The Cavity Beam Position Monitor (BPM)

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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
- 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:

\[
\begin{align*}
&\text{TM}_{010} & 4.63 \text{ GHz} \\
&\text{TM}_{110} & 6.5 \text{ GHz} \\
&\text{TM}_{210} & 9.04 \text{ GHz} \\
&\text{TM}_{020} & 10.5 \text{ GHz} \\
\end{align*}
\]

(Frequencies of the FERMI@Elettra BPM)
The dipole mode: $\text{TM}_{110}$

- 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 $\rightarrow$ port 1, 3

Y polarization $\rightarrow$ port 2, 4
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
  \[ V_{\text{acc, offset}} = \int_{-\infty}^{+\infty} E_z \cdot e^{jkz} \, dz \cong C \frac{j_{11} T_{dr} l}{2R} \]

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

→ 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:

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

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

<table>
<thead>
<tr>
<th></th>
<th>Ref. Cavity</th>
<th>BPM Cavity</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{OUT}[V] (\sigma_Z = 6\text{mm})$</td>
<td>7</td>
<td>0.40</td>
</tr>
<tr>
<td>$V_{OUT}[V] (\sigma_Z &lt; 1\text{mm})^*$</td>
<td>9</td>
<td>0.56</td>
</tr>
</tbody>
</table>

*: 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

\[ V_{BPM} = (B_\sigma \cos(\omega t) + \sin(\omega t)) e^{-t/\tau_B} \]
\[ V_{RIF} = A \cos(\omega t) e^{-t/\tau_R} \]
\[ \Sigma = (A e^{-t/\tau_R} + B_\sigma e^{-t/\tau_B}) \cos(\omega t) + \sigma e^{-t/\tau_B} \sin(\omega t) \]
\[ \Delta = (A e^{-t/\tau_R} - B_\sigma e^{-t/\tau_B}) \cos(\omega t) - \sigma e^{-t/\tau_B} \sin(\omega t) \]
\[ \Sigma_D = \sqrt{(A e^{-t/\tau_R} + B_\sigma e^{-t/\tau_B})^2 + (\sigma e^{-t/\tau_B})^2} \]
\[ \Delta_D = \sqrt{(A e^{-t/\tau_R} - B_\sigma e^{-t/\tau_B})^2 + (\sigma e^{-t/\tau_B})^2} \]

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 (\(\sum = \Delta\))
- Calibration system

\[
\begin{align*}
    V_{BPM} &= 0 \\
    V_{RIF} &= A \cos(\omega t) e^{-t/\tau_R} \\
    \sum &= Ae^{-t/\tau_R} \cos(\omega t) \\
    \Delta &= Ae^{-t/\tau_R} \cos(\omega t) \\
    \Sigma_D &= |A|e^{-t/\tau_R} \\
    \Delta_D &= |A|e^{-t/\tau_R}
\end{align*}
\]
The new electronic system

Second type of circuit

The tilt component is rejected:

\[ d = \Sigma^2_D - \Delta^2_D = 4AB_{\sigma}e^{-t/\tau_R}e^{-t/\tau_B} \]

\[ A_d \propto 4AB_{\sigma} \]

Analogous 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
    \[ f = 6.476 \, \text{GHz} \]

  - Quadrupole mode
    \[ f = 9.046 \, \text{GHz} \]

  - Rectangular waveguide
    \[ f = 7.7 \, \text{GHz} \]

  - Dipole of the reference
    \[ f = 8.47 \, \text{GHz} \]
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):
  \[
  f_L = \frac{c}{\frac{\pi}{2\pi a}} = 5 \text{ GHz}
  \]
- 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 ($H_r$) of the dipole will couple with the waveguide

The dipole (TM$_{110}$) has:

\[
E_z = C J_1 \left( \frac{\hat{z} \cos(\phi)}{R} \right)
\]

\[
H_r = -i C \frac{\omega \varepsilon_0 R^2}{J_{11}} J_1 \left( \frac{\hat{r} \sin(\phi)}{r} \right)
\]

\[
H_\phi = -i C \frac{\omega \varepsilon_0 R}{J_{11}} J_1 \left( \frac{\hat{\phi} \cos(\phi)}{R} \right)
\]

Radial component of $H$ ($H_r$)
Rejection of the TM$_{010}$ mode: Cavity-Waveguide Coupling

- The monopole does not couple with the waveguide

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

\[ E_z = C J_0 \left( \frac{i \omega r}{R} \right) \]

\[ H_\phi = -i C \frac{\omega \varepsilon_0 R}{j_1} J_1 \left( \frac{i \omega r}{R} \right) \]
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”.

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Erice, 8 April 2011
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

\[ U = k \cdot q^2 \]

\[ P_{ext} = \frac{\omega U}{Q_{ext}} = \frac{\omega}{Q_{ext}} \cdot k \cdot q^2 \]

\[ V_{out} = \sqrt{2 \cdot Z \cdot P_{ext}} = \sqrt{2 \cdot Z \cdot \frac{\omega}{Q_{ext}} \cdot k \cdot q} \]

\[ = \omega \sqrt{\frac{Z}{Q_{ext}}} \left( \frac{R}{Q} \right) \cdot q \]
Vacc, Energy, Bessel, Linearity

\[ V_n = \frac{1}{2} q \int E_z e^{i k z} \, dz = \frac{1}{2} q \int C(\sigma) J_1 \left( \frac{N_{iv}}{R} \right) T \, d\sigma \]

\[ U = \frac{3}{2} \int E_x^2 \, dV = \frac{3}{2} \int C(\sigma) J_1^2 \left( \frac{N_{iv}}{R} \right) \cos^2 \phi \, \rho \, d\phi \, dr \, d\theta \]

\[ C(\sigma) = k q J_1 \left( \frac{N_{iv}}{R} \right) \]

\[ J_1(x) = \frac{x}{2} - \frac{1}{2} \left( \frac{x}{2} \right)^3 \]

\[ J_1 \left( \frac{N_{iv}}{R} \right) \sigma < 0.2 \Rightarrow \sigma < 0.2 \times \frac{R}{3.5} = \frac{1.5}{\text{mm}} \]

\[ \sigma < 4.49 \text{mm} \quad (\text{10\%}) \]

\[ \sigma < 3.37 \text{mm} \quad (\text{5\%}) \]
Offset,

Tilt