Introduction on Pick-up Types and their Suitability for various Applications

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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
- Summary

A *B*eam *P*osition *M*onitor is an non-destructive device for bunched beams

It has a low cut-off frequency i.e. dc-beam behavior can not be monitored
The abbreviation BPM and pick-up PU are synonyms

1. It delivers information about the transverse center of the beam

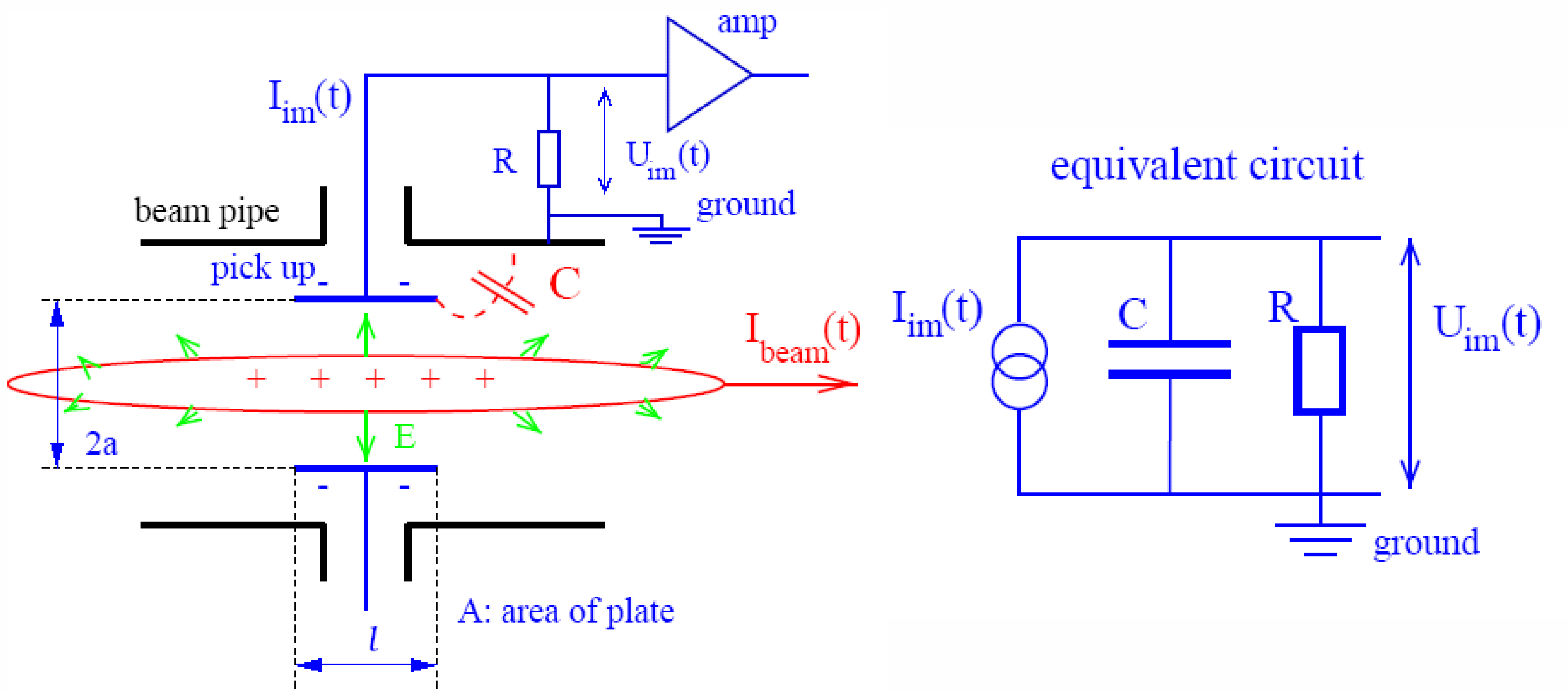
- ***Trajectory:*** Position of an individual bunch within a transfer line or synchrotron
- ***Closed orbit***: central orbit averaged over a period much longer than a betatron oscillation
- ***Single bunch position*** → determination of parameters like tune, chromaticity, ***β***-function
- Bunch position on a large time scale: bunch-by-bunch → turn-by-turn → averaged position
- Time evolution of a single bunch can be compared to 'macro-particle tracking' calculations
- Feedback: fast bunch-by-bunch damping ***or*** precise (and slow) closed orbit correction

2. Information on longitudinal bunch behavior

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

Model for Signal Treatment of capacitive BPMs

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:

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

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

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

Capacitive BPM:

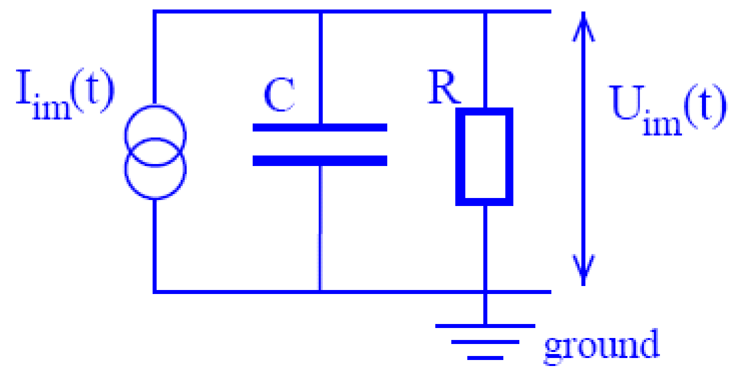
- The pick-up capacitance $\boldsymbol{C}$:
  plate ↔ vacuum-pipe and cable.
- The amplifier with input resistor $\boldsymbol{R}$.
- The beam is a high-impedance current source:

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

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

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

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 $\boldsymbol{\omega_{cut} = 1/RC}$:

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:

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

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

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

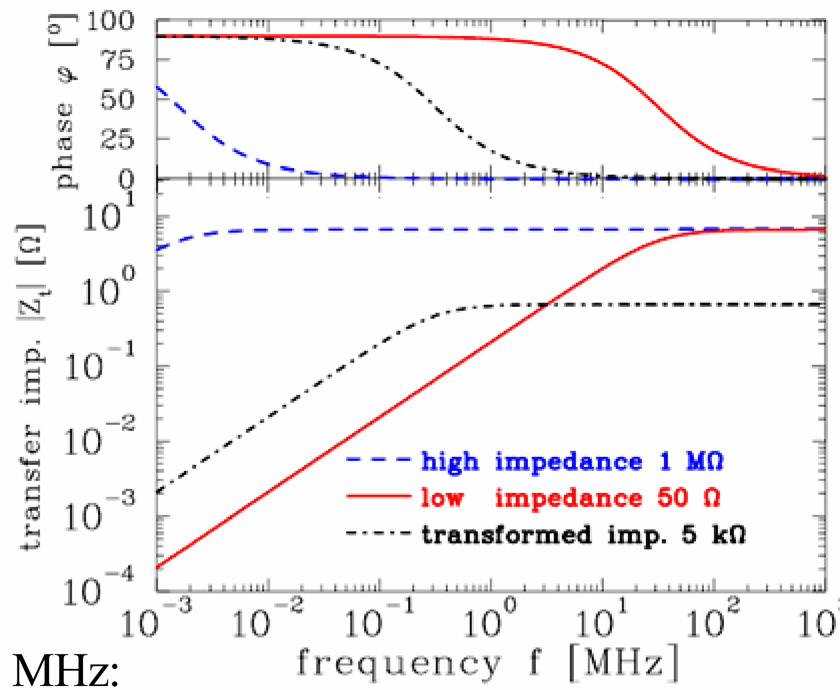
Parameter for shoe-box BPM:

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

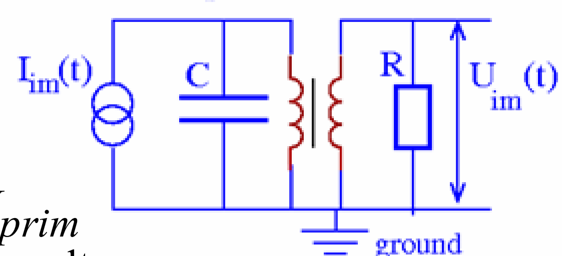


For acceleration frequency 10 MHz < f_{rf} < 10 MHz:

Large signal strength but higher noise → **high impedance**

Smooth signal transmission → **50 Ω**

equivalent circuit

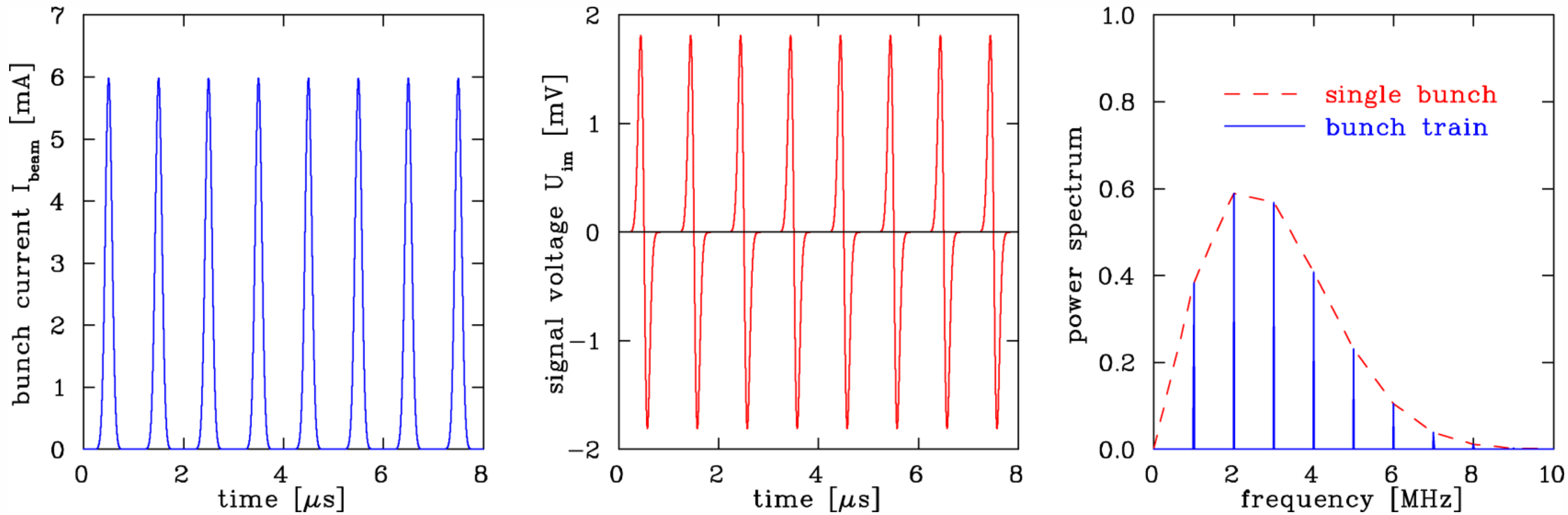


Compromise → ≈ 5 kΩ by transformer e.g. N_{prim}/N_{sec}=3:30

Impedance $Z_{prim}=(N_{prim}/N_{sec})^2 \cdot Z_{sec}$ voltage $U_{im}=N_{sec}/N_{prim} \cdot U_{prim}$

→ Smooth signal chain, medium cut-off frequency, but lower usable voltage

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



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: $\boldsymbol{R}$=50 Ω $\Rightarrow \boldsymbol{f_{cut}}$=32 MHz, $\boldsymbol{C}$=100 pF, $\boldsymbol{l}$=10 cm, $\boldsymbol{\beta}$=50 %, $\boldsymbol{\sigma_t}$ =100 ns

- Fourier spectrum is composed of lines separated by acceleration f_{rf}
- Envelope given by single bunch Fourier transformation
- Differentiated bunch shape due to $\boldsymbol{f_{cut}} >> \boldsymbol{f_{rf}}$
- Typical observation bandwidth ≈ 10·$\boldsymbol{f_{rf}}$ for broadband observation.

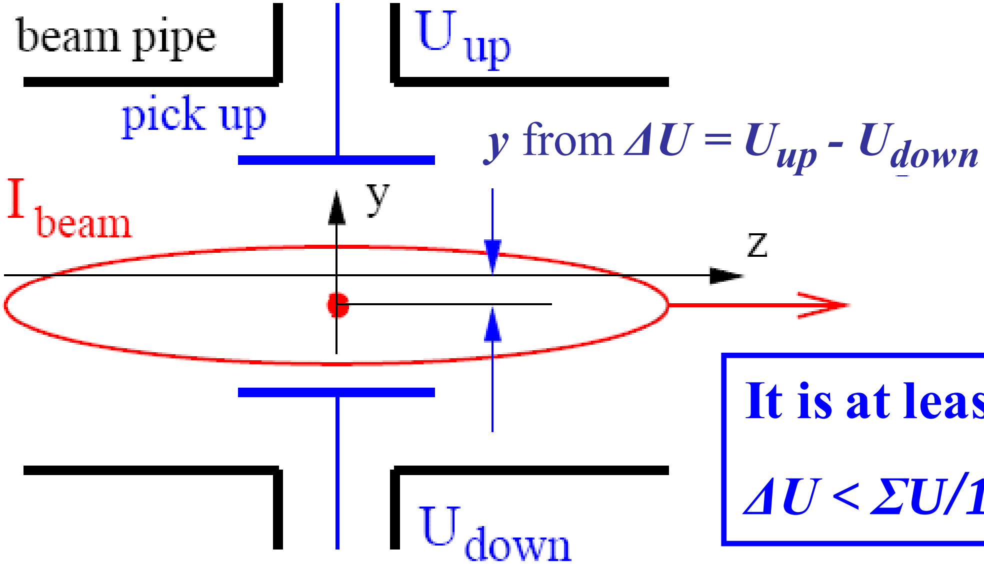
The difference between plates gives the beam's center-of-mass
→**most frequent application**

'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].

Characteristics for Position Measurement

Position sensitivity: Factor between beam position & signal quantity

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

Accuracy: Ability for position reading relative to a mechanical fix-point ('absolute position')
or Precision
- 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 for ***single bunch***: 10^{-3} of aperture ≈ 100 µm
  averaged: 10^{-5} of aperture ≈1 µm, ***typical goal:*** 1 % of beam width $\Delta x \approx 0.01 \cdot \sigma$
- 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

Detection threshold = signal sensitivity: minimum beam current for measurement

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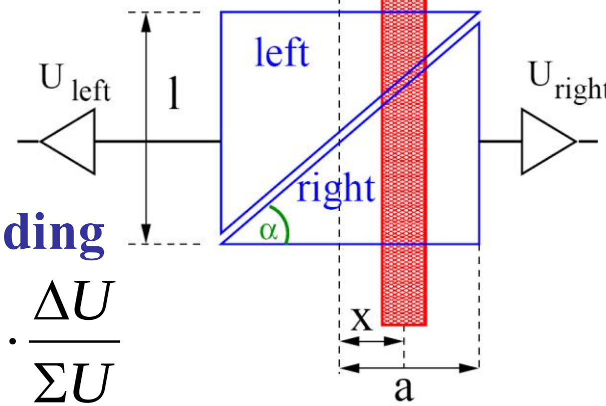
Frequency range: 1 MHz < f_{rf} < 10 MHz ⇒ bunch-length >> BPM length.

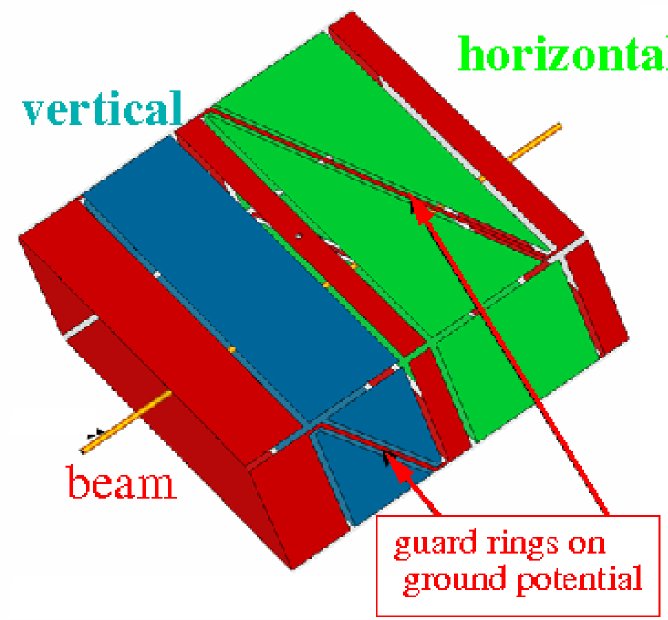
Signal is proportional to actual plate length:

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

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

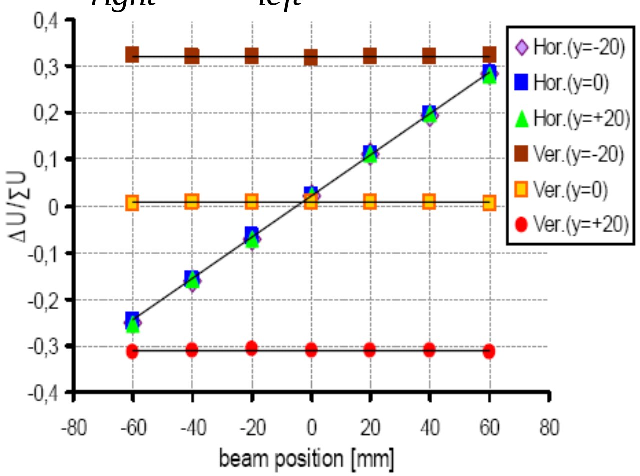


Size: 200x70 mm^2



In ideal case: linear reading

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



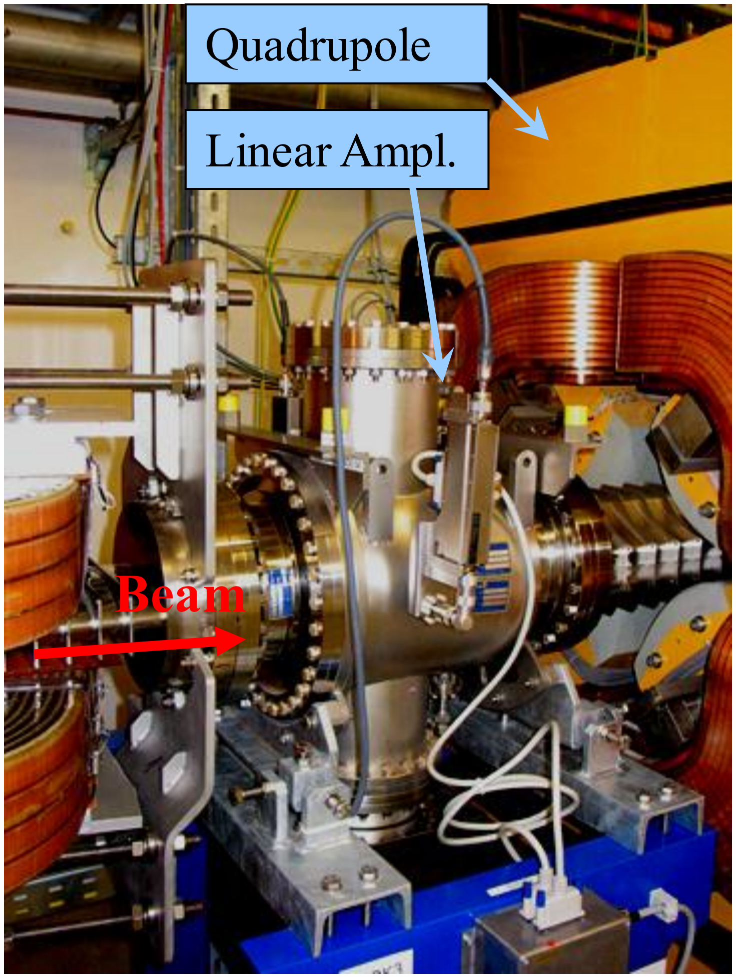
Shoe-box BPM:

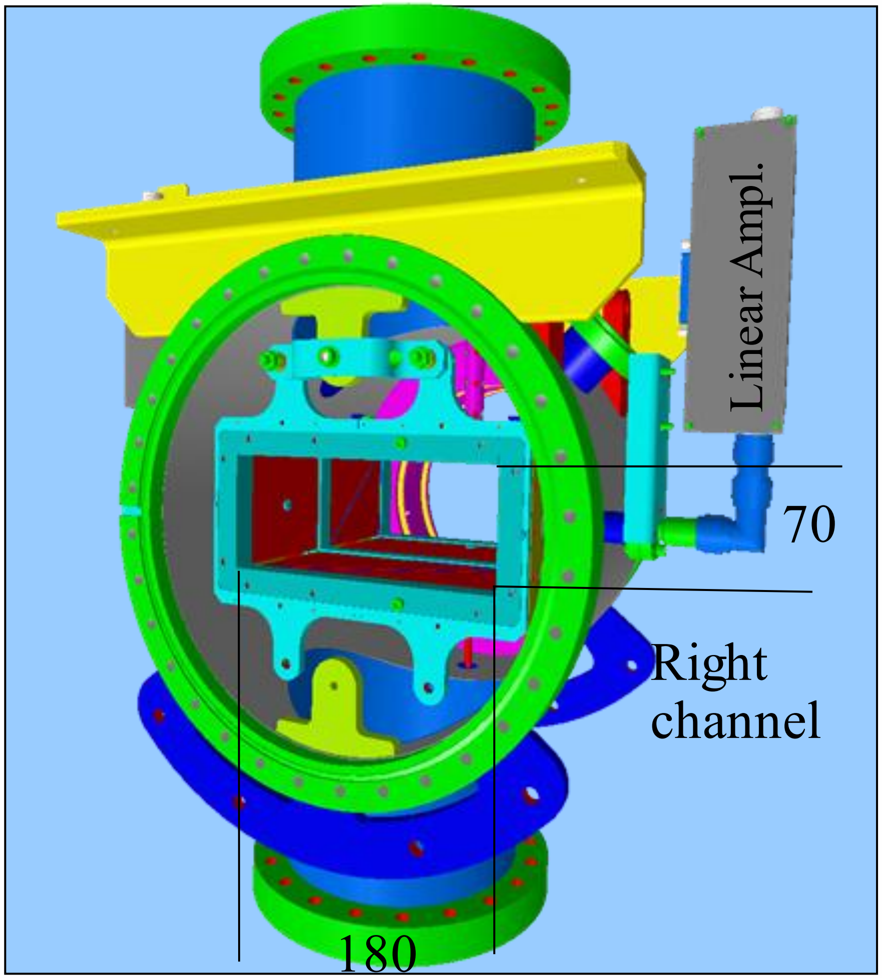
Advantage: Very linear, low frequency dependence
i.e. position sensitivity ***S*** is constant

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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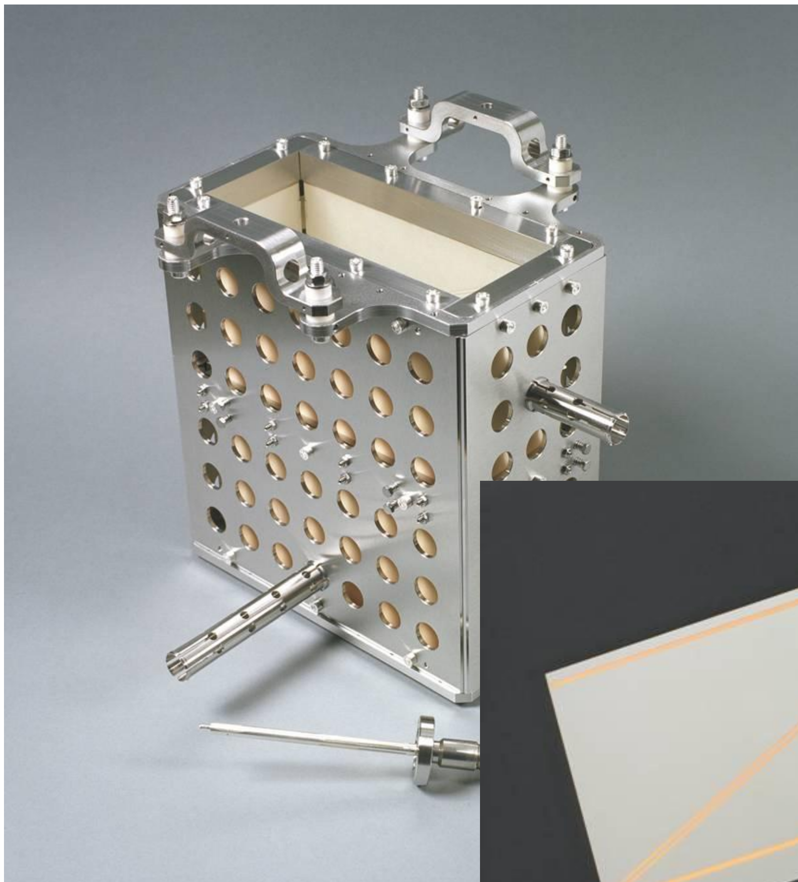
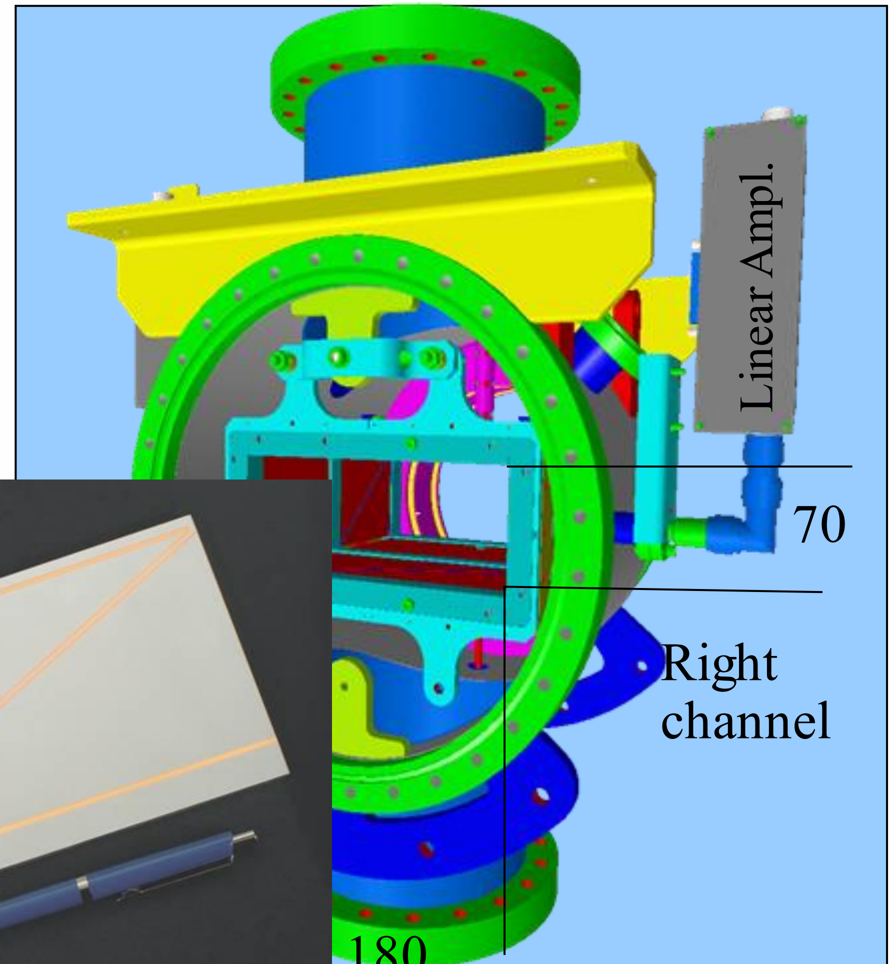
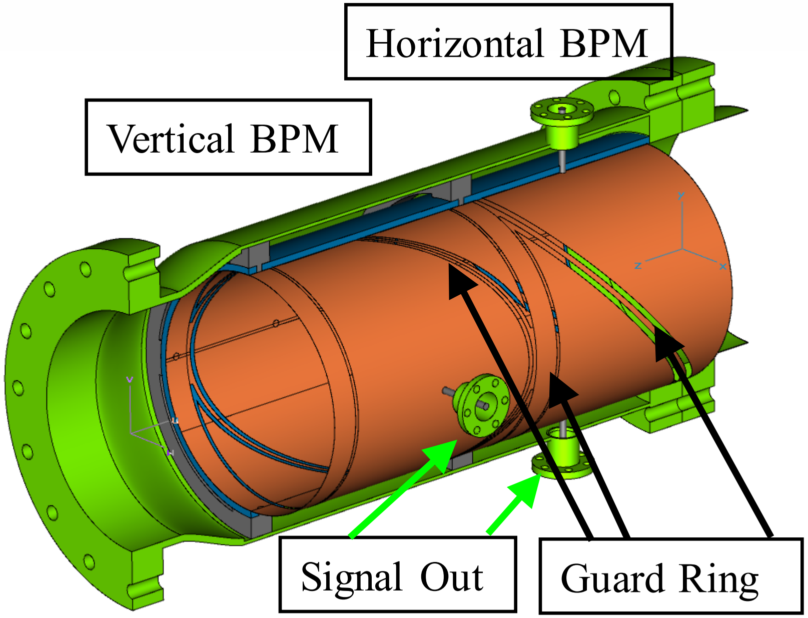




Round type: cut cylinder

Same properties as shoe-box:



Other realization: Full metal plates

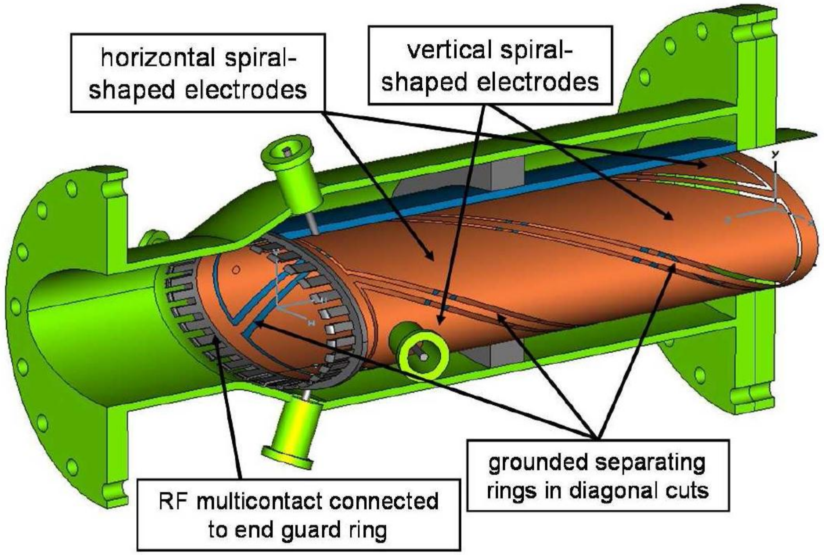
→ No guard rings required

→ but mechanical alignment more difficult

Wounded strips:

Same distance from beam and capacitance for all plates

But horizontal-vertical coupling.



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- **Button BPM for high frequencies → electro-static approach used at most proton LINACs and most electron accelerators**
- Stripline BPM → traveling wave
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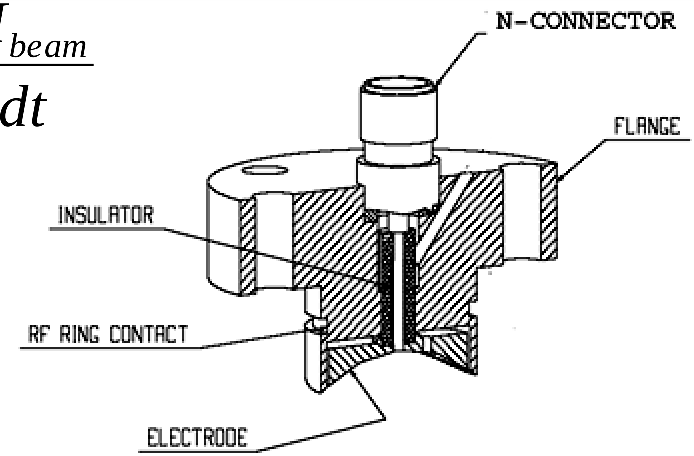
Button BPM Realization

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

→ 50 Ω signal path to prevent reflections

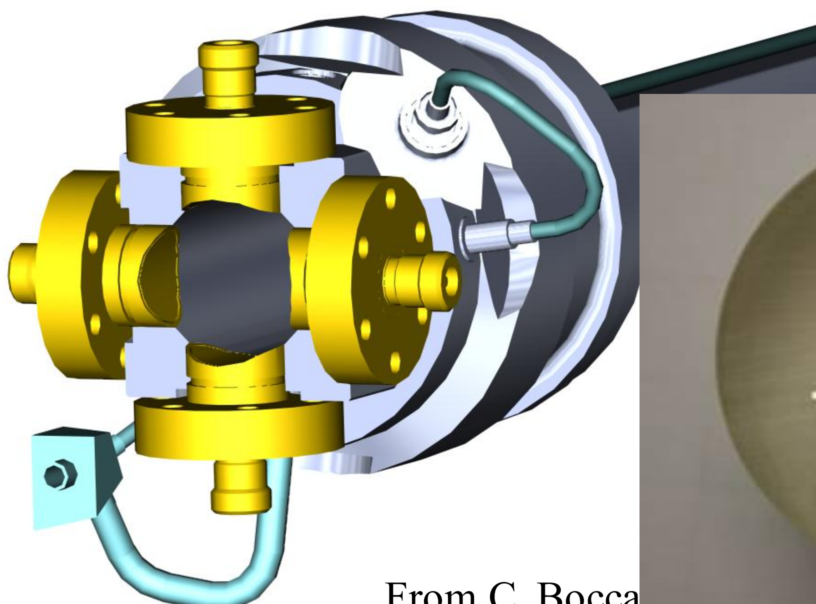
Button BPM with 50 Ω ⇒ $U_{im}(t) \approx R \cdot \frac{A}{\beta c \cdot 2\pi a} \cdot \frac{dI_{beam}}{dt}$



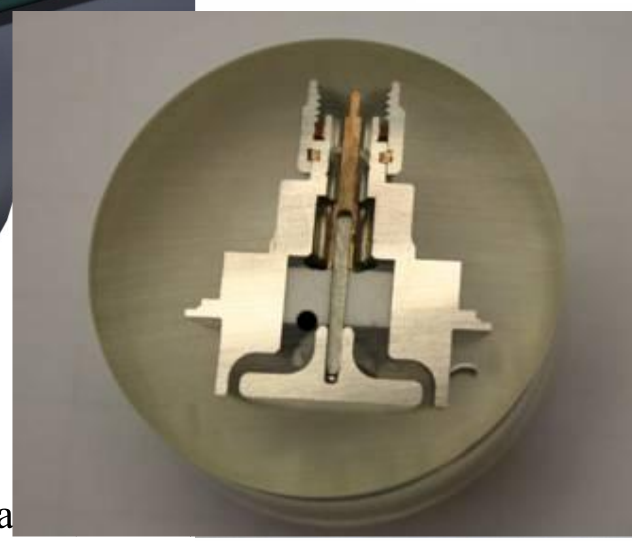
Example: LHC-type inside cryostat:

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

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

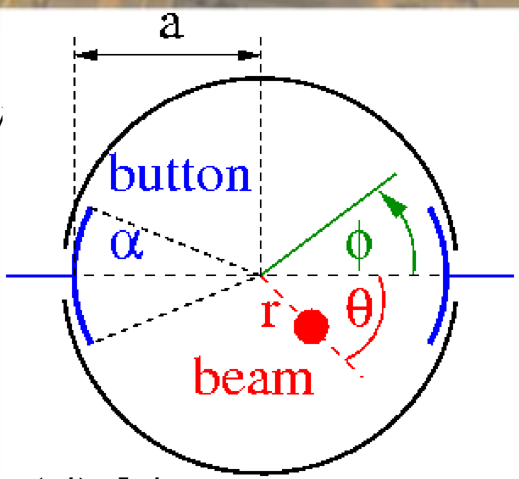


From C. Bocca



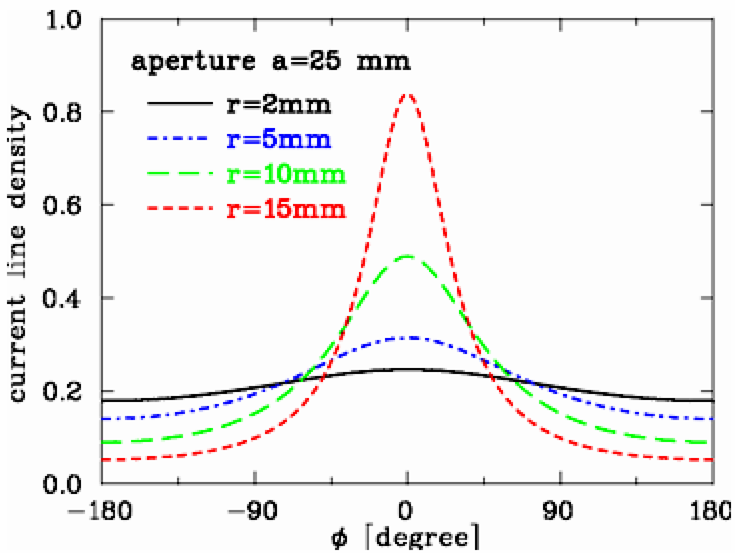
'Proximity effect': larger signal for closer plate

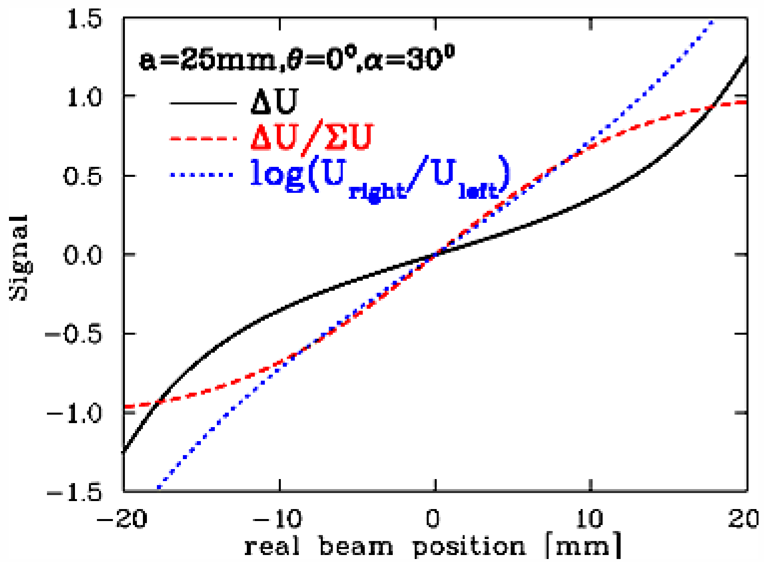
Ideal 2-dim model: Cylindrical pipe → image current density via 'image charge method' for 'pensile' beam:



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

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



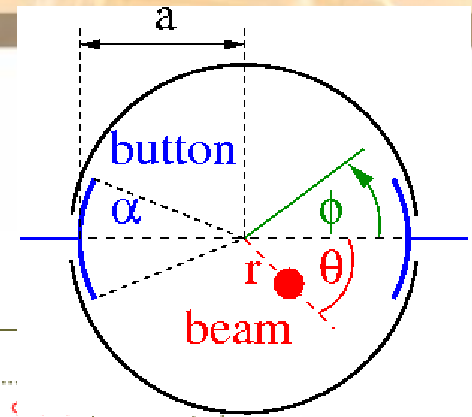


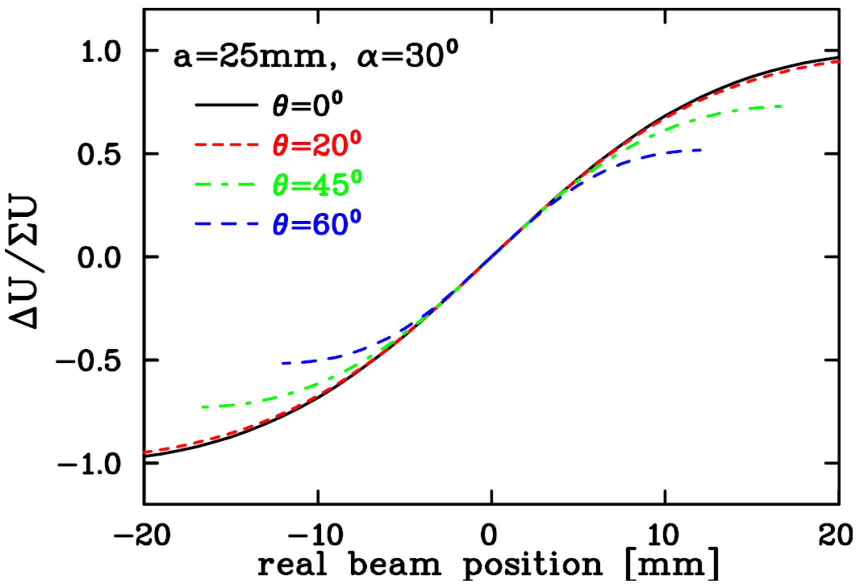
2-dim Model for Button BPM

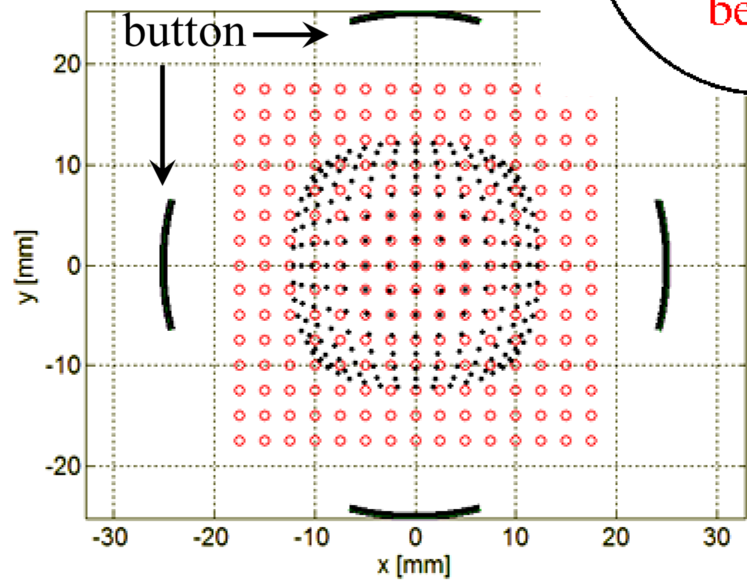
Ideal 2-dim model: Non-linear behavior and hor-vert coupling:

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

This example: center part $\boldsymbol{S}$=7.4%/mm ⇔ $\boldsymbol{k}=1/S$=14mm





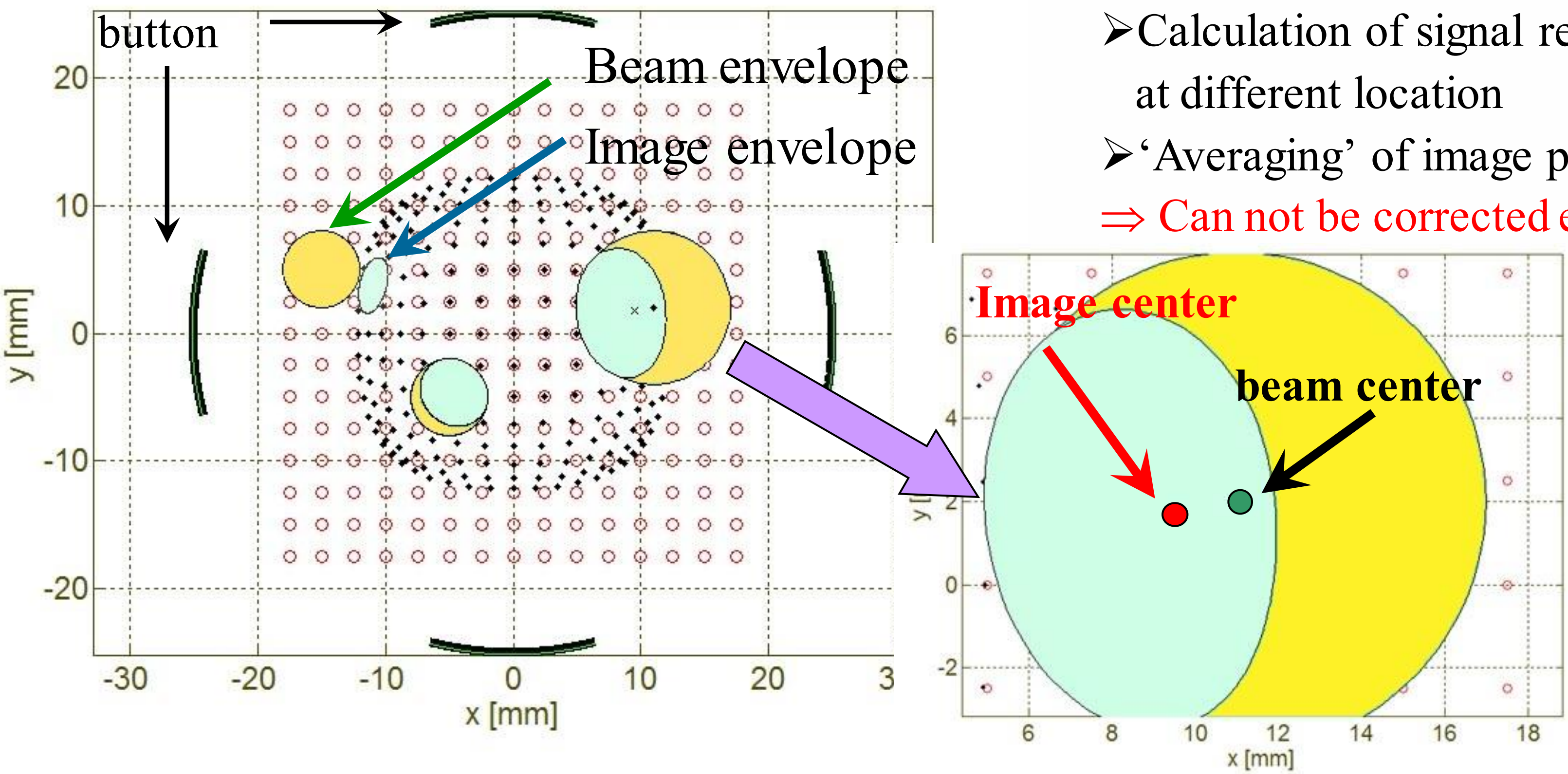


The measurement of U delivers: $x = \frac{1}{S_x} \cdot \frac{\Delta U}{\Sigma U}$ → here $\boldsymbol{S_x = S_x(x, y)}$ i.e. non-linear.

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

Ideal 2-dim model:

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



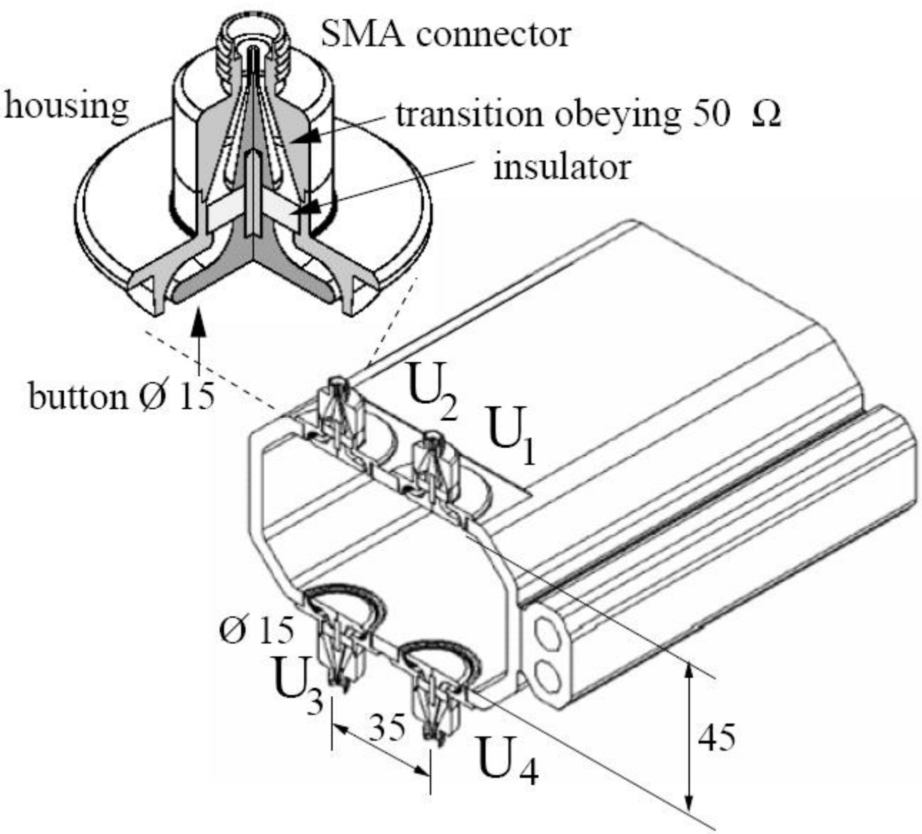
Finite beam size:

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

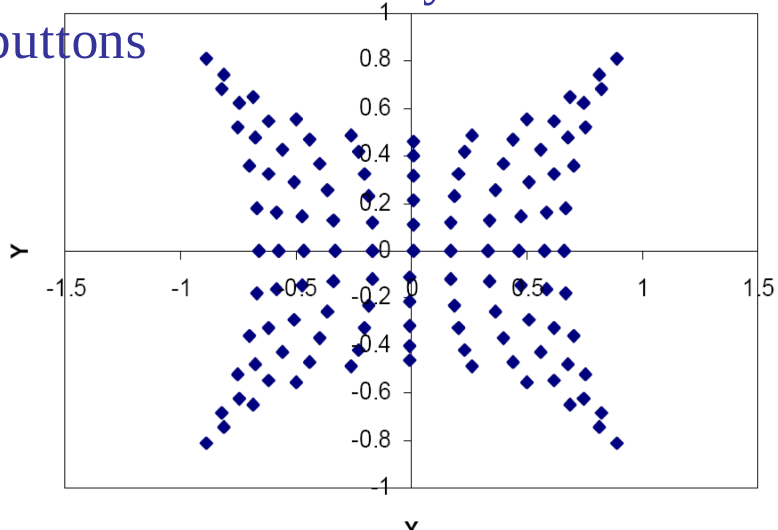
$\Rightarrow$ Can not be corrected easily!

Remark: For most LINACs: Linearity is less important, because beam has to be centered
$\rightarrow$ correction as feed-forward for next macro-pulse.

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



From S. Varnasseri, SESAME, DIPAC 2005



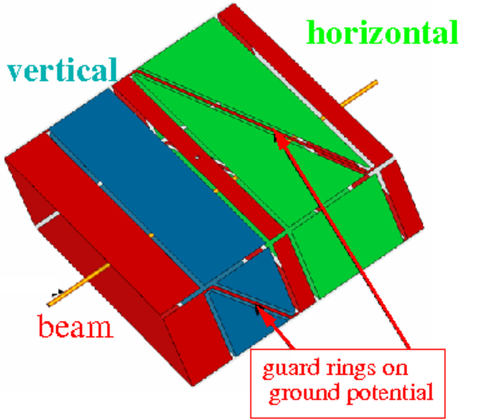
- Beam position swept with 2 mm steps
- Non-linear sensitivity and hor.-vert. coupling
- At center S_x = 8.5%/mm in this case

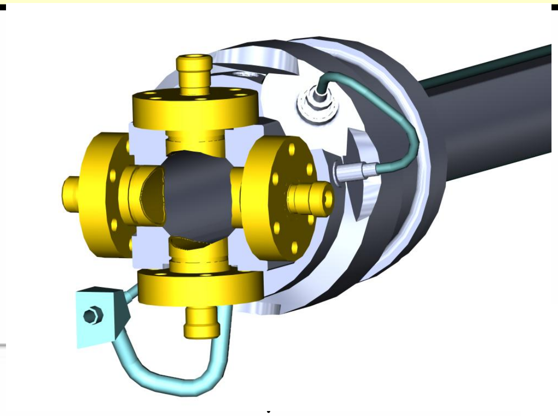
$$\text{horizontal}: x = \frac{1}{S_x} \cdot \frac{(U_1 + U_4) - (U_2 + U_3)}{U_1 + U_2 + U_3 + U_4}$$

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

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}< 100 MHz	All electron acc., proton Linacs, f_{rf}> 100 MHz





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  used at most proton synchrotrons due to linear position reading
- Button BPM for high frequencies → electro-static approach
  used at most proton LINACs and most electron accelerators
- **Stripline BPM → traveling wave**
  used at colliders & some acc. due to clean signal generation
- Cavity BPM → resonator for dipole mode
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DITANET

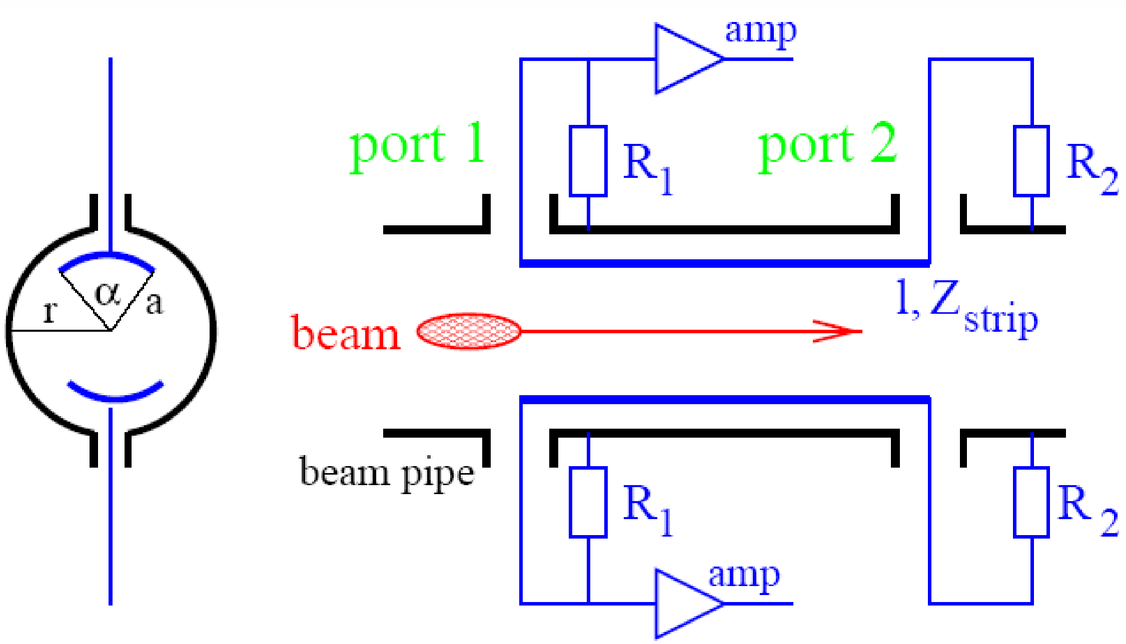
Stripline BPM: General Idea

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

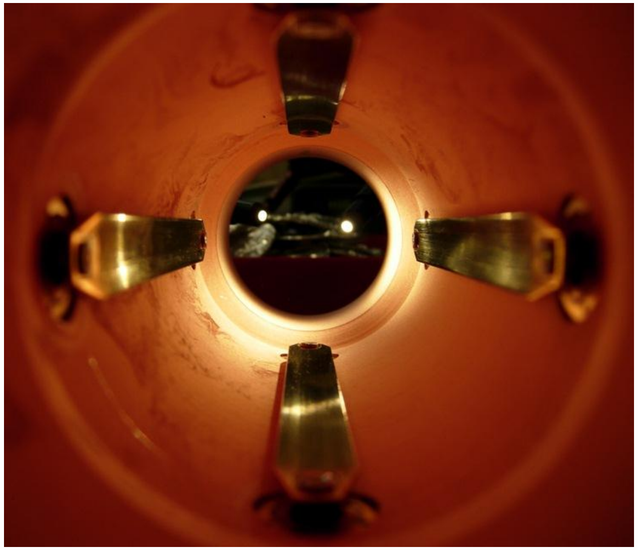
→ Relativistic beam ***β≈1*** ⇒ field of bunches nearly TEM wave

→ 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

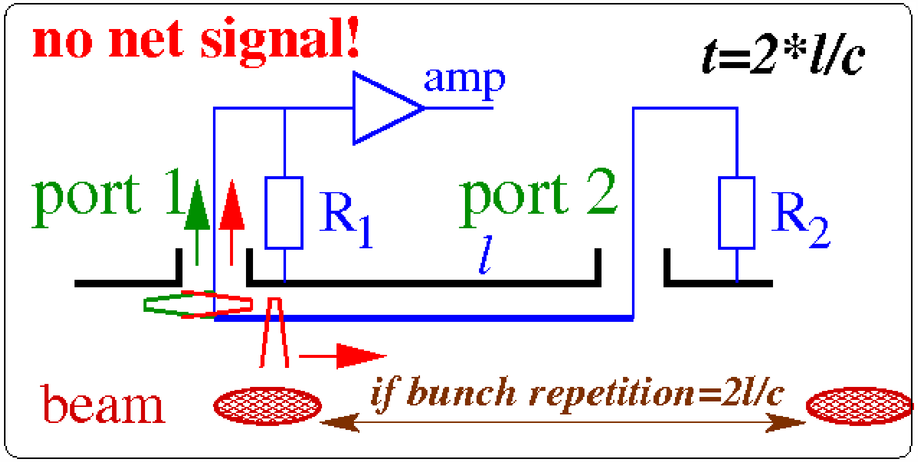
→ ***Assumption:*** $l_{bunch} << l$, $Z_{strip} = R_1 = R_2 = 50\ \Omega$ and $v_{beam} = c_{strip}$

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**

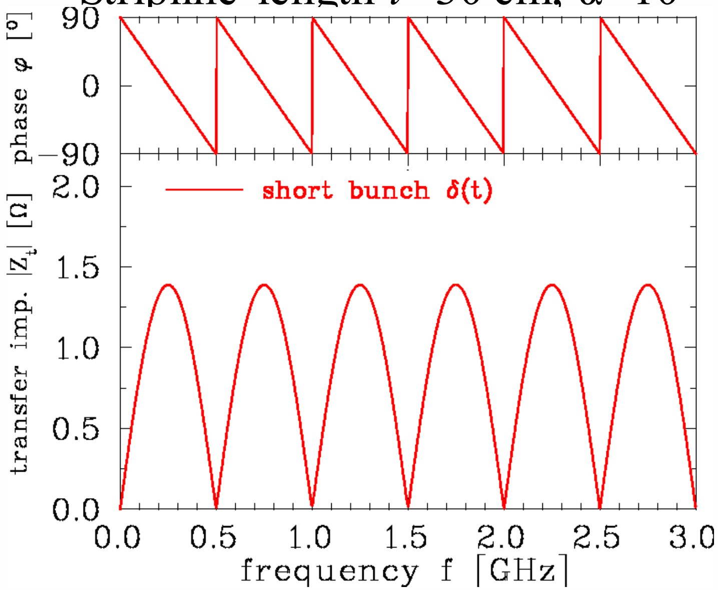
Signal at downstream port 2: Beam induced charges cancels with traveling charge from port 1
⇒ Signal depends on direction ⇔ directional coupler: e.g. can distinguish between e^- and e^+ in collider

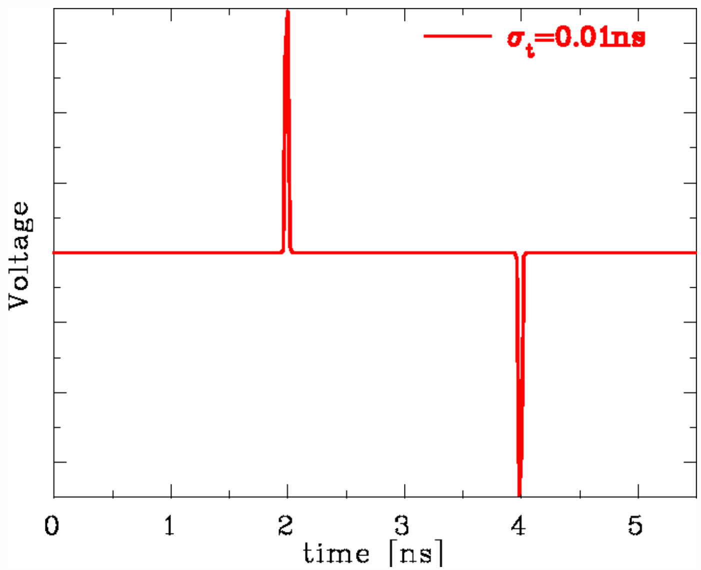
Stripline BPM: Transfer Impedance

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

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

Stripline length l=30 cm, α=10[0]





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

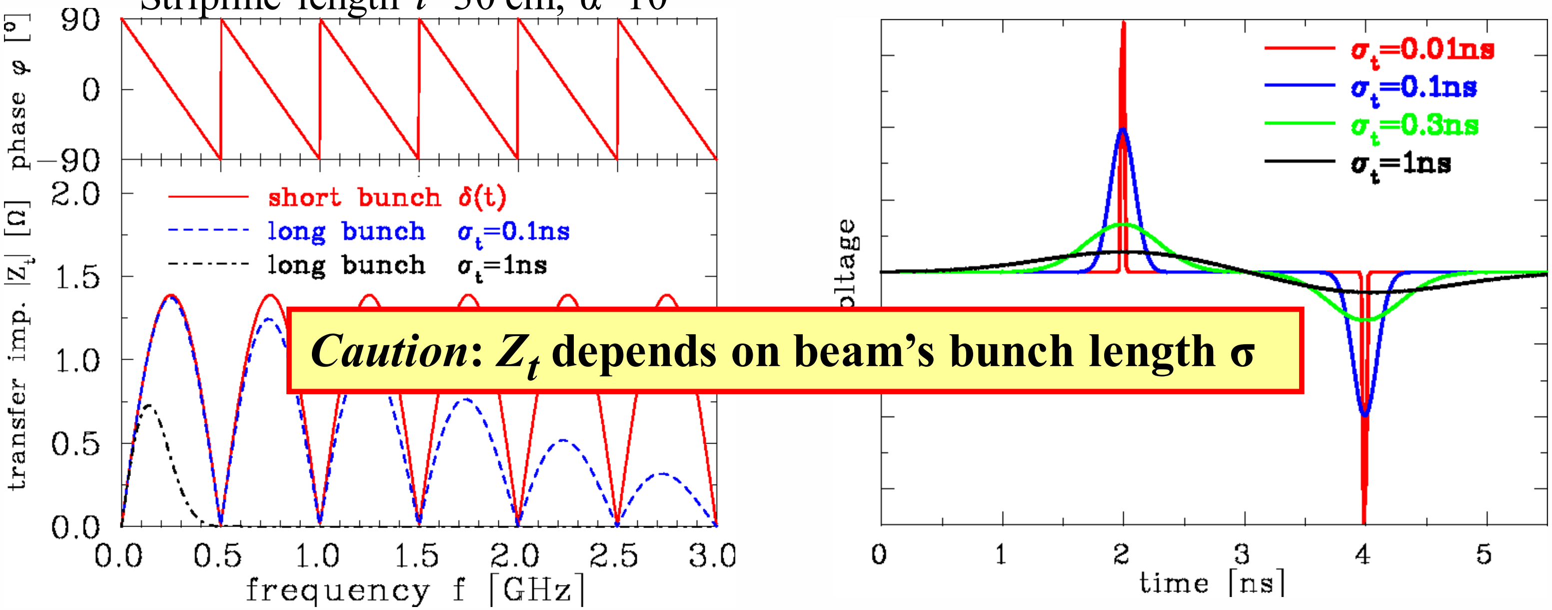
Stripline BPM: Finite Bunch Length

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]



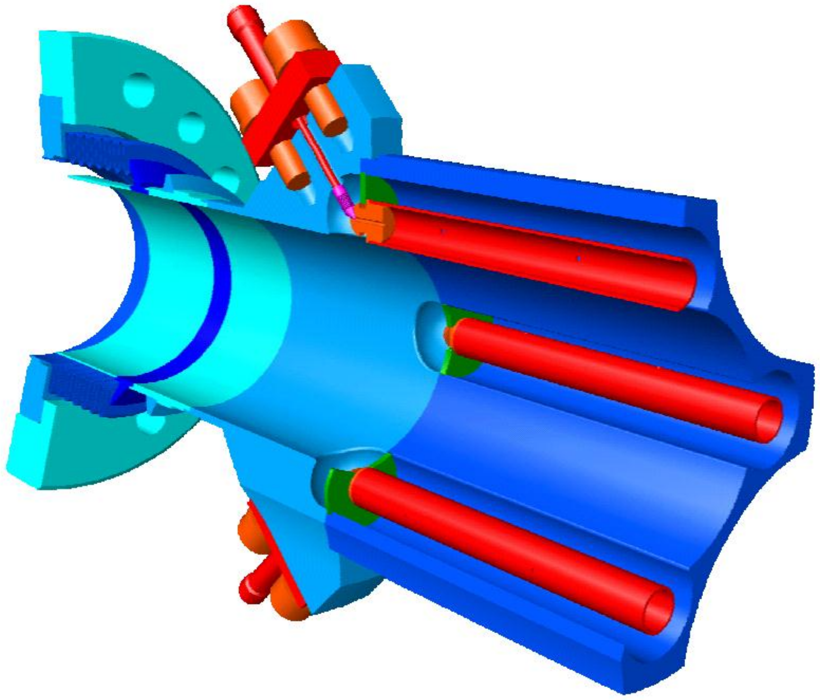
Caution: Z_t depends on beam's bunch length σ

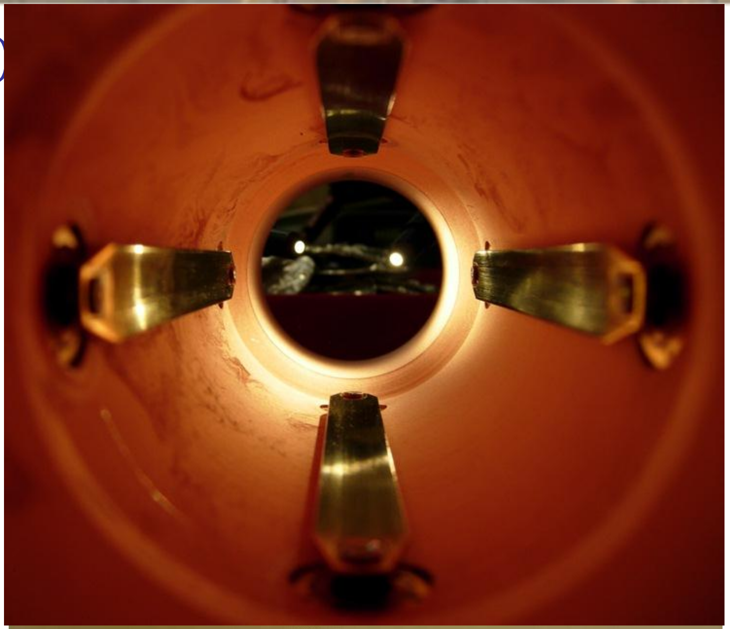
- $Z_t(\omega)$ decreases for higher frequencies
- If total bunch is too long $\pm 3\sigma_t > l$ destructive interference leads to signal damping

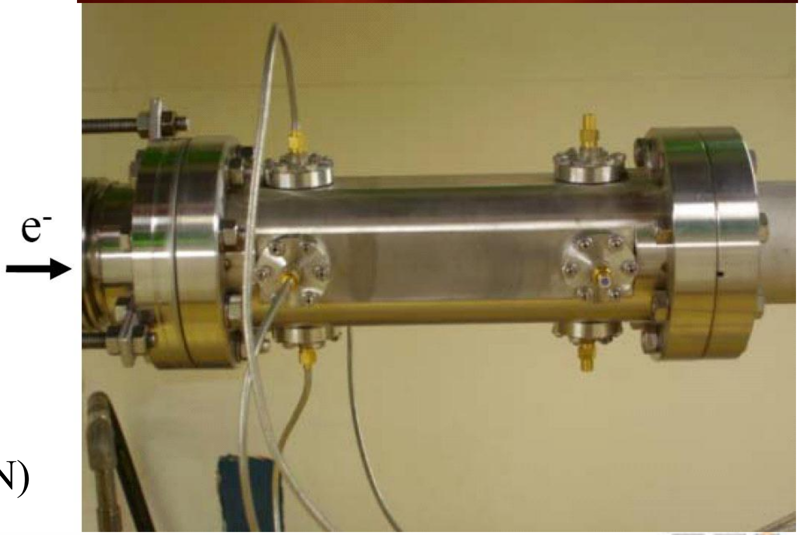
  Cure: length of stripline has to be matched to bunch length

20 cm stripline BPM at TTF2 (chamber ∅34mm)

And 12 cm LHC type:





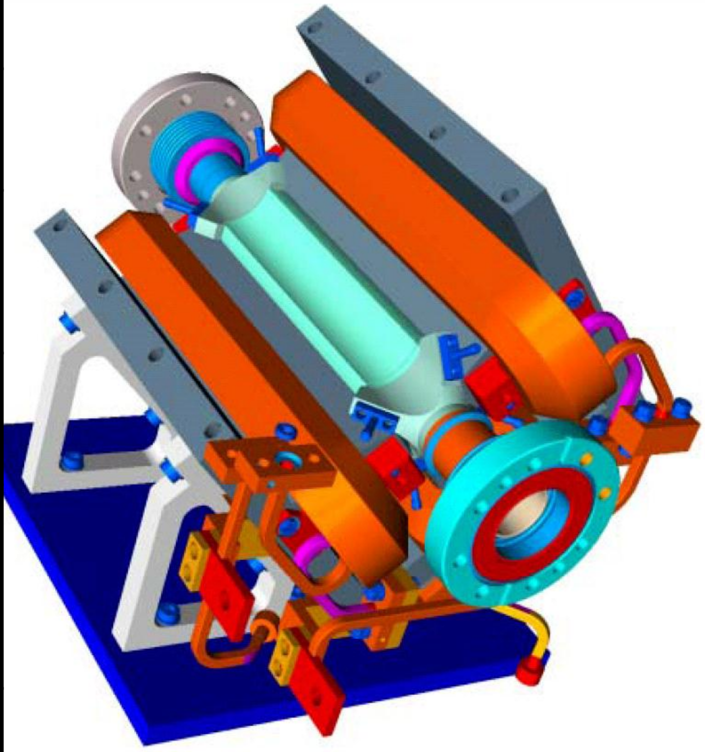


From . S. Wilkins, D. Nölle (DESY), C. Boccard (CERN)

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)

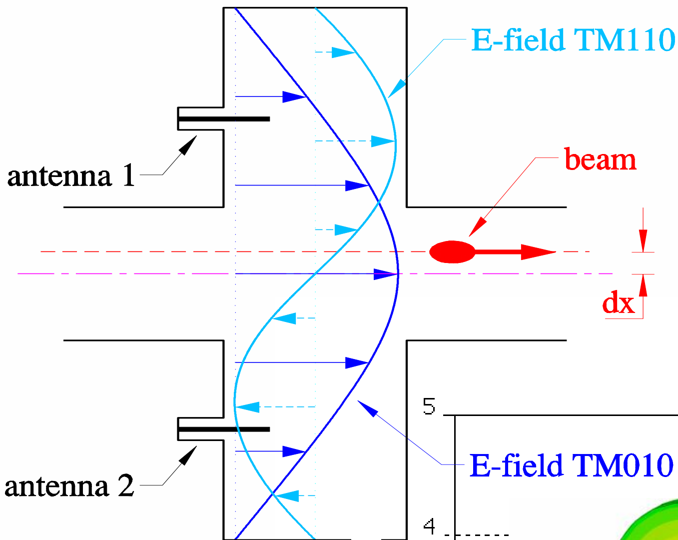
Introduction on Pick-up Types and their Suitability for various Applications

Outline:

- Signal generation → transfer impedance
- Capacitive 'Shoe box' BPM = 'linear cut' BPM → electro-static approach
  used at most proton synchrotrons due to linear position reading
- Button BPM for high frequencies → electro-static approach
  used at most proton LINACs and most electron accelerators
- Stripline BPM → traveling wave
  used at colliders & some acc. due to clean signal generation
- **Cavity BPM → resonator for dipole mode**
  used at FELs due to high resolution for short pulses
- **Summary**

Cavity BPM: Principle

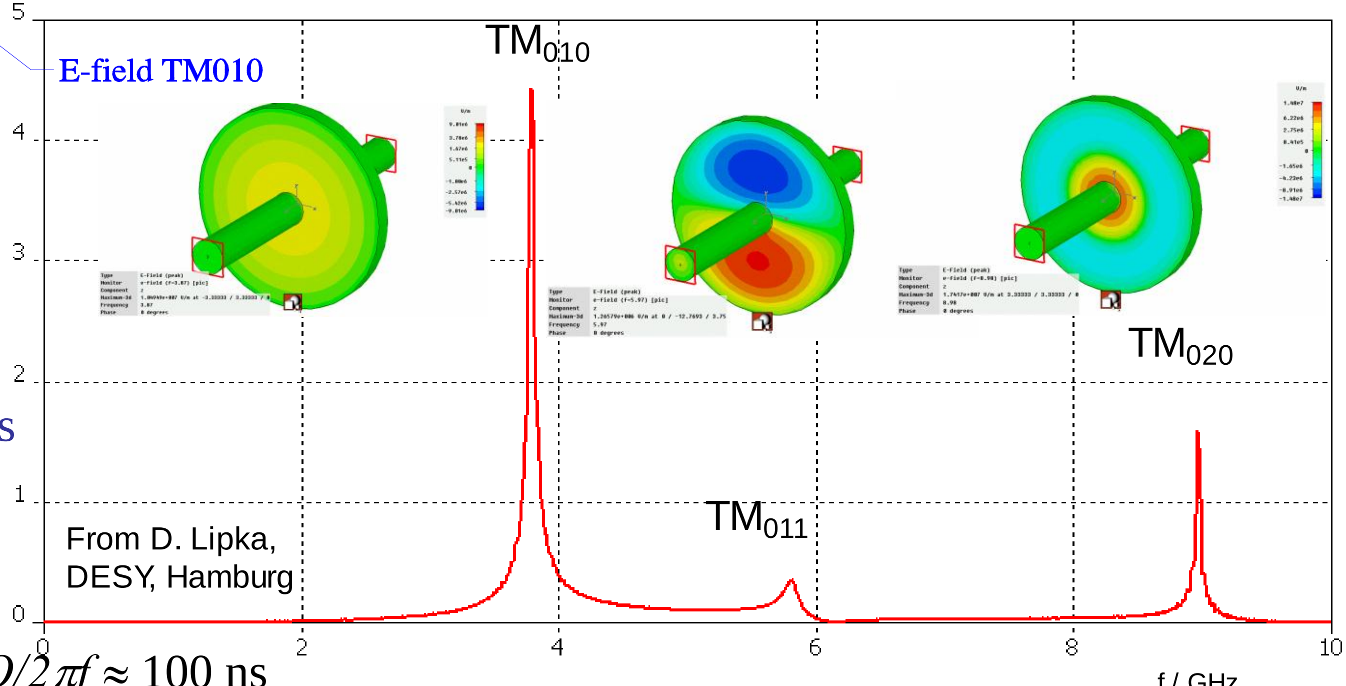
High resolution on $t < 1$ µs time scale can be achieved by excitation of a dipole mode:



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

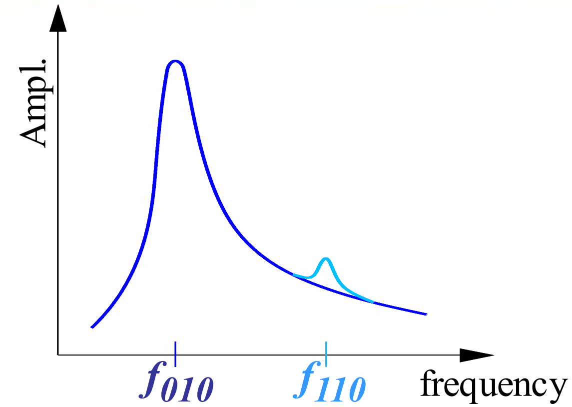
Basic consideration for detection of eigen-frequency amplitudes:

Dipole mode f_{110} separated from monopole mode

due 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} mono-pole mode



FNAL realization:

Cavity: ∅ 113 mm

Gap 15 mm

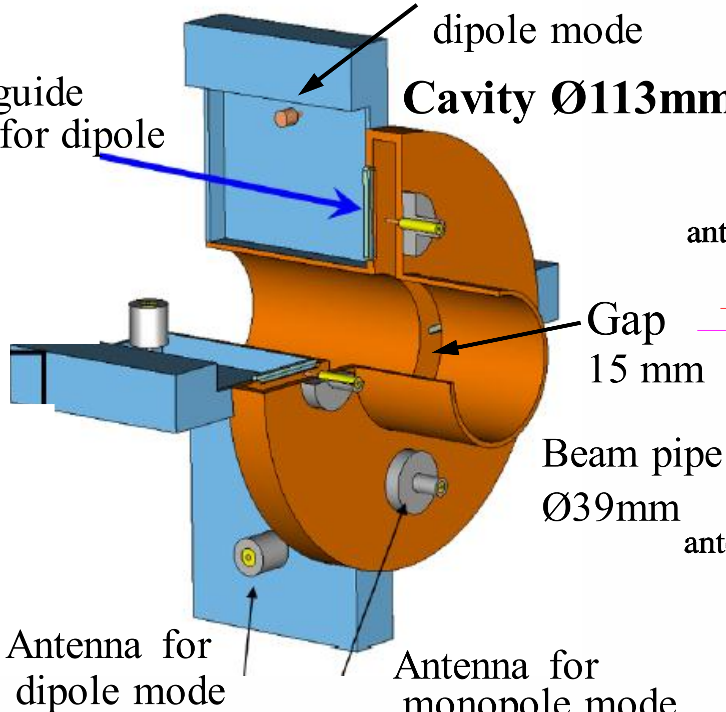
Mono. f_{010}=1.1GHz

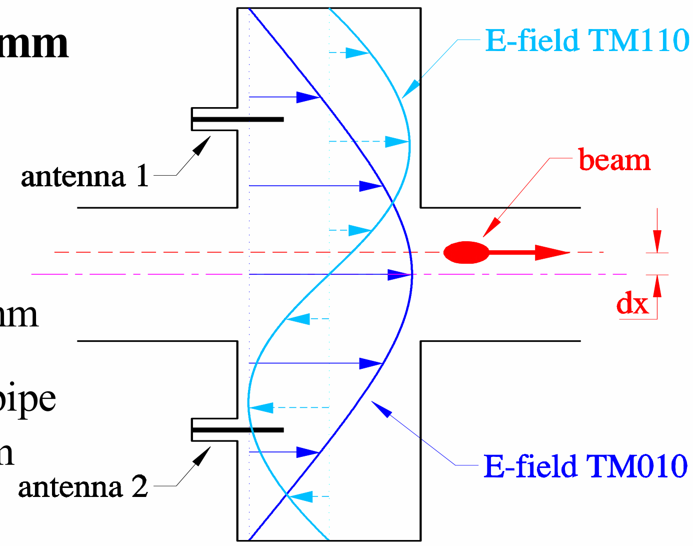
Dipole. f_{110}=1.5GHz

$Q_{load} \approx 600$

With comparable BPM

⇒0.1 µm resolution within 1 µs

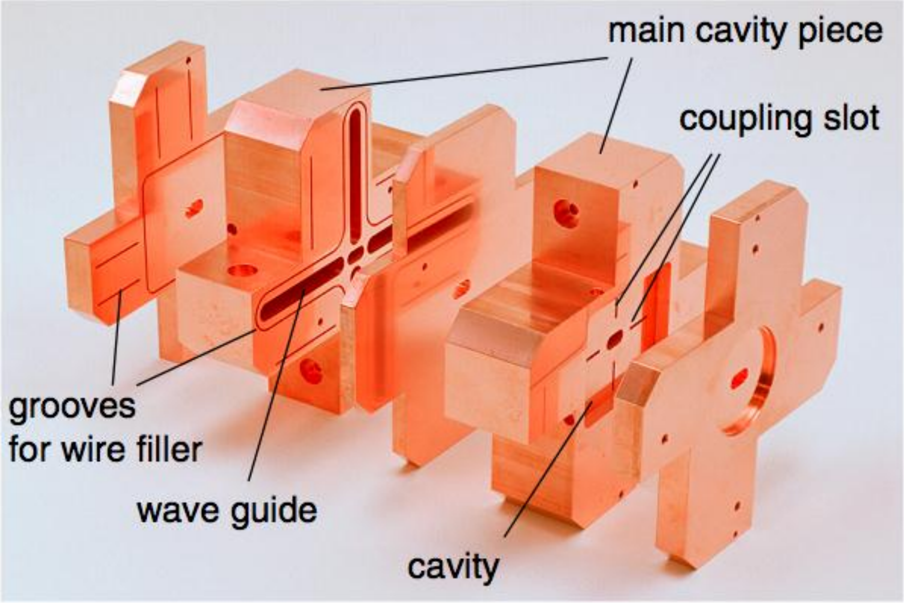




From M. Wendt (FNAL)

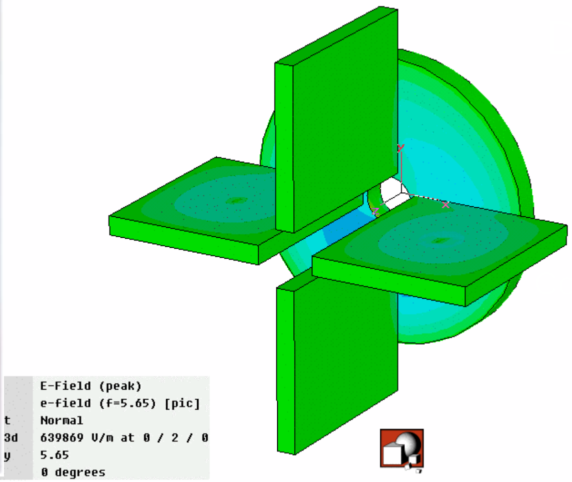
Cavity BPM: Suppression of monopole Mode

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 2 nm in a 6 × 12 mm diameter beam pipe
- Achieved World Record so far: **resolution** of 8.7 nm at ATF2 (KEK, Japan)

Summary: 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 large beams	Complex mechanics Capacitive coupling between plates
Button	p-Linacs, all e^- acc.	Short bunches 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' signals Large Signal	Complex 50 Ω matching Complex mechanics
Cavity	e^- Linacs (e.g. FEL)	Short bunches	Very sensitive	Very complex, high frequency

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