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COMPACT SUPERCONDUCTING CRABBING AND DEFLECTING CAVITIES*

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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-mode 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 Deflecting Cavity

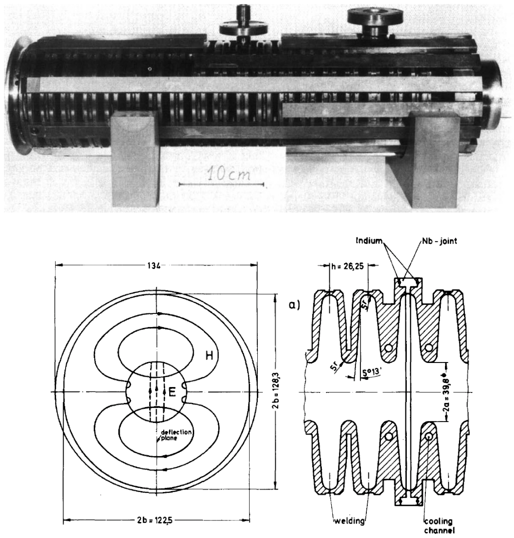

Figure 1: 19-cell end section of the 2.865 GHz rf separator cavity (top) and bi-periodic TM_{110} operating mode (bottom).

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 Crabbing 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.

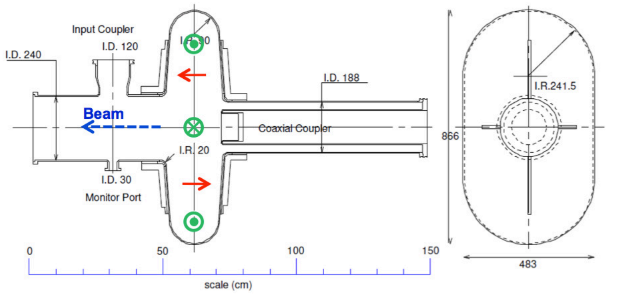

Figure 2: Superconducting 508.9 MHz KEK crabbing cavity.

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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.

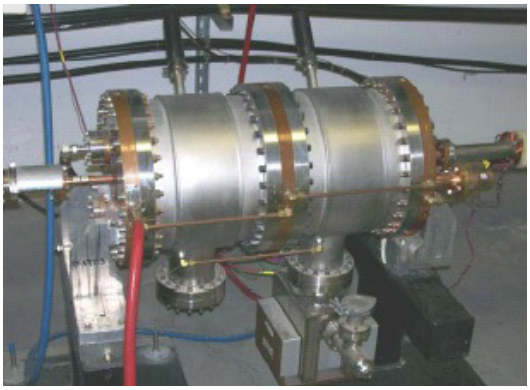


Figure 3: Normal conducting 499 MHz 4-rod rf separator cavity at Jefferson Lab.

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.

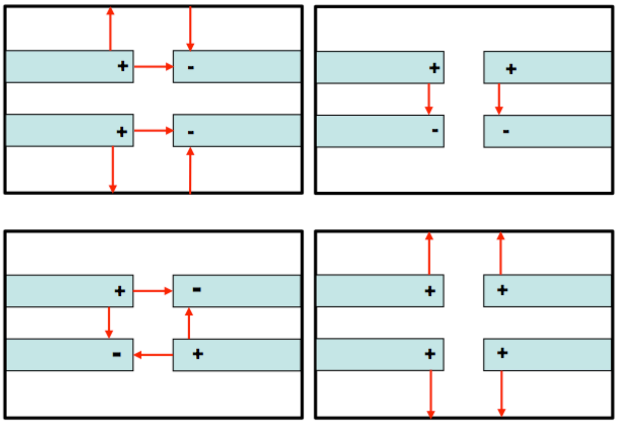


Figure 4: Electric field configuration of the 4 fundamental modes in the 4-rod geometry.

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.

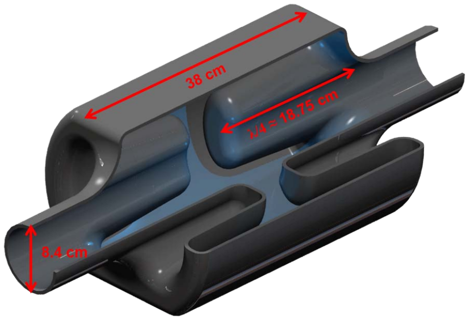


Figure 5: Superconducting 400 MHz 4-rod cavity design from University of Lancaster/Jefferson Lab.

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.

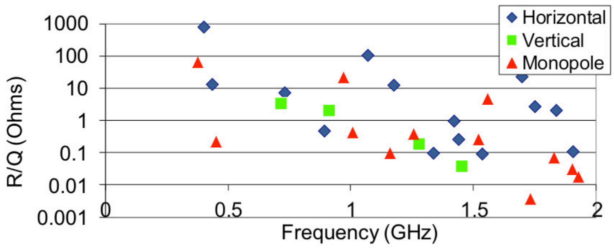


Figure 6: HOM spectrum of the 4-rod crabbing cavity.

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.

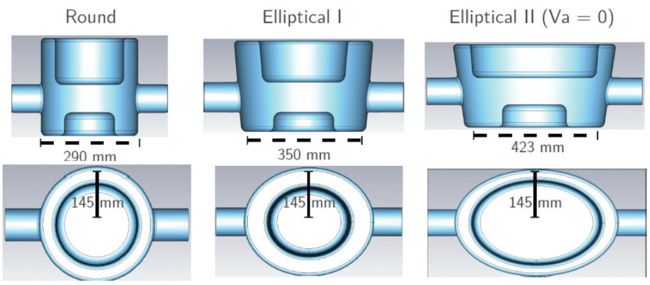


Figure 7: Superconducting 400 MHz quarter-wave deflecting/crabbing cavity by BNL.

The electric and magnetic field content of the quarter-wave crabbing cavity is shown in Fig. 8.

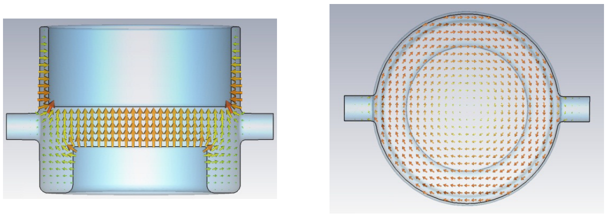


Figure 8: Electric field (left) and magnetic field (right) content of the 181 MHz quarter-wave crabbing cavity designed for eRHIC [11].

The quarter-wave cavity has two design options with the initial asymmetric geometry and a symmetric geometry to completely eliminate the longitudinal accelerating component as shown in Fig. 9. Compared to the asymmetric cavity the symmetric cavity doesn't have a longitudinal electric field component, however has a reduced mode separation between the fundamental deflecting/crabbing mode and the next HOM. The properties of the asymmetric and symmetric quarter-wave cavities are shown in Table 1. The symmetric design has improved surface fields and transverse [R/Q] however has smaller shunt impedance due to the decreased geometrical factor.

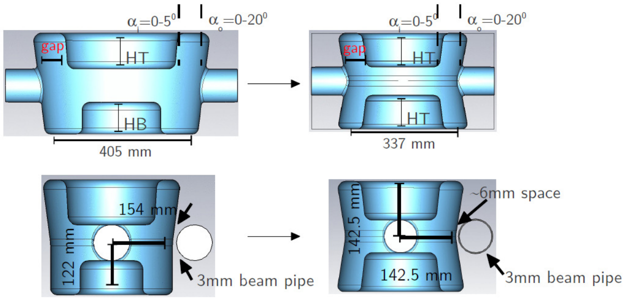


Figure 9: Asymmetric and symmetric 400 MHz quarter-wave crabbing cavities.

The HOM spectrum [8] of the asymmetric quarter-wave cavity is shown in Fig. 10, with a similar mode configuration described in the 4-rod cavity. However the asymmetric cavity also has hybrid modes present in the geometry. One of the attractive features in this design is the absence of any lower order modes.

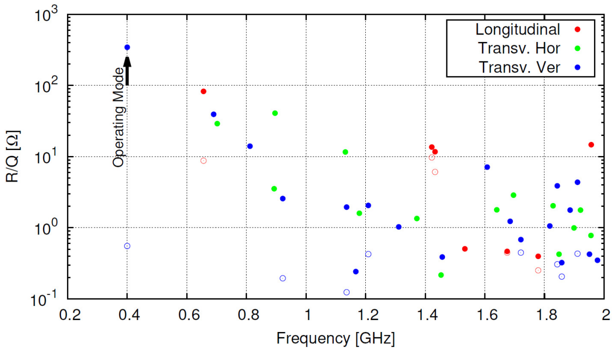


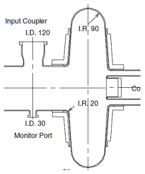
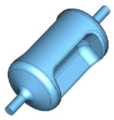
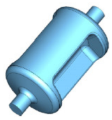
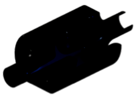
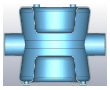
Figure 10: HOM spectrum of the asymmetric quarter-wave crabbing cavity [12].

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.

Parameter	 KEK Cavity	 RF-Dipole Cavity	 RF-Dipole Cavity	 4-Rod Cavity	 Asymmetric ¼-Wave Cavity	 Symmetric ¼-Wave Cavity	**Units**
Frequency	508.9	499.0	400.0	400.0	400.0	400.0	MHz
Aperture diameter (d)	100.0	40.0	84.0	84.0	84.0	84.0	mm
d/(λ/2)	0.34	0.13	0.22	0.22	0.22	0.22	
LOM	410.0	None	None	375.2	None	None	MHz
Nearest HOM	630.0	777.0	589.5	436.6	657.0	577.8	MHz
Peak electric field (E_P^*)	4.24	2.86	3.9	4.0	5.38	4.04	MV/m
Peak magnetic field (B_P^*)	12.23	4.38	7.13	7.56	7.6	7.2	mT
B_P^* / E_P^*	2.88	1.53	1.83	1.89	1.42	1.77	mT/ (MV/m)
$[R/Q]_T$	48.9	982.5	287.2	915.0	344.0	401.1	Ω
Geometrical factor	227.0	105.9	138.7	62.8	131.0	82.4	Ω
$R_T R_S$	1.1×10^4	1.0×10^5	4.0×10^4	5.7×10^4	4.5×10^4	3.3×10^4	Ω^2

At $E_T^* = 1$ MV/m

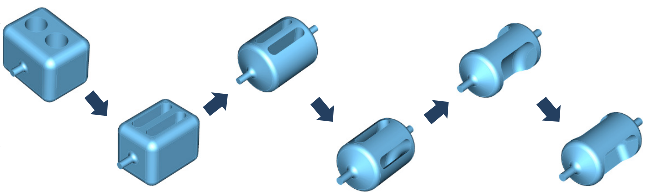


Figure 11: Design evolution of the parallel-bar cavity into the rf-dipole cavity.

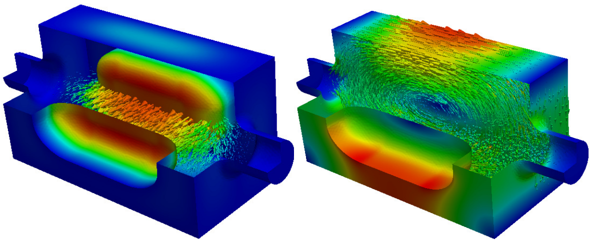


Figure 12: Ridged waveguide cavity by SLAC.

options for the LHC luminosity upgrade operating at 400 MHz, and as the 750 MHz crabbing cavity for the medium energy electron ion collider (MEIC). The field profile of the rf-dipole cavity is shown in Fig. 13.

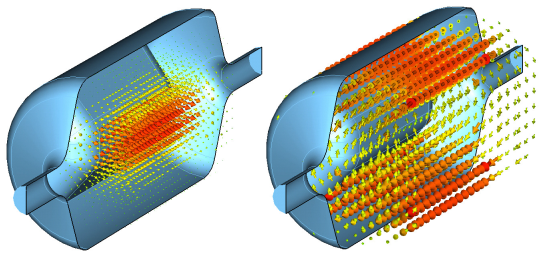


Figure 13: Electric field (left) and magnetic field (right) content in the 499 MHz rf-dipole cavity.

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.

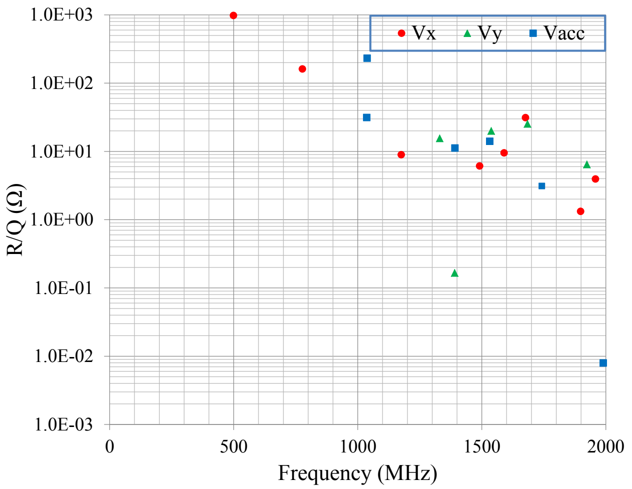


Figure 14: HOM spectrum of the 499 MHz rf-dipole cavity.

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.

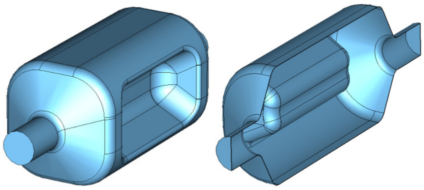


Figure 15: Square-shaped rf-dipole cavity with flat trapezoidal-shaped bar geometry (left) and with curved bar geometry (right).

CAVITY FABRICATION

First prototypes of some of the compact deflecting and crabbing cavities have already being fabricated. Fig. 16 shows the fabricated cavity designs. The prototypes of the 400 MHz 4-rod cavity, the 400MHz and 750 MHz rf-dipole cavities are fabricated at Niowave Inc. and the 499 MHz rf-dipole cavity is currently being fabricated at Jefferson Lab.

Figure 16: Prototype of the 400 MHz 4-rod cavity (top left), 400 MHz (top right), 400 MHz (bottom left) and 750 MHz (bottom right) rf-dipole cavities.

CONCLUSIONS

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. The low and balanced surface fields and high shunt impedance in these compact superconducting crabbing and deflecting cavities make them very attractive designs compared to the standard cavities operating in TM_{110} mode. The absence of lower order modes and wide separation in the higher order modes in most of the designs reduces the lower and higher mode damping complexity.

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.

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