Beam Instrumentation & Diagnostics Part 1

CAS Introduction to Accelerator Physics

Chavannes de Bogis, 29th of September 2021

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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 the beam in the real environment.

(Referring to lecture by Volker Ziemann: '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, chromaticity measurement

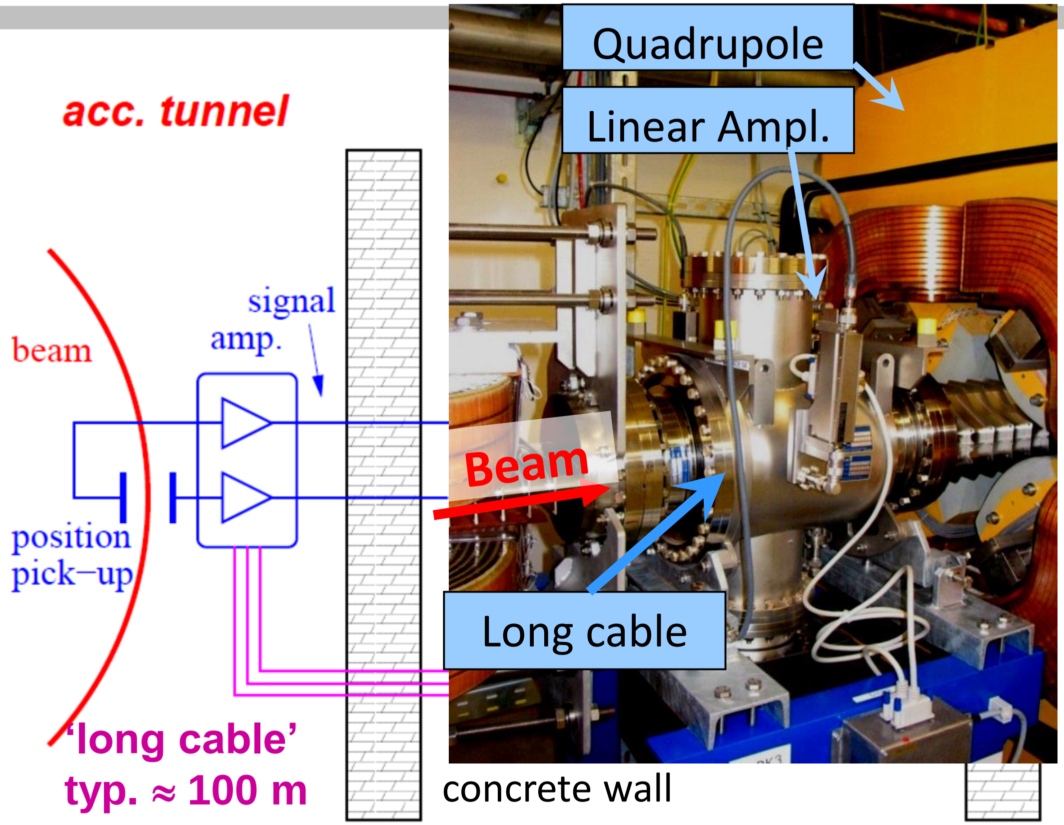
General usage of beam instrumentation:

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

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

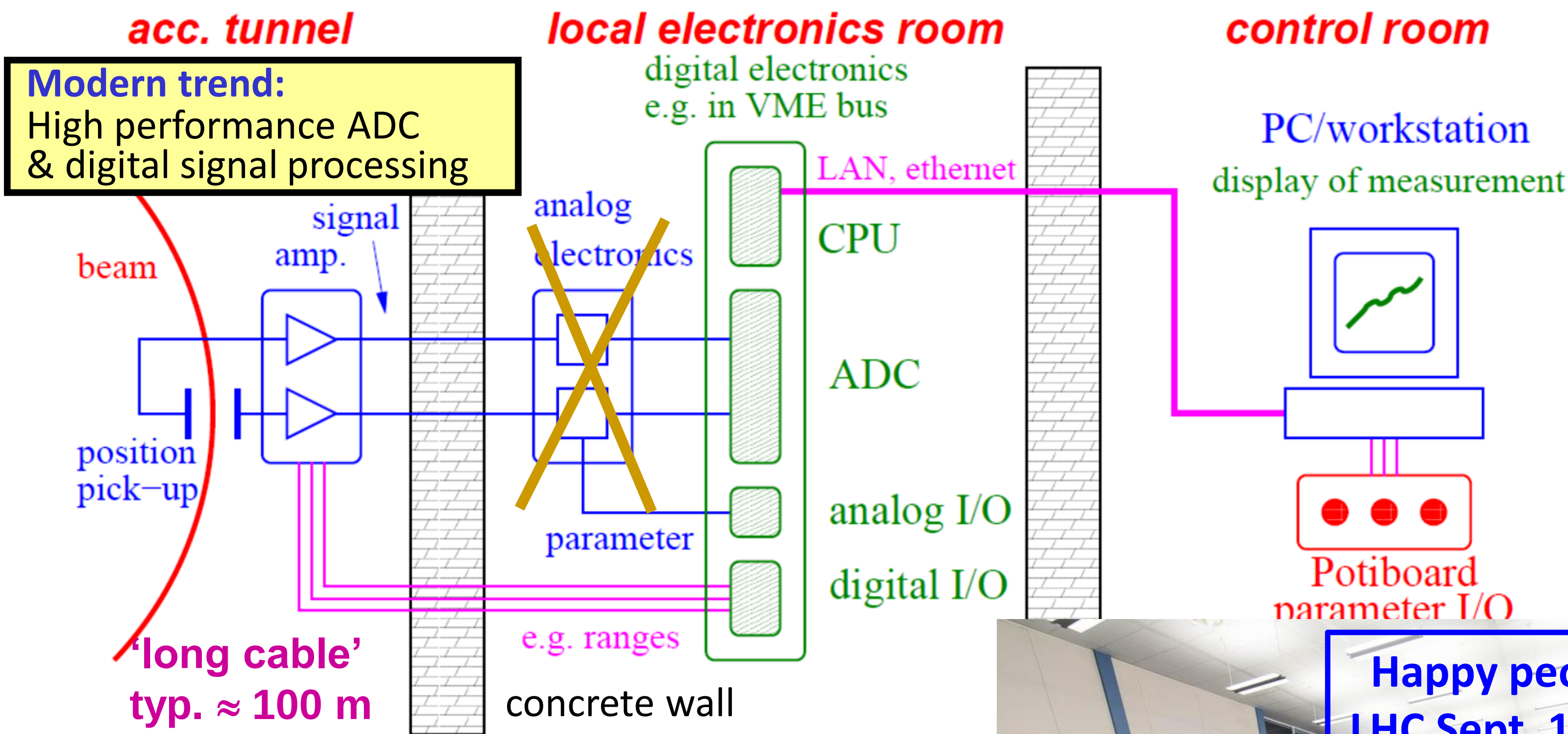
Typical Installation of a Beam Instrument



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



Accelerator tunnel: → action of the beam to th
→ low noise pre-amplifier

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

Lecture on Machine Protection System on Thursday:

- Beam loss detection as one subject

Instruments could be different for:

- Transfer lines with single pass ↔ synchrotrons with multi-pass
- Electrons are (nearly) always relativistic ↔ protons are at the beginning non-relativistic

Remark:

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

Measurement of Beam Current

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 β

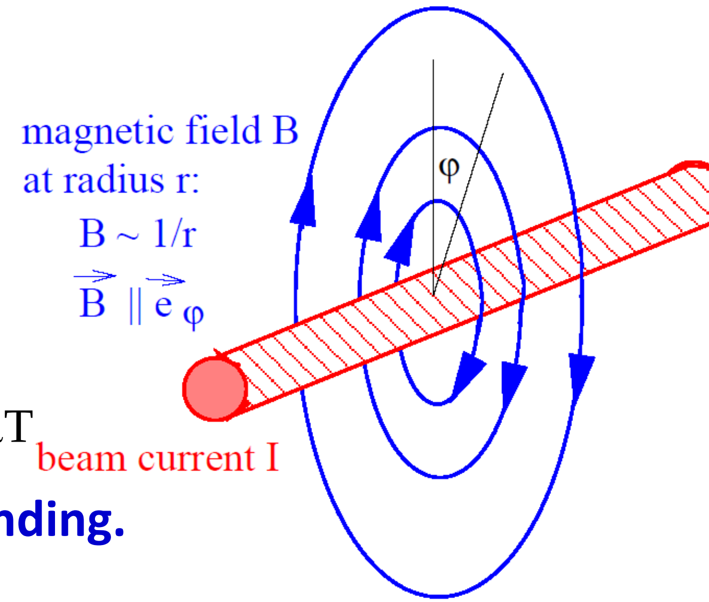
$$I_{beam} = qe \cdot \frac{N_{part}}{t} = qe \cdot \beta c \cdot \frac{N_{part}}{l}$$

- 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 sec. winding.

⇒ Loaded current transformer

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

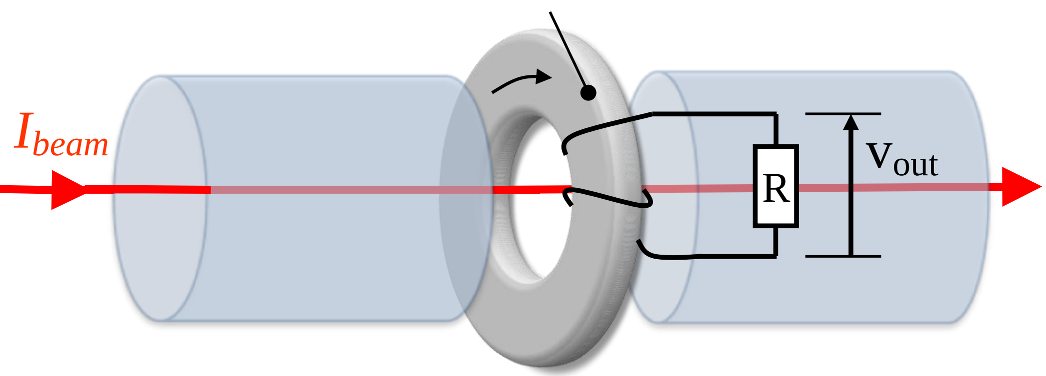
Inductance of a torus of μ_r

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

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

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

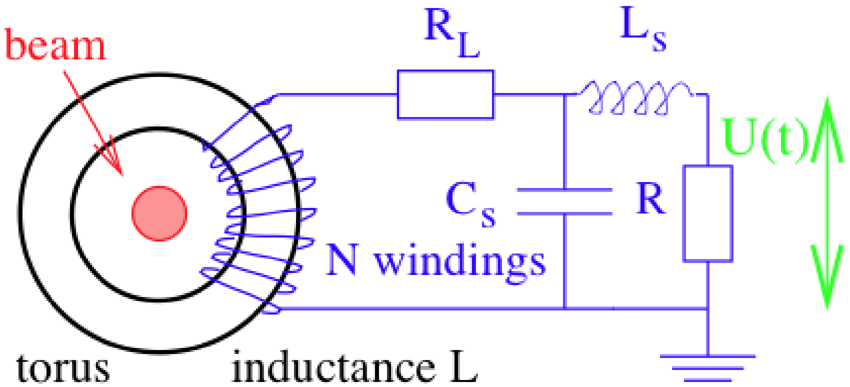
Torus to guide the magnetic field

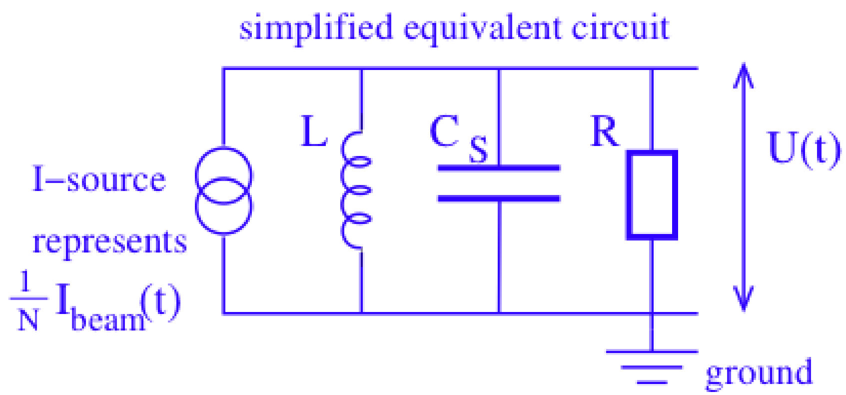


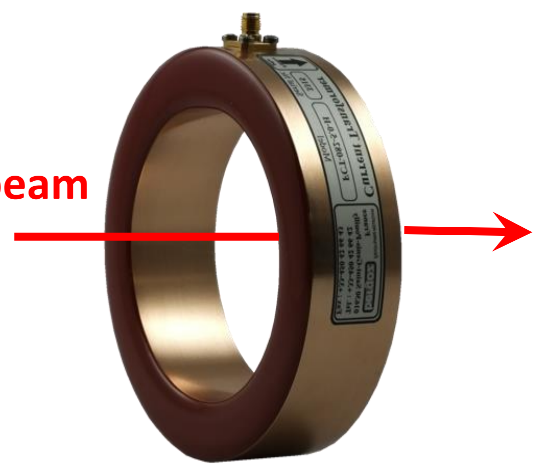
Fast Current Transformer FCT (or Passive Transformer)

Simplified electrical circuit of a passively loaded transformer:

passive transformer







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

with ***S*** **sensitivity [V/A]**,

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

Equivalent circuit for analysis of sensitivity and bandwidth

(disregarding the loss resistivity R_L)

Response of the Passive Transformer: Rise and Droop Time

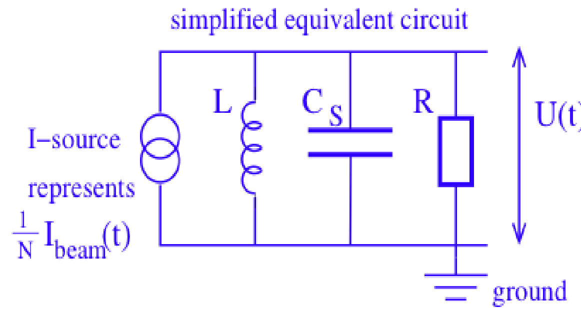
Time domain description:

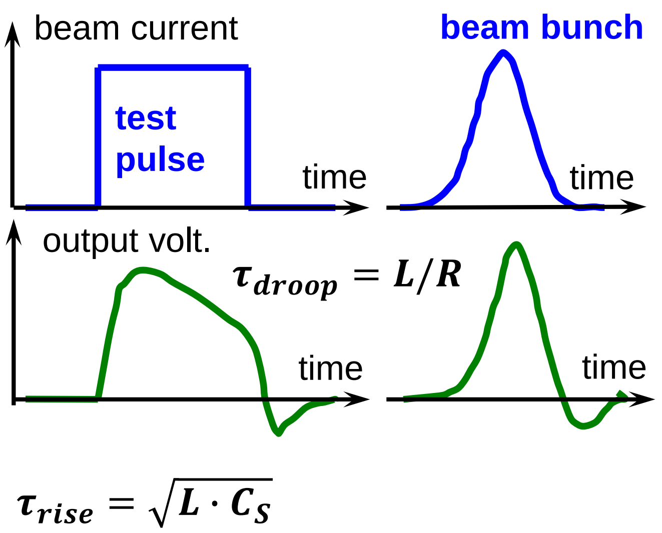
Droop time: $\tau_{droop} = 1/(2\pi f_{low}) = L/R$

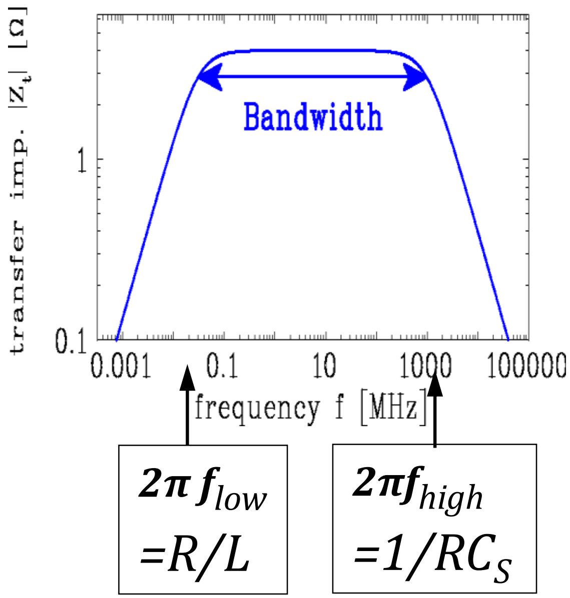
Rise time: $\tau_{rise} = 1/(2\pi f_{high}) = RC_S$ (ideal without cables)

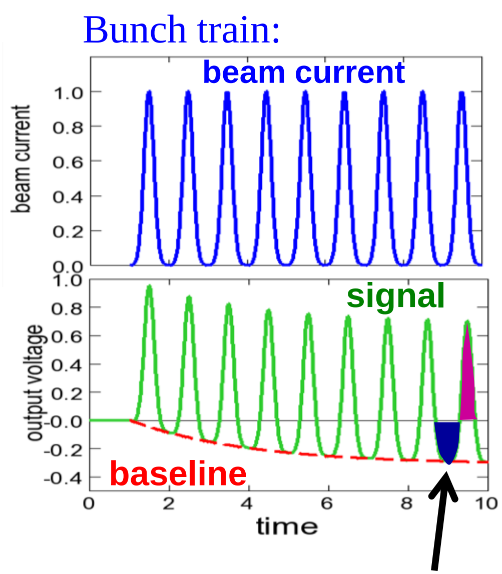
Rise time: $\tau_{rise} = 1/(2\pi f_{high}) = \sqrt{L_S C_S}$ (with cables)

R_L: loss resistivity, R: for measuring.









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

Example for Fast Current Transformer

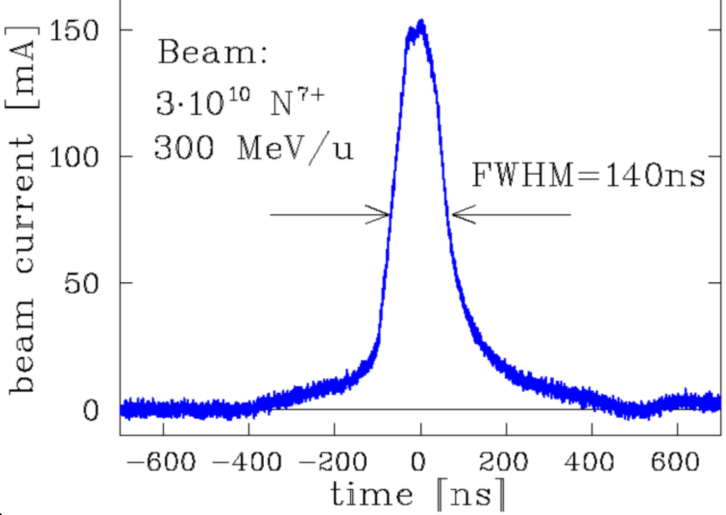
For bunch beams e.g. during accel. in a synchrotron typical bandwidth of 2 kHz < f < 1 GHz

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

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

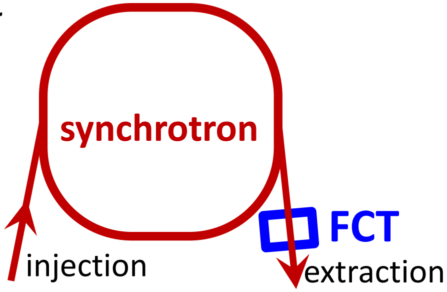
Inner / outer radius	70 / 90 mm
Permeability	$\mu_r \approx 10^5$ for f < 100 kHz $\mu_r \propto$ 1/f above
Windings	10
Sensitivity	4 V/A for R = 50 Ω
Droop time $\tau_{droop} = L/R$	0.2 ms
Rise time $\tau_{rise} = \sqrt{L_S C_S}$	1 ns
Bandwidth	2 kHz ... 500 MHz

Fast extraction from GSI synchrotron:



Numerous application e.g.:

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



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Example GSI type:

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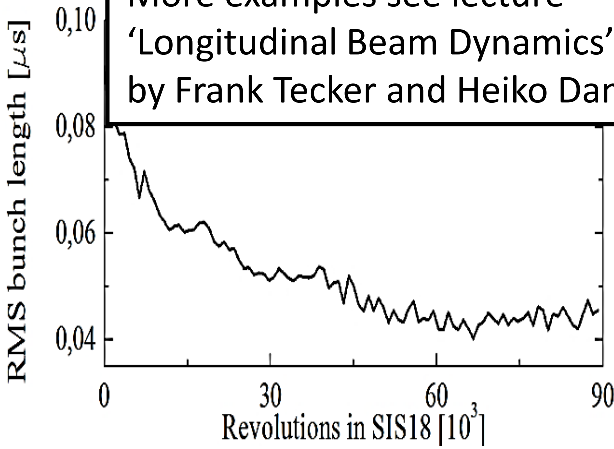
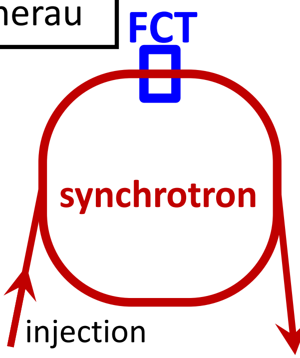
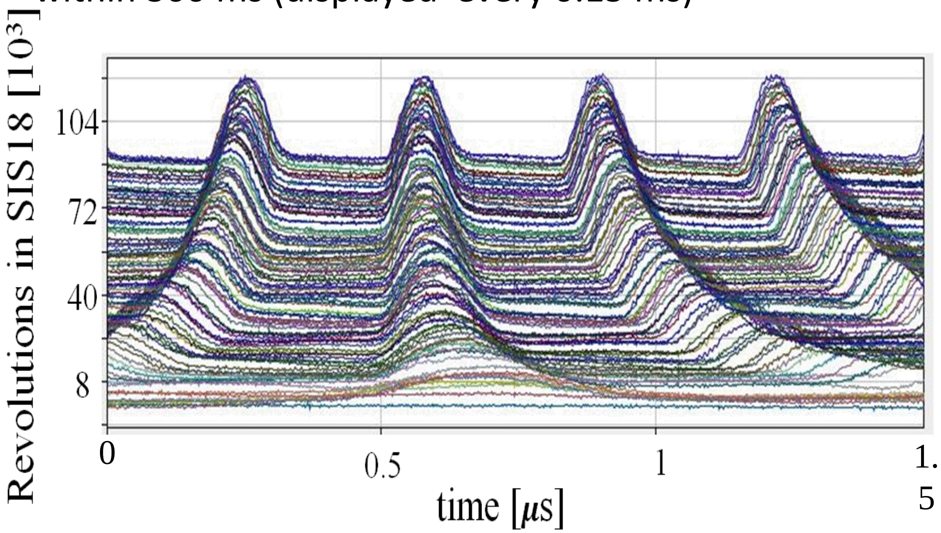
Example: U^{73+} from 11 MeV/u (β = 15 %) to 350 MeV/u within 300 ms (displayed every 0.15 ms)

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



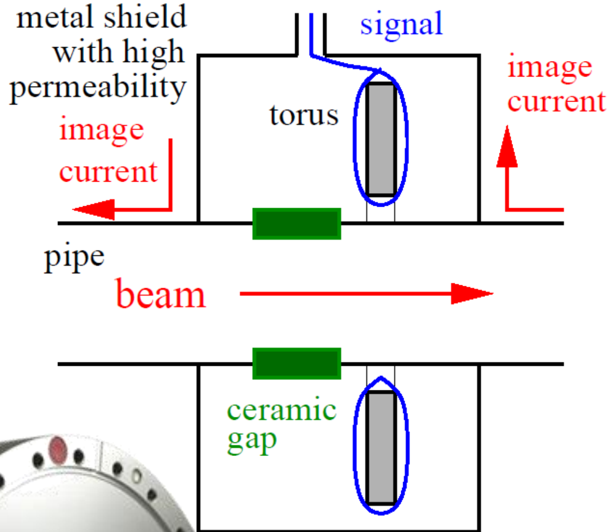


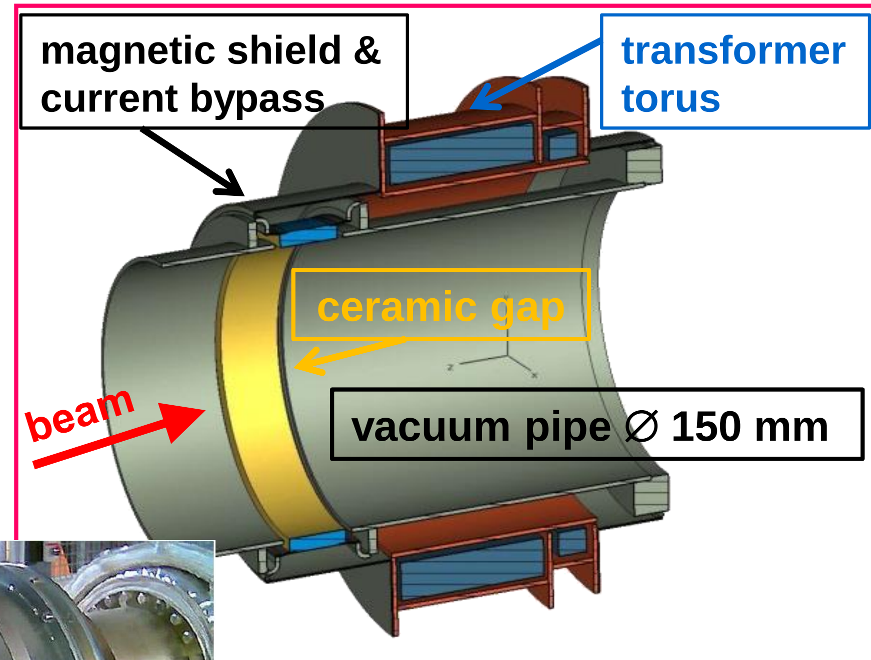


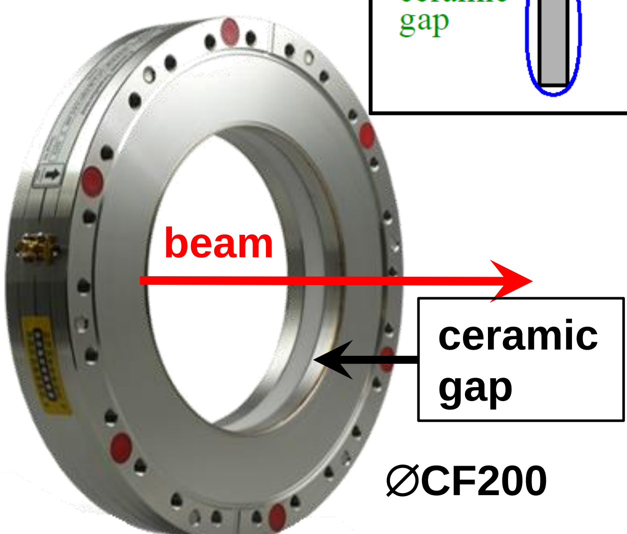
Shielding of a Transformer

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 $\Rightarrow$ B_{beam} = 2pT, earth field B_{earth} = 50 µT)







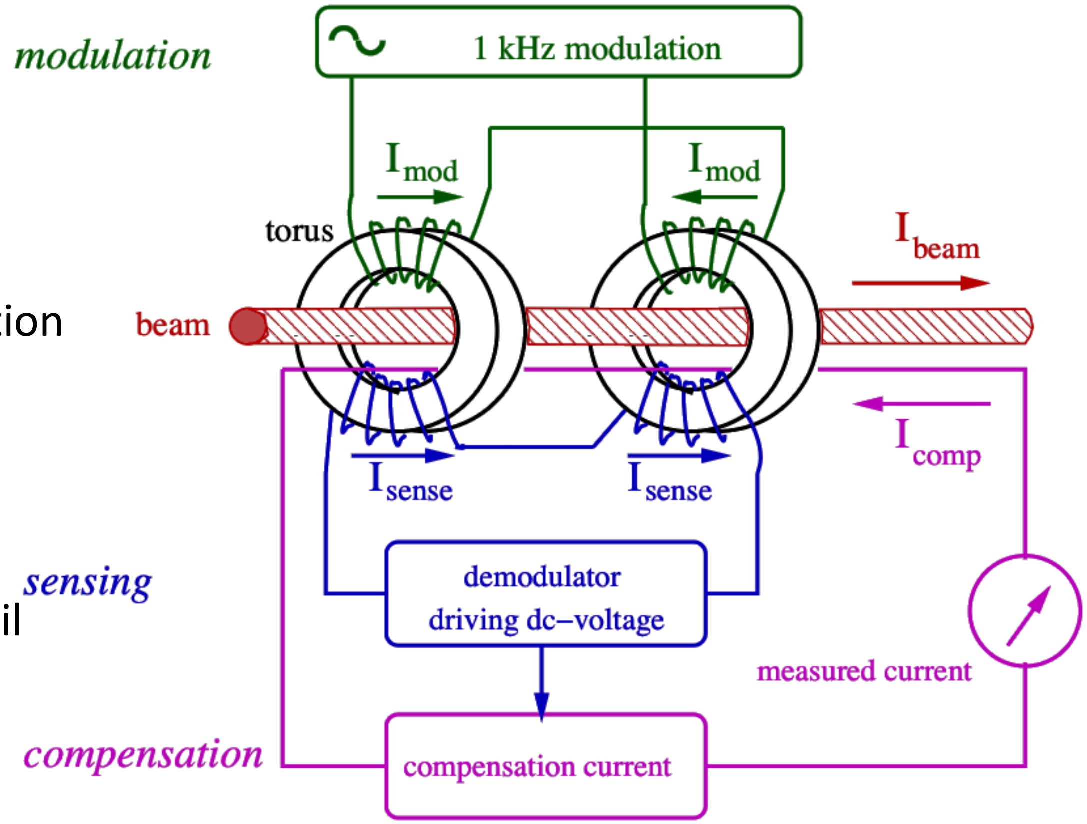
courtesy Company Bergoz

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

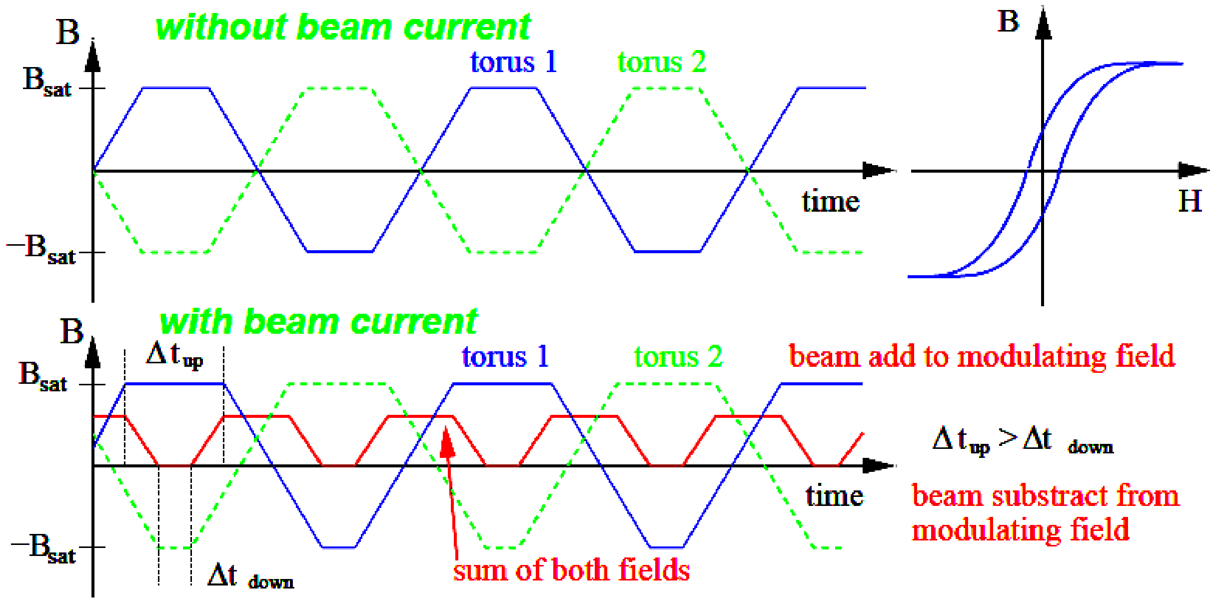
Depictive statement:

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

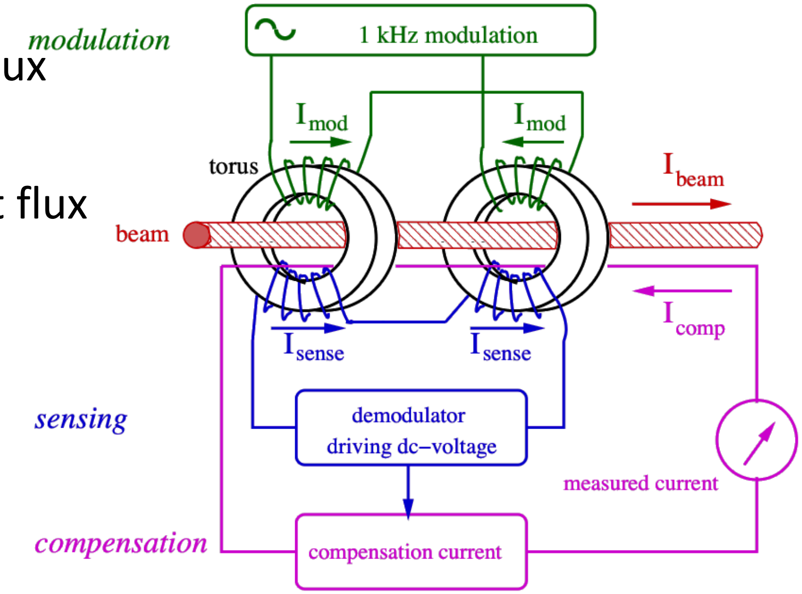


The dc Transformer



- **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.

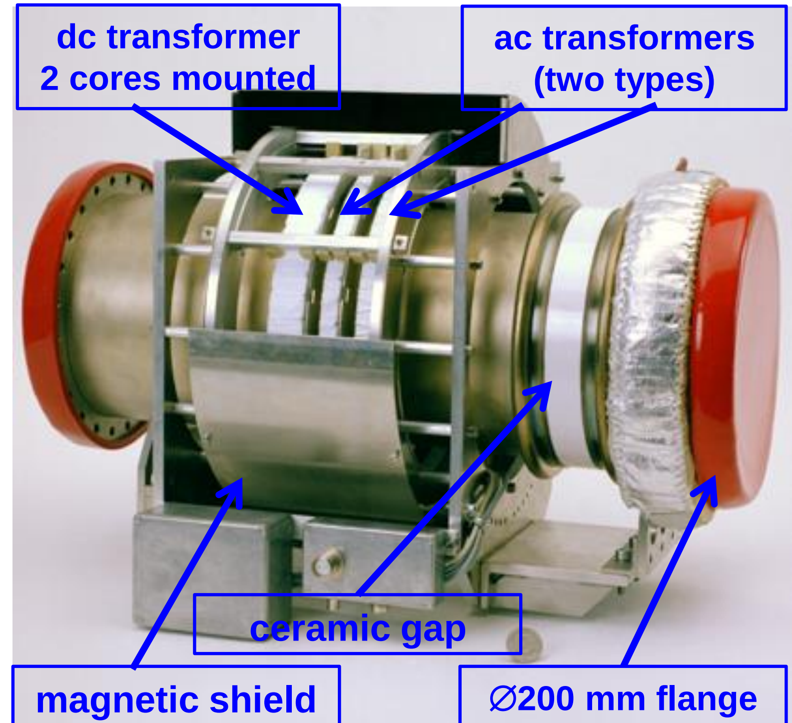
Remark: Same principle used for power suppliers



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 12 for feedback
Resolution	I^{min}_{beam} = 2 μA
Bandwidth	Δf = dc .... 20 kHz
Rise time constant	τ_{rise} = 10 μs
Temperature drift	1.5 μA/°C



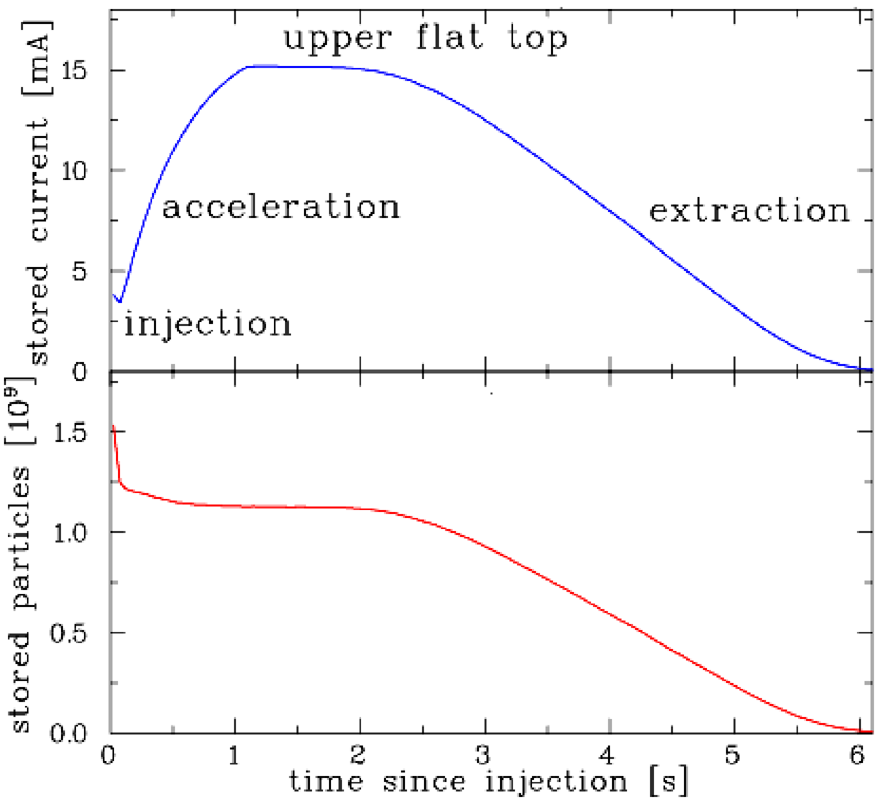
Application for dc transformer:

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

Example: The DCCT at GSI synchrotron

U^{73+} accelerated from

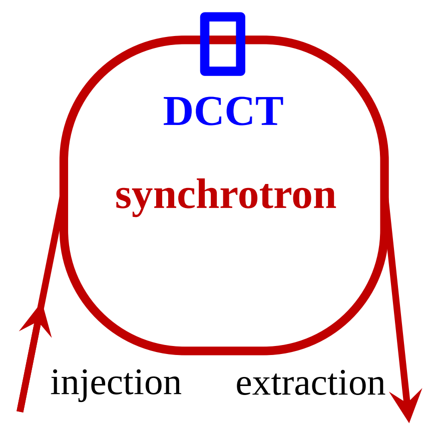
11. 4 MeV/u (β = 15.5%) to 750 MeV/u (β = 84 %)



Important parameter:

- **Detection threshold: ≈ 1 μA (= resolution)**
- Bandwidth: Δf = dc to 20 kHz
- Rise-time: t_{rise} = 20 μs
- Temperature drift: 1.5 μA/^{0}C

  ⇒ compensation required.



Measurement of Beam Current

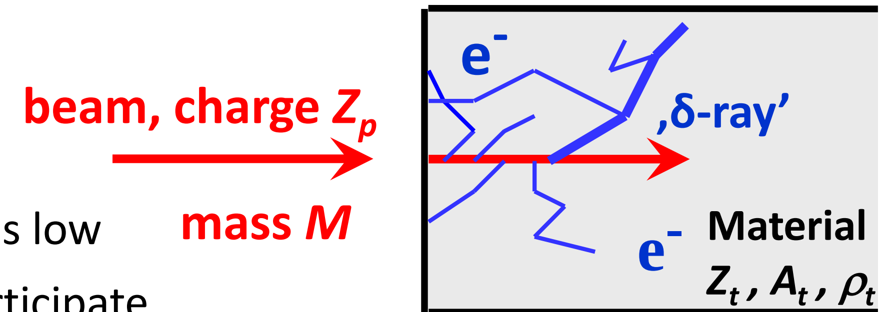
- **Transformers:** Measurement of the beam's **magnetic field**
  - Non-destructive
  - No dependence on beam type and energy
  - They have lower detection threshold.
- **Faraday cups:** Measurement of the beam's **electrical charges**
  - They are destructive
  - For low energies only
  - Low currents can be determined.

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 (γ 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: $W_{max} = \frac{2m_e c^2\beta^2\gamma^2}{1 + 2\gamma m_e/M + (m_e/M)^2}$

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 $R \propto E_{max}^{1.75}$

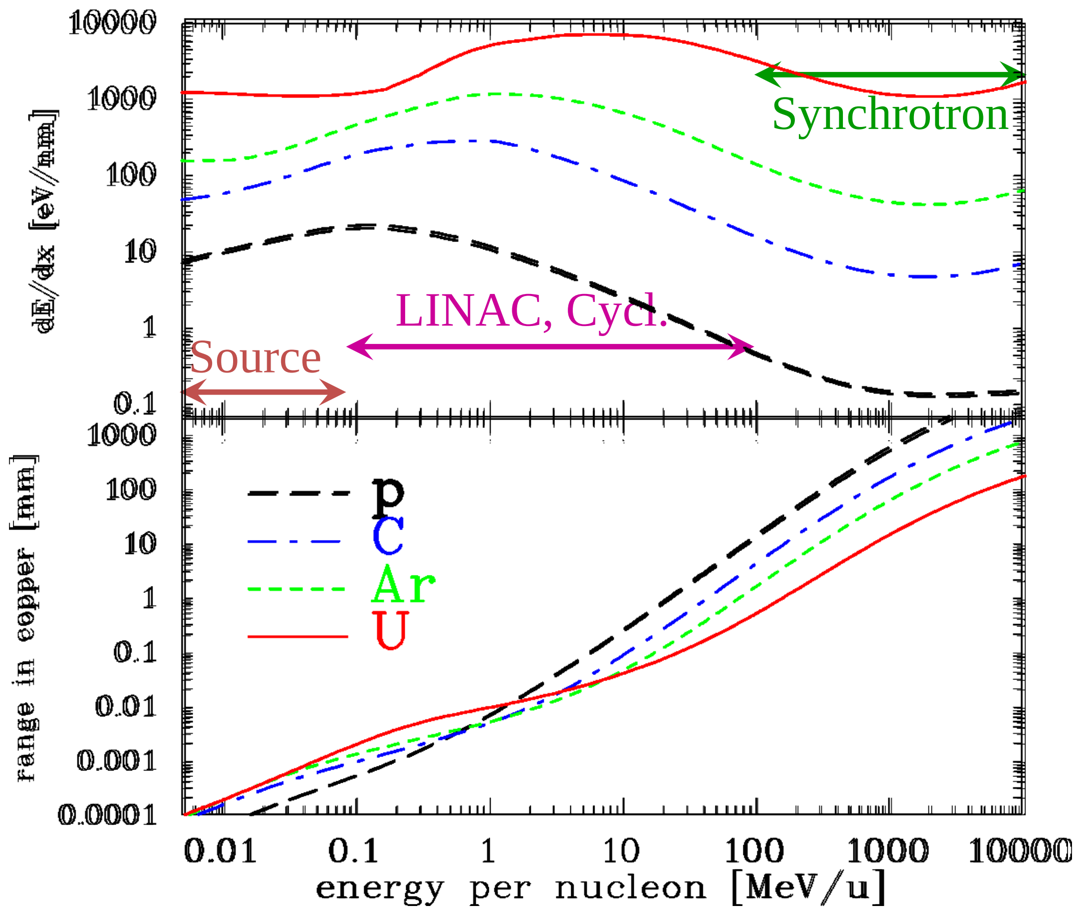
Numerical calculation for **ions**

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

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

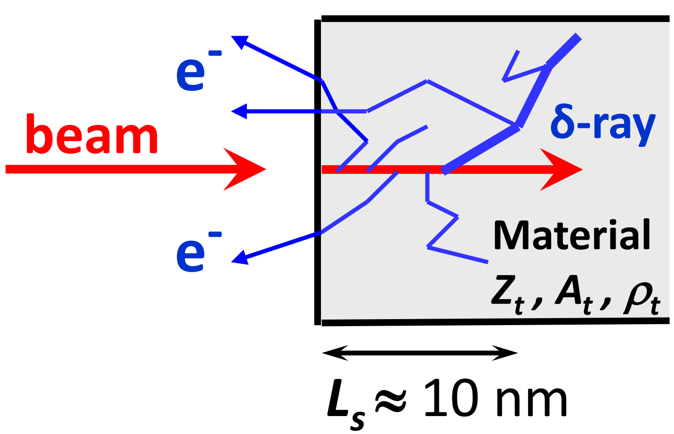
Distant collision with low energy transfer $\rightarrow$ slow e^- with $E_{kin} \leq$ 10 eV

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

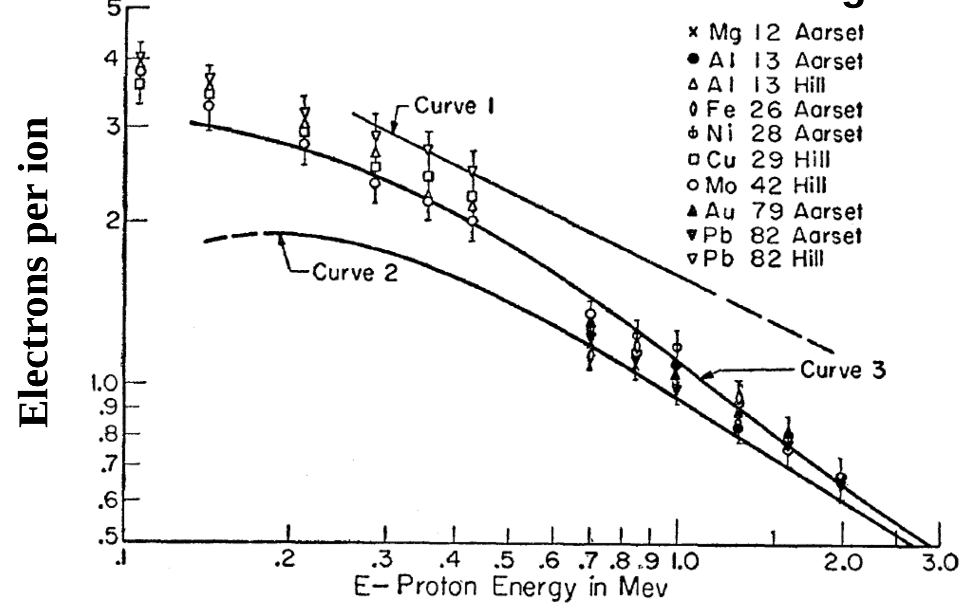
$\rightarrow$ at surface $\approx$ 90 % probability for escape

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

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



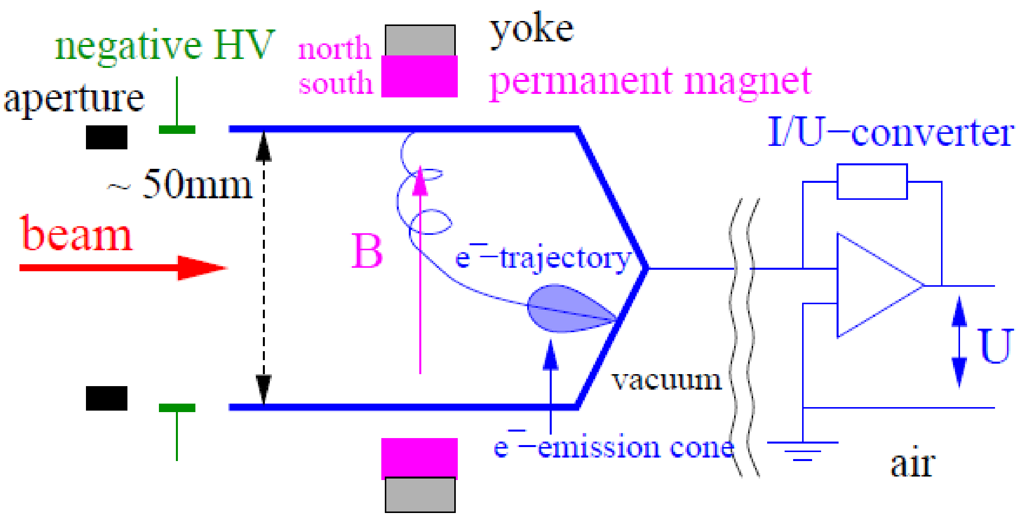
Different targets:

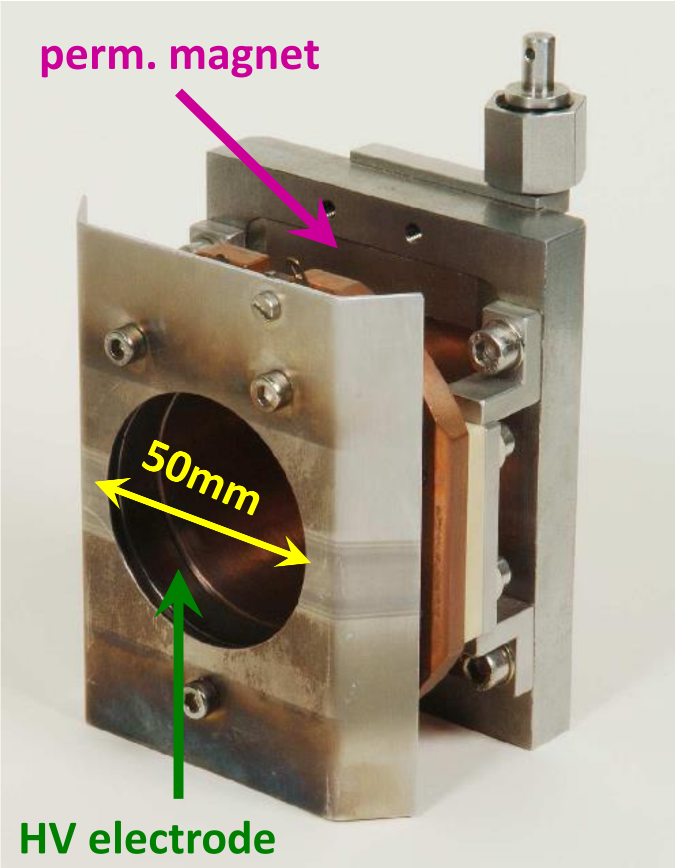


E.J. Sternglass, Phys. Rev. 108, 1 (1957)

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 $\Rightarrow r_c = \frac{mB}{e} \cdot v_\perp \approx 1$ mm .

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

Realization of a Faraday Cup at GSI LINAC

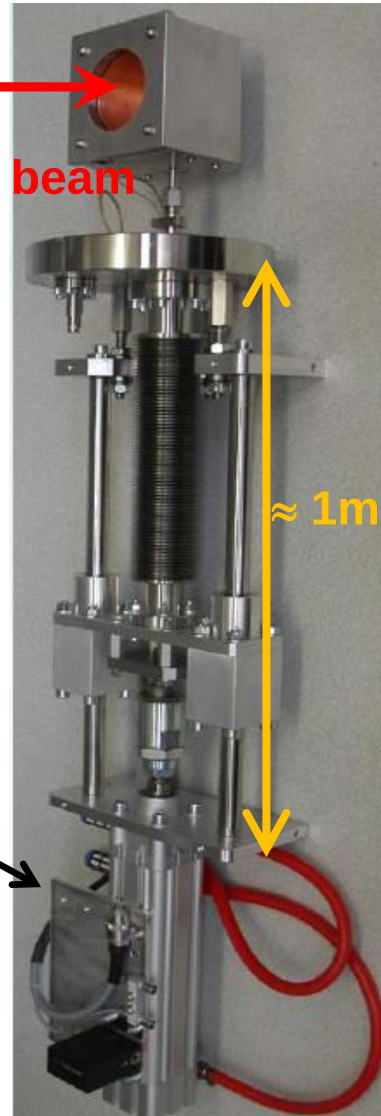
The Cup is moved into the beam pass.

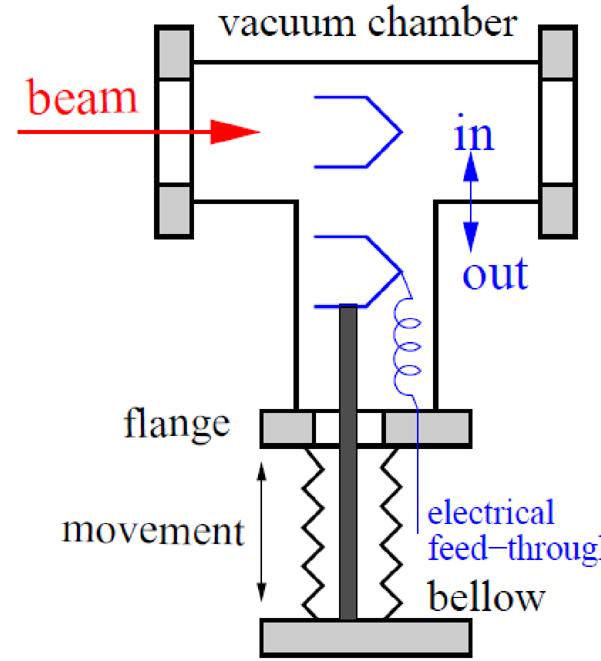
Faraday Cup ∅60 mm

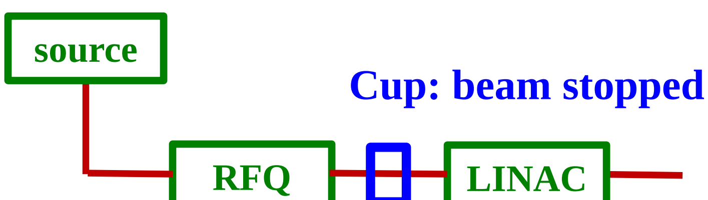
vacuum flange here ∅150 mm

bellow compression for movement

pneumatic drive







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}≈ 30 µA, BW = 10 kHz ... 500 MHz

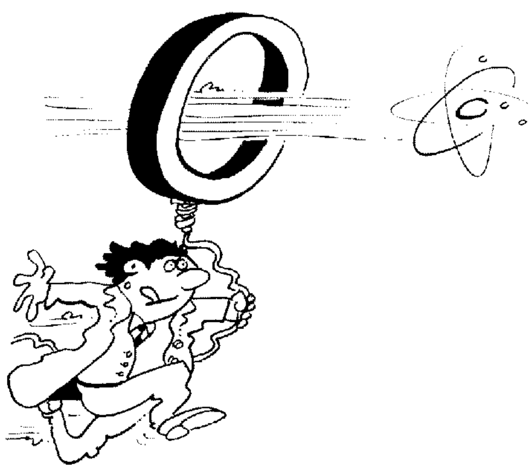
  [ACT : I_{min}≈ 0.3 µA, BW = 10 Hz .... 1 MHz, used at proton LINACs]

  DCCT: two toroids + modulation, I_{min}≈ 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

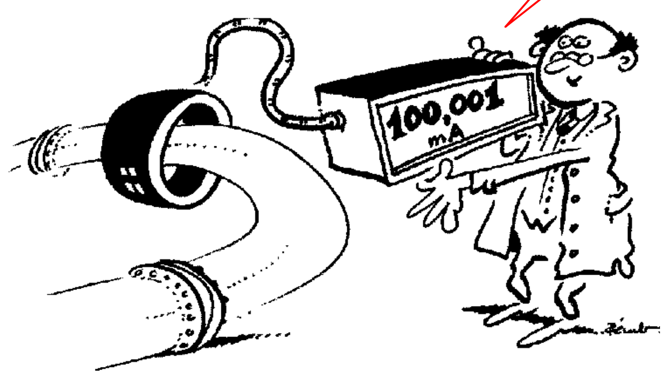
Fast Transformer FCT



Active transformer ACT

DC transformer DCCT

Resolution limit



Company Bergoz

Pick-Ups for bunched Beams

Outline:

- **Signal generation → transfer impedance**
- **Capacitive *button* BPM for high frequencies**
- **Capacitive *linear-cut* BPM for low frequencies**
- **Electronics for position evaluation**
- **BPMs for measurement**
- **Summary**

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

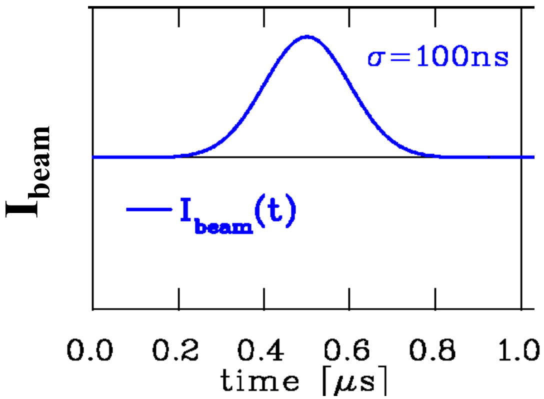
It delivers information about the transverse center of the beam:

- ***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, β-function

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

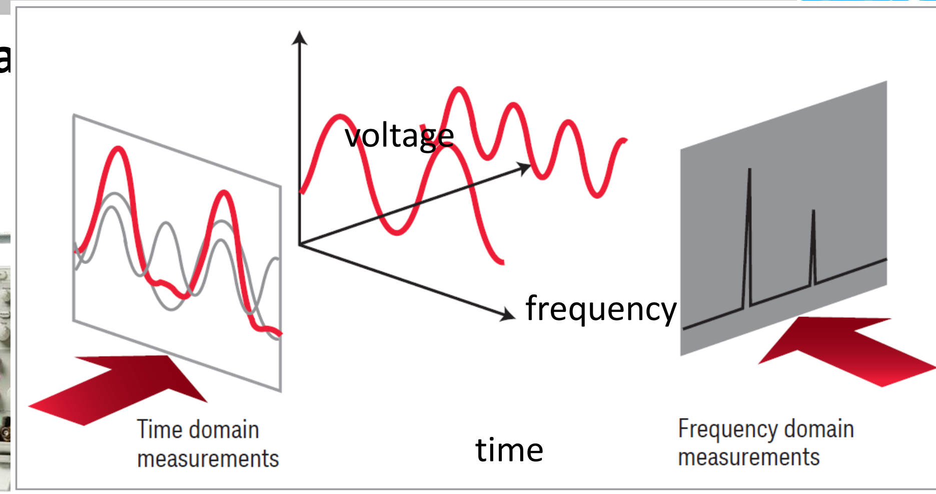
Time Domain ↔ Frequency Domain

Time domain: Recording of a voltage as a



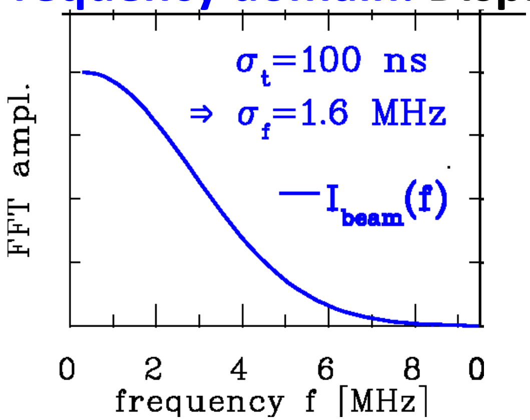
Instrument:

Oscilloscope



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

courtesy company Keysight



Instrument:

Spectrum Analyzer

Fourier Transformation:

- Contains amplitude & phase
- The **same** information is displayed differently

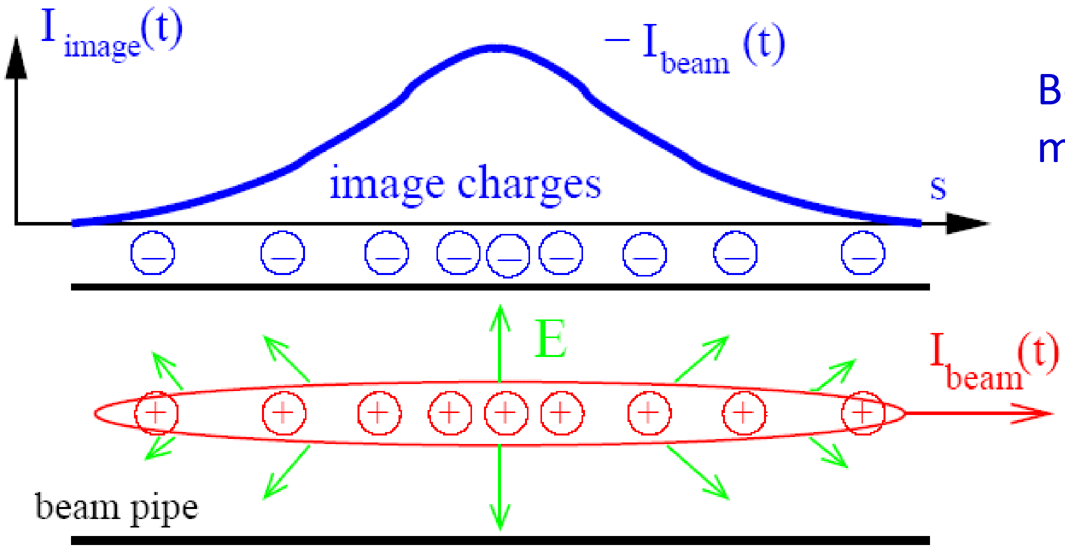
Law of Convolution: For a convolution in time: $f(t) = \int_{-\infty}^{\infty} f_1(\tau) \cdot f_2(t-\tau)\, d\tau$

$\Rightarrow \hat{f}(\omega) = \hat{f_1}(\omega) \cdot \hat{f_2}(\omega)$ ⇔ 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.



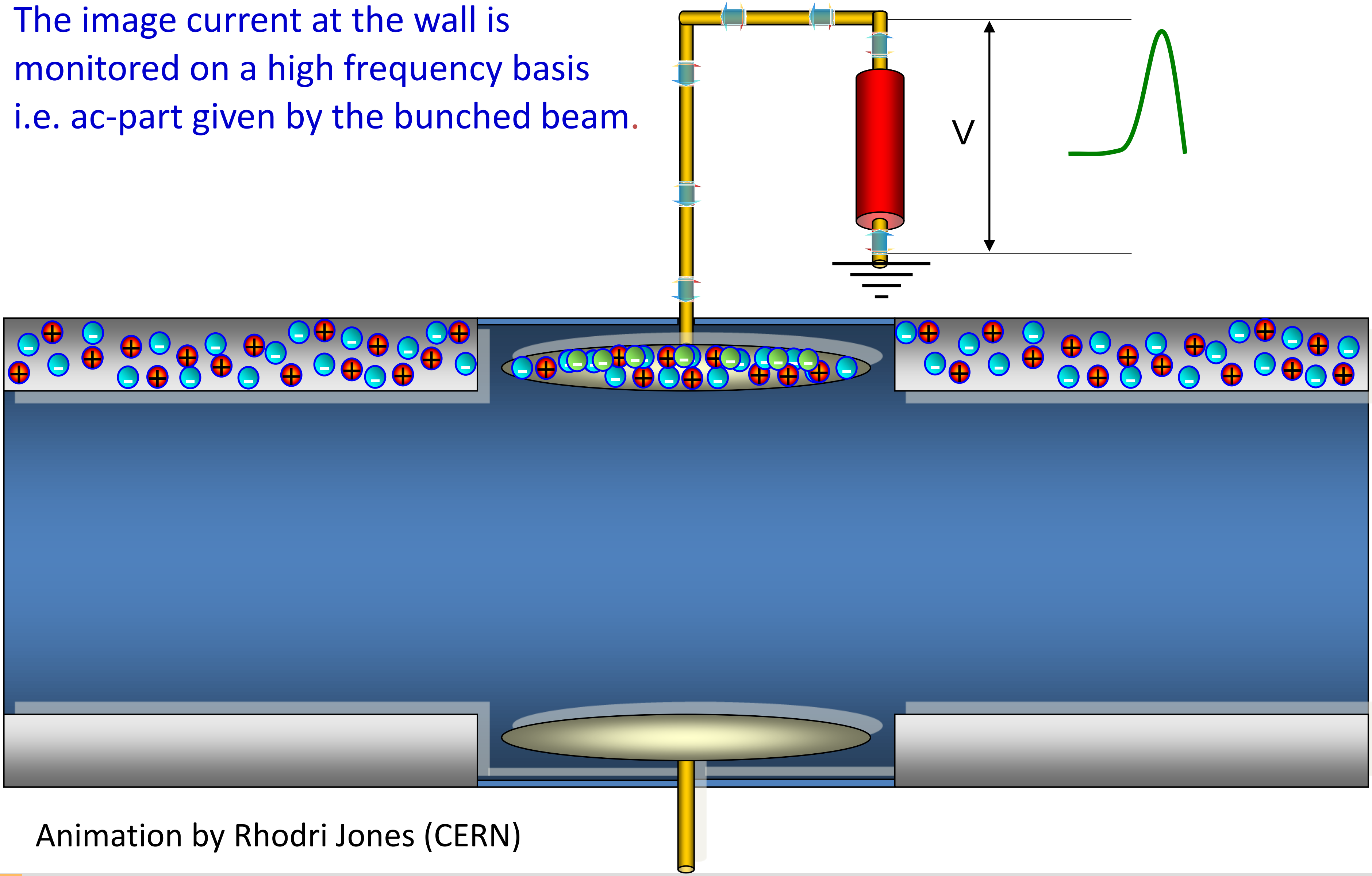
Beam Position Monitor **BPM** is the most frequently used instrument!

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

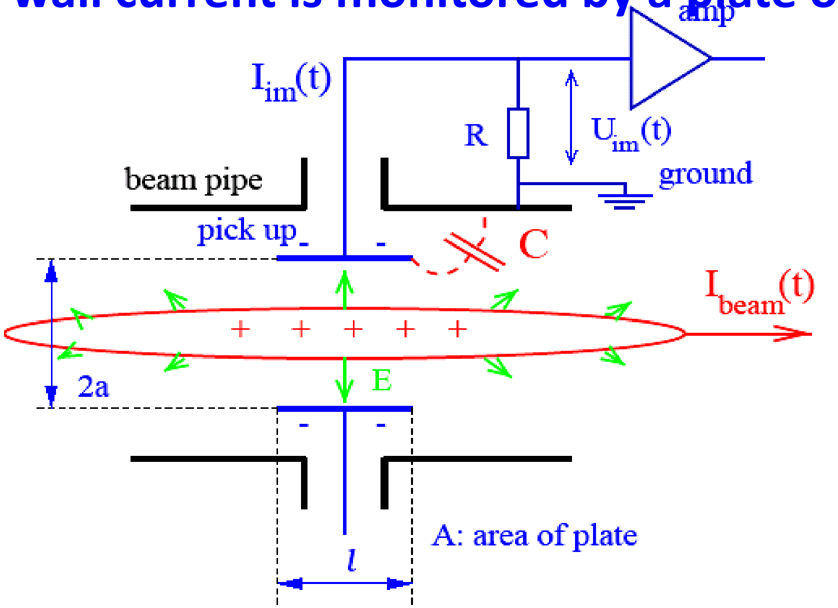
The image current at the wall is monitored on a high frequency basis i.e. ac-part given by the bunched beam.

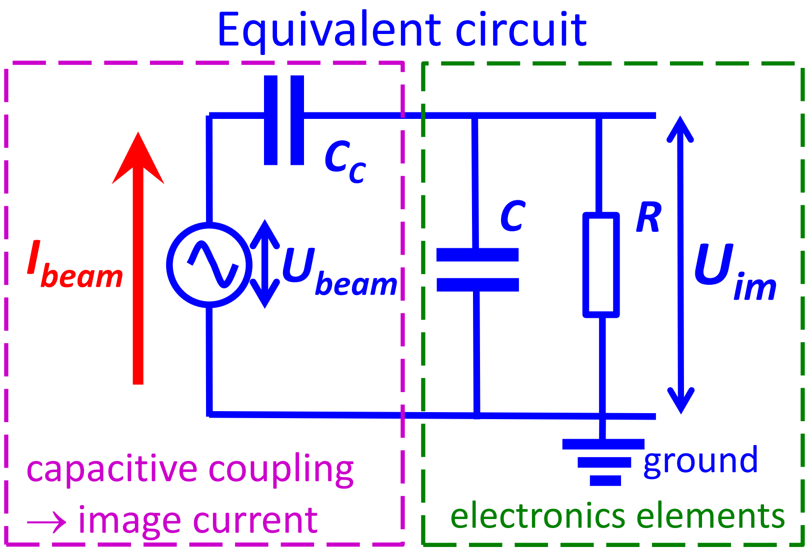


Animation by Rhodri Jones (CERN)

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

geometry — stray capacitance — frequency response

Example of Transfer Impedance for Proton Synchrotron

The high-pass characteristic for typical synchrotron BPM:

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

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

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

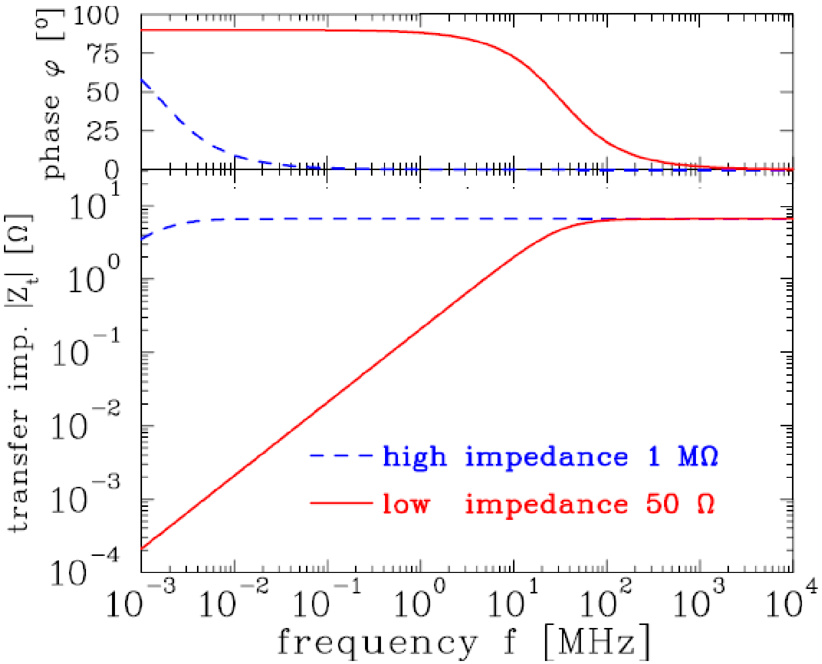
Parameter linear-cut BPM at proton synchr.:

C = 100pF, ***l*** = 10cm, β = 50%

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

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

for $R = 1\ \mathrm{M}\Omega \Rightarrow f_{cut}$ = 1.6 kHz



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

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

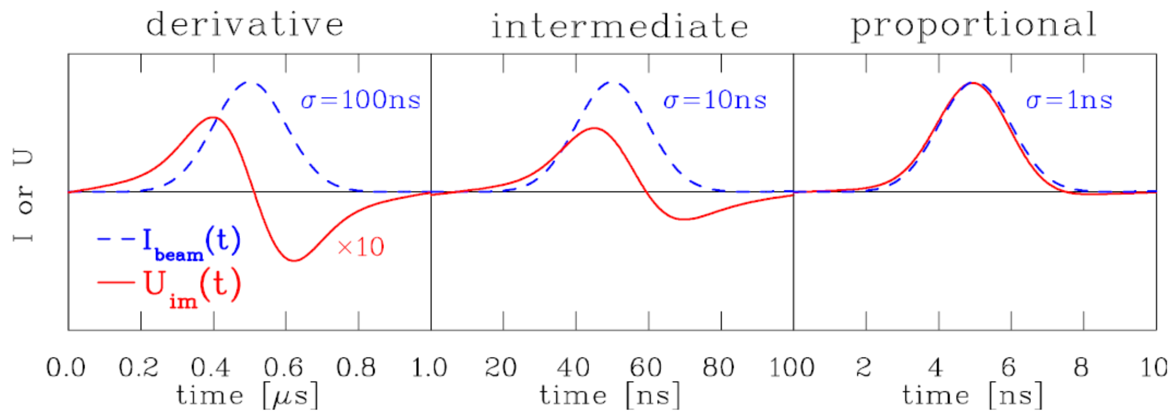
Remark: For $\omega \rightarrow 0$ it is $Z_t \rightarrow 0$ i.e. **no** signal is transferred from dc-beams e.g.

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

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

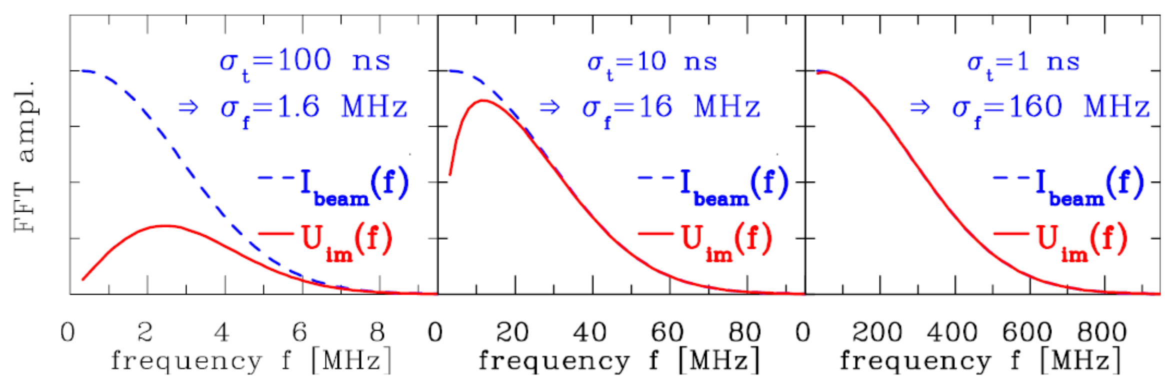
1. Start: Time domain Gaussian function $I_{beam}(t)$ having a width of σ_t

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

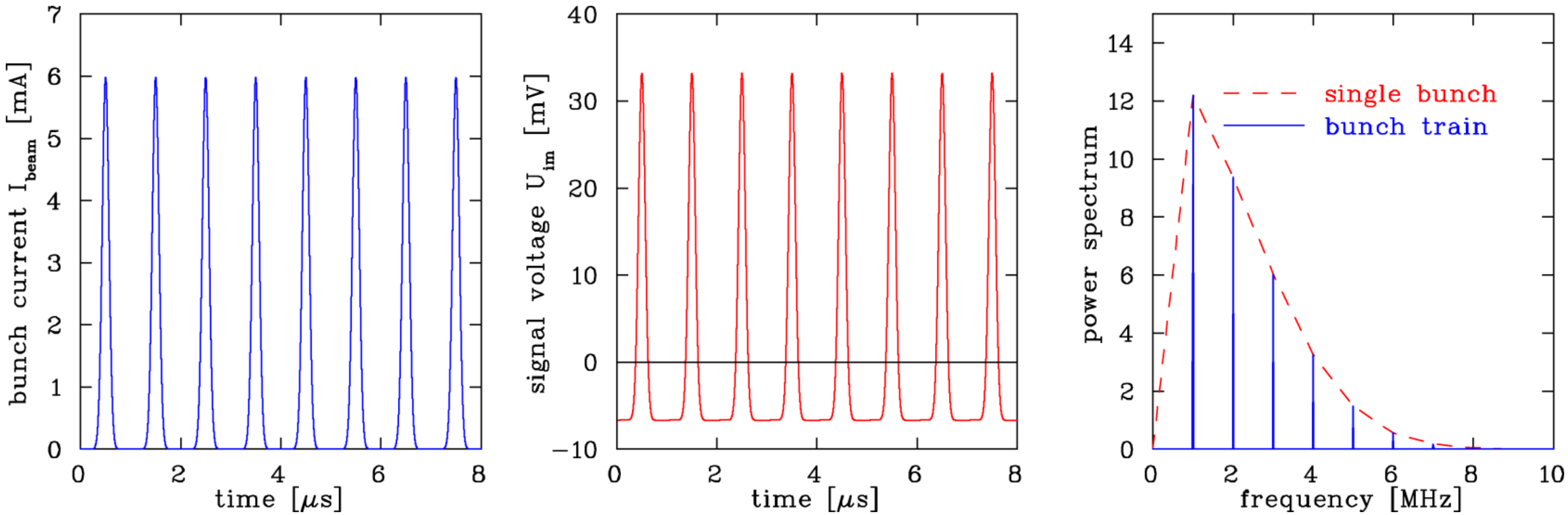
4. Inverse FFT leads to $U_{im}(t)$

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 f_{acc}=1 MHz

BPM terminated with R= 1 MΩ $\Rightarrow f_{acc} >> f_{cut}$:



Parameter: R = 1 MΩ $\Rightarrow f_{cut}$ = 2 kHz, Z_t = 5 Ω , all buckets filled

C=100pF, l=10cm, β=50%, σ_t=100 ns $\Rightarrow \sigma_l$=15m

- Fourier spectrum is composed of lines separated by acceleration f_{rf}
- Envelope given by single bunch Fourier transformation
- Baseline shift due to ac-coupling

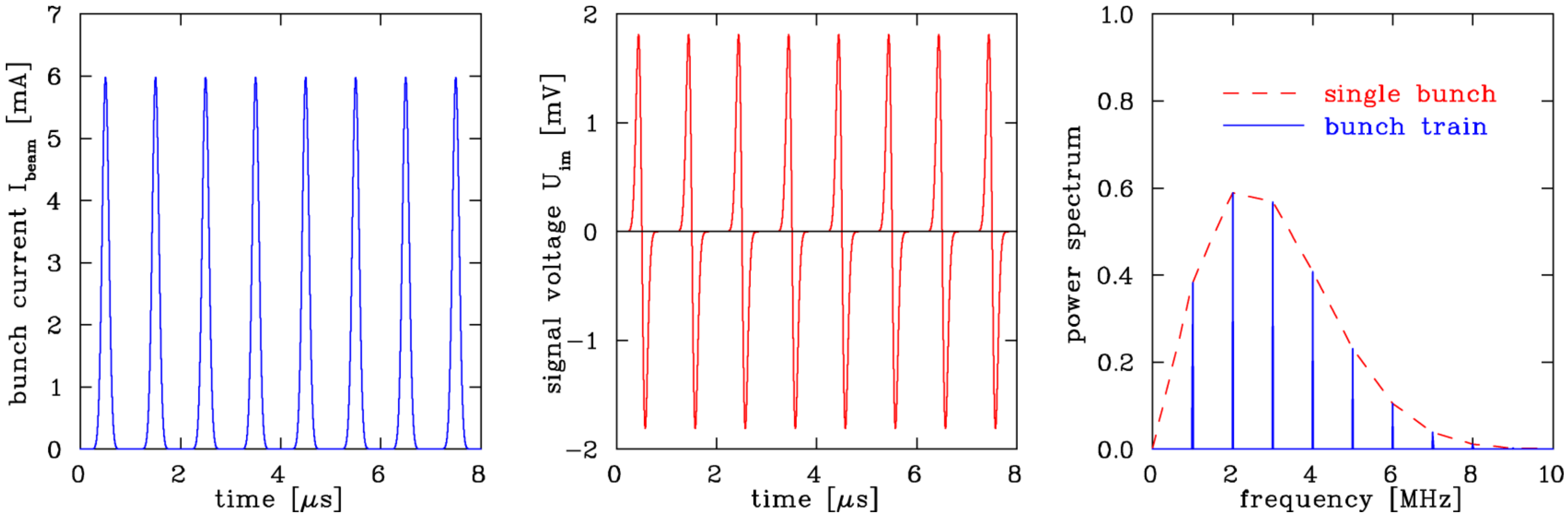
Remark: 1 MHz< f_{rf} <10MHz $\Rightarrow$ Bandwidth ≈100MHz=10 * f_{rf} for broadband observation

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

Calculation of Signal Shape: repetitive Bunch in a Synchrotron

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

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



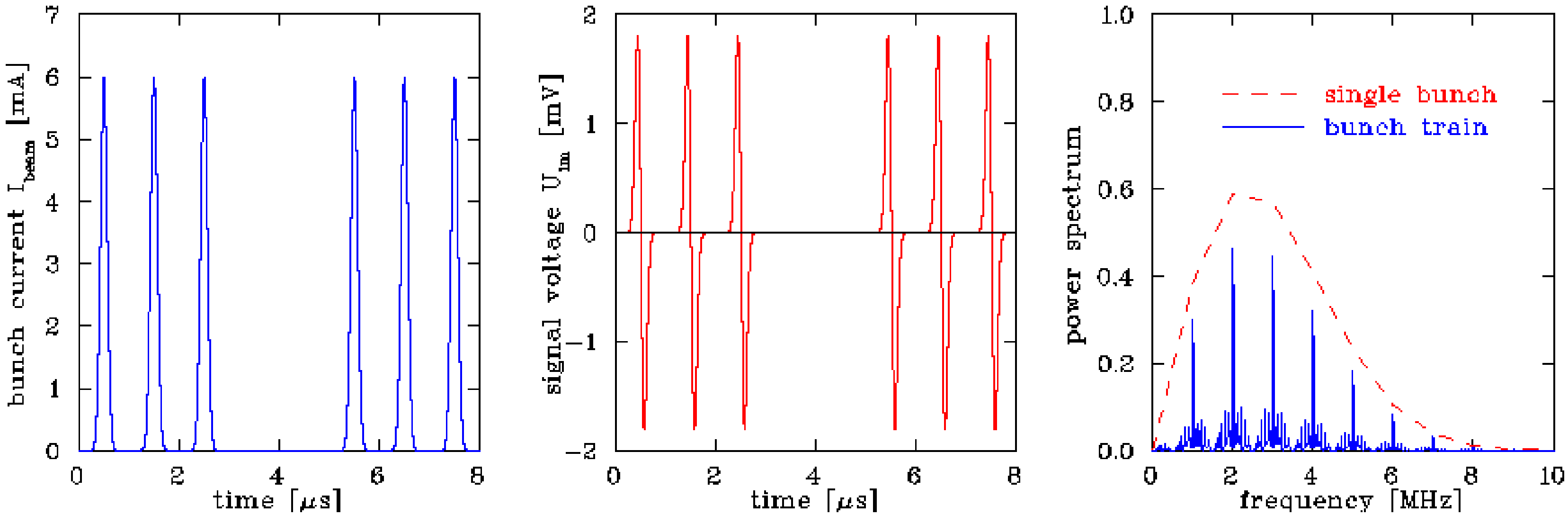
Parameter: R**=50 Ω** $\Rightarrow f_{cut}$**=32 MHz, all buckets filled**

C=100pF, l=10cm, β=50%, σ_t=100 ns $\Rightarrow \sigma_l$=15m

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

Calculation of Signal Shape: Bunch Train with empty Buckets

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

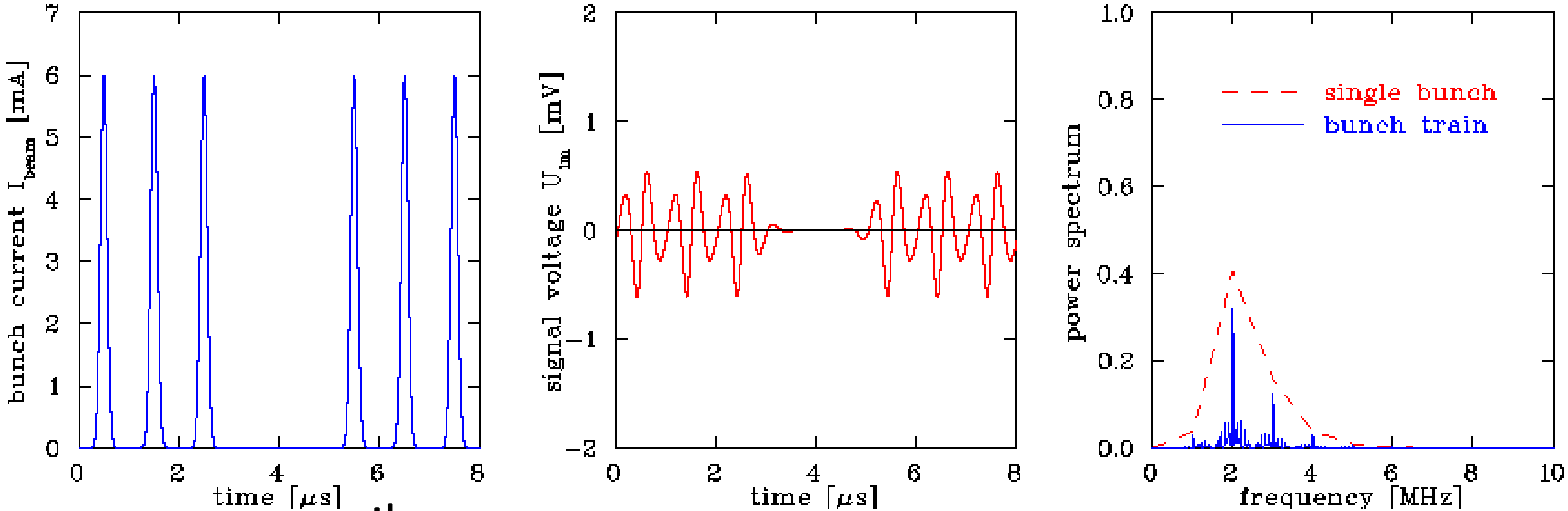


Parameter: ***R*=50 Ω ⇒ f_{cut}=32 MHz, 2 empty buckets**

C=100pF, *l*=10cm, *β*=50%, σ_t=100 ns ⇒ σ_l=15m

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

Effect of filters, here bandpass:



Parameter: ***R*=50 Ω, 4th order Butterworth filter at f_{cut}=2 MHz**

C=100pF, *l*=10cm, *β*=50%, σ=100 ns

- Ringing due to sharp cutoff
- Other filter types more appropriate

*nth order Butterworth filter, math. simple, but **not** well suited:*

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

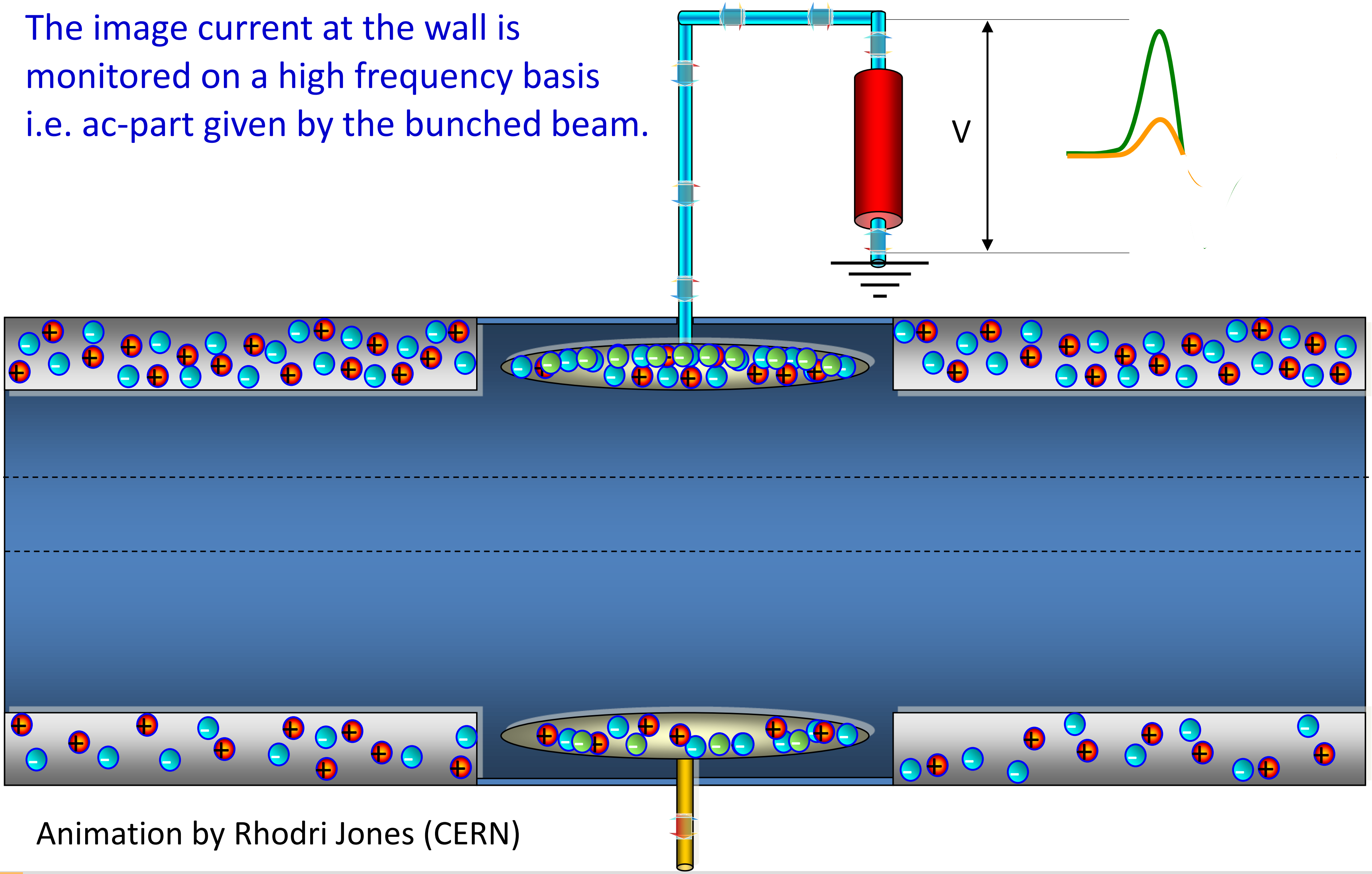
$$H_{filter} = H_{high} \cdot H_{low}$$

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)

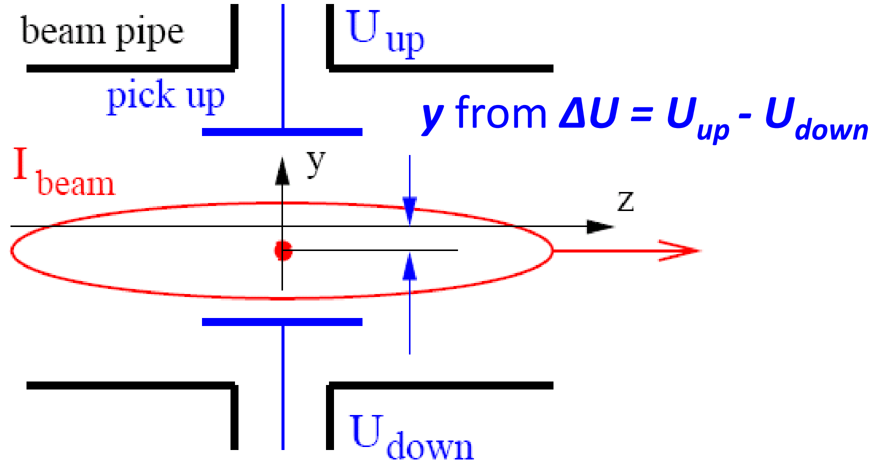
Principle of Position Determination by a BPM

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

$$y = \frac{1}{S_y(\omega)} \cdot \frac{U_{up} - U_{down}}{U_{up} + U_{down}} + \delta_y(\omega)$$

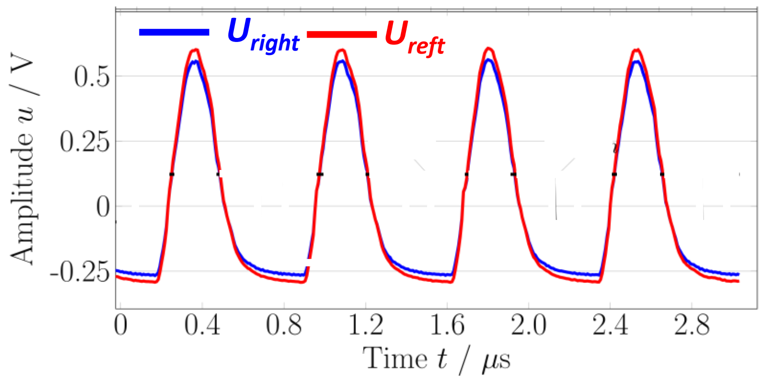
$$\equiv \frac{1}{S_y} \cdot \frac{\Delta U_y}{\Sigma U_y} + \delta_y$$

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



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

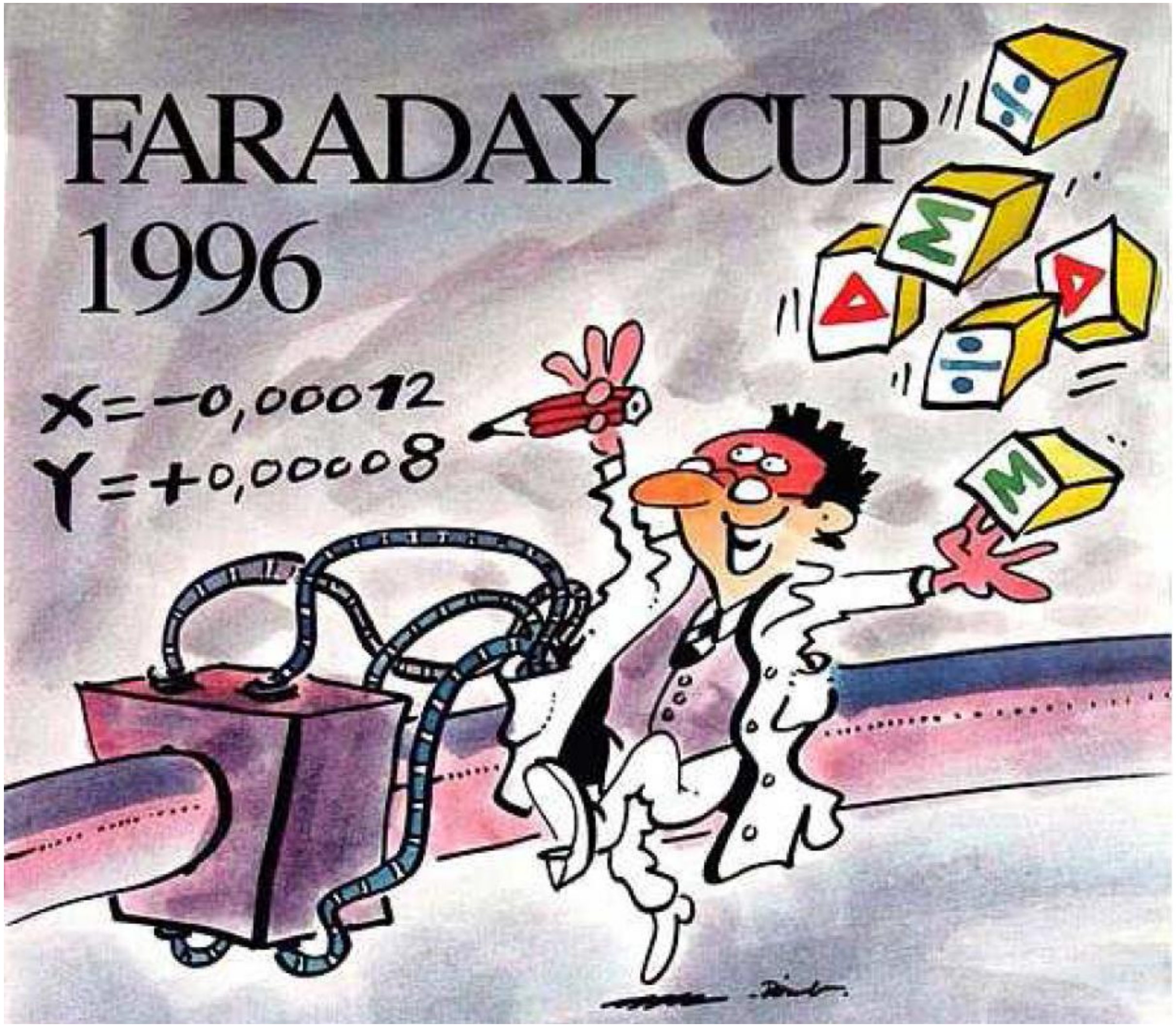


Typical desired position resolution:

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

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

The Artist View of a BPM



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
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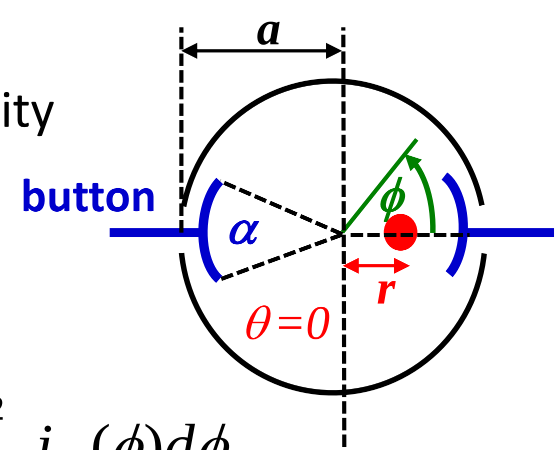
- Summary

2-dim Model for a Button BPM

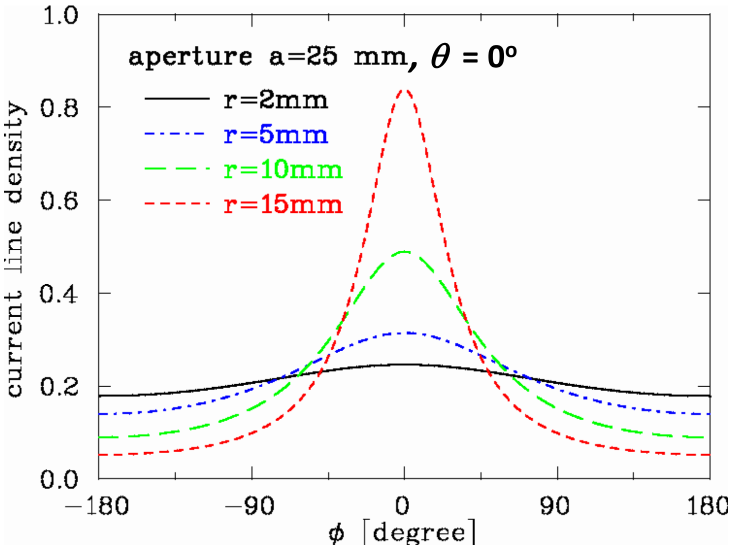
'Proximity effect': larger signal for closer plate

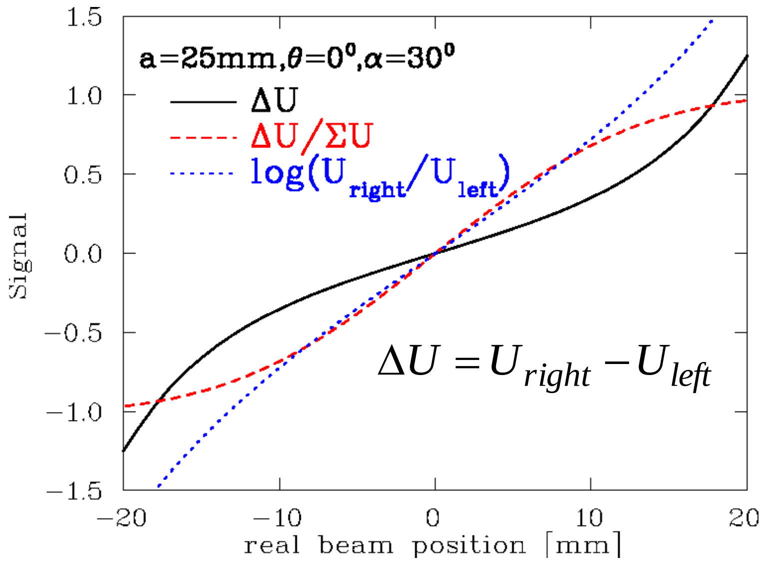
Ideal 2-dim model: Cylindrical pipe → image current density via 'image charge method' for 'pencil' beam:



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

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





2-dim Model for a Button BPM

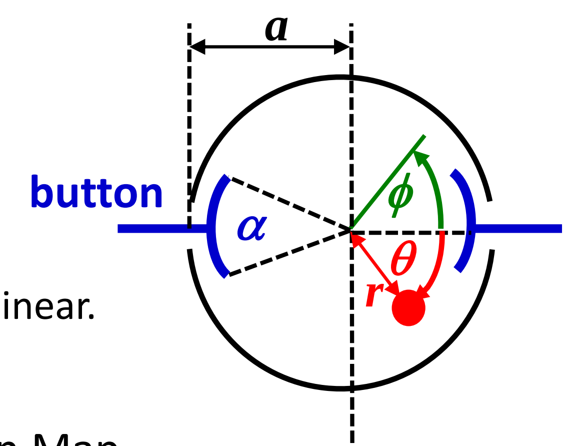
Ideal 2-dim model: Non-linear behavior and hor-vert coupling:

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

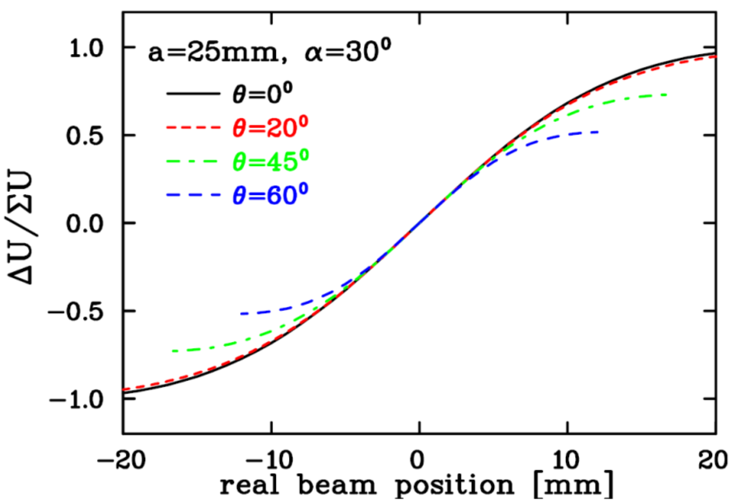
with S [%/mm] or [dB/mm]

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

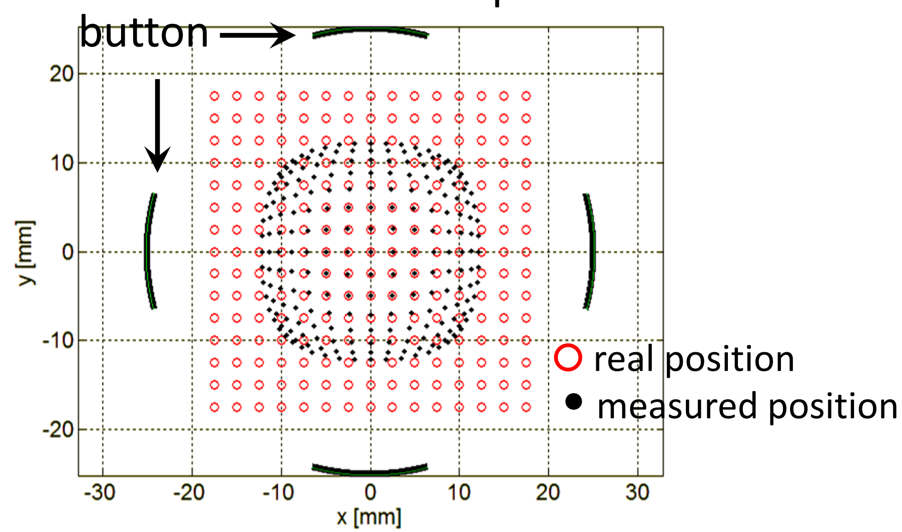
For this example: central part S=7.4%/mm ⇔ $k=1/S$=14mm



Horizontal plane



Position Map



Button BPM Realization

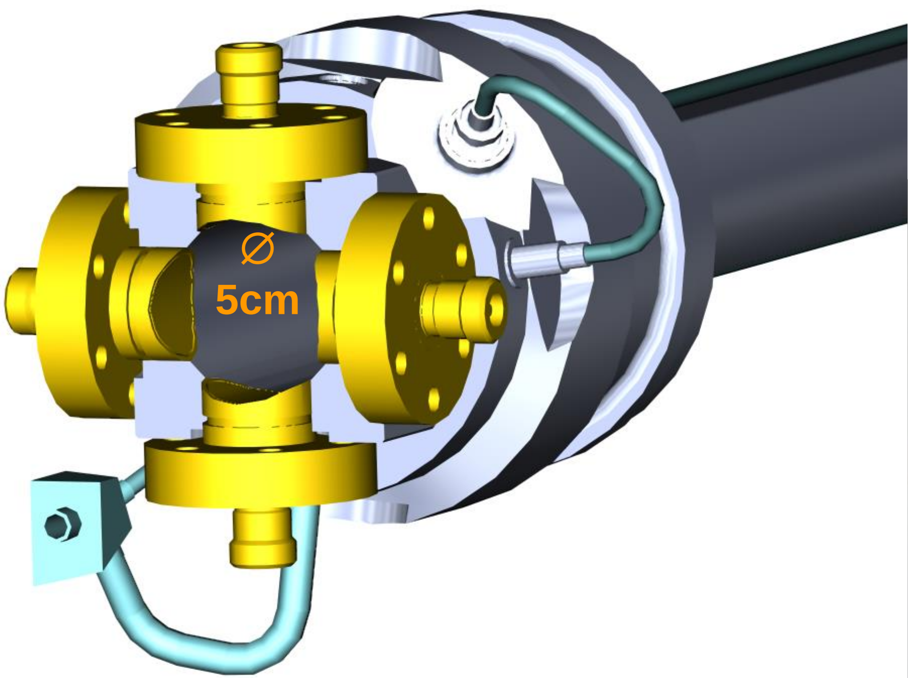
LINACs, e⁻-synchrotrons: 100 MHz < f_{rf} < 3 GHz → bunch length ≈ BPM length

→ 50 Ω signal path to prevent reflections

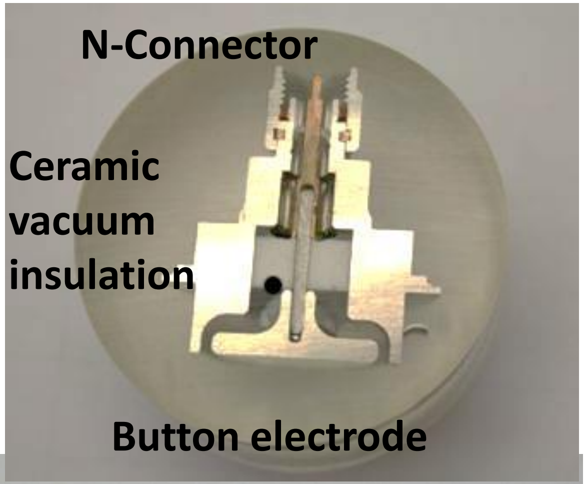
Example: LHC-type inside cryostat:

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

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



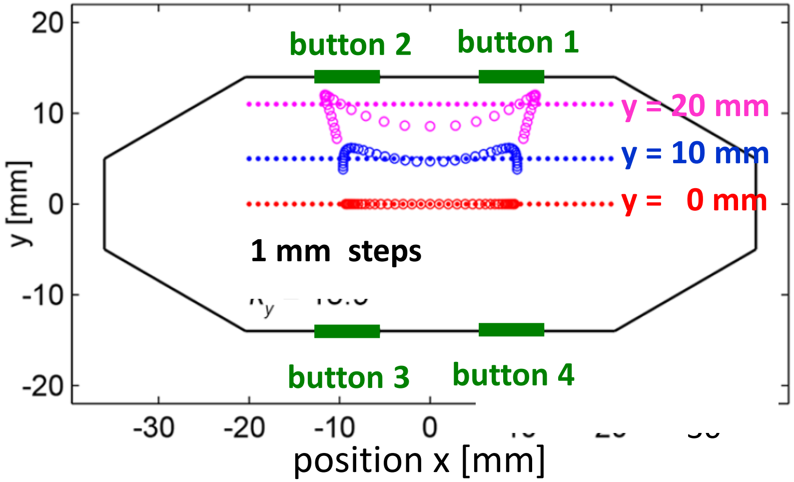
Courtesy C. Boccard (CERN)

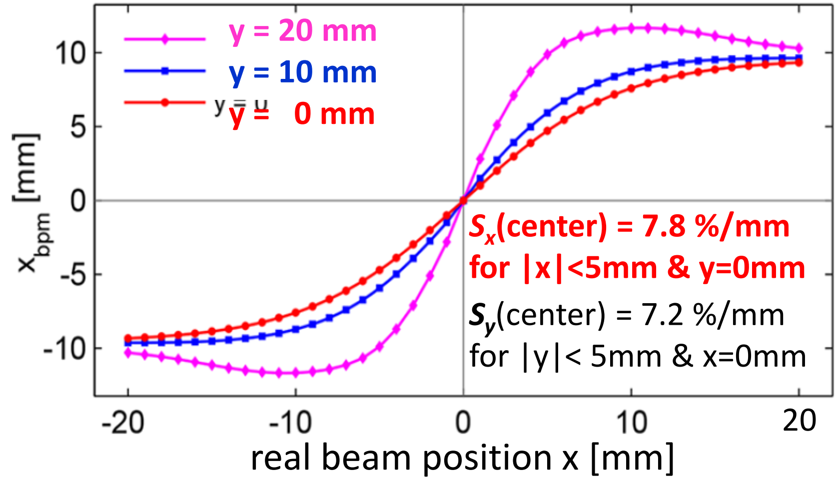


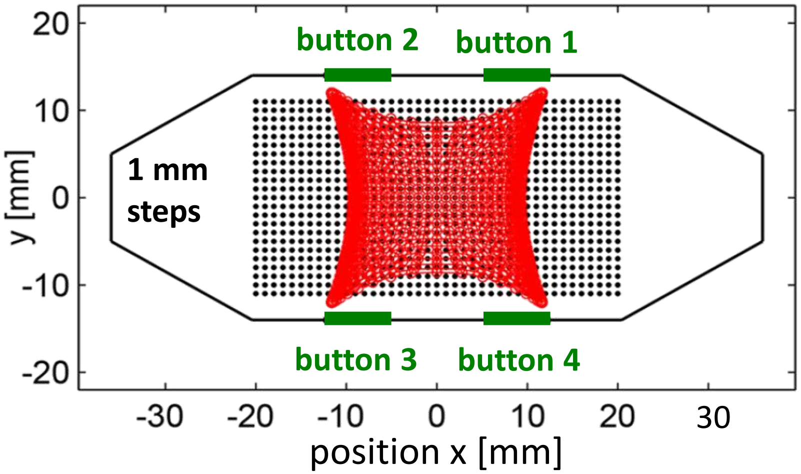
Example: Simulation for ALBA light source for 72 x 28 mm² chamber

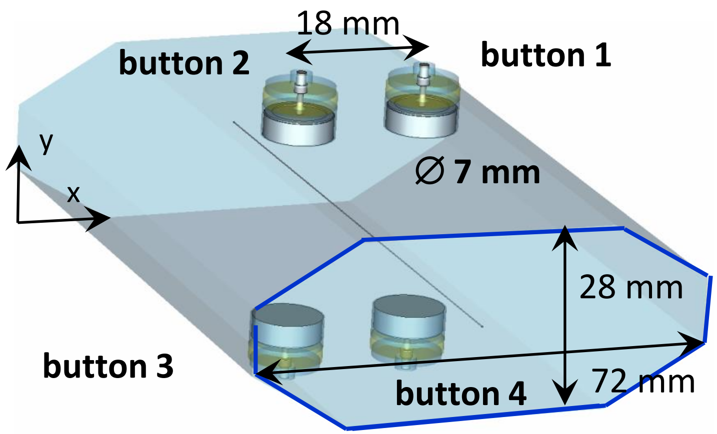
Optimization: horizontal distance and size of buttons

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









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

Outline:

- Signal generation $\rightarrow$ 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
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- Summary

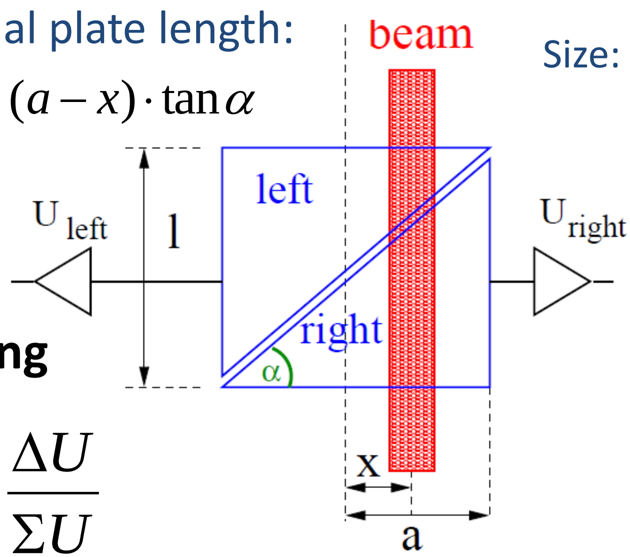
Linear-cut BPM for Proton Synchrotrons

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

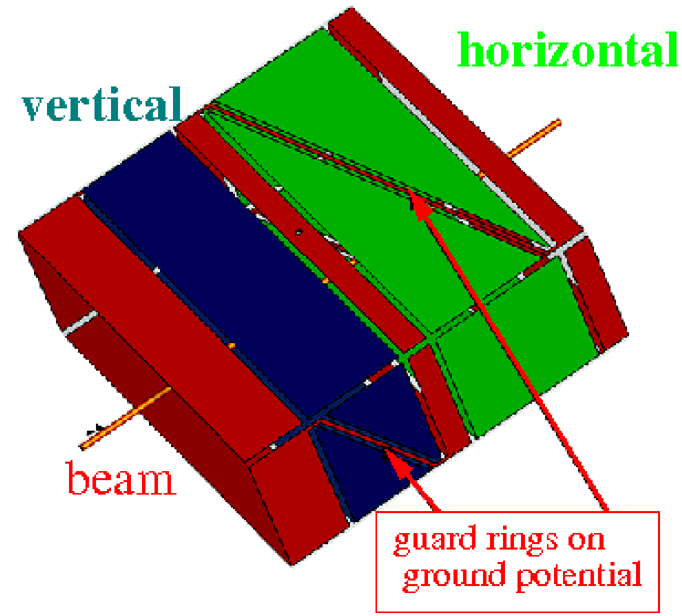
Signal is proportional to actual plate length:

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

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

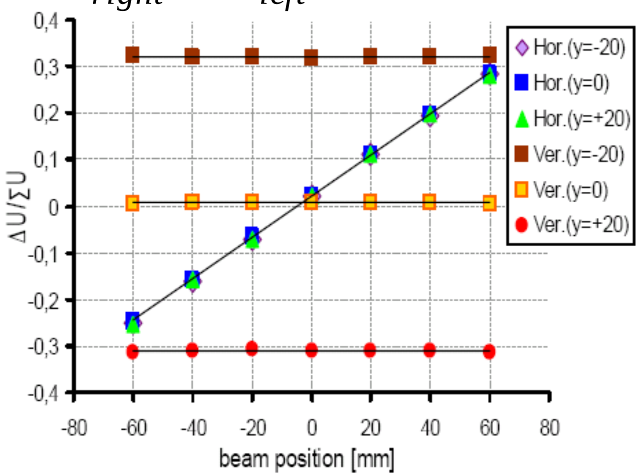


Size: 200x70 mm²



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***

⇔ no beam size dependence

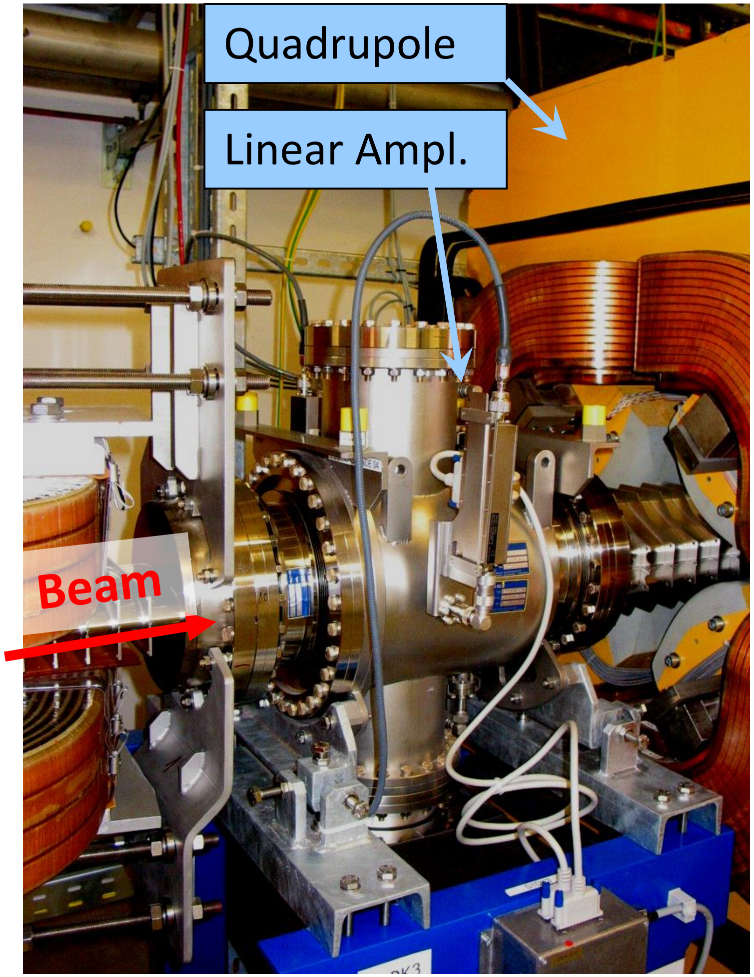
Disadvantage: Large size, complex mechanics

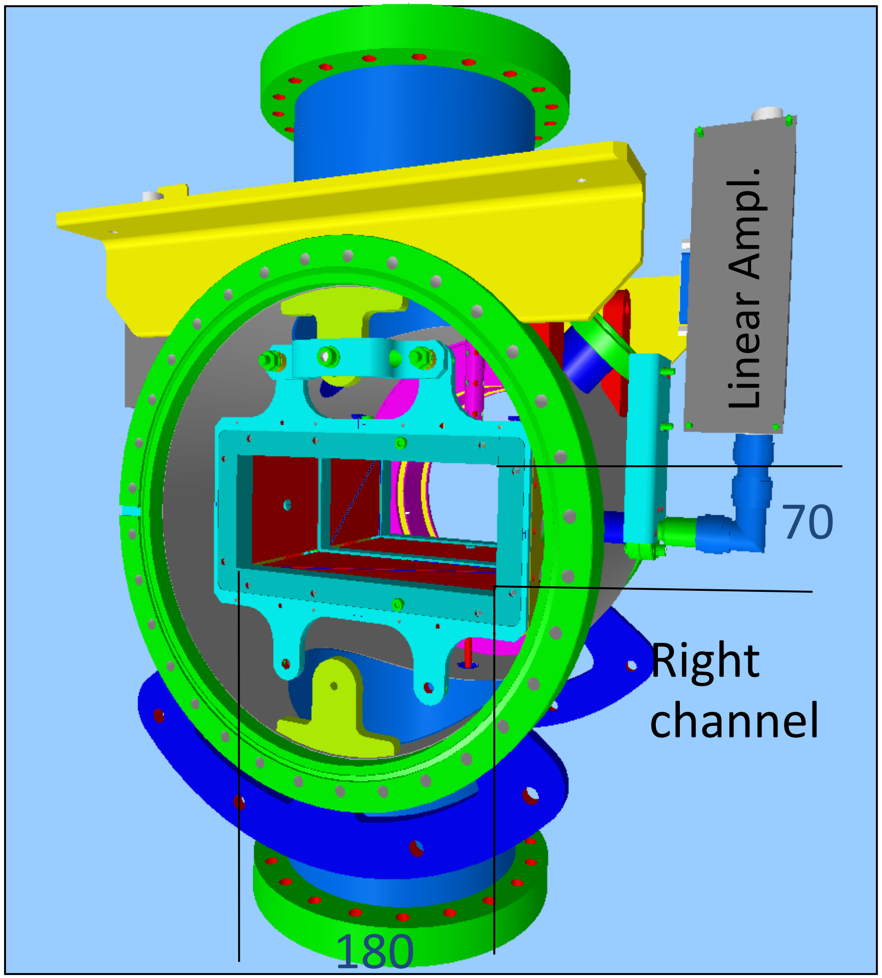
high capacitance

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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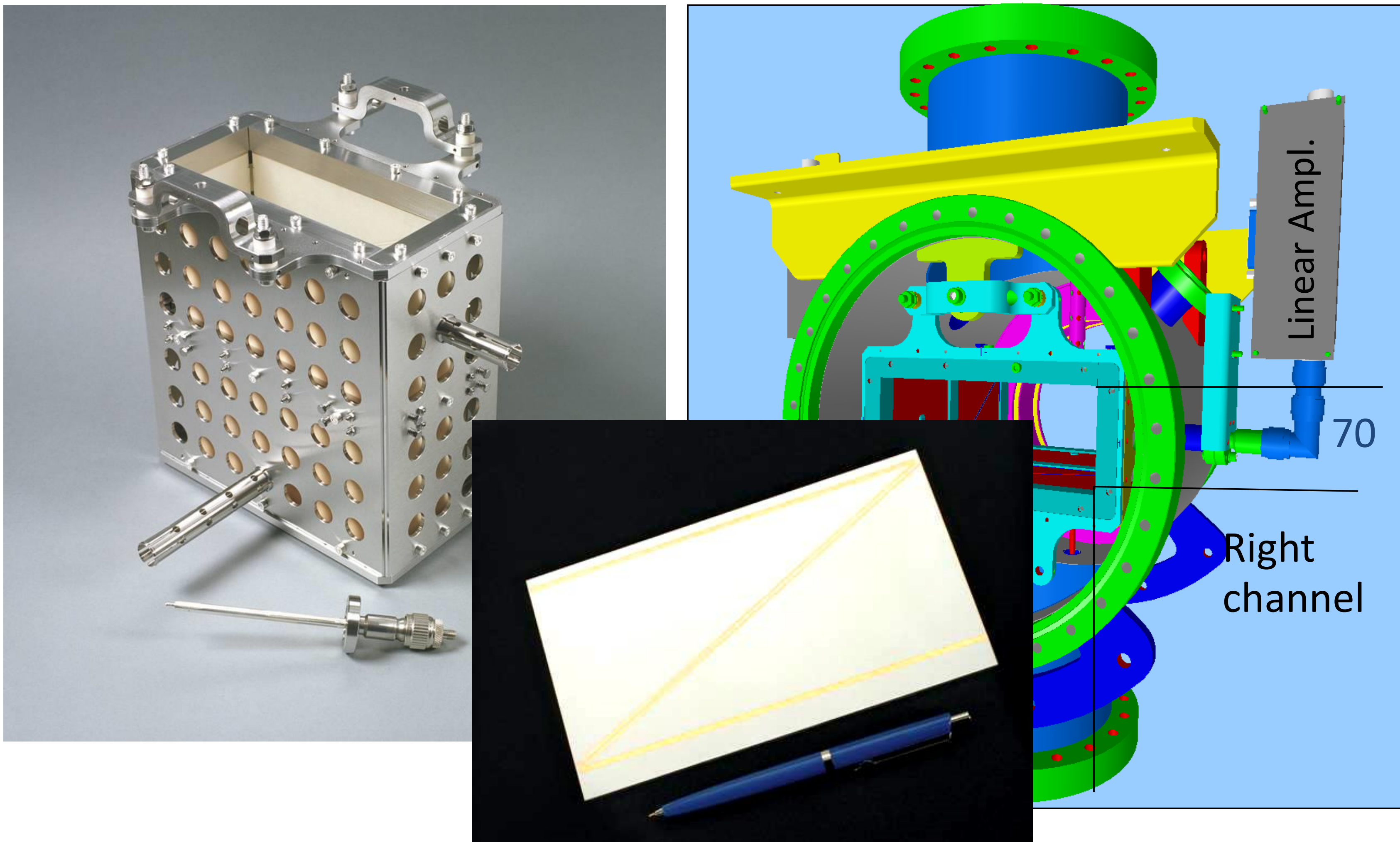
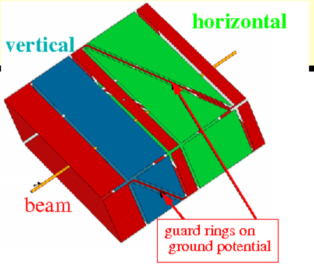
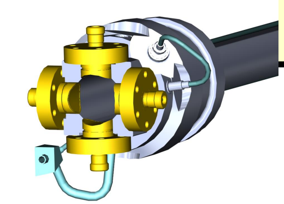


Comparison linear-cut and Button BPM

	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. wall current monitors, inductive antenna, BPMs with external resonator, cavity BPM, slotted wave-guides for stochastic cooling etc.

→stripline BPM

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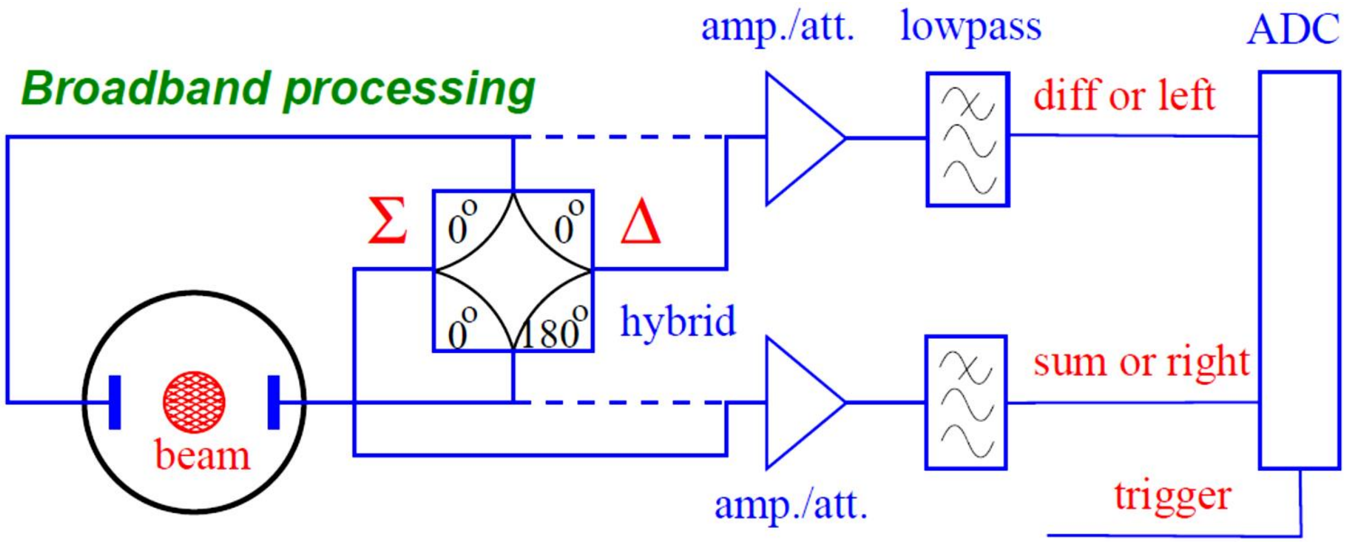
- Electronics for position evaluation
  analog signal conditioning to achieve small signal processing
- BPMs for measurement of closed orbit, tune and further lattice functions
- Summary

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 shoe box type , i.e. ≈0.1% of aperture, resolution is worse than narrowband processing, see below

Challenge: Precise analog electronics with very low drift of amplification etc.

General: Noise Consideration

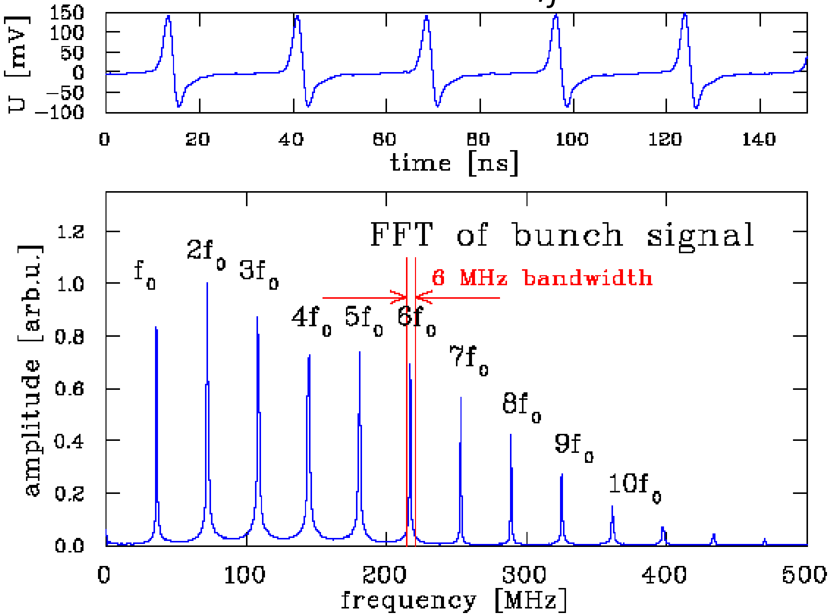
1. Signal voltage given by: $U_{im}(f) = Z_t(f) \cdot I_{beam}(f)$
2. Position information from voltage difference: $x = 1/S \cdot \Delta U / \Sigma U$
3. Thermal noise voltage given by: $U_{noise}(R, \Delta f) = \sqrt{4k_B \cdot T \cdot R \cdot \Delta f}$

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

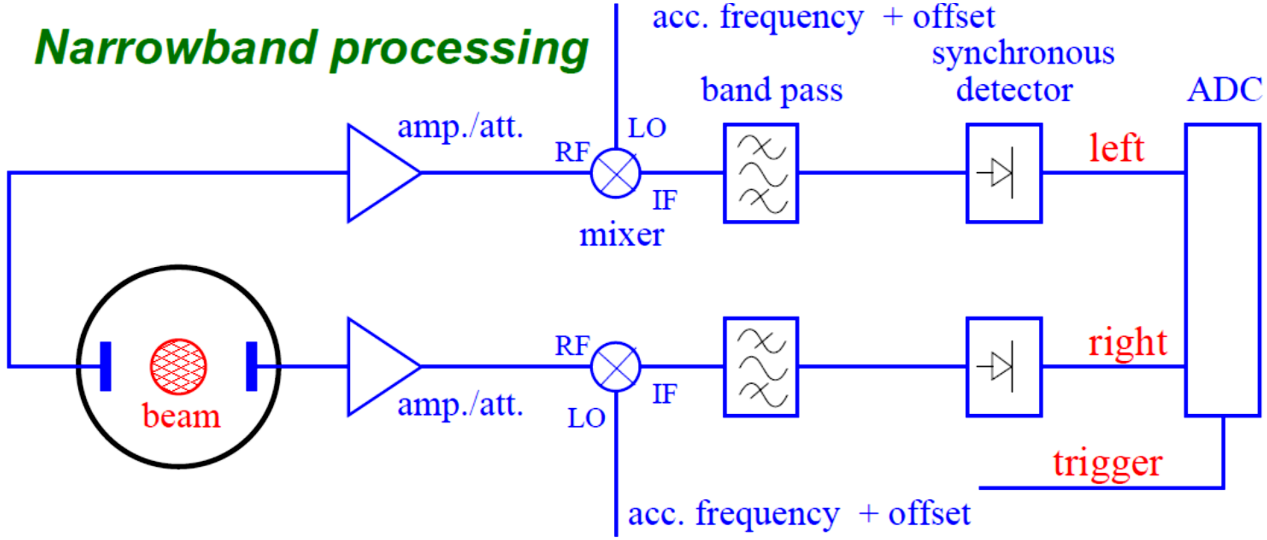
- Input signal amplitude
- Thermal noise from amplifiers etc.
- Bandwidth Δf

$\Rightarrow$ Restriction of frequency width as the power is concentrated at harm. nf_{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 spectrum analyzer)

- Attenuator/amplifier
- Mixing with accelerating frequency $f_{rf} \Rightarrow$ signal with difference frequency
- Bandpass filter of the mixed signal (e.g at 10.7 MHz)
- Rectifier: synchronous detector
- ADC: digitalization → followed calculation of ***ΔU/ΣU***

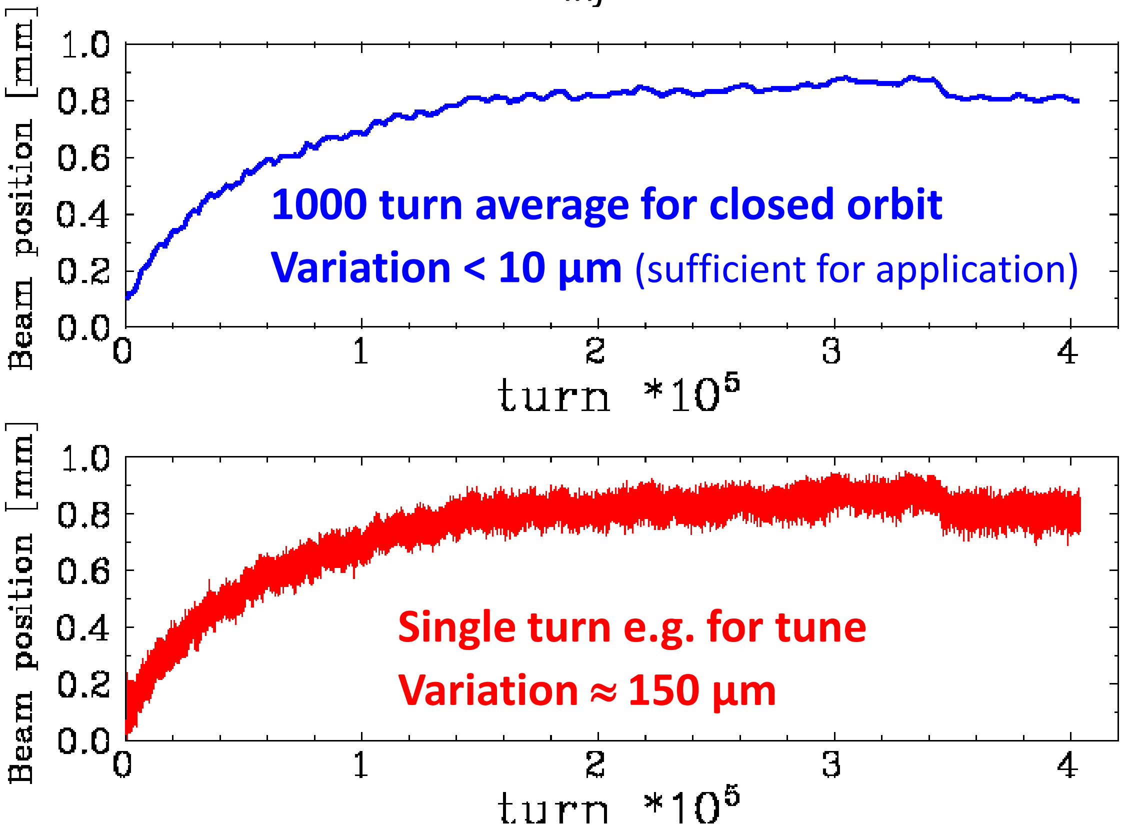
} Digital correspondence: I/Q demodulation

Advantage: Spatial resolution about 100 time better than broadband processing

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

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

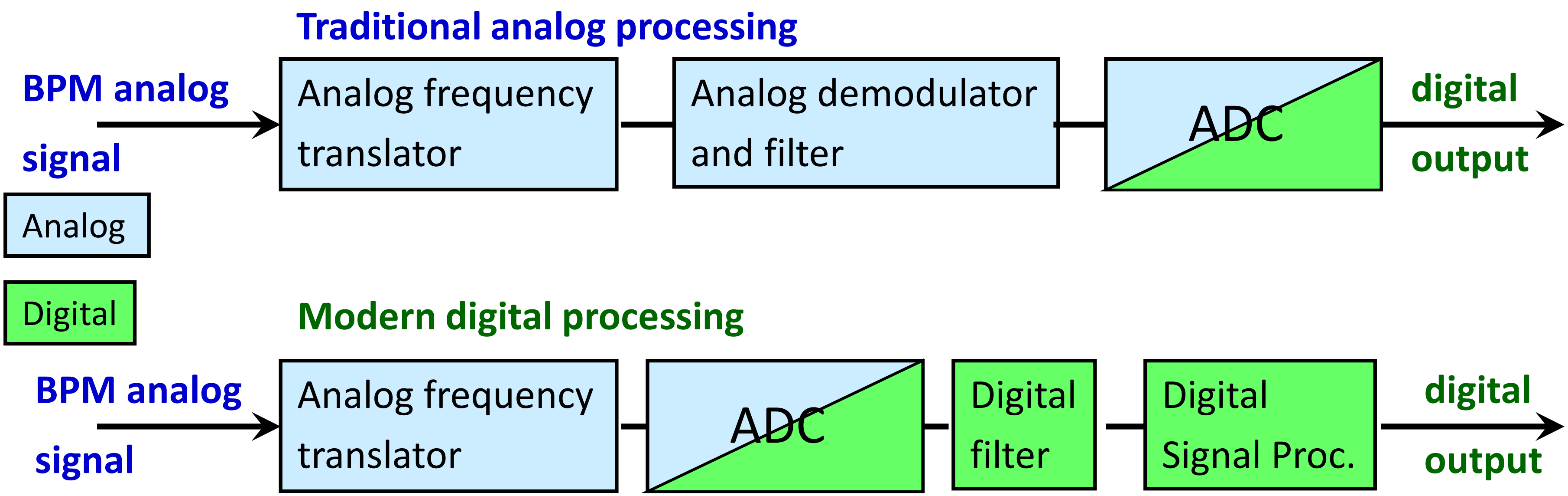


- Position resolution < 30 µm (BPM diameter d=180 mm)
- average over 1000 turns corresponding to ≈1 ms or ≈1 kHz bandwidth
- Turn-by-turn data have much larger variation

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

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 Post-processing possible **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 Complex electronics
Digital Signal Processing	all	ADC sample typ. 250 MS/s	Very flexible & versatile High resolution **Trendsetting technology for future demands**	**Basically non!** Limited time resolution by ADC $\rightarrow$ under-sampling Man-power intensive

Outline:

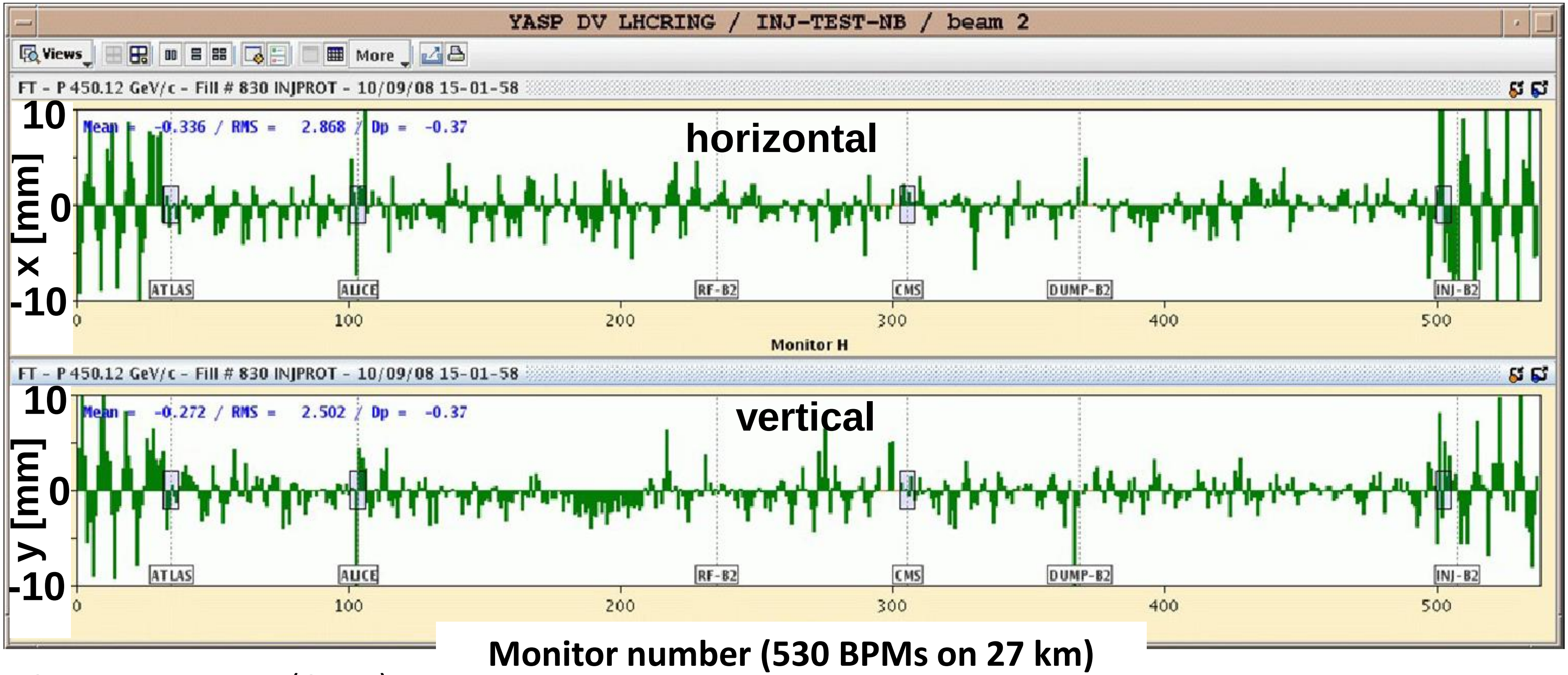
- Signal generation → transfer impedance
- Capacitive *button* BPM for high frequencies
  used at most proton LINACs and electron accelerators
- Capacitive *linear-cut* BPM for low frequencies
  used at most proton synchrotrons due to linear position reading
- Electronics for position evaluation
  analog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

Trajectory:

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 !



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):

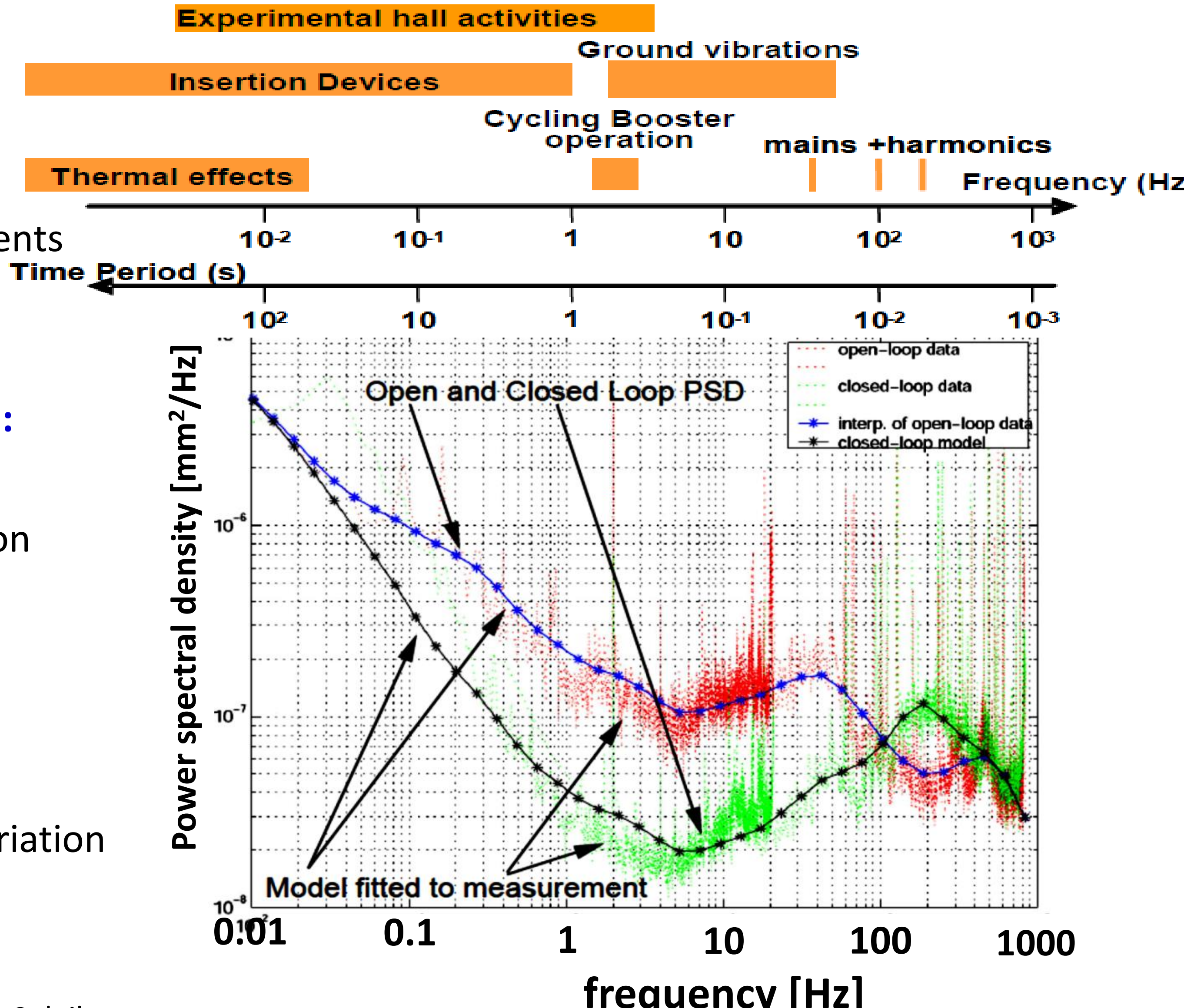
- Traffic
- Machine (crane) movements
- Water & vacuum pumps
- 50 Hz main power net

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

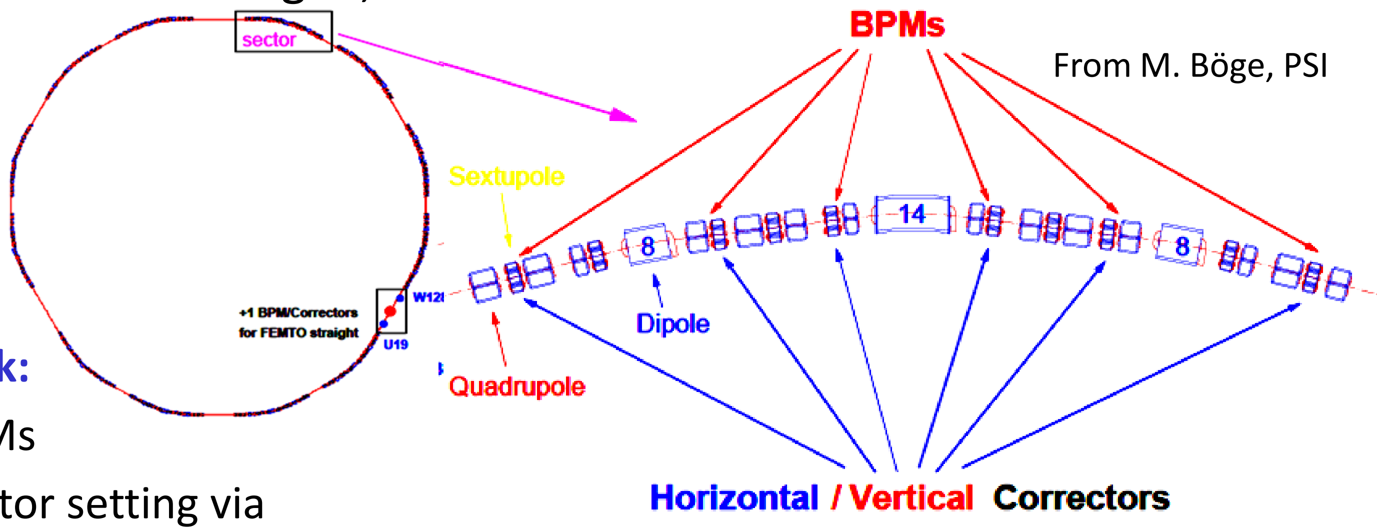


Courtesy M. Böge, PSI, N. Hubert, Soleil

Close Orbit Feedback: BPMs and magnetic Corrector Hardware

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

Example: SLS-Synchrotron at Villigen, Switzerland



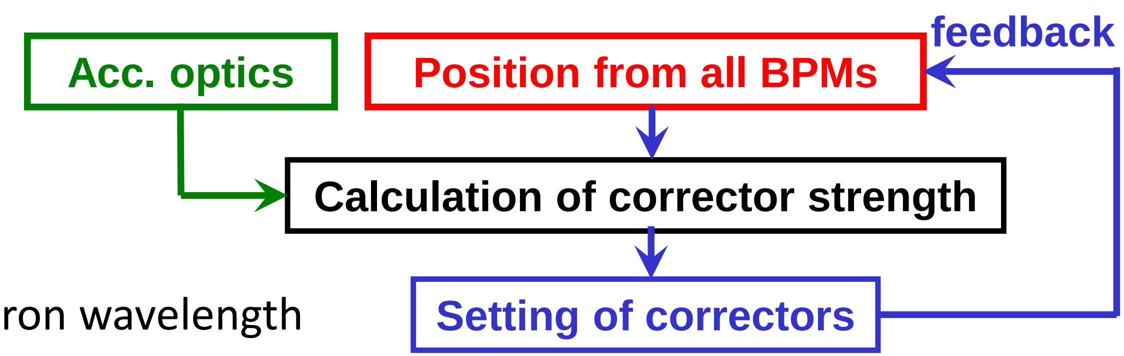
Procedure of a feedback:

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



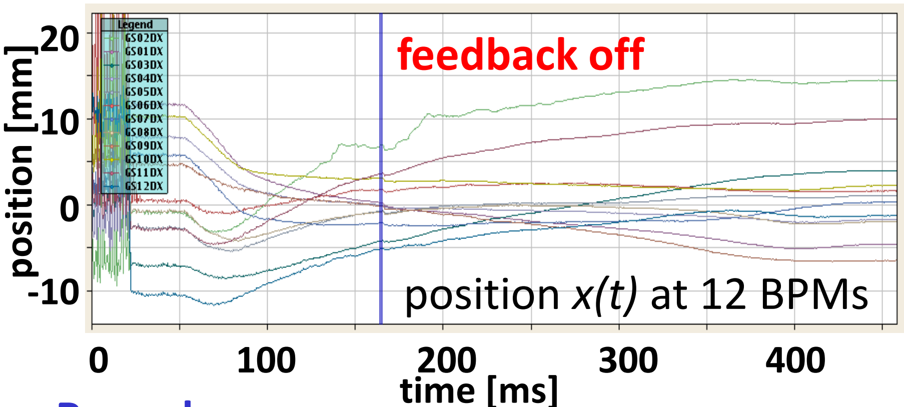
Uncorrected orbit: typ. $< x >_{rms} \approx 1$ mm

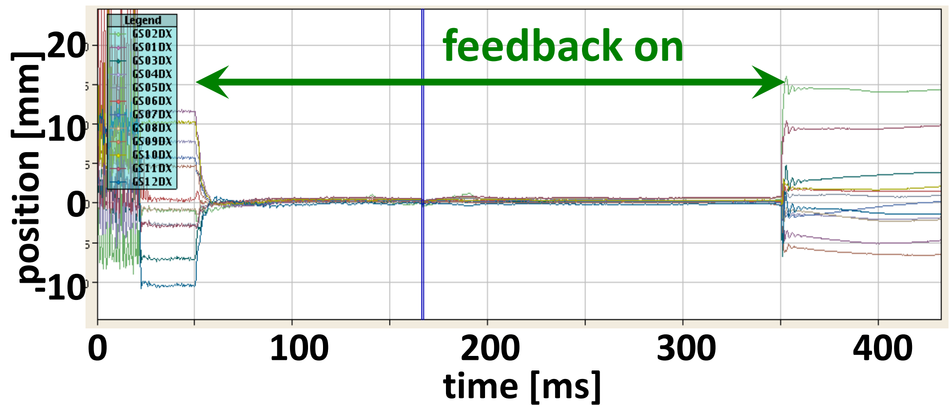
Corrected orbit: typ. $< x >_{rms} \approx 1$ µm up to ≈ 100 Hz bandwidth!

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

⇒ 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

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

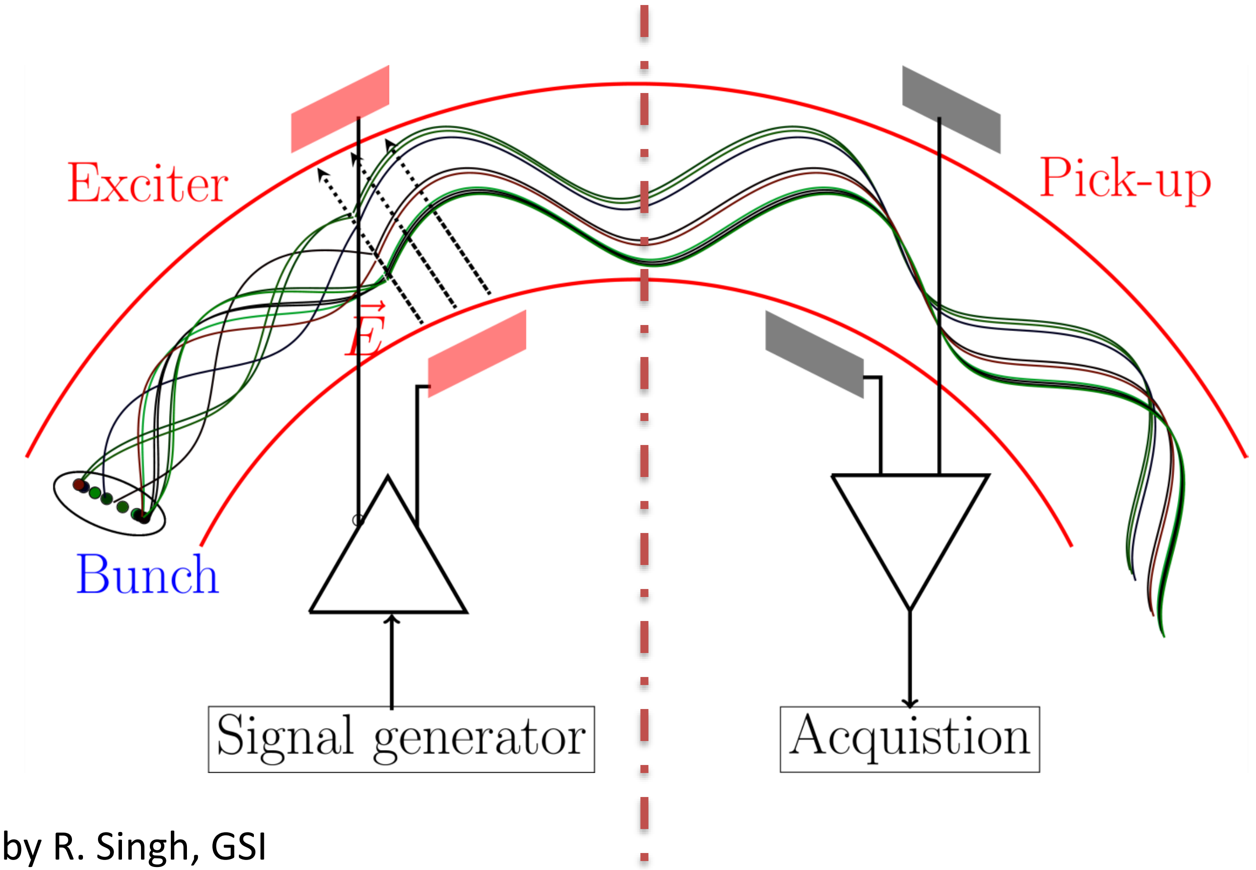
Tune Measurement: General Considerations

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

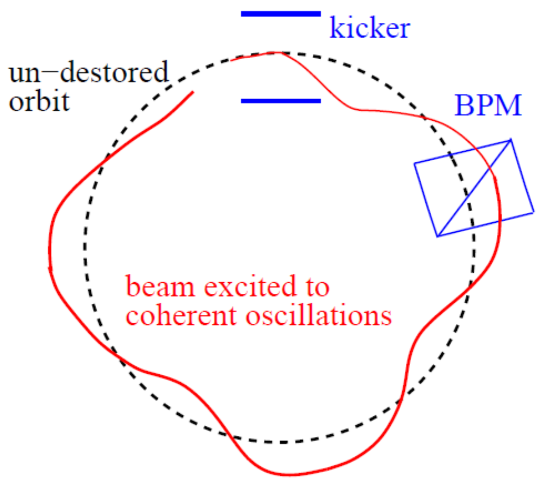
⇒ center-of-mass variation turn-by-turn i.e. center acts as **one** macro-particle

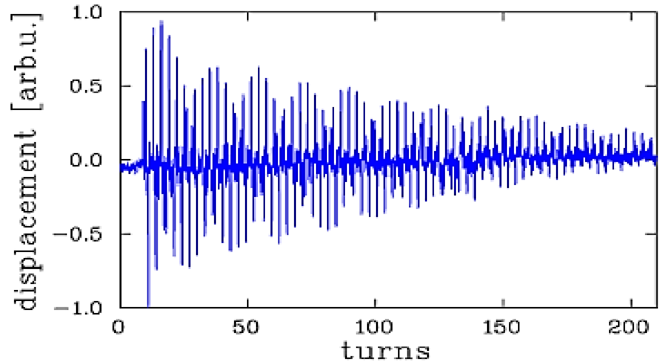


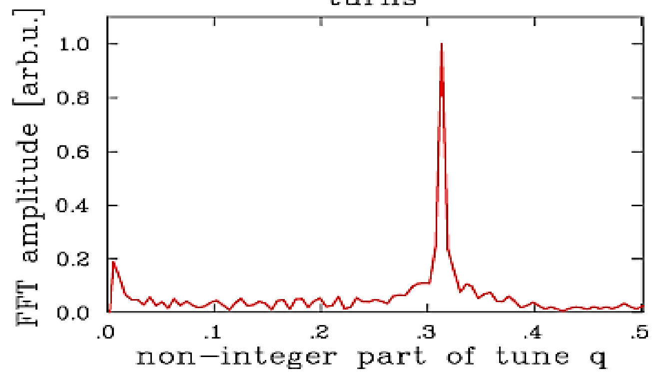
Graphics by R. Singh, GSI

Tune Measurement: The Kick-Method in Time Domain

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

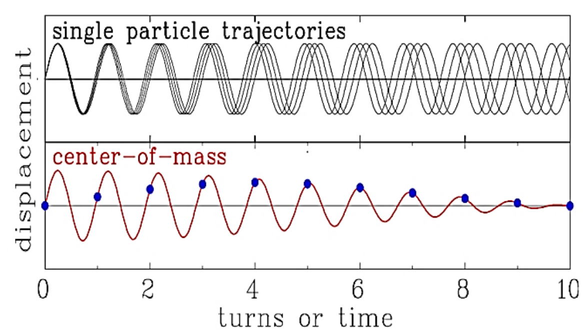






The de-coherence time limits the **resolution**:
N non-zero samples
⇒ General limit of discrete FFT: $\Delta q > \frac{1}{2N}$

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



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

Tune Measurement: *Gentle* Excitation with Wideband Noise

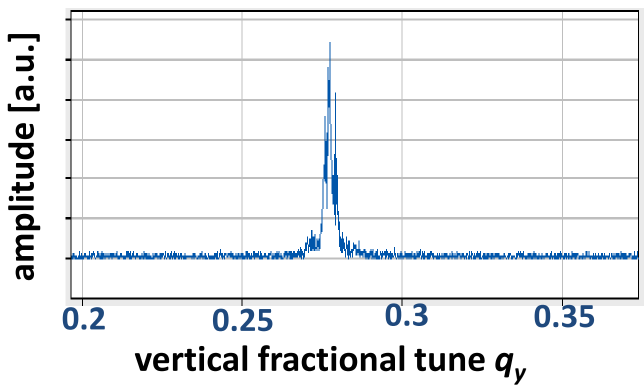
Instead of a sine wave, noise with adequate bandwidth can be applied

→ 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



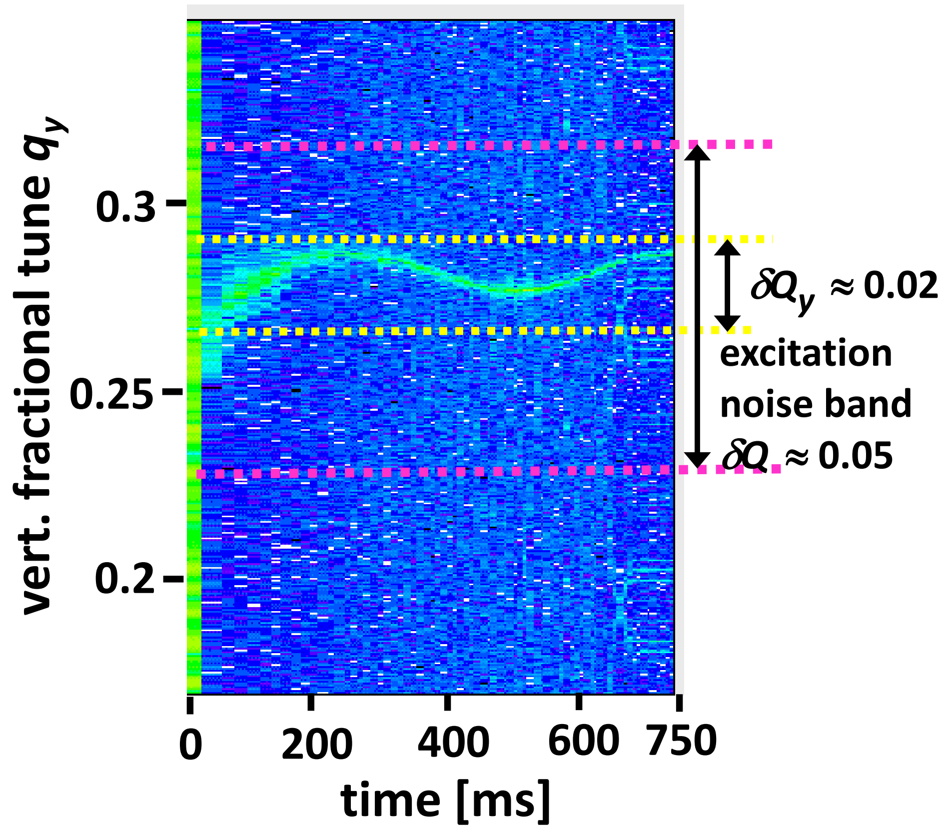
Advantage:

Fast scan with good time resolution

U. Rauch et al., DIPAC 2009

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

vertical tune versus time



Chromaticity Measurement from Closed Orbit Data

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

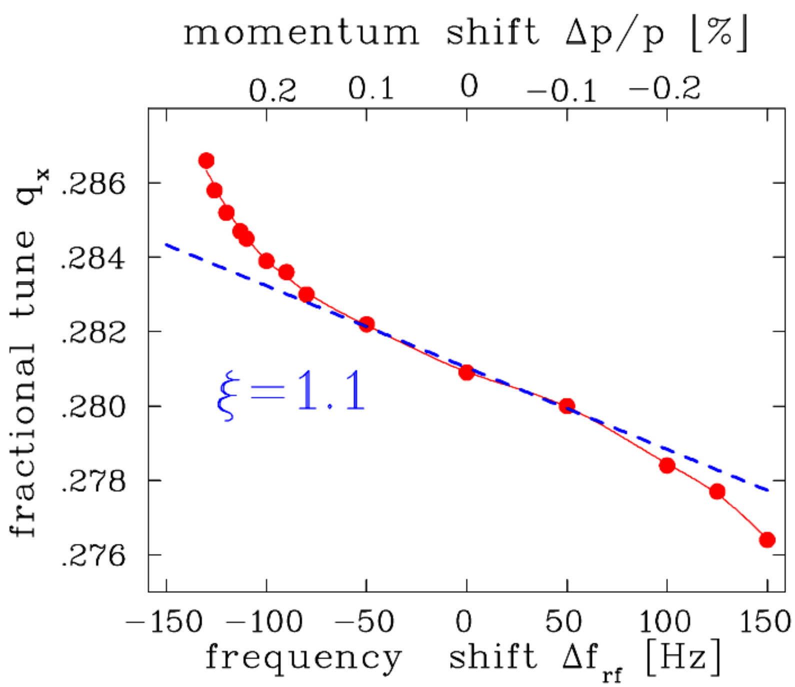
Two step measurement procedure:

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):

Example: Measurement at LEP:



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

⇒ slope is dispersion ***ξ***.

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

β-Function Measurement from Bunch-by-Bunch BPM Data

Excitation of **coherent** betatron oscillations:

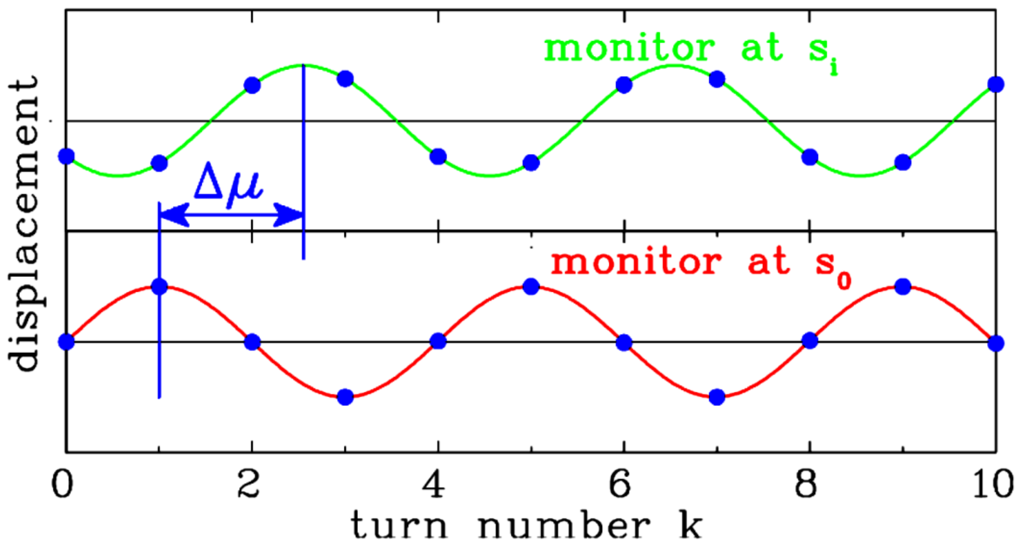
→ Time-dependent position reading results the phase advance between BPMs

The phase advance is:

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

β-function from

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



Remark: Determination of β-function with 3 BPMs:

$$\beta_{meas}(BPM_1) = \beta_{model}(BPM_1) \cdot \frac{\cot[\mu_{meas}(1\to2)] - \cot[(\mu_{meas}(1\to3)]}{\cot[\mu_{model}(1\to2)] - \cot[\mu_{model}(1\to3)]}$$

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)

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

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

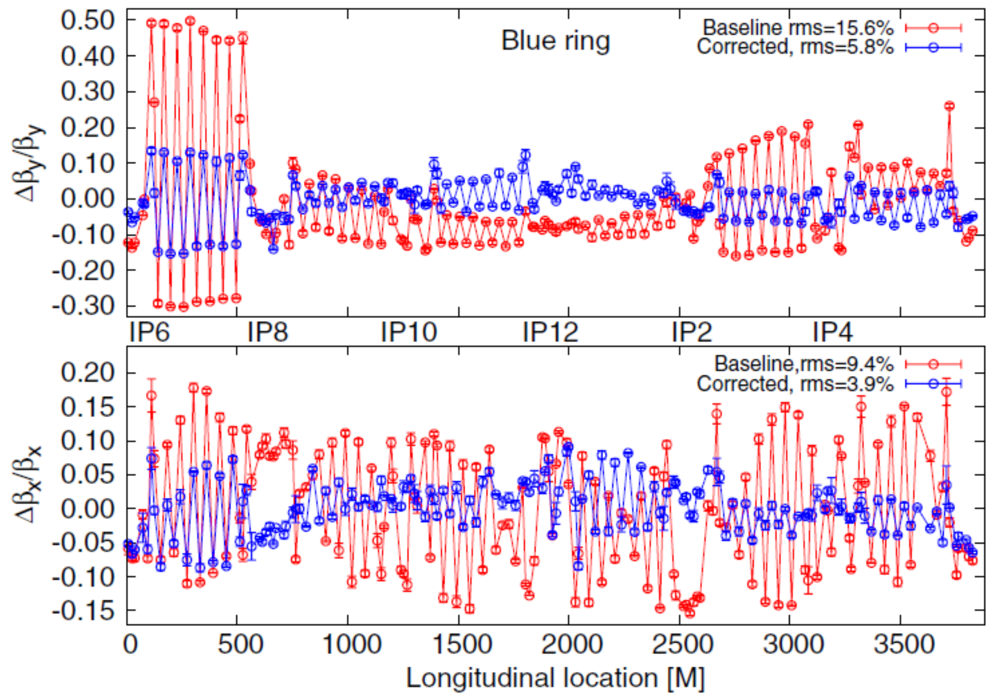
Result concerning ‘beta-beating’:

- 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

Intra-Bunch Observation

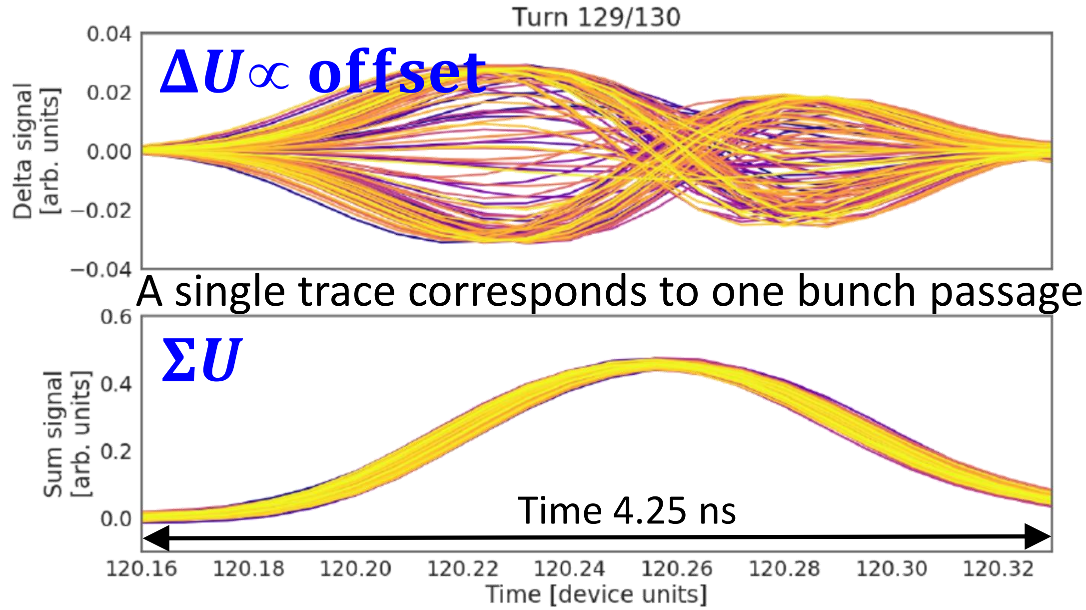
High band-width measurements delivers:

- 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

See lecture 'Collective Effects' by Kevin Li



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

Courtesy Kevin Li, CAS Proceedings 2021

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 $\leftrightarrow$ beam parameters

Proton synchrotron: 1 to 100 MHz, mostly 1 MΩ $\rightarrow$ proportional shape

LINAC, e$^-$-synchrotron: 0.1 to 3 GHz, 50 Ω $\rightarrow$ 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'*** $\rightarrow$ trajectory, ***slow*** *reading* $\rightarrow$ closed orbit
- ***Synchrotron:*** Excitation of ***coherent*** betatron oscillations $\Rightarrow$ tune ***q, ξ, β(s), D(s)...***

Remark: BPMs have high pass characteristic $\Rightarrow$ no signal for dc-beams

Thank you for your attention!

Backup slides

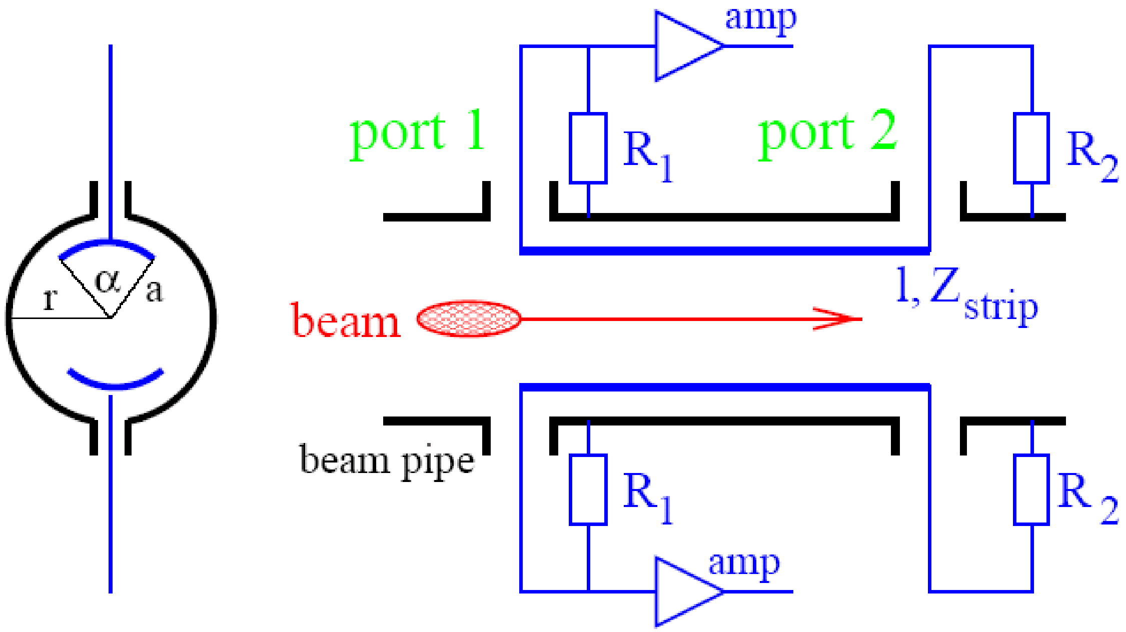
Stripline BPM: General Idea

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

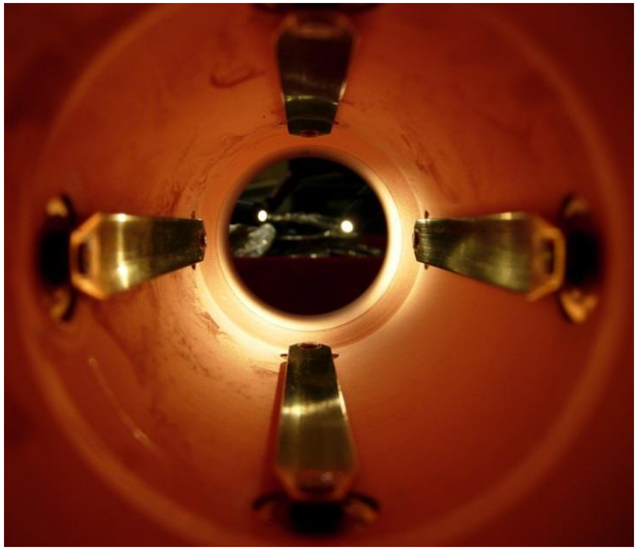
$\rightarrow$ Relativistic beam $\beta \approx 1 \Rightarrow$ field of bunches nearly TEM wave

$\rightarrow$ 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

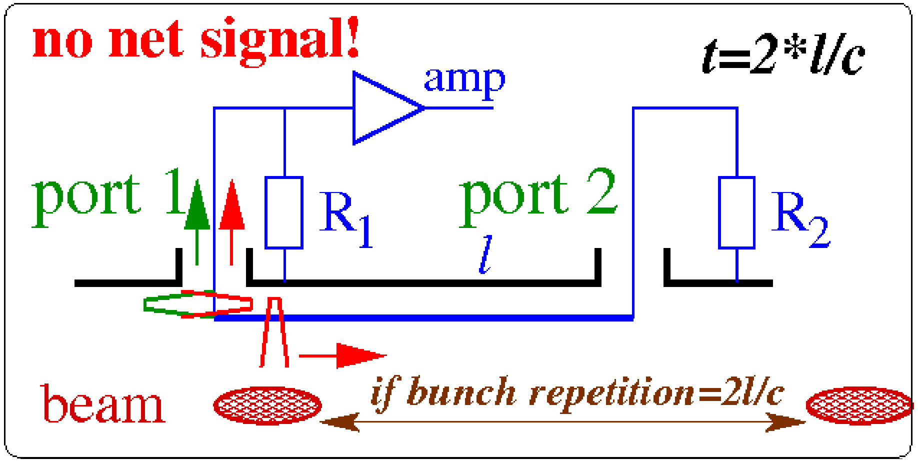
→ ***Assumption:*** $l_{bunch} << l$, $Z_{strip} = R_1 = R_2 = 50\ \Omega$ and $v_{beam} = c_{strip}$

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

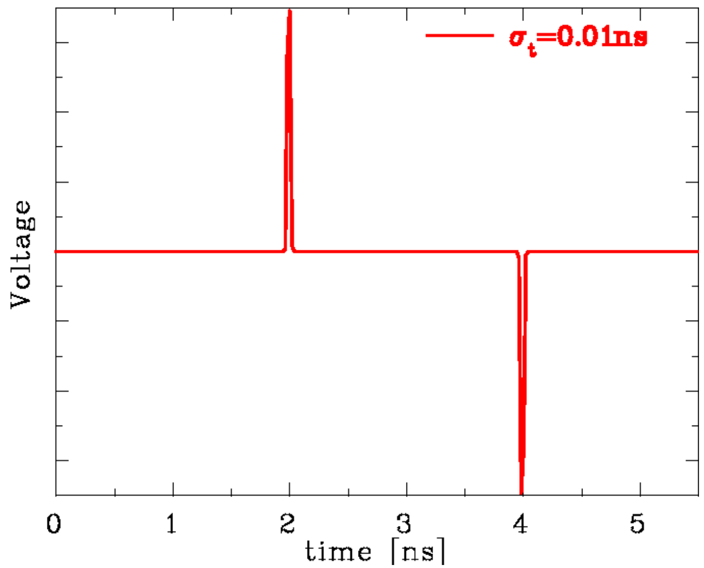
⇒ Signal depends on direction ⇔ **can distinguish between counter-propagation beams**

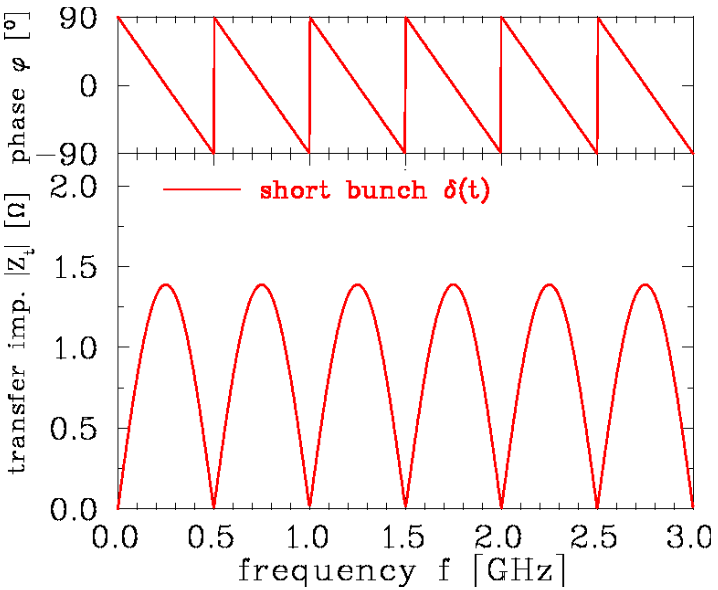
Stripline BPM: Transfer Impedance

The signal from port 1 and the reflection from port 2 can cancel ⇒ minima in Z_t.

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

Stripline length l=30 cm, α=10⁰





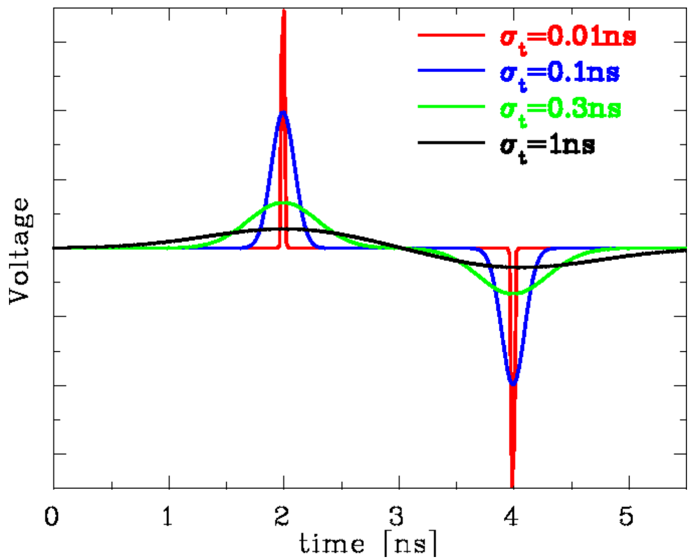
- Z_t show maximum at $l=c/4f=\lambda/4$ i.e. 'quarter wave coupler' for bunch train
  ⇒ l has to be matched to v_{beam}
- No signal for $l=c/2f=\lambda/2$ i.e. destructive interference with **subsequent** bunch
- Around maximum of $|Z_t|$: phase shift $\varphi=0$ i.e. direct image of bunch
- $f_{center}=1/4 \cdot c/l \cdot (2n-1)$. 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.

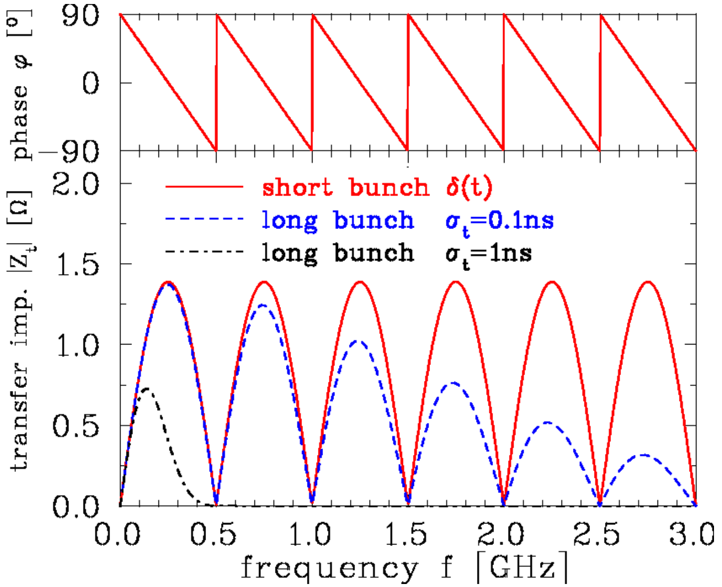
Stripline BPM: Transfer Impedance

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

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

Stripline length l=30 cm, α=10[0]





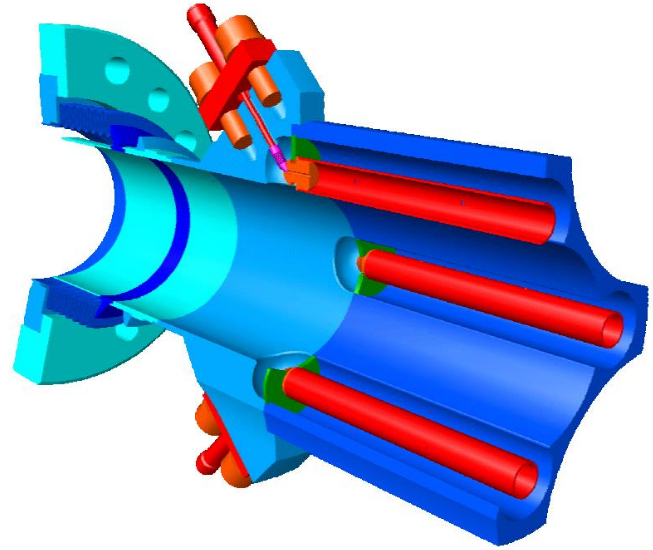
- $Z_t(\omega)$ decreases for higher frequencies
- If total bunch is too long $\boldsymbol{\pm 3\sigma_t > l}$ destructive interference leads to signal damping

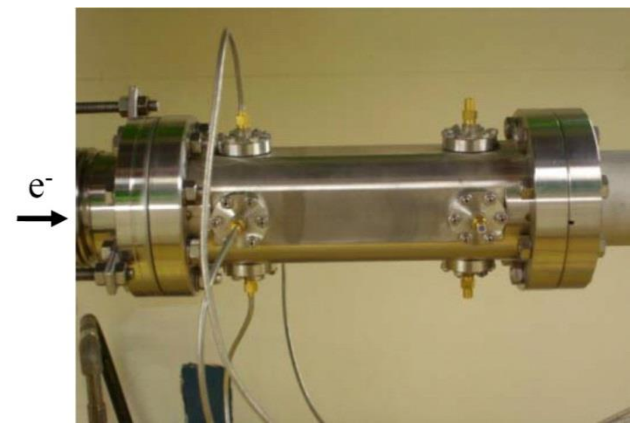
  Cure: length of stripline has to be matched to bunch length

Comparison: Stripline and Button BPM (simplified)

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

FlASH BPM inside quadrupole





From . S. Vilkins, D. Nölle (DESY)

Estimation of finite Beam Size Effect for Button BPM

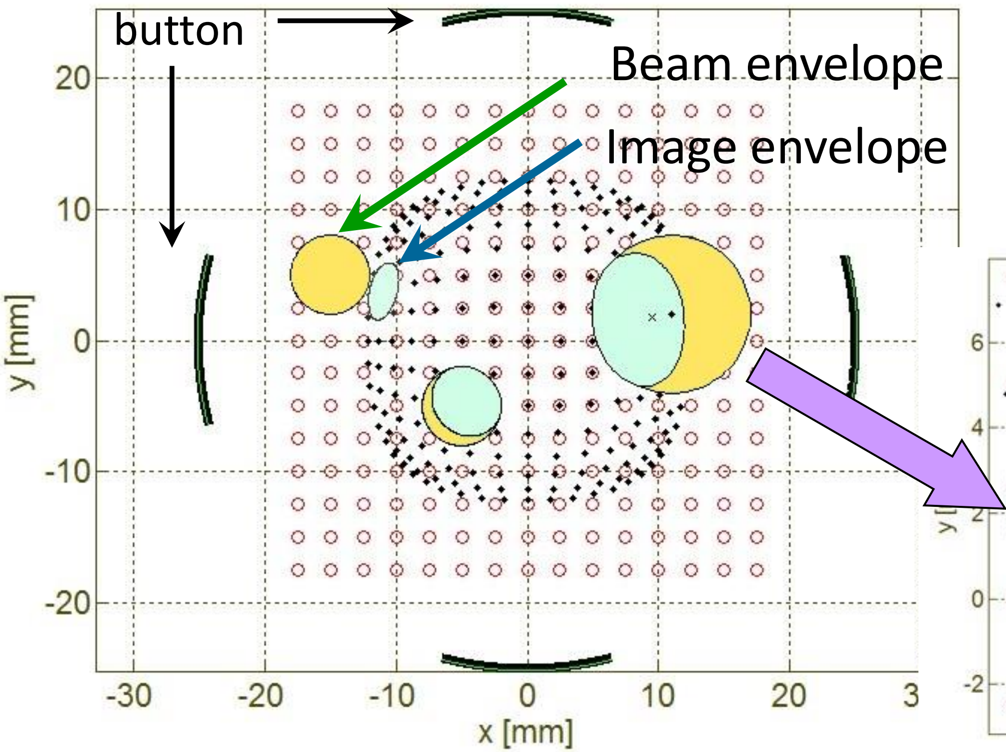
Ideal 2-dim model:

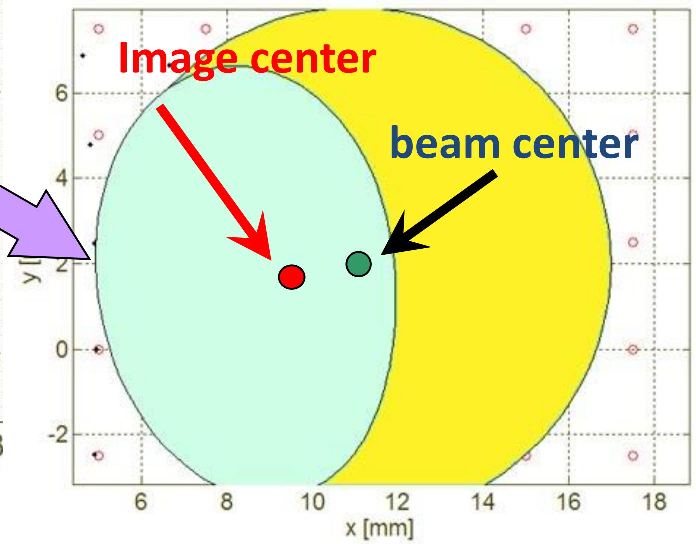
Due to the non-linearity, the beam size enters in the position reading.

Finite beam size:

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

$\Rightarrow$ 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.