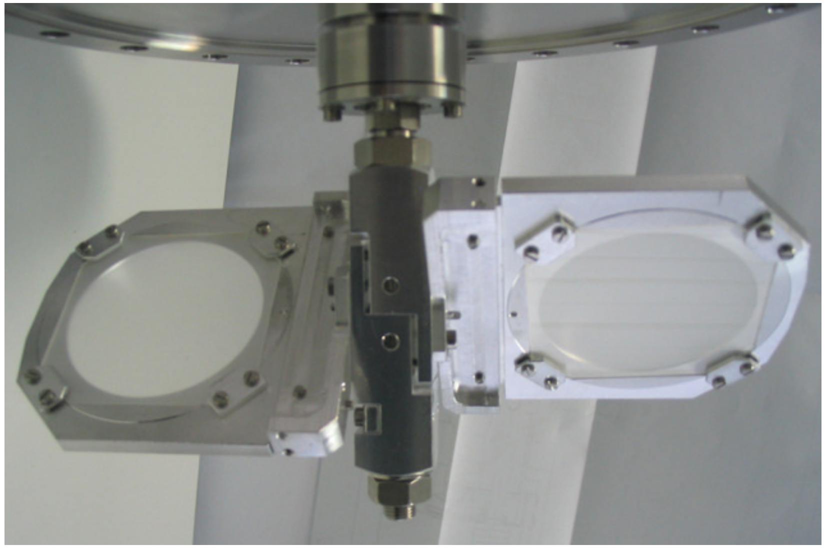




CERN SPS at injection

Beam Profile Monitoring Using Screens

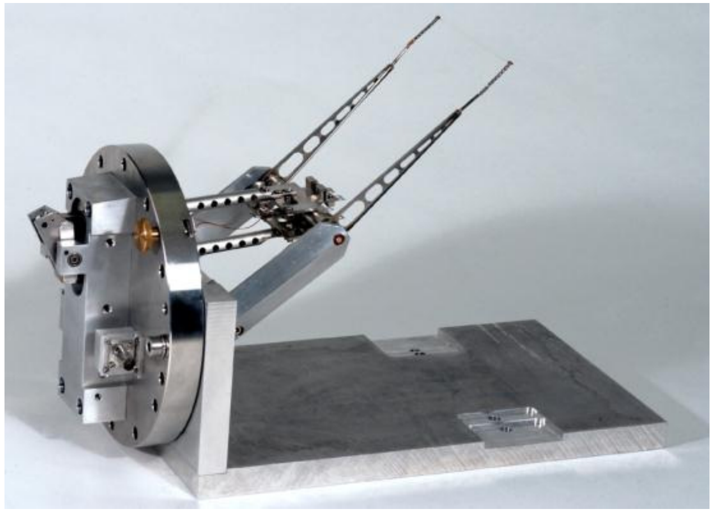
- Combine several screens in one housing e.g.
  - Al_2O_3 scintillation screen for setting-up with low intensity
  - Thin (≈10um) Ti OTR screen for high intensity measurements
  - Carbon OTR screen for very high intensity operation



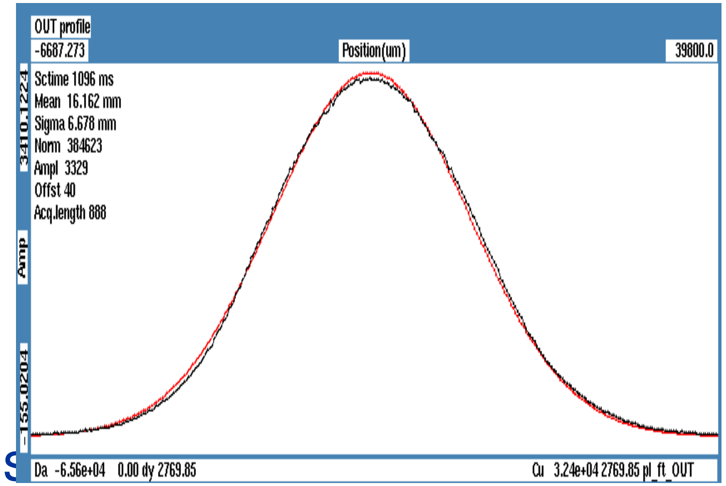
- Cameras:
  - CCD cameras are radiation sensitive
  - Analogue VIDICON camera can be used with high radiation

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)



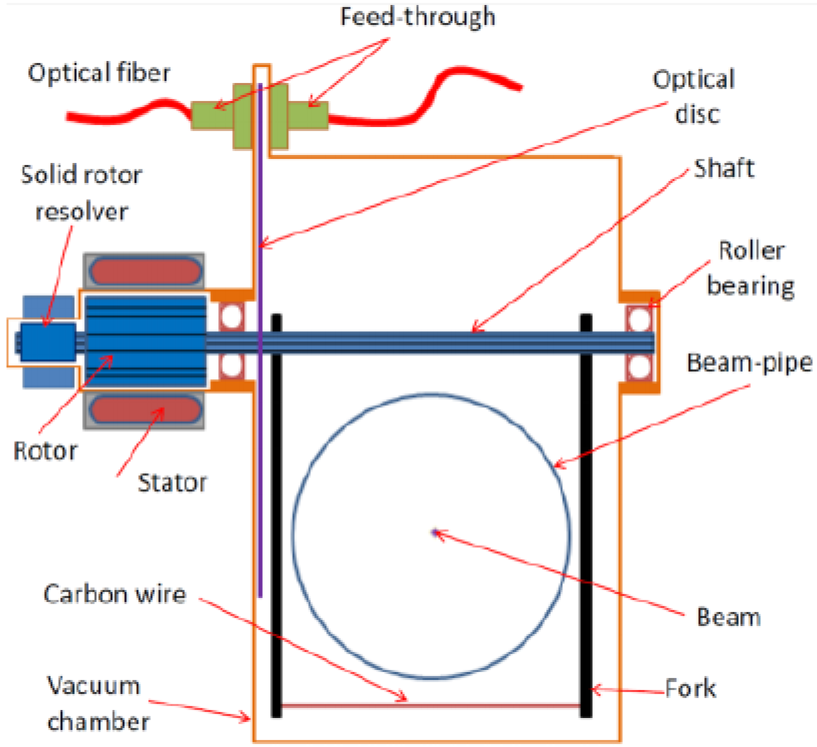
- Detection
  - Secondary particle shower detected outside the vacuum chamber e.g. using a scintillator/photo-multiplier assembly
  - Secondary emission current detected as for SEM grids



- 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

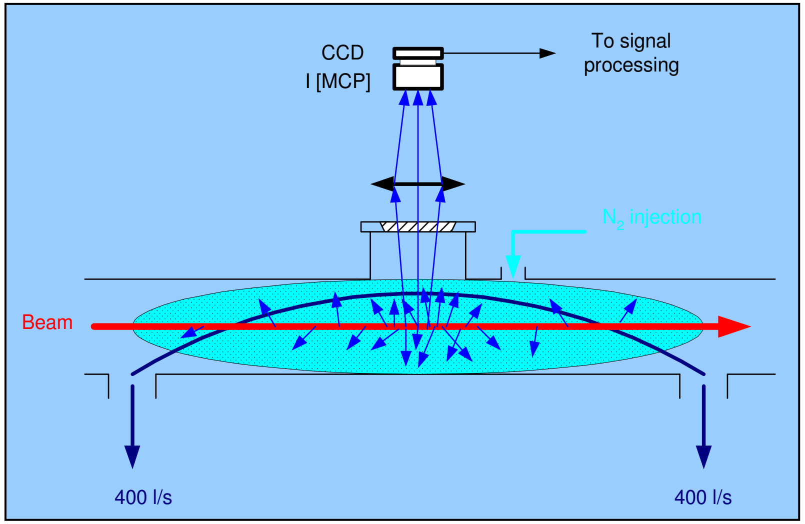


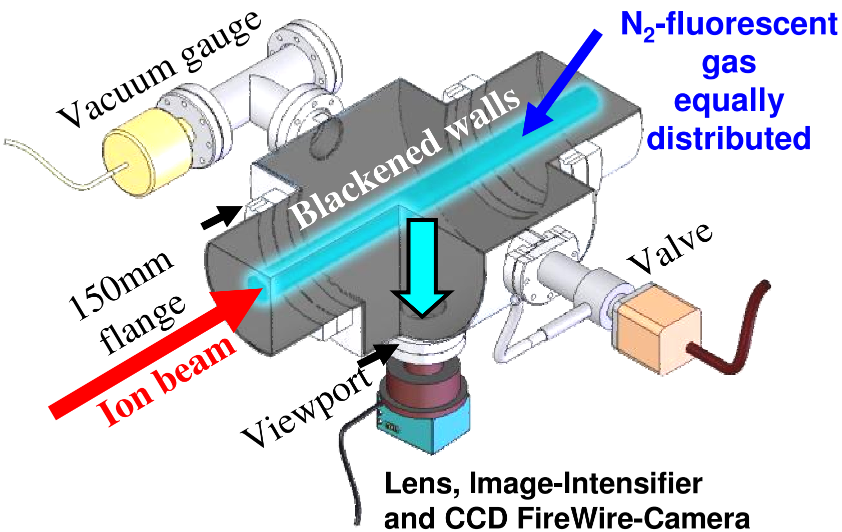
- Current Wire Scanners at CERN:
  - Dynamic range 100; accuracy 5-10%; spatial resolution 50 µm (linear type) and 200 µm (rotational)

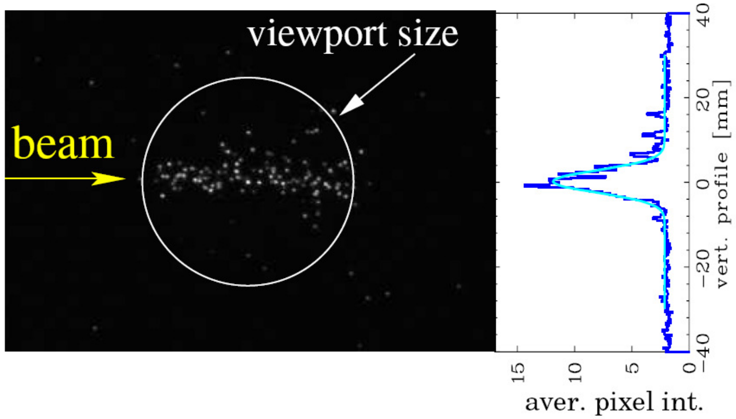
(Quasi) Non-Invasive Beam Size Measurement

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

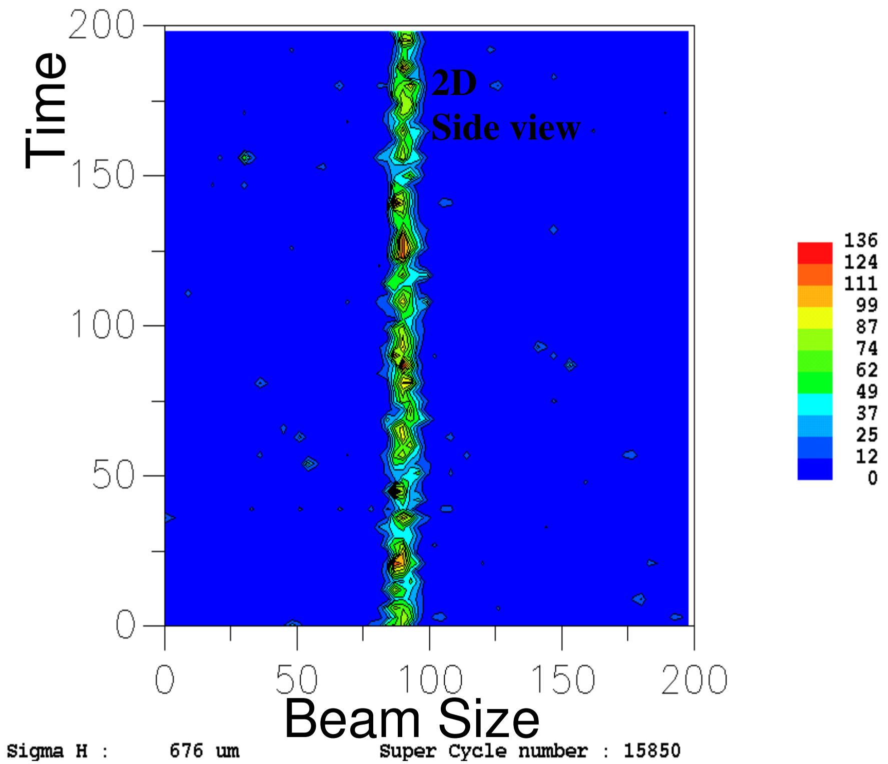


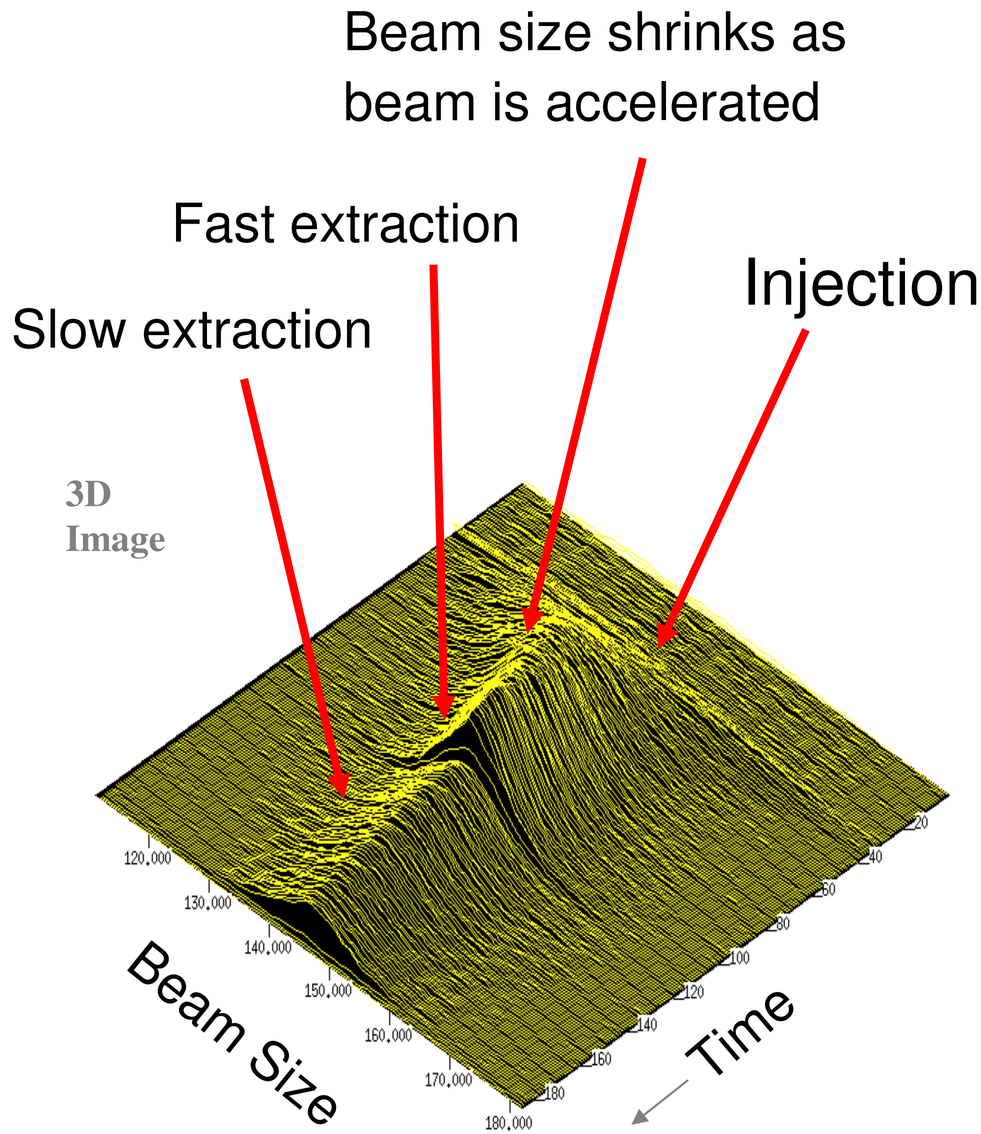




M.Schwickert, P.Forck, F.Becker, GSI

Luminescence Profile Monitor – Example CERN SPS



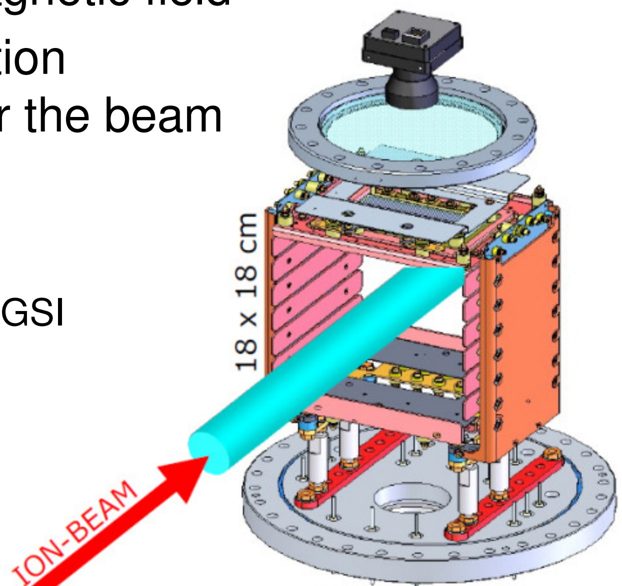


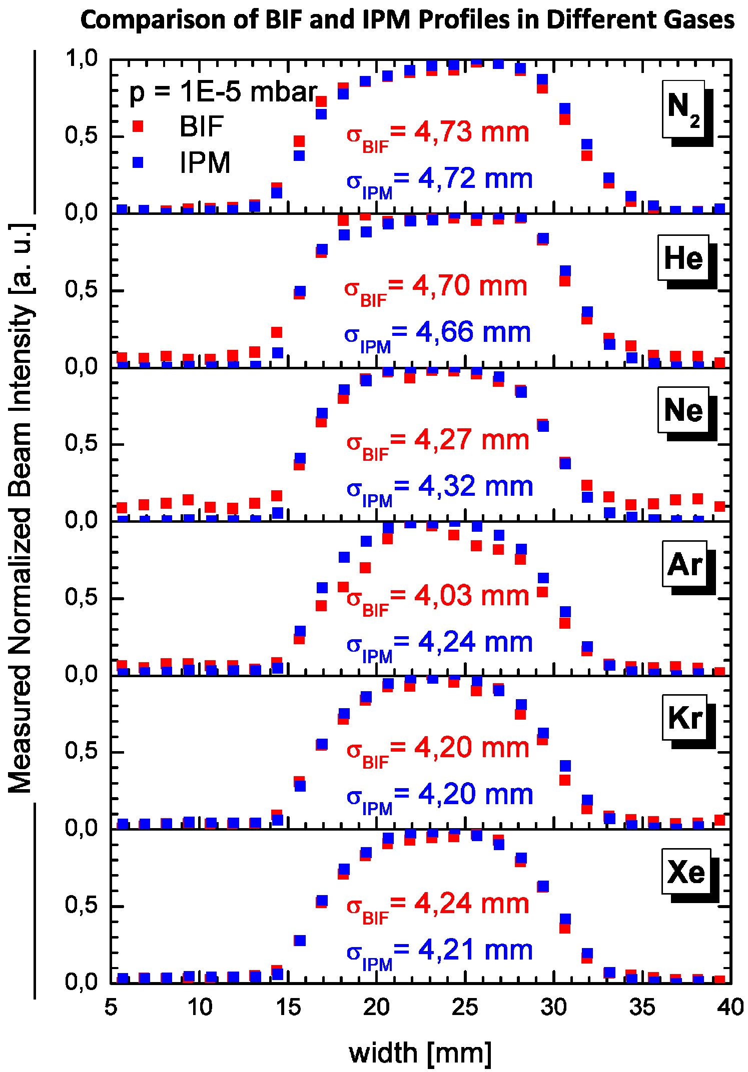
- Profile Collected every 20ms
- Local Pressure at ≈5×10^{-7} Torr

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



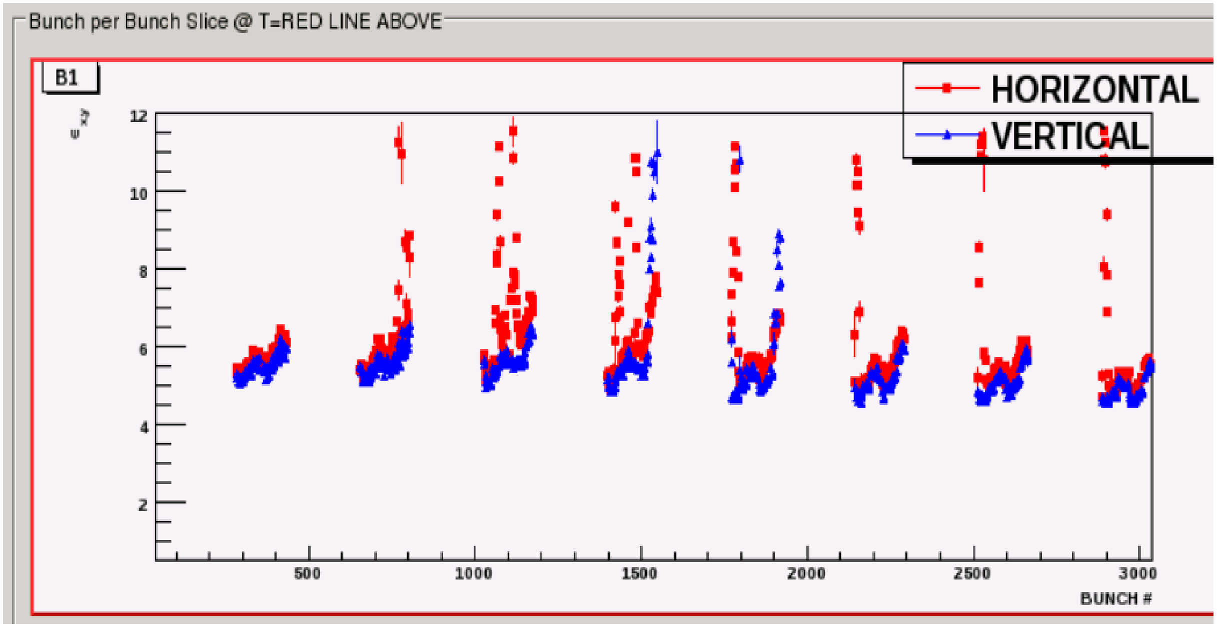


M.Schwickert, P.Forck, F.Becker, GSI

Synchrotron Light Monitor

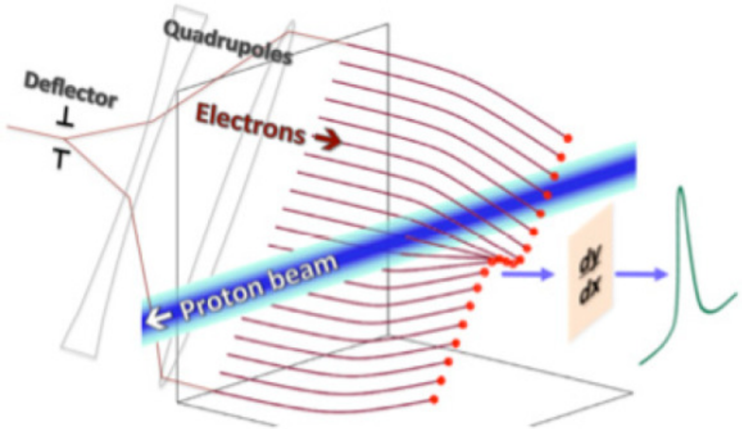
- Only for electrons & very high energy protons/ions (LHC)
- For linear machine: difficult to separate the light from the beam
- Difficult to get absolute calibration:
  Image correction factors typically bigger than the beam size
- Dynamic range 200 (10^5 by changing the attenuation)
- Accuracy 30%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

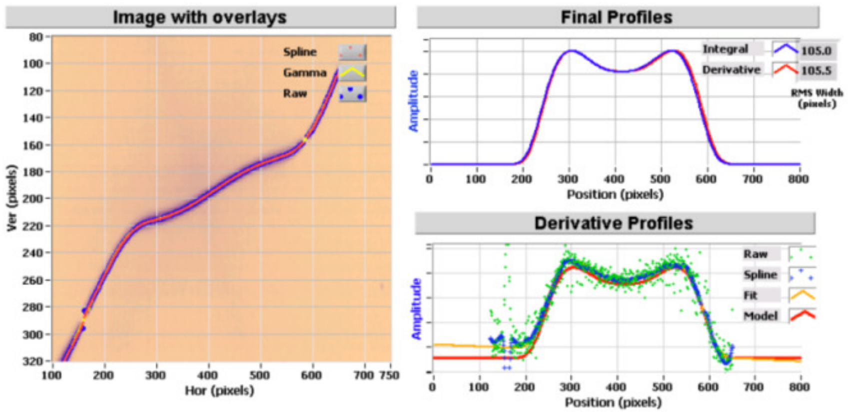
LHC: transverse blow-up of individual bunches

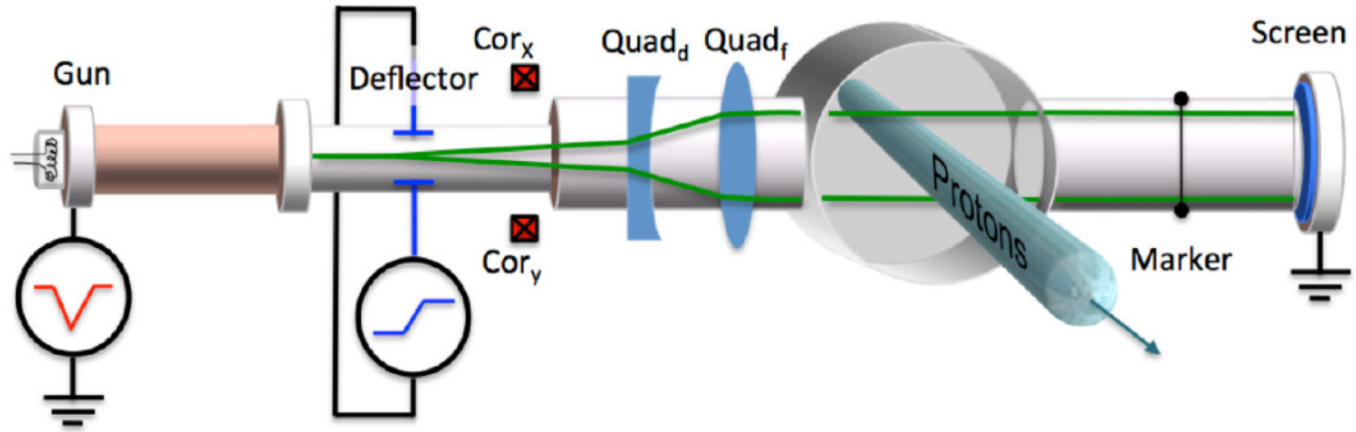


Electron Beam Scanner

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



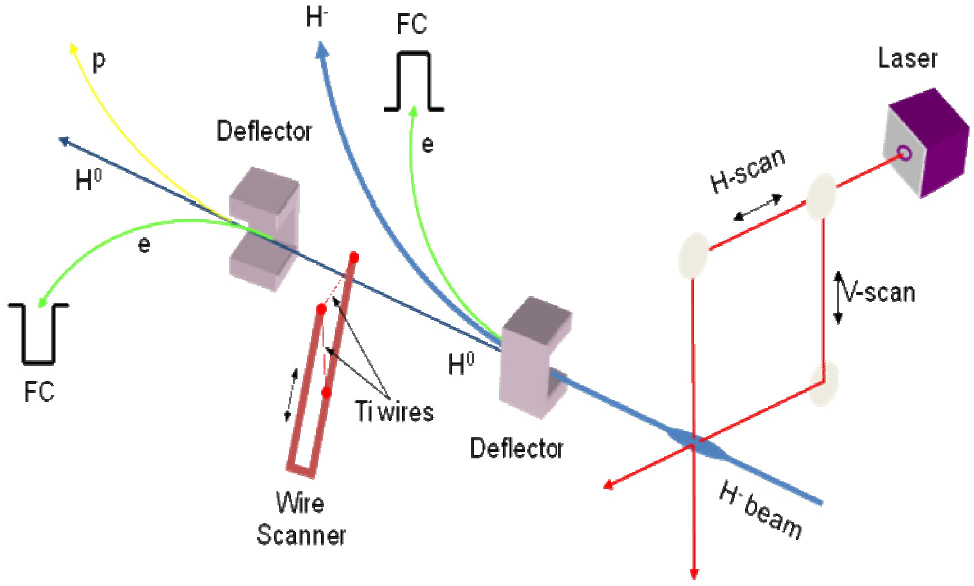




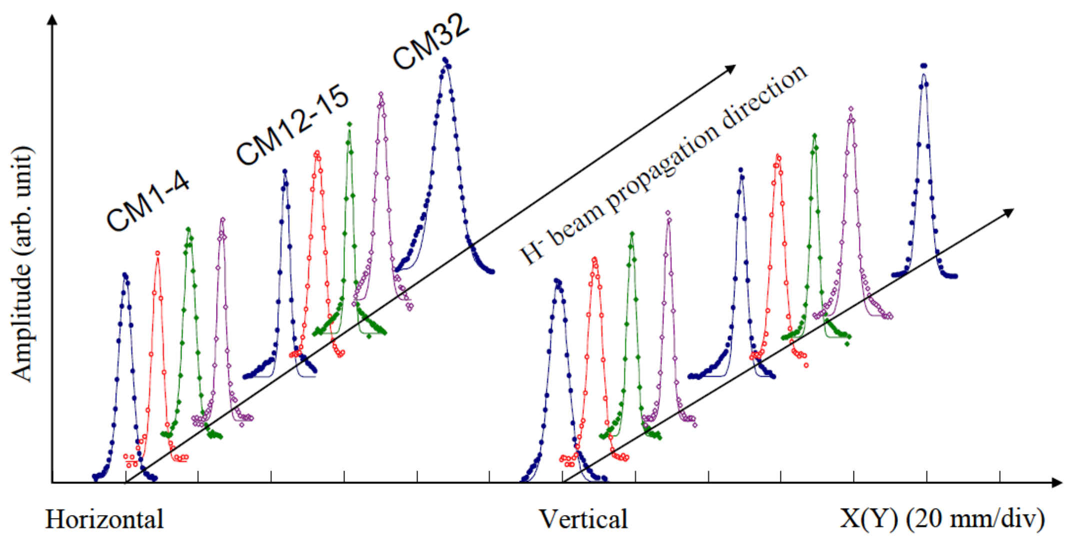
Laser wire scanner

- 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

→ see poster S. El Mousati



Courtesy of A. Alexandrov



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

Beam Loss Measurement

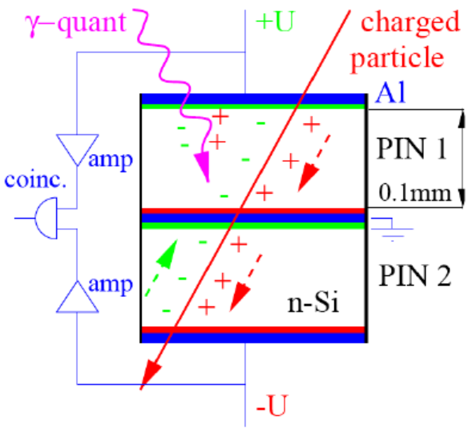
for Protection and Diagnostics

Common types of monitors

- 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 fibers
  - 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

Common types of monitors cont'd

- 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
  - Count rate proportional to beam loss
  - Speed limited by integration time
  - Dynamic range of up to 10^9
- Scintillators plus photo-multipliers
- etc. …



LHC BLM System

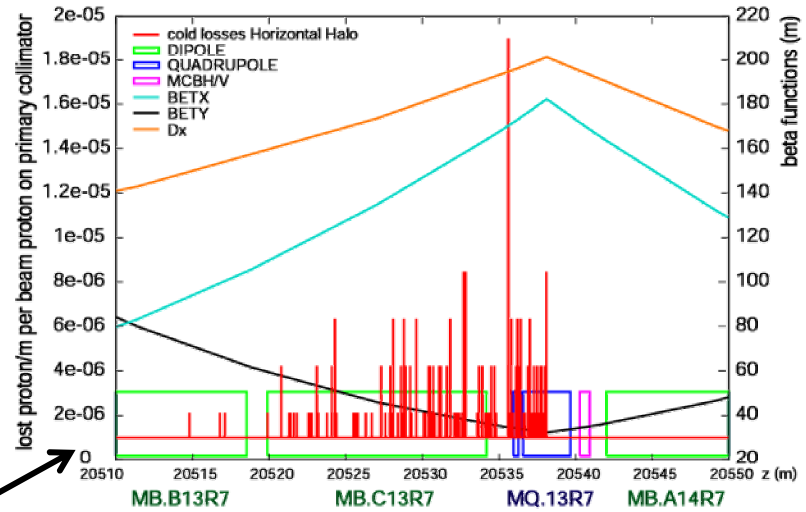
- Main purpose: **prevent damage and quench**
- 3600 Ionization chambers
- Beam abort thresholds:
  - 12 integration intervals: 40µs to 84s (32 energy levels)

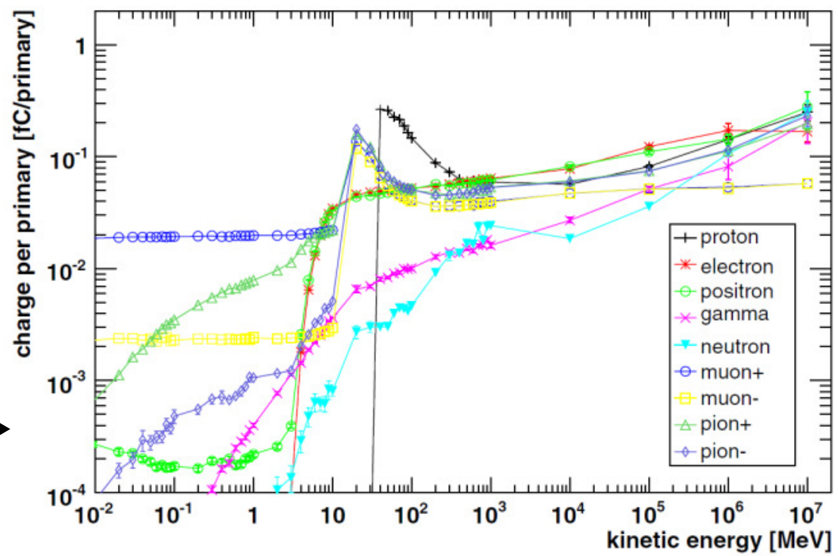
→ 1.5 Million threshold values

- 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

Threshold Determination

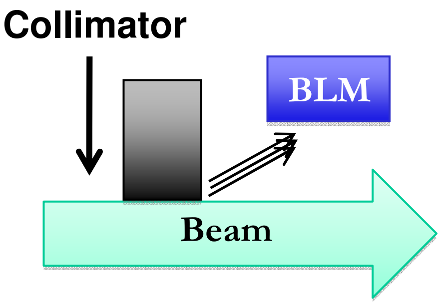
- Typically: Applied threshold set to 30% of the magnet quench level
- Relate the BLM signal to the:
  - Number of locally lost beam particles
  - Deposited energy in the machine
  - Quench and damage levels
- Extensive simulations during system design (and experimental verifications)
  - Proton loss locations (MAD-X, SIXTRACK)
  - Hadronic showers through magnets (GEANT, FLUKA)
  - Magnet quench levels as function of p energy and loss duration (SPQR)
  - Chamber response to the mixed radiation field (GEANT, FLUKA, GARFIELD)

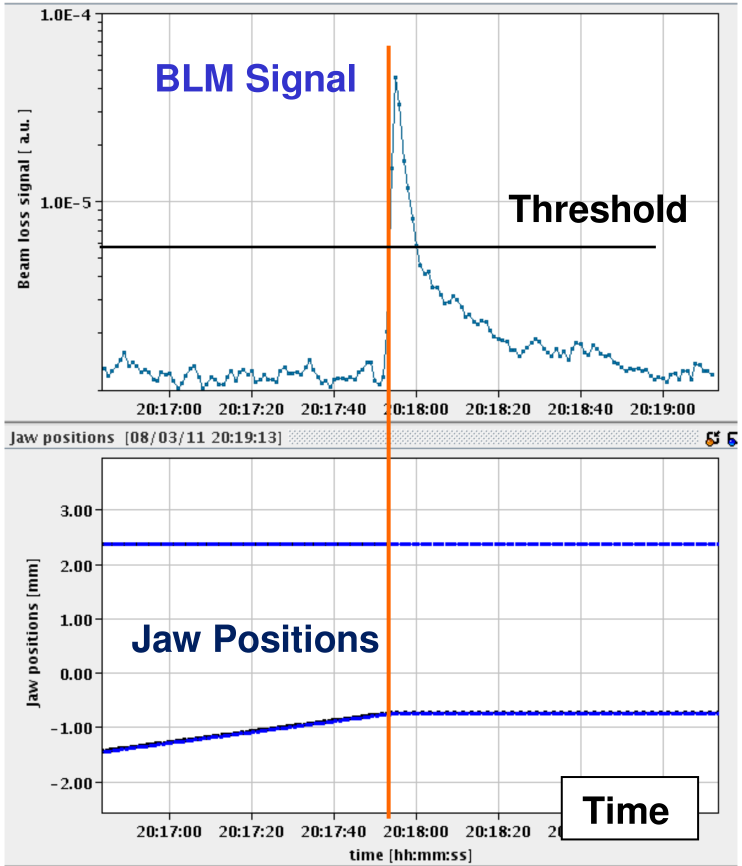


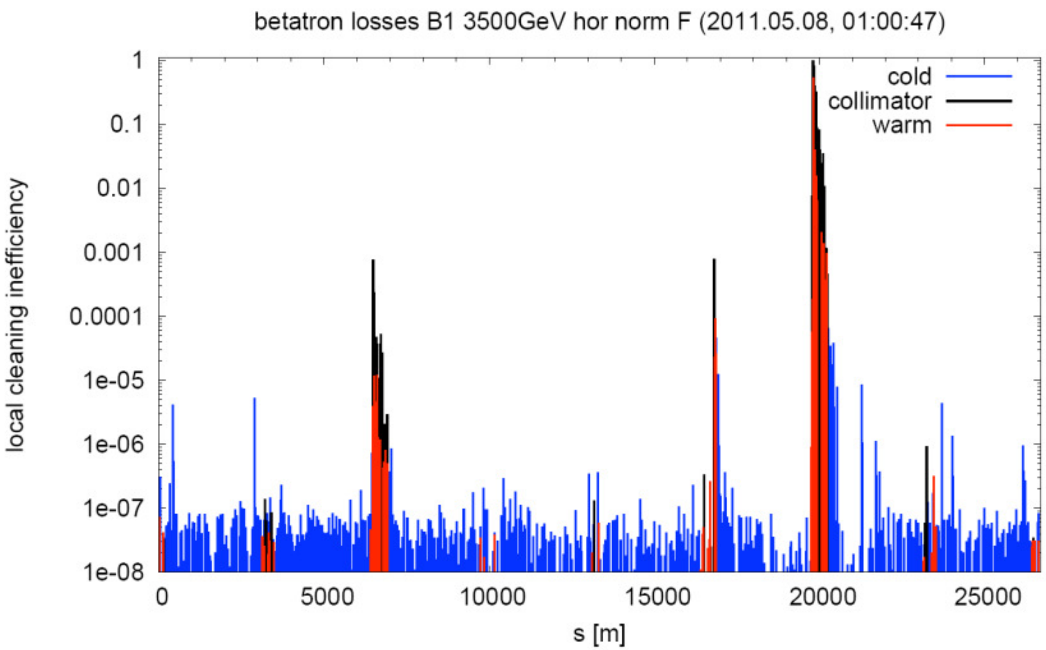


Set-up and validation of collimation performance

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



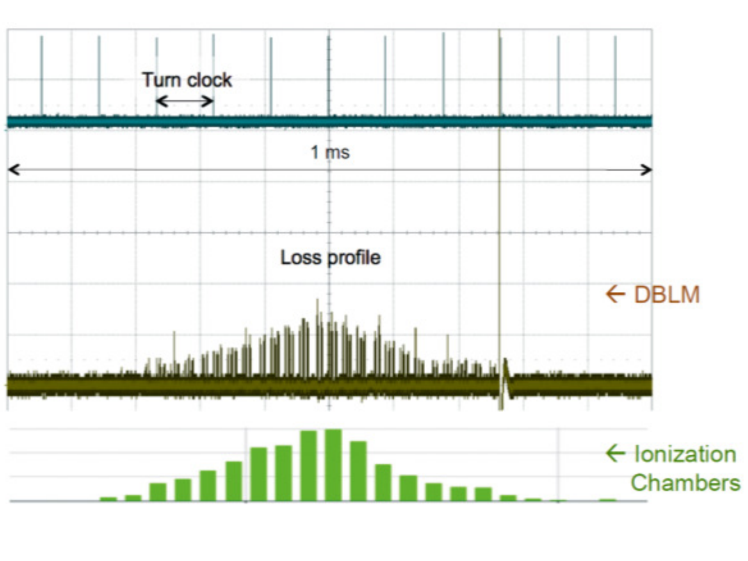


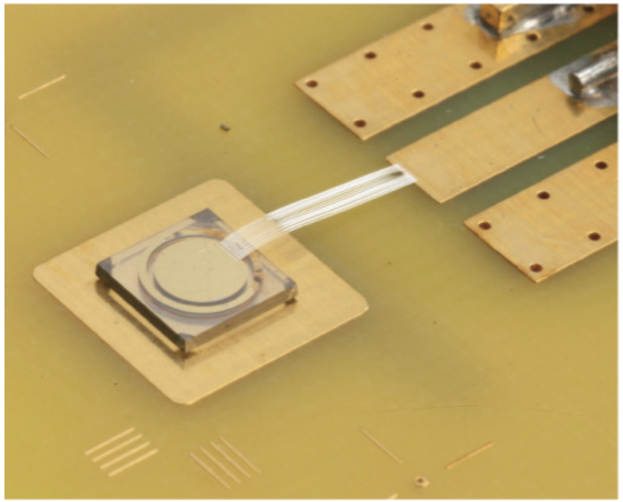


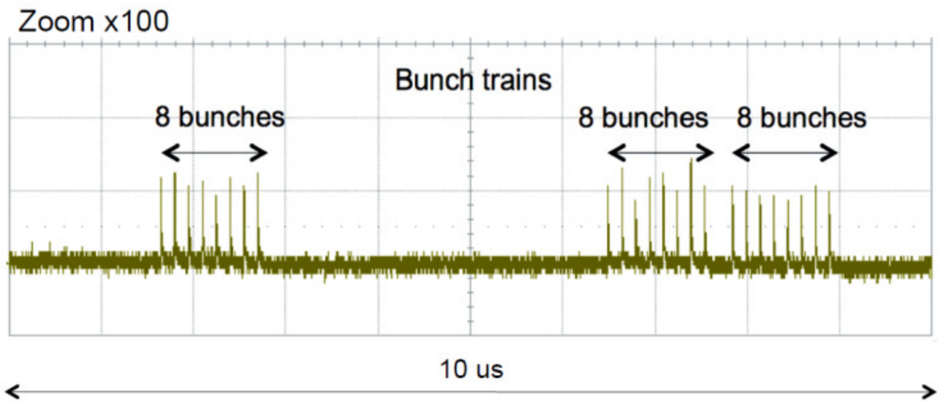
'loss map': losses along the ring normalized to the losses at the primary collimator: performance verification

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
- Investigations now ongoing to see if they can work in cryogenic conditions







Halo Measurements

Introduction

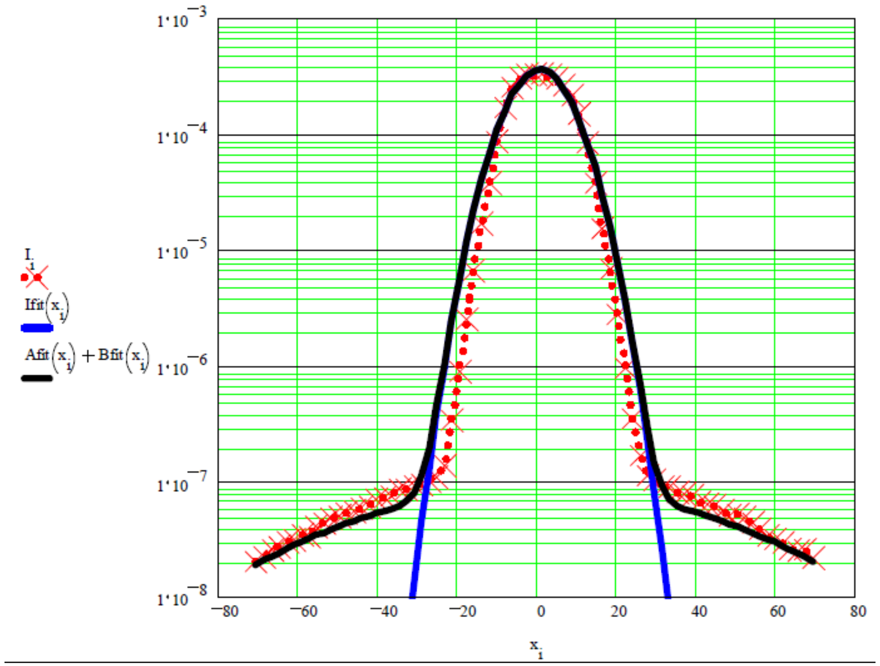
- **Beam tails (10^{-2}–10^{-3})** are just within range of standard profile measurements
- **Halo (< 10^{-4}):** need very high dynamic range >10^5
- Not one of the ‘common’ measurements
- For high intensity machines it is mandatory to limit beam losses → good understanding of the beam tail and halo very helpful
- Halo typically not well understood (simulation codes do not reproduce halo populations very well)
- Linear machines:
- Wire scanners shown to work well for halo measurements
- Often beam steered to minimize losses: steering on the beam halo rather than on the beam core
- Halo can re-populate along the machine after being scraped
- Synchrotron: collimator or scraper or wire close to the beam →
- Measure (precise relative measurement) and destroy the halo at the same time

Overview

- Counting techniques:
  - By increasing the measurement time, the dynamic range increases in proportion
- Transverse Halo Measurements
  - Wire scanners and scrapers $\rightarrow$ slow
  - Optical Methods $\rightarrow$ much faster
    - Light generated by synchrotron radiation or screens
    - Large dynamic range readout
      - CID (Charge Injection Device) cameras with RAI (random access integration) mode (automatically adjusted integration time for each pixel): dynamic range of up to 10^6
      - Micro Mirror Arrays
    - Blocking the core with coronagraph
- Longitudinal 'Halo' Measurements
  - Optical methods based on synchrotron light and counting
  - Scraping and loss measurements at momentum cleaning

Wire Scanner for Halo Measurement

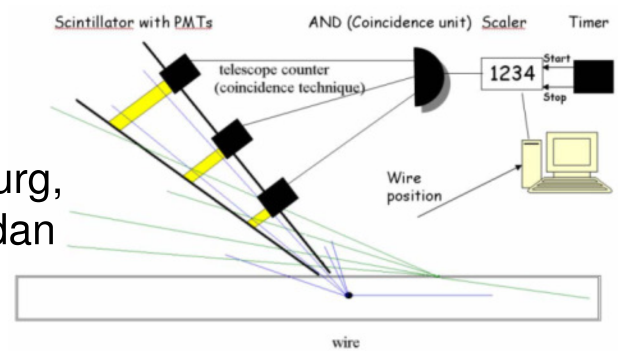
- Signal: SEM (secondary emission current) for low beam energy or by scintillator for high beam energy or 'vibrating wire' method (measured quantity: resonance frequency change due to wire heating – very precise for few interactions)
- Use of special techniques to improve S/N ratio and enhance the dynamic range
- Wire static in the halo for considerable time → suitable for linear machines and transfer lines
- A Browman et al. PAC 2003: measurement by SEM current readout at the extraction line of the Los Alamos Proton Storage Ring:
  - Each position averaging over several beam pulses
  - **dynamic range of 10^5**

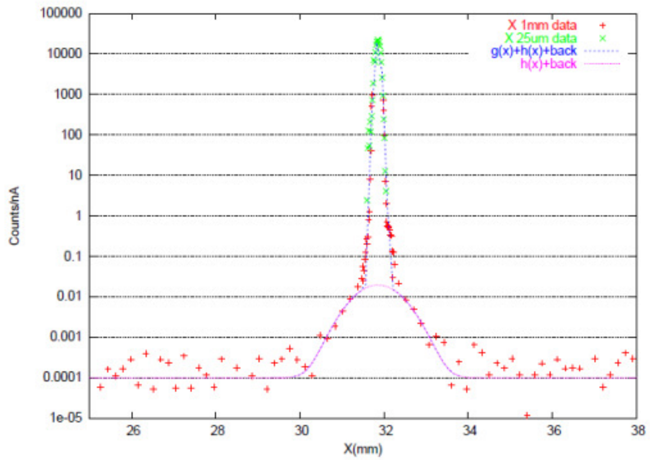


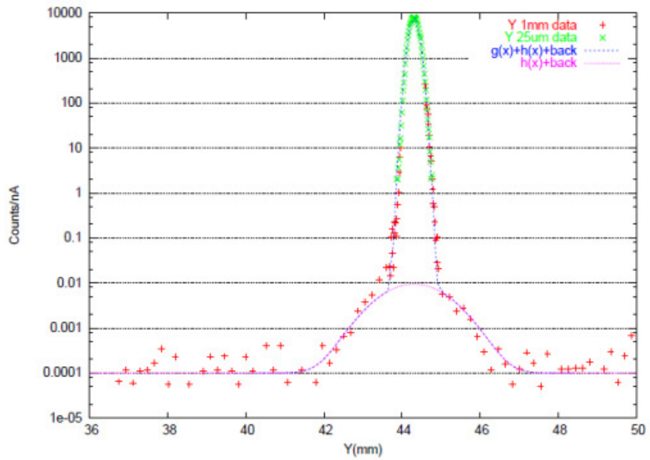
Wire Scanner cont.

- Counting with the wire at constant position in the halo can be combined with fast wire scan in the beam core
- Background reduction by coincidence method, for example with scintillator telescope

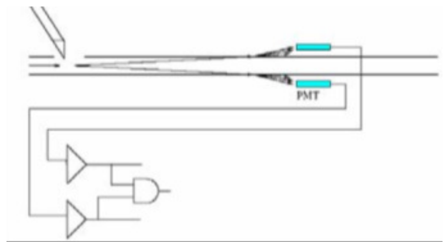
K. Wittenburg, CAS Dourdan





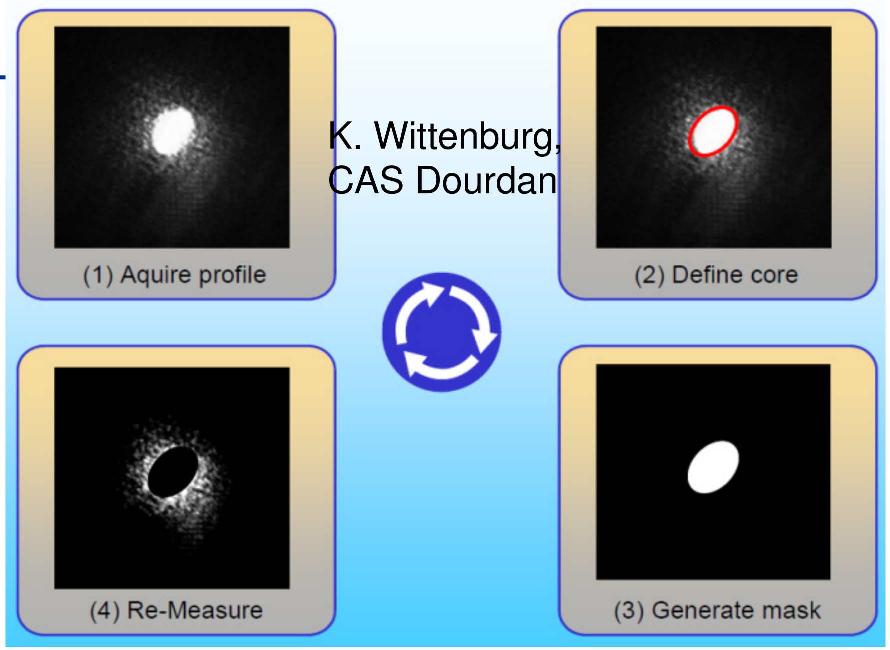


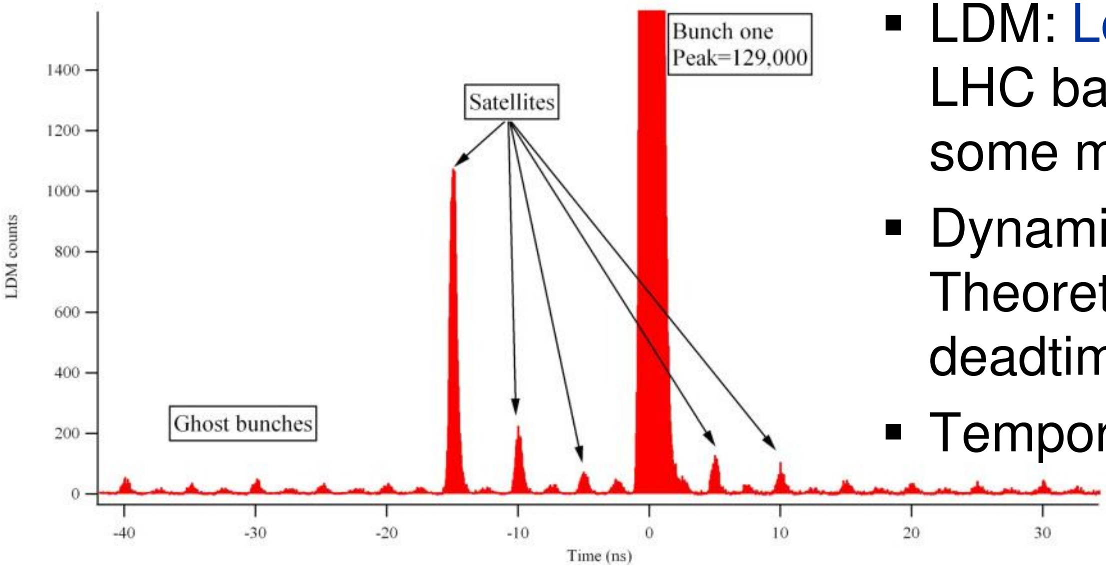
- A.P Freyberger, Jefferson Lab, PAC'03 DIPAC'05: coincident counting; combining multiple wires with different diameter (also using a plate) at target station:
- **huge dynamic range: 10^8**



More Examples

- Micro Mirror Arrays (adaptive masking method), HB2012 *Hao Dai Zhang et al.*





- LDM: Longitudinal density monitor at LHC base on synchrotron light; takes some minutes for the whole ring
- Dynamic range: At LHC at least 10^3. Theoretically 10^4- 10^5; but limited by deadtime and afterpulse
- Temporal resolution: 50ps

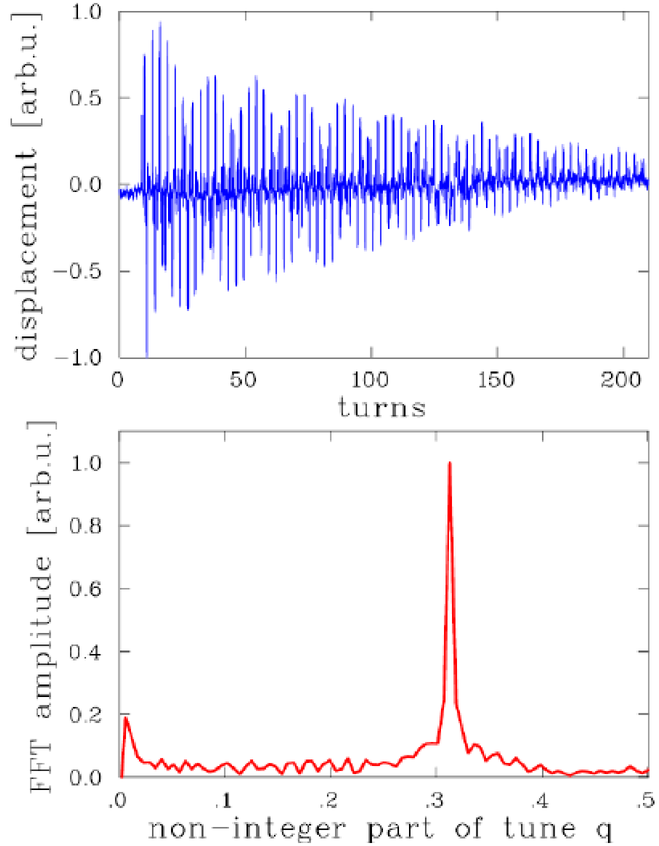
Further Reading on Halo Measurements

- Kay Wittenburg, *Beam Halo and Bunch Purity Monitoring,* CAS on beam Diagnostics, Dourdan, CERN-2009-005 (2009).
- 29th ICFA Advanced Beam Dynamics Workshop on Beam Halo Dynamics, Diagnostics, and Collimation, HALO'03, Montauk, Long Island, New York.
- Proceedings ICFA workshops: HB2004, Bensheim, Germany; HB2006, Tsukuba, Japan.

Tune and Chromaticity in a Circular Machine

Tune

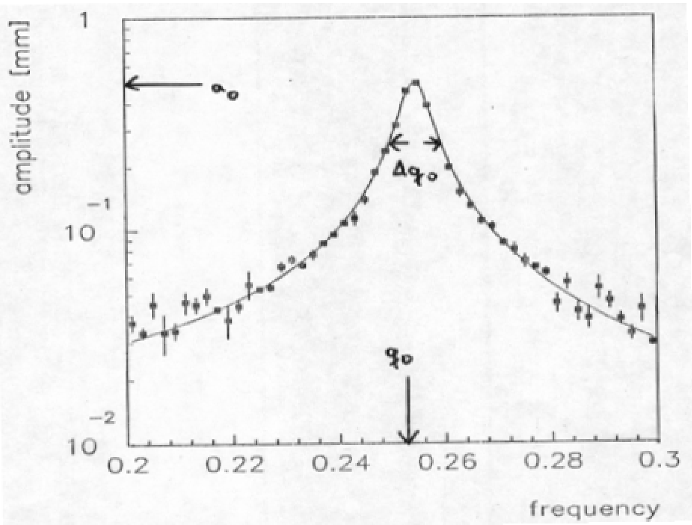
- The tune Q is the number of betatron oscillations per turn
- Measurement gives the non-integer part q; $Q = n \pm q$
  - Measure with slightly shifted tune to distinguish $q<0.5$ from $q>0.5$
- Caveat: Excitation of hadron beam leads to emittance blow-up

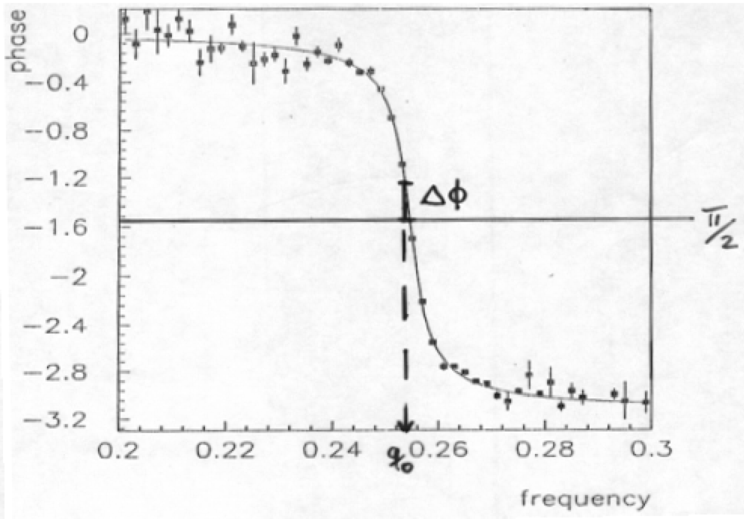


- Excite the beam with
  - Single kick (or white noise, or 'chirp')
- FFT analysis of position reading from one BPM
  - Betatron tune is the frequency with the highest amplitude response
  - In the presence of external excitation the method can even work without kick.
  - Example GSI synchrotron

Beam Transfer Function Measurement

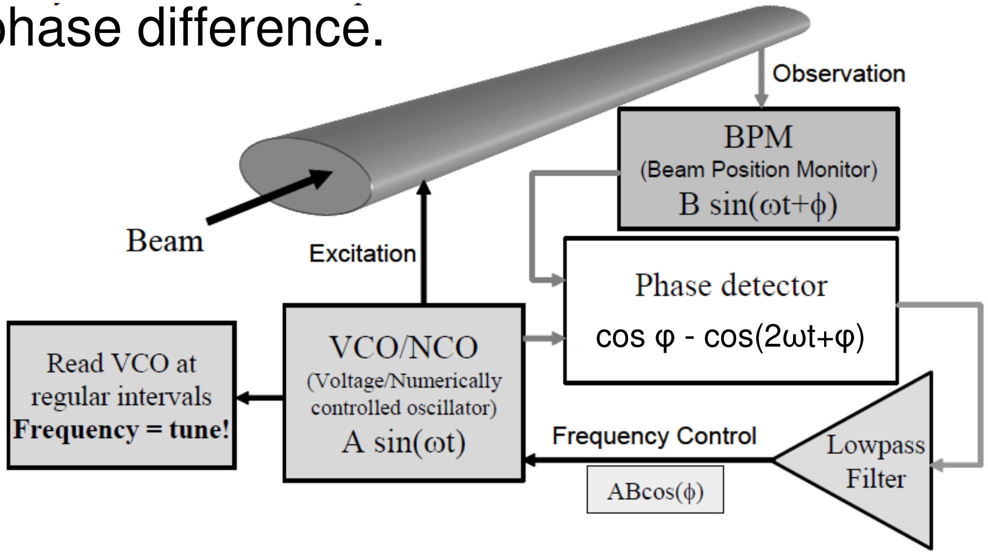
- Tune measurement with a network analyzer
  - Beam exited with sinusoidal wave; frequency is stepped over the expected tune range
  - Response of the beam (amplitude and frequency) is determined
- Beam acts like a harmonic oscillator
- Measurement of the phase response in general more precise than amplitude measurement
- High precision: up to 10^{-4} but slow (up to minutes)

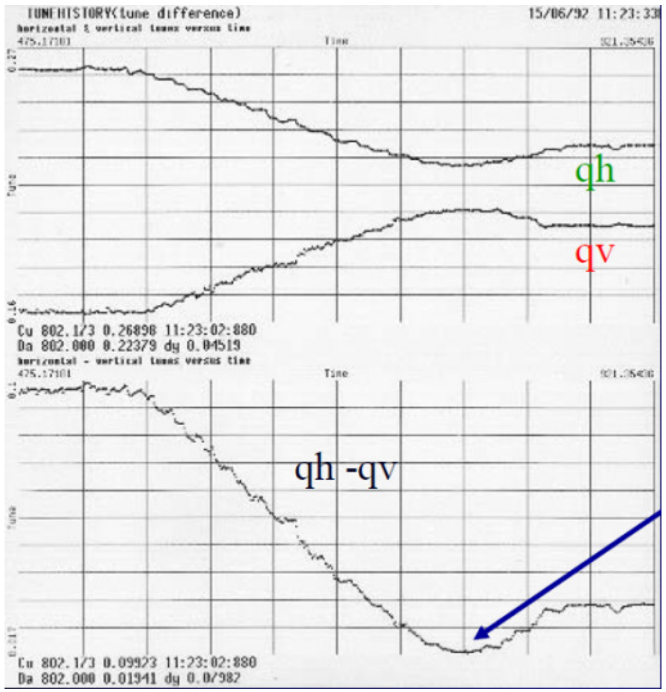




Phase Locked Loop Tune Tracking

- A voltage controlled oscillator (VCO) excites the beam with a sine wave, measures the beam response and locks the excitation frequency to the 90 degree phase difference.
  - Tracks any tune changes
  - Continuous reading



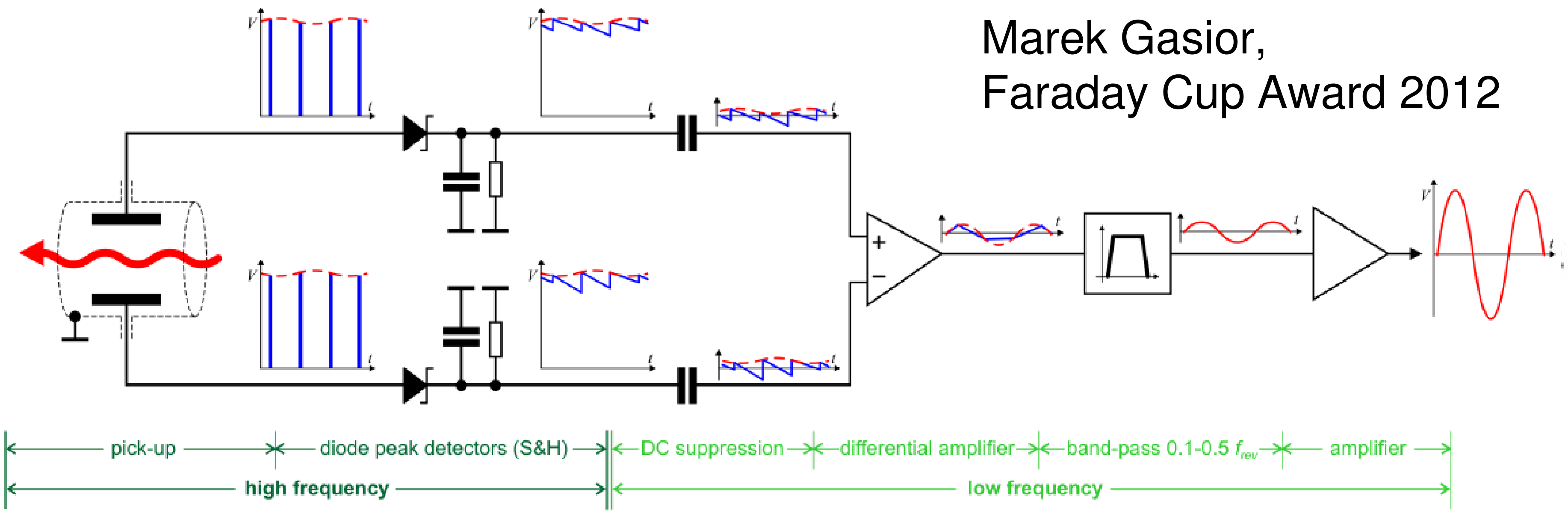


Example of continuous tune tracking while crossing horizontal and vertical tunes

Closest tune approach is a measure for coupling

High Sensitivity Tune Measurement by Direct Diode Det.

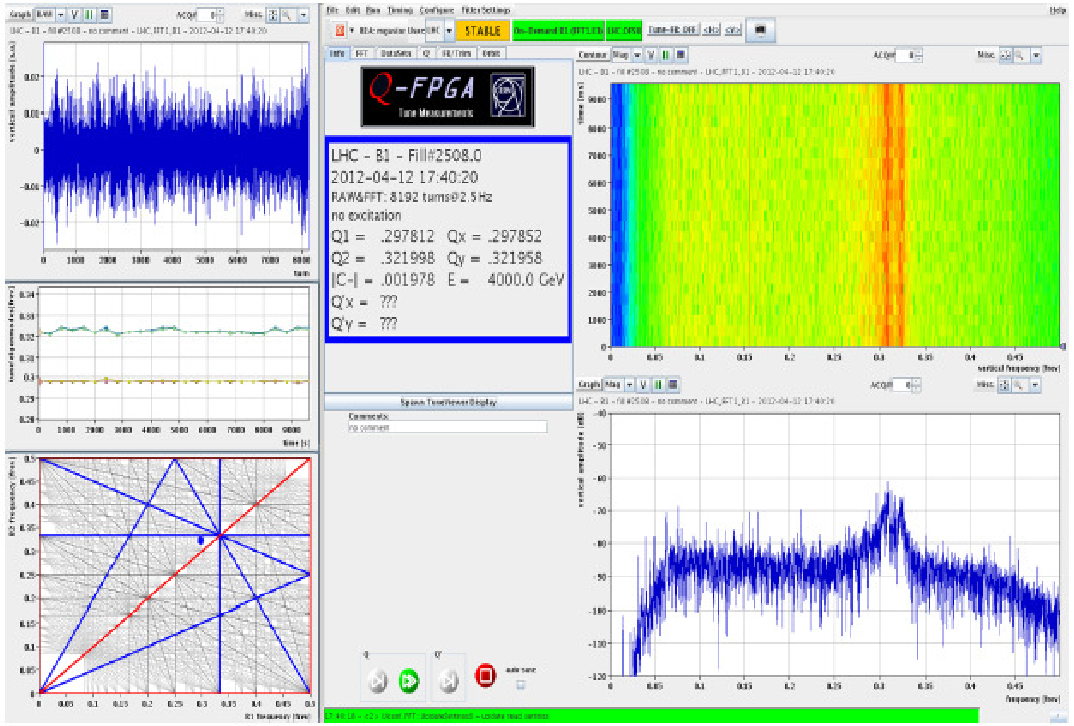
Marek Gasior,
Faraday Cup Award 2012

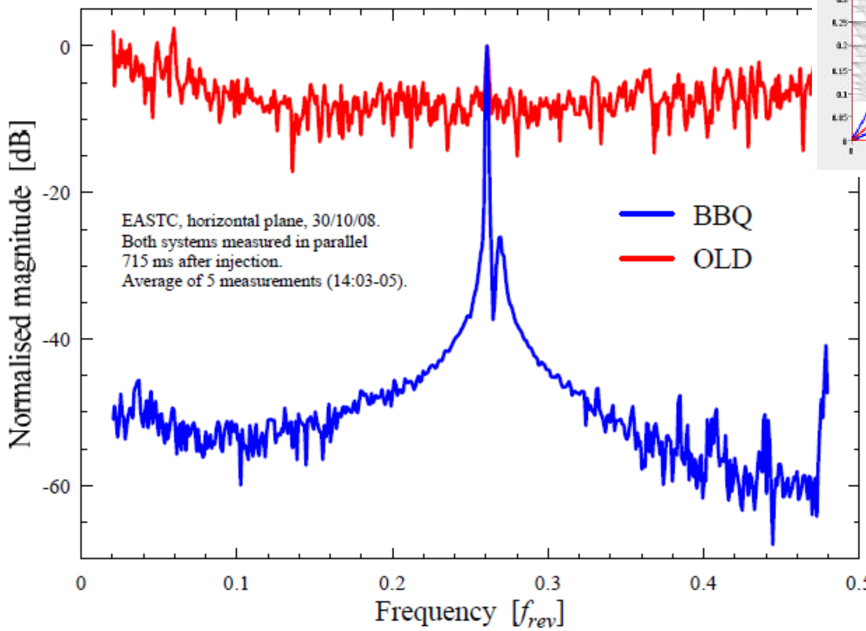


- Peak detection of position pick-up electrode signals (“collecting just the cream”)
- f_r content converted to the DC and removed by series capacitors
- beam modulation moved to a low frequency range (as after the diodes modulation is on much longer pulses)
- A GHz range before the diodes, after the diodes processing in the kHz range
- Works with any position pick-up
- Large sensitivity
- Impossible to saturate (large f_r suppression already at the detectors + large dynamic range)
- Low frequency operation after the diodes
  - High resolution ADCs available
  - Signal conditioning / processing is easy (powerful components for low frequencies)

Direct Diode Detection (BBQ - Base Band Tune) CERN

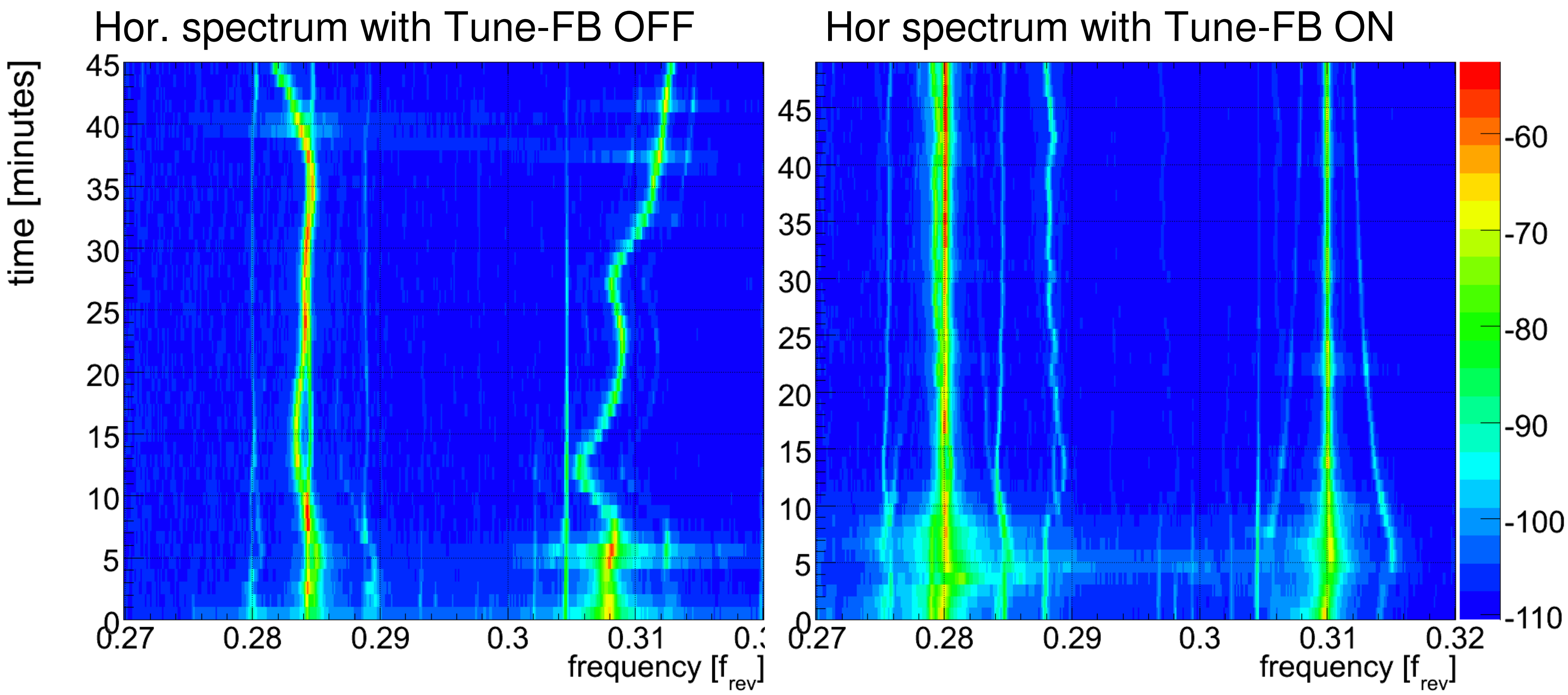
CERN LHC





CERN PS

Example LHC Tune Feed-back System



Chromaticity Measurement

- Chromaticity ξ, or $Q' = \xi Q$

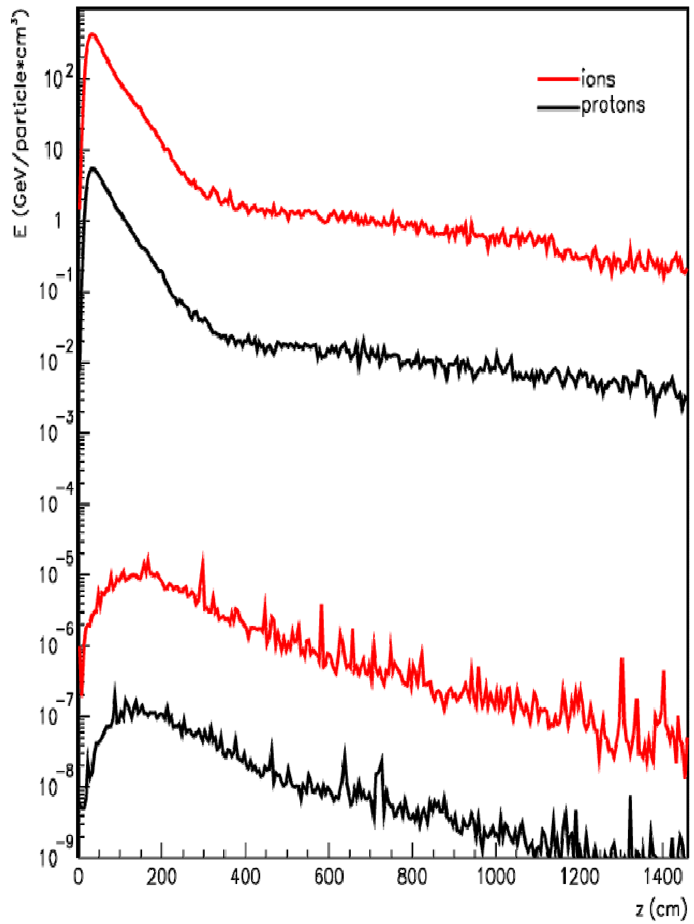
$$\Delta Q = Q' \frac{\Delta p}{p} \qquad\qquad \xi = \frac{\frac{\Delta Q}{Q}}{\frac{\Delta p}{p}}$$

- Measure tune for slightly different beam energies (by varying the RF frequency and keeping the magnetic filed constant) and calculate the gradient.
- Correct with sextupole magnets
- Chromaticity can be tracked continuously by combining RF modulation with PLL tune measurement

Thank you for your Attention

BLM for Ions II

- BFPP simulations for ALICE: loss positions (J. Jowett) and showers through dipole magnet (R. Bruce) → additional monitors
  - Main dipoles: ratio of energy deposited in magnet versus energy deposited in the BLM detector is roughly the same as for protons
    - Ratio of quench (damage) level to BLM signal about the same as for protons → Similar threshold tables for protons and ions
    - standard BLMs (local aperture limitations) at right position
  - Future simulations (other EM processes) might lead to more requests for BLMs



Energy position in the hottest part of the coil and at the BLM location (FLUKA, LHC Project Note 379, R. Bruce et al.)

per year	Requirement	Simulation	2010 (above 450 GeV)	2011 (beam with damage potential)
Damage risk	$< 10^{-3}$	5×10^{-4}	-	-
False dumps	< 20	10 – 17	**3** (7 – 14 per year of standard operation)	**3**

Example from GSI

passive transformer

For bunch observation
e.g. transfer between synchrotrons
a bandwidth of 2 kHz < ***f*** < 1 GHz
⇔ 1 ns < ***t*** < 200 μs is well suited.

Example GSI type:

Inner radius	$r_i = 70$ mm
Outer radius	$r_o = 90$ mm
Torus thickness	$l = 16$ mm
Torus material	Vitrovac 6025: $(\mathrm{CoFe})_{70\%}(\mathrm{MoSiB})_{30\%}$
Permeability	$\mu_r \simeq 10^5$ for $f < 100$ kHz, $\mu_r \propto 1/f$ above
Windings	10
Sensitivity	4 V/A at $R = 50\ \Omega$, 10^4 V/A with ampl.
Resolution	$40\ \mu A_{rms}$
$\tau_{droop} = L/R$	0.2 ms
$\tau_{rise} = \sqrt{L_S C_S}$	1 ns
Bandwidth	2 kHz to 300 MHz

active transformer

For observation of beam pulses > 10 μs e.g. at pulsed LINAC

Torus inner radius	**r_i=30 mm**
Torus outer radius	**r_o=45 mm**
Core thickness	**l=25 mm**
Core material	**Vitrovac 6025 $(\mathrm{CoFe})_{70\%}(\mathrm{MoSiB})_{30\%}$**
Core permeability	**u_r=10^5**
Number of windings	**2x10 crossed**
Max. sensitivity	**10^6 V/A**
Beam current range	**10 μA to 100 mA**
Bandwidth	**1 MHz**
Droop	**0.5 % for 5 ms**
rms resolution	**0.2 μA for full bw**

Example of Orbit Measurement

- Threading the first beam through the LHC
- One beam at a time, one hour per beam
- Collimators used to stop the beam after each sector
- Once the trajectory was corrected open the collimator for the next sector