APPLICATION OF IN-VACUUM INFRARED PYROMETRY DURING FABRICATION OF EUROPEAN XFEL NIOBIUM CAVITIES

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Abstract

A technique to measure the temperature of Niobium components in vacuum during Electron Beam Welding (EBW) operation is presented and results obtained on the large scale cavity production for the European XFEL are discussed. During the EBW process, the knowledge of the components temperature during the welding operation could help both for choosing better welding parameters and for the optimization of the production cycle. In collaboration with the Italian firm Ettore Zanon (EZ), we developed a system able to measure the temperature of Nb components in vacuum during EBW operation using an IR pyrometer placed outside the vacuum chamber through an appropriate vacuum viewport. In this paper the experience of this device during the production of Nb components for the XFEL 1.3 GHz cavity production is discussed.

INTRODUCTION

In view of the mass production of components for the upcoming European XFEL, a big effort has been spent to transfer to Industry the necessary know-how, developed in several years of R&D in Research institutes. In this framework, DESY and INFN, within Working Package W04 of XFEL [1], have transfer their knowledge and are now supervising all the phases of the production of the 800 1.3 GHz Nb SuperConducting (SC) cavities. This large production of Niobium resonators has been shared between two Companies (Ettore Zanon and Research Instruments) that have the responsibility, not only for the mechanical fabrication, but also of all subsequent required surface treatments, He tank integration and all the steps necessary to deliver to DESY a Vertical Test ready cavity [2,3].

The required production rate of 4 SC cavities per week for each Company, necessary to fulfil the overall time schedule of the accelerator installation, must comply with the high quality of the final products needed to guarantee the performance of the resonators once in operation.

One of the critical operations during cavity production is the Electron Beam Welding (EBW) of Nb and Nb-Ti parts, which is used both for subcomponents and for cavity welding. For this reason, INFN started an activity, in collaboration with Ettore Zanon (EZ), aiming at optimizing the EBW operation (higher reliability and higher quality of the welds) and reducing the total production time [4].

In this paper we present, after a short description of the requirements for EBW of Nb components, the hardware developed at LASA and the experimental set-up installed at EZ for the in vacuum temperature measurement. Furthermore, the application of this technique on dummies and subcomponents as well as real cavities is presented.

EXPERIMENTAL SET-UP

The set-up already described in a previous publication [4], has been designed, constructed and qualified to measure the temperature of components and cavities during the EBW operation, therefore able to measure the temperature of objects under high vacuum condition.

The final goal of this technique is to monitor the pieces temperature for the optimization of welding parameters and the increase of welding process reliability.

Moreover a second opportunity is the minimization of the waiting time before venting the EBW vacuum chamber, to increase productivity without any risk of pollution of the Nb parts. Hot Niobium can getter N_2 and O_2, and therefore the EBW vacuum chamber machine can be vented to atmospheric pressure only below 150 °C and 100 °C, respectively for N_2 and air.

The choice of the hardware and of a suitable experimental set-up has been done, together with EZ welding engineer, based firstly on the constrains imposed by the EBW machine layout and the welding process, such as items rotation and movement. Moreover a high reliability system is needed to avoid any interference with high power electron beam.

Prescriptions for XFEL Nb cavities Electron Beam Welding require that:

- EBW must be done in high vacuum condition ($p < 5 \cdot 10^{-5}$ mbar) during all the welding process to avoid degradation of the high RRR Nb
- EBW machine cleanliness must be guaranteed
- no material with possible loss of particle is accepted in the EBW
- no sliding contact are accepted, as sources of particles that can be incorporated in the welds.

An IR pyrometer (3MH-CF4 by OPTRIS, $\lambda = 2.3$ µm,), able to measure temperatures between 50 °C to 600 °C, was chosen as the temperature sensor for this test [5]. To avoid interferences with vacuum, it was installed outside the welding chamber.

Viewports usually installed on the EBW machine for visual control of the welds are not transparent to IR radiation. Therefore a dedicated Zinc Selenide (ZnSe) viewport was installed [6]. Viewport transparency, at the pyrometer working wavelength (λ of 2.3 µm), is 80%.

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Moreover ZnSe is transparent to visible light, at least in the red part of the spectrum, giving the possibility to use the two red laser aimers installed in the pyrometer to highlight the reading area of the pyrometer (see Fig. 1).

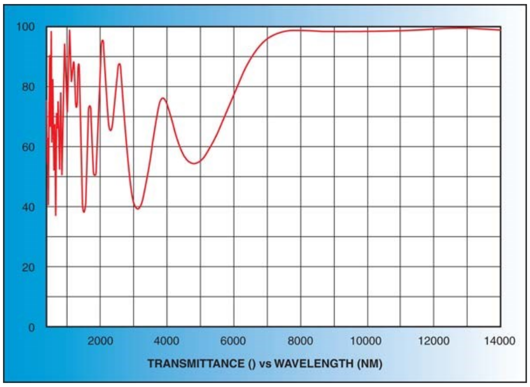

Figure 1: ZnSe viewport transmittance vs wavelength [6].

IR pyrometer measures the power emitted by the hot parts that follows the Stefan-Boltzmann law:

$$U = C\left(\varepsilon T_{obj}^4 + (1-\varepsilon)T_{amb}^4 - T_{Pyr}^4\right)$$

where ε is the emissivity of the object, T_{obj} its temperature, T_{amb} the surrounding ambient temperature, T_{Pyr} the self-radiation of the pyrometer and C a device specific constant.

Since most metals have high reflectivity and very low emissivity values in the IR range, the temperature measurement is not possible or is affected by large errors because they act like a mirror for the ambient radiation. This is the case also for Nb with ε = 0.1 ÷ 0.2 for T = 20 ÷ 300 °C [7].

To overcome this problem, we installed on a Nb target special calibrated self-adhesive high emissivity stickers (“emissive dots”) with calibrated ε = 0.95 in the temperature range of our interest. They can be found on the market (ACLSED by Optris [5]), and their maximum operative temperature is 380 °C.

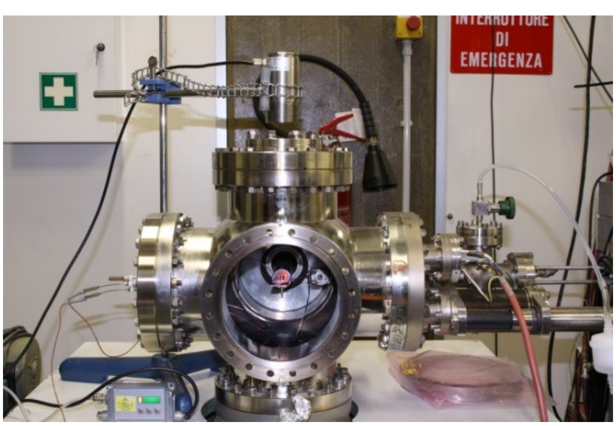

Figure 2: Set up at LASA with pyrometer mounted on top of the test chamber.

Firstly the system was tested at LASA (see Fig. 2), to calibrate pyrometer response vs. thermocouples signal directly mounted on the test piece, to verify viewport transparency and functioning of the whole system. For this test, Nb parts with “emissive dots” where installed in a vacuum chamber (p < $1 \cdot 10^{-7}$ mbar) and heated up to 300 °C. At higher temperatures, the adhesion of the stickers to the metal piece gets weaker, and dots tent to loose contact with the surface. Sensor sensitivity was adjusted with respect to calibrated thermocouples: the maximum error in the range between 20 °C ÷ 250 °C was of ± 5 °C. Vacuum quality was verified using a Residual Gas Analyser (Inficon, mass 200), and no significant contamination source was found. Moreover the loss of particles of the emissivity dots was verified in the DESY ISO4 clean room, showing that the stickers are compatible with particle free environment.

Apparatus was then transferred to EZ and installed on the EBW machine. Fig. 3 shows the sketch of the experimental set-up and photos of the final configuration of the system once connected to the EBW chamber.

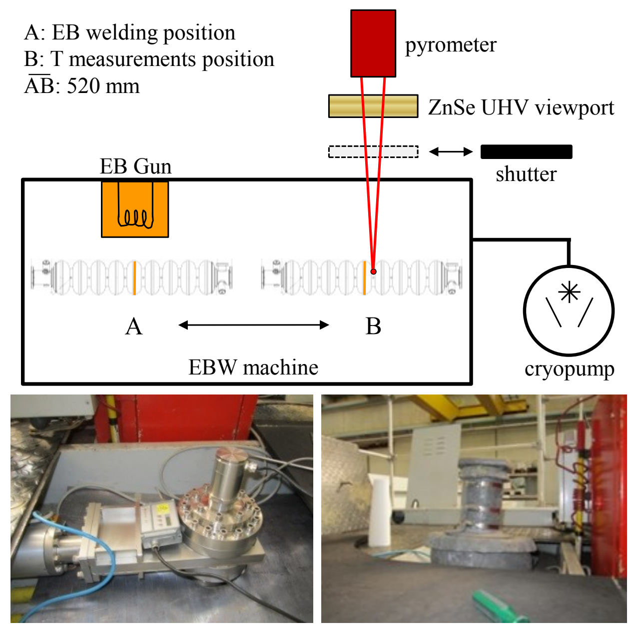

Figure 3: Sketch of the experimental setup and photo of the pyrometer mounted on a gate valve with and without X-ray shielding.

The ZnSe viewport and the pyrometer were installed in one of the vacuum top port, close to the connection of the electron gun. To avoid a decrease of the viewport transmission due to Nb evaporation during welding, a gate valve was installed between the viewport and the chamber acting as a shutter and preventing viewport metallization.

The EBW machine operates up to 150 kV, and radiation safety rules forced the installation of lead X-ray shields to avoid any radiation leakage.

During EB welding the component is located in position A, and the shutter is maintained closed. Once the welding process stops, the shutter is opened and the component is moved in position B (distance 520 mm) for temperature measurements.

ISBN 978-3-95450-143-4

TEST ON DUMMY COMPONENTS AT EZ

Two-cell Dummy Cavity

We did two sets of measurements on a 1.3 GHz two-cell dummy cavity prepared and assembled for this investigation. The dummy cavity consists of two Nb cells (ϕ_{eq} = 210 mm, ϕ_{ir} = 78 mm, 2.8 mm thickness) and one stiffening ring welded between the two cells, with a total weight of about 4.1 kg (see Fig. 4).

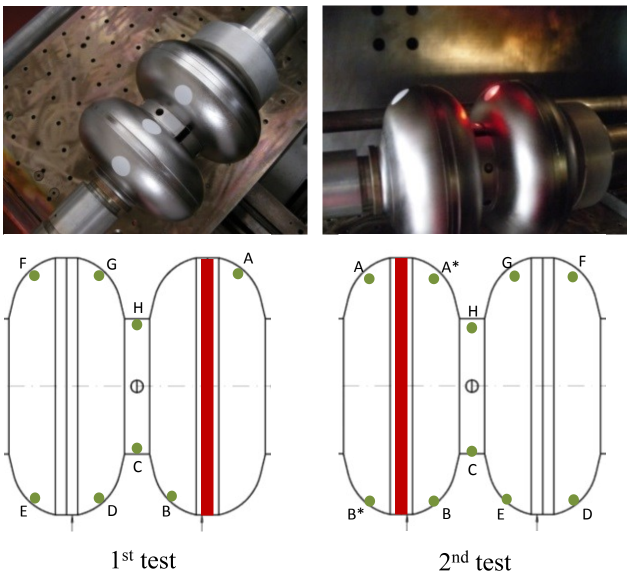

Figure 4: Up: photos of the two-cell dummy cavity before and during tests. Red laser beams are used for aligning the pyrometer on the dots. Down: positions of the “emissive dots” in the two tests configuration.

To study the temperature behaviour and heat transfer in this dummy cavity, we performed EB equatorial welds applying the same procedure and parameters used for the XFEL cavity production. In details, the electron beam power during the welding was 2.25 kW, with incident energy of 190 kJ. The temperature was measured at the end of welding process (t = 0) in several areas, at different distances with respect to the equator under weld operation using the “emissive dots”.

The goal was not only the proof of principle of the measurement, but also the identification of the best area of the component to be used as a temperature reference during production.

The first set of measurements was done after the welding of the first equator. The second test was intended to confirm data already measured and to verify that the behaviour was the same also in the new configuration, having now a better thermal contact being the first equator already welded. Moreover, in the second test the number of “emissive dots” close to the equator under investigation was increased since during the first test some of the dots, close to the high temperature region, were damage. Fig. 4, on the lower sketch, shows the position of the “emissive dots” in the two different test configurations.

Fig. 5 reports the results of the first test that have been extensively described and discusses in a previous paper [4], here shown for completeness.

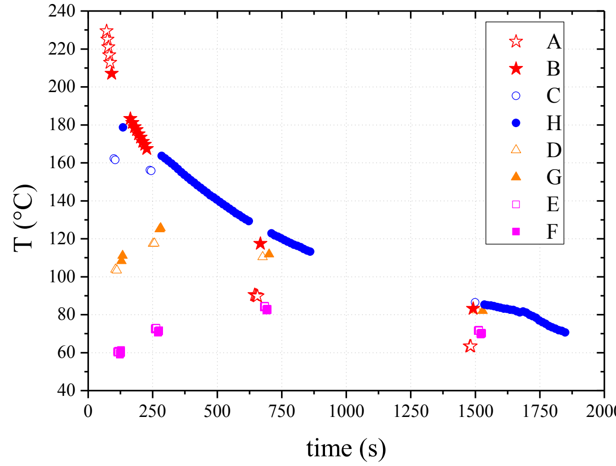

Figure 5: Temperature at different locations of the two-cell cavity (1st test). For dot positions see Fig. 4.

Main results of the first test have been that after about 630 s the entire cavity is thermalized and all measured areas start cooling down with a similar behavior. Moreover, after cavity thermalization, until the end of the cooling down the highest recorded temperature corresponds to the stiffening ring (C, H).

The main purpose of the second test was to check the temperature behavior of the stiffening area (H, C) with respect to the areas close to the equator under welding process (A, A*, B, B*) and farther away (G, E, F, D).

Fig. 6 shows results obtained with the second test. Also in this case, similarly to the first test, the stiffening ring was at the highest temperature during the cool-down of the cavity, after its complete thermalization. Moreover, the temperature measured at farther “emissive dots” respect with to the equator under weld was similar to the behavior observed in the first test, confirming the goodness of the central stiffening ring as a reference point for temperature measurement.

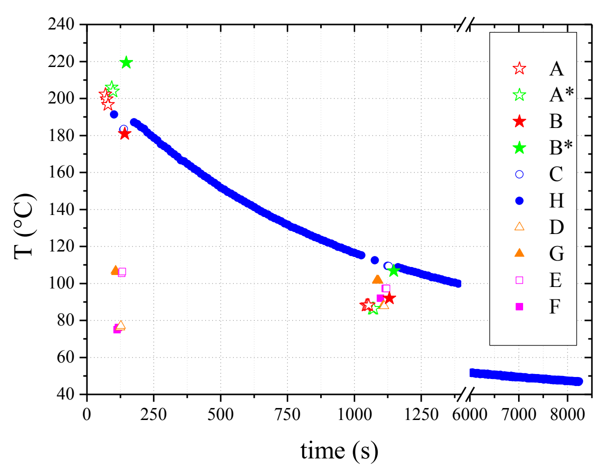

Figure 6: Temperature at different locations of the two-cell cavity (2nd test). For dot positions see Fig. 4.

Therefore, the stiffening ring is considered the most representative part to be used for following the temperature of the entire object. This is particularly relevant in the case of EBW machine venting since this indication could allow earlier starting of this process and hence a reduction of the overall welding process.

9-cell Dummy Cavity

Based on promising results obtained on the two-cell dummy cavity, we decided to investigate the temperature behaviour after equatorial welding of a more complex object such as the 9-cell cavity. The final goal was not only to achieve a reduction of the production time of the XFEL cavity in terms of optimization of the industrial fabrication but also to obtain information on the heating flow in the cavity during the EBW to optimize the welding procedure operation itself (i.e. power, time to wait between steps, etc.).

A 9-cell Nb dummy cavity, equipped with only three stiffening rings and beam pipe tubes as a “real” cavity, was used for this test. This dummy was used at EZ in the past for the optimization of welding parameters and so the equators were already welded. During our test the equatorial welds were redone and the temperature was measured after these operations. In Fig. 7 photos of the 9-cell dummy cavity equipped with “emissive dots” are shown.

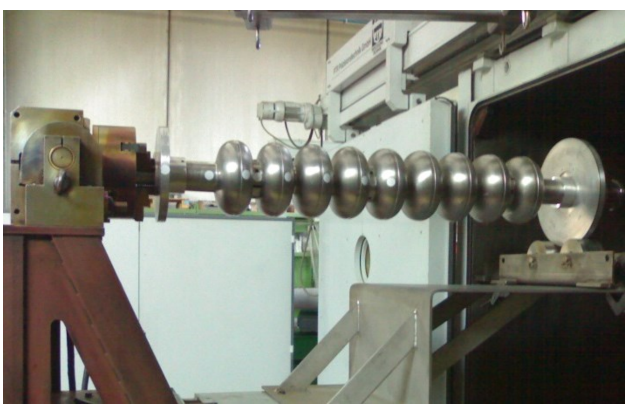

Figure 7: The 1.3 GHz 9-cell dummy cavities used for the infrared pyrometer temperature measurements. The “emissive dots” are placed not only close to the equators but also on the beam pipe tube and on the stiffening rings.

Several “emissive dots”, located at different positions, were used to measure the temperature of the cavity and welds were done following the same procedure used for the XFEL production.

We recorded temperatures after each welding operation on all “emissive dots”. It was observed that the behaviour in term of heating conduction and temperature trend was similar to the two-cell dummy cavity and the stiffening ring in the middle of the cavity (longitudinal axis) was at the highest temperature with respect to the entire cavity, after thermalization. Fig. 8 shows the temperature measured on the central stiffening ring during a natural cool-down in vacuum of the 9-cell dummy cavity after one of the typical welding sequences.

Figure 8: Cool-down in vacuum of the 9-cell dummy cavity measured on the central stiffening ring.

TEST ON XFEL COMPONENTS AT EZ

This method has been finally applied both on subcomponents and on XFEL cavities. The usage of this technique has given important information relative to the waiting time before N_2 venting, reducing considerably the production time. While End Cell Unit and Dumb Bell results have been reported in a previous publication [4], here we described the result obtained with this technique on the production of the XFEL 1.3 GHz cavities.

9-cell XFEL Cavity

The results obtained on the 9-cell dummy cavity encouraged EZ to apply this technique during the equatorial welding operation of the first 8 cavities for the XFEL project, 4 Dummy Cavities (DCV) and 4 Reference Cavities (RCV) respectively. DCV were produced for the ramp-up of the XFEL infrastructure at EZ while RCV, once treated with the so-called “flash BCP” surface process and cold RF tested at DESY, were used at EZ for infrastructures qualification [3,8].

The goal of the application of the IR temperature in-vacuum technique for DCV/RCV was mainly the optimization of the final venting operation, with a reduction of the whole production time, while fulfilling the XFEL requirements for the EBW of Nb.

For these cavities, only one “emissive dot” was used, located on the central stiffening ring as shown in Fig. 9 for a DCV cavity.

Figure 9: DCV under preparation for the equatorial welding. One “emissive dot” is used to read the stiffening temperature during welding operation.

ISBN 978-3-95450-143-4

Firstly, long run temperature measurements were done on different cavities to precisely evaluate the temperature behaviour during the natural cooling down in vacuum. Afterwards, following the XFEL prescription and well knowing the cavity temperature as measured by the IR pyrometer, N_2 was introduced in the cool down cycle to speed it up and reduce the overall process time.

Fig. 10 presents measurements done on three of the four DCV cavities. Here time t = 0 corresponds to the start of the temperature recording, just after the end of the welding operations. The green and blue curves show the temperature of two cavities during their natural cool down in vacuum. The red curve, instead, shows the cavity cool down with the N_2 inlet when its temperature was below 80 °C followed by air venting below 54 °C.

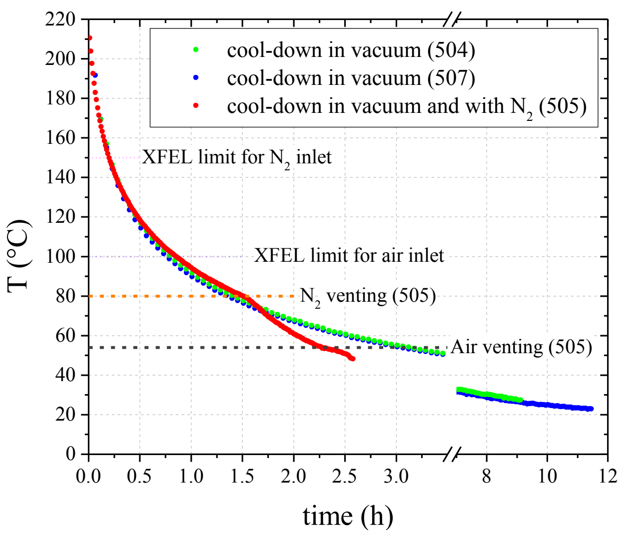

Figure 10: Measurement done during the cool-down of DCV cavities after the completion of the equatorial welding operation. Cool-down in vacuum (blue and green curve); Cool-down in vacuum and then N_2 venting (red curve).

In the first 1h and 30 min, all the three cavities show a similar behaviour since they follow their natural cool-down process in vacuum. During this time their temperature decreases from 210 °C to 80 °C. Afterwards, while two cavities (507 and 504) are kept in vacuum, N_2 inlet starts in case of cavity 505. Blue and green curves show that the temperature decrease from 80 °C to 54 °C takes about 90 min for the "in vacuum" cavities while for 505 (red curve) it takes only 45 min, halving the time of this last part of the cool-down.

Knowing the cavity temperature, a further step has been done to allow the N_2 inlet at the temperature prescribed by XFEL specification (150 °C). In this configuration, nitrogen venting is anticipated at 1 h after the end of equatorial welding, with a further decrease of the overall cooling time.

Further optimizations done by EZ allow to stabilize the actual procedure during cooling down fixing the natural cooling down in vacuum to 1h and the N_2 assisted also to 1 h, followed then by the usual venting with air. The total reduction in cool down time for XFEL cavity is 50 %, from 4 h down to 2 h.

CONCLUSION

An apparatus for in-vacuum temperature measurement of Nb components under EBW operation has been designed, developed and tested. The design of this system and the choice of hardware have been done based on constrains imposed by the EBW machine operation and also on the XFEL prescription for EBW of Nb and Nb-Ti.

Once calibrated at LASA, the system was mounted in the EBW chamber at Ettore Zanon and tested on different dummy cavities to study the temperature behaviour of pieces after welding showing that the central stiffening ring represents the overall cavity temperature variation during the resonator cool down.

The equipment has also been used during the production of components for the XFEL project, subcomponents and full cavities, showing the usefulness of this technique in reducing the cool down waiting time after welding to 50 %, from 4 to 2 hours in case of cavities.

The successful results so far obtained suggest future application of this technique, such as the improvement of the reliability of the welding procedure and the optimization of parameters.

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