VERTICAL TESTS OF XFEL 3RD HARMONIC CAVITIES

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Abstract

The 10 cavities of the E-XFEL 3rd Harmonic Cryomodule have been tested and qualified, before integration in the He-tank, in our upgraded Vertical Test stand. In this paper, we report the measured RF performances of these cavities together with the main features of the test facility.

INTRODUCTION

The 3rd 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 3rd 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 will be operated close to 180° phase with respect to the incoming beam.

INFN Milano–LASA is in charge to provide, as in-kind contribution, the main components of the 3rd harmonic module ready to be installed in the E-XFEL tunnel. An important part of this activity has been the full qualification in Vertical Test of all the cavities (eight plus two spares) produced by the Ettore Zanon S.p.A. under INFN supervision [1]. This paper reports on features of our test facility and results of cavity tests.

VERTICAL TEST FACILITY

Clean Room

The Clean Room is a 9 m^2 ISO4 facility. A High Pressure Rinsing (HPR) system, properly designed for the small bore of the 3.9 GHz cavity, is installed inside the Clean Room. An Ultra Pure Water (UPW) plant supplies a 100 bar LEWA pump (max 170 l/h) which feeds the HPR. The high pressure water is filtered down to 20 nm before entering the HPR wand and impinging on the cavity wall.

The UPW plant operates in two stages. In the first stage, three Millipore Elix devices fill a 6000 litres tank with pure water. On demand, water is taken from the intermediate tank and filtered with a Millipore SuperQ to reach an UPW grade resistivity of 18 MΩ cm and TOC value below 3 ppb.

To clean cavities and large components, we installed an Ultrasound System composed by two tanks: one with Ultrasound Transducers for cleaning and one for rinsing with UPW water.

A slow pumping system is connected directly to the Clean Room for pumping and venting cavities in a controlled way to avoid dust particle movements.

Vertical Insert Support

The Vertical Insert support has been upgraded to host two cavities for increasing the test rate of our facility and it has been routinely used for testing the E-XFEL 3.9 GHz cavities, see Fig. 1.

Figure 1: Vertical Insert with two cavities ready for Vertical Test, fully equipped with thermometers and Second Sound sensors.

Moreover, we improved the UHV vacuum system adding, to the present setup, a Turbo Molecular Pump system and an RGA. The former is used as a backup in case of leak in the cavity vacuum to avoid the SIP pumping He. The latter is generally used to control the vacuum quality before opening the UHV cavity valves towards the Vertical Insert vacuum line and the vacuum composition during test.

Cryogenic Installations

The insert with two cavities to be tested provided with the diagnostic devices, test and feeding cables, piping and all the other ancillaries needed, is transferred inside the vertical cryostat placed in a bunker, to be cooled down to 2K (and below) for the qualification tests.

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The vertical cryostat is shown in Fig. 2 on the left, where only its upper part is visible, being underground for about the 4/5th of his height (4.5 m). Its diameter is 0.7 m and can host cavities with frequencies ≥ 500 MHz. The connections of the cryostat vacuum system can be seen coming out from the cover and then on the bunker wall. Also visible, in Fig. 2, on the right, is the rack with the RF power amplifier and electronics for temperature measurements and Second Sound signal amplification.

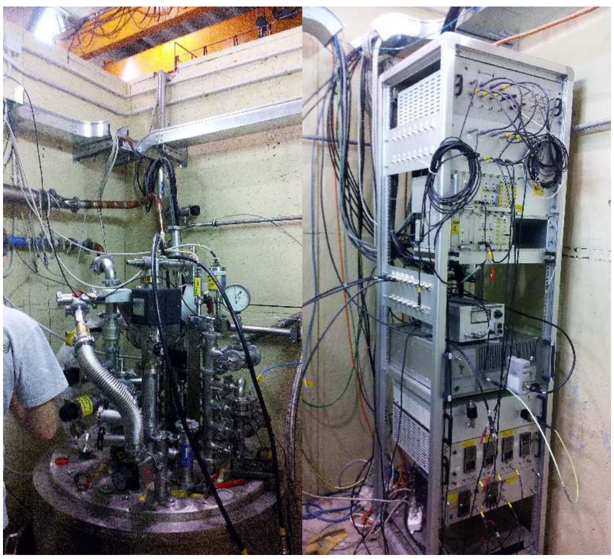

Figure 2: Inside views of the Vertical Test bunker: on the left, top flange of the cryostat with connections for RF, thermometers and vacuum; on the right, cabinet hosting electronics for signal processing and RF.

Figure 3 shows a diagram of the cryostat vacuum system that provides thermal insulation, He recovery and sub-cooling of the He bath to reach down to 1.6 K.

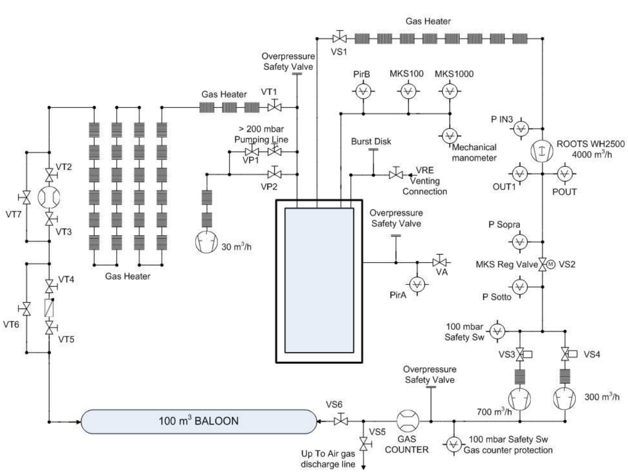

Figure 3: Sketch of the cryostat vacuum connections.

After the installation of a new 4000 m^3/h pump (Roots-type), we increased the cryogenic capacity during the subatmospheric pumping, thus reducing the subcooling time to reach 2 K, to 40 W at 2 K temperature. The LHe level during the cooldown is monitored by two Cryomagnetics level probes.

RF Cavity Characterization

A 200 W GaAs FET power amplifier from Microwave Amps, whose frequency range is 3.5 – 3.95 GHz, feeds the cavity. The amplifier is internally protected by an isolator, allowing full power operation with high SWR ratios and pulsed tests also with strong overcoupling. Incident and reflected powers are sampled through a 1:20 reflectometer, while a Rohde & Schwarz NRT power meter monitors the real amplifier power output and loading conditions via a power directional probe. The power is coupled to the cavity by a coaxial antenna (High Q Antenna) of nominal $Q_{ext}=10^9$. The power coupler port interface to the power amplifier is through a 7/16” connector and a 1/2" CELLFLEX low-loss foam dielectric coaxial cable. The connector and the cable withstand more than 500 W RF power at 4 GHz, ensuring safe operation (no cable or connector breakings) also at full reflected power and low RF loss inside the Helium bath. A block diagram of the cavity RF measurement system is shown in Fig. 4.

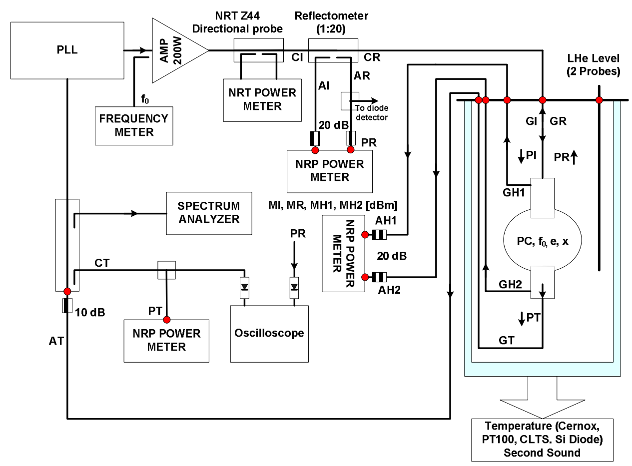

Figure 4: Block diagram of the RF system used for test 3.9 GHz cavity.

A common problem during the RF SC cavity tests in vertical cryostats is the breaking of high power RF coaxial feedthroughs, for power over 100 W, due to sparking between the outer and inner conductors. This is due to the low dielectric strength of the Helium gas. To solve this problem, we avoided any feedthrough and we directly connected the coaxial cable to the cavity input power port. We achieved this, by putting the coaxial cable into a standard vacuum weldable flanged tube, then filling the empty space between the tube and the cable with an Epoxy resin [2].

To sample the cavity dissipated power, a pick up antenna ($Q_{ext}=2\cdot10^{10}$) is installed on the cavity beam tube opposite to the main coupler, connected to an SMA connector. Normally also the HOM coupler antennas are installed in the cavities to be tested. All cavities transmitted powers are carried out from the cryostat through high screened cryogenic coaxial cables (S_04212_B type from Suhner). Finally 1/4" CELLFLEX coaxial cables with high phase stability are used to transmit the cavity powers to and from the external electronic devices and instrumentation.

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The cavity accelerating field and the quality factor Q are measured through the accurate readings of the input and reflected powers and all the cavity transmitted powers, both in CW and pulsed mode. When the cavity dissipated power is over 2 W we perform all our measurements in pulsed mode to save on helium. We use NRP2 power meters, from Rohde & Schwarz, provided with NRP-Z11 diode power sensors. The dynamic of these probes is of 90 dB, ensuring us great linearity during the power rise. Normally we stay inside 40 dB of power variation during the cavity characterization. The cavity dissipated and reflected powers are demodulated, when in pulsed mode, to get the discharge time and the input port coupling factor to compute the proper Q of the cavity at a moderate value of accelerating field, and to determine the calibration constant of the power rise. The coaxial cables that connect the test signals to the readout instrumentation are very accurately calibrated (within some tenth of dB) before starting the test.

Due to its high Q bandwidth, less than 1 Hz, the cavity must be inserted in a Phase Locked Loop (PLL) to be tested. In Fig. 5, the block diagram of the PLL for the test of 3.9 GHz SC cavities is shown.

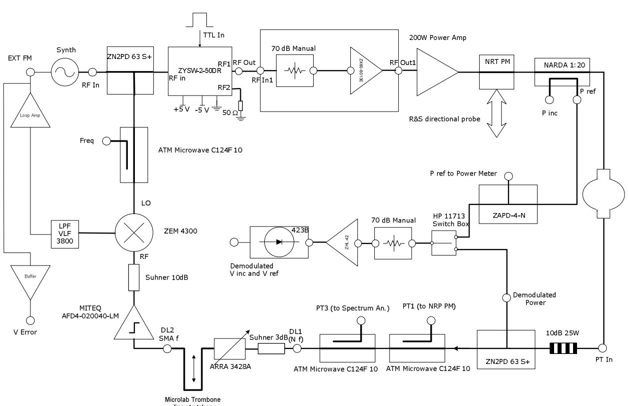

Figure 5: Block diagram of the 3.9 GHz cavity PLL.

The VCO (Voltage Controlled Oscillator) is a Rohde & Schwarz SMB-100A frequency synthesizer, frequency modulated by a signal proportional to the phase difference between the input and transmitted cavity powers. To set up the PLL working point, i.e. the cavity resonance to the desired mode, a combination of a mechanical trombone and sliding contact variable length delay lines are used. A 65 dB, 0.25 dB step, digital variable attenuator is used to vary the amplifier input power and perform the power rise. Finally the envelopes of the pulsed signals are detected through 423B Low-Barrier Schottky Diode Detectors, from Keysight.

All the readout instrumentation is interfaced to a LabVIEW™ control program that also allows setting up the pulse timings and the calibration constants for correct signal readouts. The program allows acquiring data for the different measurement sections (R_s vs. T, power rises, HOM notch).

An example of a Q vs E_{acc} curve acquired by the control program is shown in Fig. 6.

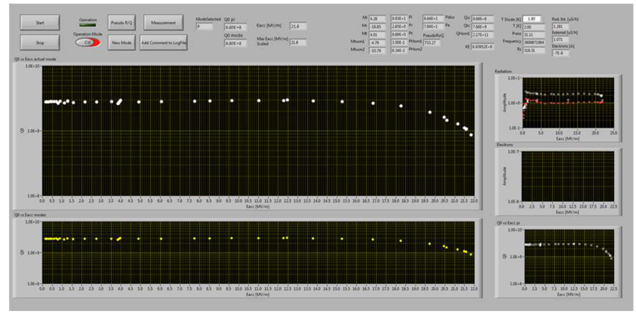

Figure 6: Typical power rise acquired from the LabVIEW ™ Control Panel. In the same panel, other parameters are displayed such as radiation level on top of the cryostat (upper plot on the left).

Cernox resistors placed on the external cavity surface are used as temperature sensors during the cooldown and to detect local heating of the resonators and quenches. Other thermal sensors like CLTS, PT100 and PT1000 are placed along the insert to monitor the cooldown behaviour. The temperature sensor signals are read by instrumentation amplifiers and are fed by a stable FET low current generator, with current range spanning from 10 μA to 100 μA. In addition to the resistor sensors, a Lakeshore DT670 silicon diode temperature sensor is employed to follow the cooling down of the cavities. The test facility is also equipped with a Second Sound system [3] for the 3D mapping of the cavity quenches.

CAVITY PREPARATION FOR VERTICAL TEST

The 3.9 GHz cavity, after its final 30 μm BCP at the production company, is shipped filled with UPW to INFN Milano - LASA, within 12 hours. The cavity has all the flanges blanked off, except the two beam pipe flanges. On these flanges, two Teflon valves are installed for filling the cavity with water.

At the reception at LASA, we enter the cavity in our Clean Room and check its water level and conductivity. The cavity is then connected to our UPW plant and rinsed until an 18 MΩ cm conductivity level is reached. All the flanges are then removed and the cavity, dressed with a frame for HPR, is 3 times (3x45 minutes) HPR rinsed and let dry overnight. The following day, the cavity is equipped with its own accessories (HOM pick-ups, field pick-up, High Q antenna, valve and flanges), slow pumped and leak checked. The cavity is then stored until it has to be prepared for the Vertical Test.

We have received the full batch of ten cavities in two and half weeks, four cavities per week, one per day. This has meant that we had to handle a couple of cavities in our Clean Room per day.

After we received all the cavities, we started preparing each single cavity for the vertical test. The preparation consisted in the following steps:

a) Enter the cavity in Clean Room
b) Remove all accessories
c) 3 times HPR of naked cavity

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d) Drying overnight
e) Install all the components, except bottom flange+valve
f) 4 times HPR
g) Drying over night
h) Slow pumping
i) Leak check
j) Cavity exit the Clean Room filled with Nitrogen for HOM tuning.
k) Cavity re-enters the Clean Room and is pumped down
l) Leak check
m) Cavity exits the Clean Room and it is ready for installation.

Six out of the ten cavities were prepared at LASA. The remaining four cavities were sent to DESY and processed there from step a) to i) before returning them to Milano, where the last steps occurred.

During the preparation phases, various process parameters of Clean Room procedures, cavity vacuum, vacuum composition and leak test are recorded.

CAVITY TEST

The LASA vertical test infrastructure allows testing two cavities at time. Given the time needed to install/remove the cavities on the Vertical Insert (VI) and to purify He gas and liquefy it, to get the quantity necessary for the test, we had a period of three weeks between tests.

During the installation, the cavities are placed on their support on the Vertical Insert. A local Clean Room is placed around the cavities while they are connected to the VI vacuum line. The vacuum line is slow pumped and leak checked. Afterwards, the SIP is switched on and, when the vacuum level is below 1 10^{-5} mbar, the cavities valves are open and pumped by the SIP. The VI forevacuum system is isolated before opening the cavity valves.

After the vacuum connection is done, we install Second Sound Detectors on each cavity and fast thermometers on the cavity body, typically on HOM cans and feedthrough and some at the equators.

The RF cables are calibrated and the cavity resonance frequencies checked.

Afterwards, the Vertical Insert is moved to the cryostat and a final check of all connections is done. The cryostat is then pumped down and an integral check of the vacuum tightness is performed.

The cryostat is then filled with liquid Helium, transferred from 450 litres dewars. We typically use five dewars to accumulate the He necessary to guarantee at least 8 hours of measurements at 2 K. The sub-cooling from 4.2 K to 2 K takes usually some hours. During the transition from 4.2 K and 2 K, we measure the surface resistance of one of the two cavities. Once the testing temperature is reached, the RF cables are rechecked and then we start the RF cavity characterization at cold. The cavity is CW tested until the dissipated power is less than 2 W and then pulsed with a typical 0.5 Hz frequency, 25% duty cycle. Figure 7 shows power rise for all the cavities at 2 K.

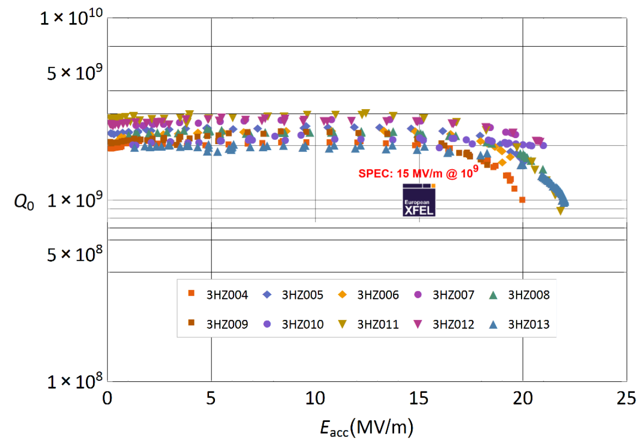

Figure 7: Summary plots for power rises of the ten E-XFEL 3.9 GHz cavities at 2 K.

All the resonators performances are above the E-XFEL specification represented by the E-XFEL icon in the plot. All cavities reached at least 18 MV/m with Q_0 above 10^9 at this field level. None of the cavities show field emission. Nearly all cavities are quench limited. Only few were instead limited by available RF power.

During the measurements, Second Sound and fast thermometers are continuously read to acquire data on occurring quench spots. At this temperature, also the HOM notches are checked but only with low power measurement to avoid any damage to the HOM feedthroughs.

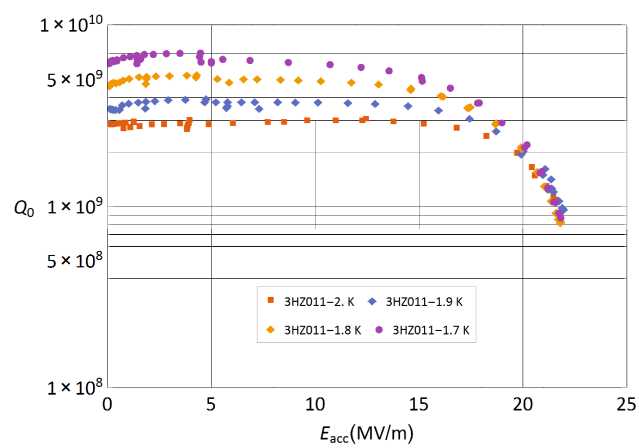

Figure 8: 3.9 GHz power rises at different temperatures for cavity 3HZ011.

Then we usually lower the He bath temperature down to 1.8 K where power rise and related quench diagnostic are repeated. In some of the tests, we performed power rises also at 1.9 K and 1.7 K. A comparison of the different power rises is shown in Fig. 8 where the improvement of Q_0 at low fields is clearly visible as expected. Moreover, the accelerating field at the quench is the same at all four temperature points.

Once the cavity is fully RF characterized, we start to warm up the He bath to 4.2 K. During this temperature rise, we measure the residual resistance of the cavity which was not monitored during cool down. Figure 9 shows a typical R_s vs T for the 3.9 GHz series cavities.

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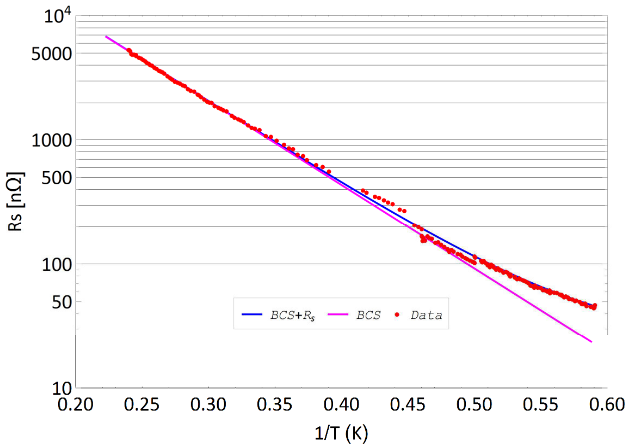

Figure 9: 3.9 GHz cavity resistance versus He bath temperature.

The experimental data are fitted with the dependence of the resistance on temperature as expected from simplified BCS theory with an additional residual resistance term [4]. The estimated residual resistance is 39 nΩ.

During the assembling of the resonators in Clean Room, we had some leaks during the connection of the cavity to the UHV valve but, only in few cases, the cavity was fully retreated. Only once, we had a leak at the cavity at cold, which however did not prevent us from performing the test. The leak was found on the HOM flange connection due to not sufficiently tightened bolts.

He-tank Integration

After the successful test, the cavity is prepared for the He tank integration. The HOM feed-troughs are removed in Clean Room to guarantee the clearance for the sliding of the He vessel, and the cavity, in vacuum condition, is sent to the company. High Q antenna and PU are left on to monitor the frequency of the cavity during He-tank welding. During the installation of the tank on the cavity and the pre welding preparation, the frequency variation is kept below few tens of kHz. This frequency variation is maintained also before and after the welding operations necessary for the integration of the tank to the cavity. The He-tank, at this stage, has the filling line installed while only a short part of the two-phase line is present.

The cavity is then shipped back to Milano where it goes through the same steps (from a) to h)) of the cavity preparation to make it ready for operation at DESY (horizontal test and string integration). The cavity performances before and after this step of the tank integration have been checked with additional Vertical Tests on two cavities. Figure 10 shows no significant degradation of the cavity performance by this operation.

Once the cavity is equipped with all the RF antennas, it is shipped back to the company for the welding of the second part of the two-phase line and the final pressure test as required by the European Pressure Equipment Directive (PED) 97/23/EC. Also during this pressure test, the frequency is carefully monitored. After acceptance, the cavities were delivered to DESY for the installation of the power coupler cold parts and the string assembly [5].

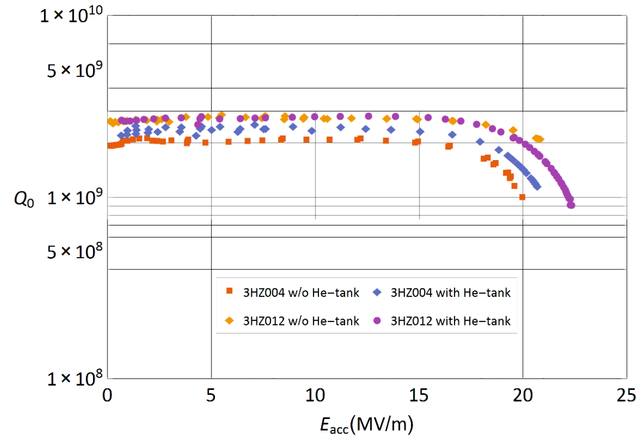

Figure 10: Power rise comparison for cavity 3HZ004 and 3HZ0012 before and after He-Tank integration.

Two of the ten cavity (3HZ007 and 3HZ010) were prepared in Halle 3 Clean Room at DESY for horizontal tests, by removing the High Q antenna and installing the Power Coupler. Cavity 3HZ010 reached, during its horizontal high power test in pulsed operation [6], higher quench fields than in the Vertical Test in Milano.

CONCLUSION

Ten cavities for the 3rd harmonic section of the E-XFEL injector were tested at INFN Milano – LASA. All resonators performed better than the requested specifications (E_{acc} = 15 MV/m, $Q_0 = 1\ 10^9$), none of them limited by field emission, but only by quenches. This successful operation lasted from Sep. '14 to Feb. '15. The cavities are now installed into the 3.9 GHz Cryomodule [7] which is ready to be moved to the E-XFEL injector.

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