Developing of superconducting niobium cavities for accelerators

I L Pobol and S V Yurevich
Physical-Technical Institute of the National Academy of Sciences of Belarus, Kuprevich 10, Minsk 220141, Belarus
E-mail: i.pobol@gmail.com

Abstract. The results of a study of structure and mechanical properties of welding joints, superconducting characteristics of the material after joining of welded components of superconducting radio frequency cavities are presented. The paper also describes the results of testing of the RF 1.3 GHz single-cell niobium cavity manufactured in the PTI NAS Belarus.

1. Introduction
A decision of scientific communities concerning development of modern particle accelerators (E-XFEL [1], International Linear Collider (ILC) [2], as well as a number of smaller projects [3]) creates a demand for accelerating elements—superconducting radio frequency (SRF) niobium cavities. Manufacturing of modern SRF cavities is an extremely complex task that requires highly specialized expensive equipment and participation of specialists from various fields of science.

As part of the JINR (Dubna) project of the ILC five scientific organizations from Belarus joined their efforts to create experimental models of single-cell 1.3 GHz niobium cavities in accordance with the requirements of the ILC project [4, 5]. The work package includes mathematical modelling of part geometry, manufacturing of half-cells according to the reference profile by liquid impact forging, mechanical and chemical treatment of blanks and half-cells, electron beam welding of units, “warm” and “cold” RF testing of cavities.

Electron beam welding (EBW), due to the ability of precise control over energy density at the heating spot and maintain of the original purity of the welded metal at the level of the base metal, is the only possible way of preparing compounds of products made from ultrapure niobium for SRF cavities [6].

2. Material, equipment and techniques
The EBW installation based on the ELA-15 power source was used for welding (accelerating voltage—60 kV; maximum beam power—15 kW; maximum beam current—250 mA). For electron beam welding the samples and parts of the cavities were mounted a clamping system made of stainless steel.

For research and manufacture of half-cells of the cavities niobium sheets (thickness—2.8 mm) produced by Ningxia OTIC (China) have been used. There were also used the tubes (Nb) and flanges (Nb-Zr alloy) by Heraeus HMT (Germany) for manufacturing of the cavities. In order to
Table 1. Superconducting properties of samples.

| Properties     | Reference samples | Welded samples |
|----------------|-------------------|----------------|
| $T_C, K$       | 8.8               | 8.6            |
| $\delta T_C, K$ | 0.55–0.6          | 0.65–0.7       |
| $H_T, T$       | 0.5               | 0.4            |
| $\delta H_T, T$ | 0.15              | 0.2–0.25       |

clean the surface prior to EBW a thin layer was removed from a niobium blank using a standard method applied for niobium cavities—buffered chemical polishing that uses an acid mixture of HF (48 wt.%), HNO$_3$ (65 wt.%) and H$_3$PO$_4$ (85 wt.%) in a volume ratio of 1:1:2.

Superconducting properties of weld were studied by measuring the superconducting transition temperature, $T_C$, and the critical magnetic fields of superconductor, $H_T$. The samples were prepared by electro-erosion cutting in transverse directions to the weld with obtaining strips 2.5 mm wide, 40 mm long. The superconducting properties of the samples were tested using the equipment of Scientific and Practical Materials Research Centre of NASB (SPMRC NASB, Minsk, Belarus).

“Warm” and “cold” RF testing of the cavity was carried out using RF stand for cavity characteristics measurements of Research Institute for Nuclear Problems of Belarusian State University (INP BSU, Minsk, Belarus) and cryogenic setup of SPMRC NASB.

3. Properties of welding joints

Welding was carried out in the vertical gun position and horizontal direction of welding. Full penetration of the joints and smooth weld seams of 3–4 mm width obtained at the inner surface of samples ensure weld parameters: accelerating voltage of 60 kV, beam current of 53–55 mA, welding speed of 7–10 mm/s, beam focus–defocusing, vacuum of $3 \times 10^{-3}$ Pa. The overall width of the weld and heat affected zone is 12–12.5 mm. The weld seams has an equiaxial microstructure with a grain size of 1000 $\mu$m in the fusion zone, 100–200 $\mu$m in the heat affected zone and 30–40 $\mu$m in the parent metal.

Microhardness was measured across the weld pool of electron beam welded niobium sample. The measurement started on the weld pool and finished on the parent metal. The values of hardness of the parent metal and the weld zone were similar with the range of 60–75 HV.

Table 1 shows the measurement results of the superconducting transition temperature of the welded samples, $T_C$, the width of the temperature transition, $\delta T_C$, the critical magnetic fields of the superconductor, $H_T$, and the width of the magnetic transition $\delta H_T$, of the two types of the niobium samples by Ningxia OTIC. The reference samples were cut from the material not subjected to thermal influence and samples cut from the welded joint.

As can be seen from table, there is insignificant degradation of the superconducting properties in the niobium welded joints: $T_C$ is reduced to 8.6 K (reference samples—8.8 K), $H_T$ is reduced to 0.4 T (reference samples—0.5 T). This insignificant degradation in the superconducting properties of the welded joints does not exert any influence on the cavity performance.

4. Cavity manufacturing and RF-Test

The half-cells of the cavities were manufactured from niobium sheets by the liquid impact forging. PTI NAS Belarus has equipment for this technology and great experience [7,8]. Preparation of compounds from the half-cells, the flanges and the tubes was carried out by EBW. There was
also conducted chemical treatment of the cavity components at different stages of manufacturing.

Two RF characteristics were tested. The resonant frequency, $f_0$, was measured to test geometric accuracy of cavities, and the quality factor, $Q$, was measured to test the manufacturing quality of the cavity.

The results of RF-measurements of the cavity (table 2) at the temperature of liquid helium showed that superconductivity in the cavity material was achieved.

### 5. Conclusion

The manufacturing technology of SRF niobium cavity using electron beam welding was developed. The RF test results indicate the preservation of superconducting properties of the cavity material and the corresponding geometry of cells size. The cavities comply with the requirements of modern accelerating devices.

**References**

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| Operating temperature, K | Fundamental frequency, GHz | Quality factor |
|--------------------------|-----------------------------|---------------|
| 293                      | 1.290197258                 | 37549         |
| 4.5                      | 1.290185765                 | 1 494 100 000 |