Diagnostics I

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DESY

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CERN Accelerator School, Sept 2004

Introduction

Accelerator performance depends critically on the ability to carefully measure and control the properties of the accelerated particle beams

In fact, it is not uncommon, that beam diagnostics are modified or added after an accelerator has been commissioned

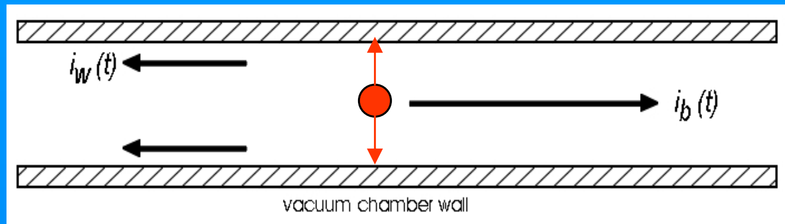
This reflects in part the increasingly difficult demands for high beam currents, smaller beam emittances, and the tighter tolerances placed on these parameters (e.g. position stability) in modern accelerators

A good understanding of diagnostics (in present and future accelerators) is therefore essential for achieving the required performance

A beam diagnostic consists of

- the measurement device ← focus of this lecture
- associated electronics and processing hardware ← subject of many recent publications and internal reports (often application specific)
- high-level applications → reference: "Beam Diagnostics and Applications", A. Hofmann (BIW 98)

Fields of a relativistic particle

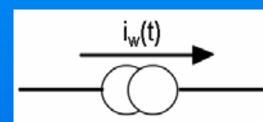


Lorentz-contracted "pancake"

induced wall current $i_w(t)$ has opposite sign of beam current $i_b(t)$: $i_b(t) = -i_w(t)$

Detection of charged particle beams – beam detectors:

i_w is a current source



with infinite output impedance, i_w will flow through any impedance placed in its path

many "classical" beam detectors consist of a modification of the walls through which the currents will flow

Sensitivity of beam detectors:

beam charge:

$$S(\omega) = \frac{V(\omega)}{I_w(\omega)}$$

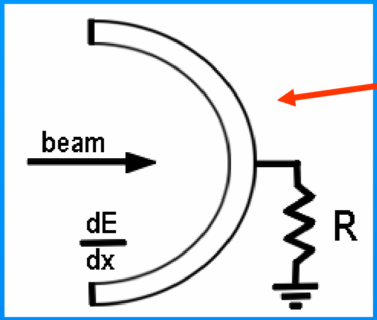
(in Ω)
= ratio of signal size developed $V(\omega)$ to the wall current $I_w(\omega)$

beam position:

$$S(\omega) = \frac{V(\omega)}{D(\omega)}$$

(in Ω/m)
= ratio of signal size developed /dipole mode of the distribution, given by $D(\omega) = I_w(\omega)\, z$, where z = x (horizontal) or z = y (vertical)

Beam Charge – the Faraday Cup

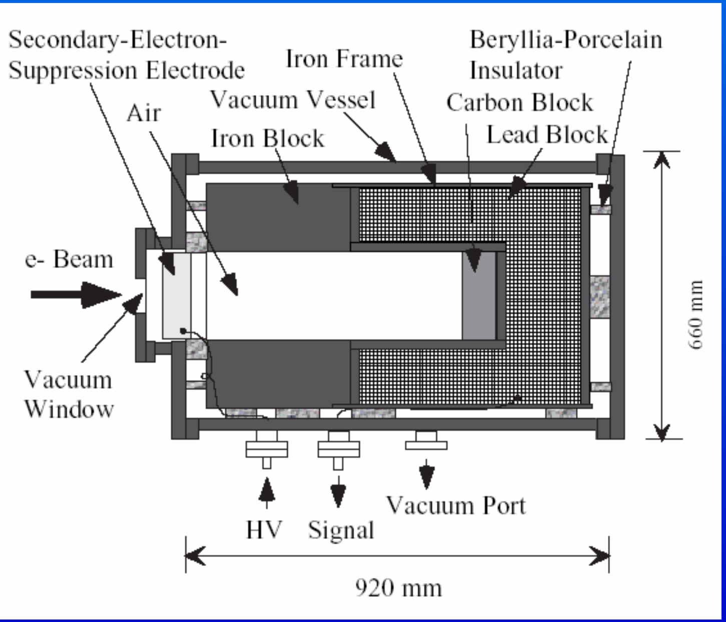


thick (e.g. ~0.4 m copper for 1 GeV electrons) or series of thick (e.g. for cooling) charge collecting recepticles

Principle: beam deposits (usually) all energy into the cup (invasive)
charge converted to a corresponding current
voltage across resistor proportional to instantaneous current absorbed

In practice:
termination usually into 50 Ω; positive bias to cup to retain e- produced by secondary emission; bandwidth-limited (~1 GHz) due to capacitance to ground

cross-sectional view of the FC of the KEKB injector linac (courtesy T. Suwada, 2003)

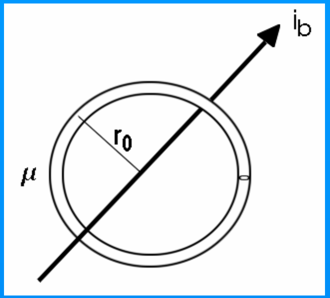


cylindrically symmetric blocks of
- lead (~35 rad lengths)
- carbon and iron
  - (for suppression of em showers generated by the lead)

bias voltage (~many 100 Volts)
- for suppression of secondary electrons

Beam Intensity – Toroids (1)

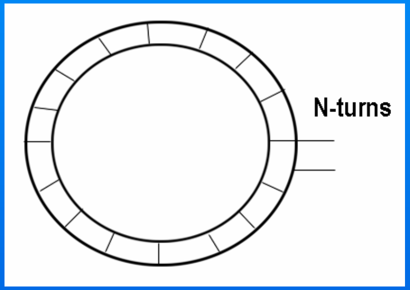
Consider a magnetic ring surrounding the beam, from Ampere's law:



$$\oint \vec{B} \cdot \vec{dl} = \mu I$$

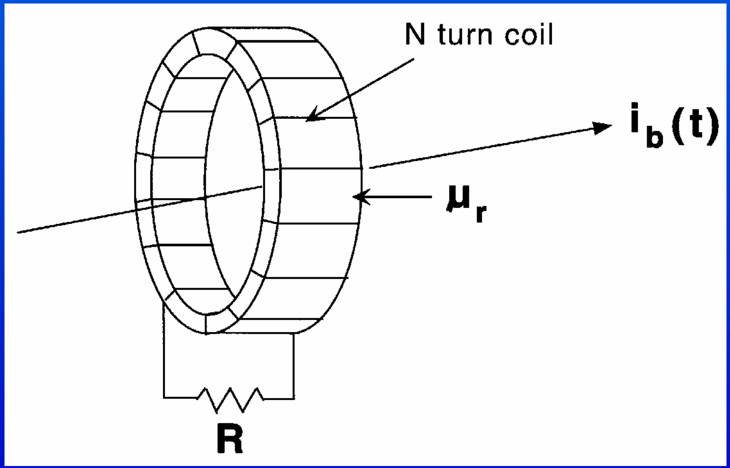
if r_0 (ring radius) >> thickness of the toroid, $B = \frac{\mu i_b}{2\pi r_0}$

Add an N-turn coil – an emf is induced which acts to oppose B:



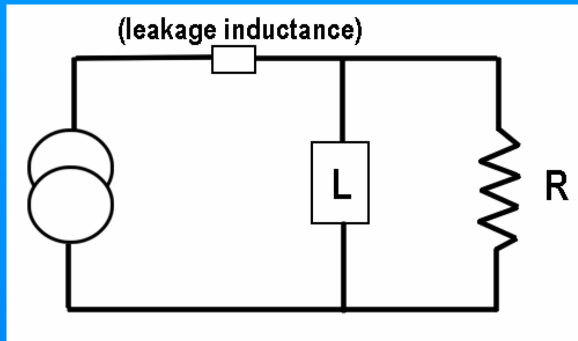
$$\begin{aligned} \epsilon &= \frac{d\phi}{dt} \quad \text{where} \quad \phi = \int \vec{B} \cdot d\vec{a} \\ &= \frac{\mu A}{2\pi r_0} \frac{di_b}{dt} \end{aligned}$$

Load the circuit with an impedance; from Lenz's law, $i_R = i_b/N$:



Principle: the combination of core, coil, and R produce a current transformer such that i_R (the current through the resistor) is a scaled replica of i_b. This can be viewed across R as a voltage.

Beam Intensity - Toroids (2)



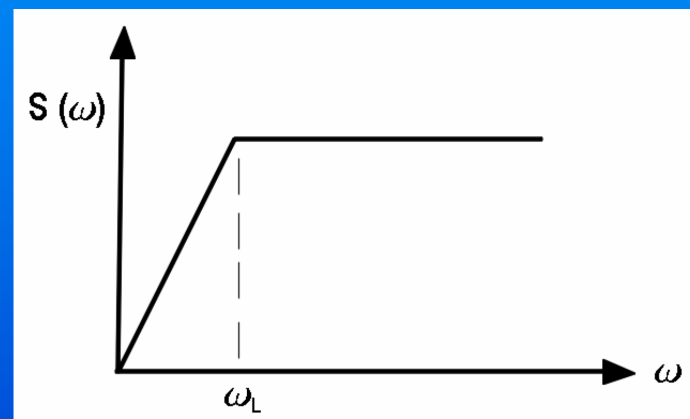
$$L = \frac{N^2}{R_h}$$

with R_h = reluctance of magnetic path

$$R_h = \frac{l}{\mu A}\ [\mathrm{H}^{-1}] \longrightarrow L = \frac{N^2 \mu_r \mu_0 A}{l}$$

sensitivity:

$$S = \frac{R}{\sqrt{1 + (\frac{\omega_l}{\omega})^2}} \qquad \omega_l = \frac{R}{L}$$



cutoff frequency, ω_L, is small if $L \sim N^2$ is large

detected voltage:

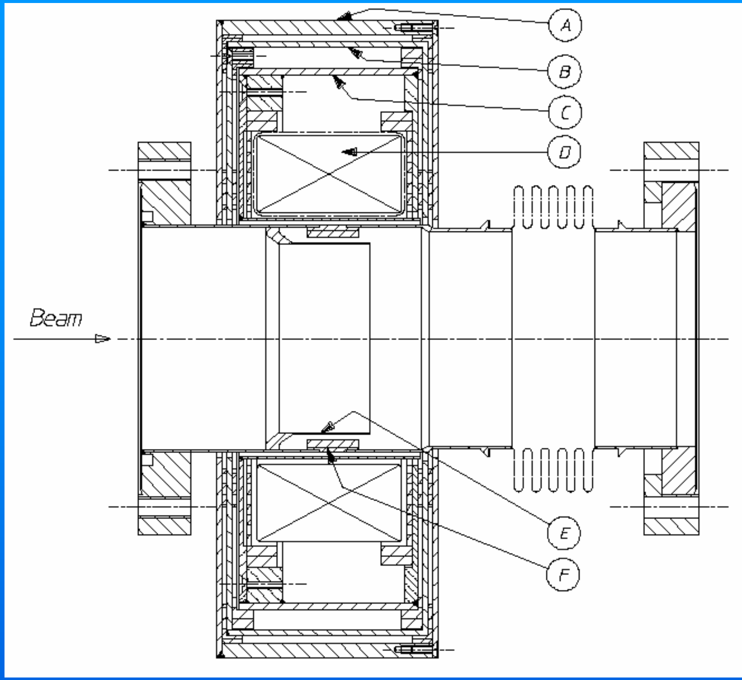
$$V(t) = \frac{i_b R}{N} e^{-(\frac{R}{L})t}$$

if N is large, the voltage detected is small

trade-off between bandwidth and signal amplitude

Beam Intensity – Toroids (3)

schematic
of the toroidal
transformer
for the TESLA
Test facility
(courtesy,
M. Jablonka,
2003)



A iron
B Mu-metal
C copper
} shielding

D "Supermalloy" (distributed by BF1 Electronique, France) with $\mu \sim 8 \times 10^4$

E electron shield

F ceramic gap

(one of many) current trans-formers available from Bergoz Precision Instru-ments (courtesy J. Bergoz, 2003)

(based on design of K. Unser for the LEP bunch-by-bunch monitor at CERN)

linacs: resolution of 3×10^6

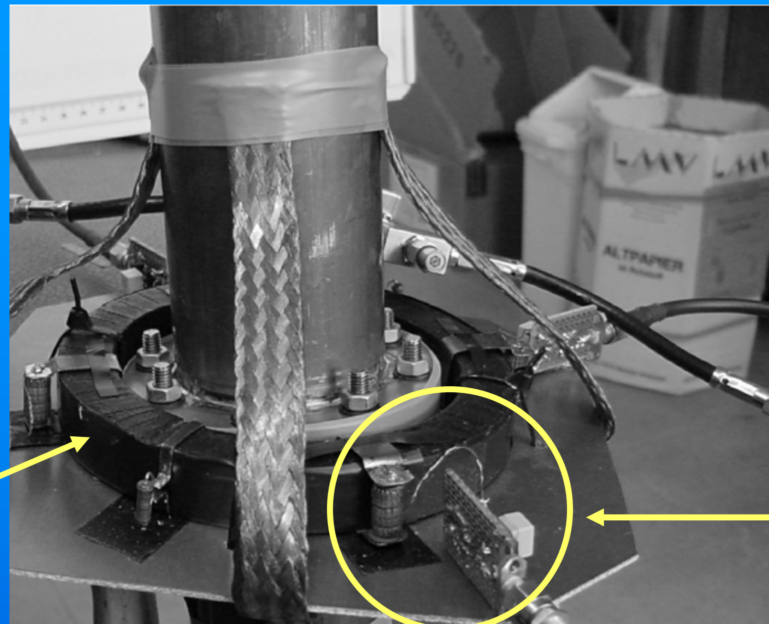
storage rings: resolution of 10 nA rms

details: www.bergoz.com

Beam Intensity – Toroids (4)

recent developments of toroids for TTF II (DESY)

2 iron halves

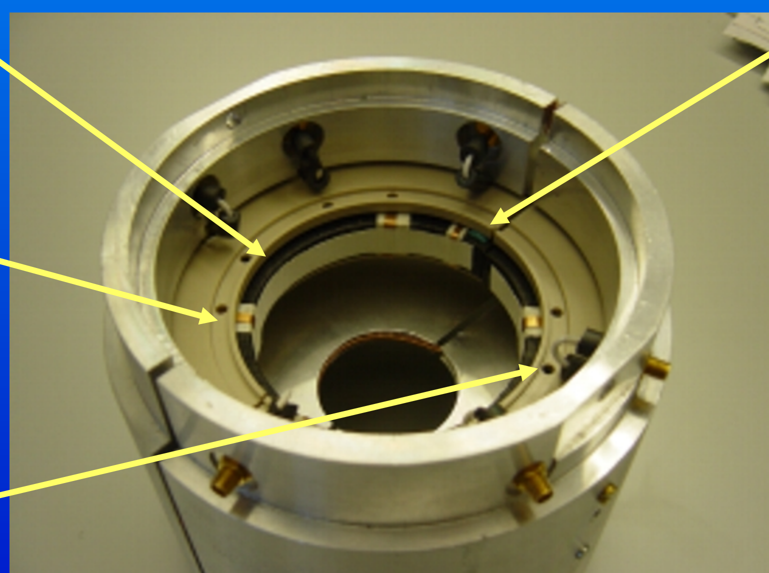


ferrite ring

50 Ω output impedance

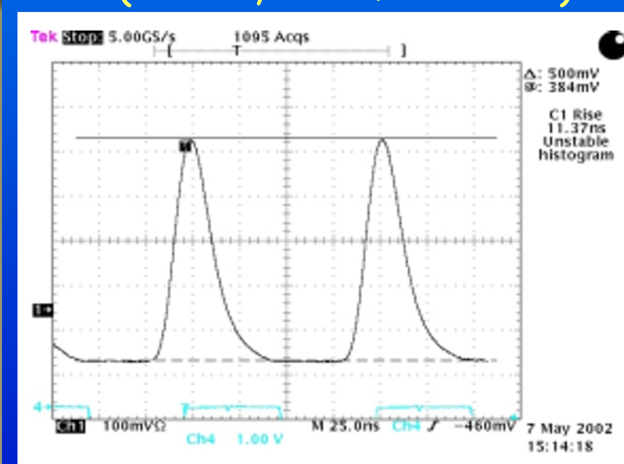
calibration windings

bronze pick-ups



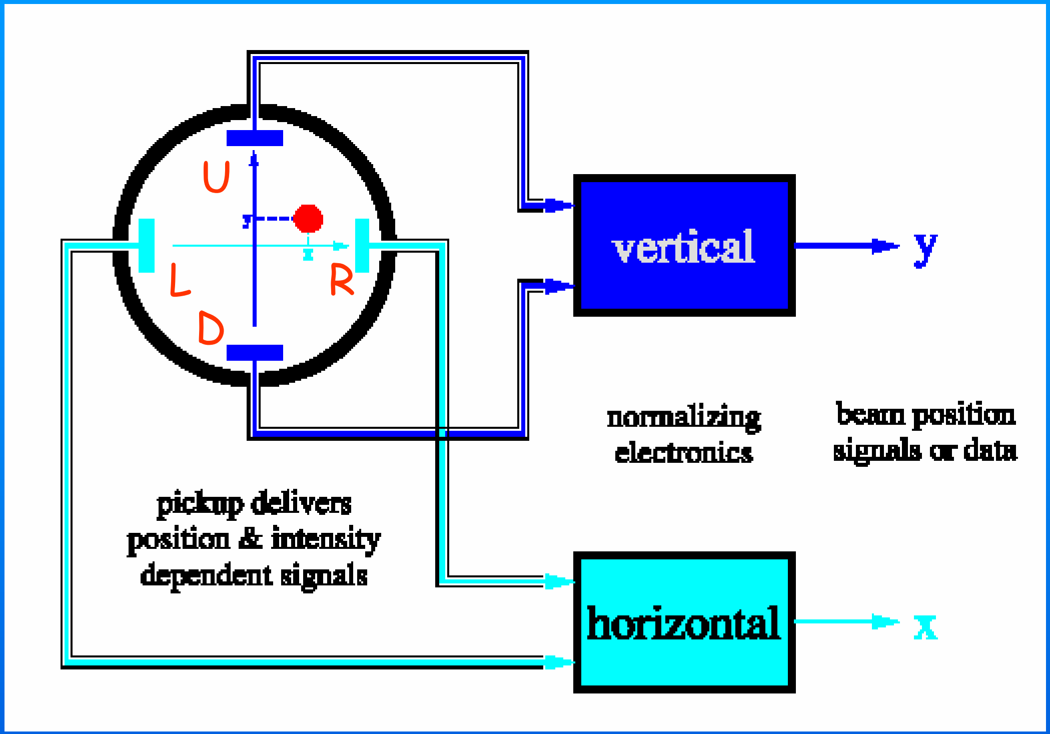
ferrite rings (for suppression of high frequency resonance)

(25 ns , 100 mV / dvsn)



(courtesy D. Noelle, L. Schreiter, and M. Wendt, 2003)

Beam Intensity – BPM Sum signals



U ~ up
D ~ down
L ~ left
R ~right

(figure, courtesy M. Wendt, 2003)

beam "position" V_R-V_L (horizontal)
V_U-V_D (vertical)

beam intensity V_R+V_L, V_U+V_D, $V_R+V_L+V_U+V_D$

normalized (intensity-independent) beam position = $\frac{\text{"position"}}{\text{intensity}}$

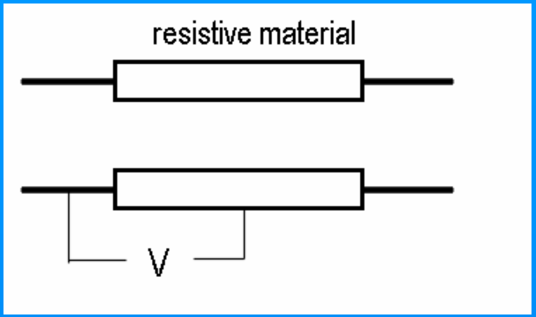
Remarks: 1) as we will see, higher-order nonlinearities must occassionally be taken into account

2) in circular $e^{+/-}$ accelerators, assembly is often tilted by 45 degrees

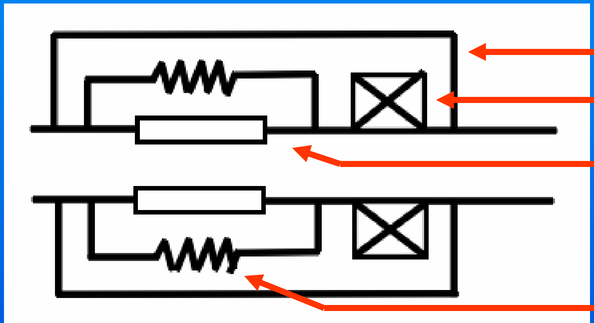
Beam Position – Wall Gap Monitor (1)

principle:
remove a portion of the vacuum chamber and replace it with some resistive material of impedance Z

detection of voltage across the impedance gives a direct measurement of beam current since $V = i_w(t)\, Z = -i_b(t)\, Z$

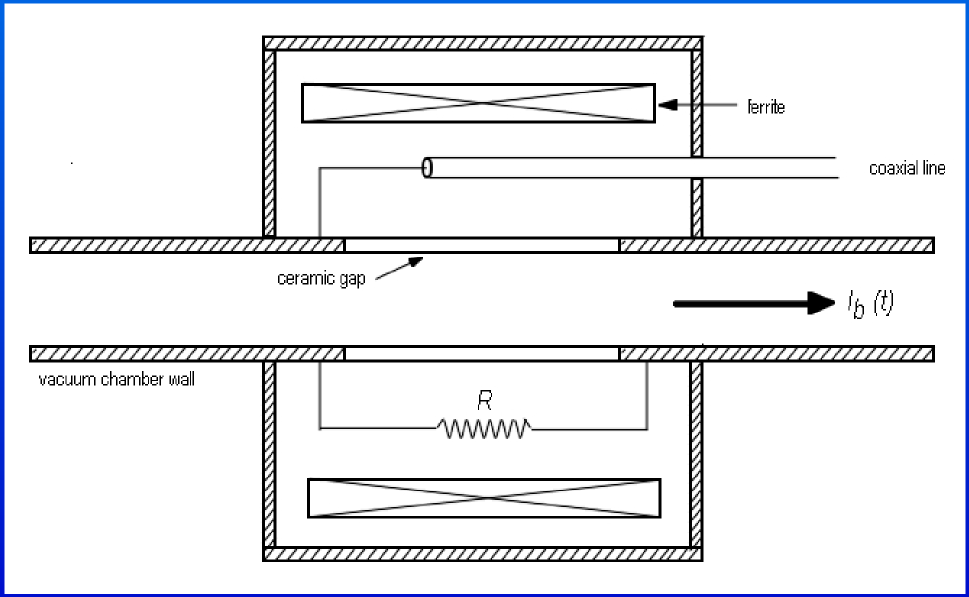


(susceptible to em pickup and to ground loops)



add high-inductance metal shield
add ferrite to increase L
add ceramic breaks
add resistors (across which V is to be measured)

alternate topology - one of the resistors has been replaced by the inner conductor of a coaxial line

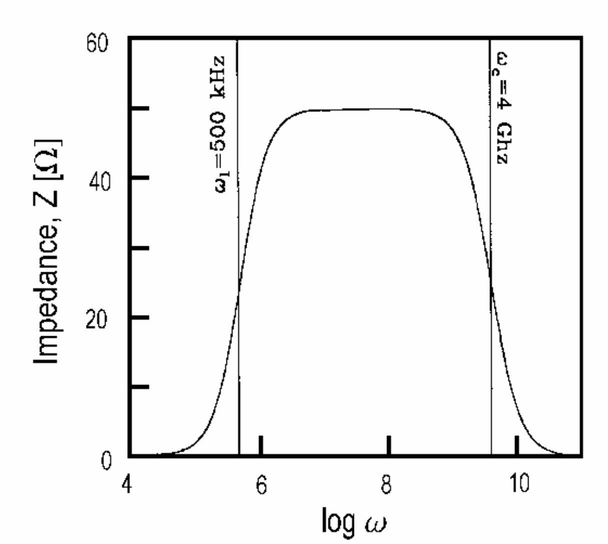


Beam Position – WGM (2)

sensitivity:

circuit model using parallel RLC circuit:

$$\frac{1}{Z} = \frac{1}{R} + \frac{1}{j\omega L} + j\omega C$$



high frequency response is determined by C:

$$|Z(\omega \to \infty)| = \frac{R}{\sqrt{1 + (\frac{\omega}{\omega_C})^2}}$$ ($\omega_C = 1/RC$)

low frequency response determined by L:

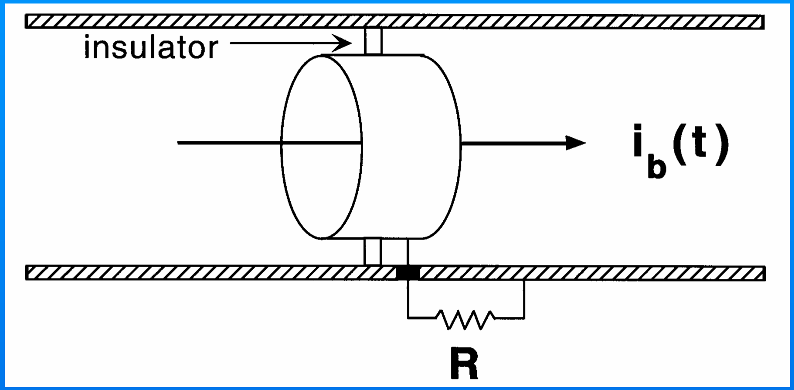
$$|Z(\omega \to 0)| = \frac{R}{\sqrt{1 + (\frac{\omega_L}{\omega})^2}}$$ ($\omega_L = R/L$)

intermediate regime: $R/L < \omega < 1/RC$ – for high bandwidth, L should be large and C should be small

remark: this simplified model does not take into account the fact that the shield may act as a resonant cavity

Beam Position – Capacitive Monitors (1)

(capacitive monitors offer better noise immunity since not only the wall current, but also PS and/or vacuum pump return and leakage currents, for example, may flow directly through the resistance of the WGM)



principle: vacuum chamber and electrode act as a capacitor of capacitance, C_e, so the voltage generated on the electrode is

$$V=Q/C_e \text{ with } Q = i_w t = i_w L/c$$

where L is the electrode length and

$$c = 3 \times 10^8 \text{ m/s}$$

long versus short bunches:

since the capacitance C_e scales with electrode length L, for a fixed L, the output signal is determined by the input impedance R and the bunch length σ

for $\omega \ll \omega_c$

(bunch long compared to electrode length $\sigma > L$)
the electrode becomes fully charged during bunch passage
signal output is differentiated
signal usually coupled out using coax attached to electrode

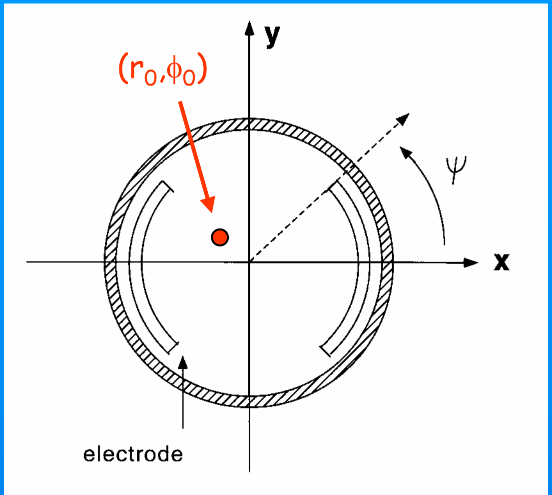
for $\omega \gg \omega_c$

output voltage rises rapidly and is followed by extended negative tail (since dc component of signal is zero)
induced voltage usually detected directly through a high impedance amplifier

Beam Position – Capacitive Monitors (2)

position information:

replace cylinder by curved electrodes (usually 2 or 4) symmetrically placed with azimuth +/- ψ (usually small to avoid reflections between the edges and the output coupling)



example – capactive split plate:

$$\sigma = \frac{1}{2\pi a}\left[1 + \sum_{n=1}^{\infty}(\frac{r_0}{r})^2 \cos n(\phi - \phi_0)\right]$$

surface charge density σ due to a unit line charge collinear to electrodes at (r_0,ϕ_0)

$$\begin{aligned} I_R &= \int_{-\psi}^{+\psi} \sigma(r d\phi) \\ &= \frac{i_w}{2\pi}[2\psi + 2\frac{x_0}{a}\sin\psi + \frac{x_0{}^2 - y_0{}^2}{a^2}\sin 2\psi + \ldots] \end{aligned}$$

$$\begin{aligned} I_L &= \int_{\pi-\psi}^{\pi+\psi} \sigma(r d\phi) \\ &= \frac{i_w}{2\pi}[2\psi - 2\frac{x_0}{a}\sin\psi + \frac{x_0{}^2 - y_0{}^2}{a^2}\sin 2\psi + \ldots] \end{aligned}$$

integrate over area of electrode

the voltage on a single electrode depends on the detector geometry via the radius a and the angle subtended by the electrode; e.g. if the signal from a *single* electrode is input into a frequency analyzer, higher harmonics arise due to these nonlinearities

voltage across impedance R

$$\begin{aligned} V &= (I_R - I_L)R \\ &= \frac{2i_w R}{\pi a}(\sin\psi)x_0 + \ldots \end{aligned}$$

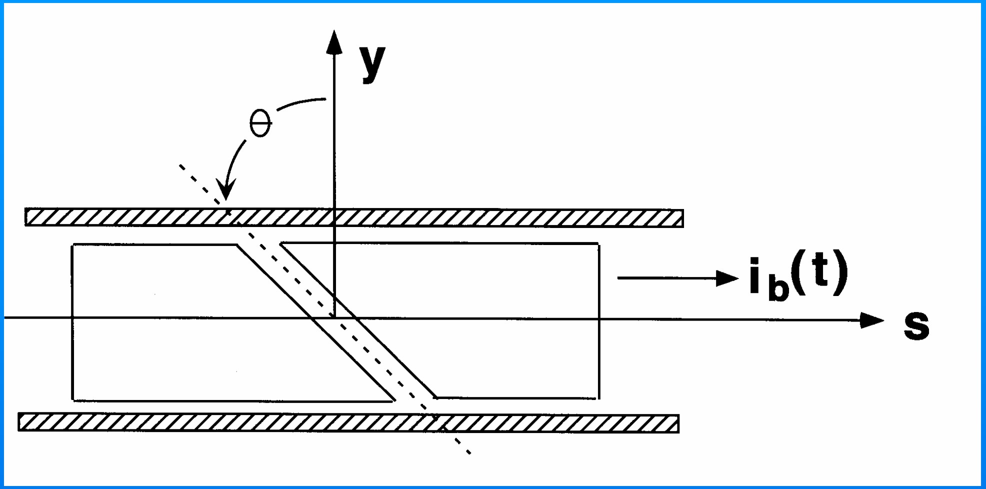
sensitivity

$$S = \frac{V}{i_w x_0} = \frac{2R}{\pi a}\sin\psi + \ldots$$

the voltage and sensitivity are large if the azimuthal coverage is large or the radius a is small; e.g. ψ = 30 deg, R = 50 Ω, a = 2.5 cm → S = 2 Ω/mm

Beam Position – Capacitive Monitors (3)

example – capactive split cylinder:



charge in each detector half is found by integrating the surface charge density:

$$Q_i = \frac{\lambda}{2}[L \pm \frac{r_0}{2\pi} \sin\phi_0 \tan\theta]$$

$$C_e = \frac{C}{2}$$

$$C = \frac{L}{Z_0 c}$$

(can be shown)

$$(\Delta x = r_0 \cos\phi_0)$$

detected voltage

$$V = \frac{Q_l - Q_r}{C_e} = \frac{Z_0 \tan\theta}{2\pi L}(-i_w)\Delta x$$

sensitivity

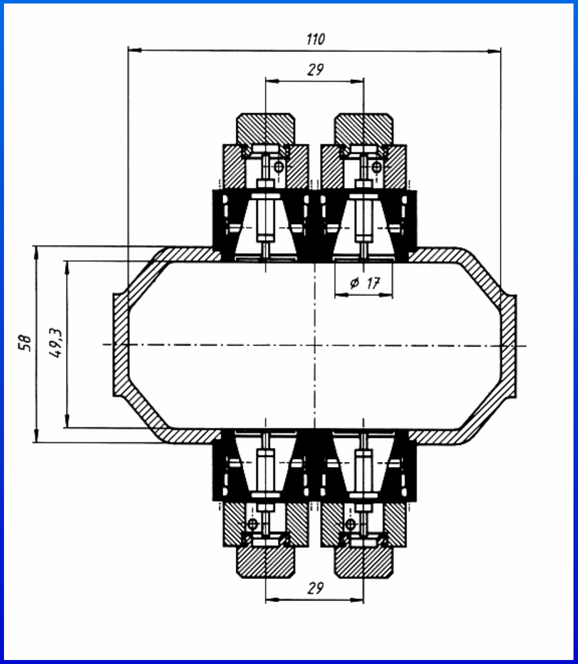
$$S = \frac{Z_0 \tan\theta}{2\pi L}$$

the capacitive split cylinder is a linear detector; there are no geometry -dependent higher order contributions to the position sensitivity.

Beam Position – Button Monitors

Buttons are used frequently in synchrotron light sources are a variant of the capacitive monitor (2), however terminated into a characterstic impedance (usually by a coax cable with impedance 50 Ω). The response obtained must take into account the signal propagation (like for transmission line detectors, next slide)

button electrode for use between the undulators of the TTF II SASE FEL (courtesy D. Noelle and M. Wendt, 2003)



cross-sectional view of the button BPM assembly used in the DORIS synchrotron light facility

design reflects geometrical constraints imposed by vacuum chamber geometry

note: monitor has inherent nonlinearities

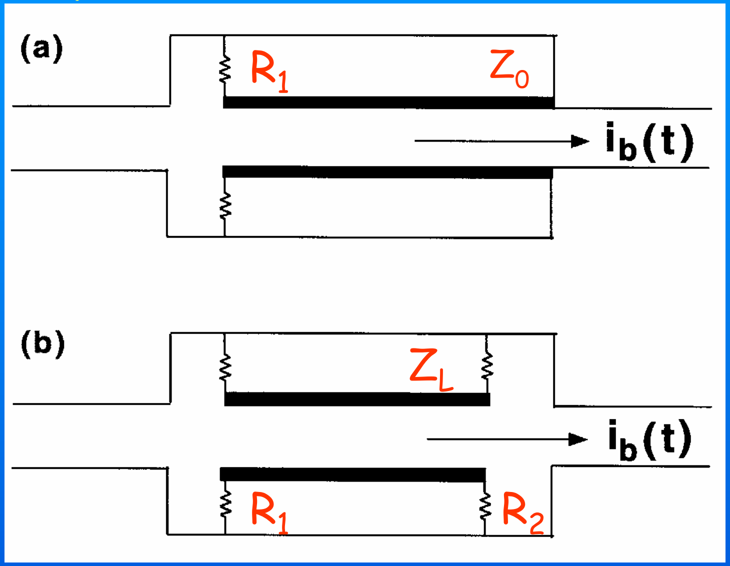
(courtesy F. Peters, 2003)

Beam Position – Stripline / Transmission Line Detectors (1)

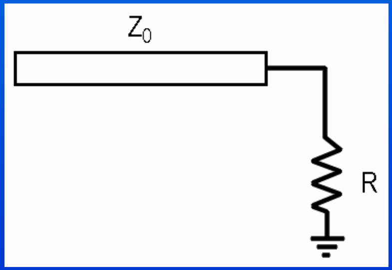
principle: electrode (spanning some azimuth ψ) acts as an inner conductor of a coaxial line; shield acts as the grounded outer conductor → signal propagation must be carefully considered

untermininated transmission line

transmission line terminated (rhs) to a matched impedance



reminder: characteristic impedance Z_0 terminated in a resistor R

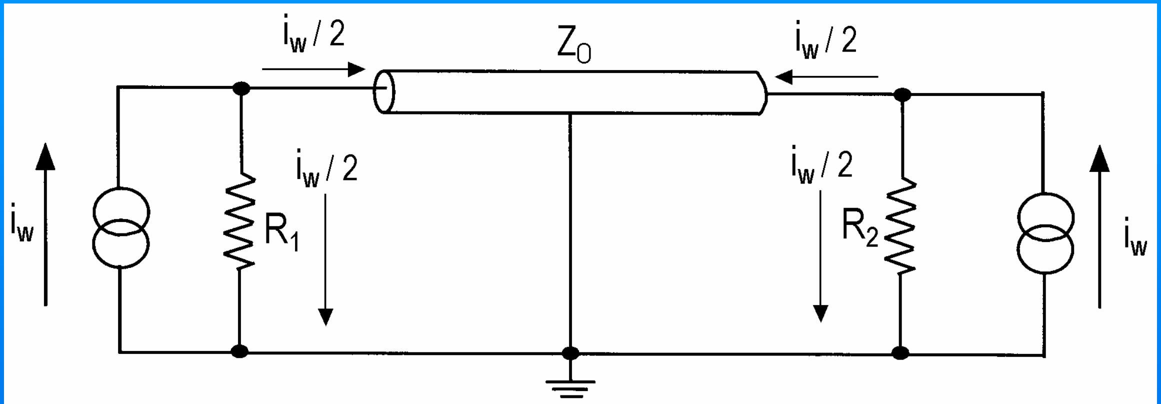


$$\rho = \text{reflection coefficient} = \frac{R-Z_0}{R+Z_0} = \begin{cases} 0 & \text{if } R=Z_0 \\ -1 & \text{if } R=0 \\ >0 & \text{if } R>Z_0 \\ <0 & \text{if } R<Z_0 \end{cases}$$

Γ = sqrt(1- ρ^2) = transmission coefficient

Beam Position – Stripline / Transmission Line Detectors (2)

equivalent circuit (approximation: velocity of i_w = velocity of i_b, approximately true in absence of dielectric and/or magnetic materials)



(matched impedances)

the voltage appearing across each resistor is evaluated by analyzing the current flow in each gap:

voltage at R_1:

$$V_{R_1,g_1} = \frac{i_w}{2}\Big[\underbrace{1}_{\text{initial}} + \underbrace{\left(\frac{R_2 - Z_0}{R_2 + Z_0}\right)e^{-2j\omega\Delta t}}_{\text{reflection}}\Big]R_1$$

$$V_{R_1,g_2} = \underbrace{-\frac{i_w}{2}e^{-j\omega\Delta t}}_{\text{beam delay}}\underbrace{\left[1 - \left(\frac{R_1 - Z_0}{R_1 + Z_0}\right)\right]}_{\text{transmission}}e^{-j\omega\Delta t}R_1$$

Beam Position – Stripline / Transmission Line Detectors (3)

similarly, voltage at R_2:

$$V_{R_2,g_1} = \underbrace{\frac{i_w}{2} e^{-j\omega\Delta t}}_{\text{signal delay}} \underbrace{\left[1 - \left(\frac{R_2 - Z_0}{R_2 + Z_0}\right)\right]}_{\text{transmission}} R_2$$

$$V_{R_2,g_2} = \underbrace{-\frac{i_w}{2} e^{-j\omega\Delta t}}_{\text{beam delay}} \left[\underbrace{1}_{\text{initial}} + \underbrace{\left(\frac{R_1 - Z_0}{R_1 + Z_0}\right) e^{-2j\omega\Delta t}}_{\text{reflection}}\right] R_2$$

voltage on each resistor:

$$\begin{aligned} V_{R_1} &= V_{R_1,g_1} + V_{R_1,g_2} \\ V_{R_2} &= V_{R_2,g_1} + V_{R_2,g_2} \end{aligned}$$

$$\Delta t = \frac{L}{c}$$

special cases:

(i) $R_1 = Z_0$, $R_2 = 0$ (terminated to ground)

$$V_{R_1} = \frac{i_w}{2}\left(1 - e^{-\frac{2j\omega L}{c}}\right) R_1$$

$$V_{R_2} = 0$$

(no signal generated at g_2)

(ii) $R_1 = R_2 = Z_L$ (matched line)

$$V_{R_1} = \frac{i_w}{2}\left(1 - e^{-\frac{2j\omega L}{c}}\right) Z_L$$

$$V_{R_2} = 0$$

(iii) $R_1 = R_2 \neq Z_L$ then solution as in (ii) to second order in ρ

Beam Position – Stripline Monitors (4)

again, $V_{R_1} = \frac{i_w}{2}\left(1 - e^{-\frac{2j\omega L}{c}}\right)R_1$

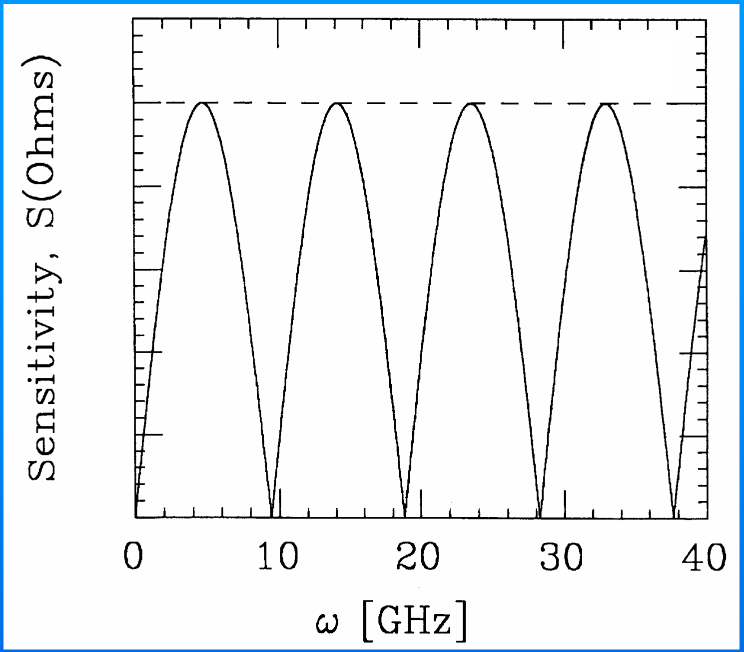
sensitivity $|S| = |\frac{V}{i_w}| = R_1|\sin^2\omega\Delta t|$

signal peaks at

$\omega\Delta t = \frac{2\pi L}{\lambda} = \frac{\pi}{2} \longrightarrow L = \frac{\lambda}{4}$

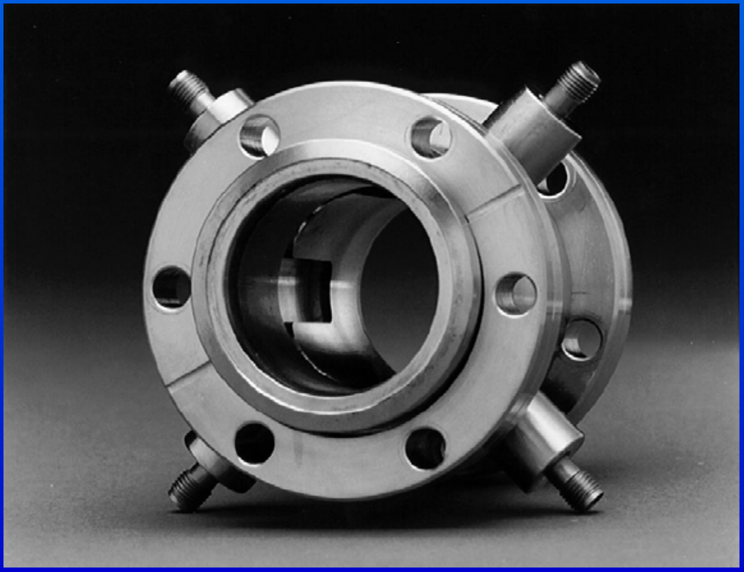
spacing between zeros

$\omega\Delta t = 0 \longrightarrow L = \frac{\lambda}{2}$



sensitivity of a matched transmission line detector of length L=10 cm

the LEUTL at Argonne shorted S-band quarter-wave four-plate stripline BPM (courtesy R.M. Lill, 2003)



specially designed to enhance port isolation (using a short tantalum ribbon to connect the stripline to the molybdenum feedthrough connector) and to reduce reflections

L=28 mm (electrical length ~7% longer than theoretical quarter-wavelength), Z_0=50 Ω

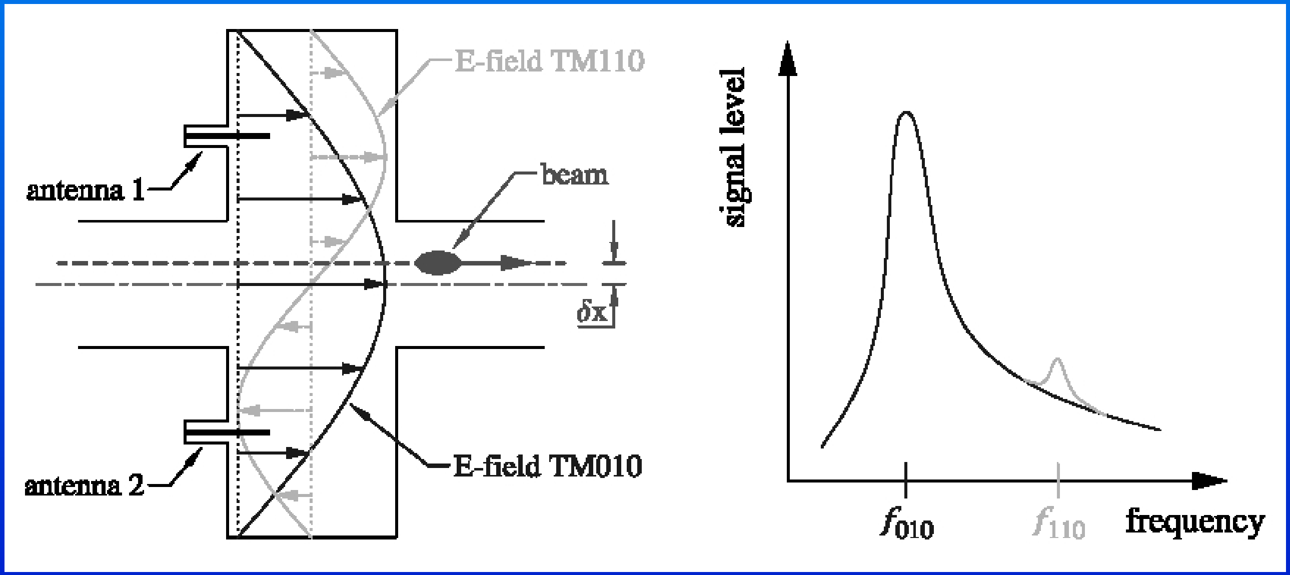
Beam Position – Cavity BPMs (1)

principle: excitation of discrete modes (depending on bunch charge, position, and spectrum) in a resonant structure; detection of dipole mode signal proportional to bunch charge, $q \times$transverse displacement, δx

theoretical treatment: based on solving Maxwell's equations for a cylindrical waveguide with perpendicular plates on two ends

motivation: high sensitivity (signal amplitude / μm displacement)
accuracy of absolute position, LCLS design report

dipole mode cavity BPM consists of (usually) a cylindrically symmetric cavity, which is excited by an off-axis beam:



reference:
"Cavity BPMs", R. Lorentz (BIW, Stanford, 1998)

TM_{010}, "common mode" ($\propto$ I)
TM_{110}, dipole mode of interest

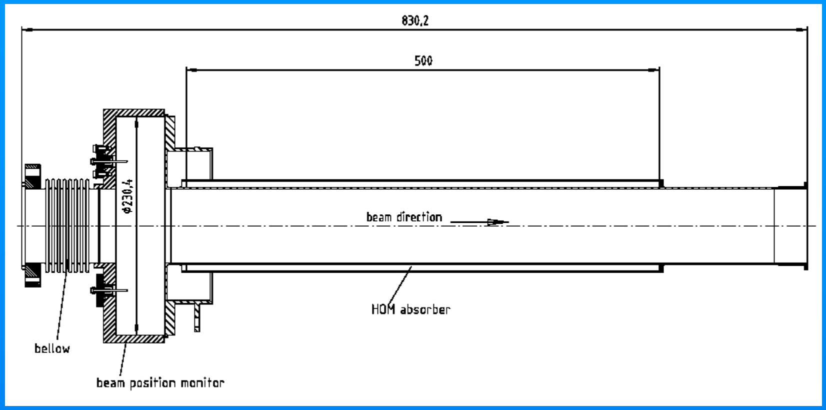
amplitude detected at position of antenna contains contributions from both modes → signal processing

Beam Position – Cavity BPMs (2)

$$V_{110}^{out}(\delta x) = V_{110}^{in}(\delta x)\left(\frac{R}{Q}\right)_{110}^{-1/2}\sqrt{\frac{50\Omega}{Q_L}}\sqrt{1-\frac{Q_L}{Q_0}}$$

$$V_{110}^{in} \approx \delta x \cdot q\frac{lT_{tr}^{\;2}}{r^3}\cdot 0.2474$$

$$T_{tr} = \frac{\sin\eta}{\eta} \quad \text{with} \quad \eta = \frac{\pi l}{\lambda_{mn0}}$$



schematic of a "cold" cavity BPM tested at TTF I (Lorenz)

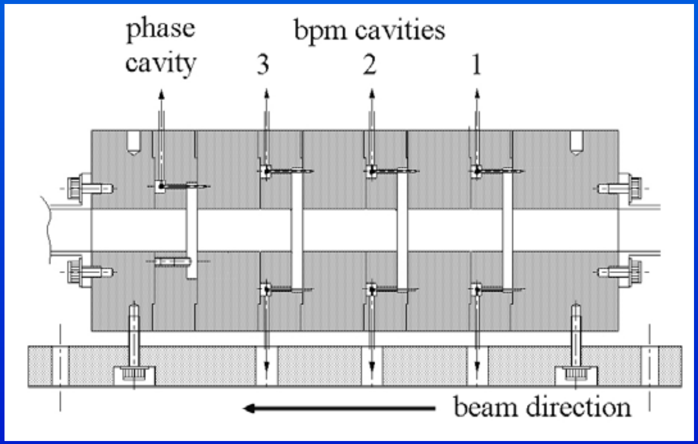
T_{tr}	transit time factor
(R/Q)	geometrical property of cavity
Q_0, Q_L	unloaded and loaded Q-factors
L	cavity length
r	cavity radius
λ_{mn0}	wavelength of mode of interest
δx	transverse displacement

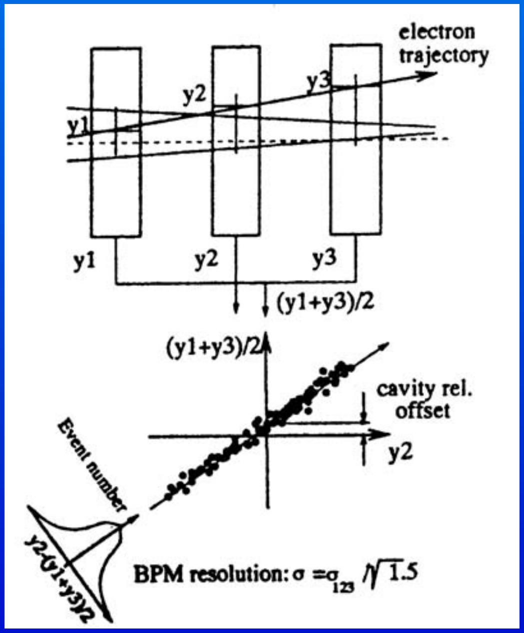
for the TTF cavity BPM:

r = 115.2mm

L = 52 mm

→ V_{110}^{out} ~115 mV/mm for 1 nC





pioneering experiments: 3 C-band cavity "RF" BPMs in series at the FFTB (SLAC)
→25 nm position resolution at 1 nC bunch charge

(courtesy, T. Shintake, 2003)

Beam Position – Reentrant Cavity BPMs

principle: detection of the evanescent field of the cavity fundamental mode (those waves with exponential attenuation below the cut-off frequency):

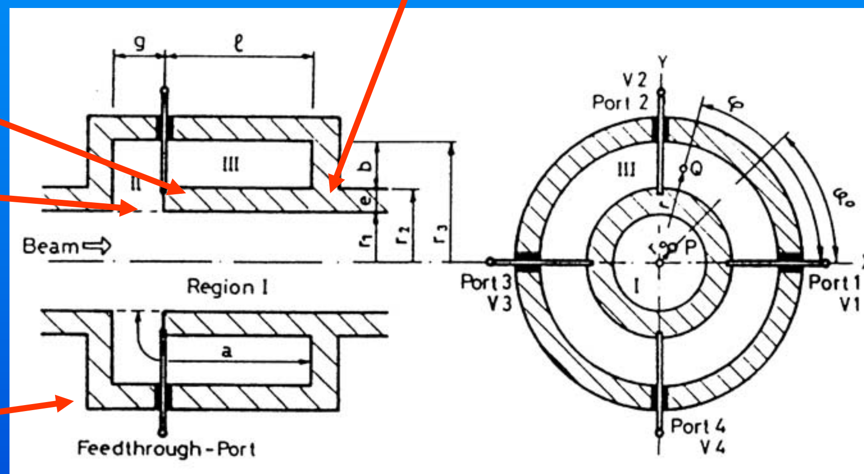
excite cavity at frequency f_0 with respect to cavity resonant frequency f_r while Q-factor decreases by sqrt(f_0/f_r), the attenuation constant of evanescent fields below ~1/2 the cut-off frequency is practically constant → maintain high signal amplitude

(short to ground)

vacuum chamber

gap

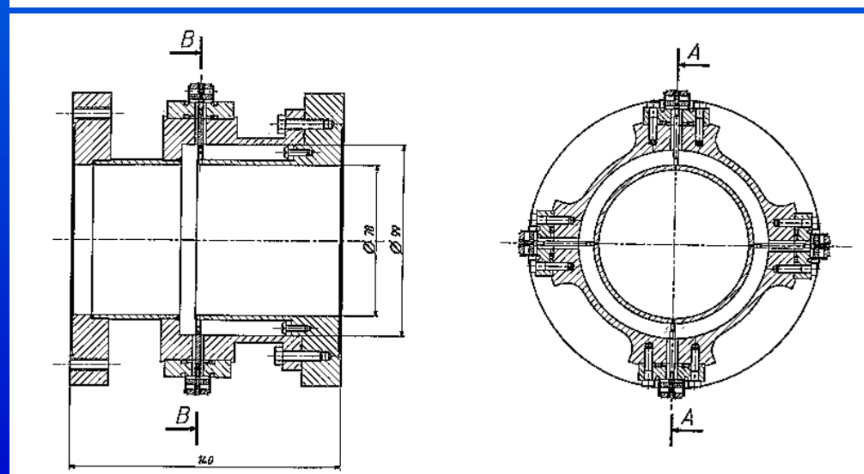
coaxial cylinder



from R. Bossart, "High Precision BPM Using a Re-Entrant Coaxial Cavity", LINAC94

using URMEL, the equivalent circuit for impedance model was developed

schematic of the reentrant cavity BPM used successfully at TTF I and planned for use at TTF II (courtesy C. Magne, 2003)



Summary

Detection of the wall current I_w allows for measurements of the beam intensity and position

The detector sensitivities are given by

$$S(\omega) = \frac{V(\omega)}{I_w(\omega)}$$ for the beam charge and intensity

$$S(\omega) = \frac{V(\omega)}{D(\omega)}$$ with $D(\omega) = I_w(\omega)x$ for the horizontal position

$D(\omega) = I_w(\omega)y$ for the vertical position

We reviewed basic beam diagnostics for measuring:

the beam charge – using Faraday cups

the beam intensity – using toroidal transformers and BPM sum signals

the beam position

- using wall gap monitors
- using capacitive monitors (including buttons)
- using stripline / transmission line detectors
- using resonant cavities and re-entrant cavities

We note that the equivalent circuit models presented were often simplistic. In practice these may be tailored given direct measurement or using computer models. Impedances in the electronics used to process the signals must also be taken into account as they often limit the bandwidth of the measurement. Nonetheless, the fundamental design features of the detectors presented were discussed (including variations in the designs) highlighting the importance of detector geometries and impedance matching as required for high sensitivity.