

XFEL THIRD HARMONIC SUPERCONDUCTING CAVITY PROTOTYPES: FABRICATION AND PROCESSING EXPERIENCE

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Abstract

Three superconducting 3.9 GHz cavity prototypes have been fabricated for the XFEL linac injector, with minor modifications to the RF structures built at FNAL for the FLASH linac. This paper describes the production procedures and the RF preparation experience, the chemical processing and the plans for the vertical test at INFN Milano for the characterization of the structure.

INTRODUCTION

The European XFEL linac injector includes a third harmonic (3.9 GHz) accelerating section in order to generate the high quality electron beam required for the short wavelength FEL operation. The third harmonic section is required for the linearization of the beam phase space before the longitudinal bunch compression performed to increase the peak current for lasing [1].

A short module of four 3.9 GHz cavities, ACC39, designed and contributed by FNAL to DESY, will be put into operation during 2010 in the FLASH FEL facility as a proof of principle of the concept. A number of cavities have been successfully fabricated and tested at FNAL, exceeding the required performances [2].

The cavity design for the XFEL third harmonic section has been derived from the FNAL design, with the minimal modifications described in ref. [3] to adapt to the slightly different XFEL modules environment.

The main components of the XFEL third harmonic system will be procured jointly by INFN and DESY as in-kind contributions to the European XFEL Project.

PRODUCTION OF CAVITY PROTOTYPES

In order to prepare for the realization of the European XFEL third harmonic system, a small preseries of three cavities has been tendered by DESY (under the supervision of INFN personnel) to one of the companies qualified for the XFEL cavity production. The vendor is responsible for the fabrication and surface processing, up to the final assembly for the vertical tests at INFN.

Cavity Mockups

For the development of the initial fabrication procedures and to assist in the commissioning of the necessary tooling for these new structures at the company (for fabrication, welding, field flatness tuning and surface processing) first a simplified copper RF mockup (with no auxiliary ports) and later a complete Niobium mockup (using non RF-grade material, from discarded sheets after scanning) have been produced. Their RF properties have been extensively characterized at warm.

The mockups have been used to determine the frequency sensitivity parameters (for trimming and tuning) and the weld shrinkages necessary to define the structure fabrication procedure in order to meet the correct frequency and length of the final structure. Furthermore, they proved useful in the development of all software tools for the RF measurements and field flatness adjustment procedures.



Figure 1: Components of the Nb mockup during intermediate fabrication steps.

Cavity Prototypes

Three structures have then been fabricated on the basis of the experience gathered from the mockups, after some further small adjustment performed during the analysis of all produced subcomponents (half-cell, dumb-bells) [4]. After fabrication, it was decided to perform a frequency adjustment and field flatness tuning prior to the BCP etching of the cavity. During this operation the cavity length was adjusted within a mm from its nominal value, and the field flatness raised to a value above 95%. In order to reach the correct length the cavities have been tuned to a frequency slightly higher (by 3 MHz) than originally estimated by our original assumptions. The further frequency adjustment to recover this offset will be therefore performed by correspondingly increasing the etch removal by approximately 100 μm .

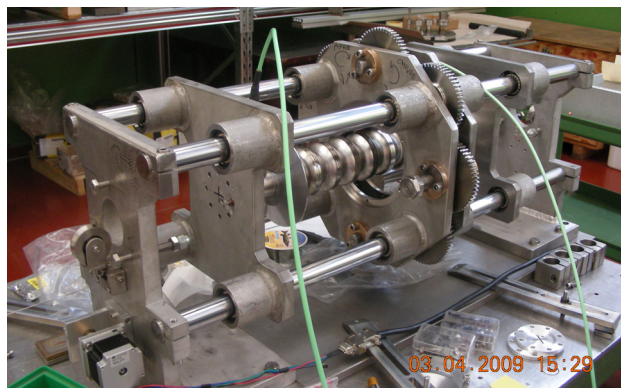


Figure 2: The field flatness tuning machine.

Table 1 summarizes the achieved cavity frequencies and lengths after the field flatness tuning.

Table 1: Cavity Frequencies and Lengths.

	Frequency MHz	Length mm
3HZ01	3903.523	506.70 (+0.7)
3HZ02	3903.516	506.85 (+0.9)
3HZ03	3902.176	506.35 (+0.4)

It is to be noted that at this stage the only unknown coefficient yet to be determined is the frequency sensitivity to the surface etching. The FNAL production experienced a sensitivity of 40 kHz/μm, but since different acid flow parameters related to a different setup could result in variations of this value, an experimental verification was performed.

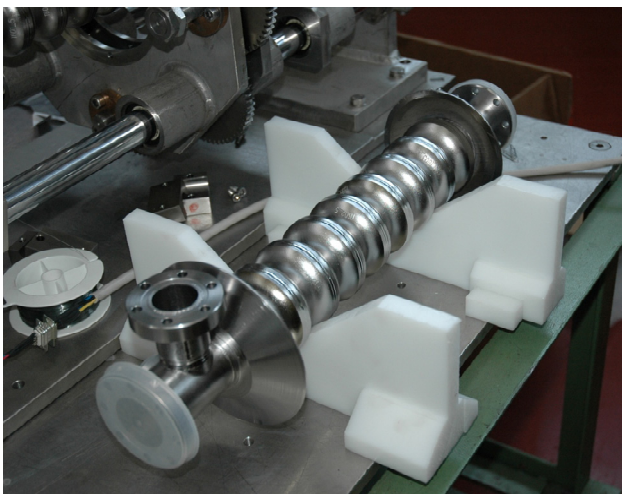


Figure 3: One of the completed prototype structures.

COMMISSIONING OF THE ETCHING FACILITY

The cavity etching facility has been designed, installed and commissioned under the vendor responsibility. The system has a closed BCP circuit, equipped with an heat exchanger to keep the acid temperature below 15°C during the whole chemical process. The cavity is mounted vertically, the forced acid flow enters the cavity from the bottom beam pipe port. Flanged pipes guide the output flow at each opening (HOMs, pickup, coupler ports).

The niobium mockup has been then used for the system commissioning and to determine the cavity sensitivity coefficient to etching. The mockup cavity went through five steps of etching with a total material removal of 250 μm. After each etching stage the cavity was dismantled and rinsed, and its frequency was monitored.

The system is shown in Figures 4 and 5.

Material removal has been measured by cavity weight reduction, and cross-checked with on-line niobium samples.

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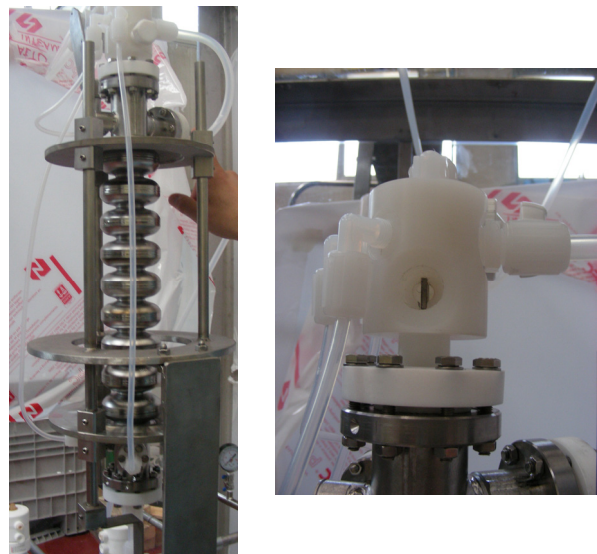


Figure 4: The cavity in the BCP etch cabinet (left) and detail of the online sample (right).



Figure 5: The etch cabinet.

Fitting the frequency change with the material removal we obtain a sensitivity factor for chemical etching of 37 kHz/μm, in line with the reported FNAL experience.

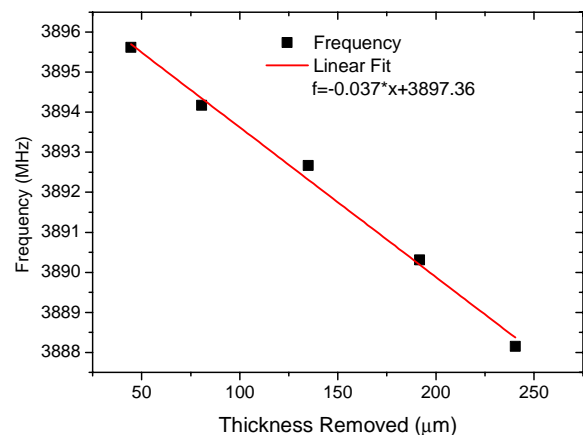


Figure 6: Frequency against removed material thickness.

Using this removal coefficient, and accounting for the change in frequency due to the thermal shrinkage, vacuum effects and tuner action, the nominal removal rate to reach the desired operating frequency at cold is shown in Table 2.

Table 2: Cavity Starting Frequencies and Estimated Removal for Correct Operating Frequency

	Frequency MHz	Removal μm
3HZ01	3903.523	~300
3HZ02	3903.516	~300
3HZ03	3902.176	~260

The values from Table 2 exceed the initially foreseen 150+30 μm removal of the cavity surface layer, but pose no problem to the cavity stiffness, due to the thickness of the starting sheets (2.8 mm) used in the production.

RF CHARACTERIZATION

Each cavity has been tuned after fabrication to the proper length and with a field flatness better than 95%. The software-assisted tuning procedure, which involves the plastic deformation of each individual cell of the structure, requires few (3-4) iterations to converge.

After the etching of the niobium mockup the field flatness has been checked again, and it was found to be reduced to approximately 50% (red dashed curve in Figure 7). After two further tuning cycles the field flatness was easily restored to 95% in two tuning iteration (blue continuous curve in Figure 7).

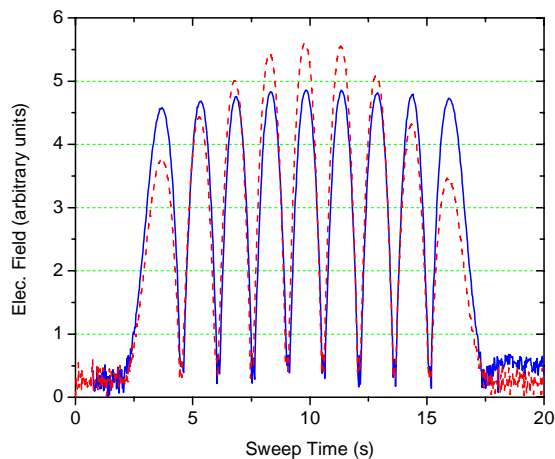


Figure 7: Field flatness deterioration after BCP etching (dashed red curve) and its restoration after tuning (continuous blue curve).

The analysis of the bandwidth variation before and after the etching provides indications of the different removal rates at the equators and at the irises, related to the different acid flows in the two regions.

By using either the frequency sensitivity coefficients of the 0 and π modes of the halfcells derived from RF simulations, or performing Slater calculations assuming a linear removal rate between the iris and the equator, we obtained preliminary indications that the removal rate at the iris is approximately twice the rate at the equator, and that the average thickness removal is approximately 30% higher than the minimum removal rate obtained at the cavity equators.

Figure 8 shows the appreciable modification of the passband before and after the BCP etch, with a 10% increase of the coupling coefficient due to the higher removal rate at the irises.

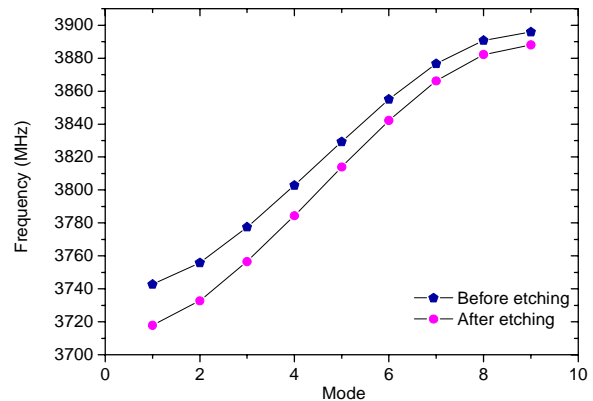


Figure 8: Evolution of the fundamental passband with the main BCP etching.

A high pressure rinsing (HPR) cabinet is being completed at the vendor cavity processing facility. The HPR has been developed on the basis of the FNAL process parameters for the production of the FLASH 3.9 GHz accelerating cavities. Since the HPR station is not yet operational, the niobium mockup has been rinsed after chemistry in a tank with standard pure water at 1 MOhm cm.

VISUAL INSPECTION OF THE CAVITY SURFACES

Using a commercial rigid boroscope system and a laboratory-developed illuminating system based on white LEDs each cavity has been fully inspected after fabrication. A complete map of all iris and equatorial welds has been stored for later comparison of the surfaces after the BCP operations. The niobium mockup has been inspected again after the main BCP etching.

Figure 9 shows an example of the optical inspection of the full equatorial weld seam of the mockup before and after the chemical treatment. The whole 360° azimuthal region is shown as a single continuous strip, in the same magnification scale. The visibility of the welding seam and the heat affected zone (HAZ) region at its sides are clearly enhanced by the etching of the damaged surface layer at the equator.

The irregular width of the HAZ is due to welding parameters being tuned during the mockup fabrication.

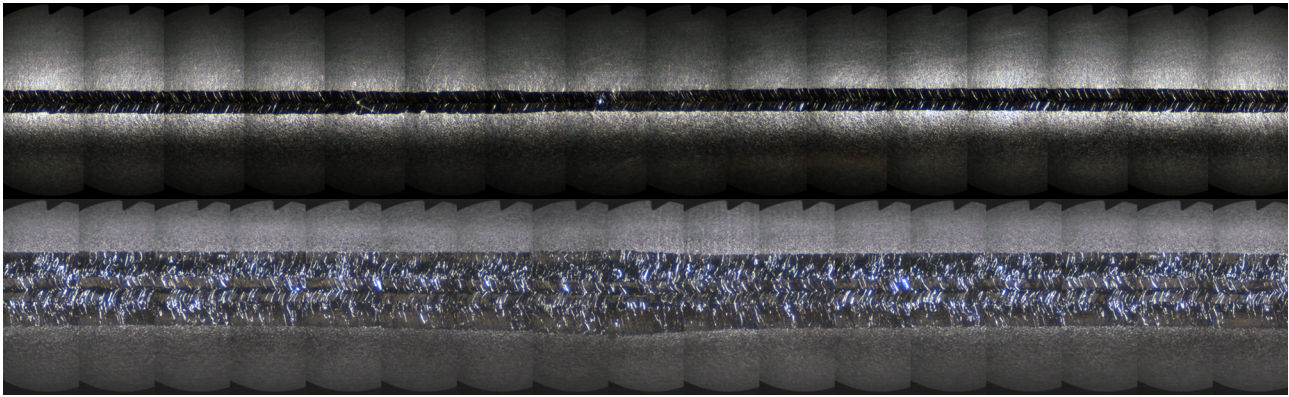


Figure 9: Inspection of an equatorial weld of the niobium mockup before (top) and after (bottom) the BCP etching.

At the iris a smoother surface is achieved as well. Several patterns that were tagged as suspect “defects” during the inspection after fabrication were no longer visible after the chemical etching, as shown in Figure 10.

The modified insert is shown in Figure 11, and is currently under procurement phase. A reduction of the large volume outer vessel to limit the required LHe inventory for tests has been realized using high-density closed-cell polyethylene foam sheets.

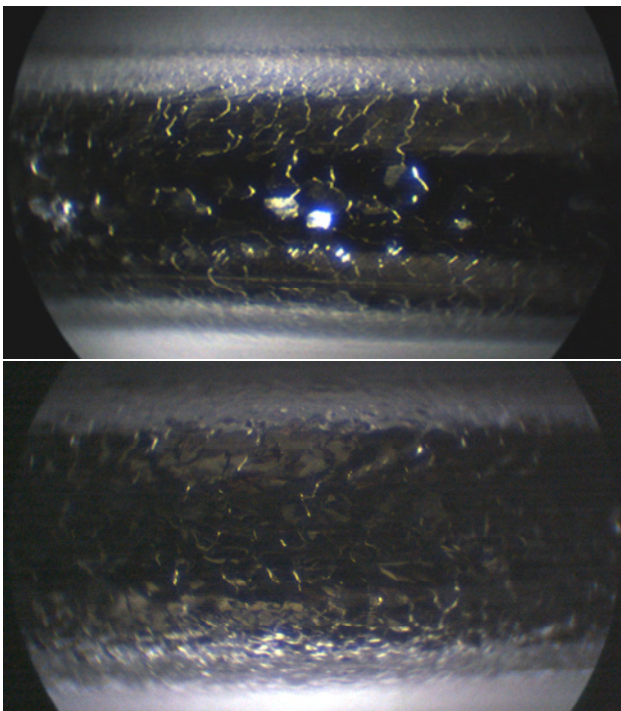


Figure 10: Iris inspection before (top) and after (bottom) the BCP etching. Bright patterns that could be interpreted as bumps in the welding area were no longer visible.

VERTICAL TEST FACILITY AT LASA

The existing large vertical cryostat available at the LASA laboratory of INFN in Milano, originally developed for the testing of 500 MHz cavities, is being modified for testing the 3.9 GHz XFEL cavities.

The vertical insert has been completely modified in order to provide variable antenna coupling from the bottom of the cavity. A room temperature linear actuator moves the cavity in its frame within a 50 mm range (with precision of 8 μm/half motor step), while the antenna is fixed to the bottom plate of the insert.

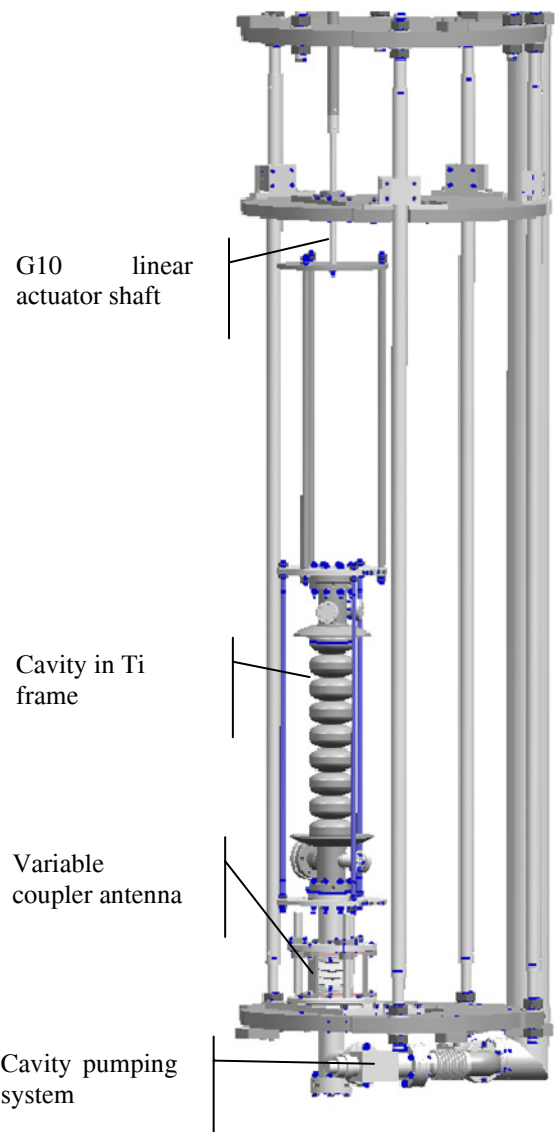


Figure 11: The modified insert for the testing of the XFEL 3.9 GHz cavities at INFN Milano.

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The variable antenna scheme provides optimal coupling to minimize reflected power.

The current subcooling pumping system available at the laboratory is able to guarantee stable 2 K operation of the test facility up to approximately 13 W of dissipated power.

A small, 10 m², ISO4 clean room for assembling and disassembling the cavity antennas, with a High Pressure Rinsing system, complete the available infrastructure at the laboratory.

Cryogenic commissioning of the upgraded facility will be performed soon. The assembly and test infrastructure will be qualified for operation using a 1.3 GHz single cell cavity of known performances from DESY.

CONCLUSIONS

We have reported here the fabrication experience of the prototype 3.9 GHz cavities for the third harmonic system of the XFEL injector. The cavities have been fabricated by a qualified vendor, which is also responsible for the treatments after fabrication and for the final surface preparation up to the testing stage at the vertical testing facility, which is currently under preparation at INFN LASA.

ACKNOWLEDGEMENTS

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