MANUFACTURE OF A COMPACT PROTOTYPE 4R CRAB CAVITY FOR HL-LHC

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Abstract

A prototype compact SRF deflecting cavity has been manufactured for LHC. The base of the cavity has been machined out of large grain niobium ingot to allow the manufacture of the complex rod profile. Stiffening rods have been used to increase the mechanical strength of the outer can. Details of the cavity design and manufacture will be discussed.

INTRODUCTION

The LHC is planned to undergo a luminosity upgrade (HL-LHC) in 2020 to increase the luminosity by a factor of ten [1]. The upgrade will reduce the beta* down to 10 cm, which will require an increase in the crossing angle to reduce long range beam-beam effects. This will reduce the overlap between colliding bunches, thereby reducing the luminosity achieved, unless the bunches are rotated prior to collision. In order to rotate the bunches, we use transverse deflecting RF cavities operated in quadrature known as crab cavities. In order to have the bunch in the linear region of the cavities they must operate at a frequency of 400 MHz or lower. The available space in the LHC tunnel for the cavity means that an elliptical deflecting cavity, such as the KEK-B cavity [2] will not fit without impinging on the opposing beamline. The LHC hence requires a compact deflector which is physically much smaller than the operating wavelength. Several compact designs have been proposed [ref] and these have been narrowed down to three options: a double quarter wave cavity [3], an RF dipole [4] and a four rod cavity [5]. In this paper we focus on the four rod crab cavity development (4RCC).

CAVITY SHAPE

The 4RCC is a TEM type deflector, which has two parallel rods supporting a TEM wave between them with a short termination at each end to create the cavity geometry. Adding a large capacitive gap in the middle, provides an open termination ensuring that the transverse forces due to the electric and magnetic fields fields do not cancel within the cavity. The cavity also has an outer Nb shell around it to keep it under vacuum. The cavity geometry is shown in Figure 1. The HL-LHC upgrade programme requires a total voltage of 10 MV by three cavities hence each cavity must reach a gradient of 3.34 MV, as the cavity must operate CW , superconducting RF technology is preferred.

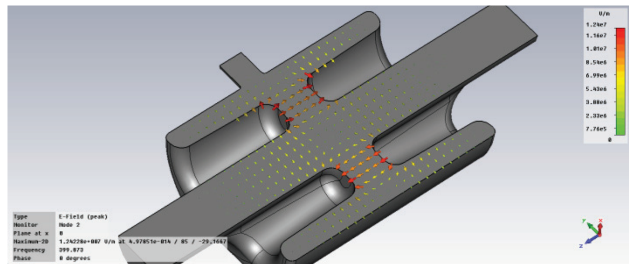

Figure 1: Cavity Geometry.

In order to reduce the peak surface fields, the rods are initially given elliptical cross sections. This allows the rod to be wide in the vertical plane while still keeping the cavity compact in the horizontal plane. However it was found that the deflecting voltage varied across the cavity aperture hence the rod has been curved to follow the circular aperture profile, as seen in Figure 1, to make the field more uniform.

MANUFACTURING OPTIONS

The complex shape of the cavity geometry make it difficult to manufacture. The length of the rods make it also difficult to fabricate with its base-plate from a single sheet using the traditional manufacturing methods of deep drawing or extruding, hence we initially investigated making these as separate pieces. A horizontal cut along the rods would involve currents running along a weld hence this option is not considered, hence we consider the two rods being made separately and electron beam welded to the base-plate. The joining of the rods to the base-plate is particularly difficult due to the complex rod profile required. While the first rod could be welded fairly easily, for the second rod the welder line of sight is obstructed, resulting in an almost parallel weld along the inside of the rod due to the complex rod cross-section. In order to simplify this weld, the geometry could be modified by moving the rods further apart at the base-plate and slanting them so that then have the correct separation at the tips of the rods or altering the rod profile near the base-plate. However these modifications made the manufacture of the rods more complex and increased the peak surface fields. In order to avoid these issues it was decided to machine the rods and base-plate as one piece from a block of large grain niobium ingot. Similar techniques had previously been realised at JLab on the SPX crab cavity [6] for Argonne National Laboratory.

WIRE EDM AND MACHINING

Machining the cavity out of Niobium ingot has a high material cost as there is potentially significant wastage as there is a lot of empty space. In order to reduce the amount of wastage and reduce the cost, it was investigated if the two sets of rods/base-plates could be made interleaved out of a single ingot, as shown in Figure 2.

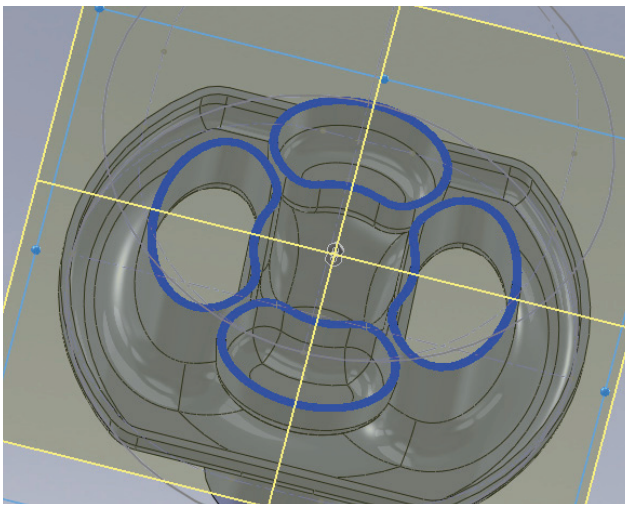

Figure 2: Alignment of the rods interleaved for wire EDM cutting from a single Nb ingot.

The initial cavity shape had wide rods meaning that the rods couldn't be interleaved, hence the rods were redesigned to make them slightly smaller to allow the rods to be interleaved leaving a 1 mm gap. This allowed for the ingot to be wire EDM into suitable shapes for machining the two parts.

The flanges on the cavity body were made from NbTi in order to reduce the RF losses on the flange, however the material was found to tear around the knife-edge and resulted in a vacuum leak when cold.

STRENGTH ASSESSMENT

The cavity should be able to withstand a pressure of 2 bar on the outside and vacuum on the inside. The stress on the vacuum vessel was calculated in ANSYS at a pressure of 2 bar [7]. It was found that the stress was around 137 N which is larger than the yield strength of niobium at room temperature. This is due to a large flat section on the cavity body. In order to reduce the stress eight NbTi bars were e-beam welded on to the cavity body to decrease the stress on the cavity body, shown in Figure 3. Although the stress is higher, the high stress regions are on the NbTi bars which have a much higher yield strength and the stress on the Nb was reduced to 70 Mpa. In future iterations of the cavity the outer can shape can be modified to add curvature to the flat section to stiffen its shape.

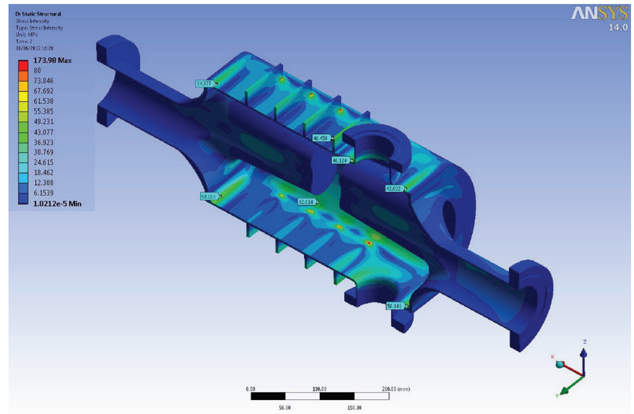

Figure 3: Stress analysis of the cavity at a 2 bar pressure.

CAVITY MANUFACTURE

The cavity was manufactured by Niowave Inc (USA). The cavity base-plates were made from RRR=224 large grain ingot niobium. The outer can and beampipes were rolled from RRR > 300 4 mm thick niobium sheets. The parts before welding are shown in Fig 4.

Figure 4: All cavity parts before welding.

All weld surfaces were given a 20 μm etch and the entire baseplate/rods were given a 50 μm etch and visually inspected before e-beam welding. The cavities were electron beam welded, and visually inspected. The weld seam between the outer can and the base-plate is shown in Figure 5 and the finished prototype is shown in Figure 6. After welding the cavity was leak checked to 1×10^{-10} Torr -L/s.

Before welding the cavity frequency was measured and a beadpull measurement was performed to ensure cavity symmetry. The cavity frequency was measured after welding to be 399.557 MHz which is around 500kHz lower than before welding. The simulated frequency was 399.8 MHz. It had an ohmic Q of 3324 when warm.

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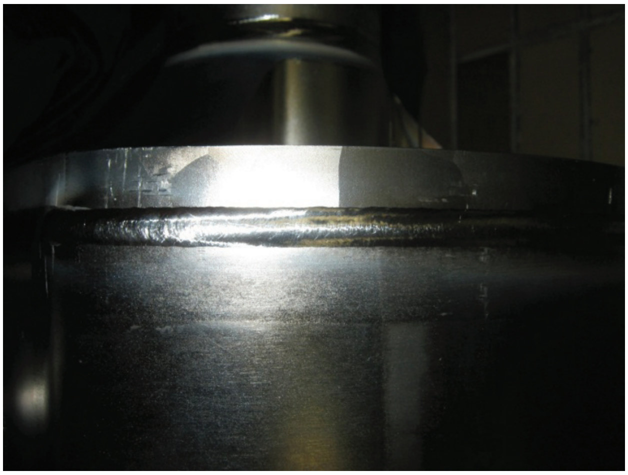

Figure 5: Cavity weld seam between outer can and the base-plate.

Superconducting cavities with components machined by wire EDM have performed very well, exceeding 100 mT peak magnetic fields.[8] However, these manufacturing techniques remain relatively new, and it was decided to remove a significant layer material with a 150 μm BCP etch and ultra-pure water rinse before shipping to CERN for testing. The acid flow rate was controlled to 0.32 l/sec and then later reduced to 0.13 l/sec for a slower removal rate. During the BCP etch, the cavity body was cooled by spraying chilled water on to the surface to keep the temperature between 5 – 9°C.

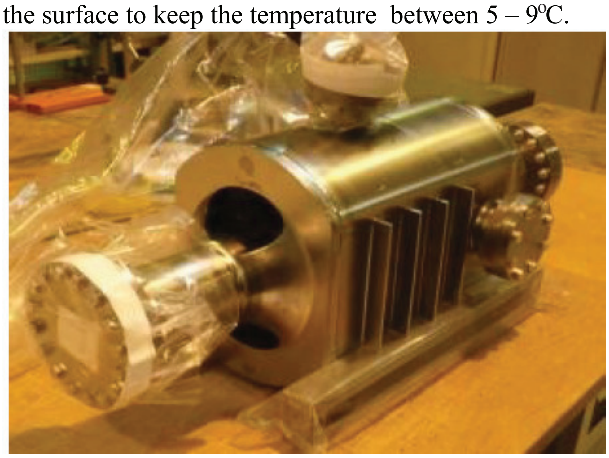

Figure 6: Finished prototype four rod crab cavity.

CONCLUSIONS

A prototype four rod crab cavity has been manufactured by Niowave. The cavity rods were machined from large grain Nb ingot in order to create the complex shape and has stiffening ribs e-beam welded on to reduce the stress on the outer can when under vacuum. The cavity has been delivered to CERN to undergo vertical testing. The cavity has undergone initial testing at SM18 at CERN and is now undergoing final processing before further testing to achieve the design deflecting voltage of 3.3 MV [9].

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