COMPACT SUPERCONDUCTING CAVITIES FOR DEFLECTING AND CRABBING APPLICATIONS*

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Abstract

There is increasing interest in using superconducting cavities as rf separators (e.g. Jefferson Lab 12 GeV upgrade and Fermilab Project X) or as crabbing systems to increase the luminosity in colliders (e.g. LHC upgrade and electron-ion colliders). Several of these applications have severe dimensional constraints that would prevent the use of cavities operating in the TM_{110} mode. A number of compact designs for deflecting/crabbing cavities have been designed and are under development; their properties are presented.

INTRODUCTION

While most superconducting cavities for use in accelerators are for accelerating particles, they can also be used for deflecting beams or crabbing bunches. Accelerating cavities provide a longitudinal voltage in order to increase the forward momentum of the particles while deflecting/crabbing cavities apply a transverse voltage. Deflecting and crabbing cavities are identical, the only difference being in the phase between the rf transverse fields and the bunches. Deflecting cavities operate at maximum –or close to maximum– phase so the whole bunch acquires a transverse momentum. Crabbing cavities operate at zero phase so there is no net deflection of the center of the bunch but the front and back of the bunch are deflected in opposite direction.

Deflecting systems were one of the first applications of superconducting rf to particle accelerators. In the early 1970's an rf separator, shown in Fig.1, was designed and fabricated at KfK Karlsruhe [1]. It was comprised of 104 cells and the frequency of the deflecting mode was 2.865 GHz. The separator was operated at CERN between 1977 and 1981 and is now being resurrected at IHEP.

The first superconducting crabbing system was developed, implemented, and operated at KEK [2]. The crabbing system consisted of two cavities, shown in Fig. 2, one for each of the two rings. The cavities operated at 508 MHz in the TM110 mode. In order to remove the degeneracy between the two polarizations of the TM110 mode, the cavity was designed with a race-track shape cross-section. The cavities were installed in the rings in 2007 and were operated until recently. Although there were some difficulties associated with amplitude instabilities and mechanical tuner resolution, luminosity increase using a crabbing scheme was clearly demonstrated.

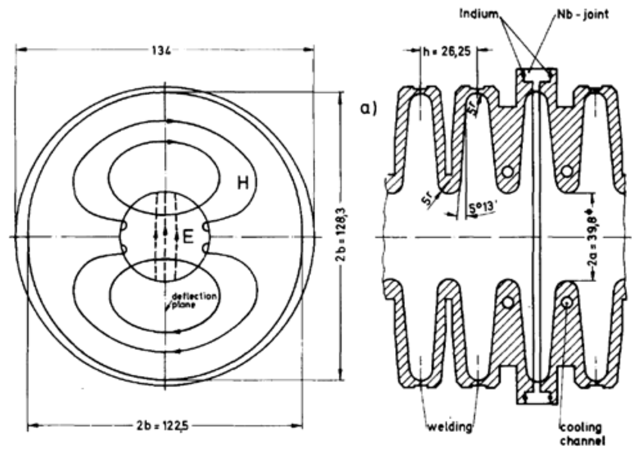

Figure 1: Karlsruhe/CERN superconducting rf separator.

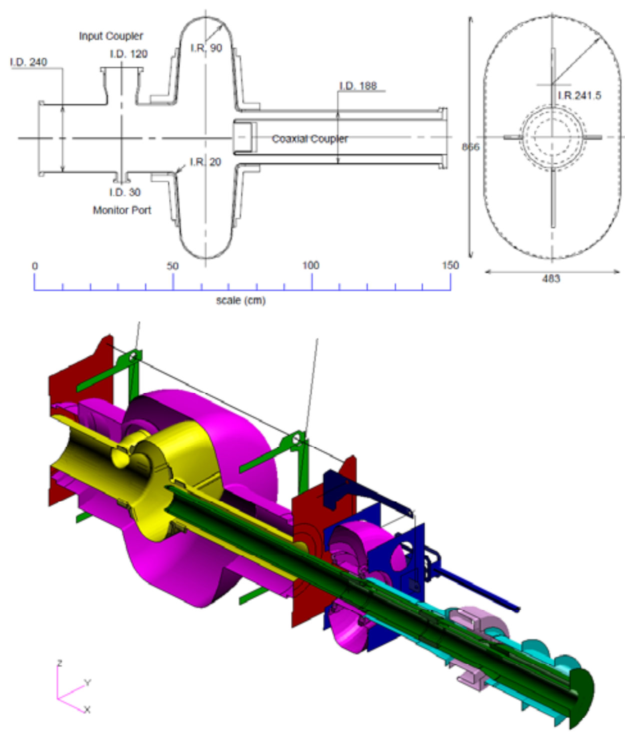

Figure 2: 508 MHz crab cavity used at KEKB

Those cavities operate in the TM110 mode, where the deflection results from the interaction with the transverse magnetic field. Because of the mode used these cavities are larger (by about 30%) than accelerating cavities of the

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same frequency that operate in the TM110 mode. For example the 508 MHz KEK crab cavity had a transverse dimension of 87 cm.

Recently there has been interest in crabbing and deflecting applications where dimensional requirements could not be met by cavities operating in the TM110 mode as was done previously.

One is a crabbing system for a contemplated LHC luminosity upgrade. The distance between centers of the two beamlines is 150 mm while the preferred frequency of the crabbing system is 400 MHz. Additionally the same cavity design should be used for both horizontal and vertical crabbing.

Another application is a deflecting system for the Jefferson Lab 12 GeV Upgrade. In this case the required frequency is 499 MHz but the 4th pass beam line and existing plumbing limit the size of the crabbing system as shown in Fig. 3.

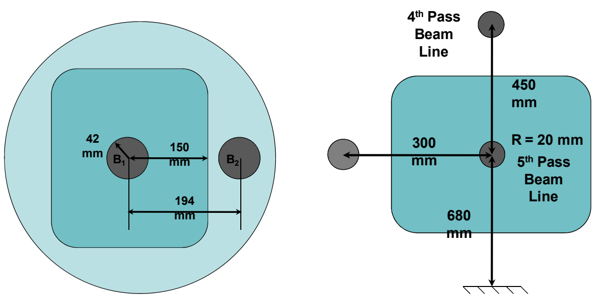

Figure 3: Dimensional constraint for the 400 MHz LHC crabbing system (left) and the JLab Upgrade 499 MHz deflecting system (right).

COMPACT CAVITIES

In response to the need for compact deflecting/crabbing systems new cavity geometries have been developed.

A concept developed at KEK makes use of a TM010 cavity but with the beamline traversing the cavity along a diameter instead of the axis as is the case when it is used as an accelerating cavity [5,6]. In this configuration the cavity can be made very thin (see Fig.4). However, since in this mode the electric field is purely transverse there cannot be any deflecting voltage since, according to the Panofsky-Wenzel theorem, the deflecting voltage in one direction is equal to the gradient of the accelerating voltage in the same direction. This is due to the fact that the deflection caused by the magnetic field exactly cancels that caused by the electric field. In order to reduce the effect of the magnetic field the geometry needs to be modified (break the translational invariance along the axis) in order to create a gradient of electric field along the beam line. Two possible modifications are shown in Fig. 4. Since this cavity is operating in the TM010 mode it does not have any lower-order mode. While this geometry is very compact, the deflecting voltage, at given surface fields, is relatively small and this geometry is not actively pursued at present. In the latest design for a 400 MHz LHC crab cavity, the ratio of peak surface electric field and deflecting field was $E_p / E_t = 10.9$ and for the peak surface magnetic field $B_p / E_t = 18.7$ mT/(MV/m) where the deflecting field is defined as $E_t = \dfrac{V_t}{\lambda / 2}$.

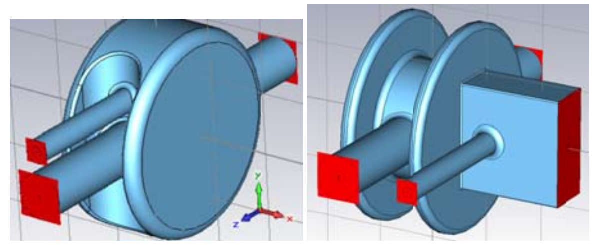

Figure 4: Pill-box TM010 crabbing cavities.

The University of Lancaster has been developing in collaboration with Jefferson Lab a 4-rod design based on the normal-conducting cavities in used as rf separators at JLab. In this geometry [7-8], four quarter-wave resonators are operating in opposite phase as shown in Fig. 5. In this configuration the deflecting voltages produced by the electric and magnetic fields add while, in the lower-order mode where the facing pairs of rods are in phase, they cancel.

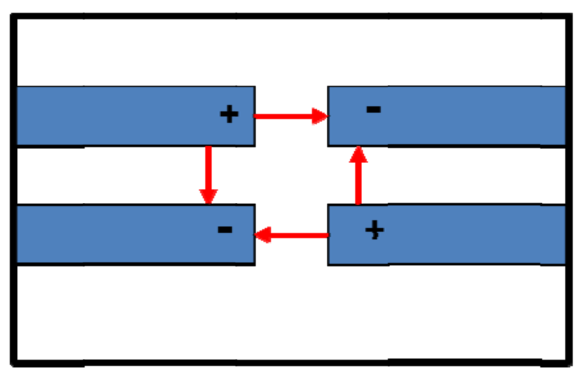

Figure 5: Mode of operation of a 4-rod cavity.

Extensive simulations have been done to minimize the surface electric and magnetic fields and the non-linear effects for particles travelling off-axis. The most recent design is shown in Fig. 6.

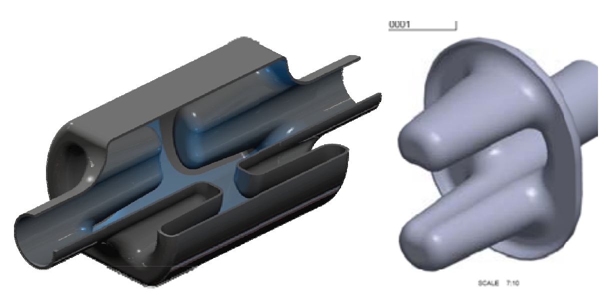

Figure 6: Design of a 4-rod superconducting crabbing/deflecting cavity.

The lower-order and higher-order modes have been identified and are shown in Fig. 7. The 4-rod geometry is characterized by a high shunt impedance.

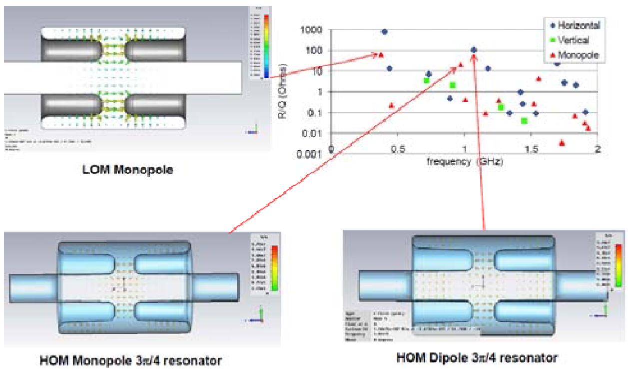

Figure 7: Lower-order and higher-order modes of a superconducting 4-rod cavity.

SLAC has been proposing a "half-wave" geometry [9-11] shown in Fig. 8. While it may look like a half-wave resonator, the operating mode is actually a TE11-like mode where the deflection is produced by the magnetic field

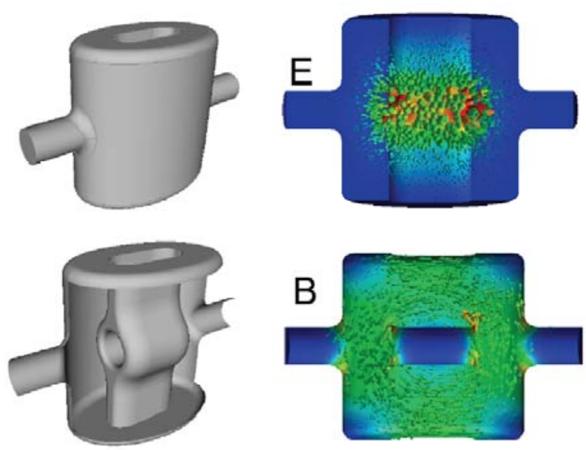

Figure 8: "Half-wave" resonator operating in a TE11-like mode.

This geometry is very compact in one dimension and an extensive analysis has been done of its lower-order and higher-order modes properties (see Fig. 9) and its multipacting behaviour. This geometry is not pursed anymore for the LHC luminosity upgrade since the new requirements are that the same geometry should be able to be used in the horizontal and vertical configuration and still meet the dimensional requirements shown in Fig. 3.

Another compact geometry is the "parallel-bar" whose concept is shown in Fig. 10 [12-17]. It consists of two half-wave resonant lines operating in opposite phase (π-mode). A transverse deflecting electric field is generated in the mid-plane between the two bars which produces a deflecting voltage to a particle travelling along the beamline between the bars.

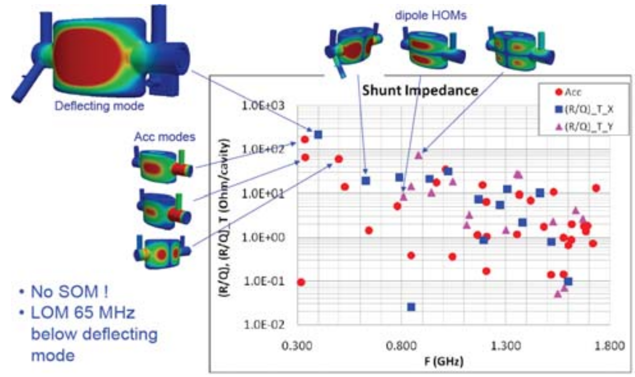

Figure 9: Lower-order and higher-order mode properties of the SLAC "half-wave" cavity.

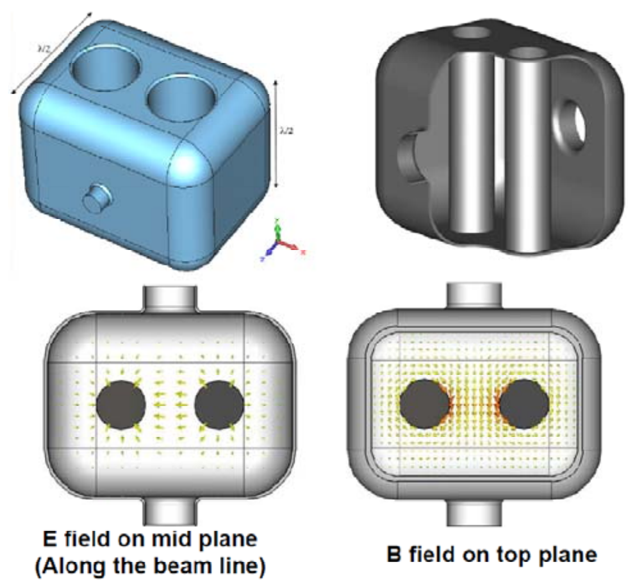

Figure 10: Concept for the parallel-bar deflecting/crabbing cavity.

This concept can be improved and optimized in several ways. First, in order to take full advantage of the voltage generated at the center of the bars, their cross-section can be extended so the deflecting voltage is a maximum. This happens when the width of the bars along the beamline is roughly $\lambda/2$ as shown in Fig. 11 top left. The mode where the two bars oscillate in phase (0-mode) is, to first-order, degenerate with the deflecting mode. The degeneracy can been removed and the frequency of the accelerating mode can be almost doubled by changing the cross section from a rectangular to a cylindrical shape as shown in Fig. 11 top right. In cavities operating in a TEM mode, irrespective of the cross-sections of the inner and outer conductors and as long as the geometry has translational invariance (as in Fig. 11 top right), the ratio of peak surface magnetic field to peak surface electric field is a constant 3.33 mT/(M/m). While this may have been a good ratio in the past, advance in cavity cleaning procedures allows operation at higher surface electric fields and a ratio of ~1.8 mT/(MV/m) is more appropriate. This can be accomplished by bending the bars as shown in Fig. 11 bottom left. This increases the volume available to the magnetic field thus lowering it at the expense of an increased surface electric field. The resulting geometry (Fig.11 lower left) has a widely separated fundamental mode and well-balanced peak surface electric and magnetic fields. However, the fields in the region between the bars and outer walls are very small; this could lead to multipacting, and that region can be eliminated without impact on the fundamental mode. Thus the outer side of the bars can be extended to the wall, resulting in the geometry of Fig. 11 bottom left.

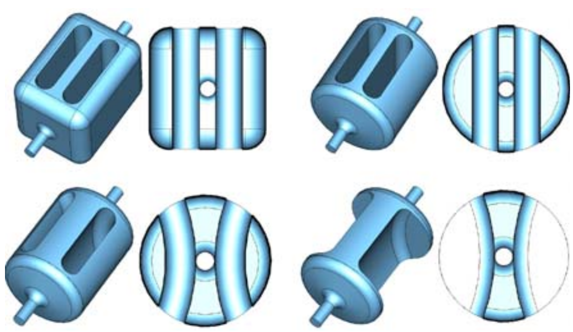

Figure 11: Evolution of the design of parallel-bar cavities.

A number of deflecting and crabbing cavities for several applications based on this geometry have been designed and are shown in Fig. 12.

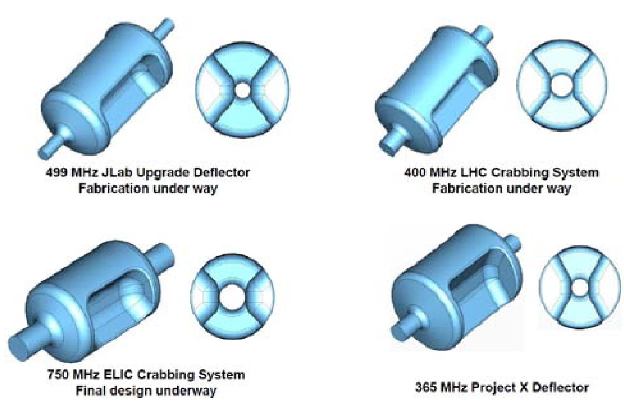

Figure 12: Parallel-bar cavities for several deflecting and crabbing applications.

The higher-order modes of the 499 MHz cavity are shown in Fig. 13. As can be seen this cavity has no lower-order mode and the nearest higher-order mode is ~750 MHz or 1.5 the frequency of the fundamental deflecting mode. Furthermore the higher-order mode spectrum is quite sparse. This is representative of all the designs based on this geometry.

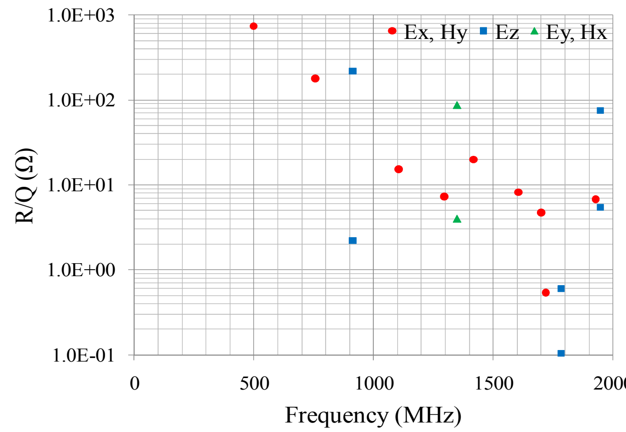

Figure 13: Higher-order modes of a 499 MHz parallel-bar cavity.

Recently SLAC has proposed the geometry shown in Fig. 14 [11] for a 400 MHz crabbing cavity for the LHC upgrade. It is conceptually identical to the cavity shown in Fig. 12 and has similar properties. The only difference being that the outer shell is rectangular instead if cylindrical.

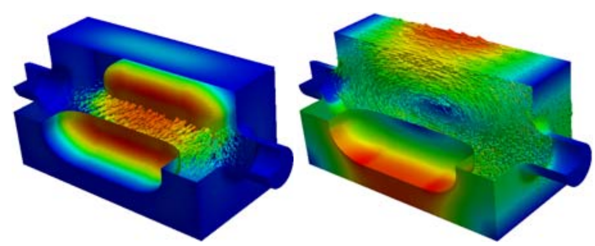

Figure 14: 400 MHz ridged-waveguide cavity [11].

Fermilab has proposed the cavity shown in Fig. 15 for the Project X deflector. It is a 3-cell version of the cavity shown in Fig.12.

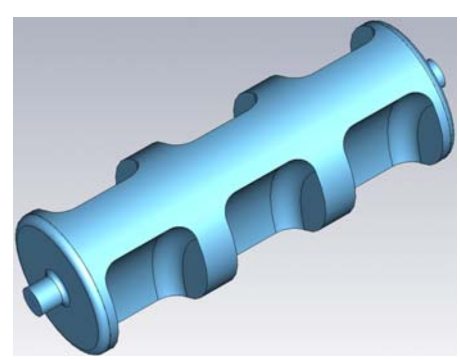

Figure 15: 3-cell version of the cavity in Fig. 12.

Brookhaven has proposed a geometry based on a quarter-wavelength resonant line [18-20]. A preliminary implementation for the 400 MHz LHC crabbing system is shown in Fig. 16. This geometry could also be understood as a wave-guide with only one ridge as opposed to two for the geometries of Figs. 12 and 14.

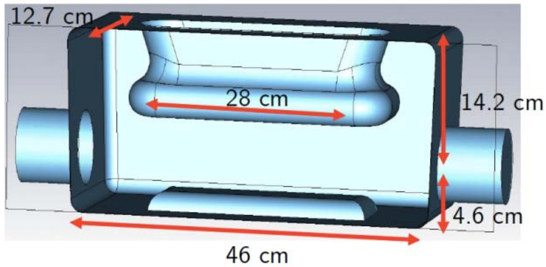

Figure16: 400 MHz quarter-wave geometry for the LHC crabbing system.

Another preliminary design for a 181 MHz crabbing system for eRHIC is shown in Fig. 17.

Figure 17: Preliminary design for a 181 MHz crabbing cavity for eRHIC.

This geometry is obviously quite compact, has no lower-order mode, and a well-separated nearest higher order mode. It differs from all the other geometries discussed so far in that the beam line is not an axis of symmetry. This means that there could exist a longitudinal electric field on axis resulting in an accelerating voltage. This could in principle be reduced by careful shaping of the geometry. Another consequence is that, unlike the symmetrical geometries where the deflecting voltage has a quadratic dependence on lateral offsets from the nominal beamline, in this case the dependence could be linear.

CONCLUSIONS

Recently, a number of geometries have been proposed for deflecting and crabbing applications which are much more compact than the traditional TM110 geometry. In most cases these designs rely on a transverse electric field to provide the deflection instead of the magnetic field. Several of them have no lower-order mode with the nearest high-order mode frequency being at least 1.5 that of the fundamental deflecting mode; this should significantly ease the damping of the higher-order modes in high-current applications.

Properties of five designs for a crabbing system for LHC luminosity upgrade are shown in Fig. 18. These designs are preliminary and could improve after further optimization. In all cases the frequency is 400 MHz, and the beamline aperture is 84 mm. The transverse electric field is defined as $E_t = \dfrac{V_t}{\lambda / 2}$

	Reel	4-rod	Half-wave	Par-bar/ Ridged	Quarter -wave
E_p/E_t	10.9	4	3.9	3.8	7.2
B_p/E_t mT/(MV/m)	18.7	7.6	7.3	7.1	16.5
R/Q Ω		765	215	312	132

Figure 18: Electromagnetic properties of a number of 400 MHz crabbing cavities.

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