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Burt, G et al (ULAN-CI/STFC/CERN)

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DELIVERABLE REPORT

LHC CRAB CAVITIES

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Abstract:

A compact 400 MHz SRF crab cavity is designed for LHC. The design has low surface fields, has no hard multipactor barriers and fits within the transverse space available on the HL-LHC. The structure has been designed to have a constant deflecting voltage across the beam-pipe aperture and this has been verified on an aluminium model. The structure includes designs for the input and lower order mode couplers.

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	Name	**Partner**	**Date**
Authored by	G. Burt, B. Hall, A. C. Dexter, C. Lingwood, P.K. Ambattu, D. Doherty C. Hill, P. Goudket E. Jensen, R. Calaga	[ULAN-CI] [STFC] [CERN]	01/10/12
Edited by	G. Burt, E. Jensen,	[ULAN-CI] [CERN]	01/10/12
Reviewed by	P. McIntosh O. Napoly	[STFC] CEA	18/11/12 1/3/2013
Approved by Project Coord.	Jean-Pierre Koutchouk	CERN	13/3/2013

Executive Summary

Crab cavities are required for all next generation colliders, including ILC, CLIC and LHC. Each of these machines has different beam properties and hence require different cavity solutions.

The LHC has a very long bunch length (8 cm) hence a low frequency cavity of less than 400 MHz is required to avoid non-linear crabbing. This leads to extreme size constraints as the separation between incoming and outgoing beams close to the LHC interaction points is smaller than the size of a suitable pillbox cavity at 400 MHz. This means a novel compact crab cavity is required. A four rod deflecting cavity is proposed, consisting of four parallel quarter wavelength rods. The structure has been optimised for low surface fields and low sextupole components to the deflecting field. Input Power and HOM couplers have been designed and a prototype aluminium cavity has been produced, which has been characterised in terms of its electro-magnetic field performance. Based upon these results, an aluminium cavity prototype has also been fabricated, which has been used to verify simulation results. In addition, further funding has been secured which has enabled a niobium high-power cavity prototype to be fabricated, which is currently being prepared for vertical testing at the SM18 test facility at CERN.

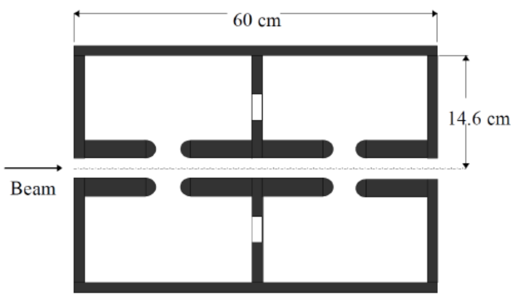
1.1 LHC Crab Cavity

The LHC Luminosity Upgrade will involve a reduced beta* from 55 cm to 15 cm to further increase the beam brilliance at the crossing points and thereby potentially enhance the luminosity. However, the beam crossing angle will have to be increased correspondingly to around 0.5 mrad to minimize the parasitic long-range beam-beam interactions on either side of the crossing points. The resulting reduction of the beam overlap would almost completely cancel the luminosity gain by beta* reduction. In order to restore the overlap and hence provide an effective head-on collision, RF deflecting cavities known as crab cavities, are used to rotate the bunch prior to collision at the interaction point [1]. In order to give a complete geometric overlap a voltage of around 10 MV is required. There is limited space between opposing beamlines hence the cavity must be less than 143 mm in horizontal size in the direction of the opposing line. For a pillbox cavity this would limit the frequency to over 800 MHz however as the LHC bunch length is around 80 mm the bunch would not be entirely in the linear region of the sinusoidal deflecting field hence giving the bunch an S shape. In order to fit the cavity in the available space without giving the bunch an S shape, a novel compact lower frequency cavity is required [2]. In order to realise a compact cavity design, a TEM mode must be used which requires two or more separate conductors separated by a large distance. Such a cavity has been utilised at CEBAF as a bunch separator [3]. It consists of two parallel rods with a capacitive gap in the centre to provide a 180 degree field rotation to remain in synchronism with the bunch, and is hence known as a 4 rod crab cavity (4RCC). However, the CEBAF cavity is normal conducting which will provide a much lower kick in CW operation compared to an SRF cavity. As the LHC energy is high, a large kick is required hence an SRF system has been adopted. Although a CEBAF-type deflector is proposed for LHC, several design changes are required for an equivalent SRF system [4].

1.2 Crab Cavity Structure design

There are several differences between the CEBAF cavity and what is required for LHC. Most importantly, the beam is much larger in all 3-planes and hence the beam-pipe aperture and the rod separation must be larger. The rods must also be much stiffer to reduce microphonic vibration. In addition, as the LHC is a circular machine, the transverse voltage must not vary across the beam envelope as each particle will vary its position in the bunch, turn after turn governed by its betatron motion. The two cavities are shown in Figure 1.

a)



b)

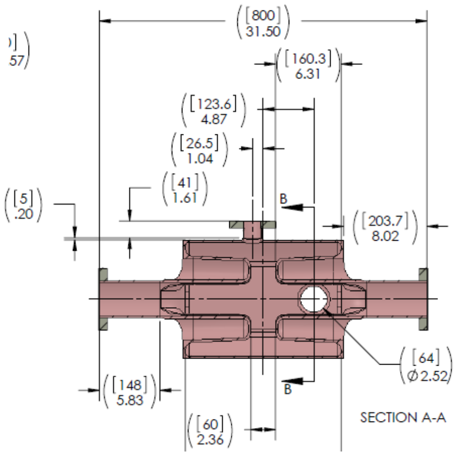


Figure 1 a) CEBAF deflector, and b) LHC crab cavity, with dimensions in mm.

Increasing the rod separation decreases the cavity voltage almost linearly with separation, hence it is necessary to reduce the surface fields to allow a higher voltage. The peak surface magnetic field can be reduced by making the base of the rod as large as possible, as shown in Figure 2. However the gap between the rod and outer can must also be increased to avoid magnetic field enhancement, resulting in an increase in the size of the cavity. The outer can is limited to 143 mm and this also limits the rod size. The rod size can be increased slightly by making the rods elliptical, as the vertical width is more important than the horizontal as the currents flow mainly on the vertical sides of the rod. The peak surface electric field is more difficult to reduce as it is linked to transverse voltage, however by rounding the rod tip increasing the capacitive gap between the tips and by slightly increasing the tip radius, an optimally reduced peak surface field has been achieved. Having a larger rod radius also helps reduce microphonic vibrations.

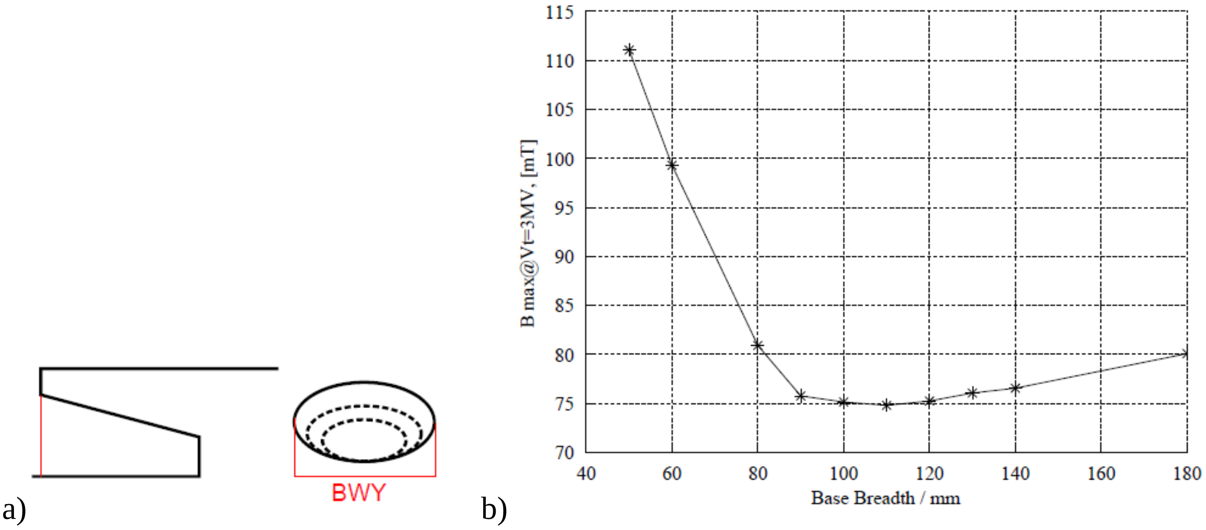


Figure 2. a) Schematic showing the rod base breadth and b) Variation in peak magnetic field as the rod base profile is altered.

A more complex issue is ensuring that the kick is roughly constant across the aperture. Effect of the non-linearity of the transverse voltage is still being studied at CERN but the approximate specification is it should not vary by more than 2% over 20 mm radii, which is approximately what is achieved with a pillbox cavity. If the rods were replaced with infinitely wide parallel plates then the fields in the gap would be constant however the shorter elliptical rods that fit the space requirements have a variation in transverse field across the aperture, as higher order multipole terms appear[5]. These higher order terms disrupt the linearity of the dipole field and are unwanted [6] and in order to make the fields uniform, two focus electrodes are added to each rod (creating a kidney shape), which transforms the equipotential lines to be linear across the beam-pipe aperture, as can be seen in Figure 3.

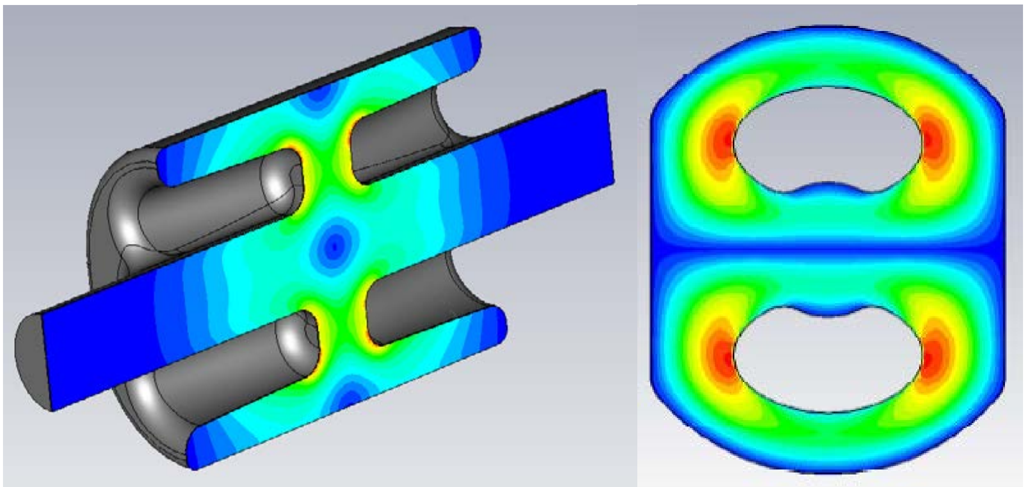


Figure 3. Geometry of the LHC 4RCC with electric field amplitude

The position of the focus electrodes was carefully optimised to reduce the sextupole component, which is the strongest multipole term after dipole. This was achieved by altering the profile of the rod to increase the length of the electrodes. As the length increases, the sextupole component decreases before becoming negative. It was thus possible to almost entirely eliminate the sextupole component. The reduction in sextupole components is shown by the increased linearity of the deflecting field [6,7]. This is shown in Figure 4 for the horizontal and vertical offsets anticipated. The final cavity parameters are shown in Table 1.

Table 1. Key parameters of the LHC 4RCC

Parameter	**Value**
Full Gap	60 mm
Length	380.7 mm
Beam-pipe radius	42 mm
Outer radius	140 mm
Beam-pipe rounding	60 mm
Rod, base and face rounding	20 mm
Tip rounding	20 mm
Tip width	110 mm
Tip breadth	70 mm
Mid width	72.5 mm
Mid breadth	125 mm
Base width	75 mm
Base breadth	140 mm
Emax @ 3 MV	37.2 MV/m
Bmax @ 3 MV	60.5 mT
R_T/Q	912.67 Ohms
Geometry factor	62.8 Ohms

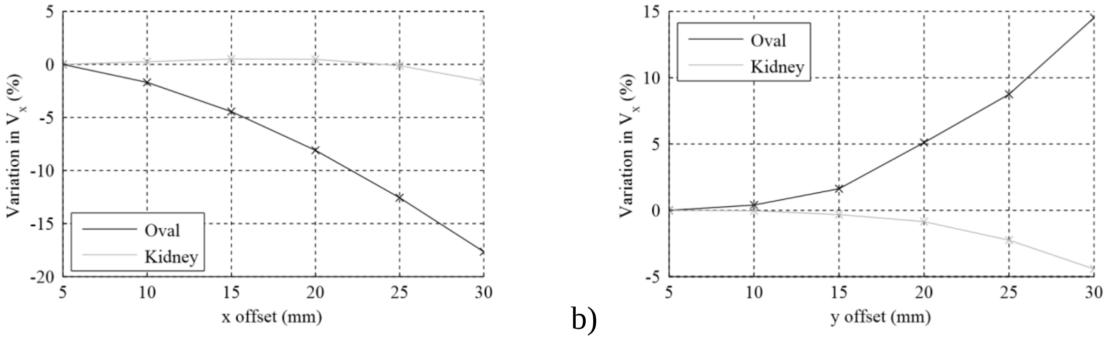


Figure 4. Percentage variation in the deflecting field in the a) horizontal [x] and b) vertical [y] directions.

The cavity design was studied for its multipole components. Assuming the variation in the dipole field follows the expansion:

$$V_z = a r\cos(\theta) + b r^3\cos(3\theta) + c r^5\cos(5\theta) \quad (1)$$

where r is the radial offset from the centre of the cavity and theta is the azimuthal angle. A Fourier transform was performed and the following multipole components were obtained which can be used by beam dynamics experts at CERN to investigate the effect of these on beam stability. The final multipole amplitudes are given in Table 2.

Table 2. Multipole components of the 4RCC

Component	Value
Dipole	$1.27*10^7$
Sextupole	$-5.62*10^7$
Decapole	$-1.47*10^{11}$

1.3 Multipactor

Due to the complex shape of the cavity, it was necessary to ensure that multipactor would not be a limiting factor to the cavity operation. Multipactor simulations were performed using CST Particle studio. The simulations are run for at least 200 ns, and the total number of secondary electrons created is divided by the total number of impacts to give an averaged secondary emission yield, <SEY>, for the simulation. As the simulation is run for at least 100 RF cycles only electrons involved in multipactor should remain and electrons not involved in multipactor should die out quickly and hence multipacting electrons should dominate the simulation. The simulations are ran over a number of phases and power levels. For each power level the highest <SEY> over all phases is recorded [8].

The simulations are dependent on the secondary emission yield of the material used. The secondary emission yield is strongly dependant on the surface properties rather than the bulk material itself and so the secondary emission yield for Niobium depends fundamentally on the preparation of the RF surface. Three different yield profiles were used to represent three levels of cleanliness:

1. A wet treated surface,
2. A 300 deg baked surface and
3. A discharge cleaned surface.

The wet treatment simulations showed a strong level of multipactor at voltages higher than 0.5 MV, located in the aperture of the beampipe close to the region of highest surface magnetic field. This is similar to the multipactor intrinsically found in the KEKB crab cavity. This multipactor was significantly reduced for baked cavities and only occurs at deflecting voltages above 2 MV. For discharged cleaned cavities no multipactor evidence was observed. The results for all three surfaces are shown in Figure 5. When multipactor occurs the electrons striking the surface often clean the surface similar to discharge cleaning, hence if multipactor occurs the simulations suggest that it can be processed through. Such multipactor is referred to as a soft multipacting barrier and should not introduce a major operational restriction.

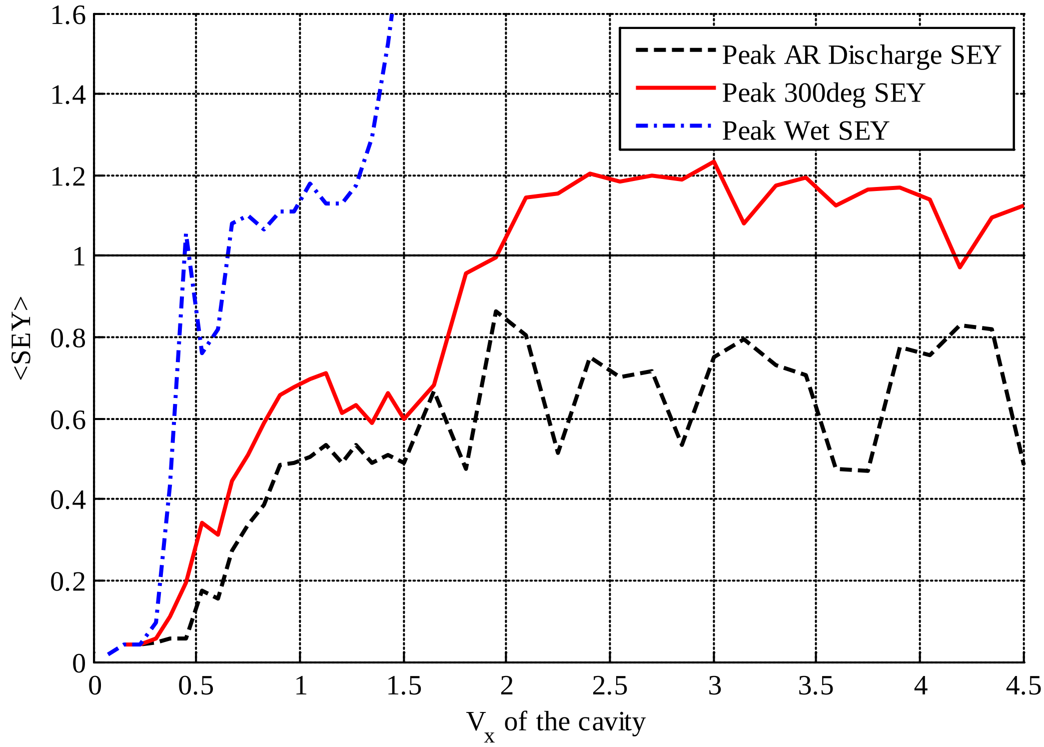


Figure 5. Peak SEY for the three different surface emission properties.

1.4 Input Power Coupler

The input coupler on the LHC crab cavity is required to deliver around 10 kW of CW power at 400 MHz to the 4RCC cavity. Space requirements do not allow the power to be fed horizontally to the cryomodule hence the power connections must come from either above or below the cavity. Feeding power to the cavity vertically would require magnetic coupling due to the polarisation of the crabbing mode, either through a waveguide or loop coupler. As the cavity is compact, a waveguide coupler would be as large as the cavity itself, even if ridged waveguide was used, hence coaxial coupling is the preferred solution. Loop coupling is complex as there must be a connection between the inner and outer conductor (although there may be a capacitive gap) and so are not preferred for high power couplers. It was therefore proposed to use the more standard electrical probe coupling, with the transmission line configured to be vertically mounted.

A 400 MHz, coaxial coupler with a power handling of a few 10's of kW CW is required hence it was decided to base the coupler on the LHC accelerating mode cavity coupler [9]. This has a 145 mm outer conductor diameter and a 75 Ohm impedance, and can handle a power of 100 kW CW. The outer conductor diameter is quite large compared to the cavity, hence it is tapered to a smaller p diameter of 64 mm. Initially the 145 mm diameter is tapered down to a 50 Ohm line keeping the same inner conductor diameter. Then the line is coupled at 90 degrees to a 50 Ohm T-section. One side of the T is terminated in a capacitive gap that can be adjusted to ensure a good match at 400 MHz. A smaller 64 mm 50 Ohm line is then coupled to the 4RCC cavity as shown in Figure 6. The 75 Ohm line will then be connected to the LHC coupler using the existing doorknob transition and RF window designs for the LHC accelerating cavities.

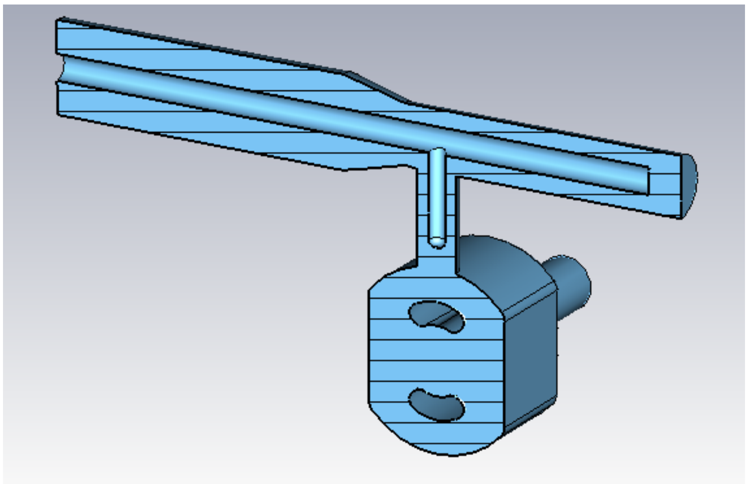


Figure 6. Position of the input coupler

1.5 HOMs and Couplers

The 4RCC cavity also has a lower order mode (LOM) as well as HOMs, which is a monopole type mode with a frequency at a lower frequency than the operating mode of around 360 MHz. Whilst this mode has a R/Q much less than the crabbing mode it is still around 125 Ohms and must be strongly damped. The R/Q of all modes have been calculated up to 2.5 GHz and are shown in Figure 7. The LHC monopole impedance specification is 0.6 MΩ, hence a Q of 4800 must be achieved to damp this mode [10]. As the LHC has a beam current of 0.5 Amps, this equates to a power of ~19 kW which will be deposited into the cavity if this mode is optimally excited by the LHC beam. In order to reduce this power to tolerable limits, the LOM impedance must be strongly damped, however a Q of 100 still equates to ~1.5 kW. It is clear that this mode requires a low Q to reduce the lower order mode power as much as possible and a LOM coupler that can handle high powers.

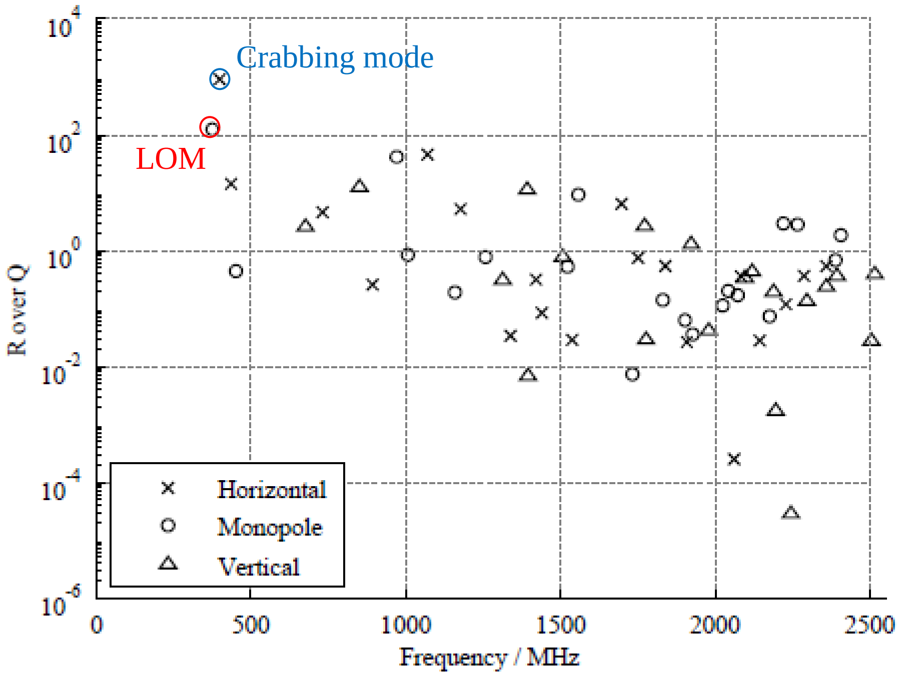


Figure 7. R/Q spectrum for the 4RCC

As the impedances of the LOM at 360 MHz and the next highest R/Q monopole mode at 950 MHz are much higher than the other monopole modes, a special narrowband coupler, with pass-bands at 360 MHz and 950 MHz is required. This coupler will be specially designed to handle high powers and will take this power outside the cryostat to an external load. As the LOM is close in frequency to the operating mode it would be difficult to design an adequate notch filter, therefore the coupler is positioned in the vertical plane to avoid coupling to the crabbing mode. A notch filter may also be used in case of misalignment but the geometry means that this filter doesn't need as much rejection as it otherwise would. The largest fields on the outer cavity walls are the magnetic and so magnetic coupling is required to achieve the low Q targets as identified above. Both waveguide and loop couplers have been considered, and both are capable of achieving Q factors of at least 100. A coaxial loop solution was however chosen, due to its smaller physical size. The loop coupler has been designed to be demountable to allow access for cleaning the cavity, hence any stubs or connections had to be located further up the outer conductor. The final design has two stubs for cooling, mechanical stability and to allow matching to both dangerous modes as shown in Figure 8. The coupler is capable of achieving Q factors as low as 100 but can be reduced by varying its penetration. Further electromagnetic design work is required to reduce the surface fields, and to design the vacuum window which requires incorporating into the LOM coupler design due to its potential high power operation.

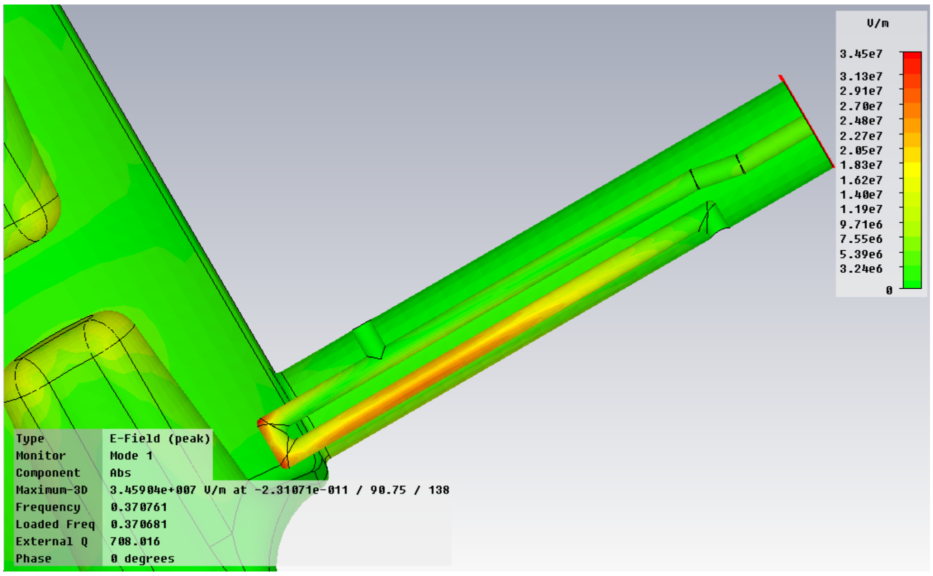


Figure 8. Proposed LOM coupler.

In addition to the LOM coupler, additional HOM couplers are also required to damp the HOMs to acceptable levels. These couplers, unlike the LOM coupler, must be broadband in order to effectively couple to all HOMs. It was decided to place a HOM coupler directly opposite the LOM coupler to help symmetrise the fields in the cavity. This coupler will magnetically couple to the horizontal and monopole HOMs. A fourth additional coupler may also be required to damp the remaining vertical HOMs and this is currently under investigation.

1.6 Prototype 4RCC Characterisation

An aluminium prototype of the LHC cavity has been manufactured by SG Instruments in the UK which is shown in Figure 9.

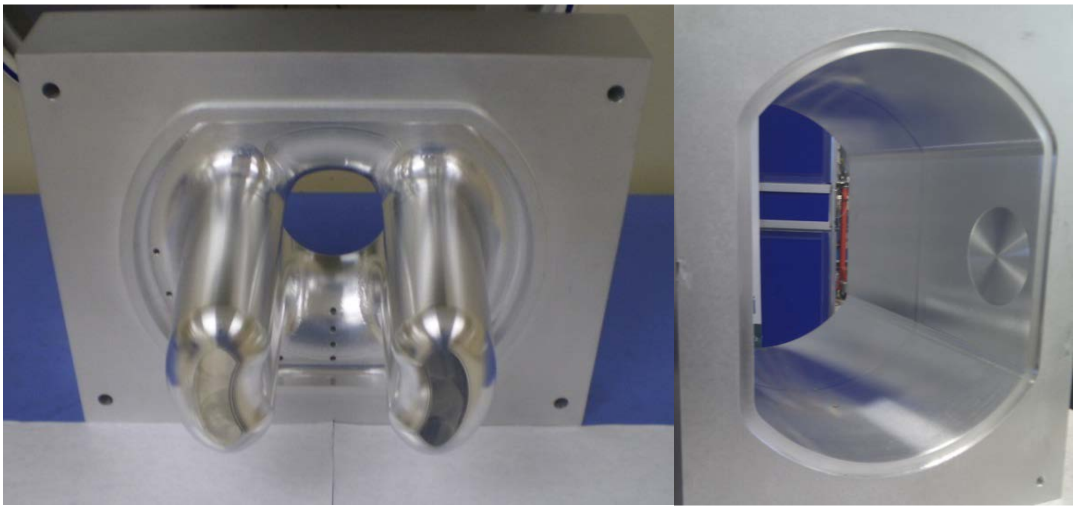


Figure 9. Aluminium prototype for low power testing.

The cavity has been used for perturbation measurements of the cavity fields to ensure the kick is constant across the aperture. This is performed by pulling a small metal cylinder through the cavity and observing the phase, and hence frequency shift, caused by the perturbation of the fields [11]. The simplest way to calculate the transverse kick is to create a map of the longitudinal voltage and use Panofsky-Wenzel theorem. The geometry of the cylinder is critical as the ratio of diameter to the length is proportional to the sensitivity of transverse fields, which add errors to the measurement. However if the cylinder is too long, the sharp peaks cannot be resolved and if the cylinder is too thin it will be hard to thread on the kevlar wire used to support it. A computational study was undertaken and a 30mm long needle with a 1 mm diameter was chosen [12]. The transverse fields provide a 5-10% error for a cylinder of this size, however a method of reducing this to under 1 % was devised. The transverse fields do not vary very much over the aperture due to the fact that the cavity has been designed to have a constant kick. This allows an on-axis measurement, where the longitudinal field is zero, to be subtracted from the off-axis measurement to leave only the longitudinal field.

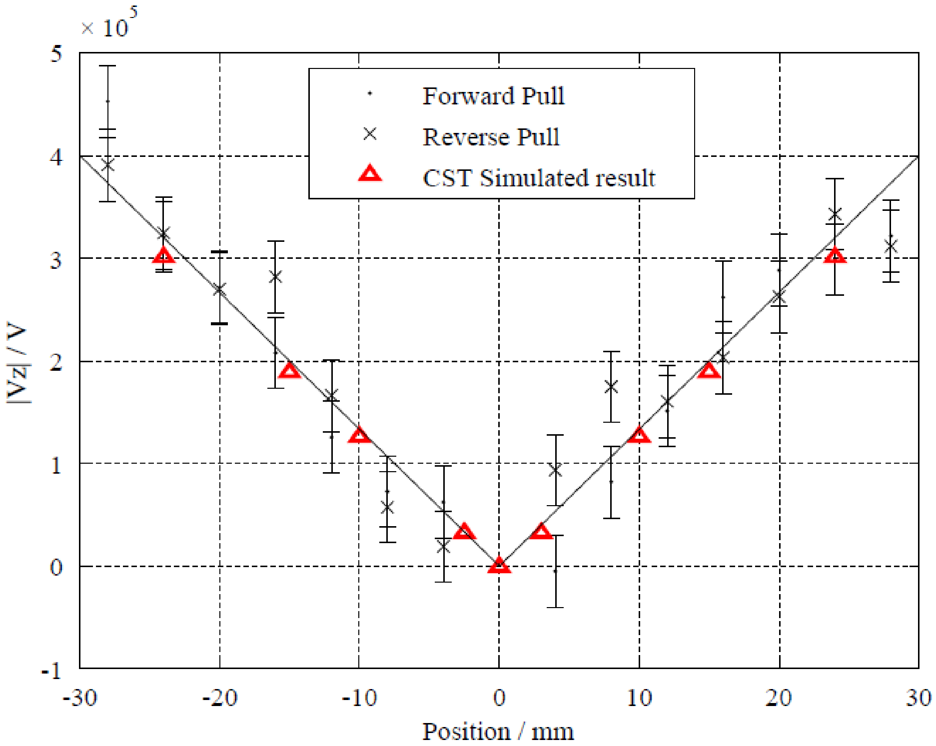


Figure 10. Comparison of beadpull and simulation of longitudinal voltage across the beam-pipe aperture.

The errors are still not at sufficient level to demonstrate linearity of the deflecting field to a sufficient level, as can be seen in Figure 10, and further work is ongoing to reduce the errors to a suitable level. Field profiles of the LOM was also taken, shown in Figure 11.

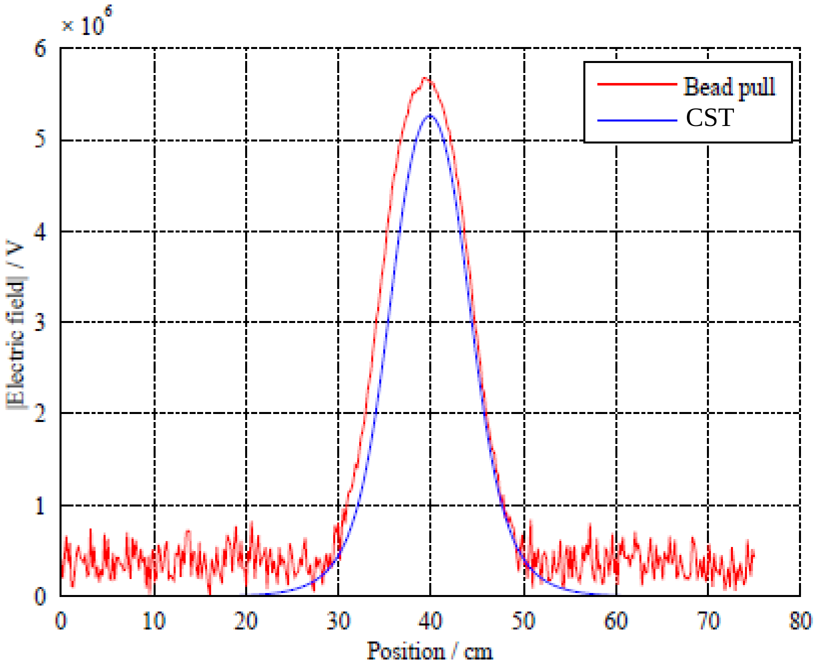


Figure 11. On axis electric field of the LOM measured by beadpull.

1.7 Niobium Prototype Cavity

A number of options for creating a niobium prototype were investigated, including deep drawing, extruding and CNC machining. The fundamental difficultly is in fabricating the rods and connecting them to the baseplate. Due to the shape of the rods an e-beam weld parallel to the surface would be required if the rod was to be made separately from the base plate. Changing the shape of the rod in the region of the weld was also investigated, but this made the manufacture of the rod more difficult or otherwise increased the surface magnetic fields in this region. It was decided that deep drawing or extruding the rods and baseplate from a single sheet was too difficult, hence decided solution was adopted to machine the baseplate and rods out of a solid niobium ingot. In order to reduce the total amount of Niobium required, and to reduce wastage, the rod widths were reduced so that the two parts could be interleaved, if rotated by 90 degrees, and hence made from a single block of niobium ingot, as shown in Figure 12.

Figure 12. Rod alignment for wire EDM cutting from single niobium ingot.

An order was placed with Niowave to produce a niobium prototype of the cavity which was completed March 2012. The final prototype cavity as fabricated by Niowave in the USA is shown in Figure 13. Beadpull measurements were performed at Niowave to ensure field uniformity in the cavity was maintained.

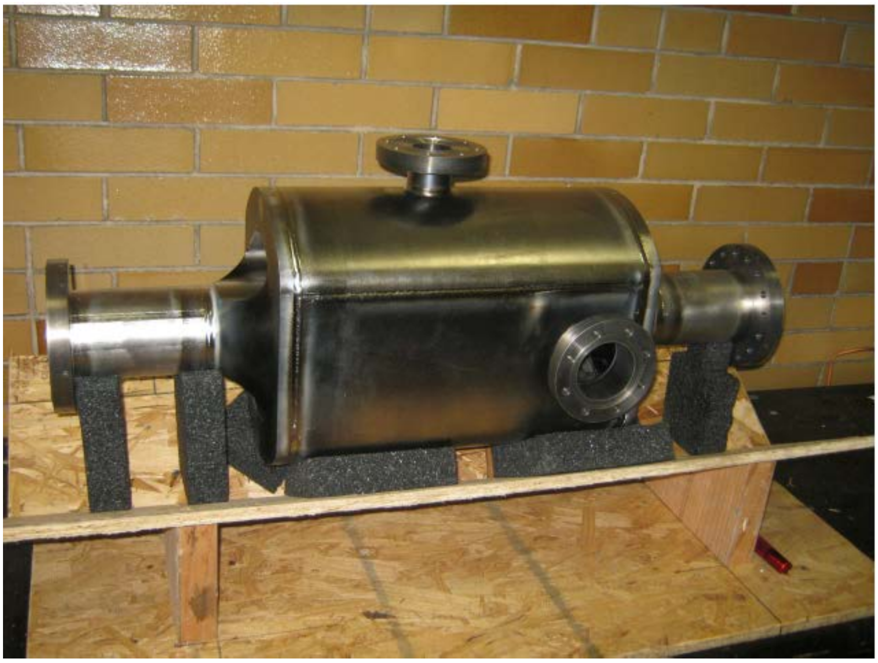


Figure 13. Assembled niobium cavity.

Niowave have subsequently performed a heavy BCP to remove 150 μm from the structure and performed an ultrapure water rinse before shipping to CERN. The cavity is currently being prepared for vertical testing at the SM18 test facility at CERN, which is expected to take place in November 2012.

1.8 Conclusions

A novel compact SRF deflecting structure has been designed for HL-LHC. The LHC cavity studied is a four rod deflecting structure which makes it ultra-compact and appropriately applicable for local crab crossing on LHC, which has been optimised for low surface fields, with a very high shunt impedance and highly compact transverse cross-section. The rod shape has been specially configured to minimise the sextupole component of the deflecting voltage to provide a uniform deflecting field as a function of transverse beam offset. The input power coupler is a coaxial type coupler with a T-section which interfaces to a cavity coupler design which is identical to that of the existing LHC accelerating mode 400 MHz SRF cavities. A special loop type coupler has been developed for damping the LOM and HOM impedances, with optimisation still being performed for the HOM coupler solutions.

An aluminium model was constructed to study the measurement of the field non-uniformity using a beadpull approach. The funding available under EUCARD meant that it was not originally proposed to fabricate and test an SRF cavity prototype, however through additional funding secured through the Cockcroft Institute, the collaboration has been able to design and fabricate a high power prototype SRF cavity which is currently being prepared for vertical testing at SM18 at CERN before the end of this current calendar year. This will be the world's first high field test of a compact SRF deflector and will be a major success of this programme. It was therefore felt worthwhile to delay the deliverable to include this as part of the final deliverable.

1.9 References

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1.10 Acknowledgements

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