STUDY OF THE VARIATION OF TRANSVERSE VOLTAGE IN THE 4 ROD CRAB CAVITY FOR LHC

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Abstract

The planned high luminosity upgrade to LHC will utilise crab cavities to rotate the beam in order to increase the luminosity in the presence of a finite crossing angle. A compact design is required in order for the cavities to fit between opposing beam-lines. In this paper we discuss we discuss one option for the LHC crab cavity based on a 4 rod TEM deflecting cavity. Due to the large transverse size of the LHC beam the cavity is required to have a large aperture while maintaining a constant transverse voltage across the aperture. The cavity has been optimised to minimise the variation of the transverse voltage while keeping the peak surface electric and magnetic fields low for a given kick. This is achieved while fitting within the strict design space of the LHC. The variation of deflecting voltage across the aperture has been studied numerically and compared with numerical and analytical estimates of other deflecting cavity types. Performance measurements an aluminium prototype of this cavity are presented and compared to the simulated design.

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 2020) 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 high CW voltage is required the LHC cavity will have to be superconducting. Like coaxial line, parallel bars can support TEM waves but are better suited to deflecting cavities as they have a transverse field between the rods [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 normal conducting transversely compact four rod transverse deflecting cavity is utilised [5]. For LHC we propose to optimise the cavity geometry for a superconducting variant with a larger beampipe size. 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 and a similar reduction in transverse size is possible for LHC.

VARIATION IN THE TRANSVERSE VOLTAGE ACROSS THE APERTURE

It is normally thought that the transverse kick is constant across the aperture of a dipole cavity, however this is only true for high beta symmetric cavities. For non-cylindrically symmetric cavities there is a variation of the transverse kick across the aperture. One potential problem associated with this is the change in bunch rotation at the IP. Ideally a collision in an accelerator would be head on, as this would provide complete overlap of bunches. However due to the crossing angle, bunch rotation is required to generate the effective head on collision. Variation in the angle of rotation will produce an incomplete overlap and hence a reduction in luminosity. This loss can be calculated from the geometric loss factor R [7]

$$R = \frac{1}{\sqrt{1+\phi^2}} \quad (1)$$

Where φ is the Piwinski factor, which can be calculated as;

$$\phi = \frac{\theta_c \sigma_z}{2\sigma_x} \quad (2)$$

θ_c is the crossing angle, σ_x is the transverse beam size and σ_z is the longitudinal beam size.

Variation in deflection from the cavity could result in the bunch colliding with a small crossing angle. Assuming a direct dependence in variation of the deflection angle on the change in deflecting voltage, the angle between the bunches at the IP can be given as,

$$\Delta\theta_c(x,y) = \theta_c \frac{V_x(x,y) - V_x(0,0)}{V_x(0,0)} \quad (3)$$

Where $V_x(x,y)$ is the defecting voltage at position (x,y). The proportional loss in luminosity can be calculated for a given change in deflecting voltage.

The Final crossing angle for the LHC has not as yet been finalised but will lie between 315 µrad and 509 µrad. This corresponds to a nominal piwinski factor between 1.4 and 2.5 depending on the scheme finaly chosen [8].

The drop in luminosity for the two extremes expected for the LHC is summarised in table 1. For a piwinski angle of 2.5 a 10% variation in transverse kick would result in a 3% luminosity loss from an incorrect bunch rotation.

Table 1. Drop in luminosity for a Piwinski factor of 1.4 and 2.5 with a voltage variation of 3% and 10%

Piwinski factor	Luminosity loss with 3% variation	Luminosity loss with 10% variation
1.4	0.088%	0.966%
2.5	0.280%	2.986%

The variation in deflecting voltage will ideally be minimal at any offset from the centre of the cavity to ensure minimal loss of luminosity.

There are several other affects related to a variation in deflecting voltages such as incorrect cancellation of the crabbing voltage at the other side of the IP. However these effects have not yet been quantified.

VOLTAGE VARIATION ACROSS CAVITY

The initial cavity proposed as the 4 rod deflecting cavity had significant variation in transverse voltage across the aperture of the beam pipe. A partial redesign was undertaken to eliminate this variation..

It is well known that the electric field between two wide parallel plates is constant and hence has equipotential lines parallel to the plates. To reduce the change in transverse voltage at various offsets, a study was performed on simple plate-like rods. As the width of the plates decreases, fringing fields at the edges start to play a role in the linearity of the equipotentials, giving a large variation in transverse voltage for short plates. Large plate like rods unfortunately result in a significant drop in transverse R/Q as seen in figure 1.

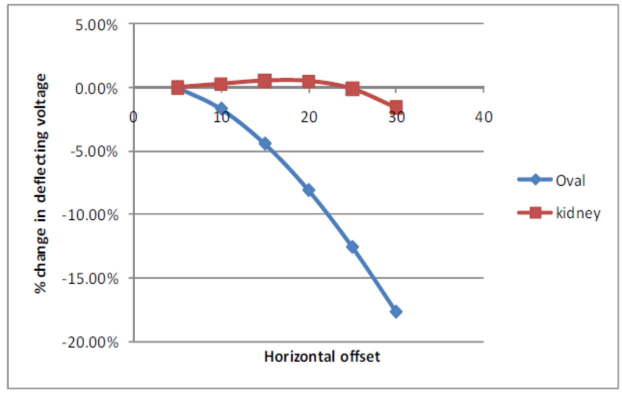

Figure 4. Proportional variation in the transverse voltage for old [oval] and new [kidney] shape.

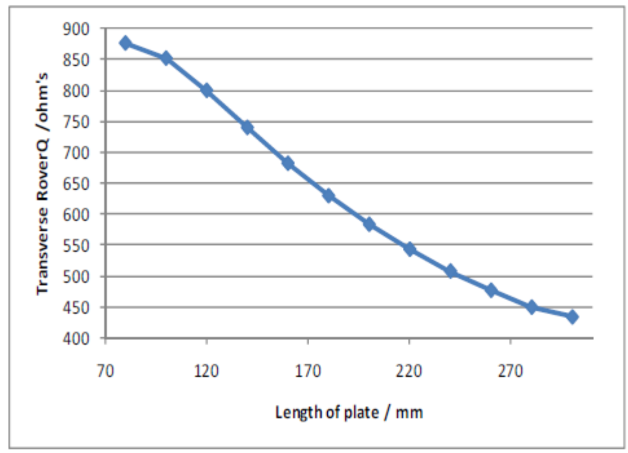

Figure 2. Variation in R/Q at increasing rod width.

The decrease in transverse R/Q, and an increase in the normalised peak electric and magnetic field at the operating voltage. To maintain acceptable peak surface fields while reducing the variation in transverse voltage the rod shape was altered by adding specially shaped electrodes to mimic the effect of wider rods by bending the finging fields inwards. This resulted in a rod that curved around the beampipe aperture. This produced a more uniform deflecting voltage across the centre of the aperture. The outer can shape was also altered to maintain low surface magnetic fields around between the outer can and rods as shown in figure 3, due to the slightly longer rods.

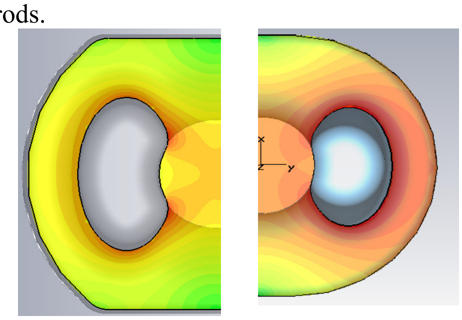

Figure 3. Comparison between new [Left] and old [Right] shapes showing the magnetic field amplitude at on a plane parallel to the rods.

The variation in transverse voltage is shown in figure 4 for the original and modified cavities. The horizontal offset is the offset in the plane of the rods, the vertical offset is that perpendicular to the rods. As can be seen there is a significant improvement in the uniformity of the deflecting voltage across the aperture particularly in the horizontal plane.

The final cavity has a peak surface electric field of 33.4 MV/m and peak magnetic field of 63.3 mT/m at a deflecting voltage of 3MV,

ALUMINIUM CAVITY MODEL

In order to verify the cavity design a full size prototype has been manufactured in aluminium by SG Instruments in the UK. Initial cavity measurements of modal frequencies, shown in Figure 7, and field profile from beadpull measurements are in good agreement with the CST simulations.

In future the beadpull measurements will be performed at various positions across the beampipe aperture allowing the verification of the variation in transverse voltage across the aperture.

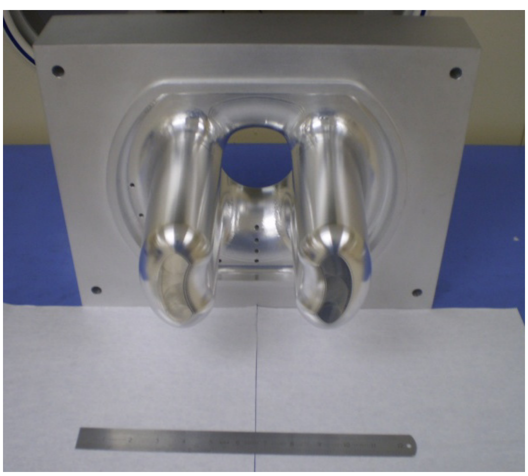

Figure 6. Base plate of the aluminium prototype.

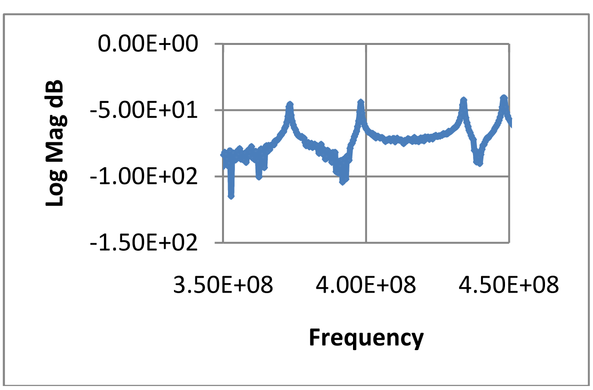

Figure 7. S21 measurement of the aluminium prototype cavity showing the first 4 TEM modes.

The measured modes correspond well with the simulations as seen in table 2. A slight shift of a few MHz is seen due to perturbations from the probes used to measure the cavities S parameters.

Table 2. Frequency comparison between simulation and initial tests.

Mode	Simulated Frequency (GHz)	Aluminium Frequency (GHz
LOM	0.3752	0.3734
Operating Mode	0.4000	0.3981
1st dipole HOM	0.4298	0.4341
1st monopole HOM	0.4350	0.4481

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 size constraints as well as providing suitably low peak magnetic and electric fields and provides low variation in transverse deflection to minimise luminosity loss.

The final design has a variation in transverse voltage of around 3% at a radial offset of 20 mm from the cavity centre. This cavity has has a peak surface electric field of 33.4 MV/m and peak magnetic field of 63.3 mT/m at a deflecting voltage of 3MV.

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