

# Validation of the superconducting 3.9 GHz cavity package for the European X-ray Free Electron Laser

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A full test of the cavity package concept under realistic operating condition was a necessary step before the assembly of the European XFEL (EXFEL) 3.9 GHz superconducting system and its installation in the accelerator. One cavity, equipped with magnetic shielding, power coupler and frequency tuner has been tested in a specially designed single cavity cryostat in one of the test benches of the DESY Accelerator Module Test Facility (AMTF). The cavity was operated at high pulsed power up to an accelerating field of 24 MV/m, above the quench accelerating field of 21 MV/m achieved during the continuous wave (CW) vertical qualification test and with a large margin with respect to the EXFEL maximum operating specification of 15 MV/m for the 3.9 GHz system. All subsystems under test—coupler, tuner, waveguide tuners, low level radio-frequency (LLRF) system—were qualified to their design performances.

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## I. THE NEED FOR CAVITY PACKAGE VALIDATION

The correct operation of a superconducting cavity in an accelerator under nominal conditions requires a number of active and passive subcomponents. Among these, a cold tuning system (CTS) is needed to finely adjust the cavity frequency to the master frequency reference of the facility; a fundamental power coupler (FPC) is used to deliver the necessary fundamental mode power for the cavity excitation and beam acceleration; a magnetic shield (MS) provides the necessary attenuation of the earth field to the superconducting material and the higher order modes (HOM) couplers transfer the power of the beam-excited wake fields out of the cold cavity (while properly notching the main accelerating mode frequency component); and a pick up antenna (PU) is used to probe the cavity field. In addition, the cryomodule mechanical environment around the cavity needs to allow for the relative differential thermal contraction of different materials without introducing uncontrolled forces on the cavities that could affect their natural resonant frequencies.

Frequently, in order to validate the complete design of the cavity package in its operating environment a complete test of a cavity dressed with all its ancillary components is performed in a short horizontal cryostat, which preferably provides a mechanical environment similar to that of the cryomodules in the accelerator [1,2]. Such an activity took place at the DESY AMTF facility, in joint collaboration between DESY and INFN, for the characterization of the EXFEL 3.9 GHz cavity package.

## II. THE EUROPEAN XFEL 3.9 GHz SYSTEM

The European XFEL injector hosts a cryomodule composed of 8 superconducting radio-frequency (SCRF) cavities resonating at 3.9 GHz, to manipulate the longitudinal beam phase space before the three bunch compressor stages occurring downstream along the linac [3–5]. The module design has been derived from the third-harmonic section at FLASH, developed by FNAL [6], with some major modifications to the cavity package design, in particular in order to provide alternate coupler orientation with respect to the beamline, for dipole coupler kick cancellation [7]. The cavities have been procured by INFN and vertically tested at the LASA laboratory [8] and the module has been jointly prepared by INFN and DESY for tunnel installation, as described in several contributions to various particle accelerator conference proceedings [9–12].

Figure 1 shows a 3D model of the 3.9 GHz dressed cavities (illustrating both coupler orientation variants as foreseen in the accelerator module), equipped with the cold tuners, the cold fundamental power coupler part, the low

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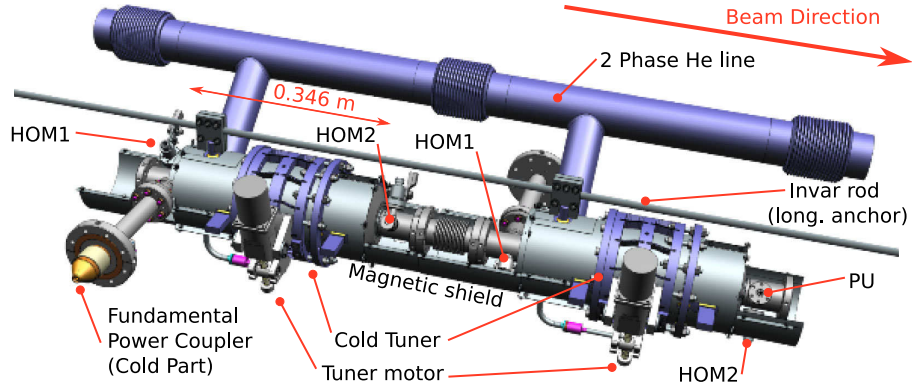


FIG. 1. The two EXFEL 3.9 GHz cavity packages in the cavity string, with opposing coupler orientations.

coupling radio frequency antennas for the field pick-up probe and HOMs, and the magnetic shield (the top half of the parts connecting the cavities and the support structure of the module have been blanked for clarity).

### III. THE AMTF CRYOADAPTERS

All EXFEL 1.3 GHz main linac modules were qualified in the DESY AMTF after their assembly [13]. The qualification test foresees the individual cavity performance characterization and the procedure includes the verification of the correct functionality of all cavity ancillaries [14]. After the successful outcome of the AMTF test each module was then equipped with its individually tailored rf distribution system and prepared for the installation in the tunnel. The third harmonic system was technically commissioned and characterized by means of rf measurements performed directly in the injector building after installation. This was decided to limit the infrastructure work needed for adapting the AMTF for the testing of 3.9 GHz modules, to avoid slowing down the test schedule of the 101 1.3 GHz modules needed for the EXFEL linac, and considering the moderate performances needed by the 3.9 GHz cavities [5]. Due to this decision, the qualification of the cavity package in a horizontal test represented an important verification needed well before the start of the module assembly activities.

Even if no horizontal tests of single cavities were envisaged during the EXFEL construction, two short ( $\approx 2.2$  meter) cryostats fitting the cryogenic connections of the AMTF test caves were delivered by the Budker Institute of Nuclear Physics (BINP) as part of the Russian in-kind contribution to EXFEL [15]. These adapters will allow future testing and R&D activities on single 1.3 GHz cavities in a mechanical environment close to their operating conditions.

In order to establish testing capabilities for the 3.9 GHz cavities at the AMTF in DESY, one of the cryoadapters has been extensively modified in collaboration with BINP, adding a second fundamental power coupler port on the opposite side of the existing one (to allow the installation of

both 3.9 GHz cavity package variants) and providing a new internal cavity sliding suspension support, based on the geometry of the 3.9 GHz module developed at INFN-LASA. Figure 2 shows the cavity supported through the sliding roller bearings to the stainless steel tray inside the adapter. Additionally, one of the EXFEL accelerator test benches (XATB1) in the AMTF at DESY has been equipped with the rf infrastructure needed to test cavities at 3.9 GHz (a 80 kW klystron, a modulator to provide the nominal EXFEL pulse, a waveguide system, LLRF/technical interlock crates and motor driver racks for the actuation of the cavity frequency tuner and coupler stub

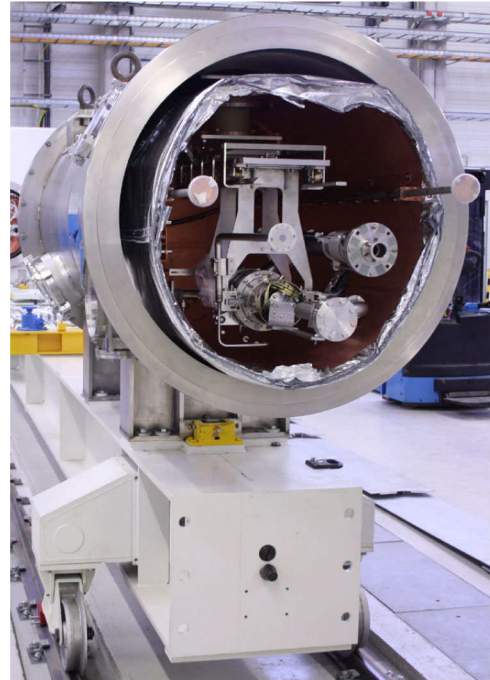


FIG. 2. The cavity package installed in the cryoadapter before connection to the XATB1 cryogenic feedbox. The cavity is supported by a sliding mechanism to the stainless steel suspension support, which reproduces the mechanical installation in the accelerating module cryostat.

tuner). The standard diagnostic crates of the XATB1 used for the 1.3 GHz module testing allow the monitoring of all the module signals (cavity and coupler temperatures and the rf signal sampling from the cavity rf ports).

The test activities were performed in collaboration between INFN-LASA and DESY, which jointly developed the 3.9 GHz system as an in-kind contribution to the EXFEL Project [16].

## IV. THE VALIDATION TEST

### A. Motivations

While the electromagnetic design of the EXFEL 3.9 GHz cavity has not been altered with respect to the cavities used in the FLASH ACC39 module [6], several important modifications have been implemented in the cavity package design, including important mechanical details of the cavity and its titanium helium vessel, and a complete revision of all ancillary components. The differences between the EXFEL design and the original cavity design by FNAL [17] are extensively described in Ref. [8].

To avoid emittance dilution in the injector, beam dynamics studies indicated that a scheme for coupler dipole kick compensation was required, resulting in a string with an alternate orientation of the couplers with respect to the beamline, as shown in Fig. 1. Two versions of the dressed cavity assembly, differing only in the relative rotation of 180-degree of the cavity around its axis during integration in its vessel, allow for such an arrangement.

Concerning the ancillaries, a scaled version of the ILC blade tuner CTS [18] was developed for the EXFEL 3.9 GHz cavities [19] to profit from its smaller size with respect to the ACC39 CTS and to allow installation with the lateral 2-phase circuit position of the EXFEL modules. The roller bearing pads [20] needed for the string support from the helium gas return pipe (that acts as the structural backbone of the accelerating module) have been moved to a different position in the tank, no longer attached to the tuner disks, but now directly welded to it, which required the development of a new compact roller bearing assembly. The two cavity variants required the development of a different magnetic shield design, fitting both cavity orientations.

Finally, the different EXFEL beam parameters required a setting for the coupler loaded quality factor ( $Q_L$ ) of nearly twice the FLASH value. This was achieved with a different length of the coupler antenna.

The several changes performed on the cavity package with respect to the ACC39 design motivated the need of a validation test of a complete unit. The test was performed to demonstrate the ability to reach the nominal performances before proceeding to the EXFEL 3.9 GHz system assembly.

### B. Selection of the test cavity

One of the cavities produced for the installation into the EXFEL 3.9 GHz system, cavity 3HZ010, was selected and

prepared for the horizontal test in the AMTF cryoadapter prior to its use in the module. The cavity was vertically tested at INFN-LASA in September 2014, during the test campaign of the series of the ten cavities produced for the 3.9 GHz string [10]. The vertical test (VT), performed in a bath cryostat at 2 K, is meant to qualify the cavity in quasi-CW conditions (with 25% RF duty cycle at 0.5 Hz to limit cryogenic losses and HOM heating) up to the nominal accelerating gradient and quality factor set by the project:  $E_{acc} = 15$  MV/m and  $Q_0 = 10^9$ .

All the cavities were tested before the He vessel integration [8,9], equipped with a fixed high- $Q$  antenna (i.e., close to the critical coupling conditions for the cavity), a field pick up and two HOM antennas (one at both cavity ends), and after the successful tuning of the HOM coupler notch filters for the rejection of the fundamental cavity mode. The maximum accelerating field  $E_{acc}$  in the test was reached close to a quench occurring at approximately 21 MV/m, with the cavity showing a  $Q_0$  of  $\approx 2 \times 10^9$  with no decrease from low field levels up to the quench limit. No field emission was detected. The cavity thus achieved its full qualification and proceeded to the He vessel integration and to its preparation for the installation in the module.

### C. He vessel integration and assembly of the ancillaries

The integration tool used for the welding of the titanium He vessel on the cavity ensures that any material shrinkage occurring during welding does not have a chance to mechanically load the constrained Niobium structure, avoiding the possibility to induce permanent deformations which would cause an uncontrolled detuning from its goal frequency. Additionally, the integration was performed under frequency control with a vector network analyzer (VNA) during all critical stages of the welding process.

After the vessel integration, the installation of the pick up and HOM antennas and the high pressure rinse in the LASA clean room, the cavity was sent from LASA to DESY in vacuum conditions (pressure  $< 10^{-8}$  mbar), ready to be dressed for the vertical test. At DESY the standard mechanical and rf incoming tests were performed upon acceptance and the cavity entered in the clean room after degreasing and rinsing of the external surfaces, for the venting and installation of the FPC and the pump manifold to connect to the active pumping system of the test stand. No further treatment or cleaning of the internal rf surfaces was performed at DESY.

The complete installation of the cavity ancillaries (i.e., fundamental power coupler, the cold magnetic shield, and the cold frequency tuner) was then performed at the DESY cavity preparation infrastructure. Any undesired cavity elongation or contraction that could be induced by mechanical assemblies, as the tuner or magnetic shield installation, was performed under the control of the stability of its resonant frequency, within a few tens of kHz.



### D. Warm rf preparation procedures

The 3.9 GHz cavity tuner (blade type) is designed to elastically extend the cavity, inducing a positive frequency shift of about 180 kHz for each turn of the motor spindle, for a potential maximal tuning range of about 1.5 MHz at 0.7 mm elongation [19]. Cavities were tuned during the last fabrication stages to reach at cold a frequency approximately 400–500 kHz below the operation frequency of 3.9 GHz, in order to avoid tuner operation around its mechanical neutral point, thus avoiding a potentially significant residual hysteresis. After tuner installation, the cavity was transferred on the cryoadapter internal suspension support. The support was then inserted in the vacuum vessel and a check of the tuner operation was performed a few times, on a short range (single turn of the motor spindle), to verify the correct assembly operation and the proper frequency response of the cavity. A larger excursion of the tuner action at warm may induce permanent plastic deformation on the resonator, resulting in an uncontrolled detuning from the goal frequency. The cavity installed in its suspended position in the cryoadapter is shown in Fig. 2.

The results of the tuner operation at warm, after inserting the cavity support in the cryostat adapter, are shown in Table I.

Before installation in the cryostat adapter the transmissions across all opposed cavity ports—i.e., power coupler pick-up (FPC-PU), power coupler HOM2 (FPC-HOM2), and pick-up HOM1 (PU-HOM1), where HOM1 is the HOM antenna at the FPC side and HOM2 at the PU side—were checked. After any mechanical operation around the cavity (e.g., the assembly of the tuner and magnetic shield) a detuning of the HOM coupler notch filters is possible, due to their high sensitivity with respect to mechanical deformations. Thus the whole fundamental passband spectrum was measured to verify the proper HOM transfer functions and the correct position of the notch filters for the rejection of the fundamental mode.

The main effect experienced in several cavities during the module preparation is the detuning of HOM1, (the one which directly faces the FPC port), due to the installation of the FPC antenna, which slightly changes the field pattern in the end region of the cavity with respect to the high- $Q$  antenna case used for the vertical tests. Figure 3 shows the evolution of the HOM relative transmissions, starting from the 3HZ010 cavity reception at DESY with the high- $Q$

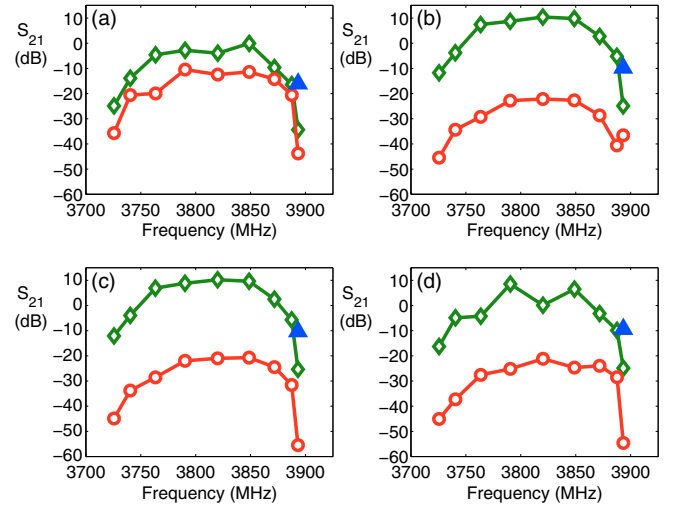


FIG. 3. Evolution of the relative HOM transmission spectra of the fundamental passband modes, from cavity reception (inset a), FPC installation (inset b, showing the detuning of the HOM1 notch filter), HOM retuning (inset c) and after installation of all ancillaries (inset d). In each plot, diamonds show the FPC-HOM2 passband, circles the PU-HOM1 passband and the triangle indicates the fundamental mode FPC-PU transmission.

fixed antenna (inset a) and following its preparation stages for the horizontal test (insets b to d). The detuning of the HOM1 coupler notch filter position after the FPC installation (inset b) required to perform the retuning operation shown in inset c, whereas the analysis of the relative transmissions measured before and after the installation of the CTS and MS show that these operations did not induce any detuning of the notch filter positions (as shown in inset d).

Although no operational experience existed with these cavities at the time of the qualification test, the specifications for a satisfactory notch filter tuning were set to the following requirements: (I) a transmission from FPC-HOM2 at least 10 dB lower than the FPC-PU on the fundamental mode and (II) a PU-HOM1/FPC-HOM2 transmission on the fundamental mode less than 20 dB than its maximum on the fundamental bandwidth and 10 dB less than the neighboring ( $8\pi/9$ ) mode. These requirements are satisfied in the last set of curves shown in Fig. 3 after the installation of all cavity ancillaries, right after the connection of the cryostat adapter to the cryogenic cap. During VT no substantial HOM power leakage of the fundamental mode was observed after the notch filter tuning. These conservative criteria will be updated when the full experience of the EXFEL 3.9 GHz system becomes available.

### E. Installation in the XATB1 test bench

The cavity 3HZ010 is supported in the cryostat adapter through a sliding mechanism using spring-loaded linear roller bearings similar to those used in the cryomodule for

TABLE I. Tuner operation at warm. Each test cycle consists of a full motor spindle turn followed by the return to the initial position.

Motor action	Frequency shift/turn	Hysteresis
First cycle	172 kHz	<1 kHz
Second cycle	177 kHz	<1 kHz

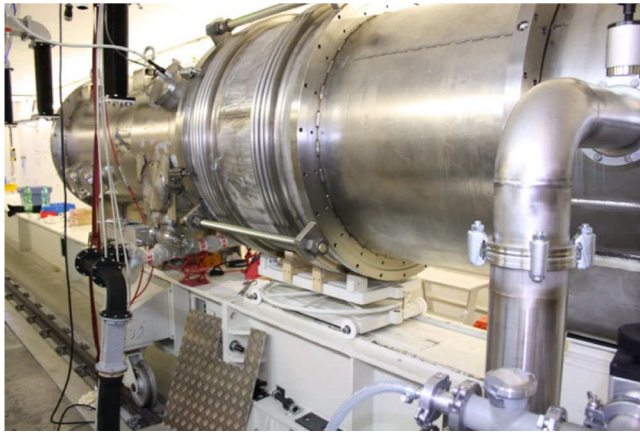


FIG. 4. The cryostat adapter during its connection to the XATB1 cryogenic feedbox.

operation [20], allowing the differential thermal contraction of the Nb/Ti cavity assembly with respect to the stainless steel support, while maintaining the coupler longitudinal position fixed at the warm module port. The warm coupler components were assembled using a local clean room after the installation of the cavity in the adapter.

The cryoadapter has a single thermal shield connected to the 40–70 K circuit and the cavity suspension support slides on a fixed rail suspended from fiberglass posts and thermalized by the 5–8 K circuit of the XATB (See Fig. 2). All rf and temperature sensor connections are routed to patch panels in the adapter to reduce the setup test time.

After the assembly of the cavity in the adapter the vacuum vessel was moved onto the cryomodule support rail of XATB1 and rolled into the test cave to connect the cryogenic circuits, the cavity beam vacuum line and the 3.9 GHz waveguides from the klystron to the warm coupler waveguide box. The insulation vacuum was then closed using the large feed cap sliding bellow and all circuits were leak checked. Figure 4 shows the cryoadapter connected to the feed box.

## V. CAVITY PACKAGE TESTING

### A. Cooldown and warmup cycle

Cooldown started on March 19, 2015, with the standard fast cooling procedures used for the main linac module tests in AMTF [13], where process pipes are cooled down to the nominal temperatures in approximately 14 hours. Figure 5 shows the inlet and outlet temperatures of the thermal shields and the temperature of the cold box in the feed cap which provides the 2 phase He to the 2 K cavity line. After the full thermalization of the cold mass the pump-down to subatmospheric pressure to reach the 2 K operation started on March 23, 2015, followed by the cold tuning and low power measurements for calibration. High power operation and LLRF tests started on March 25, 2015. Warmup started on March 27, 2015.

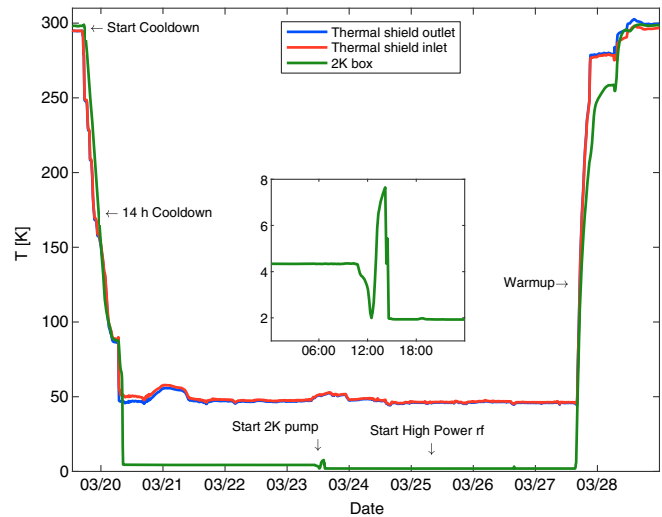


FIG. 5. Cooldown/warmup cycle of the cryoadapter for the 3.9 GHz horizontal tests. The cryogenic circuits are cooled and warmed with a standard procedure requiring approximately 14 h. More than 48 hours were needed for complete thermalization of the cold mass before the 2 K pump down.

### B. Cold rf preparation procedures

The warm-to-cold frequency shift experienced during all vertical tests of the cavities before integration was  $6.1 \pm 0.1$  MHz [9]. The frequency of 3HZ010 after cooldown increased by 6.17 MHz, in full agreement with the VT experience and indicating that tank integration and the cavity support scheme in the module lead to no undesirable or uncontrolled stresses on the rf structure due to differential material shrinkage. The cavity tuning and preparation scheme foresees a target frequency approximately 500 kHz lower than the operation frequency, in order to always operate the blade tuner far from its mechanical neutral (rest) point, as discussed previously.

After reaching a stable 2 K cavity condition, the cavity was tuned to 3.9 GHz by the CTS action under the control of a VNA, to monitor the cold tuning action and to verify the tuner performance. Each motor screw turn requires

TABLE II. 3HZ010 frequency history and tuner parameters.

Cavity status	Frequency
Warm frequency before cooldown	3893.279 MHz
Cold frequency after cooldown	3899.449 MHz
Cold-warm frequency Shift	+6.17 MHz
Tuner parameter	Value
Motor turns to 3.9 GHz	$\approx 3.5$
Motor steps to tune position	$\approx 246200$
Frequency offset/turn	171 kHz (1st turn) 166 kHz (2nd turn) 160 kHz (3rd turn)
Frequency offset/motor step	2.2–2.4 Hz

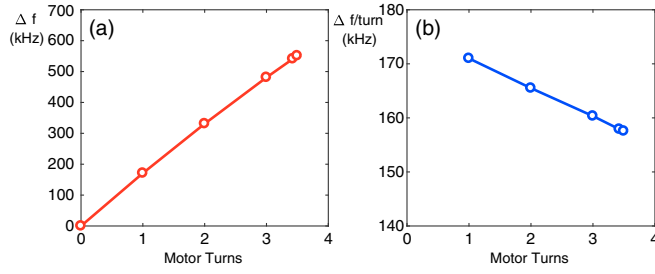


FIG. 6. Cavity frequency offset (left) and frequency offset per motor turn (right) during the tuning process.

70400 steps of the stepper motor and the cavity was brought to the frequency target with 246200 steps, corresponding to roughly 3.5 screw turns and providing the necessary 551 kHz of tuning action. The maximal tuning stroke for the tuner design is obtained by 15 screw turns, corresponding to a frequency tuning action in excess of 1.5 MHz [19], which is still expected to be below the onset of cavity plasticity in cold condition.

Table II summarizes the cold-warm cavity frequencies and the tuner characterization results.

Figure 6 shows the cavity frequency shift from the unloaded rest position of the CTS and the frequency offset/turn evolution during the tuning process.

After bringing the tuner back to its original position the cavity restored its original frequency: no hysteresis effects below the 10–20 kHz range could be measured with a VNA given the relatively large noise environment in the low transmission measurement performed through the rf sampling channels of the AMTF facility.

## VI. LOW POWER MEASUREMENTS AND CALIBRATION

The accelerating gradient is one of the key parameters to qualify the cavity performance, thus the cavity  $Q_L$  and the constant  $k_t$  relating accelerating gradient to the probe power were determined at moderate forward power from the fundamental power coupler ( $P_f \approx 1$  kW), by measuring the decay constant  $\tau$  of the transmitted probe power  $P_t$  and estimating the accelerating field  $E_{acc}$  from the forward power  $P_f$  to the cavity driven with a rectangular rf calibration pulse (see Fig. 7). In detail  $E_{acc}$  is estimated by:

$$E_{acc} = \frac{1}{L_{eff}} \sqrt{\frac{R}{Q}} 4Q_L P_f \left( 1 - \exp\left(-\frac{t}{2\tau}\right) \right) \quad (1)$$

where  $L_{eff}$  is the cavity rf length,  $R/Q$  is the cavity shunt impedance of 750  $\Omega$  for 3.9 GHz cavities,  $Q_L = \pi f \tau$  and  $f$  is the cavity frequency. Therefore the constant  $k_t$  is computed by  $k_t = E_{acc}/\sqrt{P_t}$  at this calibration point. Subsequently, the cavity accelerating field is determined from the measured transmitted probe power  $P_t$  with the simple relation  $E_{acc}[\text{V/m}] = k_t \sqrt{P_t[\text{W}]}$ .

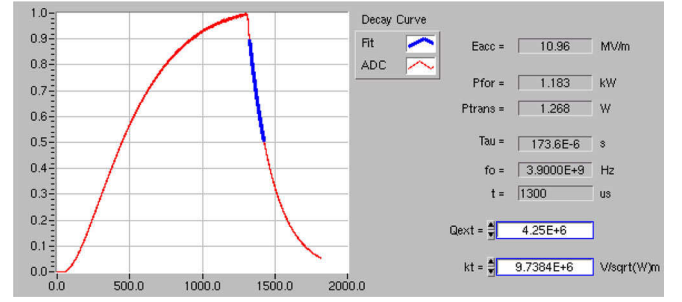


FIG. 7. Cavity transmitted power (shown in arbitrary units) using a rectangular low power rf pulse with 1.3 ms length. The bold (blue) region shows the portion of the pulse used for decay time and  $Q_L$  evaluation.

The 3.9 GHz coupler is of the fixed coupling type [21], and the nominal EXFEL beam parameters require a coupling with  $Q_L = 3.2 \times 10^6$ , i.e., nearly twice the design value the FLASH third-harmonic system [22]. Thus each coupler antenna was trimmed to a different length with respect to the original design, based on the extrapolation of the FNAL antenna trimming experience. Three stub tuners on the waveguides allow for fine tuning of the coupling factor, at least a factor of 2 in both directions, and the adjustment of the relative cavity phases for correct beam operation under vector sum control in the accelerating modules. The measurement of the 3HZ010 cavity yielded a value of  $Q_L = 4.25 \times 10^6$ , well within the adjustment range.

Table III summarizes the calibrations performed during the 3HZ010 test, for the external quality factor,  $Q_{ext}$ , of all antennas and for  $k_t$ , with comparison to the values determined during the VT at LASA. The comparison is within acceptable limits and, in particular, within the specifications (which were for the pick up a factor of ten above the nominal cavity quality factor,  $Q_0^{spec} = 10^9$ , and for the HOM a corresponding factor of 100).

### A. High power measurements

The cavity was then operated in open loop with 10 Hz pulses with a filling time of 500  $\mu\text{s}$  and a flat-top time of 600  $\mu\text{s}$ . The cavity was fine tuned in frequency under the control of the LLRF system (which is synchronized to the master reference system) by maximizing the transmitted power on the LLRF control panel, after which the input

TABLE III. Comparison of rf calibrations in the vertical and horizontal tests.

Item	VT	HT
$Q_{PU}$	$1.3 \times 10^{10}$	$1.5 \times 10^{10}$
$Q_{HOM1}$	$8.8 \times 10^{13}$	$2.2 \times 10^{13}$
$Q_{HOM2}$	$2.5 \times 10^{12}$	$1.5 \times 10^{13}$
$k_t$ , in $\text{V}/(\text{m}\sqrt{\text{W}})$	$9.16 \times 10^6$	$9.74 \times 10^6$



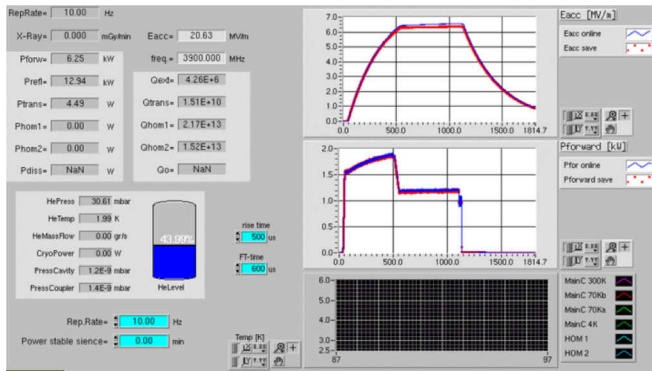


FIG. 8. Typical pulse measured during the long stable operation at 20 MV/m, 10 Hz operation with a 0.5 ms fill time and 0.6 ms flat top pulse in feed forward mode.  $E_{acc}$  (top plot) and forward power (bottom plot) are displayed in arbitrary units. Power readings and computed  $Q_{ext}$  values are shown in the left part of the control system panel.

power was raised to bring the cavity to its quench limit, before the cavity reached 24 MV/m, above the quench level experienced in the vertical tests (21 MV/m) under quasi-CW conditions.

Stable operation was kept at 20 MV/m for nearly 48 hours in feed forward mode using a fill time of 500  $\mu$ s and a flat top of 600  $\mu$ s. No appreciable sign of field emission was measured. Two gamma ray detectors for field emission detection are placed near the beam line on both ends of the module (by the end caps). No cavity heating was measured by the 8 CERNOX sensors positioned on the cavity vessel (2 on both cavity sides) and in three positions at each HOM coupler. A typical pulse measurement is shown in Figure 8.

### B. Comparison of vertical and horizontal test performances

The stable 2 K operation of the small cryostat adapter in the AMTF required a 25 W offset for the cold box heater, as the cryogenic infrastructure has been designed to absorb the high heat load generated by a 8 cavity module of the EXFEL main linac. The average cavity dissipated power at 20 MV/m is only 0.35 W at 1% rf duty cycle at the  $Q_0$  measured during the vertical test, therefore no precise measurements of dynamic heat losses are possible. Still a rough estimation of the cavity dynamic load could be performed in two different setups: the first keeping the He level control and evaluating the heater offset difference from rf-on and rf-off states; the second using a precise mass flow controller, switching off the heaters and closing the Joule-Thompson valve (i.e., running with decreasing He level, so-called boil-off test). These two methods, close to their measurement limits, indicated values of 0.2 W and 0.6 W, respectively, compatible with the estimation of the cavity dissipation given above by means of the extrapolation of the VT results, and with the large uncertainty of the

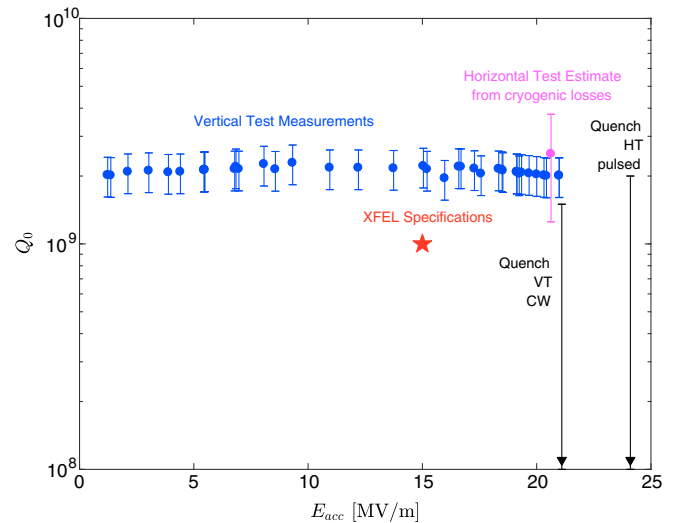


FIG. 9. Comparison between the vertical test measurements of the cavity at INFN-LASA and the qualification test in the horizontal cryostat at the AMTF.

setup. In both cases the measurement has an error close to 100% (the heater on and off method required a 0.2 W difference over the 25 W offset and in the boil-off method a difference of 0.03 g/s was measured on top of a fluctuation of 0.02 g/s in the rf-on and rf-off states).

Figure 9 shows the comparison of the quality factor  $Q_0$  vs the accelerating voltage  $E_{acc}$  obtained during the vertical characterization test at LASA with the analysis of the measurement obtained during the horizontal testing.

### C. $Q_L$ adjustment

The 3-stub tuner at the waveguide was used to change the system  $Q_L$  values, with more than a factor 2 variation being achieved, reaching a maximum  $Q_L \approx 10^7$ . However, the central step-motor connection was damaged during the installation phase and inoperative during the test. Hence the system could not be used to set to the nominal design value of  $Q_L = 3.2 \times 10^6$ .

## VII. CONCLUSIONS

The cavity package for the 3.9 GHz EXFEL system was fully qualified in a horizontal test in the AMTF facility at DESY. This activity was necessary before the start of the installation activities for the full system, due to the several modifications introduced in the cavity and ancillaries design with respect to the FLASH system. The qualification allowed the verification of the correct operation of all subsystems and the readiness of the cavity preparation and measurement procedures.

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