NOVEL GEOMETRIES FOR THE LHC CRAB CAVITY

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Abstract

The planned luminosity upgrade to LHC is likely to necessitate a large crossing angle and a local crab crossing scheme. For this scheme crab cavities align bunches prior to collision. The scheme requires at least four such cavities, a pair on each beam line either side of the interaction point (IP). Upstream cavities initiate rotation and downstream cavities cancel rotation. Cancellation is usually done at a location where the optics has re-aligned the bunch. The beam line separation near the IP necessitates a more compact design than is possible with elliptical cavities such as those used at KEK. The reduction in size must be achieved without an increase in the operational frequency to maintain compatibility with the long bunch length of the LHC. This paper proposes a suitable superconducting variant of a four rod coaxial deflecting cavity (to be phased as a crab cavity), and presents analytical models and simulations of suitable designs.

INTRODUCTON

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. This scheme utilised transverse deflecting cavities where the cavities are phased such that the head and tail of the bunch are deflected in opposite directions, causing an effective rotation of the bunch. Such cavities are known as crab cavities.

A crab cavity is being proposed for the LHC luminosity upgrade in order to allow a larger crossing angle and a bunch with a smaller cross section without the loss of luminosity.

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. 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 150 mm due to the separation between opposing beamlines and the beam pipe radius is limited, due to the large transverse size of the LHC bunch, to a minimum of 42 mm. As a higher CW voltage is required the LHC cavity will have to be superconducting.

Like coaxial line, parallel bars can support TEM waves [4]. This allows the construction of cavities where the resonant frequency is independent of the transverse size. The bars can either be orientated perpendicular to the beam [5] or parallel to it with a gap [6].

In order to separate bunches in CEBAF a four rod transverse deflecting cavity is utilised [5]. The cavity comprises of two parallel bars supporting a TEM mode. By placing a gap in the centre of each rod we obtain the transverse fields required to produce a kick to the bunches. In the CEBAF cavity it was possible to reduce the transverse radius of the cavity at 500 MHz to 120 mm compared to the 800 mm of an equivalent pillbox cavity supporting a TM_{110} mode. A compact crab cavity for LHC is proposed based on this concept.

Figure 1 shows the electric fields in the LHC cavity for the operating mode. A beam passing through the cavity will be defected by both the electric and magnetic fields.

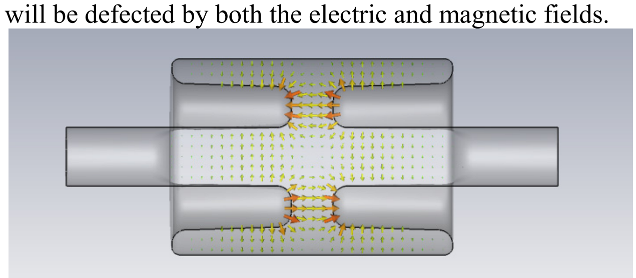

Figure 1: Electric field plot of cavity.

Previous methods of calculating the length of parallel bar cavity for a given frequency [7] did not include the capacitance between longitudinally opposing rods hence each rod is exactly a quarter wavelength long. The accuracy of the calculation can be increased by including this capacitance as has been applied to quarter wave resonators.

The length of a quarter wave resonator can be calculated by setting the admittance Y_{aa} of the equivalent circuit to zero [5].

$$Y_{aa} = i\omega C + \frac{1}{iZ_0 \tan\left(\frac{2\pi}{\lambda} l\right)} \tag{1}$$

Where C is the capacitance between the end of the rod and the wall, λ is the wavelength ω is the angular frequency, Z_0 is the characteristic impedance of the line and *l* is the length of the rod.

By slightly modifying the previous equation by including the Capacitance of the gap C_g and re arranging, the length of the rods for the cavity can be calculated.

$$l = \frac{\lambda}{2\pi} \tan^{-1}\left(\frac{\lambda}{2\pi c C_g Z_0}\right) \tag{2}$$

SRF FOUR ROD CAVITY OPTIMISATION

Initial studies were conducted in Microwave Studio [3] with simple round rod structures similar to the CEBAF cavity, to determine the effect various parameters had upon the performance and operational frequency[4].

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 [8] 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 varied was the longitudinal gap between the rods. 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 transit time factor. Thus once the gap is large enough there is little benefit in increasing it further.

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 1. By applying a large rounding radius to each of the intersection in this region is was possible to reduce the surface magnetic fields in this location and shift the peak to the sides of the rods. Figure 2 shows the abs. distribution of the peak magnetic field.

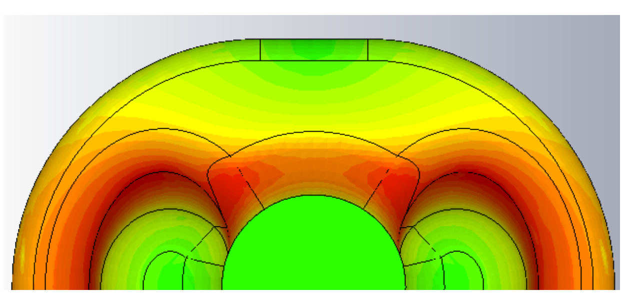

Figure 2: Absolute peak magnetic field of operating mode.

Initially rods with a circular cross-section were used but upon changing the profile to be that of an oval shape a marked improvement in the peak magnetic field was noted with no appreciable 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 base of the rod is almost entirely concerned with the magnetic field whilst the tip of the rod is mainly concerned with electric field but also can play a significant role in the peak magnetic field

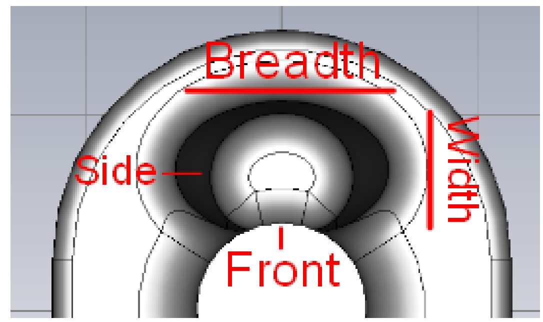

Figure 3: Descriptive terms used for the rod

Figure 4 Shows how varying the breadth [breadth is the direction perpendicular to the plane of the rods, width is the direction in the plane of the rods] of the base of the rods effects the peak magnetic field. There is a minimum around 105mm with a gentle increase with increasing breadth; however a sharp increase occurs if the breadth is decreased. This increase occurs as the surface peak magnetic field shifts from the sides of the rods to the rounded area around the beam pipe join

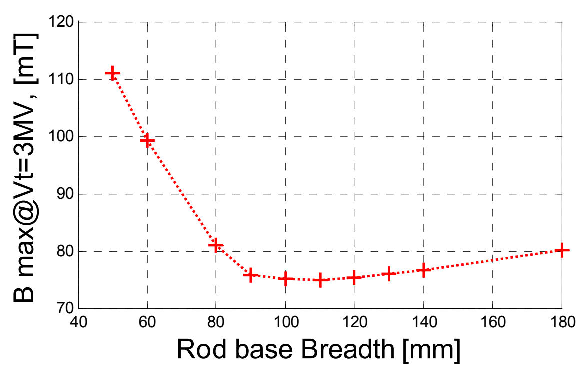

Figure 4: Peak magnetic field vs. rod base breadth.

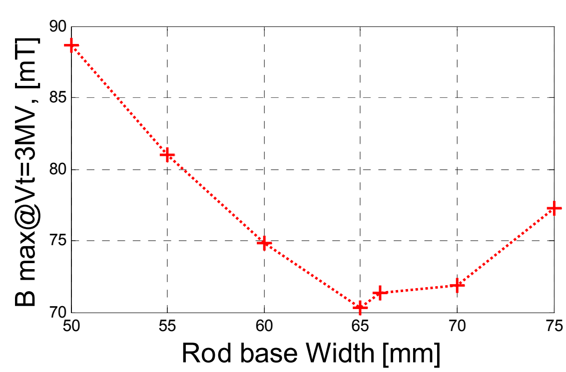

Figure 5: Peak magnetic field vs. Rod base width.

Figure 5 shows the variation of magnetic field as the base width is varied. Increasing the width decreases the distance between the outer wall of the cavity and the base of the rod, this has the undesirable effect of squashing the magnetic fields and causing the location of the surface magnetic field peak to shift to the back side of the rods, closest to the wall. Whereas decreasing the rod width causes the sides of the rods to become pointed and focus the magnetic field to this area. A minimum was found at 65mm.

The breadth and width are intrinsically linked as increasing the breadth causes the sides of the rods to become pointed, causing the area of peak magnetic field to shift to the side requiring an increase in width to compensate for this. Similarly, a narrow width necessitates a smaller breadth.

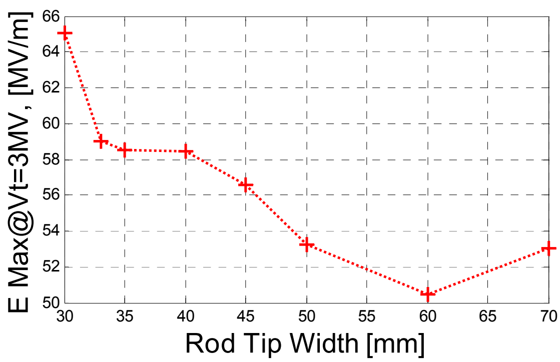

Figure 6: Peak electric field vs. rod tip width.

Varying the tip size allows both the electric and magnetic field to be varied. As shown in figure 6increasing the tip width decreases the peak electric field until the rod becomes straight, at 60mm then it increase. However increasing the tip width flattens the profile of the sides of the rods as well as decreasing the distance to the walls, thus a more gentle increase in magnetic field with increasing width can be seen in figure 7 when compared to the previous figure 5.

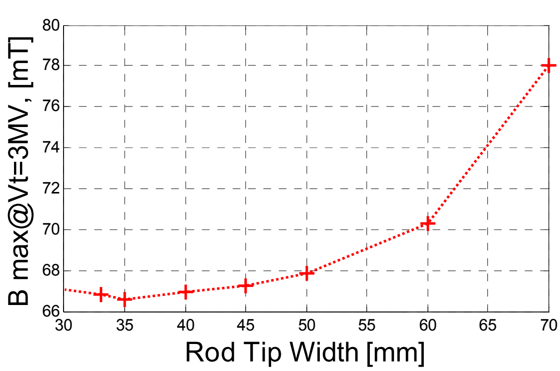

Figure 7: Peak electric field vs. rod tip breadth.

With the cavity being superconducting, microphonics were a concern in the design of the cavity shape. For this reason the tapered nature of the rods is an advantage adding mechanical stability of the structure.

Figure 8: Cut-away of cavity.

Figure 8 shows a cut away view of the cavity demonstrating the conical nature of the rods as well as the kidney shape. This design is able to meet the design specifications with a peak surface field of 39.2 MV/m and 59.1 mT/m at a deflecting gradient of 3MV/m

Within the cavity there exists an LOM equivalent to the TE_{01} mode at 372.2MHz. the first two HOM's consist of a dipole like mode at 429.8MHz and a monopole like HOM at 435.0MHz.

CONCLUSIONS

A novel cavity geometry has been proposed for the LHC crab cavity. The design 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.

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