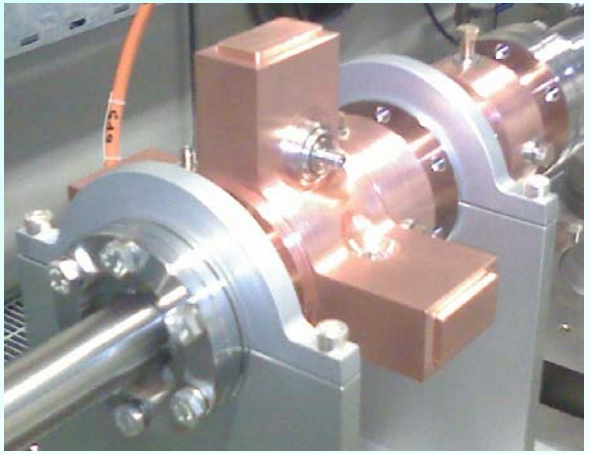
The Cavity Beam Position Monitor (BPM)



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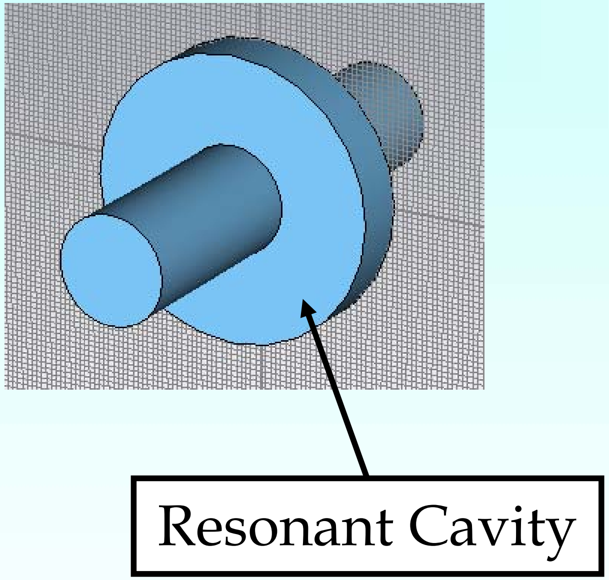
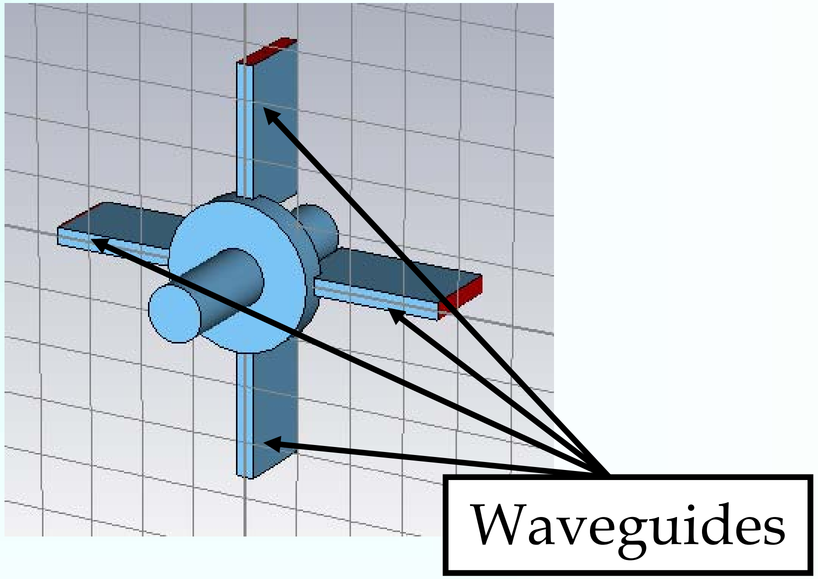
Contents

Introduction: The Cavity BPM

- Devices able to determine the X and Y position of the electron beam in the beam pipe
- Based on a resonant cavity


Resonant Cavity

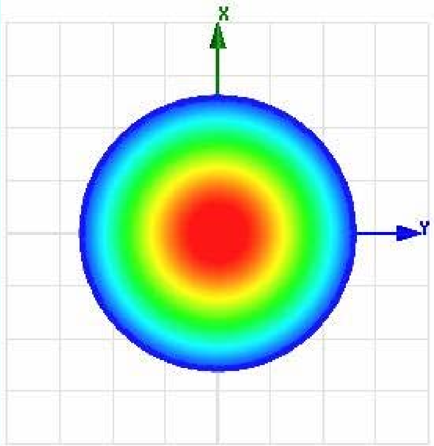

Waveguides

- Good resolution (~1μ target for FERMI@Elettra),
- High signal level in single shot (good for FELs)

The resonant modes of the cavity

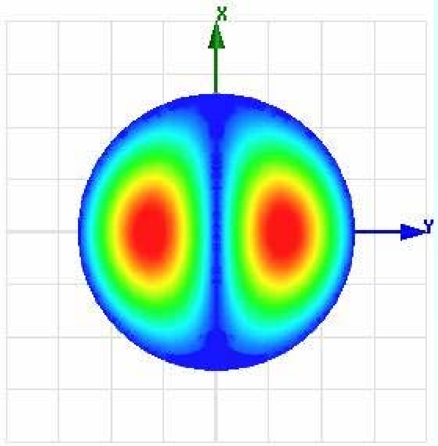
- The electron beam excites the resonant modes of the cavity
- The first four resonant modes are the following:

TM_{010}



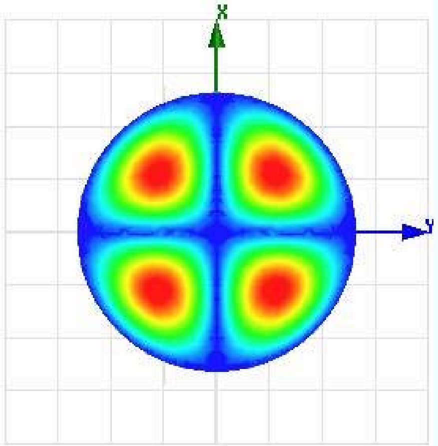
4.63 GHz

TM_{110}



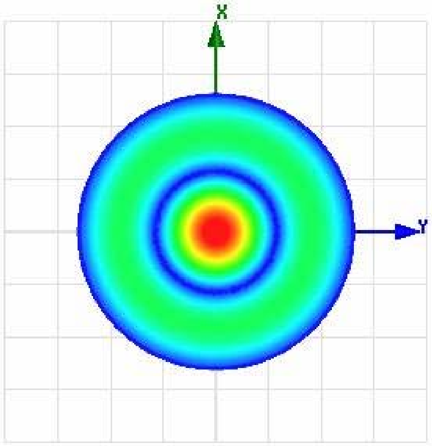
6.5 GHz

TM_{210}



9.04 GHz

TM_{020}

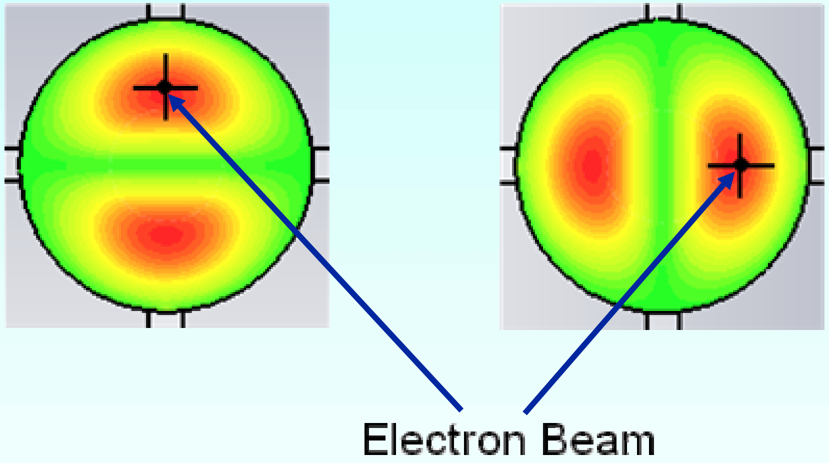


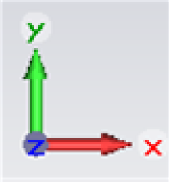
10.5 GHz

(Frequencies of the FERMI@Elettra BPM)

The dipole mode: TM_{110}

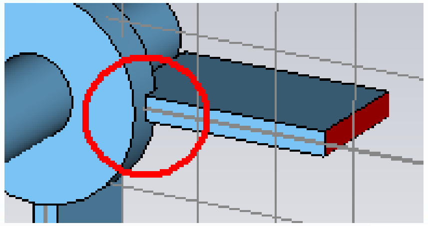
- It is the position sensing mode
- Its intensity is proportional to the beam offset
- There are two different polarizations: vertical and horizontal





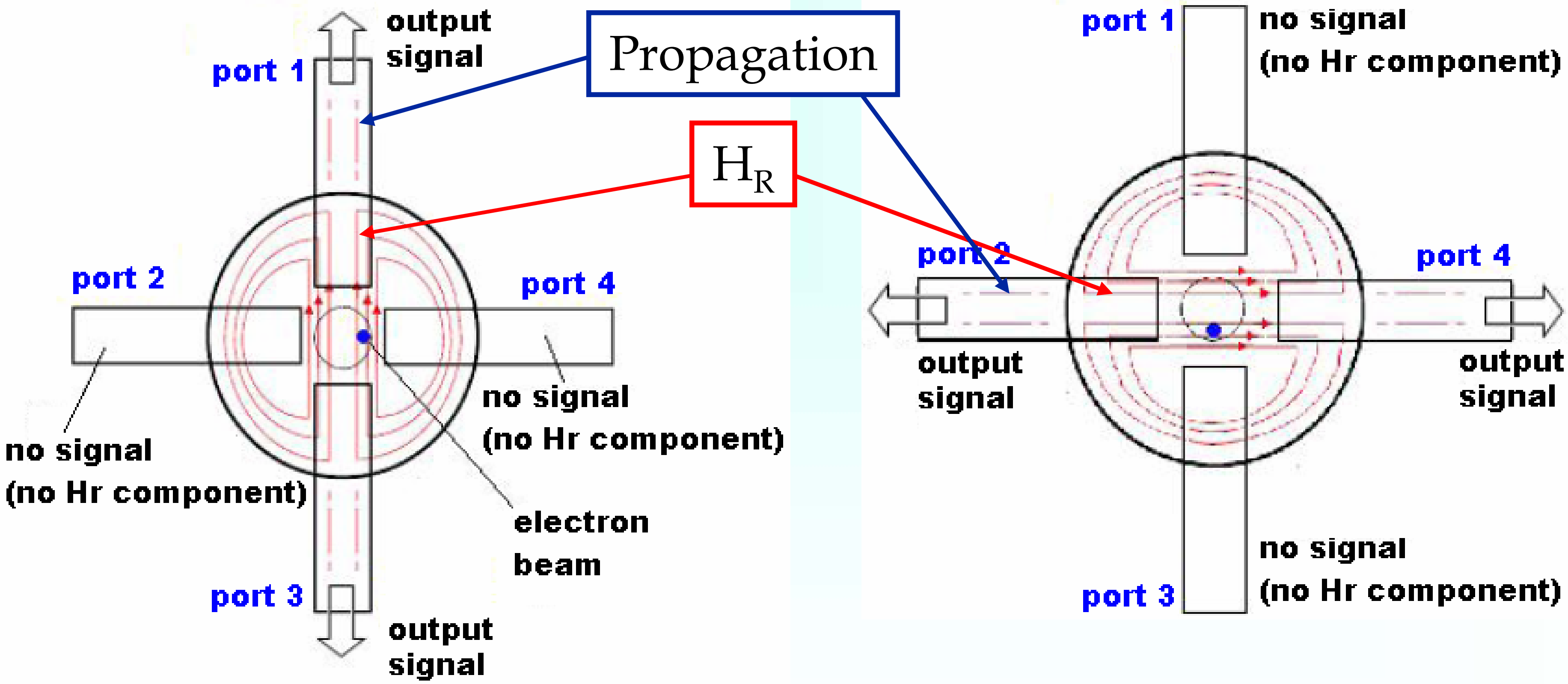
Working Frequency:
~6.5 GHz

- The separation of the monopole and of the two polarizations is achieved with the cavity-waveguide coupling



Separation of the two dipole polarizations

- The magnetic coupling works with “H_R” (radial component of H)
- Allows the separation of the two polarizations

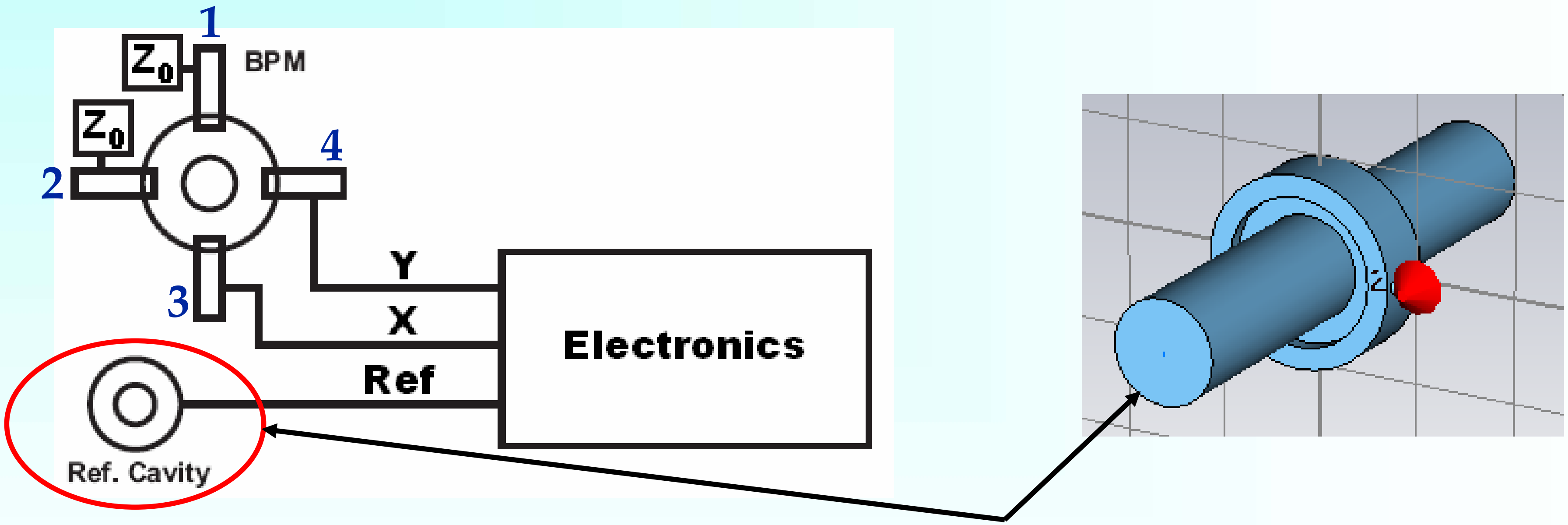


X polarization → port 1, 3

Y polarization → port 2, 4

Signal processing

- The signal of port 1, 3 is proportional to the X position
- The signal of port 2, 4 is proportional to the Y position



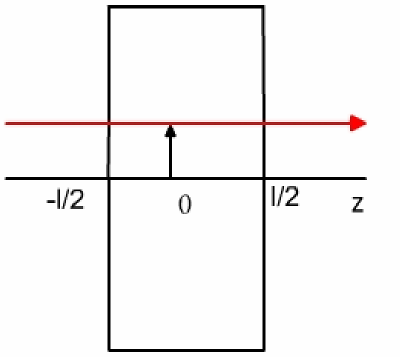
- An additional signal is used as “reference signal”, to:
  - Obtain a bipolar output signal (for ±X, ±Y),
  - Separate the offset from the tilt component

Beam offset and tilt effects on the output signals

- Only offset

$$V_{acc,\,offset} = \int_{-\infty}^{+\infty} E_z \cdot e^{jkz}\,dz \cong C\,\frac{j_{11}}{2R}T_{dr}\,l$$

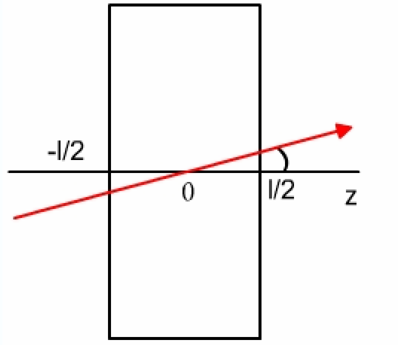
Purely real



- Only tilt

$$V_{acc,\,tilt} = \int_{-\infty}^{+\infty} E_z \cdot e^{jkz}\,dz \cong jC\,\frac{j_{11}\,tg\alpha}{k^2 a}\left\{\sin\left(\frac{kl}{2}\right) - \frac{kl}{2}\cos\left(\frac{kl}{2}\right)\right\}$$

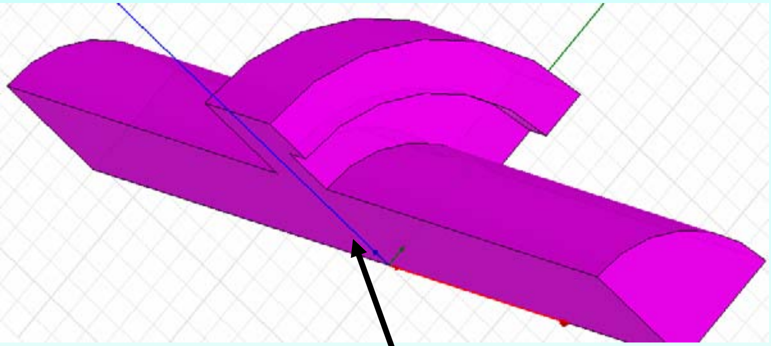
Purely immaginary



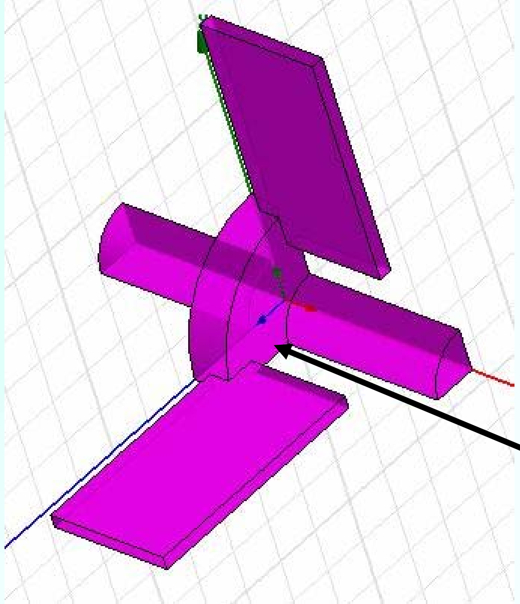
→ The electronics must separate the offset from the tilt component in quadrature (IQ demodulation or our approach)

HFSS Simulations

- Aim: Simulating the RF parameters of the cavities with 90°, 180° and no symmetry planes:



Reference cavity



BPM cavity

- Aim: Estimating the output signal levels, the voltage is given by the following relation:

$$V_{OUT} = \sqrt{2Z_0 \frac{\omega}{Q_{EXT}} k_{010} q}$$

HFSS Simulations results

reference cavity	
f_{RES} (MHz)	6457
Q_0	6314
Q_{EXT}	42351
k_{010} (V/nC)	731
V_{OUT}@1nC (V)	8.4

BPM cavity	
f_{RES} (MHz)	6485
Q_0	7900
Q_{EXT}	150000
k_{110} $(V/nC/mm^2)$	9.4
V_{OUT}@1nC (V)	0.5

- Workbench measured frequencies:

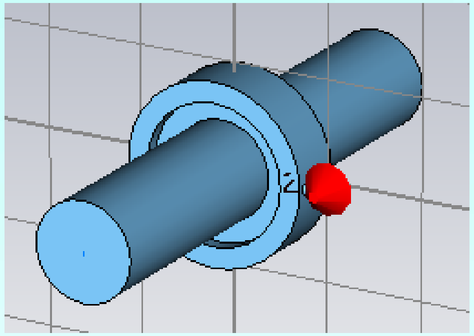
reference cavity	
f_{RES} (MHz)	6476

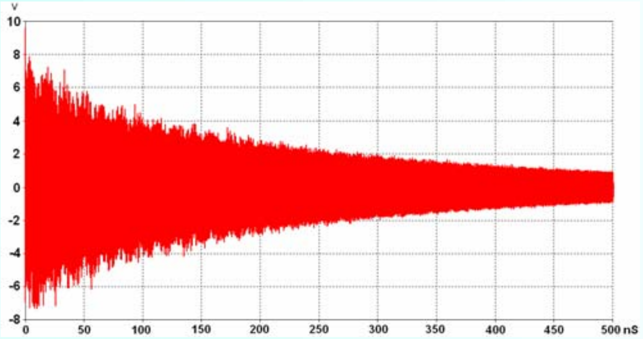
BPM cavity	
f_{RES} (MHz)	6474

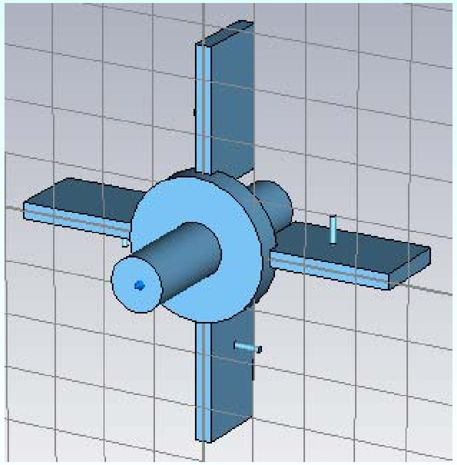
The simulation result is 19 MHz different from the measured value

CST Simulations

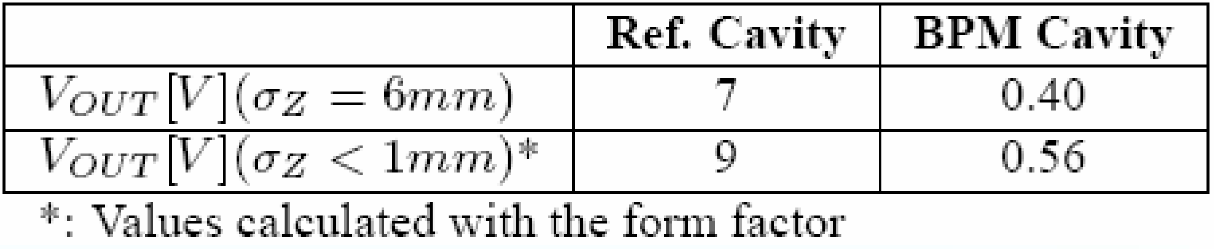
- Aim: Simulating the output signal levels with 1 nC of bunch charge







Summary of the sigal levels:



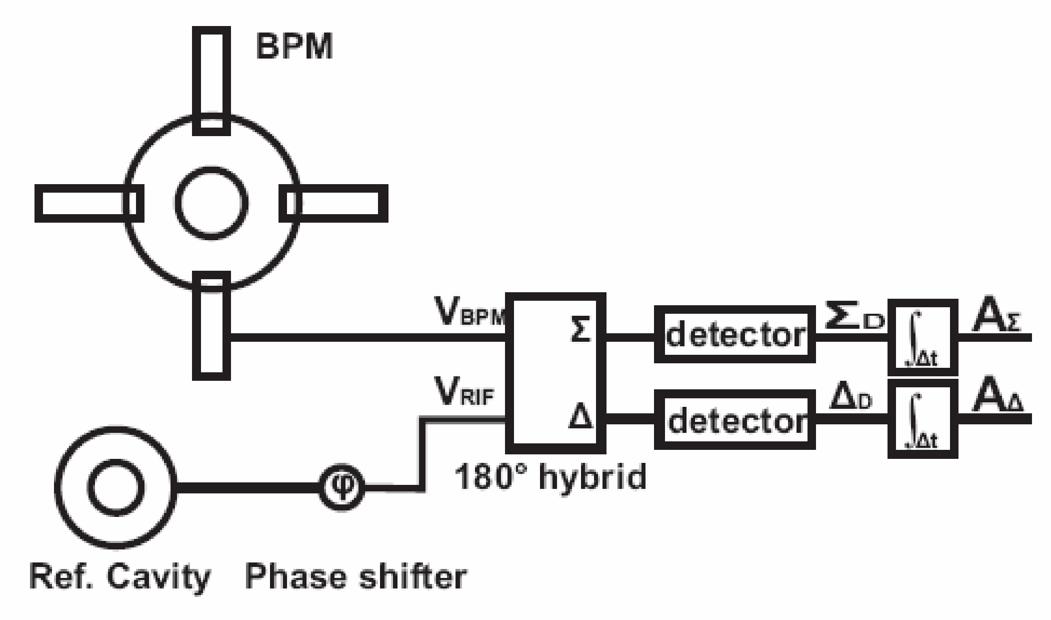
	Ref. Cavity	BPM Cavity
$V_{OUT}[V](\sigma_Z = 6mm)$	7	0.40
$V_{OUT}[V](\sigma_Z < 1mm)$*	9	0.56

*: Values calculated with the form factor

The new electronic system

- Aim: designing a new electronic system that avoids the IQ demodulation

First type of circuit



$$\begin{cases} V_{BPM} = (B_\sigma \cos(\omega t) + \cancel{B_t} \sin(\omega t))e^{-t/\tau_B} \\ V_{RIF} = A\cos(\omega t)e^{-t/\tau_R} \end{cases}$$

$$\begin{cases} \Sigma = (Ae^{-t/\tau_R} + B_\sigma e^{-t/\tau_B})\cos(\omega t) + \cancel{B_t} e^{-t/\tau_B} \sin(\omega t) \\ \Delta = (Ae^{-t/\tau_R} - B_\sigma e^{-t/\tau_B})\cos(\omega t) - \cancel{B_t} e^{-t/\tau_B} \sin(\omega t) \end{cases}$$

$$\begin{cases} \Sigma_D = \sqrt{(Ae^{-t/\tau_R} + B_\sigma e^{-t/\tau_B})^2 + (\cancel{B_t} e^{-t/\tau_B})^2} \\ \Delta_D = \sqrt{(Ae^{-t/\tau_R} - B_\sigma e^{-t/\tau_B})^2 + (\cancel{B_t} e^{-t/\tau_B})^2} \end{cases}$$

The tilt component must be negligible with respect to the offset (for 1µm, the tilt must be < 0.1 mrad)

The new electronic system

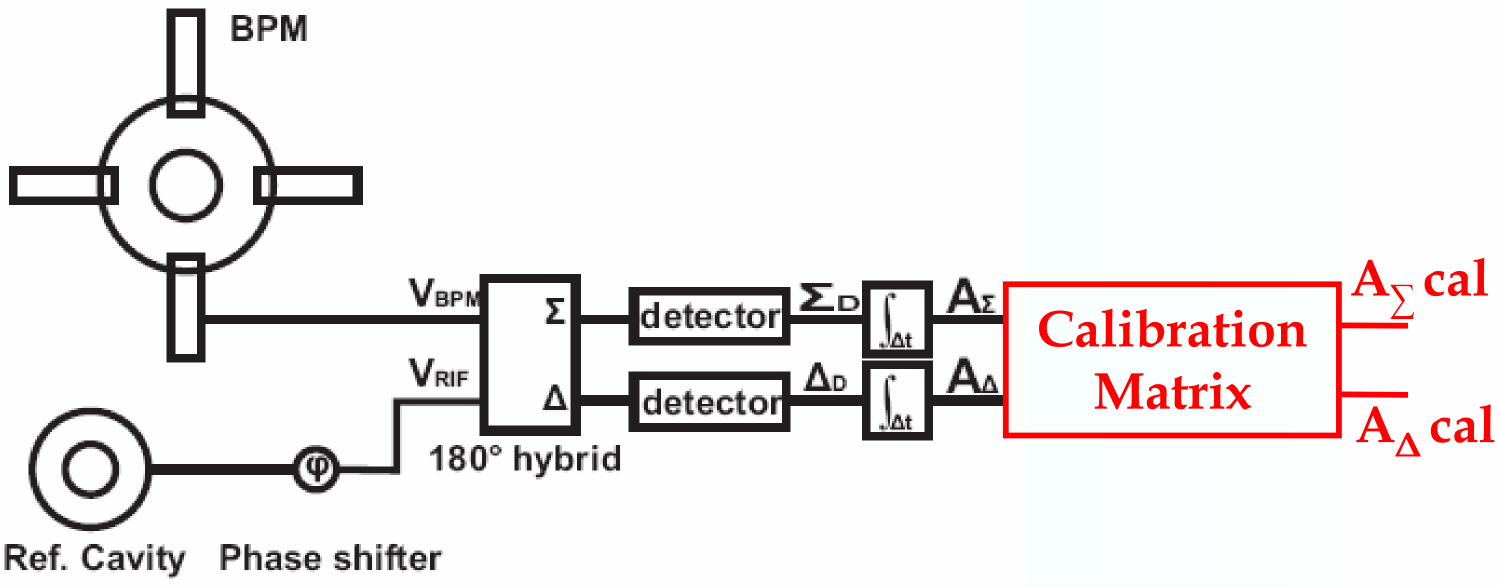
Advantages:

- Beam in the centre → High output signal level (∑=Δ)
- Calibration system

$$\begin{cases} V_{BPM} = 0 \\ V_{RIF} = A\cos(\omega t)e^{-t/\tau_R} \end{cases}$$

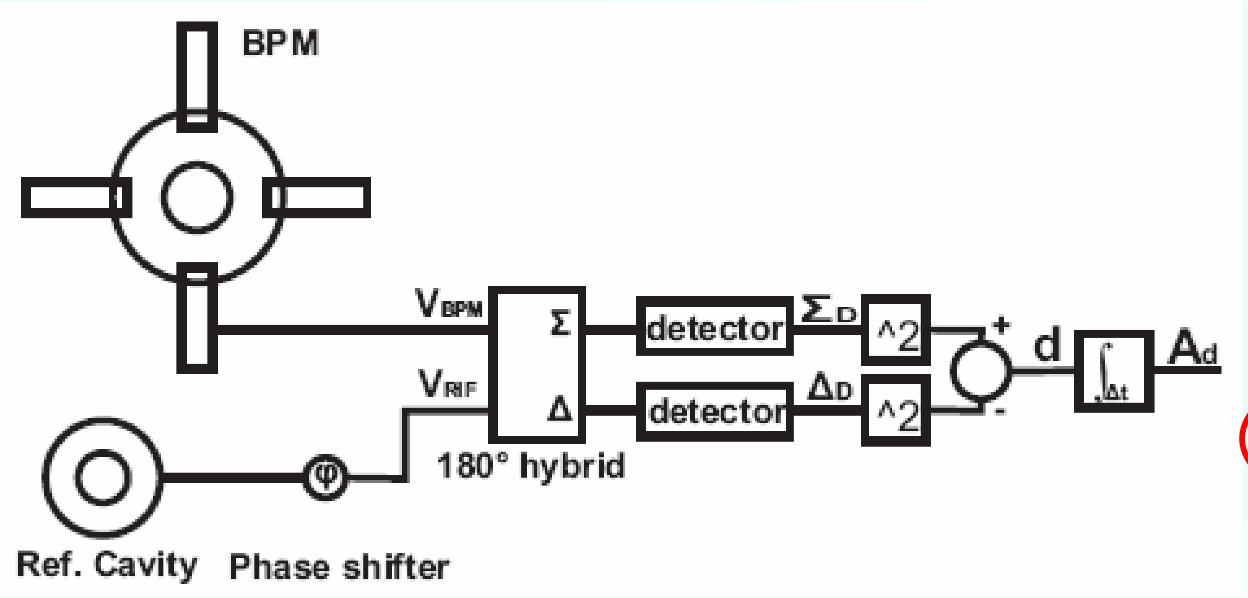
$$\begin{cases} \sum = Ae^{-t/\tau_R}\cos(\omega t) \\ \Delta = Ae^{-t/\tau_R}\cos(\omega t) \end{cases}$$

$$\begin{cases} \Sigma_D = |A|e^{-t/\tau_R} \\ \Delta_D = |A|e^{-t/\tau_R} \end{cases}$$



The new electronic system

Second type of circuit



The tilt component is rejected:

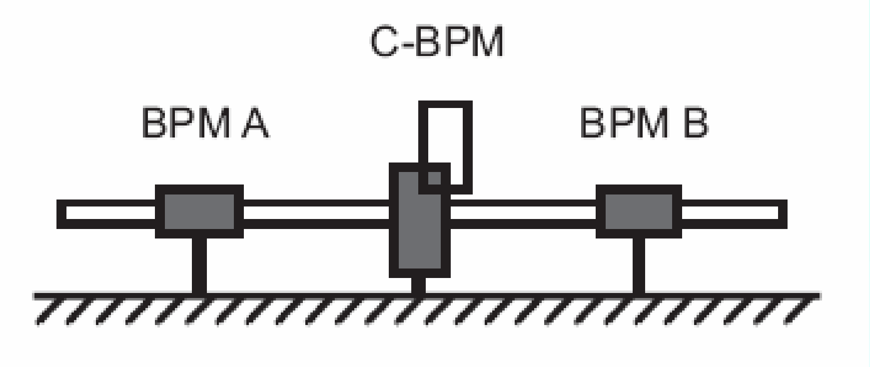
$$d = \Sigma_D^2 - \Delta_D^2 = 4AB_\sigma e^{-t/\tau_R} e^{-t/\tau_B}$$

$$\boxed{A_d \propto 4AB_\sigma}$$

Anologous result to the coherent demodulation

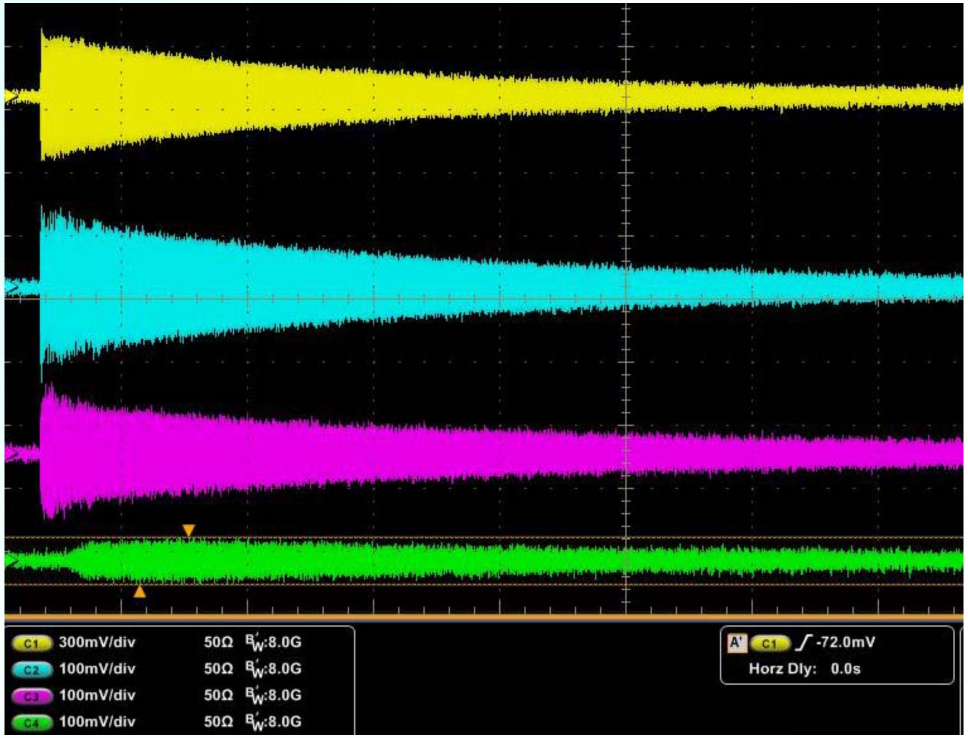
The in-tunnel test

- The prototype has been installed in tunnel
- Aim: determining the output voltage with 1 nC of bunch charge



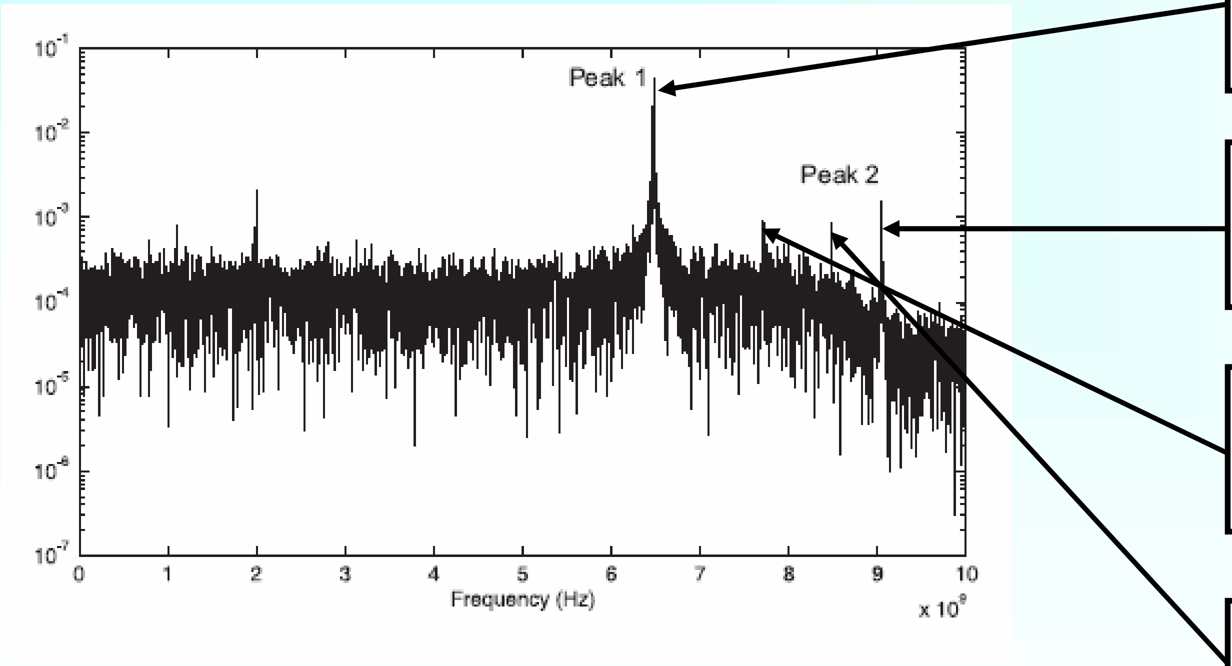
Signal levels:

- Reference cavity: 2.52 V
- Cavity BPM, X offset: 0.33 V/mm
- Cavity BPM, Y offset: 0.30 V/mm



The in-tunnel test

- Spectrum (FFT) of the BPM output signal



Dipole mode
f = 6.476 GHz

Quadrupole mode
f= 9.046 GHz

Rectangular waveguide
f= 7.7 GHz

Dipole of the reference
f = 8.47 GHz

Resolution

- 10 cavity BPMs have been installed in the undulator hall
- Each one has a mover (Encoder resolution: 1 µm)

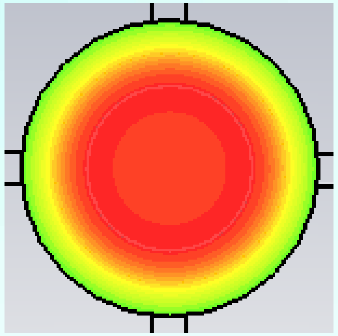
→End the electronics
→Measure the resolution

Thank you for your attention

Questions?

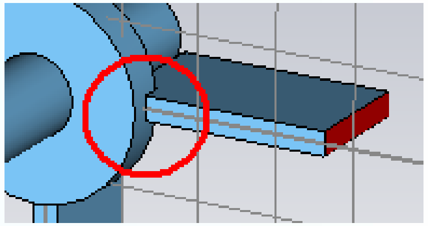
The monopole mode: TM_{010}

- It is an unwanted mode
- Its signal voltage is only proportional to the beam intensity and does not depend on the beam position.



Working Frequency:
4.63 GHz

- Rejection achieved with:
  - Cut-off frequency of the rectangular waveguide
  - Cavity-Waveguide Coupling
  - Band pass filter centred on the dipole frequency

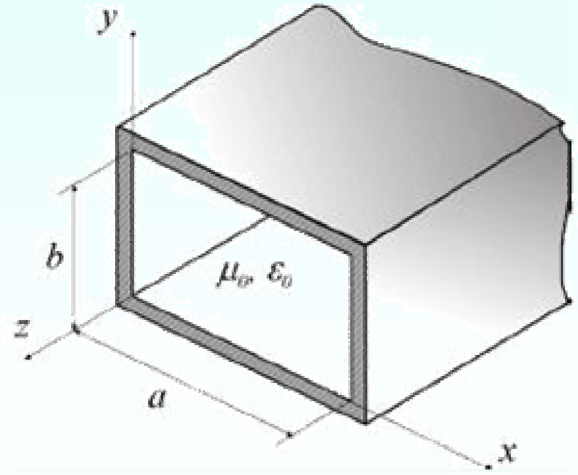


Rejection of the TM_{010} mode: Cut-off frequency of the waveguide

- Waveguides behave as high-pass filter
- Cut-off frequency for the fundamental mode (TE10):

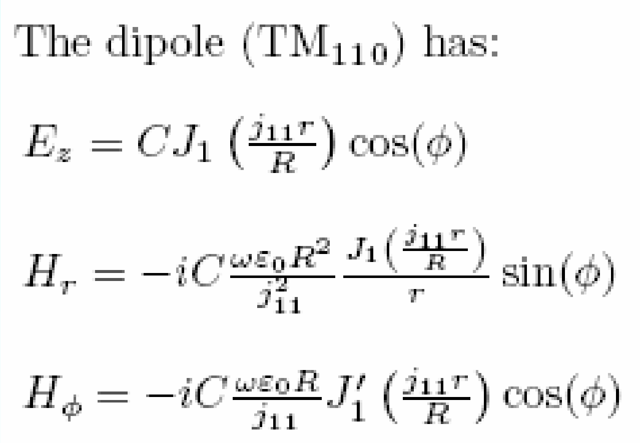
$$f_L = \frac{c}{2\pi}\frac{\pi}{a} = 5\,GHz$$

- The monopole, at 4.63 GHz is under cut-off



Rejection of the TM_{010} mode: Cavity-Waveguide Coupling

- Magnetic coupling: only the magnetic field (*Hr*) of the dipole will couple with the waveguide

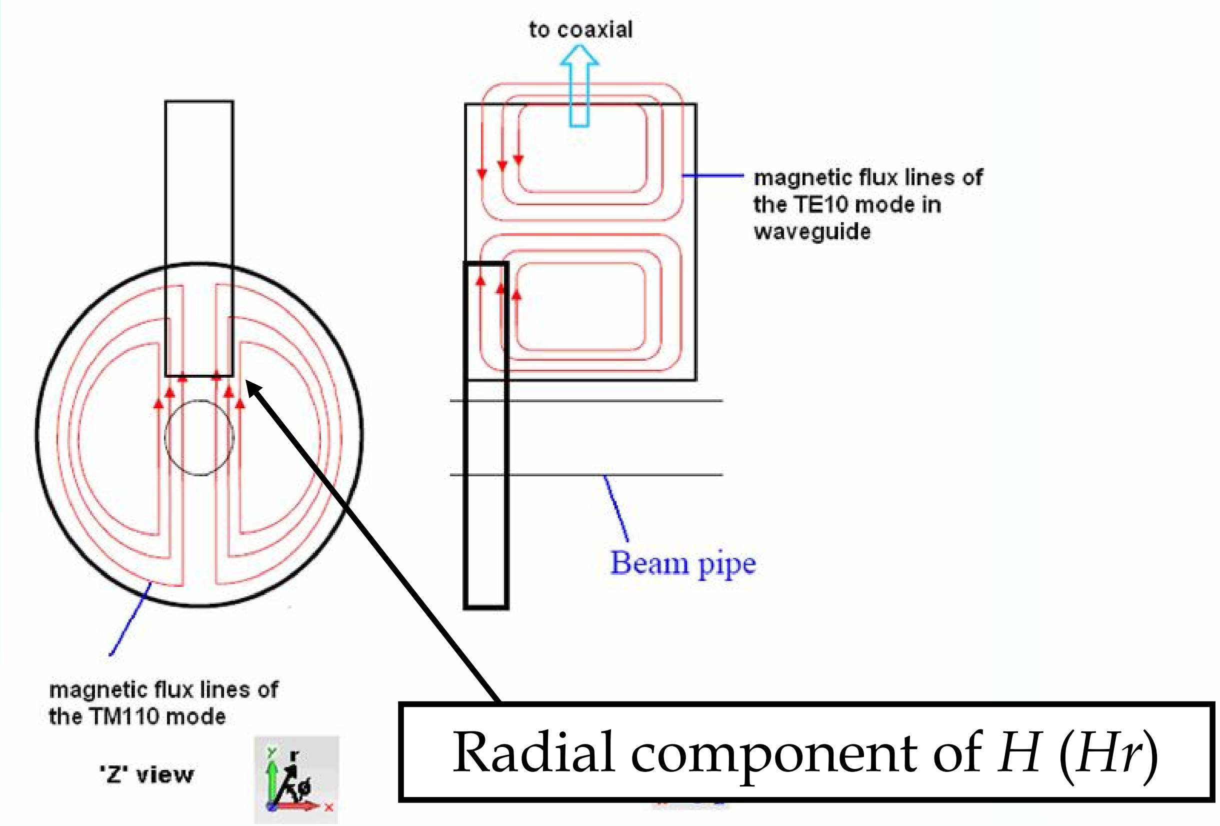


The dipole (TM_{110}) has:

$$E_z = C J_1\left(\frac{j_{11} r}{R}\right)\cos(\phi)$$

$$H_r = -iC\frac{\omega\varepsilon_0 R^2}{j_{11}^2}\frac{J_1\left(\frac{j_{11} r}{R}\right)}{r}\sin(\phi)$$

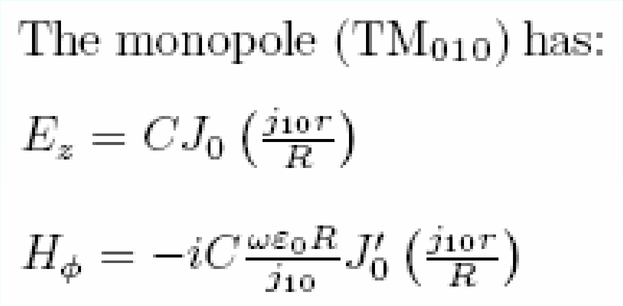
$$H_\phi = -iC\frac{\omega\varepsilon_0 R}{j_{11}}J_1'\left(\frac{j_{11} r}{R}\right)\cos(\phi)$$



Radial component of *H* (*Hr*)

Rejection of the TM$_{010}$ mode: Cavity-Waveguide Coupling

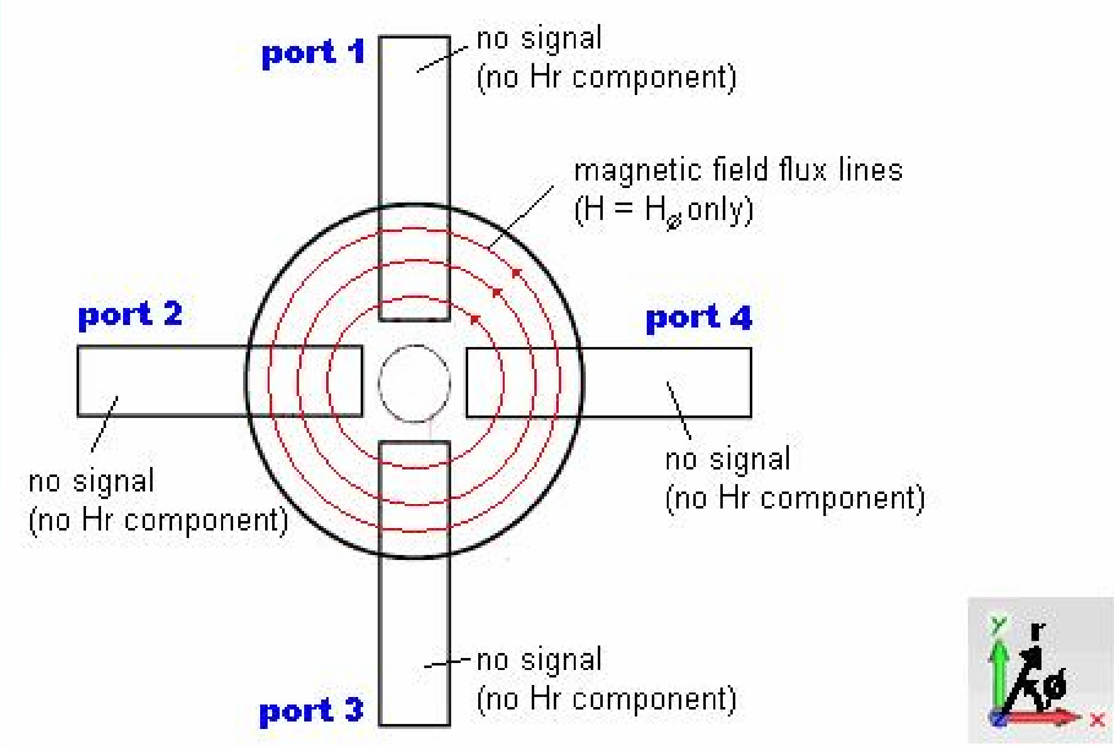
- The monopole does not couple with the waveguide



The monopole (TM$_{010}$) has:

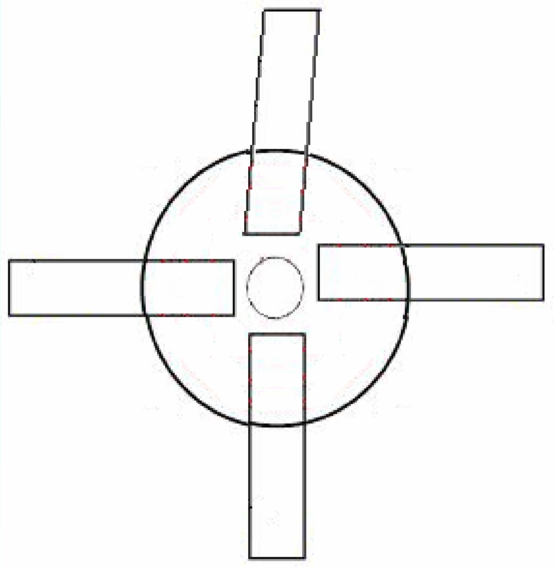
$$E_z = C J_0\left(\frac{j_{10} r}{R}\right)$$

$$H_\phi = -iC\frac{\omega \varepsilon_0 R}{j_{10}} J_0'\left(\frac{j_{10} r}{R}\right)$$



Cavity-Waveguide Coupling: Separation of the two dipole polarizations

- However, due to the mechanical tolerances, the two polarizations are not perfectly orthogonal



- The orthogonal ports are not isolated between them
- This phenomena is called “Cross-Talking”

Rejection of the TM_{010} mode: Cavity-Waveguide Coupling

Consequences of the cavity-waveguide coupling

- The monopole does not couple with the waveguide
- It separates the vertical and the horizontal polarizations

An additional band-pass filter is placed to have only the dipole signal and to reject the higher modes

■ Vout

Energy

$$U = k \cdot q^2$$

$$Pext = \frac{\omega U}{Qext} = \frac{\omega}{Qext} \cdot k \cdot q^2$$

$$Vout = \sqrt{2 \cdot Z \cdot Pext} = \sqrt{2 \cdot Z \cdot \frac{\omega}{Qext} \cdot k} \cdot q \qquad \left(= \omega \sqrt{\frac{Z}{Qext}\left(\frac{R}{Q}\right)} \cdot q \right)$$

Vacc, Energy, Bessel, Linearity

$$U_{(\sigma)} = \frac{1}{2} Q \dot{V} = \frac{1}{2} Q \int \boxed{E_z} e^{-jkz} dz = \frac{1}{2} Q\, C(\sigma)\, J_1\left(\frac{\nu_u}{R}\sigma\right) T_{dr}$$

$$U = \frac{\varepsilon}{2} \int_V |E_z|^2 dV = \frac{\varepsilon}{2} \int_{-l/2}^{l/2}\int_0^a\int_0^{2\pi} C^2(\sigma)\, J_1^2\left(\frac{\nu_u}{R} r\right) |\cos\phi|^2 r\, d\phi\, dr\, dz \propto C^2(\sigma)$$

$$\Rightarrow C(\sigma) = k Q J_1\left(\frac{\nu_u}{R}\sigma\right)$$

$$J_1(x) \simeq \frac{x}{2} - \frac{1}{2}\left(\frac{x}{2}\right)^3 \qquad \frac{1}{2}\left(\frac{x}{2}\right)^3 \overset{?}{<} \frac{1}{100}\frac{x}{2} \qquad \underline{x < 0.2}$$

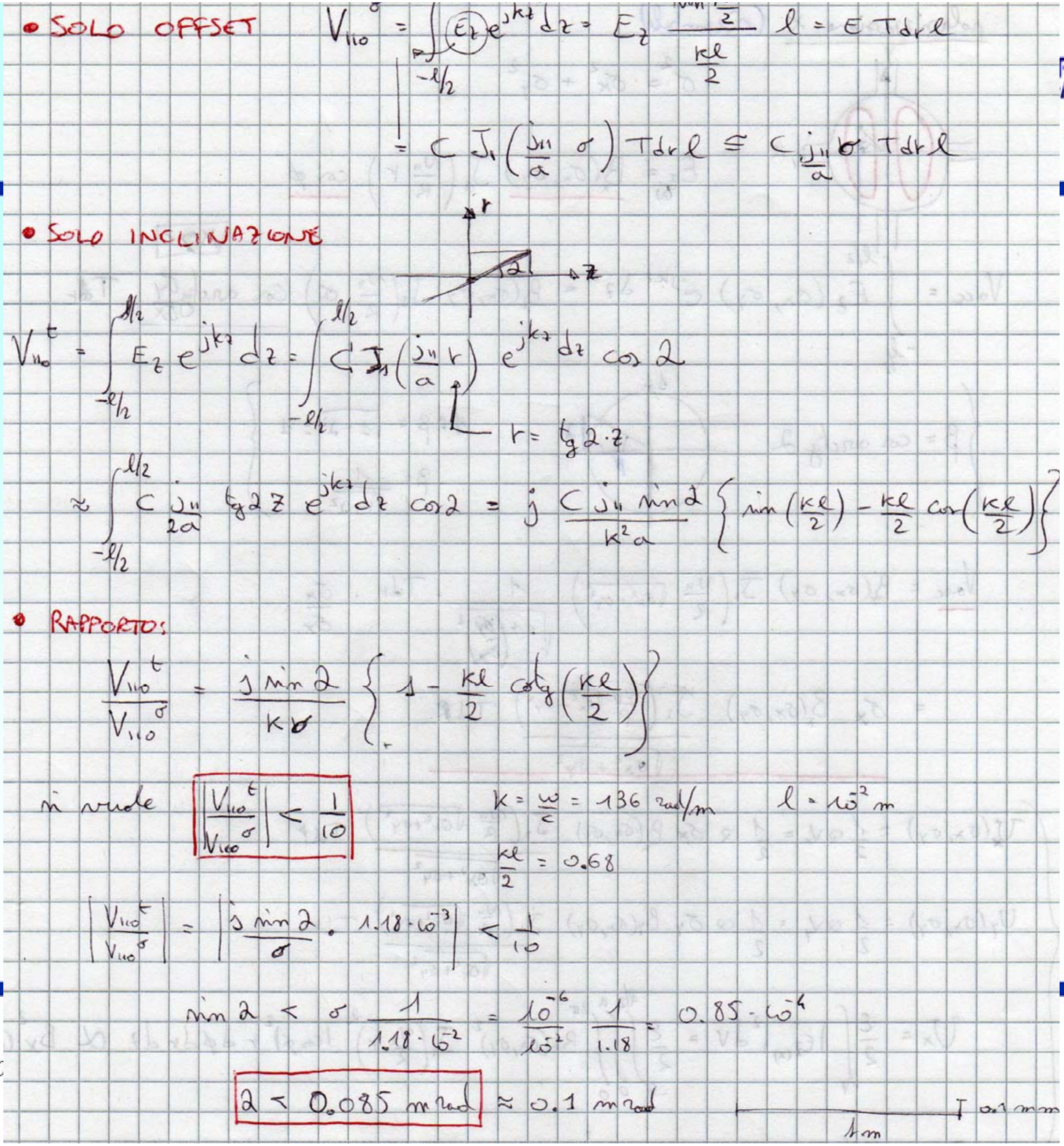
$$J_1\left(\frac{\nu_u}{R}\sigma\right) \qquad \frac{\nu_u}{R}\sigma < 0.2 \Rightarrow \sigma < \frac{0.2}{3.5} \cdot R \simeq \underline{1.5\ \text{mm}} \qquad (1\%)$$

oppure $\frac{1}{2}\left(\frac{x}{2}\right)^3 < \frac{1}{10}\frac{x}{2}$ $\underline{x < 0.63}$

$$\underline{\sigma < 4.74\ \text{mm}} \qquad (10\%)$$

$$(\sigma < 3.37\ \text{mm} \ @\ 5\%)$$

- Offset,
- Tilt



- SOLO OFFSET $$V_{110}^{\sigma} = \int_{-\ell/2} \boxed{E_z} e^{jkz}\,dz = E_z \frac{\frac{}{2}}{\frac{k\ell}{2}}\,\ell = E\,T_{dr}\,\ell$$
$$= C\,J_1\!\left(\frac{j_{11}}{a}\sigma\right) T_{dr}\,\ell \cong C\,\frac{j_{11}}{a}\sigma\,T_{dr}\,\ell$$

- SOLO INCLINAZIONE

$$V_{110}^{t} = \int_{-\ell/2}^{\ell/2} E_z e^{jkz}\,dz = \int_{-\ell/2}^{\ell/2} C\,J_1\!\left(\frac{j_{11}}{a} r\right) e^{jkz}\,dz\,\cos\alpha$$

$r = \mathrm{tg}\,\alpha \cdot z$

$$\approx \int_{-\ell/2}^{\ell/2} C\,\frac{j_{11}}{2a}\,\mathrm{tg}\,\alpha\, z\, e^{jkz}\,dz\,\cos\alpha = j\,\frac{C\,j_{11}\sin\alpha}{k^2 a}\left\{\sin\left(\frac{k\ell}{2}\right) - \frac{k\ell}{2}\cos\left(\frac{k\ell}{2}\right)\right\}$$

- RAPPORTO:

$$\frac{V_{110}^{t}}{V_{110}^{\sigma}} = \frac{j\sin\alpha}{k\sigma}\left\{1 - \frac{k\ell}{2}\,\mathrm{cotg}\left(\frac{k\ell}{2}\right)\right\}$$

si vuole $\boxed{\left|\frac{V_{110}^{t}}{V_{110}^{\sigma}}\right| < \frac{1}{10}}$ $\qquad k = \frac{\omega}{c} = 136$ rad/m $\qquad \ell = 10^{-2}$ m

$\frac{k\ell}{2} = 0.68$

$$\left|\frac{V_{110}^{t}}{V_{110}^{\sigma}}\right| = \left|\frac{j\sin\alpha}{\sigma}\cdot 1.18\cdot 10^{-3}\right| < \frac{1}{10}$$

$$\sin\alpha < \sigma\,\frac{1}{1.18\cdot 10^{-2}} = \frac{10^{-6}}{10^{-2}}\,\frac{1}{1.18} = 0.85\cdot 10^{-4}$$

$$\boxed{\alpha < 0.085\ \text{mrad}} \approx 0.1\ \text{mrad}$$