ENGINEERING OF A SUPERCONDUCTING 400 MHZ CRABBING CAVITY FOR THE LHC HILUMI UPGRADE*

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Abstract

The recently developed new simplified design for the 400 MHz LHC crabbing cavity presents attractive properties compared to conventional designs. The proposed approach can be equally compact in both transverse dimensions and allows horizontal as well as vertical deflection of the beam in the collider. The significant modification of the parallel-bar design with the bars merged to the side walls of the cavity gives improved properties, such as better mode separation and reduced surface fields [1]. A transverse deflecting voltage of 4.2 MV in a single cavity can be expected with the peak surface electric field lower then 45 MV/m and peak magnetic field below 80 mT. This paper presents engineering issues of the proof-of-concept crabbing cavity design and discusses the manufacturing techniques. The paper discusses present status of the project including fabrication of the niobium cavity, as well as room temperature and cryogenic testing.

INTRODUCTION

Superconducting radio frequency (SRF) cavities are being successfully used for acceleration of charged particle beams worldwide. The application of the SRF cavities for manipulation of the beam properties in the transverse direction is both immanent and appropriate. The use of superconducting (SC) structures helps maximize the accelerating gradient, which is a highly desirable trait for applications involving manipulations of the charged particle beams at the point of delivery, such as Final Focus point or the experimental areas. Compact equipment utilizing SRF cavities can be successfully used in the broad range of applications from increasing of the beam luminosity in colliders, manipulation of the correlation between the longitudinal and transverse phase space projections of the beam particle distribution, to assistance in generation of the sub-picosecond x-ray pulses.

This paper describes the development of a 400 MHz superconducting parallel-bar crabbing cavity capable of tilting the proton beam with energy of up to 7 TeV at the Final Focus point with help of a single unit. The transverse size of the cavity is significantly reduced due to using the parallel-bar geometry compared to the traditional elliptical accelerating structures. Work in collaboration between Niowave, Inc [2], and Old Dominion University (ODU) demonstrated the technical feasibility of the project by completing cavity design and manufacturing the reduced scale aluminium as well as full scale niobium prototypes.

Series of the room temperature RF tests of the completed niobium cavity were performed at Niowave, and the cryogenic tests will be carried out by ODU in collaboration with the Thomas Jefferson National Laboratory (JLAB). Demonstration of this new type of SRF crabbing cavity creates many new possibilities for scientific and industrial applications.

ELECTROMAGNETIC DESIGN

The Large Hadron Collider (LHC), whose commissioning was finished in 2009, will be at the energy frontier in high energy physics for many years to come. Even before being operational, plans have been under discussion for an upgrade, in particular toward an increase of its luminosity.

One venue for doing this is the introduction of a bunch crabbing scheme to restore the luminosity lost due the finite crossing angle. The LHC bunches are fairly long and, in order to gain the maximum benefit from crabbing technique, the curvature introduced by the RF field must be kept to a minimum, which implies low RF frequency of 400 MHz or lower. Unfortunately, all conventional designs for RF crabbing cavities are larger at that frequency than space allows.

Recently, a new design for deflecting/crabbing cavities was introduced that is about half the size of conventional design and, at the same time, has other attractive properties. The goal of this research is to develop a 400 MHz superconducting crabbing cavity that would satisfy the requirements of the LHC luminosity upgrade.

RF cavities for the deflection or crabbing of particle beams have been developed for many years. Most of the existing devices performing this function are comprised of superconducting cavities operating in the TM_{110} mode [3-6] although some are room temperature structures operating in a $\lambda/4$ mode [7] or are of *H*-type [8]. Crabbing RF structures have been of interest for the increase of luminosity in colliders [9,10], and more recently for the generation of sub-picosecond x-ray pulses [11,12].

The concept of the parallel-bar deflecting structure is shown in Figure 1. It consists of 2 parallel $\lambda/2$ TEM resonant lines operating in opposite phase. The voltages generated are maximum and of opposite sign in the middle of the rods and generate a transverse electric field. The magnetic field is null in the mid-plane containing the beam line and is maximum where the bars meet the shorting planes. Thus, unlike TM_{110} structures where the deflection is produced by interaction with the magnetic

* This work is supported by the US DOE-HEP SBIR/STTR program and the US DOE through the US LHC Accelerator Research Program (LARP).
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ISBN 978-3-95450-115-1

field, in the parallel-bar structure, the deflection is produced by interaction with the electric field.

Figure 1: Concept of the parallel-bar deflecting structure.

Further research of the proposed structure reviled the possibility to significantly improve the critical parameters by extending the bars to the side walls of the outer conductor of the cavity [1]. The resulting cavity shape is shown in Figure 2 with the corresponding configuration of the electric and magnetic fields shown in Figure 3. Major cavity design parameters are given in Table 1.

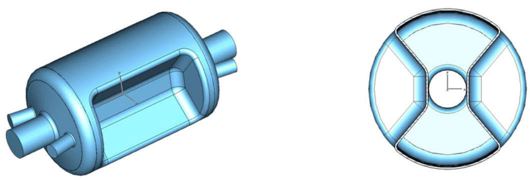

Figure 2: Improved parallel-bar deflecting structure.

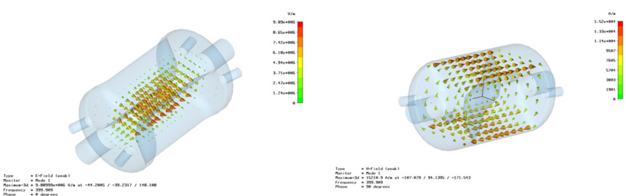

Figure 3: Electric (left) and magnetic (right) field distribution in the improved parallel-bar deflecting structure for the operating fundamental mode.

MECHANICAL DESIGN

Niobium cavity fabrication process, besides manufacturing of the niobium parts, includes electron-beam welding and the chemical processing with following high-pressure rinsing of the inner cavity surface in the clean room environment – all, except the EBW, done in house at Niowave.

Figure 4 shows the final assembly mechanical drawing of the manufactured cavity. On the first stage three separate subassemblies of the Outer Conductor (central) part, and two End-Cup subassemblies are manufactured and electron-beam welded (EBW), as shown in Figure 5. And at the final stage the three subassemblies are welded together with electron beam.

RF MEASUREMENTS

The first round of room temperature RF measurements is performed before the final EB welding of three subassemblies in the vertical stack-up configuration. After the final welding the follow-up room temperature RF measurements are performed at the same time as the leak-check of the cavity is done, as shown in Figure 6.

Table 1: Major geometric and RF design parameters of the improved parallel-bar crabbing cavity.

Parameter	Prototype Design	Units
π-mode frequency	400.0	MHz
π-mode half-wave length	375.0	mm
0-mode frequency	729.5	MHz
Nearest HOM frequency	593.4	MHz
β_0	1.0	
Cavity Geometry		
Length	633.2	mm
Radius	174.4	mm
Bars length	633.2	mm
Bars inner height	15.0	mm
Angle	50.0	deg
Aperture diameter	40.0	mm
Cavity RF Properties		
Deflecting voltage V_T	4.2	MV
E_T	11.2	MV/m
E_{peak}	42.8	MV/m
B_{peak}	79.4	mT
Stored energy U	23.8	J
$[R/Q]_T$	312.2	Ω
$G=R_s \cdot Q$	119.7	Ω
$R_T \cdot R_s$	3.7×10^4	Ω^2
P_{loss}	40.4	W

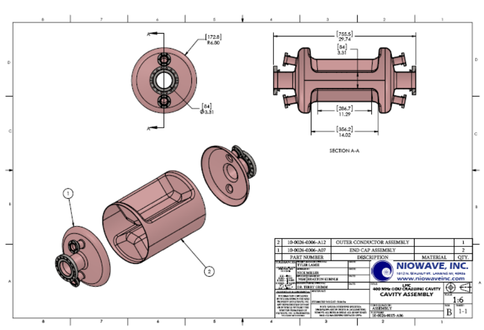

Figure 4: Final assembly mechanical drawing of the 400 MHz Crabbing cavity for LHC HiLumi Upgrade.

Figure 5: Crabbing cavity subassemblies (left and middle) and the full EB welded cavity (right).

Figure 6: Finished cavity leak-check and final round of room temperature RF measurements.

Figure 7 shows the preliminary RF measurements of the cavity before the final EB welding in the stack-up configuration, and the measurements of the welded cavity after the final weld. An additional 18 dB RF amplifier was used for the preliminary measurement due to weakening of the signal in the stack-up configuration.

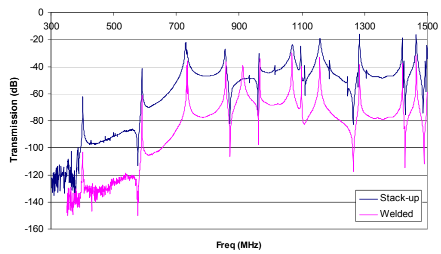

Figure 7: Preliminary RF measurements of cavity before final EB welding in the stack-up configuration, and measurements of welded cavity after final weld.

After the final welding of the cavity, additional measurements took place in parallel with the final welded cavity leak-check. The resulting dependence of the frequency on vacuum pressure inside the cavity is shown in Figure 8. The residual inelastic deformation of the cavity shape after several consecutive pumping stages was quickly diminished after the first two pump-downs, and was found insignificant. Further investigation of the need for reinforcing ribs is part of the new project that includes full design of the cryomodule for the crabbing cavity for the LHC HiLumi Upgrade.

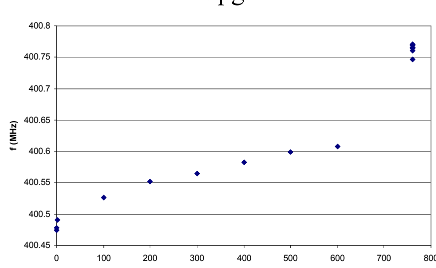

Figure 8: Finished cavity leak-check and final round of room temperature RF measurements.

NEW DESIGN FOR 750 MHZ

The immediate follow-up of the present project is the design of the new crabbing cavity at 750 MHz for Jefferson Laboratory (JLab) CEBAF accelerator upgrade [13]. The proposed cavity design is very scalable, and it can be successfully used for different frequencies and beam requirements. The proposed cavity design is shown in Figure 9. In the framework of this new project Niowave is building a vertical dewar for making the cryotest of the prototype cavities in house.

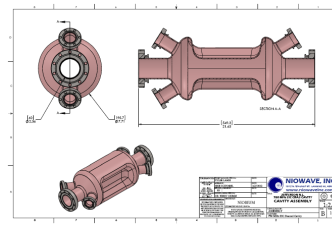

Figure 9: 750 MHz crabbing cavity design.

CONCLUSION

The most significant accomplishment of this work is the successful development of a new type of the superconducting RF crabbing/deflecting cavity. The transverse size of the cavity is significantly reduced compared to the traditional elliptical structure.

The next significant accomplishment is the continued emergence of the US industrial capability to build superconducting cavities that are ready to be used in existing and perspective projects. This capability had previously only existed inside the national laboratories. With the cryotesting capability moving to industry, many opportunities open up for commercial applications of the efficient SRF technology.

ACKNOWLEDGMENT

Authors thank Alejandro Castilla from ODU for information on the new developments of the 750 MHz JLab crabbing cavity design. Special regards are due to the technical personnel at Niowave, Inc., especially Brian Deimling, Tyler Lamie, Brett Kuhlman, and Cody Knowles, for their professional assistance in conducting the manufacturing and testing of the cavity.

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ISBN 978-3-95450-115-1