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# RECENT DEVELOPMENTS IN SUPERCONDUCTING DEFLECTING-MODE CAVITIES\*

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## Abstract

The last few years have seen significant activities directed towards the development of superconducting cavities operating in the deflecting mode. The stringent requirements imposed by new requirements necessitated the development of new cavity geometries. Proofs-of-principle cavities have been fabricated and tested, and have shown excellent properties. Prototype cavities and cryomodules for operation and testing with beam are now under development as part of a world-wide collaboration. The status of these activities is being 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 [2-4]. 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 TM<sub>110</sub> mode. In order to remove the degeneracy between the two polarizations of the TM<sub>110</sub> 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 instabili-

ties and mechanical tuner resolution, luminosity increase using a crabbing scheme was clearly demonstrated.

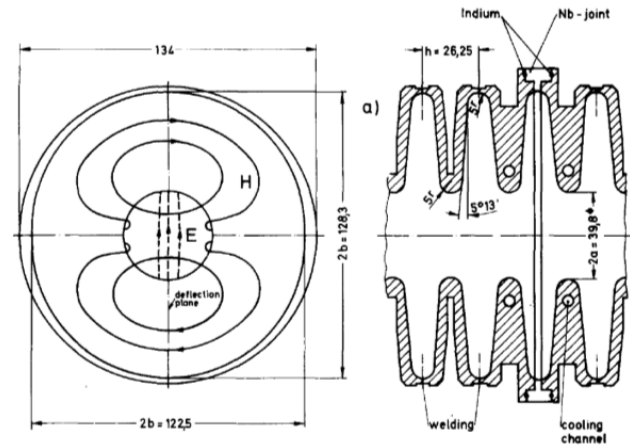


Figure 1: Karlsruhe/CERN superconducting rf separator.

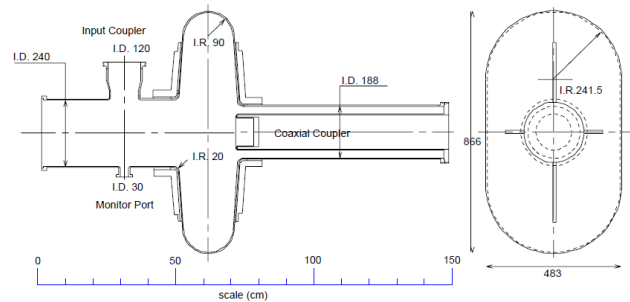


Figure 2: 508 MHz crab cavity used at KEKB.

## TM CLASS CAVITIES

Those cavities operated in the TM<sub>110</sub> 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 the accelerating cavities of the same frequency that operate in the TM<sub>010</sub> mode. For example the 508 MHz KEK crab cavity had a transverse dimension of 87 cm. This would prevent their application when low frequency is needed but there are dimensional constraints

On the other hand, the fact that these cavities are relatively large at a given wavelength can be an advantage when a high frequency is needed. For example a TM<sub>010</sub> 2.815 GHz cavity, shown in Fig. 3, was developed by JLab and ANL [5]. This can also be an advantage when a large aperture is needed.

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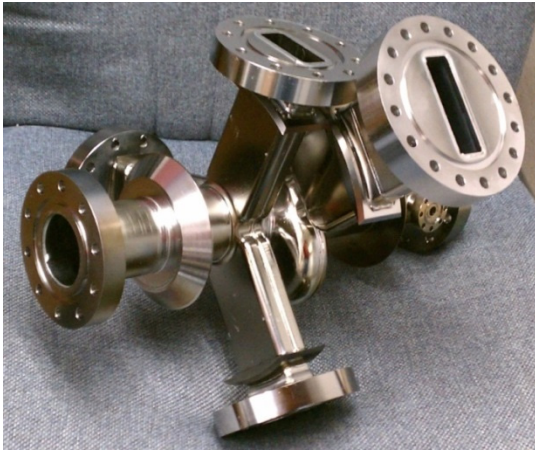


Figure 3: 2.815 GHz  $TM_{010}$  crabbing cavity.

The  $TM_{010}$  mode clearly never is the lowest frequency mode. Therefore, in high current applications, the damping of lower-order and higher-order modes while maintaining a high  $Q$  for the fundamental can be challenging and necessitate the design complex filters or accurate location and geometry of waveguides.

Recently there has been interest in crabbing and deflecting applications where dimensional requirements could not be met by cavities operating in the  $TM_{110}$  mode as has been 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 [6]. Other potential applications are crabbing systems for electron-ion colliders.

These new applications of deflecting-mode cavities require low frequency and compact transverse dimensions. This has led to the development of new concepts and geometries for deflecting-mode cavities. They fall into two broad classes: cavities operating in a “TEM-like” mode and those operating in a “TE-like” mode

### “TEM-LIKE” CLASS CAVITIES

Lancaster University has developed a 4-rod design based on the normal-conducting cavities in use 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. Since it consists of four identical resonant lines operating in a TEM mode, this resonator sustains four same-order modes depending on the relative phase of the rf fields of each quarter-wave resonator. In one of the modes, the adjacent lines operate in phase resulting in an accelerating mode whose frequency is lower than that of the deflecting mode.

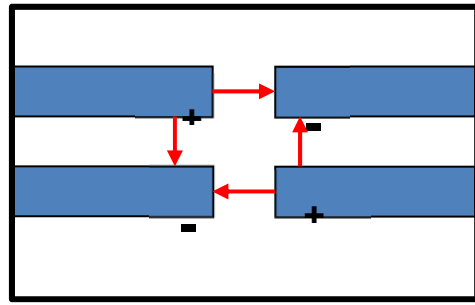


Figure 4: Mode of operation of a 4-rod cavity.

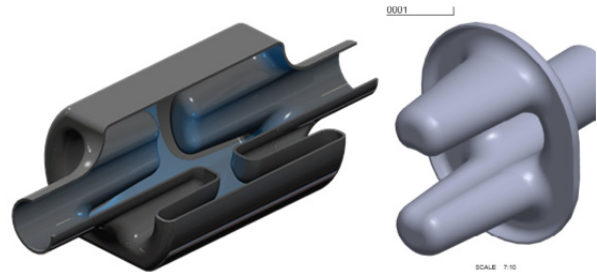


Figure 5: Concept of a 4-rod superconducting crabbing/deflecting cavity

Another “TEM-like” geometry originally proposed by Old Dominion University (ODU) and Jefferson Lab is the parallel-bar shown in Fig. 6 [9]. It consists of two half-wave resonant lines operating  $180^\circ$  out of phase. The deflection takes place through the interaction with a transverse electric field generated between the two resonant lines. After a series of optimizations the parallel-bar geometry has evolved into the rf-dipole geometry and thus was transformed from a “TEM-like” structure into a “TE-like” structure [10, 11].

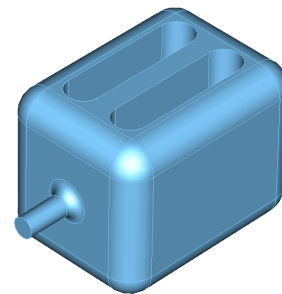


Figure 6: Concept for the parallel-bar cavity.

### “TE-LIKE” CLASS CAVITIES

Since, according to the Panofsky-Wenzel theorem the transverse voltage imparted on a particle is directly related to the transverse gradient of the longitudinal voltage, no pure TE mode can be used to deflect particles. In a pure TE mode, the transverse voltage provided by interaction with the electric field is exactly cancelled by the interaction with the magnetic field. In “TE-like” deflecting cavities, the geometry has been deformed locally in order to break the longitudinal invariance; this reduces the cancellation due to the magnetic field.

Several “TE-like” cavities have been investigated. They operate in the same fundamental electromagnetic mode but differ slightly in the geometry and have acquired different names depending on the point of departure for their optimization, namely the rf-dipole (RFD) developed by ODU shown in Fig. 7 [10, 11], the double-quarter-wave (DQW) developed by BNL shown in Fig. 8 [12, 13], and the ridged wave guide originally suggested by SLAC shown in Fig. 9 [14] but whose further development was subsequently merged with that of the RFD.

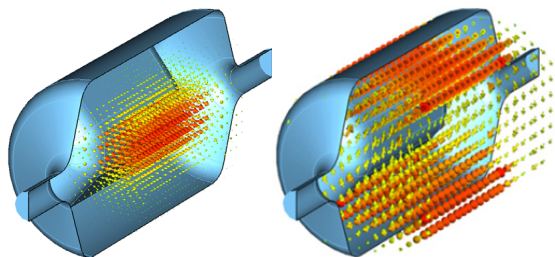


Figure 7: Electric (left) and magnetic (right) fields in the rf-dipole cavity.

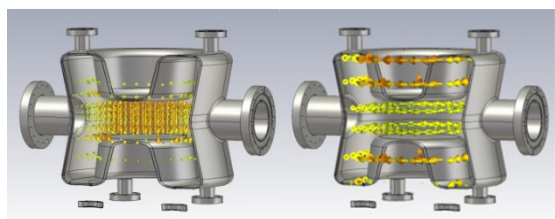


Figure 8: Electric (left) and magnetic (right) fields in the double quarter-wave cavity.

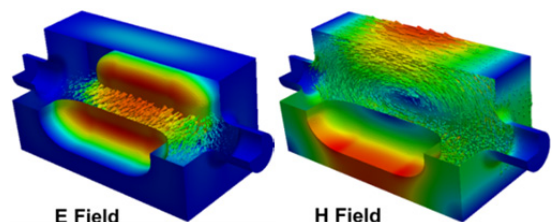


Figure 9: Electric (left) and magnetic (right) fields in the ridged waveguide cavity.

## PROPERTIES OF COMPACT DEFLECTING MODE CAVITIES

### *Dependence of Frequency and Optimal Particle Velocity on External Dimensions*

The frequency of the deflecting mode of the 4-rod cavity is directly related to the longitudinal length of the cavity but is not affected by its transverse dimension. Therefore, in principle, this geometry could be used at lower frequency than other geometries while still being compact in the transverse dimension. Because of the nature of the operating mode, the 4-rod geometry is most effective for particle velocities close to the speed of light.

For the parallel-bar, the rf-dipole, and the double quarter-wave, the frequency depends mostly on the transverse dimension while it is almost independent of the longitudinal dimension. Therefore those cavities would get much larger than the 4-rod at very low frequency. On the other hand they could be designed for the deflection of particles travelling at velocities much smaller than the velocity of light by shortening the length of the cavity to  $\sim \beta\lambda/2$ .

### *Lower- and Higher-order Modes*

Since the 4-rod resonator consists of 4 quarter wave-length resonant lines it can sustain 4 same-order modes depending on the relative phase of the 4 resonant lines [7, 8]. In the deflecting mode the adjacent resonant lines oscillate  $180^\circ$  out of phase, as do opposite lines, as shown in Fig. 4. In one of the same-order modes, opposite lines also oscillate  $180^\circ$  out of phase, while adjacent line oscillate in phase. This is an accelerating mode that would couple strongly with the beam. Furthermore, its frequency is lower than, and relatively close to, that of the deflecting mode as shown in Fig. 10. Other higher-order modes are also relatively close to the fundamental. Therefore, damping of all the unwanted modes in the 4-rod resonator presents real challenges and requires the design of notch filters shown in Fig. 11 to damp the lower frequency mode while being decoupled to the fundamental.

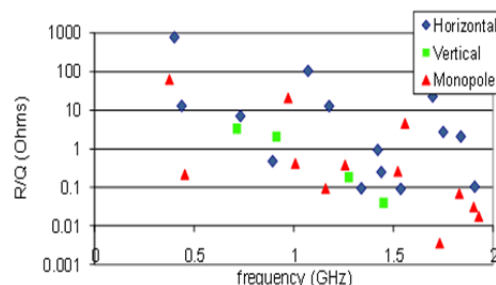


Figure 10: Mode spectrum in a 400 MHz 4-rod cavity.

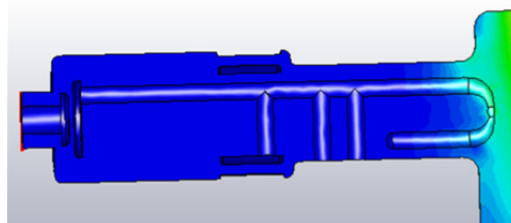


Figure 11: HOM coupler with filter for the 400 MHz 4-rod cavity.

In the “TE-like” geometries, on the other hand, the deflecting mode is the lowest-frequency mode and the frequency of nearest high-order mode is about 1.5 that of the deflecting mode. For example, in the newest design of the 400 MHz crabbing cavities for the LHC upgrade, the frequency of the nearest HOM is 630 MHz for the RFD and 570 MHz for the DQW. The HOM spectrum of the RFD is shown in Fig. 12 [15]. The DQW has a similar HOM spectrum,



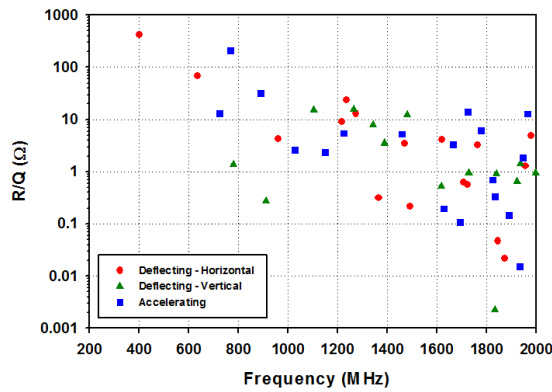


Figure 12: HOM spectrum for a 400 MHz rf-dipole cavity.

Damping of the HOM in the DQW, shown in Fig. 13, is provided by 3 HOM couplers located at the bases of the poles where the field of the fundamental mode is relatively high. Therefore they couple to the fundamental mode and filters to decouple the fundamental mode are required at those 3 locations.

The RFD relies on 2 HOM couplers as shown in Fig. 14 [15]. One is located where there is no coupling to the fundamental; therefore no filter is required. The other HOM coupler is located where the fields of the fundamental mode are present and a filter is required.

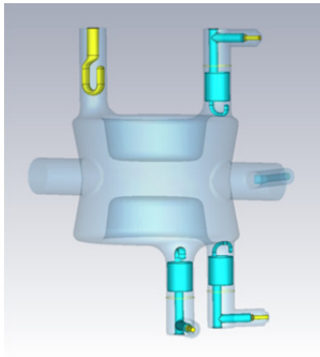


Figure 13: Fundamental and HOM couplers for a 400 MHz double quarter-wave cavity.

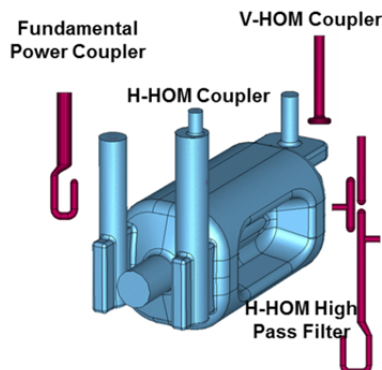


Figure 14: Fundamental and HOM couplers for a 400 MHz rf-dipole cavity.

## Multipacting

One of the main concerns whenever a new type of superconducting cavity is developed is the sensitivity to multipacting. This is particularly true for 3-dimensional geometries since multipacting simulations are time and computational intensive. With the development of new simulation codes, in particular the ACE3P suite developed at SLAC it is now possible to explore the sensitivity to multipacting of fairly complex electromagnetic structures.

Extensive simulations (see Figs. 15 for the DQW and 16 for the RFD) have been performed on several of the proof-of-concept compact deflecting mode cavities at different frequencies [10, 17, 18] and, in all cases, behaviour observed during cryogenic testing was consistent with what was expected from simulations. This, coupled with what has been observed on spoke cavities, is giving us an increased level of confidence in 3-D multipacting simulation codes.

It is also true that there is always a high potential for multipacting in couplers, whether the fundamental power ones or those for the damping of LOM or HOM modes. Since fully dressed cavities with all the couplers have not been tested yet there is still potential for surprises.

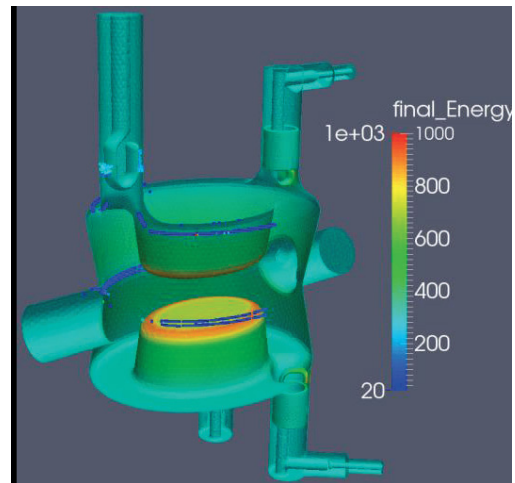


Figure 15: Simulation of multipacting in a 400 MHz double quarter-wave cavity.

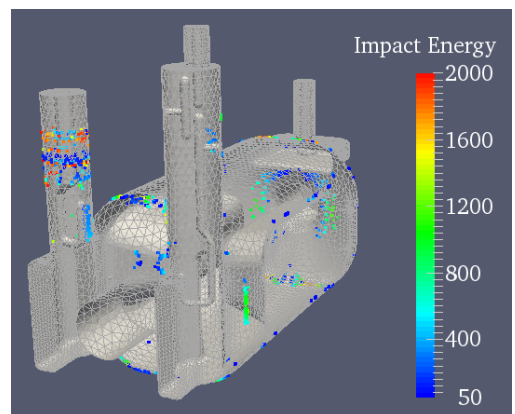


Figure 16: Simulation of Multipacting in a 400 MHz rf-dipole cavity.

## Multipoles

In some applications, especially those where emittance growth must be minimized, the transverse dimension of the beam is large, or there is potential for instabilities, the multipole components of the deflecting mode must be tightly controlled. Because of their geometry and the large number of degrees of freedom they provide, the new compact cavities can be tailored to adjust the multipole content of the deflecting voltage to a particular set of requirements [19]. Figure 17 shows how shaping of the rods in a 4-rod cavity can improve the field uniformity and Fig. 18 shows the same for the RFD. There are always a number of compromises involved: a reduction of multipole components for a given beamline aperture is obtained at the cost of increased surface fields and reduced shunt impedance.

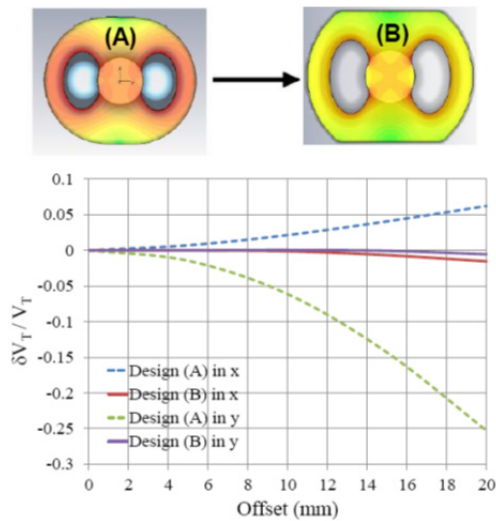


Figure 17: Improvement in the uniformity of the deflecting fields by shaping the rods of a 4-rod cavity.

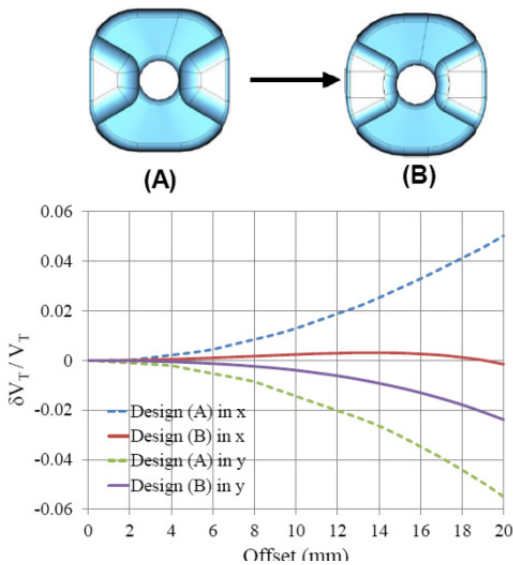


Figure 18: Improvement in the uniformity of the deflecting fields by shaping the poles of an rf-dipole cavity [19].

## Beamline Aperture

Because of their compact size, the new deflecting-mode cavities are limited in the size of beam aperture –the gap between the rods or the poles. For the “TE-like” cavities, an important parameter is the ratio of pole separation and half-wavelength, which is roughly the transverse dimension of the cavity. As this ratio increases, the ratio of peak electric or magnetic field and deflecting field increases and the shunt impedance decreases. This is illustrated in Fig. 19 which shows the shunt impedance for the RFD [10, 11].

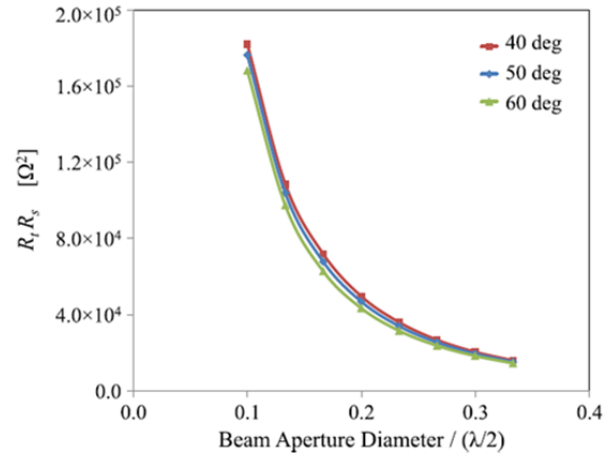


Figure 19: Reduction of the shunt impedance of an rf-dipole cavity due to the increased separation between the poles.

## CRYOGENIC TEST RESULTS OF PROOF-OF-PRINCIPLE CAVITIES

Proof-of-principle 4-rod (Fig. 20), rf-dipole (Fig. 21), and double quarter-wave (Fig. 23) cavities have been built and cryogenically tested. They were designed as potential candidates for a crabbing system for the HLC High Luminosity Upgrade and operated at 400 MHz. The tests were quite successful. For example, as shown in Fig. 22, the RFD showed a high Q and reached a deflecting voltage of 7 MV, twice the specification of 3.4 MV. Multipacting was easily processed and did not reoccur. The cavity was tested at Jefferson Lab and CERN with the same results [20].

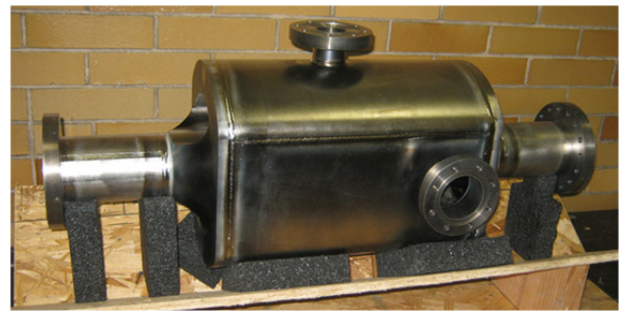


Figure 20: Prof-of-principle 400 MHz 4-rod cavity.



Figure 21: Prof-of-principle 400 MHz rf-dipole cavity.

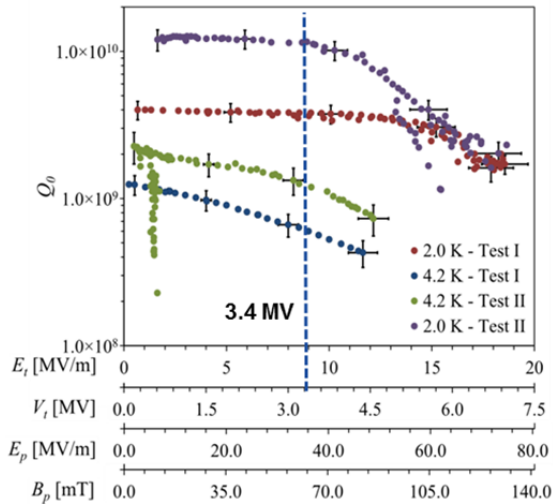


Figure 22: Results of the cryogenic tests of the 400 MHz proof-of-principle rf-dipole cavity [20].

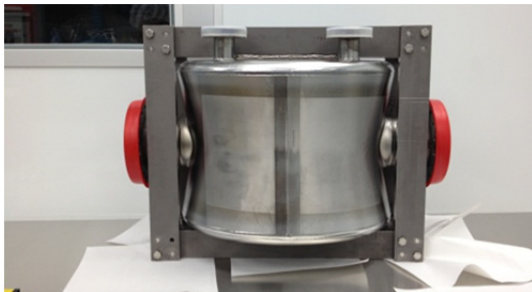


Figure 23: Prof-of-principle 400 MHz double quarter-wave cavity.

Two additional proof-of-principle RFD cavities have been built and cryogenically tested; one at 499 MHz and the other at 750 MHz. Those two cavities also showed excellent results and in both case Multipacting was easily processed and did not reoccur. There is therefore an increased level of confidence that these new geometries can find a wide range of applicability

A 3-cell cavity of similar geometry operating at 2.815 GHz and shown in Fig. 24 has been developed at ANL [21]. Such a cavity would be used for the manipulation of the 4D phase space of beams in light sources. Multi-cell cavities are of course more compact than single cell cavities. However same-order modes are being intro-

duced which may be a disadvantage in high-current applications.

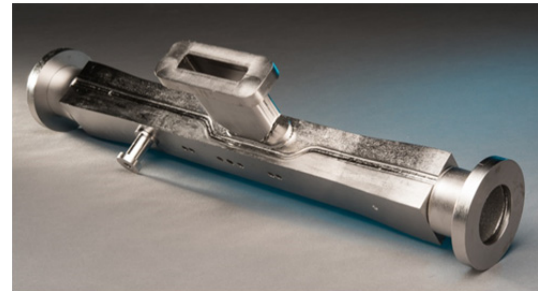
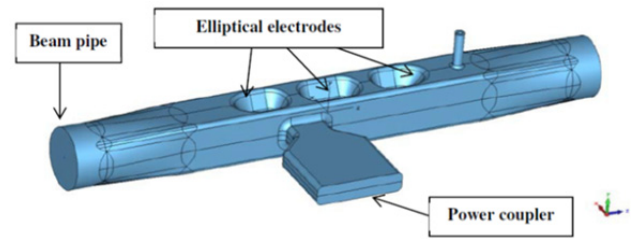


Figure 24: 3-cell 2.815 GHz deflecting cavity developed at ANL for beam phase space manipulation.

## DESIGN AND ENGINEERING OF PROTOTYPE CAVITIES AND CRYOMODULES

Following the successful test of the proof-of-principle cavities, fully engineered prototype cavities and cryomodules for the RFD and DQW are being developed as part of an international collaboration with the goal of installing and testing them on the SPS at CERN. A picture of a fully engineered rf-dipole cavity showing the helium tank, frequency tuner, fundamental power coupler, HOM couplers is shown in Fig. 25. The double quarter-wave cavity has been similarly engineered [22, 23].

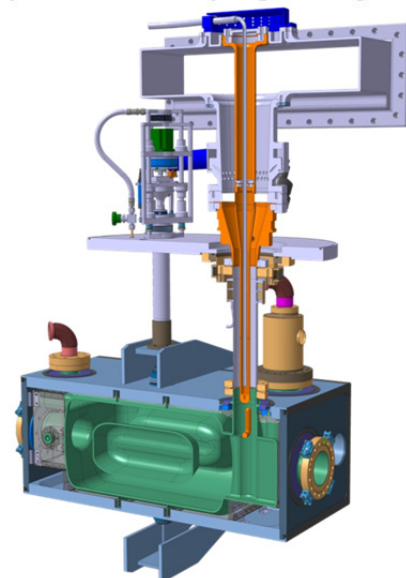


Figure 25: Engineered 400 MHz rf-dipole cavity for test at the CERN SPS.



Figure 26 shows fully engineered cryostat housing two double quarter-wave cavities [24]. A similar cryostat has been engineered for the rf-dipole cavity.

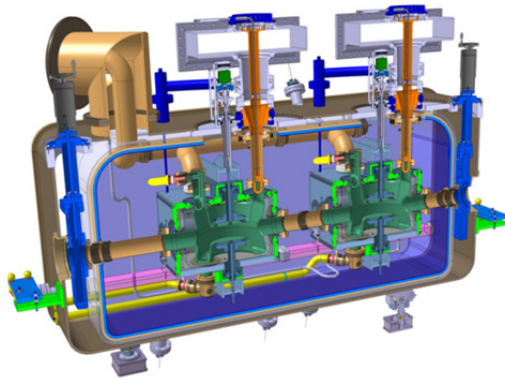


Figure 26: Engineered cryostat for 2 double quarter-wave cavities to be tested at the CERN SPS.

## ACKNOWLEDGMENTS

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