Beam Position Monitors:

Detector Principle, Hardware and Electronics

Peter Forck, Piotr Kowina and Dmitry Liakin

Gesellschaft für Schwerionenforschung, Darmstadt

Outline:

- *Signal generation → transfer impedance*
- *Capacitive shoe box BPM for low frequencies → electro-static approach*
- *Capacitive button BPM for high frequencies → electro-static approach*
- *Stripline BPM → traveling wave*
- *Cavity BPM → resonator for dipole mode*
- *Electronics for position evaluation*
- *Summary*

Usage of BPMs

A BPM is an non-destructive device

It has a low cut-off frequency i.e. dc-beam behavior can not be monitored
(exception: Schottky spectra, here the physics is due to finite number of particles)

⇒Usage with bunched beams!

It delivers information about:

1. The center of the beam

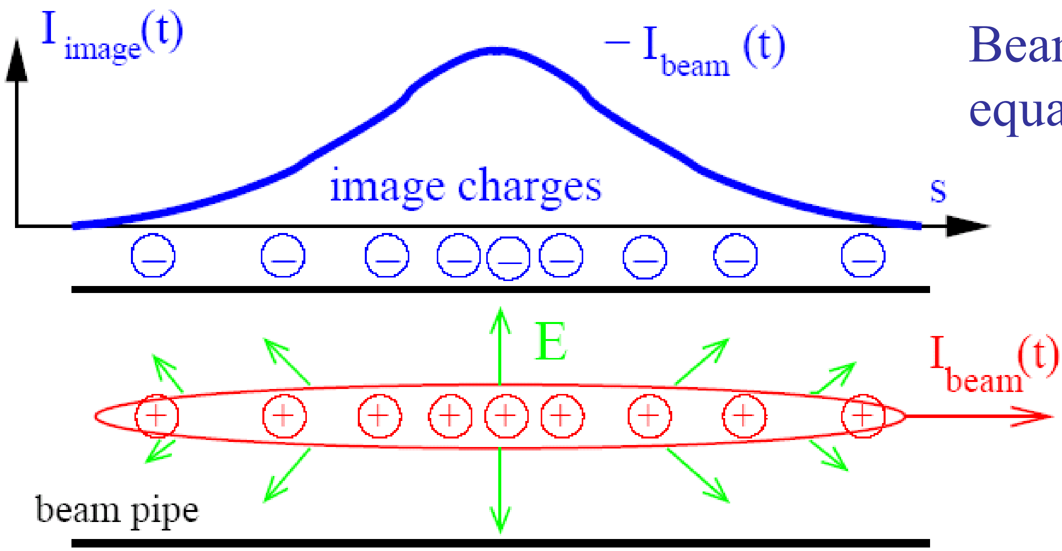
- **Closed orbit:** central orbit averaged over many turns, i.e. over many betatron oscillation
- **Trajectory:** bunch-by-bunch position, e.g. injection matching
  ⇒ Position on a large time scale: bunch-by-bunch → turn-by-turn → averaged position
- **Single bunch** position → determination of parameters like tune, chromaticity, ***β***-function
- **Time evolution** of a single bunch can be compared to 'macro-particle tracking' calculations
- **Feedback:** fast bunch-by-bunch damping up to slow and precise closed orbit correction

2. Longitudinal bunch shapes

- **Bunch evolution** during storage and acceleration
- For proton LINACs: the **beam velocity** can be determined by two BPMs
- ***Relative*** low current measurement down to 10 nA.

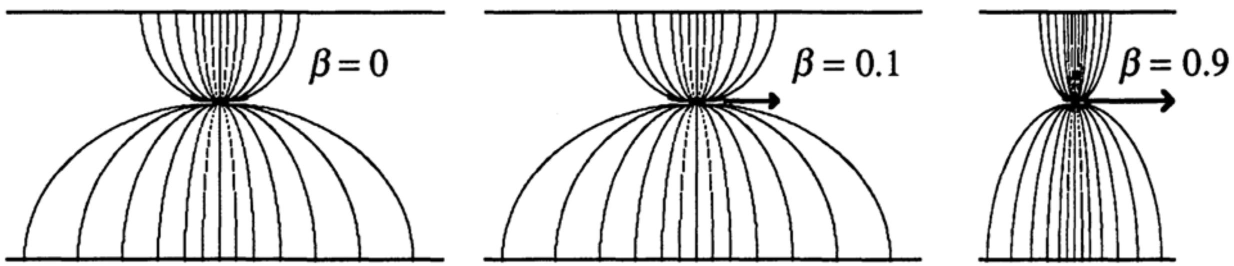
General Idea: Detection of Wall Charges

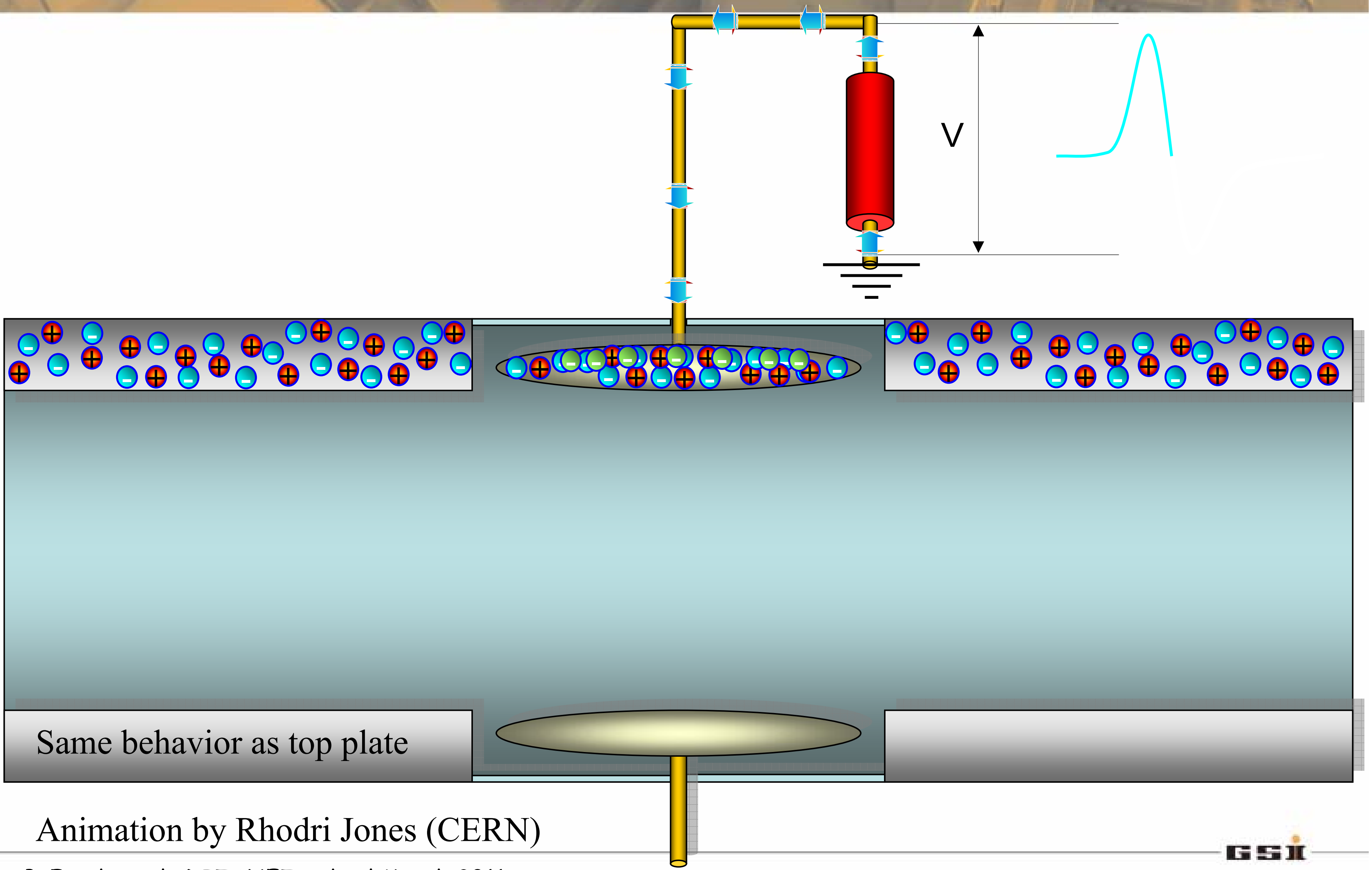
The image current at the vacuum wall is monitored on a high frequency basis i.e. the ac-part given by the bunched beam.



Beam Position Monitor **BPM** equals Pick-Up **PU**

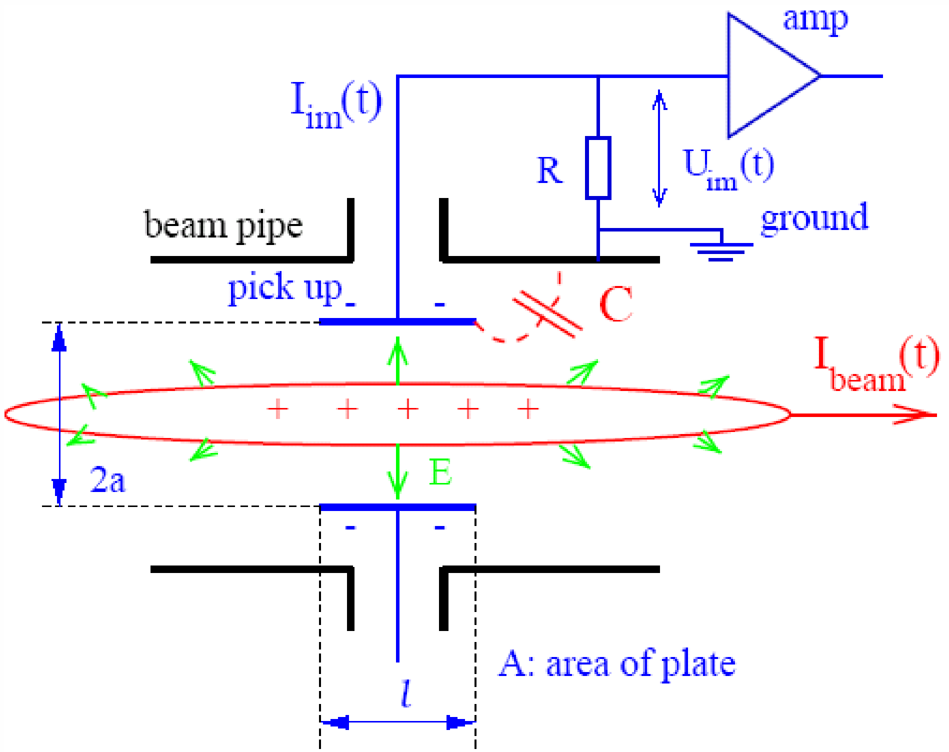
For relativistic velocities, the electric field is mainly transversal: $E_{\perp,lab}(t) = \gamma \cdot E_{\perp,rest}(t)$

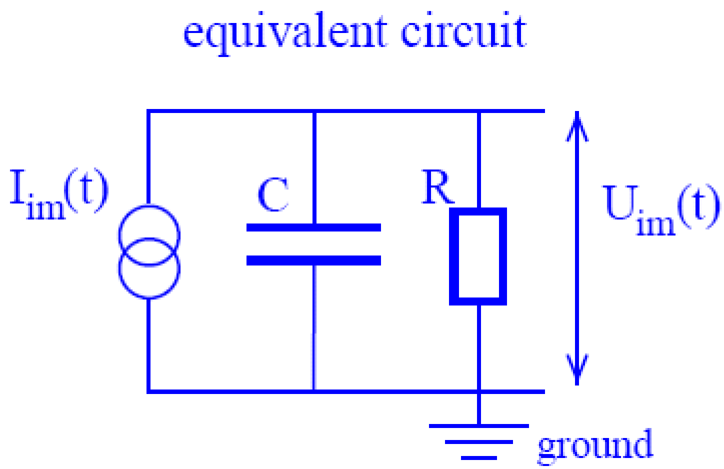




Animation by Rhodri Jones (CERN)

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





The image current I_{im} at the plate is given by the beam current and geometry:

$$I_{im}(t) = \frac{dQ_{im}(t)}{dt} = \frac{A}{2\pi a l} \cdot \frac{dQ_{beam}(t)}{dt} = \frac{A}{2\pi a} \cdot \frac{1}{\beta c} \cdot \frac{dI_{beam}(t)}{dt} = \frac{A}{2\pi a} \cdot \frac{1}{\beta c} \cdot i\omega I_{beam}(\omega)$$

Using a relation for Fourier transformation: $I_{beam} = I_0 e^{i\omega t} \Rightarrow dI_{beam}/dt = i\omega I_{beam}$.

Transfer Impedance for capacitive BPM

At a resistor ***R*** the voltage U_{im} from the image current is measured.
The transfer impedance Z_t is the ratio between voltage U_{im} and beam current I_{beam} in ***frequency domain***: $U_{im}(\omega) = R \cdot I_{im}(\omega) = Z_t(\omega, \beta) \cdot I_{beam}(\omega)$.

Capacitive BPM:

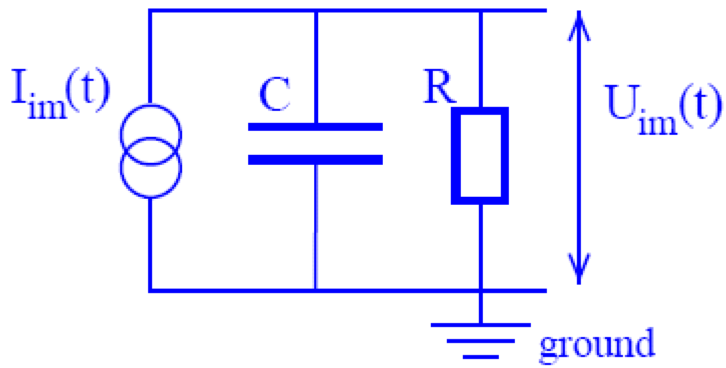
- The pick-up capacitance ***C***:
  plate ↔ vacuum-pipe and cable.
- The amplifier with input resistor ***R***.
- The beam is a high-impedance current source:

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

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

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

equivalent circuit



$$\frac{1}{Z} = \frac{1}{R} + i\omega C \Leftrightarrow Z = \frac{R}{1+i\omega RC}$$

This is a high-pass characteristic with $\omega_{cut} = 1/RC$:

Amplitude: $|Z_t(\omega)| = \frac{A}{2\pi a} \cdot \frac{1}{\beta c} \cdot \frac{1}{C} \cdot \frac{\omega / \omega_{cut}}{\sqrt{1+\omega^2/\omega^2_{cut}}}$ **Phase:** $\varphi(\omega) = \arctan(\omega_{cut}/\omega)$

Example of Transfer Impedance for Proton Synchrotron

The high-pass characteristic for typical synchrotron BPM:

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

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

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

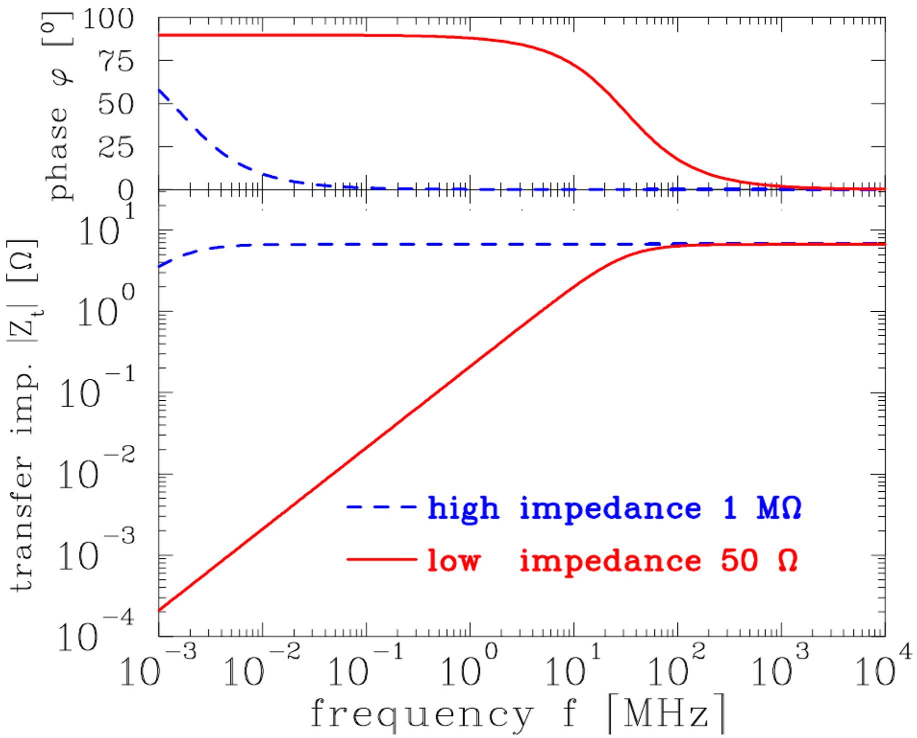
Parameter for shoe-box BPM:

C=100pF, l=10cm, β=50%

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

for R=50 Ω ⇒ f_{cut}= 32 MHz

for R=1 MΩ ⇒ f_{cut}= 1.6 kHz



For acceleration frequency 10 MHz < f_{rf} < 10 MHz:

Large signal strength → **high impedance**

Smooth signal transmission → **50 Ω**

Depending on the frequency range ***and*** termination the signal looks different:

➢ ***High frequency range $\omega >> \omega_{cut}$:***

$$Z_t \propto \frac{i\omega/\omega_{cut}}{1+i\omega/\omega_{cut}} \rightarrow 1 \Rightarrow U_{im}(t) = \frac{1}{C}\cdot\frac{1}{\beta c}\cdot\frac{A}{2\pi a}\cdot I_{beam}(t)$$

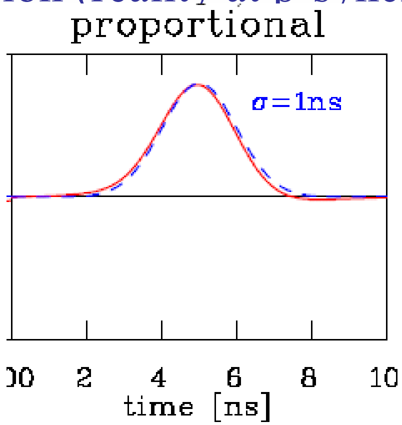
⇒ **direct image** of the bunch. Signal strength $\boldsymbol{Z_t \propto A/C}$ i.e. nearly independent on length

➢ ***Low frequency range $\omega << \omega_{cut}$:***

$$Z_t \propto \frac{i\omega/\omega_{cut}}{1+i\omega/\omega_{cut}} \rightarrow i\frac{\omega}{\omega_{cut}} \quad \Rightarrow \quad U_{im}(t) = R\cdot\frac{A}{\beta c\cdot 2\pi a}\cdot i\omega I_{beam}(t) = R\cdot\frac{A}{\beta c\cdot 2\pi a}\cdot\frac{dI_{beam}}{dt}$$

⇒ **derivative** of bunch, single strength $\boldsymbol{Z_t \propto A}$, i.e. (nearly) independent on ***C***

Example from synchrotron BPM with 50 Ω termination (reality at p-synchrotron : ***σ***>>1 ns):



Examples for differentiated & proportional Shape

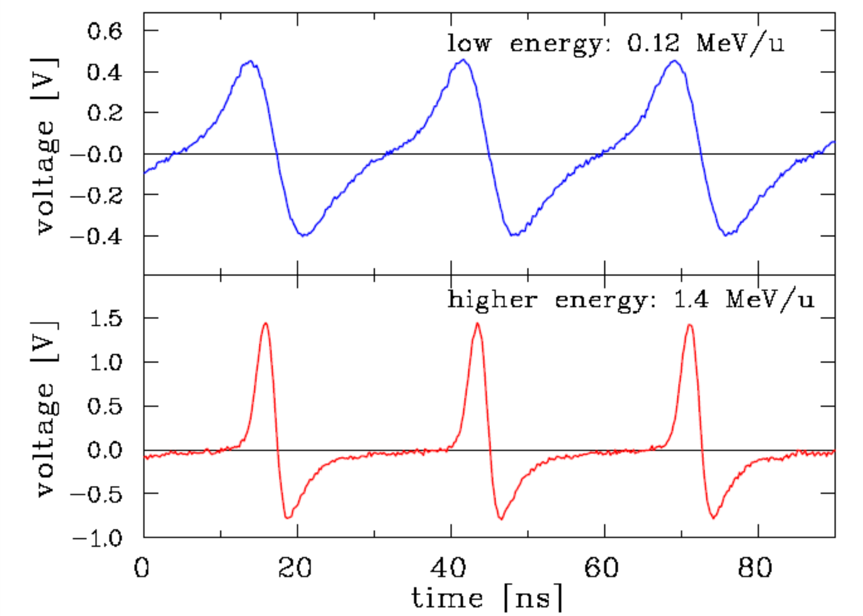
Proton LINAC, e⁻-LINAC&synchtrotron:

100 MHz < f_{rf} < 1 GHz typically

R=50 Ω processing to reach bandwidth

C≈5 pF ⇒ $f_{cut} = 1/(2\pi RC) \approx$ 700 MHz

Example: 36 MHz GSI ion LINAC



Proton synchrotron:

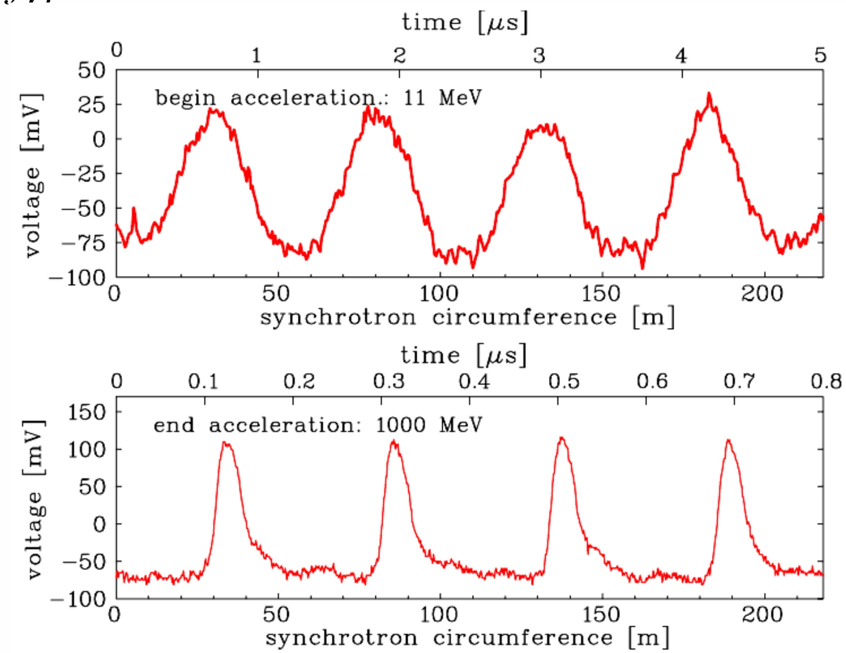
1 MHz < f_{rf} < 30 MHz typically

R=1 MΩ for large signal i.e. large Z_t

C≈100 pF ⇒ $f_{cut} = 1/(2\pi RC) \approx$10 kHz

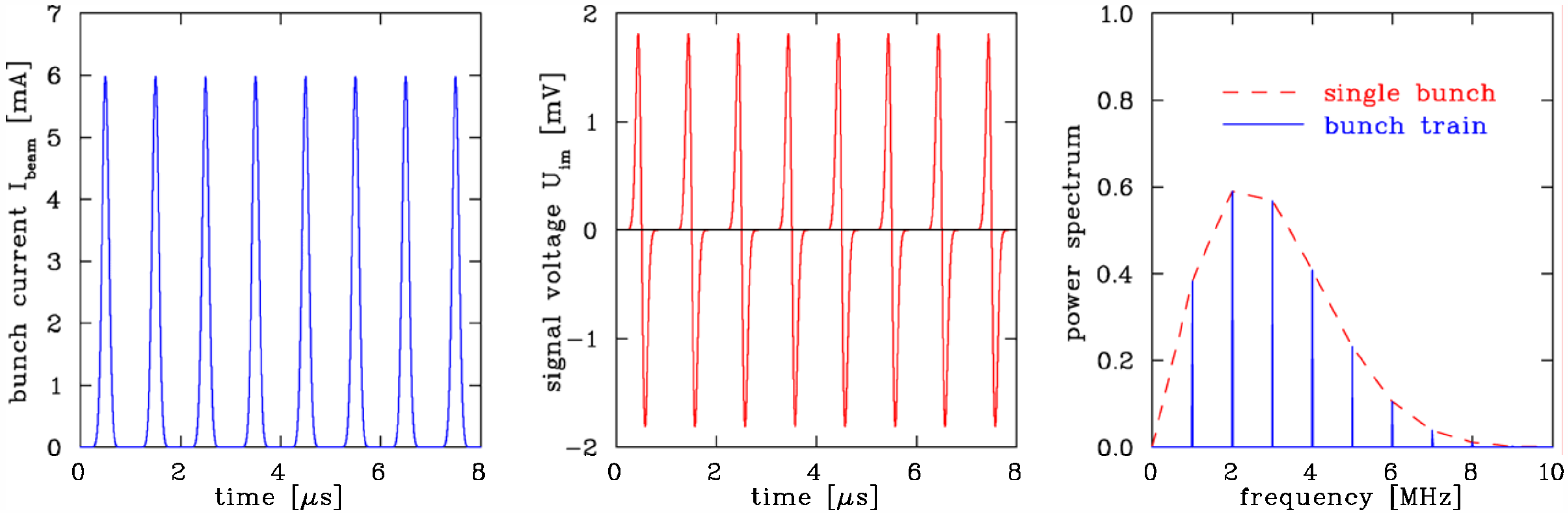
Example: non-relativistic GSI synchrotron

f_{rf}: 0.8 MHz → 5 MHz



Remark: During acceleration the bunching-factor is increased: 'adiabatic damping'.

Train of bunches with R=50 Ω termination ⇒ $f \ll f_{cut}$:



Calculation: $I_{beam}(t) \xrightarrow{\text{FFT}} I_{beam}(\omega) \rightarrow U_{im}(\omega) = Z_{tot}(\omega) \cdot I_{beam}(\omega) \xrightarrow{\text{invFFT}} U_{im}(t)$

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

C=100pF, l=10cm, β=50%, σ_t=100 ns

- Fourier spectrum is composed of lines separated by acceleration f_{rf}
- Envelope given by single bunch Fourier transformation
- Differenciated bunch shape due to $f_{cut} \gg f_{rf}$

Remark: 1 MHz< f_{rf} <10MHz ⇒ Bandwidth ≈100MHz = 10·f_{rf} for broadband observation.

Principle of Position Determination with BPM

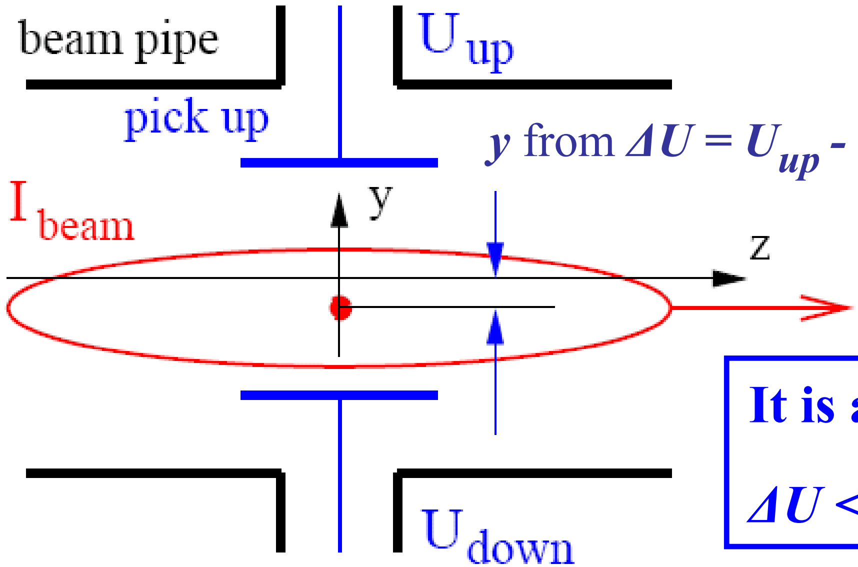
The difference between plates gives the beam's center-of-mass
→**most frequent application**

'Proximity' effect leads to different voltages at the plates:

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

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

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



It is at least:

$\Delta U < \Sigma U/10$

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

Outline:

- *Signal generation → transfer impedance*
- ***Capacitive 'shoe box' = 'linear cut' BPM***

  used at most proton synchrotrons
- ***Capacitive button BPM for high frequencies → electro-static approach***
- ***Stripline BPM → traveling wave***
- ***Cavity BPM → resonator for dipole mode***
- ***Electronics for position evaluation***
- ***Summary***

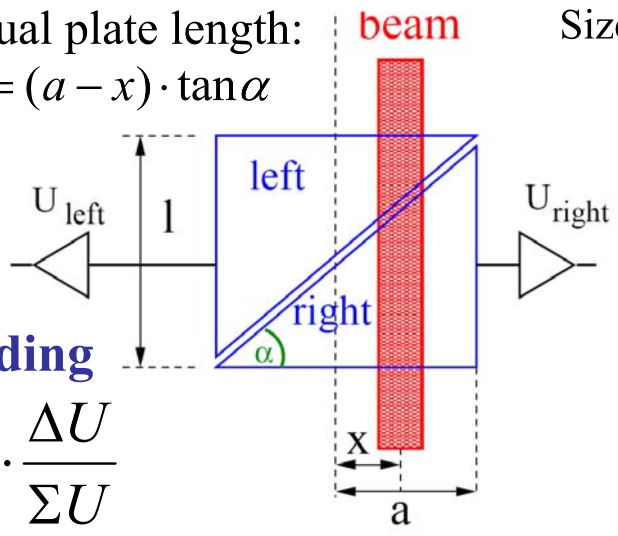
Shoe-box BPM for Proton or Ion Synchrotron

Frequency range: 1 MHz < f_{rf} < 10 MHz ⇒ bunch-length >> BPM length.

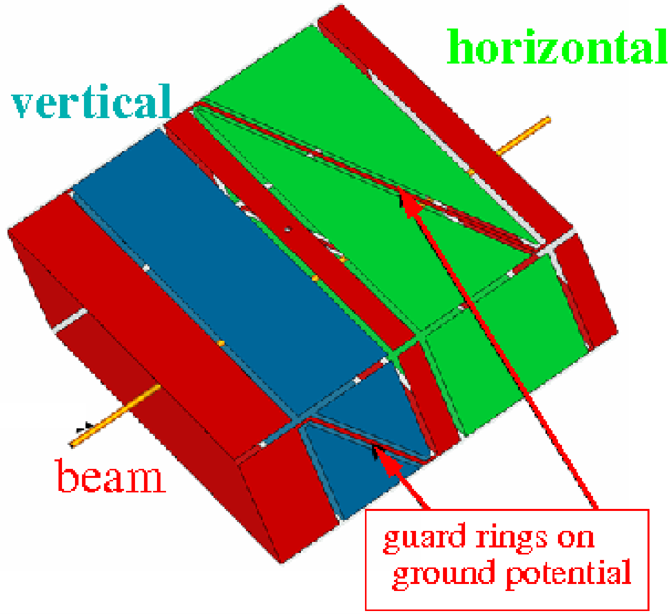
Signal is proportional to actual plate length:

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

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

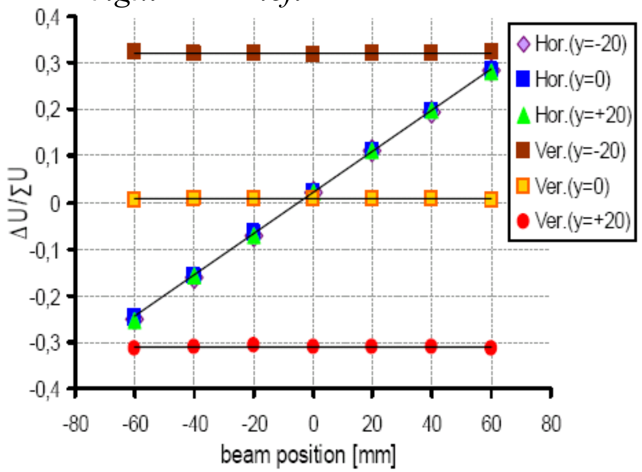


Size: 200x70 mm^2



In ideal case: linear reading

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



Shoe-box BPM:

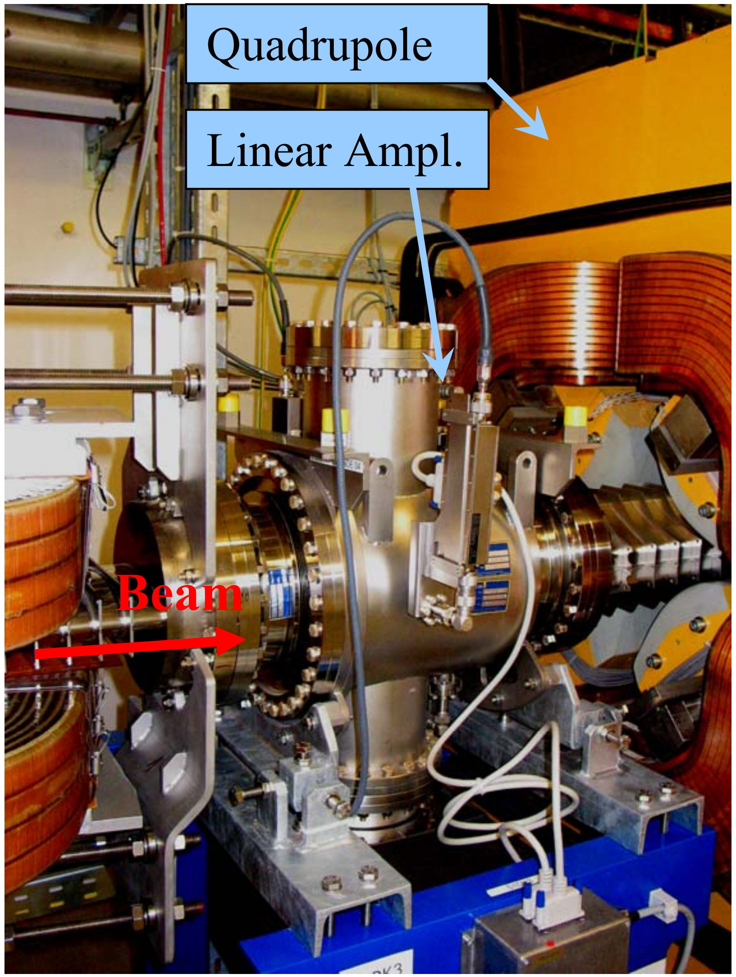
Advantage: Very linear, low frequency dependence
i.e. position sensitivity ***S*** is constant

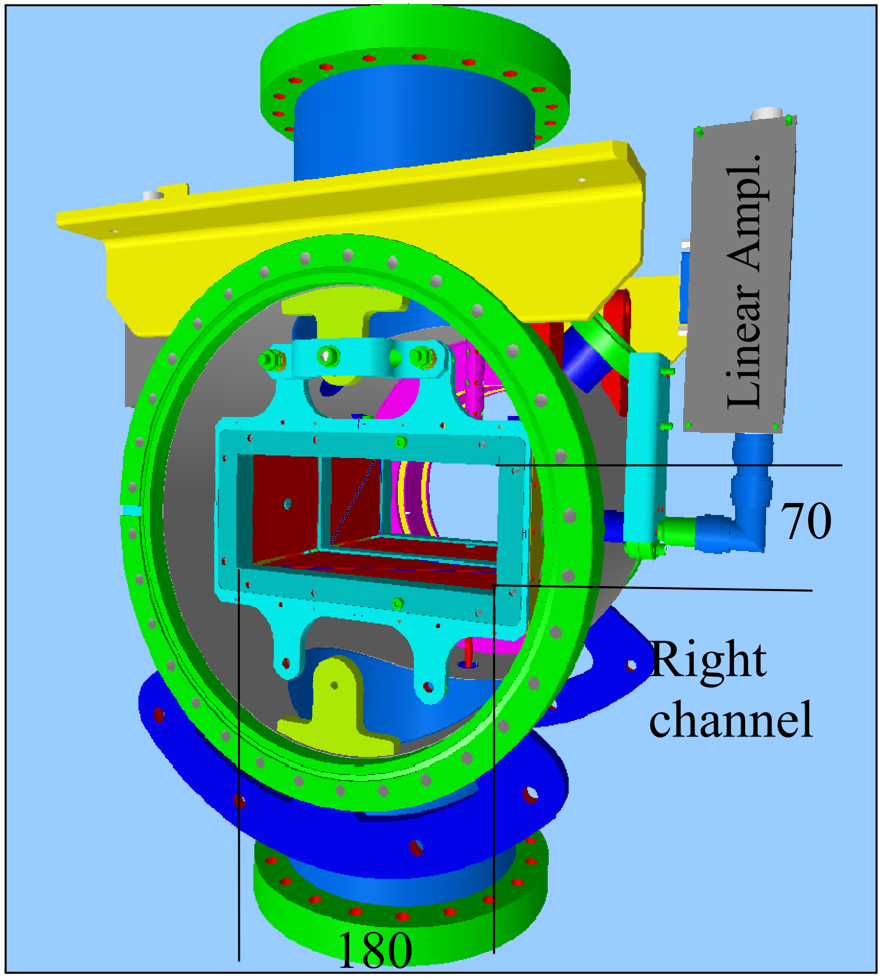
Disadvantage: Large size, complex mechanics
high capacitance

Technical Realization of Shoe-Box 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.





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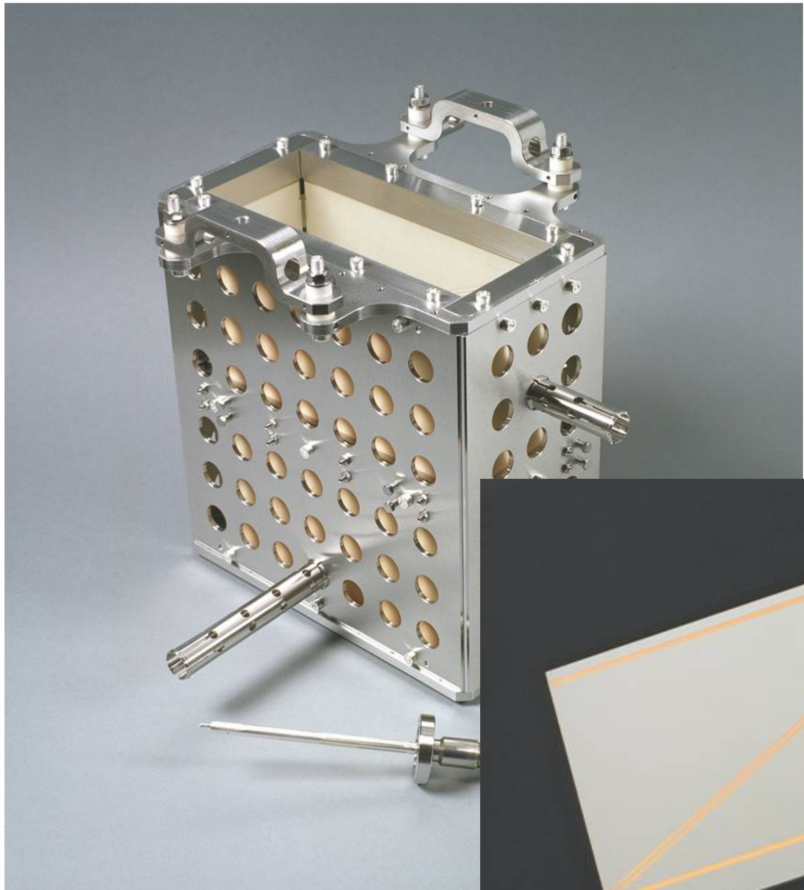
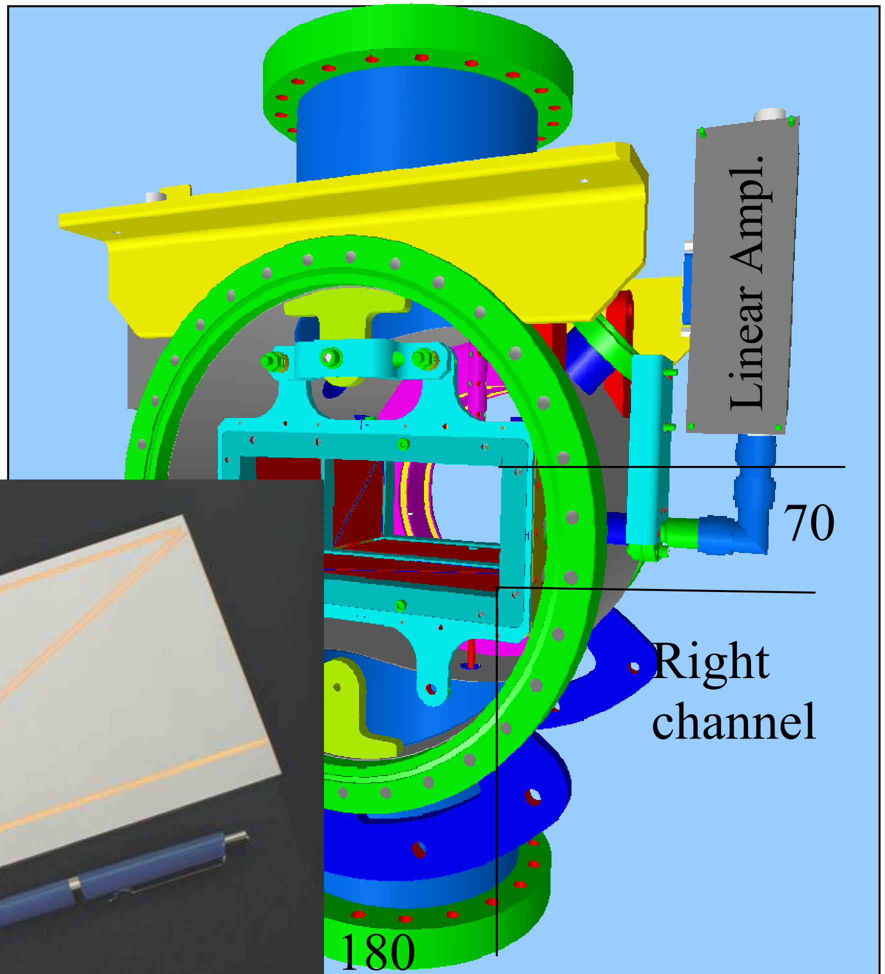
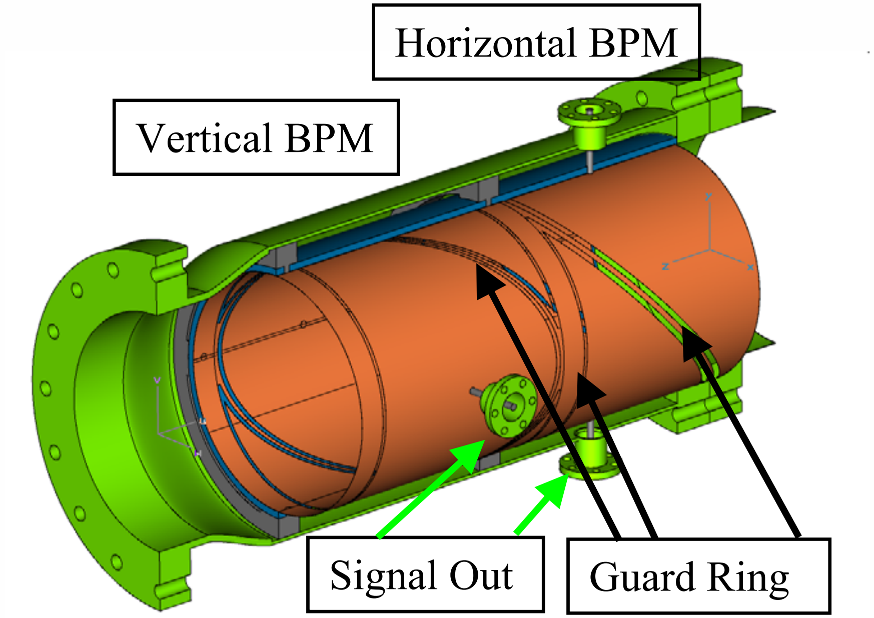




Round type: cut cylinder

Same properties as shoe-box:



Other realization: Full metal plates

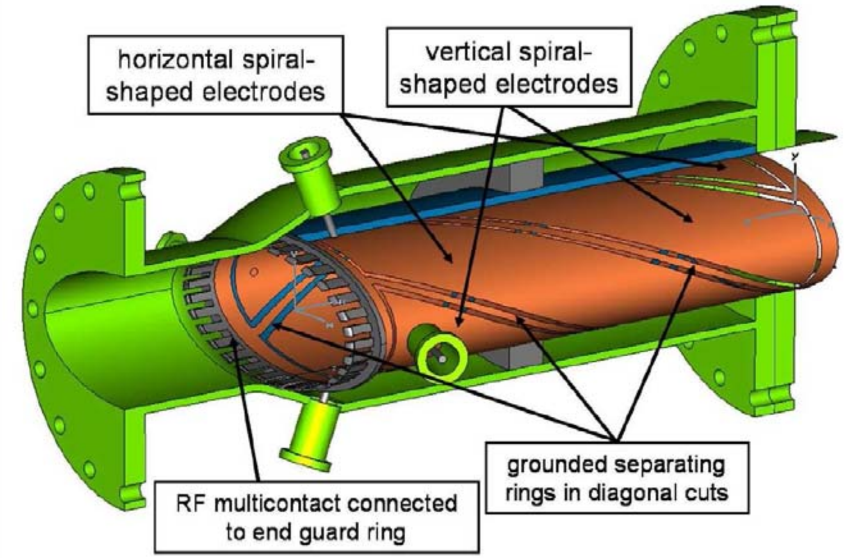
→ No guard rings required

→ but mechanical alignment more difficult

Wounded strips:

Same distance from beam and capacitance for all plates

But horizontal-vertical coupling.



Outline:

- *Signal generation → transfer impedance*
- *Capacitive shoe box BPM for low frequencies → electro-static approach*
- ***Consideration for capacitive button BPM***

  Simple electro-static model,, modification for synchrotron light source

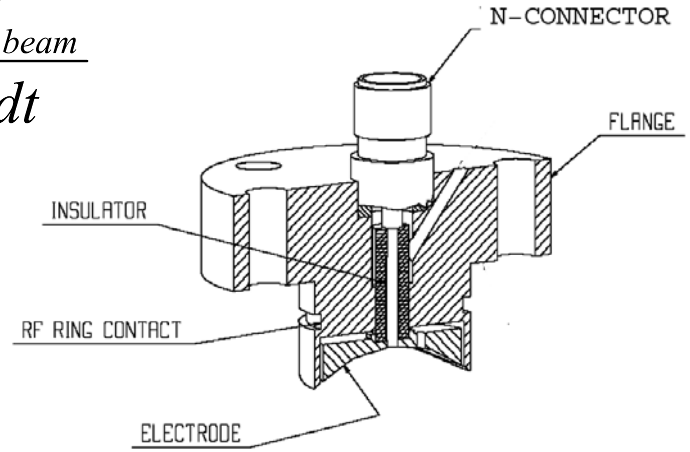
  Comparison shoe box versus button BPM
- ***Stripline BPM → traveling wave***
- ***Cavity BPM → resonator for dipole mode***
- ***Electronics for position evaluation***
- ***Summary***

Button BPM Realization

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

→ 50 Ω signal path to prevent reflections

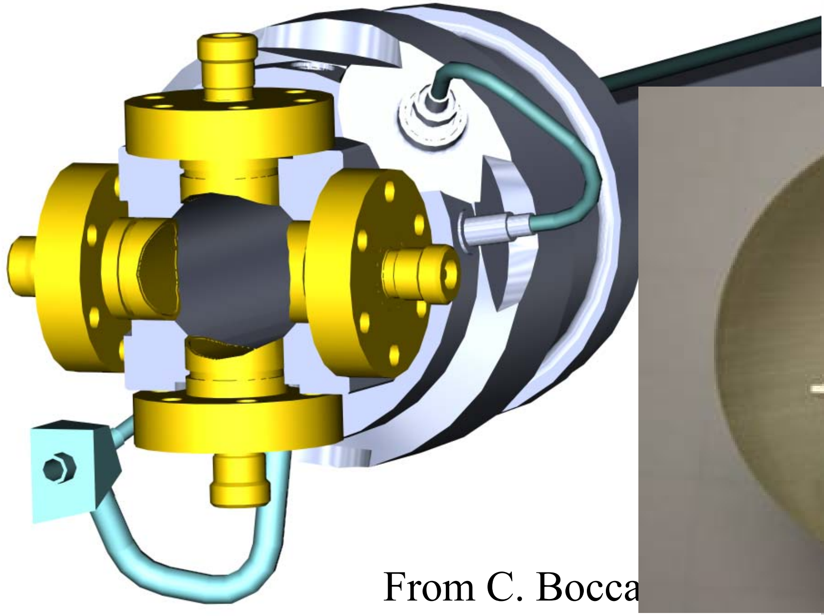
Button BPM with 50 Ω ⇒ $U_{im}(t) \approx R \cdot \frac{A}{\beta c \cdot 2\pi a} \cdot \frac{dI_{beam}}{dt}$



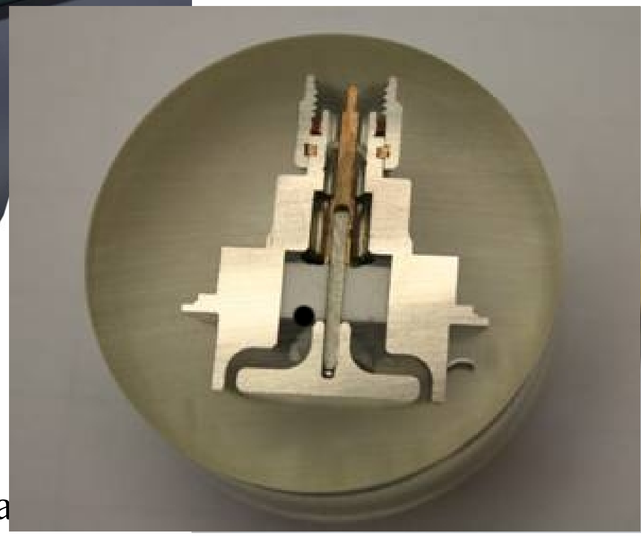
Example: LHC-type inside cryostat:

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

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

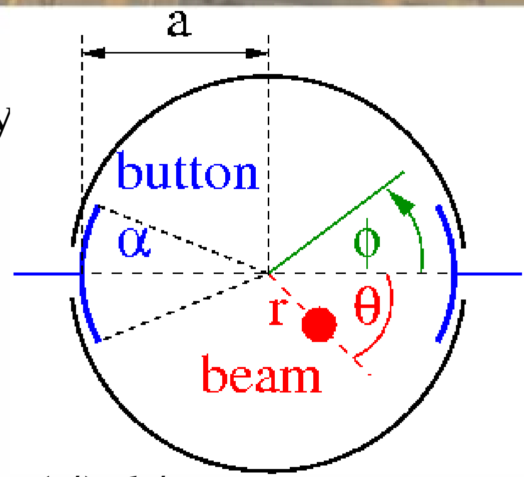


From C. Bocca



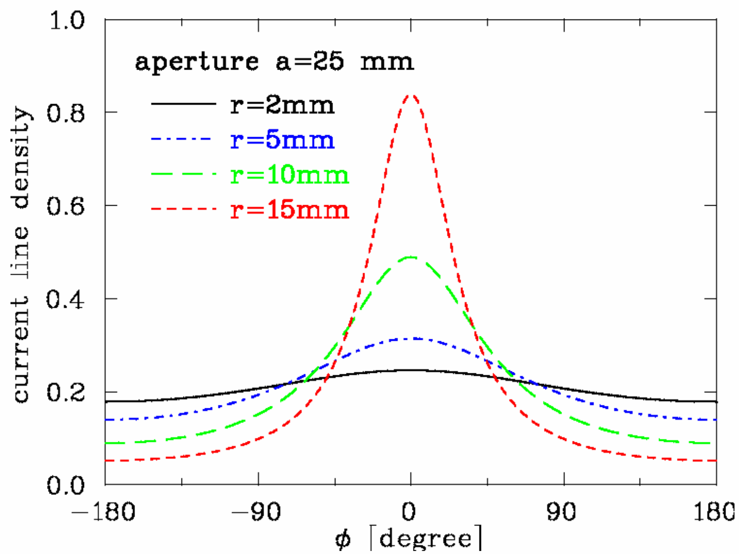
‘Proximity effect’: larger signal for closer plate

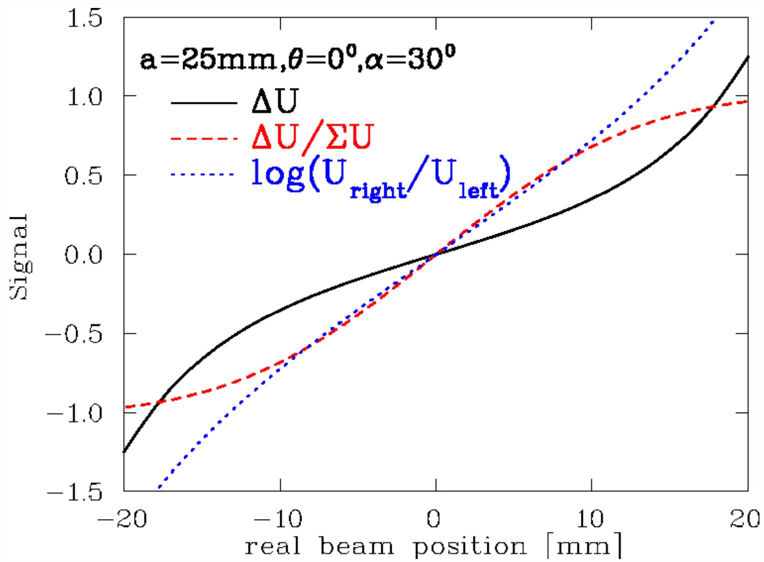
Ideal 2-dim model: Cylindrical pipe → image current density via ‘image charge method’ for ‘pensile’ beam:



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

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

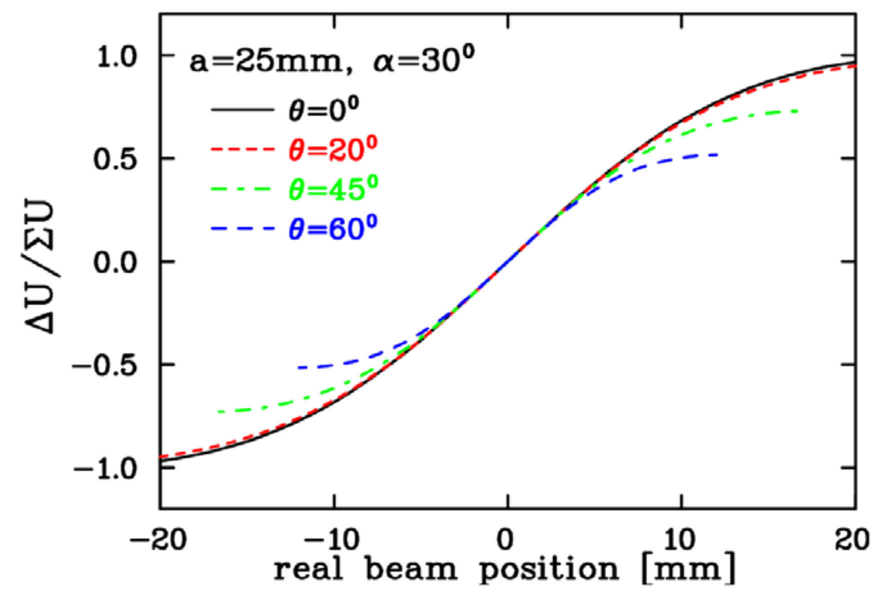


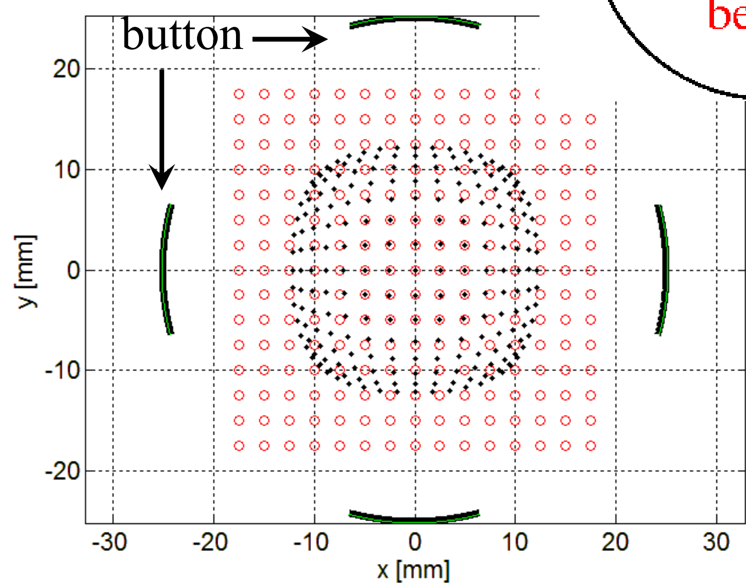


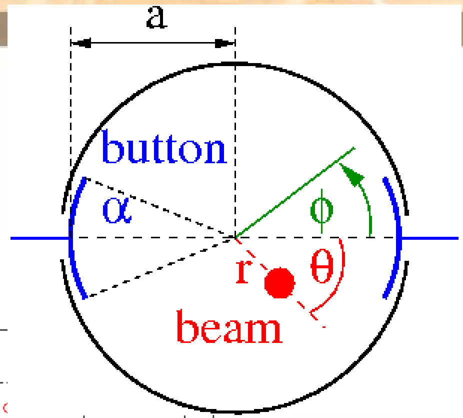
Ideal 2-dim model: Non-linear behavior and hor-vert coupling:

Sensitivity: $x = 1/S \cdot \Delta U / \Sigma U$ with S [%/mm] or [dB/mm]

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





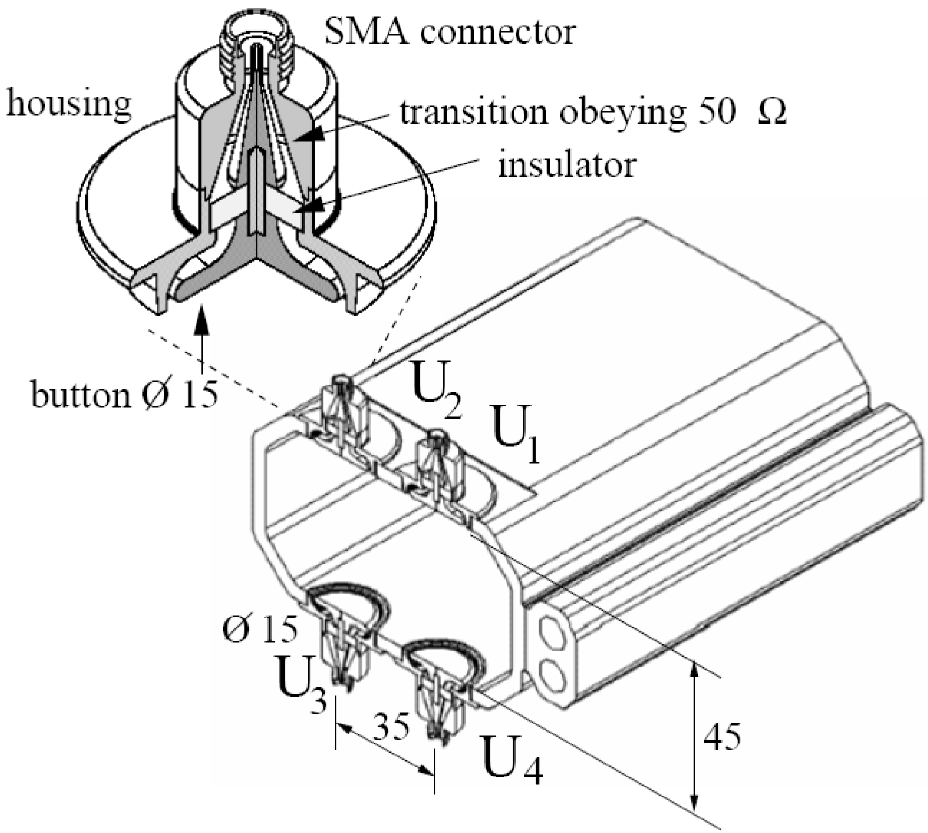


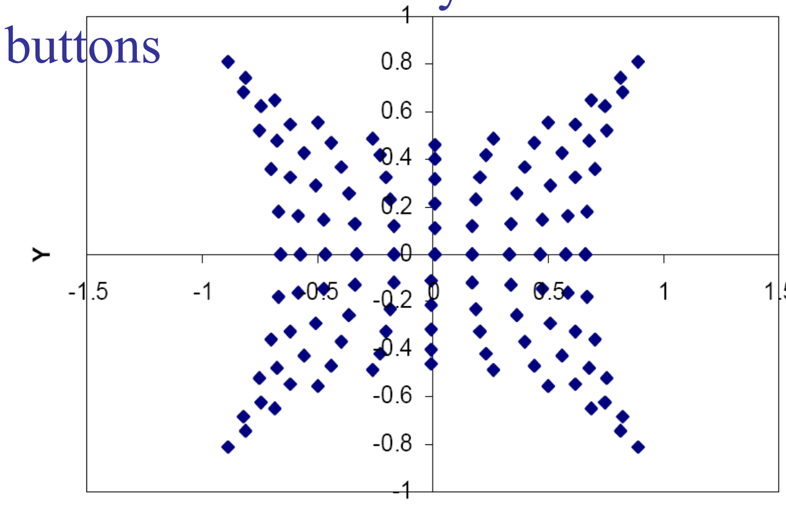
The measurement of U delivers: $x = \frac{1}{S_x} \cdot \frac{\Delta U}{\Sigma U}$ → here $S_x = S_x(x, y)$ i.e. non-linear.

In addition, frequency dependence can be calculated by analytic model or numerically.

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
Optimization: horizontal distance and size of buttons





- Beam position swept with 2 mm steps
- Non-linear sensitivity and hor.-vert. coupling
- At center $S_x = 8.5\%/\text{mm}$ in this case

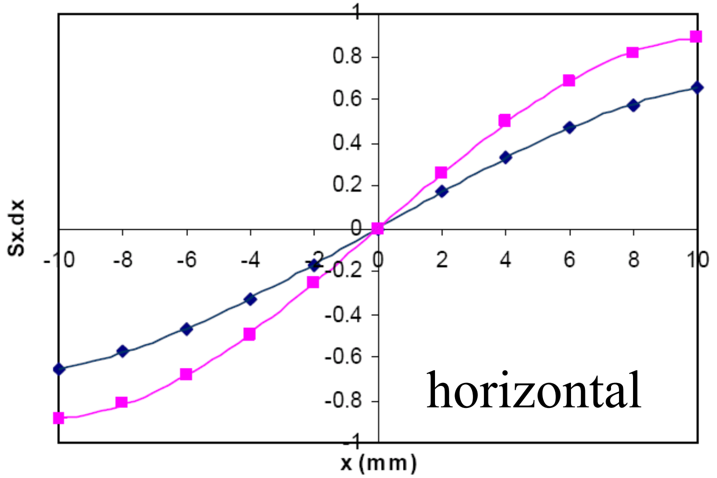
$$\text{horizontal}: x = \frac{1}{S_x} \cdot \frac{(U_1 + U_4) - (U_2 + U_3)}{U_1 + U_2 + U_3 + U_4}$$

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

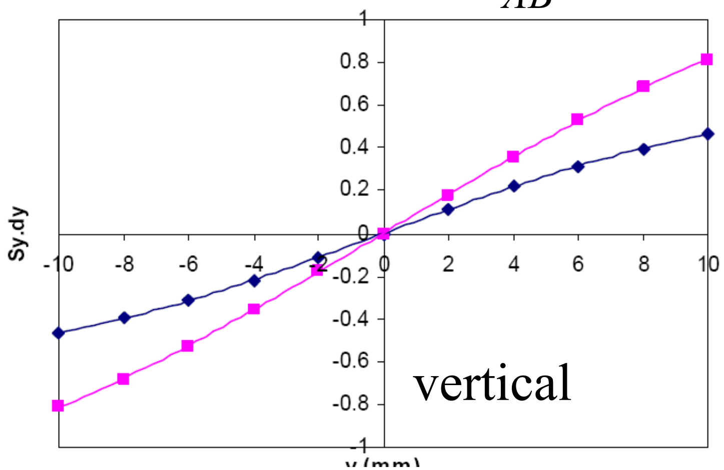
From S. Varnasseri, SESAME, DIPAC 2005

2-dim electro-static simulation:

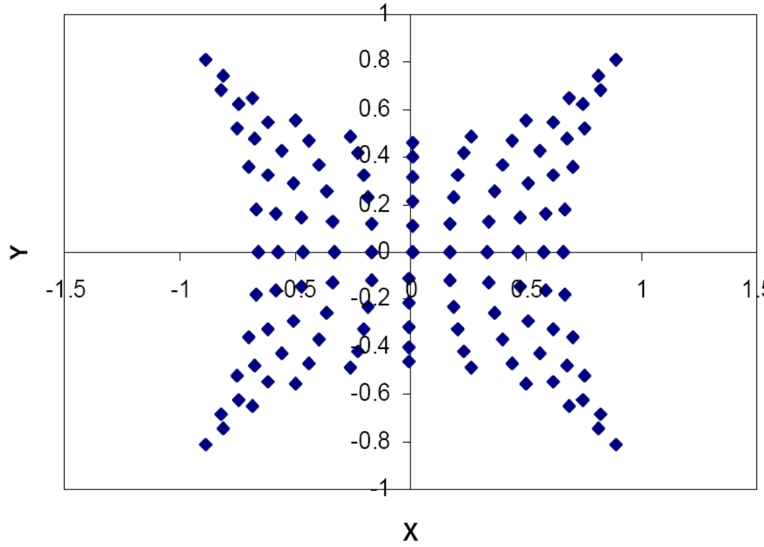
d_{AB}=24 mm



d_{AB}=24 mm

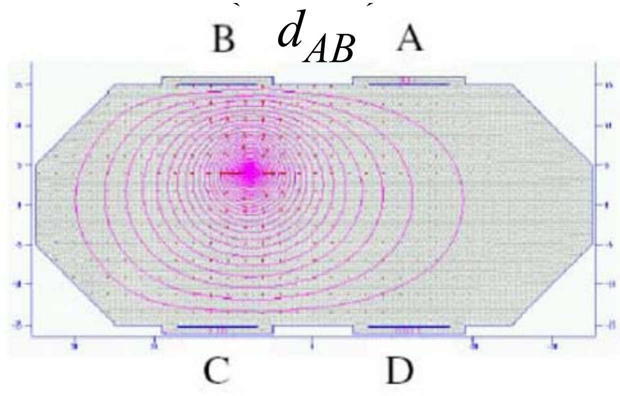


d_{AB}=24 mm



Result:

- Hori. S_x= 8.5%/mm
- Vert. S_y = 5.6%/mm
- x&y dependent polynomial fit possible

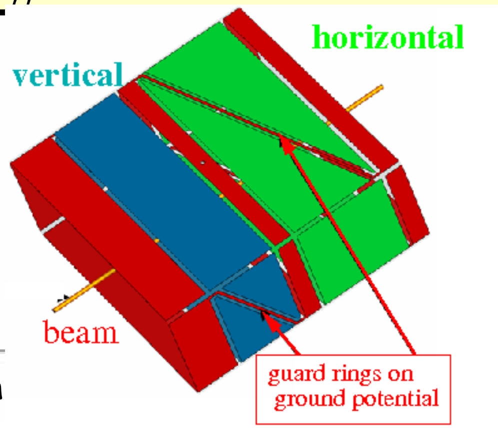


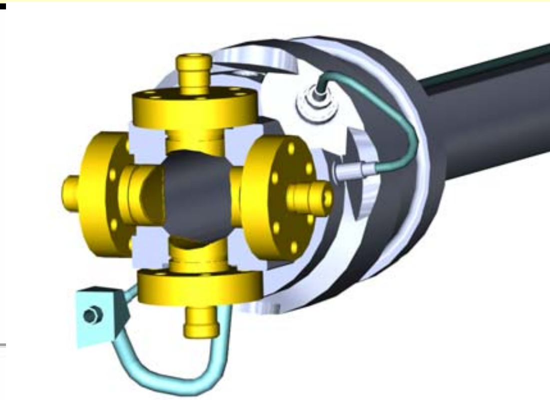
Beam position swept with 2 mm steps

From S. Varnasseri, SESAME, DIPAC 2005

Comparison Shoe-Box and Button BPM

	Shoe-Box 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





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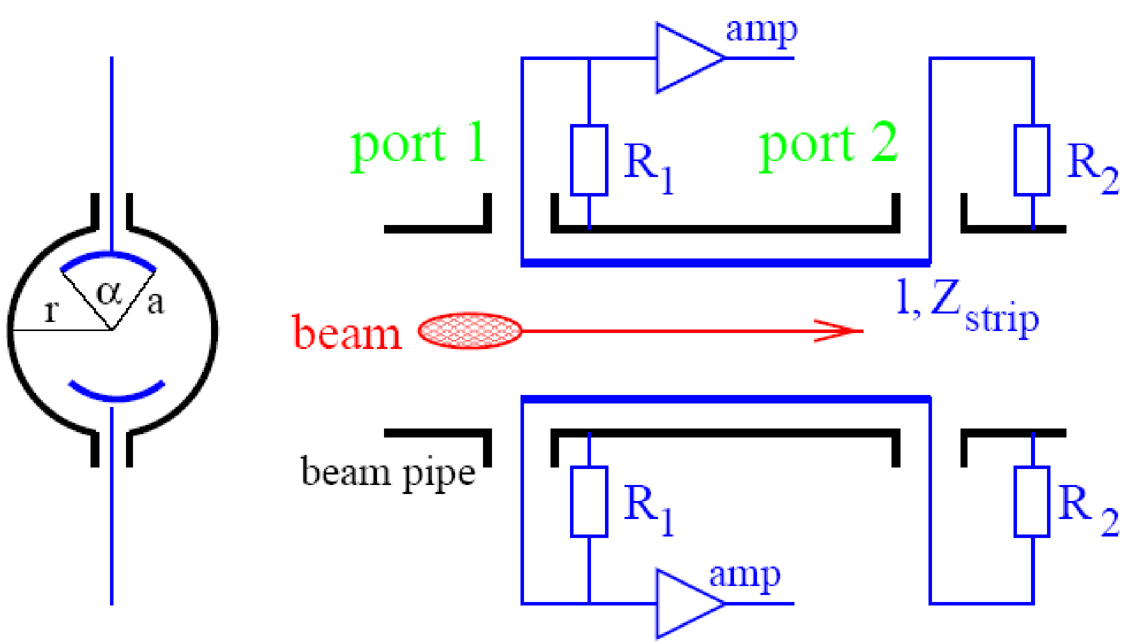
- *Capacitive button BPM → electro-static approach*
- ***Stripline BPM → traveling wave e.g. for collider***
- ***Cavity BPM → resonator for dipole mode***
- ***Electronics for position evaluation***
- ***Summary***

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

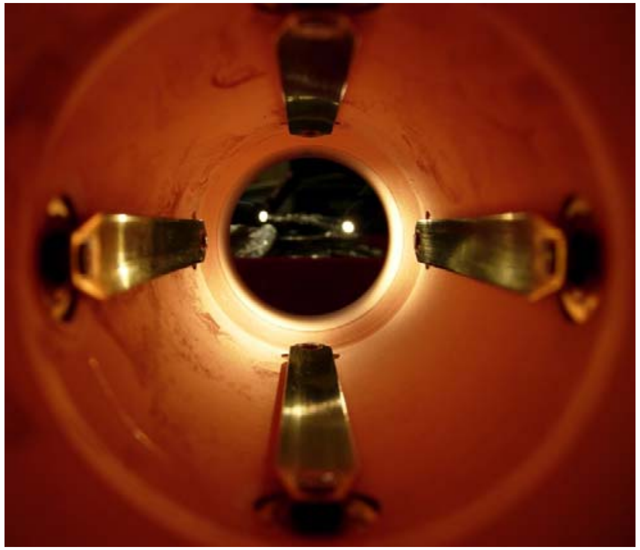
→ Relativistic beam ***β≈1*** ⇒ field of bunches nearly TEM wave

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

→ 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

For relativistic beam with ***β≈1*** and short bunches:

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

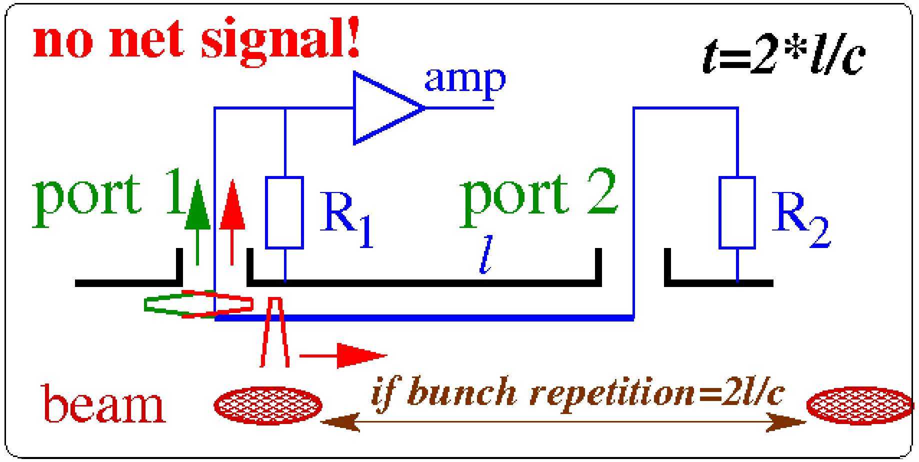
→ ***Assumption:*** $l_{bunch} << l$, $Z_{strip}=R_1=R_2=50\ \Omega$ and $v_{beam}=c_{strip}$

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**

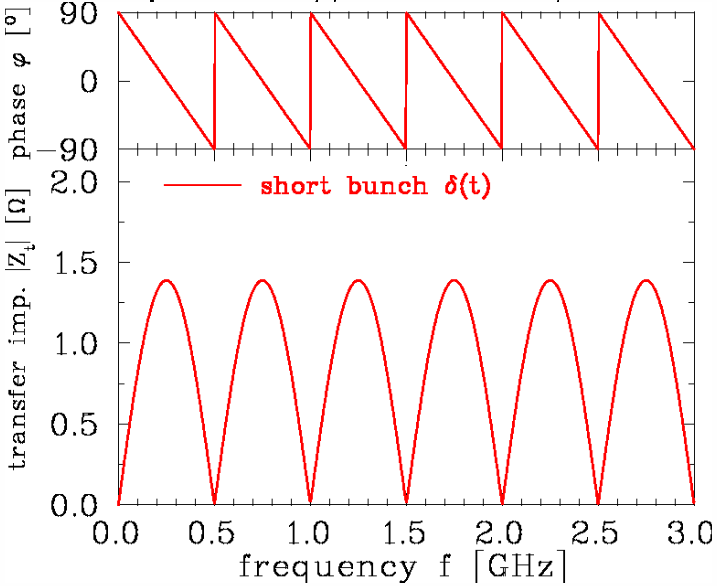
Signal at downstream port 2: Beam induced charges cancels with traveling charge from port 1

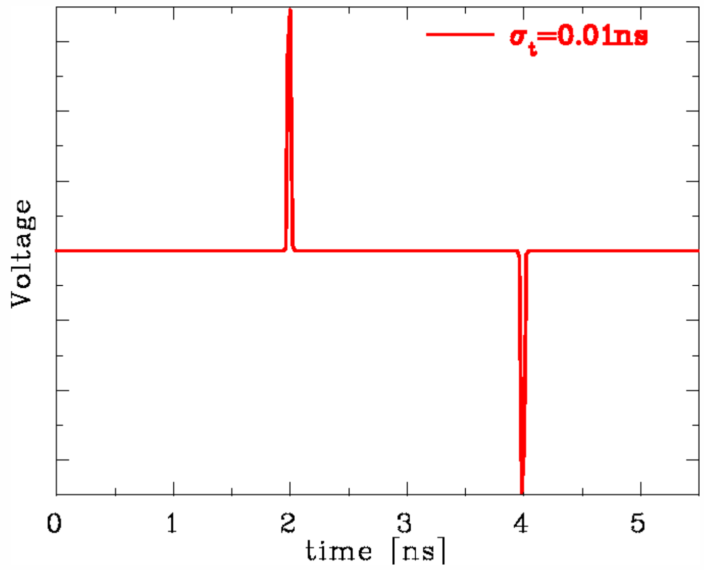
⇒ Signal depends on direction ⇔ directional coupler: e.g. can distinguish between e^- and e^+ in collider

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, $\alpha = 10^0$





- 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.

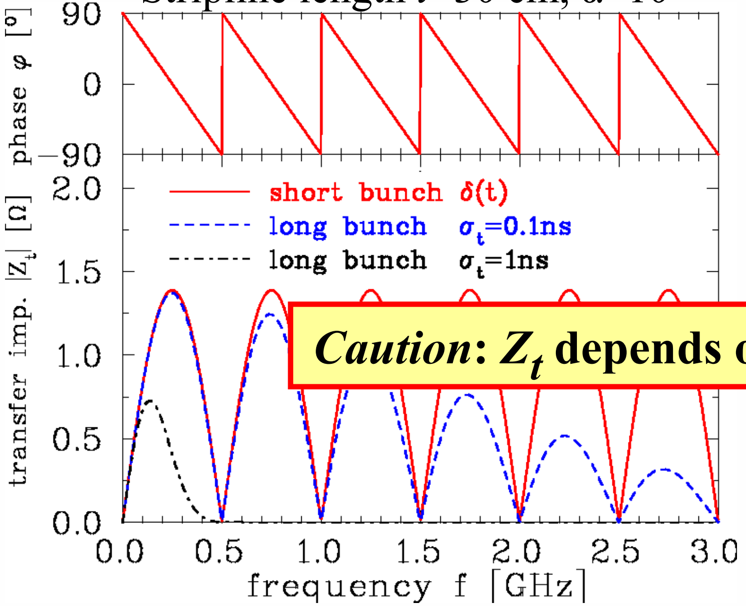
Stripline BPM: Finite Bunch Length

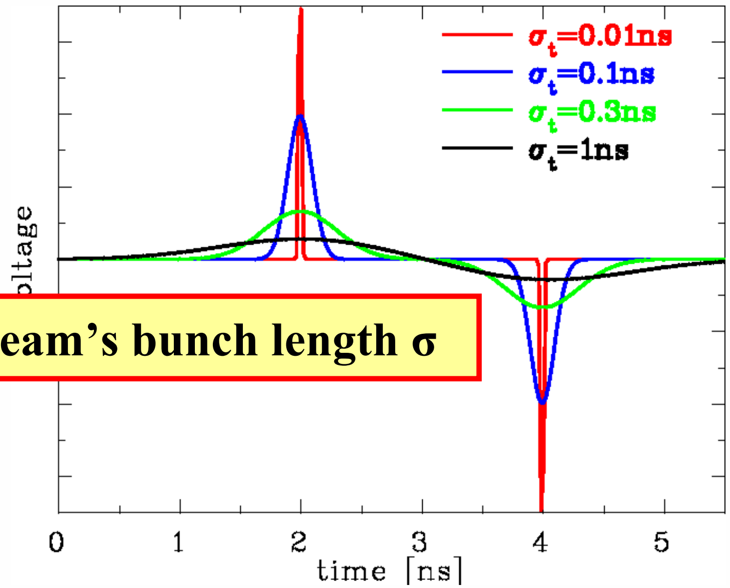
The signal at port 1 for a finite bunch of length σ: $I_{beam}(t) = I_0 \cdot e^{-t^2/2\sigma^2}$

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

$$\Rightarrow \text{in time domain}: U_{im}(t) = Z_{strip} \cdot \frac{\alpha}{2\pi} \cdot \left(e^{-(t+l/c)^2/2\sigma^2} - e^{-(t-l/c)^2/2\sigma^2}\right) \cdot I_0$$

Stripline length l=30 cm, α=10[0]





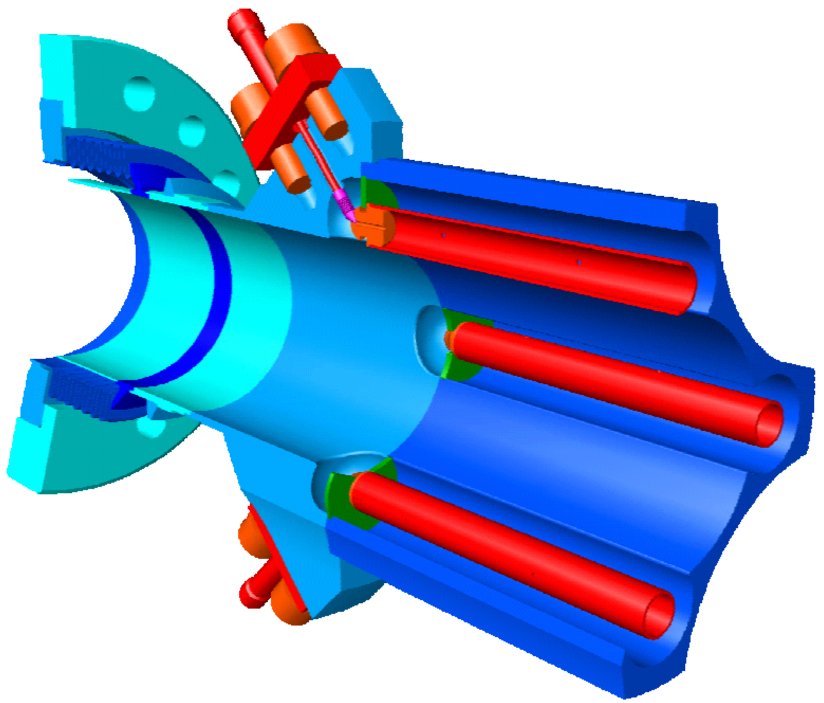
Caution: **Z_t depends on beam's bunch length σ**

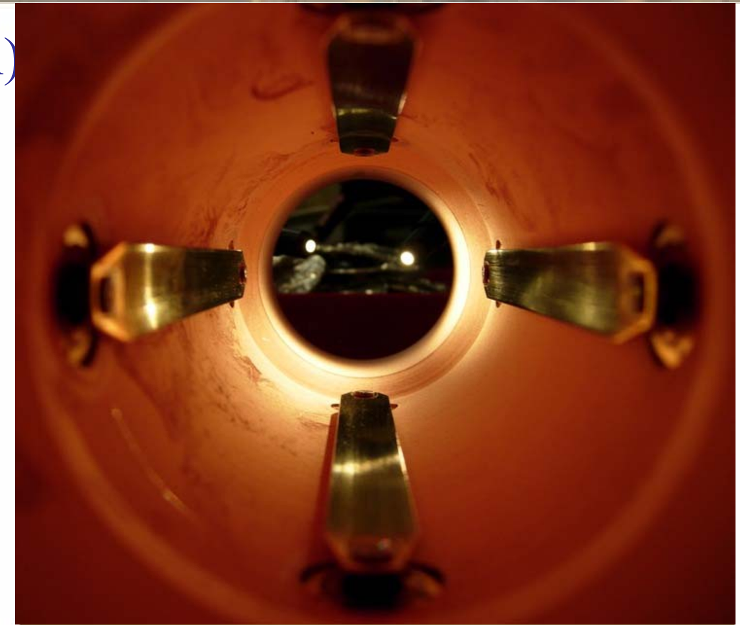
- $Z_t(\omega)$ decreases for higher frequencies
- If total bunch is too long $(\pm 3\sigma_t > l)$ destructive interference leads to signal damping

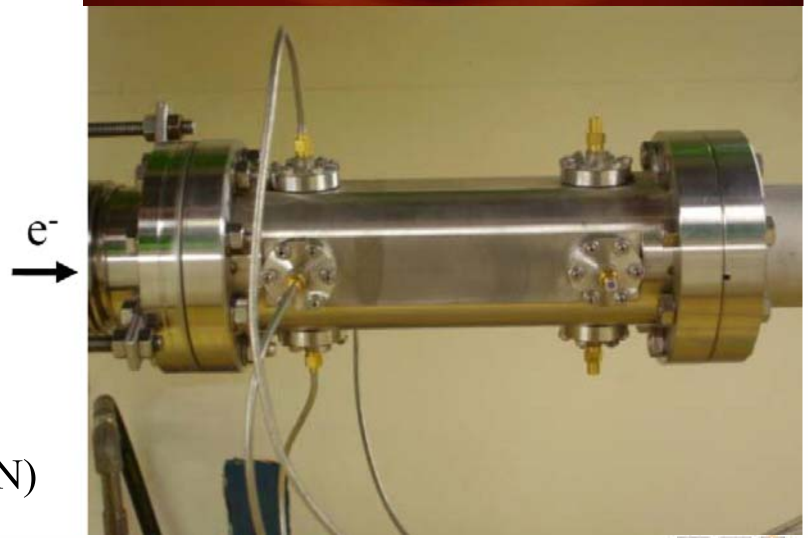
  Cure: length of stripline has to be matched to bunch length

Realization of Stripline BPM

20 cm stripline BPM at TTF2 (chamber ∅34mm)
And 12 cm LHC type:





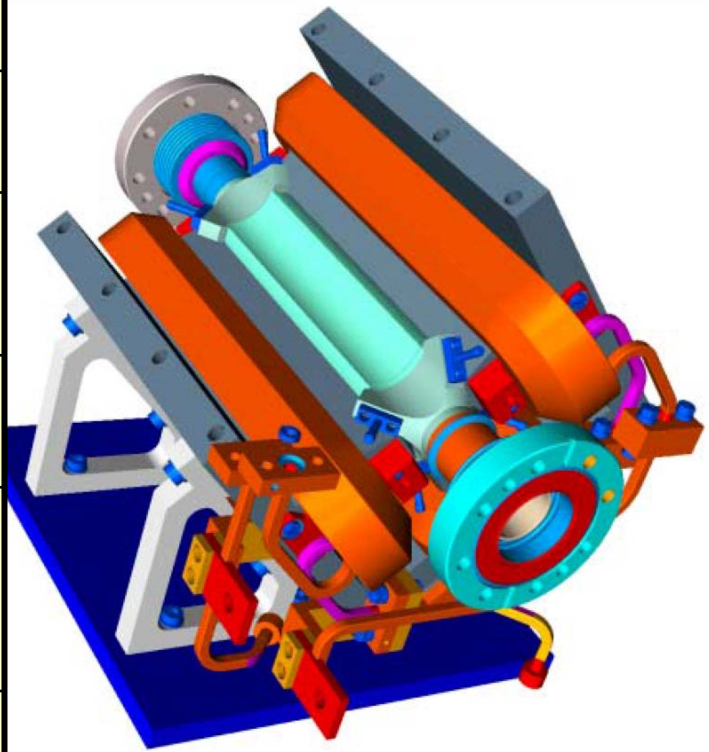


From . S. Wilkins, D. Nölle (DESY), C. Boccard (CERN)

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

TTF2 BPM inside quadrupole



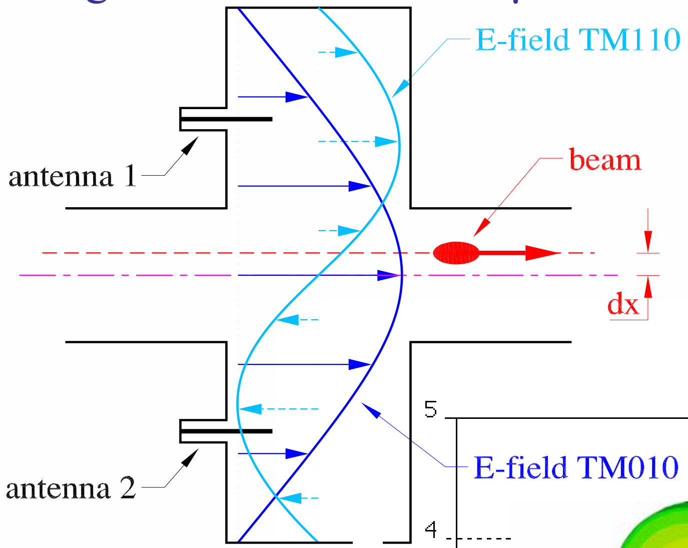
From . S. Wilkins, D. Nölle (DESY)

Outline:

- *Signal generation → transfer impedance*
- *Capacitive shoe box BPM → electro-static approach*
- *Capacitive button BPM → electro-static approach*
- *Stripline BPM → traveling wave e.g. for collider*
- *Cavity BPM → resonator for dipole mode e.g. for FEL*
- *Electronics for position evaluation*
- *Summary*

Cavity BPM: Principle

High resolution on $t < 1$ μs time scale can be achieved by excitation of a dipole mode:



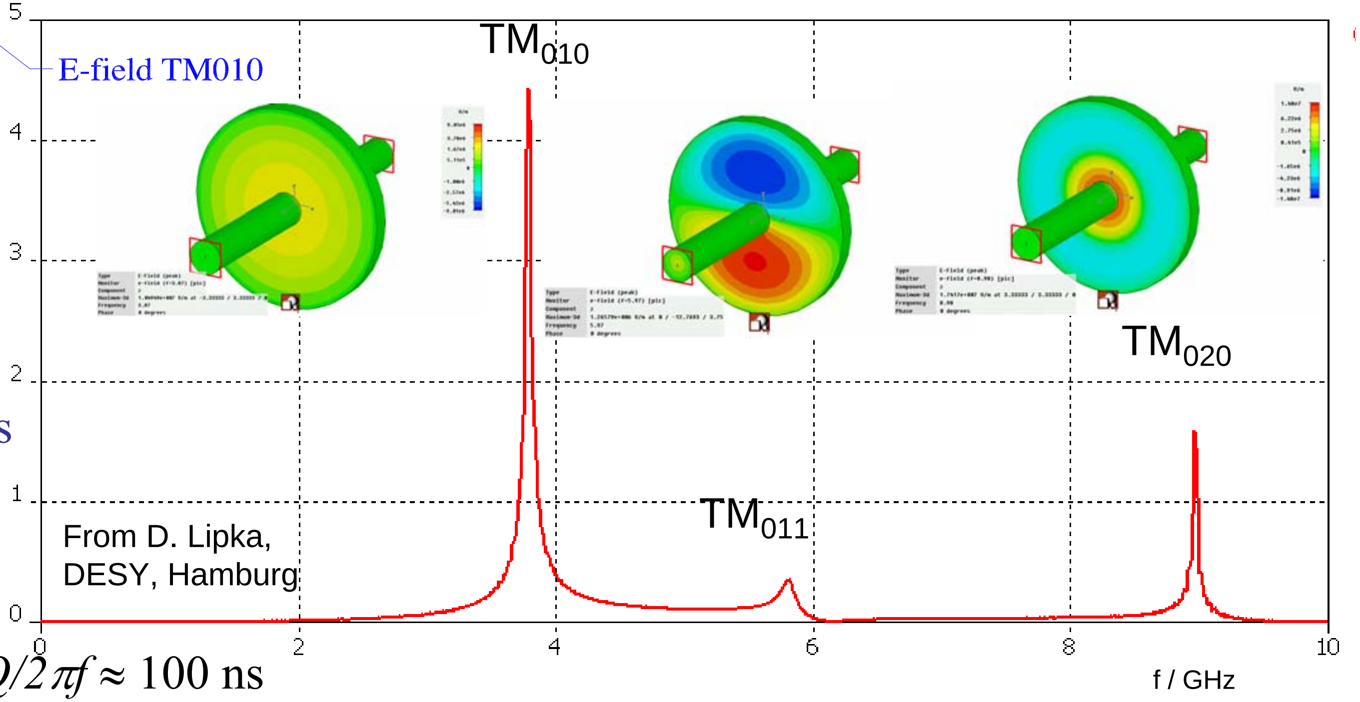
For pill box the resonator modes given by geometry:

- monopole TM_{010} with f_{010}
  → maximum at beam center ⇒ strong excitation
- Dipole mode TM_{011} with f_{011}
  → minimum at center ⇒ excitation by beam offset

⇒ Detection of dipole mode amplitude

Application:
small e⁻ beams
and short pulses < ns
(ILC, X-FEL…)

'δ-excitation'
→oscillation with
$Q \approx 1000$ and $\tau = 2Q/2\pi f \approx 100$ ns

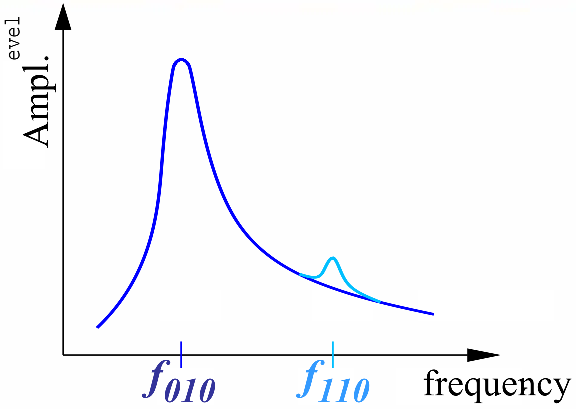


Basic consideration for detection of Eigen-frequency amplitudes:

Dipole mode f_{110} separated from monopole mode

but to finite quality factor $\boldsymbol{Q \Rightarrow \Delta f = f/Q}$

- Frequency $f_{110} \approx 1 \ldots 10$ GHz
- Waveguide house the antennas
  (task: suppression of TM_{010} mode signal)



FNAL realization:

Cavity: ∅ 113 mm

Gap 15 mm

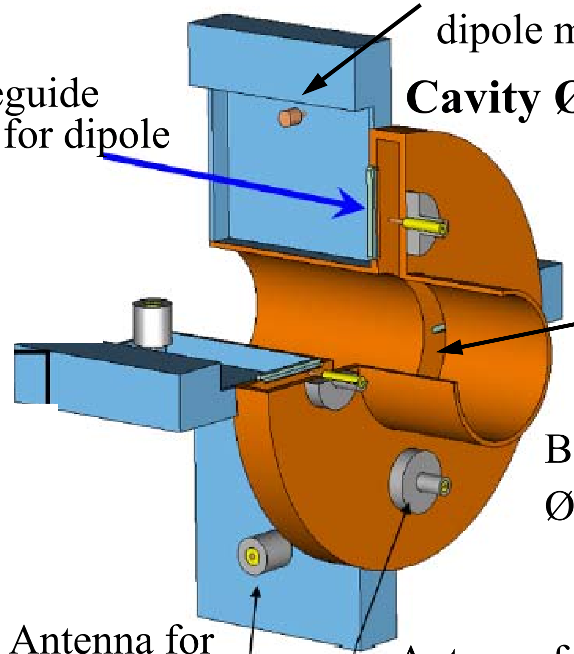
Mono. f_{010}=1.1GHz

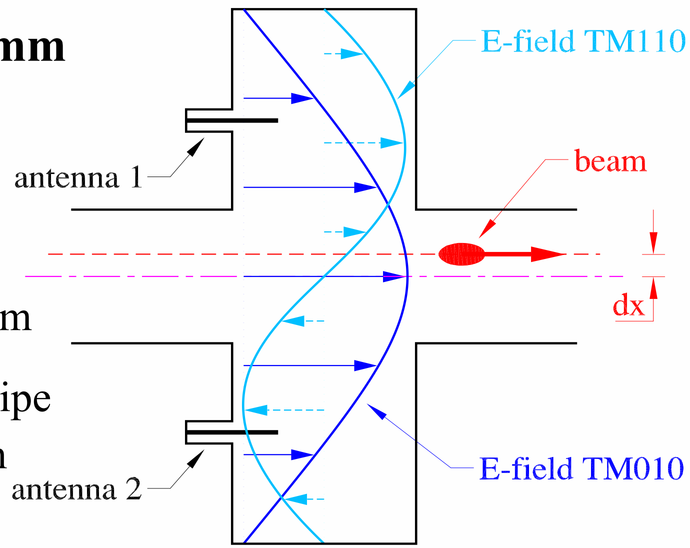
Dipole. f_{110}=1.5GHz

$Q_{load} \approx 600$

With comparable BPM

⇒0.1 µm resolution within 1 µs



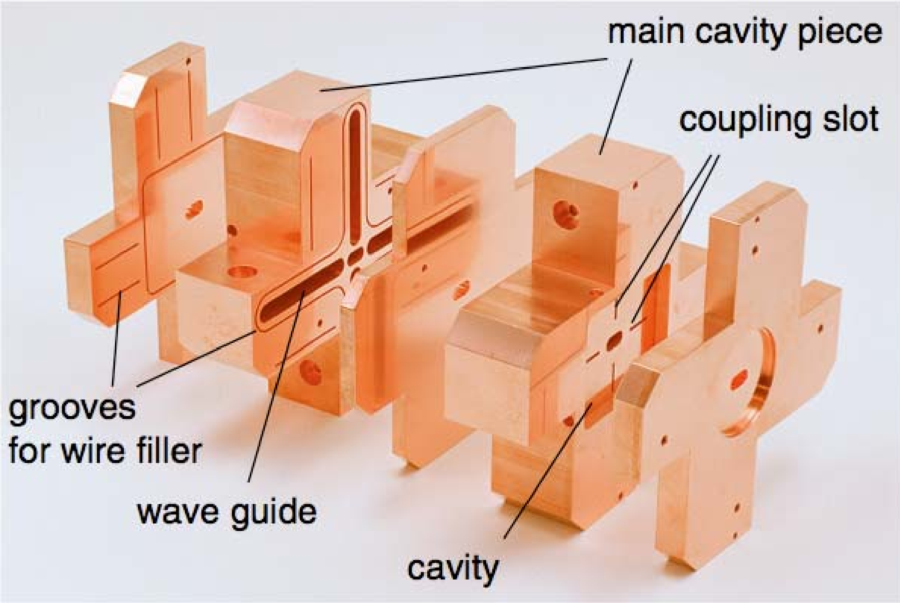


From M. Wendt (FNAL)

Cavity BPM: Suppression of monopole Mode

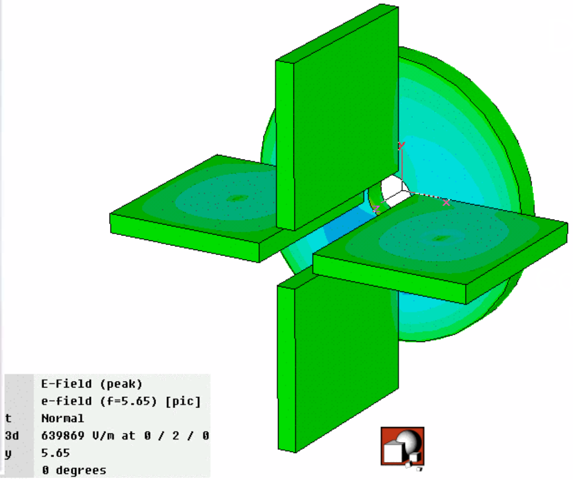
Suppression of mono-pole mode: waveguide that couple only to dipole-mode

due to $f_{mono} < f_{cut} < f_{dipole}$



Courtesy of D. Lipka and Y. Honda

Dipole-pole mode



Courtesy of D. Lipka, DESY, Hamburg

Prototype BPM for ILC Final Focus:

- Required resolution of 5 nm (yes nano!) in a 6×12 mm diameter beam pipe
- Achieved world record resolution of 8.7 nm ±0.28(stat)± 0.35(sys) nm at ATF2 (KEK, Japan).

Comparison of BPM Types (simplified)

Type	Usage	Precaution	Advantage	Disadvantage
Shoe-box	p-Synch.	Long bunches $f_{rf} < 10$ MHz	Very linear No x-y coupling Sensitive For broad beams	Complex mechanics Capacitive coupling between plates
Button	p-Linacs, all e^- acc.	$f_{rf} > 10$ MHz	Simple mechanics	Non-linear, x-y coupling Possible signal deformation
Stipline	colliders p-Linacs all e^- acc.	best for $\beta \approx 1$, short bunches	Directivity 'Clean' signal Large signal	Complex 50 Ω matching Complex mechanics
Cavity	e^- Linacs (e.g. FEL)	Short bunches Special appl.	Very sensitive	Very complex, high frequency

Remark: Other types are also some time used, e.g. wall current, inductive antenna, BPMs with external resonator, slotted wave-guides for stochastic cooling etc.

Beam Position Monitors:
Detector Principle, Hardware and Electronics

Outline:

- *Signal generation → transfer impedance*
- *Capacitive shoe box BPM → electro-static approach*
- *Capacitive button BPM → electro-static approach*
- *Stripline → traveling wave*
- *Cavity BPM → resonator for dipole mode*
- ***Electronics for position evaluation***
  Noise consideration, broadband and narrowband analog processing, digital processing
- ***Summary***

Characteristics for Position Measurement

Position sensitivity: Factor between beam position & signal quantity ($\Delta U/\Sigma U$ or $\log U_1/U_2$)

defined as $$S_x(x,y,f) = \frac{d}{dx}\left(\Delta U_x / \Sigma U_x\right) = [\%/\mathrm{mm}]$$

Accuracy: Ability for position reading relative to a mechanical fix-point ('absolute position')

- influenced by mechanical tolerances and alignment accuracy and reproducibility
- by electronics: e.g. amplifier drifts, electronic interference, ADC granularity

Resolution: Ability to determine small displacement variation ('relative position')

- typically: ***single bunch***: 10^{-3} of aperture ≈ 100 μm
  averaged: 10^{-5} of aperture ≈1 μm, with dedicated methods ≈0.1 μm
- in most case much better than accuracy
- electronics has to match the requirements e.g. bandwidth, ADC granularity

Bandwidth: Frequency range available for measurement

- has to be chosen with respect to required resolution via analog or digital filtering

Dynamic range: Range of beam currents the system has to respond

- position reading should not depend on input amplitude

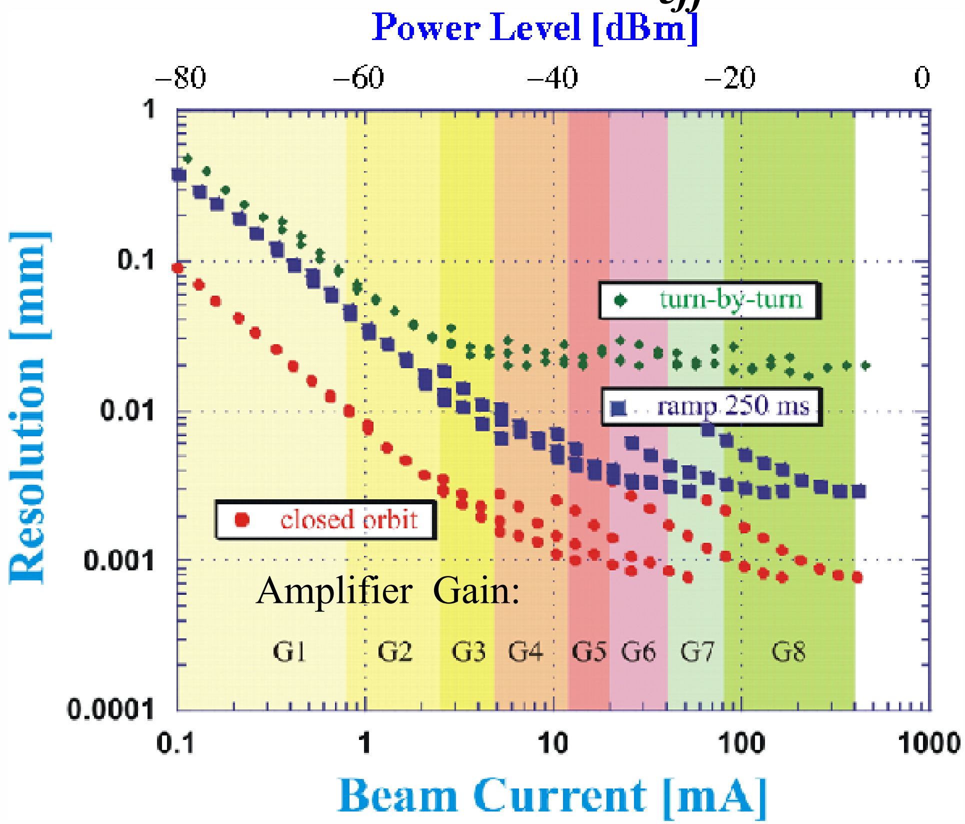
Signal-to-noise: Ratio of wanted signal to unwanted background

- influenced by thermal and circuit noise, electronic interference
- can be matched by bandwidth limitation

Signal sensitivity = detection threshold: minimum beam current for measurement

Example for Signal-to-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: $U_{eff}(R, \Delta f) = \sqrt{4k_B \cdot T \cdot R \cdot \Delta f}$
4. Signal-to-noise ratio $\boldsymbol{\Delta U / U_{eff}}$ calculation and expressed in spatial resolution $\boldsymbol{\sigma}$



***Example:** button BPM resolution at Synchrotron Light Source SLS at PSI:*

Bandwidth:

Turn-by turn = 500 kHz

Ramp 250 ms = 15 kHz

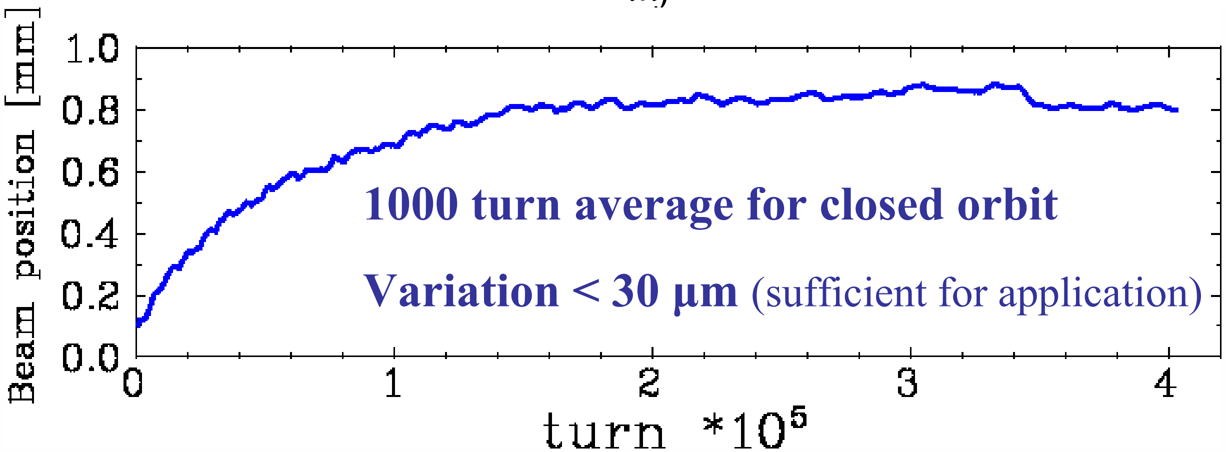
Closed orbit = 2 kHz

Result:

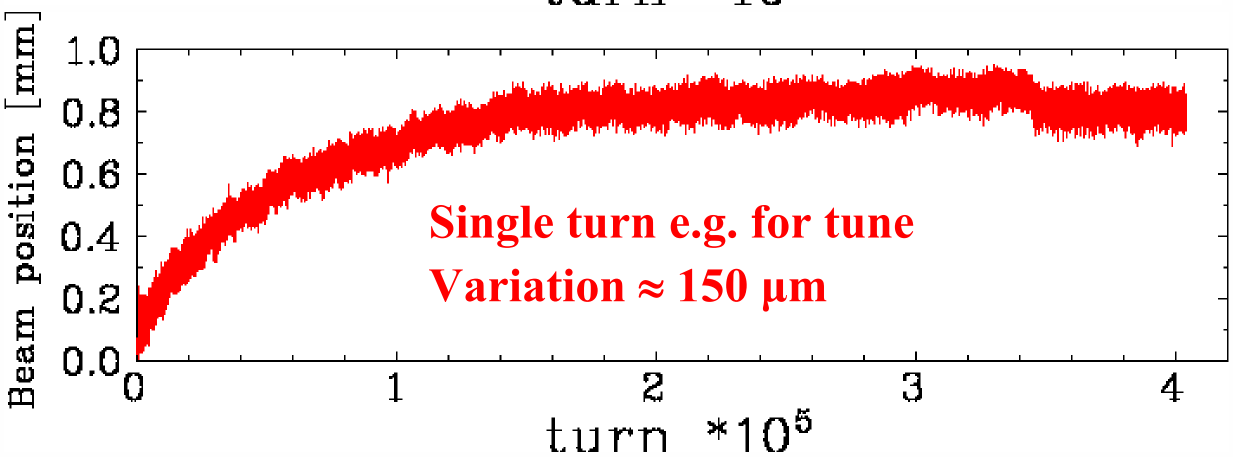
- **Slow readout** ⇔ low Δf
  ⇒ low $\boldsymbol{\sigma}$ due to $\sigma \propto \sqrt{\Delta f}$
- **Low current** ⇔ low signal
  ⇒ input noise dominates

From V. Schlott et al. (PSI) DIPAC 2001, p. 69

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



- Position resolution < 30 µm (BPM half aperture a=90 mm)
- average over 1000 turns corresponding to ≈1 ms or ≈1 kHz bandwidth

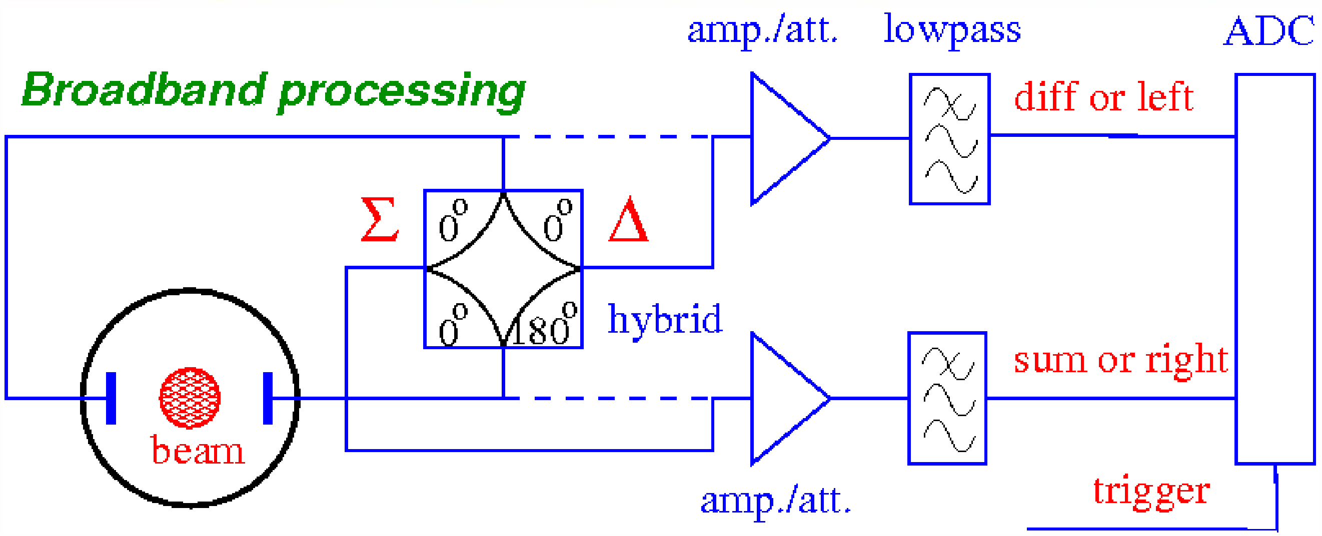


- Turn-by-turn data have much larger variation

However: not only noise contributes but additionally **beam movement** by betatron oscillation

⇒ broadband processing i.e. turn-by-turn readout for tune determination

General Idea: Broadband 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 $\Delta U / \Sigma U$

Advantage: Bunch-by-bunch 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

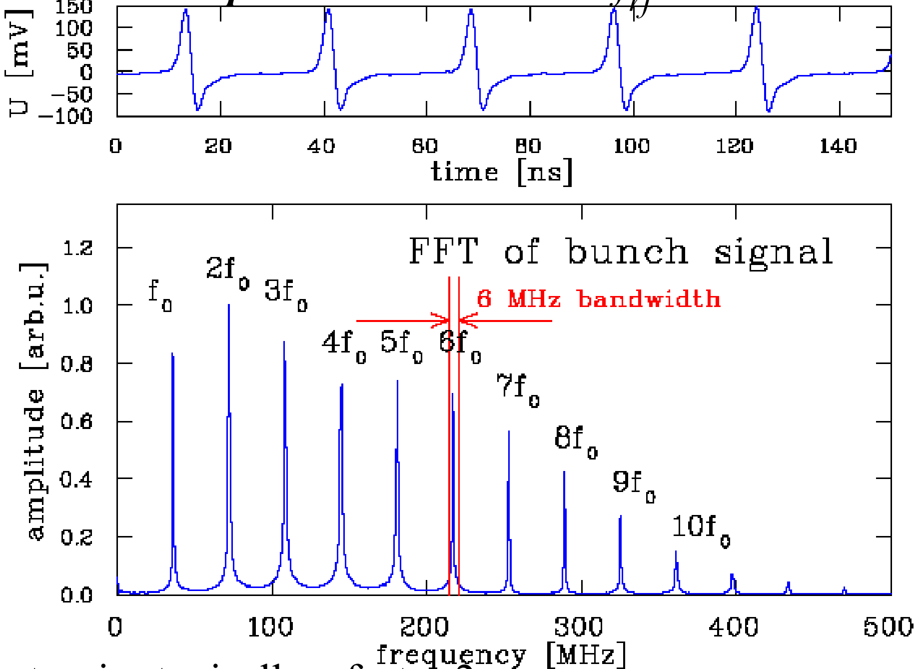
General: Noise Consideration

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: $U_{eff}(R, \Delta f) = \sqrt{4k_B \cdot T \cdot R \cdot \Delta f}$
4. Signal-to-noise ratio $\boldsymbol{\Delta U / U_{eff}}$ calculation and expressed in spatial resolution $\boldsymbol{\sigma}$

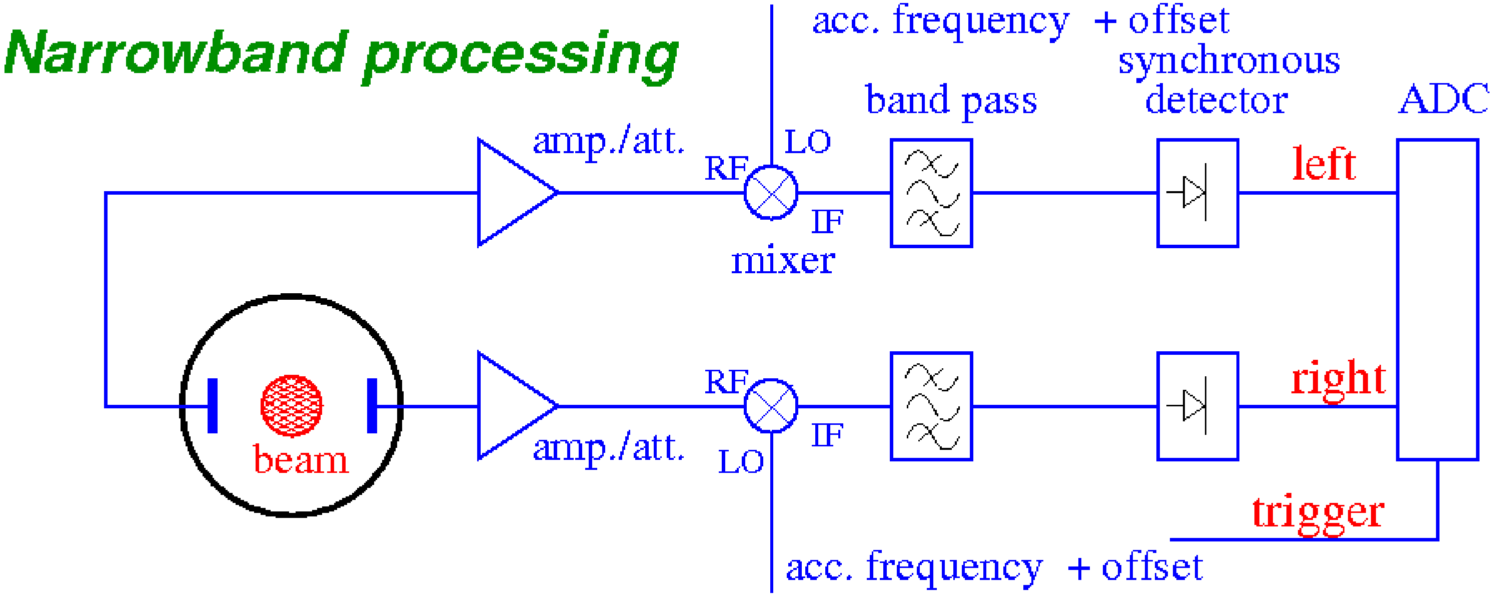
Signal-to-noise $\boldsymbol{\Delta U / U_{eff}}$ is influenced by:

- Input signal amplitude
  $\rightarrow$ large or matched Z_t
- Thermal noise at $\boldsymbol{R} = 50\ \Omega$ for $\boldsymbol{T} = 300$ K
  or for shoe box $\boldsymbol{R} = 1$ MΩ
- Bandwidth $\boldsymbol{\Delta f}$
  $\Rightarrow$ Restriction of frequency width
  because the power is concentrated
  on the harmonics of $\boldsymbol{f_{rf}}$

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



Remark: Additional contribution by non-perfect electronics typically a factor 2
Moreover, pick-up by electro-magnetic interference can contribute $\Rightarrow$ good shielding required



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

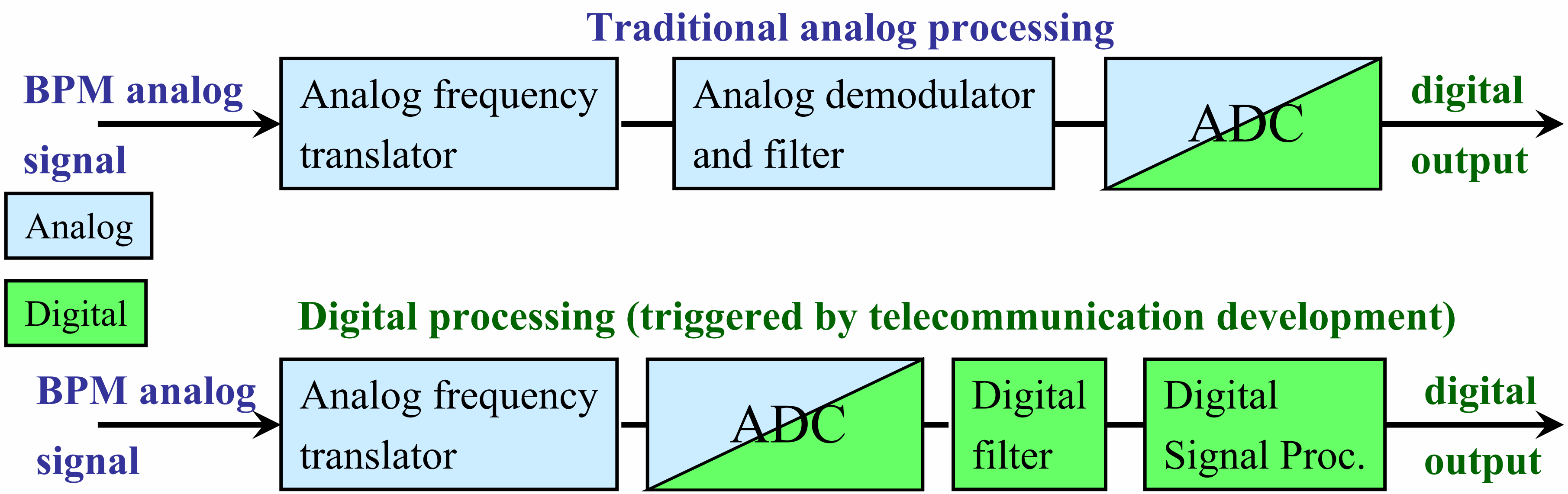
- Attenuator/amplifier
- Mixing with accelerating frequency $f_{rf} \Rightarrow$ signal with sum and difference frequency
- Bandpass filter of the mixed signal (e.g at 10.7 MHz)
- Rectifier: synchronous detector
- ADC: digitalization ⟶ followed calculation of $\Delta U/\Sigma U$

Advantage: spatial resolution about 100 time better than broadband processing.

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

For non-relativistic p-synchrotron: → variable f_{rf} leads via mixing to constant intermediate freq.

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



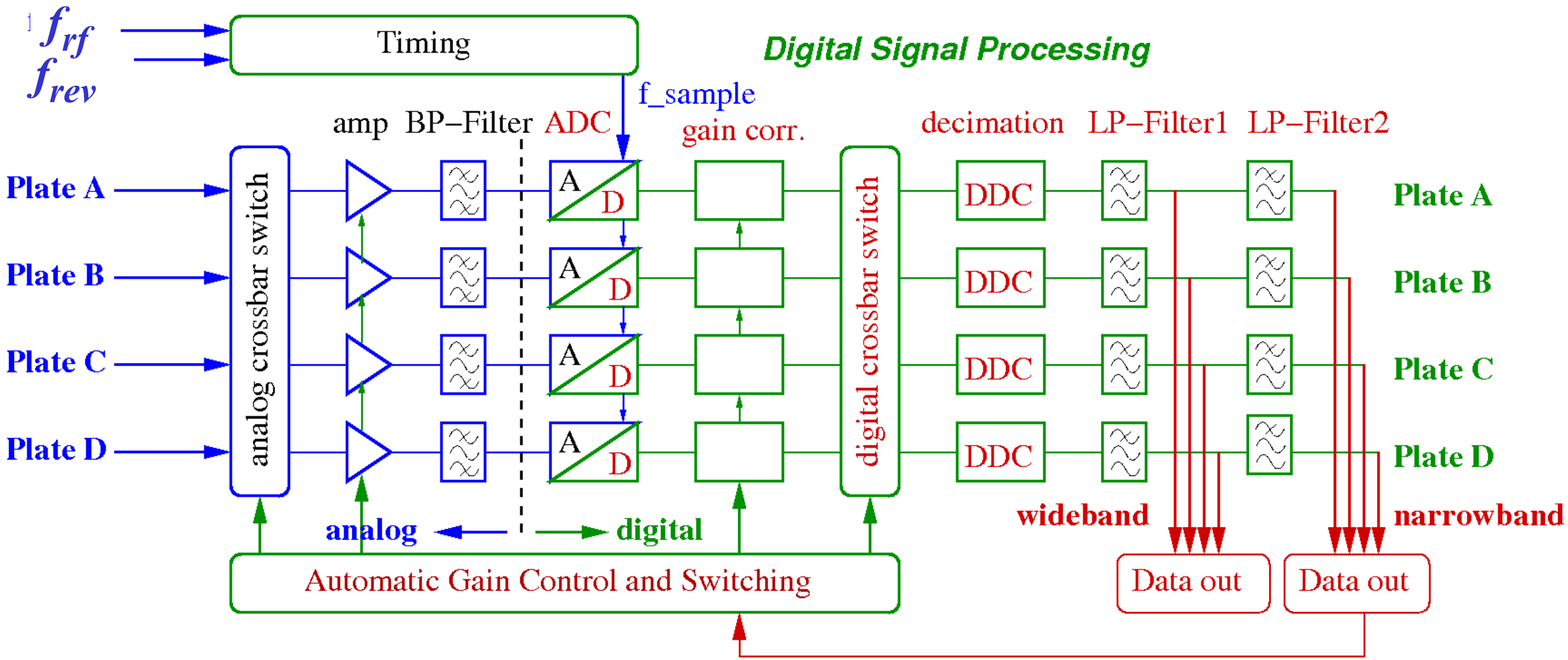
Digital receiver as modern successor of super heterodyne receiver

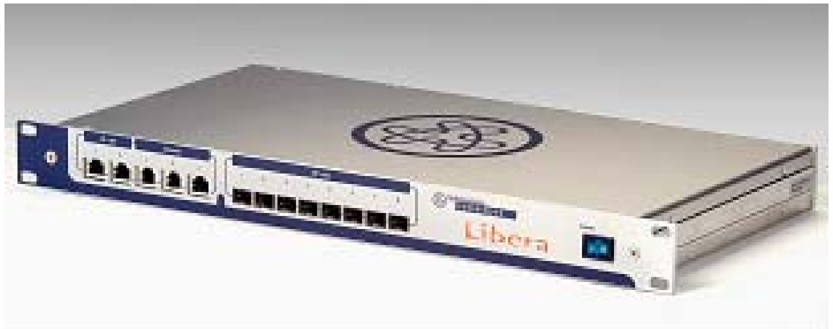
- Basic functionality is preserved but implementation is very different
- Digital transition just after the amplifier & filter or mixing unit
- Signal conditioning (filter, decimation, averaging) on FPGA

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

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

Digital Signal Processing Realization

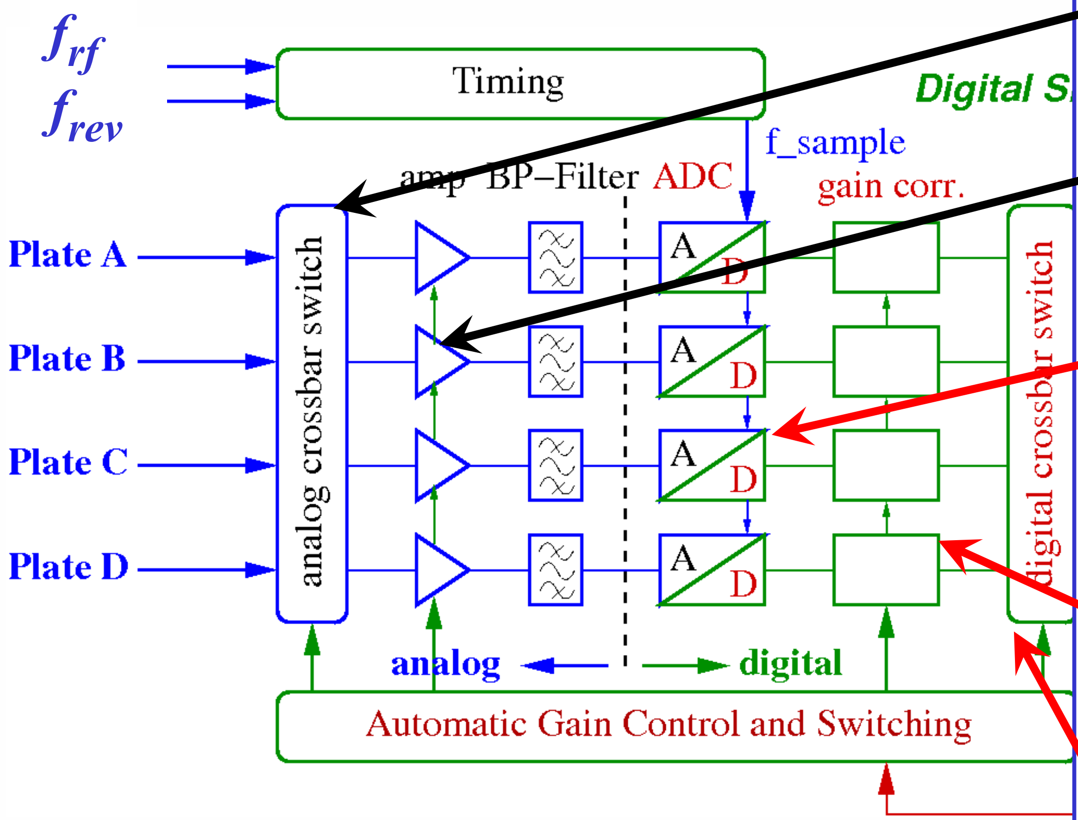




- Analog multiplexing and filtering
- Digital corrections and data reduction on FPGA

Commercially available electronics
used at many synchrotron light sources

LIBERA Digital BPM Readout: Analog Part and Digitalization



Crossbar multiplexing of **all** channels at ≈13 kHz (analog)

Automatic gain control by 0…31 dB filter 10 MHz@f_{rf} (analog)

Digitalization with ≈117 MHz matched to sub-harmonics of $\mathbf{f_{rf}}$
⇒ Undersampling: every 4th bunch

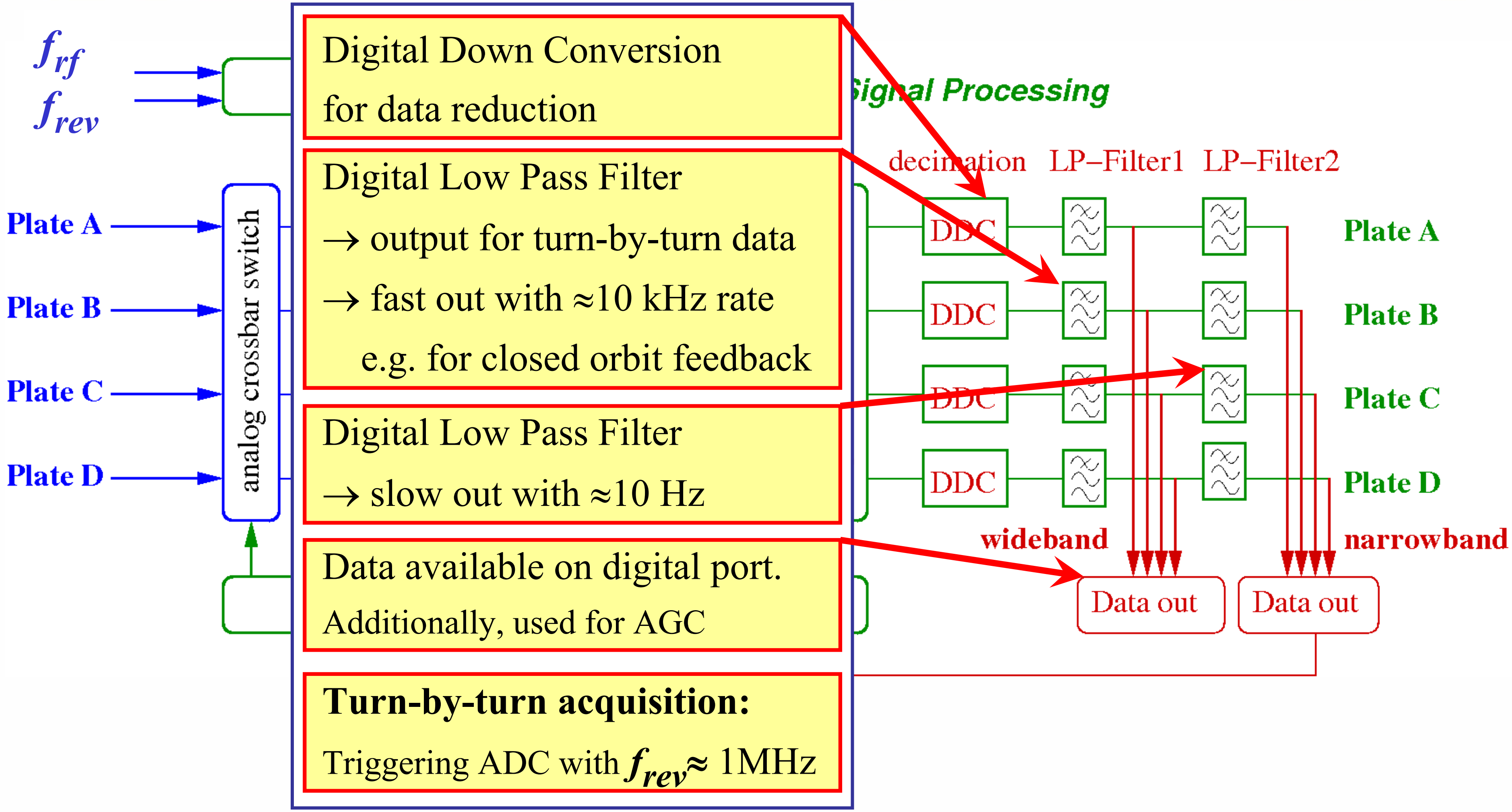
Digital compensation of amplification variation

Digital de-multiplexing

Typical values for a Synchrotron Light Source:

f_{rf} = 352 or 500 MHz, revolution f_{rev} ≈ 1 MHz, sampling at 4/(4*4+1) * f_{rf} = 117.6 MHz for 500 MHz

LIBERA Digital BPM Readout: Digital Signal Processing



Digital Down Conversion for data reduction

Digital Low Pass Filter
→ output for turn-by-turn data
→ fast out with ≈10 kHz rate
e.g. for closed orbit feedback

Digital Low Pass Filter
→ slow out with ≈10 Hz

Data available on digital port.
Additionally, used for AGC

Turn-by-turn acquisition:
Triggering ADC with $f_{rev} \approx$ 1MHz

Remark: For p-synchrotrons direct 'baseband' digitalization with 125 MS/s due to f_{rf}<10 MHz.

Comparison of BPM Readout Electronics (simplified)

Type	Usage	Precaution	Advantage	Disadvantage
Broadband	p-sychr.	Long bunches	Bunch structure signal Post-processing possible Required for fast feedback	Resolution limited by noise
Narrowband	all synchr.	Stable beams >100 rf-periods	High resolution	No turn-by-turn Complex electronics
Narrowband +Multiplexing	all synchr.	Stable beams >10ms	Highest resolution	No turn-by-turn, complex Only for stable storage
Digital Signal Processing	all	Several bunches ADC 125 MS/s	Very flexible High resolution **Trendsetting technology for future demands**	Limited time resolution by ADC $\rightarrow$ undersampling complex and expensive

Summary

With BPMs the center in the transverse plane is determined for bunched beams.

Beam → detector coupling is given by transfer imp. $Z_t(\omega)$ ⇒ signal estimation $I_{beam} \rightarrow U_{im}$

Different type of BPM:

Shoe box = linear cut: for p-synchrotrons with f_{rf} < 10 MHz

Advantage: very linear. **Disadvantage:** complex mechanics

Button: Most frequently used at all accelerators, best for f_{rf} > 10 MHz

Advantage: compact mechanics. **Disadvantage:** non-linear, low signal

Stripline: Taking traveling wave behavior into account, best for short bunches

Advantage: precise signal. **Disadvantage:** Complex mechanics for 50 Ω, non-linear

Cavity BPM: dipole mode excitation → high resolution '1μm@1μs' ↔ application: FEL

Electronics used for BPMs:

Thank you for your attention !

Basics: Resolution in space ↔ resolution in time i.e. the bandwidth has to match the application

Broadband processing: Full information available, but lower resolution, for fast feedback

Analog narrowband processing: high resolution, but not for fast beam variation

Digital processing: very flexible, but limited ADC speed, more complex → state-of-the-art.

References

Proceedings related to this talk:

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