NOVEL GEOMETRIES FOR THE LHC CRAB CAVITY

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Abstract

In 2017 the LHC is envisioned to increase its luminosity via an upgrade. This upgrade is likely to require a large crossing angle hence a crab cavity is required to align the bunches prior to collision. There are two possible schemes for crab cavity implementation, global and local. In a global crab cavity the crab cavity is far from the IP and the bunch rotates back and forward as it traverses around the accelerator in a closed orbit. For this scheme a two-cell elliptical squashed cavity at 800 MHz is preferred. To avoid any potential beam instabilities all the parasitic modes of the cavities must be damped strongly, however crab cavities have lower order and same order modes in addition to the usual higher order modes and hence a novel damping scheme must be used to provide sufficient damping of these modes.

In the local scheme two crab cavities are placed at each side of the IP two start and stop rotation of the bunches. This would require crab cavities much smaller transversely than in the global scheme but the frequency cannot be increased any higher due to the long bunch length of the LHC beam. This will require a novel compact crab cavity design. A superconducting version of a two rod coaxial deflecting cavity as a suitable design is proposed in this paper.

INTRODUCTON

Crab cavities have been used for beam diagnostics and splitting for many years. R. Palmer [1] first proposed the crab crossing scheme in 1988 as an idea to enable effective head-on collisions with a crossing angle in linear colliders.

Crab cavities are transverse deflecting cavities where the head and tail of the bunch are deflected in opposite directions, causing an effective rotation of the bunch.

During the Phase I upgrade of the LHC (circa 2013) it is envisioned that a proof-of-principle crab cavity will be installed. Due to space constraint this cavity will operate at 800 MHZ. This cavity has tight damping requirements for the lower-order and same-order modes of the cavity and requires a novel damping scheme.

For the proposed LHC Phase II upgrade (circa 2017-2018) a frequency of 400 MHz is preferred due to the long bunch length of the proton beam (7.55cm). [2] However due to the size constraints imposed by the desired location of the crab cavities a novel compact design is required. The cavity is required to be superconducting to allow CW operation at high transverse gradients.

TWO CELL ELLIPTICAL CAVITY WITH ON-CELL DAMPING

It is envisioned that a proof-of-principle test of crab cavities with hadron beams will be completed prior to the inclusion of crab cavities within the LHC. In this test it is proposed that a single standard elliptical cavity is placed within the LHC to observe the effects of a crab cavity on the LHC beam. However in order to ensure that no additional instabilities occur due to the added impedance of the cavity, the parasitic modes of this cavity must be strongly damped.

Several designs exist for this cavity [2], including the design reported in this paper. Due to space constraints all the proposed cavities are required to operate at 800 MHz as opposed to the preferred 400 MHz operation. In the design described in this paper, a two cell elliptical cavity is proposed with on-cell waveguide damping, shown in Figure 1. In this scheme the lower-order-mode (TM010) and the dipole same-order-mode (SOM) are damped by a waveguide attached to the equator of each cell. This arrangement is made possible due to the polarised nature of dipole modes; hence the operating mode has almost no electric or magnetic field near the damping waveguide. This design is supplemented with two additional waveguides in the beam pipes for power input and for damping the HOMs. The external Q of the SOM was calculated in Microwave Studio [3] to be around 30, and the external Q of the LOM was calculated to be around 100.

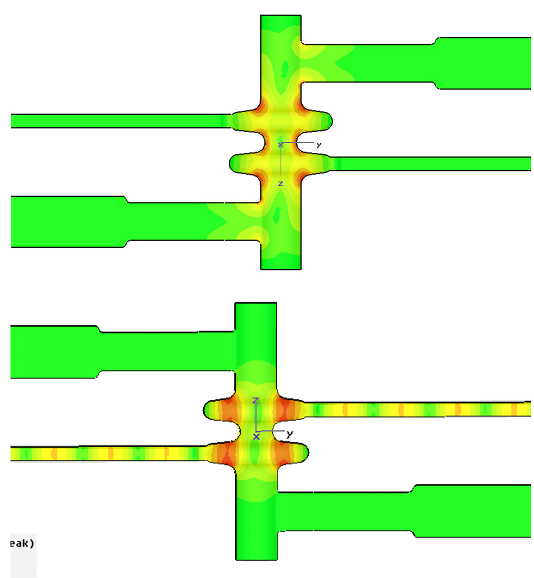

Figure 1: H magnitude plot for the operating mode (top) and E magnitude plot for the SOM (bottom)

This design uses azimuthally symmetric cavities and relays on the strong asymmetric damping of the dipole modes to polarise the cavity and create a frequency separation between the operating mode and the SOM. This method of polarisation reduces the effect of angular offset of the damping waveguide during manufacture, which can be a major problem for other designs.

CEBAF COAXIAL DEFLECTING CAVITY

In the 1990 Linac conference a coaxial design for a deflecting cavity was proposed by C. Leemann [4] for CEBAF's Deflecting separator. By placing 2 rods along the *z* direction of a pillbox cavity he was able to cut down the outer radius of the 500 MHz cavity from 800mm to 120mm, while compressing the dipole fields to the centre of the cavity.

The coaxial nature of the cavity reduces the frequency dependence on cavity radius and instead the length of the cavity becomes the dominant feature in determining the frequency of operation.

A compact crab cavity for LHC is proposed based on this cavity design. Although the CEBAF deflector is in principle operationally similar to the proposed cavity, situationally they are very different. As the CEBAF cavity deflects electron it only needed a beam pipe diameter of 1.5cm and thus could have a pair of 2cm diameter rods very close to each other. This requires a complete redesign although the shape works in principle, the LHC's stringent requirements must be met.

SCRF COAXIAL DEFLECTING CAVITY

For the LHC we are constrained both in the maximum transverse size of the cavity and the minimum beam pipe aperture. The maximum cavity radius is limited to 250 mm and the beam pipe radius is limited, due to the large transverse size of the LHC bunch, to a minimum of 50 mm. This means the rods must have a significant separation compared to the cavity wavelength. In addition the requirement to use a superconducting design meant that the cavity must be made more rigid to avoid excessive microphonics.

Initial studies were conducted in Microwave Studio [3] with simple round rod structures similar to the CEBAF cavity, to determine the effect of various parameters had upon the performance and operational frequency. With the cavity being superconducting, microphonics were a concern in the design of the cavity shape. For this reason the cavity was designed with the rods tapered to improve the mechanical stability of the structure.

To optimise the shape of the cavity a search over various parameters was undertaken. The length of the cavity was chosen to be the prime variable as it had no limitations and thus could always be adjusted to bring the cavity back to the desired frequency. Those parameters that had a larger impact upon the peak surface fields and deflecting voltage were focused on, with the aim of reducing the peak magnetic and electric fields below 80mT and 50MV/m respectively at the proposed operating transverse voltage of 3MV.

Panofsky-Wenzel theorem [5] states that the transverse voltage is proportional to the rate of change of the longitudinal voltage hence increasing the transverse separation between the rods, as required by the LHC bunch transverse size, decreases the transverse voltage as would be expected. This meant that the cavity required significant work to recover the lost voltage without dramatically increasing the peak surface fields.

The first parameter we varied was the longitudinal gap between the rods. As can be seen from figure 2 there is an inverse relationship between the peak electric and peak magnetic field. The peak electric field decreases with rod spacing as the electric field between the rods decreases linearly but the voltage only decreases due to the variation in the transit time factor. Thus the best trade off between these two must be found.

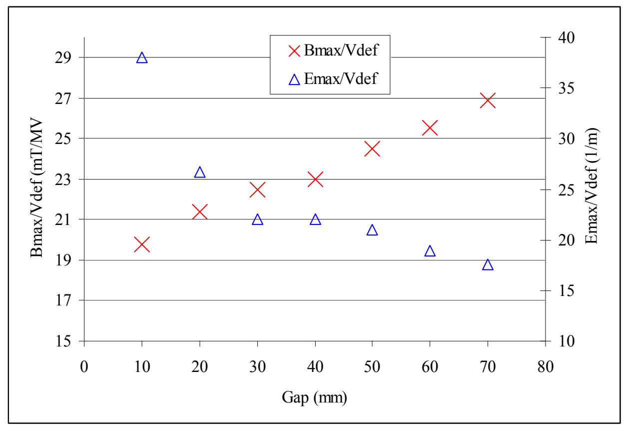

Figure 2: Plot of E_{max}/V_{def} and B_{max}/V_{def} at various Rod gaps

The maximum surface magnetic field was found to be concentrated around the base of the rods near the beam pipe aperture, as shown in figure 3. By applying a large rounding radius to each of the intersection in this region is possible to reduce the surface magnetic fields in this location. Figure 3 shows the abs. distribution of the peak magnetic field.

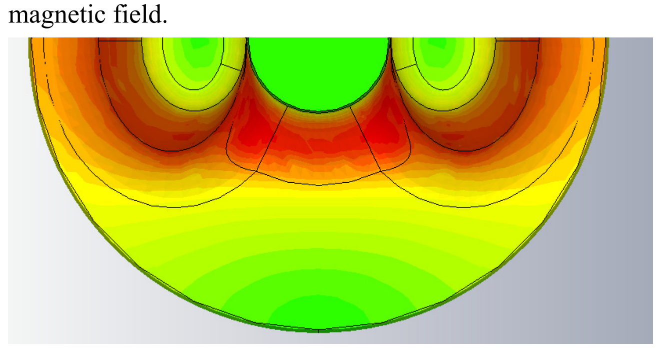

Figure 3: The absolute peak magnetic field.

Initially rods with a circular cross-section were used but upon changing the profile to be that of an oval shape a remarked improvement in the peak magnetic field was noted with appreciable no difference in deflecting voltage, thus the oval shape was chosen. This improvement is most likely due to the shape of the rods following the path of magnetic flux in the dipole-like mode. It was also chosen to alter the taper of the rods, allowing for both concave and convex geometries to be explored. By varying the shape of the rod it was possible to make a trade-off between the maximum E field and maximum B field.

The shape with the lowest surface fields achieved so far consists of two oval tapered rods that protrude into the cavity from each end. Figures 4 & 5 show cut away sections of the cavity. In both cases the beam pipe runs from left to right. It was found that the outer face of the rod, where the farthest from the beam pipe was more effective when straight, where ran down the side was more effective when slightly convex. The front of the rod is straight and runs along the same line as that of the beam pipe.

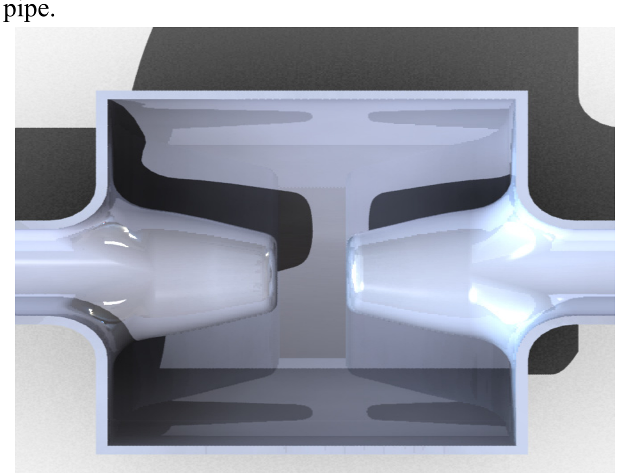

Figure 4: Cut away of cavity shape showing 2 facing rods.

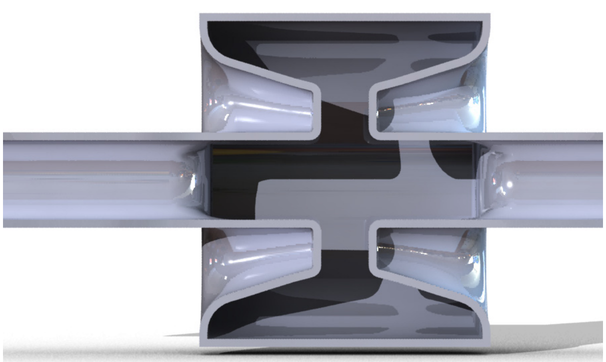

Figure 5: Cut away showing alternative angle, with all 4 rods visible.

For this design the Peak surface magnetic field has been limited to be under 45 mT while the peak electric field has been limited to 48 MV/m at a transverse voltage of 3 MV. The cavity was also found to have an exceedingly high R/Q as most of the energy is concentrated around the rods. In addition the losses on the cavity outer walls is found to be very low such that the cavity cylinder could possibly be constructed of low RRR Nb and the rods made from high RRR Nb without affecting cavity performance.

The first 4 modes of the cavity are shown if table 1. The other polarisation of the deflecting mode has been pushed to a much higher frequency. When compared to a pillbox cavity of similar size, the frequencies of the modes in the compact design are shifted down by about 1/3rd compared to their equivalent in the pillbox.

Table 1: The frequencies of the first 4 modes.

Mode	Frequency (GHz)	R/Q (Ω)	R_T/Q (Ω)
LOM	0.3356	185.4	
Operating mode	0.4000		774
1st dipole HOM	0.4866		0.19
1st monopole HOM	0.5178	5.4×10^{-6}	

Where $\frac{R}{Q}=\frac{V^2}{\omega U}$ and $\frac{R_T}{Q}=\left(\frac{c}{\omega r}\right)^2\frac{V(r)^2}{\omega U}$

V is the voltage integrated on a given off-axis distance r, ω is the angular frequency, c is the speed of light, U is the total stored energy.

CONCLUSIONS

Two novel cavity geometries have been proposed for the LHC crab cavity. One is based on a two-cell elliptical cavity with 'on-cell' waveguide damping of the LOM and SOM. The other is a coaxial-type 4 rod cavity based on the CEBAF deflecting cavities.

The space requirements of the LHC demand that the crab cavity be of a novel shape to allow it to be placed in the desired location. The design proposed here fulfils both the size constraints as well as providing suitably low peak magnetic and electric fields.

Further study with the aid of an evolutionary algorithm and neural networks is planned to produce further optimisation over a larger parameter range and multipactor modelling is planned to ensure an optimal design.

ACKNOWLEDGMENTS

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