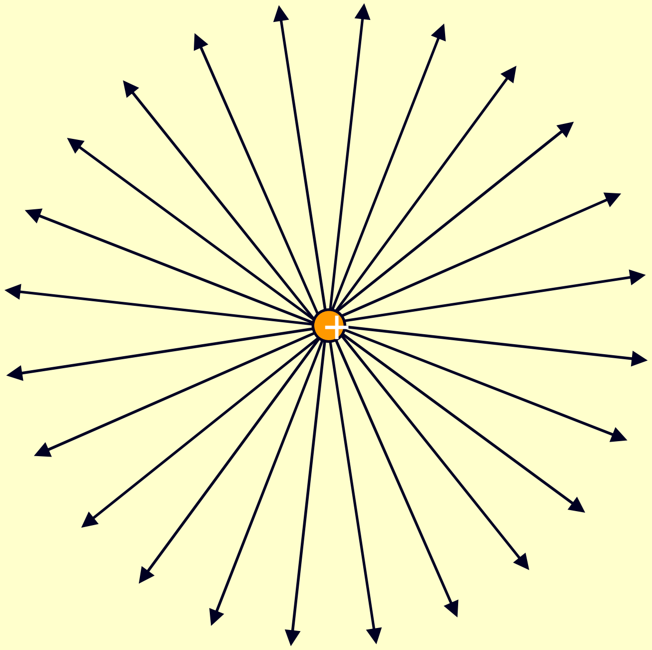
BPM design

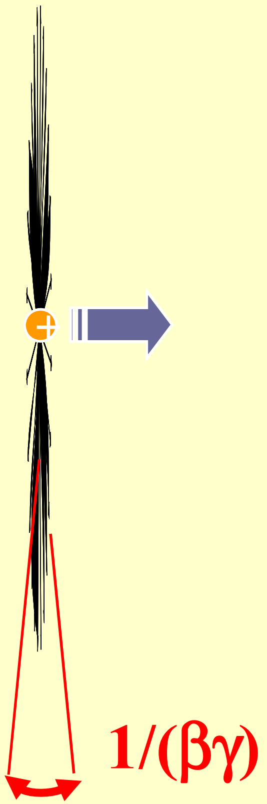
- Introduction
- BPM types
- Bench measurements
- Other requirements
- Conclusion

Introduction

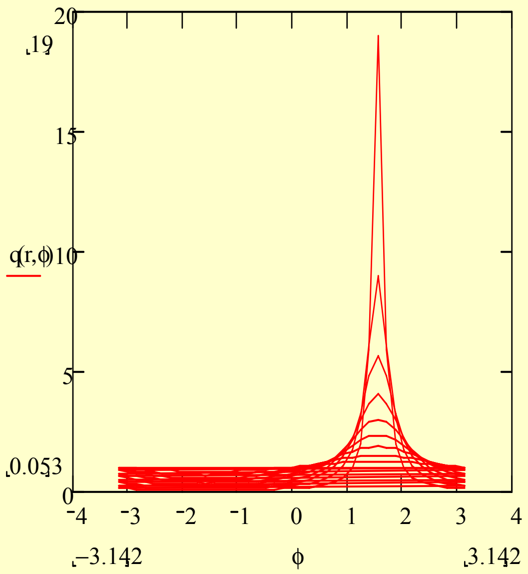
E-Field



TEM Wave



$$q(r,\phi w) := \frac{b - r^2}{b + r^2 - 2 \cdot b \cdot r \cdot \cos(\phi w - \chi)}$$



Static Point Charge

Relativistic Point Charge

Image current distribution

Different BPM types

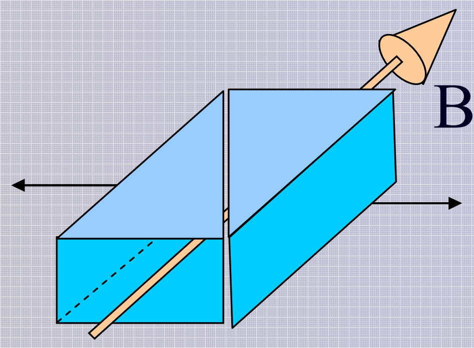
- Electrostatic
- Button
- Electromagnetic coupler
- Resistive
- Inductive
- Cavity
- Re-entrant cavity

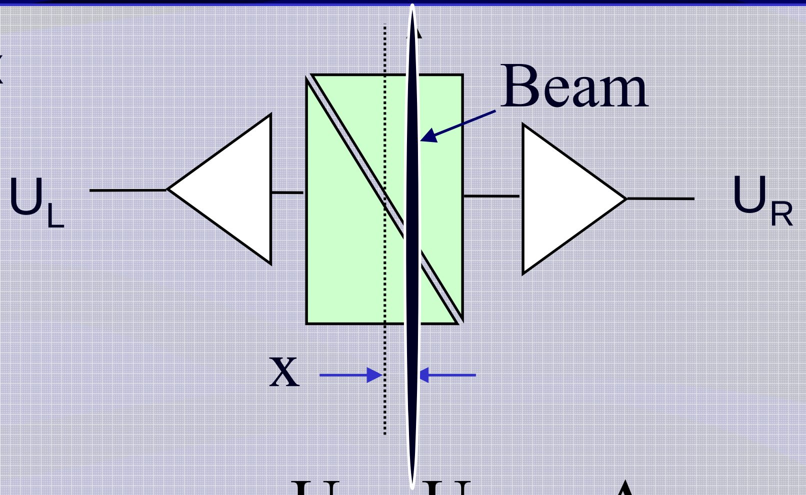
} Image current

} HOM
HF electron beams

Electrostatic shoebox BPM

Linear cut through a shoebox





Linear Response across the aperture

$$x \propto \frac{U_L - U_R}{U_L + U_R} = \frac{\Delta}{\Sigma}$$

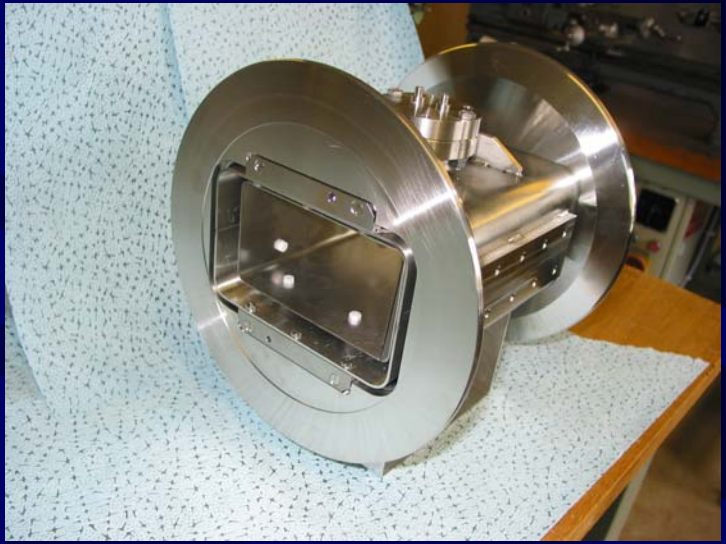
Induced charges carried away by low-impedance circuit or sensed on a high impedance as a voltage

$$V = \frac{\phi_{elec} \cdot l_{elec.}}{2 \cdot \pi \cdot C_{elec}} \cdot \frac{I_B(t)}{\beta \cdot c}$$

- ✓ Linear within ¾ of half aperture
- ✓ Low frequency cutoff (kHz) with high RL
- ✗ Sensitive to spray particles
- ✗ Complicated design ⇒ high cost

$$C_{elec} = \frac{\varepsilon_0 \cdot \varepsilon_r \cdot A}{d}$$

Electrostatic BPM



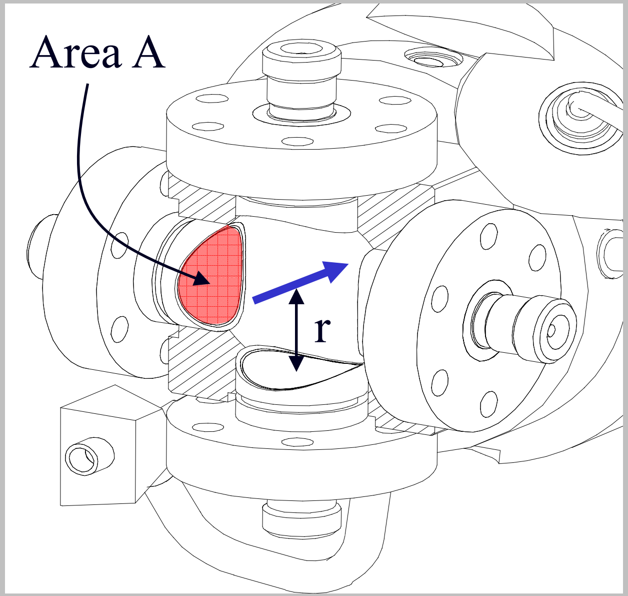
Same principle applied to a cylindrical pick-up

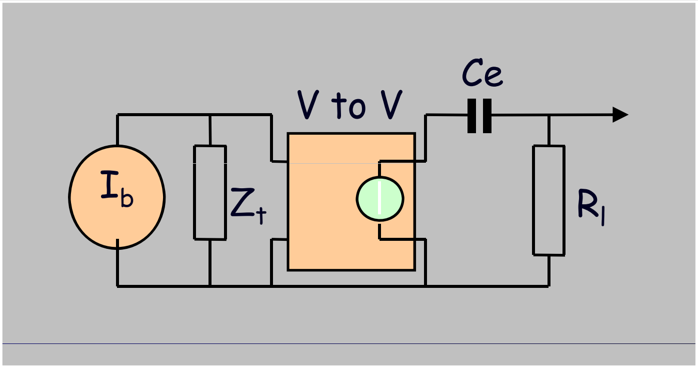
- The cuts can be made by photo-chemical, sand-blasting or other mechanical means.
  - → Here done by photo-chemical process

Button BPM

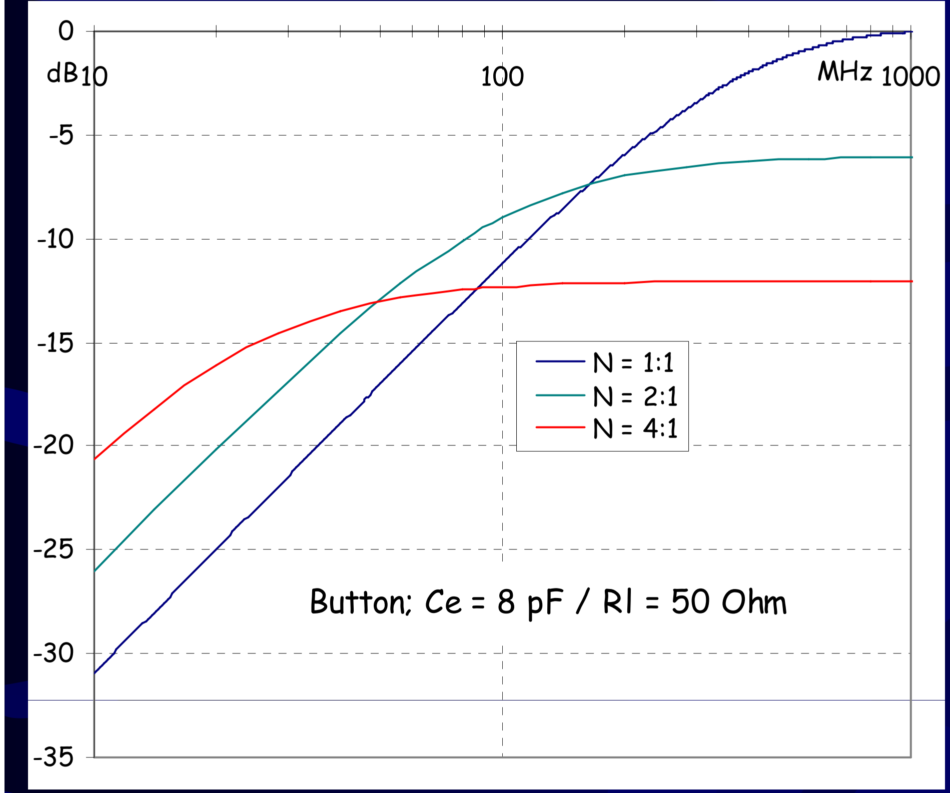
- ✓ Lowest longitudinal impedance
- ✓ Low cost ⇒ most popular
- ✗ Non-linear
  - requires correction algorithm when beam is off-centre
- ✗ Low frequency cut-off
  - T = $R_l C_e$ (few hundreds MHz)
  - RL =50 ohm, C very small

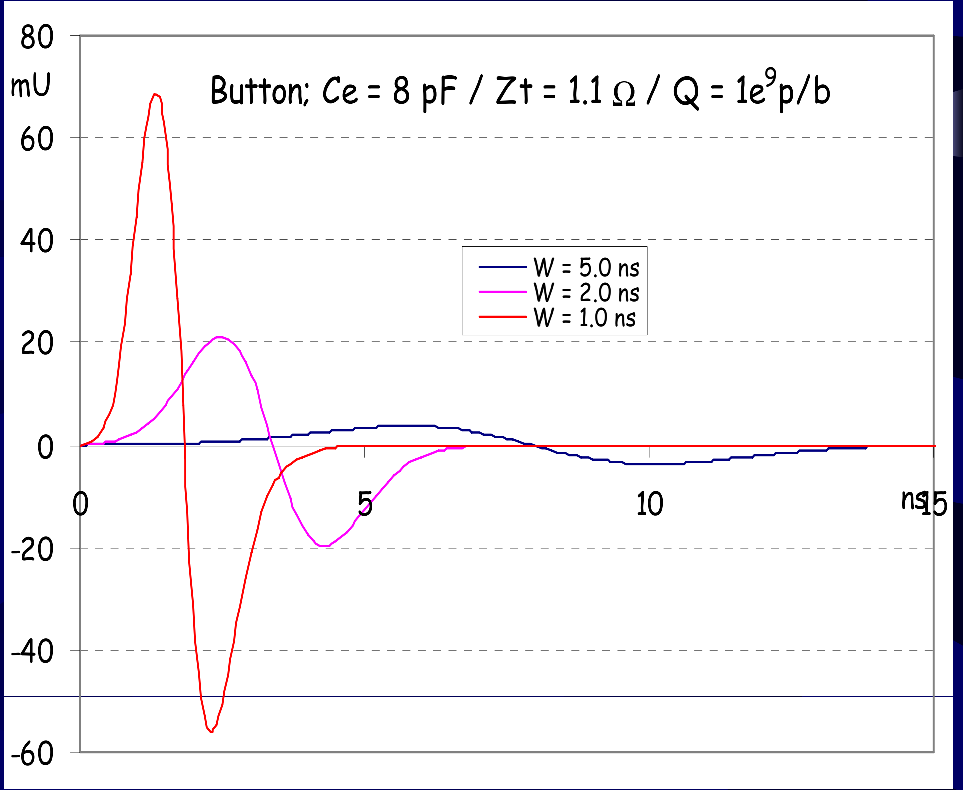
$$V = \frac{A_{elec} \cdot R_L}{2 \cdot \pi \cdot r \cdot \beta \cdot c} \cdot \frac{dI_B(t)}{dt}$$





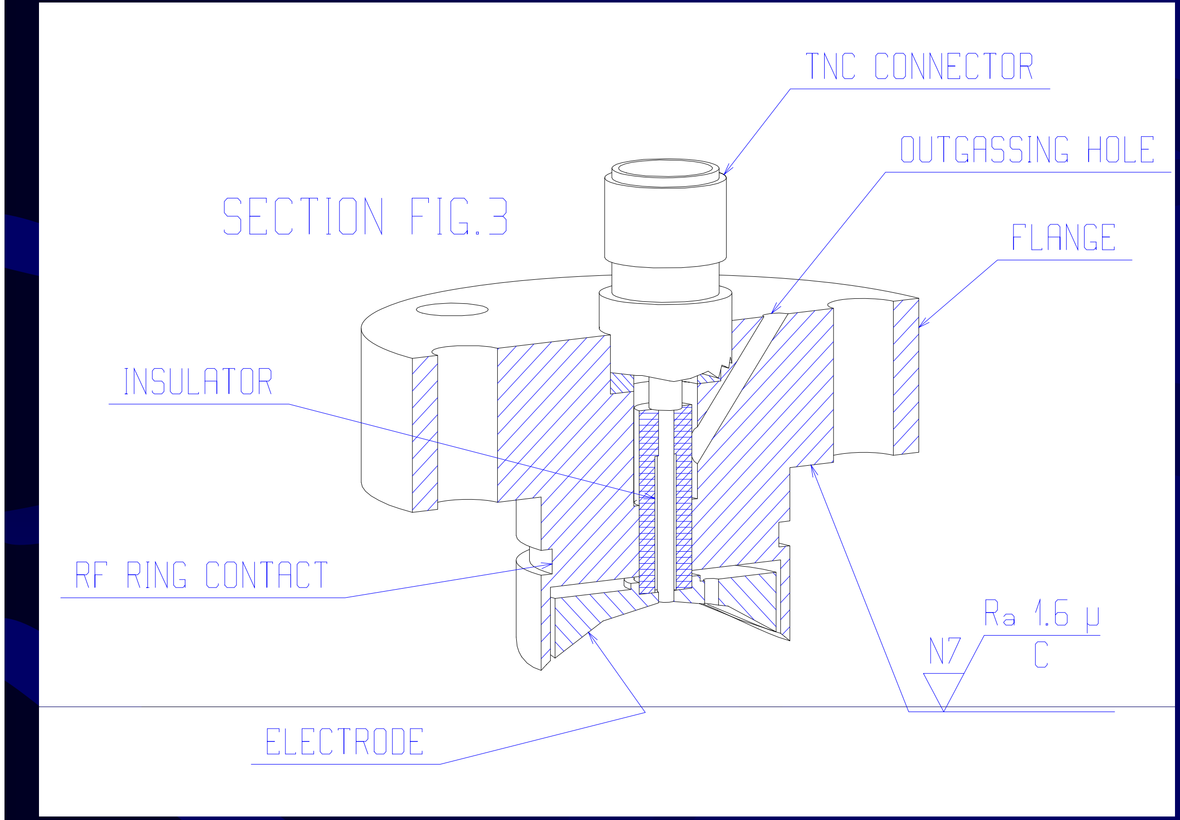
Button Frequency & Time Response





- Frequency domain:
  - → Impedance transformers improve the low frequency levels at the expense of the high frequency
- Time domain:
  - → Differentiated pulse
  - → Exponential dependence of amplitude on bunch length

What does a real (LHC) electrostatic button monitor look like?



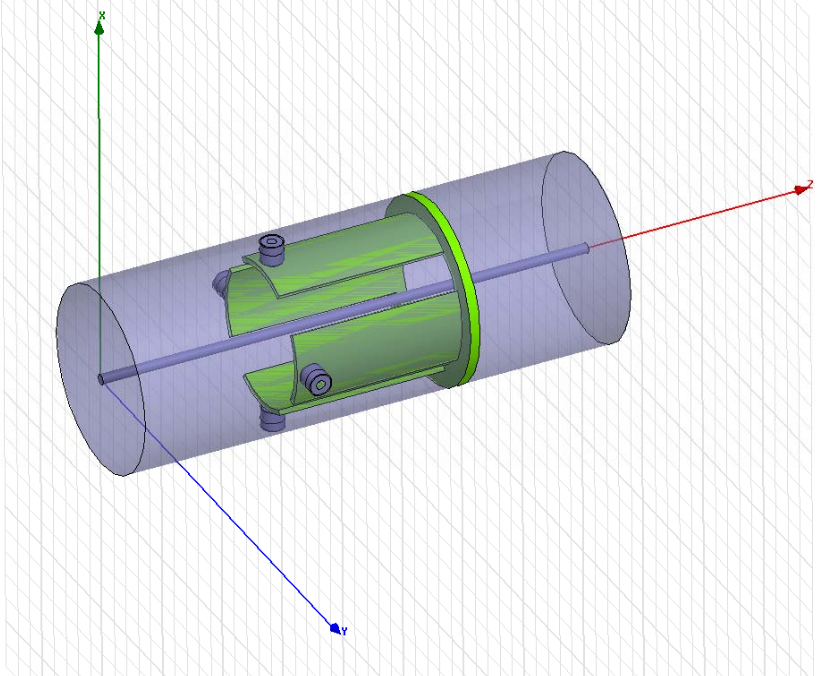
Electromagnetic (Directional) coupler

- Four 50Ω lines.
- Directional if terminated in both ends

✓ Linear if optimized ($\varphi_{elec} \approx 60^{o}$)

× Higher cost but shorted version is a possible cheaper option.

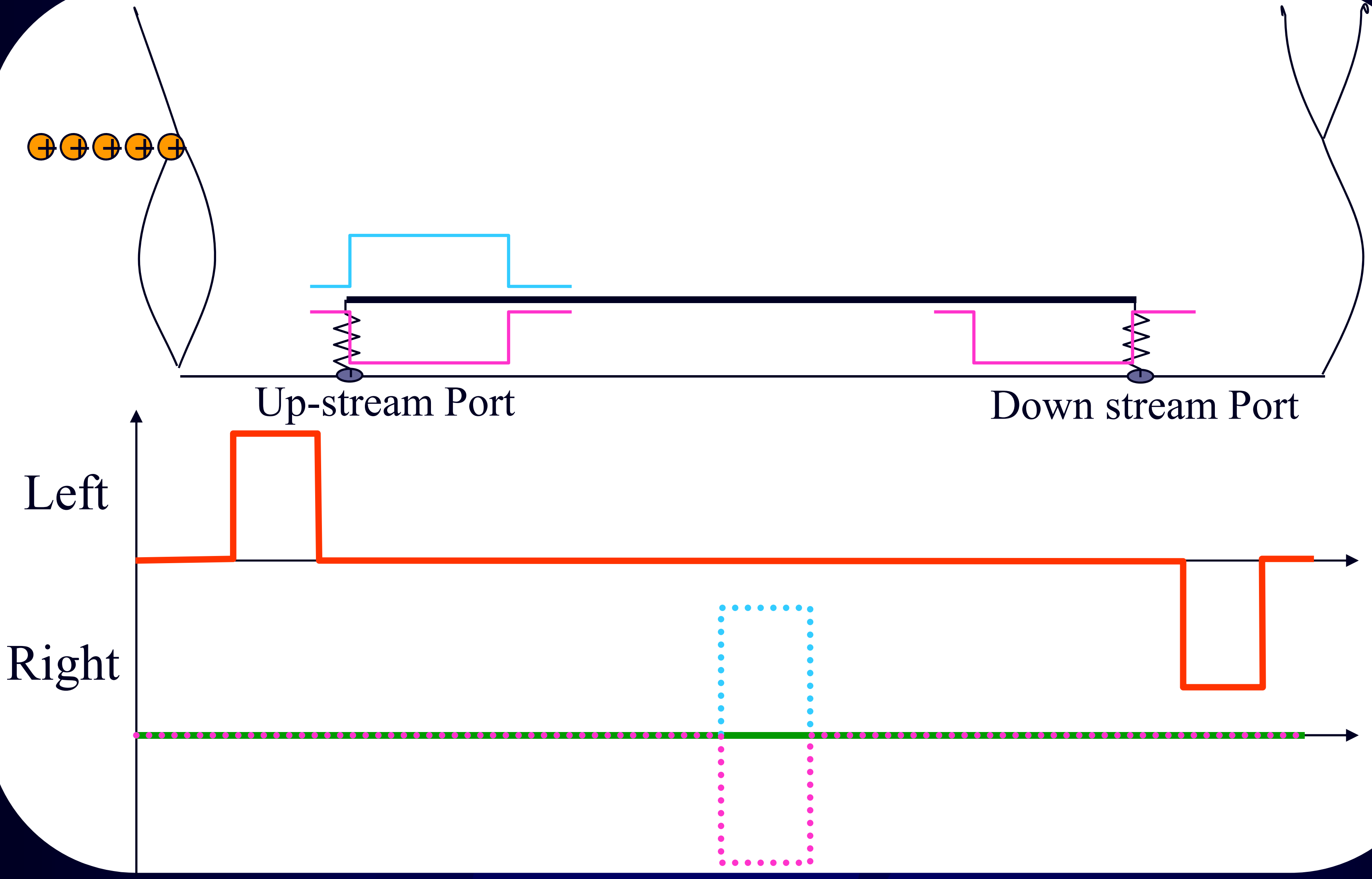
× Narrow band device.



$$V_U = \frac{\phi_{elec}\cdot Z_0}{4\cdot\pi}\cdot\left[I_B(t) - I_B\left(t - \frac{l}{\beta_b\cdot c} - \frac{l}{\beta_s\cdot c}\right)\right]$$

$$V_U = \frac{\phi_{elec}\cdot Z_0}{4\cdot\pi}\cdot\left[I_B(t) - I_B\left(t - \frac{2\cdot l}{c}\right)\right]$$

EM Stripline Coupler – right travelling beam

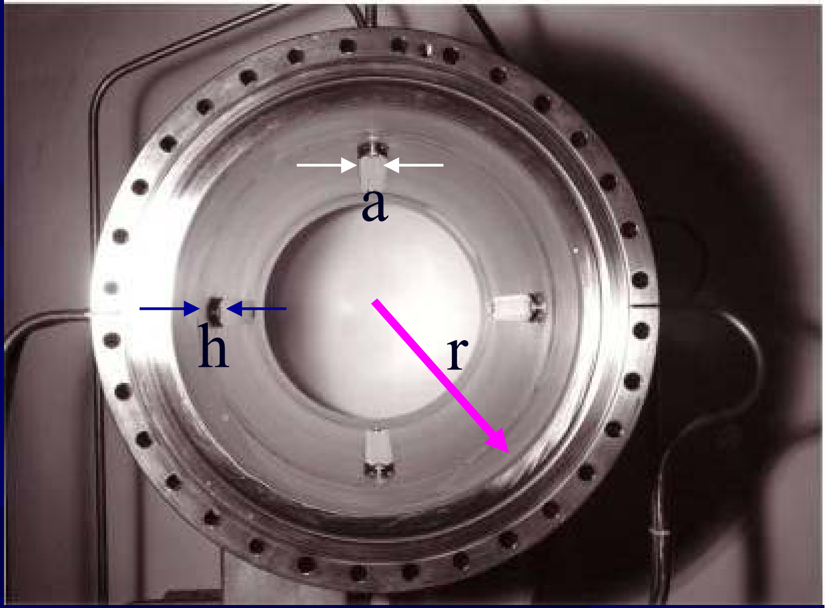


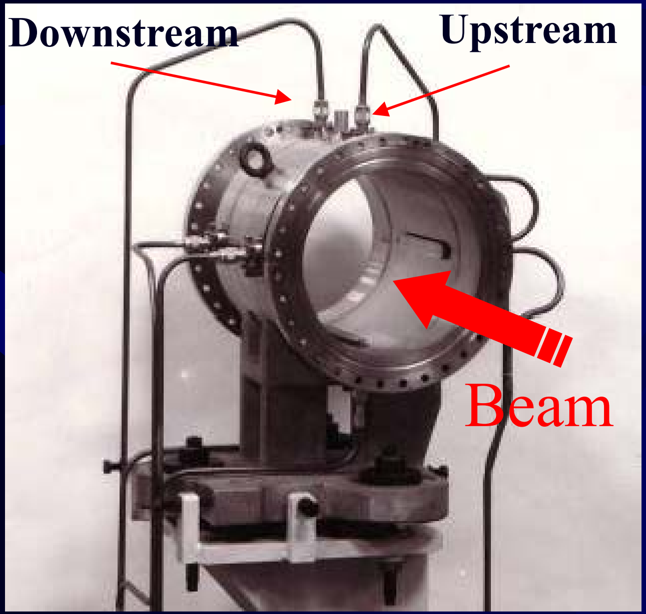
Electromagnetic (Directional) coupler

- Is a transmission line (strip line) which couples to the transverse electromagnetic (TEM) beam field

$$Z_{t\,\infty} = 60\ \ln[(r+h)/r] \equiv Z_0 * [a/2\pi(r+h)]$$

  - Z_0 is the characteristic impedance
  - a, r, h, l are the mechanical dimensions
  - t = l/c is the propagation time in the coupler

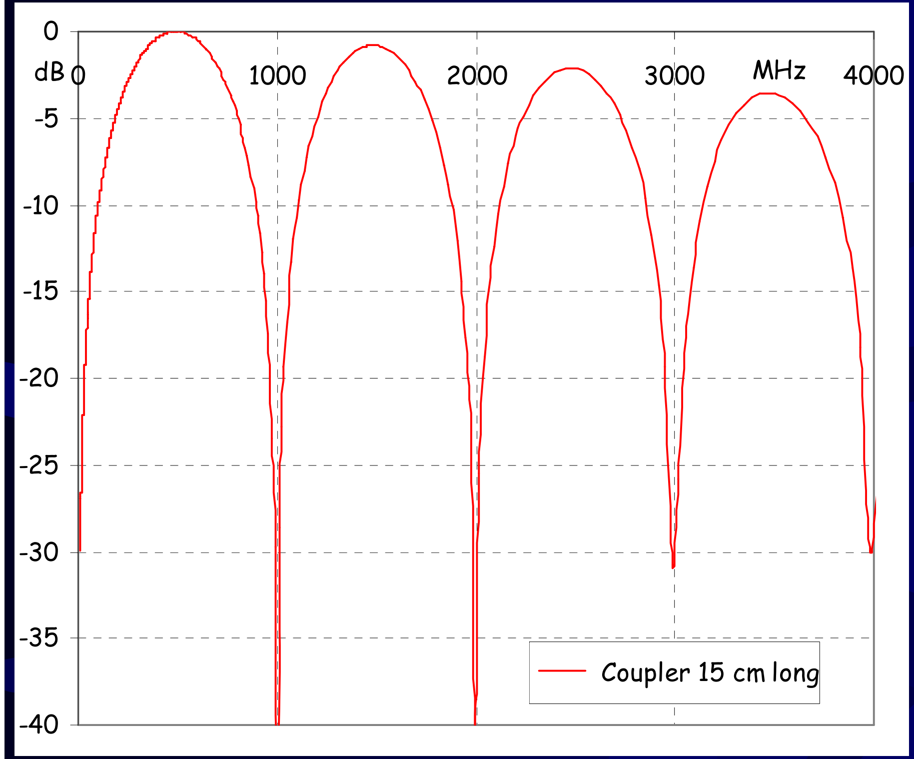


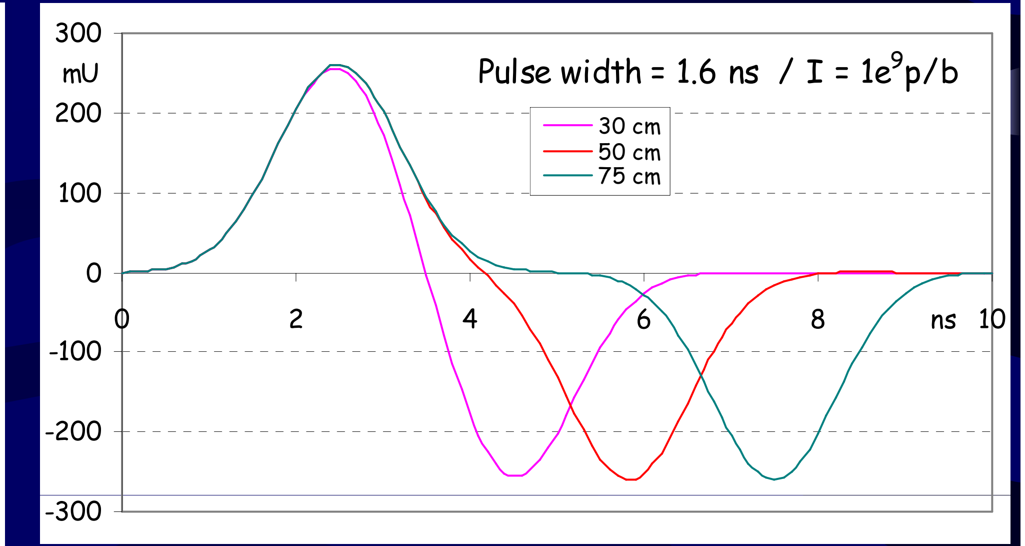


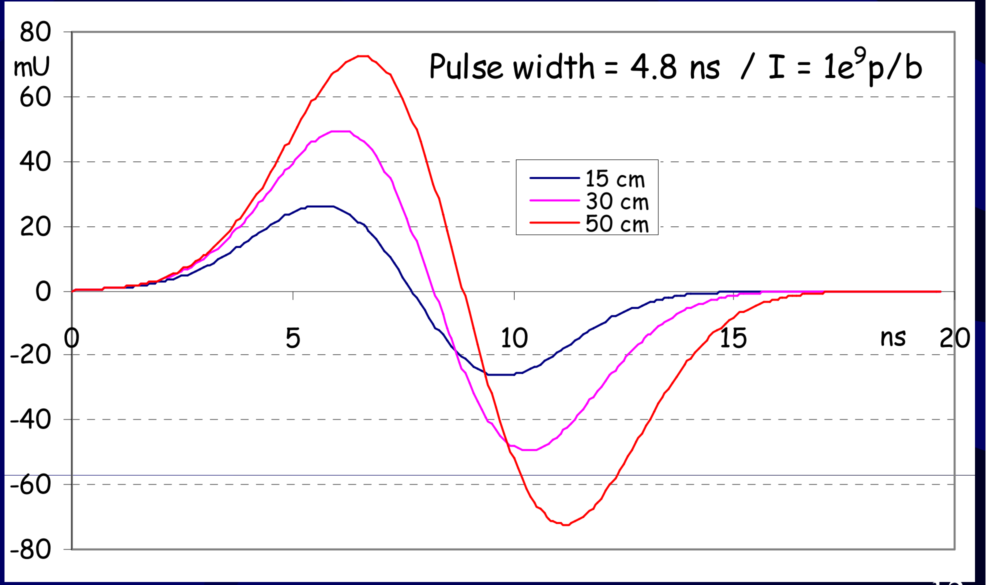
- Two termination ports
  - → Upstream: usually used to acquire signal.
    - Same signal seen whether Downstream port is open, shorted or terminated by Z_0
  - → Downstream: 2 cases
    - Upstream terminated by $Z_0 \Rightarrow$ no signal
    - Upstream short circuit $\Rightarrow$ delayed & inverted signal

Directivity!

Coupler frequency & time response

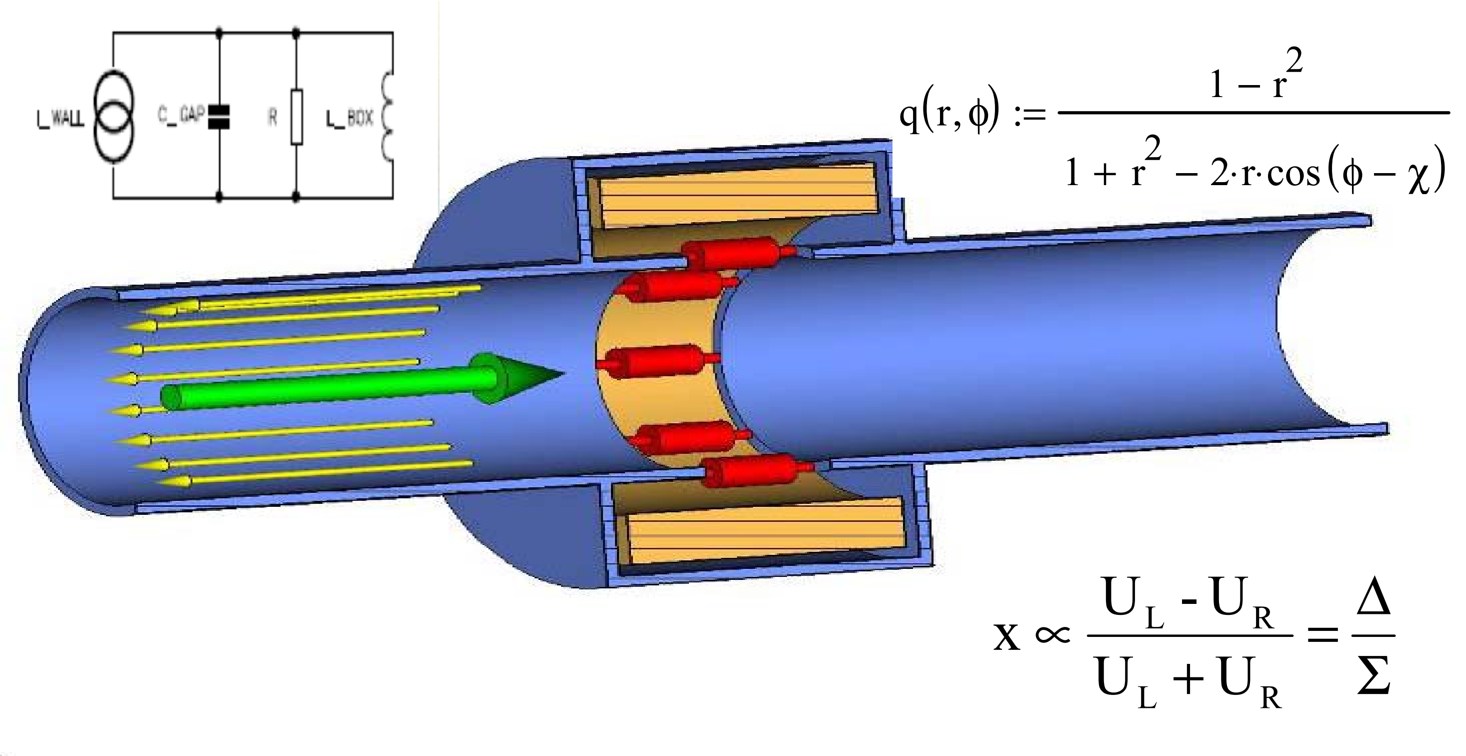






- Sinusoidal amplitude response
  - → Maximum signal for f = 1/4*t
  - → Zero signal for f = 1/2*t
- Time domain:
  - •Bipolar pulse

Resistive BPM (WCM)



$$q(r,\phi) := \frac{1 - r^2}{1 + r^2 - 2\cdot r\cdot \cos(\phi - \chi)}$$

$$x \propto \frac{U_L - U_R}{U_L + U_R} = \frac{\Delta}{\Sigma}$$

- [illegible]
- A voltage proportional to the beam current and the beam position develops on the **RESISTORS** in the beam pipe gap
- The gap must be closed by a box to avoid floating sections of the beam pipe
- The box is filled with the **FERRITE** to force the image current to go over the resistors

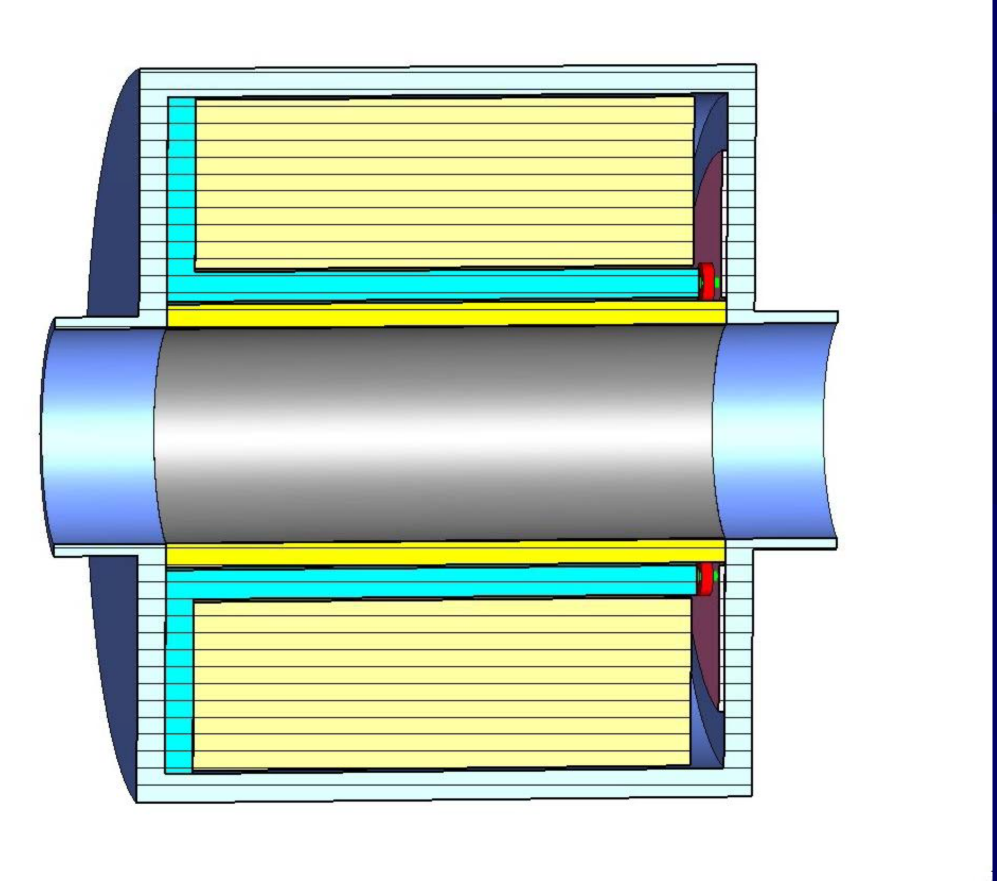
A Beam Position Sensitive WCM

- A position sensitive WCM is still used in the CERN PS.
- It contains 96 resistors of 10 Ω in 32 groups of 3 in series), $V_{\Sigma}/I_B \approx 1\ \Omega$.
- Position measurement bandwidth is 9 MHz – 1.5 GHz (2.2 decade)
- Current measurement bandwidth is 3 MHz – 1.5 GHz (2.7 decade)

G.C. Schneider, *A 1.5 GHz Wide-Band Beam Position and Intensity Monitor for the Electron-Positron Accumulator (EPA),* CERN/PS 87-9 (BT), 1987

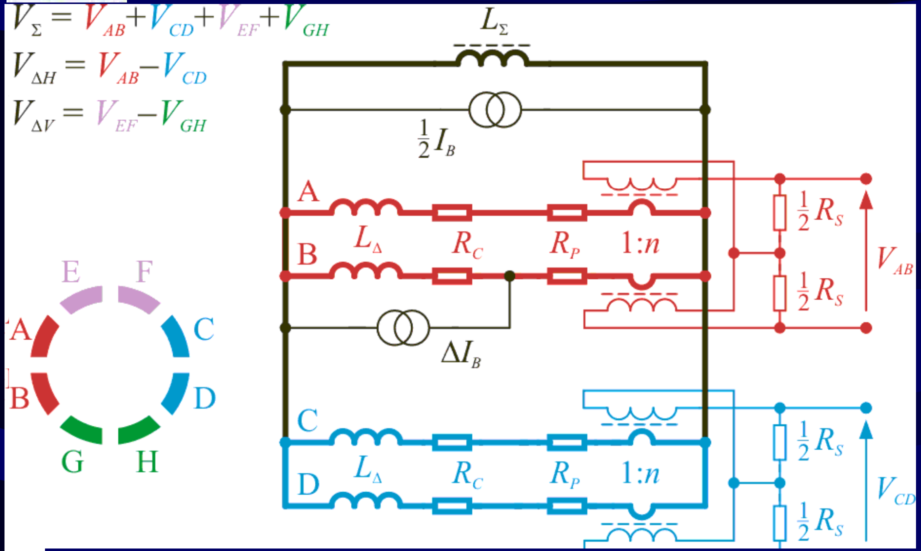
Inductive Pick-Up

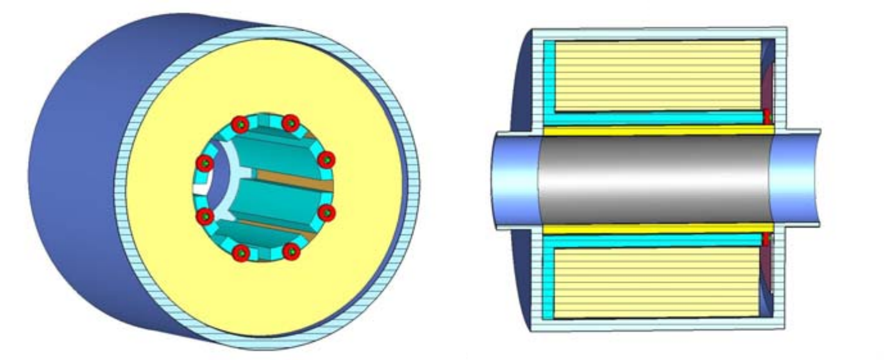
MORE INDUCTANCE **LESS RESISTANCE**



- Four or eight electrodes, which covers up to 75 % of the circumference. No feed-thru’s
- The small electrode diameter step is occupied by a titanium coated ceramic tube. Low longitudinal impedance
- Small current transformers guides the image currents to an external load.
- The current transformers (mounted on a PCB) are as small as possible to gain high frequency cut-off with many turns
- The connection between the electrodes and the cover is made by screws.

IPU – A Low Frequency Model





$$R_P = \frac{R_S}{2n^2}$$

$$R_T = \frac{V_\Sigma}{I_B} = \frac{R_S}{2n}$$

- Electrodes are combined in pairs so that each transformer sees half of the load
- Frequency low cut-offs are limited by connection parasitic resistances
- Each transformer has one calibration turn (not shown)

$$f_{L\Sigma} = \frac{1}{2\pi L_\Sigma}\left(\frac{R_S}{2n^2} + R_C\right)$$

$$f_{L\Delta} = \frac{1}{2\pi L_\Delta}\left(\frac{R_S}{2n^2} + R_C\right)$$

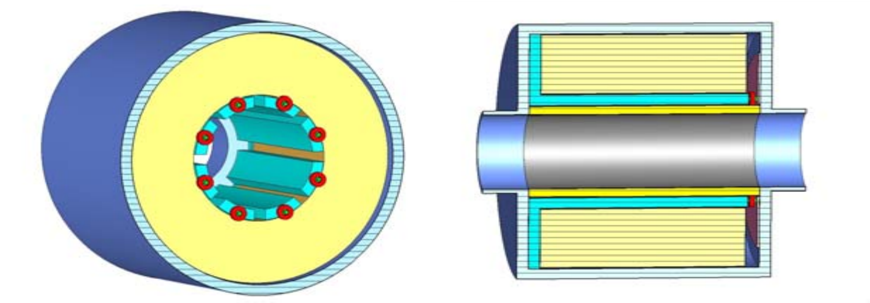
$n = 30$, $R_S \cong 7\ \Omega$ giving $R_T \cong 0.1\ \Omega$ and $R_P \cong 4\ \mathrm{m}\Omega$

$f_{L\Sigma} \cong 150$ Hz (R_P with $L_\Sigma \cong 5\ \mu$H)

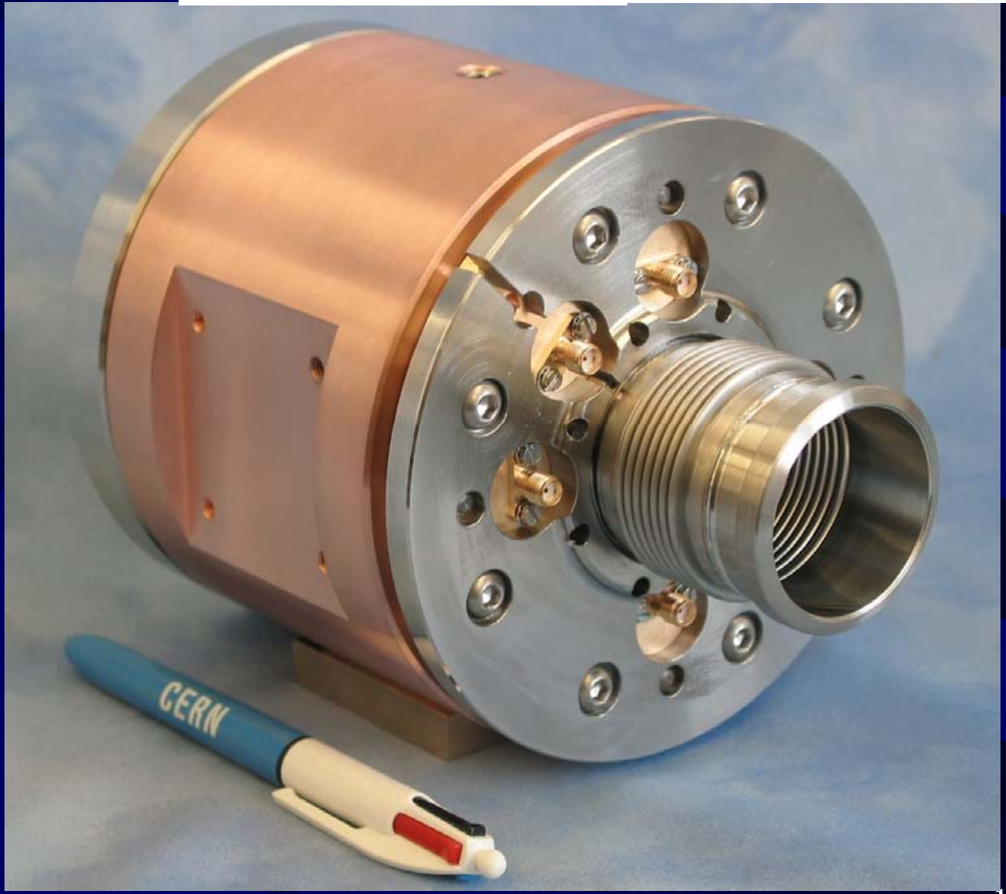
$f_{L\Delta} \cong 10$ kHz (R_P with $L_\Delta \cong 70$ nH)

The electrode signal high cut-off frequency is beyond 300 MHz

Inductive Pick



- The ceramic tube is coated with low resistance titanium layer, resistance: end-to-end ≈10 Ω, i.e. ≈ 15 Ω/square
- Primary circuit has to have small parasitic resistances (Cu pieces, CuBe screws, gold plating)
- Tight design, potential cavities damped with the ferrite



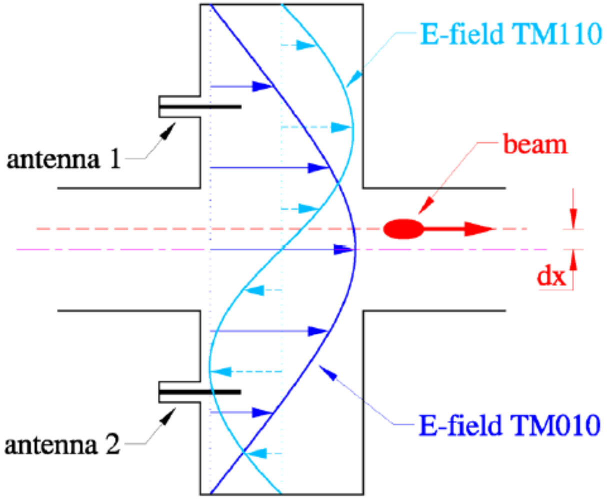
Cavity BPM

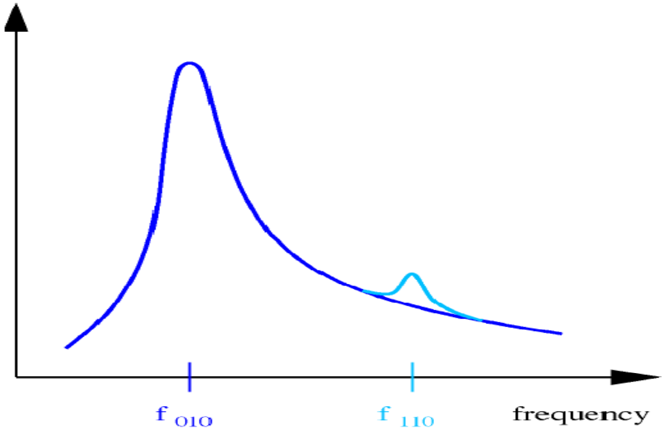
- Difference of large numbers problem reduced to rejection of the primary fundamental peak. Frequency domain.
- Damping time quite high due to intrinsic high Q.

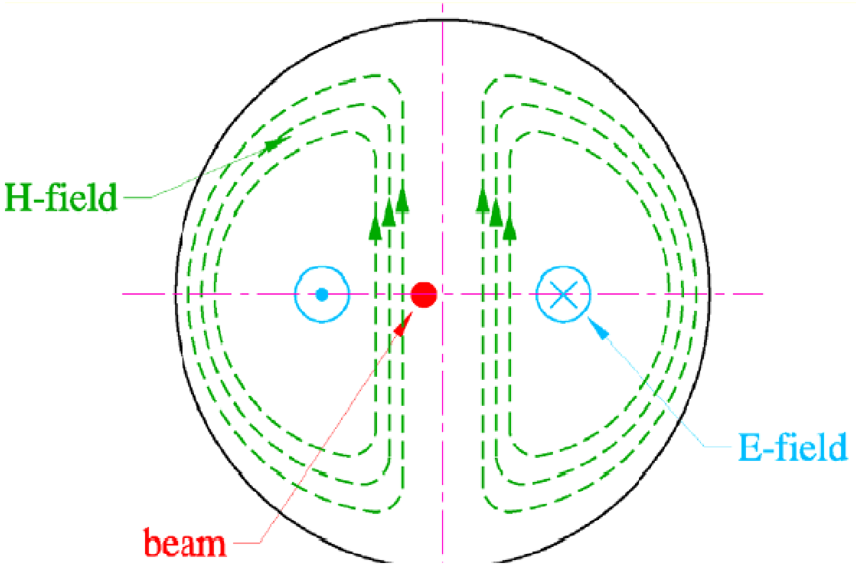
$$\tau = \frac{Q_{ld}}{\pi * f_{Dip}}$$

→ Poor time resolution (~100ns)

- Need of extra cavities for orthogonal plane and normalization.
- Sub-micron resolution.

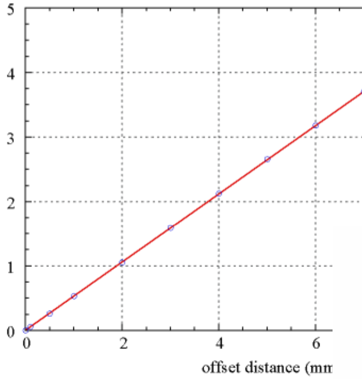


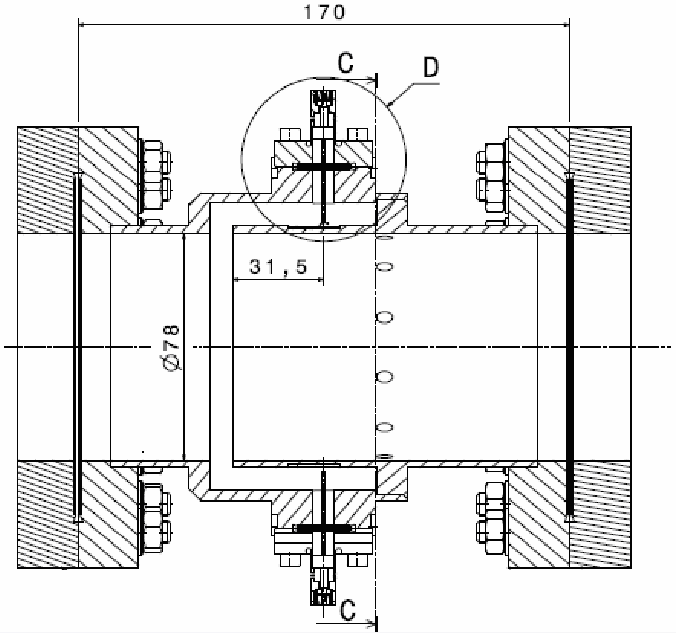




Re-entrant cavity BPM

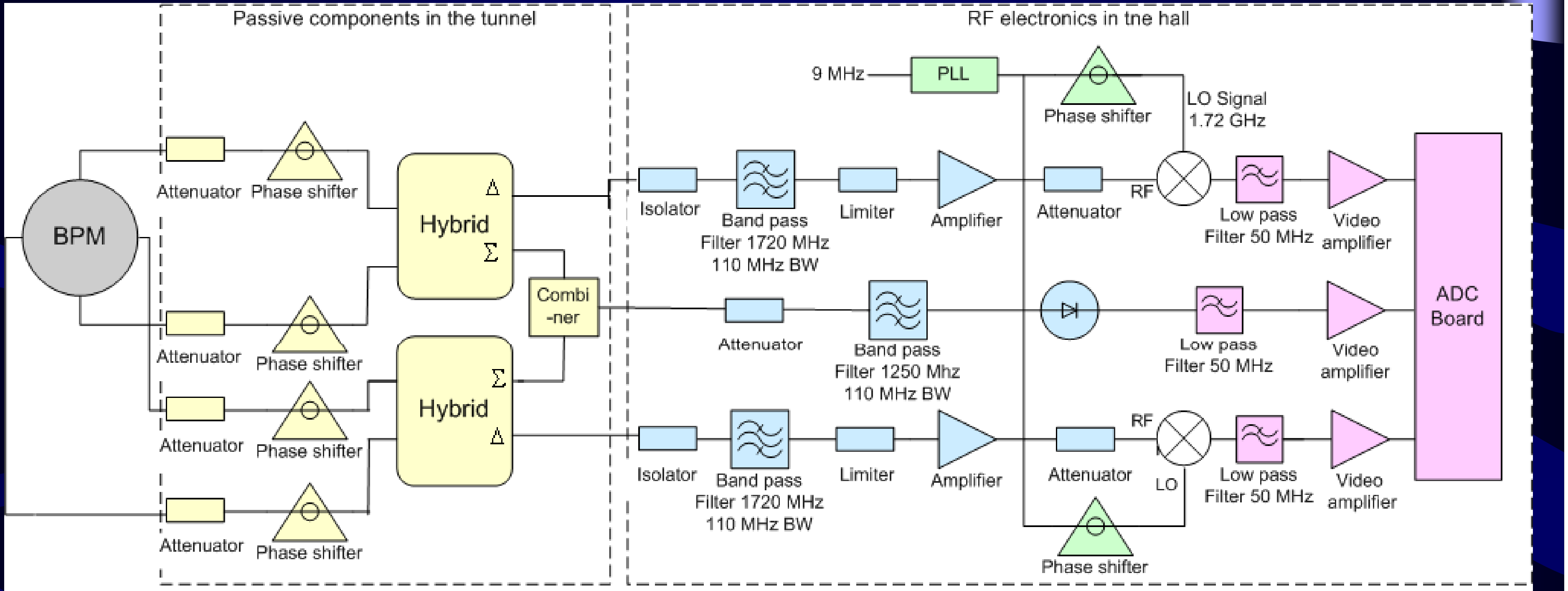
- Re-entrant geometry for a higher frequency separation between the monopole and dipole modes. → Better CMRR
- Resolution: CARE ~ 1um (CALIFES ~5um)
- Dynamic range: 5mm
- $Q_{ld} = 50$ →
  Time resolution ~ 10ns
- ID 78mm; Length ~170mm





Eigen modes	F (MHz)			Q_l			$(R/Q)_l$ (Ω) at 5 mm	$(R/Q)_l$ (Ω) at 10 mm
	HFSS	Meas. in lab.	Meas. in tunnel	HFSS	Meas. in lab.	Meas, in tunnel	Calc.	Calc.
Monop. mode	1250	1254	1255	22.95	22.74	23.8	12.9	12.9
Dipole mode	1719	1725	1724	50.96	48.13	59	0.27	1.15

Re-entrant cavity BPM electronics



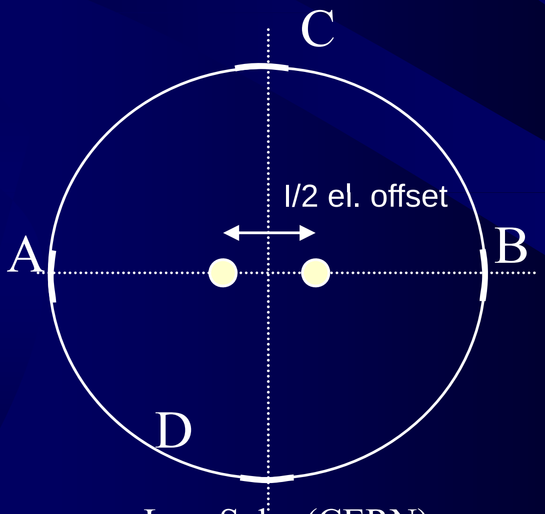
Bench tests

- **Position = $K_{x,y} \times (A-B)/(A+B)$ + offset = $K_{x,y} * \Delta_{x,y} / S$ + offset**

  - $K_{x,y}$ = BPM sensitivity estimated from simulations or measured. Linear or polynomial fits can be used.
  - Offset = Difference between mechanical center and electrical center. For high precision this must be measured using metrology and a stretched wire.

  - To find the offset with micron precision (with respect to an external reference) move the wire to the electrical center, rotate the BPM 180º, and move the wire the new electrical center.

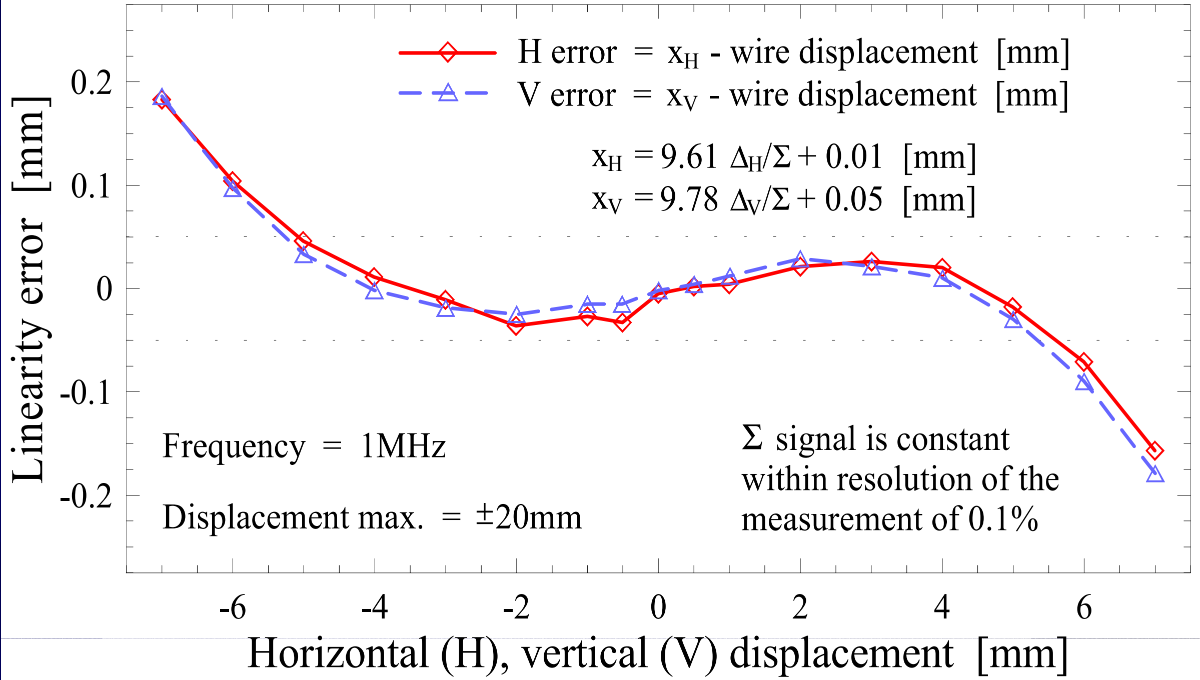
- The difference between the two RELATIVE measurements Is equal to two times the electrical offset



IPU Bench test

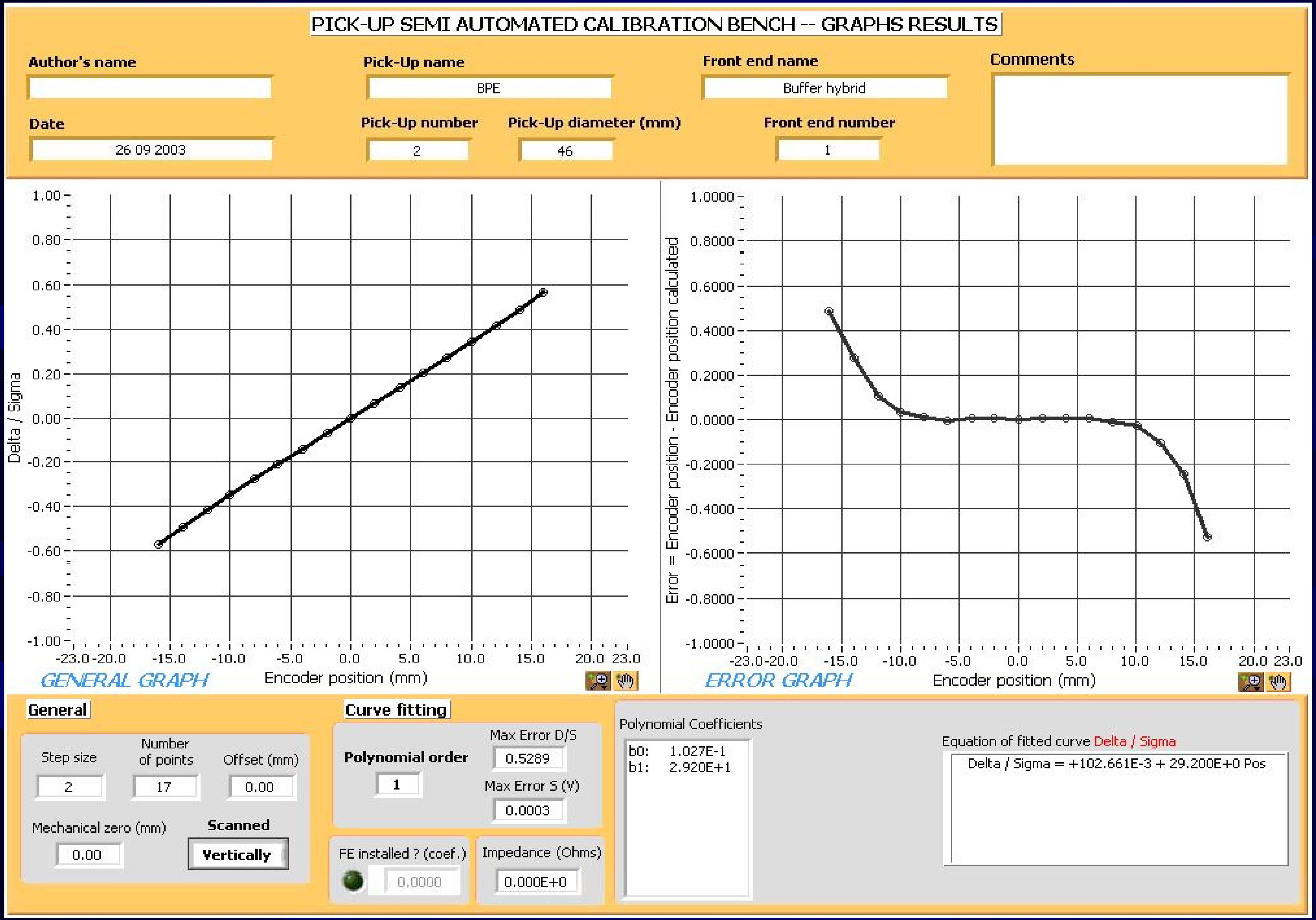
$$\text{horizontal position} = 9.61\frac{\Delta_H}{\Sigma} + 0.01 \ \ [\text{mm}]$$

$$\text{vertical position} = 9.78\frac{\Delta_V}{\Sigma} + 0.05 \ \ [\text{mm}]$$



A thin wire forming a coaxial line was displaced diagonally across the pick-up aperture.
The measurement was done with a network analyzer: signal was applied to the wire and hybrid signals were observed.

Electrostatic BPM bench measurement


PICK-UP SEMI AUTOMATED CALIBRATION BENCH -- GRAPHS RESULTS

Author's name:
Pick-Up name: BPE
Front end name: Buffer hybrid
Comments:
Date: 26 09 2003
Pick-Up number: 2
Pick-Up diameter (mm): 46
Front end number: 1

General

Step size: 2
Number of points: 17
Offset (mm): 0.00
Mechanical zero (mm): 0.00
Scanned: Vertically

Curve fitting

Polynomial order: 1
Max Error D/S: 0.5289
Max Error S (V): 0.0003
FE installed ? (coef.): 0.0000
Impedance (Ohms): 0.000E+0

Polynomial Coefficients
b0: 1.027E-1
b1: 2.920E+1

Equation of fitted curve Delta / Sigma
Delta / Sigma = +102.661E-3 + 29.200E+0 Pos

Δ=Σ=29.2mm
Offset = 0.1mm

Other requirements

- Must be vacuum tight down to 10^{-9} Torr.
- Must be bake able to 150º C. Watch out for stresses due to different thermal expansions, i.e ceramic and metal.
- External reference directly connected to the detector or via WPS-system.
- Minimize front-end electronics due to radiation.

BPM overview

	Electrostatic	Button	Strip line	WCM	Inductive	Cavity	Re-entr. Cavity
Linearity	Very good	Bad	Good	Good	Good	Good	Good
Sensitivity	Good	Good	Good	Good	Good	Very good	Very good
Load imp.	High	50Ω	50Ω	50Ω	50Ω	50Ω	50Ω
FE close?	Yes	No	No	No	No	No	No
Feed-thru's	Yes	Yes	Yes	Yes	No	Yes	yes
Long. Imp	Bad	Very good	Good	Good	Good	Bad	Good
Cost	Expensive	Cheap	Medium	Medium	Medium	Medium	Medium

Conclusion

- To be filled in later……