Fabrication of niobium superconducting accelerator cavity by electron beam welded joints

T.K.Saha[1], J. Mondal[2], K.C.Mittal[2], K.G.Bhushan[3] and A.V.Bapat[1]

[1] Power Beam Equipment Design Section
[2] Accelerator and Pulsed Power Division
[3] Technical Physics Division
Bhabha Atomic Research Centre, *Mumbai-400085, India*

Email. tanmay@barc.gov.in

Abstract. Fabrication of superconducting cavities has been taken up as a part of the development of accelerator driven sub critical system (ADSS) by Bhabha Atomic Research Centre. Large grain (RRR>99) pure niobium was chosen as the material for the cavity. Niobium,for its application as superconductor requires extremely high quality joints, feasible only by electron beam welding at high vacuum environment. An indigenously developed 100kV, 4kW high vacuum electron beam welding machine has been utilized to carry out the welding operations. Planning of the weld sequences was chalked out. Holding fixtures for the cavity, consists of seven numbers of joints have been fabricated beforehand. A few coupons were welded for optimization of the weld parameters and for inspection of the weld purity by indigenously developed secondary ion mass spectroscopy. The report describes the welding equipment and the stage wise joining operations of the cavity in details and also discusses the qualification testing of the welded cavity.

1. Introduction

High purity large grain bulk niobium is the most suitable material used in fabrication of SRF cavities for its excellent superconducting properties [1]. Although niobium is a refractory material, it exhibits strong affinity towards gases and react with oxygen, hydrogen, nitrogen at elevated temperature. Inclusion of these gases exceeding few tens to few hundred parts per million in the cavity material is detrimental to its quality [2]. Electron beam welding has been chosen for welding of cavity as the process is carried out under high vacuum, which is being considered to be the best inert environment for welding [3].

2.1 Description of the Equipment:

The welding has been carried out by a 100kV 4kW electron beam welding machine developed in house in early eighties [4]. After extensively being utilized for Nuclear and Defence applications for more than two and half decades in BARC, the equipment has been relocated in Nashik under MOU between BARC and M/s Precise Vacuum System Pvt Ltd to explore its industrial applications.

General specifications of the equipment are:

Accelerating voltage:	0-100 kV
Beam current:	0-40mA

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Work Chamber size:	1500mm × 1000mm × 1000mm.
Work table size:	800mm × 500mm.
Table displacement:	700mm at X and 400mm at Y direction
Table speed:	20mm/min to 2000mm/min, in the X and Y directions and 0.5-20 rpm for the rotary table. All motions are programmable.
Gun vacuum:	2×10^{-6} mbar
Chamber vacuum:	5×10^{-5}mbar

2.2 Description of the Cavity

A single cell prototype elliptical RF cavity has been designed at f_0=1050 MHz, β = 0.49. Our design is based on the circular equator and elliptic iris for ease of mechanical fabrication. The schematic of the cavity dimensions is shown in Figure 1. The basic geometrical and RF parameters of the cavity are shown in Table1. Design and mechanical fabrication of the cavity in details has been reported elsewhere [5].

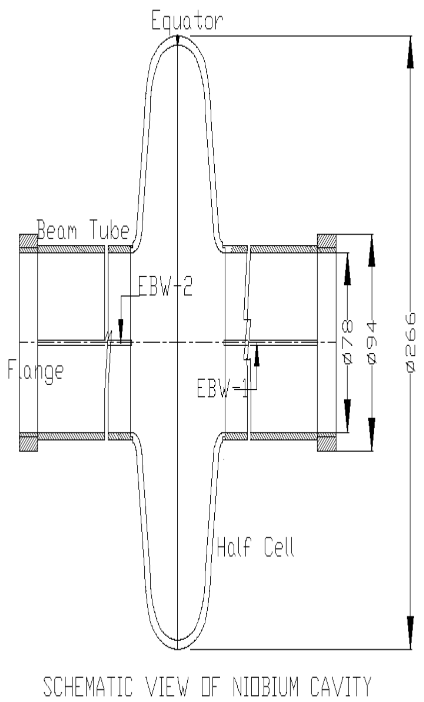

Fig. 1. Schematic drawing of designed Cavity

Table 1: 1050 MHz, β = 0.49 Single Cell Cavity Parameters

Parameters	Present Design
Frequency (MHz)	1050
Geometrical β	0.49
Iris Radius (cm)	3.9
Cavity Diameter (cm)	25.833
Dome Aspect ratio	1
Iris Aspect Ratio	1.43
Wall Angle (Deg.)	6.5
Wall Distance [mm]	7.37
r/Q (Ω)	9.19
Geometry Factor G (Ω)	141.91
E_{peak}/E_{acc}	4.26
B_{peak}/B_{acc} (mT/(MV/m)	8.02

3. Electron Beam Welding:

Niobium single cell cavity consists of 7 nos. weld joints in total. Fixtures for electron beam welding of various parts of the cavity have been designed and fabricated in advance. Sequence for welding is shown in Fig.2. All the weld parameters were optimised by welding trial on dummy coupons having similar contour and thicknesses as actual joints. The actual weld parameters used for joining of different components of cavity are tabulated in **Table-II.**

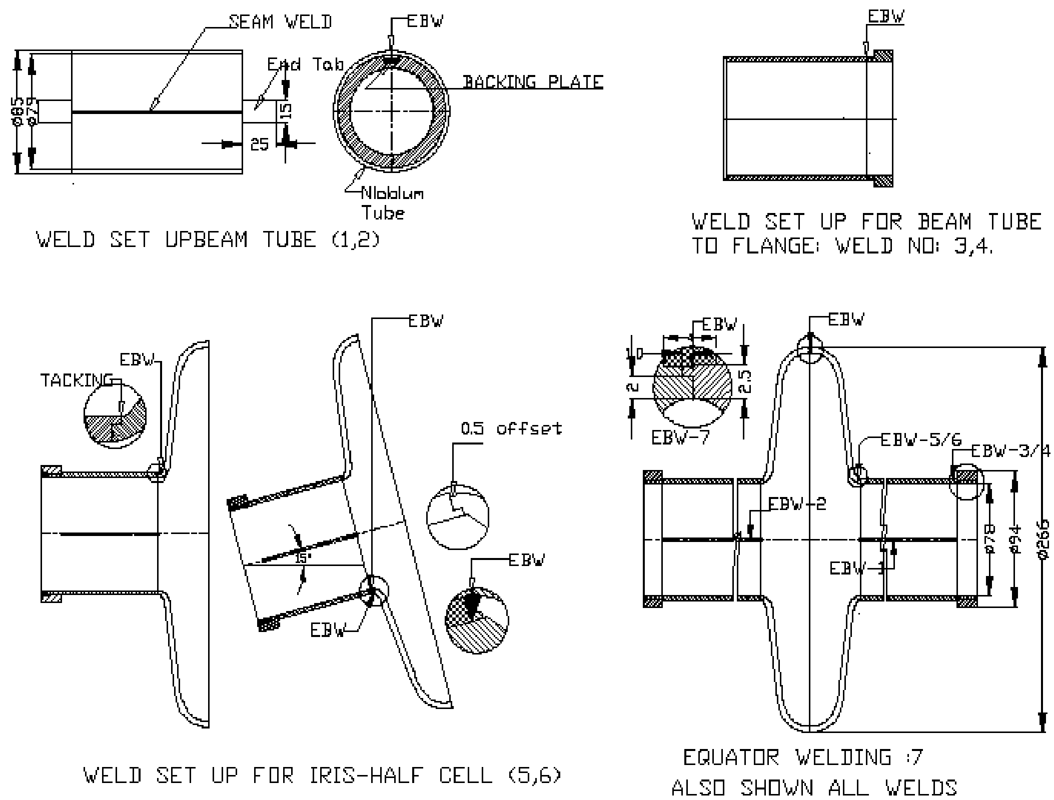

Fig.2. Sequence of electron beam welding of the components of the Cavity

Table-II: Weld Parameters for the Components

Name of the components And joint type	Accelerating Energy (kV)	Beam Current (mA)	Linear weld speed (mm/min)	Chamber vacuum (mbar)	Observations
Beam tube: Seam joint (right):	100	22	600	$5x10^{-5}$	Full penetration
Beam tube: Seam joint (left):	100	22	600	$5x10^{-5}$	Full penetration
Beam tube to Flange Step joint (right)	100	18	600	$5x10^{-5}$	Smooth joint Uniform U/B
Beam tube to Flange Step joint (right)	100	18	600	$5x10^{-5}$	Smooth joint Uniform U/B
Half cell to Iris (right) Tacking vertically	80	10	_	$8x10^{-5}$	Tacked at 12 places
Half cell to Iris (right) Inside weld at an angle	100	20	600	$5x10^{-5}$	Smooth bead
Name of the components And joint type	Accelerating Energy (kV)	Beam Current (mA)	Linear weld speed (mm/min)	Chamber vacuum (mbar)	Observations

Half Cell- Iris (right) Outside cosmetic pass	100	10	600	$5x10^{-5}$	Smooth bead
Half cell to Iris (left) Tacking vertically	80	10	_	$8x10^{-5}$	Tacked at 12 places
Half cell to Iris (left) Inside weld at an angle	100	20	600	$5x10^{-5}$	Smooth bead
Cosmetic pass (outside)	100	10	600	$5x10^{-5}$	Smooth bead
Equator welding : Tacking	100	10		$5x10^{-5}$	Tacked at 16 places
Equator weld	100	32	600	$5x10^{-5}$	Shrinkage of the lip took place on some portion.
Equator weld cosmetic pass at defocused beam	100	22	600	$5x10^{-5}$	Good upper bead.

3.1 Beam tubes (weld-1 and 2):

Beam tubes have been formed by rolling of 3.2mm niobium plates. Butt welding along seam of the tubes was carried out. Fig.3 shows photograph of one of the two welded beam tubes.

3.2 Beam tube to flange (Iris): Photograph of welded Iris (beam tube to flange) is shown in Fig.4.

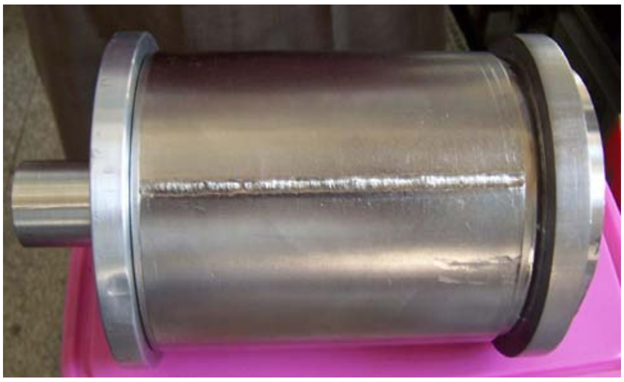

Fig 3. Photograph of Seam welded Beam Tube

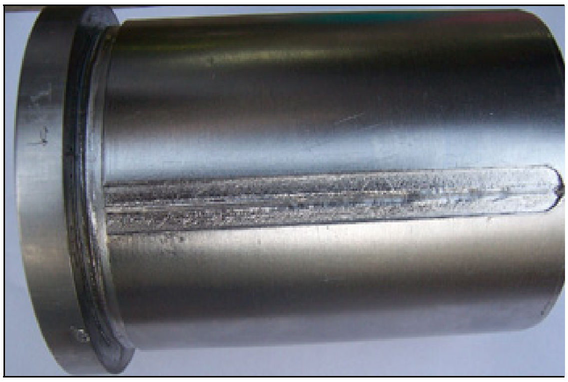

Fig.4. Photograph of welded Iris

Fig.5.Half cell to beam tube assembly

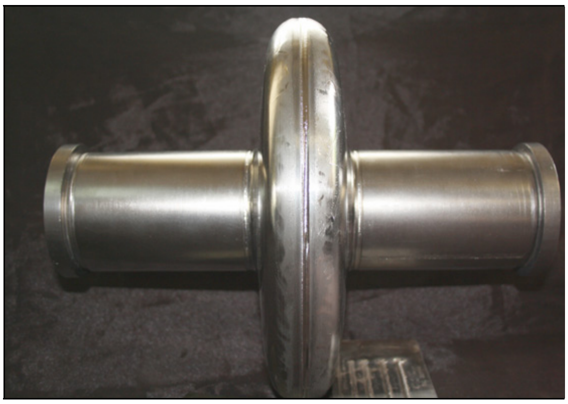

Fig. 6. EB welded Cavity (after final welding)

3.3 Half Cell to Iris

Welding has been carried out from inside at an angle of 15° with the axis of rotation and was followed after weld tacks. Fig.5 shows photograph of welded half cell to Irish in which very smooth weld is noticeable.

3.4: Equator Joint

Joint contour was step butt with 0.5mm thick upper and 2.5mm thick lower step. Actual joint line was along the lower step which was 1mm offset from upper joint line [fig.2]. A notch was provided on top to locate the lower step. 16 nos. weld tacks were provided on top joint to resist distortion of the joint due to asymmetric thermal expansion. It has been observed that shrinkage of the lip was taken place during welding at two places (25mm long each) along the weld periphery. Although full penetration was felt with finger, a cosmetic pass (table-II) was provided after machining of the deformed upper step.

4. Results and Discussions:

4.1. Leak Test:

All welded components of the cavity were leak tested by in MSLD process and found acceptable. Results of MSLD are shown in Table-III.

Mass Spectrometer Leak Detection results (TABLE-III)

Sl no	Name of the components	He leak rate (mbar-litre/sec)
1	Beam tube after seam welding (left)	$< 1x10^{-9}$
2	Beam tube after seam welding (right)	$< 1x10^{-9}$
3	Beam tube to flange welded (left)	$< 1x10^{-9}$
4	Welded beam tube to flange (right)	$< 1x10^{-9}$
5	Beam tube assembly to half cell welded (left)	$< 1x10^{-9}$
6	Beam tube assembly to half cell welded (right)	$< 1x10^{-9}$
7	Equator assembly after welding	$< 1x10^{-9}$

4.2. Micro Hardness Measurement

Micro hardness was measured across the weld pool of electron beam welded niobium sample. The measurement was taken at three stages (1,2,3) along the depth started on parent metal advanced to weld pool and stopped on parent metal (Fig.7). 25 gm load has been used with 5 sec dwell time. The hardness profile near top and middle of the weld profile showed homogenous mixture and more uniform values across the weld zone. Profile near the root of the weld shows a fluctuation of the values.

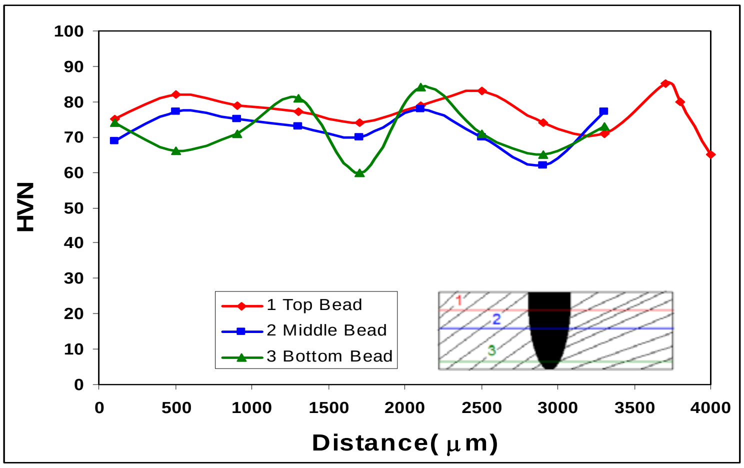

Fig.7. Micro-hardness profile of EB welded niobium sample

4.3. RF measurements and Electric field distribution

RF measurement of the cavity before EB welding and after EB welding with vector network analyzer is shown in **Table-IV.** The values measured after welding has been found at per with the

Table-IV: RF Values measured before and after EB weld

Parameters	Simulated value without Beam tube	Measured value before EBW without beam tube	Simulated value with Beam tube	Measured value after EBW with Beam tube
Frequency [MHz]	1050	1048	1036.856	1036.507
Q Value	17000	459	17032	8076 (not cleaned after EBW)
Effective Shunt Impedance [MΩ/m]	4.469	0.175	4.711	3.61 (not cleaned)
R/Q [Ω]	9.225	8.59	9.675	9

values before welding. Electric field distribution before and after welding has shown in fig.8 & fig.9.

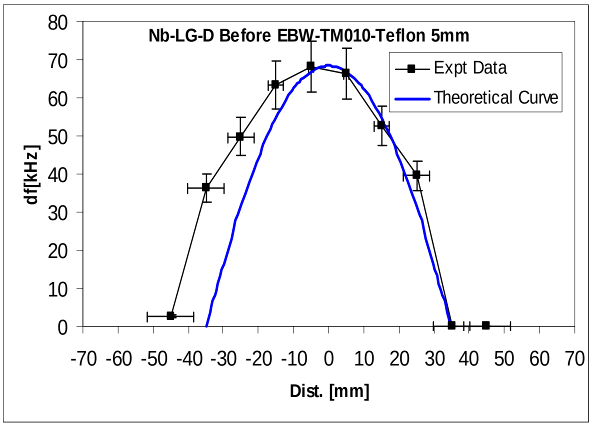

Fig.8. Axial electric field distribution before welding

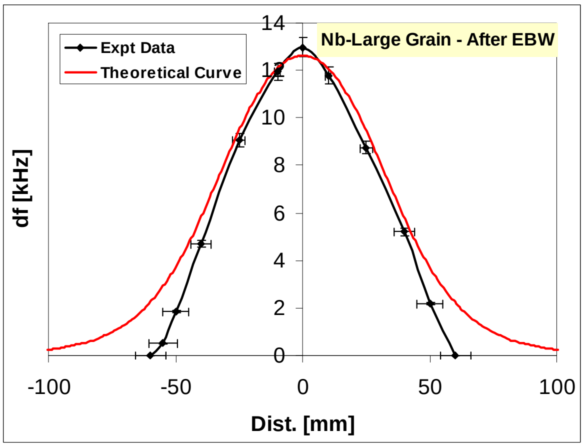

Fig. 9. Axial electric field distribution after welding

4.4: SIMS analysis of the weld profile

EB welded coupon was analyzed with the time of flight secondary ion mass spectrometry equipment (TOF-SIMS) developed in Technical Physics Division, BARC. A primary beam of mono-isotopic Gallium ions at an energy of 25 KeV is allowed to bombard the sample surface. Secondary ions emitted from the surface are mass analyzed with the help of reflectron TOFMS

The mass spectra were collected across the weld profile of the niobium starting from parent metal to weld profile to parent metal of the coupon [same as fig.7]. The relative concentration of NbH, NbO and NbOH levels were mapped and are shown in fig-10. Similarly evolved oxygen and hydrogen profiles were mapped and are shown in fig-11. It can be seen from the figs-10 and 11 that the oxygen and hydrogen profile in the weld zone has increased over the back ground i.e. parent metal.

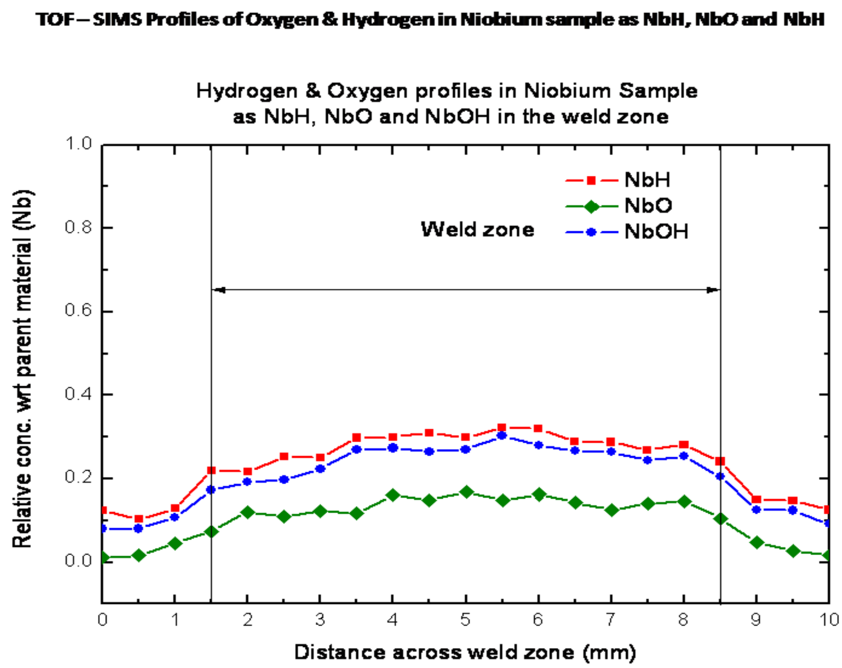

Fig.10. Time of flight secondary ion mass spectroscopic profiles on EB welded Nb specimen

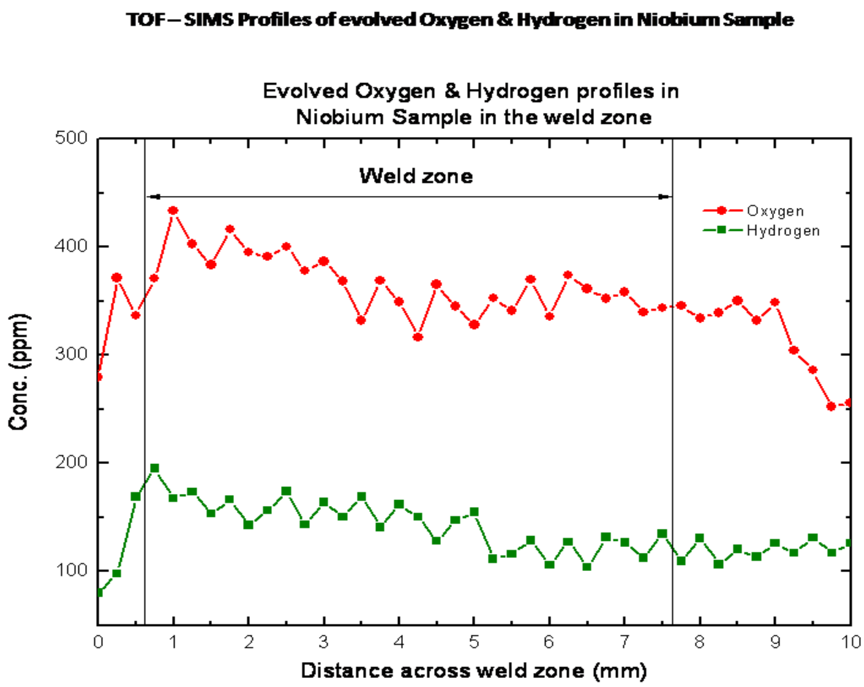

Fig.11.Time of flight secondary ion mass spectroscopic profiles on EB welded Nb specimen

5. Conclusion:

Welding of a single cell niobium superconducting cavity has been carried out by one of our in house developed electron beam welding machines. Tests like MSLD, electric field distribution and RF measurements at room temperature carried out on the welded component shown encouraging result. Analysis of the welded specimen showed an alarming level of oxygen and hydrogen pick up in weld pool. Chemical cleaning and vacuum heat treatment of the cavity is expected to reduce these levels to a significant extent. Results of the evaluation of the cavity at 2K are awaited. Depending on the above results desired modifications in welding environment or technique will be taken place for future cavities.

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References:

[1] “Ingot niobium RF cavity design and development at BARC”: Mittal KC et al: AIP Conf proceedings1352.100-115 (2011)

[2] “RF properties 1050 MHz, =0.49 elliptical cavity for high current proton accelerator” Roy Amitava et al: Journal of Instrumentation, P04002, 2008 (IOP Publication)

[3] “Vacuum-The ideal environment for welding of Reactive and Refractory materials” by Saha TK et al: Journal of Physics: 114(2008)02047, (IOP Publication)

[4] “Industrial perspectives of electron beam welding” by Saha TK et al proceedings of SEBTA-2005 p-283-292 held during Sept 28-30, 2005.

[5] “Design ,fabrication, room temperature RF test of 1050 MHz =0.49 single cell large grain niobium cavity” by Mondal J: will be reported in same conference IVS-2012.