COMPACT SUPERCONDUCTING CRABBING AND DEFLECTING CAVITIES

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Introduction

• New geometries for compact superconducting crabbing and deflecting cavities have been developed

• They have significantly improved properties over those of the standard $TM_{110}$–type cavities
  – They are smaller
  – Have low surface fields
  – High shunt impedance
  – Some of the designs have no lower-order-mode with a well-separated fundamental mode
Crabbing/Deflecting Cavity Applications

• Luminosity management in linear or circular colliders
• Separation or merge of multiple beams
• Emittance exchange in beams
• X-ray pulse compression
• Beam diagnostics
The 1st Superconducting RF Deflecting Cavity

2.865 GHz Karlsruhe/CERN RF Separator*

- 104 cells
- At IHEP since 1998
- Operating mode: bi-periodic TM$_{110}$ mode

* A. Citron et al., NIM 164, 31-55, (1979)
The 1st Superconducting Crabbing Cavity

Operating mode: TM\textsubscript{110} mode
Required transverse deflection: 1.44 MV
Operation: 2007-2010

KEK Crabbing Cavity

<table>
<thead>
<tr>
<th>Frequency</th>
<th>LOM</th>
<th>Nearest HOMs</th>
</tr>
</thead>
<tbody>
<tr>
<td>508.9 MHz</td>
<td>410.0 MHz</td>
<td>630.0, 650.0, 680.0 MHz</td>
</tr>
</tbody>
</table>

| $E_p^*$ | 4.24 MV/m |
| $B_p^*$ | 12.23 mT |
| $B_p^*/E_p^*$ | 2.88 mT/(MV/m) |
| $[R/Q]_T$ | 48.9 Ω |
| Geometrical Factor ($G$) | 227.0 Ω |
| $R_T R_S$ | 1.11×10^4 Ω^2 |

At $E_T^* = 1$ MV/m

- Operating mode: TM\textsubscript{110} mode
- Required transverse deflection: 1.44 MV
- Operation: 2007-2010

Potential Applications of Compact Superconducting Deflecting/ Crabbing Cavities

499 MHz Deflecting Cavity for Jefferson Lab 12 GeV Upgrade

400 MHz Crabbing Cavity for LHC High Luminosity Upgrade

- Requires a crabbing system at two interaction points (IP1 and IP5)
  - Vertical crossing at IP1
  - Horizontal crossing at IP5

Deflecting Cavity for Project–X*

- Bunch frequency \( f_0 = 162.5 \text{ MHz} \)
- Deflecting cavity frequency = \( f_0 \times (m \pm 1/4) \)
- Frequency options:
  - \( m=2 \rightarrow f_0 \times (m+1/4) = 365.625 \text{ MHz} \)
  - \( m=3 \rightarrow f_0 \times (m-1/4) = 446.875 \text{ MHz} \)

How To Achieve Compact Designs

• Karlsruhe/CERN deflector and KEK crabbing cavity used magnetic field
  – Operating in $TM_{110}$ mode which is not the lowest mode

• Current compact designs use electric field or both electric and magnetic fields
  – TEM-like designs
  – TE-like designs

• Compact superconducting crabbing/deflecting cavity designs
  – University of Lancaster / Jefferson Lab – 4-Rod Cavity
  – BNL – Quarter Wave Cavity
  – ODU/SLAC – Parallel-Bar Cavity and RF-Dipole Cavity
4-Rod Cavity

- 499 MHz normal conducting rf separator* at Jefferson Lab
- High shunt impedance

- Operates in a TEM-like mode
  - Uses both electric field and magnetic field
  - Deflecting mode is not the lowest mode

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Accelerating lower order mode

Fundamental deflecting mode

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4-Rod Cavity (U. Lancaster/Jefferson Lab)

- 400 MHz superconducting 4-rod cavity*
- Rod shaping
  - To reduce surface electric and magnetic fields
  - To reduce offset field non-uniformities

*B. Hall, “LHC-4R Crab Cavity”, EUCARD SRF Annual Review, March 2012
Lower and Higher Order Modes of the 4-Rod Cavity

Lower Order Monopole Mode – 374.9 MHz

3\pi/4 Higher Order Monopole Mode

3\pi/4 Higher Order Dipole Mode
## 4-Rod Cavity Properties

<table>
<thead>
<tr>
<th>Frequency</th>
<th>400.0</th>
<th>MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOM</td>
<td>375.2</td>
<td>MHz</td>
</tr>
<tr>
<td>Nearest HOMs</td>
<td>436.6, 452.1</td>
<td>MHz</td>
</tr>
<tr>
<td>$E_p^*$</td>
<td>4.0</td>
<td>MV/m</td>
</tr>
<tr>
<td>$B_p^*$</td>
<td>7.56</td>
<td>mT</td>
</tr>
<tr>
<td>$B_{p^<em>}/E_{p^</em>}$</td>
<td>1.89</td>
<td>mT/(MV/m)</td>
</tr>
<tr>
<td>$[R/Q]_T$</td>
<td>915.0</td>
<td>Ω</td>
</tr>
<tr>
<td>Geometrical Factor ($G$)</td>
<td>70.35</td>
<td>Ω</td>
</tr>
<tr>
<td>$R_TR_S$</td>
<td>6.4×10^4</td>
<td>Ω²</td>
</tr>
</tbody>
</table>

At $E_T^* = 1$ MV/m

**Surface Electric Field**

**Surface Magnetic Field**
Quarter-Wave Cavity (BNL)

100 MHz ¼-Wave Cavity

- Attractive at low frequencies
- Strong reentrant form makes the field pattern at the outer radius predominately TEM

400 MHz superconducting asymmetric ¼-wave cavity

*E. Haebel, “Superconducting Cavities and Minimum RF Power Schemes for LHC”, CERN/EF/RF 84-4

181 MHz ¼-wave cavity for eRHIC#

Quarter-Wave Cavity

- Two design options at 400 MHz
- Asymmetric cavity*
  - $V_{acc} = 0.12$ MV at $V_t = 3.0$ MV
  - Higher mode separation between fundamental mode and nearest HOM
- Symmetric cavity (similar to rf-dipole cavity)
  - $V_{acc} = 0$ V
  - Better field non-uniformity

<table>
<thead>
<tr>
<th></th>
<th>Asymmetric Cavity</th>
<th>Symmetric Cavity</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOM</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>Nearest HOM</td>
<td>657 MHz</td>
<td>582 MHz</td>
</tr>
<tr>
<td>$E_p^*$</td>
<td>5.38 MV/m</td>
<td>4.04 MV/m</td>
</tr>
<tr>
<td>$B_p^*$</td>
<td>7.6 mT</td>
<td>7.2 mT</td>
</tr>
<tr>
<td>$B_p^<em>/E_p^</em>$</td>
<td>1.42 mT/(MV/m)</td>
<td>1.77 mT/(MV/m)</td>
</tr>
<tr>
<td>$[R/Q]_T$</td>
<td>344.0 Ω</td>
<td>401.1 Ω</td>
</tr>
<tr>
<td>Geometrical Factor ($G$)</td>
<td>131.0 Ω</td>
<td>82.4 Ω</td>
</tr>
<tr>
<td>$R_T R_S$</td>
<td>$4.5 \times 10^4$</td>
<td>$3.3 \times 10^4$</td>
</tr>
</tbody>
</table>

At $E_T^* = 1$ MV/m

Higher Order Modes of the ¼-Wave Cavity

- No Lower Order Modes
- Hybrid modes with both deflection and acceleration

Parallel-Bar Cavity to RF-Dipole Cavity (ODU)

499 MHz Deflecting Cavity

TEM-type mode

TE-like mode

E Field

H Field

Surface E Field

Surface H Field

Design Evolution of the 499 MHz Deflecting Cavity

- To increase mode separation between fundamental modes
  - $\sim 18$ MHz $\rightarrow$ $\sim 130$ 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 of the 499 MHz Deflecting Cavity

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

- To lower peak magnetic field
- Reduced peak magnetic field by ~25%
- To achieve balanced peak surface fields
  - $B_p/E_p \approx 1.5 \text{ mT}/(\text{MV/m})$

Balanced Peak Fields

$$\frac{B_p}{E_p} \leq 2.0 \text{ mT}/(\text{MV/m})$$
**Ridged Waveguide Cavity (SLAC)**

- 400 MHz Crabbing Cavity*
- Operating at a TE$_{11}$-like mode

<table>
<thead>
<tr>
<th>Frequency</th>
<th>400.0</th>
<th>MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOM</td>
<td>None</td>
<td>MHz</td>
</tr>
<tr>
<td>Nearest HOM</td>
<td>617.0</td>
<td>MHz</td>
</tr>
<tr>
<td>$E_p^*$</td>
<td>3.38</td>
<td>MV/m</td>
</tr>
<tr>
<td>$B_p^*$</td>
<td>7.05</td>
<td>mT</td>
</tr>
<tr>
<td>$B_p^<em>/E_p^</em>$</td>
<td>2.09</td>
<td>mT/(MV/m)</td>
</tr>
<tr>
<td>$[R/Q]_T$</td>
<td>330.0</td>
<td>Ω</td>
</tr>
</tbody>
</table>

At $E_T^* = 1$ MV/m

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 $B_P/E_P$

• 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 ( $\sim 1.5$ fundamental mode)
  – Good uniformity of deflecting field due to high degree symmetry
Optimization of Bar Shape of the RF-Dipole Cavity

Bar Height
- 50 mm
- 60 mm
- 70 mm
- 80 mm
- 90 mm
- 100 mm
- 110 mm
- 120 mm

499 MHz Deflecting Cavity

$B_p / E_p = 2.0 \text{ mT/(MV/m)}$
$B_p / E_p = 1.75 \text{ mT/(MV/m)}$
$B_p / E_p = 1.5 \text{ mT/(MV/m)}$

$E_p / E_t$ vs. $B_p / E_t$

Bar Height =
- 4.0
- 4.5
- 5.0
- 5.5
- 6.0
- 6.5
- 7.0
- 7.5

$B_p / E_p$ (mT/(MV/m))

$E_p / E_t$
# 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>
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<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>Ω²</td>
</tr>
</tbody>
</table>

At $E_T^* = 1$ MV/m

- **499 MHz Deflecting Cavity for Jefferson Lab 12 GeV Upgrade**
  - Aperture Diameter: 44 cm
- **400 MHz Crabbing Cavity for LHC High Luminosity Upgrade**
  - Aperture Diameter: 34 cm
- **750 MHz Crabbing Cavity for MEIC at Jefferson Lab**
  - Aperture Diameter: 19 cm

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

Height and Width < 145 mm
HOM Properties of the RF-Dipole Cavity

• Widely separated Higher Order Modes
• No Lower Order Modes

499 MHz Deflecting Cavity

E field
H field
LOM and HOM Damping

4-Rod Cavity*

¼-Wave Cavity*

RF-Dipole Cavity*

Magnetic loop-type HOM couplers

Coaxial two-stage high-pass filter coupler

*Presented at LARP CM 18 / HiLumi LHC Meeting, Fermilab, May 2012
Multipacting Analysis

4-Rod Cavity*

- Soft multipactor barriers were found in the cavity above 0.5 MV
- No Hard barriers were found
- Multipacting on the beam pipe was found on the beam pipe at ~1.6MV

¼-Wave Cavity*

RF-Dipole Cavity*

Resonant Particles Distribution at 0.6MV

*Presented at LARP CM 18 / HiLumi LHC Meeting, Fermilab, May 2012
Field Non-Uniformity

- **Shaped rods**
  - To reduce filed non-uniformity across the beam aperture
  - Suppress higher order multipole components

**4-Rod Cavity**

- **Voltage deviation at 20 mm**
  - Horizontal: 6.2% → 1.5%
  - Vertical: 25.3% → 0.6%

**RF-Dipole Cavity**

- **Voltage deviation at 20 mm**
  - Horizontal: 5.0% → 0.2%
  - Vertical: 5.5% → 2.4%
400 MHz 4-Rod Cavity Fabrication
499 MHz RF-Dipole Cavity Fabrication
400 MHz RF-Dipole Cavity Fabrication

[Images of various components of a 400 MHz RF-Dipole Cavity Fabrication process]
## Summary

<table>
<thead>
<tr>
<th></th>
<th>KEK Crabbing Cavity</th>
<th>RF-Dipole Cavity</th>
<th>RF-Dipole Cavity</th>
<th>4-Rod Cavity</th>
<th>Asymmetric ¼-Wave Cavity</th>
<th>Symmetric ¼-Wave Cavity</th>
<th>Units</th>
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<tbody>
<tr>
<td>Frequency</td>
<td>508.9 MHz</td>
<td>499.0 MHz</td>
<td>400.0 MHz</td>
<td>400.0 MHz</td>
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<td>MHz</td>
</tr>
<tr>
<td>Aperture Diameter (d)</td>
<td>100.0 mm</td>
<td>40.0 mm</td>
<td>84.0 mm</td>
<td>84.0 mm</td>
<td>84.0 mm</td>
<td>84.0 mm</td>
<td>mm</td>
</tr>
<tr>
<td>d/(λ/2)</td>
<td>0.34</td>
<td>0.13</td>
<td>0.22</td>
<td>0.22</td>
<td>0.22</td>
<td>0.22</td>
<td></td>
</tr>
<tr>
<td>LOM</td>
<td>410.0 MHz</td>
<td>None</td>
<td>None</td>
<td>375.2 MHz</td>
<td>None</td>
<td>None</td>
<td>MHz</td>
</tr>
<tr>
<td>Nearest HOM</td>
<td>630.0 MHz</td>
<td>777.0 MHz</td>
<td>589.5 MHz</td>
<td>436.6 MHz</td>
<td>657.0 MHz</td>
<td>577.8 MHz</td>
<td>MHz</td>
</tr>
<tr>
<td>$E_p^*$</td>
<td>4.24</td>
<td>2.86</td>
<td>3.9</td>
<td>4.0</td>
<td>5.38</td>
<td>4.04</td>
<td>MV/m</td>
</tr>
<tr>
<td>$B_p^*$</td>
<td>12.23</td>
<td>4.38</td>
<td>7.13</td>
<td>7.56</td>
<td>7.6</td>
<td>7.2</td>
<td>mT</td>
</tr>
<tr>
<td>$B_p^<em>/E_p^</em>$</td>
<td>2.88</td>
<td>1.53</td>
<td>1.83</td>
<td>1.89</td>
<td>1.42</td>
<td>1.77</td>
<td>mT/(MV/m)</td>
</tr>
<tr>
<td>$[R/Q]_T$</td>
<td>48.9</td>
<td>982.5</td>
<td>287.2</td>
<td>915.0</td>
<td>344.0</td>
<td>401.1</td>
<td>Ω</td>
</tr>
<tr>
<td>Geometrical Factor (G)</td>
<td>227.0</td>
<td>105.9</td>
<td>138.7</td>
<td>70.35</td>
<td>131.0</td>
<td>82.4</td>
<td>Ω</td>
</tr>
<tr>
<td>$R_TR_S$</td>
<td>$1.1 \times 10^4$</td>
<td>$1.0 \times 10^5$</td>
<td>$4.0 \times 10^4$</td>
<td>$6.4 \times 10^4$</td>
<td>$4.5 \times 10^4$</td>
<td>$3.3 \times 10^4$</td>
<td>Ω²</td>
</tr>
</tbody>
</table>

At $E_T^* = 1$ MV/m
Summary

• The development of compact deflecting/crabbing cavities was in response to the strict dimensional requirements in some current applications

• All these compact designs have attractive properties in meeting the requirements
  – Low and balanced surface fields
  – High shunt impedance
  – Some of the designs have no lower-order-mode with a well-separated fundamental mode

• HOM damping, multipacting and mechanical analysis have been addressed

• Most of the compact designs are currently being fabricated and prototype testing is underway
ACKNOWLEDGEMENTS

• Jefferson Lab
  – HyeKyoung Park
• ODU
  – Alejandro Castilla
• SLAC
  – Zenghai Li, Lixin Ge
• Niowave
  – Dmitry Gorelov, Terry Grimm
• The work done at ODU is towards my PhD carried out under the supervision of Dr. Jean Delayen

• CERN
  – Rama Calaga
• University of Lancaster
  – Graeme Burt, Ben Hall
• BNL
  – Ilan Ben-Zvi, Qiong Wu

THANK YOU
Mechanical Analysis

4-Rod Cavity* ~ 1mm displacement for 4mm thickness
~ 0.1mm displacement for 4mm thickness

¼-Wave Cavity* Vibration of flat surfaces and/or change in ellipticity ~ MHz/mm (constrain with stiffeners)

Pressure sensitivity - 212 Hz/torr

Baseline Cavity (No stiffeners)

Frequency (Hz)
498.04E+06
498.02E+06
498.00E+06
497.98E+06
497.96E+06
497.94E+06
497.92E+06
497.90E+06
497.88E+06
497.86E+06
497.84E+06

External Pressure (Pa)

RF-Dipole Cavity*
Beam Aperture Dependence

At 499 MHz
Beam Aperture Dependence

At 499 MHz

\[ R_T R_S = \left[ \frac{R}{Q} \right] Q R_S \]

\[ = \left[ \frac{R}{Q} \right] G \]
Transverse Voltage

- Lorentz Force
  \[ \vec{F} = \frac{d\vec{p}}{dt} = q[\vec{E} + \vec{v} \times \vec{B}] \]

- Transverse Voltage experienced by a particle
  \[ V_T = \left| \int_{-\infty}^{\infty} \left[ \vec{E}_T(z) + i \left( \vec{v} \times \vec{B}(z) \right)_T \right] e^{i\omega z} dz \right| \]

- Panofsky Wenzel Theorem
  \[ V_T = \frac{-i}{\omega / c} \nabla_T V_Z = \frac{-i}{\omega / c} \frac{1}{r_0} \left| \int_{-\infty}^{\infty} \vec{E}_Z(r_0, z) e^{i\omega z} dz \right| \]
- **Longitudinal \([R/Q]\)**
  
  \[
  \left[ \frac{R}{Q} \right] = \left| \frac{V_z}{\omega U} \right|^2 = \left[ \int_{-\infty}^{\infty} E_z(z, x = 0) e^{j\omega z} dz \right]^2
  \]

- **Transverse \([R/Q]\)**
  - **Direct Integral Method**
    
    \[
    \left[ \frac{R}{Q} \right]_T = \left| \frac{V_z}{\omega U} \right|^2 = \left[ \int_{-\infty}^{\infty} \left[ \mathcal{E}_x(z, x = 0) + j \left( \mathbf{v} \times \mathbf{B}_y(z, x = 0) \right) \right] e^{j\omega z} dz \right]^2
    \]
  
  - **Using Panofsky Wenzel Theorem \((x_0=5 \text{ mm})\)**
    
    \[
    \left[ \frac{R}{Q} \right]_T = \left| \frac{V_z(x = x_0)}{\omega U} \right|^2 = \left[ \int_{-\infty}^{\infty} E_z(z, x = x_0) e^{j\omega z} dz \right]^2 = \left[ \int_{-\infty}^{\infty} \frac{1}{(kx_0)^2} e^{j\omega z} dz \right]^2 = \left( \frac{\omega}{c} \right)^2
    \]
    
    \[
    k = \frac{\omega}{c}
    \]