# Beam Instrumentation & Diagnostics Part 1

## *CAS Introduction to Accelerator Physics*

## Santa Susanna, 1st of October 2024


**Peter Forck**

**Gesellschaft für Schwerionenforschung (GSI)**

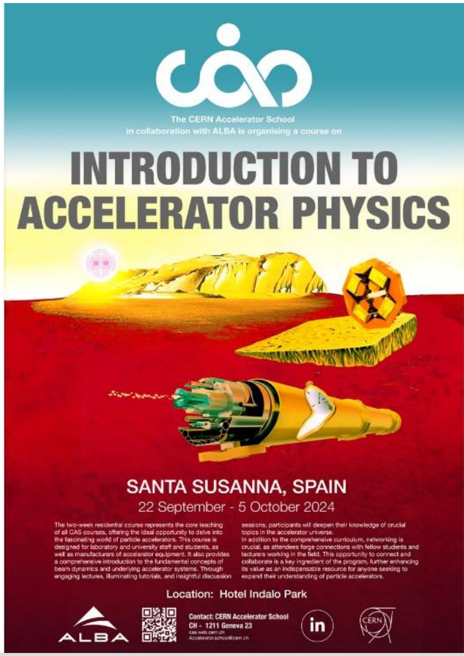
**p.forck@gsi.de**


**Beam Instrumentation:**

**Functionality of devices & basic applications**

**Beam Diagnostics:**

**Usage of devices for complex measurements**



# Demands on Beam Diagnostics

**Diagnostics is the 'sensory organs' for a real beam in a real environment.**

(Referring to lecture by Volker Ziemann about 'Detecting imperfections to enable corrections')

**Different demands lead to different installations:**

- **Quick, non-destructive measurements leading to a single number or simple plots**
  Used as a check for online information. Reliable technologies have to be used
  ***Example:*** **Current measurement by transformers**
- **Complex instruments for severe malfunctions, accelerator commissioning & development**
  The instrumentation might be destructive and complex
  ***Example:*** **Emittance determination, tune measurement**

**General usage of beam instrumentation:**

- Monitoring of beam parameters for operation, beam alignment & accel. development
- Instruments for automatic, active beam control
  ***Example:*** **Closed orbit feedback at synchrotrons using position measurement by BPMs**

# Demands on Beam Diagnostics

## Diagnostics is the 'sensory organs' for a real beam in a real environment.

(Referring to lecture by Volker Ziemann about 'Detecting imperfections to enable corrections')

**Non-invasive ( = 'non-intercepting' or 'non-destructive') methods are preferred:**

- The beam is not influenced $\Rightarrow$ the **same** beam can be measured at several locations
- The instrument is not destroyed due to high beam power

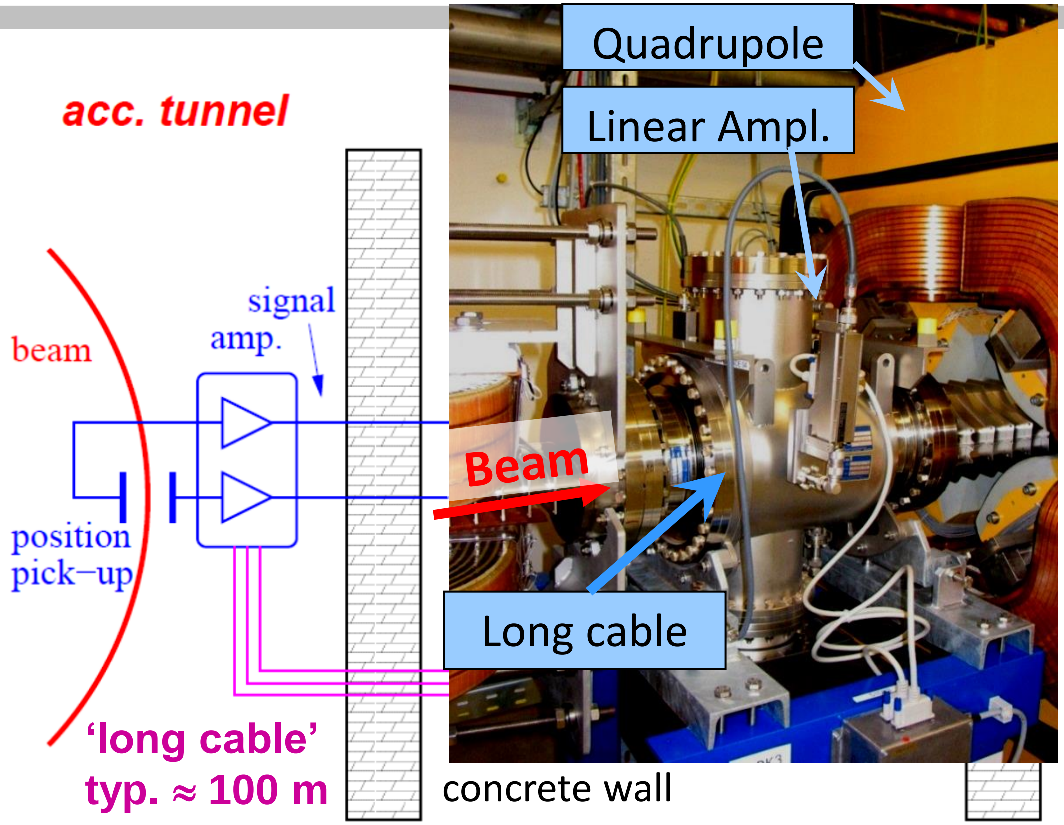
**Instruments could be different for:**

- Transfer lines with single passage $\leftrightarrow$ synchrotrons with multi-passages
- Electrons are mostly relativistic $\leftrightarrow$ protons are at the beginning non-relativistic

**Remark:**

Most instrumentation is installed outside of rf-cavities to prevent for signal disturbance

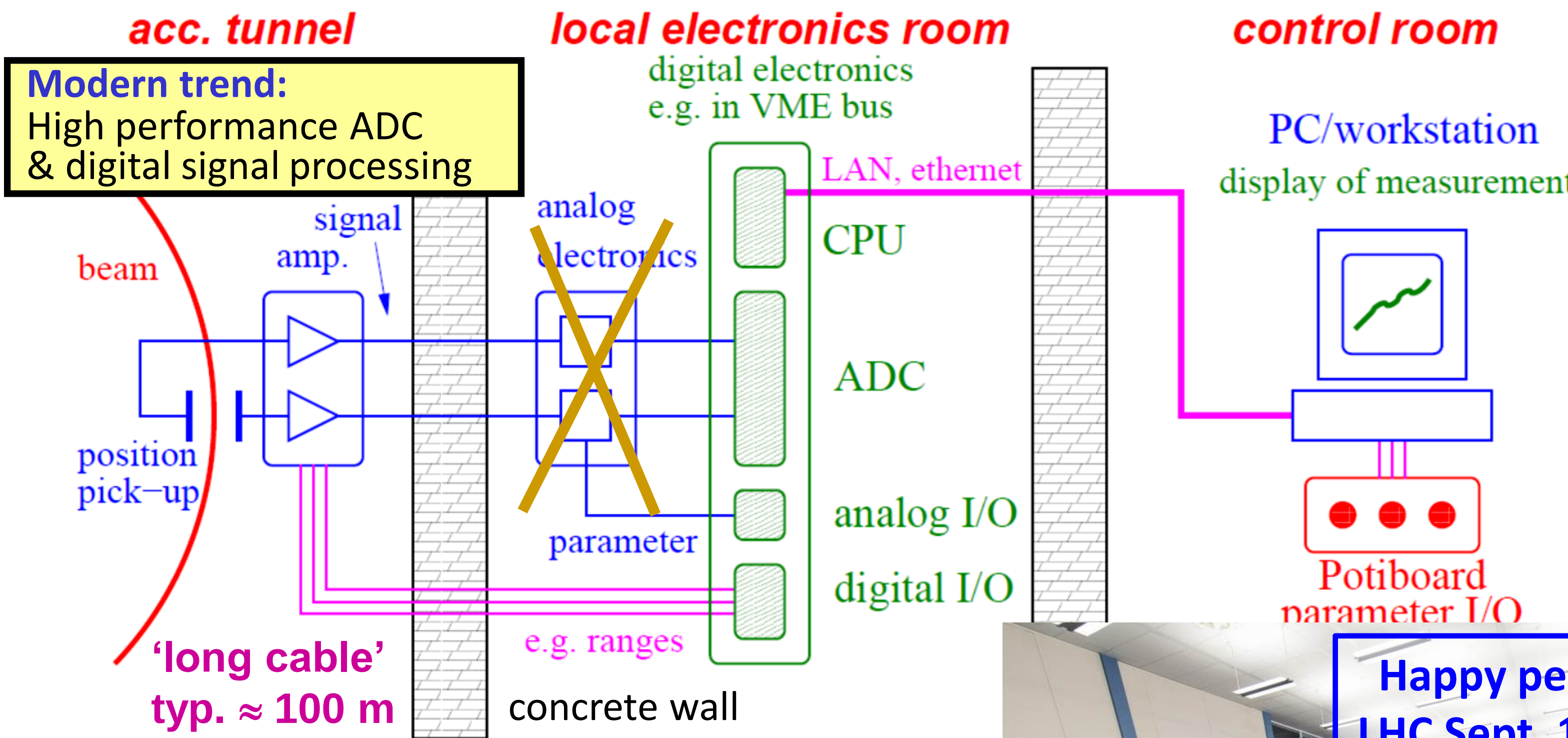
# Typical Installation of a Beam Instrument




**Accelerator tunnel:** → action of the beam to the detector
→ low noise pre-amplifier and first signal shaping

**Local electronics room:** → analog treatment, partly combining other parameters
→ digitalization, data bus systems (GPIB, VME, cPCI, µTCA...)

# Typical Installation of a Beam Instrument

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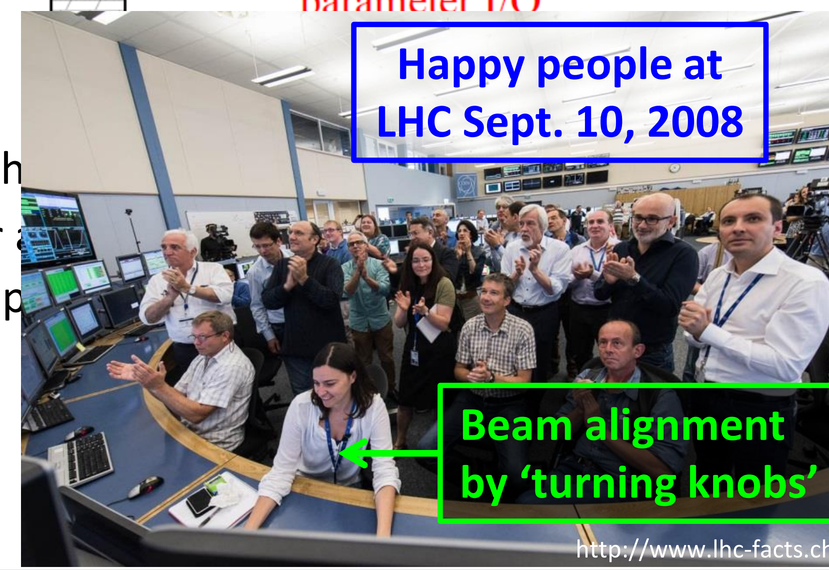
**Local electronics room:** { → analog treatment, p
→ digitalization, data

**Control room:** { → visualization and storage
→ parameter setting



# Outline of the Lectures

**The ordering of the subjects is oriented by the beam quantities:**

**Part 1 of the lecture on electro-magnetic monitors:**

- Current measurement
- Beam position monitors for bunched beams

**Part 2 of the lecture on transverse and longitudinal diagnostics:**

- Profile measurement
- Transverse emittance measure
- Measurement of longitudinal parameters

## The beam current and its time structure the basic quantity of the beam:

- It this the first check of the accelerator functionality
- It has to be determined in an absolute manner
- Important for transmission measurement and to prevent for beam losses.

## Different devices are used:

- **Transformers:** Measurement of the beam's **magnetic field**

  Non-destructive

  No dependence on beam type and energy

  They have lower detection threshold.
- **Faraday cups:** Measurement of the beam's **electrical charges**

# Magnetic Field of the Beam and the ideal Transformer

- Beam current of $N_{part}$ charges with velocity $\beta$

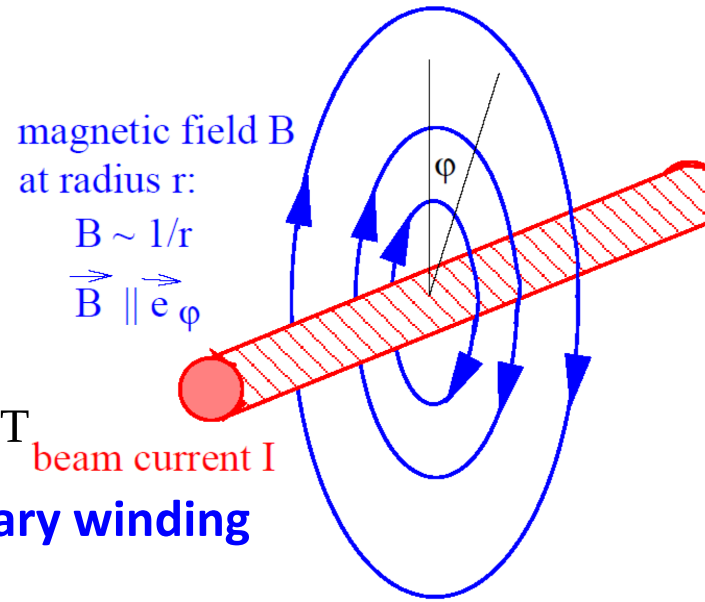
$$I_{beam} = qe \cdot \frac{N_{part}}{t} = qe \cdot \beta c \cdot \frac{N_{part}}{l}$$

- cylindrical symmetry

→ only azimuthal component

$$\vec{B} = \mu_0 \frac{I_{beam}}{2\pi r} \cdot \vec{e}_\varphi$$

Example: $I$ =1µA, $r$ =10cm ⇒ $B_{beam}$= 2pT, earth $B_{earth}$= 50µT




**Idea: Beam as primary winding and sense by secondary winding**

⇒ Loaded current transformer

$$I_1/I_2 = N_2/N_1 \Rightarrow I_{sec} = 1/N \cdot I_{beam}$$

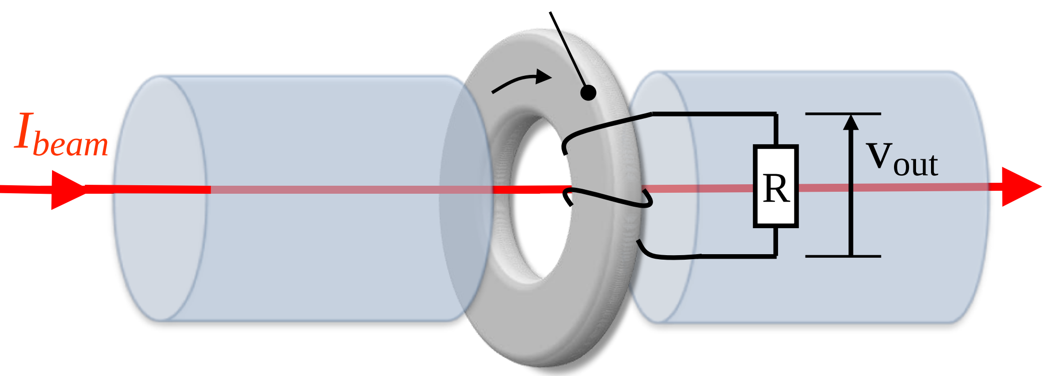
Inductance of a torus of $\mu_r$

$$L = \frac{\mu_0 \mu_r}{2\pi} \cdot l N^2 \cdot \ln \frac{r_{out}}{r_{in}}$$

- Goal of torus: Large inductance $L$ ***and*** guiding of field lines.

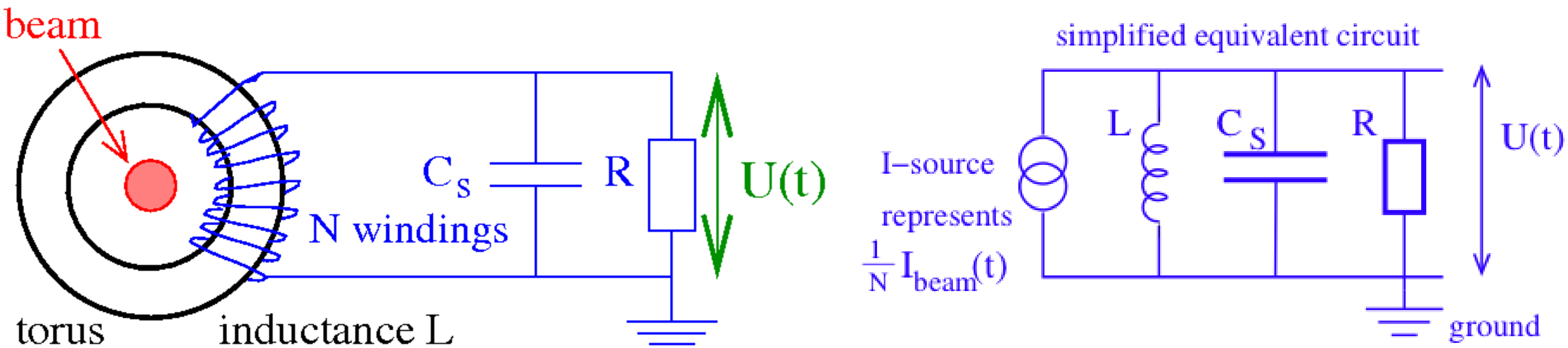
Definition: $U = L \cdot dI/dt$

Torus to guide the magnetic field



# Fast Current Transformer FCT (also called Passive Transformer)

## Simplified electrical circuit of a passively loaded transformer:





Equivalent circuit for analysis of sensitivity and bandwidth

(disregarding the loss resistivity $R_L$)

A voltages is measured: $U = R \cdot I_{sec} = R/N \cdot I_{beam} \equiv S \cdot I_{beam}$

with ***S* sensitivity [V/A]** to determine **beam** current $I_{beam}$

equivalent to transfer function or transfer impedance ***Z***

# Response of the Fast Current Transformer: Droop Time

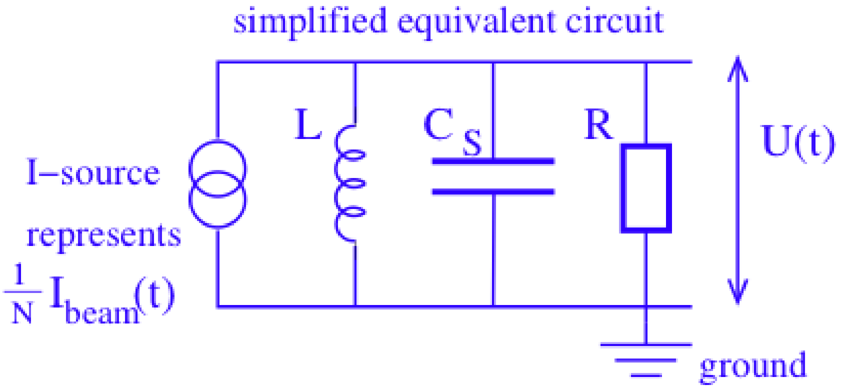
***Time domain description:***

A transformer is a ac-coupled device,

i.e. it does **not** transfer dc-currents

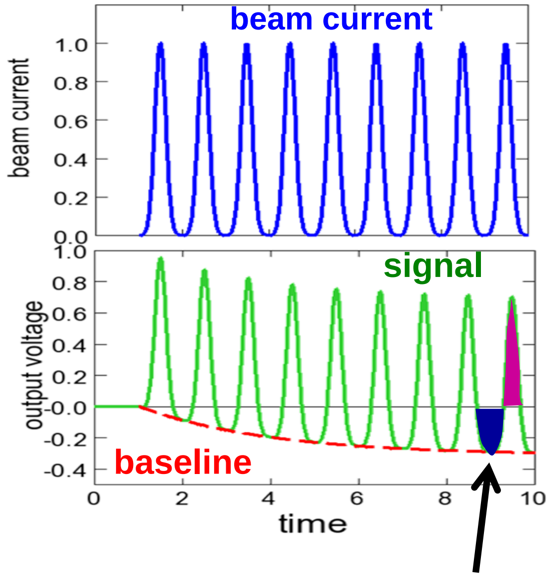
Characterization with droop time:

$\tau_{droop} = 1/(2\pi f_{low}) = L/R$




***Effect for bunched beam:*** Shift of 'baseline'

**Bunch train:**




**Baseline**: $U_{base} \propto 1 - \exp(-t/\tau_{droop})$
**positive** & **negative** areas are equal

# Example for Fast Current Transformer

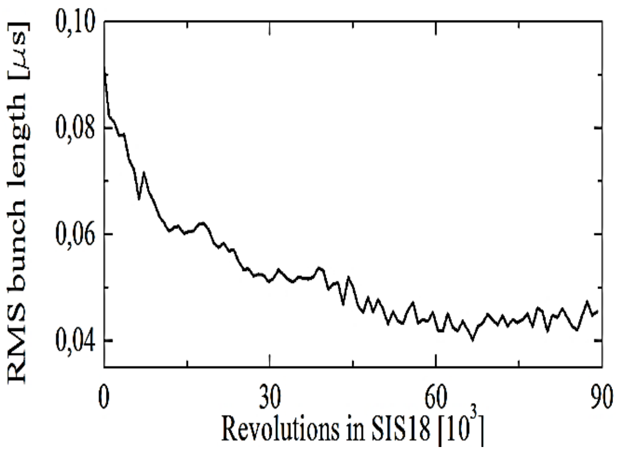
For bunch beams e.g. during accel. in a synchrotron typical bandwidth of 2 kHz < $f$ < 1 GHz

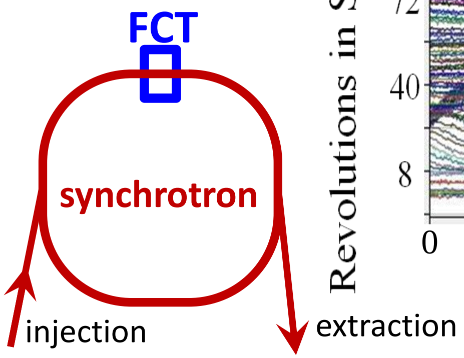
⇔ 10 ns < $t_{bunch}$ < 1 µs is well suited

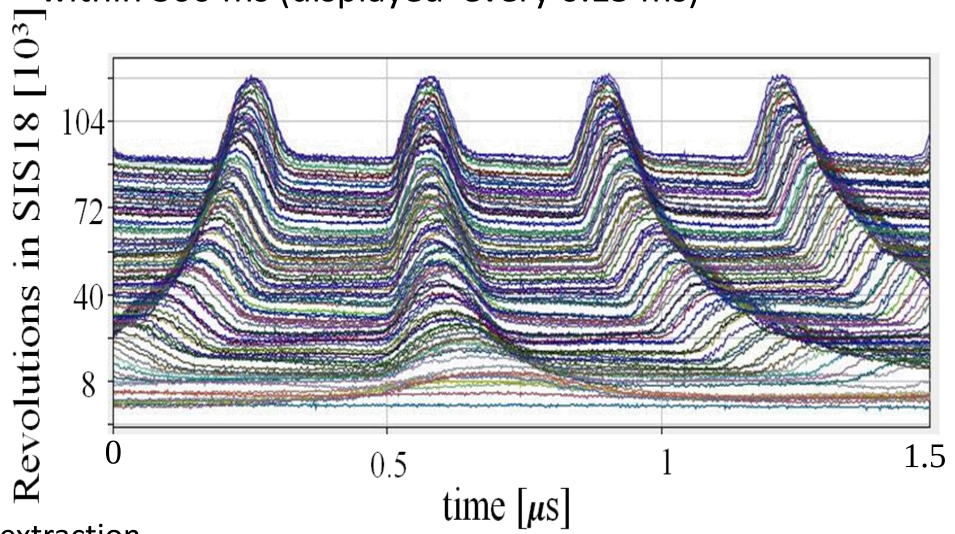
*Example: GSI Fast Current Transformer* ***FCT****:*

| **Inner / outer radius** | **70 / 90 mm** |
|---|---|
| Permeability | $\mu_r \approx 10^5$ for f < 100 kHz<br>$\mu_r \propto$ 1/f above |
| Windings | 10 |
| Sensitivity | 4 V/A for R = 50 Ω |
| Droop time $\tau_{droop} = L/R$ | 0.2 ms |
| Rise time $\tau_{rise} = \sqrt{L_S C_S}$ | 1 ns |
| Bandwidth | 2 kHz ... 500 MHz |


*Example:* $U^{73+}$ from 11 MeV/u ($\beta$ = 15 %) to 350 MeV/u within 300 ms (displayed every 0.15 ms)



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Numerous application e.g.:
- Transmission optimization
- Bunch shape measurement
- Input for synchronization of 'beam phase'

More examples see lecture
'Longitudinal Beam Dynamics'
by Frank Tecker & Heiko Damerau

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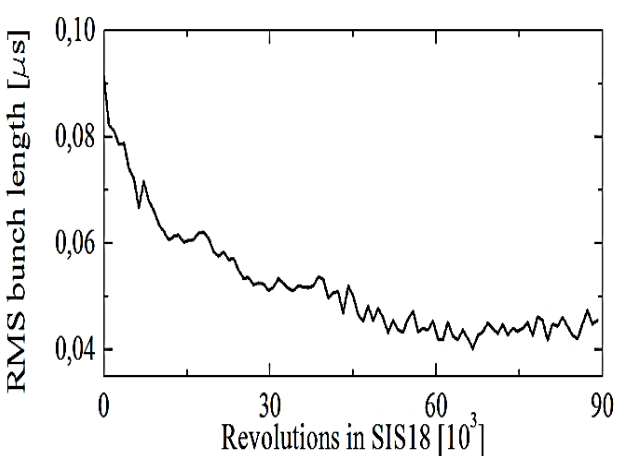
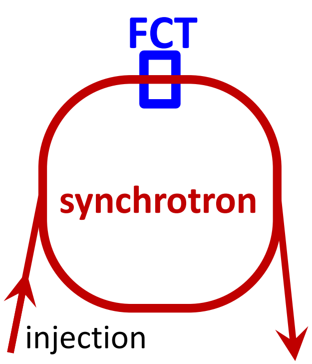
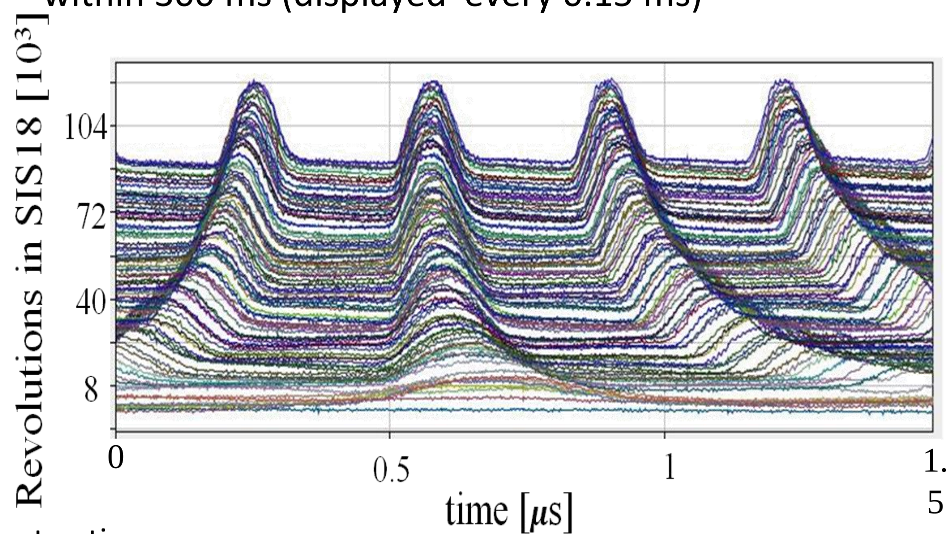


# The dc Transformer DCCT

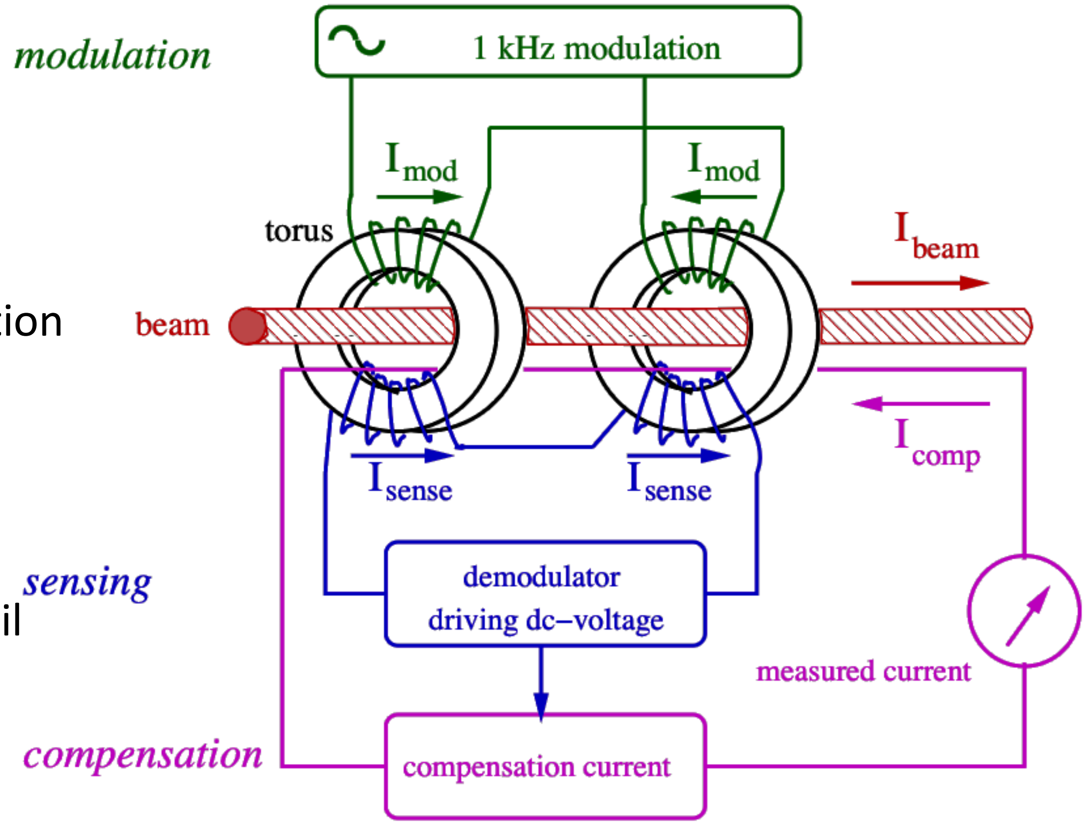
How to measure the DC current? The current transformer discussed sees only B-flux ***changes***.
The DC Current Transformer (DCCT) $\rightarrow$ magnetic saturation of two torii.

**Depictive statement:**
A single transformer needs varying beam. The trick is to ‘switch two transformers’!

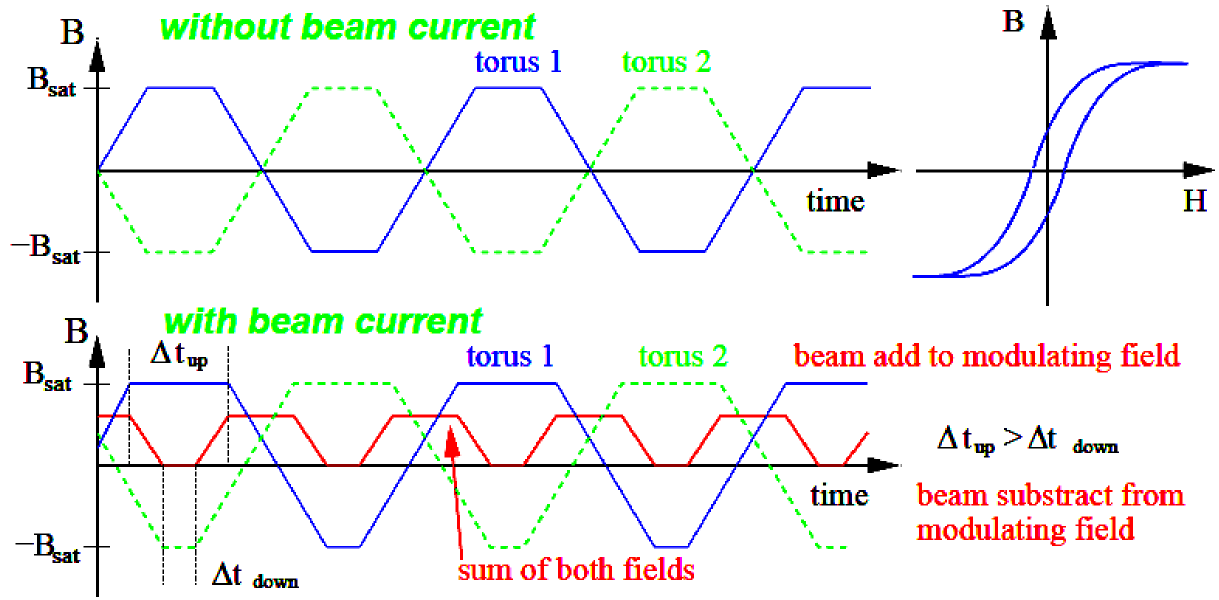
- **Modulation** of the primary windings forces both torii into saturation twice per cycle
- **Sense windings** measure the modulation signal and cancel each other.
- But with the $I_{beam}$, the saturation is shifted and $I_{sense}$ is not zero
- **Compensation current** adjustable until $I_{sense}$ is zero once again

**Remark:**

Same principle installed in power supplier



# The dc Transformer



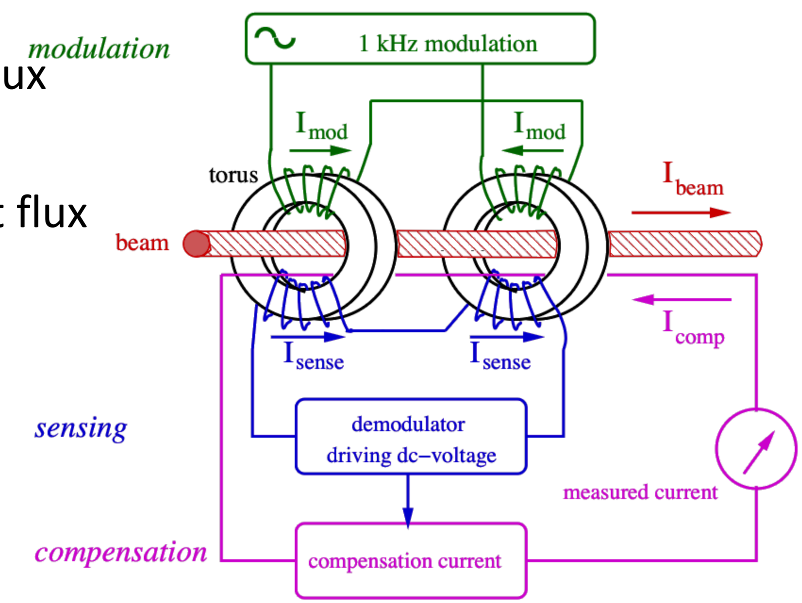

- **Modulation without beam:**

  typically about 9 kHz to saturation → **no** net flux
- **Modulation with beam:**

  saturation is reached at different times, → net flux
- **Net flux:** double frequency than modulation
- **Feedback:** Current fed to compensation winding

  for larger sensitivity
- **Two magnetic cores:** Must be very similar.

Remark: Same principle used for power suppliers



# Measurement with a dc Transformer

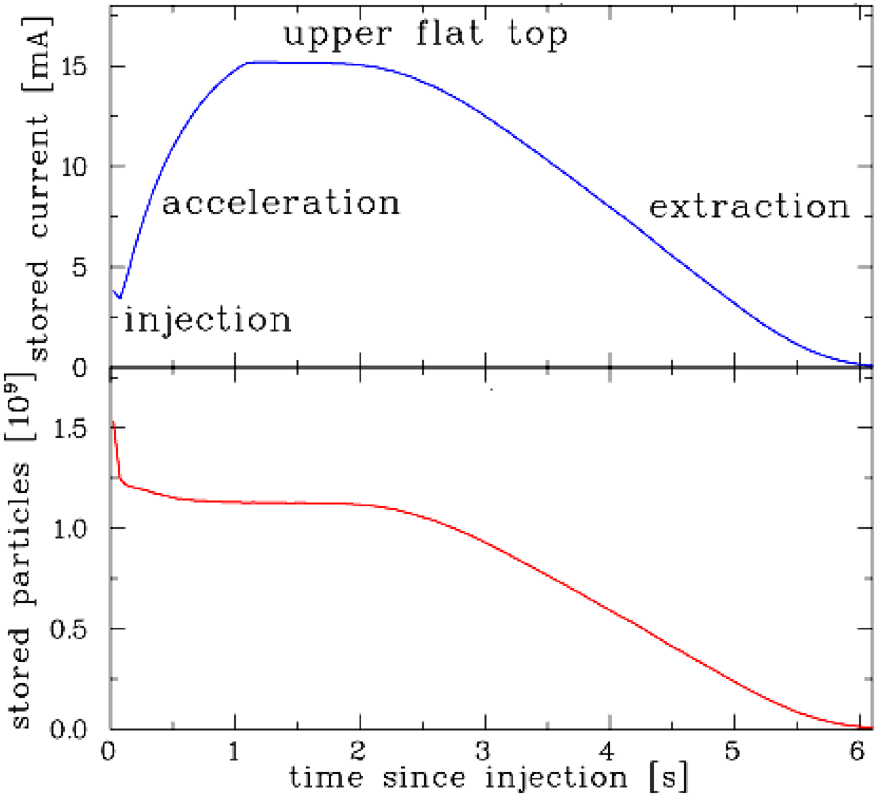
***Application for dc transformer***:

⇒ Observation of beam behavior with typ. 20 µs time resolution → **the basic operation tool**

*Example:* The DCCT at GSI synchrotron

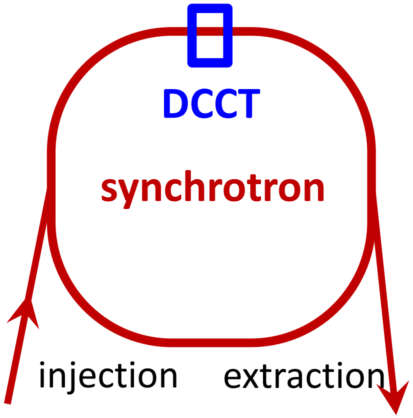
$U^{73+}$ accelerated from

11. 4 MeV/u ($\beta$ = 15.5%) to 750 MeV/u ($\beta$ = 84 %)




**Important parameter:**

- **Detection threshold: ≈ 1 µA (= resolution)**
- Bandwidth: $\Delta f$ = dc to 20 kHz
- Rise-time: $t_{rise}$ = 20 µs
- Temperature drift: 1.5 µA/$^0$C
  ⇒ compensation required.




For slow extraction: See lecture 'Injection and Extraction' by Pablo Arrutia

# Measurement of Beam Current

- **Transformers:** Measurement of the beam's **magnetic field**

  Non-destructive

  No dependence on beam type and energy

  They have lower detection threshold.

- **Faraday cups:** Measurement of the beam's **electrical charges**

  They are destructive

  For low energies only

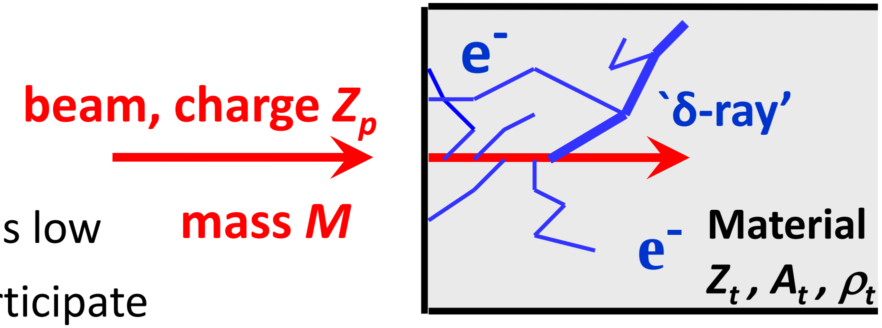
  Low currents can be determined.

# Excurse: Energy Loss of Protons & Ions

**Bethe-Bloch formula:** $-\frac{dE}{dx} = 4\pi N_A r_e^2 m_e c^2 \cdot \frac{Z_t}{A_t}\rho_t \cdot Z_p^2 \cdot \frac{1}{\beta^2}\left(\frac{1}{2}\ln\frac{2m_e c^2\beta^2\gamma^2 \cdot W_{max}}{I^2} - \beta^2\right)$

(simplest formulation)

**Semi-classical approach:**




- Projectiles of mass ***M*** collide with free electrons of mass ***m***
- If ***M >> m*** then the relative energy transfer is low

⇒ many collisions required many elections participate

proportional to target electron density $n_e = \frac{Z_t}{A_t}\rho_t$

⇒ low straggling for the heavy projectile i.e. 'straight trajectory'

- If projectile velocity $\beta \approx 1$ low relative energy change of projectile ($\gamma$ is Lorentz factor)
- ***I*** is mean ionization potential including kinematic corrections $I \approx Z_t \cdot 10\ eV$ for most metals
- Strong dependence an projectile charge $Z_p$ as $\frac{dE}{dx} \propto Z_p^2$

Constants: $N_A$ Advogadro number, $r_e$ classical e⁻ radius, $m_e$ electron mass, ***c*** velocity of light

Maximum energy transfer from projectile ***M*** to electron $m_e$: $W_{max} = \frac{2m_e c^2\beta^2\gamma^2}{1 + 2\gamma m_e/M + (m_e/M)^2}$

# Excurse: Energy Loss of Protons & Ions in Copper

Bethe-Bloch formula: $-\frac{dE}{dx} = 4\pi N_A r_e^2 m_e c^2 \cdot \frac{Z_t}{A_t}\rho_t \cdot Z_p^2 \cdot \frac{1}{\beta^2}\left(\frac{1}{2}\ln\frac{2m_e c^2\beta^2\gamma^2 \cdot W_{max}}{I^2} - \beta^2\right)$

(simplest formulation)

Range: $$R = \int_0^{E_{max}} \left(\frac{dE}{dx}\right)^{-1} dE$$

with approx. scaling $R \propto E_{max}^{1.75}$

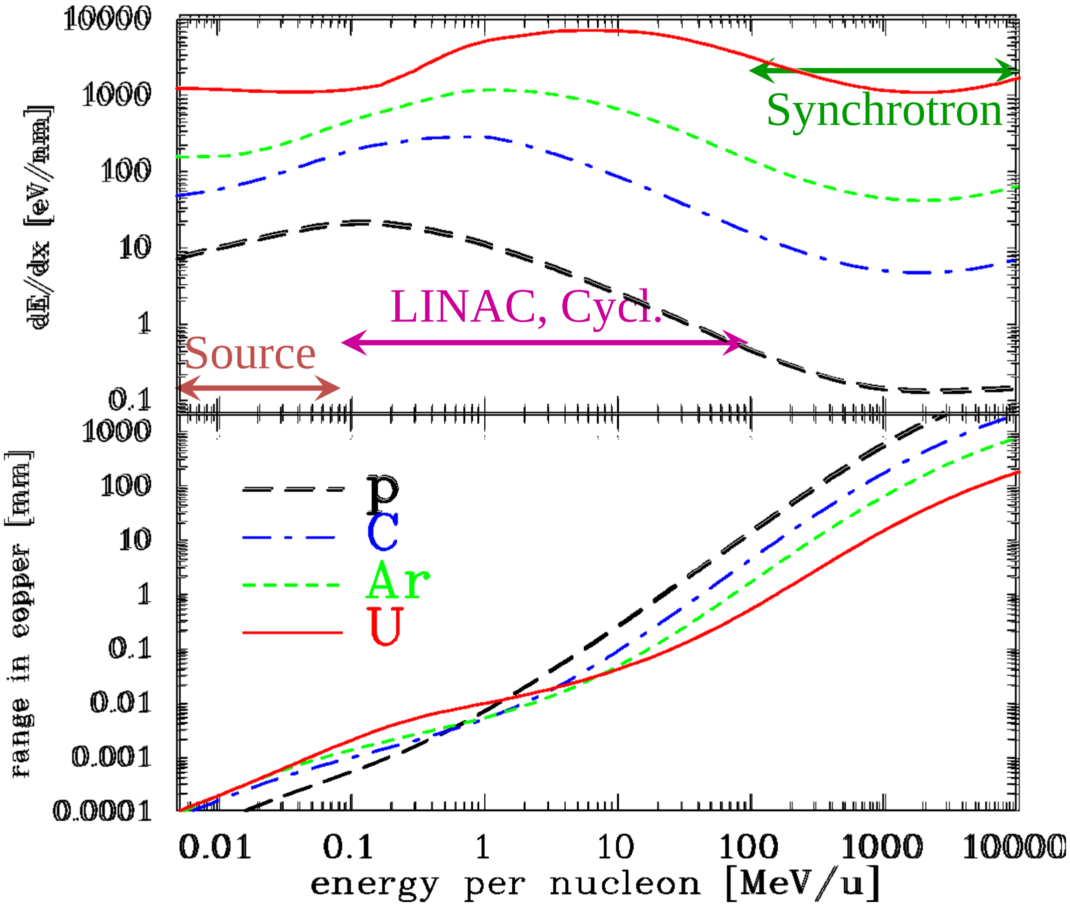
Numerical calculation for **ions**

with semi-empirical model e.g. SRIM

Main modification $Z_P \rightarrow Z_p^{eff}(E_{kin})$

$\Rightarrow$ Cups only for

***E**$_{kin}$* < 100 MeV/u due to ***R*** < 10 mm




Approximation e.g. $Z_p^{eff} \approx Z_p\left[1 - \exp\left(-Z_p^{-2/3} c\beta \,/\, V_{Bohr}\right)\right]$

# Excurse: Secondary Electron Emission caused by Ion Impact

Energy loss of ions in metals close to a surface:

Closed collision with large energy transfer: $\rightarrow$ fast $e^-$ with $E_{kin}$ > 100 eV

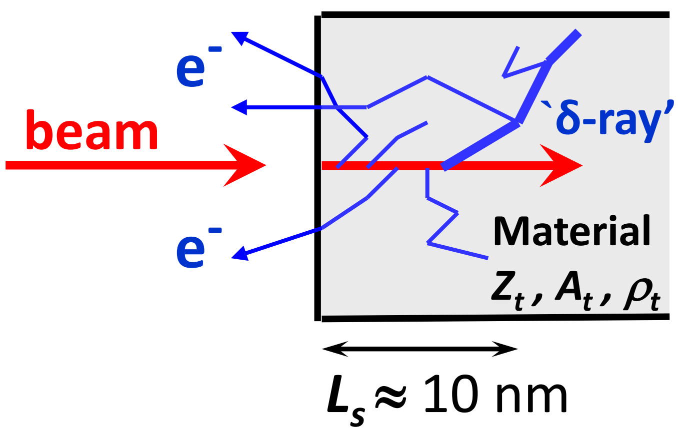
Distant collision with low energy transfer $\rightarrow$ slow $e^-$ with $E_{kin} \leq$ 10 eV

$\rightarrow$ 'diffusion' & scattering with other $e^-$: scattering length $L_s \approx$ 1 - 10 nm

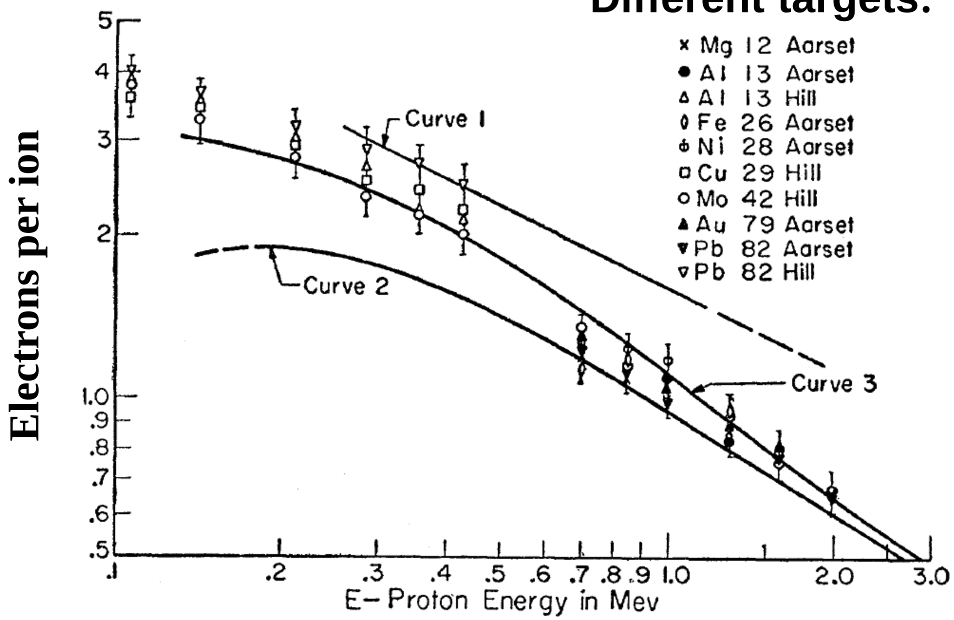
$\rightarrow$ at surface $\approx$ 90 % probability for escape

Secondary **electron yield** and energy distribution comparable for all metals!

$\Rightarrow$ ***Y = const. * dE/dx*** (Sternglass formula)



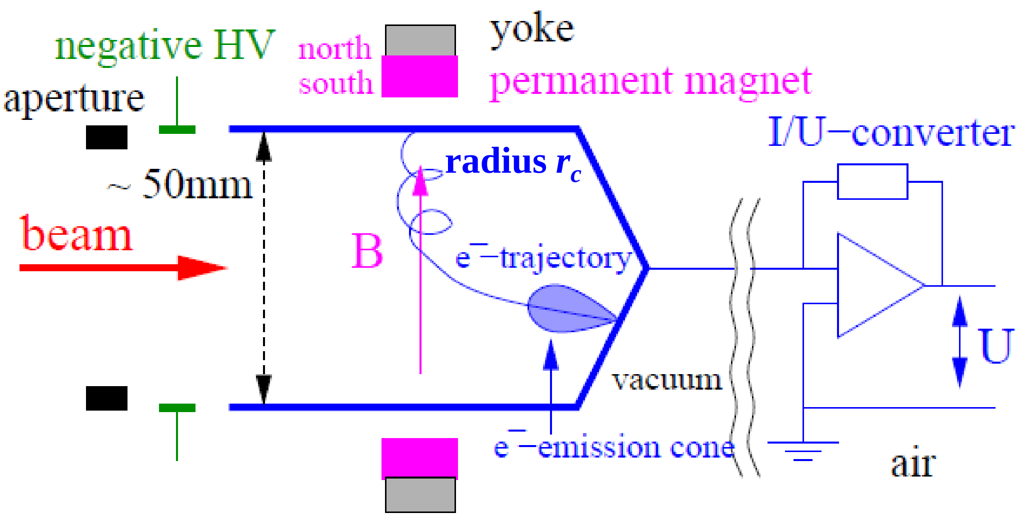

E.J. Sternglass, Phys. Rev. 108, 1 (1957)

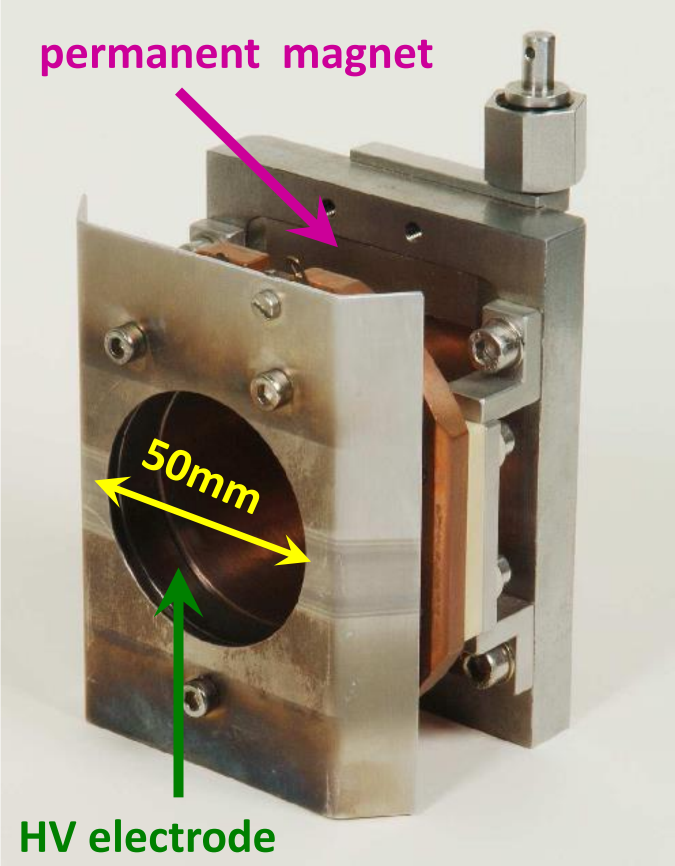


# Faraday Cups for Beam Charge Measurement

**The beam particles are collected inside a metal cup**
**⇒ The beam's charge are recorded as a function of time.**

The cup is moved in the beam pass
→ destructive device




**Currents down to 10 pA with bandwidth of 100 Hz!**

To prevent for secondary electrons leaving the cup

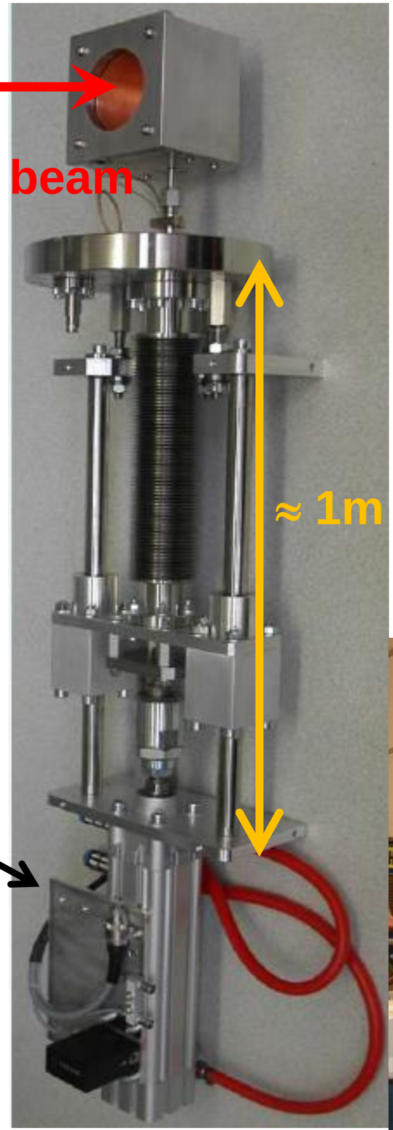
**Magnetic field:** The central field is $\boldsymbol{B} \approx 10$ mT

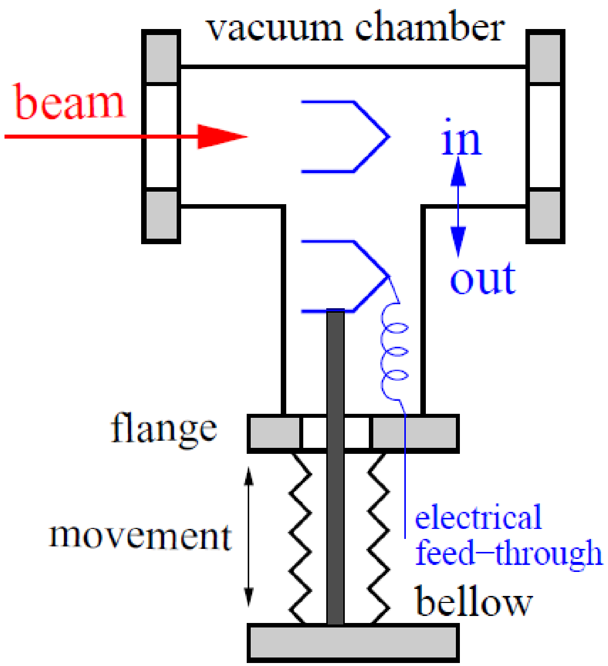
for $E_\perp = 10 \text{ eV} = \frac{1}{2} m v_\perp^2 \Rightarrow r_c = \frac{m}{e} \cdot \frac{1}{B} \cdot v_\perp \approx 1$ mm.

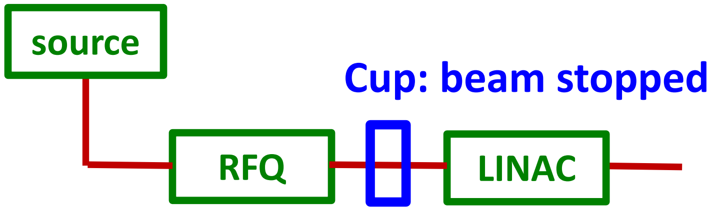
***or* Electric field:** Potential barrier at the cup entrance $\boldsymbol{U} \approx 1$ kV.

# Realization of a Faraday Cup at GSI LINAC

The Cup is moved into the beam pass.




# Summary for Current Measurement

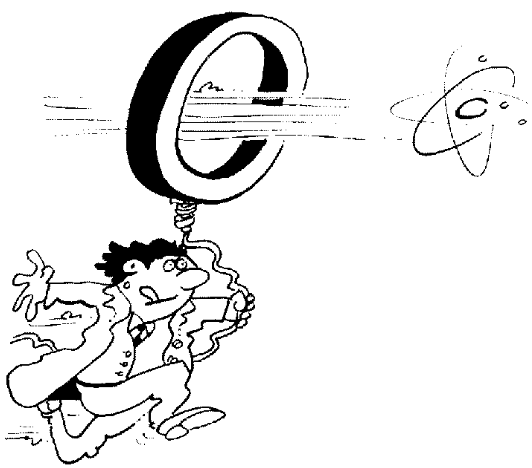
***Transformer:* → measurement of the beam's magnetic field**

- Magnetic field is guided by a high μ toroid
- **Types:** FCT → large bandwidth, $I_{min} \approx$ 30 μA, BW = 10 kHz ... 500 MHz
  [ACT : $I_{min} \approx$ 0.3 μA, BW = 10 Hz .... 1 MHz, used at proton LINACs ]
  DCCT: two toroids + modulation, $I_{min} \approx$ 1 μA, BW = dc ... 20 kHz
- Non-destructive, used for all beams

***Faraday cup:* → measurement of beam's charge,**

- Low threshold by I/U-converter: $I_{beam}$ > 10 pA
- Totally destructive, used for low energy beams only

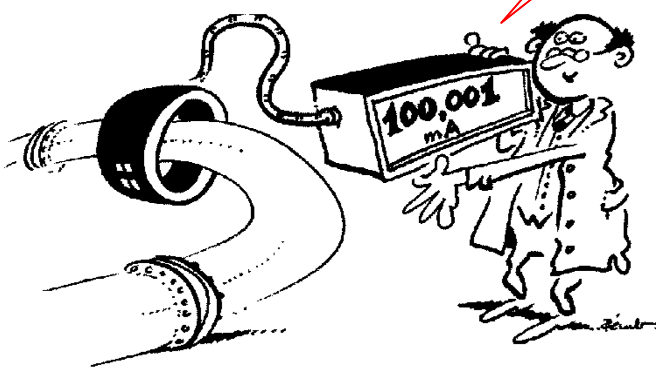
Fast Transformer FCT



Active transformer ACT


DC transformer DCCT

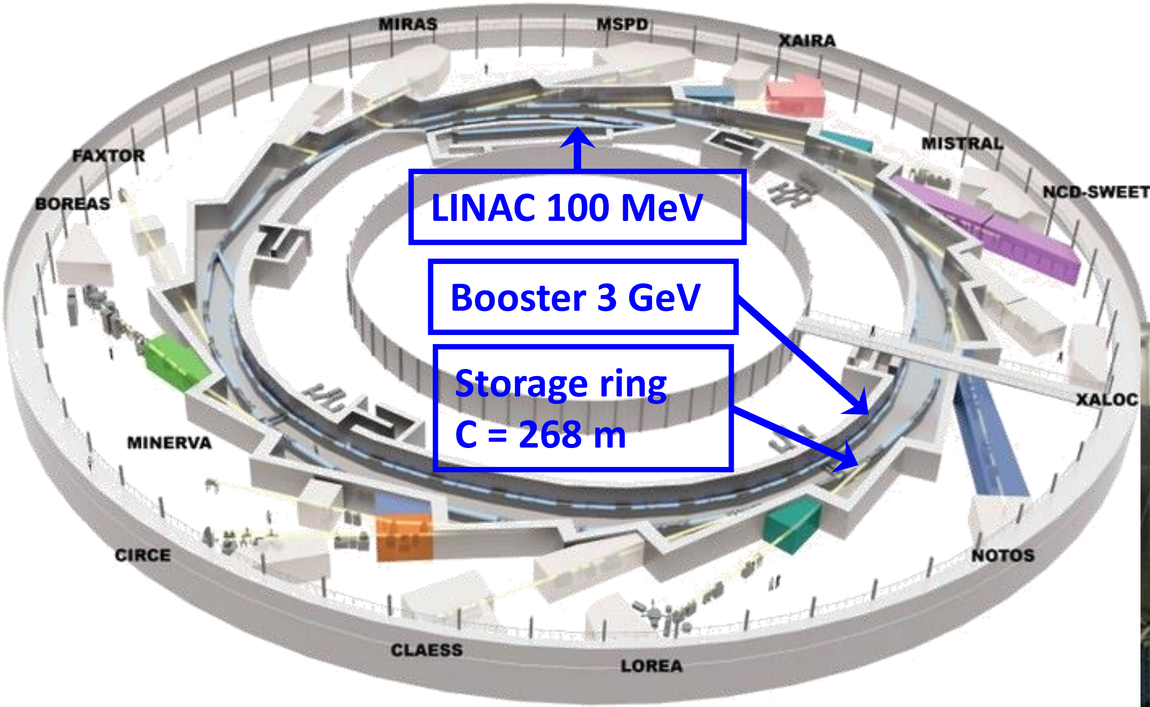
Resolution limit




Company Bergoz

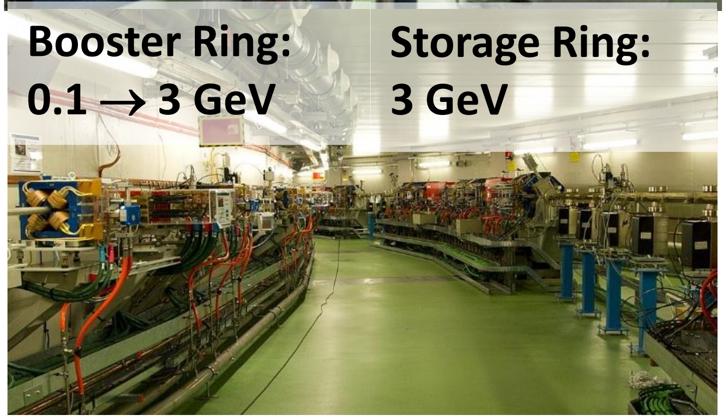
# Example → Synchrotron Light Facility ALBA

## 3rd generation Spanish synchr. light facility in Barcelona

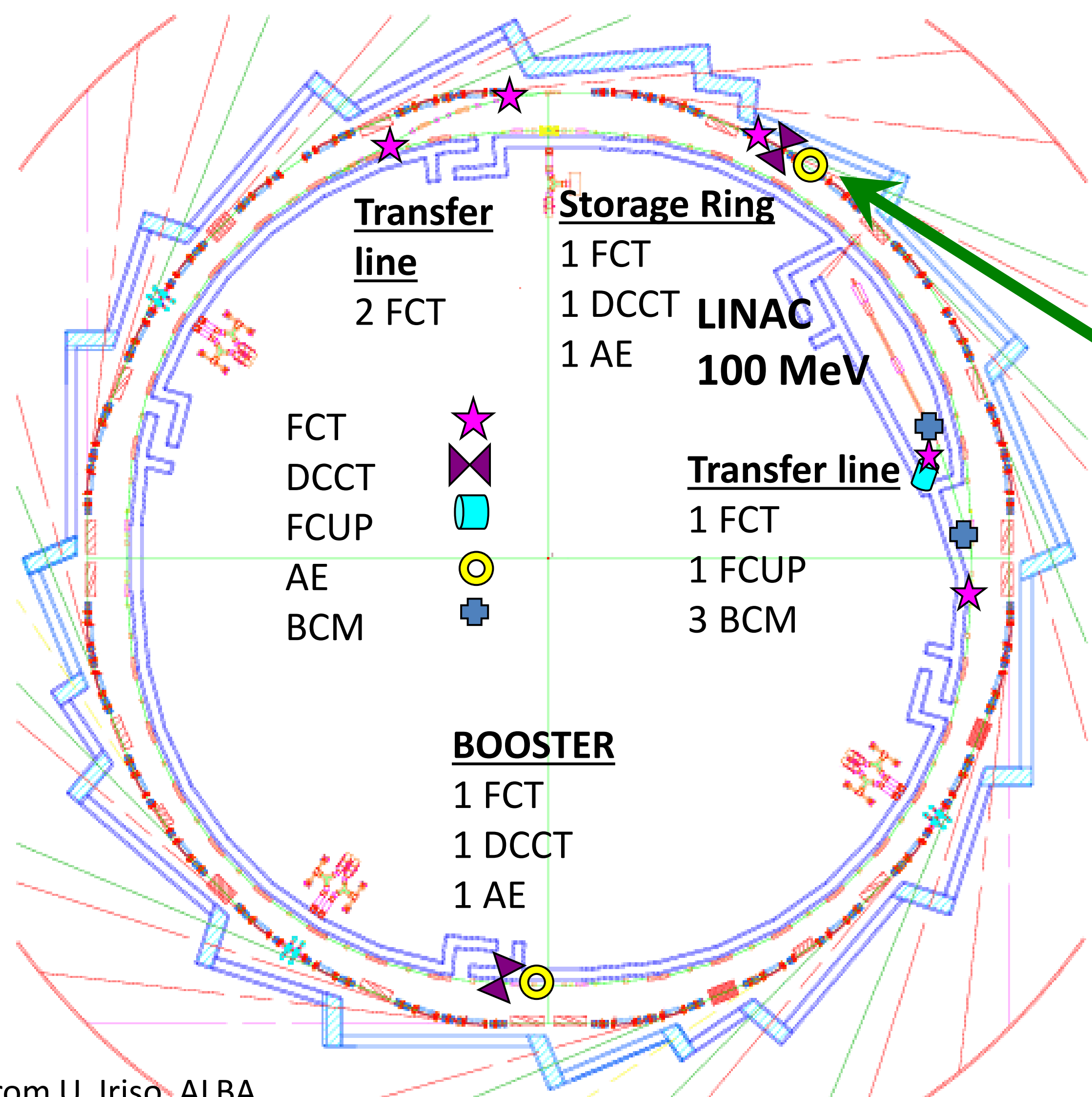



**Layout:**

- Storage ring length: 268 m
- Electron energy: 3 GeV
- Top-up injection
- Max. beam current: 0.4 A

# Appendix: The Synchrotron Light Facility ALBA: Current Meas.

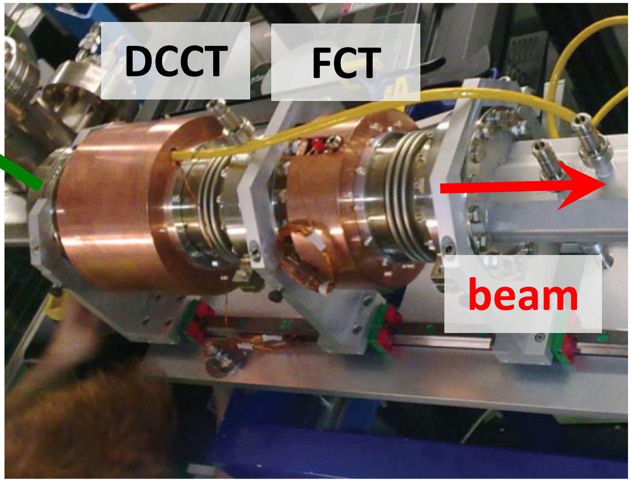



From U. Iriso, ALBA

## Beam current measurements:

Several in transport lines

- One per ring




## Abbreviation:

**FCT**: Fast Current Transformer
**DCCT**: dc transformer
**FCUP:** Faraday Cup
**AE**: Annular Electrode
**BCM:** Bunch Charge Monitor

## Outline:

- Signal generation $\rightarrow$ transfer impedance
- Capacitive *button* BPM for high frequencies
- Electronics for position evaluation
- BPMs for measurement
- Summary

**A Beam Position Monitor is an non-destructive device for bunched beams**

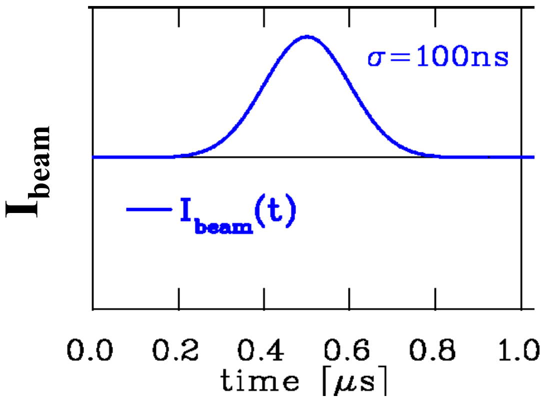
**It delivers information about the transverse center of the beam:**

- ***Trajectory:*** Position of an individual bunch within a transfer line or synchrotron
- ***Closed orbit***: Central orbit averaged over a period much longer than a betatron oscillation
- ***Single bunch position:*** Determination of parameters like tune, chromaticity, $\beta$-function

**Remarks:** - BPMs have a low cut-off frequency $\Leftrightarrow$ dc-beam can't be monitored
- The abbreviation **BPM** and pick-up **PU** are synonyms

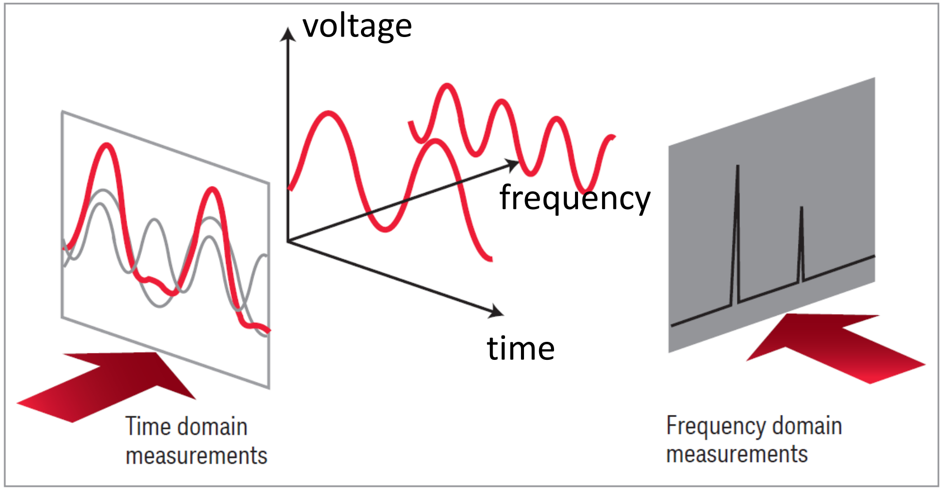
# Time Domain ↔ Frequency Domain: Instrumentation

**Time domain:** Recording of a voltage as a function of time:



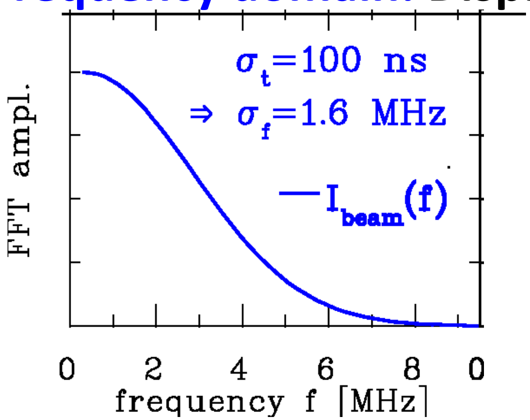

**Instrument:**

**Oscilloscope**




courtesy company Keysight

**Frequency domain:** Displaying of a voltag




**Instrument:**

**Spectrum Analyzer**

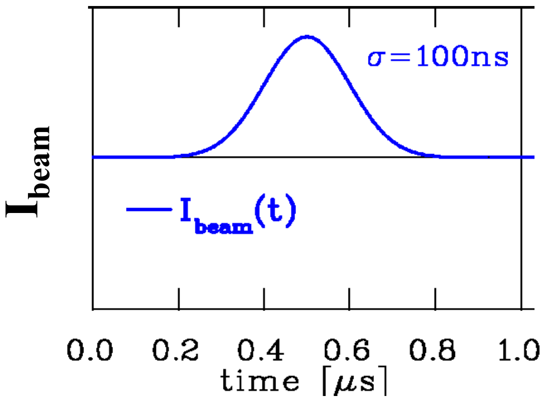


Photos and idea by Piotr Kowina

See lecture 'Time and Frequency Domain Signals' by Hermann Schmickler

# Time Domain ↔ Frequency Domain: Mathematics

**Time domain:** **Recording of a voltage as a function of time:**

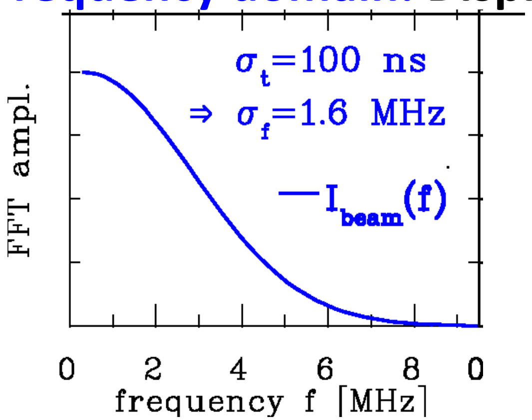



**Mathematics for function $f(t)$:**

**Fourier Transformation:**

$$\hat{f}(\omega) = \int_{-\infty}^{\infty} f(t) \cdot e^{-i\omega t}\, dt$$

**Frequency domain:** **Displaying of a voltage as a function of frequency:**




**Fourier Transformation:**

- Contains amplitude & phase as the values are $\hat{f}(\omega) \in \mathbb{C}$ (complex in math. sense)
- The **same** information is displayed differently

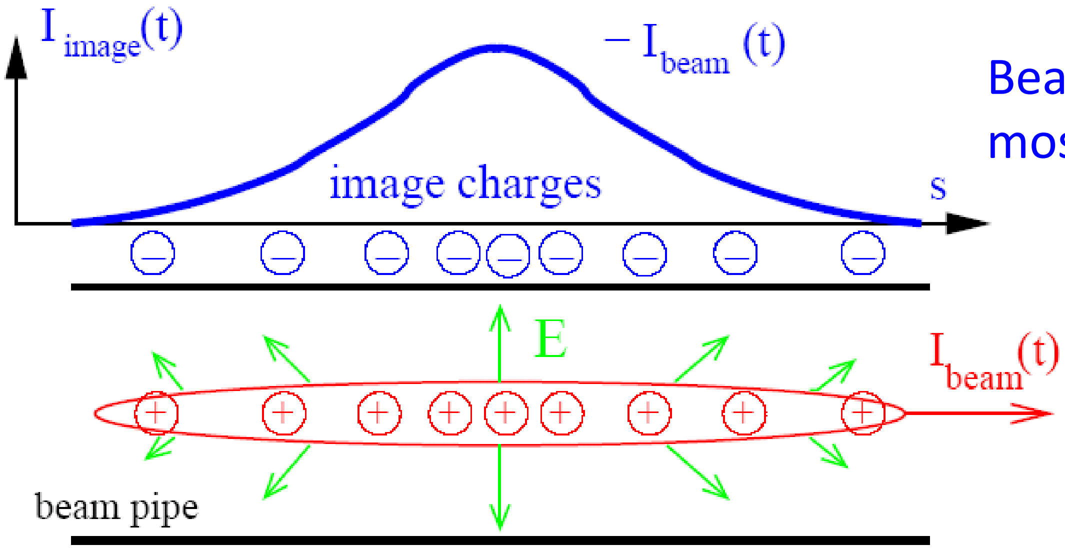
**Law of Convolution:** For a convolution in time: $f(t) = \int_{-\infty}^{\infty} f_1(\tau) \cdot f_2(t-\tau)\, d\tau$

$\Rightarrow \hat{f}(\omega) = \hat{f_1}(\omega) \cdot \hat{f_2}(\omega)$ ⇔ convolution be expressed as multiplication of FTs

See lecture 'Time and Frequency Domain Signals' by Hermann Schmickler

# Pick-Ups for bunched Beams

The image current at the beam pipe is monitored on a high frequency basis i.e. the ac-part given by the bunched beam.



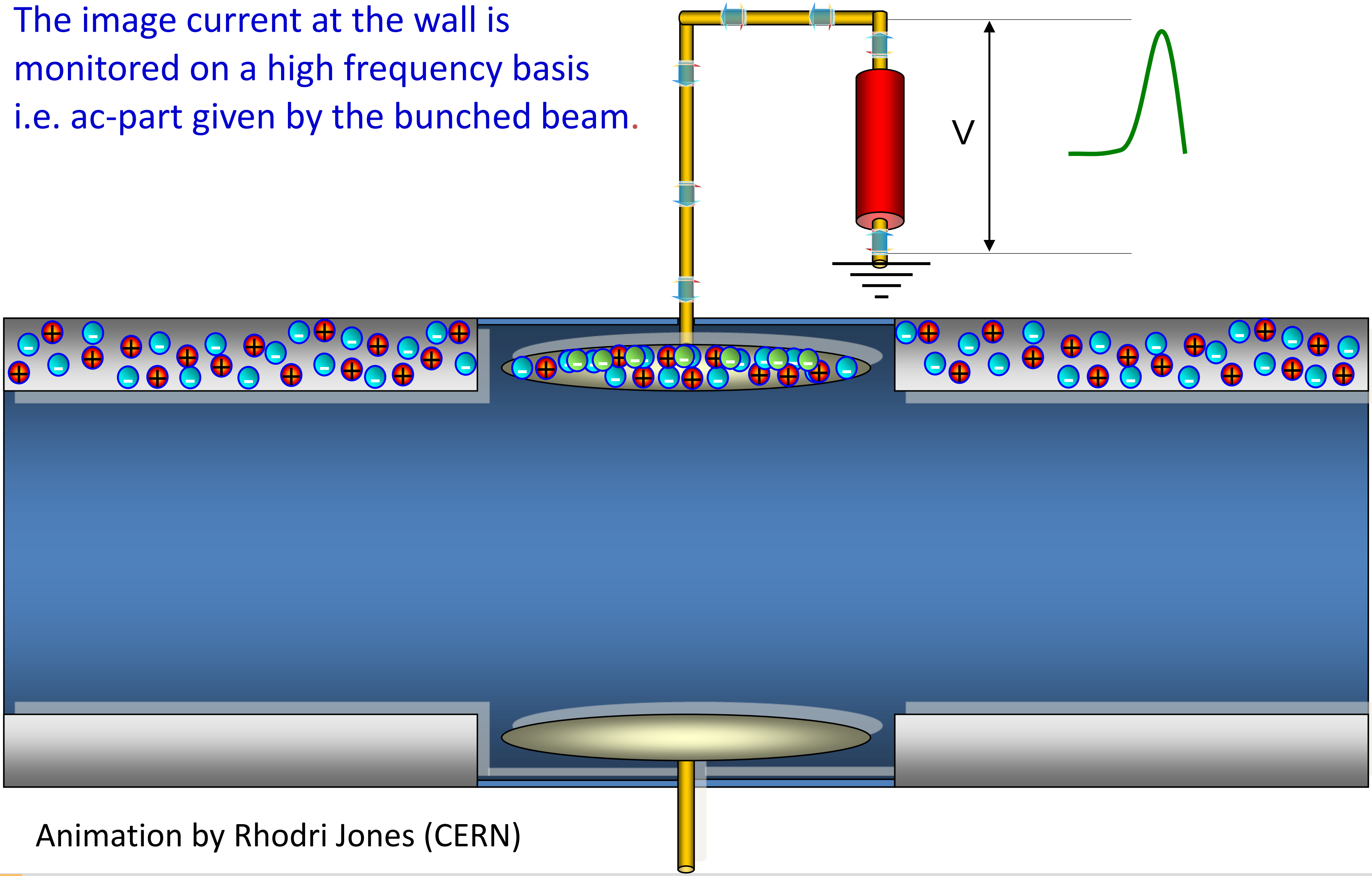

Beam Position Monitor **BPM** is the most frequently used instrument!

For relativistic velocities,
the electric field is transversal:

$$E_{\perp,lab}(t) = \gamma \cdot E_{\perp,rest}(t')$$

# Principle of Signal Generation of a BPMs, centered Beam

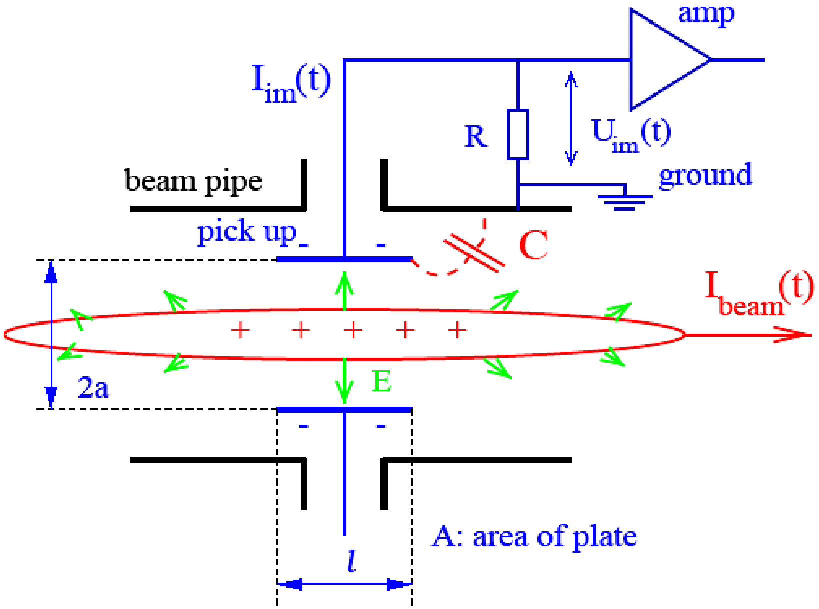
The image current at the wall is monitored on a high frequency basis i.e. ac-part given by the bunched beam.

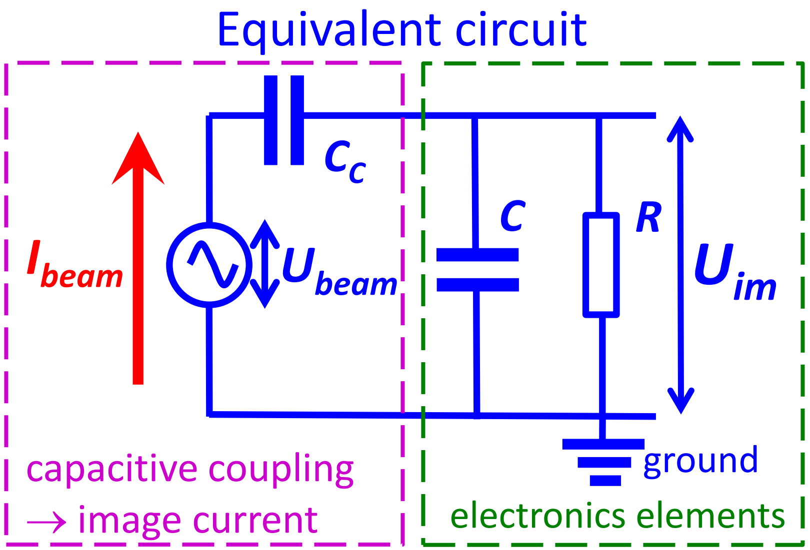



Animation by Rhodri Jones (CERN)

# Model for Signal Treatment of capacitive BPMs

**The wall current is monitored by a plate or ring inserted in the beam pipe:**




At a resistor ***R*** the voltage $U_{im}$ from the image current is measured.

**Goal:** Connection from beam current to signal strength by transfer impedance $Z_t(\omega)$

in frequency domain: $U_{im}(\omega) = R \cdot I_{im}(\omega) = Z_t(\omega) \cdot I_{beam}(\omega)$

**Result:** $Z_t(\omega) = \frac{A}{2\pi a} \cdot \frac{1}{\beta c} \cdot \frac{1}{C} \cdot \frac{i\omega RC}{1+i\omega RC}$ $\in \mathbb{C}$ i.e. complex function

geometry — stray capacitance — frequency response

# Example of Transfer Impedance for Proton Synchrotron

The high-pass characteristic for typical synchrotron BPM:

$$U_{im}(\omega)=Z_t(\omega)\cdot I_{beam}(\omega)$$

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

$$\varphi = \arctan(\omega_{cut}/\omega)$$

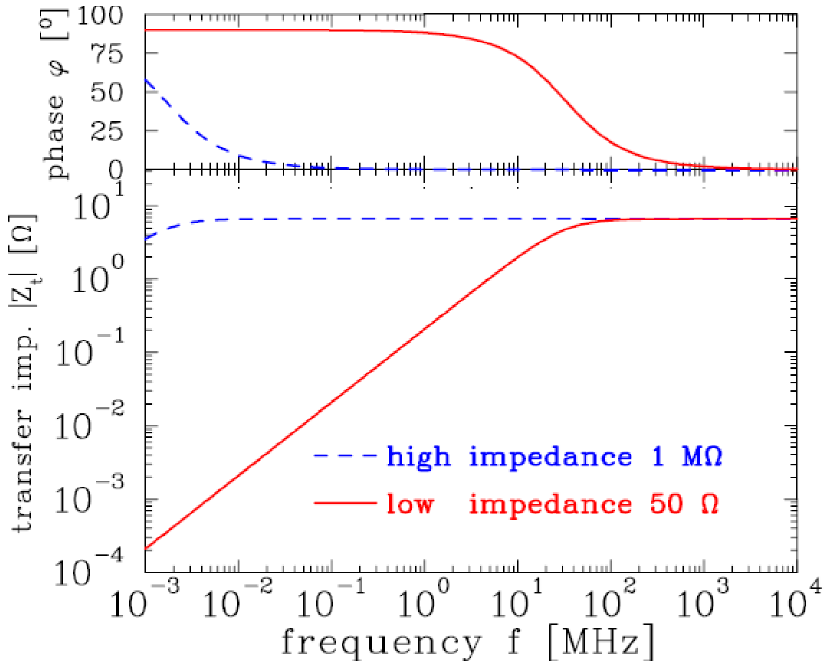
Parameter linear-cut BPM at proton synchr.:

$C$ = 100pF, $l$ = 10cm, $\beta$ = 50%

$f_{cut} = \omega/2\pi = (2\pi RC)^{-1}$

for $R$ = 50 Ω $\Rightarrow f_{cut}$ = 32 MHz

for $R$ = 1 MΩ $\Rightarrow f_{cut}$ = 1.6 kHz




Large signal strength for long bunches $\rightarrow$ **high impedance**

Smooth signal transmission important for short bunches $\rightarrow$ **50 Ω**

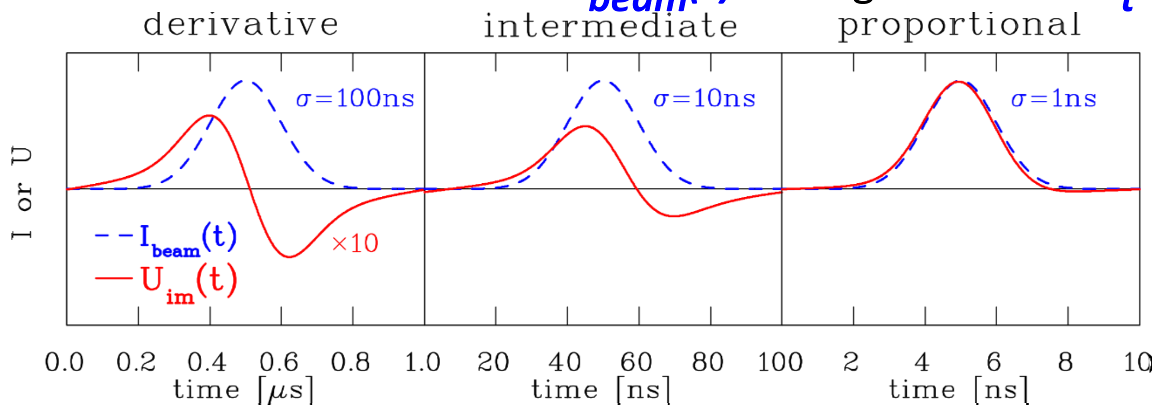
**Remark:** For $\omega \rightarrow 0$ it is $Z_t \rightarrow 0$ i.e. **no** signal is transferred from dc-beams e.g.

- de-bunched beam inside a synchrotron
- for slow extraction through a transfer line

# Calculation of Signal Shape (here single Bunch)

The transfer impedance is used in frequency domain! The following is performed:

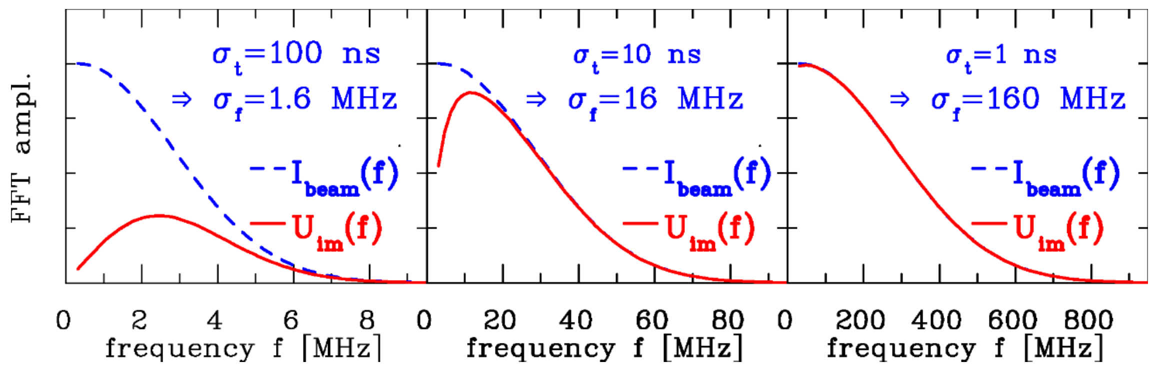
**1. Start:** Time domain Gaussian function $I_{beam}(t)$ having a width of $\sigma_t$




Fourier trans.

inverse Fourier trans.

**2. FFT** of $I_{beam}(t)$ leads to the frequency domain Gaussian $I_{beam}(f)$ with $\sigma_f = (2\pi\sigma_t)^{-1}$




**3. Multiplication** with $Z_t(f)$ with $f_{cut}$ = 32 MHz leads to $U_{im}(f) = Z_t(f) \cdot I_{beam}(f)$

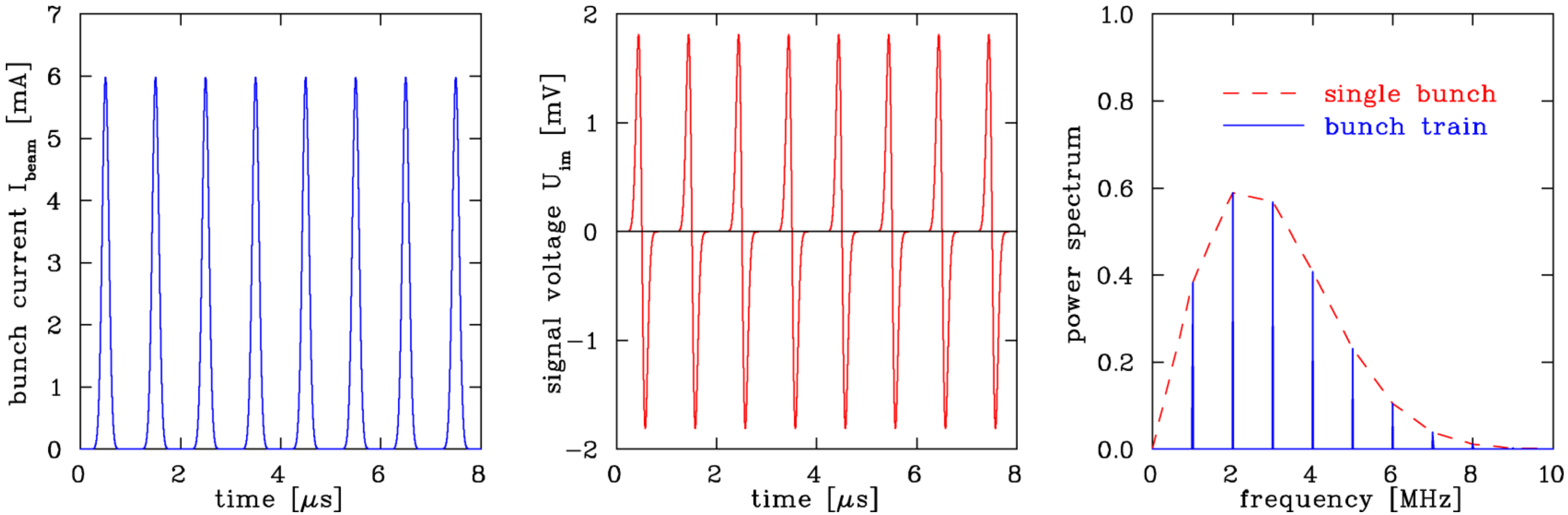
**4. Inverse FFT** leads to $U_{im}(t)$

**Remark:** Time domain processing via convolution or filters (FIR and IIR) are possible

# Calculation of Signal Shape: repetitive Bunch in a Synchrotron

Synchrotron filled with 8 bunches accelerated with $\boldsymbol{f_{acc}}$= 1 MHz

BPM terminated with $\boldsymbol{R}$=50 Ω $\Rightarrow \boldsymbol{f_{acc} \ll f_{cut}}$ :




**Parameter: *R*=50 Ω ⇒ $f_{cut}$=32 MHz, all buckets filled**

*C*=100pF, *l*=10cm, $\beta$=50%, $\sigma_t$=100 ns ⇒ $\sigma_l$=15m

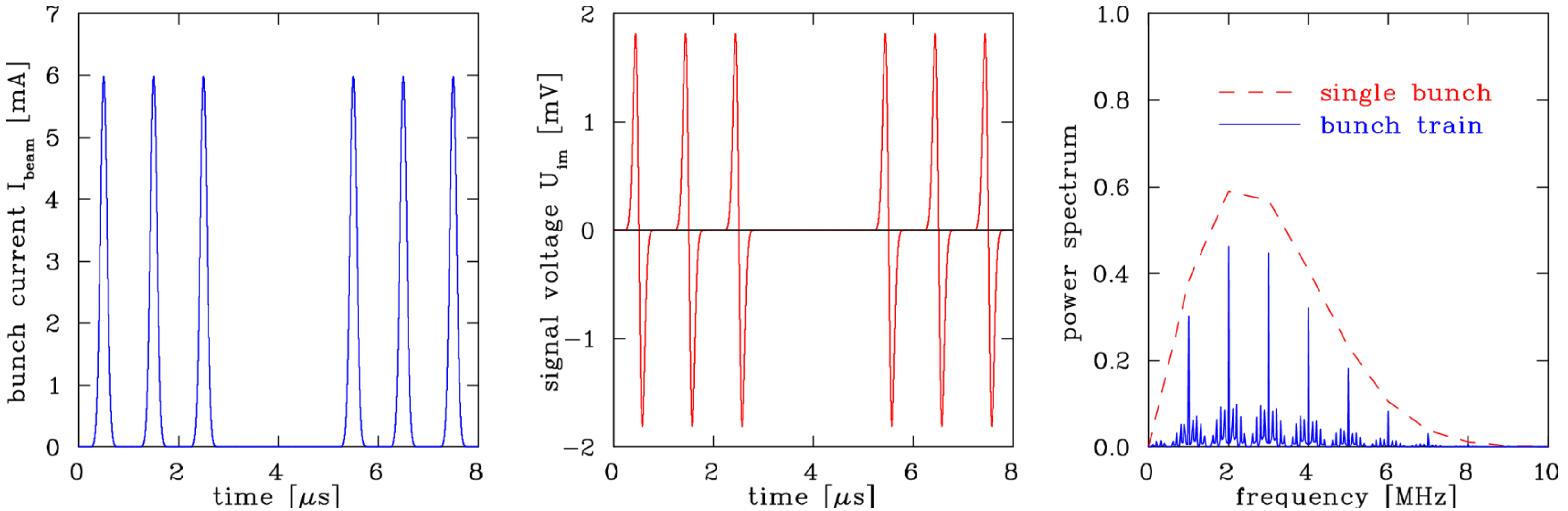
- Fourier spectrum is concentrated at acceleration harmonics with single bunch spectrum as an envelope.
- Bandwidth up to typically 10*$\boldsymbol{f_{acc}}$

See lecture 'Time and Frequency Domain Signals' by Hermann Schmickler

# Calculation of Signal Shape: Bunch Train with empty Buckets

## Synchrotron during filling: Empty buckets, *R*=50 Ω:

BPM terminated with ***R***=50 Ω $\Rightarrow f_{acc} << f_{cut}$




**Parameter: *R*=50 Ω ⇒ $f_{cut}$=32 MHz, 2 empty buckets**

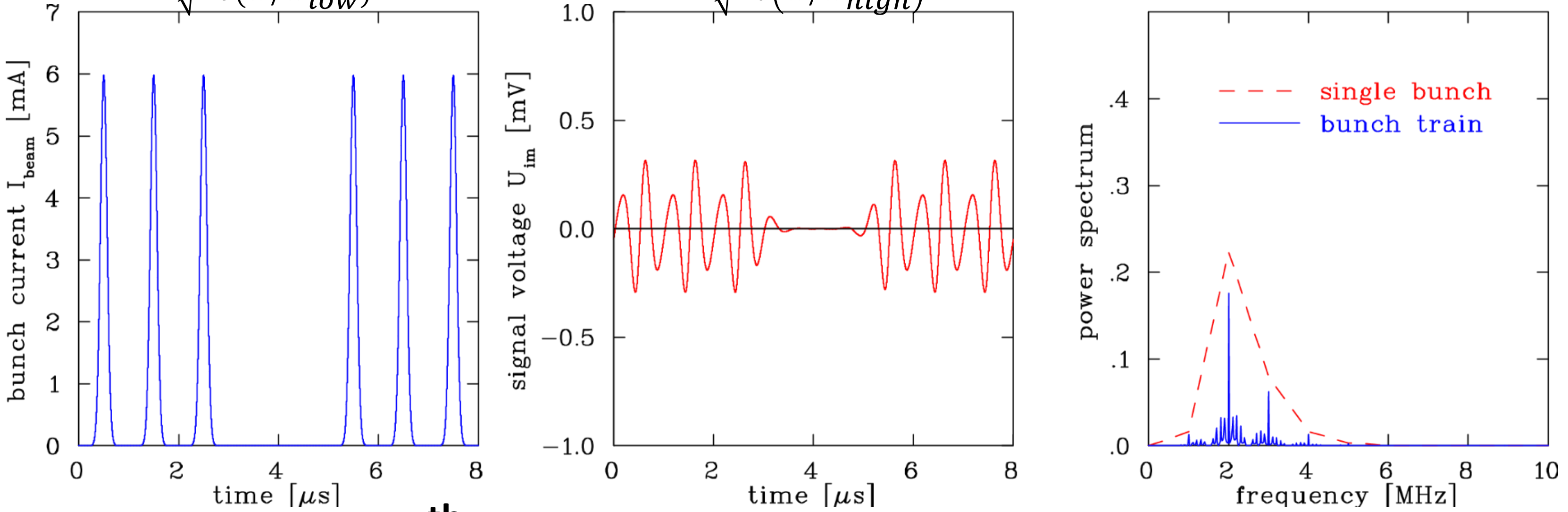
*C*=100pF, *l*=10cm, $\beta$=50%, $\sigma_t$=100 ns ⇒ $\sigma_l$=15m

- Fourier spectrum is more complex, harmonics are broader due to sidebands

# Calculation of Signal Shape: Filtering of Harmonics

Effect of filters, here 4th order Butterworth bandpass filter:

$$|H_{low}| = \frac{1}{\sqrt{1+(\omega/\omega_{low})^{2n}}} \text{ and } |H_{high}| = \frac{(\omega/\omega_{high})^{n}}{\sqrt{1+(\omega/\omega_{high})^{2n}}} \quad with\ H_{filter} = H_{low} \cdot H_{high}$$




**Parameter:** ***R*=50 Ω, 4th order Butterworth filter at $f_{low}$=1.8 MHz & $f_{high}$=2.2 MHz**

*C*=100pF, *l*=10cm, $\beta$=50%, $\sigma_t$=100 ns ⇒ $\sigma_l$=15m

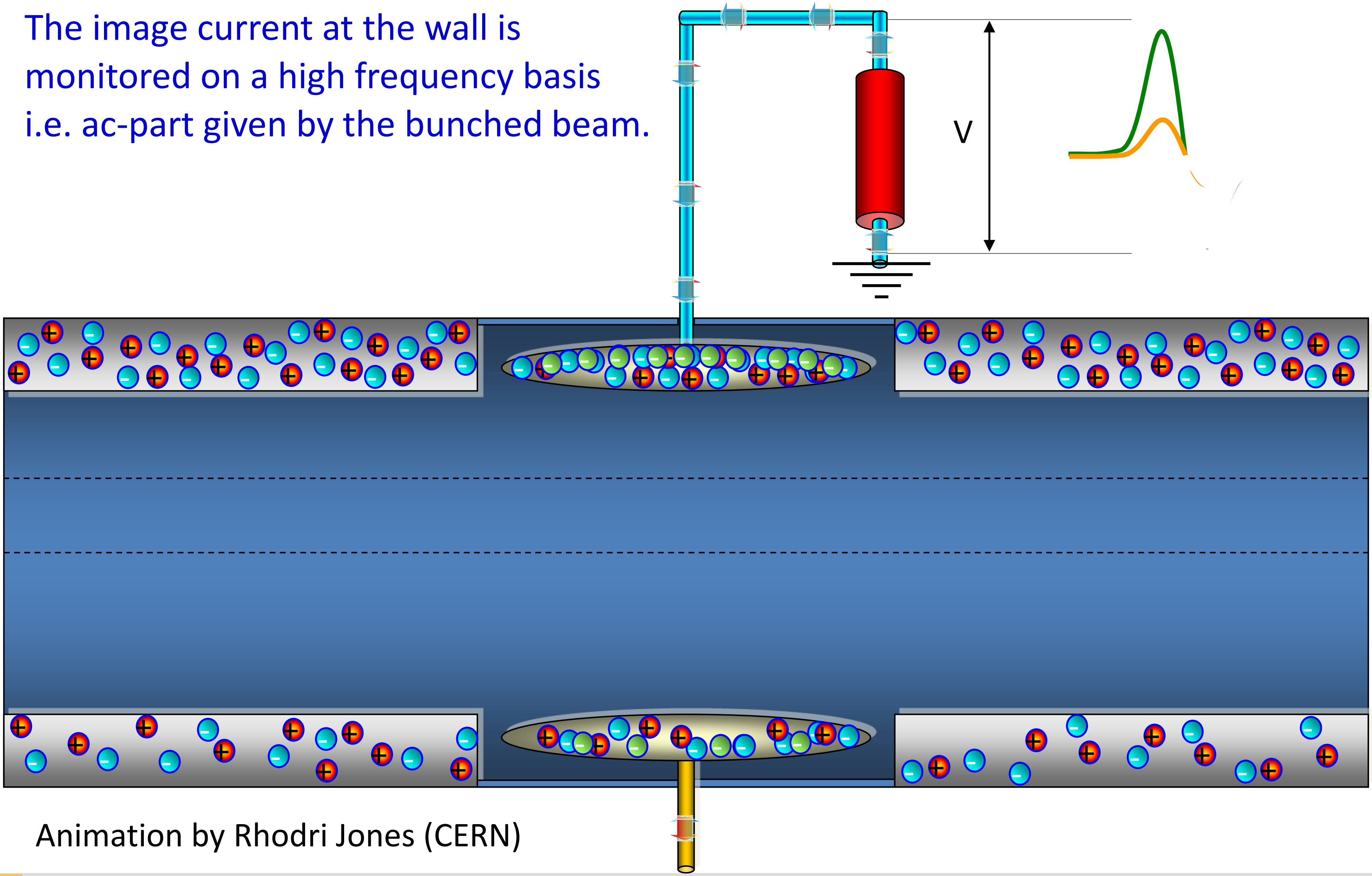
- Only few frequency components leading to 'ringing' due to sharp cutoff
- Other filter types more appropriate

**Generally:** $Z_{tot}(\omega) = H_{cable}(\omega) \cdot H_{filter}(\omega) \cdot H_{amp}(\omega) \cdot \ldots \cdot Z_t(\omega)$

Remark: For numerical calculations, time domain filters (FIR and IIR) are more appropriate

# Principle of Signal Generation of a BPMs: off-center Beam

The image current at the wall is monitored on a high frequency basis i.e. ac-part given by the bunched beam.



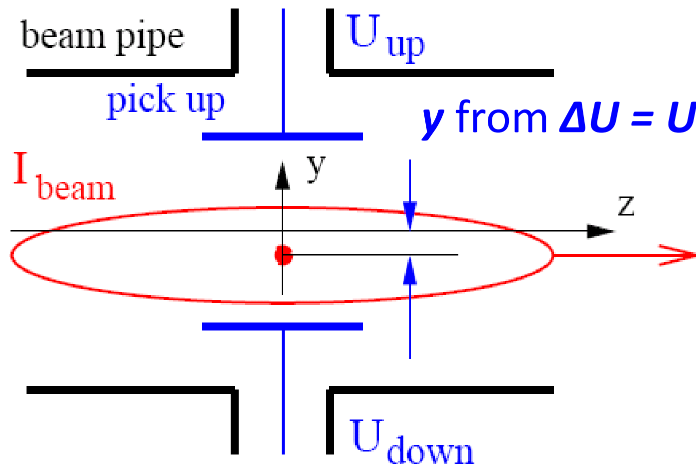

Animation by Rhodri Jones (CERN)

# Principle of Position Determination by a BPM

The difference voltage between plates gives the beam's center-of-mass
**→most frequent application**

$$y = \frac{1}{S_y(\omega)} \cdot \frac{U_{up} - U_{down}}{U_{up} + U_{down}}$$
$$\equiv \frac{1}{S_y} \cdot \frac{\Delta U_y}{\Sigma U_y}$$

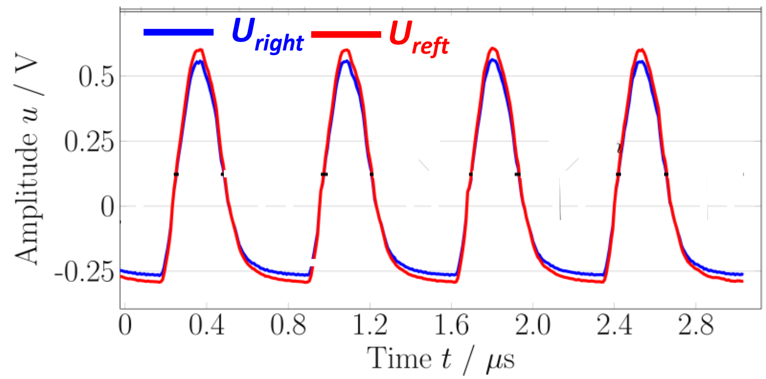
$$x = \frac{1}{S_x(\omega)} \cdot \frac{U_{right} - U_{left}}{U_{right} + U_{left}}$$




***y*** **from** $\Delta U = U_{up} - U_{down}$

***S(ω,x)*** is called **position sensitivity,** sometimes the inverse is used ***k(ω,x)=1/S(ω,x)***
***S*** is a geometry dependent, non-linear function,
Units: ***S***=[%/mm], sometimes ***S***=[dB/mm] or ***k***=[mm].

*Example:* One turn = 4 bunches @ 35 MeV/u




**Typical desired position resolution:**

$\Delta x \approx 0.1 \ldots 0.3 \cdot \sigma_x$ of beam width

**It is at least:** $\Delta U \ll \frac{1}{10} \Sigma U$

# Pick-Ups for bunched Beams

## Outline:

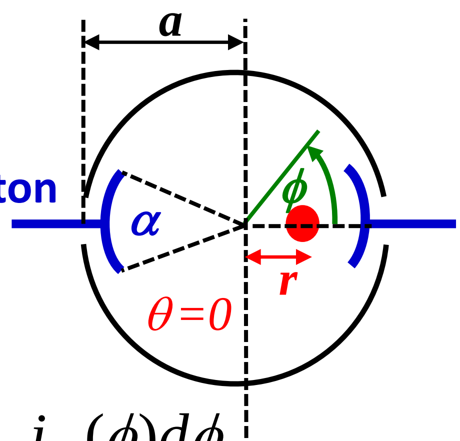
- ➢ Signal generation → transfer impedance
- ➢ Capacitive *button* BPM for high frequencies

  used at most proton LINACs and electron accelerators
- ➢ Electronics for position evaluation
- ➢ BPMs for measurement of closed orbit, tune and further lattice functions
- ➢ Summary

# 2-dim Model for a Button BPM

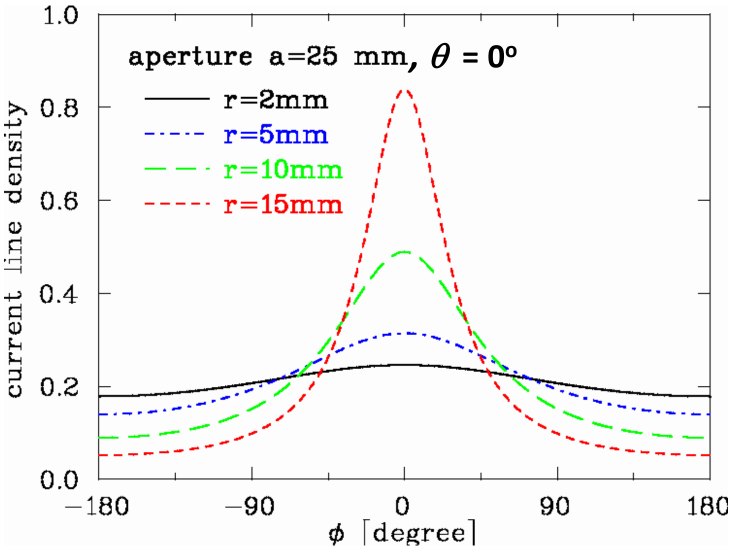
**'Proximity effect': larger signal for closer plate**

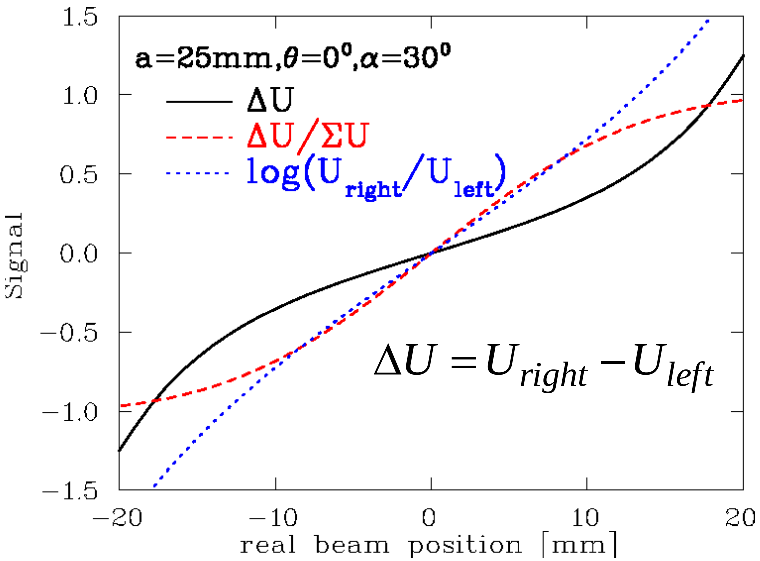
**Ideal 2-dim model:** Cylindrical pipe → image current density via 'image charge method' for 'pencil' beam:




$$j_{im}(\phi) = \frac{I_{beam}}{2\pi a} \cdot \left( \frac{a^2 - r^2}{a^2 + r^2 - 2ar \cdot \cos(\phi - \theta)} \right)$$

Image current: Integration over finite button size: $I_{im} = a \cdot \int_{-\alpha/2}^{\alpha/2} j_{im}(\phi) d\phi$



# 2-dim Model for a Button BPM

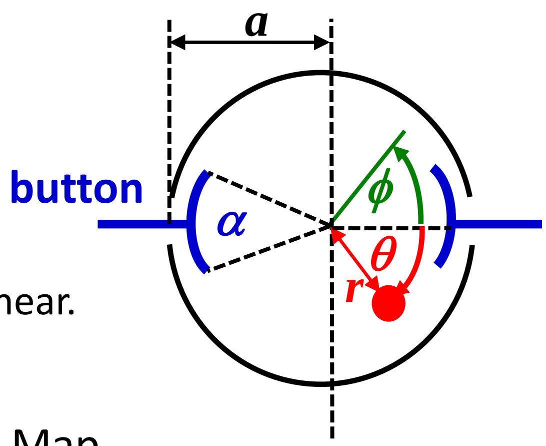
**Ideal 2-dim model**: Non-linear behavior and hor-vert coupling:

Sensitivity ***S*** converts signal to position $x = \frac{1}{S} \cdot \frac{\Delta U}{\Sigma U}$

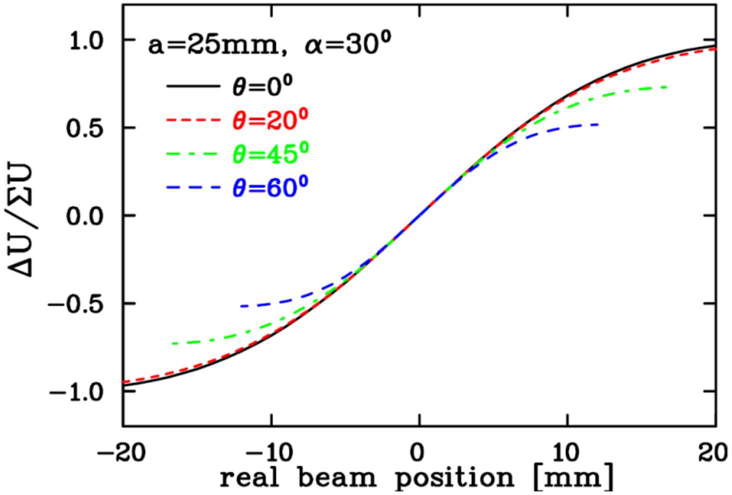
with $S$ = [%/mm] or [dB/mm]

i.e. ***S*** is the derivative of the curve $S_x = \frac{\partial(\frac{\Delta U}{\Sigma U})}{\partial x}$, here $S_x = S_x(x, y)$ i.e. non-linear.

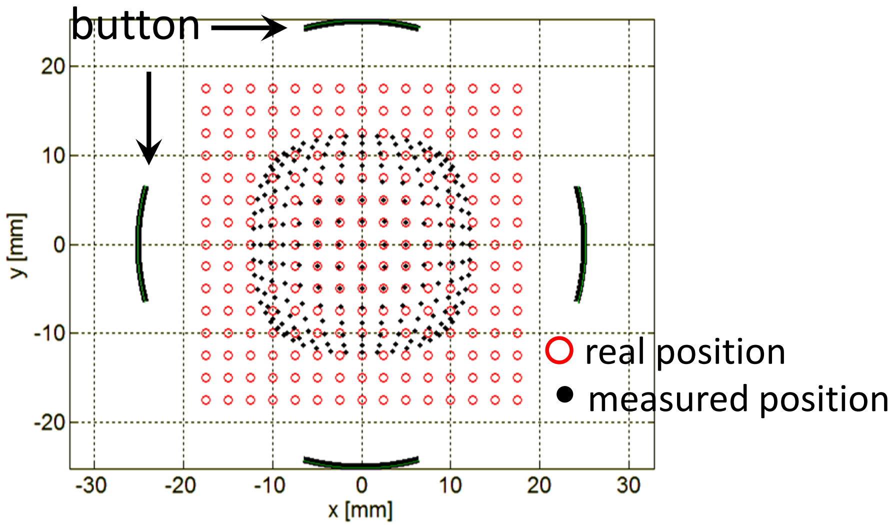
*For this example:* central part *S*=7.4%/mm ⇔ *k=1/S*=14mm




Horizontal plane




Position Map



# Button BPM Realization

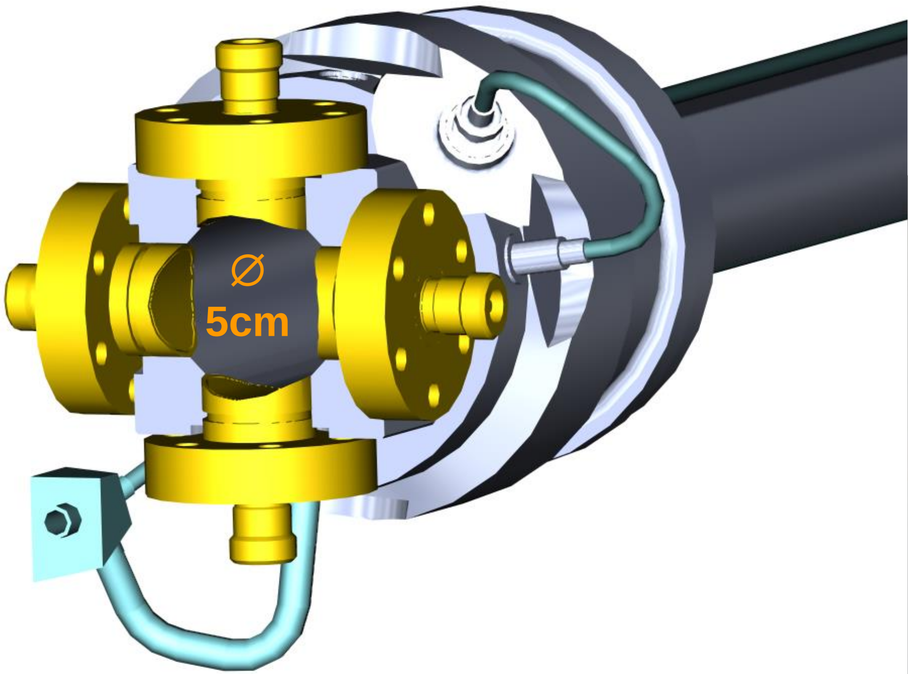
**LINACs, e⁻-synchrotrons**: 100 MHz < $f_{rf}$ < 3 GHz → bunch length ≈ BPM length

→ 50 Ω signal path to prevent reflections

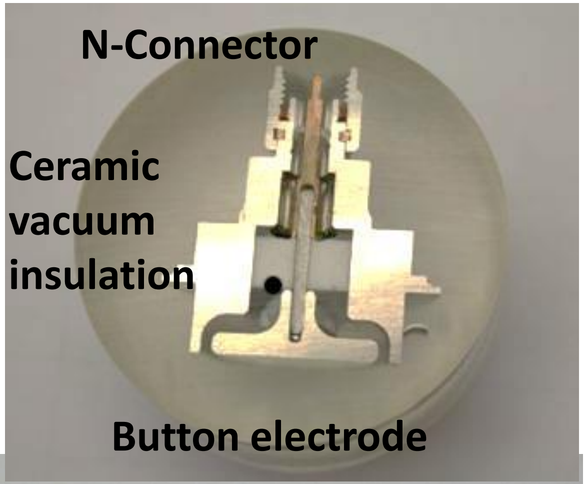
**Example:** LHC-type inside cryostat:

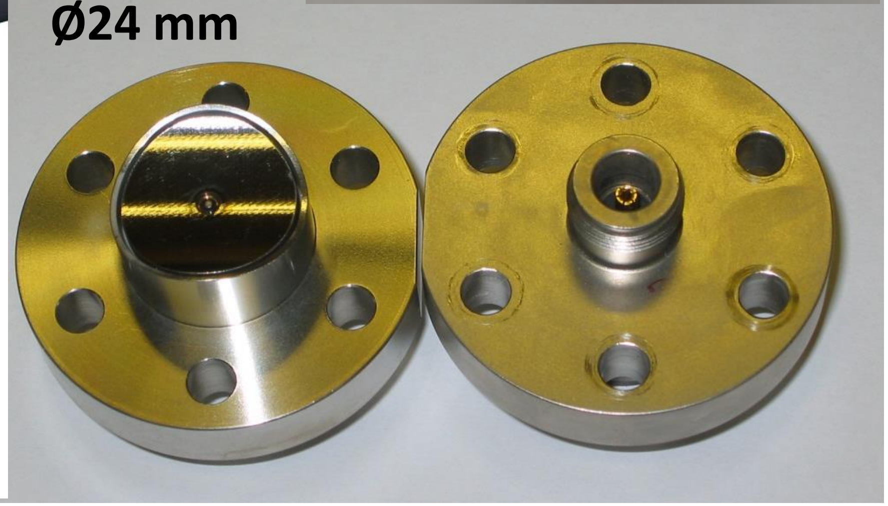
∅24 mm, half aperture $a$ = 25 mm, $C$ = 8 pF

⇒ $f_{cut}$= 400 MHz, $Z_t$ = 1.3 Ω above $f_{cut}$




Courtesy C. Boccard (CERN)



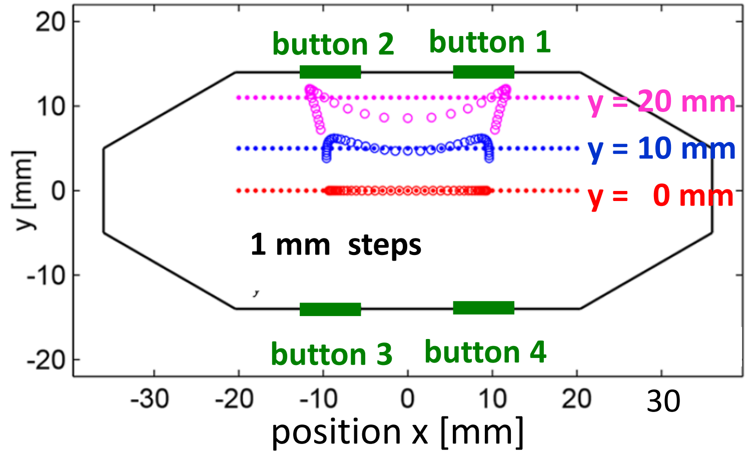



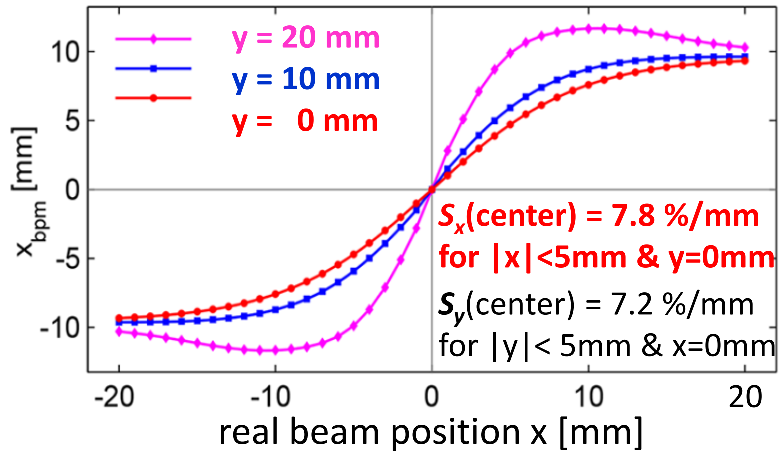
# Simulations for Button BPM at Synchrotron Light Sources

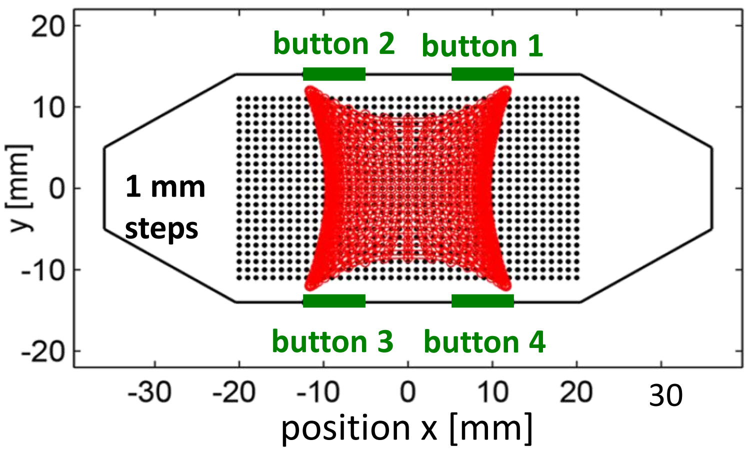
*Example:* Simulation for ALBA light source for 72 x 28 mm$^2$ chamber

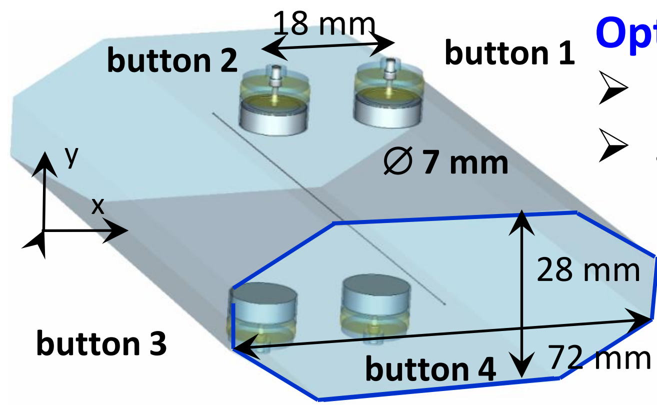
**Horizontal:** $x \propto \frac{1}{S_x}(left - right) \iff x = \frac{1}{S_x} \cdot \frac{(U_2+U_3)-(U_1+U_4)}{U_1+U_2+U_3+U_4}$

**Vertical:** $y \propto \frac{1}{S_y}(top - bottom) \iff y = \frac{1}{S_y} \cdot \frac{(U_1+U_2)-(U_3+U_4)}{U_1+U_2+U_3+U_4}$




**Optimization:**

- Horizontal distance
- Size of buttons

A.A. Nosych et al., IBIC'14

**Result:** - Non-linearity and ***xy***-coupling occur in dependence of button size and position

- Can be corrected by polynomial interpolation for beams much smaller than chamber

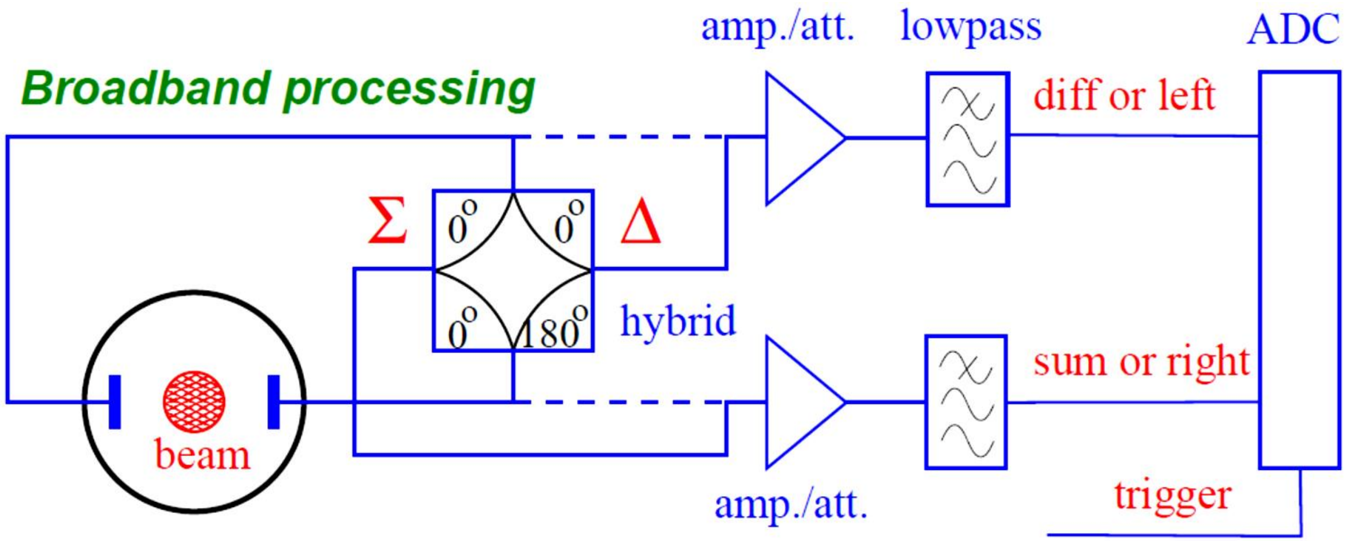
## Outline:

- Signal generation $\rightarrow$ transfer impedance
- Capacitive *button* BPM for high frequencies

  used at most proton LINACs and electron accelerators
- Electronics for position evaluation

  analog signal conditioning to achieve small signal processing
- BPMs for measurement of closed orbit, tune and further lattice functions
- Summary

# Broadband Signal Processing




- Hybrid or transformer close to beam pipe for analog ***ΔU*** & ***ΣU*** generation or $U_{left}$ & $U_{right}$
- Attenuator/amplifier
- Filter to get the wanted harmonics and to suppress stray signals
- ADC: digitalization ⟶ followed by calculation of of ***ΔU /ΣU***

**Advantage:** Bunch-by-bunch observation possible, versatile post-processing possible

**Disadvantage:** Resolution down to ≈ 100 µm for large aperture, i.e. ≈0.1% of aperture, resolution is worse than narrowband processing, see below

**Challenge**: Precise analog electronics with very low drift of amplification

# General: Noise Consideration

1. Signal voltage given by: $U_{im}(f) = Z_t(f) \cdot I_{beam}(f)$

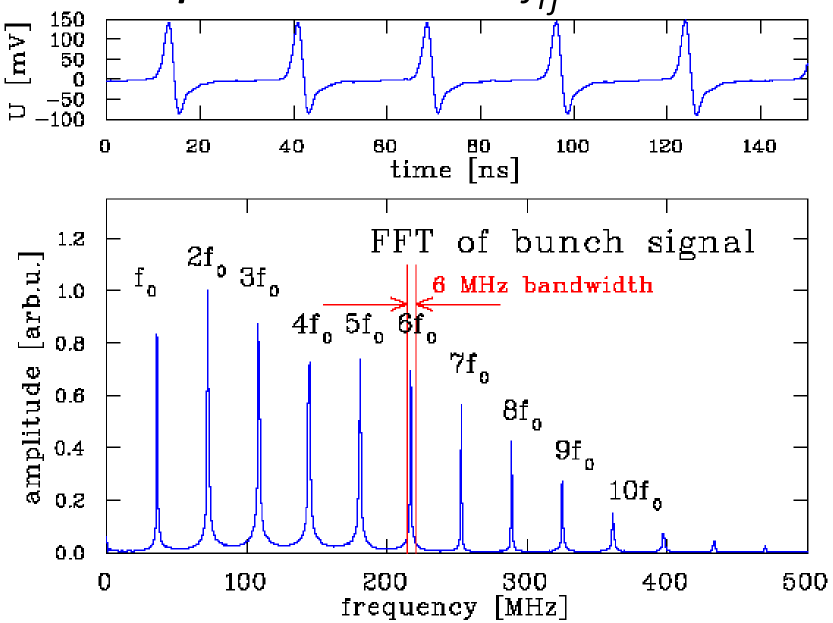
2. Thermal noise voltage given by: $U_{noise}(R, \Delta f) = \sqrt{4k_B \cdot T \cdot R \cdot \Delta f}$

Signal-to-noise $\boldsymbol{\Delta U_{im}/U_{noise}}$ is influenced by:

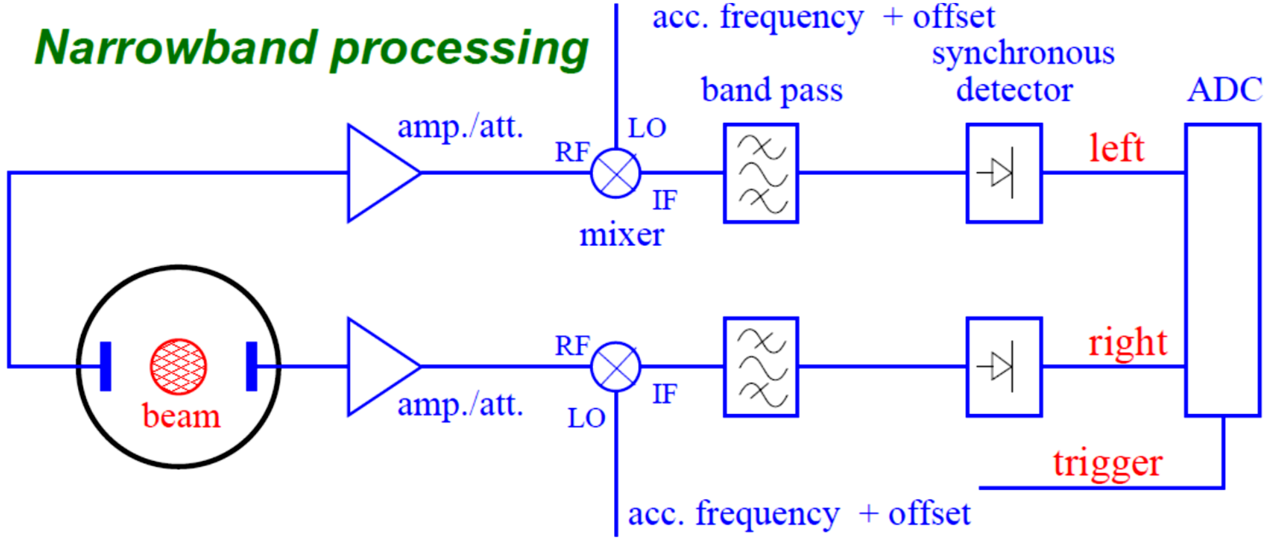
- Input signal amplitude
- Thermal noise from amplifiers etc.
- Bandwidth $\boldsymbol{\Delta f}$

$\Rightarrow$ Restriction of frequency width as the power is concentrated at harmonics $\boldsymbol{n \cdot f_{rf}}$

***Example:*** GSI-LINAC with $f_{rf}$=36 MHz



# Narrowband Processing for improved Signal-to-Noise




Narrowband processing equals heterodyne receiver (e.g. AM-radio or analog spectrum analyzer)

- Attenuator/amplifier
- Mixing with accelerating frequency $f_{LO}$

  $\Rightarrow$ IF-output: signal with difference frequency $f_{IF} = f_{LO} - f_{RF}$
- Bandpass filter of the mixed signal (e.g at 10.7 MHz)
- Rectifier: synchronous detector
- ADC: digitalization → followed calculation of $\Delta U/\Sigma U$

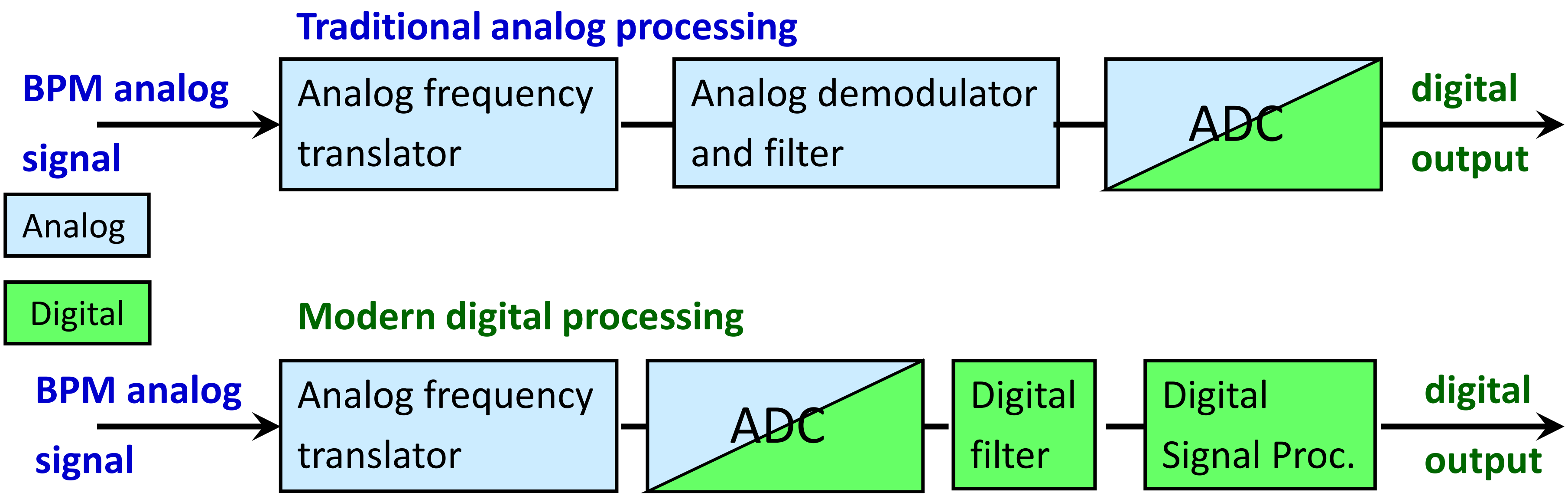
} Digital correspondence: I/Q demodulation

**Advantage:** Spatial resolution about 100 time better than broadband processing

**Disadvantage:** No turn-by-turn diagnosis, due to mixing = 'long averaging time'

# Analog versus Digital Signal Processing

Modern instrumentation uses **digital** techniques with extended functionality.




**Digital receiver as modern successor of super heterodyne receiver**

- Basic functionality is preserved but implementation is very different
- Digital transition just after the amplifier & filter or mixing unit
- Signal conditioning (filter, decimation, averaging) on FPGA

**Advantage of DSP:** Versatile operation, flexible adoption without hardware modification

**Disadvantage of DSP:** **non**, good engineering skill requires for development, expensive

# Comparison of BPM Readout Electronics (simplified)

| Type | Usage | Precaution | Advantage | Disadvantage |
|---|---|---|---|---|
| **Broadband** | p-sychr. | Long bunches | Bunch structure signal<br>Post-processing possible<br>**Required for transfer lines with few bunches** | Resolution limited by noise |
| **Narrowband** | all synchr. | Stable beams >100 rf-periods | High resolution | No turn-by-turn<br>Complex electronics |
| **Digital Signal Processing** | all | ADC sample typ. 250 MS/s | Very flexible & versatile<br>High resolution<br>**Trendsetting technology for future demands** | **Basically non!**<br>Limited time resolution by ADC $\rightarrow$ under-sampling<br>Man-power intensive |

$\longrightarrow$ Stripline BPM

## Outline:

- Signal generation → transfer impedance
- Capacitive *button* BPM for high frequencies
  used at most proton LINACs and electron accelerators
- Electronics for position evaluation
  analog signal conditioning to achieve small signal processing
- **BPMs for measurement of closed orbit, tune and further lattice functions**
  **frequent application of BPMs**
- Summary

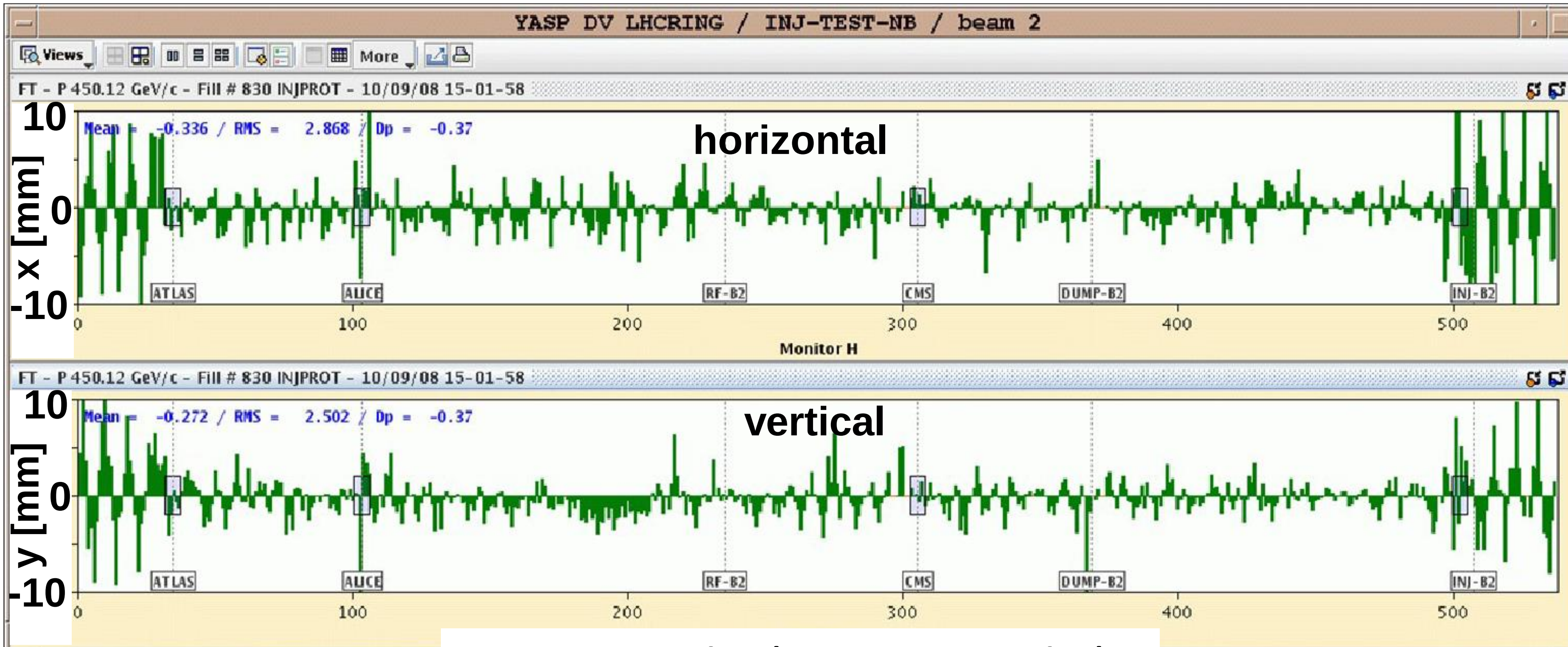
# Trajectory Measurement with BPMs

**Trajectory:**

The position delivered by an **individual bunch** within a transfer line or a synchrotron.

Main task: Control of matching (center and angle), first-turn diagnostics

***Example:*** LHC injection 10/09/08 i.e. first day of operation !




**Monitor number (530 BPMs on 27 km)**

Courtesy R. Jones (CERN)

Tune values at LHC: $Q_h = 64.3$, $Q_v = 59.3$

# Closed Orbit Feedback: Typical Noise Sources

**Beam movement:**

**Short term (min to 10 ms):**

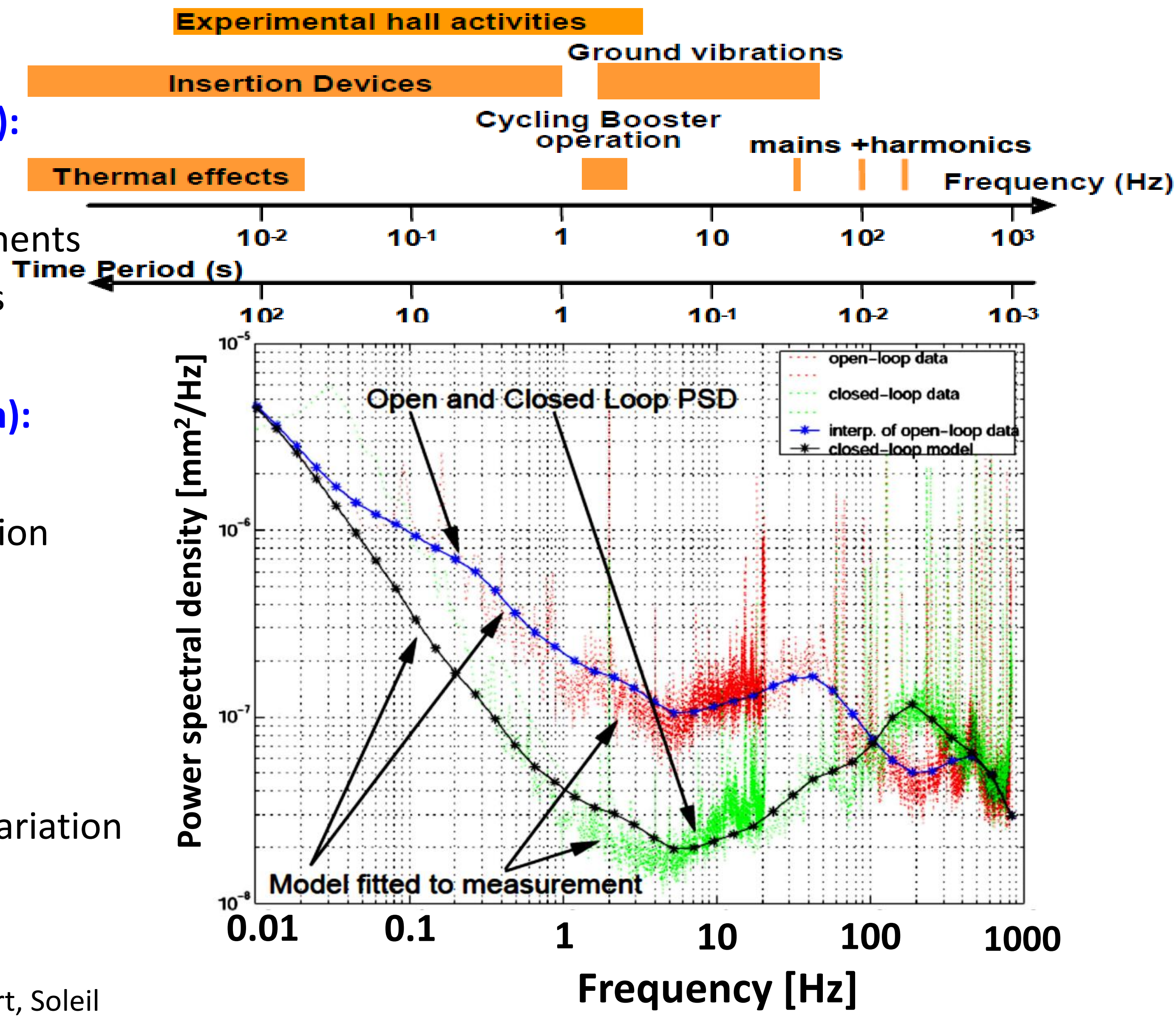
- Traffic
- Machine (crane) movements
- Water & vacuum pumps
- 50 Hz main power net

**Medium term (day to min):**

- Movement of chambers due to heating by radiation
- Day-night variation
- Tide, moon cycle

**Long term ( > days):**

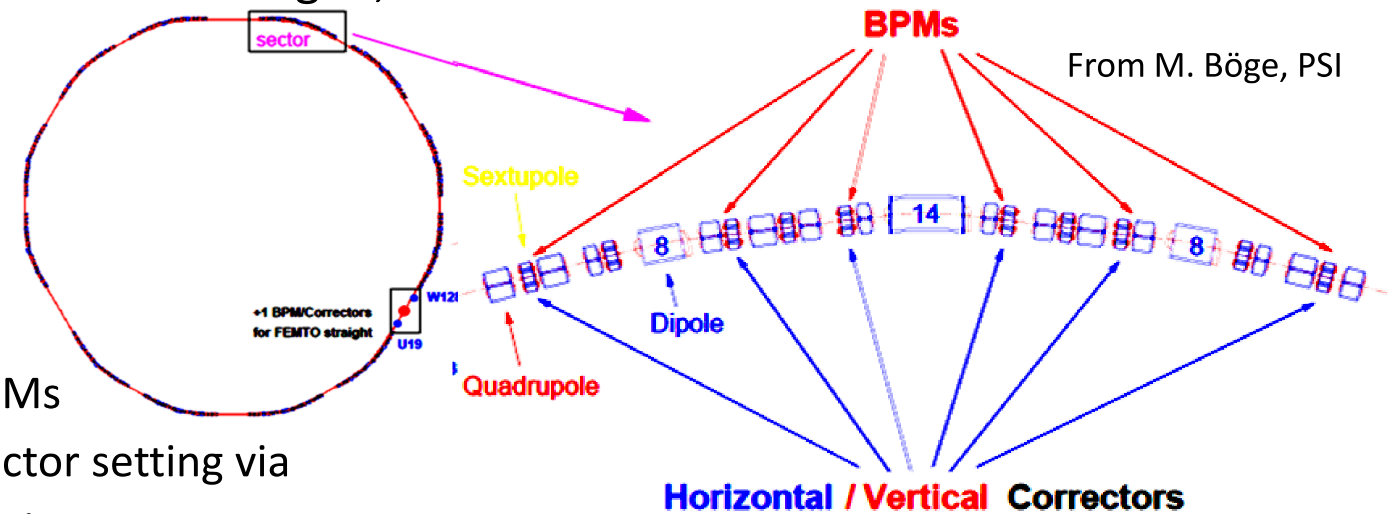
- Ground settlement
- Seasons, temperature variation




Courtesy M. Böge, PSI, N. Hubert, Soleil

**Orbit feedback:** Synchrotron light source → spatial stability of light beam

*Example:* SLS-Synchrotron at Villigen, Switzerland




**Feedback loop:**

**1.** Position from all BPMs

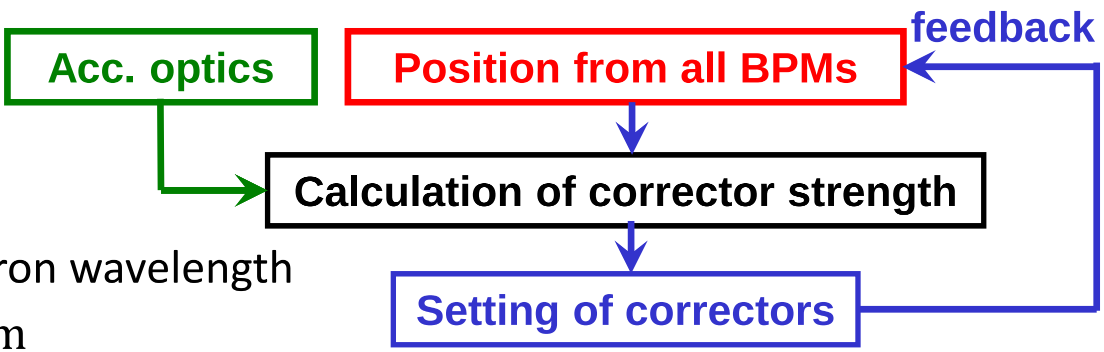
**2.** Calculation of corrector setting via Orbit Response Matrix

**3.** Change of magnet setting

**1.'** New positon measurement .....

⇒ regulation time down to 10 ms

⇒ Role od thumb: ≈ 4 BPMs per betatron wavelength




**Uncorrected orbit:** typ. $\langle x \rangle_{rms} \approx 1$ mm

**Corrected orbit:** typ. $\langle x \rangle_{rms} \approx 1$ µm up to ≈ 100 Hz bandwidth!

Orbit Response Matrix: See lecture 'Imperfections and Corrections' by Volker Ziemann

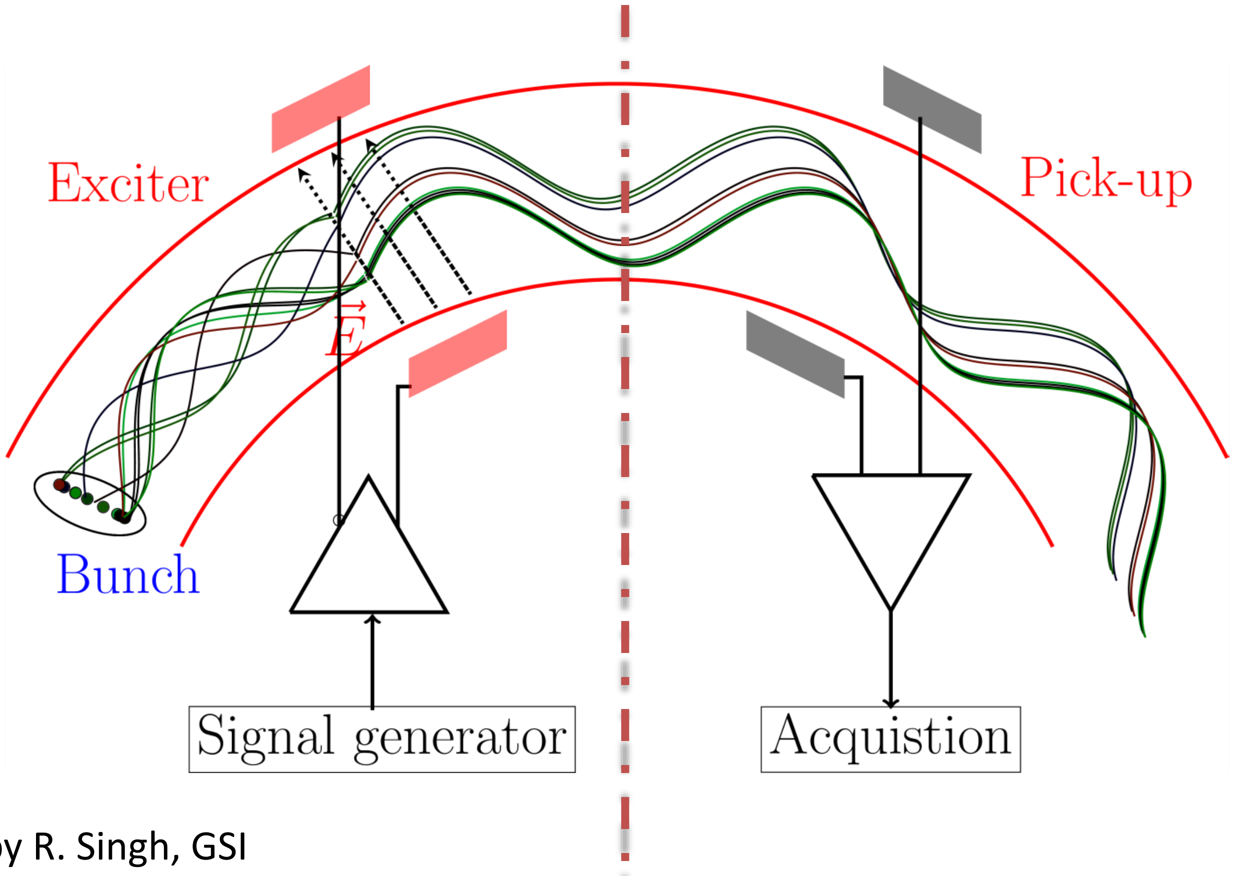
# Tune Measurement: General Considerations

**Coherent excitations are required for the detection by a BPM**

Beam particle's ***in-coherent*** motion ⇒ center-of-mass stays constant

Excitation of **all** particles by rf ⇒ ***coherent*** motion

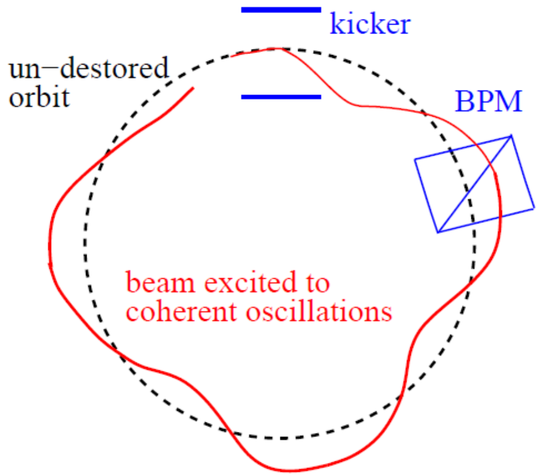
⇒ center-of-mass variation turn-by-turn i.e. center acts as **one** macro-particle

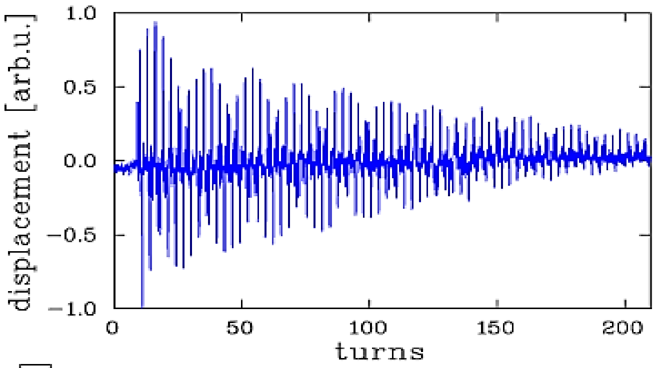


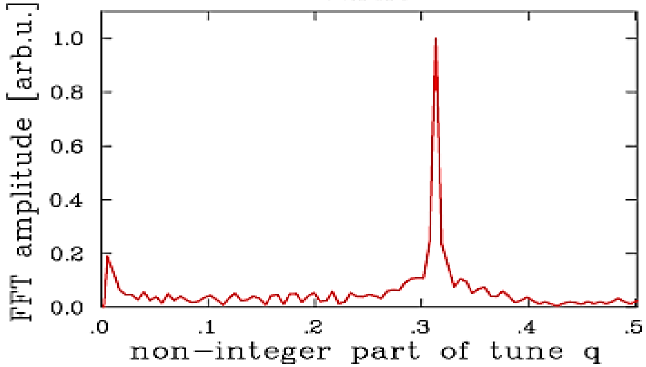

Graphics by R. Singh, GSI

# Tune Measurement: The Kick-Method in Time Domain

The beam is excited to
**coherent** betatron oscillation:
$\rightarrow$ Beam position measured each revolution ('turn-by-turn')
$\rightarrow$ Fourier Trans. gives non-integer tune ***q***.
Short kick compared to revolution.

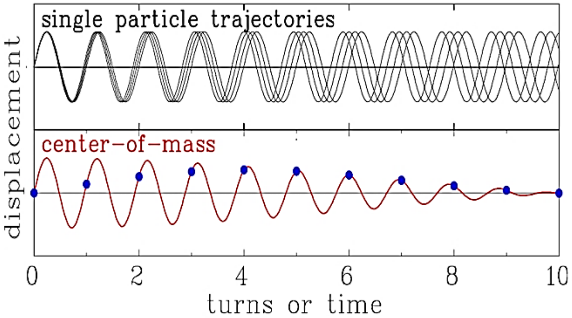



The de-coherence time limits the **resolution**:
***N*** non-zero samples
$\Rightarrow$ General limit of discrete FFT: $\Delta q > \frac{1}{2N}$

Here: ***N*** = 200 turn $\Rightarrow$ $\Delta q > 0.003$
(tune spreads can be $\Delta q \approx 0.001$!)



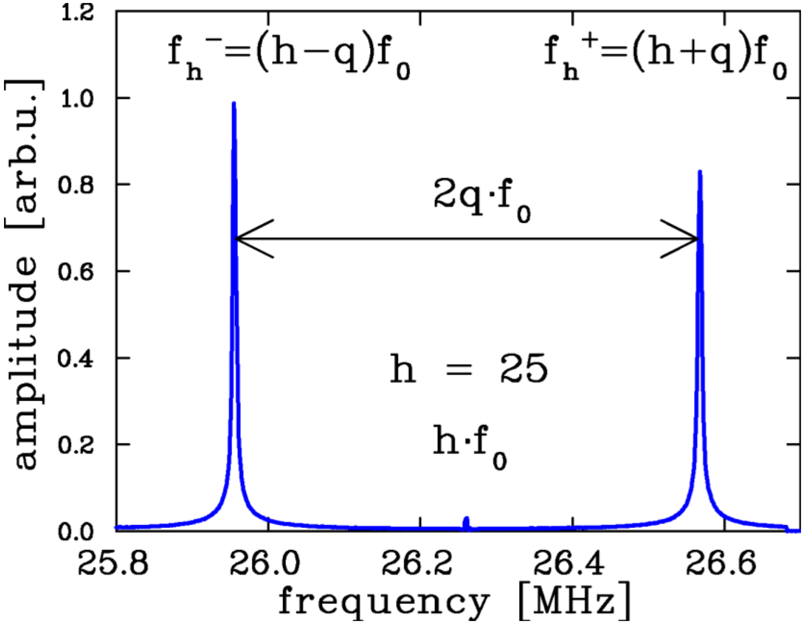

Decay is caused by de-phasing, **not** by decreasing single particle amplitude.

See lecture 'Time and Frequency Domain Signals' by Hermann Schmickler

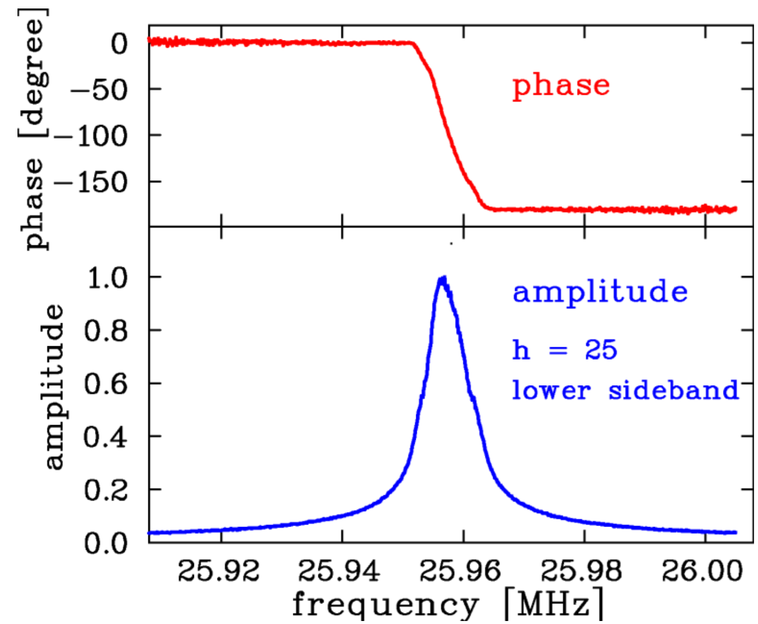
# Tune Measurement: Frequency Chirp Measurement

**Principle:** Slowly scan of the excitation frequency $\rightarrow$ beam acts as driven oscillator!
(sometimes refer to as **B**eam **T**ransfer **F**unction **BTF** measurement)

*SIS-synchrotron: A wide scan with both sidebands at h=25$^{th}$-harmonics:*




*A detailed scan for the **lower** sideband $\rightarrow$ beam acts like a driven oscillator:*




From the position of the sidebands ***q*** = 0.306 is determined.

**Advantage:** High resolution for tune and tune spread (also for de-bunched beams)

**Disadvantage:** Long sweep time (up to several seconds).

# Tune Measurement: *Gentle* Excitation with Wideband Noise

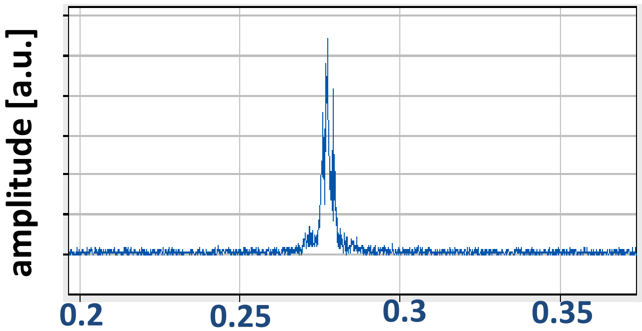
Instead of a sine wave, **noise** with adequate bandwidth can be applied

**→ beam picks out its resonance frequency:**

- Broadband excitation with white noise of ≈ 10 kHz bandwidth
- Turn-by-turn position measurement
- Fourier transformation of the recorded data

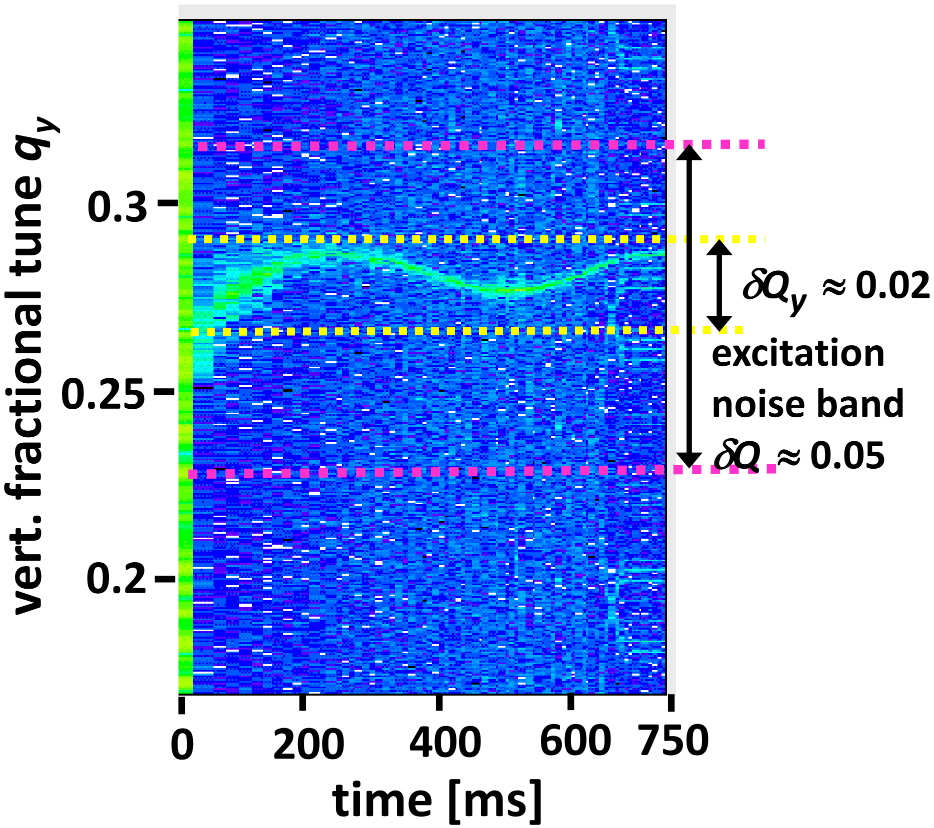
⇒ Continues monitoring with low disturbance

**vertical tune at fixed time ≈ 15ms**




***Example:*** Vertical tune within 4096 turn duration ≃ 15 ms at GSI synchrotron 11 → 300 MeV/u in 0.7 s

**vertical tune versus time**




**Advantage:**
Fast scan with good time resolution
**Disadvantage:** Lower tune resolution

U. Rauch et al., DIPAC 2009

# Chromaticity Measurement from Closed Orbit Data

***Chromaticity ξ:*** Change of tune for off-momentum particle $\frac{\Delta Q}{Q} = \xi \cdot \frac{\Delta p}{p}$

Two step measurement procedure:

1. Change of momentum ***p*** by detuned rf-frequency $\frac{\Delta p}{p} = \eta^{-1} \cdot \frac{\Delta f_{acc}}{f_{acc}}$

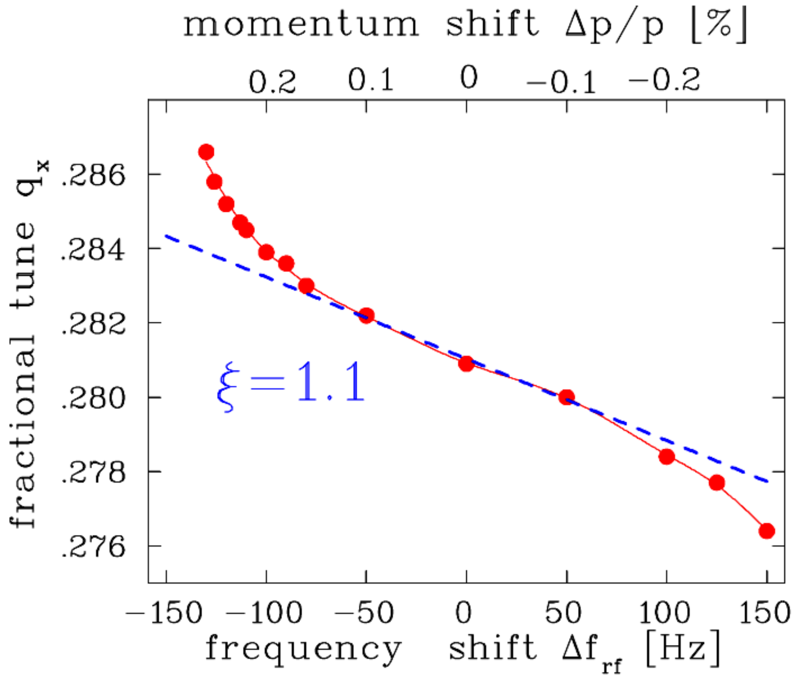
2. Excitation of coherent betatron oscillations and tune measurement

(kick-method, BTF, noise excitation):

Plot of ***ΔQ/Q*** as a function of ***Δp/p***

⇒ slope is dispersion ***ξ***.

Example: Measurement at LEP:




From M Minty, F. Zimmermann,
Measurement and Control of charged Particle Beam,
Springer Verlag 2003

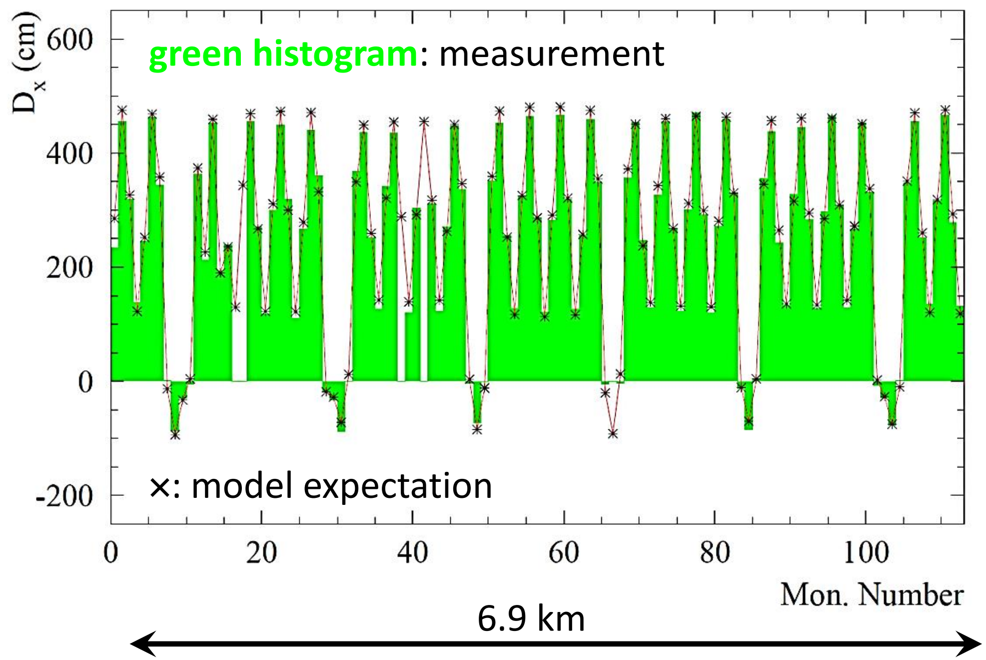
# Dispersion Measurement from Closed Orbit Data

***Dispersion $D(s_i)$:*** Change of momentum ***p*** by detuned rf-cavity

→ Position reading at one location $x_i = D(s_i) \cdot \frac{\Delta p}{p}$:

→ Result from plot of $x_i$ as a function of $\Delta p/p$ ⇒ slope is local dispersion $D(s_i)$

*Example:* Dispersion measurement ***D(s)*** at BPMs at CERN SPS




Theory-experiment correspondence after correction of

- BPM calibration
- quadrupole calibration

From J. Wenninger: CAS on BD, CERN-2009-005 & J. Wenninger CERN-AB-2004-009

See lecture 'Imperfections and Corrections' by Volker Ziemann

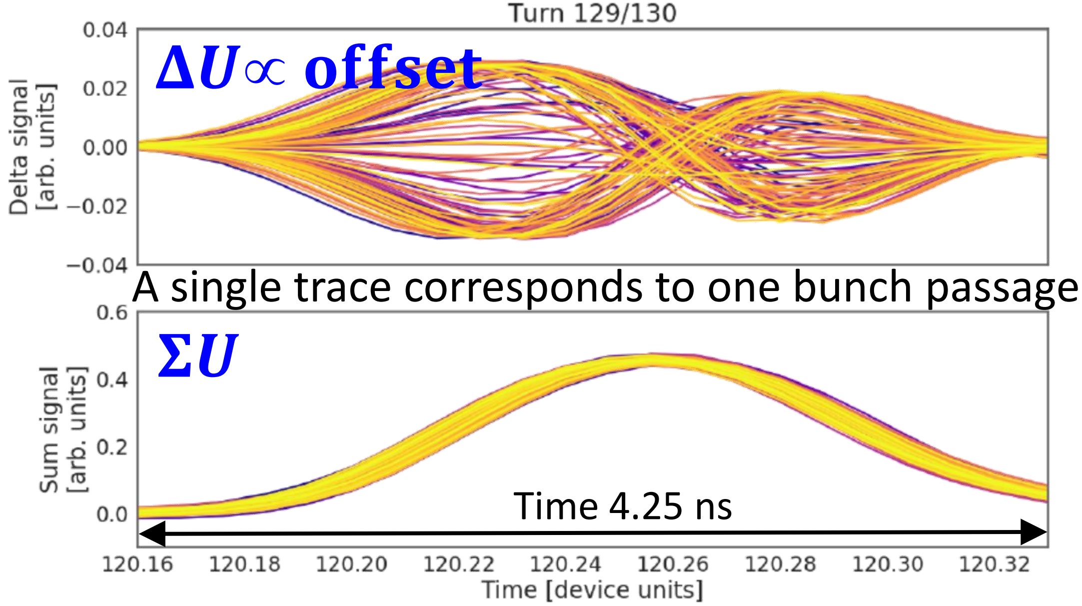
# Intra-Bunch Observation

High band-width measurements delivers:

- Bunch shape given by the sum $\Sigma U(t) = U_{right}(t) + U_{left}(t)$ of two plates
- Intra-bunch movement of the **center** by $x_{center}(t) \propto \Delta U(t) = U_{right}(t) - U_{left}(t)$

*Example:* Single bunch observation on **turn-by-turn** basis with beam excitation at SPS

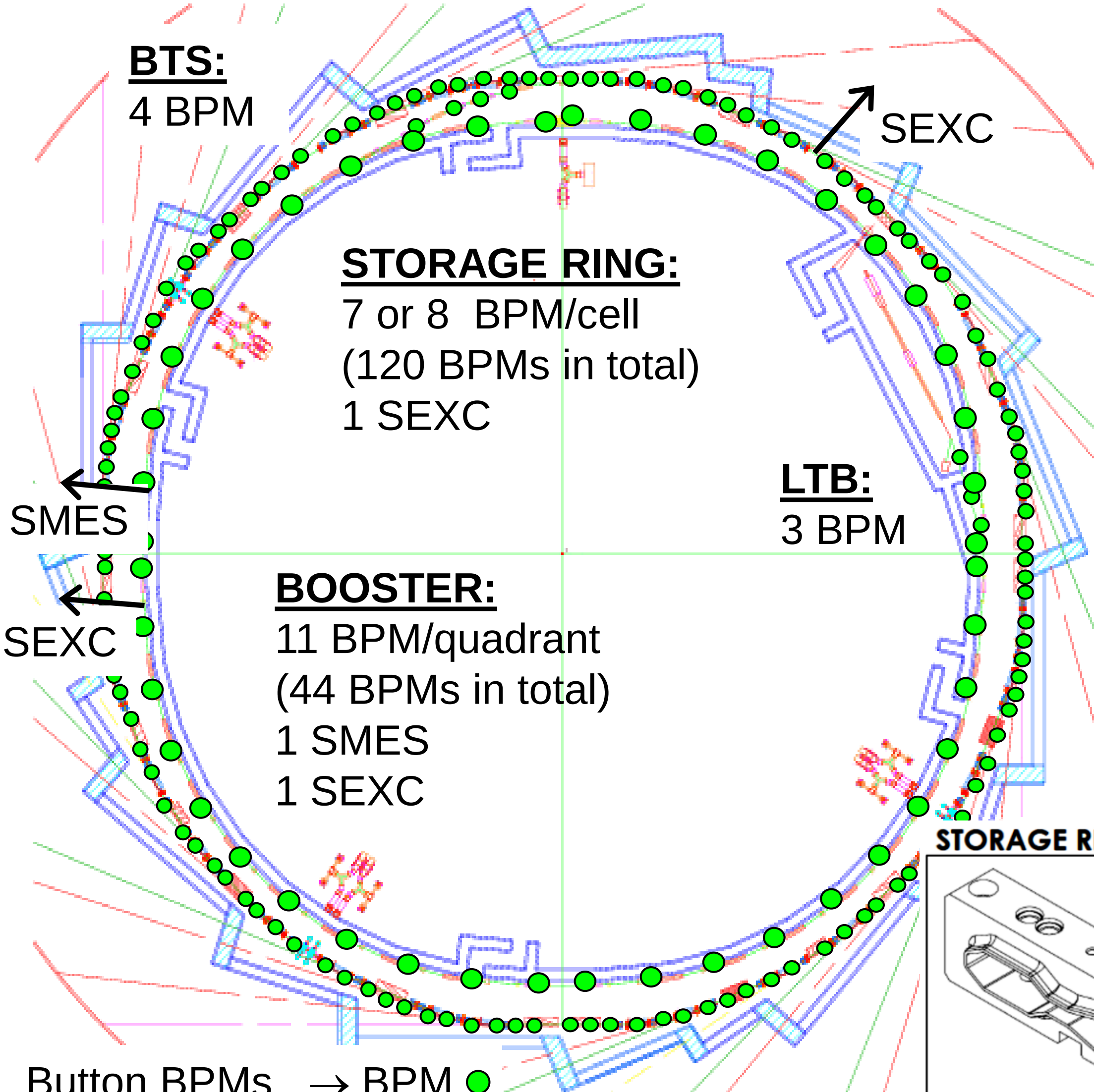
Goal: Monitoring instabilities




(a) Headtail mode 1 for chromaticity $\xi = 0.2$

*Courtesy Kevin Li, CAS Proceedings 2022*

See lecture 'Collective Effects' by Kevin Li



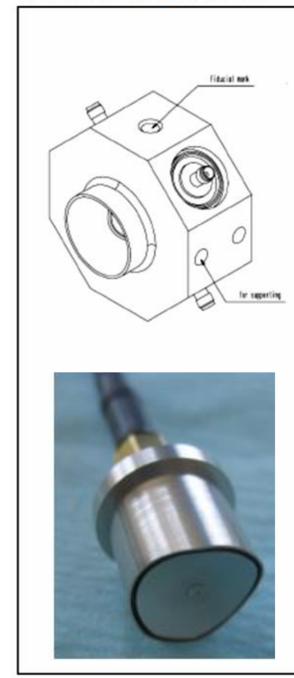

Button BPMs → BPM ●
Meas. Stripline → SMES ↑
Exc. Stripline → SEXC ↑

**Beam position:**

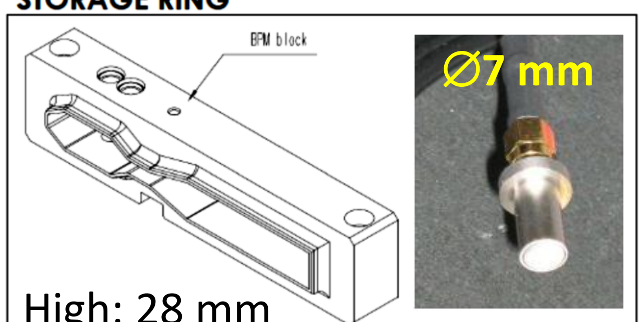
- Many locations!
- Frequent operating tool
- For position stabilization i.e. closed orbit feedback

Tune: $Q_x = 18.18$ & $Q_y = 8.37$

BOOSTER and BTS



STORAGE RING




From U. Iriso, ALBA

# Summary Pick-Ups for bunched Beams

The electric field is monitored for bunched beams using rf-technologies ('frequency domain'). Beside transformers they are the most often used instruments!

**Differentiated or proportional signal:** rf-bandwidth ↔ beam parameters

**Proton synchrotron**: 1 to 100 MHz, mostly 1 MΩ → proportional shape

**LINAC, $e^-$-synchrotron:** 0.1 to 3 GHz, 50 Ω → differentiated shape

**Important quantity:** Transfer impedance $Z_t(\omega, \beta)$.

**Types of capacitive pick-ups:**

Linear-cut (p-synch.), button (p-LINAC, $e^-$-LINAC and synch.)

**Position reading:** Difference signal of two or four pick-up plates (BPM):

- Non-intercepting reading of center-of-mass → online measurement and control
  ***Synchrotron: Fast*** reading***, 'bunch-by-bunch'*** → trajectory, ***slow** reading* → closed orbit
- ***Synchrotron:*** Excitation of ***coherent*** betatron oscillations ⇒ tune ***q, ξ, β(s), D(s)...***

Remark: BPMs have high pass characteristic ⇒ no signal for dc-beams

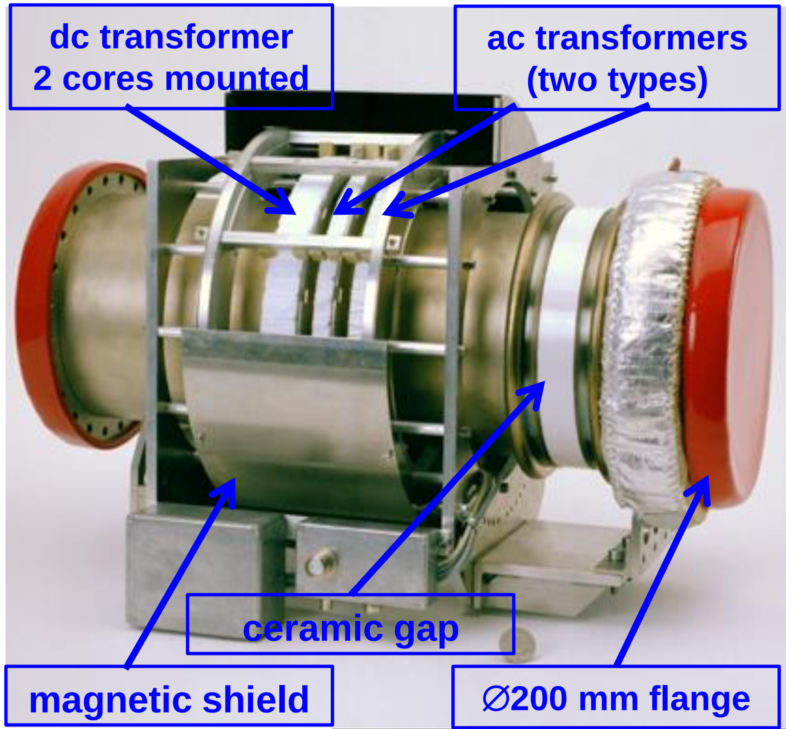
**Thank you for your attention!**

# Backup slides

# The dc Transformer Realization

## *Example*: The DCCT at GSI synchrotron

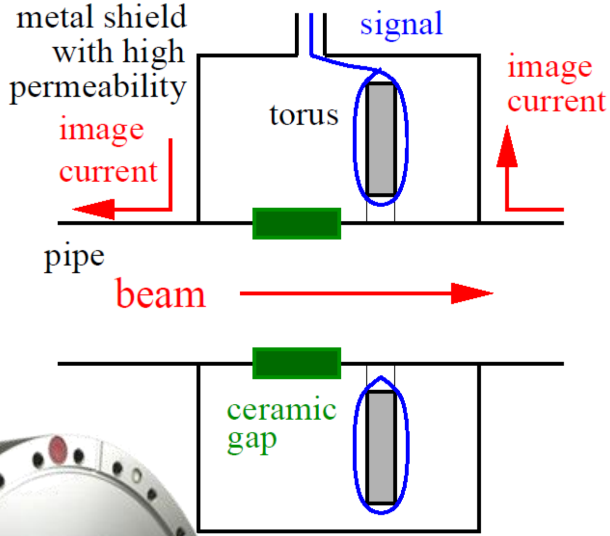
| | |
|---|---|
| Torus radii | $r_i$ = 135 mm $r_o$=145 mm |
| Torus thickness | d = 10 mm |
| Torus permeability | $\mu_r = 10^5$ |
| Saturation inductance | $B_{sat}$ = 0.6 T |
| Number of windings | 16 for modulation & sensing<br>12 for feedback |
| Resolution | $I^{min}_{beam}$ = 2 μA |
| Bandwidth | $\Delta f$ = dc .... 20 kHz |
| Rise time constant | $\tau_{rise}$ = 10 μs |
| Temperature drift | 1.5 μA/°C |

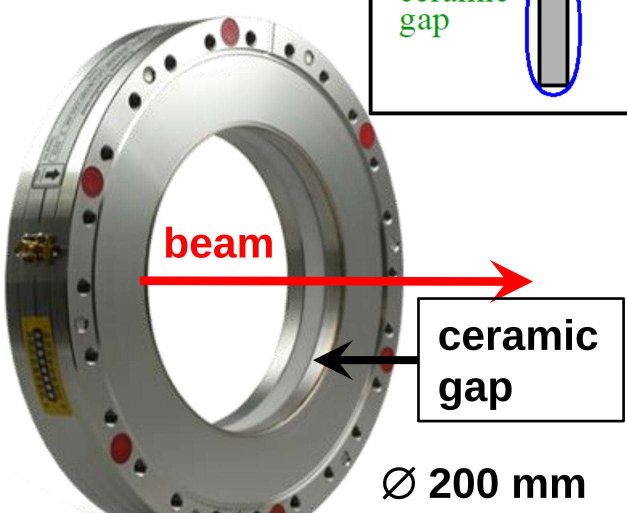



# Shielding of a Transformer

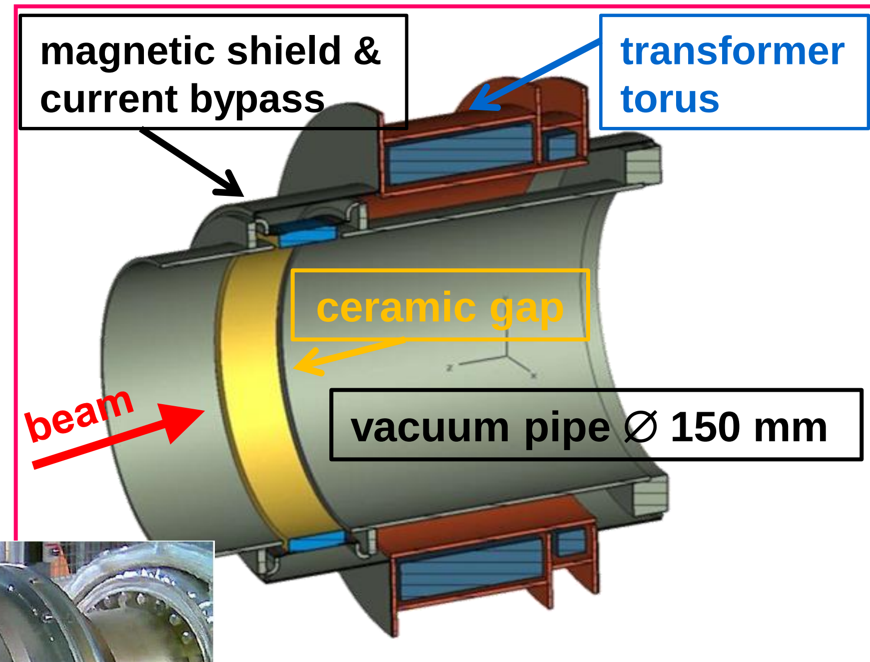
**Task of the shield:**

- The image current of the walls have to be bypassed by a gap and a metal housing.
- This housing uses μ-metal and acts as a shield of external B-field
  (remember: $I_{beam}$ = 1 μA, $r$ = 10 cm ⇒ $B_{beam}$ = 2pT, earth field $B_{earth}$ = 50 μT)




courtesy Company Bergoz



# Pick-Ups for bunched Beams

## Outline:

- Signal generation → transfer impedance
- Capacitive *button* BPM for high frequencies
  used at most proton LINACs and electron accelerators
- **Capacitive *linear-cut* BPM for low frequencies**
  **used at most proton synchrotrons due to linear position reading**
- Electronics for position evaluation
- BPMs for measurement of closed orbit, tune and further lattice functions
- Summary

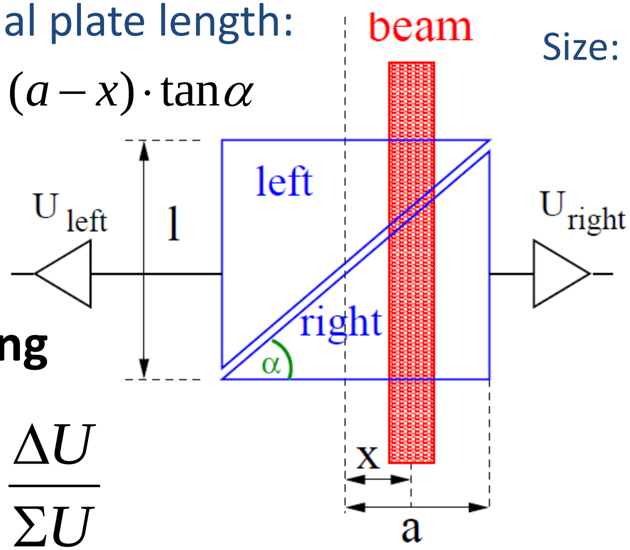
# Linear-cut BPM for Proton Synchrotrons

Frequency range: 1 MHz < $f_{rf}$ < 100 MHz $\Rightarrow$ bunch-length >> BPM length.

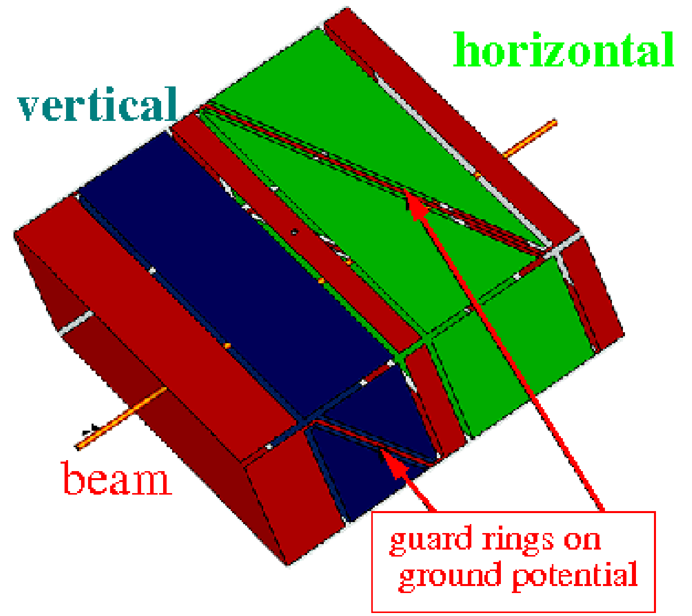
Signal is proportional to actual plate length:

$$l_{right} = (a+x)\cdot\tan\alpha, \quad l_{left} = (a-x)\cdot\tan\alpha$$

$$\Rightarrow \quad x = a \cdot \frac{l_{right} - l_{left}}{l_{right} + l_{left}}$$

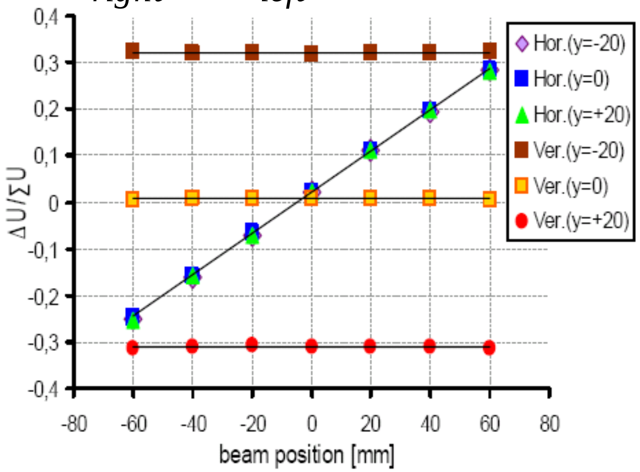



Size: 200x70 mm²




**In ideal case: linear reading**

$$x = a \cdot \frac{U_{right} - U_{left}}{U_{right} + U_{left}} \equiv a \cdot \frac{\Delta U}{\Sigma U}$$




**Linear-cut BPM:**

**Advantage:** Linear, i.e. constant position sensitivity ***S***

$\Leftrightarrow$ no beam size dependence

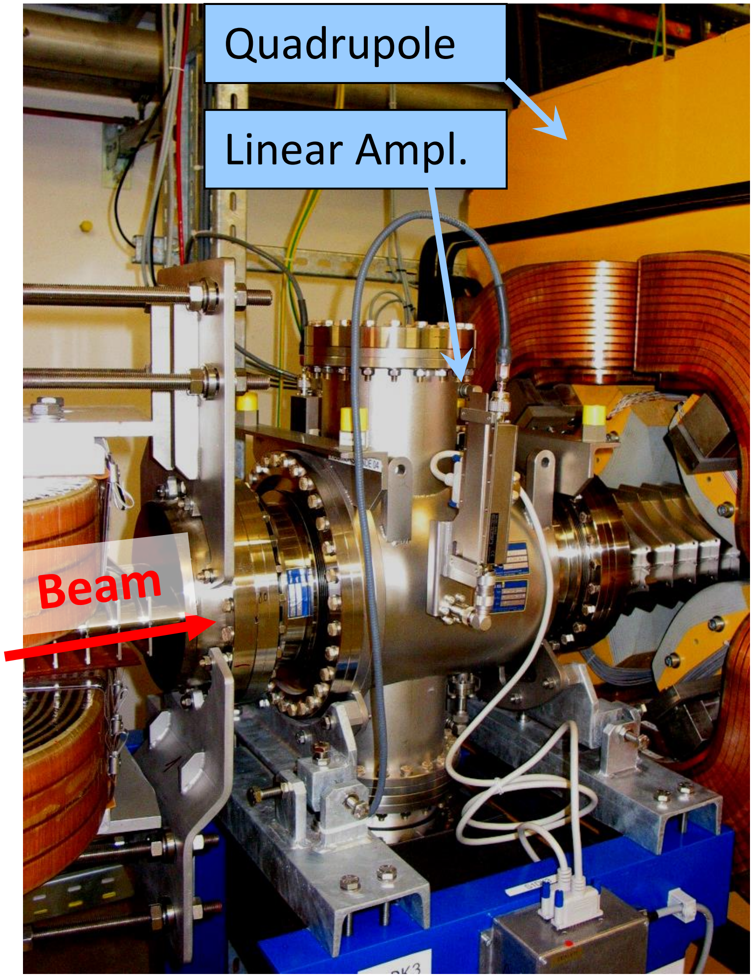
**Disadvantage:** Large size, complex mechanics

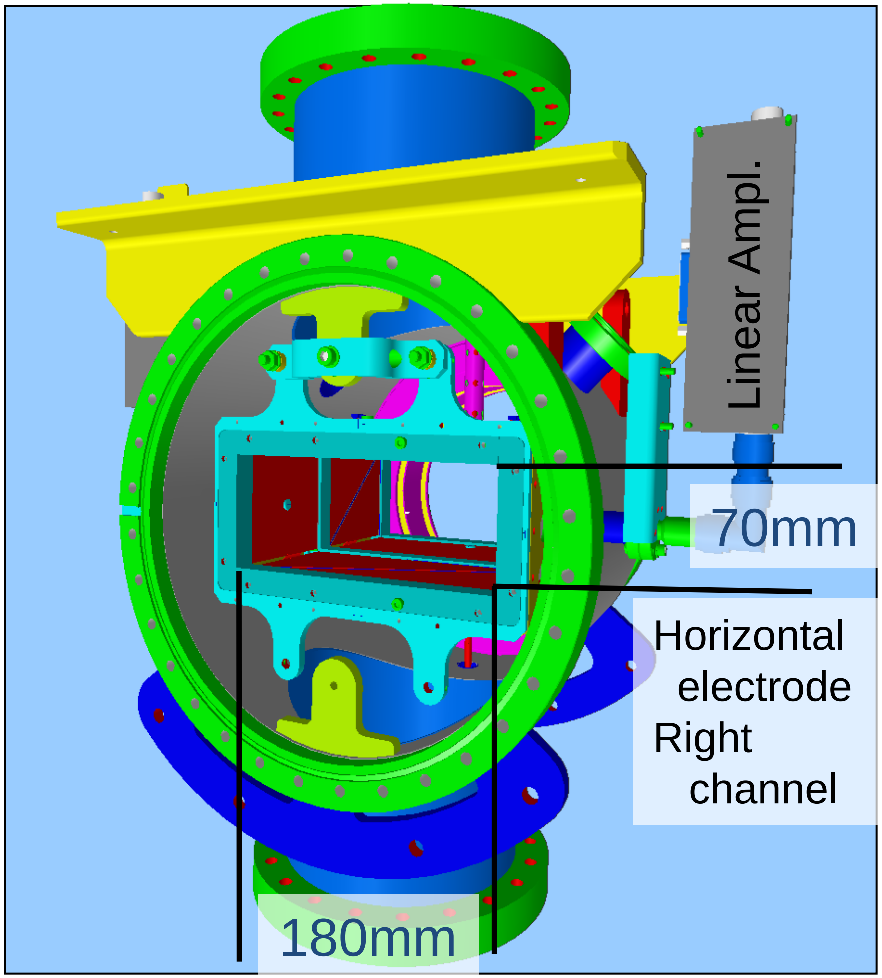
high capacitance

# Technical Realization of a linear-cut BPM

Technical realization at HIT synchrotron of 46 m length for 7 MeV/u→ 440 MeV/u

BPM clearance: 180x70 mm$^2$, standard beam pipe diameter: 200 mm.



# Technical Realization of a linear-cut BPM

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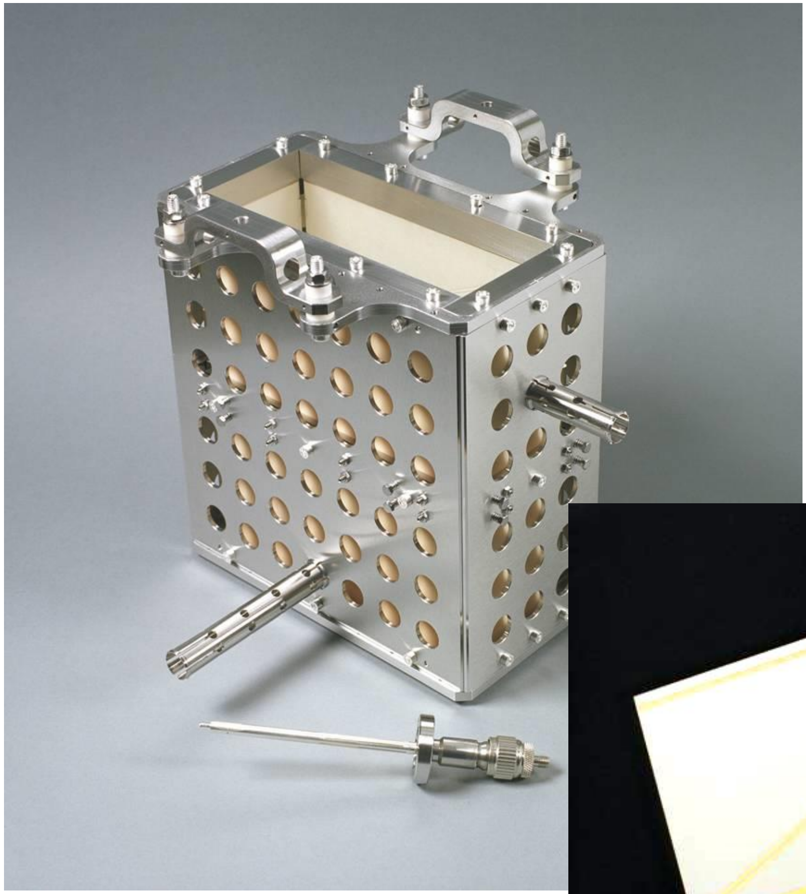
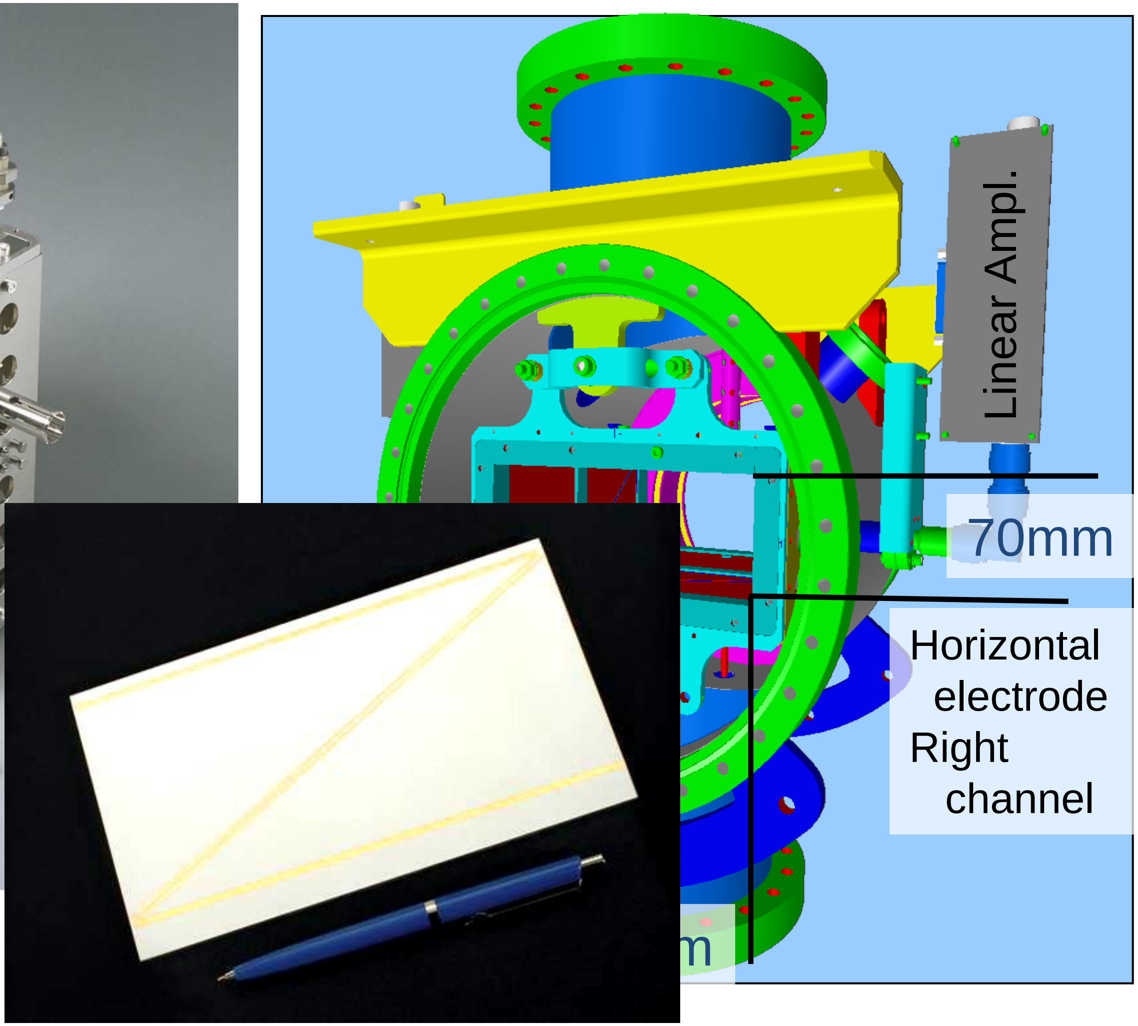
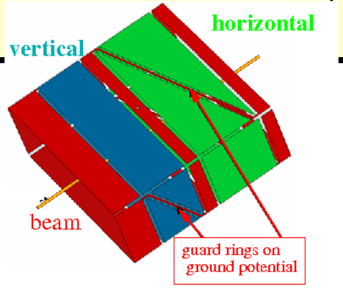
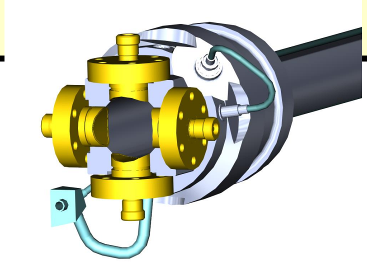




# Comparison linear-cut and Button BPM

| | Linear-cut BPM | Button BPM |
|---|---|---|
| **Precaution** | Bunches longer than BPM | Bunch length comparable to BPM |
| **BPM length (typical)** | 10 to 20 cm length per plane | ∅1 to 5 cm per button |
| **Shape** | Rectangular or cut cylinder | Orthogonal or planar orientation |
| **Bandwidth (typical)** | 0.1 to 100 MHz | 100 MHz to 5 GHz |
| **Coupling** | 1 MΩ or ≈1 kΩ (transformer) | 50 Ω |
| **Cutoff frequency (typical)** | 0.01… 10 MHz ($C$=30…100pF) | 0.3… 1 GHz ($C$=2…10pF) |
| **Linearity** | Very good, no x-y coupling | Non-linear, x-y coupling |
| **Sensitivity** | Good, care: plate cross talk | Good, care: signal matching |
| **Usage** | At proton synchrotrons, $f_{rf}$ < 10 MHz | All electron acc., proton Linacs, $f_{rf}$ > 100 MHz |



**Remark:** Other types are also some time used: e.g. strip-line, wall current monitors, inductive antenna, BPMs with external resonator, cavity BPM, slotted wave-guides etc.

## Outline:

- Signal generation $\rightarrow$ transfer impedance
- Capacitive *button* BPM for high frequencies
  used at most proton LINACs and electron accelerators
- **Stripline BPMs for hight frequencies**
  **used at colliders with counter-propagating beams**
- Electronics for position evaluation
- BPMs for measurement of closed orbit, tune and further lattice functions
- Summary

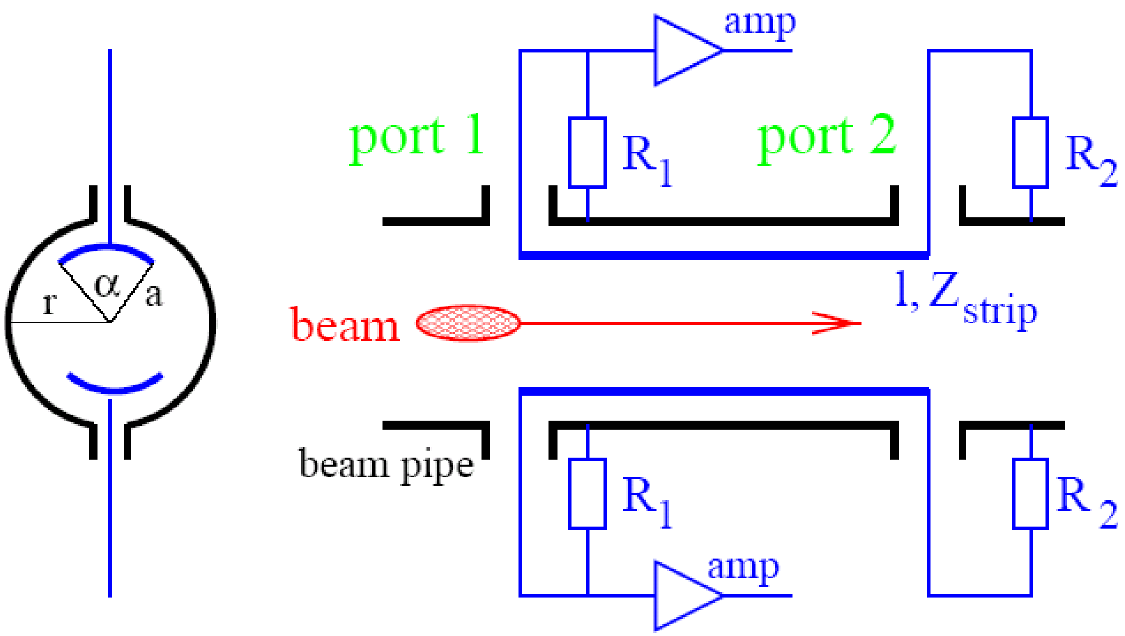
# Stripline BPM: General Idea

For short bunches, the ***capacitive*** button deforms the signal

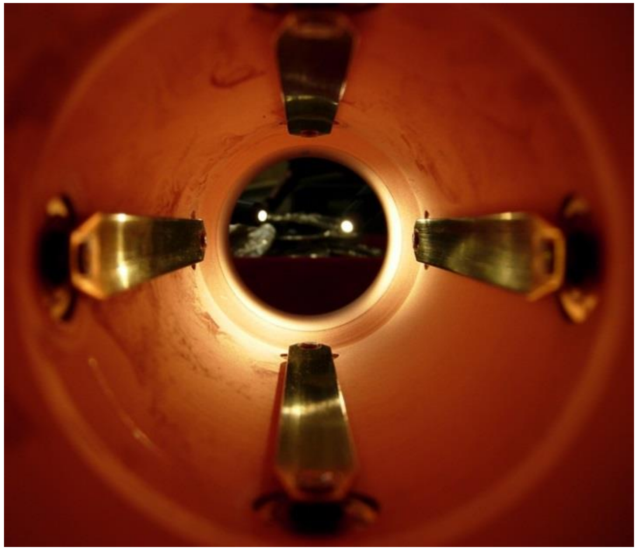
$\rightarrow$ Relativistic beam $\beta \approx 1 \Rightarrow$ field of bunches nearly TEM wave

$\rightarrow$ Bunch's electro-magnetic field induces a **traveling pulse** at the strips

$\rightarrow$ Assumption: Bunch shorter than BPM, $Z_{strip} = R_1 = R_2 = 50\ \Omega$ and $v_{beam} = c_{strip}$




LHC stripline BPM, $l$ = 12 cm



From C. Boccard, CERN

# Stripline BPM: General Idea

For relativistic beam with $\beta \approx 1$ and short bunches:

→ Bunch's electro-magnetic field induces a **traveling pulse** at the strip

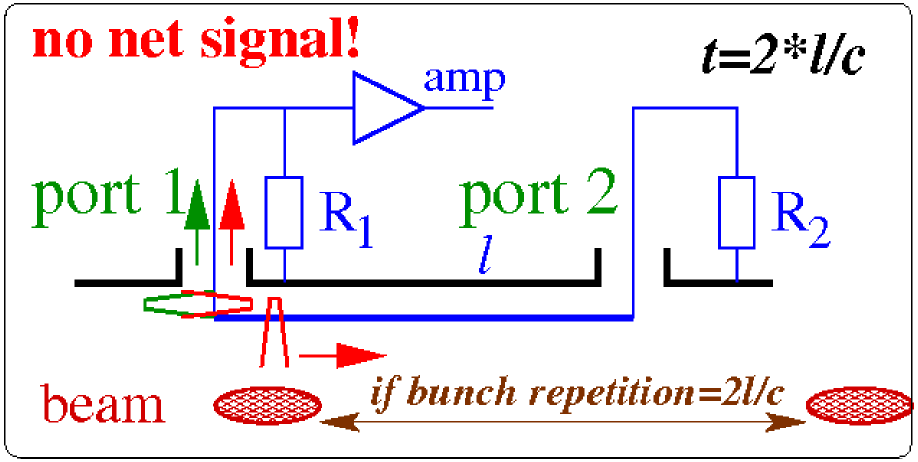
→ ***Assumption:*** $l_{bunch} << l$, $Z_{strip}=R_1=R_2=50\ \Omega$ and $v_{beam}=c_{strip}$

**Signal treatment at upstream port 1:**

***t=0:*** Beam induced charges at **port 1**:
→ half to $R_1$, half toward **port 2**

***t=l/c:*** Beam induced charges at **port 2**:
→ half to $R_2$, ***but*** due to different sign, it cancels with the signal from **port 1**
→ half signal reflected

***t=2·l/c:*** reflected signal reaches **port 1**




$$\Rightarrow U_1(t) = \frac{1}{2} \cdot \frac{\alpha}{2\pi} \cdot Z_{strip} \left( I_{beam}(t) - I_{beam}(t - 2l/c) \right)$$

***If beam repetition time equals 2·l/c: reflected preceding port 2 signal cancels the new one***:
→ no net signal at **port 1**

**Signal at downstream port 2:** Beam induced charges cancel with traveling charge from port 1

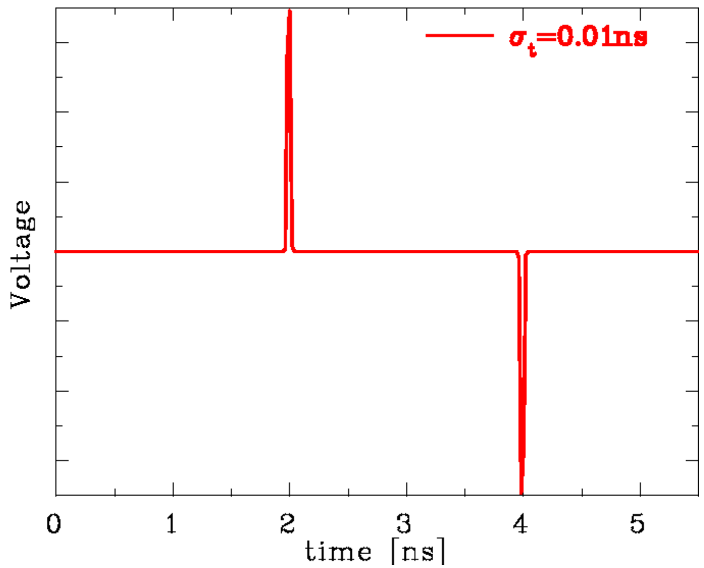
⇒ Signal depends on direction ⇔ **can distinguish between counter-propagation beams**

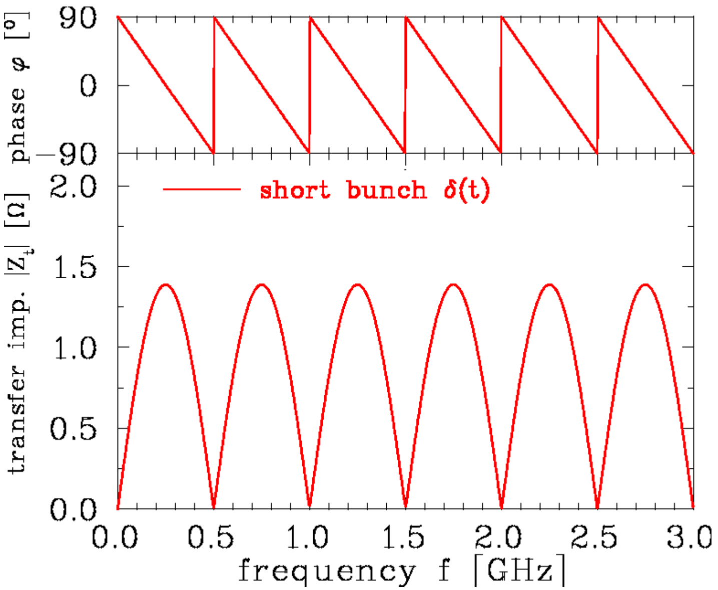
# Stripline BPM: Transfer Impedance

The signal from port 1 and the reflection from port 2 can cancel ⇒ minima in $\boldsymbol{Z_t}$.

For short bunches $\boldsymbol{I_{beam}(t) \to Ne \cdot \delta(t)}$: $$Z_t(\omega) = Z_{strip} \cdot \frac{\alpha}{2\pi} \cdot \sin(\omega l / c) \cdot e^{i(\pi/2 - \omega l/c)}$$

Stripline length $l$=30 cm, α=10$^0$



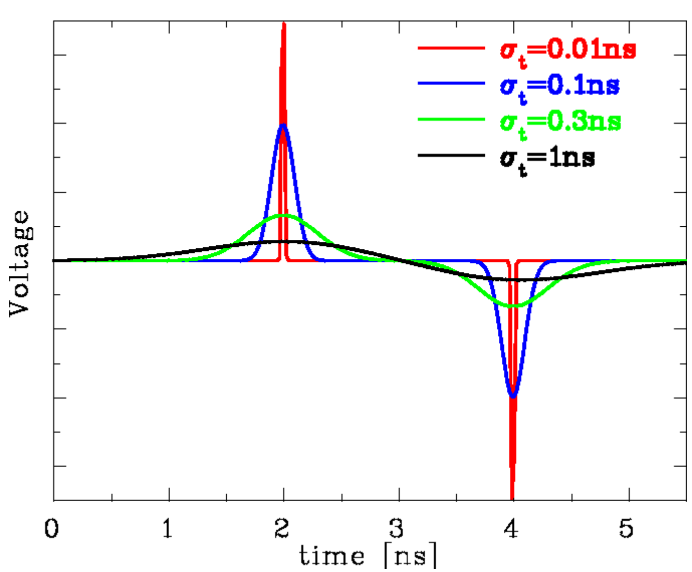

- $Z_t$ show maximum at $l=c/4f=\lambda/4$ i.e. 'quarter wave coupler' for bunch train
  ⇒ $l$ has to be matched to $v_{beam}$
- No signal for $l=c/2f=\lambda/2$ i.e. destructive interference with **subsequent** bunch
- Around maximum of $|Z_t|$: phase shift $\varphi=0$ i.e. direct image of bunch
- $f_{center}=1/4 \cdot c/l \cdot (2n-1)$. For first lope: $f_{low}=1/2 \cdot f_{center}$, $f_{high}=3/2 \cdot f_{center}$ i.e. bandwidth $\approx 1/2 \cdot f_{center}$
- Precise matching at feed-through required t o preserve 50 Ω matching.

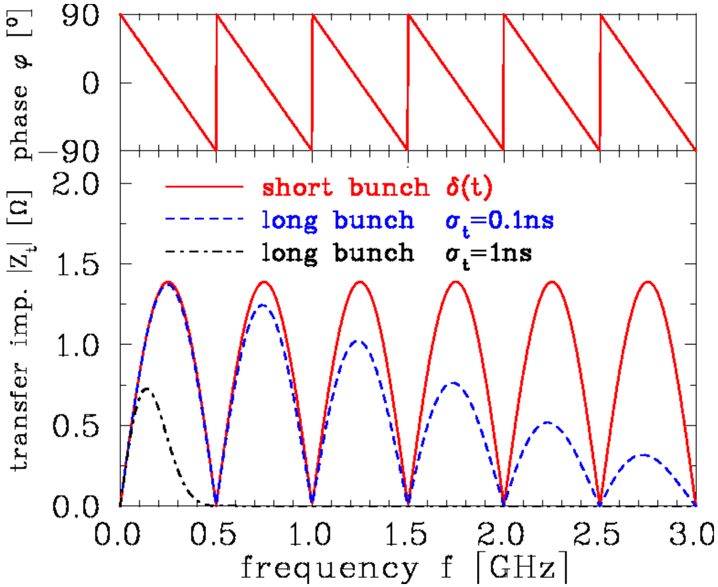
# Stripline BPM: Transfer Impedance

The signal from port 1 and the reflection from port 2 can cancel $\Rightarrow$ minima in $\boldsymbol{Z_t}$.

For bunches of length $\boldsymbol{\sigma}$: $\Rightarrow Z_t(\omega) = Z_{strip} \cdot \frac{\alpha}{2\pi} \cdot e^{-\omega^2\sigma^2/2} \cdot \sin(\omega l/c) \cdot e^{i(\pi/2-\omega l/c)}$

Stripline length *l*=30 cm, α=10⁰




- *$Z_t(\omega)$* decreases for higher frequencies
- If total bunch is too long **$\pm 3\sigma_t > l$** destructive interference leads to signal damping

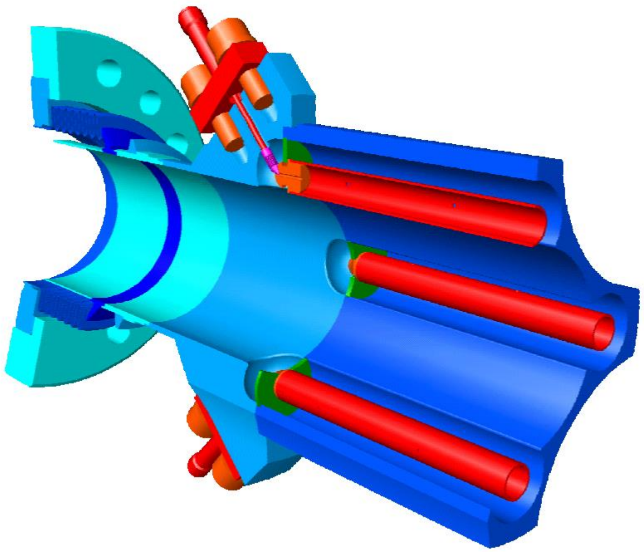
  ***Cure:*** length of stripline has to be matched to bunch length

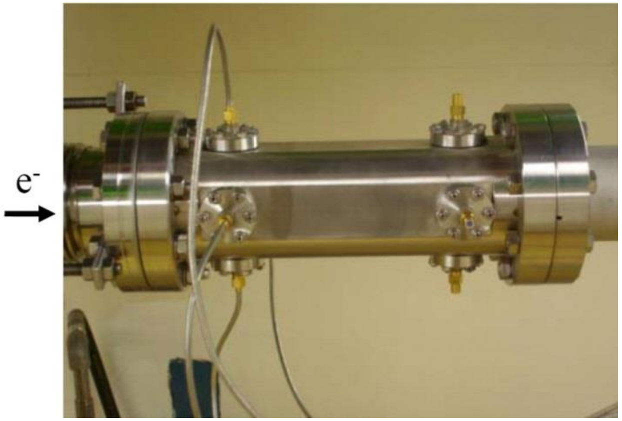
Further advantage: Linear phase propagation $\Rightarrow$ good for coupled bunch feedback

# Comparison: Stripline and Button BPM (simplified)

| | **Stripline** | **Button** |
|---|---|---|
| **Idea** | traveling wave | electro-static |
| **Requirement** | Careful $\boldsymbol{Z_{strip}} = 50\ \Omega$ matching | |
| **Signal quality** | Less deformation of bunch signal | Deformation by finite size and capacitance |
| **Bandwidth** | Broadband, but minima | Highpass, but $\boldsymbol{f_{cut}} < 1$ GHz |
| **Signal strength** | Large<br>Large longitudinal and transverse coverage possible | Small<br>Size <∅3cm,<br>to prevent signal deformation |
| **Mechanics** | Complex | Simple |
| **Installation** | Inside quadrupole possible<br>⇒improving accuracy | Compact insertion |
| **Directivity** | **YES** | No |

FLASH BPM inside quadrupole






From . S. Vilkins, D. Nölle (DESY)

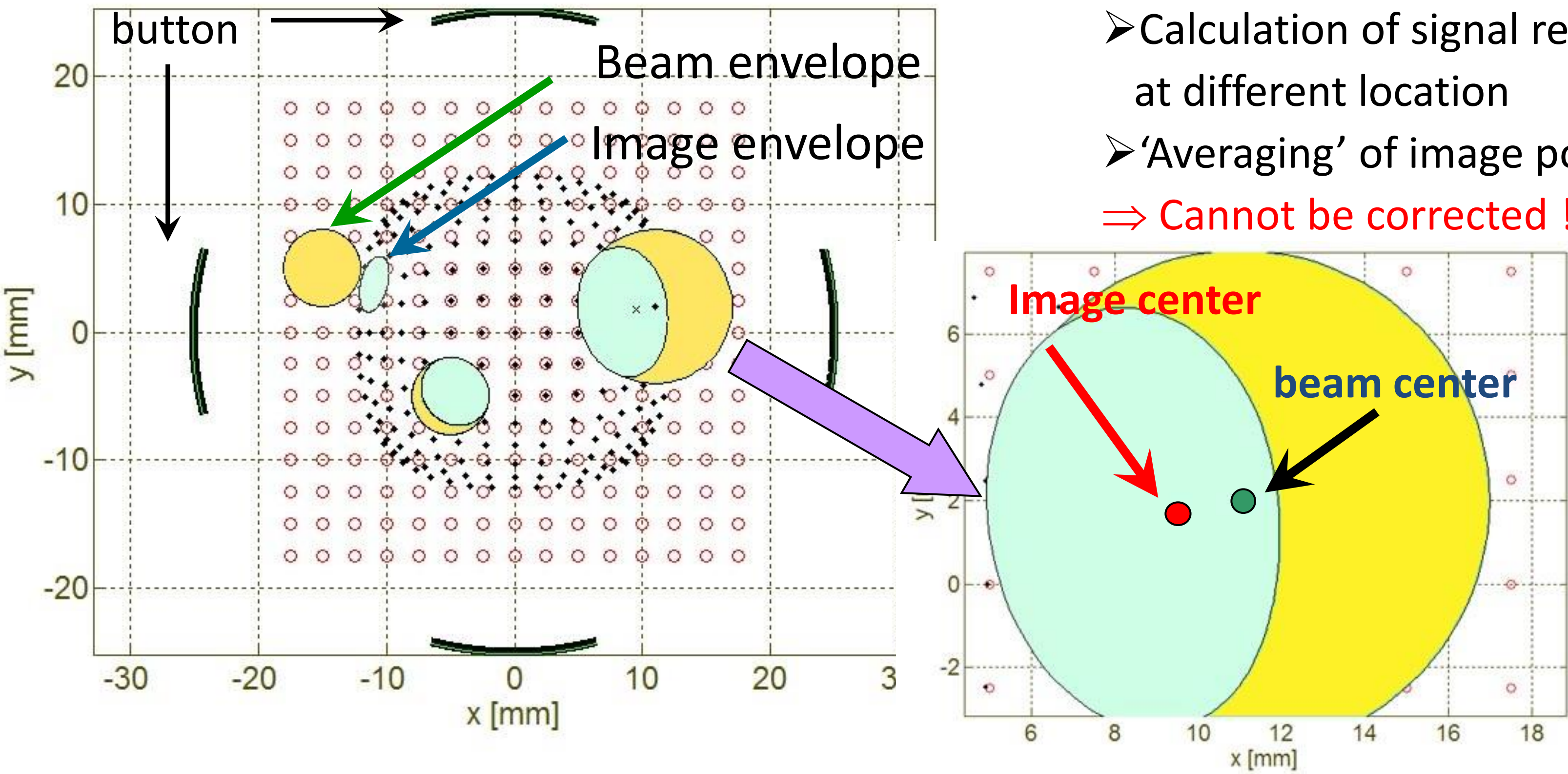
## Ideal 2-dim model:

Due to the non-linearity, the beam size enters in the position reading.

**Finite beam size:**

- Calculation of signal response at different location
- 'Averaging' of image position

⇒ Cannot be corrected !

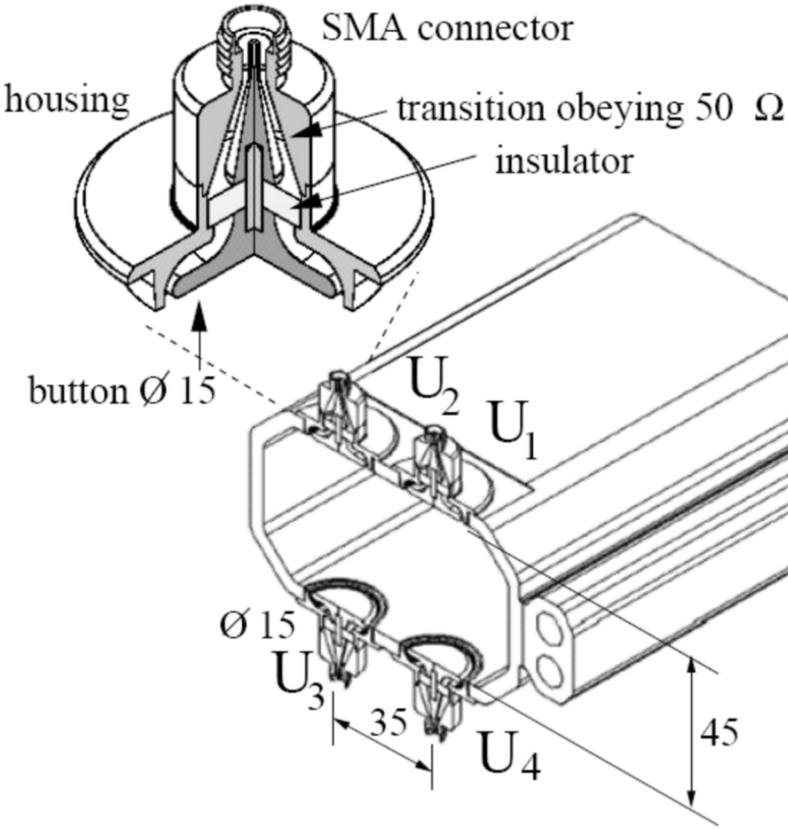



**Remark:** For most LINACs: Linearity is less important, because beam has to be centered

Position correction as feed-forward for next macro-pulse.

# Button BPM at Synchrotron Light Sources

Due to synchrotron radiation, the button insulation might be destroyed
⇒buttons only in vertical plane possible ⇒ increased non-linearity




HERA-e realization

$$\text{horizontal: } x = \frac{1}{S_x} \cdot \frac{(U_1 + U_4) - (U_2 + U_3)}{U_1 + U_2 + U_3 + U_4}$$

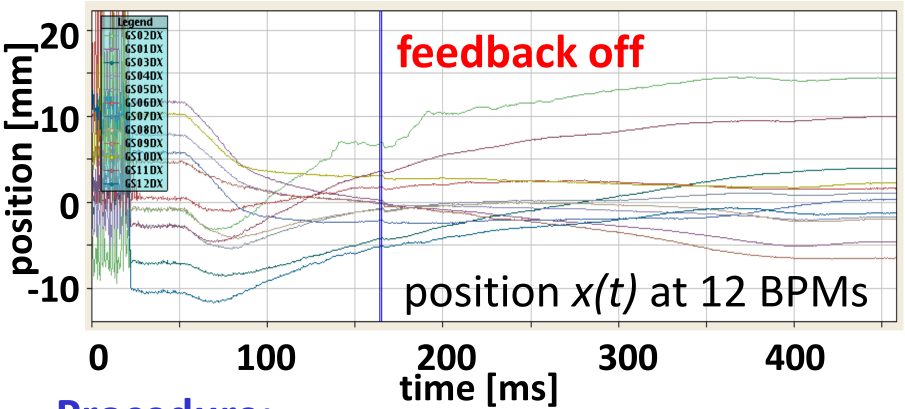
$$\text{vertical: } y = \frac{1}{S_y} \cdot \frac{(U_1 + U_2) - (U_3 + U_4)}{U_1 + U_2 + U_3 + U_4}$$

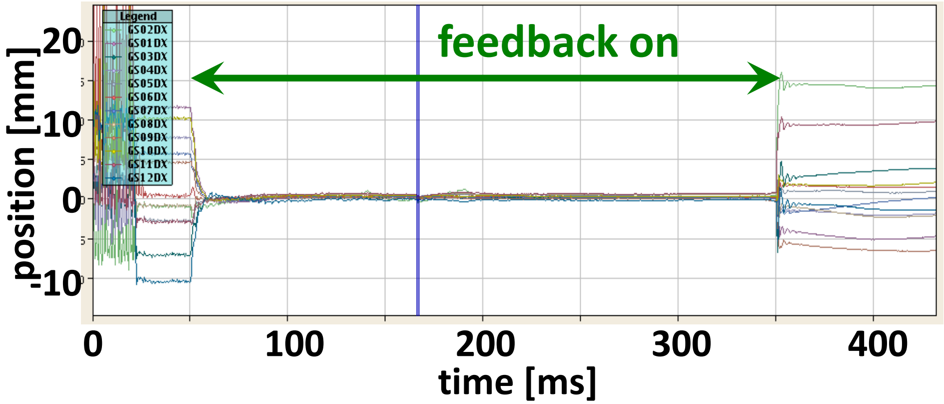
PEP-realization: N. Kurita et al., PAC 1995

# Close Orbit Feedback: Results

## Orbit feedback:

*Example:* 12 beam positions at GSI-SIS during ramping from 8.6 to 500 MeV/u for $Ar^{18+}$




**Procedure:**

**1.** Position from all 12 BPMs

**2.** Calculation of corrector setting on fast (FPGA-based) electronics

**3.** Submission to corrector magnets

**4.** New position measurement

$\Rightarrow$ regulation time down to 10 ms

**Role of thumb:**

Movement related to tune i.e. 'natural oscillations by periodic focusing'

To determine the 'sine-like' oscillation 4 BPMs per oscillation are required

$\Rightarrow$ 4 BPMs per tune value (but detailed investigation required to determine the # of BPMs)

# $\beta$-Function Measurement from Bunch-by-Bunch BPM Data

Excitation of **coherent** betatron oscillations:

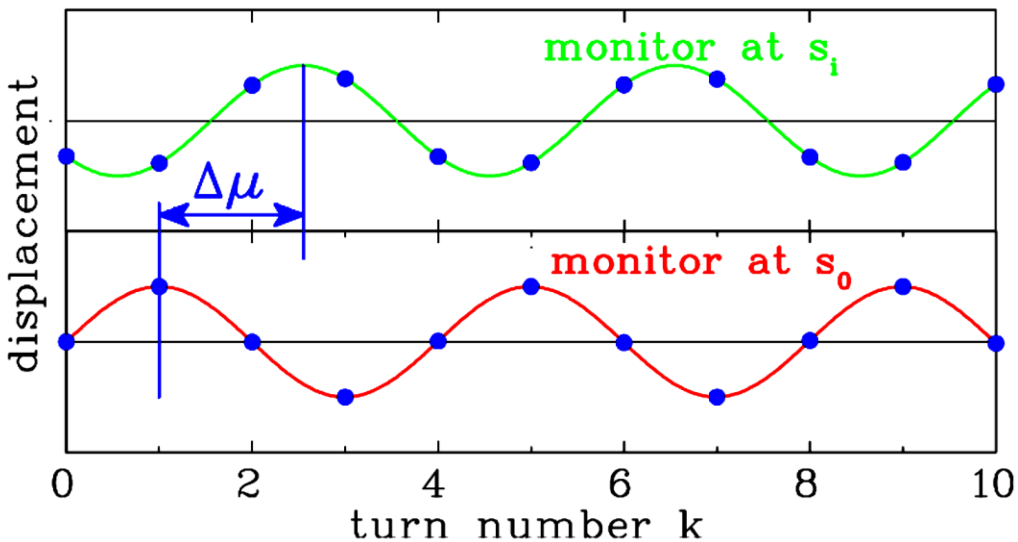
→ Time-dependent position reading results the phase advance between BPMs

The phase advance is:

$$\Delta\mu = \mu_i - \mu_0$$

$\beta$ - function from

$$\Delta\mu = \int_{S0}^{Si} \frac{ds}{\beta(s)}$$




**Remark:** Determination of $\beta$-function with 3 BPMs:

$$\beta_{meas}(BPM_1) = \beta_{model}(BPM_1) \cdot \frac{\cot[\mu_{meas}(1\rightarrow 2)] - \cot[(\mu_{meas}(1\rightarrow 3)]}{\cot[\mu_{model}(1\rightarrow 2)] - \cot[\mu_{model}(1\rightarrow 3)]}$$

See e.g.: R. Tomas et al., Phys. Rev. Acc. Beams **20,** 054801 (2017)

A. Wegscheider et al., Phys. Rev. Acc. Beams **20,** 111002 (2017)

See lecture 'Imperfections and Corrections' by Volker Ziemann

# ‘Beta-beating’ from Bunch-by-Bunch BPM Data

*Example:* ‘Beta-beating’ at BPM $\Delta\beta = \beta_{meas} - \beta_{model}$ with measured $\beta_{meas}$ & calculated $\beta_{model}$ for each BPM at BNL for RHIC (proton-proton or ions circular collider with 3.8 km length)

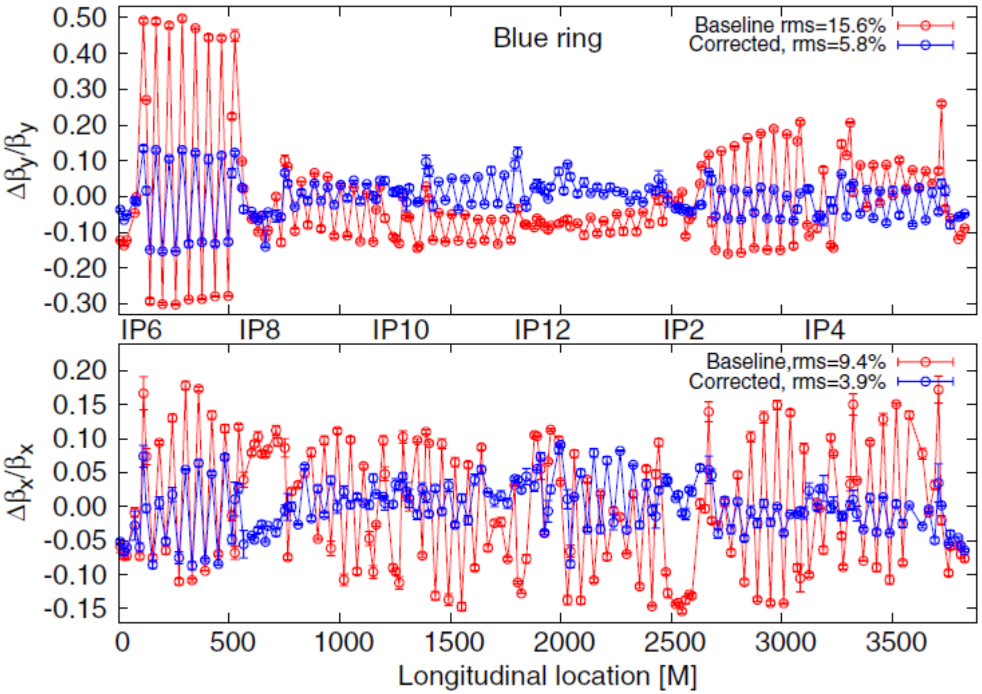
**Result concerning ‘beta-beating’:**

- Model doesn’t fit reality completely e.g. caused by misalignments
- Corrections executed
- Increase of the luminosity

**Remark:**

Measurement accuracy depends on

- BPM accuracy
- Numerical evaluation method




From X. Shen et al., Phys. Rev. Acc. Beams **16**, 111001 (2013)

See lecture ‘Imperfections and Corrections’ by Volker Ziemann

# Example for Fast Current Transformer

For bunch beams e.g. during accel. in a synchrotron typical bandwidth of 2 kHz < $f$ < 1 GHz

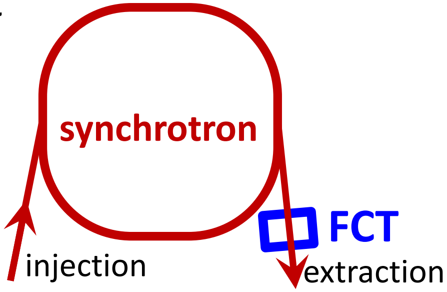
⇔ 10 ns < $t_{bunch}$ < 1 µs is well suited

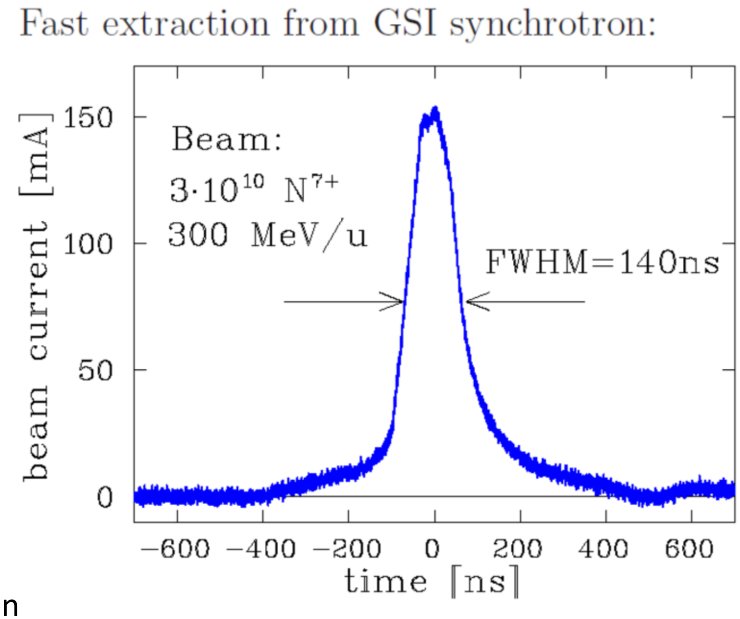
*Example: GSI Fast Current Transformer* ***FCT****:*

| **Inner / outer radius** | **70 / 90 mm** |
|---|---|
| Permeability | $\mu_r \approx 10^5$ for f < 100 kHz<br>$\mu_r \propto$ 1/f above |
| Windings | 10 |
| Sensitivity | 4 V/A for R = 50 Ω |
| Droop time $\tau_{droop} = L/R$ | 0.2 ms |
| Rise time $\tau_{rise} = \sqrt{L_S C_S}$ | 1 ns |
| Bandwidth | 2 kHz ... 500 MHz |


Numerous application e.g.:

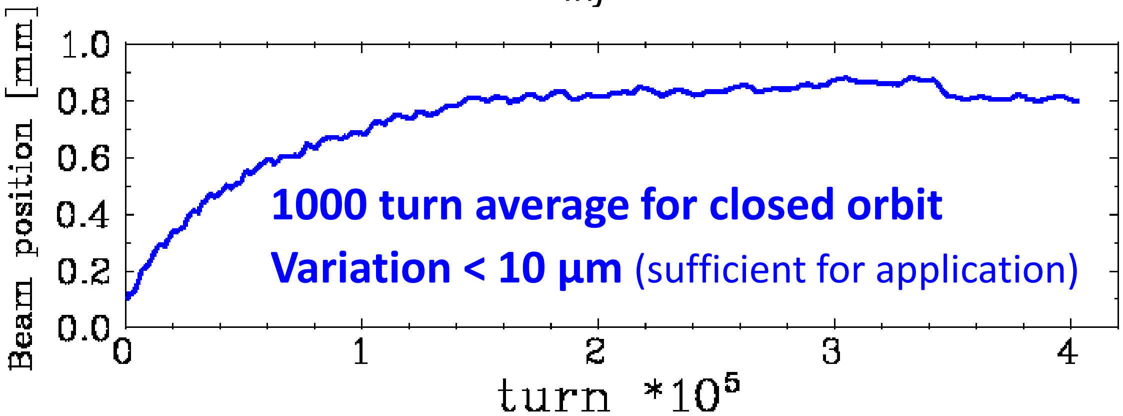
- Transmission optimization
- Bunch shape measurement
- Input for synchronization of 'beam phase'



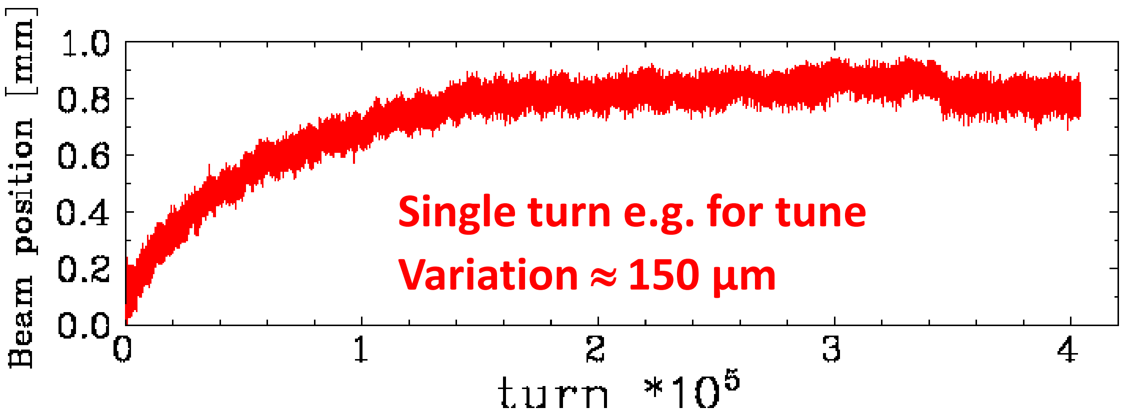



# Comparison: Filtered Signal ↔ single Turn

***Example:*** GSI Synchr.: $U^{73+}$, $E_{inj}$ = 11.5 MeV/u→ $E_{out}$ = 250 MeV/u within 0.5 s, $10^9$ ions



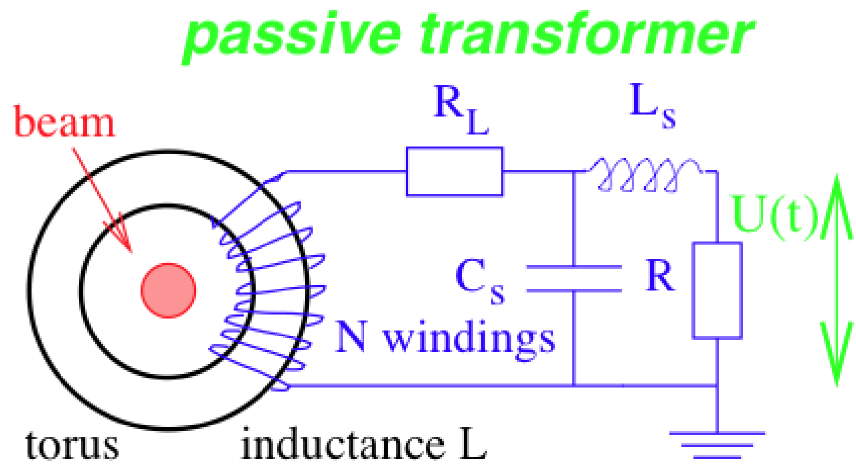

- Position resolution < 30 µm (BPM diameter d=180 mm)
- average over 1000 turns corresponding to ≈1 ms or ≈1 kHz bandwidth

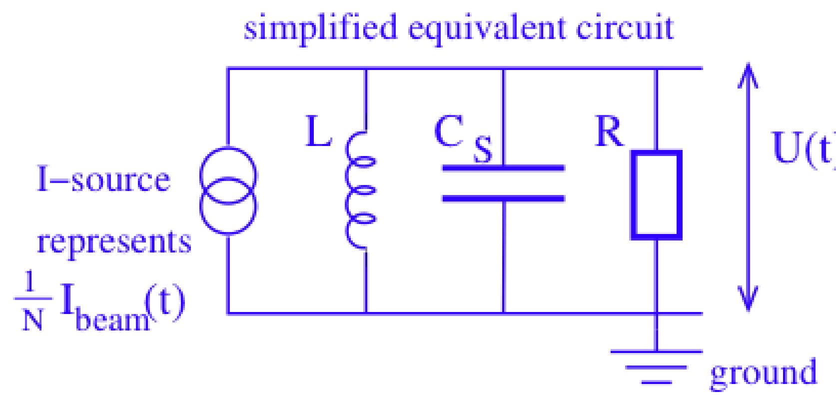



- Turn-by-turn data have much larger variation

***However:*** Not only noise contributes but additionally **beam movement** by betatron oscillation
⇒ broadband processing i.e. turn-by-turn readout for tune determination.

## Simplified electrical circuit of a passively loaded transformer:





Equivalent circuit for analysis of sensitivity and bandwidth

(disregarding the loss resistivity $R_L$)

A voltages is measured: $\boldsymbol{U = R \cdot I_{sec} = R / N \cdot I_{beam} \equiv S \cdot I_{beam}}$

with ***S*** **sensitivity [V/A]** to determine **beam** current $\boldsymbol{I_{beam}}$

equivalent to transfer function or transfer impedance ***Z***

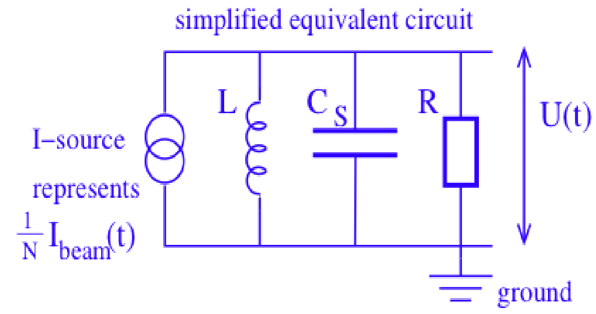
## *Time domain description:*

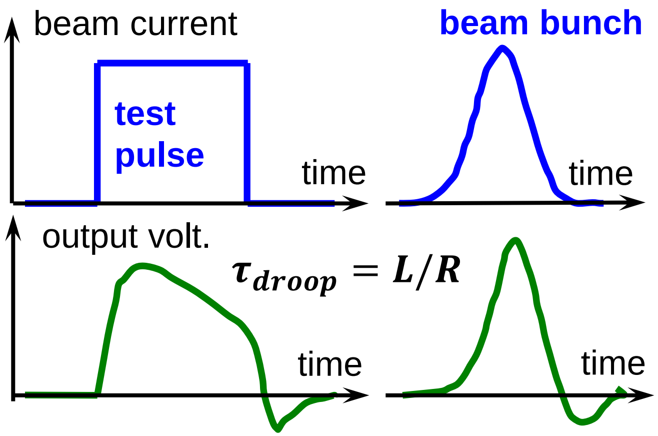
Droop time: $\tau_{droop} = 1/(2\pi f_{low}) = L/R$

Rise time: $\tau_{rise} = 1/(2\pi f_{high}) = RC_S$ (ideal without cables)

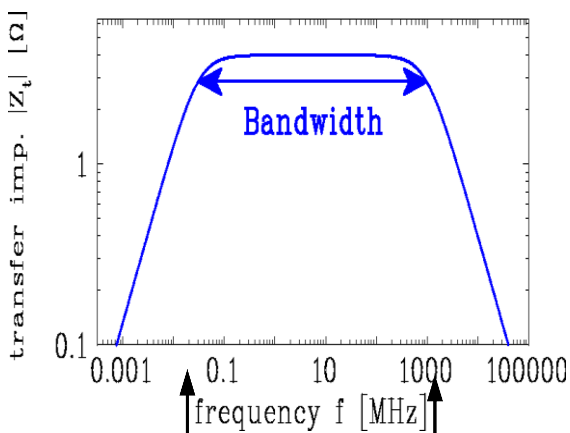
Rise time: $\tau_{rise} = 1/(2\pi f_{high}) = \sqrt{L_S C_S}$ (with cables)

$R_L$: loss resistivity, $R$: for measuring.



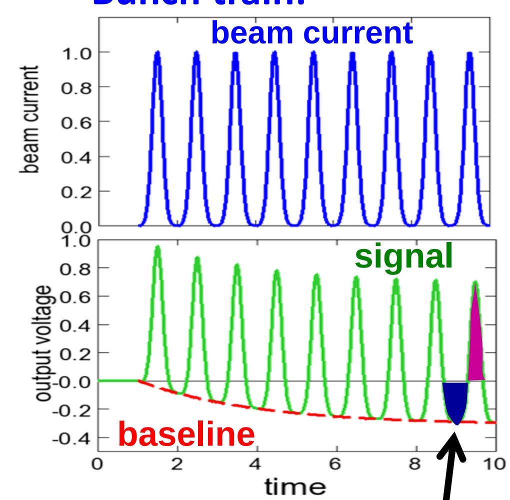




$\tau_{rise} = \sqrt{L \cdot C_S}$




$2\pi f_{low} = R/L$

$2\pi f_{high} = 1/RC_S$




**Baseline:** $U_{base} \propto 1 - \exp(-t/\tau_{droop})$

**positive** & **negative** areas are equal

# Basic Idea of Beam Loss Monitors

**Basic idea for Beam Loss Monitors BLM:**

A loss beam particle must collide with the vacuum chamber or other insertions

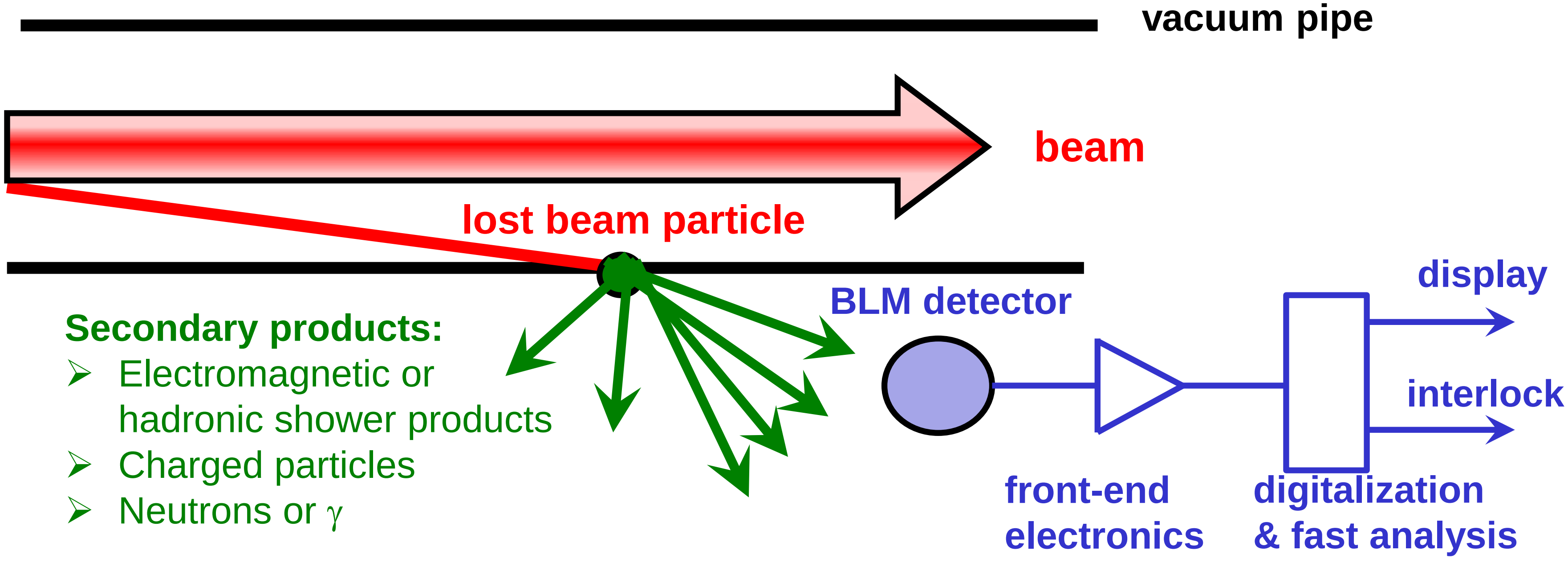
⇒ Interaction leads to some shower particle:

e⁻, $\gamma$, protons, neutrons, excited nuclei, fragmented nuclei

→ Detection of these secondaries by an appropriate detector outside of beam pipe

→ Relative cheap detector installed at many locations

Remark: Due to grazing angle a thin vacuum chamber might be a ‘thick target’



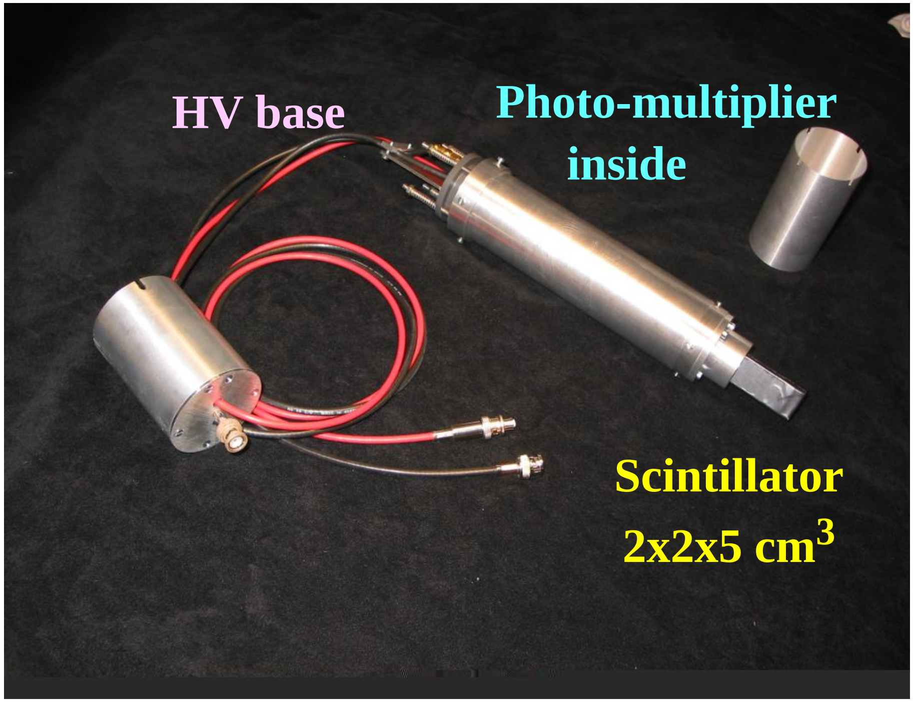
# Scintillators as Beam Loss Monitors

**Plastics or liquids are used:**

- Detection of **charged particles** by electronic stopping
- Detection of **neutrons** by elastic collisions n on p in plastics and fast p electronic stopping.

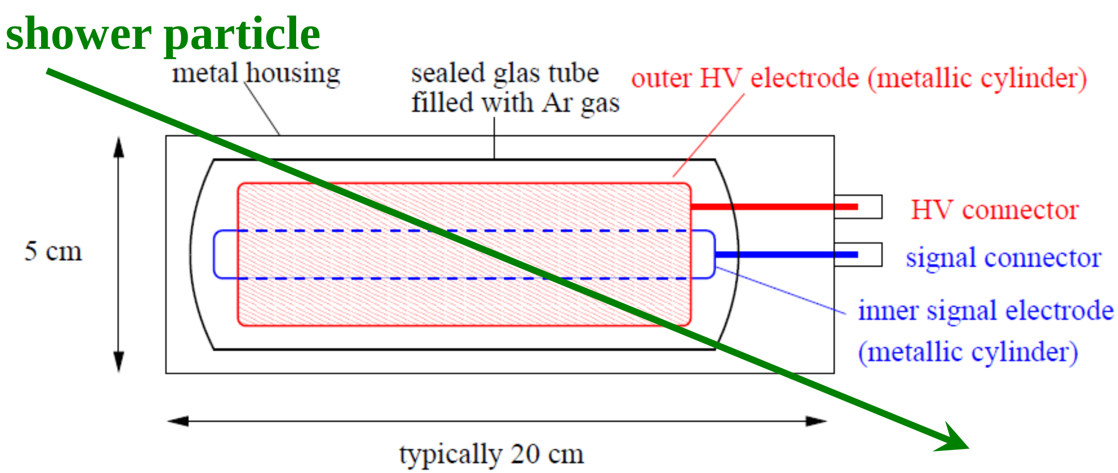
**Scintillator + photo-multiplier:**

counting (large PMT amplification)
or analog voltage ADC (low PMT amplification)
Radiation hardness:
plastics 1 Mrad = $10^4$ Gy
liquid 10 Mrad = $10^5$ Gy




**Energy loss of charged particles in gases → electron-ion pairs → current meas.**

$$I_{sec} \propto \frac{1}{W} \cdot \frac{dE}{dx} \Delta x$$




*W* is average energy for creation for one $e^-$ -ion pair:

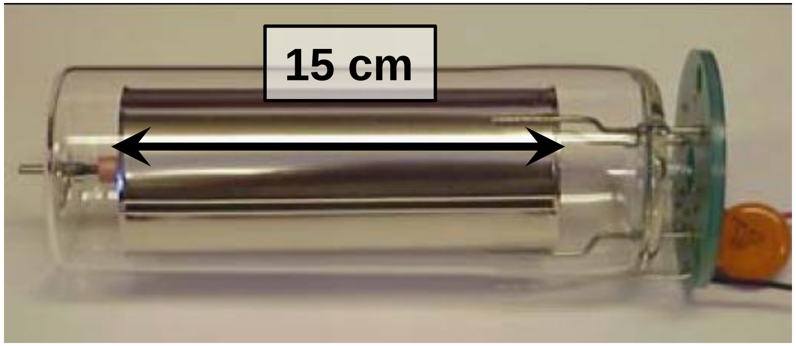
| Gas | Ionization Pot. [eV] | W-Value [eV] |
|---|---|---|
| Ar | 15.7 | 26.4 |
| $N_2$ | 15.5 | 34.8 |
| $O_2$ | 12.5 | 30.8 |
| Air | | 33.8 |

**Sealed tube Filled with Ar or $N_2$ gas:**

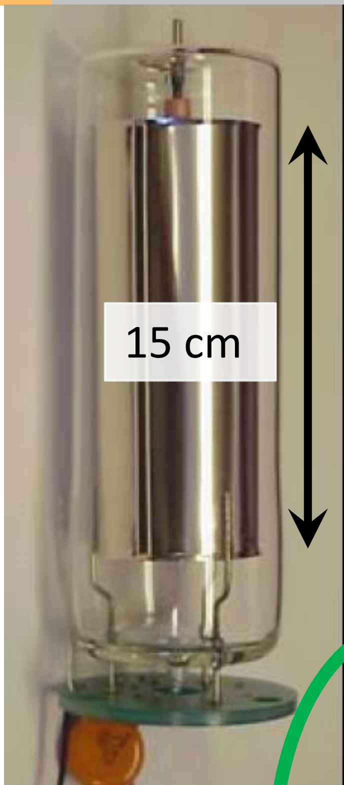
- Creation of $Ar^+$-$e^-$ pairs, average energy ***W*** = 32 eV/pair
- measurement of this current
- Slow time response

  due to ≈ 10 μs drift time of $Ar^+$.

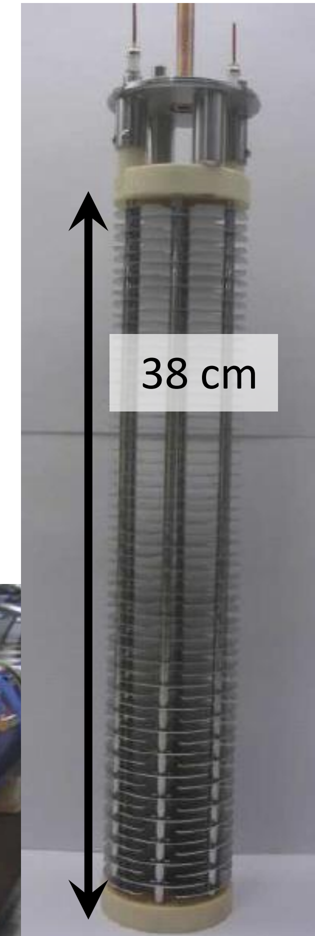
**Per definition: Direct measurement of dose !**



# Ionization Chamber as BLM: TEVATRON and CERN Type



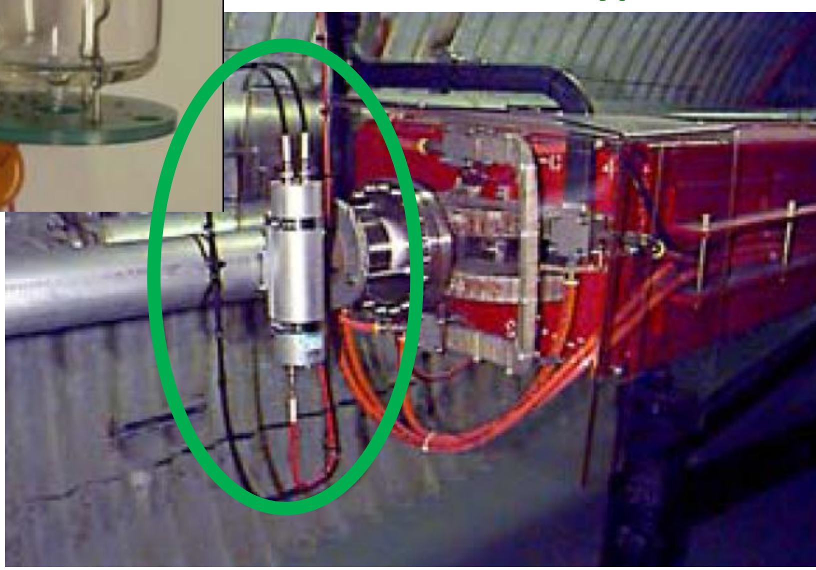

| Parameter | TEVATRON, RHIC | CERN type |
|---|---|---|
| Size | 15cm, ∅ 6 cm | 50 cm, ∅ 9 cm |
| Gas | Ar at 1.1 bar | $N_2$ at 1.1 bar |
| # of electrodes | 3 | 61 |
| Voltage | 1000 V | 1500 V |
| Reaction time | 3 μs | 0.3 μs |

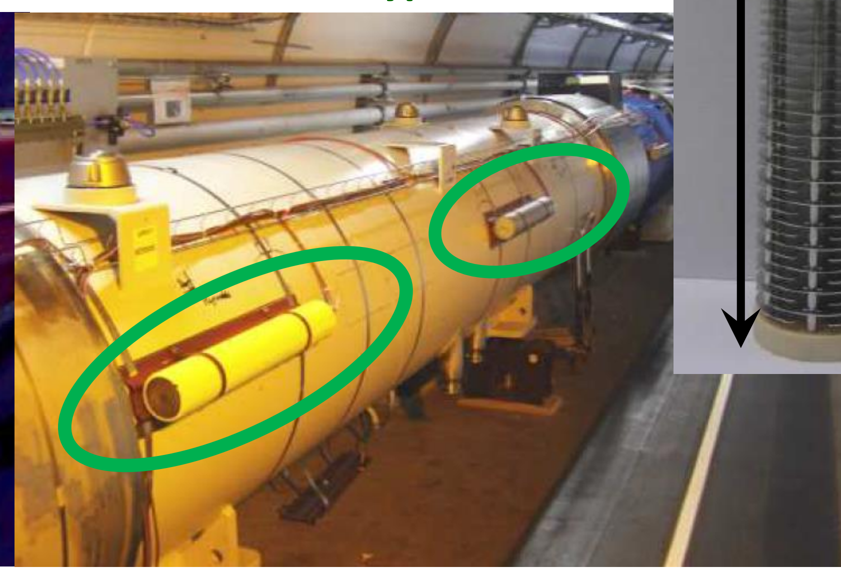



**4000 BLMs at LHC⇔ each ≈ 6m**

**TEVATRON, RHIC type**

**CERN type**





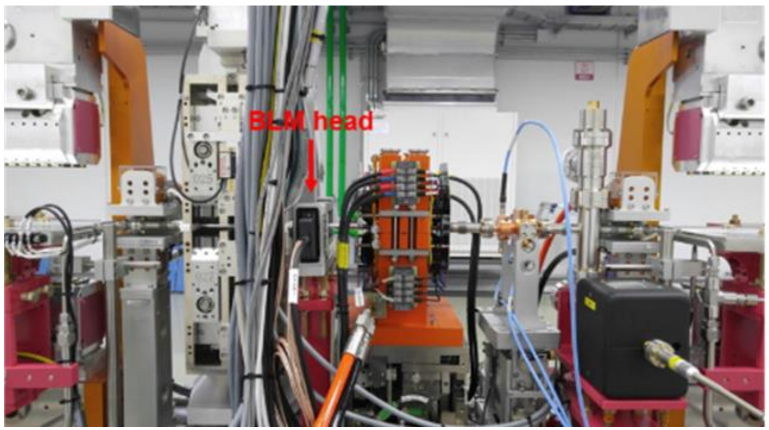
# Cherenkov Light Detectors as Beam Loss Monitors

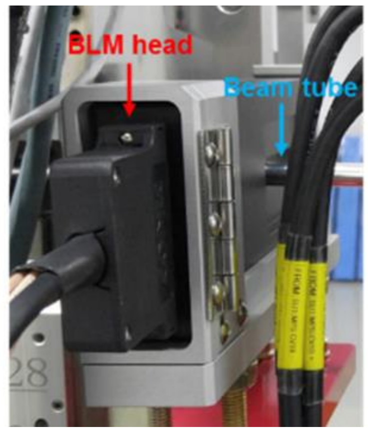
## Cherenkov detectors:

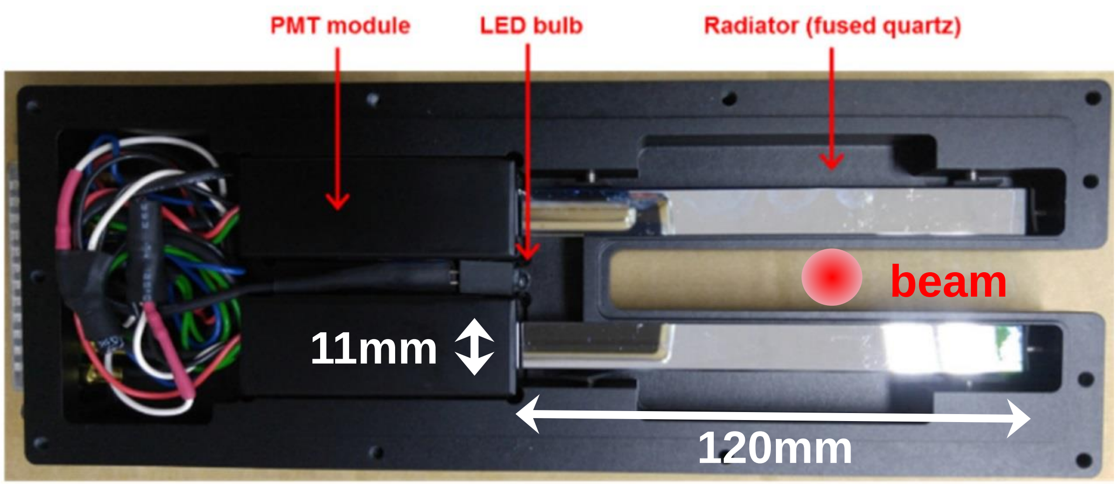
Passage of a charged particle ***v*** faster than propagation of light ***v*** > $c_{medium} = c/n$

**Technical:** Quartz rod ***n*=1.5** & photomultiplier

Example: Korean XFEL behind undulator



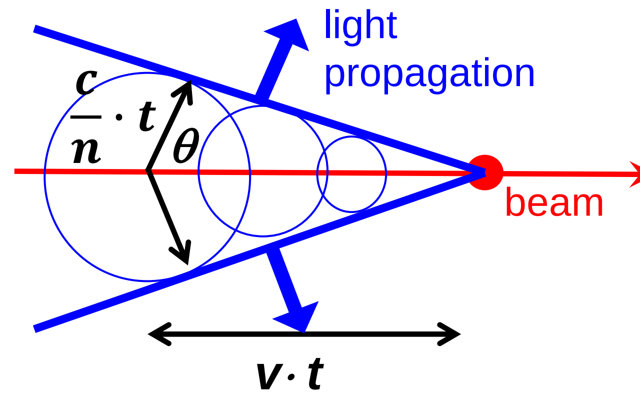




## Cherenkov light emission:

For ***v*** > $c_{medium} = c/n$

light wave-front like a wake

broadband light emission




**Advantage:**

- **Detection of fast electrons only**
  not sensitive to $\gamma$ & synch. photons
- No saturation effects
- Prompt light emission

**Usage:** Mainly at FELs for short and intense pulses

H. Yang, D.C. Shin, FEL Conf. 2017

# Comparison of different Types of BLMs

**Different detectors are sensitive to various physical processes very different count rate, but basically proportional to each other**

**Typical choice of the detector type:**

- **Ionization Chamber:**

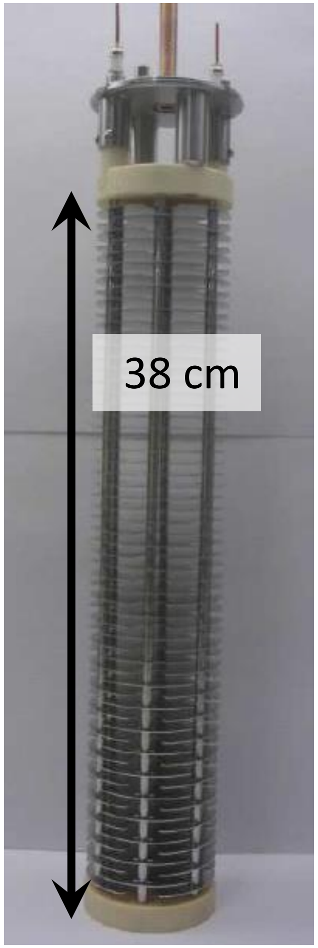
  **Advantage:**

  - Measurement of absolute dose

  **Disadvantage:**

  - Low signal (low $\gamma$, eff, no neutron detection),
  - Sometimes slow, ion drift time 10 ... 100 µs

  $\Rightarrow$ Often used at **proton** accelerators




- **Scintillator, Cherenkov detector:**

  **Advantage:**

  - Fast current reading or particle counting
  - Can be fabricated in any shape, cheap

  **Disadvantage:**

  - Need calibration in many cases
  - Might suffer from radiation

  $\Rightarrow$ Often used at **electron** accelerators