# Beam Position Monitors:
# Detector Principle and Signal Estimation

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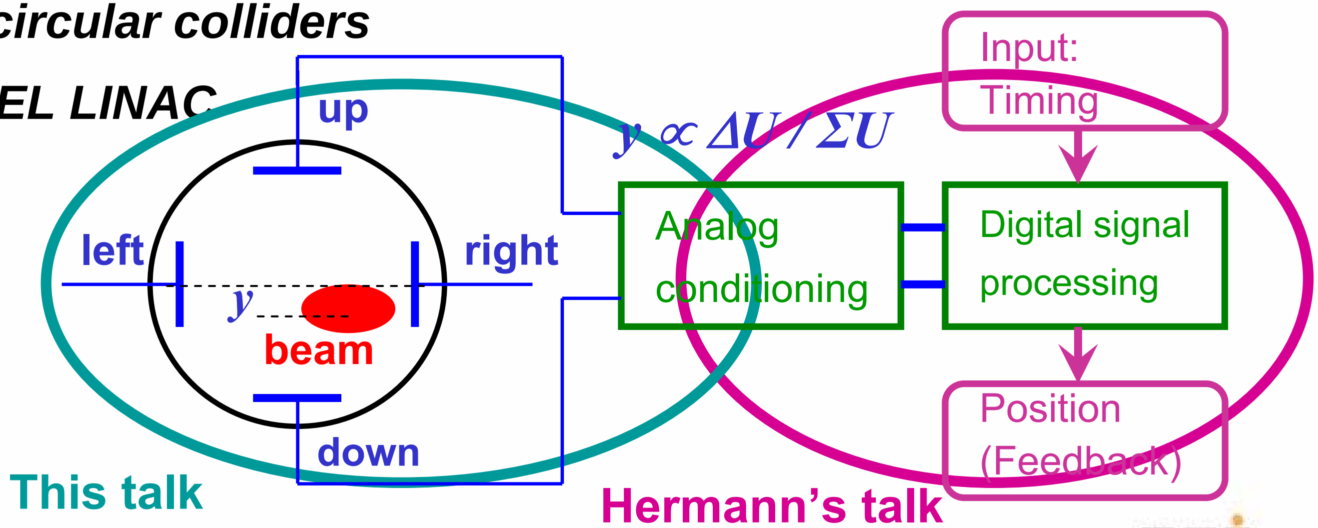
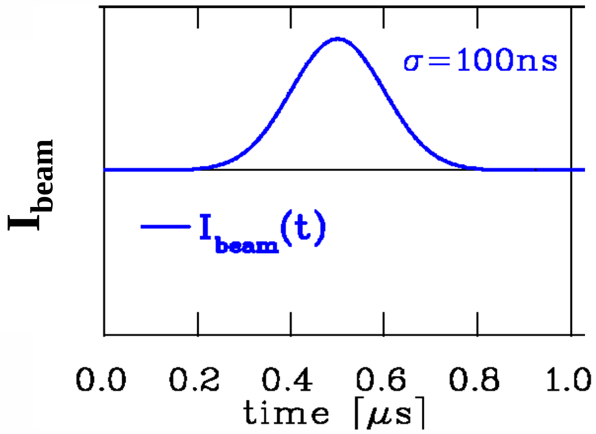
## Outline:

- General discussion on BPM features and specification
- Sum signal estimation, example 'shoe box' BPM for proton synchrotron
- Differential signal estimation, example 'button' BPM for p-LINAC and $e^-$
- 'Stripline' BPM for circular colliders
- 'Cavity' BPMs for FEL LINAC

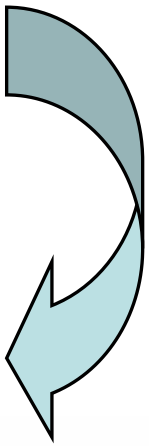


# Preface: Time Domain ↔ Frequency Domain

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



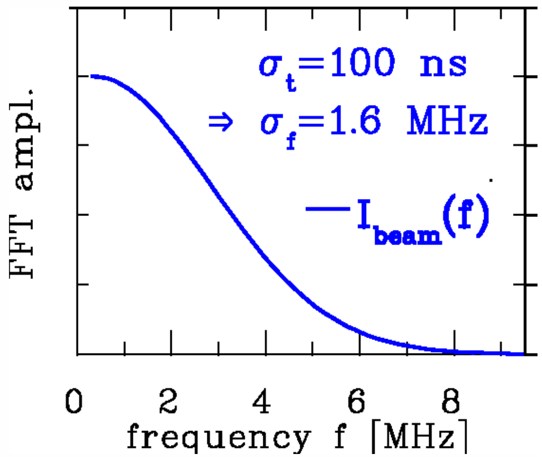

**Instrument:**
**Oscilloscope**



**Fourier Transformation:**

$$\tilde{f}(\omega) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} f(t) e^{-i\omega t} dt$$

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




**Instrument:**
**Spectrum Analyzer**
**or Fourier Transformation of time domain data**
**Care: Contains amplitude *and* phase**

# Usage of BPMs

**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

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

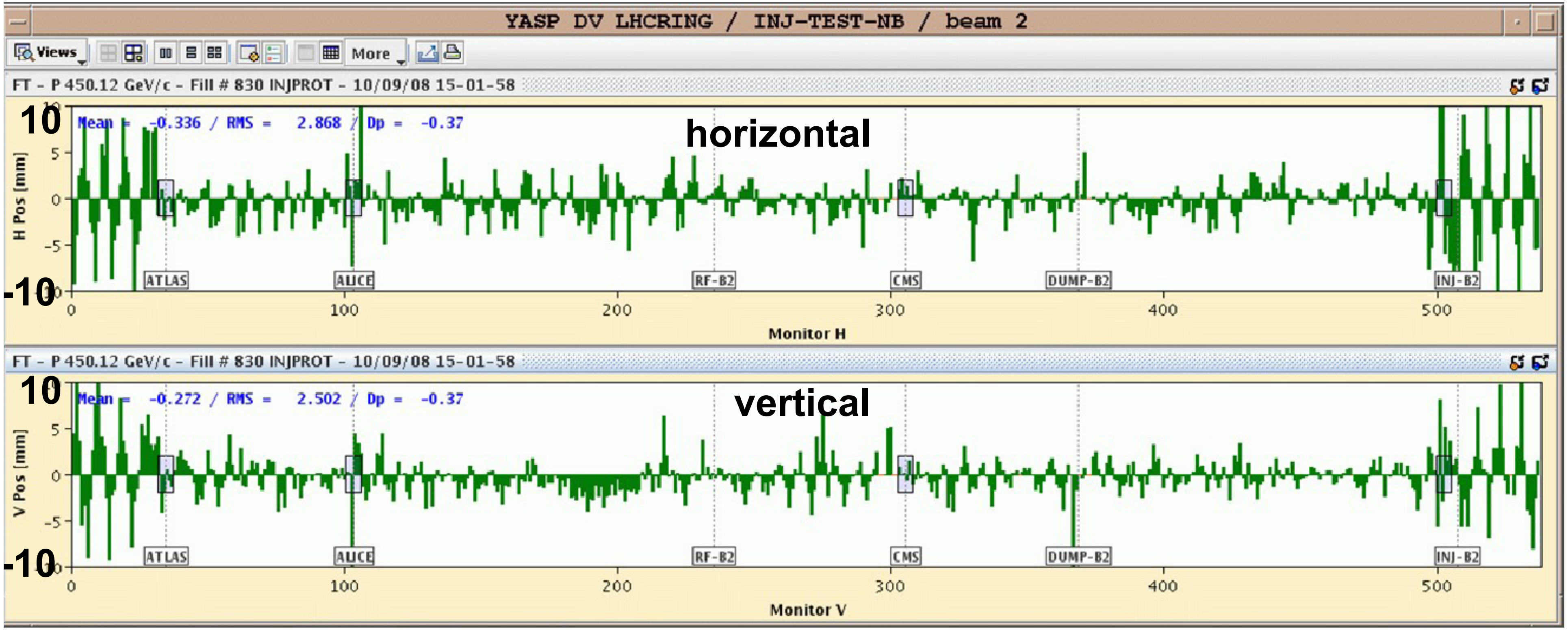
- ***Trajectory:*** Position of an individual bunch within a transfer line or synchrotron
- ***Closed orbit***: central orbit averaged over a period much longer than a betatron oscillation
- ***Single bunch position*** → determination of parameters like tune, chromaticity, β-function
- Bunch position 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

## Trajectory:

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

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

***Example:*** LHC injection 10/09/08 (y-axis: -10 → 10 mm, x-axis: monitor number 0 →530)

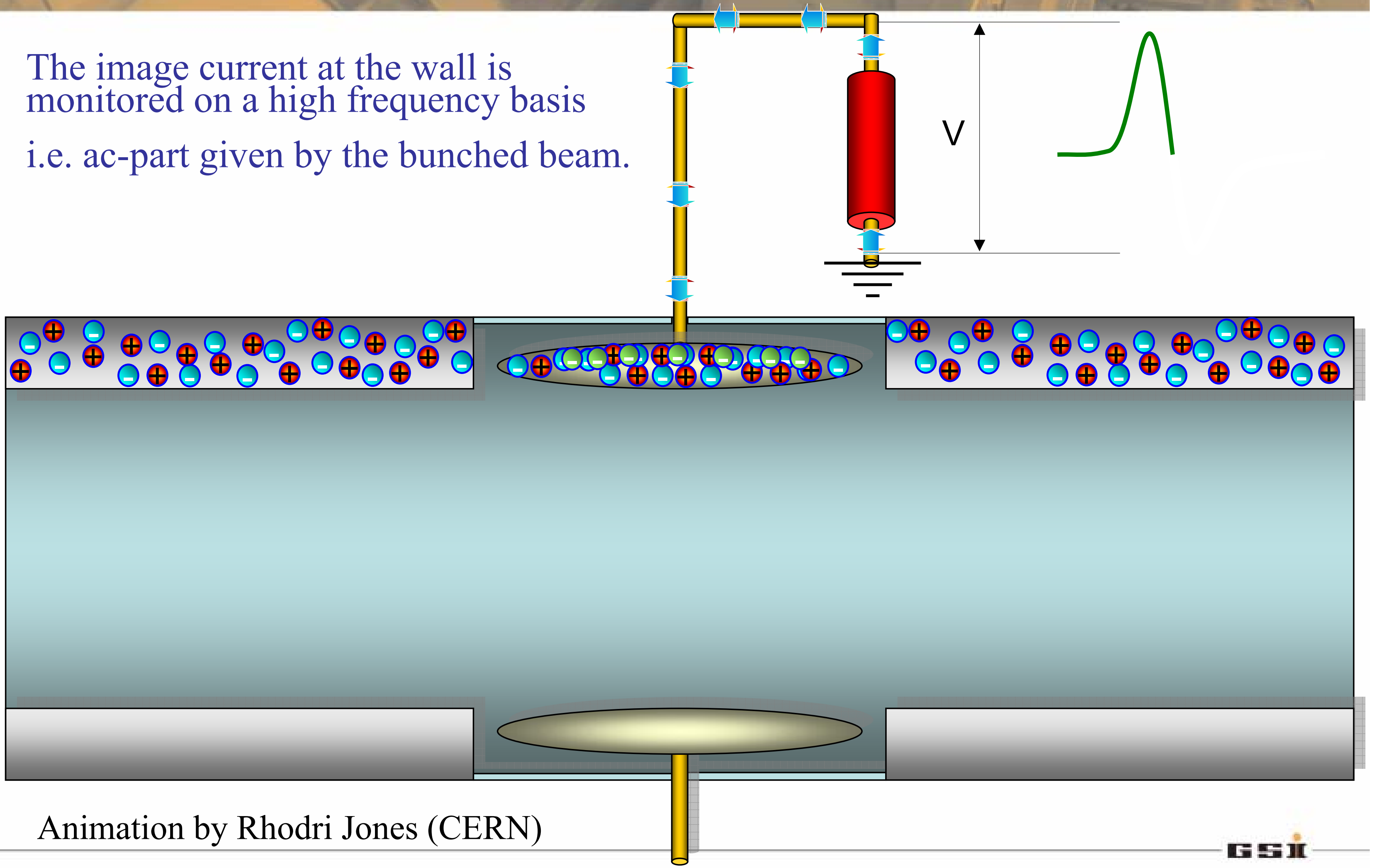



From R. Jones (CERN)

# Principle of Signal Generation of capacitive BPMs

The image current at the wall is monitored on a high frequency basis

i.e. ac-part given by the bunched beam.




Animation by Rhodri Jones (CERN)

**What are the general demands for a proper choice of BPMs?**

**What are the basic properties to characterize a BPM?**

**What are adequate technical terms required for the BPM specification?**

**What are reasons for the choice of an appropriate type?**

# 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')

- 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, ***goal:*** 10 % of beam width $\Delta x \approx 0.1 \cdot \sigma$
- 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

# Comparison of BPM Types (simplified)

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

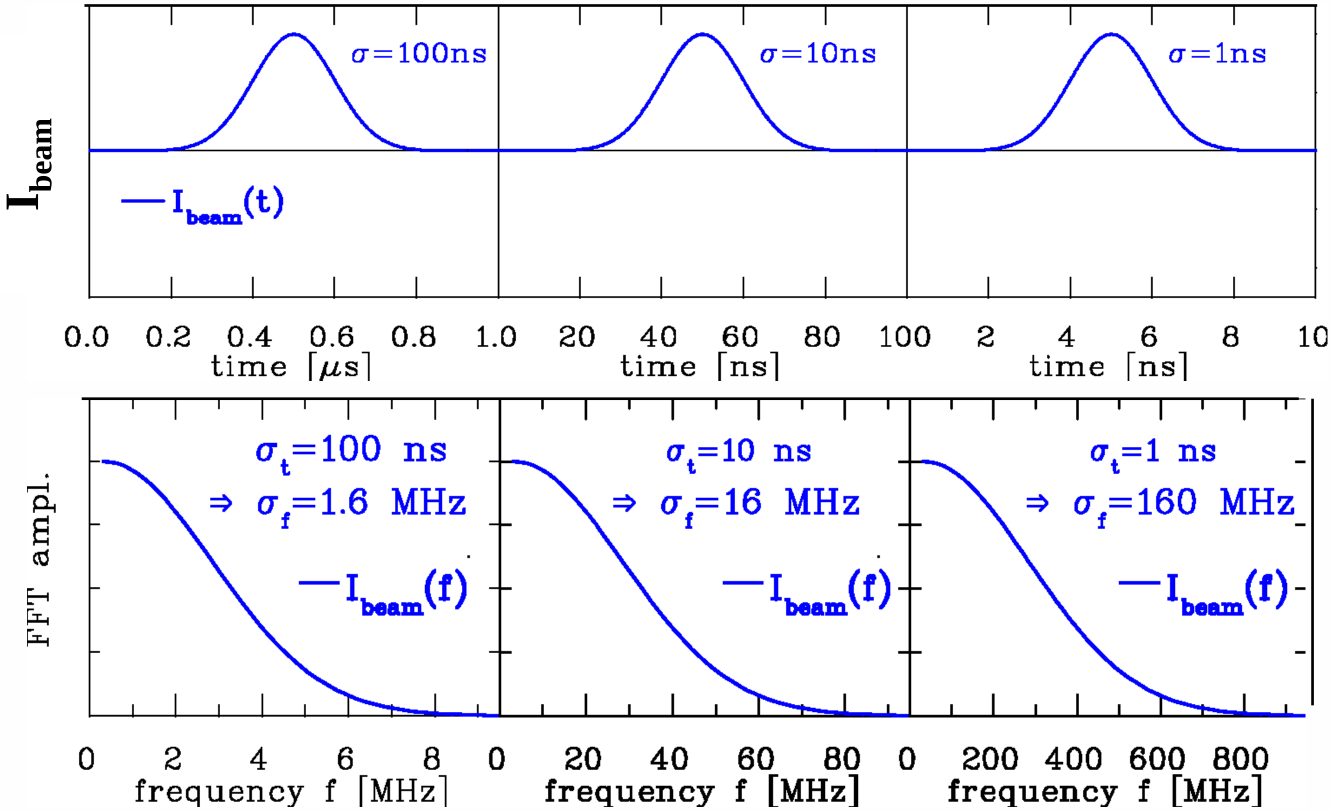
**2.1.1** What is the spectral function of a **single bunch?**

Assume a single bunch of Gaussian width $\sigma_t$=100 ns passing a BPM.

Sketch the spectral beam current $I_{beam}(f)$ as a function of frequency!

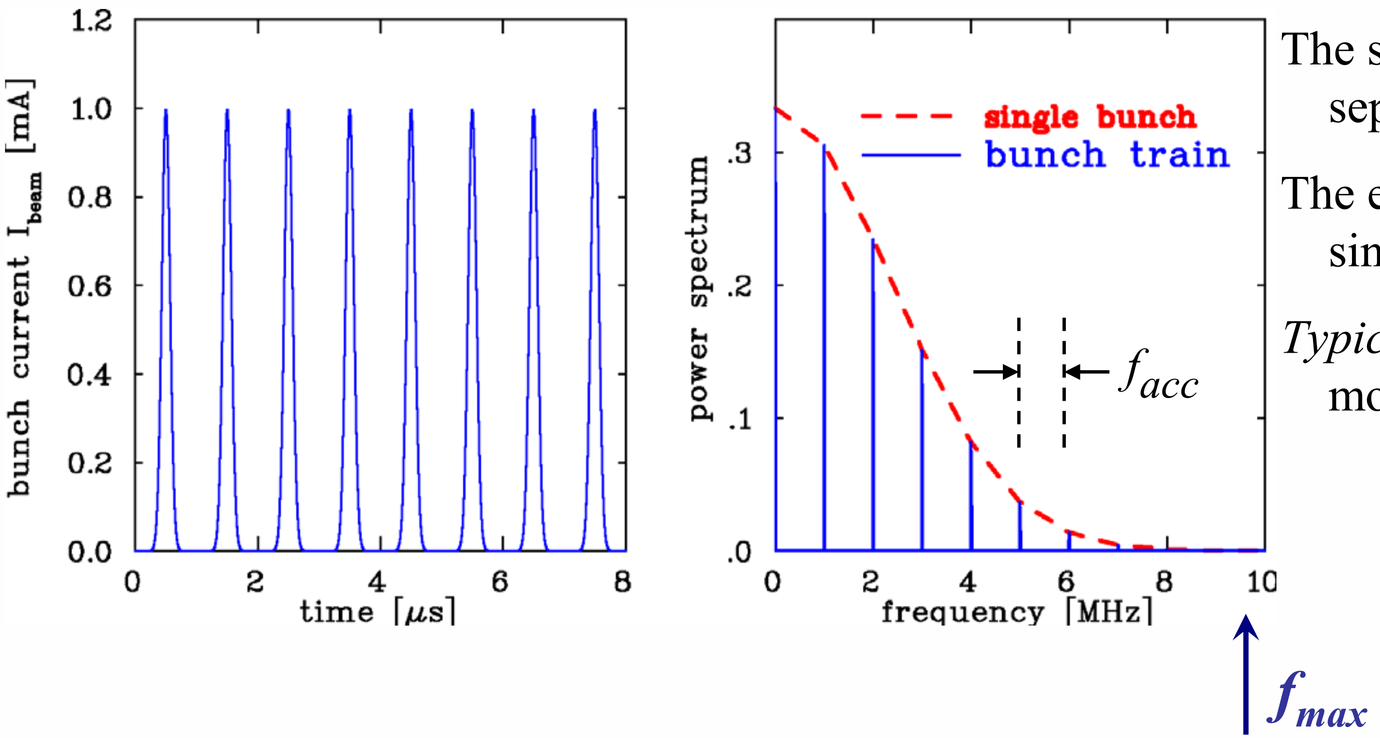
What are the corresponding values for $\sigma_t$=10 ns and $\sigma_t$=1 ns?

*Note*: The Fourier transformation of a Gaussian with $\sigma_t$ is a half Gaussian with $\sigma_f = 1/(2\pi\sigma_t)$.



## 2.1.2 What is the spectral function of a **train of bunches?**

Assume a train of bunches with $\sigma_t$=100 ns width and a repetition of $f_{acc}$=1 MHz.
Sketch the spectral beam current $I_{beam}(f)$ as a function of frequency!




The spectrum consists of line separated by $f_{acc}$.

The envelope is given by the single bunch.

*Typical* value for p-synch.: most power below ≈$10 \cdot f_{max}$.

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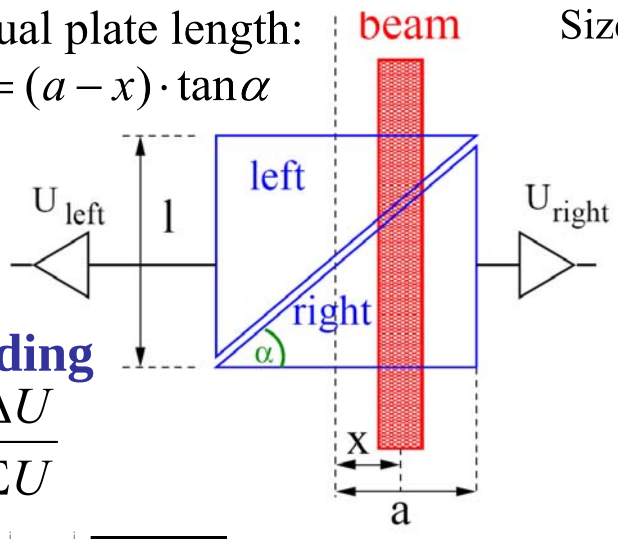
# Shoe-box BPM for Proton or Ion Synchrotron

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

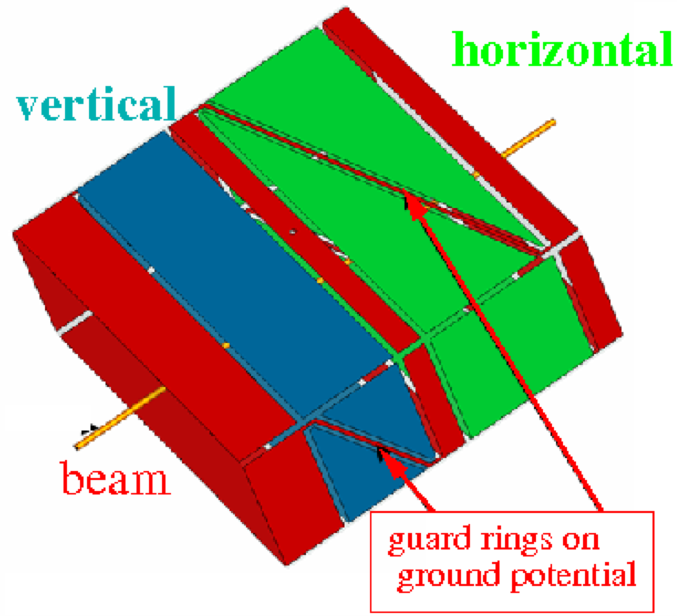
Signal is proportional to actual plate length:

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

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

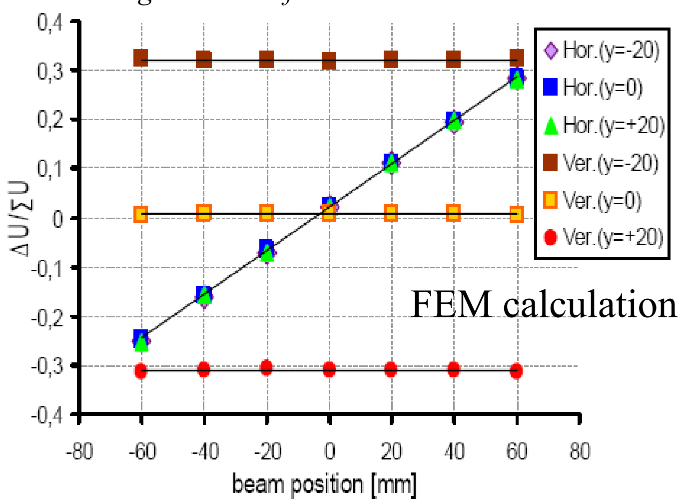



Size: 200x70 mm$^2$




**In ideal case: linear reading**

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

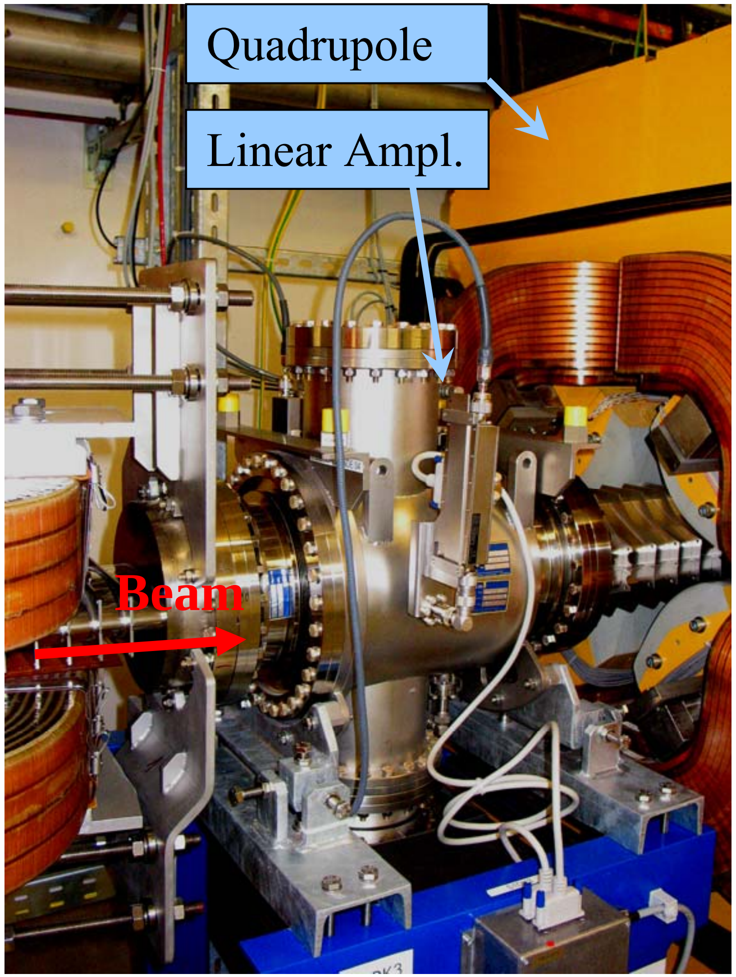


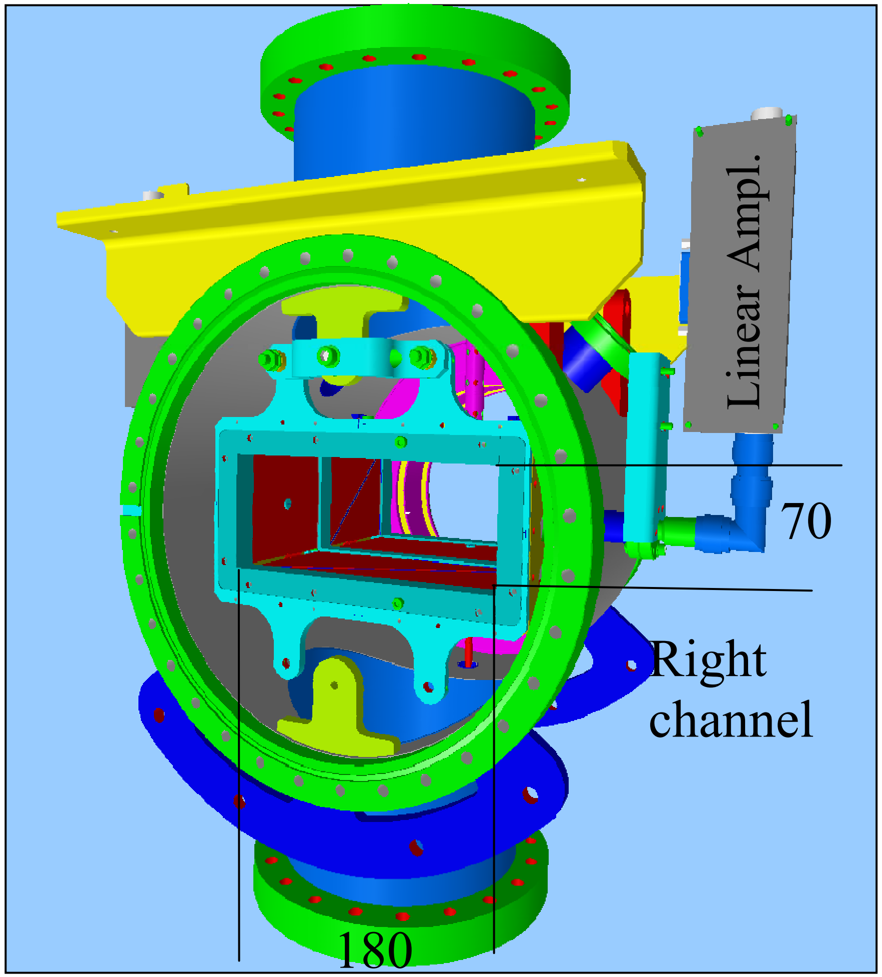

**Shoe-box BPM:**

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

**Disadvantage:** Large size, complex mechanics high capacitance

Technical realization at HIT synchrotron of 46 m length for 7 MeV/u→440 MeV/u
BPM clearance: 180x70 mm$^2$, standard beam pipe diameter: 200 mm.

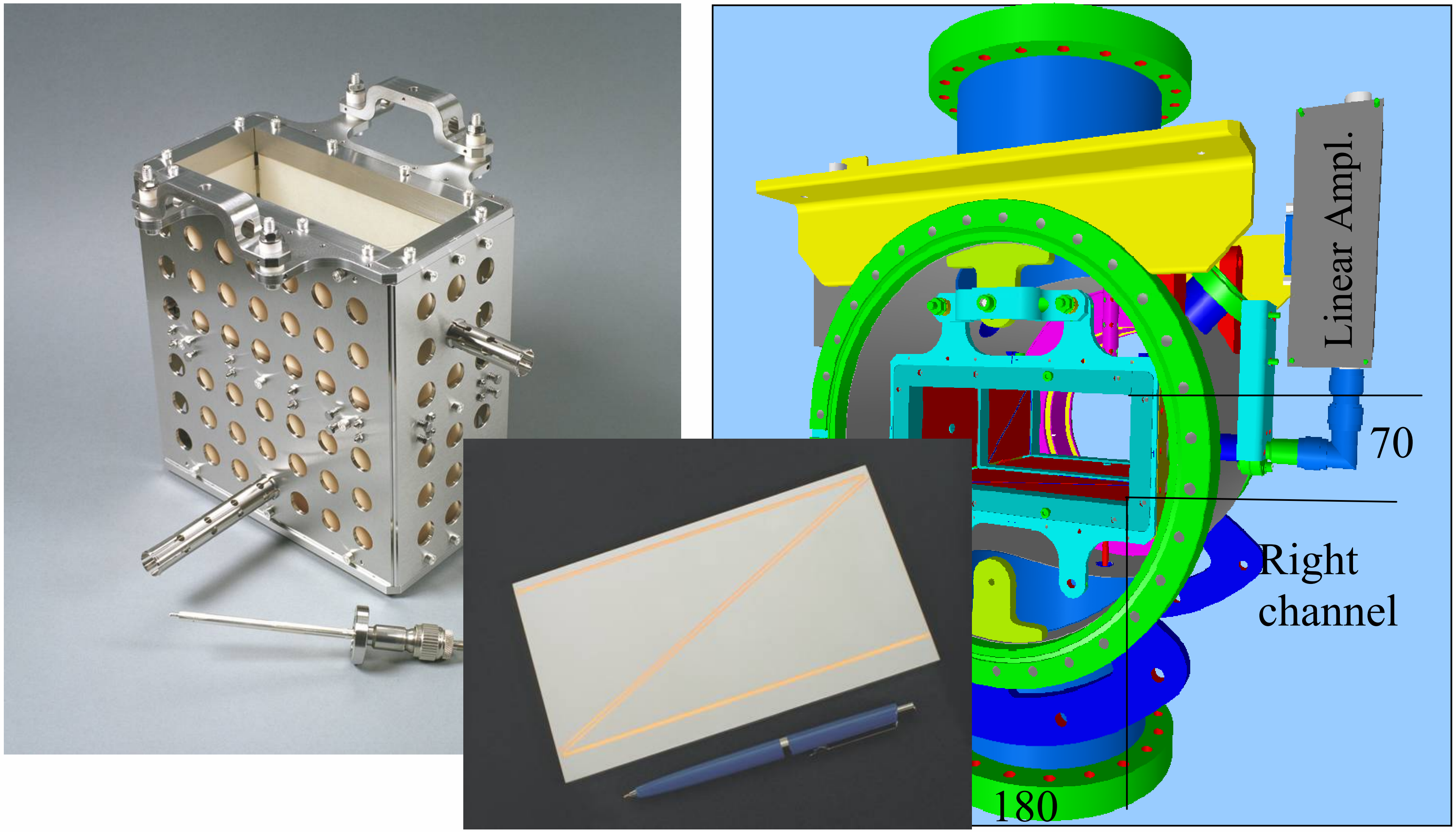


# Technical Realization of Shoe-Box BPM

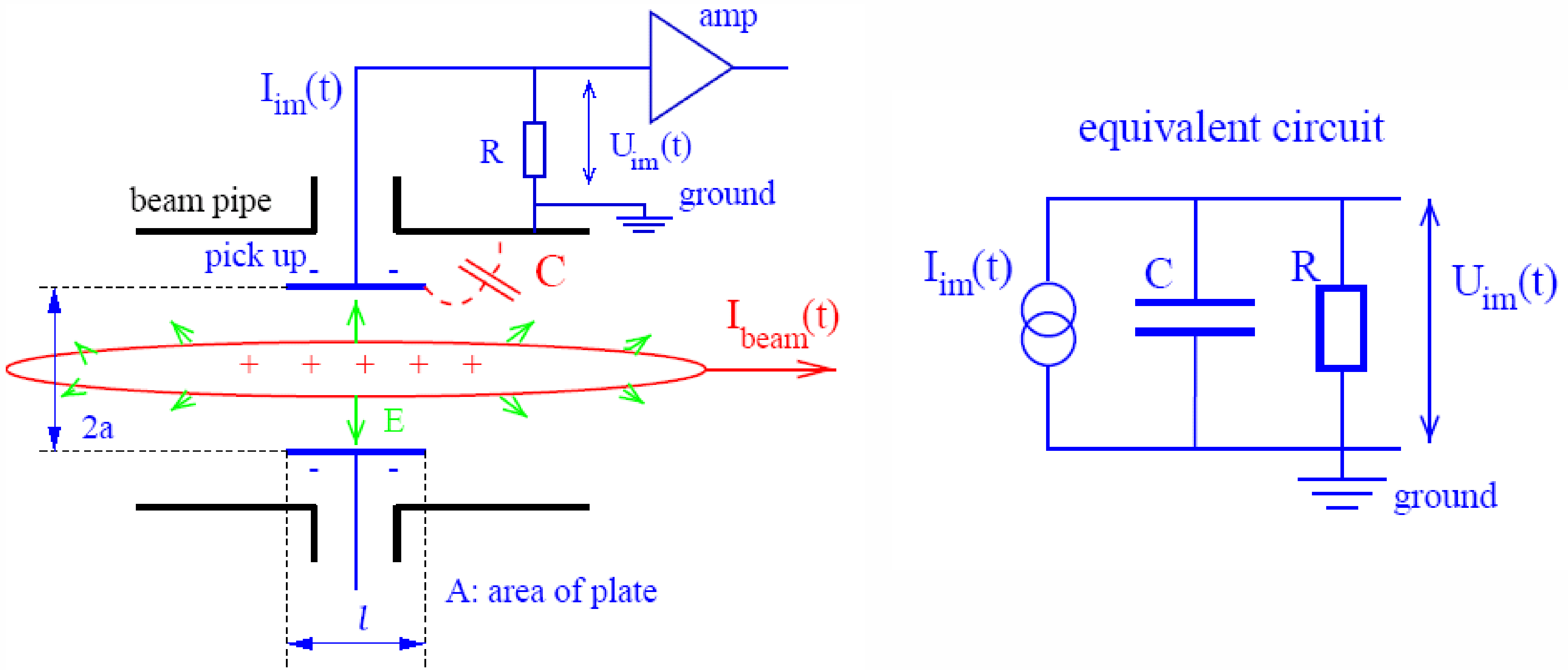
Technical realization at HIT synchrotron of 46 m length for 7 MeV/u→440 MeV/u

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



# 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 geometry and the capacitive coupling:

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

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

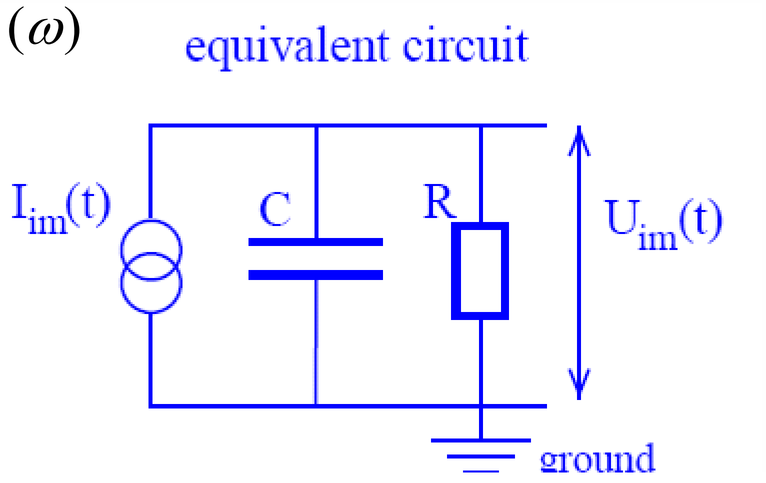
# Transfer Impedance for capacitive BPM

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

***Capacitive coupling:*** $I_{im}(\omega) = \frac{A}{2\pi a} \cdot \frac{1}{\beta c} \cdot i\omega I_{beam}(\omega)$

***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:




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

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

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

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

$\Rightarrow$ this is a **high-pass** with $\omega_{cut} = 1/(RC) \Leftrightarrow f_{cut} = 1/(2\pi RC)$:

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

**What is the spectral function of a bunched beam seen by the capacitive BPM?**

**2.2.1** Calculate the cut-off frequency $f_{cut}=1/(2\pi RC)$ for $R$=50 Ω (for voltage measurement) and $C$=100 pF (capacitance BPM-Plates-wall, cable etc.)!

Sketch the transfer impedance $Z_t(f)$ as a function of frequency! (high-pass characteristic)

The cut-off frequency is

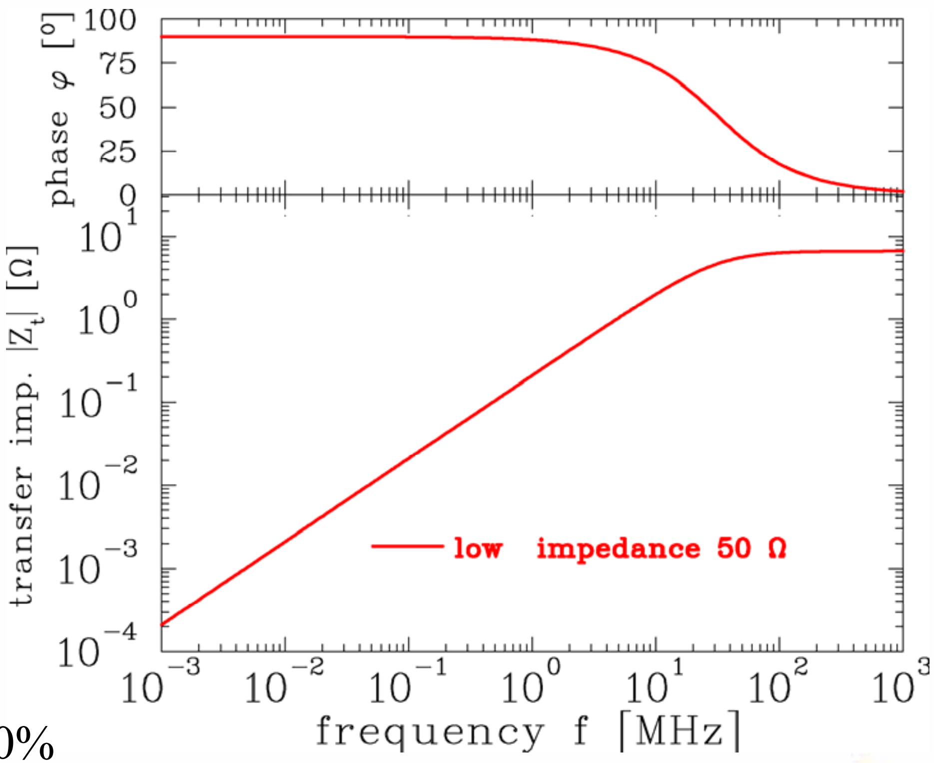
$f_{cut}=1/(2\pi RC)$=32 MHz.

$Z_t(f)$ is described by a first order high-pass:

$$|Z_t(f)| = \frac{A}{2\pi a}\cdot\frac{1}{\beta c}\cdot\frac{1}{C}\cdot\frac{f/f_{cut}}{\sqrt{1+f^2/f^2_{cut}}}$$

geometry — capacitance — high-pass

$|Z_t(f>f_{cut})|$=7 Ω for a 10 cm long cylinder, $\beta$=50%

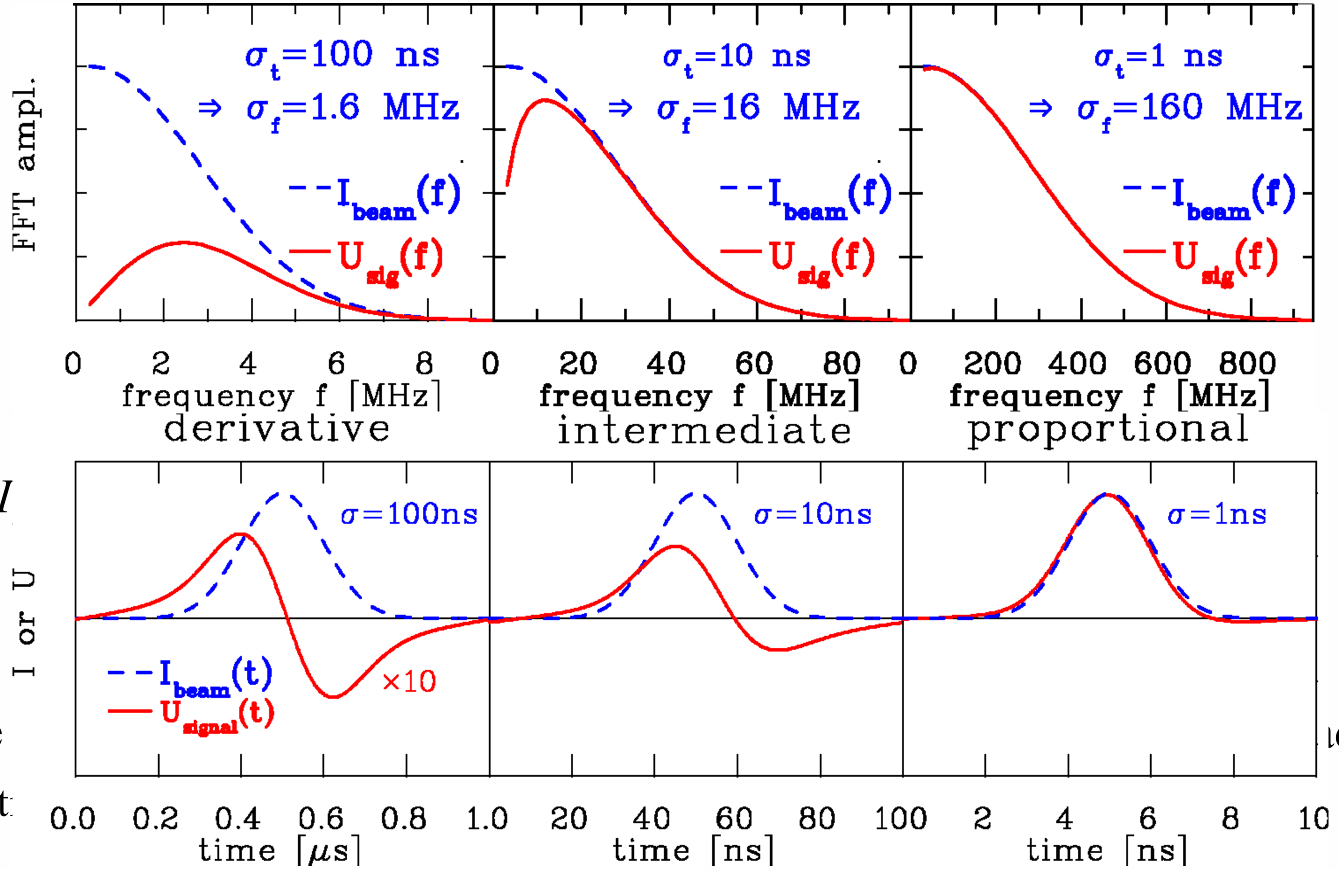


**2.2.2** What is the voltage spectrum for the case of a **single** bunch with

$\sigma_t$=100 ns, $\sigma_t$=10 ns and $\sigma_t$=1 ns as discussed above with $f_{cut}=1/(2\pi RC)$=32 MHz ?

What type of math. algorithm is used for the calculation of the time dependent $U_{signal}(t)$?

Sketch the time dependent voltage $U_{signal}(t)$ for these cases !




Given *I*

For the ... ıdding φ(*f*)

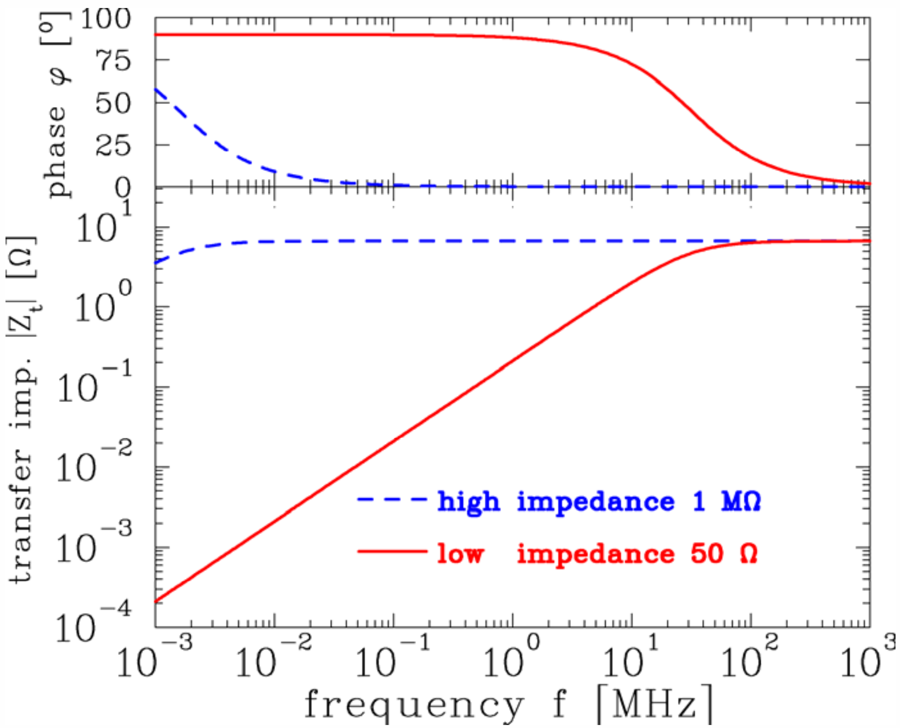
Calculat

**2.2.4** Sometimes a high impedance termination with $R$=1 MΩ is used for shoe-box BPMs.
What is the cut-off frequency $f_{cut}=1/(2\pi RC)$ in this case ($C$=100 pF) ?
Sketch and discuss the signal voltage for the case of a bunch train with $\sigma_t$=100 ns !
What might be reasons for this choice?

The cut-off frequency is

$f_{cut}=1/(2\pi RC)$=1.6 kHz

⇒ the proportional shape is recorded



# Numerical Value of $U_{signal}(t)$ with 1M$\Omega$ Termination

**2.2.4** Sometimes a high impedance termination with $R$=1 M$\Omega$ is used for shoe-box BPMs.
What is the cut-off frequency $f_{cut}=1/(2\pi RC)$ in this case ($C$=100 pF) ?
Sketch and discuss the signal voltage for the case of a bunch train with $\sigma_t$=100 ns !
What might be reasons for this choice?

The cut-off frequency is

$f_{cut}=1/(2\pi RC)$=1.6 kHz

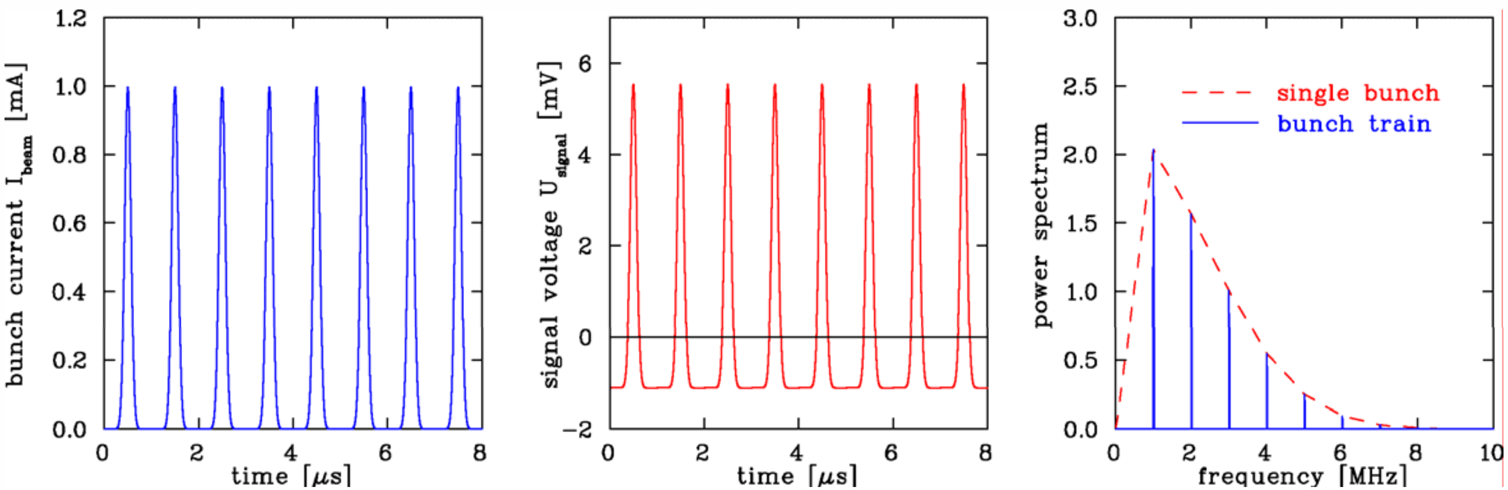
$\Rightarrow$ the proportional shape is recorded

Signal strength for long bunches is $U_{signal}=Z_t(f>f_{cut}) \cdot I_{beam}$

A baseline shift occur i.e. no dc-transmission

Reason for this choice: larger signal *independent* on bunch length

***However:*** larger thermal noise due to $U_{eff}=(4kB \cdot T \cdot \Delta f \cdot R)^{1/2}$



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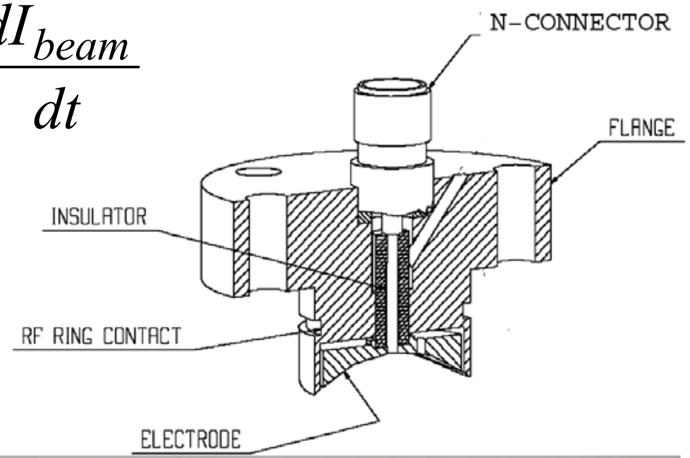
LINACs, e$^-$-synchrotrons: 100 MHz < $f_{rf}$ < 3 GHz → bunch length ≈ BPM length

→ 50 Ω signal path to prevent reflections

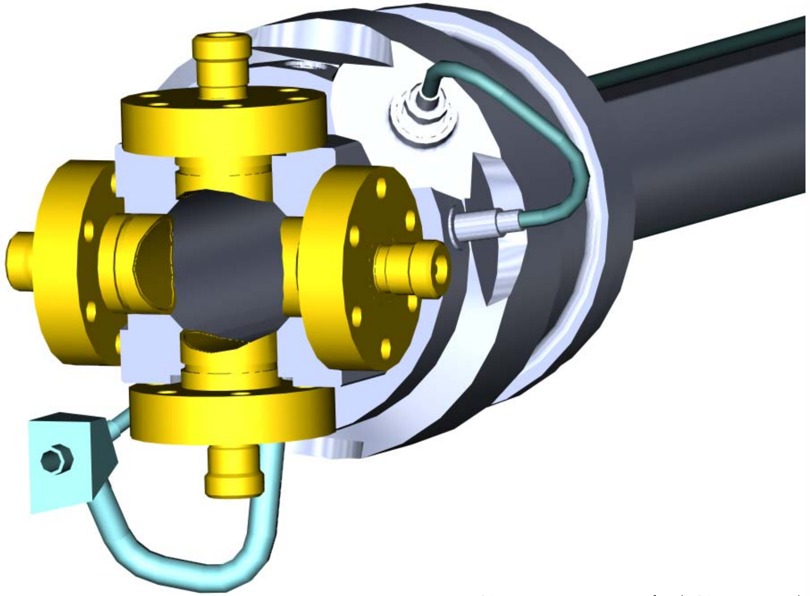
Button BPM with 50 Ω ⇒ $U_{sig}(t) = R \cdot \frac{A}{2\pi a} \cdot \frac{1}{\beta c} \cdot \frac{dI_{beam}}{dt}$




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)

# Button BPM for short Bunches

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

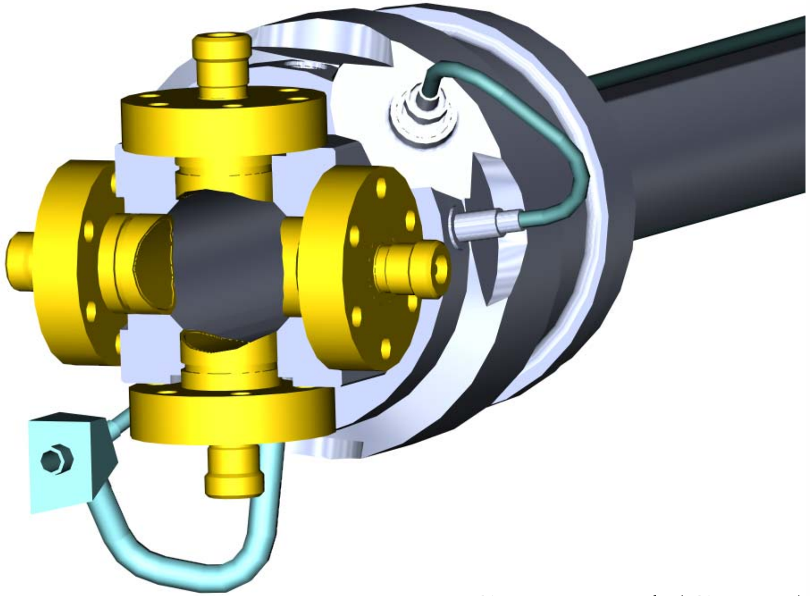
→ 50 Ω signal path to prevent reflections

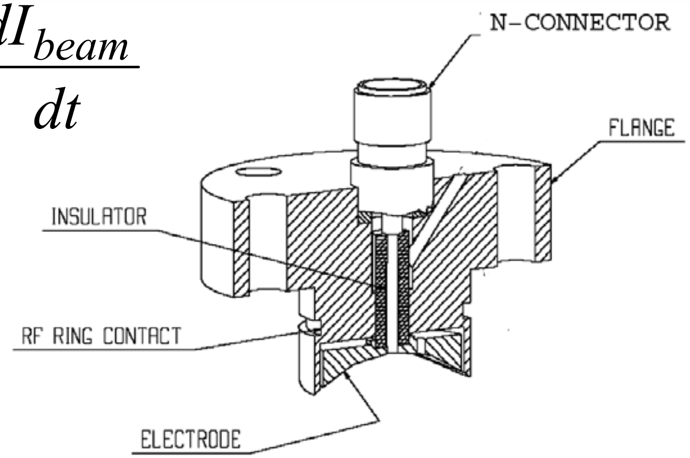
Button BPM with 50 Ω $\Rightarrow U_{sig}(t) = R \cdot \frac{A}{2\pi a} \cdot \frac{1}{\beta c} \cdot \frac{dI_{beam}}{dt}$

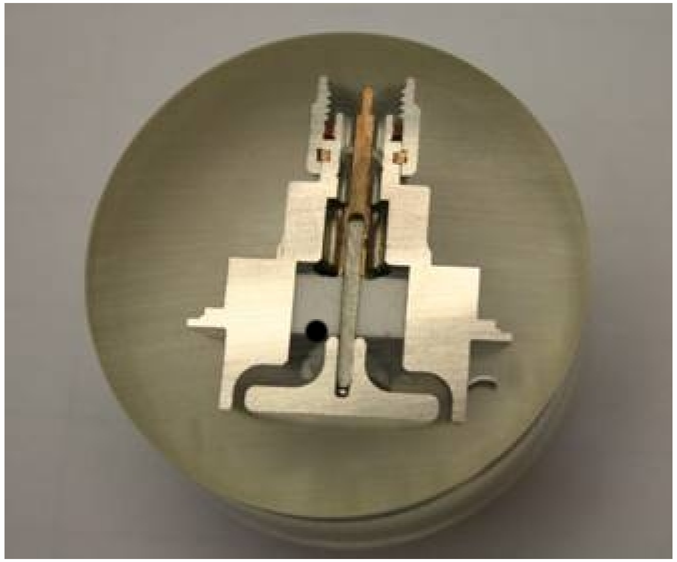
Example: LHC-type inside cryostat:

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

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





From C. Boccard (CERN)

From K.Wittenburg (DESY)

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

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

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

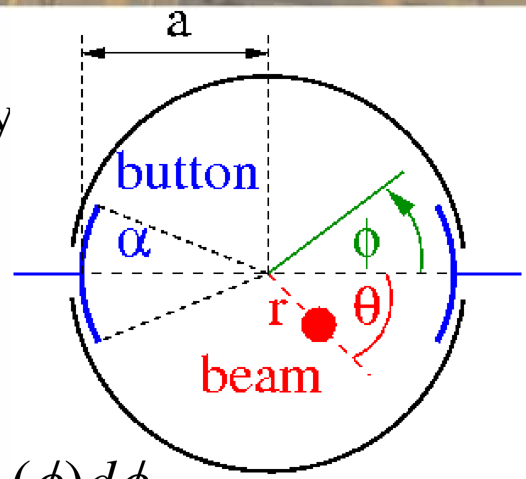
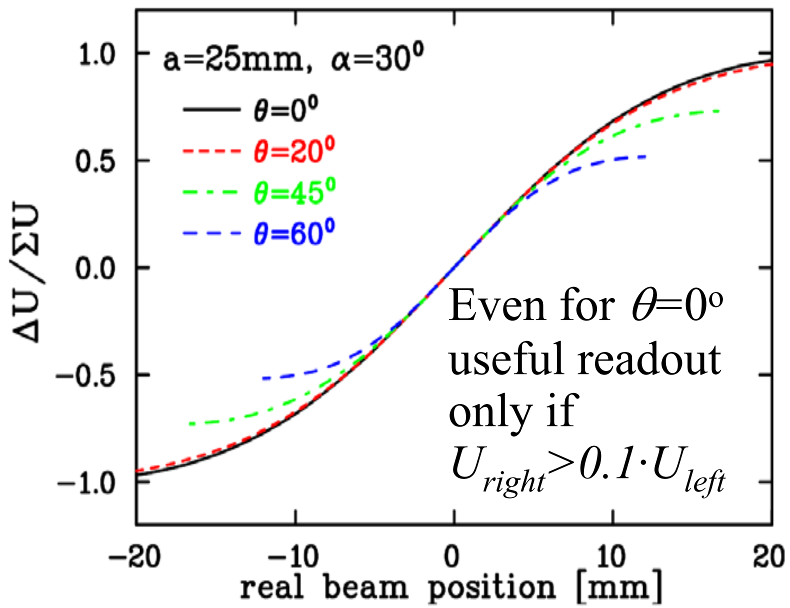
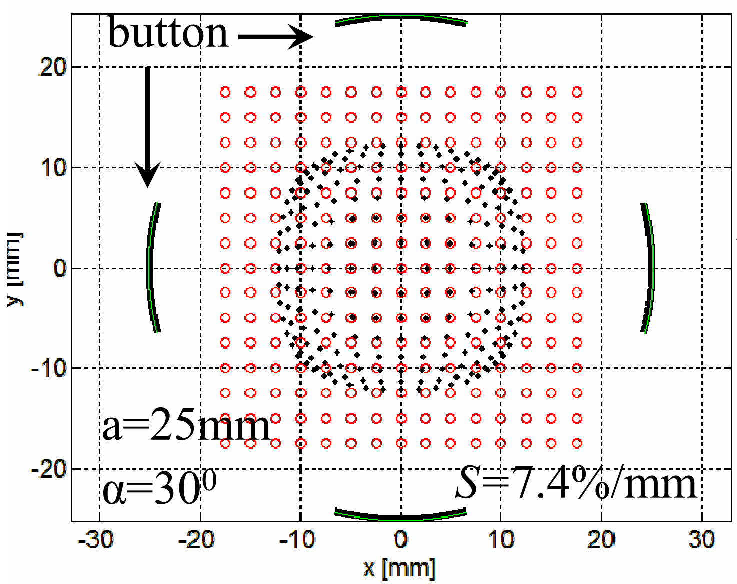



Image current: Integration of finite BPM size: $I_{im} = a \cdot \int_{-\alpha/2}^{\alpha/2} j_{im}(\phi) d\phi$




**Position map:**
Beam position & result using ΔU/ΣU
⇒non-linear *S(x,y)*
⇒ beam size dependent

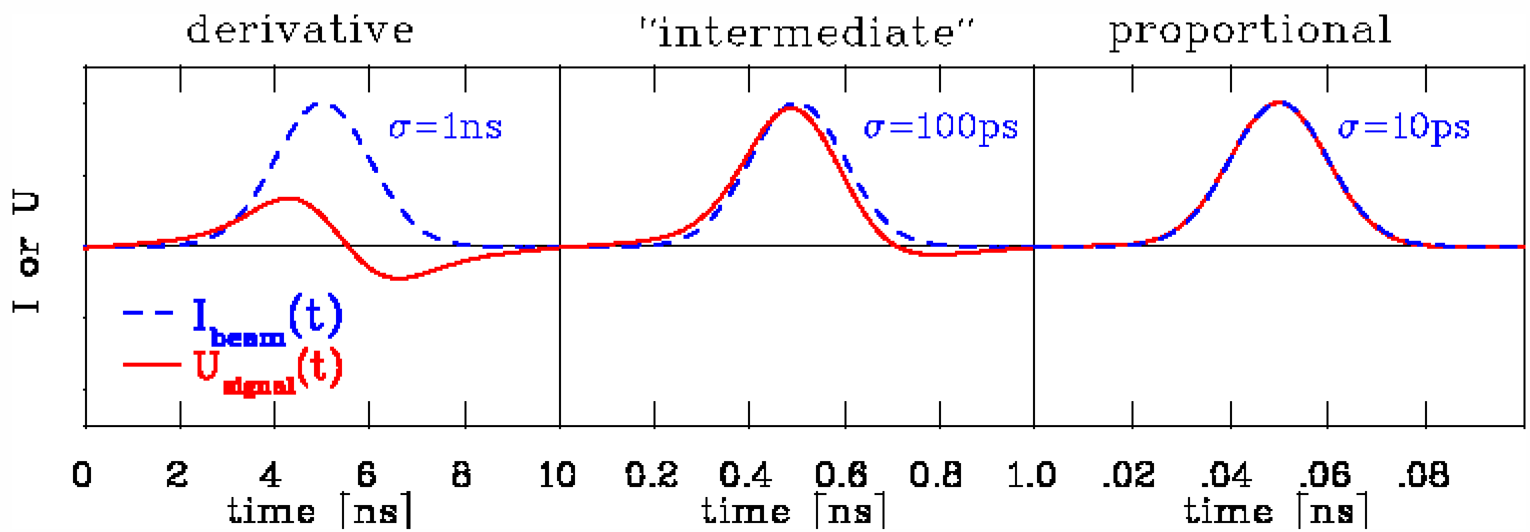
# Estimation of Signal Voltage for Button BPM

**2.3.1** What is the signal voltage shape for a single bunch of $\sigma_t$=1 ns, $\sigma_t$=100 ps and $\sigma_t$=10 ps?
Sketch the time dependent voltage $U_{signal}(t)$ for these cases !
Assume a termination of $R$=50 Ω and a capacitance $C$=5 pF.

The cut-off frequency is $f_{cut}=1/(2\pi RC)$=640 MHz.

For $\sigma_t$=1 ns $\Rightarrow \sigma_f=1/2\pi\sigma_t$ = 160 MHz i.e. main component below $f_{cut}$ ⇒ derivative

For $\sigma_t$=10 ps $\Rightarrow \sigma_f=1/2\pi\sigma_t$ = 16 GHz i.e. main component above $f_{cut}$ ⇒ proportional

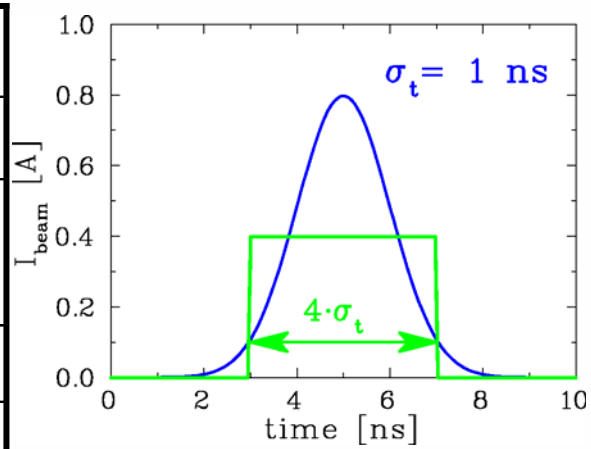


# Numerical Value of Signal Voltage for Button BPM

**2.3.2** Calculate the signal voltage $U_{signal}(t)$ for the cases $\sigma_t$=1 ns, $\sigma_t$=100 ps and $\sigma_t$=10 ps?
Assume $N=10^{10}$ electrons per bunch and transfer impedance $|Z_t(f>f_{cut})|=1\ \Omega$,.
Use a boxcar like bunch shape of width $4\cdot\sigma$, $e = 1.6\cdot10^{-19}$ C, $v_{beam} = c$.
Discuss briefly possible problems for short bunch observations!

For $N=10^{10}$ electron within *boxcar-like* bunch shape of $6\sigma_t$ the beam current is: $I_{beam}=eN/6\sigma_t$

| **Bunch length $\sigma_t$ [ps]** | **1000** | **100** | **10** |
|---|---|---|---|
| **Current $I_{beam}$ [A]** | 0.4 | 4 | 40 |
| **Signal $U_{signal}$ [V]** | 0.4<br>due to $f>f_{cut}\approx0.2$ V | 4 | 40 |
| **Bunch length $\sigma_l$ [cm]** | 30 | 3 | 0.3 |
| **Spectrum width $\sigma_f$ [GHz]** | 0.16 | 1.6 | 16 |




If one assumes a *Gaussian bunch shape*: Maximum voltage ≈2 larger than the average value.
⇒ *e.g.* $U_{signal}$ = 80 V for $\sigma_t$=10 ps !

If the bunch length is comparable to button size→ signal propagation must be considered

Technical item: Bandwidth of feed-through typically below ≈ 3 GHz.

# Difference Voltage for position Measurement

**2.3.3** The beam position is obtained via $x = 1/S \cdot (U_{right} - U_{left})/(U_{right} + U_{left})$ (linear processing)

***S*** is the position sensitivity with a typical value of $S$ = 10 %/mm (at the BPM center).

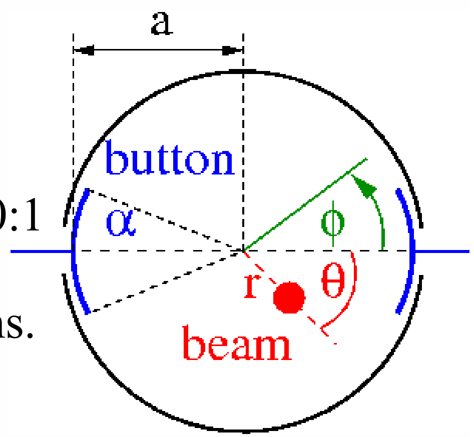
What is the precision of the voltage reading for the detection of 10 µm offset ?

What is the related numerical value of $\Delta U=(U_{right}-U_{left})$ for a single bunch of $\sigma_t$=1 ns ?

Thermal noise $U_{eff}=(4k_B \cdot T \cdot \Delta f \cdot R)^{1/2}$ contributes to any signal, $k_B=1.4 \cdot 10^{-23}$ J/K.

Calculate the thermal noise for $\Delta f$=1 GHz and $T$=300 K!

What is the beam current for a S-to-N of 2:1? What is a strategy for enlarged resolution?




Due to $S$=10 %/mm an 10 µm offset transforms to ratio $\Delta U/\Sigma U$ = 0.1 %

For the case of $\Sigma U$=400 mV it is $\boldsymbol{\Delta U=10^{-3} \cdot \Sigma U=}$ **400 µV** only

The thermal noise for $\Delta f$=1 GHz is $U_{eff}$=30 µV → S-to-N = $\Delta U/U_{eff} \approx$ 10:1

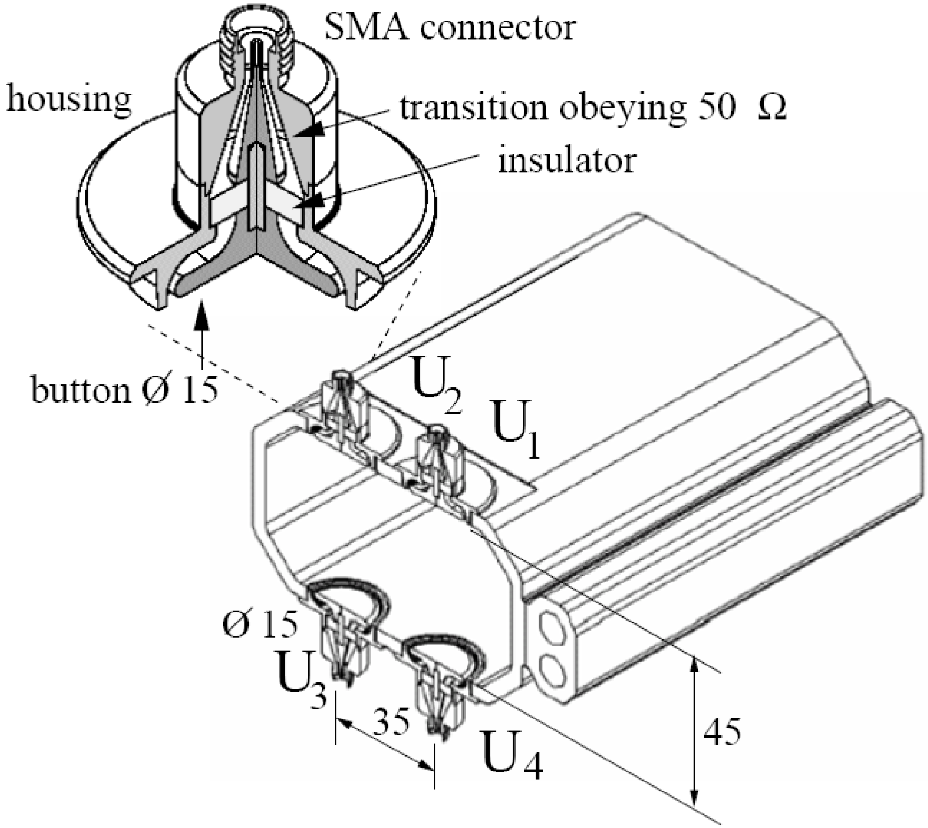
For a S-to-N=2:1 a current of $I_{beam}$=50 µA is required i.e. $N=10^9$ electrons.

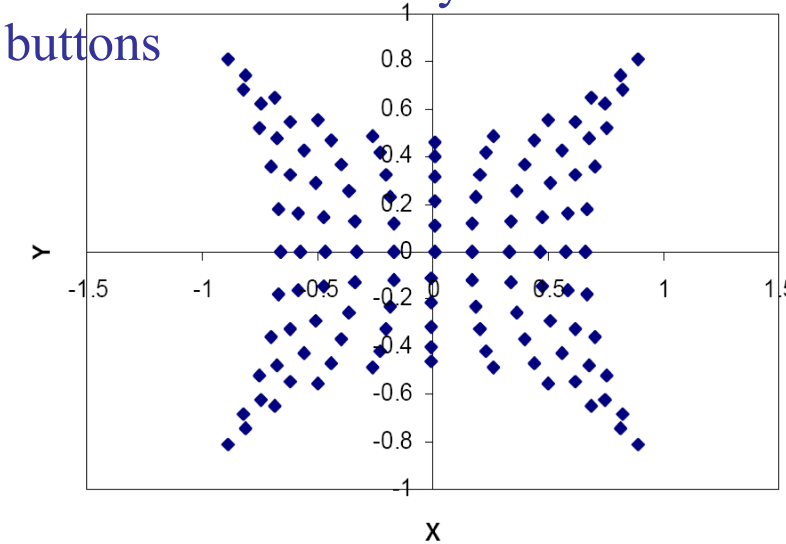
Realistic value: Amplifier has at least 3 time higher noise.

The main improvement is gained by a restriction of bandwidth $\Delta f$, down to kHz.
Correspondingly the time resolution of any position variation decreases!

# 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%/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

## Outline:

- General discussion on BPM features and specification
- Sum signal estimation, example 'shoe box' BPM for proton synchrotron
- Differential signal estimation, example 'button' BPM for p-LINAC and $e^-$
- **Stripline BPM for circular colliders**
- Cavity BPMs for FEL LINAC

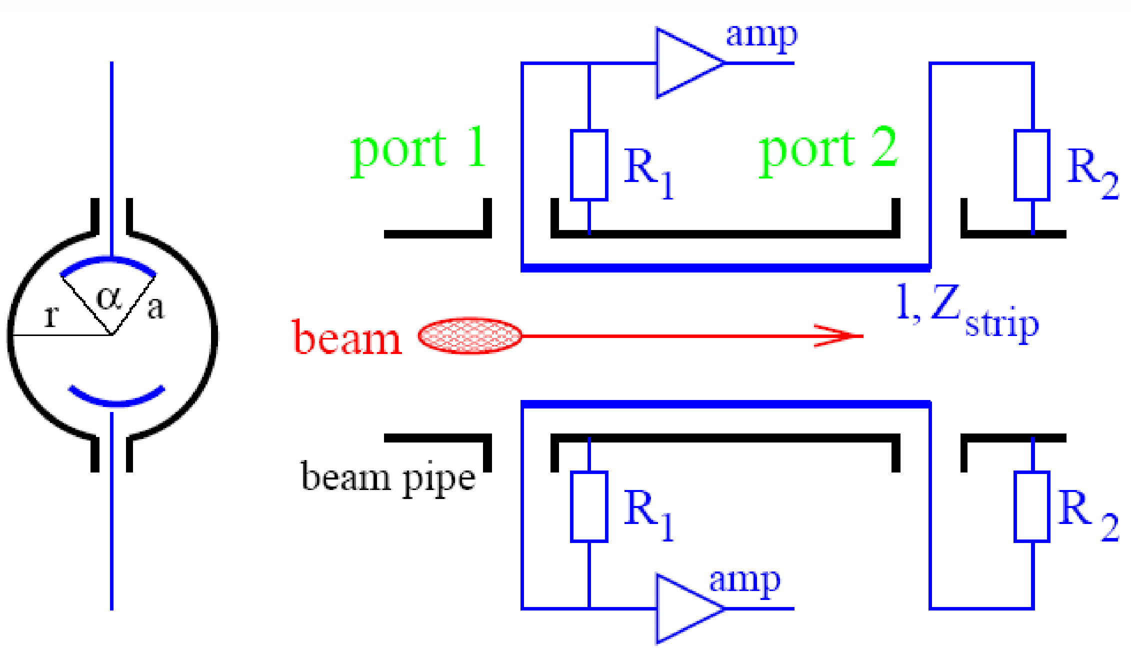
# Stripline BPM: General Idea

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

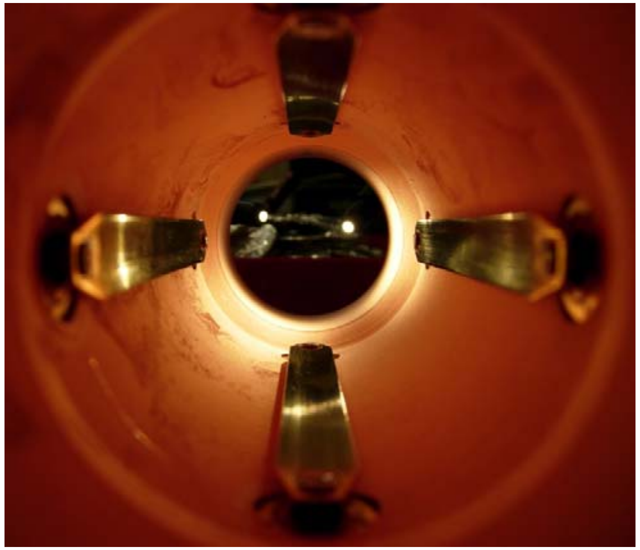
→ Relativistic beam $\boldsymbol{\beta \approx 1}$ ⇒ field of bunches nearly TEM wave

→ 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



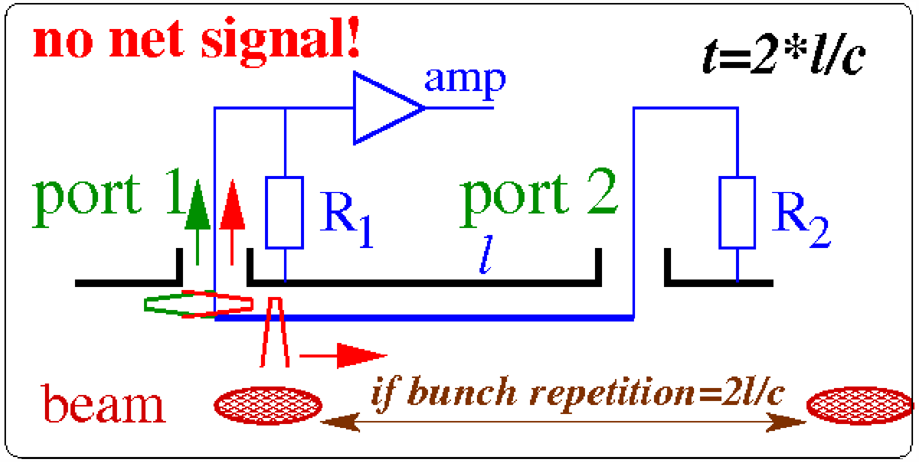
From C. Boccard, CERN

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 $\boldsymbol{R_1}$, 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 direction ⇔ directional coupler: e.g. can distinguish between $e^-$ and $e^+$ in collider

# Signal Voltage for stripline BPM

**3.2** Sketch the signal voltage of a stripline BPM for a single bunch with $\sigma_t$=100 ps !

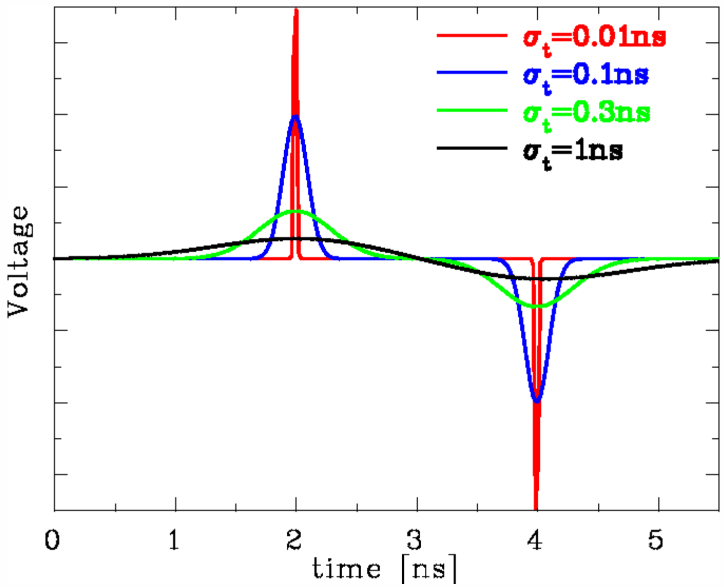
Use the following parameter: Strip length $l$=30 cm, transfer imp. $Z_t$=1.5 Ω at its maximum.

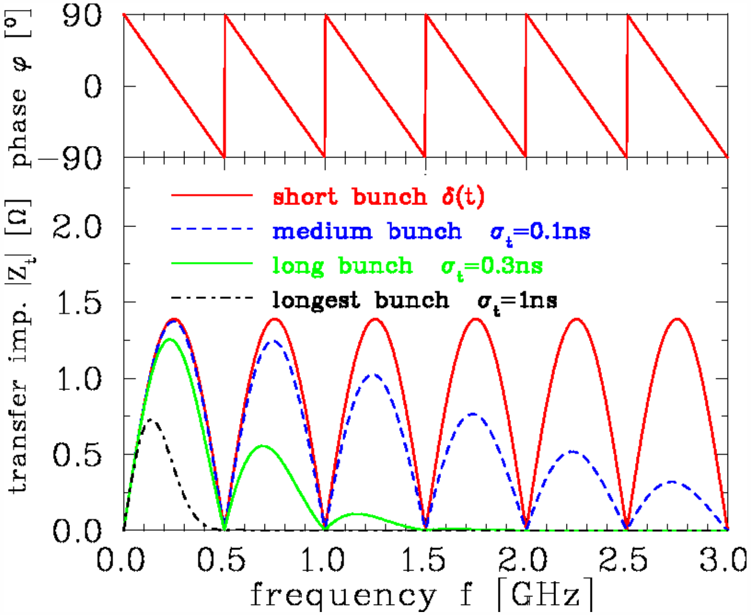
Sketch the transfer impedance!

How is the signal shape and transfer impedance modified for longer bunches ?

*The bunch length* $\sigma_t$=100 ps is short compared to the transit time $2l/c \Rightarrow$ no overlap

The shape of $Z_t(f)$ are comps with minima at $n \cdot c/2l$ with a envelop given by $\sigma_f = 1/2\pi\sigma_t$ .




Short bunches: $Z_t$ is periodic, for long bunches ($\sigma_t$>0.3ns) overlapping occur, $Z_t$ max. not reached

## *Outline:*

- ***General discussion on BPM features and specification***
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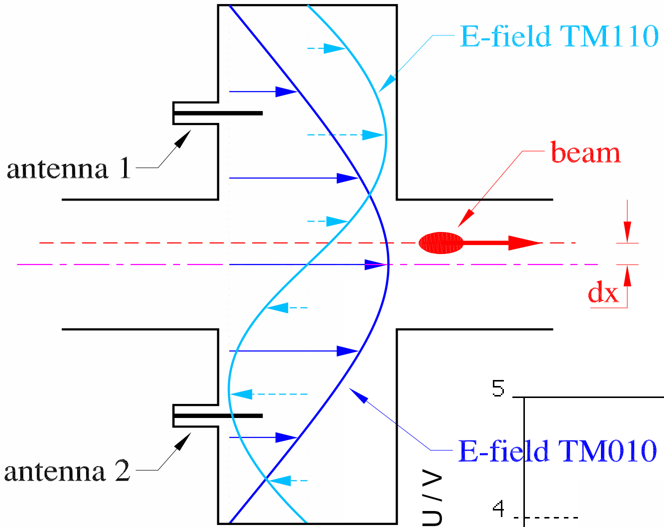
- ***Differential signal estimation, example 'button' BPM for p-LINAC and $e^-$***
- ***Stripline BPM for circular colliders***
- ***Cavity BPMs for FEL LINAC***

# Cavity BPM: Principle

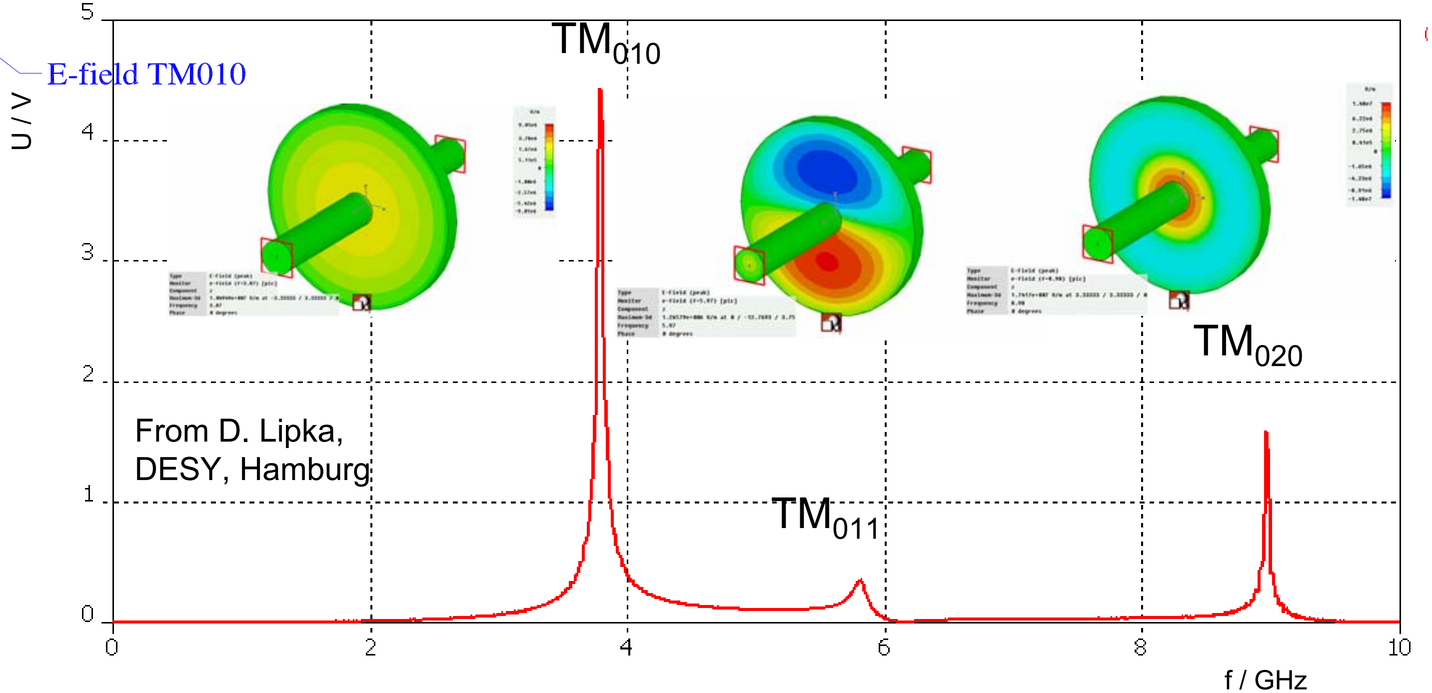
High resolution on µs time scale can be achieved by excitation of a dipole mode:




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
(ILC, X-FEL…)

# Cavity BPM: Example of Realization

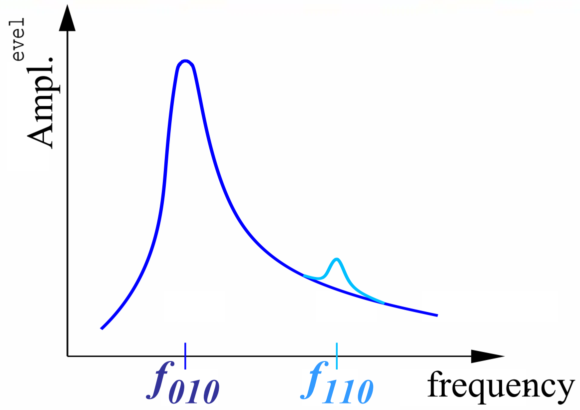
Basic consideration for detection of eigen-frequency amplitudes:

Dipole mode $f_{110}$ separated from monopole mode

due to finite quality factor $Q \Rightarrow \Delta f = f/Q$

- Frequency $f_{110} \approx 1 \dots 10$ GHz
- Waveguide house the antennas

Task: suppression of $TM_{010}$ mono-pole mode




FNAL realization:

Cavity: ∅ 113 mm

Gap 15 mm

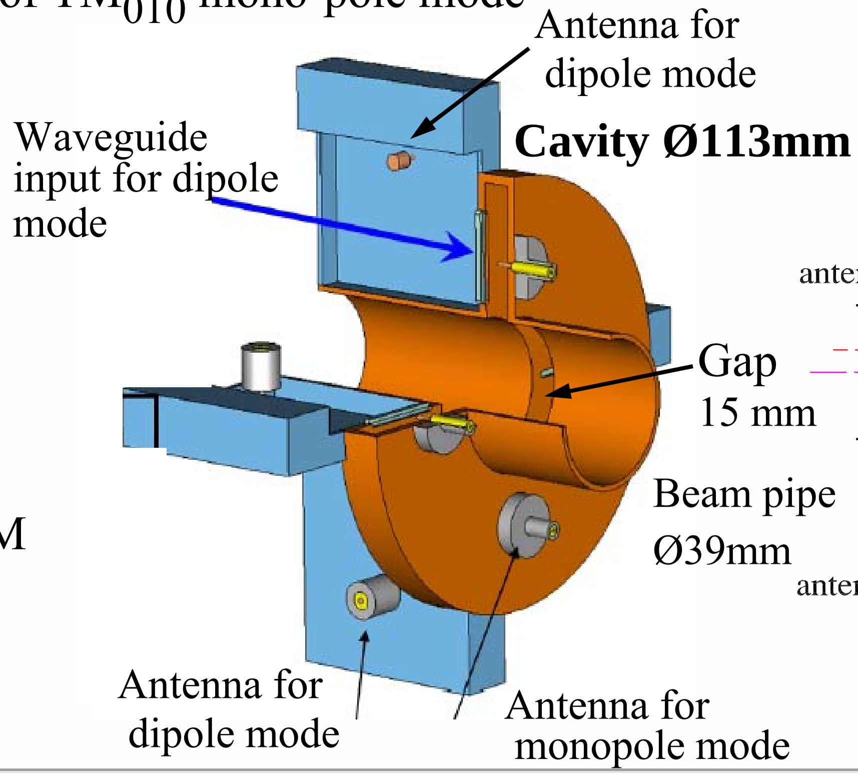
Mono. $f_{010}$=1.1GHz

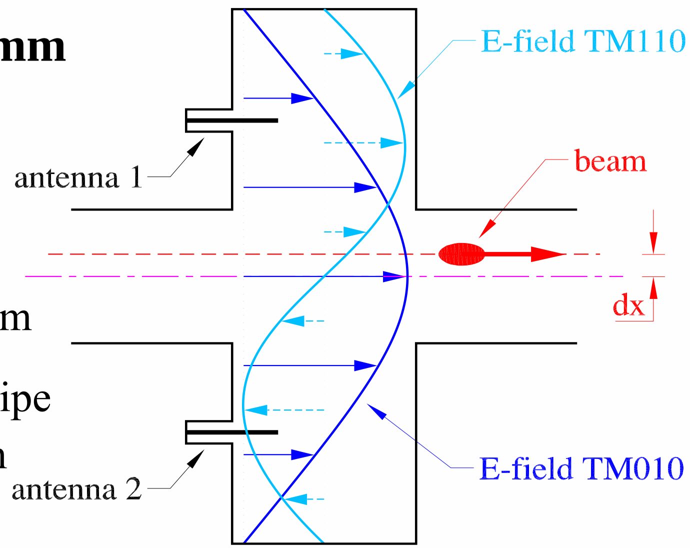
Dipole. $f_{110}$=1.5GHz

$Q_{load} \approx 600$

With comparable BPM

**⇒0.1 μm resolution within 1 μs**



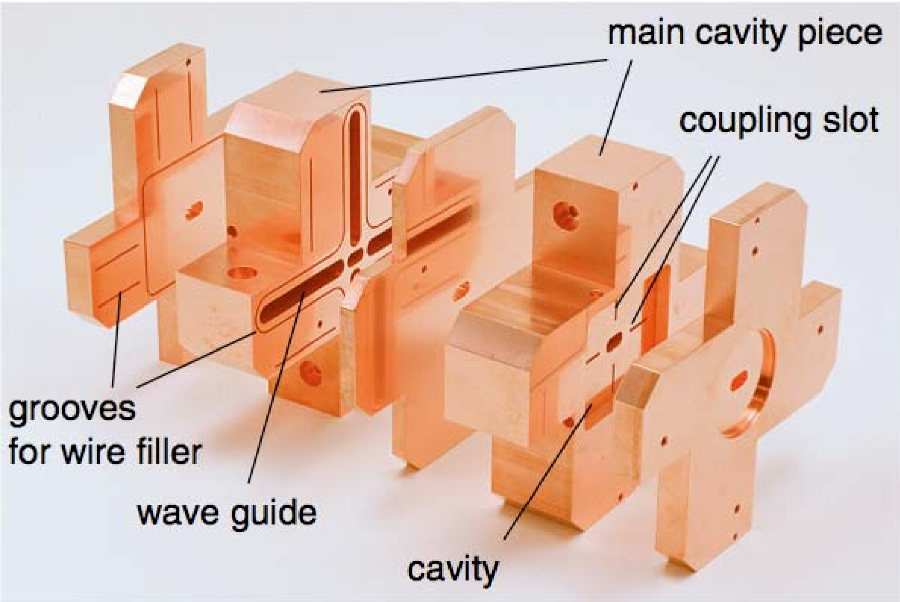

From M. Wendt (FNAL)

Courtesy of D. Lipka & Y. Honda

# Cavity BPM: Suppression of monopole Mode

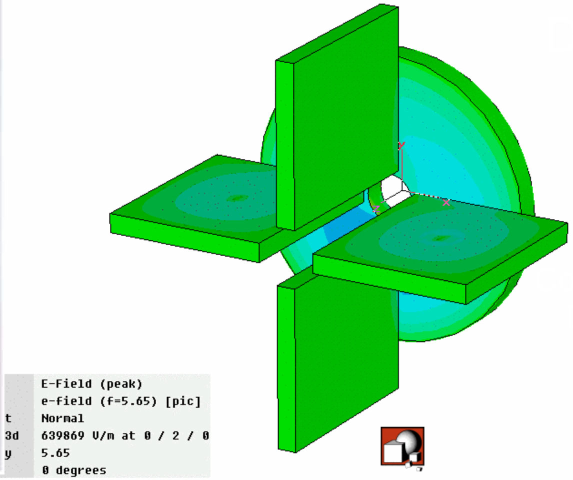
Suppression of mono-pole mode: waveguide that couple only to dipole-mode

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

**3.3** Sketch the signal voltage of a cavity BPM for a single bunch with $\sigma_t$=100 ps !

Use the following parameter: Resonance frequency $f$=4 GHz, quality factor $Q_L$=1000.

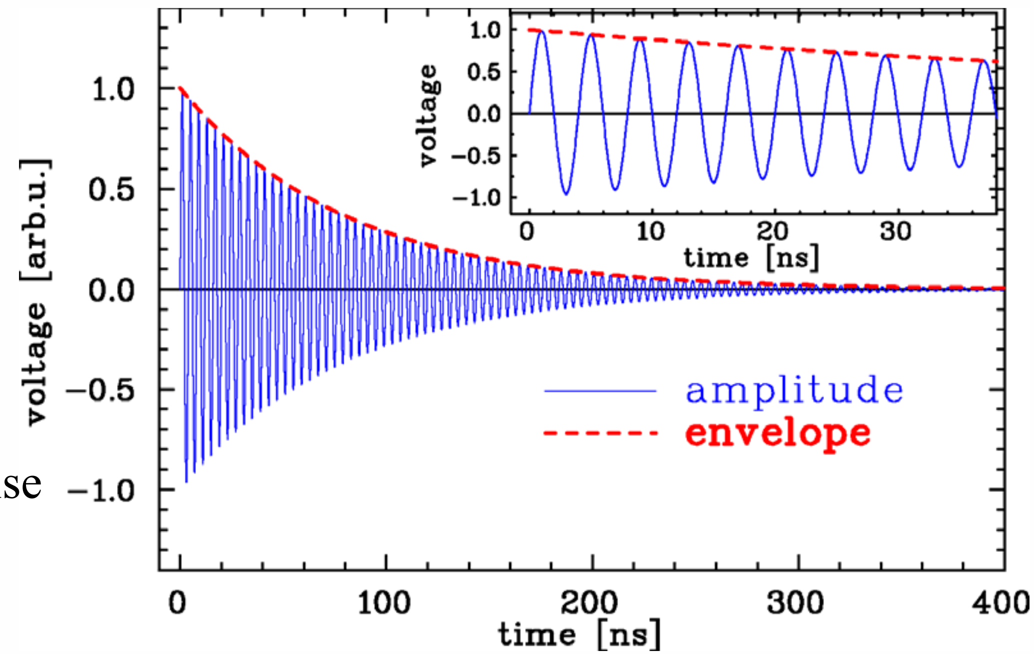
What influences the choice for the value of $Q_L$?

The excited oscillation is described by $U_{signal}(t) = U_0 \cdot e^{-2\pi f/2Qt} \cdot \sin(2\pi f \cdot t)$.

For the given quality factor $Q_L$ the damping time is $\tau = 2Q_L/2\pi f \approx 80$ ns .

**Large $Q_L$**: larger integrated signal
larger position sensitivity

**Small $Q_L$** : Faster reaction to acceding pulse
broadband
→ better excited by bunch.



# Signal Voltage for stripline BPM

**3.4** Discuss briefly the reasons for an appropriate choice of shoebox button, stripline and cavity types !

- ***Shoebox:*** for low frequencies (proton synchrotron)
  Linear position reading, no beam-size dependence
- ***Button:*** BPMs are easier to produce and have simpler processing scheme.
- ***Stripline:*** BPMs have lower signal deformation and offer directivity for colliders
  i.e. counter-propagating beams within one beam pipe.
- ***Cavity:*** BPMs have much higher single pass resolution.

# Comparison of BPM Types (simplified)

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

**Thank you for your attention!**