

## UPDATE ON THIRD HARMONIC XFEL ACTIVITIES AT INFN LASA

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### Abstract

After the successful installation and beam operation of the first batch of 3.9 GHz cavities into the XFEL Third Harmonic Injector Module, ten more cavities have been tested and delivered to DESY to be assembled into a spare cryomodule. In this paper, we report on the activities related to the cavities fabrication, treatment and vertical testing at INFN LASA.

### INTRODUCTION

The 3<sup>rd</sup> harmonic 3.9 GHz section at the European XFEL (E-XFEL) injector provides linearization of the longitudinal beam phase space after the first accelerating section. To compensate the effect of the space charge, a long bunch is generated in the RF gun. The subsequent RF acceleration in the first 1.3 GHz module produces cosine sinusoidal curvature in the longitudinal phase space of the incoming bunch. To remove this effect, a 3.9 GHz module is placed afterwards to linearize the longitudinal phase space and prepare the beam for the following compression and acceleration stages.

The E-XFEL 3<sup>rd</sup> harmonic module is an 8-cavity module that provides a maximum voltage of 40 MV, corresponding to an accelerating field of about 15 MV/m per cavity. All the cavities are operated close to 180° phase with respect to the incoming beam.

INFN Milano–LASA has provided, as in-kind contribution, the main components of the 3<sup>rd</sup> harmonic module now in operation in the E-XFEL tunnel [1, 2]. An important follow-up of this activity has been the full qualification, in our Vertical Test infrastructure, of additional ten cavities (eight plus two spares) produced by the firm E. Zanon S.p.A., under INFN supervision, in order to prepare in the near future a complete spare module of the 3.9 GHz system. This paper reports results of vertical tests of these additional ten cavities.

### CAVITY FABRICATION

The cavities were fabricated and treated at E. Zanon S.p.A., an E-XFEL qualified cavity vendor. The procedure we established for the fabrication of these cavities was based on the experience of three prototypes and the previous batch of ten cavities we produced for the E-XFEL Injector module [3].

The main steps are summarized in Table 1 and are aimed to reach the correct frequency and length of the cavity at the operating temperature of 2 K.

The relevant difference in the fabrication process between the present batch of cavities and the previous one is the duration of the “Final BCP” that has been reduced from

30 to 15 minutes in order to reduce the spread in the final cavity frequency due to the large uncertainties of this chemical attack.

Table 1: Cavity Fabrication Main Steps

Main Cavity Preparation Step
▪ 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
▪ Bulk BCP of cavity (approx. 120 $\mu\text{m}$ )
▪ 800 °C annealing
▪ RF Field flatness and frequency tuning
▪ Final BCP of inner surface

During all these operations RF and process parameters were monitored to detect deviations from nominal expected values and specific inspection activities (e.g. optical inner surface inspections with a high resolution camera) were performed to identify possible surface contaminants or fabrication defects (like weld droplets or inclusions) that could prevent nominal performances. Indeed, in one case, the optical inspection revealed scratches at the iris position that were removed and followed by an additional “Final BCP”.

### VERTICAL TEST FACILITY

Our Vertical Test Facility has been successfully used for testing the first batch of ten cavities for the E-XFEL 3<sup>rd</sup> harmonic module [4].

An ISO 5 clean room allows assembling the cavity with the required ancillaries for RF test (High Q Antenna, Pick Up and HOM antenna feedthroughs). Inside the Clean Room, an HPR system, fed by 100 bar Ultra Pure Water (UPW), is used to clean the cavity after assembly of components and before the RF test.

A slow pumping system is directly connected to the clean room for pumping and venting the cavity in a controlled way to avoid particle motion.

The Vertical Insert support hosts up two cavities and it is fully equipped for cryogenic measurements. The cryostat that hosts the VT is 4.5 m deep and 0.7 m in diameter. Moreover, a Residual Gas Analyzer, mounted on the Ultra High Vacuum line dedicated to the cavity, monitors gas evolution during the test.

The cryogenic subcooling system consists of two rotary and one Roots pumps allowing about 40 W of cryogenic power at 2 K. The system allows lowering the bath temperature down to 1.6 K.

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For the RF characterization of the cavity, we use a solid state 200 W power amplifier. The power is coupled to the cavity by a coaxial antenna (High Q Antenna) whose (nominal) quality factor is  $Q_{\text{ext}}=10^9$ . To sample the accelerating field, a pick up antenna (typ.  $Q_{\text{ext}}=10^{10}$ ) is installed on the opposite side of the cavity. Usually, also the HOM coupler antennas are installed, mainly to probe the proper tuning of their notch filters at the accelerating mode ( $\pi$ ) frequency. Due to its narrow bandwidth (less than 1 Hz), the cavity is driven, during the test, using a Phase Locked Loop.

A LabVIEW program monitors all RF parameters and allows acquiring data for  $R_s$  vs T,  $Q$  vs  $E_{\text{acc}}$ , HOM notch, etc.

During the RF test, the cavity has thermometers mounted on the surface as well as Second Sound sensors positioned around the cavity. These diagnostic tools are used to identify quench spots during the high power cavity tests.

## CAVITY TEST

After fabrication and treatments, the cavities are delivered at INFN Milano - LASA filled with UPW water to preserve the internal surface status.

Once the cavity is ready for assembly on the Vertical Insert (VT), a temporary “portable” Clean Room is prepared for the final vacuum connection of the cavity to the VT UHV line. The line is then slow pumped down and the connections leak checked.

Afterwards, the thermometers are mounted on the cavity as well as the Second Sound sensors around it. Finally all RF and thermometers devices and connections are checked.

Once all checks are passed, the VT is moved into the cryostat for a final integral leak check before the cool down to 2 K for the RF cavity characterization.

To reach the 900 litres of LHe necessary for guaranteeing a sufficient RF test time window at 2 K, we transfer typically about 2250 litres of LHe (5x450 litres dewar). This operation takes about 2 and half days. Once the proper LHe level is reached, we start the subcooling from 4.2 K to 2 K. During this phase, we measure the cavity surface resistance of one of the two installed cavities. Once we reach 2 K, the RF cable are calibrated and we start the power tests of the cavity.

The cavity is typically tested CW up to a dissipated power of about 2 W to avoid damaging the HOM antennas feedthrough. The test is then switched to pulsed mode to reduce the mean dissipated power with 0.5 Hz frequency pulses, 25 % duty cycle.

## CAVITY RESULTS

As for the previous batch of cavities, we have measured two cavities at each cooldown to increase the test efficiency and reduce the overall time required for the cavity characterization up to nominal specifications.

Fig. 1 shows the summary of the performance of the spare module cavities. Nine cavities out of ten fully reached the E-XFEL specifications ( $E_{\text{acc}} \geq 15$  MV/m,  $Q_0 \geq 10^9$ ) both in term of quality factor and of accelerating field.

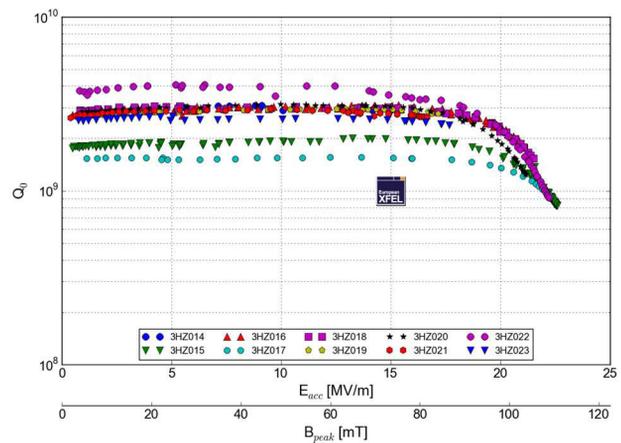


Figure 1:  $Q_0$  versus  $E_{\text{acc}}$  for the second batch of cavities tested at INFN Milano – LASA. The only cavity barely reaching the E-XFEL performance in term of  $E_{\text{acc}}$  is 3HZ014 that instead maintains a good  $Q_0$ .

Cavity 3HZ014 is the only one that marginally misses the nominal E-XFEL specification, with a hard quench occurring approximately at 15 MV/m. This and 3HZ021 cavity have been tested twice, being the two units with the lowest performance of the whole batch. Indeed, 3HZ021 reaches an accelerating gradient of 17 MV/m well within the requirements for operation in the E-XFEL 3<sup>rd</sup> Harmonic Module.

Fig. 2 shows a summary of the power rises performed on cavity 3HZ014 up to now. During the first set of power rises (“test 1”), the cavity reached up to 16 MV/m but with field emission. After conditioning (“test1-2K(3)”), the field emission was lower and we could reach 17 MV/m. To cure the field emission, we performed an additional complete HPR (without and with accessories installed) and then we retested the cavity. During this second test, the field emission was indeed cured but the maximum field was only barely 15 MV/m. From the optical inspection, done before the “Final BCP”, we identify as a possible cause of this quench a pitting on the equatorial weld region that might increase locally the magnetic field and induce the quench.

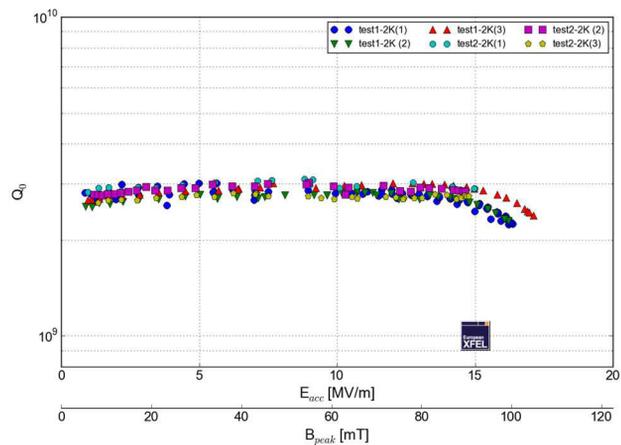


Figure 2: 3HZ014 power rises during the first (“test1”) and second (“test2”) tests.

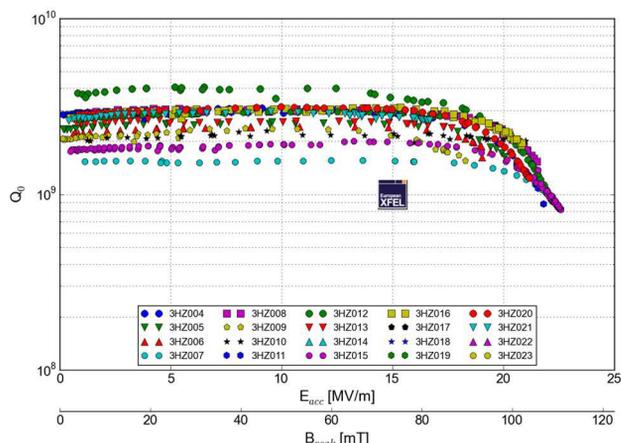


Figure 3: Overall  $Q_0$  versus  $E_{acc}$  for the cavities tested at LASA in the framework of the E-XFEL project.

Finally, Fig. 3 reports an overview of the best performances of the two batches of cavities. Both  $Q_0$  and  $E_{acc}$  are comparable between the two set of cavities, showing a good reproducibility of the results besides the differences in the fabrication process as reported in Table 2.

Table 2: E-XFEL 3.9 GHz Cavities Performances

	$E_{acc}$ [MV/m]	$Q_0^*$ [ $10^9$ ]
<b>First Batch</b>	20.4±1.1	2.39±0.29
<b>Second Batch</b>	19.9±2.4	2.77±0.65
<b>All</b>	20.1±1.9	2.58±0.54

\* $Q_0$  calculated at  $E_{acc} \approx 4.5$  MV/m

### CAVITY DIAGNOSTIC

During the test of the cavities, we equipped the cavity with thermometers on HOM cans and ports to monitor temperature rises during the RF test. We have noticed no abnormal increase of temperatures on these components.

While thermometers covers limited cavity areas, we use Second Sound detectors to monitor quench spots [5]. We install usually ten sensors per cavity to cover the largest possible area. The signal generated by the quench at the sensors are amplified and then converted to time of flight by a proper amplification and acquisition system. A LabVIEW program analyses the data and applies the proper reconstruction models to detect the quench spot area (see Fig. 4).

Differently from our previous measurement on prototypes, we could not use the modal analysis to cross check the Second Sound data. In fact, due to the presence of HOM antennas on the cavity, we had to limit the cavity excitation on all passband modes different from the  $\pi$  mode to prevent failures on cables and feedthroughs possibly resulting from the large power extraction from the broadband antennas.

For the second batch of cavities, we have detected no quenches in cell 1, 8 and 9 (1 is coupler side, 9 is Pick Up side). All the other cells are equally affected by quenches at the maximum reached field.

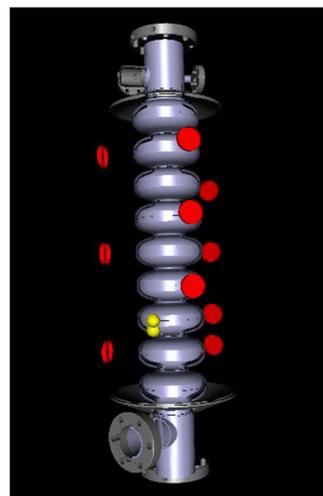


Figure 4: Second Sound quench event on 3HZ015 cavity. Red cylinders are the sensors installed around the cavity. The quench spot (yellow spheres) are the possible locations of the quench based on the minimization process implemented in the analysis software.

### CONCLUSIONS

A second batch of cavities, to be used to prepare a spare module at E-XFEL Injector, have been successfully tested at INFN Milano – LASA.

Nine cavities have fully reached the requested specification. Only one cavity is below this specification and we are evaluating the possibility to grind the observed pitting to recover full specifications. We have observed no differences in the power rise tests with respect to the previous batch of cavities now successfully operated in the E-XFEL Injector.

After the successful tests, these cavities will be assembled in the string in the next fall at DESY and the spare cryomodule will be tested later on in the AMTF facility.

### ACKNOWLEDGEMENTS

We acknowledge the support of Cornell colleagues for providing some of the Second Sound Detectors and a code for quench position reconstruction.

### REFERENCES

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