S-Band Cavity BPM For ILC

Zenghai Li
Advanced Computations Department
Stanford Linear Accelerator Center

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- Selective coupling scheme
- Beam simulation
- Resolution estimation
- Mechanical tolerance
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ILC Cryomodule

Space tight
Design Considerations

• Resolution requirement: 1 μm
• Response time < bunch spacing (300ns) – Q~500
• Need to fit in tight space
• BPM in cryomodule clean environment, need be cleanable
• Choice of frequency: L or S band
• Beam pipe radius:
  – 30-mm
    • L-band good choice, but BPM large in dimension
    • S-band is possible
  – 17.81-mm (1.5 inch OD) (Chris)
    • Both S and L band
    • Beampipe need to step down from 30 to 17.81mm. Wakefield is OK (Bane)
• Prototype design: S-band with 17.81mm beampipe radius
Resolution v.s. Frequency

- Comparison
  - Beampipe radius is 5mm for all cavities
  - Resolution is relative to X-band resolution

- Beam pipe radius limits cavity frequencies to lower than the C-band
TM11-TE10 Selective Coupling

- Waveguide does not cut through the beampipe
- Waveguide matched to coax
- Need “larger” space for the waveguides
- Not easy to clean
- No waveguide modes

Coax coupling

- Waveguide cut through beampipe
- Easy to clean
- Overall size small
- Coax do not need to be fully matched
- Coax adaptor far from cavity so not couple to other modes
- Will have waveguide modes?
X-band Design For NLC

- Waveguide does not cut through beampipe
- Waveguide matched to coax
**S-band Cavity BPM Spectrum**

**Time domain Simulation**
- Beam off in x direction
- One more dipole like mode below TM01 frequency. Waveguide dimensions were chosen to have this mode much lower in frequency so can be easily filtered. Only TM11 mode will be used for position measurement
- No significant x-y coupling
- No significant TM01 coupling
Beam Impedance And Pickup Spectrum In Detail

Beam Impedance Spectrum

Voltage At Coax Pickup Ports

Y-port (*100)  
X-port

Wg10  
K_{loss}=0.28

TM11  
K_{loss}=0.63

wg+D

wg30

TM31
RF Parameters That Affect Resolution

- Beam-cavity interaction – loss factor
  - Position signal strength
- Thermal noise
  - N/S ratio
- Mode contamination (TM01, 02…)
  - Dynamic range
- Others, instrumentation, etc
Thermal Noise

• Position signal

\[ V_{dipole} = q x \sqrt{Z_0 \frac{k_{loss, TM11}}{2} \frac{\omega_0}{Q_L} \beta} \]

(1/2 is due to the power splitted to two pickups)

• Thermal Noise

\[ V_{therm} = \sqrt{Z_0 kT \Delta F} \]

• NS ratio

\[ \frac{V_{dipole}}{V_{therm}} = q x \sqrt{\frac{\pi}{kT} \frac{\beta}{1 + \beta}} k_{loss, TM11} \]

\[ \frac{V_{dipole}}{V_{therm}} = 0.7 / (nC \cdot nm) \]

\[ V_{dipole} = 0.78 \cdot 10^{-6} V / (nC \cdot nm) \]

cavity gap = 10mm, \( Q_L = 500 \)

\[ V_{therm} = 1.1 \cdot 10^{-6} V \]

at 300°K, \( \Delta F = 5.6MHz \)

\[ \begin{array}{|c|c|}
\hline
\text{Cavity gap (mm)} & \text{Kloss_11 (V/nC/mm^2)} \\
\hline
10.000 & 0.633 \\
15.000 & 0.998 \\
\hline
\end{array} \]
Mode Contamination

TM01/02 mode leakage

- Mechanical imperfection
- Evanescent coupling if coax adaptor too close to cavity
- Q finite, large tail signal at dipole frequency

![High Q TM01 mode](image1.png)

![Low Q TM01 mode](image2.png)
TM01 Leakage Due To Imperfection

- Azimuthal offset and azimuthal rotation of a waveguide cause TM01 to TE01 coupling
- Coupling mechanism for both type misalignments is similar
- The radial offset of waveguide is less important

- Consider the +x waveguide is off 0.5mm in the y direction
- The tail of the TM01 mode at the dipole frequency is still much smaller than dipole signal at 1nm beam offset
- The mechanical tolerance on waveguide position is reasonably loose

<table>
<thead>
<tr>
<th>F (GHz)</th>
<th>2.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kloss (V/nC)</td>
<td>150</td>
</tr>
<tr>
<td>Q0</td>
<td>1.0E+10</td>
</tr>
<tr>
<td>Qext (0.5mm offset)</td>
<td>5.0E+06</td>
</tr>
</tbody>
</table>

\[ V_{TM01}(2.856GHz) = 2.3 \times 10^{-8} \text{ V} \]

\[ V_{TM11} = 0.78 \times 10^{-6} \text{ V/(nC.nm)} \]
TM01 Leakage Due To Evanescent Coupling

• Coax adaptor is far from the cavity
• Evanescent coupling for the S-band prototype is negligible
• Need to evaluate if need more compact waveguide design
Wakefield

- Selective coupling result in high Qs of TM01/02 modes
- Wakefield damping needed
- Scheme
  - Coupling probes on cavity end wall?
  - Should not break mode symmetry
- How low should $Q_{\text{ext}}$ be? 1E+5?
Resolution Of The X-Band Design

<table>
<thead>
<tr>
<th>F (GHz)</th>
<th>Cavity gap (mm)</th>
<th>Rpipe (mm)</th>
<th>Kloss (V/nC/mm^2)</th>
<th>Theoretical Resolution (nm/nC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.856</td>
<td>10</td>
<td>17.81</td>
<td>0.63</td>
<td>1.5</td>
</tr>
<tr>
<td>2.856</td>
<td>15</td>
<td>17.81</td>
<td>1.00</td>
<td>1.2</td>
</tr>
</tbody>
</table>

- Assuming point charge
  - need to scale by the bunch spectrum for finite bunch length
- No cable attenuation included
- Assuming reasonable mechanical tolerance achieved
  (e.g. <0.5mm azimuthal offset for the waveguides)
# S-Band Cavity BPM Prototype

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (GHz)</td>
<td>2.856</td>
</tr>
<tr>
<td>External Q</td>
<td>553</td>
</tr>
<tr>
<td>Beam pipe radius (mm)</td>
<td>17.81</td>
</tr>
<tr>
<td>Cell radius (mm)</td>
<td>60.0</td>
</tr>
<tr>
<td>Cavity gap</td>
<td>10.0</td>
</tr>
<tr>
<td>Waveguide radial dimensions (mm)</td>
<td>70.0</td>
</tr>
<tr>
<td>Waveguide axial dimension (mm)</td>
<td>75.0</td>
</tr>
<tr>
<td>Waveguide height</td>
<td>10.0</td>
</tr>
</tbody>
</table>
Summary

• **S-band prototype cavity BPM was design for the ILC**
  – Selective coupling scheme to reject TM01 mode
  – Compact coupling waveguide to save space
  – Waveguide dipole like mode frequency was designed 1 GHz lower than the position dipole mode so can be filtered

• Much better than 1 micron resolution can be achieved

• Tolerance is reasonably loose

• Prototype dimensions are being finalized