FABRICATION OF THE 3.9 GHZ SRF STRUCTURES FOR THE EUROPEAN XFEL

P. Pierini, INFN/LASA, Italy and DESY, Hamburg
C. G. Maiano, E. Vogel, DESY, Hamburg
M. Bertucci, A. Bosotti, J. Chen, P. Michelato, L. Monaco,
M. Moretti, R. Paparella, D. Sertore, INFN/LASA, Italy
C. Pagani, Università degli Studi di Milano & INFN/LASA, Italy
A. Gresele, M. Rizzi, Ettore Zanon, Italy

Abstract

One batch of 10 cavities has been completed and eight structures have been installed in the 3.9 GHz cryomodule for the European XFEL (E- XFEL) Injector operation. A second batch of 10 RF structures for a spare injector module is under fabrication. The fabrication has been performed according to the European Pressure Vessel regulations, as needed for the E-XFEL operation. This paper describes the fabrication, quality control/assurance procedures and frequency preparation steps in order to achieve cavities at the correct frequency and length within the specifications.

INTRODUCTION

The E-XFEL injector includes a third harmonic section after the RF photocathode gun and the first 1.3 GHz accelerating module [1-2], in order for the linac to deliver beams with sufficiently low emittances for the production of 1 Å FEL light to the experimental users. The high quality beam is generated in the injector complex, where the 3.9 GHz section removes the non-linear distortions in the phase space after the first acceleration stage. The third harmonic system at 3.9 GHz of the European XFEL (E-XFEL) injector section is a joint INFN and DESY contribution to the project.

The 3rd harmonic section consists of a single module with 8 SRF cavities at 3.9 GHz and a quadrupole magnet package, currently being installed in the injector building [3]. A second module is in fabrication stage to provide the facility with a complete spare component in case of necessity.

This paper reports a short summary of the experience achieved with the production of pre-series [4] and two batches of the series cavities [5] for the 2 modules, and all the fabrication and preparation procedures followed to meet the specifications. The mechanical fabrication was planned according to the European Pressure Equipment Directive (PED) 97/23/EC [6], under the supervision of the TÜV-Nord acting as Notifying Body [7], according to the E-XFEL project specifications.

PED AND CAVITY PRODUCTION.

All superconducting components of the E-XFEL linac need to comply with the European PED norms [8], under the pressure conditions set by the Project of a Maximum Allowable Working Pressure (MAWP) of 4 bar in the 2 K circuits. The most restricting procedure for Category IV vessels has been conservatively chosen, following the Module G certification path for the 3.9 GHz structures. As the cavity construction materials are not listed in the harmonised standards for the fabrication of pressure vessels, a Particular Material Appraisal (PMA) for the fabrication of the resonator has been issued by the Notifying Body, together with the design examination and the approval of fabrication drawings. Furthermore all standard provision for the fabrication of pressure vessels was followed, as the traceability of all subcomponents and components at all stages, starting from the raw material to the final cavities. All welds on pressure-bearing parts followed a weld qualification process (with the preparation of several weld specimens) with the Notifying Body and cavity fabrication was performed under its supervision, including a final pressure test of the helium tank space (up to 1.43 times the MAWP, according to the norm).

Even if a similar certification path has been followed for the 1.3 GHz cavities of the main linac [8], all formal certification steps (e.g. PMA, assessments, …) had to be officially released before the critical fabrication steps, leading in strong delays in the final cavity production.

DEVELOPMENT OF THE CAVITY FREQUENCY PREPARATION STRATEGY

High frequency superconducting RF structures have a strong sensitivity to geometry variations and preparation processes. Furthermore, the small size of the 3.9 GHz resonators require several adaptations to the processing infrastructure used for cavities of much larger volumes, to optimize and stabilize process parameters (e.g. BCP, HPR, …). As many of the sensitivity parameters depend on the actual fabrication and processing infrastructure, not all the FNAL 3.9 GHz experience for ACC39 could be applied without verification, in order to reach the desire frequency/length and performance goals.

A pre-series of 3 cavities have been launched early in the development phase in order to develop a fabrication strategy for the series, by cooperation with the industrial qualified vendor.

The series cavity for the 3.9 GHz section were fabricated, processed and tested according to the experience of the pre-series, integrating the slight variations of the weld preparation and execution

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procedures needed for PED compliance. The procedure included the standard subcomponent preparation procedures for elliptical cavities fabrication, and its main steps in order to achieve the RF goals were:

- formation of Half-Cells, HC, with overmetals
- iris weld of HC into Dumb Bells
- trimming DBs with a frequency/length goal
- preparation of complete End Groups
- trimming of EG, as DBs
- equatorial welding
- pre-tuning of the fabricated structure (conservative provision to confirm weld shrikages)
- bulk BCP of cavity (approx. 120 um)
- 800 °C annealing
- RF Field flatness and frequency tuning
- Fine BCP of inner surface (approx. 35 um)
- Preparation of the functional surface (e.g. cleaning and rinsing)

During all these operations RF and process parameters were monitored and specific inspection activities (e.g. optical inner surface inspections with a high resolution camera) were performed to avoid possible contaminations and defect (like weld droplets or inclusions) that could prevent nominal performances.

The evaluation of all the frequency effects is important in order to reach the correct operating frequency within the design tuner range. Table 1 shows the cavity operational parameters and the cavity frequency sensitivities to different conditions during its lifecycle, as assessed with the experience of the prototype and the first series of components. Error bars derive from the data.

Table 1: Main Cavity Operational Parameters and Frequency (f) Sensitivity Coefficients.

Design Parameter	Value	Units
Nominal operating frequency	3900	MHz
Maximum tuner range	>1	MHz
Chosen tuner loading preparation	0,6±0.3	MHz
Frequency sensitivity	**Value**	**Units**
Longitudinal (tuning) cavity sensitivity	2,3	MHz/mm
Max f variation in elastic limit	1,6	MHz
Air to vacuum f shift	1,0±0,1	MHZ
RT to 2 K f shift	6,1±0,1	MHz
BCP removal effects:		
Bulk BCP	50,5±5,0	kHz/um
Fine BCP	40,0±10,0	kHz/um

Cavities produced in the first series were tested above nominal performances (reported in [9]), and the main fabrication goals (in terms of frequency, length, and geometry) were generally met, as shown in Table 2.

Table 2: XFEL Series Production Results

Item	Average value	Spread (max-min)	Goal
Cavity Length (after fabrication)	506.28 mm	1.33 mm	506 ±4 mm
Frequency (after fabrication)	3901.28 MHz	3.22 MHz	3903 MHz
Cavity Length (after tuning)	506.01 mm	1.54 mm	506 ±4 mm
Frequency (at end, warm, air)	3892.47 MHz	0.16 MHz	3892.4 ±0.2 MHz
Field flatness	96.8%	2.8%	>95%
Average Cells Runout	0.53 mm	0.39 mm	0.4 mm

However, as a consequence of the spread in the final BCP effects reported in the following paragraphs, the frequency goal was met within the useful range only after an additional tuning of a few hundreds kHz of seven cavities after their integration in the tank. Analysis of the bandwidth modification before and after this operation suggests no influence on the achieved field flatness levels. This experience allowed us to revise the process control parameters and frequency preparation steps for the spare series, to prevent the need for post-integration tuning, mainly by controlling the process and limiting the spread of the last BCP step. Table 1 presents the BCP sensitivity coefficients achieved after stabilization of the process, and confirmed by the first treatments of the spare series.

Another important outcome of the first cavity series experience is the final strategy for reaching the correct frequency at the nominal cavity length, used for the spare production: Table 3 summarizes the frequency goals at the main steps of the cavity preparation cycle, from the fabrication to the operating conditions.

Table 3: Frequency Preparation Goals

Fabrication steps	Frequency [MHz]
Fabricated, in air at RT, before BCP	3899.5 (±1.6 expected)
After bulk BCP, in air at RT	3893.0 (±2.3 expected)
Goal for FF tuning	3893.0 (±0.1)
After fine BCP, in air at RT	3892.3 (±0.3 expected)
At cold, in vacuum, tuner unload	3899.4 (±0.4)

ANALYSIS OF THE MECHANICAL FABRICATION EXPERIENCE

In order to achieve the fabrication goals set in Table 3 at the correct cavity nominal length a good knowledge of the effects of the weld procedures (weld shrinkages and their stability, influence of weld seam perturbations …) is needed in order to prepare the subcomponents (half-cells, dumb-bells, end groups) with the proper over-metals for weld shrinkages compensation and sufficient material for the RF-based trimming operations.

Moreover, a control of the execution of the correct trimming instructions with small errors and great stability is needed in order to limit the spread in the frequencies of the fabricated cavities. During the cavity production all the mechanical, RF, and process steps (dimensional control, RF measurements, trimming instructions, chemistry process parameters and outcomes, …) were documented at the component (HC), subcomponent (DB and EG) and cavity level in certificates, for the production control and supervision at the vendor and by INFN.

Figure 1 shows the error in the implementation of the trimming instructions for the Dumb Bells in the three productions series (3 prototypes, in red, 10 series cavities in blue and 10 spare cavities in green), as retrieved from the DB certificates. A clear decrease in the spread of the values have been achieved, whereas a small

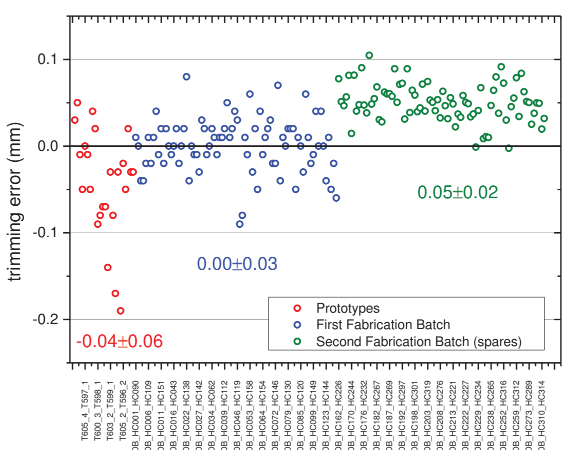

Figure 1: Errors in the implementation of the trimming instructions (i.e. difference between the post/trimming survey with respect to the trimming instruction) in the three production batches. In the label the averages and standard deviations.

Figure 2 shows the equatorial weld shrinkage experienced in the 23 cavities currently produced. A stabilization of the fabrication experience can be seen also from this trend, with a reduction of the weld shrinkage uncertainty. The cavity in the first series that experienced a lower shrinkage than average, 3HZ007, had a correspondingly higher frequency than expected. A cause for this anomalous value could not be found, but could be caused by an insufficient spring loading of the tool used for the equatorial weld in the electron welding machine.

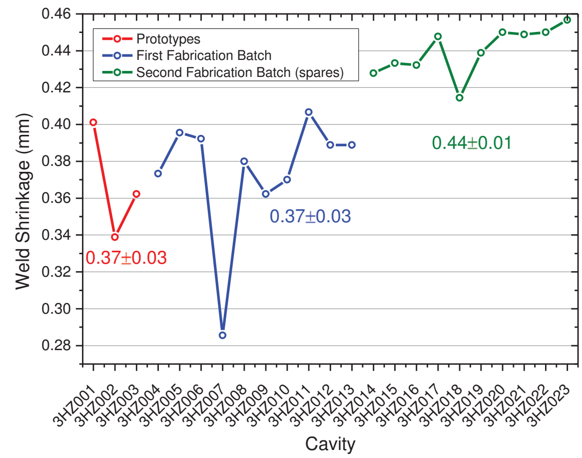

Figure 2: Equatorial Weld shrinkages (per weld seam) experiences in the three production batches of the 3.9 GHz E-XFEL cavities. In the labels the averages and standard deviations.

Finally, Figure 3 shows the cavity frequencies after the fabrication stage, for all the cavities of the three production batches, along with the evolution of the fabrication goals in the three activities (which were revised with the better assessment of parameters like weld shrinkages and frequency sensitivity to the chemistry). Also in this case the decrease of the uncertainties shown in Figures 1 and 2 led to a closer correspondence to the goal and to a decrease of the final spread of the cavity frequencies. The labels in the picture show the average frequencies of all three production and the full spread of the population (maximum-minimum frequency). The pretuning step has been avoided in the spare production, as the cavity meet the fabrication goal of Table 3.

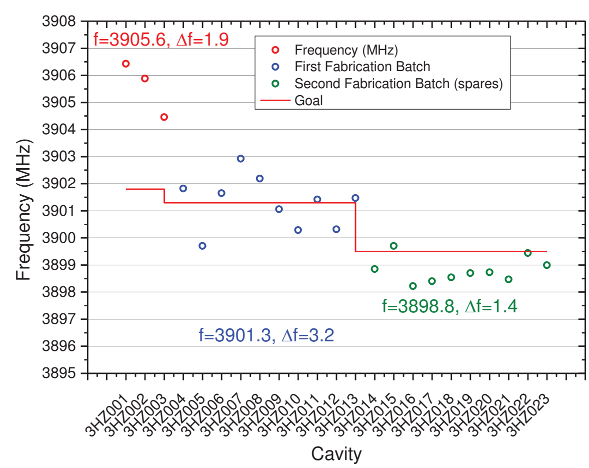

Figure 3: Frequencies of the cavities as fabricated, for the three production series. In the label the averages and the full spread of the production. The continuous red line shows the production goal, which was revised in the cavity frequency preparation procedure after each iteration pass with the better knowledge of the fabrication and treatment parameters and cavity response.

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ANALYSIS OF THE CHEMISTRY EXPERIENCE

The control of the frequency goals for the post-fabrication stages set in Table 3 requires a monitoring of the frequency effects during the processing stages of these sensitive resonators.

The BCP treatments of the 3.9 GHz cavities were performed in the etching facility of the vendor used for the treatment of the main linac E-XFEL cavities at 1.3 GHz. Due to the high sensitivity of these structures, as experienced during the prototype production which were treated in a separate cabinet [4], the bulk BCP treatment was split in three steps, flipping the cavity orientation at each treatment to minimize longitudinal etching variations.

- The first (shorter) steps were performed in the "external BCP" cabinet, in order to remove the first surface layer of the cavities, which underwent mechanical operations. This provision is taken to avoid polluting the BCP mixture used in the final surface preparation of the 1.3 GHz cavities with possible traces of contaminants.
- The second and third steps (of equal duration) were performed in the same cabinet used for the final BCP of the 1.3 GHz production.

Between these treatment steps a rinsing, weighting, and frequency control was implemented in order to monitor the frequency response of the cavity to the etching.

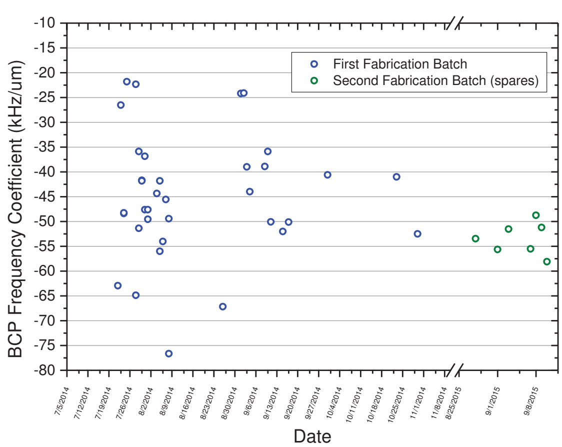

Figure 4: Evolution along time of the frequency response of the cavity to the BCP etching (in units of kHz/um of average material removal). The achievement of a better stability during the first fabrication batch, and especially in the first treatments of the spare series can be appreciated.

Due to the large operating flows of the BCP systems, designed for the larger volume 1.3 GHz cavities, it was initially difficult to operate under stable conditions of cavity frequency (and bandwidth) response to the treatment.Even regulating the system pumps at the lower possible speeds to decrease the acid flow for these small cavities, it was difficult to obtain a stable etching process, as it is seen by the large variation of the cavity frequency response (variation of the fundamental mode frequency per removed micron) shown in the leftmost part of Figure 4. It was necessary to install a smaller acid pumping system, and to introduce more precise acid flow meters in order to stabilize the system, as shown by the rightmost points of the first fabrication series.

The large spread of the frequency response in the bulk BCP was later recovered by the final tuning stage. However, the spread of the fine BCP treatments required a post-integration correction to the cavity frequency in order to bring them within the tuner range.

The first treatments of the spare cavity series, currently under way, show the great stabilization of the cavity response. Moreover, the cavity frequency preparation was revised to further decrease the impact of the fine BCP uncertainties by shortening the fine BCP time from the 30 minutes used for the first series to 15 minutes.

CONCLUSIONS

An analysis of the procurement of 23 3.9 GHz cavities for the E-XFEL and the consequent decrease of uncertainties in the mechanical fabrication and treatment processes is presented here. The first series of cavities are currently installed in the E-XFEL X3M1 module in the injector, to be commissioned in Fall 2015. The second series of cavities for the spare module has been mechanically fabricated and are undergoing chemical treatments for the preparation of the spare X3M2 module. A better understanding and control of the fabrication steps and preparation procedures is so far allowing the reduction of the cavity frequency uncertainties.

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