RF beam diagnostics

- *Basics of beam monitoring with RF cavities*
- *Example devices*
- *Quantitative analysis*
- *Measuring rms bunch length*

CAS "RF for Accelerators"
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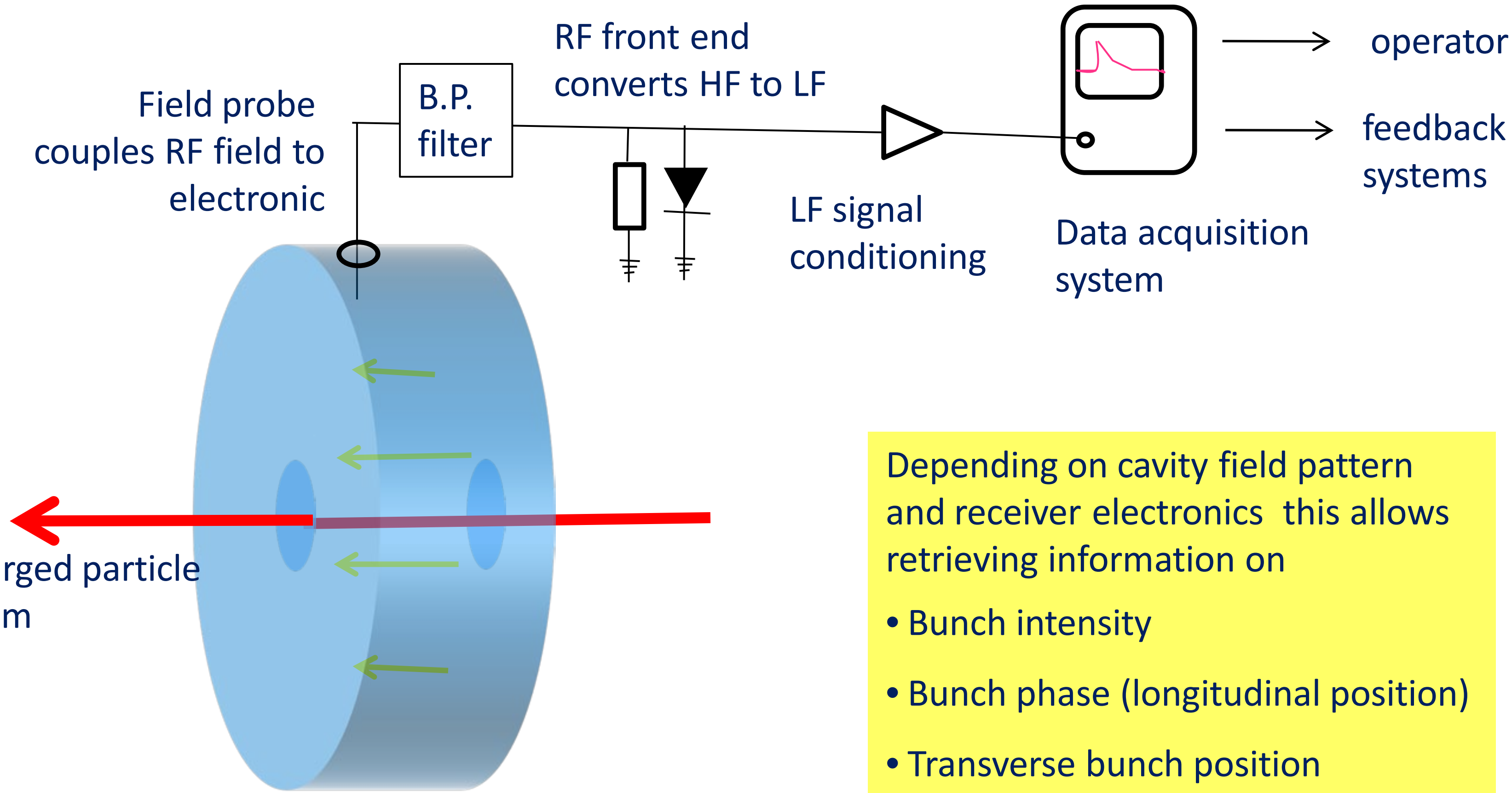
Hans-H. Braun / PSI

Basics of RF cavities for beam measurements



Depending on cavity field pattern and receiver electronics this allows retrieving information on

- Bunch intensity
- Bunch phase (longitudinal position)
- Transverse bunch position
- Beam angle
- Bunch length

Energy transfer from beam to cavity

Electric field of a resonant cavity mode $\vec{E}(\vec{x},t) = A\vec{E}(\vec{x})e^{i\omega t}$

Power flow between cavity and a traversing charge $\frac{dW_q}{dt} = q\frac{d\vec{x}}{dt} \cdot \vec{E}(\vec{x})e^{-i\omega t}$

Beams are in good approximation paraxial

$$\frac{d\vec{x}}{dt} \approx \begin{pmatrix} 0 \\ 0 \\ v \end{pmatrix}$$

$$\frac{dW_q}{dq} = \int E_z(\vec{x})e^{-i\frac{\omega}{v}z}dz = V$$

$$dW_q = -dW_{cav}$$

$$W_{cav} = \iiint \varepsilon_0 \vec{E}^2 dV$$

Energy transfer from beam to cavity

Voltage induced by charge

$$\frac{dV}{dq} = \frac{dV}{dW_{cav}} \frac{dW_{cav}}{dq}$$

$$= \frac{V}{2W_{cav}} \cdot V = \frac{V^2}{2W_{cav}} = \frac{\left(\int E_z(\vec{x})\, e^{-i\frac{\omega}{v}z} dz \right)^2}{2\varepsilon_0 \iiint \vec{E}(\vec{x})^2 \, dV}$$

Definition loss factor

$$k_{loss} \equiv \frac{dV}{2dq} = \frac{V^2}{4W_{cav}} = \frac{R_{shunt}\omega}{4Q_0} = \frac{\left(\int E_z(\vec{x})\, e^{-i\frac{\omega}{v}z} dz \right)^2}{4\varepsilon_0 \iiint \vec{E}(\vec{x})^2 \, dV}$$

Voltage induced by traversing charge $V = 2k_{loss}q$

Energy deposited in empty cavity $W = k_{loss}q^2$

k_{loss} depends only on field distribution $\vec{E}(\vec{x})$,

beam position and particle velocity v!

Energy transfer for finite bunchlength

For a particle bunch of finite length with $\frac{dq}{dt} = i_b(t) = q_b f(t)$

each time slice contributes with different phase to the induced voltage of a resonant mode with frequency ω

The induced voltage is in this case $V = 2k_{loss} q_b F_b$

and the energy deposited in an initially empty cavity $W = k_{loss} q_b^{\ 2} F_b^{\ 2}$

with the "bunch Formfactor" $F_b = \left| \int f(t) \cdot e^{i\omega t} dt \right|$

For a gaussian bunch with $i_b(t) = \frac{q_b}{\sqrt{2\pi}\sigma_b} \exp\left(\frac{-t^2}{2\sigma_b^{\ 2}} \right)$

$$F_b = \exp\left(\frac{-\omega^2 \sigma_b^{\ 2}}{2} \right)$$

Example: ω=2π· 3 GHz, σ_b=10 ps $\Rightarrow$ F_b=0.982

Dissipation of energy in cavity

Power loss in RF cavity $P_C = \frac{R_{Surf}}{2\mu_0^{\ 2}} \oint\!\!\oint_S B^2 dS$

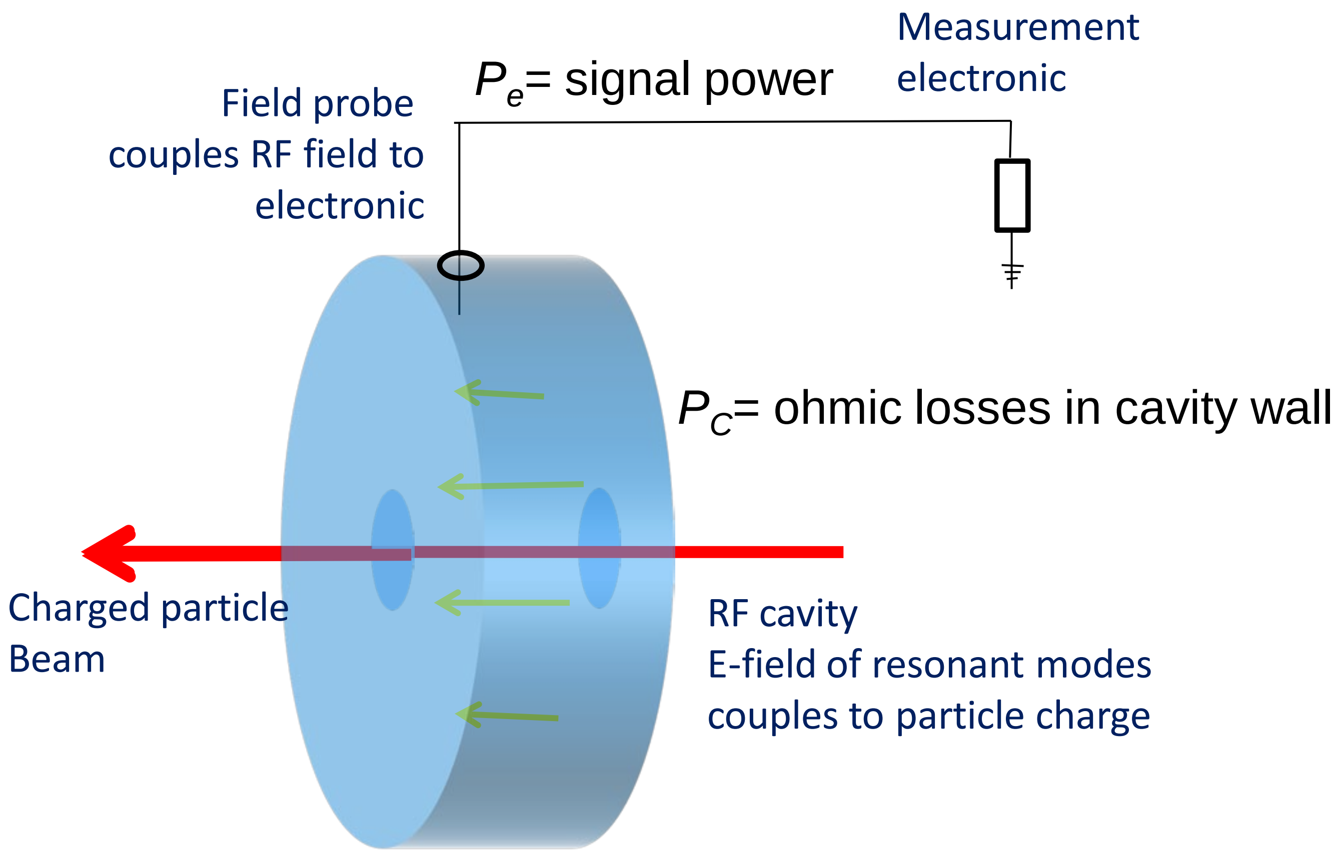
with $R_{Surf} = \frac{1}{\sigma\,\delta} = \sqrt{\frac{\mu_0 \omega}{2\sigma}}$

Cavity quality factor $Q_0 \equiv \frac{\omega W}{P_{\mathrm{C}}}$

$$W(t) = W(0)\exp\left(-\frac{\omega}{Q_0}t\right)$$

$$= k_{loss} q_b^{\ 2} F_b^{\ 2} \exp\left(-\frac{\omega}{Q_0}t\right)$$

Energy flow



Measurement
electronic
P_e= signal power
Field probe
couples RF field to
electronic
P_C= ohmic losses in cavity wall
Charged particle
Beam
RF cavity
E-field of resonant modes
couples to particle charge

Dissipation of energy in cavity and external measurement electronic

Dissipated power $P_t = P_C + P_E$

coupling factor $\beta \equiv \frac{P_E}{P_C}$

Loaded quality factor $Q_L \equiv \frac{\omega W}{P_C + P_E} = \frac{Q_0}{1+\beta}$

$$W(t) = W(0)\exp\left(-\frac{\omega}{Q_L}t\right) = k_{loss}q_b^{\,2}F_b^{\,2}\exp\left(-\frac{\omega(1+\beta)}{Q_0}t\right)$$

Signal power $P_E(t) = \frac{\omega W(t)}{Q_L\left(1+\frac{1}{\beta}\right)} = \frac{\omega k_{loss}q_b^{\,2}F_b^{\,2}}{Q_0}\beta\exp\left(-\frac{\omega(1+\beta)}{Q_0}t\right)$

Cavity driven by continuous bunch train

Steady state voltage in cavity $V = \frac{R_{Shunt} I_b F_b}{(1+\beta)} = \frac{4Q_0 k_{loss} I_b F_b}{\omega(1+\beta)}$

External signal power $P_E = R_{Shunt} I_b{}^2 F_b{}^2 \frac{\beta}{(1+\beta)^2} = \frac{4Q_0 k_{loss}}{\omega} I_b{}^2 F_b{}^2 \frac{\beta}{(1+\beta)^2}$

An error between bunch frequency ω and resonant cavity frequency ω_0

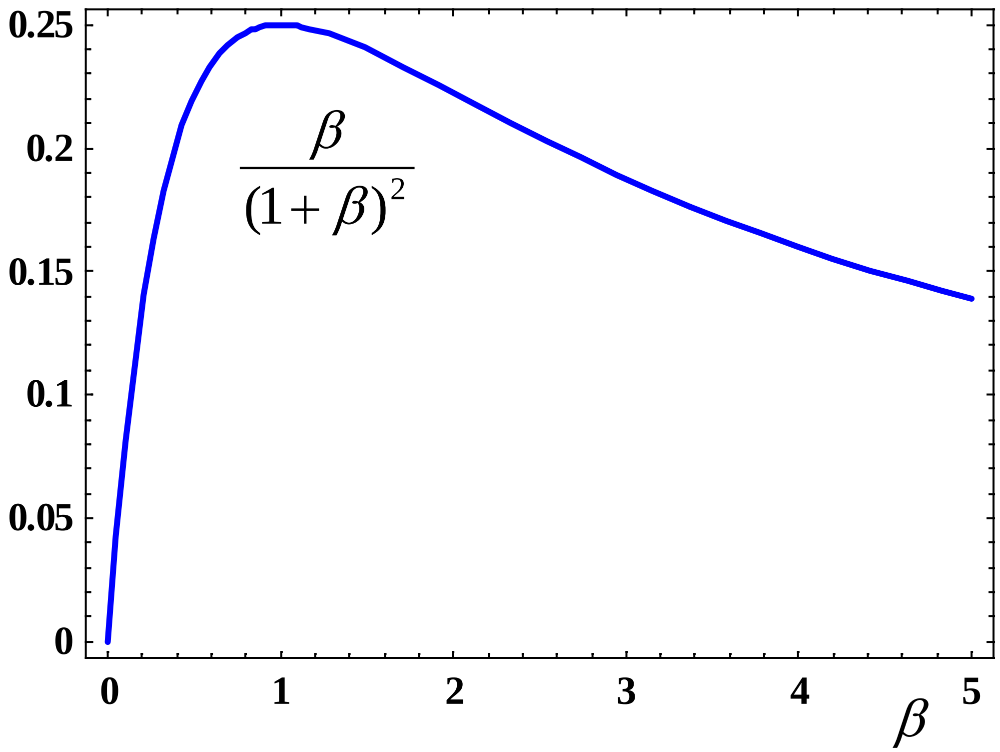
leads to a phase error ψ of the induced voltage with $\tan\psi = \frac{-2Q_0}{1+\beta} \frac{\omega - \omega_0}{\omega_0}$

a reduced voltage amplitude $V = \frac{R_{Shunt} I_b F_b}{(1+\beta)} \cos\psi$

and a reduced external signal power $P_E = R_{Shunt} I_b{}^2 F_b{}^2 \frac{\beta}{(1+\beta)^2} \cos^2\psi$

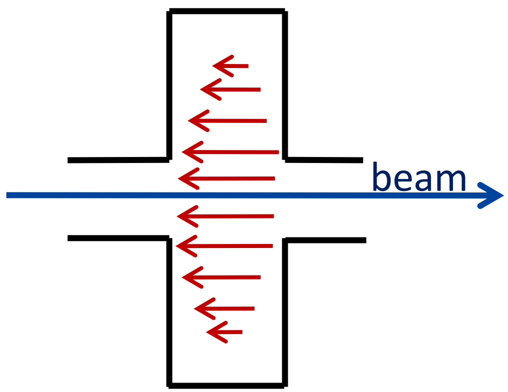
Signal power vs. coupling factor β for c.w. beams

External signal power $$P_E = R_{Shunt} I_b^{\,2} F_b^{\,2} \frac{\beta}{(1+\beta)^2} = \frac{4 Q_0\, k_{loss}}{\omega} I_b^{\,2} F_b^{\,2} \frac{\beta}{(1+\beta)^2}$$



Beam measurement types

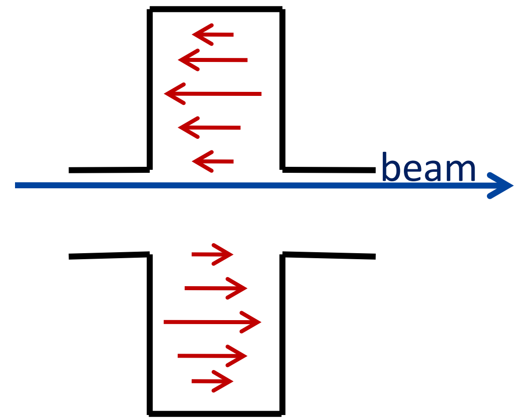
Measurement of beam intensity
or beam timing/phase relative to some external RF reference



Cavity mode with rotational symmetry
and electric field maximum on beam axis

"Monopole mode" , "TM_{010} like mode"

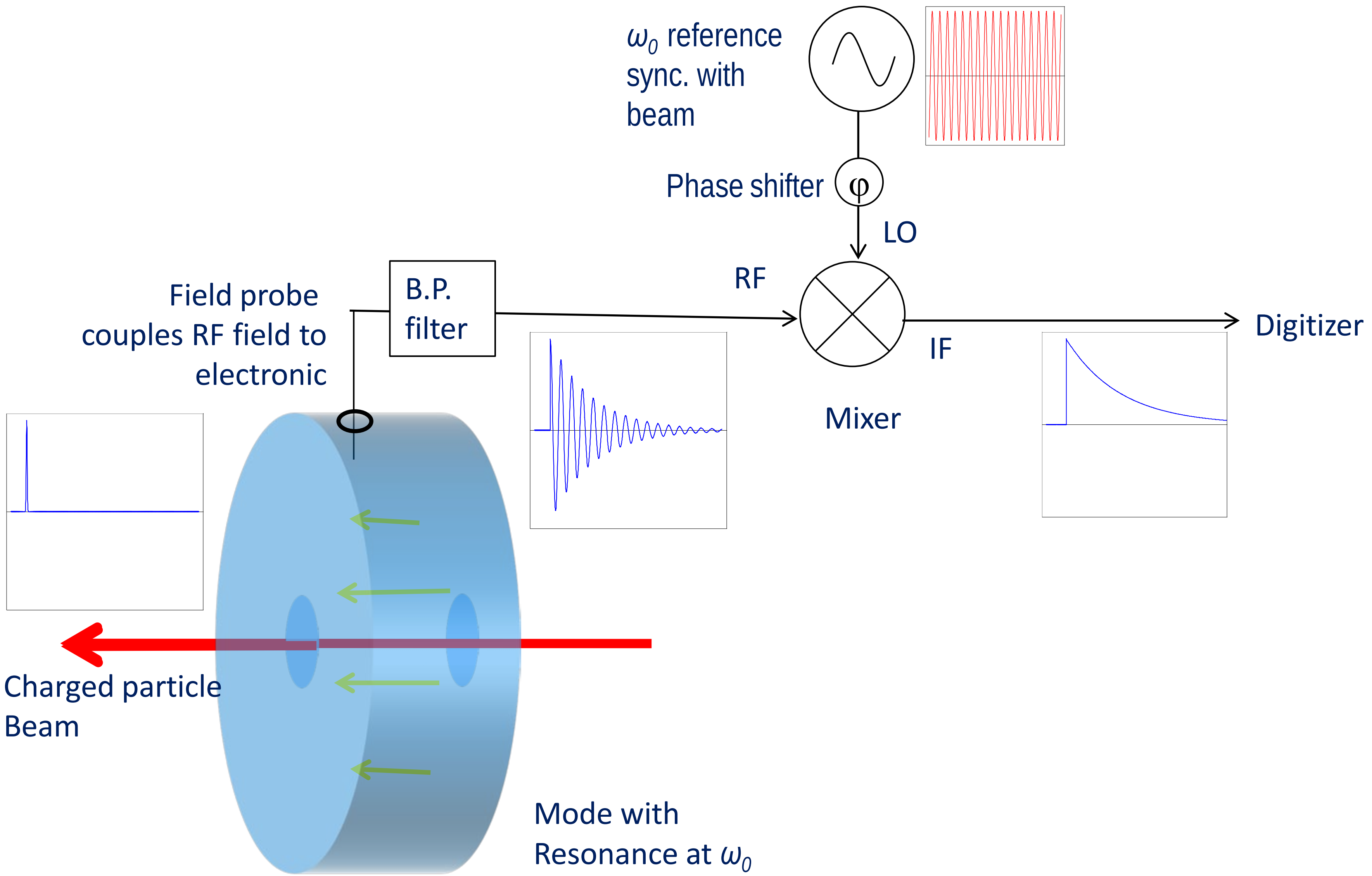
Measurement of beam position



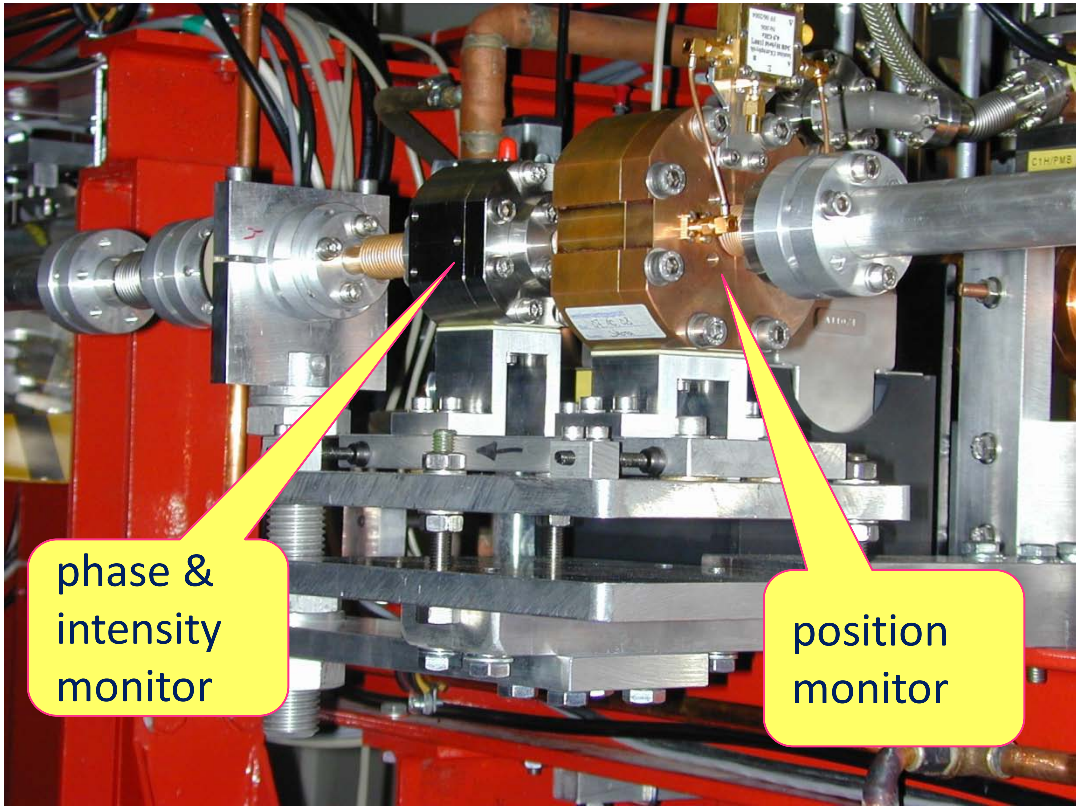
Cavity mode with Zero electric field on axis, azimuthal field dependence like Cos(θ)
and field strength dependence on beam position approximately linear with displacement *r*

"Dipole mode", "TM_{110}" like mode

Signal path in RF frontend



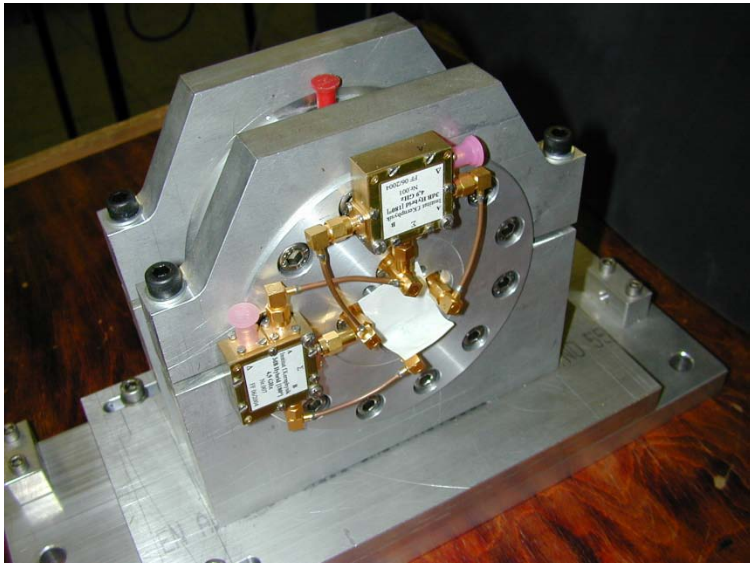
Example of RF monitors in MAMI

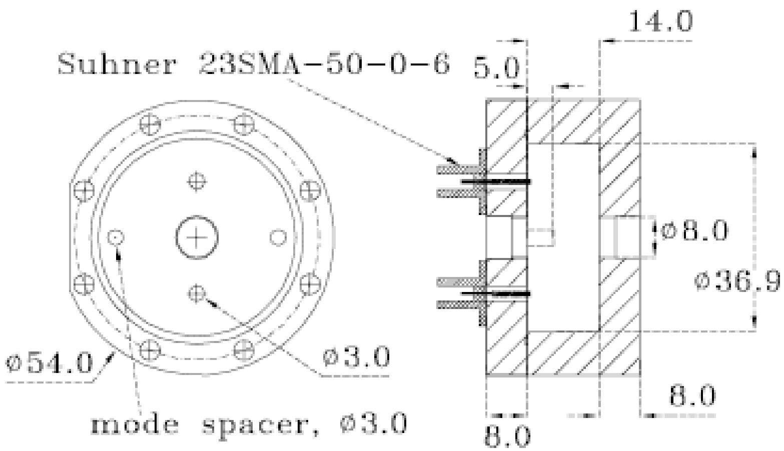


4.9 GHz Phase and Position Resonators in MAMI double sided Microtron (at Mainz University)

Courtesy H. Euteneuer and O. Chubarov

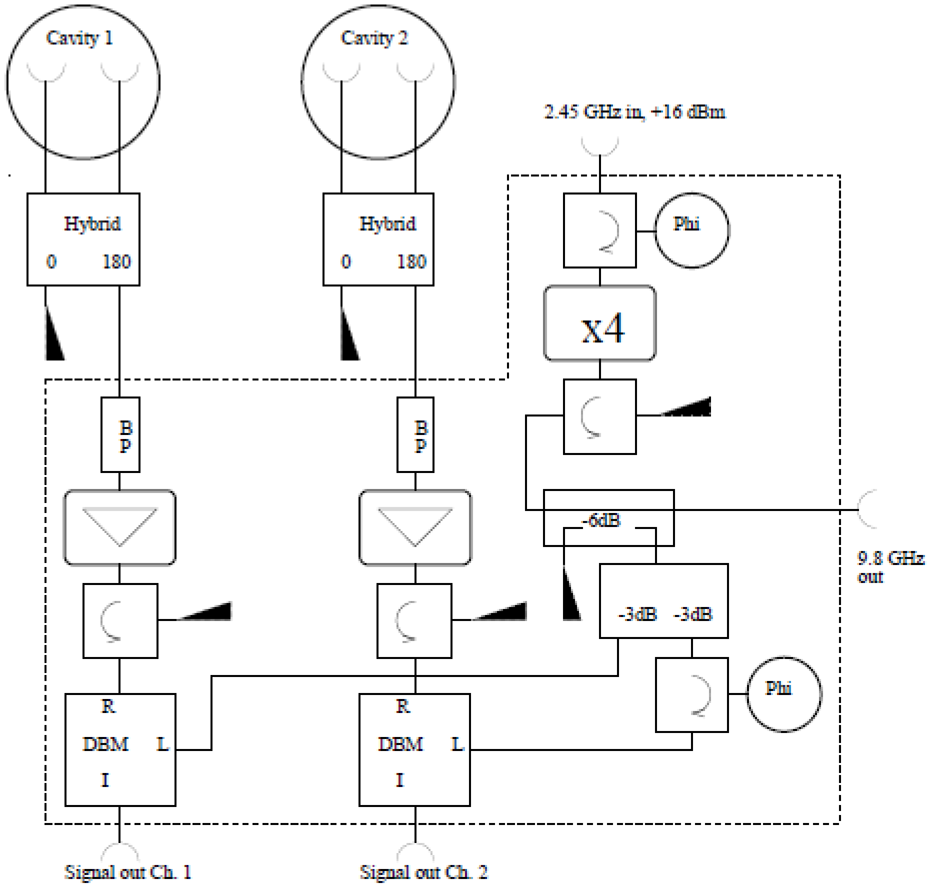
MAMI monitors cont.

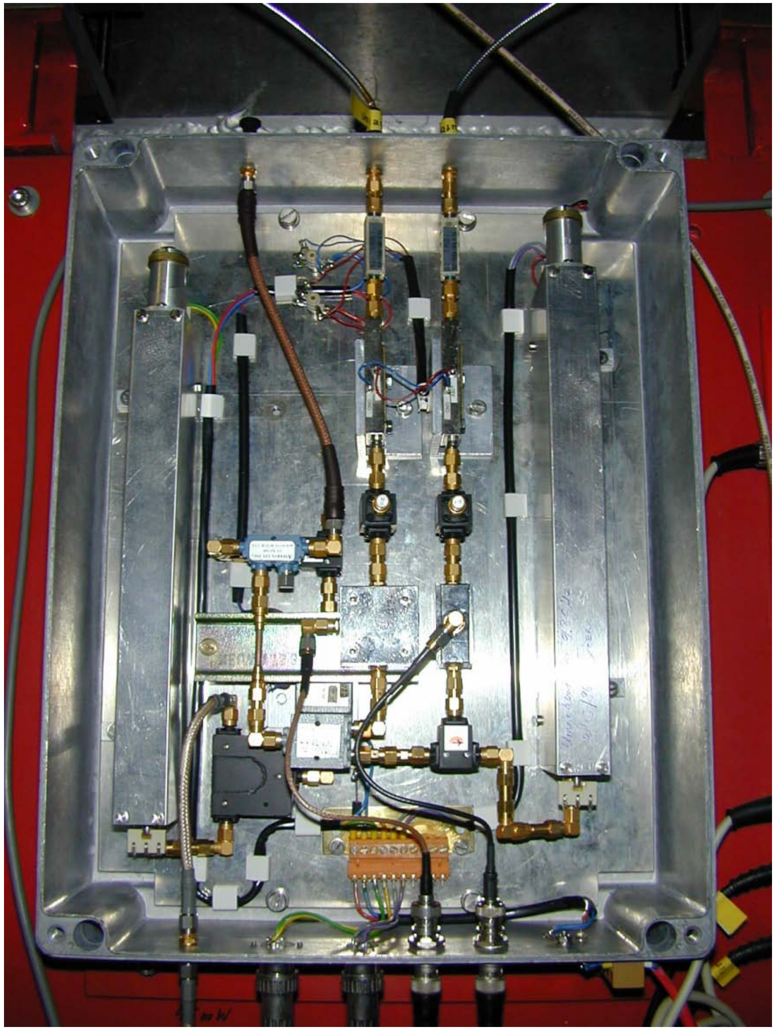




Drawing of a similar cavity
(but at 9.8GHz)

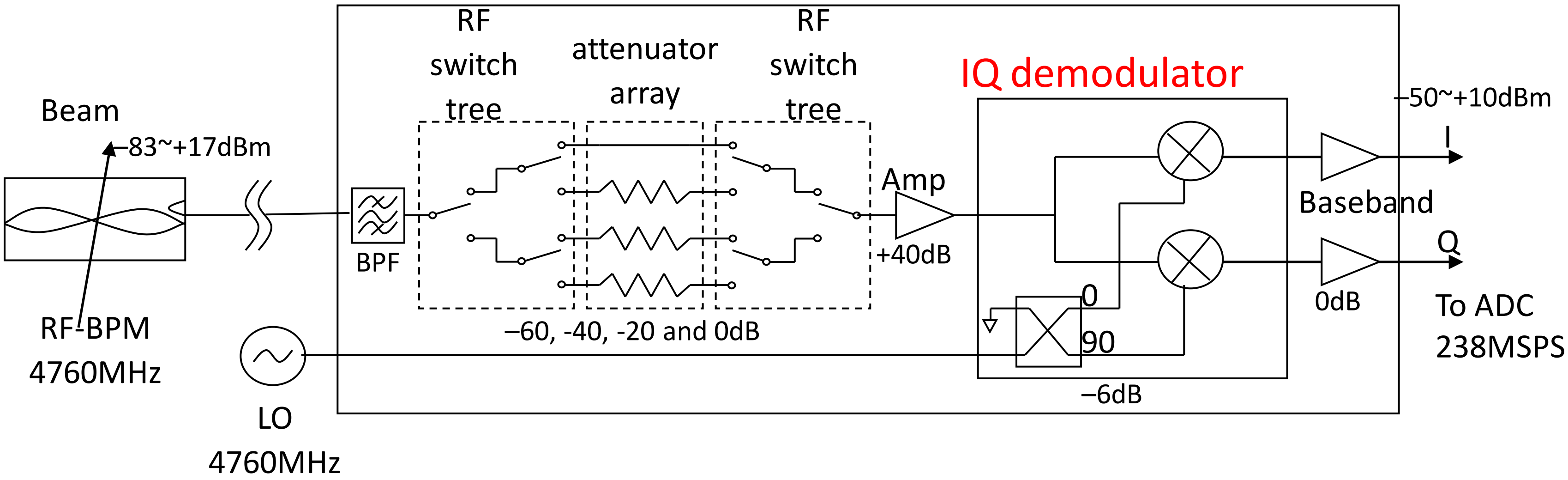
RF electronic for 9.8 GHz RF BPM's in MAMI





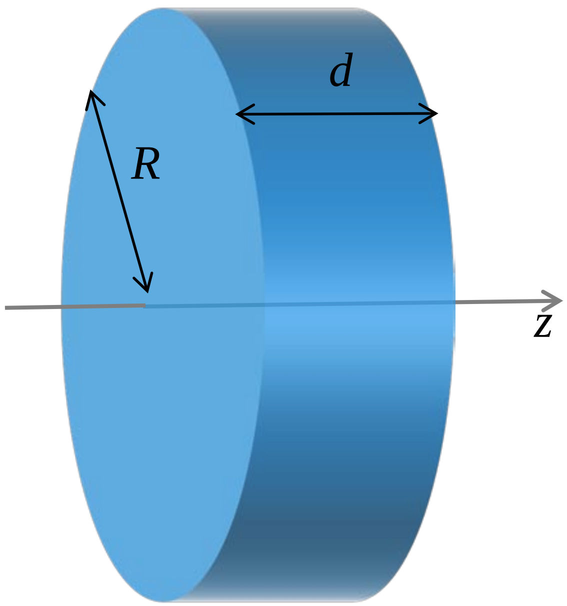
Courtesy H. Euteneuer and T. Doerk

Example of RF front with IQ demodulation and switchable gain



Schematic from SCSS/Spring8

Properties of "Pillbox" cavity TM_{mn0} modes



$$E_z = A\, J_m(k\,r)\cos(m\vartheta)\, e^{i\omega t}$$

$$B_r = A\,\frac{-i}{\omega r}\, J_m(k\,r)\sin(m\vartheta)\, e^{i\omega t}$$

$$B_\vartheta = A\,\frac{-i}{2c}\left(J_{m-1}(k\,r) - J_{m+1}(k\,r)\right)\cos(m\vartheta)\, e^{i\omega t}$$

$$E_\vartheta = E_r = B_z = 0$$

with $k \equiv \frac{\omega}{c}$, $\omega = \frac{c\, X_{mn}}{R}$ and $J_m(X_{mn}) = 0$

Properties of "Pillbox" cavity TM_{mn0} modes cont.

$$V(r,\vartheta) = \int_{-d/2}^{d/2} E_z(\vec{x}) e^{-i\frac{\omega}{v}z} dz$$

$$= A \frac{2v}{\omega} J_m(kr)\cos(m\vartheta)\sin\left(\frac{\omega}{2v}d\right)$$

$$W = \frac{\varepsilon_0}{2} \int_{-d/2}^{d/2} \int_0^{2\pi} \int_0^{R} E_Z{}^2 r\, dr\, d\vartheta\, dz$$

$$= A^2 \frac{\pi\varepsilon_0 R^2 d}{2} J_1(X_{0n})^2 \quad \text{for } m = 0$$

$$= A^2 \frac{-\pi\varepsilon_0 R^2 d}{4} J_{m-1}(X_{mn}) \cdot J_{m+1}(X_{mn}) \quad \text{for } m > 0$$

$$k_{loss}(r,\vartheta) = \frac{V^2}{4W}$$

$$= \frac{2v^2}{\pi\varepsilon_0 R^2 \omega^2} \frac{J_0(kr)^2}{J_1(X_{0n})^2} \frac{\sin^2\left(\frac{\omega}{2v}d\right)}{d} \quad \text{for } m = 0$$

$$= \frac{4v^2}{\pi\varepsilon_0 R^2 \omega^2} \frac{-J_m(kr)^2}{J_{m-1}(X_{mn}) \cdot J_{m+1}(X_{mn})} \frac{\sin^2\left(\frac{\omega}{2v}d\right)}{d} \cos^2(m\vartheta) \quad \text{for } m > 0$$

Properties of "Pillbox" cavity TM_{mn0} modes cont.

Power loss in RF cavity $$P_C = \frac{R_{Surf}}{2\mu_0^{\,2}} \oiint_S B^2 dS$$

with $$R_{Surf} = \frac{1}{\sigma\,\delta} = \sqrt{\frac{\mu_0\omega}{2\sigma}}$$

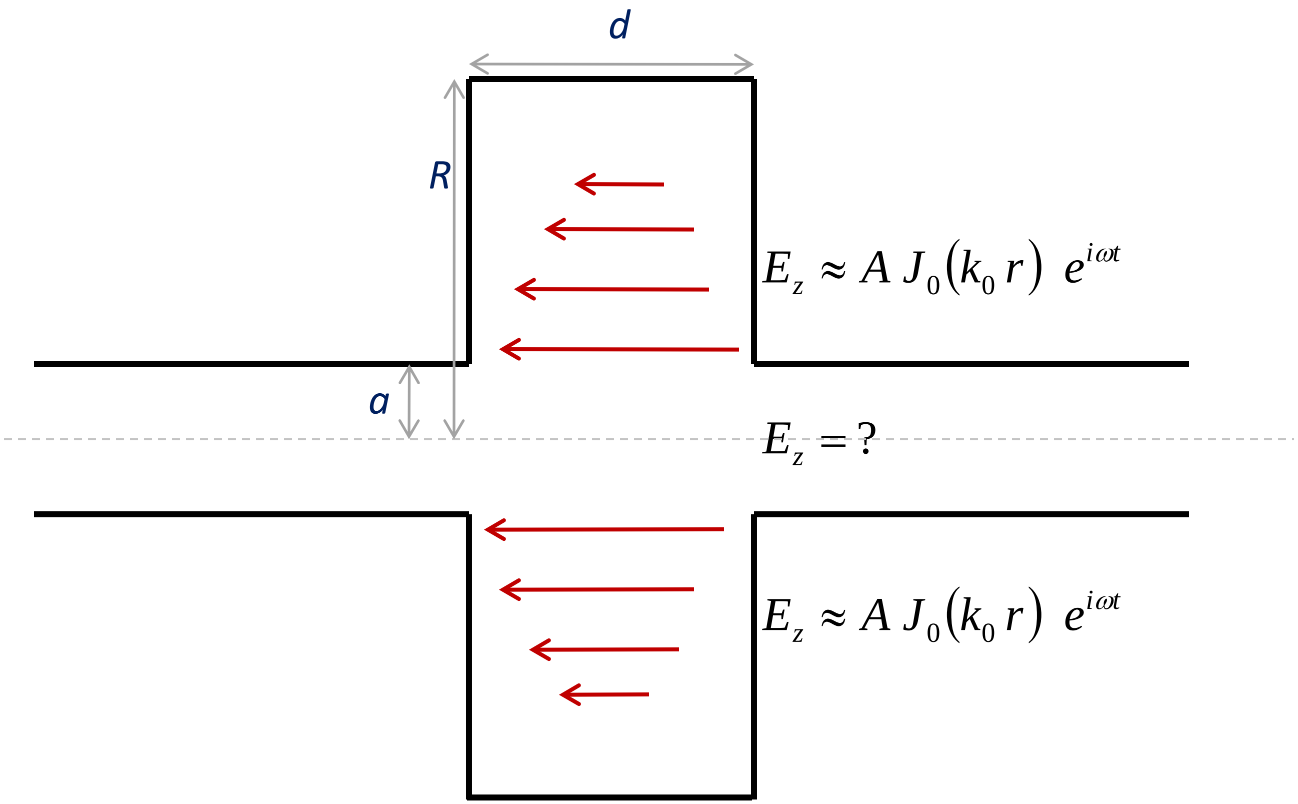
Cavity quality factor $$Q_0 = \frac{\omega W}{P_C}$$

$$Q_0 = \frac{\mu_0}{2}\frac{\omega}{R_{Surf}}\frac{d\ R}{d+R}$$

Shunt impedance $$R_{Shunt} = \frac{4}{\pi\varepsilon_0^{\,2}c^2}\frac{v^2}{R_{Surf}\,\omega^2 R(d+R)}\frac{J_0(k\,r)^2}{J_1(X_{0n})}\ \sin^2\left(\frac{\omega}{2v}d\right) \quad \text{for } m=0$$

Shunt impedance $$R_{Shunt} = \frac{8}{\pi\varepsilon_0^{\,2}c^2}\frac{v^2}{R_{Surf}\,\omega^2 R(d+R)}\frac{J_m(k\,r)^2}{J_{m-1}(X_{mn})\cdot J_{m+1}(X_{mn})}\sin^2\left(\frac{\omega}{2v}d\right)\cos^2(m\vartheta) \quad \text{for } m>0$$

Pillbox cavity with beam pipe, monopole mode



Energy transfer for off axis beam, monopole modes

$$E_z(r,z,t)=\int_{-\infty}^{\infty} A(k_z)\,J_0(k_r r)\,e^{i(k_z z-\omega t)}dk_z$$

$$k_r=\sqrt{k_0^{\,2}-k_z^{\,2}}\quad \text{with}\quad k_0\equiv\frac{\omega}{c}$$

$$=\int_{-\infty}^{\infty} A(k_z)\,J_0\!\left(\sqrt{k_0^{\,2}-k_z^{\,2}}\;r\right)e^{ik_z z-\omega t}dk_z$$

$$V(r)=\int_{-\infty}^{\infty} E_z(r,z,t)\,dz=\int_{-\infty}^{\infty} E_z\!\left(r,z,\frac{z}{v}\right)dz$$

$$=\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} A(k_z)\,J_0\!\left(\sqrt{k_0^{\,2}-k_z^{\,2}}\;r\right)e^{ik_z z-\frac{\omega}{v}z}dk_z\,dz$$

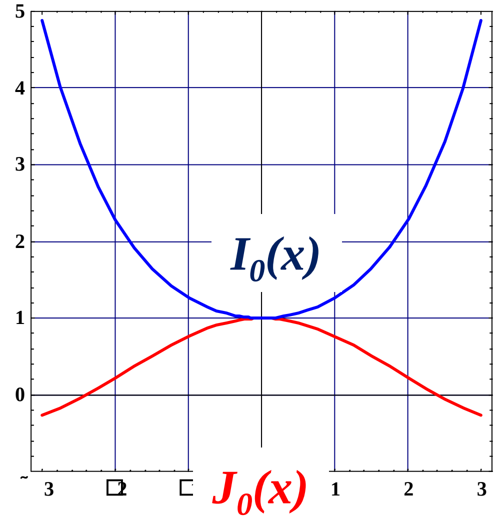
$$=\int_{-\infty}^{\infty} A(k_z)\,J_0\!\left(\sqrt{k_0^{\,2}-k_z^{\,2}}\;r\right)\left(\int_{-\infty}^{\infty} e^{ik_z z-\frac{\omega}{v}z}dz\right)dk_z$$

$$=\int_{-\infty}^{\infty} A(k_z)\,J_0\!\left(\sqrt{k_0^{\,2}-k_z^{\,2}}\;r\right)\delta\!\left(k_z-\frac{\omega}{v}\right)dk_z$$

$$=A\!\left(\frac{\omega^{2}}{v^2}\right)J_0\!\left(\sqrt{k_0^{\,2}-\frac{\omega^{2}}{v^2}}\;r\right)$$

$$J_0(ix)=I_0(x)$$

$$V(r)=A\!\left(\frac{\omega^{2}}{v^2}\right)I_0\!\left(\sqrt{\frac{\omega^{2}}{v^2}-k_0^{\,2}}\;r\right)$$



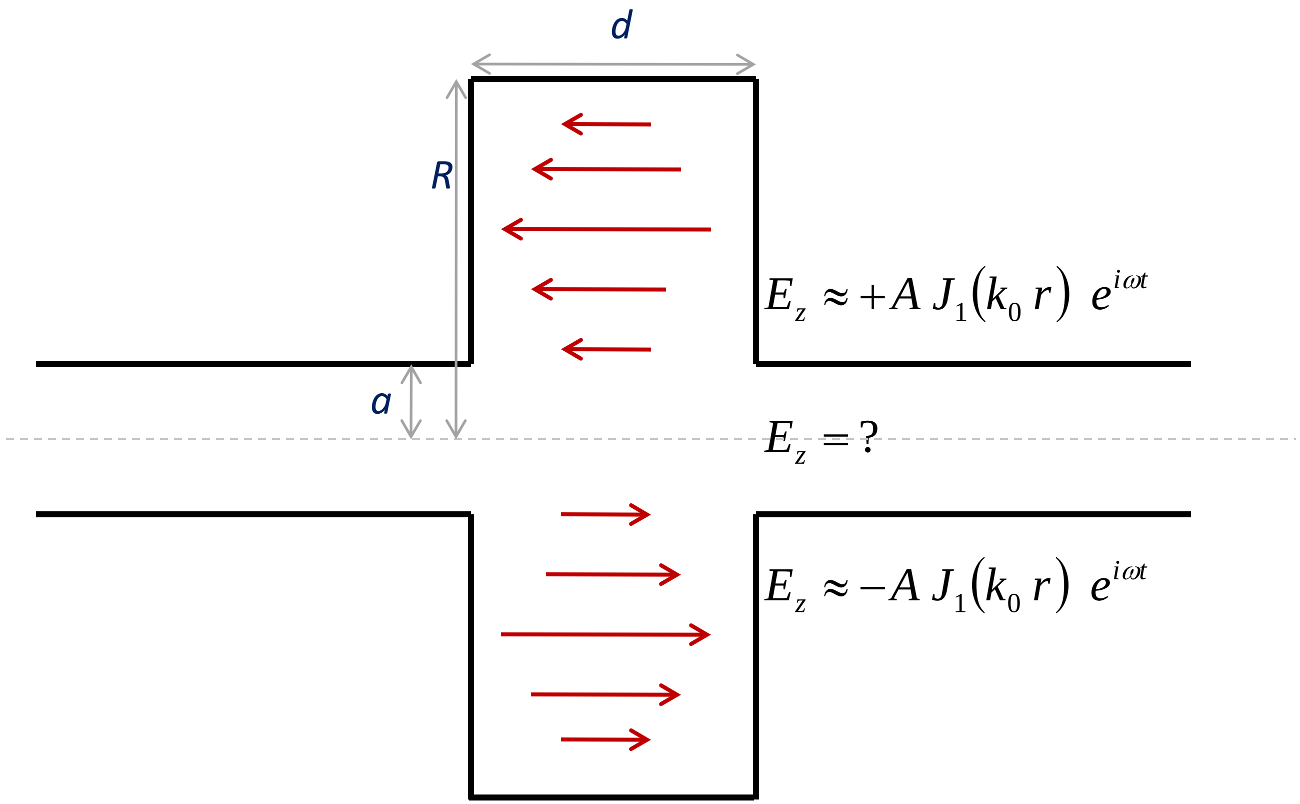
valid for arbitrary cavity geometries with rotational symmetry :

$$V(r)\propto I_0\!\left(\frac{\omega}{c}\sqrt{\frac{1}{\beta_{rel}^2}-1}\;r\right)$$

$$k_{loss}(r)\propto I_0\!\left(\frac{\omega}{c}\sqrt{\frac{1}{\beta_{rel}^2}-1}\;r\right)^2$$

$$V(r)=\text{const.},\quad k_{loss}(r)=\text{const.},\quad \text{for}\;\;\beta\approx 1$$

Pillbox cavity with beam pipe, dipole mode



$$E_z \approx +A\, J_1(k_0\, r)\; e^{i\omega t}$$

$$E_z = ?$$

$$E_z \approx -A\, J_1(k_0\, r)\; e^{i\omega t}$$

Energy transfer for off axis beam, dipole modes

$$E_z(r,\vartheta,z,t) = \int_{-\infty}^{\infty} A(k_z)\, J_1(k_r r)\cos(\vartheta)\, e^{i(k_z z-\omega t)} dk_Z$$

$$k_r = \sqrt{k_0^{\,2} - k_z^{\,2}} \qquad \text{with} \quad k_0 \equiv \frac{\omega}{c}$$

$$= \int_{-\infty}^{\infty} A(k_z)\, J_1\left(\sqrt{k_0^{\,2} - k_z^{\,2}}\; r\right)\; \cos(\vartheta)\, e^{ik_z z-\omega t} dk_Z$$

$$V(r,\vartheta) = \int_{-\infty}^{\infty} E_z(r,\vartheta,z,t)\, dz = \int_{-\infty}^{\infty} E_z\left(r,\vartheta,z,\frac{z}{v}\right) dz$$

$$= \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} A(k_z)\, J_1\left(\sqrt{k_0^{\,2} - k_z^{\,2}}\; r\right)\; e^{ik_z z-\frac{\omega}{v}z} dk_Z\, dz$$

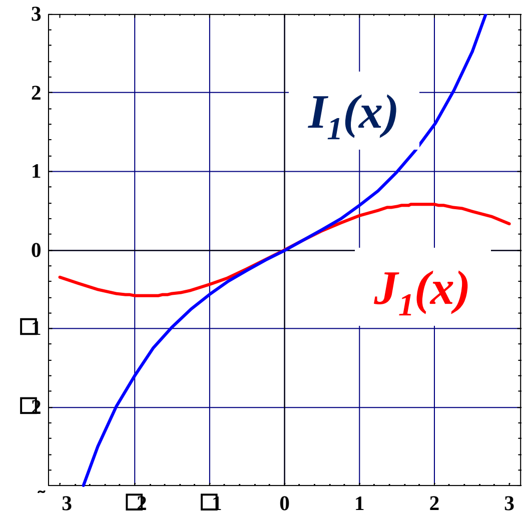
$$= \cos(\vartheta) \int_{-\infty}^{\infty} A(k_z)\, J_1\left(\sqrt{k_0^{\,2} - k_z^{\,2}}\; r\right)\left(\int_{-\infty}^{\infty} e^{ik_z z-\frac{\omega}{v}z} dz\right) dk_Z$$

$$= \cos(\vartheta) \int_{-\infty}^{\infty} A(k_z)\, J_1\left(\sqrt{k_0^{\,2} - k_z^{\,2}}\; r\right)\delta\left(k_z - \frac{\omega}{v}\right) dk_Z$$

$$= \cos(\vartheta)\, A\left(\frac{\omega^2}{v^2}\right) J_1\left(\sqrt{k_0^{\,2} - \frac{\omega^2}{v^2}}\; r\right)$$

$$\cos(\vartheta) = \frac{x}{r}\;, \qquad J_1(ix) = i\, I_1(x)$$

$$V(r,x) = \frac{x}{r}\, iA\left(\frac{\omega^2}{v^2}\right) I_1\left(\sqrt{\frac{\omega^2}{v^2} - k_0^{\,2}}\; r\right)$$



valid for arbitrary cavity geometries with rotational symmetry :

$$V(x) \propto I_1\left(\frac{\omega}{c}\sqrt{\frac{1}{\beta_{rel}^2} - 1}\; r\right)\cdot\frac{x}{r}$$

$$k_{loss}(x) \propto I_1\left(\frac{\omega}{c}\sqrt{\frac{1}{\beta_{rel}^2} - 1}\; r\right)^2\cdot\frac{x^2}{r^2}$$

for $\beta \approx 1,\;\; V(x) \propto x\,,\;\; k_{loss}(x) \propto x^2$

Loss factors for Pillbox cavities with beam aperture ø=2a

$$k_{loss}(r,\vartheta) = \frac{2v^2}{\pi\varepsilon_0 R^2\omega^2}\frac{J_0(ka)^2}{J_1(X_{0n})^2}\frac{\sin^2\left(\frac{\omega}{2v}d\right)}{d}\frac{I_0\left(k\sqrt{\frac{c^2}{v^2}-1}\,r\right)^2}{I_0\left(k\sqrt{\frac{c^2}{v^2}-1}\,a\right)^2} \qquad \text{for } m=0$$

$$k_{loss}(r,\vartheta) = \frac{4v^2}{\pi\varepsilon_0 R^2\omega^2}\frac{-J_m(ka)^2}{J_{m-1}(X_{mn})\cdot J_{m+1}(X_{mn})}\frac{\sin^2\left(\frac{\omega}{2v}d\right)}{d}\frac{I_m\left(k\sqrt{\frac{c^2}{v^2}-1}\,r\right)^2}{I_m\left(k\sqrt{\frac{c^2}{v^2}-1}\,a\right)^2}\cos^2(m\vartheta) \qquad \text{for } m>0$$

for $v \approx c$

$$k_{loss}(r,\vartheta) = \frac{2v^2}{\pi\varepsilon_0 R^2\omega^2}\frac{J_0(ka)^2}{J_1(X_{0n})^2}\frac{\sin^2\left(\frac{\omega}{2v}d\right)}{d} \qquad \text{for } m=0$$

$$k_{loss}(r,\vartheta) = \frac{4v^2}{\pi\varepsilon_0 R^2\omega^2}\frac{-J_m(ka)^2}{J_{m-1}(X_{mn})\cdot J_{m+1}(X_{mn})}\frac{\sin^2\left(\frac{\omega}{2v}d\right)}{d}\frac{r^{2m}}{a^{2m}}\cos^2(m\vartheta) \qquad \text{for m} > 0$$

Scaling of Cavity properties with frequency

Monopole mode cavities

$$k_{loss} \propto \omega$$

$$R_{Shunt} \propto \sqrt{\omega}$$

Dipole mode cavities

$$k_{loss} \propto \omega^3 r^2$$

$$R_{Shunt} \propto \omega^{\frac{3}{2}} r^2$$

Quality Factor

$$Q \propto \frac{1}{\sqrt{\omega}}$$

Always stay below cut-off frequency of lowest waveguide mode in beam-pipe (TE_{11})

$$\omega < \frac{1.841\, c}{R_{\text{beampipe}}}$$

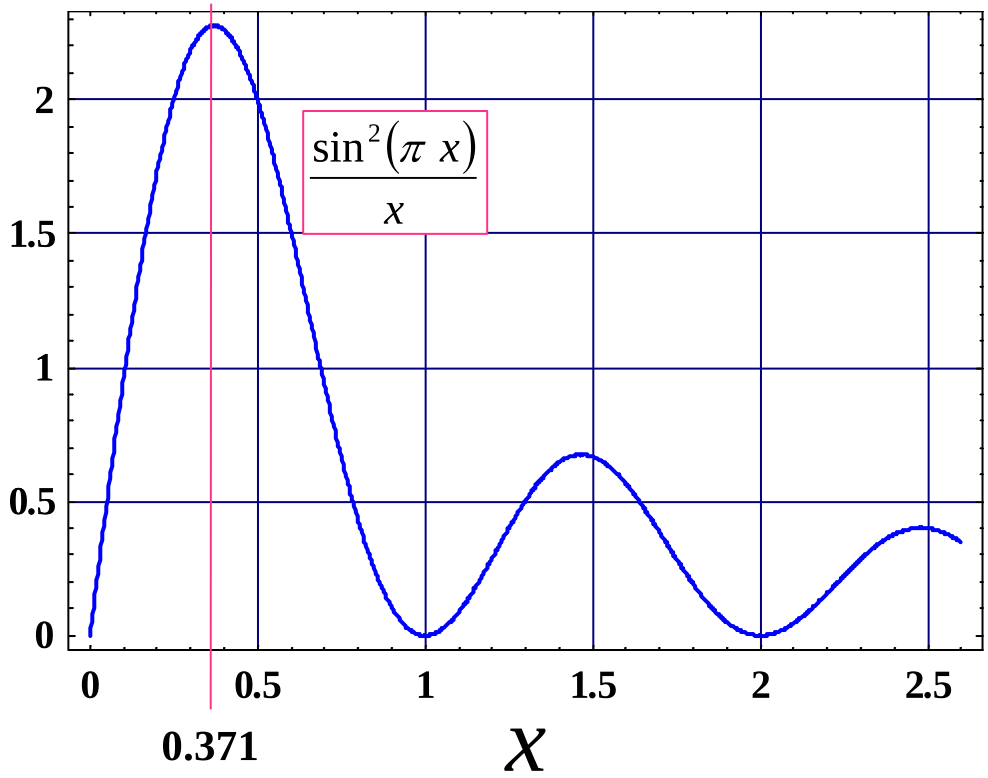
Example: $R_{beampipe}$=2 cm

$\Rightarrow$ stay well below 4.4GHz

Optimum cavity length for single bunch BPM

$$k_{loss} \propto \frac{\sin^2\left(\frac{\omega}{2v}d\right)}{\frac{\omega}{2v}d} \qquad \frac{\omega}{2v}d = \frac{\pi\, d}{\beta_{rel.}\lambda}$$

$$d_{opt} = 0.371 \cdot \frac{v}{c}\lambda$$

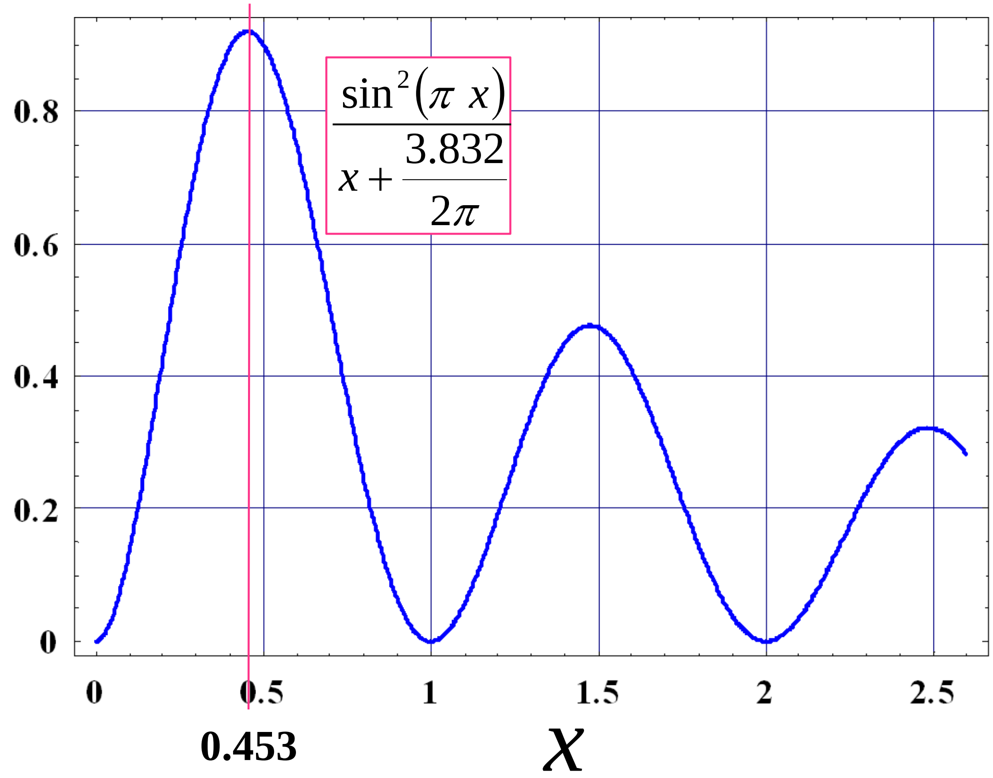


Optimum cavity length for c.w. beam BPM

$$R_{Shunt} \propto \frac{\sin^2\left(\frac{\omega}{2v}d\right)}{d + \frac{X_{mn}c}{\omega}} = \frac{\sin^2\left(\frac{\pi}{\beta_{rel.}}\frac{d}{\lambda}\right)}{\lambda\left(\frac{d}{\lambda} + \frac{X_{mn}}{2\pi}\right)}$$

$$X_{11} = 3.832$$

$$d_{opt} = 0.453 \cdot \frac{v}{c}\lambda$$



Numerical example

Position resolution and measurement range of a 3GHz RF BPM
with a=15mm, d=25mm, β=5
Material copper $\sigma=5.88\cdot 10^7$

for single bunch beam with
q=100pC
σ_t=3ps
T=100 MeV ($v\approx c$).

RF front end can resolve
P_e = -50dBm.

$$P_E(t) = \frac{\omega k_{loss} q_b{}^2 F_b{}^2}{Q_0} \beta \exp\left(-\frac{\omega(1+\beta)}{Q_0} t\right)$$

$$R = \frac{c}{\omega} X_{11} = \frac{c}{2\pi 3\mathrm{GHz}} 3.83171 = 61\mathrm{mm}$$

$$k_{loss} = \frac{4v^2}{\pi\varepsilon_0 R^2 \omega^2} \frac{-J_1(k\,a)^2}{J_0(X_{11})\cdot J_2(X_{11})} \frac{\sin^2\left(\frac{\omega}{2v} d\right)}{d} \frac{r^2}{a^2} \cos^2(m\vartheta)$$

$$= \frac{4c^2}{\pi\varepsilon_0 61^2\mathrm{mm}^2\omega^2} \frac{-J_1\left(\frac{2\pi\cdot 3\mathrm{GHz}}{c} 15\mathrm{mm}\right)^2}{J_0(3.83171)\cdot J_2(3.83171)} \frac{\sin^2\left(\frac{\pi\cdot 3\mathrm{GHz}}{c} 25\mathrm{mm}\right)}{25\mathrm{mm}} \frac{x^2}{15^2\mathrm{mm}^2}$$

$$k_{loss} = 950\cdot\frac{V}{pC\cdot m^2} x^2$$

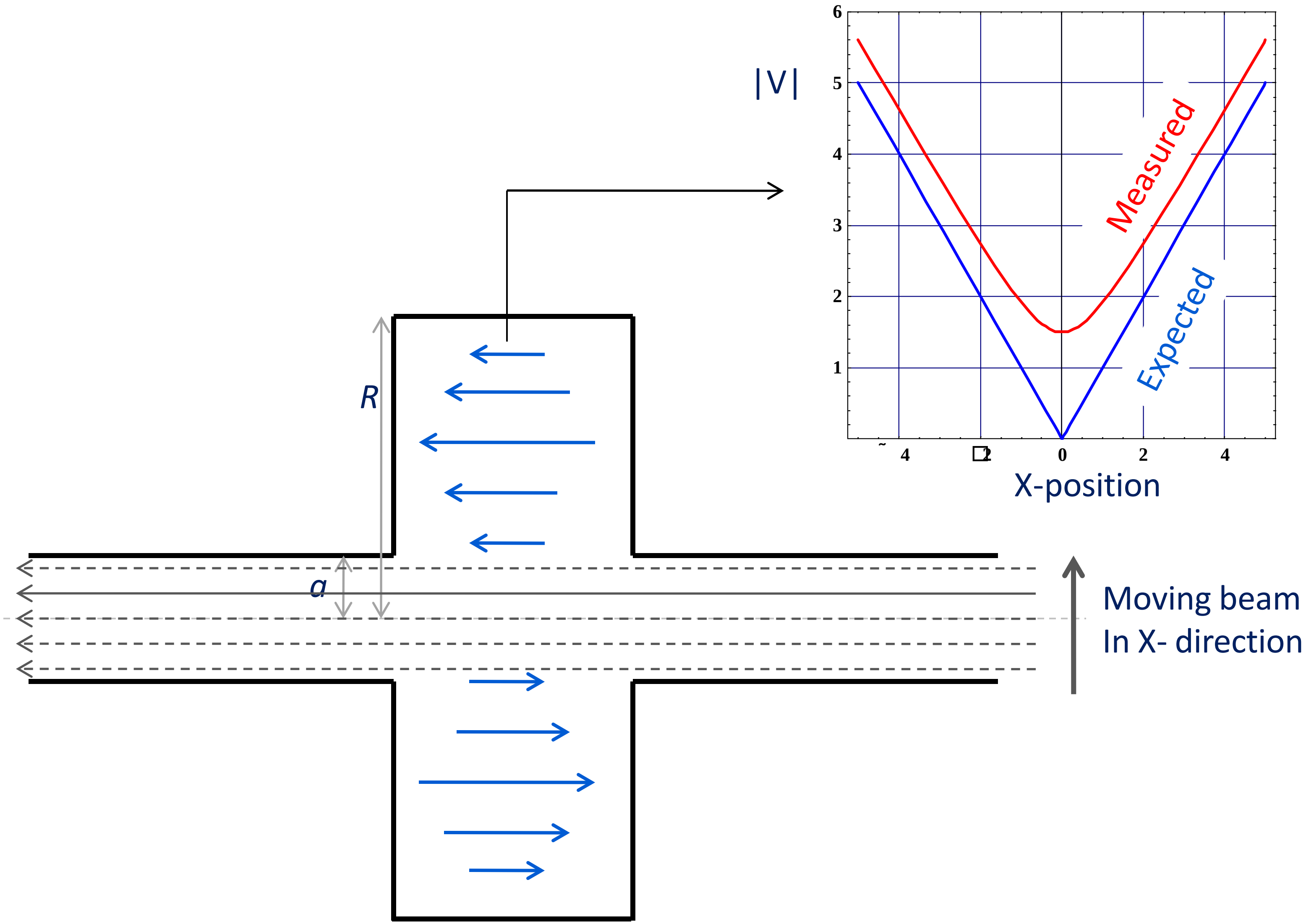
$$F_b = \exp\left(\frac{-\omega^2\sigma_b{}^2}{2}\right) = \exp\left(\frac{-(2\pi\cdot 3\mathrm{GHz}\cdot 3\mathrm{ps})^2}{2}\right) = 0.998 \;, \qquad R_{Surf} = \sqrt{\frac{\mu_0\omega}{2\sigma}}$$

$$Q_0 = \frac{\mu_0}{2}\frac{\omega}{R_{Surf}}\frac{d\,R}{d+R} = \frac{\mu_0}{2}\frac{2\pi\cdot 3\mathrm{GHz}}{\sqrt{\frac{4\pi\cdot 10^{-7}\cdot 2\pi\cdot 3\mathrm{GHz}}{2\cdot 5.88\cdot 10^7\mathrm{Sm}^{-1}}}}\frac{25\mathrm{mm}\cdot 61\mathrm{mm}}{25\mathrm{mm}+61\mathrm{mm}} = 14795$$

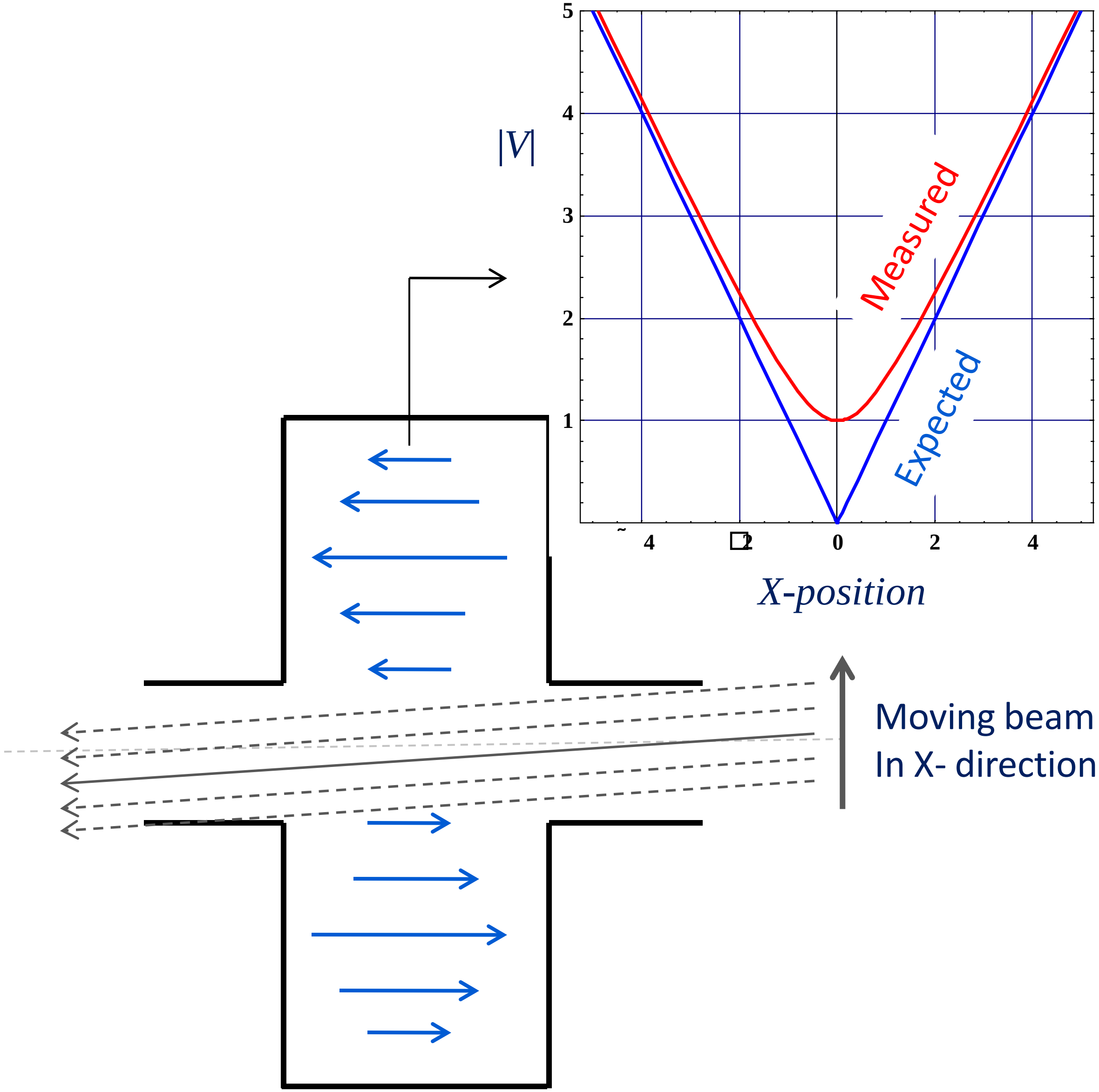
$$P_E(t) = 60.3\mathrm{W}\, x^2 \exp\left(\frac{-t^2}{131\,\mathrm{ns}}\right)$$

$$x_{\min} = \sqrt{\frac{10^{-50dBm/10}}{60.3\mathrm{W}}} = 13\mu\mathrm{m}$$

Measurement troubles



Sensitivity to beam angle

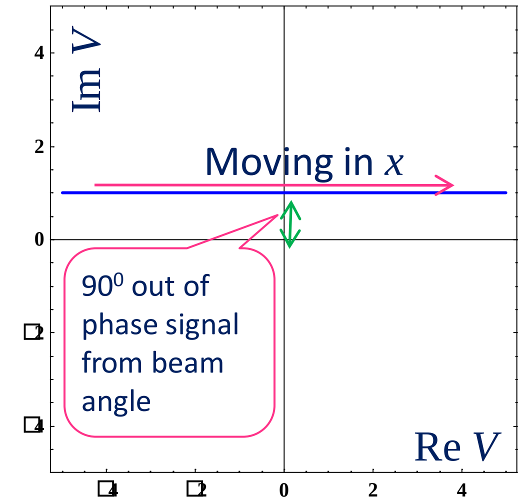


Reasons:

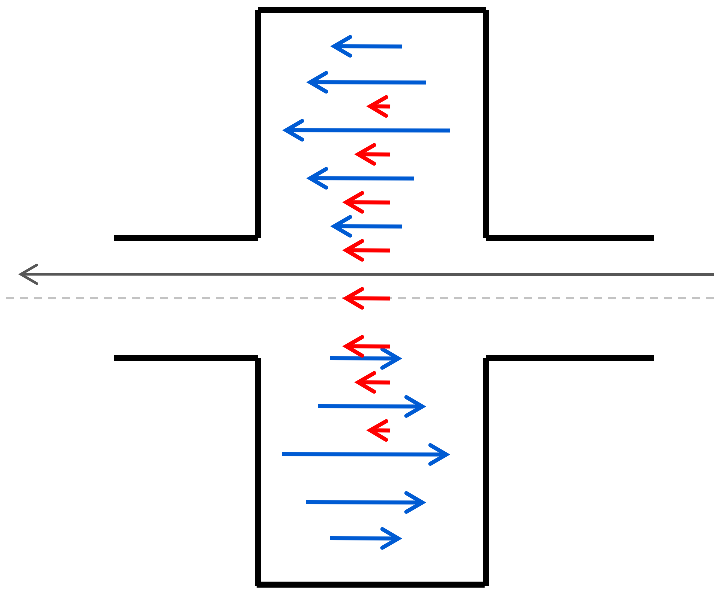
- Beam comes with an angle
- Cavity is tilted

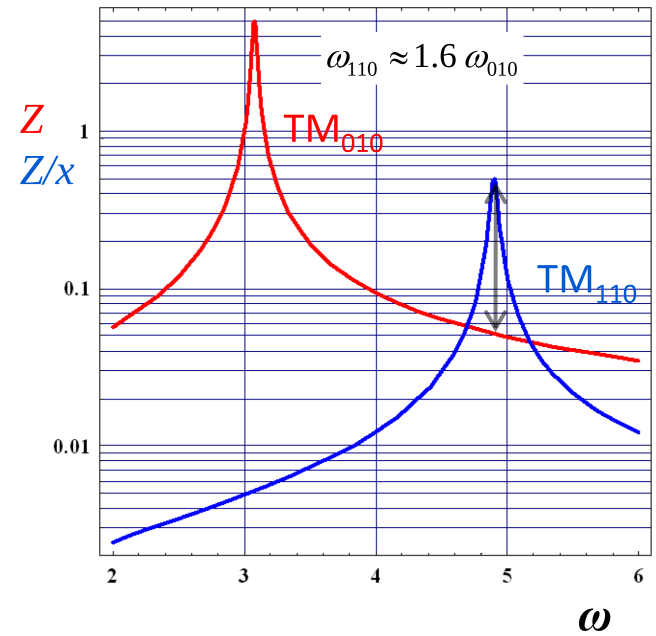
Remedies

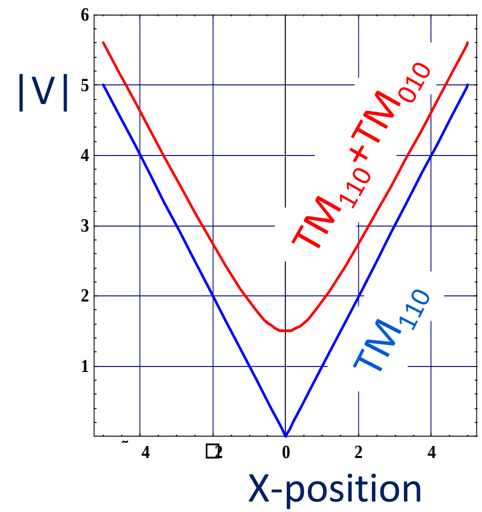
- Improve cavity angle alignment
- Shorten cavity length
  (at the expense of reduced sensitivity)
- Use it as a feature
  (requires IQ demodulation)



Common mode signal from monopol signals





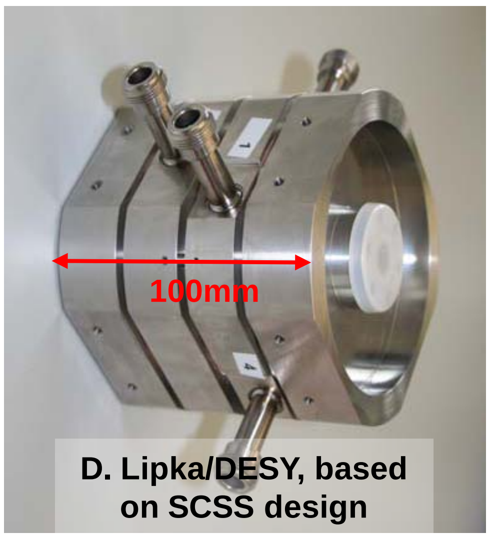


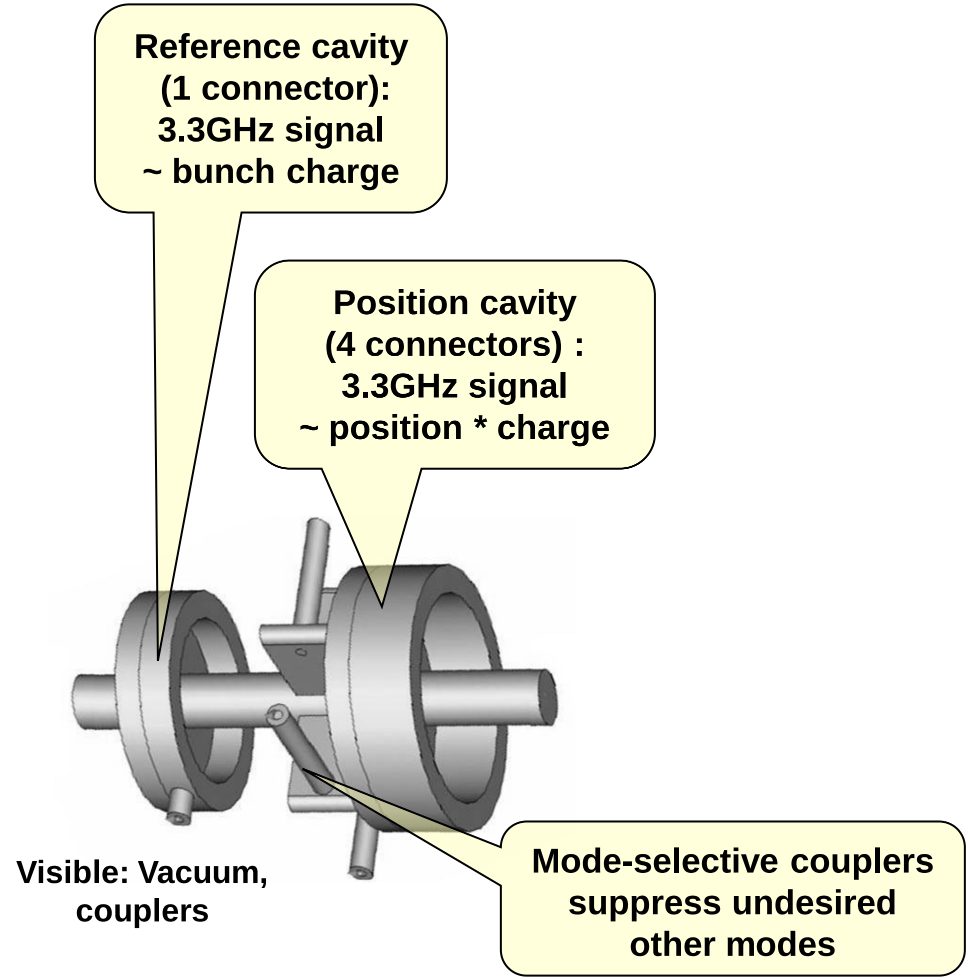
Remedies:

- Symmetric coupling with 180^0 Hybrid
- Mode selective couplers

RF-BPM (similar designs for SCSS, European-XFEL, SwissFEL)

Dual-resonator,
coaxial connectors,
mode-selective
(E-XFEL, 3.3GHz)



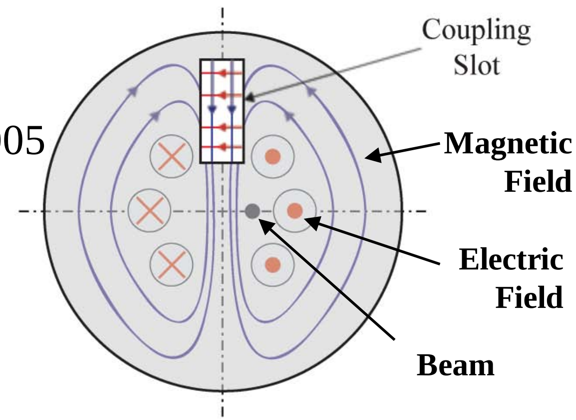


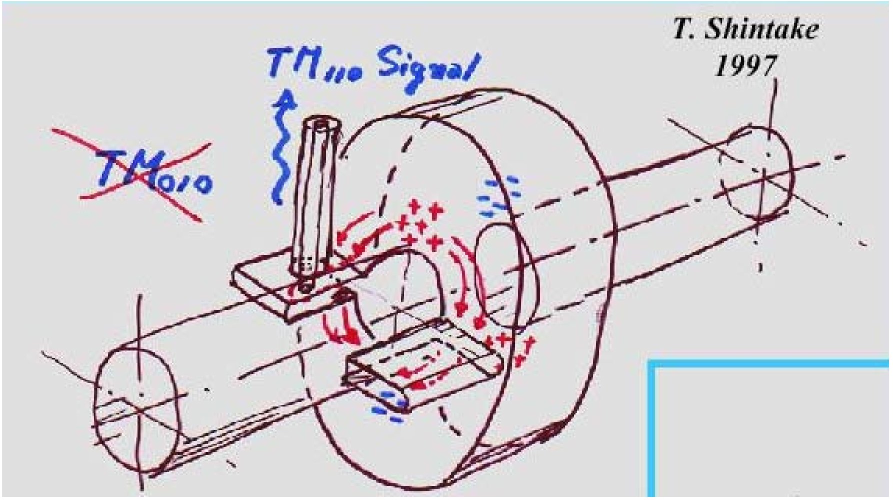
Beam Position = k * (V_{Pos_Cav} / V_{Ref_Cav}). Factor k: Not fixed, variable via attenuator.

Courtesy B. Keil/PSI

Reject Monopole Mode

Ref: V. Vogel
Nanobeam 2005



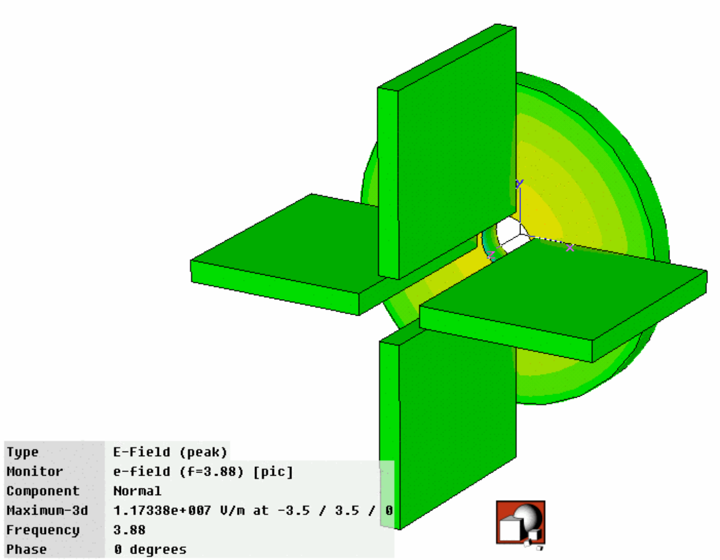


Coupling waveguides couples to TM_{110} mode, not to TM_{010}

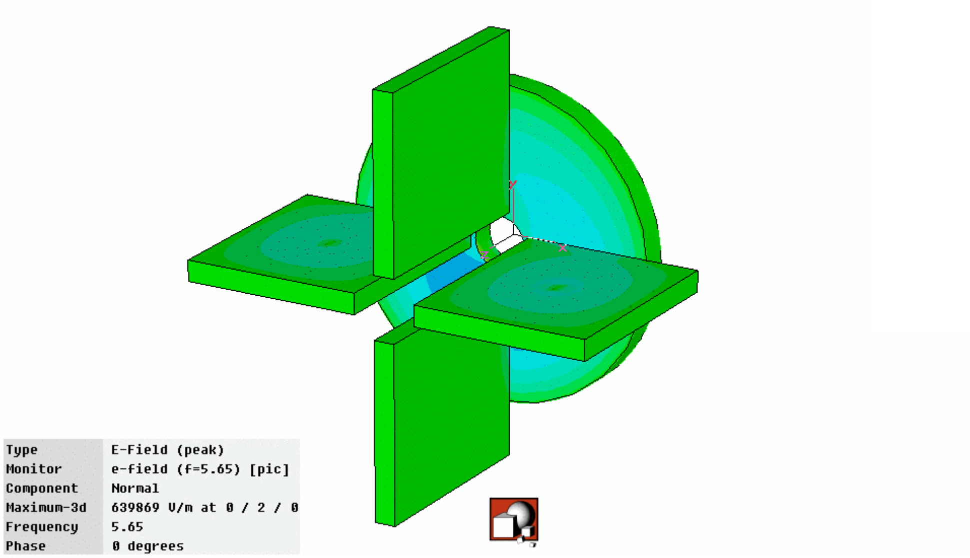
Courtesy D. Lipka/DESY

Reject Monopole Mode

Monopole Mode



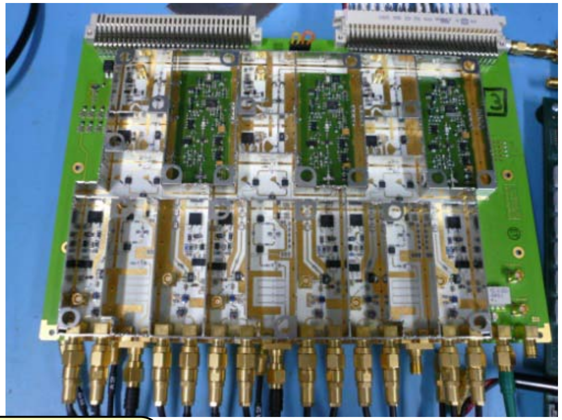
Dipole Mode



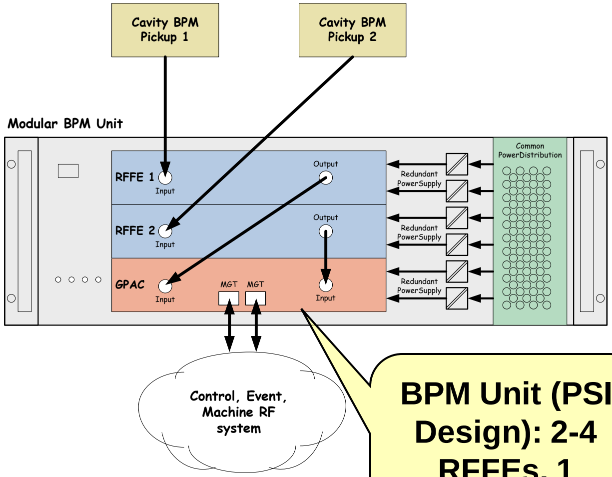
- propagation of dipole mode in waveguide
- monopole mode no propagation in waveguide

Courtesy D. Lipka/DESY

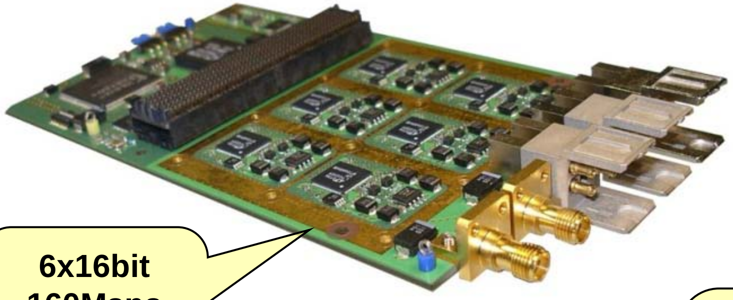
PSI Cavity BPM Electronics for Eu-XFEL and SwissFEL



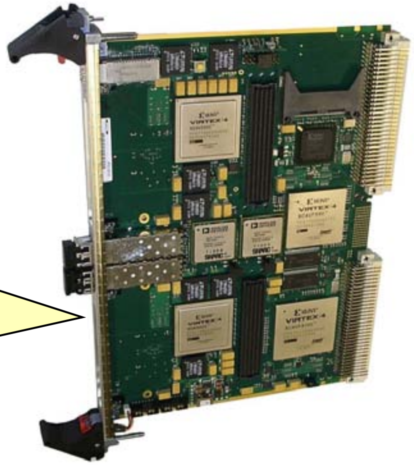
3.3GHz RFFE



BPM Unit (PSI Design): 2-4 RFFEs, 1 FPGA Board.



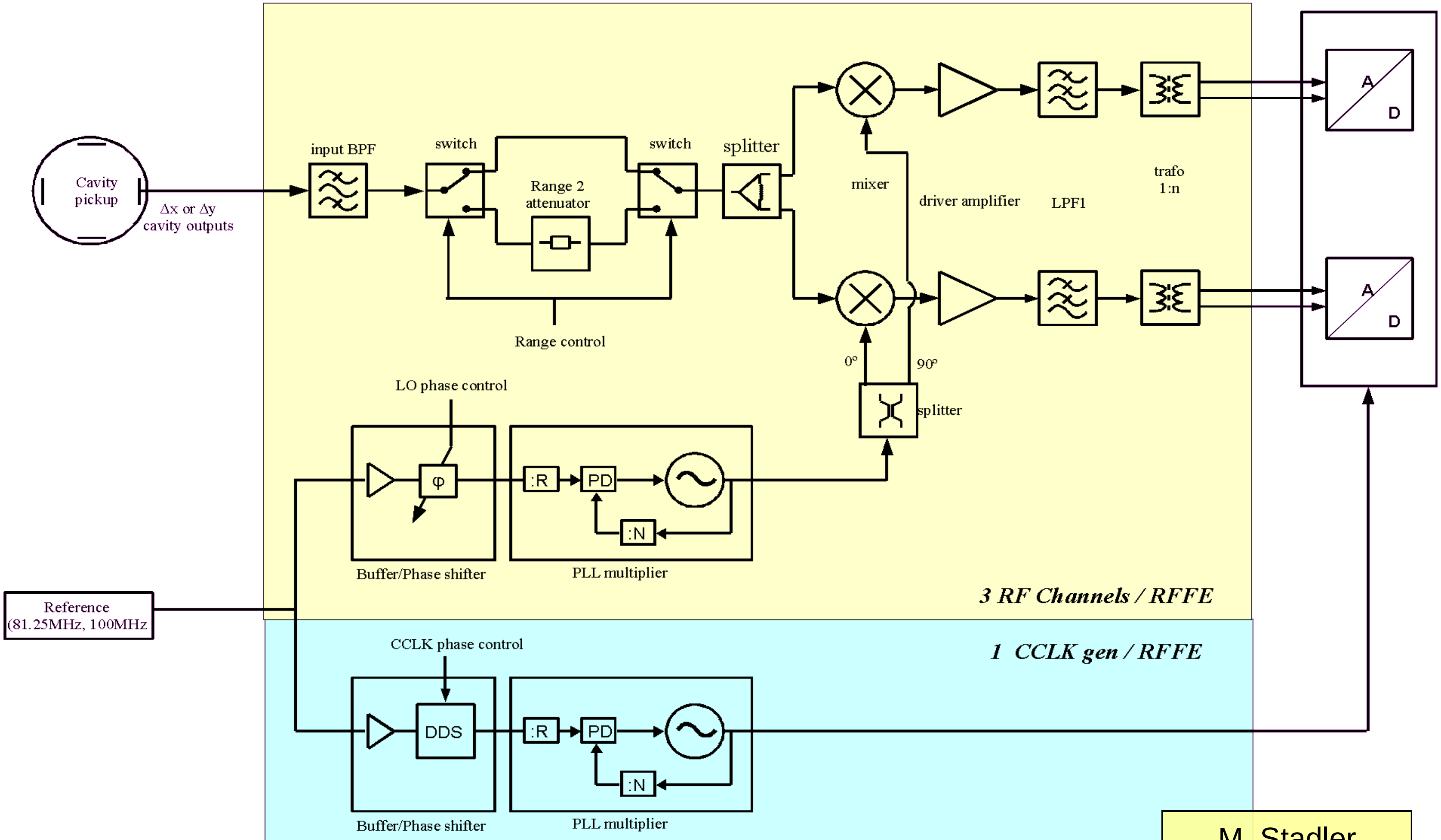
6x16bit 160Msps ADC Mezzanine



FPGA Mezzanine Carrier Board (IBFB version)

Courtesy B. Keil/PSI

Cavity BPM Electronics: RFFE



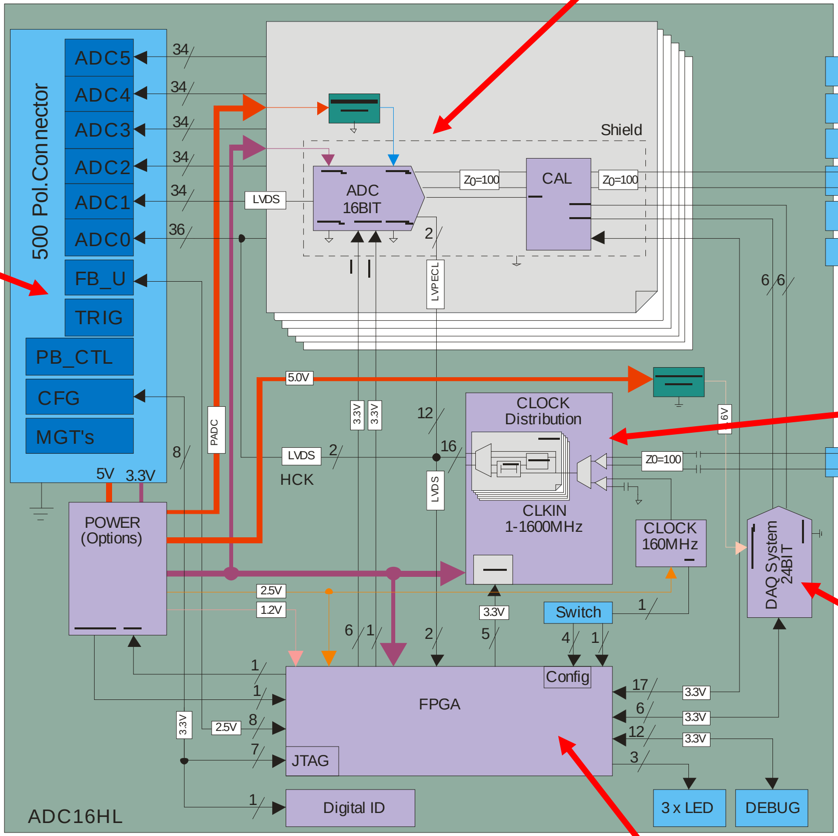
M. Stadler

Courtesy B. Keil/PSI

Cavity BPM Electronics: ADC Mezzanine Board

500pol. High Speed Connector (Carrier Board FPGA Interface)

Six 16-bit 160Msps ADCs



Differential Inputs

Low Jitter Clock Distribution (80fs)

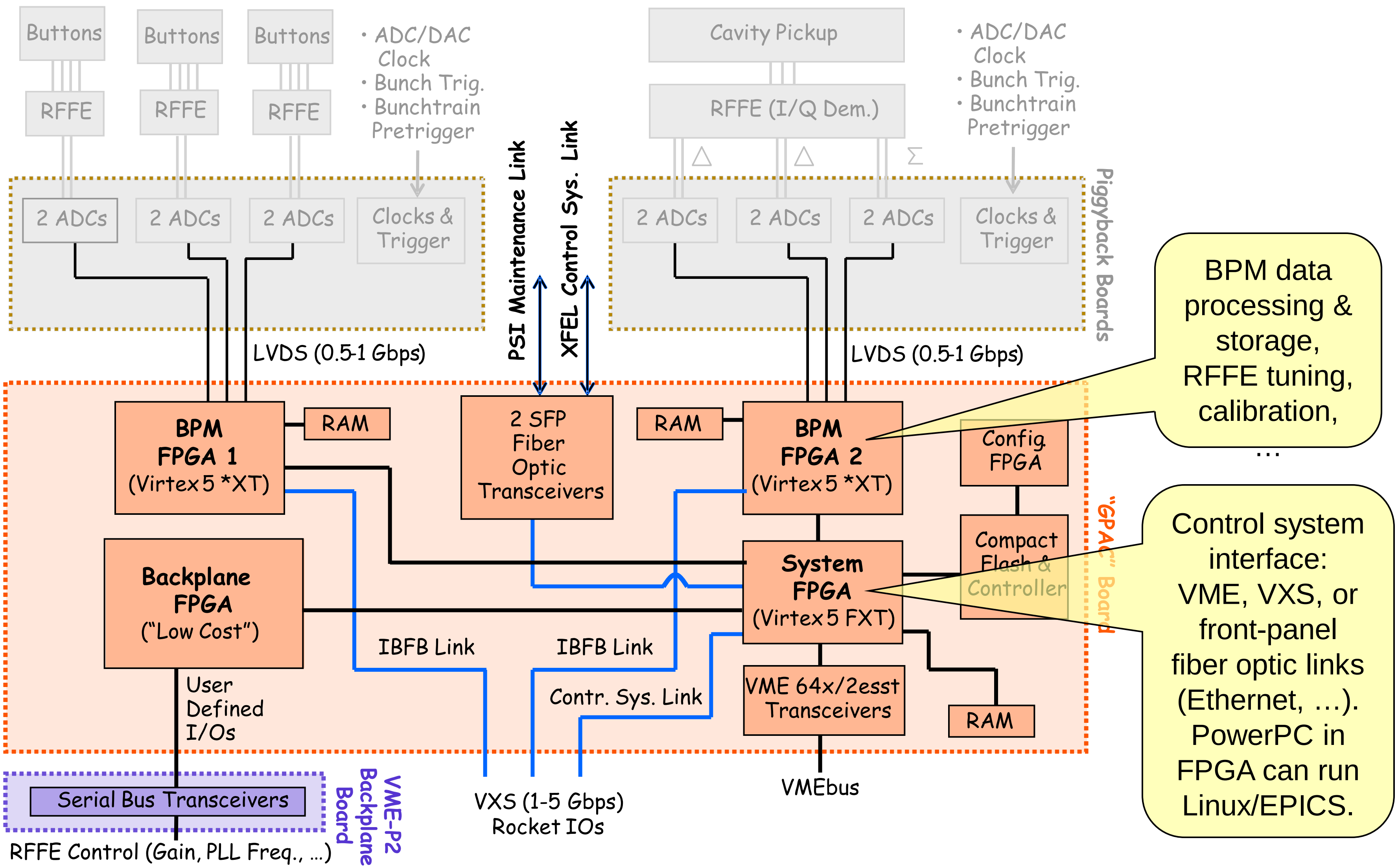
On-Board Gain and Offset Calibration

Control Unit

M. Roggli

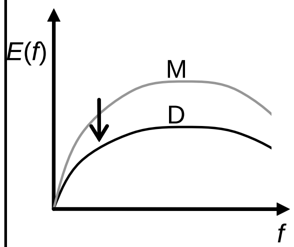
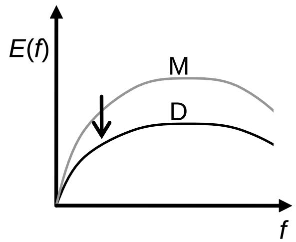
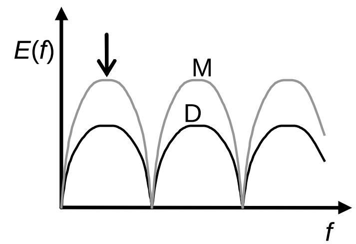
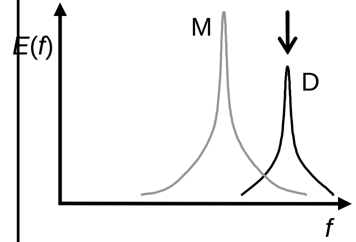
Courtesy B. Keil/PSI

BPM Electronics: Digital/FPGA Carrier Board



Courtesy B. Keil/PSI

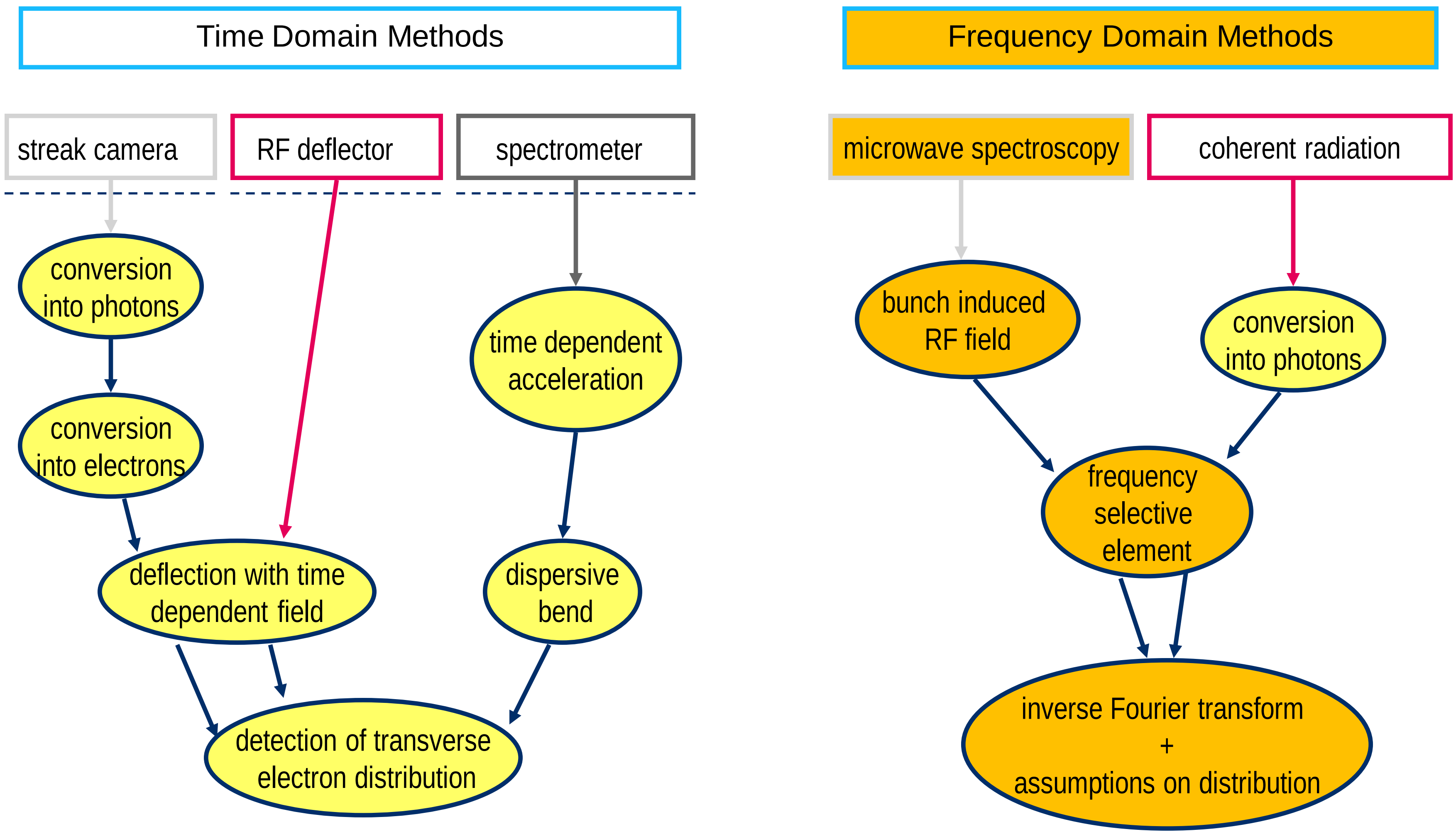
Comparison of different BPM types

Pickup	Transformer	Button	Matched Stripline	RF Cavity
Spectrum				
Monopole Mode Suppression	Modal (hybrid) / electronics	Modal (hybrid) / electronics	Modal (hybrid) / electronics	Modal (coupler), frequency,
Typical RMS Noise, 10pC, *20mm pipe*	>50μm	>100μm	~60μm	<1μm
Typical Electronics Frequency	0.1…200MHz	300…800MHz	300…800MHz	1-12GHz
Pictures				

Comparison of different BPM types cont.

	Transformer	Button	Stripline	RF Cavity
flexibility bunch spacing, train length, bunch length	++	+	-	-
precision & resolution	+	+	+	++
sensitivity for low charges	+	-	+	++
difficulty of calibration	+	+	+	-
impedance (collective instabilities)	+	+	+	-
complexity of electronics	+	+	+	-
size	-	++	+	+

Measurement methods for short bunch length



Bunch Length Measurements with RF methods

For beam intensity and position measurement the bunch length affects the signal in proportion with bunch form factor

Induced voltage $V = 2k_{loss} q_b F_b$

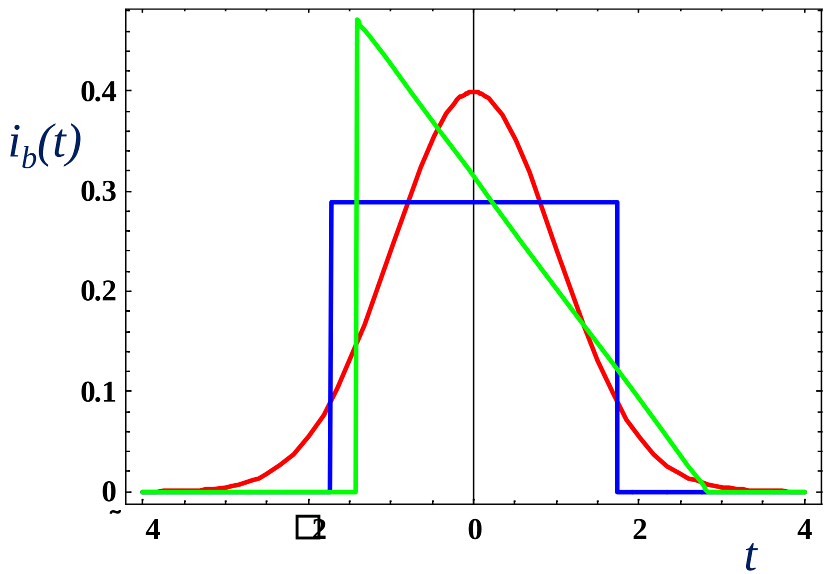
Energy deposited $W = k_{loss} q_b^{\ 2} F_b^{\ 2}$

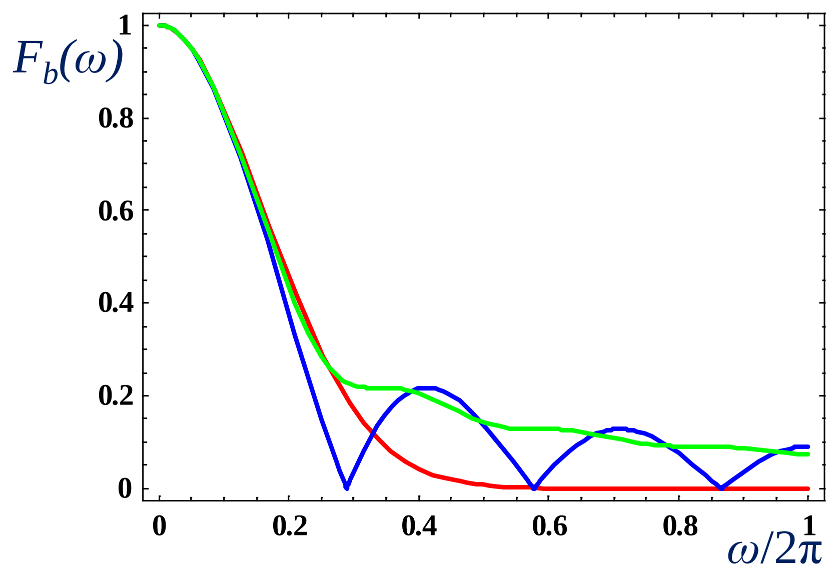
with "bunch Formfactor" $F_b = \frac{\left| \int i_B(t) \cdot e^{i\omega t} dt \right|}{\int i_B(t)\, dt} = \frac{\left| \int i_B(t) \cdot e^{i\omega t} dt \right|}{q_B}$

By sampling F_b at different frequencies information of bunch length and shape can be obtained !

Relation bunch spectrum / r.m.s. bunch length

Three bunch shapes with same q_b *and* σ_b





$$F_b(\omega) = \frac{1}{q_b}\left|\int_{-\infty}^{+\infty} i_b(t)\, e^{i\omega t} dt\right| = \frac{1}{q_b}\left|\int_{-\infty}^{+\infty} i_b(t)\,(1 + i\omega t - \frac{\omega^2 t^2}{2} + \ldots)\; dt\right| = \frac{1}{q_b}\left(1 - \frac{\omega^2}{2}\int_{-\infty}^{+\infty} i(t)\, t^2 dt\right) + \ldots$$

$$F_b(\omega) \approx \frac{1}{q_b}\left(1 - \frac{\omega^2}{2}\sigma_{rms}{}^2\right)$$ for low frequencies

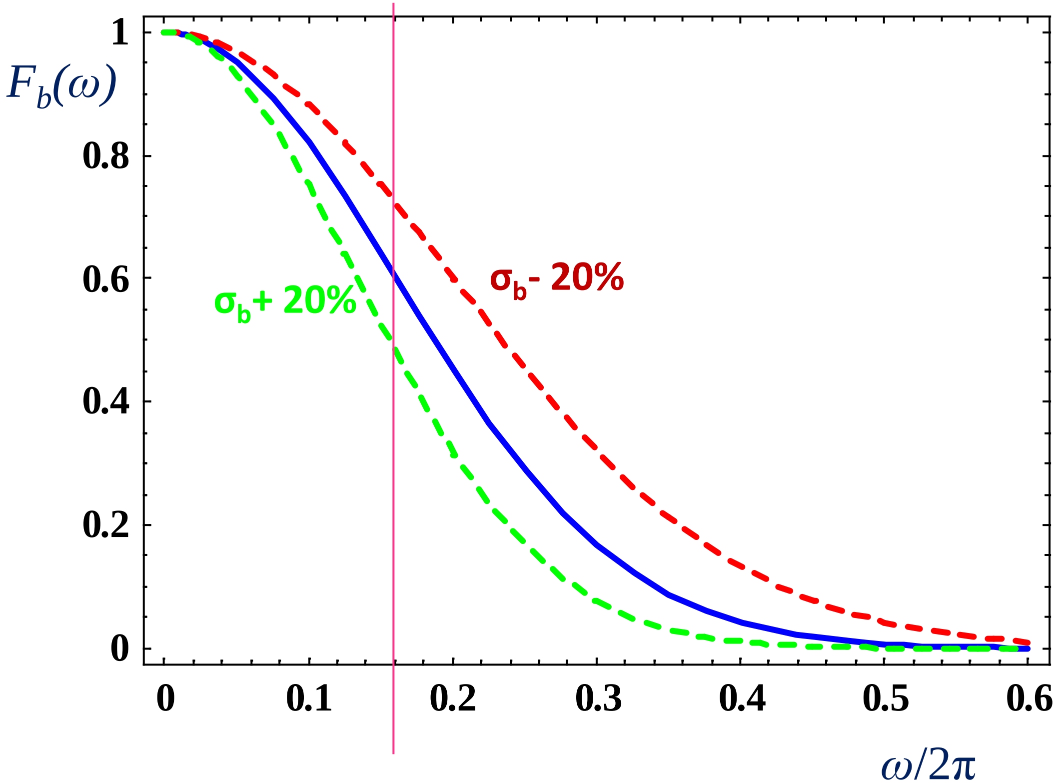
Best frequency choice for σ_b determination

$$i_b(t) = \frac{q_b}{\sqrt{2\pi}\sigma_b}\exp\left(\frac{-t^2}{2\sigma_b^{\ 2}}\right)$$

$$F_b(\omega) = \frac{q_b\sigma_b}{\sqrt{2\pi}}\exp\left(\frac{-\omega^2\sigma_b^{\ 2}}{2}\right)$$

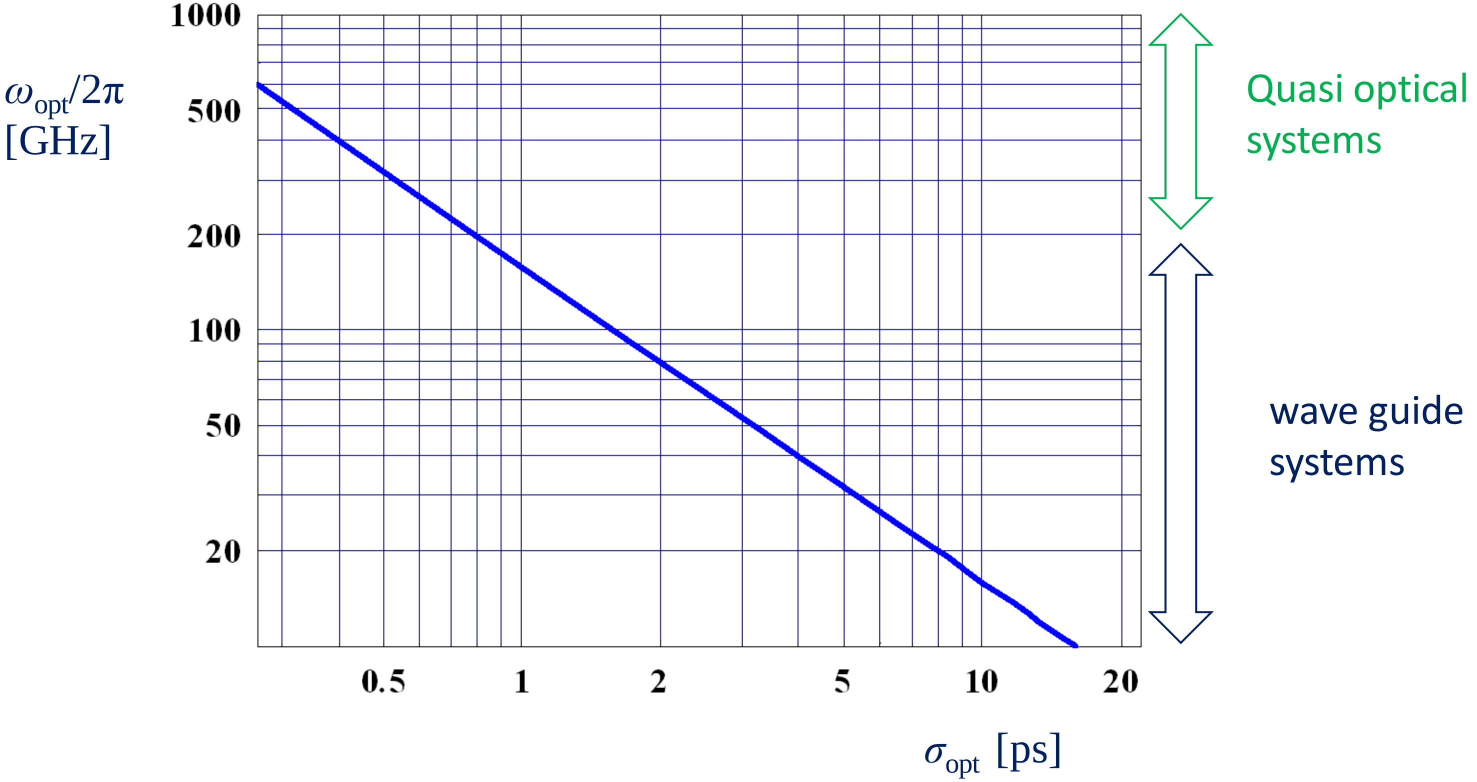
$$\frac{d^2F_b(\omega)}{d\omega^2} = 0 \quad \Rightarrow \quad \omega_{opt} = \frac{1}{\sigma_b}$$

Best frequency for maximum sensitivity



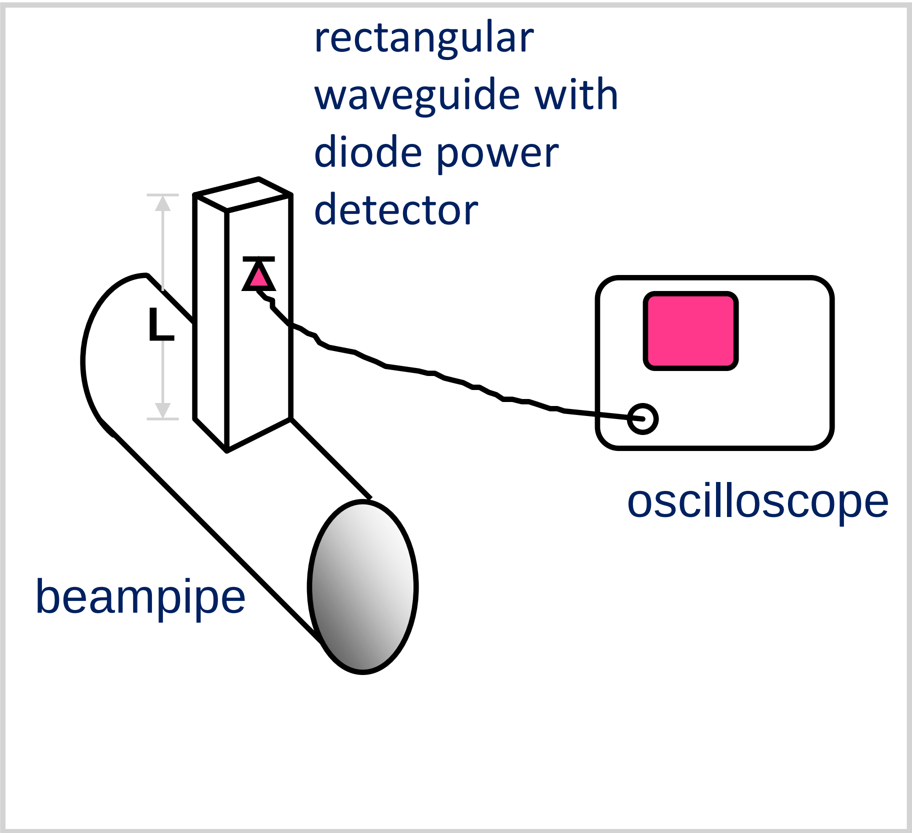
$\omega_{opt}/2\pi = 0.159/\sigma_b$

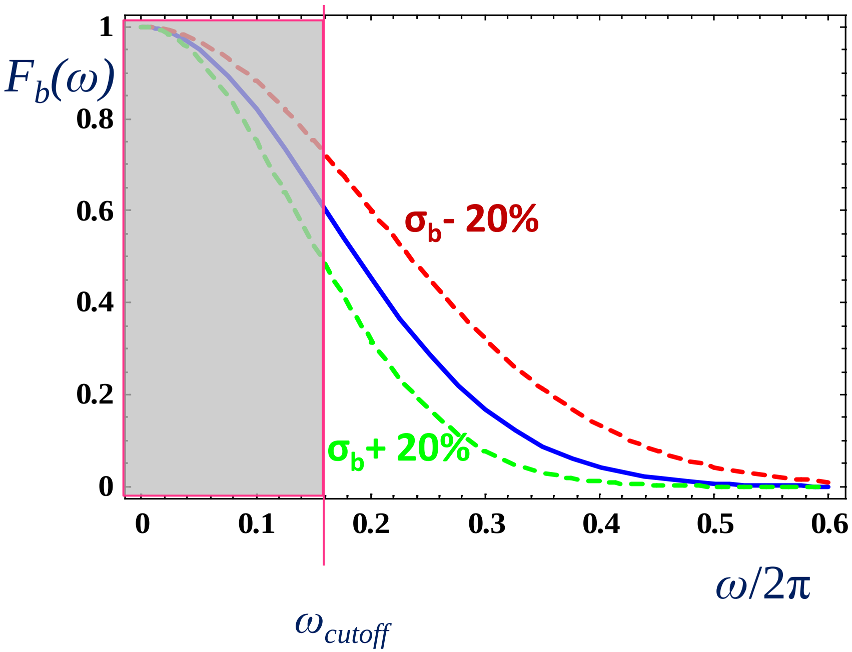
Range of microwave methods



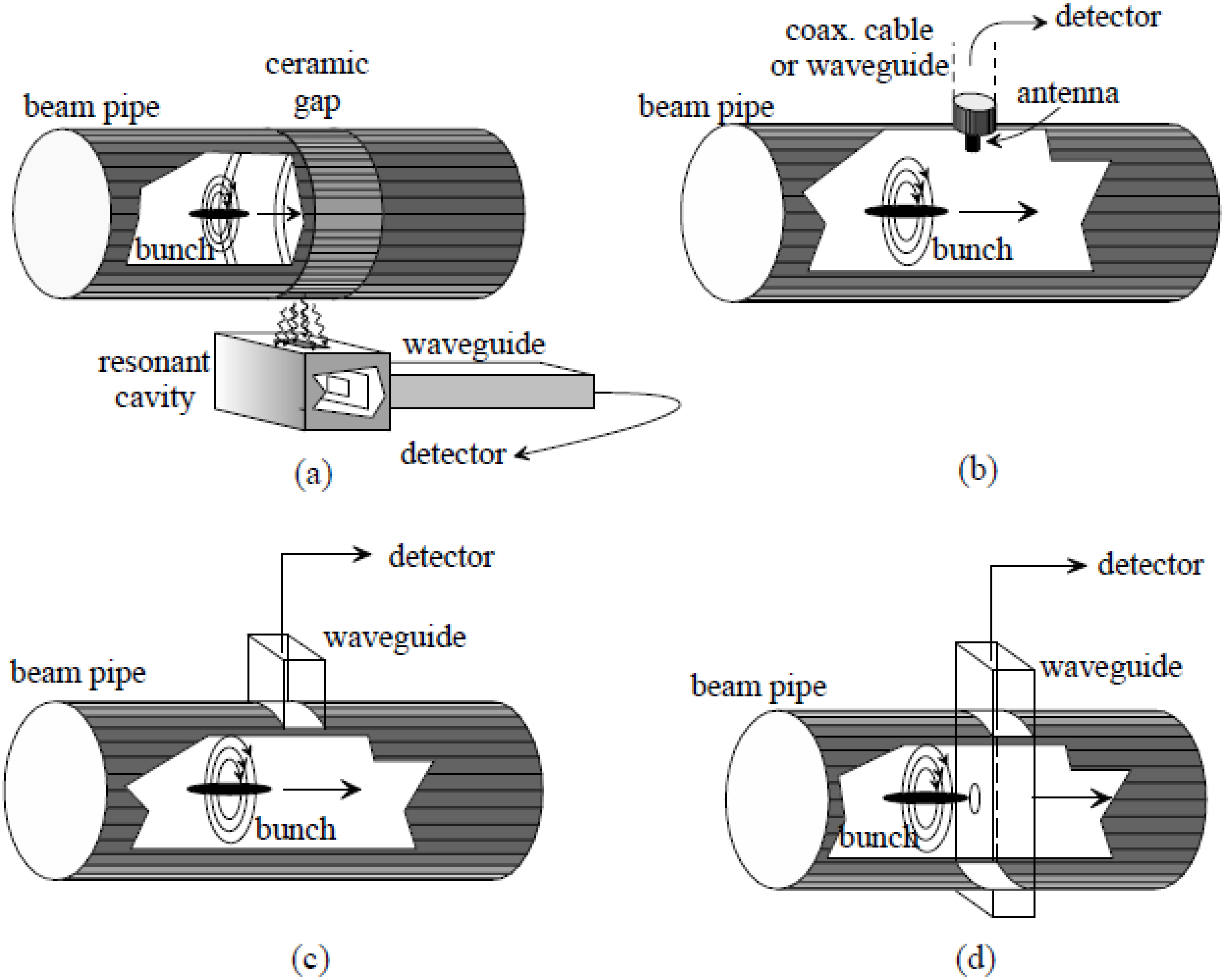
A very simple system

Choose rectangular waveguide with $\omega_{cutoff} \approx \omega_{opt}$. Connect waveguide to beampipe.
Detector will measure integrated spectrum integrated above ω_{cutoff}





Different configurations for coupling the electron bunch field



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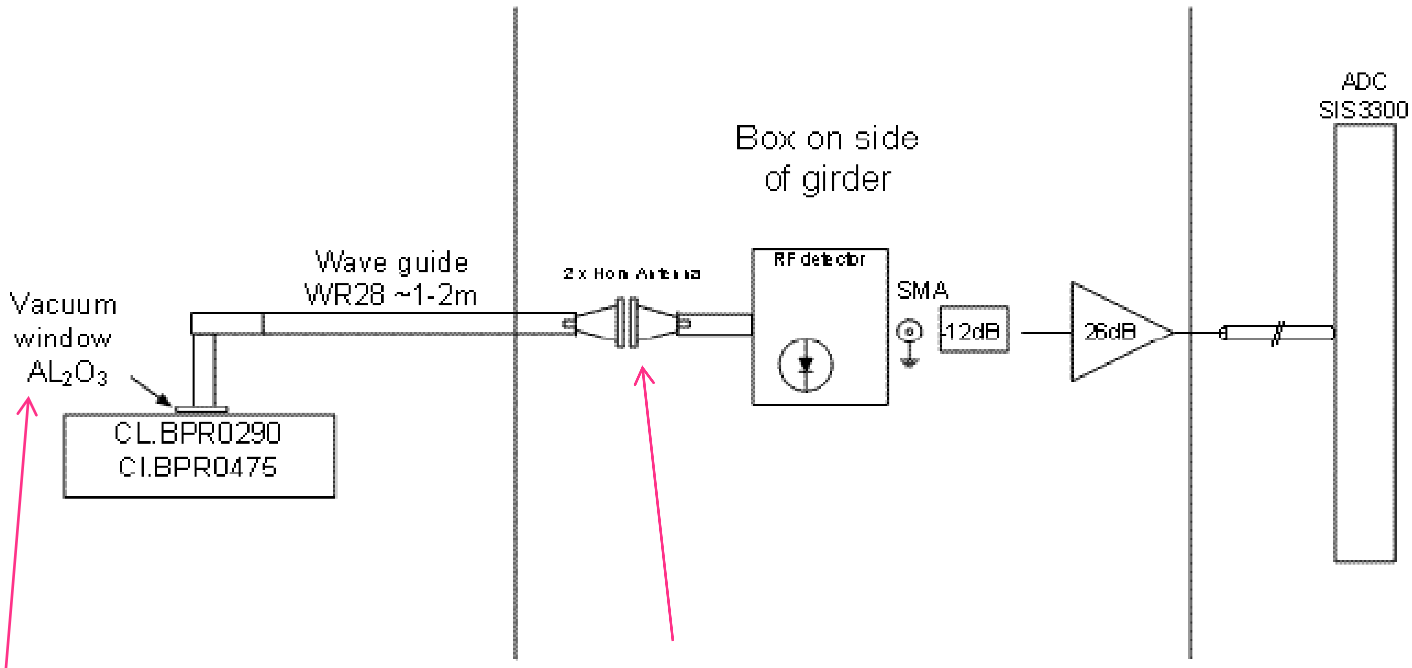
CERN-THESIS-2009-011
01/09/1999

Waveguide pick-up system design



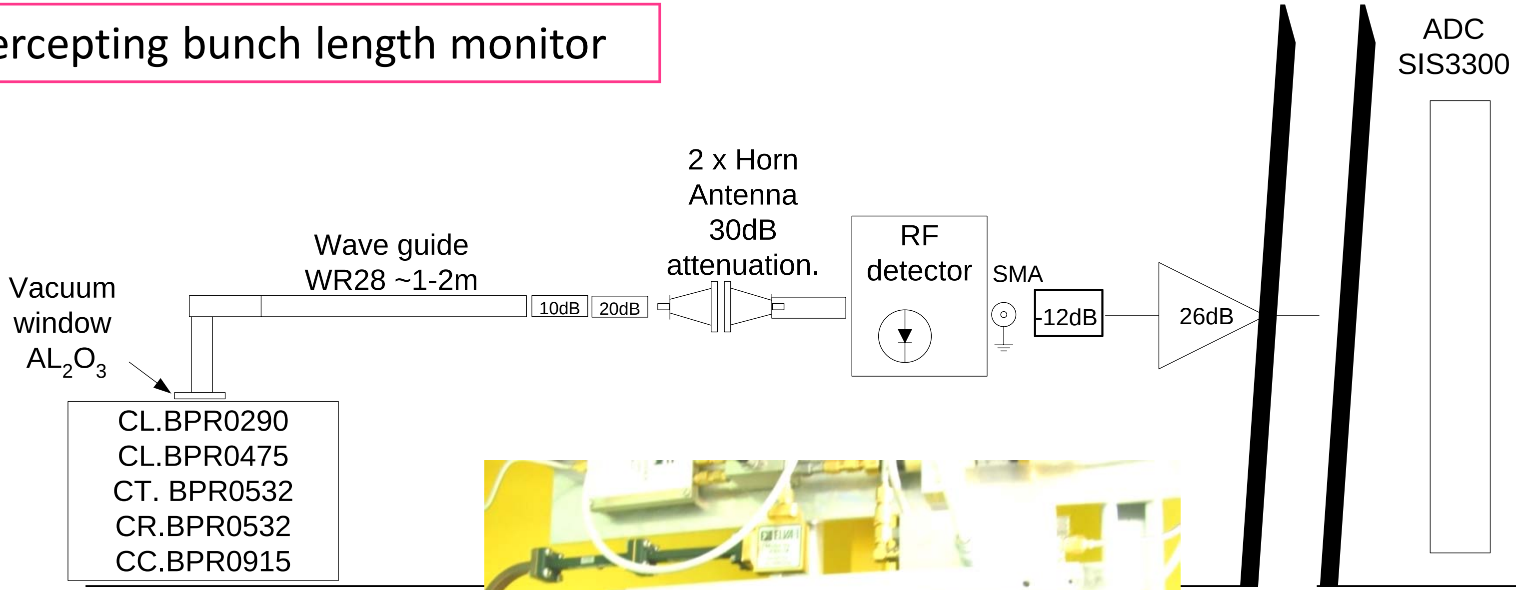
capton foil is better
but your vacuum group will kill you!

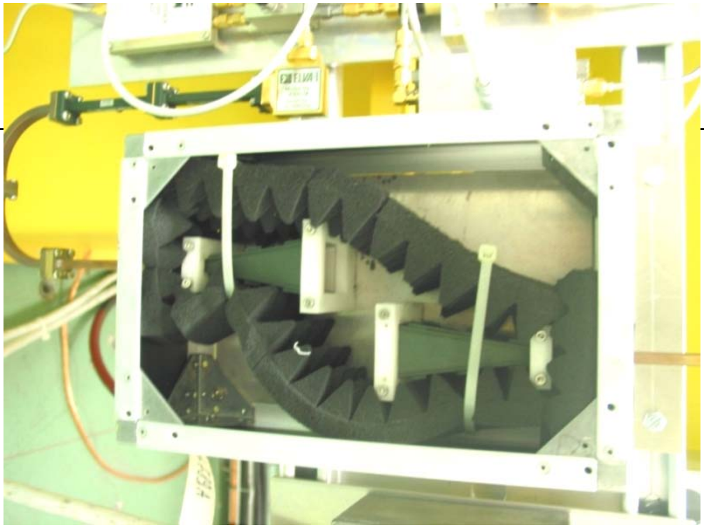
DC block to protect RF detector against beam induced

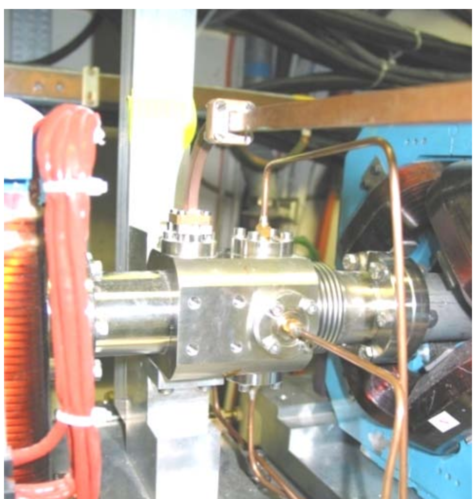
Courtesy L. Søby, CERN

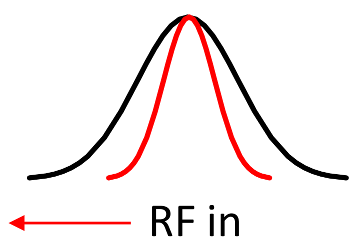
Waveguide pick-up of CTF3 at CERN

Non intercepting bunch length monitor





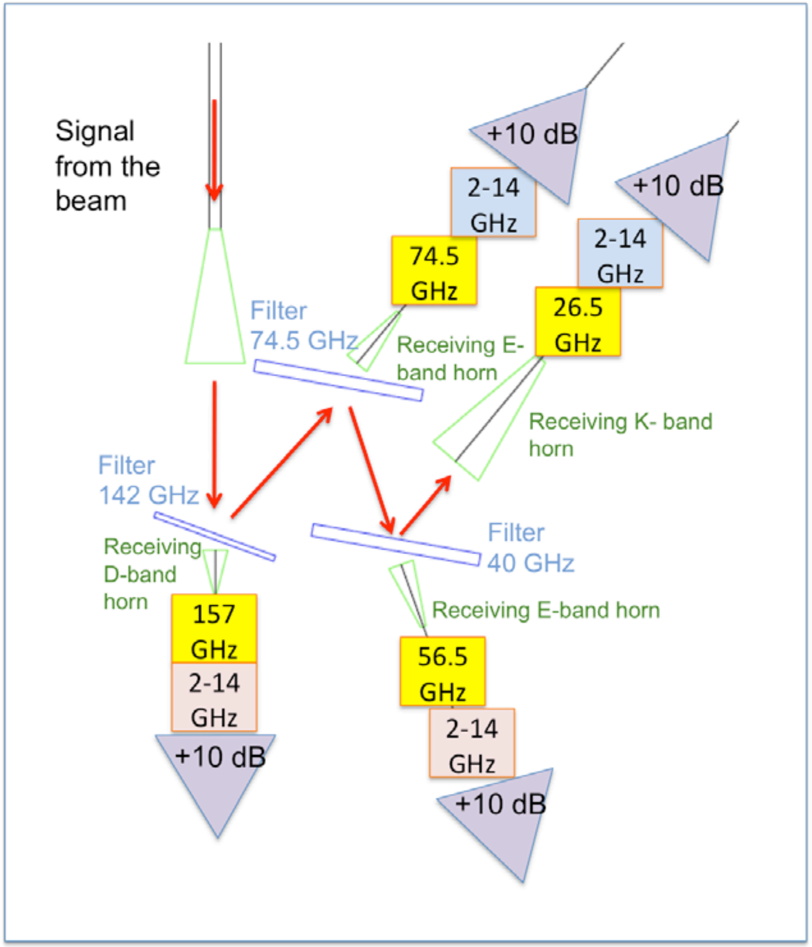




Shorter bunches means more power

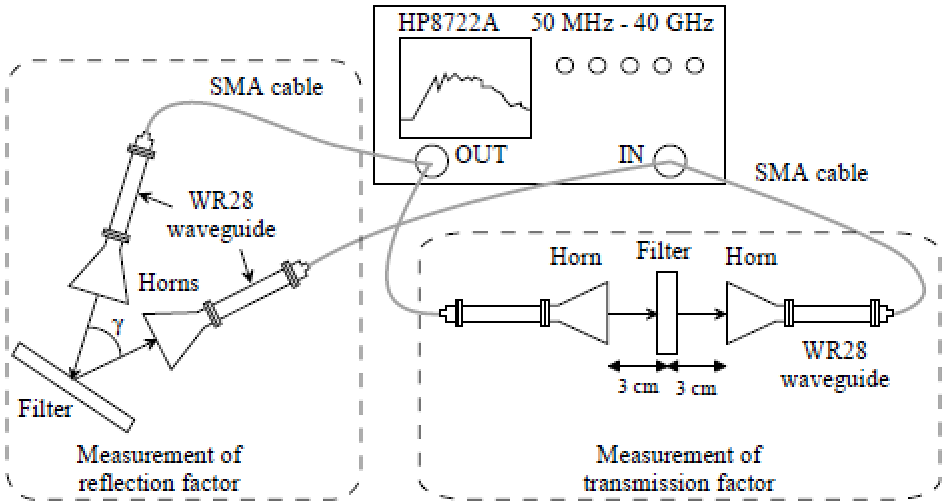
Courtesy L. Søby, CERN

A more sophisticated system
CTF3(CERN) mm-wave spectrometer



Courtesy A. Dabrowski, CERN

Filter for mm-wave



Reflection=low pass

Transmission=high pass

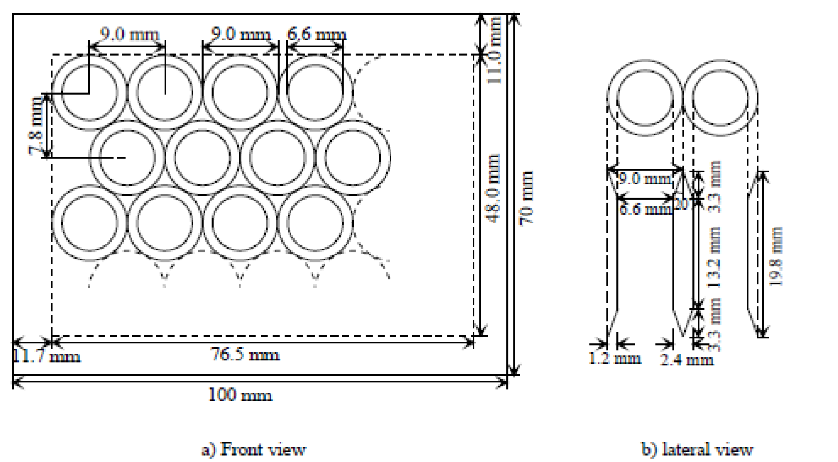


Figure 3.27: Filter with cut-off frequency at 26.5 GHz and conical edges at an angle of 20°.

PhD thesis C.Martinez

CERN-THESIS-2009-011
01/09/1999

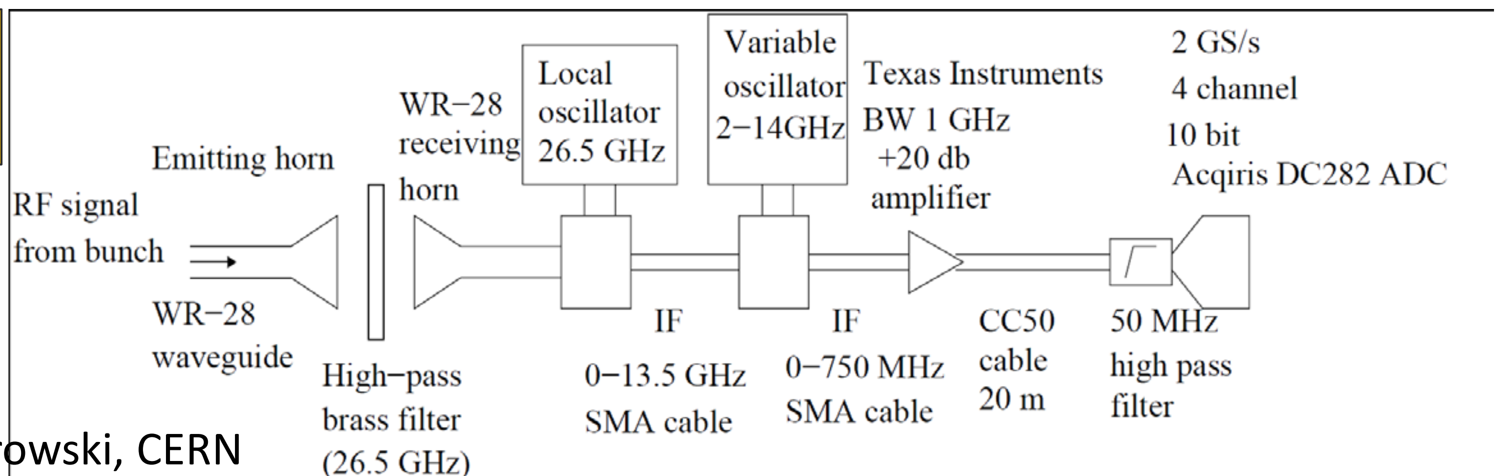
Example of one down mixing stage - RF-pickup

Example:

1. 33 GHz beam harmonic (11th of 3 GHz)
2. ADC is 2 GS/s, typically use 4000 points, 2 micro second time window, delta t = 0.5 ns
3. Depending on the period of the bunch length variations along the pulse & parasitic noise optimize the choice of the second LO mixing stage
4. choose to down mix to a high frequency LO signal, choose 716 MHz

Beam acceleration	Beam harmonic #	Beam harmonic	Fixed first Mixing	Variable Mixing	IF	IF (measured)
2.99855 GHz	11	32.984 GHz	26.5 GHz	7.2 GHz	716 MHz	735 MHz

Example Schema K-band down mixing scheme

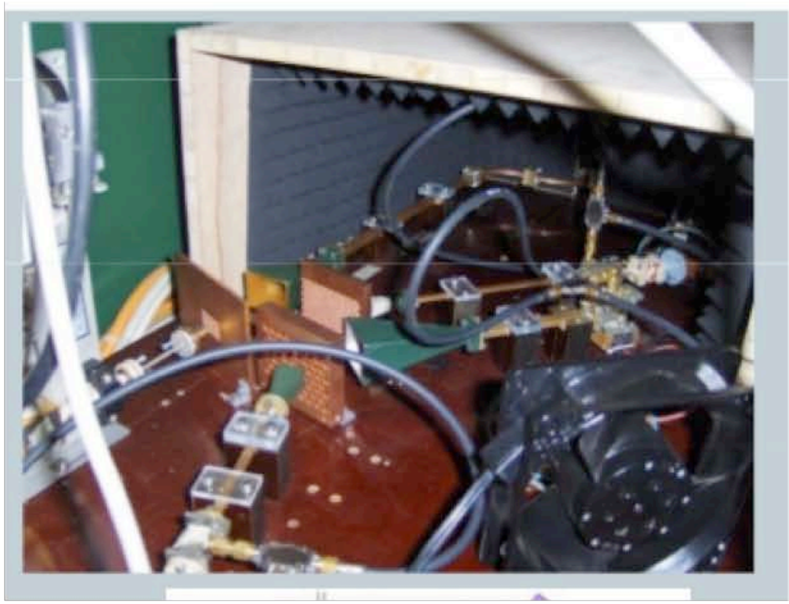


Courtesy A. Dabrowski, CERN

Example CTF3 mm-wave spectrometer

Power supplies for the 3 mixing stages & 4 amplifiers

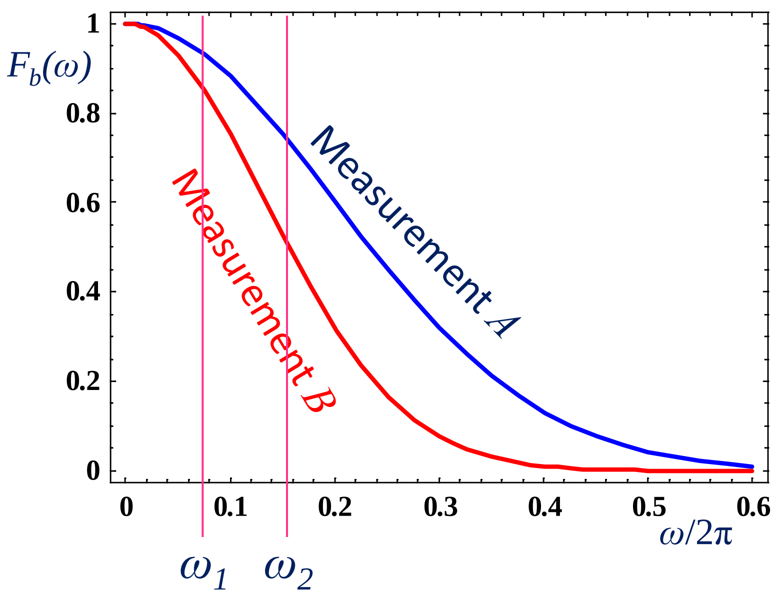
4 Amplifier Channels



Courtesy A. Dabrowski, CERN

Self consistent calibration of spectral bunch length measurment

1. Measure RF signal S_1 and S_2 at two frequencies ω_1 and ω_2
2. Change machine setting to obtain a different (yet unknown) bunch-length
3. Measure again RF signal S_1 and S_2 at two frequencies ω_1 and ω_2
4. Compute response function R_1 and R_2 at ω_1 and ω_2 and bunch-lengths σ_A and σ_B for the two machine settings from knowledge of spectral shape
5. Store R_1 and R_2 for future measurements



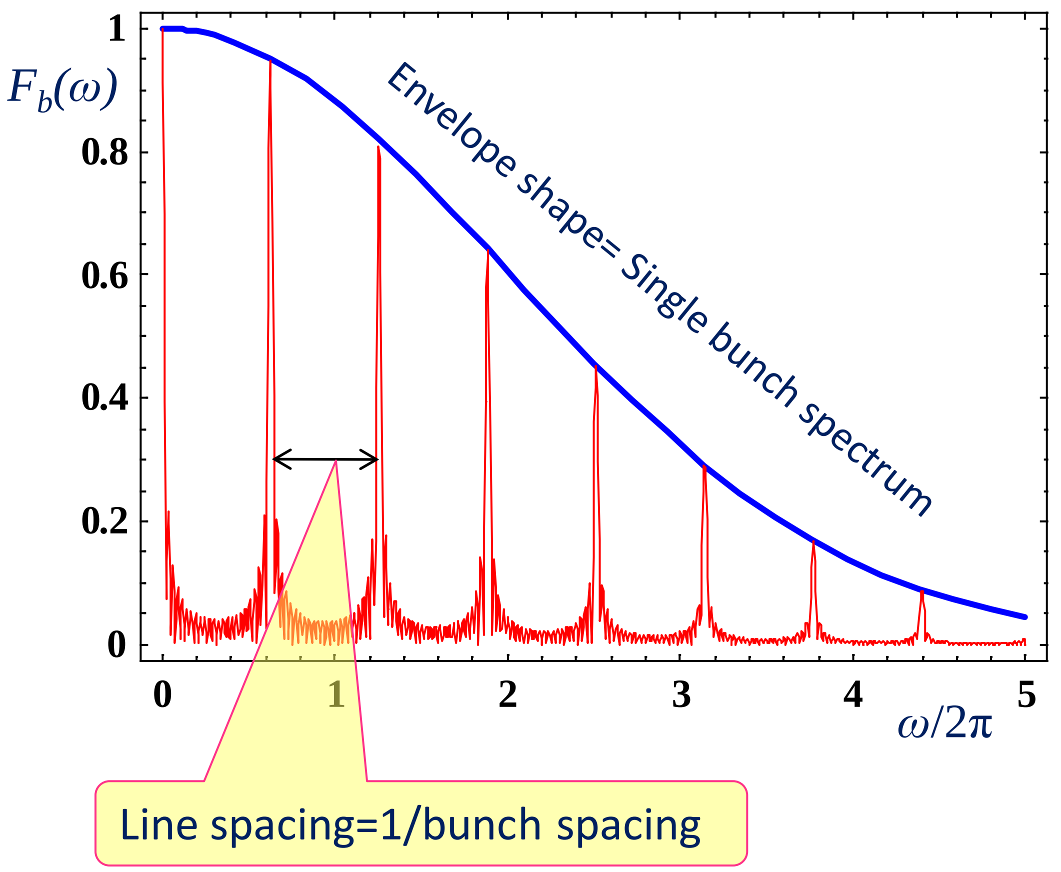
$$S_{1A} = R_1\left(1 - \frac{\omega_1^2 \sigma_A^2}{2}\right) \quad S_{2A} = R_2\left(1 - \frac{\omega_2^2 \sigma_A^2}{2}\right)$$

$$S_{1B} = R_1\left(1 - \frac{\omega_1^2 \sigma_B^2}{2}\right) \quad S_{2B} = R_2\left(1 - \frac{\omega_2^2 \sigma_B^2}{2}\right)$$

$$\Rightarrow \quad R_1 = \frac{\omega_2^2 (S_{1A}S_{2B} - S_{1B}S_{2A})}{(\omega_1^2 - \omega_2^2)(S_{2A} - S_{2B})} \quad \sigma_A = \sqrt{\frac{2S_{1A}(S_{2A} - S_{2B})\,\omega_1^2 - 2S_{2A}(S_{1A} - S_{1B})\,\omega_2^2}{(S_{1B}S_{2A} - S_{1A}S_{2B})\,\omega_1^2\omega_2^2}}$$

$$R_2 = \frac{\omega_1^2 (S_{1A}S_{2B} - S_{1B}S_{2A})}{(\omega_1^2 - \omega_2^2)(S_{1A} - S_{1B})} \quad \sigma_B = \sqrt{\frac{2S_{2B}(S_{1A} - S_{1B})\,\omega_2^2 - 2S_{1B}(S_{2A} - S_{2B})\,\omega_1^2}{(S_{1A}S_{2B} - S_{1B}S_{2A})\,\omega_1^2\omega_2^2}}$$

Spectrum of bunch trains



Thank you for your attention !

& Have fun measuring your beam parameters!