RF DIPOLE
DEFLECTING/CRABBING CAVITIES

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Compact Deflecting/Crabbing Designs

- Operate in TE-like or TEM-like modes
  - 4-Rod Cavity (University of Lancaster / Jefferson Lab)
  - Parallel-Bar / RF-Dipole Cavity (ODU / SLAC)
  - Quarter Wave Cavity (BNL)

- RF Dipole design has
  - Low surface fields and high shunt impedance
  - Good balance between peak surface electric and magnetic field
  - No LOMs
  - Nearest HOM is widely separated (~ 1.5 fundamental mode)
  - Good uniformity of deflecting field due to high degree symmetry
Current Applications of RF Dipole Cavity

**499 MHz Deflecting Cavity for Jefferson Lab 12 GeV Upgrade**

- Deflecting voltage – 5.6 MV

**400 MHz Crabbing Cavity for LHC High Luminosity Upgrade**

- Crabbing voltage – 10 MV per beam per side
- Requires a crabbing system at two interaction points (IP1 and IP5)
  - Vertical crossing at IP1
  - Horizontal crossing at IP5

**750 MHz Crabbing Cavity for MEIC**

- Crabbing voltage
  - Electron beam – 1.5 MV
  - Proton beam – 8.0 MV

RF Dipole Cavity

- Operates in a TE-like mode (cannot be a pure TE mode – Panofsky Wenzel Theorem)
- Deflecting/Crabbing mode is the lowest operating mode
- Net deflection is mainly due to the transverse electric field
- Transverse voltage

\[ V_t = \int_{-\infty}^{+\infty} \left( E_x(z) \cos \left( \frac{\omega z}{c} \right) + cB_y \sin \left( \frac{\omega z}{c} \right) \right) \, dz. \]
Characteristics of the RF-Dipole Cavity

- Properties depend on a few parameters
  - Frequency determined by diameter of the cavity design
  - Bar Length $\sim \lambda/2$
  - Bar height and aperture determine $E_P$ and $B_P$
  - Angle determines $B_P/E_P$

![Diagram of a RF-Dipole Cavity with parameters](image)

<table>
<thead>
<tr>
<th>Bar Height (mm)</th>
<th>$B_P/E_P$ (mT/(MV/m))</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>1.5</td>
</tr>
<tr>
<td>60</td>
<td>1.75</td>
</tr>
<tr>
<td>70</td>
<td>2.0</td>
</tr>
<tr>
<td>80</td>
<td>2.2</td>
</tr>
<tr>
<td>90</td>
<td>2.2</td>
</tr>
<tr>
<td>100</td>
<td>2.2</td>
</tr>
<tr>
<td>110</td>
<td>2.2</td>
</tr>
<tr>
<td>120</td>
<td>2.2</td>
</tr>
</tbody>
</table>
RF-Dipole Square Cavity Options

- Square-type rf-dipole cavity to further reduce the transverse dimensions
- Frequency is adjusted by curving radius of the edges
- RF-dipole cavity with modified curved loading elements across the beam aperture to reduce field non-uniformity

- Voltage deviation at 20 mm
  - Horizontal: 5.0% → 0.2%
  - Vertical: 5.5% → 2.4%

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Height and Width < 145 mm
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400 MHz Crabbing Cavity

\[ \delta V_T / V_T \]

\[ \text{Offset (mm)} \]

\[ 0 \ 2 \ 4 \ 6 \ 8 \ 10 \ 12 \ 14 \ 16 \ 18 \ 20 \]

\[ -0.06 \ -0.04 \ -0.02 \ 0 \ 0.02 \ 0.04 \ 0.06 \]

- Design (A) in x
- Design (B) in x
- Design (A) in y
- Design (B) in y
## RF-Dipole Cavity Designs

<table>
<thead>
<tr>
<th>Frequency</th>
<th>499.0</th>
<th>400.0</th>
<th>750.0*</th>
<th>MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aperture Diameter (d)</td>
<td>40.0</td>
<td>84.0</td>
<td>60.0</td>
<td>mm</td>
</tr>
<tr>
<td>d/(λ/2)</td>
<td>0.133</td>
<td>0.224</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td>LOM</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>MHz</td>
</tr>
<tr>
<td>Nearest HOM</td>
<td>777.0</td>
<td>589.5</td>
<td>1062.5</td>
<td>MHz</td>
</tr>
<tr>
<td>$E_p^*$</td>
<td>2.86</td>
<td>3.9</td>
<td>4.29</td>
<td>MV/m</td>
</tr>
<tr>
<td>$B_p^*$</td>
<td>4.38</td>
<td>7.13</td>
<td>9.3</td>
<td>mT</td>
</tr>
<tr>
<td>$B_p^<em>/E_p^</em>$</td>
<td>1.53</td>
<td>1.83</td>
<td>2.16</td>
<td>mT/(MV/m)</td>
</tr>
<tr>
<td>$[R/Q]_T$</td>
<td>982.5</td>
<td>287.2</td>
<td>125.0</td>
<td>Ω</td>
</tr>
<tr>
<td>Geometrical Factor ($G$)</td>
<td>105.9</td>
<td>138.7</td>
<td>136.0</td>
<td>Ω</td>
</tr>
<tr>
<td>$R_TR_S$</td>
<td>$1.0 \times 10^5$</td>
<td>$4.0 \times 10^4$</td>
<td>$1.7 \times 10^4$</td>
<td>$\Omega^2$</td>
</tr>
</tbody>
</table>

At $E_T^* = 1$ MV/m

* Alex Castilla (ODU)
HOM Properties of the RF-Dipole Cavity

- Widely separated Higher Order Modes
- No Lower Order Modes

499 MHz Deflecting Cavity

750 MHz Crabbing Cavity

400 MHz Crabbing Cavity
Wakefield and Impedance

- T3P – EM Time Domain Solver in the SLAC ACE3P Suite
- For the 400 MHz crabbing cavity
- Bunch Parameters
  - $\sigma = 1.4$ cm
  - charge = 1 pC

$$\lambda(s) = \frac{1}{\sigma \sqrt{2\pi}} \exp\left[-\frac{(s-s_0)^2}{2\sigma^2}\right]$$

- Two bunches at an offset of ±5 mm in horizontal direction
- Excites deflecting modes
- On axis single bunch
- Excites accelerating modes
HOM Damping

- Widely separated HOMs from the operating mode allows more options in the design of damping schemes

**Waveguide Damping**
- Strong damping was achieved with waveguide couplers

**Coaxial Coupling**
- A high pass coaxial couplers to exclude the operating mode

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Multipacting Analysis

- Track3P – Particle tracking code in the SLAC ACE3P Suite
- For the 400 MHz square-shaped crabbing cavity

Deflecting Voltage

- 0.5MV to 2.6 MV
- 1.8 MV to 2.8MV
- 3.0 MV to 6.0 MV
Mechanical Analysis – 499 MHz Cavity

- Without any kind of stiffening or pressure sensitivity optimization

### Pressure
- Pressure sensitivity - 212 Hz/torr

**Lorentz Detuning**

Room temperature cavity with a uniform 3 mm thickness
- $\Delta f = 6.15$ kHz @ $V_T = 3.0$ MV
- $k_L = 61.54$ Hz/(MV/m)$^2$

Fabricated cavity at 4 K
- $\Delta f = 4.93$ kHz @ $V_T = 3.0$ MV
- $k_L = 49.27$ Hz/(MV/m)$^2$
- Deformation = 1.2 $\mu$m

**Frequency Variation**

- $497.81$ MHz

**Mechanical Modes**

- Cavity with a 3 mm uniform thickness
- At room temperature and under vacuum

**Coupler Port**

**Outer Conductor**

**Slope**
Tuning Sensitivity – 499 MHz Cavity

- Cavity as fabricated at 4 K under vacuum
- Tuning sensitivity – 1.4 kHz/μm
499 MHz RF-Dipole Cavity Fabrication
400 & 750 MHz RF-Dipole Cavity Fabrication

400 MHz Crabbing Cavity

750 MHz Crabbing Cavity

11°

32°
## Properties of Cavities Under Development

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Alex Castilla (ODU)</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>400.0 499.0 750.0</td>
<td>MHz</td>
</tr>
<tr>
<td>Particle</td>
<td>p e- e- p</td>
<td></td>
</tr>
<tr>
<td>Deflecting voltage ($V_T^-$)</td>
<td>0.375 0.3 0.2</td>
<td>MV</td>
</tr>
<tr>
<td>Peak electric field ($E_P^-$)</td>
<td>3.9 2.86 4.29</td>
<td>MV/m</td>
</tr>
<tr>
<td>Peak magnetic field ($B_P^-$)</td>
<td>7.13 4.38 9.3</td>
<td>mT</td>
</tr>
<tr>
<td>Required transverse voltage per beam</td>
<td>10.0 5.6 1.5 8.0</td>
<td>MV</td>
</tr>
<tr>
<td>No. of cavities</td>
<td>3 2 1 4</td>
<td></td>
</tr>
<tr>
<td>Transverse voltage per cavity</td>
<td>3.4 3.0 1.5 2.0</td>
<td>MV</td>
</tr>
<tr>
<td>Peak magnetic field ($B_P$)</td>
<td>64.7 43.8 69.8 93.0</td>
<td>mT</td>
</tr>
<tr>
<td>Peak electric field ($E_P$)</td>
<td>35.4 28.6 32.2 42.9</td>
<td>MV</td>
</tr>
<tr>
<td>$R_TR_S$</td>
<td>3.7×10^4 3.6×10^4 3.7×10^4</td>
<td>Ω²</td>
</tr>
<tr>
<td>Operating temperature</td>
<td>2.0 4.0 2.0 4.0 2.0 4.0 2.0 4.0</td>
<td>K</td>
</tr>
<tr>
<td>Surface Resistance ($R_S$) **</td>
<td>11.3 70.0 12.0 100.0 14.0 200.0 14.0 200.0</td>
<td>nΩ</td>
</tr>
<tr>
<td>Power dissipation per cavity **</td>
<td>3.6 21.9 3.0 25.0 0.9 12.2 1.6 21.7</td>
<td>W</td>
</tr>
<tr>
<td>At $E_T^-$ = 1 MV/m</td>
<td>** Estimated</td>
<td></td>
</tr>
</tbody>
</table>
Summary

- Development of compact deflecting/crabbing cavities was in response to the strict dimensional requirements in some current applications

- Compact rf-dipole design has
  - Low and balanced surface fields
  - High shunt impedance
  - Has no lower-order-mode with a well-separated fundamental mode

- Work in progress
  - 499 MHz deflecting cavity
    • Fabrication will be completed by Nov-Dec
  - 400 MHz crabbing cavity
    • Preparation for processing
    • Bulk BCP – Fixtures and parts are being fabricated for both cavities (Nov-Dec)
  - 750 MHz crabbing cavity
    • Cavity processed with bulk BCP of 150 μm
Acknowledgements

- Jefferson Lab
  - HyeKyoung Park
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- Niowave
  - Dmitry Gorelov, Terry Grimm

The work done at ODU is towards my PhD carried out under the supervision of Dr. Jean Delayen
**Design Evolution**

- To increase mode separation between fundamental modes
- $\sim 18 \text{ MHz} \rightarrow \sim 130 \text{ MHz}$
- To improve design rigidity $\rightarrow$ Less susceptible to mechanical vibrations and deformations

- To lower peak magnetic field
- Reduced peak magnetic field by $\sim 20\%$
Design Evolution

TEM-type mode

• To remove higher order modes with field distributions between the cavity outer surface and bar outer surface
• Eliminate multipacting conditions

TE-like mode

Balanced Peak Fields

\[
\frac{B_p}{E_p} \leq 2.0 \text{ mT/(MV/m)}
\]

• To lower peak magnetic field
• Reduced peak magnetic field by ~25%
• To achieve balanced peak surface fields
• \( B_p/E_p \approx 1.5 \text{ mT/(MV/m)} \)
Stress Analysis – 499 MHz Cavity

A: YTA Cool down (Room Temp 1.4 atm)
Equivalent Stress
Type: Equivalent (von-Mises) Stress
Unit: MPa
Time: 1

- 38.631 Max
- 34.348
- 30.065
- 25.782
- 21.499
- 17.216
- 12.933
- 8.6505
- 4.3676
- 0.084744 Min

F: YTA Test condition (4K 1 atm)
Equivalent Stress
Type: Equivalent (von-Mises) Stress
Unit: MPa
Time: 1

- 27.585 Max
- 24.526
- 21.468
- 18.41
- 15.352
- 12.294
- 9.2353
- 6.1771
- 3.1189
- 0.060644 Min

- Fixed support from the top
- Pressure = 0.14186 MPa
- With standard earth gravity