DEVELOPMENT OF 1.3 GHz PROTOTYPE NIOBIUM SINGLE CELL SUPERCONDUCTING CAVITY UNDER IIFC COLLABORATION

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Abstract

Under Indian Institutions Fermilab Collaboration (IIFC), Raja Ramanna Centre for Advanced Technology (RRCAT), Indore, Inter University Accelerator Centre (IUAC), New Delhi and Fermi National Accelerator Laboratory (FNAL) have developed two prototype 1.3 GHz niobium single cell superconducting (SC) cavities. Development of forming tools, forming of half-cells, machining of components, development of welding fixtures along with RF & vacuum qualification were carried out at RRCAT. The electron beam welding was carried out at IUAC. The fabricated prototype cavities were tested for RF and vacuum leak tightness up to 77 K at RRCAT before shipment to FNAL. Processing, consisting of Centrifugal Barrel Polishing (CBP), Electro Polishing (EP), and heat treatment was carried out jointly by FNAL and Argonne National Laboratory in USA. Both the prototype cavities were tested at 2 K in the VTS facility at FNAL and achieved the accelerating gradients of ~ 19 to 23 MV/m with Q>1.5 E+10. This paper will report the development efforts carried out in the tooling, forming, machining, welding & various qualification procedures adopted. The paper will also present the processing and the 2 K test results.

INTRODUCTION

Development of two 1.3 GHz bulk niobium single cell SCRF cavities was completed within the framework of the MoU between Indian Institution and FNAL concerning collaboration in "Superconducting Radio Frequency (SCRF) Science and Technology Addendum-I". These single cell 'elliptical' cavity use the TESLA shape design. The aim of these fabrication efforts is to gain experience in this highly specialized technology that will be needed for various upcoming accelerator projects employing SCRF technology.

CAVITY DEVELOPMENT

Fabrication & testing of single cell cavity is a standard practice for development of various crucial elements of the cavity development cycle.

Forming Tool Development & Cell Forming

Cavity development started with design and development of the half cell forming tools. Correct cell form is important to reach the desired resonant frequencies (accelerating mode and higher order modes) at specified cavity length. This governs the geometrical profile accuracy requirement of the cell form to less than 0.2 mm. Under IIFC collaboration, RRCAT has designed & developed two sets of forming tooling. One set was delivered to FNAL and second set was used for all forming work performed at RRCAT. The highlights of the forming tool development include several; unique improvements in the die shape, strategy for handling unavoidable thickness variation, orthogonal error correction of the formed parts and high degree of parallelism obtained on the equator and iris surfaces of the cells. A number of forming trials were taken in aluminum and copper before forming niobium half cells. The forming tool is made of aluminum alloy AA7075-T6. Four precisely shaped parts viz. male forming die, female forming die, hold down plate and coining ring (Fig-1a) constitute the forming die. A 200 ton hydraulic press with a die pillar set was used to form the half cells.

Figure 1: a) Forming tool, b) Half cell forming

Cavity Engineering Design & Fabrication:

For cavity fabrication the standard DESY recipe [1] was followed to the extent possible with added FNAL experience of 3.9 GHz cavity fabrication [2]. Design for manufacturing was done that included square butt joint type weld edge design, welding lip at the backside of flange joint and no recess in the flange bore. The HF Emag eigen mode analysis was done with ANSYS using 20 noded hexahedral (HF120) element. RF frequency estimation was also done for change in frequency (Table-1) with temperature and extra lengths at equator. The equator frequency sensitivity coefficient K_{eq} is estimated to be -5.1 MHz/mm.

Table 1: Estimated Frequency at Different Temperatures

Temperature	300 K	77K	2K
Frequency MHz	1297.2872	1299.8814	1300.00

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A detailed manufacturing plan was developed consisting of stage wise machining with intermediate RF measurement and mechanical inspection. Frequency measurements were made at the half cell assembly stage that determined the required material trimming from the half cell equator. The beam tubes were rolled using dedicated precision rolling machine. Fabrication of the machining fixture, parts machining as well as inspection of various tooling and completed components were all done at RRCAT. [3]

Electron Beam Welding

In order to satisfy the joining requirement of high RRR Nb for the RF performance, the joining of parts of SC cavity is done by EB welding. EB welding was performed at IUAC (Fig-2b). Welding fixtures, suitable for Nb welding, were designed & developed in collaboration with IUAC. Weld shrinkages were accounted for during machining of parts to control the final frequency with additional length needed at operating temperature. Intermediate frequency measurement were made and cell length tuned at the equator. The bulk BCP etching (20µm) was skipped due to limitation in the available infrastructure. The parts were ultrasonically degreased (Fig-2a) and subjected to pre-weld etch (3µm) just before welding. Pre-loading was used during welding to compensate the weld shrinkage. The welding was performed at $<5\times10^{-5}$ mbar pressure.

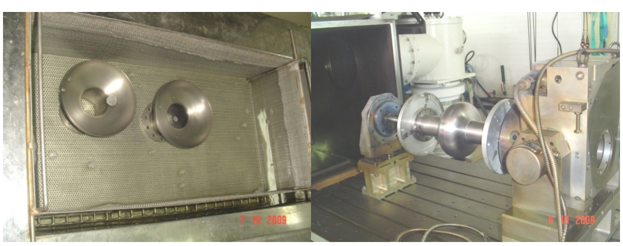

Figure 2: a) Ultrasonic cleaning of welded half cell assemblies, b) Final equator welding setting at IUAC, EBW facility

PRE QUALIFICATION

The completed cavities were subjected to pre-dispatch inspection qualification that included mechanical dimensional control followed by RF & vacuum leak test both at 300 K & 77K (Fig 3 a,b).

Table 2: Mechanical, Weld Shrinkage, Frequency data

Cavity ID	Length (mm)	welding shrinkage (mm)	Frequency (MHz) 300K	Q-factor at 300K
TE1CAT001	393.58	0.46	1296.926	9076
TE1CAT002	392.96	0.42	1296.675	9328

Figure 3: a) RF measurement at 300 K, b) Leak testing & RF measurement at 77K.

Table-3: Frequency Measurements Results at 300 & 77 K

Cavity No.	Measured RF Frequency (MHz)	
	At room temp (Vacuum)	At 77 K
TE1CAT001	1297.2666	1299.3333
TE1CAT002	1296.73333	1298.8666

The shift in frequency from 300 K to 77 K was measured to be about 2 MHz which corresponded well with the estimated values.

After all the pre-dispatch inspection and testing the cavities were shipped to FNAL for processing and performance evaluation at 2 K.

PROCESSING AND TESTING

Upon arrival at FNAL, these cavities received RF measurement and internal optical inspection. The internal optical inspection revealed certain features at the inner equator weld bead suggesting the need of polishing stage. The cavity TE1CAT001 was taken for CBP followed by post processing while TE1CAT002 was prepared using standard processing steps consisting of EP ~120µm (Fig 4a) , high pressure rinsing (85 bar, 6 hrs) followed by clean room (class-10) assembly (Fig-4b). Before 2 K testing the cavity was subjected to low temperature bake (120°C, 48 hrs). The cavity when tested at 2K was field emission free and was quench limited at E_{acc} of 21 MV/m with Q > 1.5E+10.

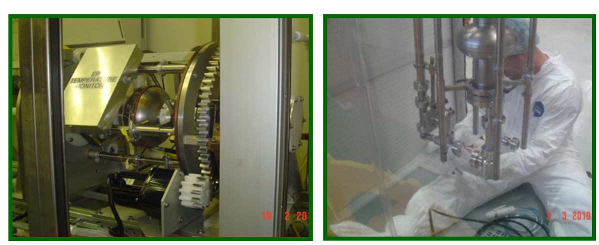

Figure 4: a): EP set-up, b) Preparation of cavity for 2 K test.

TE1CAT001 was subjected to CBP to even out and polish the inner-equator weld features. A total of four polishing cycles were done with different media. The measured material removed near equator was 140µm while that near iris was 40µm. (Fig-5)

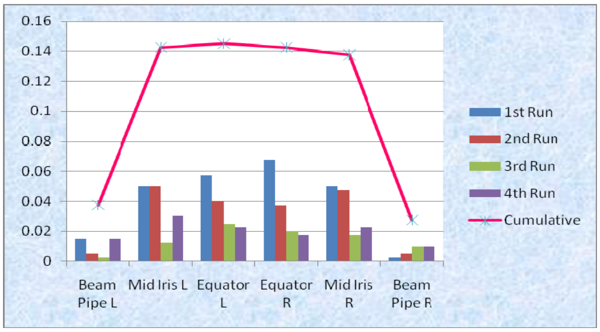

Figure 5: Plot of material removed during CBP.

The cavity was subjected to optical inspection before & after the CBP and inner weld feature is shown in Fig 6a and b)

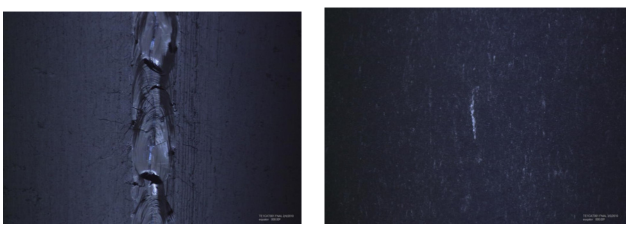

Figure 6: Inner equator bead before & after the CBP.

The CBP treated cavity was subjected to additional heat treatment under vacuum at 800°C for 6 hrs to remove hydrogen. This was followed by light EP 20µm, HPR, clean room assembly and low temp bake 120°C for 48 hrs before the vertical test.

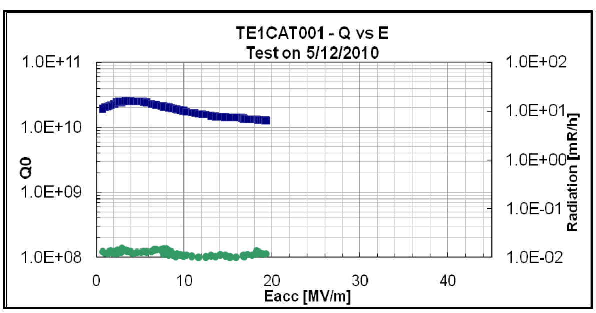

Figure 7: Q vs E plot of TE1CAT001

The cavity achieved E_{acc} of 19.3 MV/m with Q > 1.5E+10. It was also field emission free and quench limited. (Fig-7)

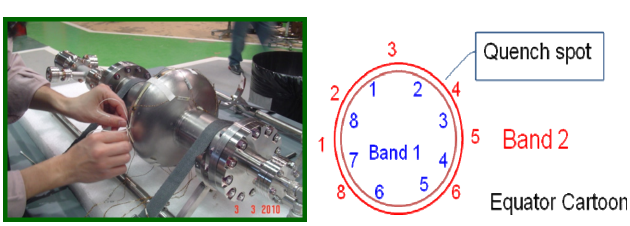

Figure 8 a) Cavity preparation with temp sensor & b) equator cartoon of sensors on each band.

During 2 K testing 16 temperature sensors (cernox) were mounted near the equator (Fig 8 a & b). Strongest quench (temperature) signal was on sensor #2, band1. Next strongest was on sensor #4 of band 2, Then sensor #3 of band 2. The internal inspection of quench spot showed some unfinished weld bead spot.

As a repeat effort, the cavity TE1CAT002 was also subjected to CBP similar to that done on TE1CAT001. This again was followed by the processing steps consisting of vacuum heat treatment (800 °C- 6hrs), light EP (20µm), high pressure rinsing and a low temperature bake (120°C-48 hrs). The cavity when tested at 2 K in the VTS test showed a further improvement of E_{acc} to 23 MV/m. (Fig-9 shows the result and also compares the test result of run 1). In the fast thermometry system, temperature spikes indicative of a quench origin were observed. It was concluded from optical inspection and t-map that the quench locations definitely were away from the remaining poor geometrical weld beads after tumbling or EP. Subsequent X-Ray tomography inspection of the weld showed voids at certain location of equator.

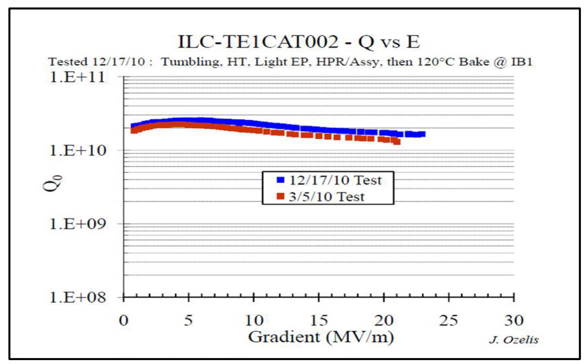

Figure 9: Q vs E plot of TE1CAT002

SUMMARY

Two protootype 1.3 GHz bulk niobium single cell cavities have been fabricated & tested as a technology demonstration phase. The 2-K testing results, though moderate are comparable with some of the other initial results and have given invaluable experience both in assimilation of SCRF technology and in exploring International collaborations in this technology. A number of lessons were learnt that will help improve the cavity manufacturing process. Key area identified for further improvements include 20µm bulk BCP etching and better quality in equator welding. Our present focus is on making two more single cell cavities utlising the improved manufacturing technique.

REFERENCES

[1] DESY- specification of welded 1.3 G Hz Superconducting resonator for TTF-FEL, D. Proch, MHF-SL, 1-1999

[2] 3.9 GHz, 3rd Harmonic SCRF, Fabrication of the Niobium Cavity and End-Groups, FNAL Note 8/3/2005. Mike Foley, Don Mitchell, Al Beutler, Scott Reeves.

[3] Technology Developments efforts on fabrication of Superconducting Cavities at RRCAT A. Puntambekar, M. Bagre, S C Joshi at el, InPAC, February 2011 IUAC, INDIA