Beam Position Monitor:
Detector Principle, Hardware and Electronics

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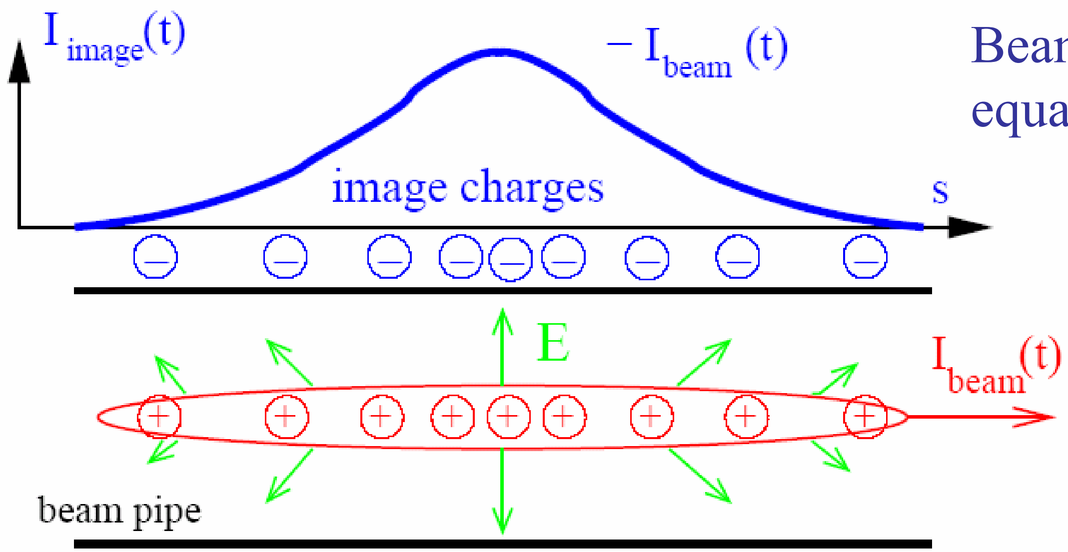
Outline:

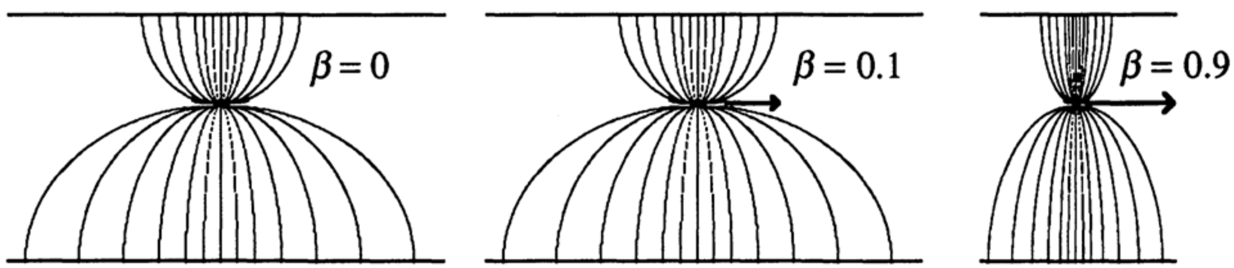
- *Signal generation $\rightarrow$ transfer impedance*
- *Consideration for capacitive shoe box BPM*
- *Consideration for capacitive button BPM*
- *Other BPM principles: stripline $\rightarrow$ traveling wave*
  inductive $\rightarrow$ wall current
  cavity $\rightarrow$ resonator for dipole mode
- *Electronics for position evaluation*
- *Some examples for position evaluation and other applications*
- *Summary*

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: $E_{\perp,lab}(t) = \gamma \cdot E_{\perp,rest}(t)$



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:

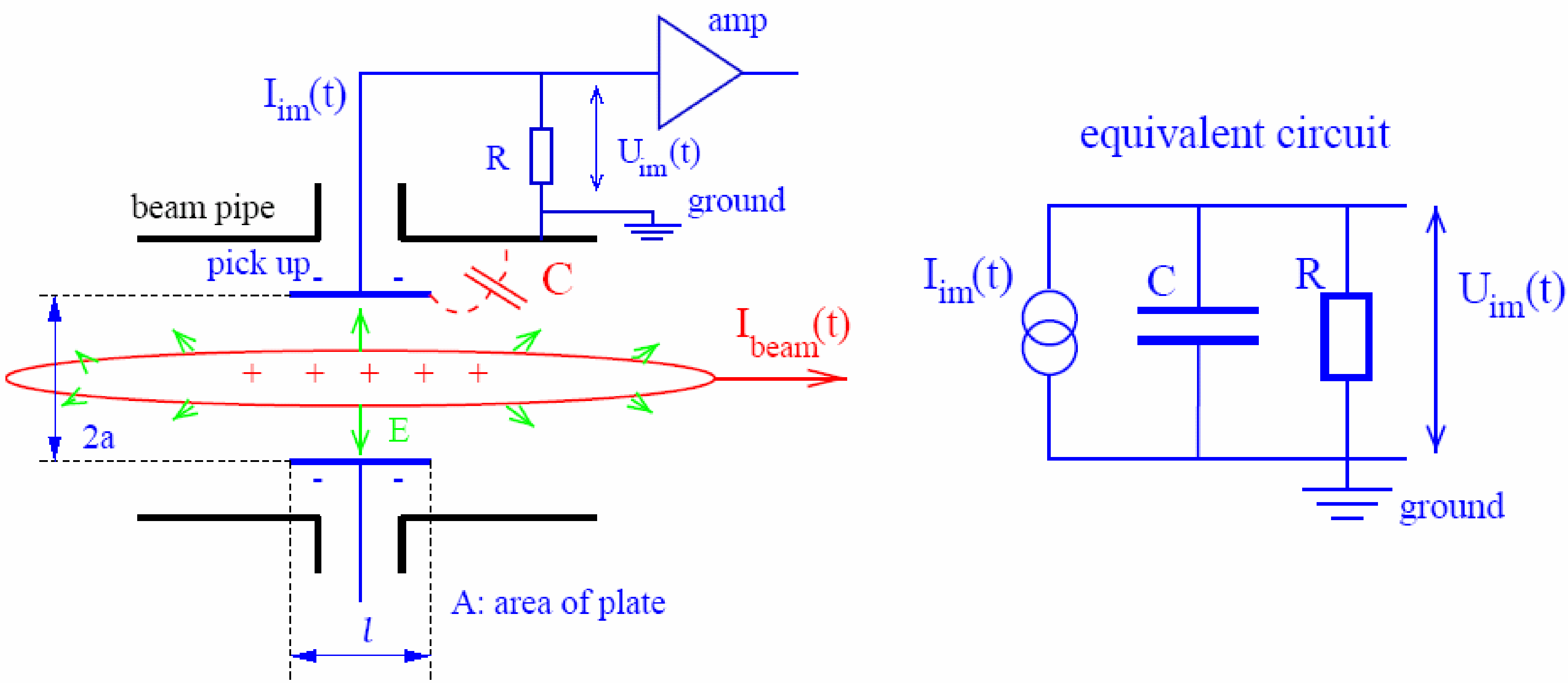
1. The center of the beam

- Closed orbit
  i.e. central orbit averaged over a period much longer than a betatron oscillation
- Bunch 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 → precise (and slow) closed orbit correction

2. Longitudinal bunch shapes

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

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:

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

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***: $\boldsymbol{U_{im}(\omega) = R \cdot I_{im}(\omega) = Z_t(\omega, \beta) \cdot I_{beam}(\omega)}$.

Capacitive BPM:

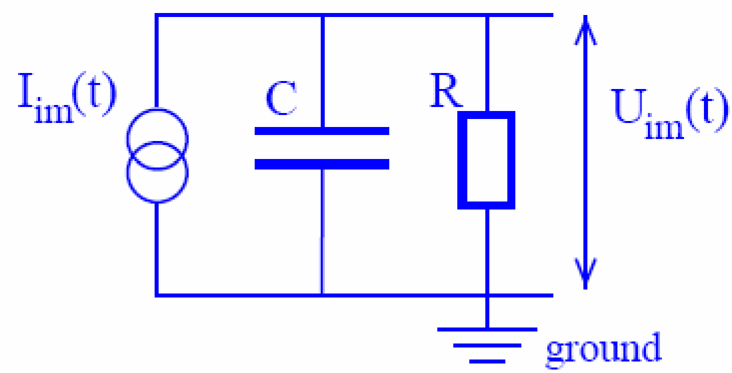
- The pick-up capacitance C:
  plate ↔ vacuum-pipe and cable.
- The amplifier with input resistor R.
- The beam is a high-impedance current source:

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

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

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

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

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

The high-pass characteristic for typical synchrotron BPM:

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

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

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

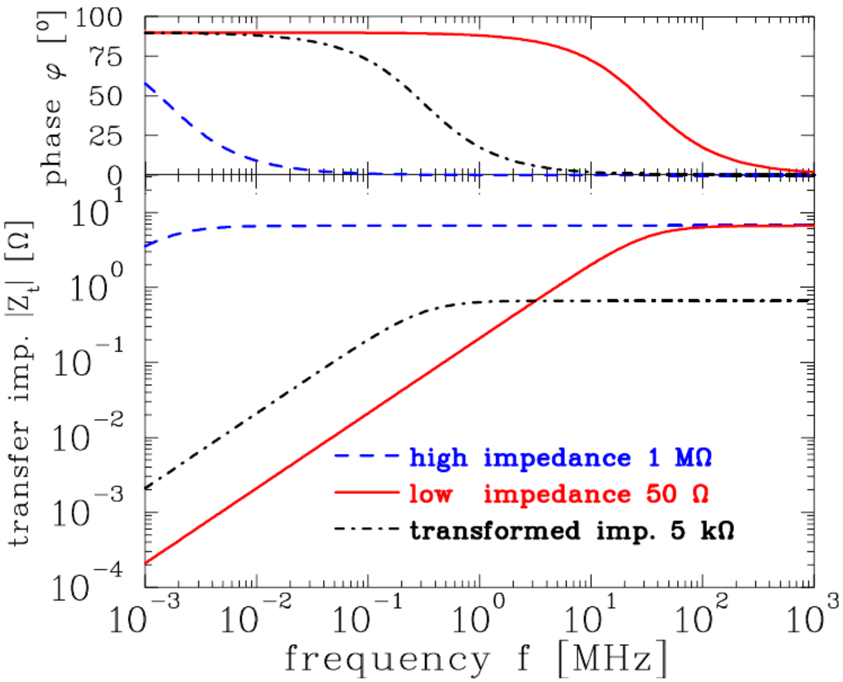
Parameter for shoe-box BPM:

C=100pF, l=10cm, β=50%

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

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

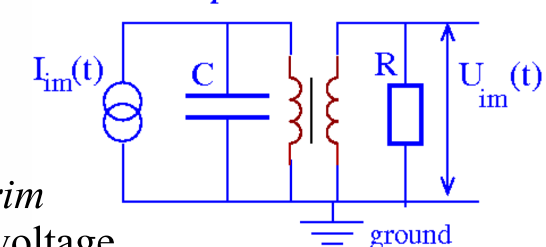
for R=1 MΩ $\Rightarrow f_{cut}$= 1.6 kHz



Large signal strength → **high impedance**

Smooth signal transmission → **50 Ω**

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

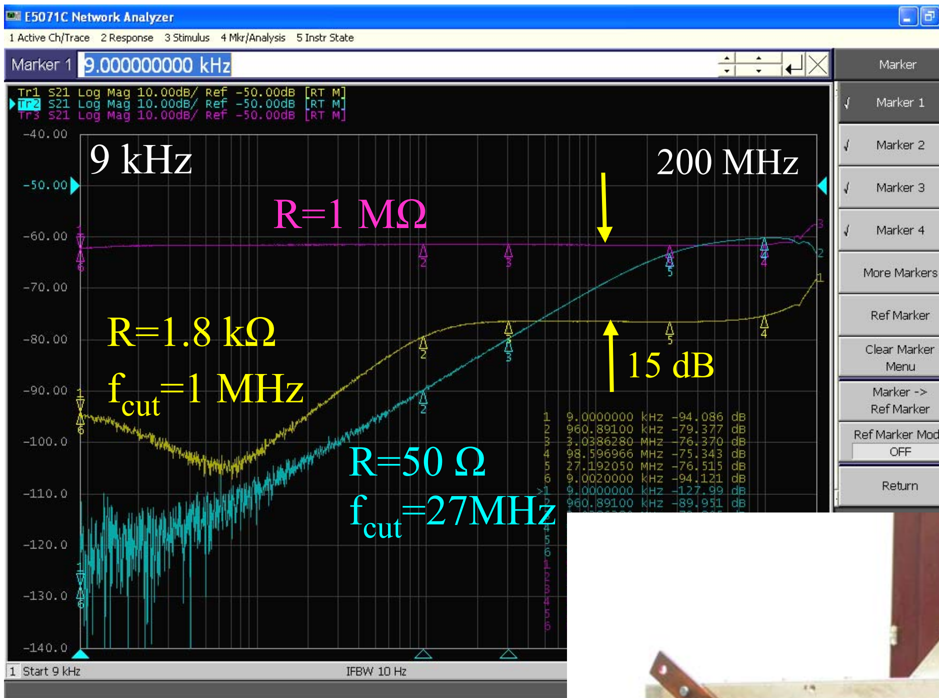


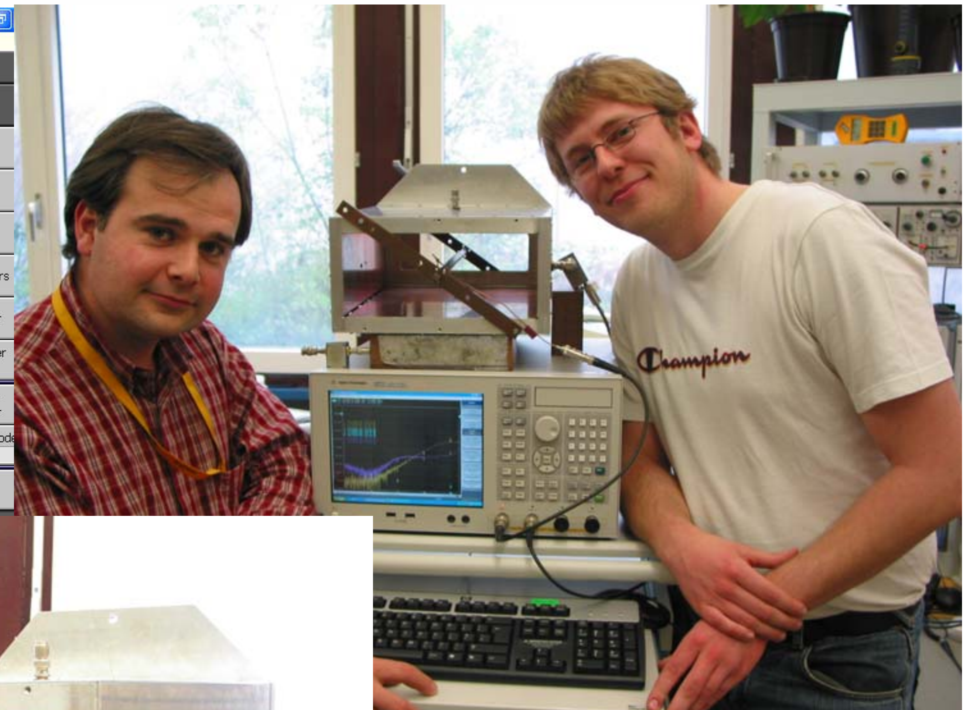
Impedance $Z_{prim}=(N_{prim}/N_{sec})^2\cdot Z_{sec}$ voltage $U_{im}=N_{sec}/N_{prim}\cdot U_{prim}$

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

Transfer Impedance Measurement

With a network analyzer and an antenna the BPM properties can be determined.





Test BPM of 250x 80 mm^2 using a stripline antenna of 300 MHz bandwidth

Signal Shape for capacitive BPMs: differentiated ↔ proportional

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

- ***High frequency range $\omega \gg \omega_{cut}$:***

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

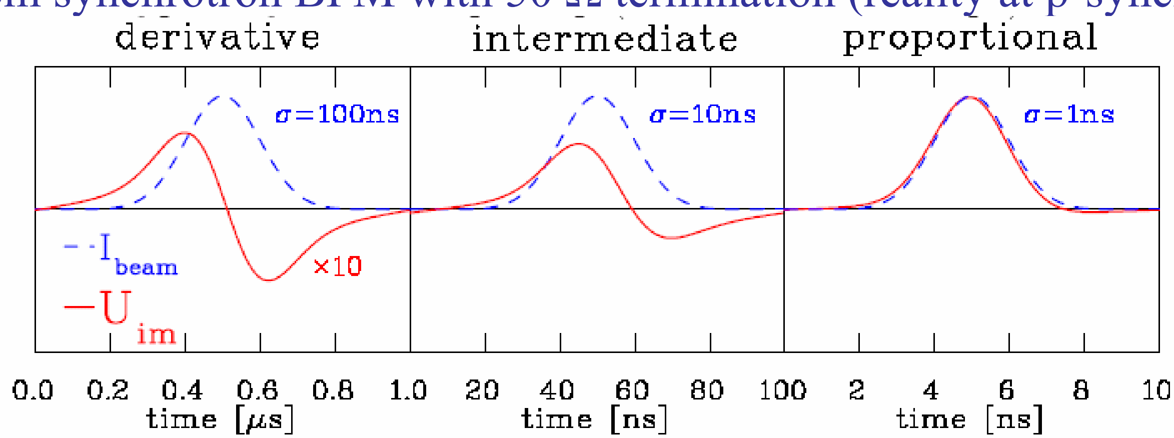
$\Rightarrow$ **direct image** of the bunch. Signal strength $Z_t \; \alpha \; A/C$ i.e. nearly independent on length

- ***Low frequency range $\omega \ll \omega_{cut}$:***

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

$\Rightarrow$ **derivative** of bunch, single strength $Z_t \; \alpha$ 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

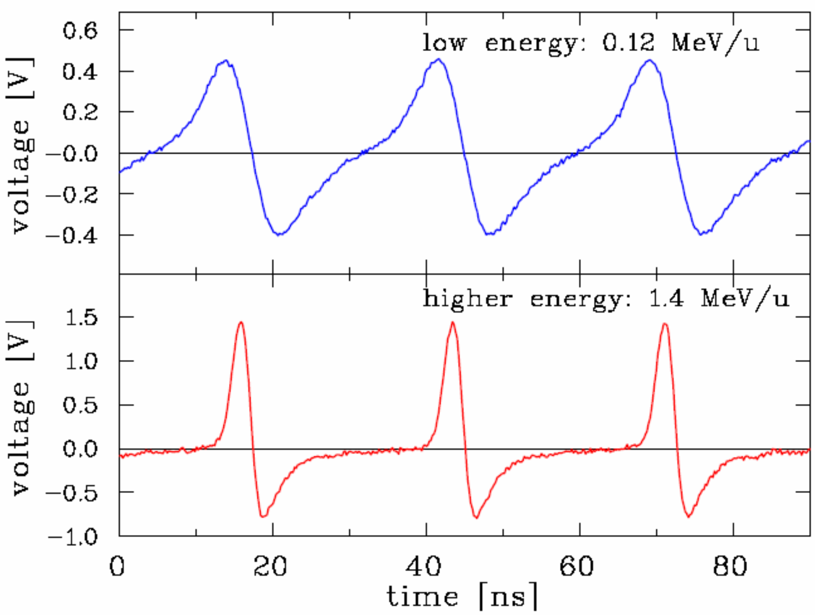
Proton LINAC, e⁻-LINAC&synchtrotron:

100 MHz < f_{rf} < 1 GHz typically

R=50 Ω processing to reach bandwidth

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

Example: 36 MHz GSI ion LINAC



Proton synchtrotron:

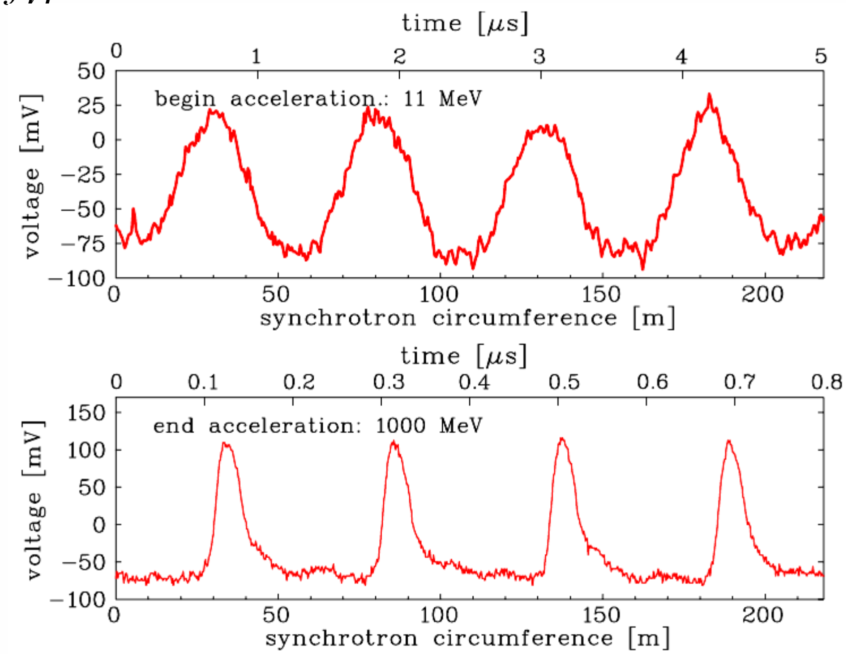
1 MHz < f_{rf} < 30 MHz typically

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

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

Example: non-relativistic GSI synchrotron

f_{rf}: 0.8 MHz → 5 MHz



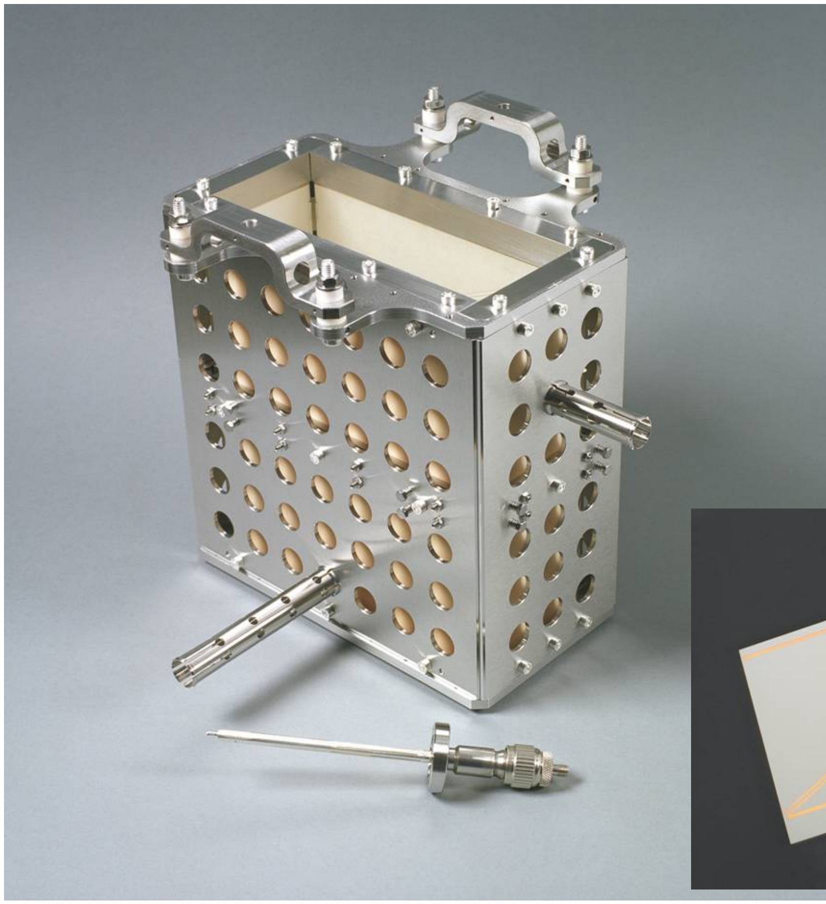
Remark: During acceleration the bunching-factor is increased: 'adiabatic damping'.

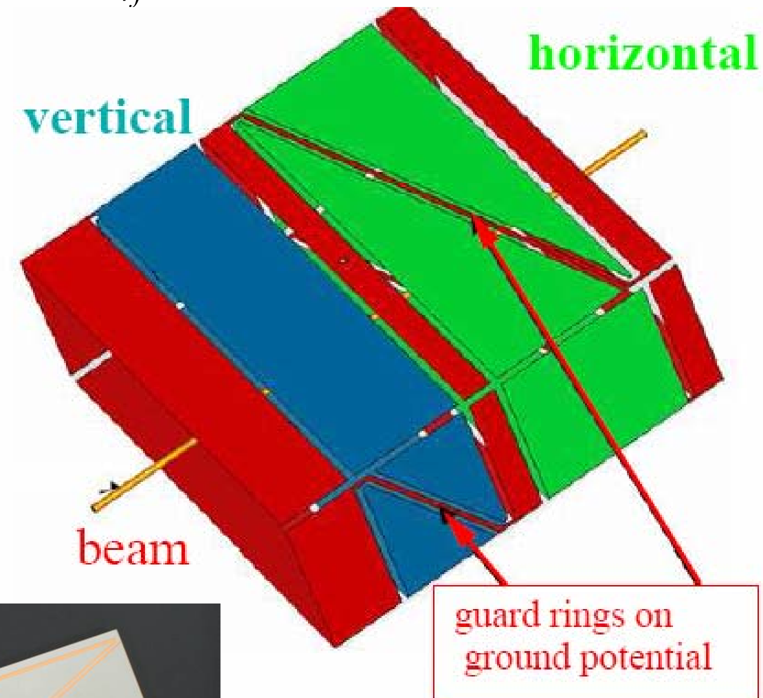
Example Shoe-box BPMs

Shoe-box BPMs used at low β proton & ion synchrotron for 1MHz < f_{rf} < 10MHz.

Example: HIT cancer therapy synchrotron 0.8 MHz < f_{rf} < 5 MHz

Aperture 180x70 mm^2

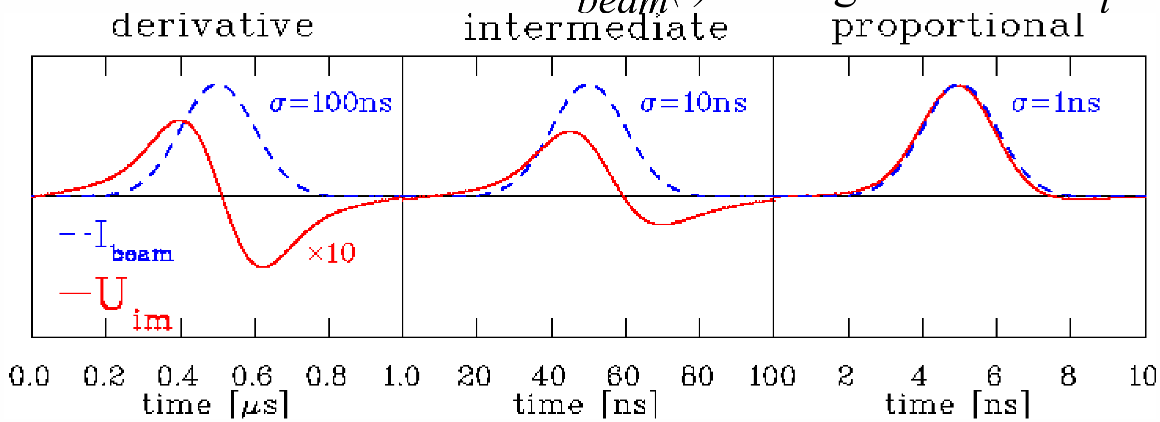




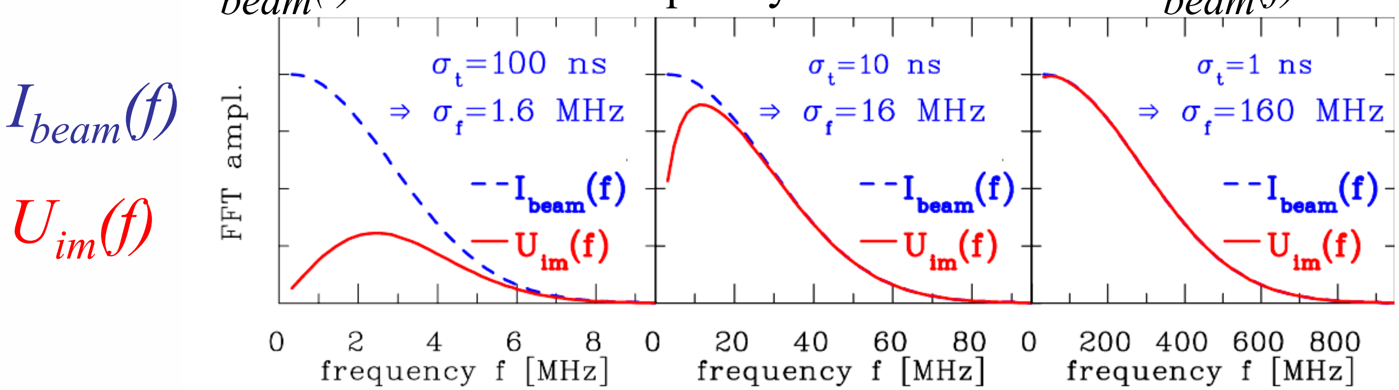
Calculation of Signal Shape: Single Bunch

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

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



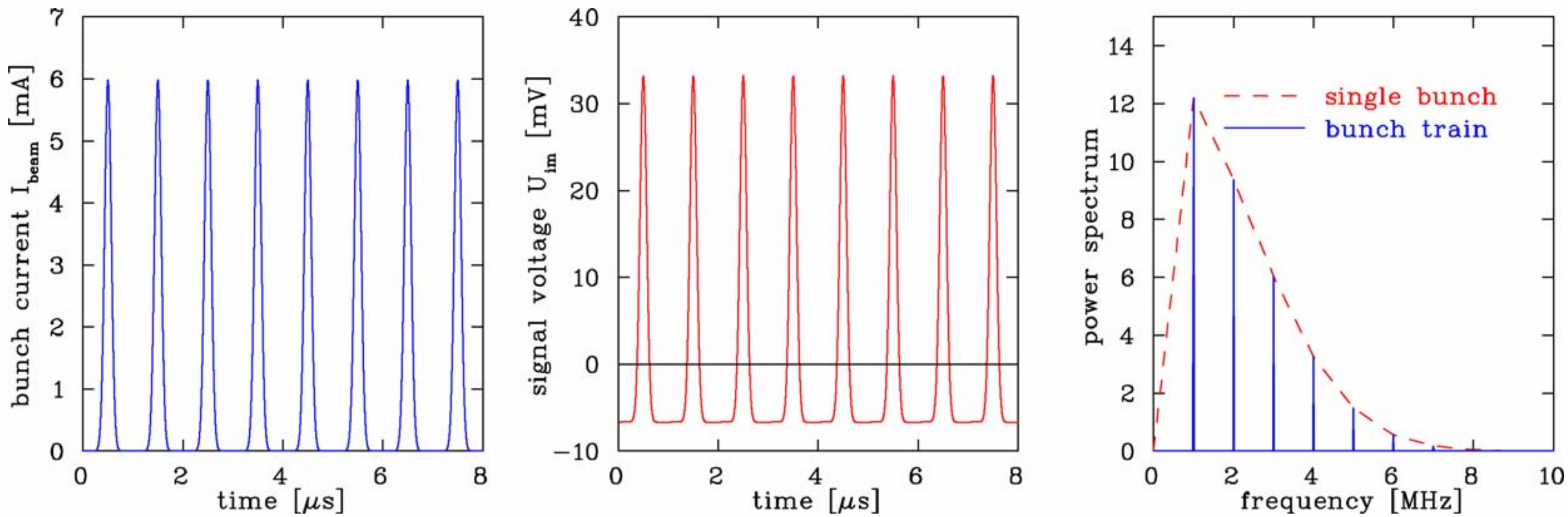
2. FFT of $I_{beam}(t)$ leads to the frequency domain Gaussian $I_{beam}(f)$ with $\sigma_f=(2\pi\sigma_t)^{-1}$



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 $U_{im}(t)$

Example for low energy proton synchrotron: Train of bunches with R=1 MΩ



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=1 MΩ ⇒ f_{cut}=2kHz, Z_t=5Ω all buckets filled, no amp

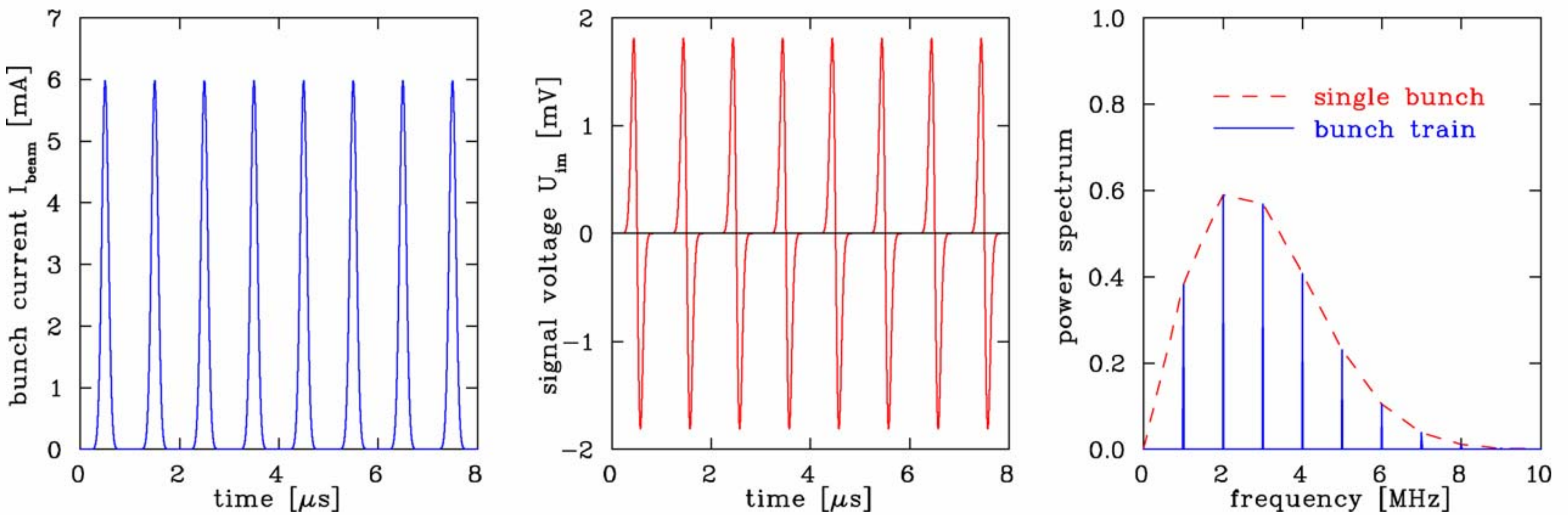
C=100pF, l=10cm, β=50%, σ_t=100 ns ⇒ σ_l=15m

- 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 ⇒ Bandwidth ≈100MHz=10·f_{rf} for broadband observation

Calculation of Signal Shape: Bunch Train

Train of bunches with R=50 Ω termination:



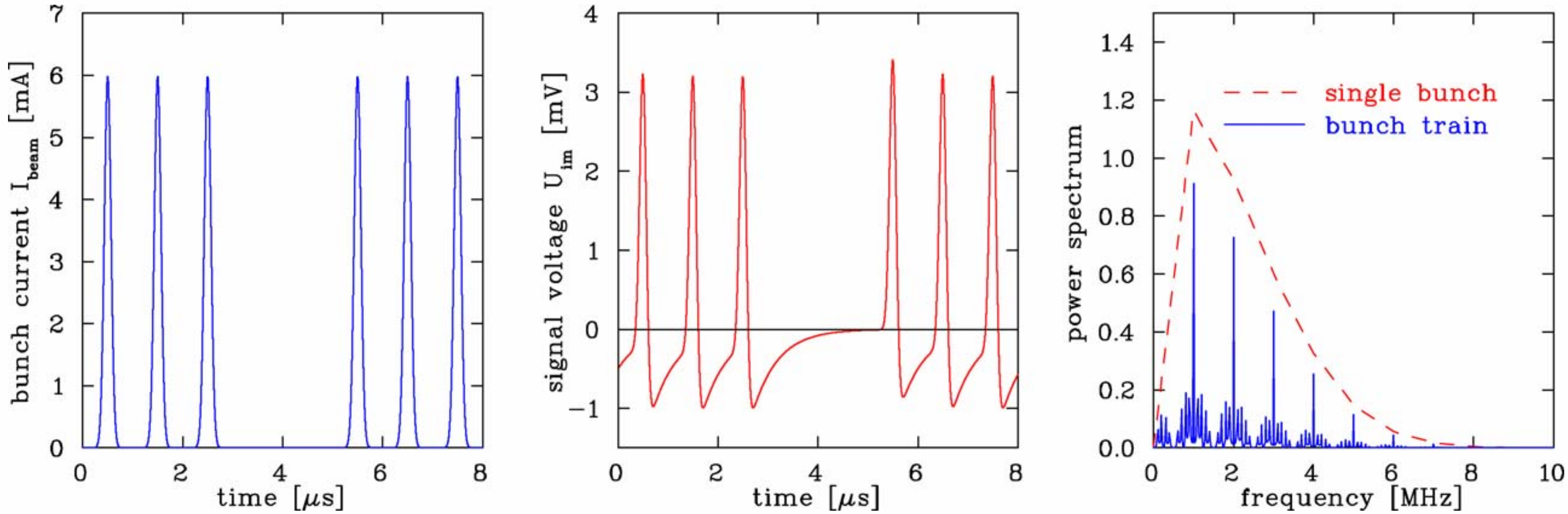
Parameter: R=50 Ω ⇒ f_{cut}=32 MHz, all buckets filled, no amp

C=100pF, l=10cm, β=50%, σ_t=100 ns

- Low frequency cut-off due to f_{cut}=32 MHz
- Differentiated bunches, 15 fold lower amplitude
- Modified Fourier spectrum with low amplitude value, maximum shift to higher frequencies

Calculation of Signal Shape: Bunch Train with empty Buckets

Synchrotron during filling: Empty buckets, R=5 kΩ termination:



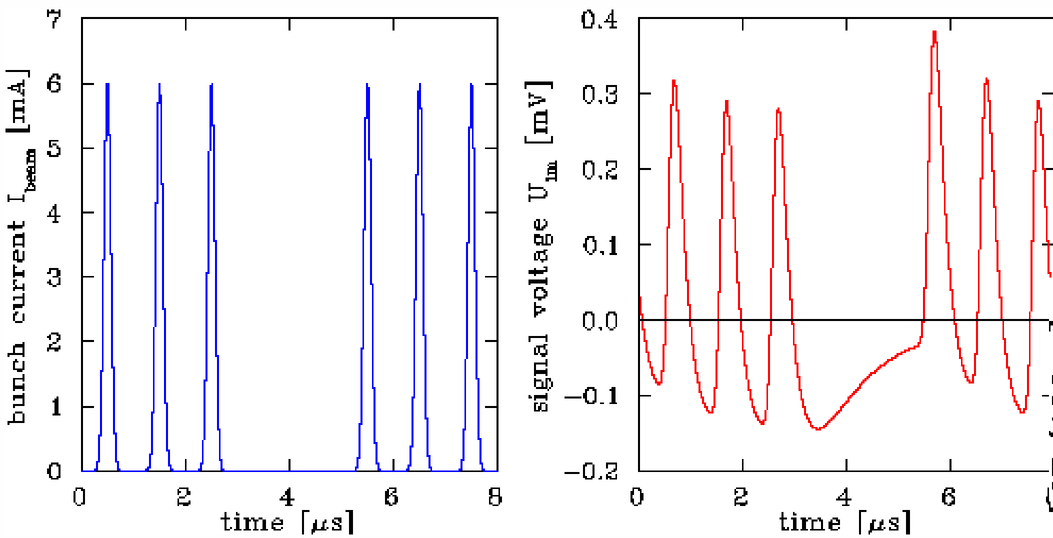
Parameter: R=5 kΩ ⇒ f_{cut}=320 kHz, 2 empty buckets

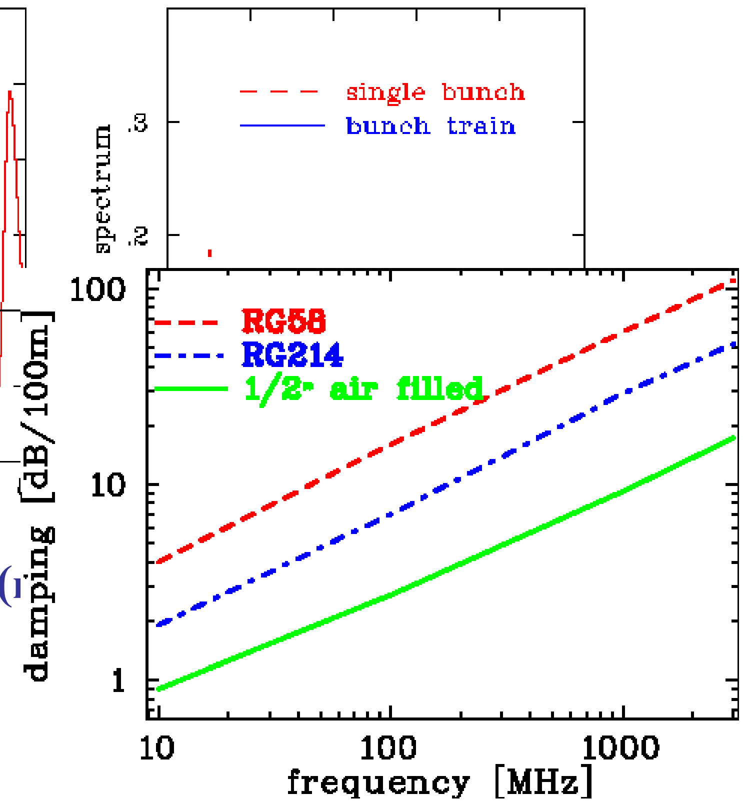
C=100pF, l=10cm, β=50%, σ=100 ns

- Fourier spectrum is more complex, harmonics are broader
- Varying baseline with $\tau \approx (3f_{cut})^{-1} = 1$ µs
- Baseline shift calls for dedicated restoring algorithm for time domain processing.

Calculation of Signal Shape: Bunch Train with Cable Damping

Effect of cable or other electronics:





Parameter: *R*=5 kΩ, cable damping with f_e=0.3 MHz (r

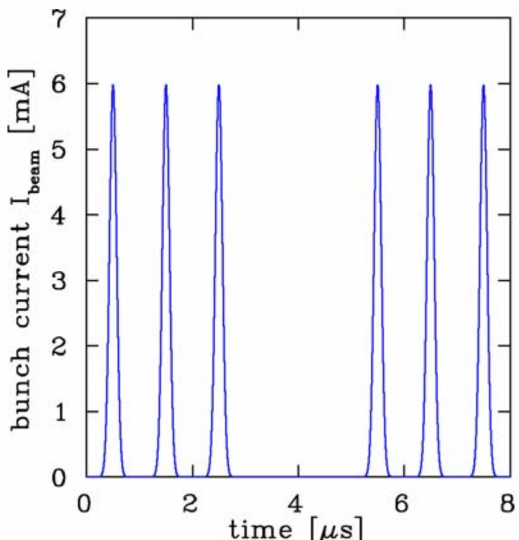
Cable damping: $H_{cable}(\omega) = e^{-\sqrt{f/f_e}} \cdot e^{-i\sqrt{f/f_e}}$

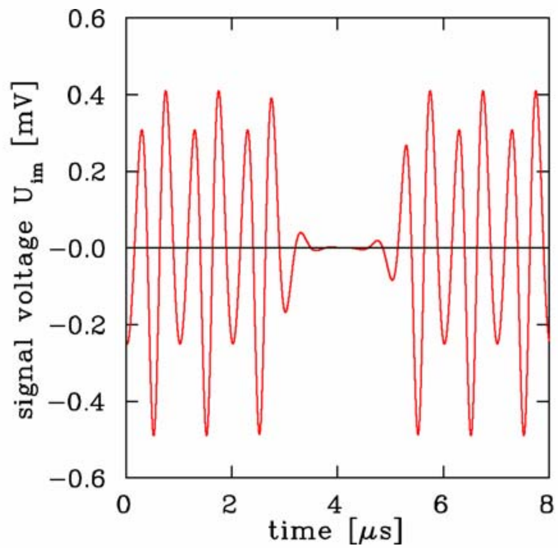
f_e: amplitude damping by 20 dB, here: f_e=0.3 MHz

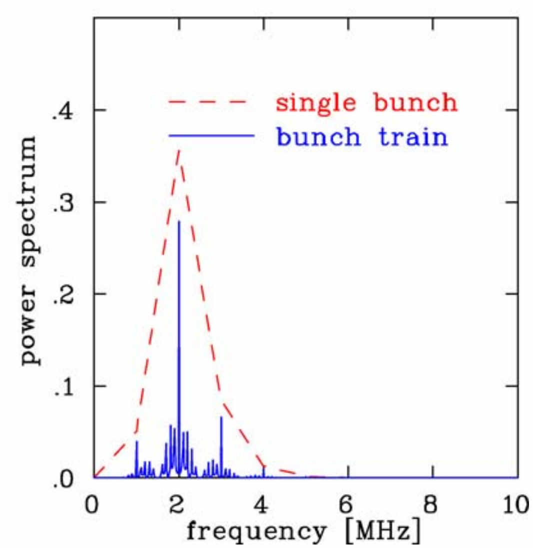
- Bunch signal is damped; 10 fold lower amplitude, higher frequencies are damped stronger
- Bunch signal gets asymmetric, baseline did not reach zero
- ⇒ 'Good cables' are a precaution for broadband signal transmission

Calculation of Signal Shape: Filtering of Harmonics

Effect of filters, here bandpass:







Parameter: *R*=5 kΩ, 4^{th} 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

*n^{th} 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 electronics calculation, time domain filters (FIR and IIR) are more appropriate

Principle of Position Determination with BPM

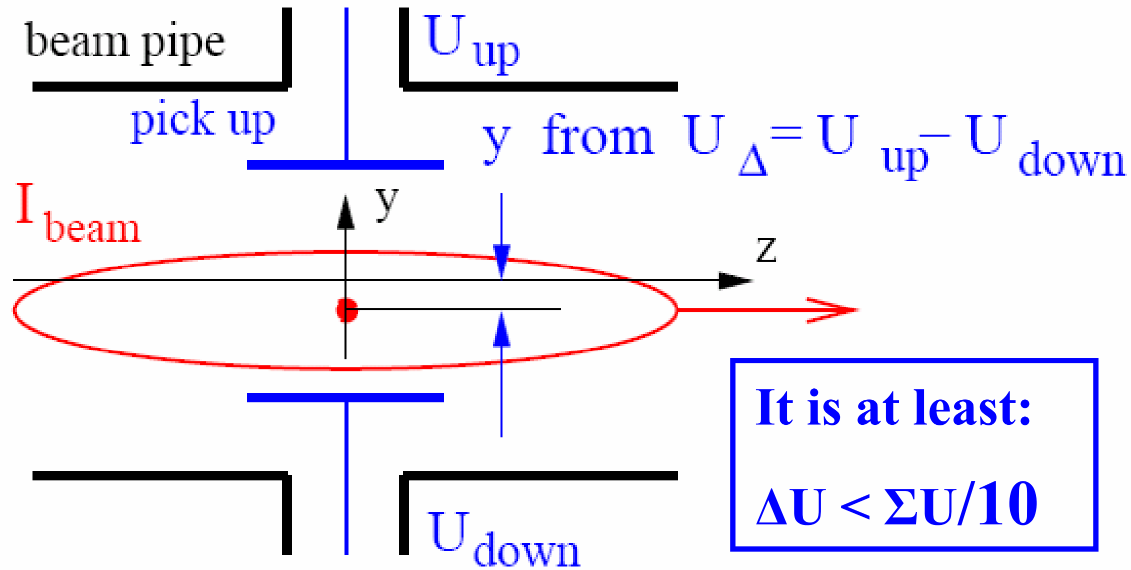
The difference between plates gives the beam's center-of-mass
→**most frequent application**

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

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

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

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



It is at least:

$\Delta U < \Sigma U/10$

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, which have to be optimized.
Units: ***S***=[%/mm] and sometimes ***S***=[dB/mm] or ***k***=[mm]

Sometimes the transverse transfer impedance is defined via $U_\Delta = Z_\perp(\omega) \cdot x I_{beam}$

It can be assumed: $Z_\perp(\omega,x) = Z_t(\omega)/S(\omega,x)$

Beam Position Monitor:

Detector Principle, Hardware and Electronics

Outline:

- *Signal generation $\rightarrow$ transfer impedance*
- ***Consideration for capacitive 'shoe box' = 'linear cut' BPM***

  position sensitivity calculation, crosstalk, realization
- ***Consideration for capacitive button BPM***
- ***Other BPM principles: stripline $\rightarrow$ traveling wave***

  inductive $\rightarrow$ wall current

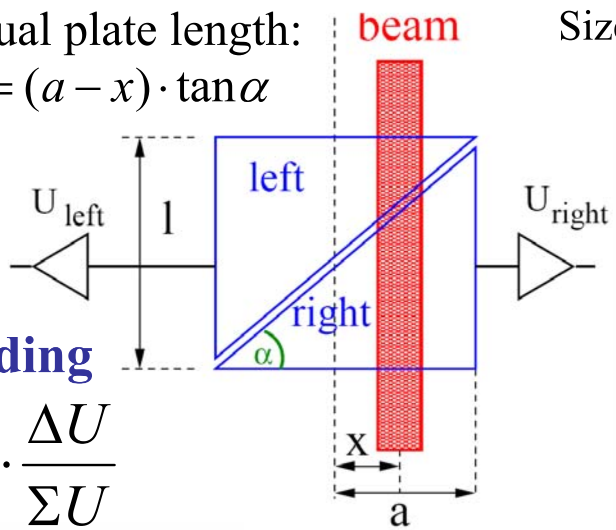
  cavity $\rightarrow$ resonator for dipole mode
- ***Electronics for position evaluation***
- ***Some examples for position evaluation and other applications***
- ***Summary***

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

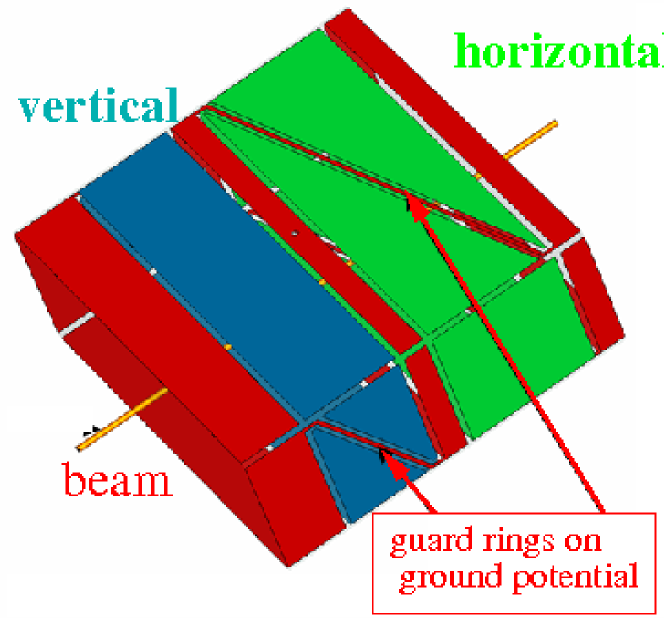
Signal is proportional to actual plate length:

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

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

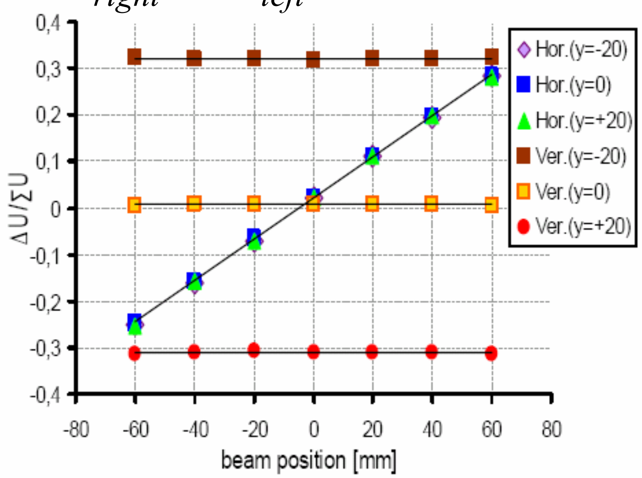


Size: 200x70 mm^2



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

Boundary Contribution ⇒ FEM Calculation required

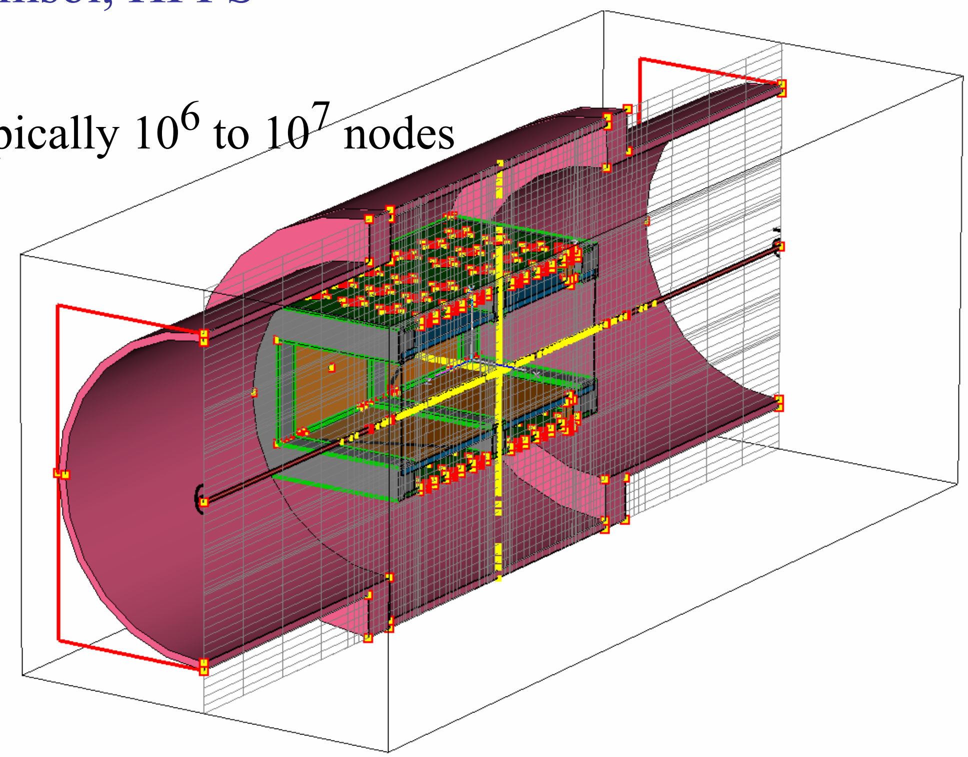
Boundary condition by the environment can significantly influence BPM properties

⇒ real properties have to be calculated numerically by **F**inite **E**lement **M**ethod:

Examples are: CST-Studio (MAFIA), Comsol, HFFS

General idea of FEM calculations:

- Volume is divided in 3-dim meshes with typically 10^6 to 10^7 nodes
- The beam is simulated by a traveling wave on a wire
- Goal: Field distribution within the meshes
- The Maxwell equations are solved by iterative matrix inversion
- Time domain: Propagation of source terms (here: Gaussian shaped pulse corresponding to 200 MHz bandwidth)
- Frequency domain: e.g. eigenmodes



- Output: time dependent signal, frequency dependences, S-parameters, field distribution etc.

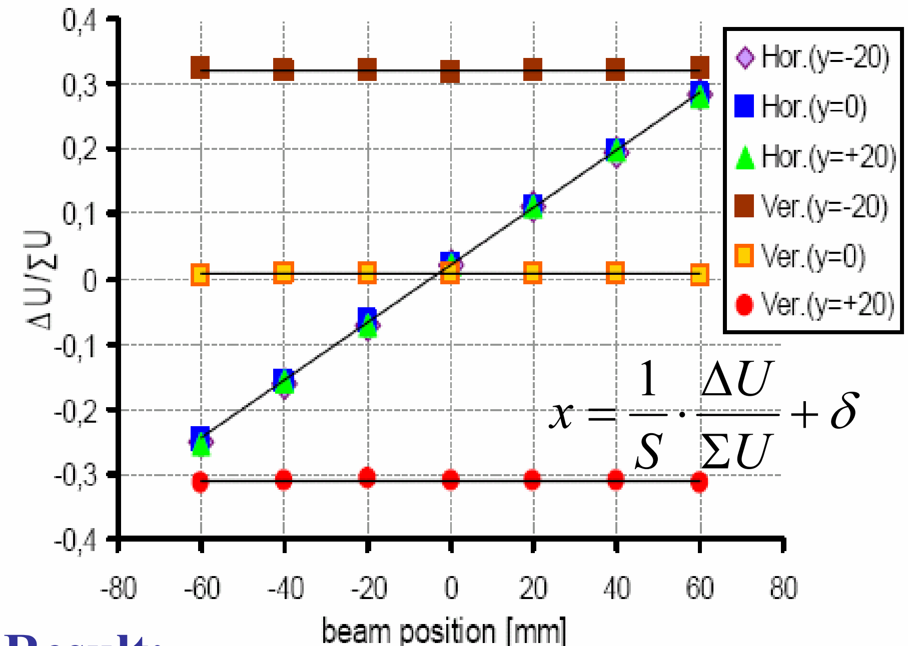
Optimization of Position Sensitivity

Simulation: Gaussian pulse travels on wire on different positions

→ induced voltage calculated on matched output ports

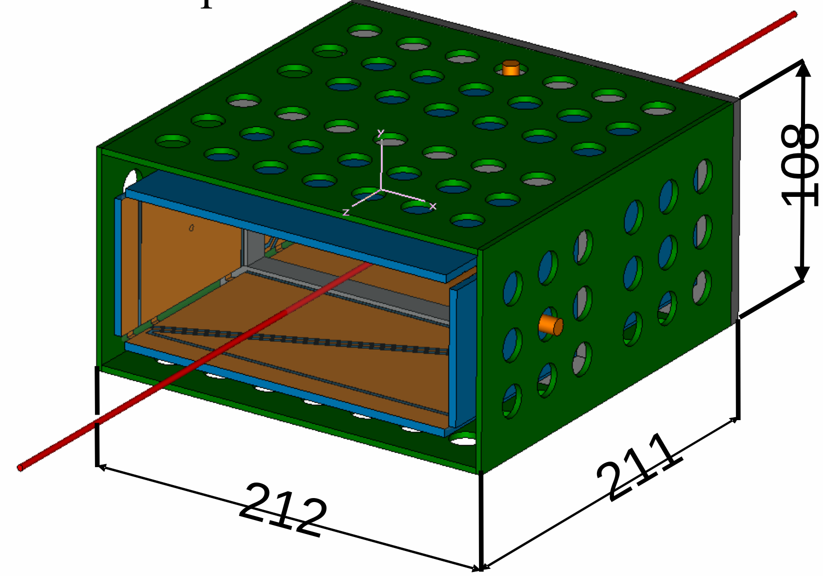
→ calculation of $\Delta U/\Sigma U$

Criteria of optimization: linearity, sensitivity, offset reduction, x-y plane independence



$$x = \frac{1}{S} \cdot \frac{\Delta U}{\Sigma U} + \delta$$

Aperture: 180x70 mm^2



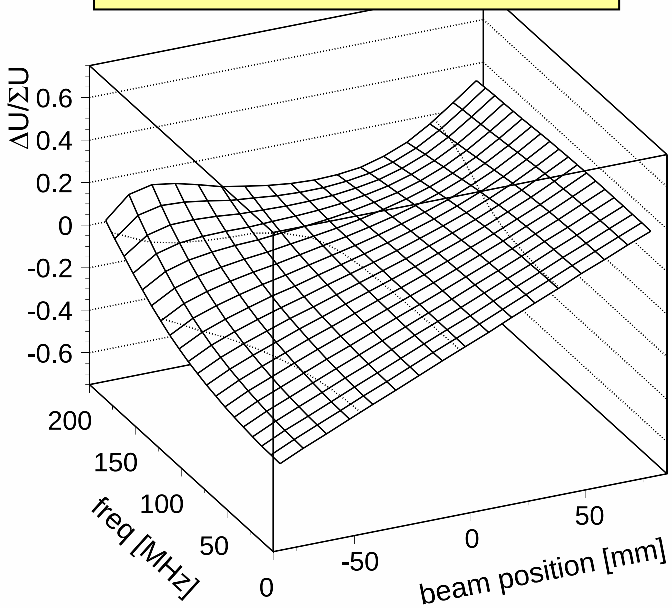
Result:

Nearly perfect: S_x=0.96 %/mm, δ_x=-0.4mm (ideal value S_x=1.1 %/mm, δ=0)

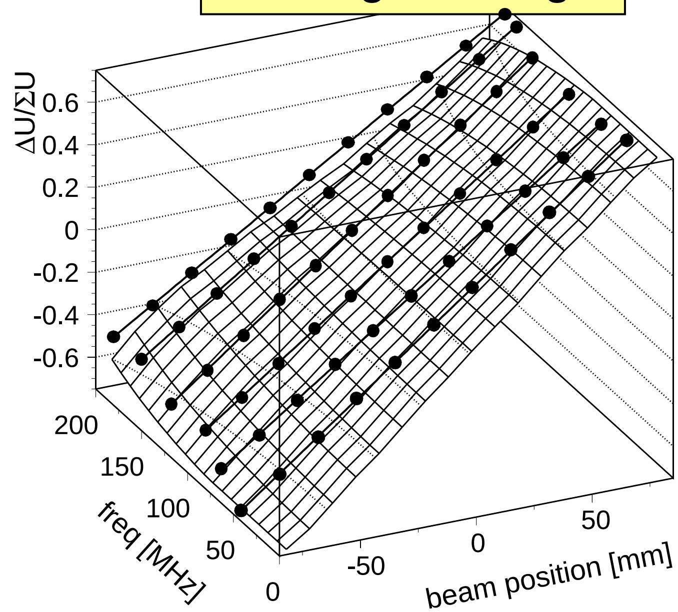
S_y=2.6 %/mm, δ_y=-0.04mm (ideal value S_y=2.9 %/mm, δ=0) **at 1 MHz**

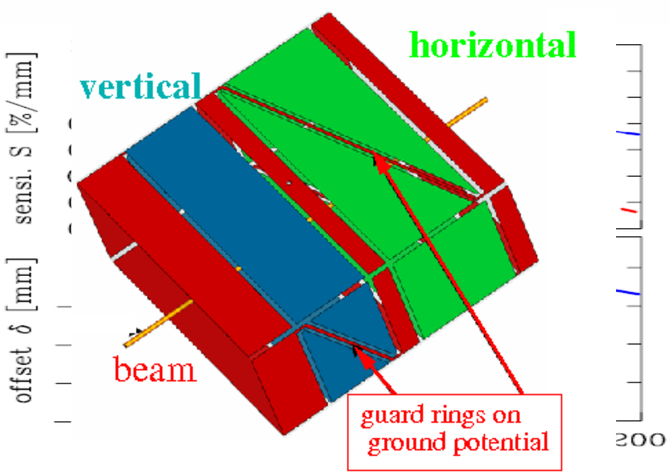
Frequency Dependence of Position Sensitivity

Without guard ring



With guard ring





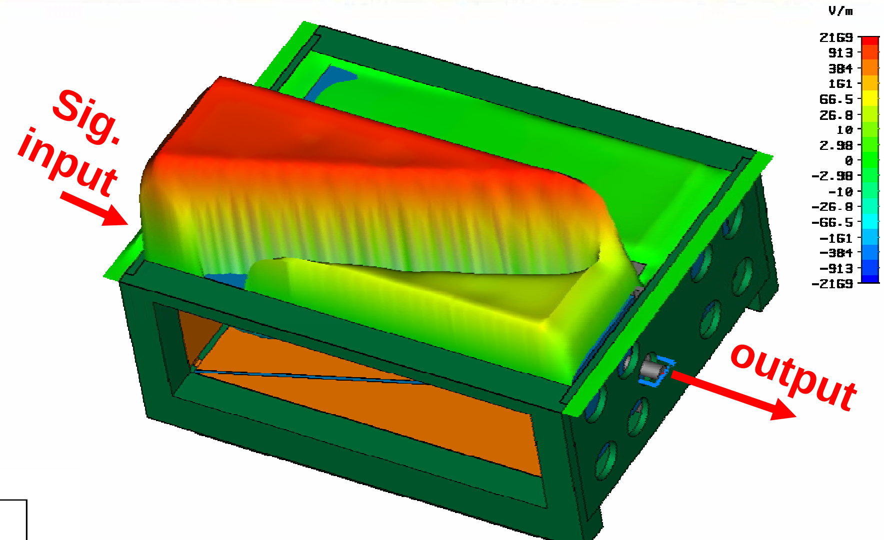
$$x = \frac{1}{S(\omega)} \cdot \frac{\Delta U}{\Sigma U} + \delta(\omega)$$

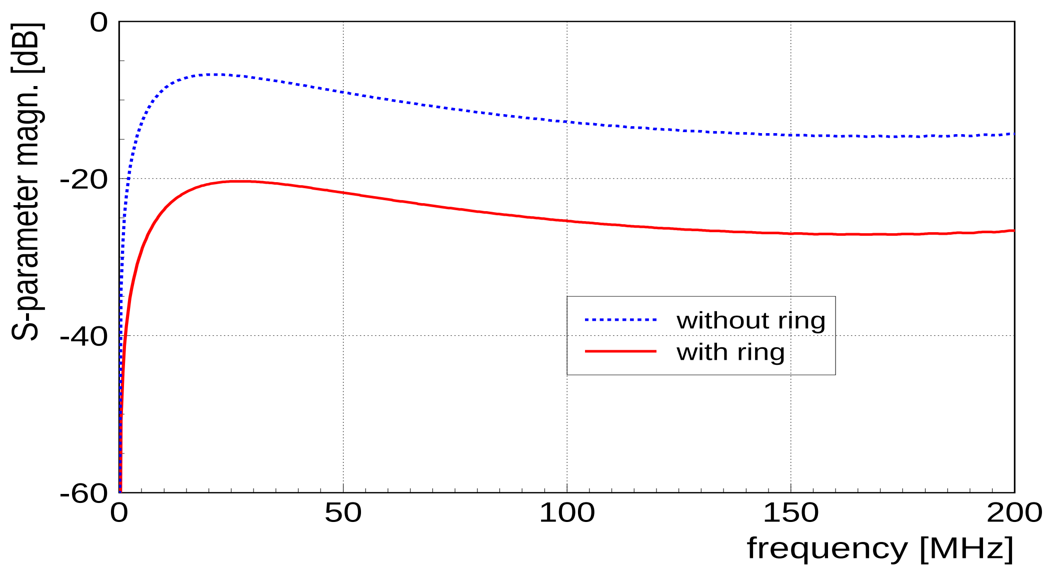
- Displacement sensitivity is nearly frequency independent only with separating guard rings
- Sensitivity with separating rings is a factor of two larger as without ring.
- Capacitive cross talk spoils the sensitivity

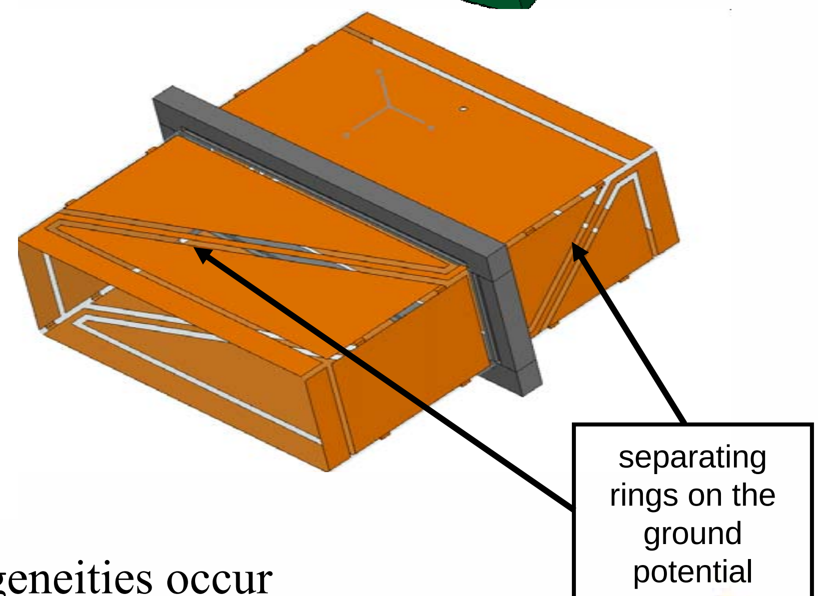
Plate—to-Plate Cross-Talk reduces Sensitivity

- Capacitive coubling determines position sensitivity
- Plate-to-plate cross talk caused by ceramic permittivity ε=9.6 resulting in high coupling capacitance between adjacent plates

⇒Insertion of the guard-ring between plates reduces cross talks by more than 10dB



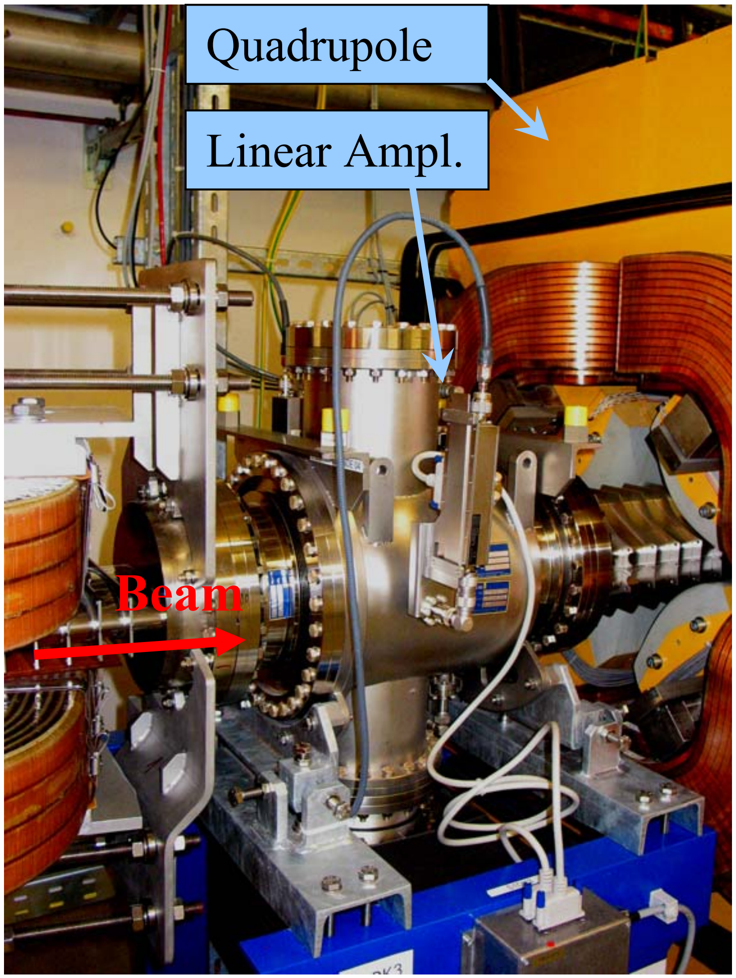


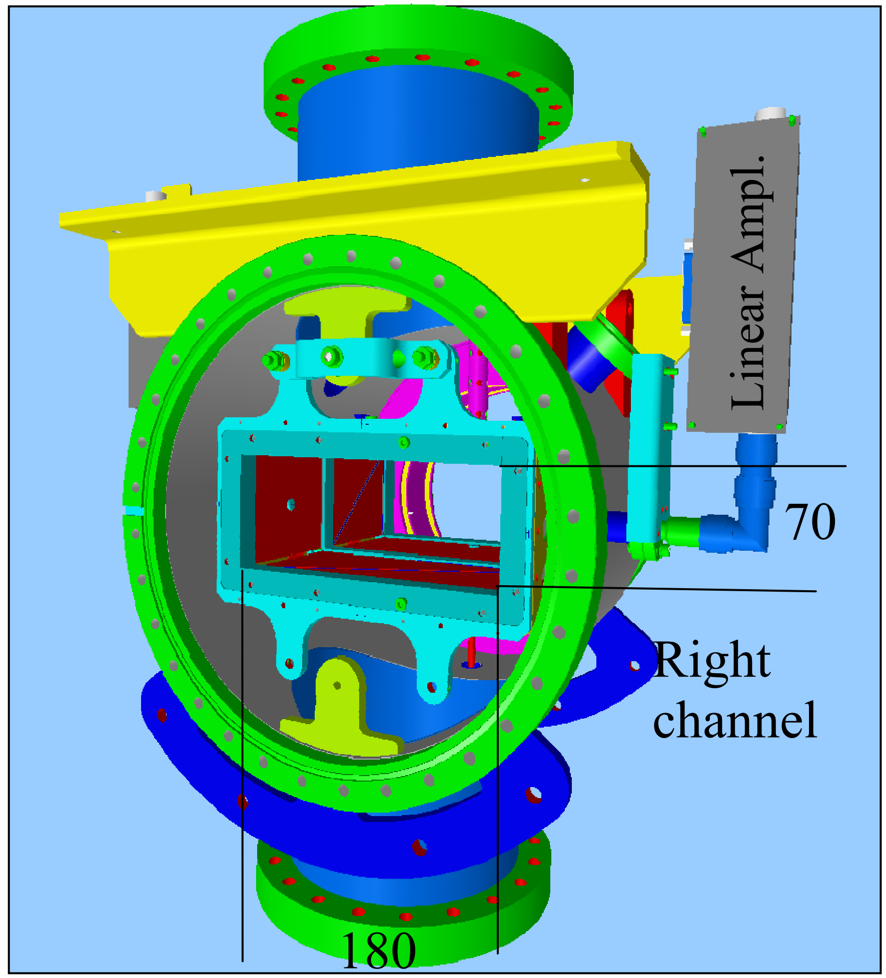


Remark: If guard rings are too large: E-field in-homogeneities occur

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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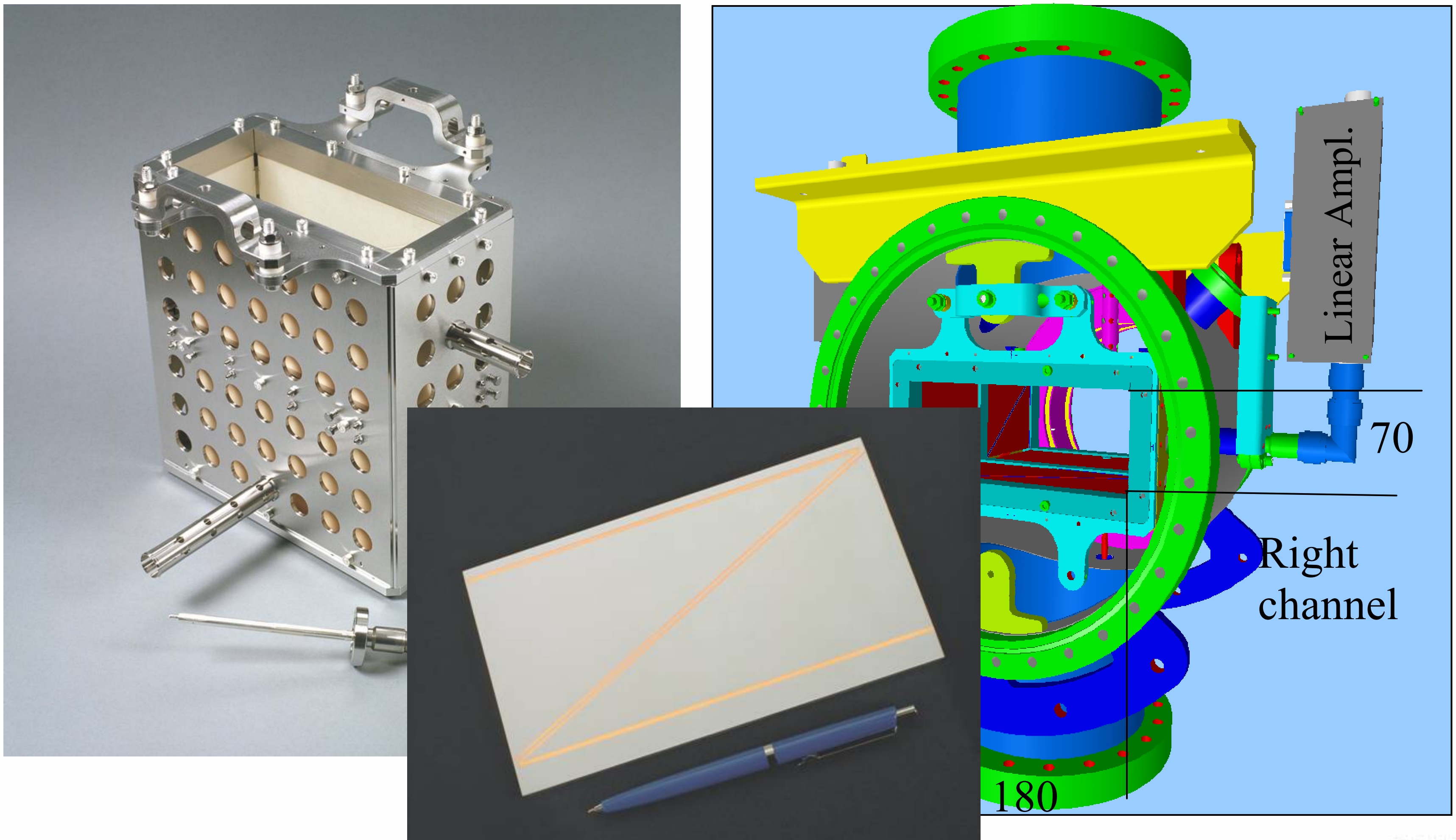
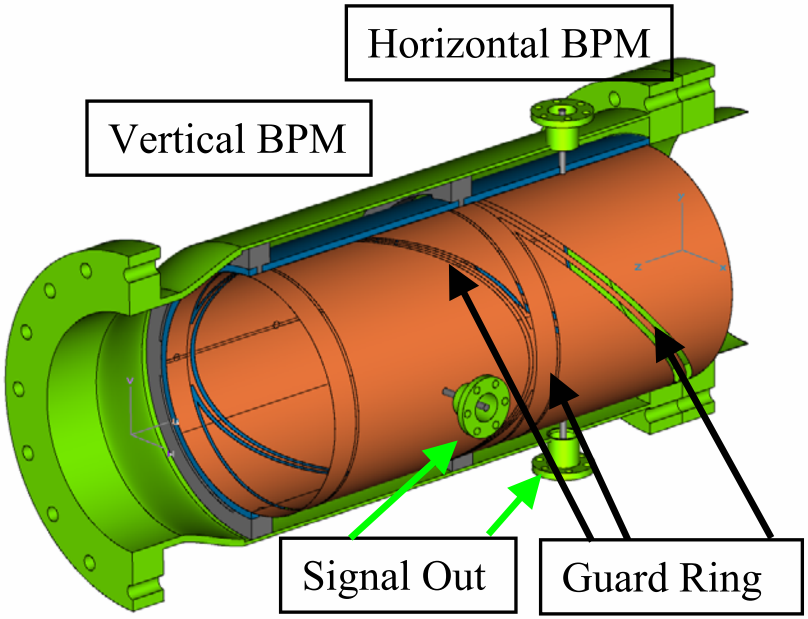


Other Types of diagonal cut BPM

Round type: cut cylinder

Same properties as shoe-box:



Other realization: Full metal plates

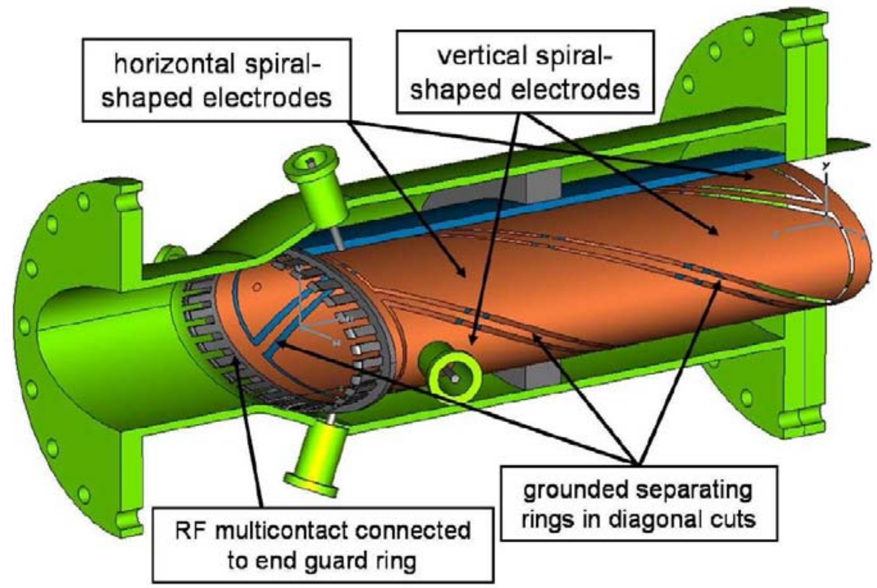
→ No guard rings required

→ 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*
- *Consideration for capacitive shoe box BPM*
- ***Consideration for capacitive button BPM***

  simple electro-static model, low β effect, modification for synch. light source

  Comparison shoe box button BPM
- ***Other BPM principles: stripline → traveling wave,***

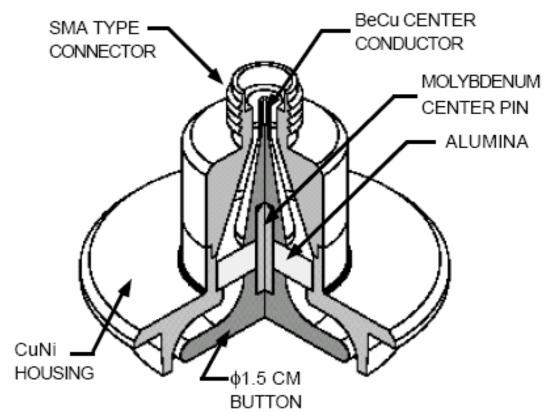
  inductive → wall current, cavity → resonator for dipole mode
- ***Electronics for position evaluation***
- ***Some examples for position evaluation and other applications***
- ***Summary***

Button BPM for short Bunches

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

→ 50 Ω signal path to prevent reflections

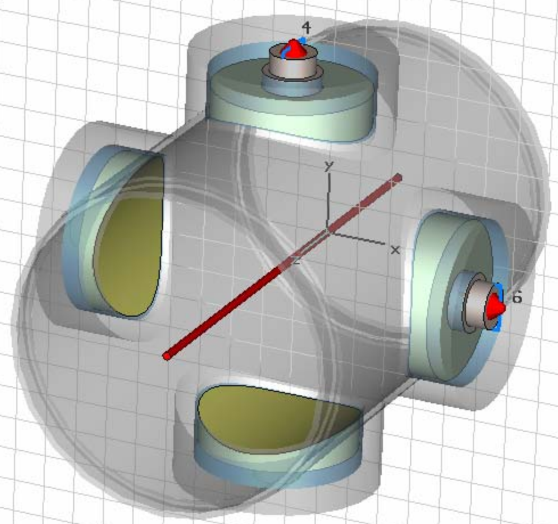
Button BPM with 50 Ω ⇒ $U_{im}(t) = R \cdot \frac{A}{\beta c \cdot 2\pi a} \cdot \frac{dI_{beam}}{dt}$



Example: LHC-type inside cryostat:

∅24 mm, half aperture a=25 mm, C=8 pF

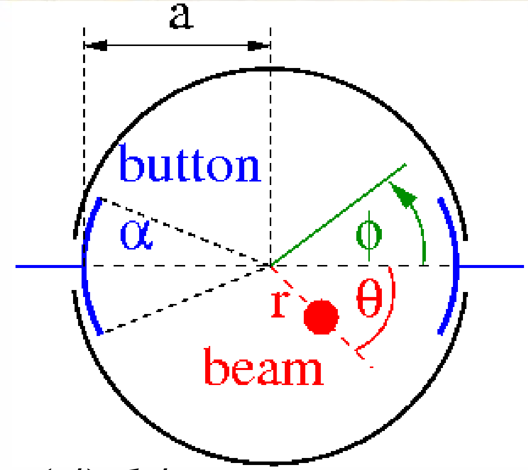
⇒ f_{cut}=400 MHz, Z_t = 1.3 Ω above f_{cut}



From C. Boccard (CERN)

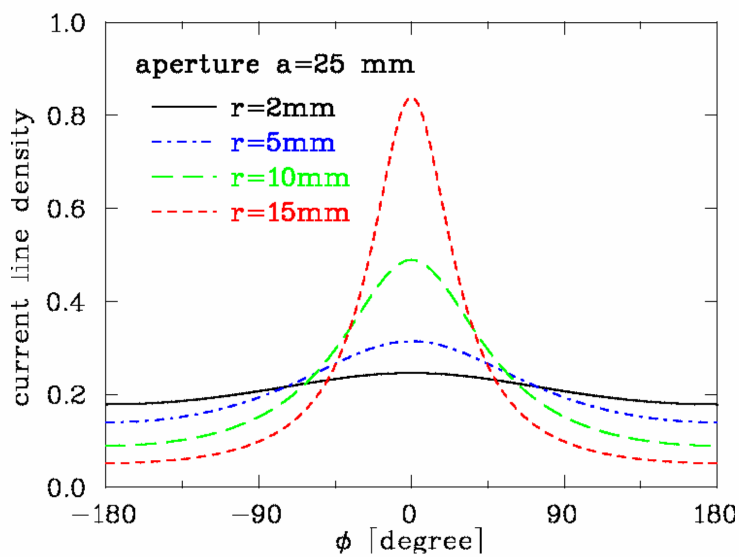
'Proximity effect': larger signal for closer plate

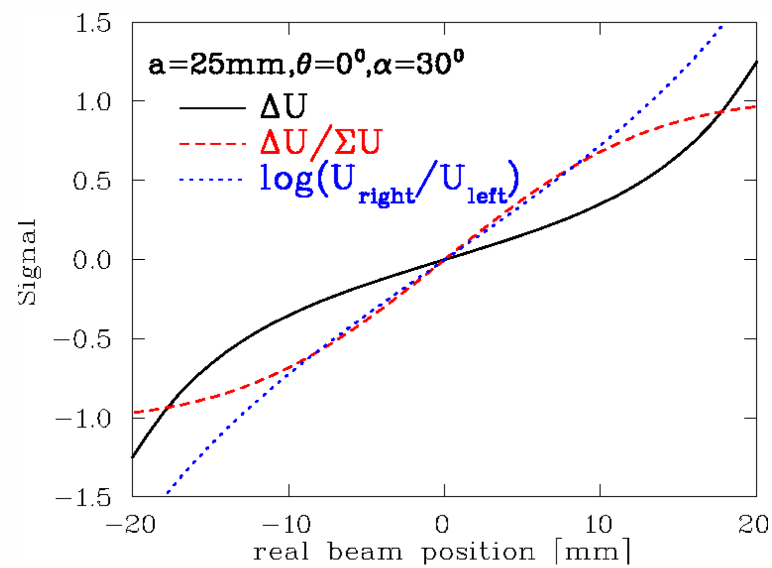
Ideal 2-dim case: Cylindrical pipe → image current density via 'image charge method' for 'pensile' beam:



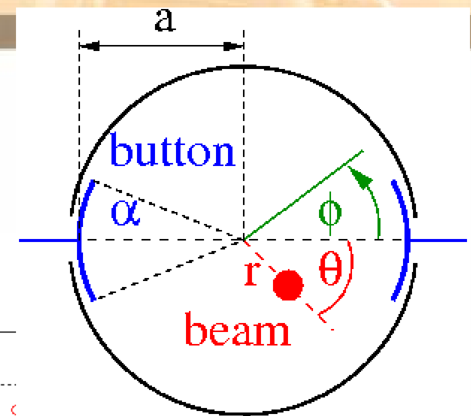
$$j_{im}(\phi) = \frac{I_{beam}}{2\pi a} \cdot \left(\frac{a^2 - r^2}{a^2 + r^2 - 2ar \cdot \cos(\phi - \theta)} \right)$$

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





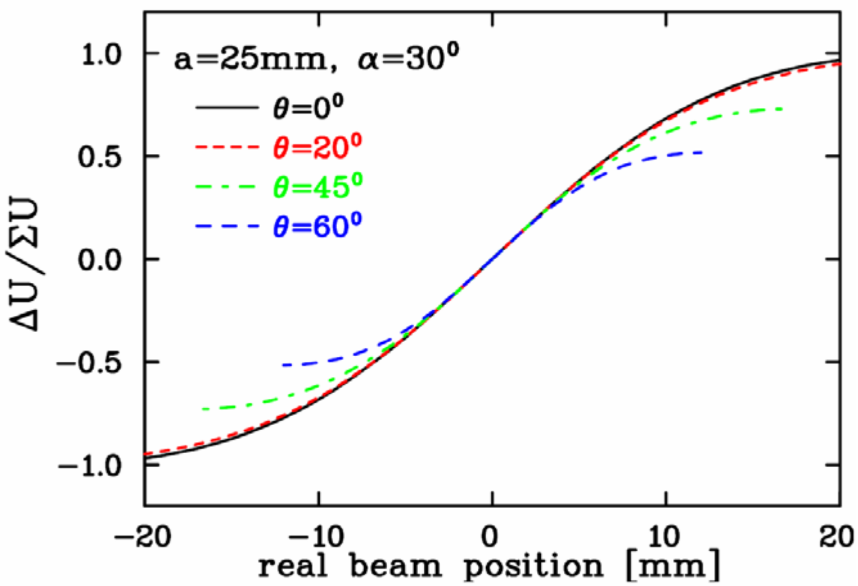
2-dim Model for Button BPM

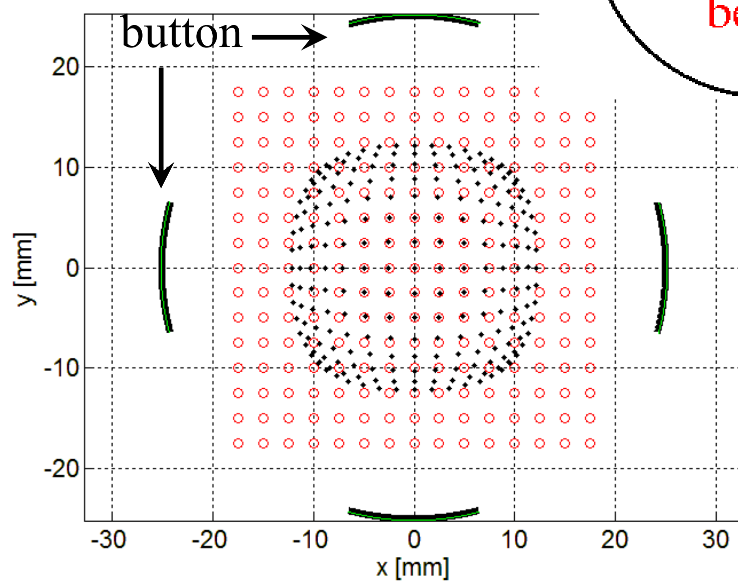


Ideal 2-dim model: Non-linear behavior and hor-vert coupling:

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

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





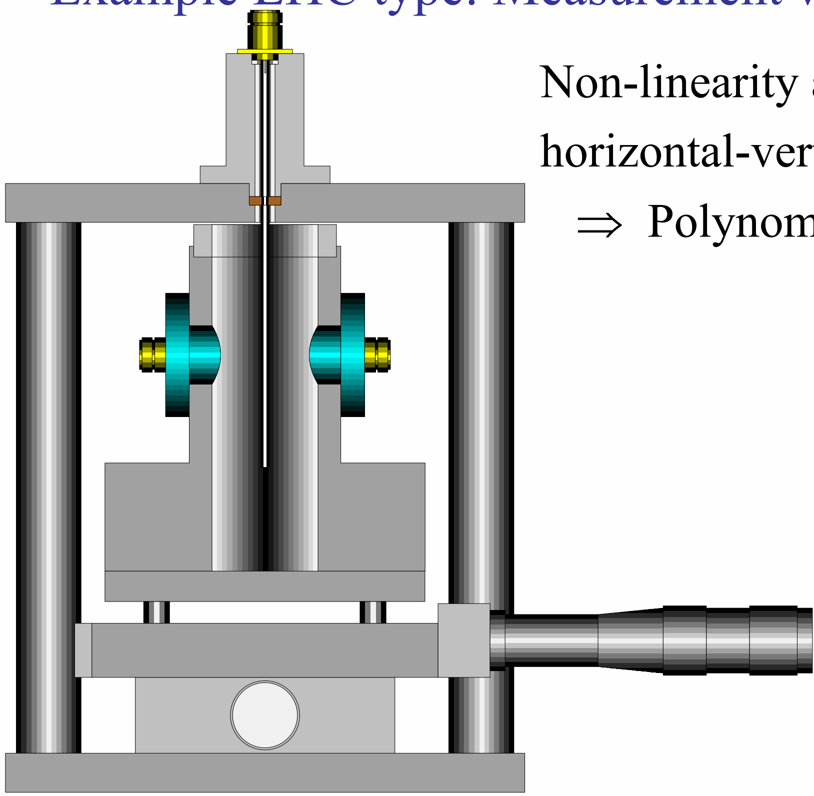
Current density can also be calculated by Laplace equation for Fourier components

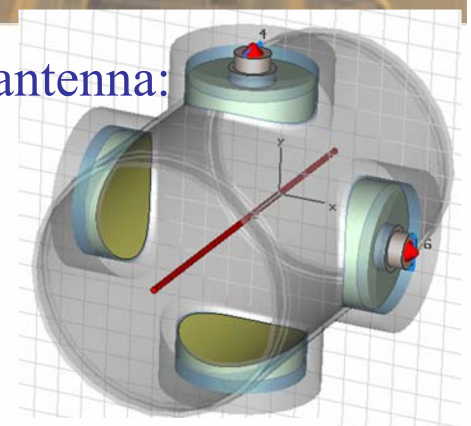
$$I_{beam} = \langle I_{beam} \rangle + 2\langle I_{beam} \rangle \cdot \sum_{n=1}^{\infty} A_n \cos(n\omega_0 t) \quad \text{for Gaussian bunches}: A_n = \exp(-n^2\omega^2\sigma_t^2/2)$$

In addition, frequency dependence can be calculated by this method.

Position Measurement for Button BPM

Example LHC type: Measurement with movable 50 Ω matched antenna:

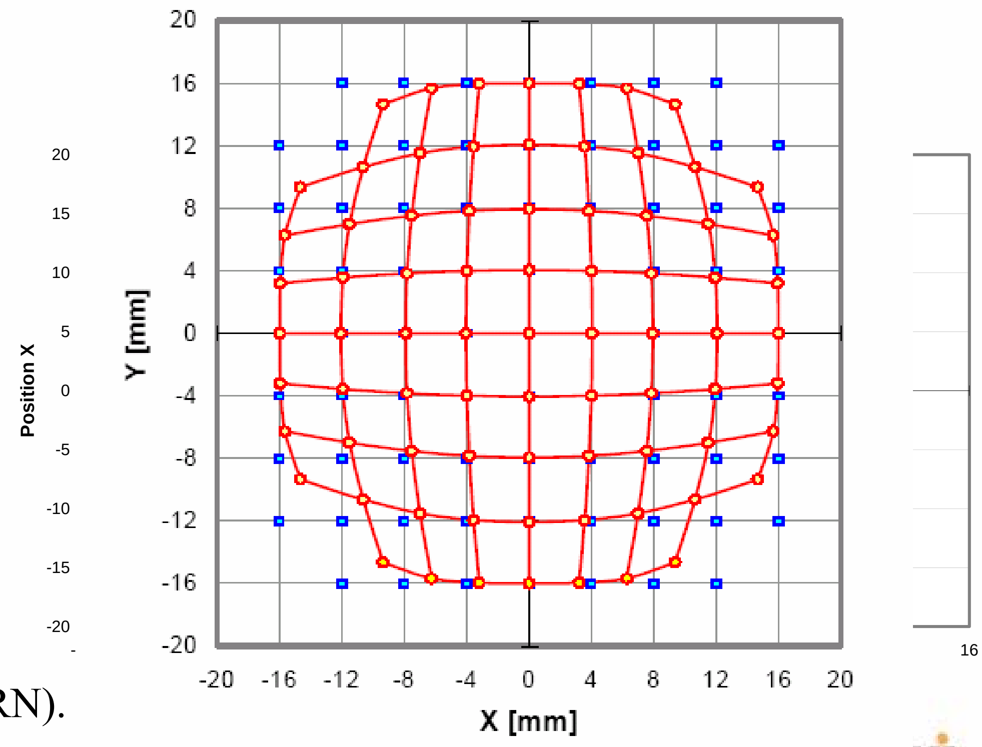




Non-linearity and

horizontal-vertical coupling

⇒ Polynomial fit with x and y dependence



From C. Boccard, C. Palau-Montava et al.(CERN).

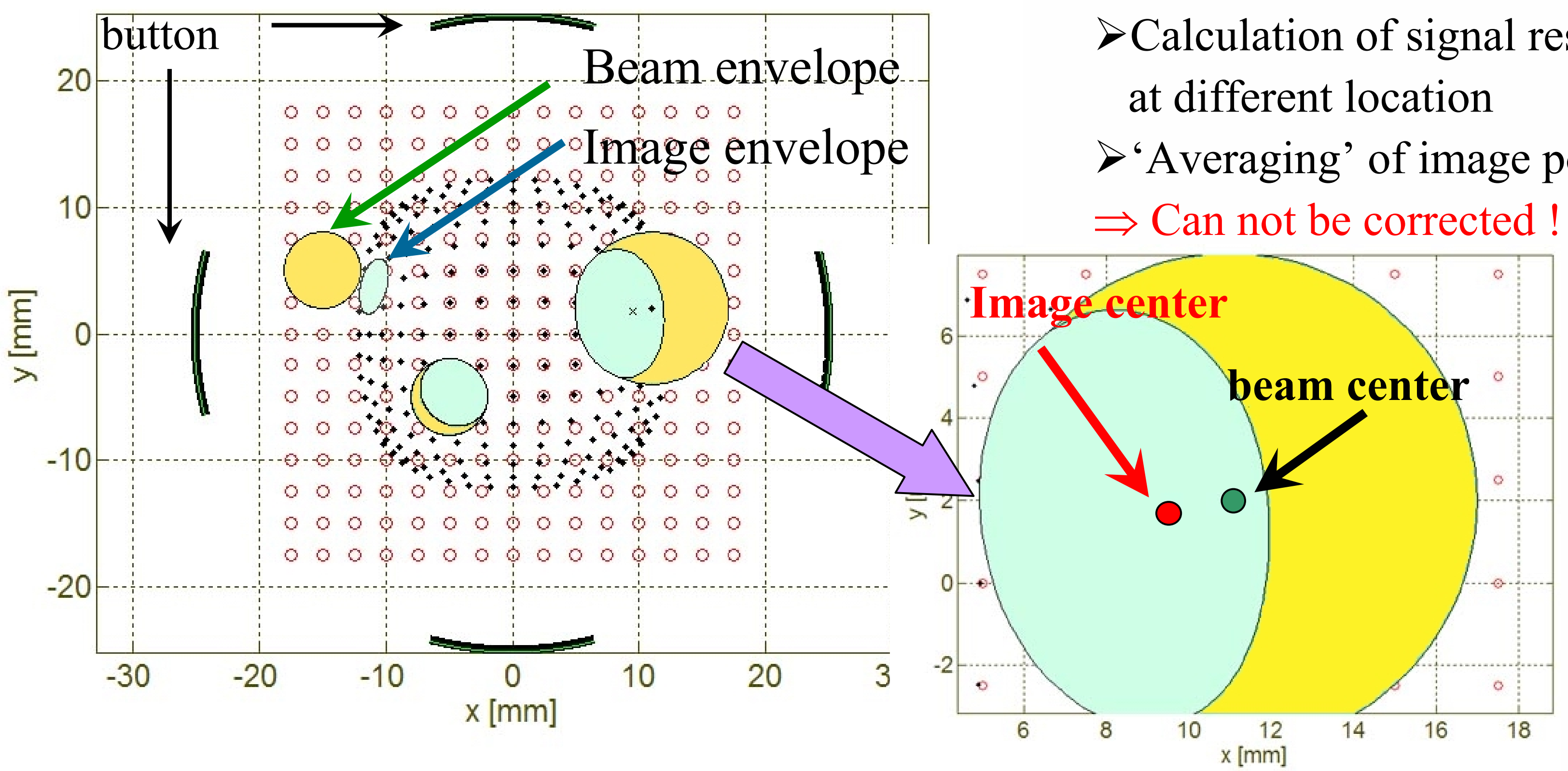
Ideal 2-dim model:

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

⇒ Can not be corrected !



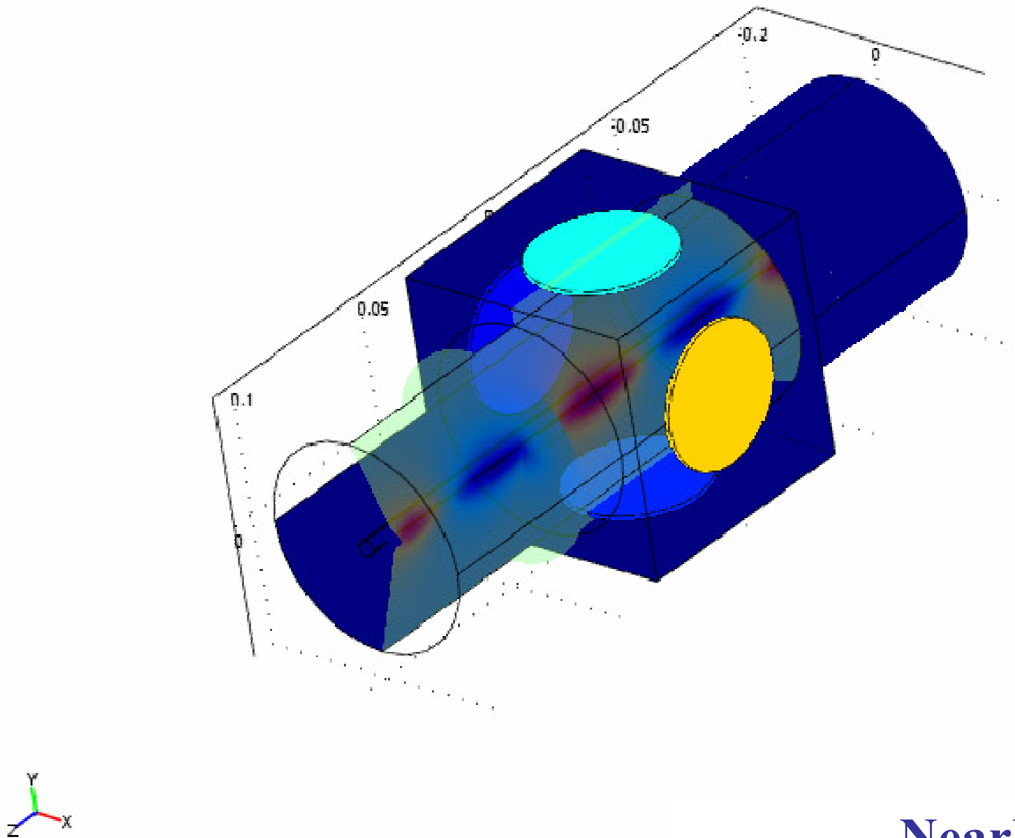
Remark: For most LINACs: Linearity is less important, because beam has to be centered

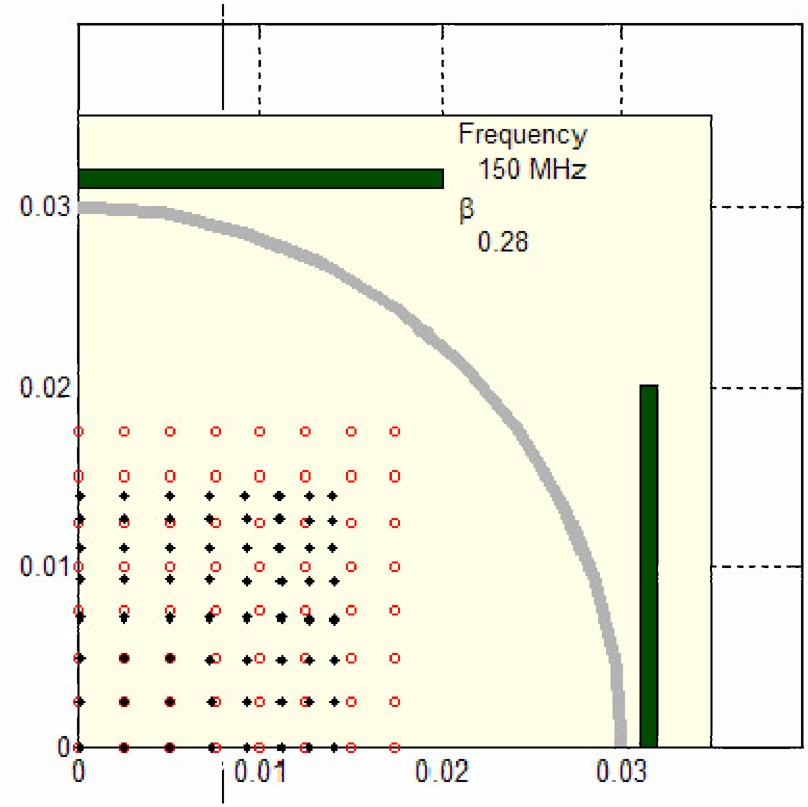
→ correction as feed-forward for next macro-pulse.

For realistic beam, 3-dim FEM calculations are required.

Example: Button BPM at r=3 cm beam-pipe, flat, round ∅ 4cm

frequency f_{rf}=150 MHz, effect for higher harmonics calculated





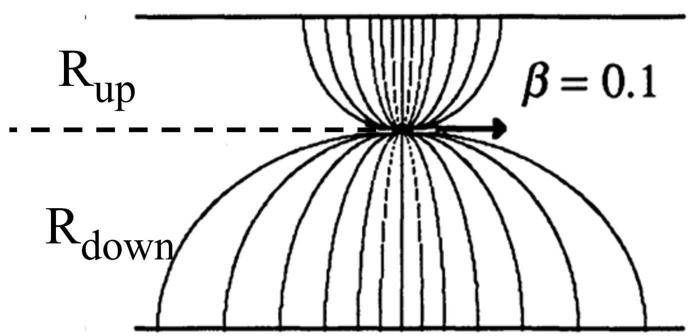
Nearly same result as ideal case!

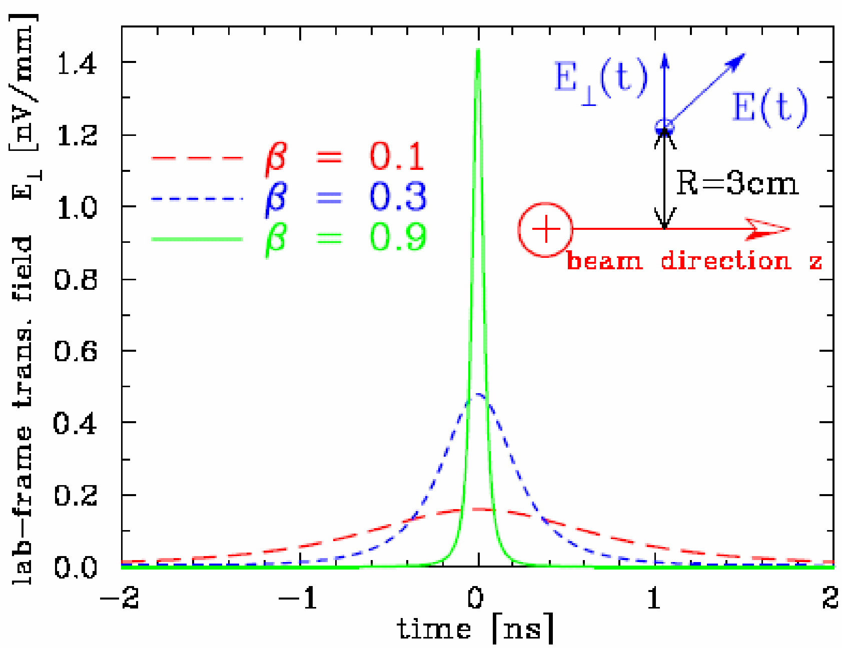
Low Velocity Effect: General Consideration

Simple Lorentz transformation of single point-like charge:

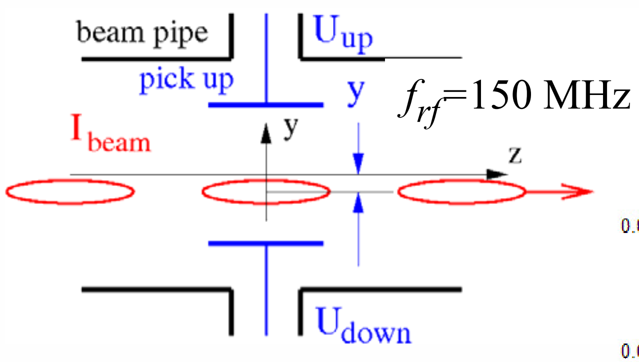
Lorentz boost and transformation of time: $E_\perp(t) = \gamma E'(t')$ and $t \rightarrow t'$

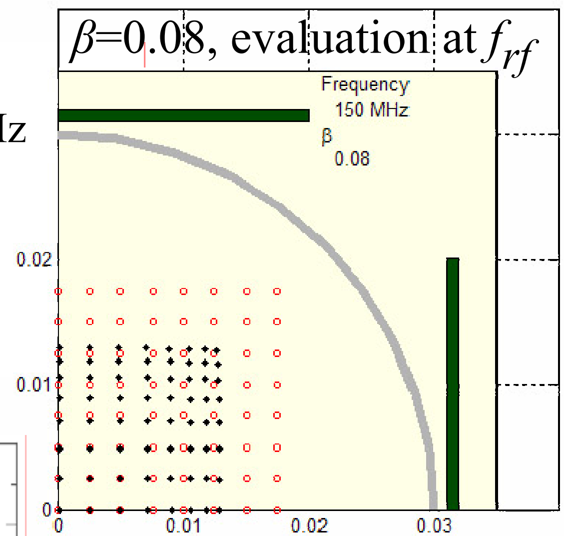
E-field of a point-like charge: $$E_\perp(t) = \frac{e}{4\pi\varepsilon_0} \cdot \frac{\gamma R}{\left[R^2 + (\gamma\beta ct)^2\right]^{3/2}}$$

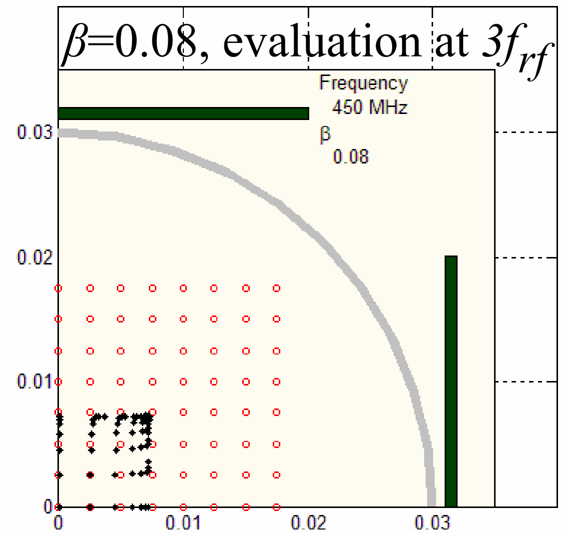


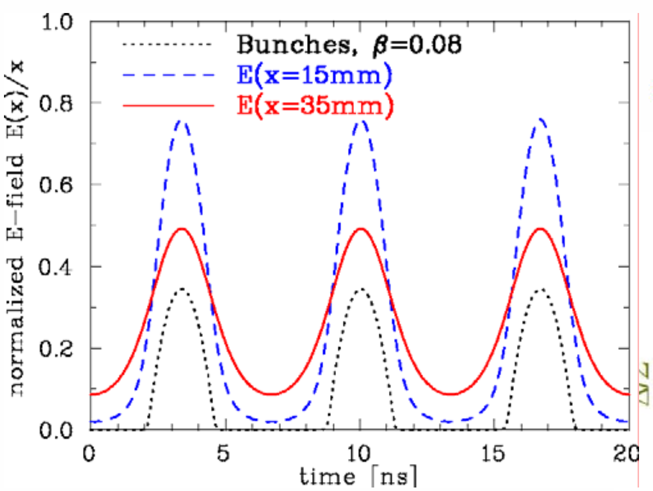


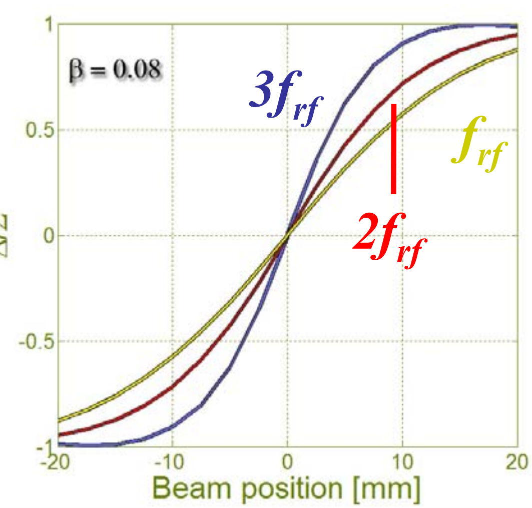
FEM Calculation of low β Effect for p-LINAC

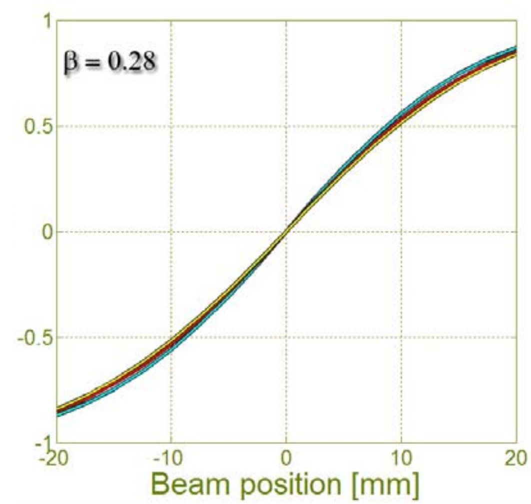










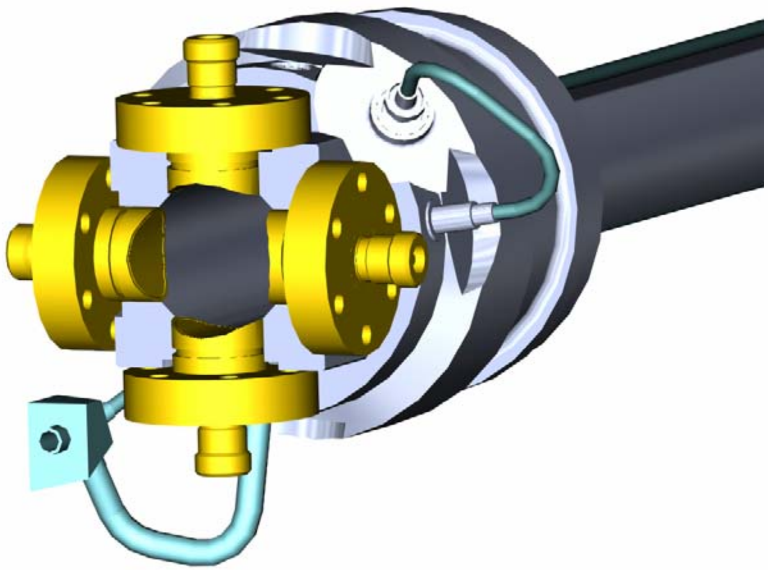


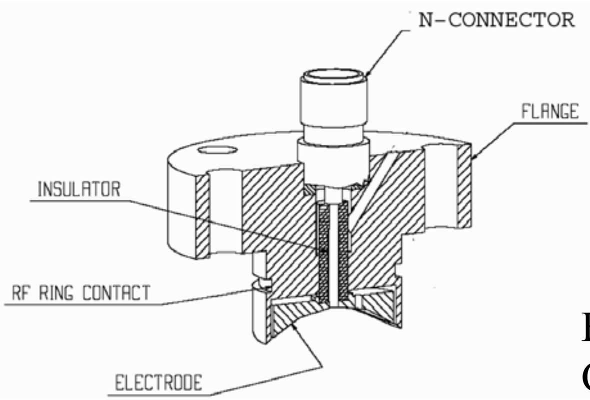
- Effect increases with f_{rf}
- Can also be calculated by Fourier-components.

Realization of Button BPM at LHC

Example LHC: ∅ 24 mm, half aperture a=25 mm, installed inside cryostat

Critically: 50 Ω matching of button to standard feed-through.





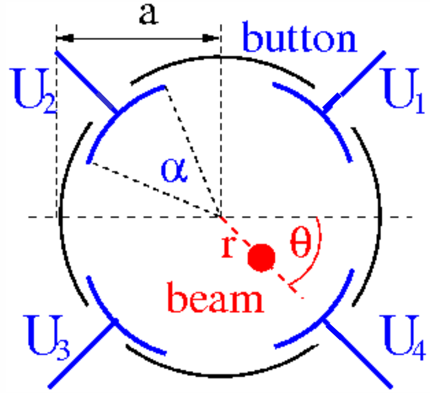
From C. Boccard,
C. Palau-Montava et al.(CERN).

Button BPM at Synchrotron Light Sources

The button BPM can be rotated by 45^0

to avoid exposure by synchrotron light:

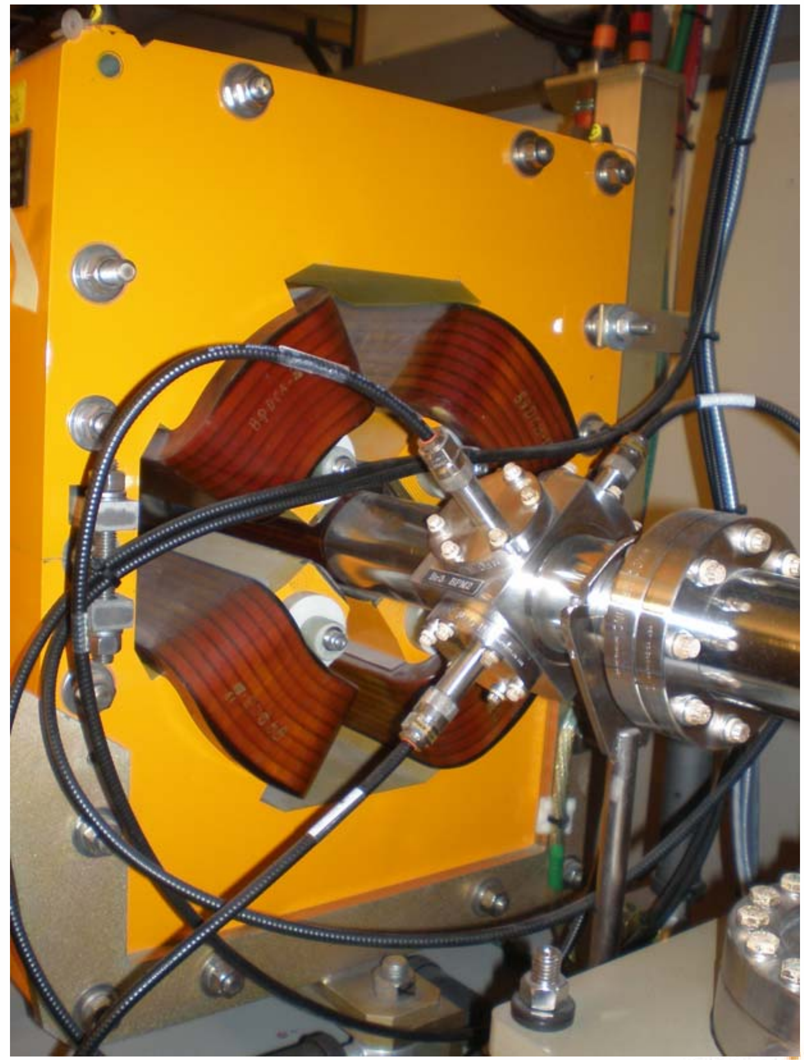
Frequently used at boosters for light sources



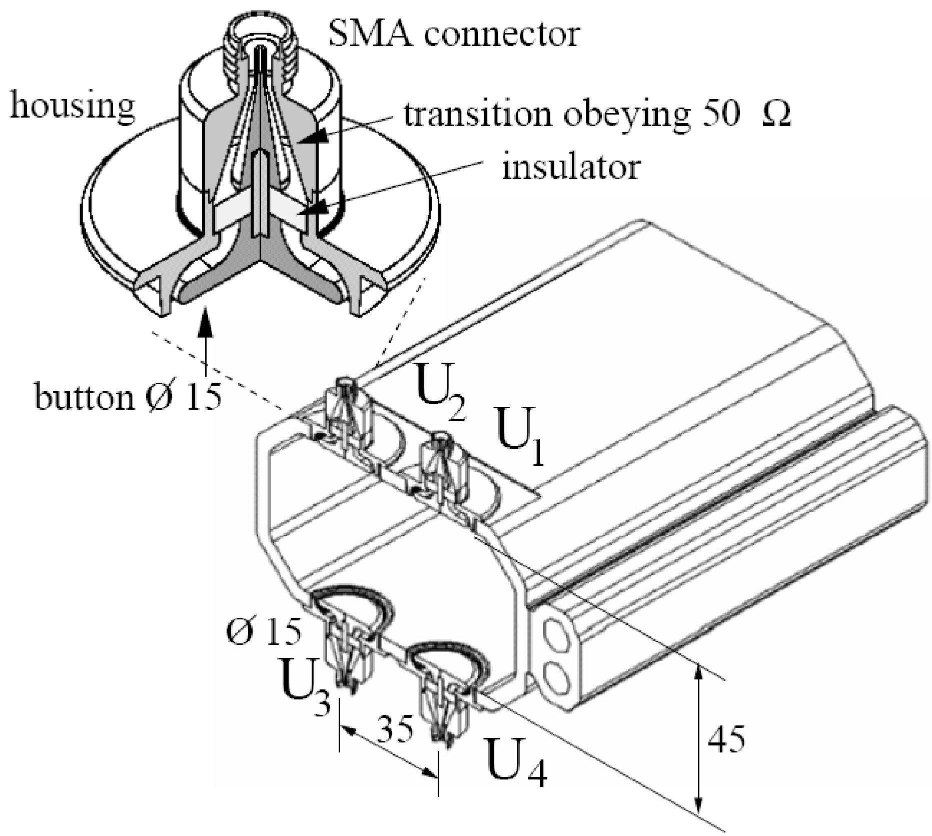
$$\text{horizontal}: x = \frac{1}{S} \cdot \frac{(U_1 + U_4) - (U_2 + U_3)}{U_1 + U_2 + U_3 + U_4}$$

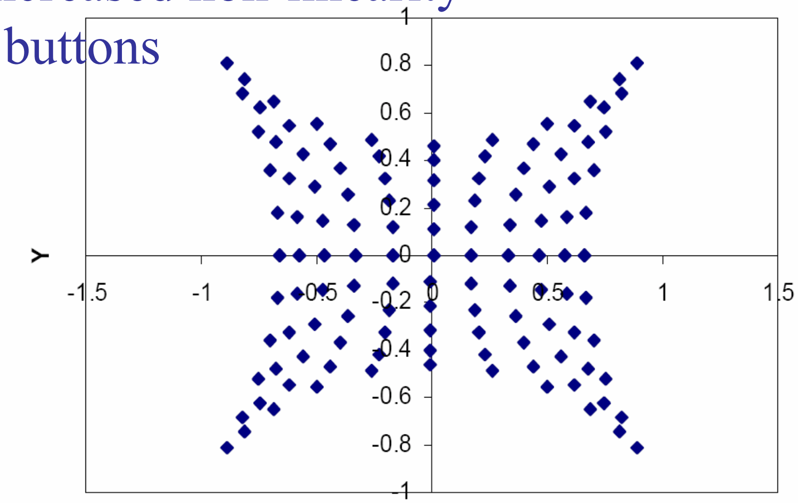
$$\text{vertical}: \quad y = \frac{1}{S} \cdot \frac{(U_1 + U_2) - (U_3 + U_4)}{U_1 + U_2 + U_3 + U_4}$$

Example: Booster of ALS, Berkeley



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%/mm in this case

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

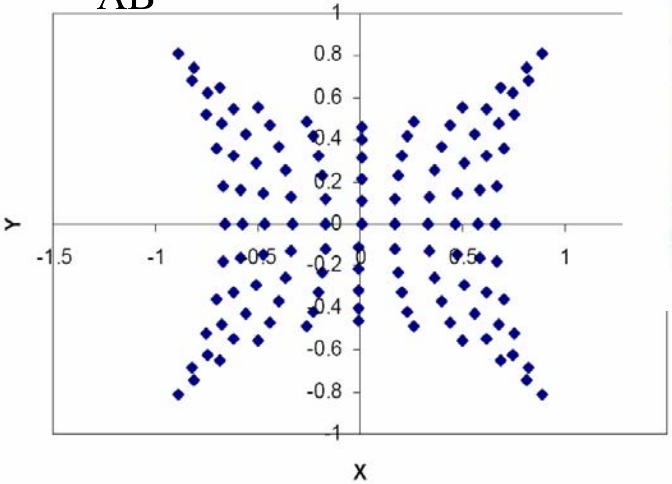
$$\text{vertical}: y = \frac{1}{S_y} \cdot \frac{(U_1+U_2)-(U_3+U_4)}{U_1+U_2+U_3+U_4}$$

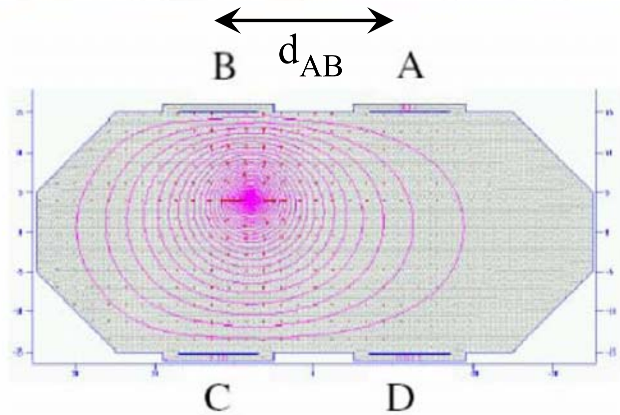
From S. Varnasseri, SESAME, DIPAC 2005

Button BPM at Synchrotron Light Sources

2-dim electro-static simulation:

d_{AB}=24 mm

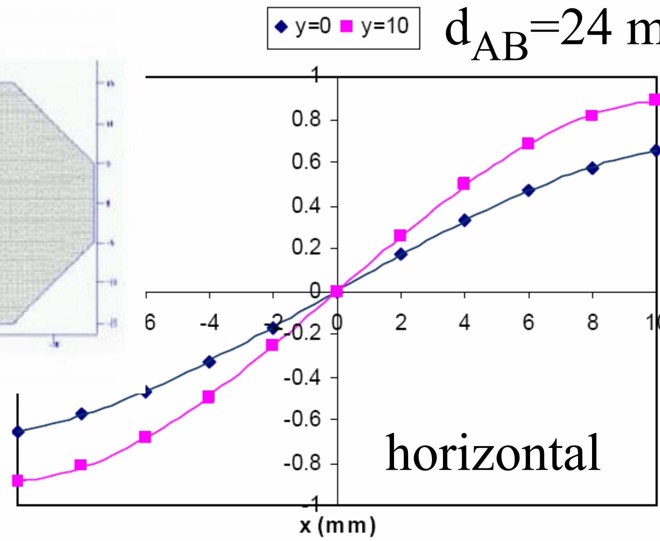




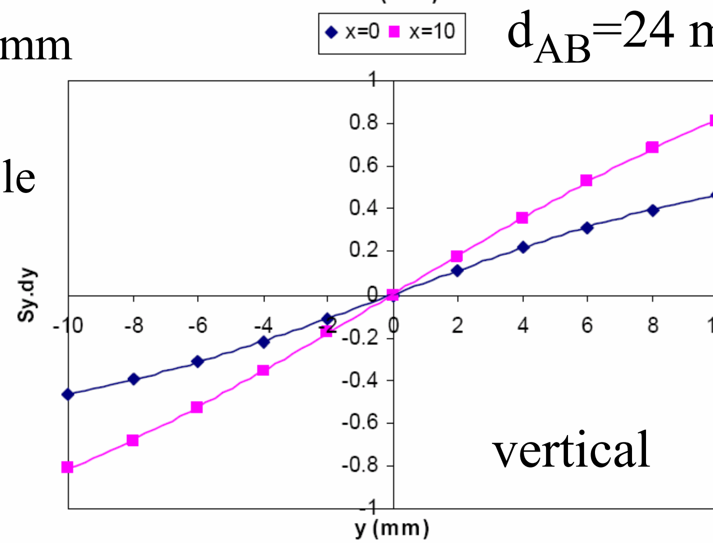
Result:

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

d_{AB}=24 mm



d_{AB}=24 mm

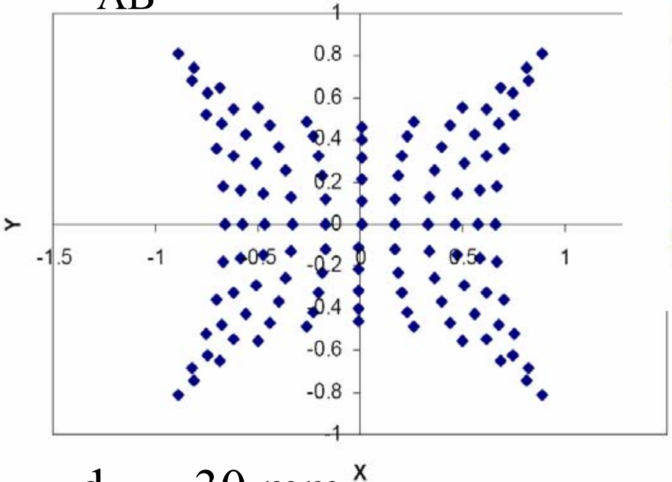


Beam position swept with 2 mm steps

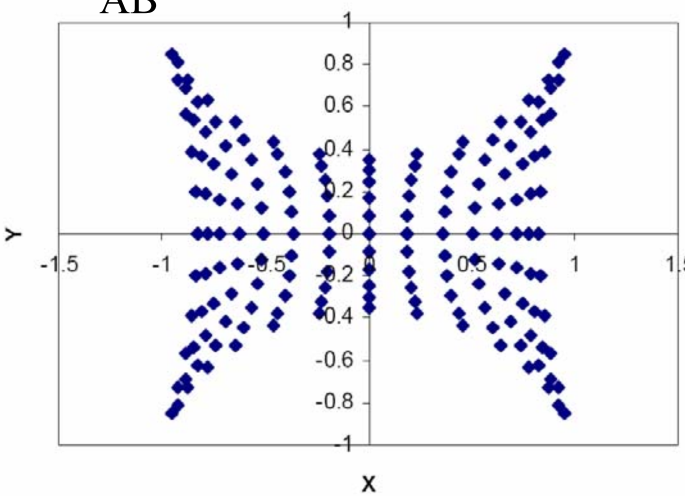
From S. Varnasseri, SESAME, DIPAC 2005

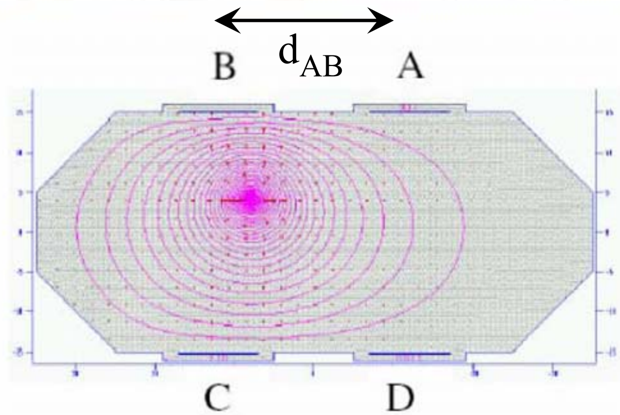
2-dim electro-static simulation:

d_{AB}=24 mm



d_{AB}=30 mm





Result:

Distance d_{AB} influences the sensitivity

Larger d_{AB} has the effect:

- higher sensitivity in x-direction
- lower sensitivity in y-direction
- linearity in influenced

$\Rightarrow$ Numerical optimization required

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