Abstract
Recently, new geometries for superconducting crabbing and deflecting cavities have been developed that have significantly improved properties over those of the standard TM$_{110}$ cavities. They are smaller, have low surface fields, high shunt impedance and, more importantly for some of them, no lower-order modes with a well-separated fundamental mode. This talk will present the status of the development of these cavities.

INTRODUCTION
Primarily the crabbing and deflecting structures are used to restore luminosity in particle colliders or in separating a single beam into multiple beams. The crabbing concept was initially proposed by R.B. Palmer for collider rings [1] and was later proven for linear colliders [2] as well. The applications of crabbing and deflecting cavities are not limited to the above-mentioned applications but also can be used in many applications for beam diagnostics, emittance exchange, in generating compressed x-ray beams etc. Some of the potential applications at present are the deflecting cavity needed for the Jefferson Lab 12 GeV upgrade [3] to separate the maximum energy beam into the three experimental halls and the deflecting cavity system required for the multi experimental project under Project-X [4]. One of the crabbing applications is the LHC luminosity upgrade that requires a crabbing system for vertical and horizontal crossing at the integrations regions of IP$_1$ and IP$_5$ [5].

The stringent dimensional constraints set by these current applications especially operating at low frequencies demands the design and development of compact crabbing and deflecting cavities. Compared to the crabbing and deflecting cavities operating in TM$_{110}$ these compact designs that has been developed have improved properties with low surface fields, high shunt impedance. Most of the designs have no lower order modes (LOMs) with a widely separated higher order mode (HOM) spectrum.

The First Superconducting Crabbing Cavity

The early research in superconducting crabbing and deflecting structures was done in 1970s where the first superconducting rf deflecting cavity as shown in Fig. 1 was designed and developed in KfK, Karlsruhe in collaboration with CERN [6]. The 2.865 GHz, 104-cell cylindrical-shaped standing wave rf particle separator shown in Fig. 1 installed at CERN in 1977 was capable of delivering a deflection in the vertical plane. The rf separator driven at 1.8 K, in a bi-periodic TM$_{110}$-type mode (Fig. 1) was in operation until 1981.

The First Superconducting Deflecting Cavity

The first crabbing cavity system was developed and installed in 2007 at KEK [7] for the KEKB electron-positron collider. The crabbing cavity shown in Fig. 2, operating in TM$_{110}$ mode at 508.9 MHz was the only crabbing cavity system that has been in operation in a particle collider until 2010 after the installation in 2007.
The KEK crabbing cavity has a squashed elliptical geometry in order to separate the two polarizations of the TM$_{110}$ mode. Since the TM$_{110}$ mode is not the lowest mode in the cavity the crabbing cavity system has larger dimensions to that of a TM$_{010}$ mode of the same frequency and was also required to have a complex higher order mode (HOM) damping scheme in order to damp the lower order mode (LOM) and near by HOMs that were close to the operating crabbing mode. The properties of the KEK crabbing cavity are listed in Table 1. The squashed elliptical geometry at 508.9 MHz operating frequency has higher surface magnetic fields with low shunt impedance.

**COMPACT CAVITY DESIGNS**

The standard crabbing and deflecting cavities with elliptical geometries operate in TM$_{110}$ mode, which is not the lowest mode in these geometries. Also the squashed elliptical have very large structures at low frequencies. The current compact designs operate in TE or TEM like modes, where the deflection is given by either the electric field or by both the electric and magnetic fields. Some of those compact superconducting crabbing and deflecting cavity designs are:

- 4-Rod Cavity by University of Lancaster and Jefferson Lab
- Quarter-Wave Cavity by Brookhaven National Laboratory
- Parallel-Bar Cavity/RF-Dipole Cavity by Old Dominion University and SLAC Accelerator National Laboratory

**4-Rod Cavity - U. of Lancaster/ Jefferson Lab**

The 400 MHz superconducting 4-rod crabbing cavity [8] is an adaptation of the 499 MHz normal conducting rf separator designed by C. Leemann and C.G. Yao at Jefferson Lab for separating the 6 GeV beam into the three experimental halls in the beam switchyard area [8]. The rf separator is a two cell design as shown in Fig. 3, with each cell of ~λ/2 length and diameter.

![Figure 3: Normal conducting 499 MHz 4-rod rf separator cavity at Jefferson Lab.](image)

The normal conducting 4-rod cavity has a rod configuration that gives 4 fundamental modes, with the electric field configuration shown in Fig. 4. The top left field configuration corresponds to the accelerating mode, which is the lowest mode in the design. The next mode is the deflecting/crabbing mode with the field configuration shown in bottom left of Fig. 4 with the magnetic field circulating around the rods near the end plates. In this geometry both electric and magnetic fields contribute to the net deflection.

![Figure 4: Electric field configuration of the 4 fundamental modes in the 4-rod geometry.](image)

The superconducting 4-rod cavity design (Fig. 5) [9] adapted from the normal conducting design has improved bar geometry and outer conductor that gives a compact design with low surface electric and magnetic fields. The rods are further curved to suppress the higher order multipole components in the cavity.

![Figure 5: Superconducting 400 MHz 4-rod cavity design from University of Lancaster/Jefferson Lab.](image)

The properties of the superconducting 4-rod cavity are shown in Table 1. This design has very high transverse [R/Q] therefore high shunt impedance compared to other compact crabbing and deflecting cavities. However the LOM at 375 MHz present close to the fundamental operating mode and the low separation between the operating mode and the next HOM as shown in the HOM spectrum in Fig. 6 require a complex damping scheme in order to damp these modes. The compact crabbing and deflecting structures have a HOM configuration with modes giving a net deflection in horizontal direction or in vertical direction and accelerating modes as shown in Fig. 6. Additionally in the 4-rod cavity there are no hybrid modes present in the geometry.
Quarter-Wave Cavity - BNL

The standard quarter-wave cavity is modified into a crabbing and deflecting cavity utilizing the strong reentrant shape that gives a TEM field configuration near the outer conductor [10]. However the quarter-wave cavities have a strong on axis longitudinal electric field component that gives rise to an accelerating mode, present within the fundamental deflecting/crabbing mode. The quarter-wave design is modified with a pedestal at the bottom of the cavity to suppress the accelerating field component as shown in Fig. 7 [11]. The length of the longer pedestal at the top of cavity controls the frequency of the design. As shown in Fig. 7 the quarter-wave geometry at 400 MHz is optimized to reduce the surface fields and minimize the longitudinal accelerating component present in the cavity.

Parallel-Bar and RF-Dipole Cavity - ODU/SLAC

The parallel-bar cavity [13] with a rectangular outer conductor with cylindrical-shaped bars operating in a TEM-like mode is being evolved into a cylindrical-shaped design with trapezoidal-shaped bar geometry [14] (Fig. 11). The latter design named rf-dipole cavity operates in a TE_{11}-like mode, where the main contribution to the net deflection is given by the transverse electric field.

A similar design was proposed by Zenghai Li at SLAC named the ridged waveguide cavity as shown in Fig. 12 [11] operates in TE_{11}-like mode. Currently ODU and SLAC are collaborating on designing a 400 MHz compact crabbing cavity. Currently the rf-dipole cavity is considered as the 499 MHz rf separator for the Jefferson Lab 12 GeV upgrade, as one of the crabbing cavity.
Table 1: Properties of superconducting crabbing and deflecting cavities.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>KEK Cavity</th>
<th>RF-Dipole Cavity</th>
<th>RF-Dipole Cavity</th>
<th>4-Rod Cavity</th>
<th>Asymmetric 1/4-Wave Cavity</th>
<th>Symmetric 1/4-Wave Cavity</th>
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<tbody>
<tr>
<td>Frequency</td>
<td>508.9</td>
<td>499.0</td>
<td>400.0</td>
<td>400.0</td>
<td>400.0</td>
<td>400.0</td>
</tr>
<tr>
<td>Aperture diameter (d)</td>
<td>100.0</td>
<td>40.0</td>
<td>84.0</td>
<td>84.0</td>
<td>84.0</td>
<td>84.0</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>
</tr>
<tr>
<td>LOM</td>
<td>410.0</td>
<td>None</td>
<td>None</td>
<td>375.2</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>Nearest HOM</td>
<td>630.0</td>
<td>777.0</td>
<td>589.5</td>
<td>436.6</td>
<td>657.0</td>
<td>577.8</td>
</tr>
<tr>
<td>Peak electric field ($E_P^*$)</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>
</tr>
<tr>
<td>Peak magnetic field ($B_P^*$)</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>
</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>
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<tr>
<td>$[R/Q]_F$</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>
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<tr>
<td>Geometrical factor</td>
<td>227.0</td>
<td>105.9</td>
<td>138.7</td>
<td>62.8</td>
<td>131.0</td>
<td>82.4</td>
</tr>
<tr>
<td>$R_T R_S$</td>
<td>$1.1 \times 10^4$</td>
<td>$1.0 \times 10^3$</td>
<td>$4.0 \times 10^3$</td>
<td>$5.7 \times 10^4$</td>
<td>$4.5 \times 10^4$</td>
<td>$3.3 \times 10^5$</td>
</tr>
<tr>
<td>At $E_T^* = 1$ MV/m</td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

The properties of the 499 MHz and 400 MHz rf-dipole cavities are given in Table 1. The inner bar height and the angle of the trapezoidal shaped bars connecting to the outer conductor allows the rf-dipole design to have both reduced surface electric and magnetic fields. Therefore an rf-dipole cavity can be designed at a given design frequency and beam aperture, with a balanced ratio of peak surface magnetic field to the peak surface electric field as required by the application.

The HOM spectrum of the rf-dipole cavity is shown in Fig. 14. The rf-dipole cavity has no low order modes and the HOMs are well separated.

Figure 11: Design evolution of the parallel-bar cavity into the rf-dipole cavity.

Figure 12: Ridged waveguide cavity by SLAC.

Figure 13: Electric field (left) and magnetic field (right) content in the 499 MHz rf-dipole cavity.

The rf-dipole design can be reduced into a more compact design with fixed transverse dimensions with a square-shaped outer conductor as shown in Fig. 15 where...
the frequency of the design is controlled by the curvature of the edges of the cavity. The rf-dipole design is further modified with curved trapezoidal-shaped bar geometry to suppress the higher order multipole components.

The 4-rod cavity design uses coaxial type couplers in damping the LOM and HOMs. The quarter-wave cavity design uses magnetic loop type couplers placed at the bottom of the cavity to damp the HOMs. The rf-dipole cavity is considering both the options of using the waveguide or a coaxial high-pass filter type coupling in damping the HOMs. Further studies are done on these compact cavities on addressing the important rf-related issues such as multipacting, mechanical analysis, field non-uniformity etc. The fabricated prototypes are in preparation for rf testing.

REFERENCES