HIGHLIGHTS OF THE XM-3 CRYOMODULE TESTS AT DESY

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Abstract

To investigate the feasibility of the continuous wave (CW) upgrade [1] of the European X-ray free electron laser (XFEL), on-going tests are performed on XFEL prototype and production cryomodules since 2011. For these studies, DESY's cryomodule test bench (CMTB) has been equipped with a 105 kW CW capable inductive output tube (IOT) in addition to the 10 MW pulsed klystron, making CMTB a very flexible test stand, enabling both CW and pulsed operation. XFEL-like low level radio frequency (LLRF) electronics is used for these tests to stabilize amplitude and phase of the voltage vector sum (VS) of all 8 cavities of the cryomodule under test. The cryomodule most often tested is the pre-series XM-3, unique since it is housing one fine grain niobium and seven large grain niobium cavities. Modified flanges were installed in autumn 2017 on all 8 input couplers to increase the maximum reachable loaded quality factor (Q_L) beyond 2E7. With higher Q_L, up to 6E7 for 6 cavities and 3E7 for 2 cavities, we have investigated the VS stability and SRF-performance of this cryomodule under various conditions of cooling down rate and operation temperature 1.65K, 1.8K and 2K, at gradients up to 21.5 MV/m. The results of these tests are presented in this paper.

INTRODUCTION

The cryomodule test bench at CMTB offers versatile test conditions to investigate superconducting radio frequency (SRF) cryomodules under various conditions. It is equipped with a 10 MW klystron used for pulsed operations and a 105 kW inductive output tube used for continuous wave (CW) or long pulse (LP) operations. Two independent LLRF systems can be used to perform single cavity or vector sum field regulation. The LLRF system includes RF field feedback and resonance control using stepper motors and fast piezo feedback looped around individual cavities [2]. The waveguide distribution system can be adjusted to distribute power according to the different cavity performance. The cryogenic plant, supporting both the free electron laser in Hamburg (FLASH) and CMTB has a cooling capacity of 6.8 kW at 4.3K making it robust to heat load intensive experiments. Since 2011, several test runs have been carried out at CMTB to investigate the challenges associated with CW operation of XFEL-like cryomodules. The dynamic heat load and in particular the impact of end-cell heating was investigated as a function of RF pulse duty factor and gradient in [3].

More recently RF stability measurements for Q_L as high as 1.5E7 were reported in vector sum [4] and for single cavity operation [5]. To investigate issues related to narrow bandwidth and high gradient operations the input power couplers have been modified to reach higher Q_L, as described in section I. The dynamic heat load of individual cavities was measured to estimate the cavity unloaded quality factor (Q_0) as a function of gradient for different cryogenic temperatures. These results are reported in section II. Section III reports on the RF field stability performance demonstrated in CW for various gradient as high as 21.5 MV/m and various Q_L up to 8.2E7. A short summary and perspectives are given in the conclusion.

COUPLER MODIFICATIONS

The eight couplers of the XFEL pre-series cryomodule XM-3 were modified to move the Q_L range towards higher values. This was achieved by inserting a modified iso-vac flange, shown in blue in the figure below, moving the warm part of the coupler 10 mm further away from the 70K window. The motorized coupler allows for an additional 5mm displacement.
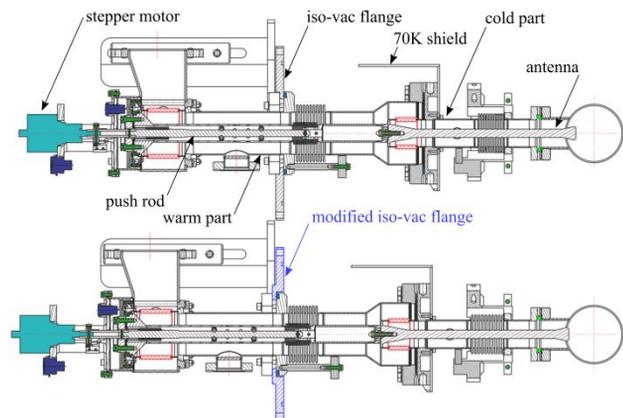
Figure 1: Unmodified XFEL power coupler (top) and with the modified iso-vac flange (bottom), shifting outwards the warm part of the coupler.

The achievable Q_L ranges before and after modification are listed in Table 1. Simulation predicts that a 5 mm displacement induces a Q_L increase from 2E7 to 8E7 which would suffice. In practice this increase in Q_L value was achieved by a 10 mm displacement, due to the fact that the coupling antenna also moved sideways. The improved Q_L range was limited in the case of cavity 7 and 8. This is due to a collision between the coupler 70K shield and the cryomodule 70K shielding cut out appearing after cool down for larger coupler movements on the last cavities (C7 and C8).

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Table 1: Coupler Range Before and After Modifications

Cavity	Q_L max (before)	Q_L min (after)	Q_L max (after)
C1	2.8E7	0.6E7	8.4E7
C2	1.9E7	0.5E7	6.8E7
C3	2.2E7	0.8E7	11.0E7
C4	2.0E7	0.6E7	9.1E7
C5	2.0E7	0.5E7	7.5E7
C6	1.9E7	0.4E7	6.6E7
C7	1.8E7	0.5E7	**3.0E7**
C8	2.0E7	0.5E7	**3.0E7**

Another two XFEL cryomodules, not yet installed in the XFEL tunnel are being modified in a similar way: XM46 and XM50 and will be tested in CW mode this year. The shielding cut outs will be adjusted to avoid the misalignment observed on XM-3.

HEAT LOAD MEASUREMENTS

Dynamic heat load studies have been conducted at various temperatures, both for individual cavities and for the whole cryomodule. The goal was to investigate the potential benefit to operate large grain cavities at temperatures lower than 2K. In these measurements Q_0 is computed by measuring the difference in helium mass flow when one (or several) cavities are in operation. Results are summarized in Fig. 2 for the whole cryomodule and Fig. 3 for individual cavities.
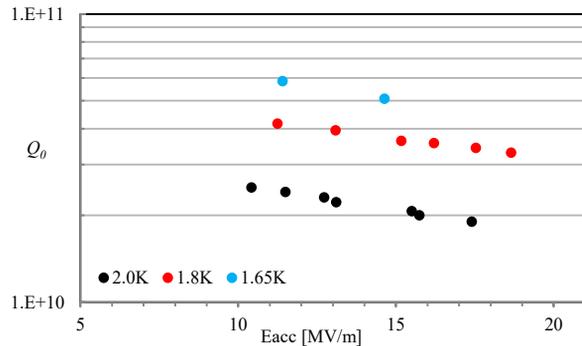
Figure 2: Q_0 vs Eacc for the whole cryomodule at 2K, 1.8K and 1.65K.

The first conclusion is that the Q_0 mean values measured for individual cavities at 1.8K (red dots in both figures) and 2K (black dots in both figures) agree very well with values measured for the whole cryomodule at these temperatures. This validates the accuracy of the dynamic heat load measurement using helium mass flow in the range from 1W (single cavity at 7.0 MV/m, 1.8K) to 140W (whole cryomodule at 17.4 MV/m, 2K). The gain in Q_0 for 1.8K operation compared to 2K operation is about 80%. Further investigation is required to find out if operation at 1.8K will be more efficient for the first 136

cavities (17 cryomodules in the injector section of the European XFEL accelerator). The main linac, extended from 84 to 96 cryomodules, could operate in CW around 8 MV/m. The dynamic heat load at this lower gradient is very low and operation at 1.8K would not be beneficial due to the static heat load.
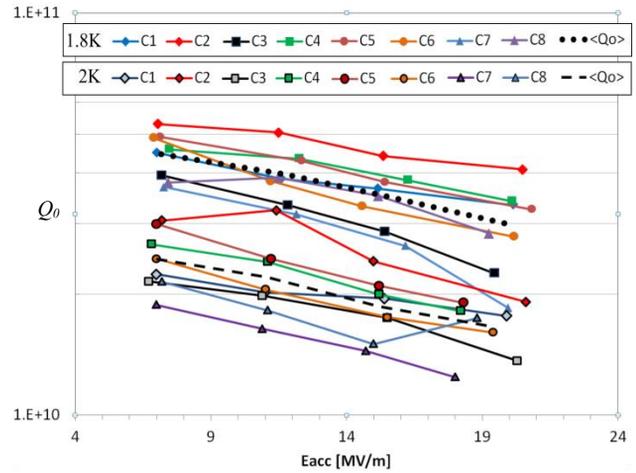
Figure 3: Single cavity tests at 1.8K and 2K.

RF STABILITY MEASUREMENTS

Before proceeding to any RF stability measurement, Q_L is measured for individual cavities. This is performed in pulsed mode where the amplitude decay is used by the diagnostic server to compute Q_L for every cavity. The expected cavity voltage $V_{CAV} = \sqrt{4Q_L R/Q P_{FWR}}$ is estimated based on the forward power P_{FWR} measured by power meters ($R/Q = 1012\ \Omega$ is the cavity shunt impedance). This estimated voltage assumes perfect tuning of the cavity. In practice a first tuning is performed with the stepper motor, and fine tuning is completed applying piezo DC bias. Due to the narrow cavity bandwidth (~ 20 Hz for $Q_L = 6$E7) and the presence of microphonics, keeping the cavity on resonance requires piezo feedback. Several piezo feedback operation modes are implemented in the LLRF system; the one typically used is a purely integral feedback using the phase difference between forward and probe signals as input. An active noise cancellation (ANC) algorithm [6] is also applied to notch out the dominant microphonics frequencies (typ. $\sim$30 Hz and 49 Hz), further helping the feedback controller. While the center frequency of the ANC notch filter can be identified by looking at the FFT of the probe and picking out the dominant frequencies, the other ANC parameters (learning rate and delay) are still optimized based on experience. Further work and understanding is required to automate this step. When all cavities are set on resonance, RF feedback can be applied around the vector sum (or around a single cavity field), typically with proportional gain only.

Vector Sum Operation

Due to several boundary conditions (limitation in Q_L range for C7 and C8 and high radiation level at high gradient operation for C3), the operating parameters and corresponding bandwidth (BW) listed in Table 2 were chosen.

Table 2: Individual Cavity Settings for the VS Test

Parameter		C1	C2	C3	C4	C5	C6	C7	C8
E_{ACC}	[MV/m]	16	16	8	16	16	16	11	11
Q_L	[x10^7]	6	6	**1.4**	6	6	6	**2.5**	**2.5**
BW	[Hz]	22	22	93	22	22	22	52	52

The amplitude and phase regulation level achieved during this study met the XFEL specifications of 0.01% and 0.01°. Figure 4 shows the RMS amplitude stability (dA/A) over one and half hour during which the XFEL amplitude regulation was achieved. On average the phase stability is still a factor of 2 above specifications (i.e. 0.02° RMS) but can be controlled for short periods of time (i.e. minutes) as low as 0.009°. This work is ongoing.
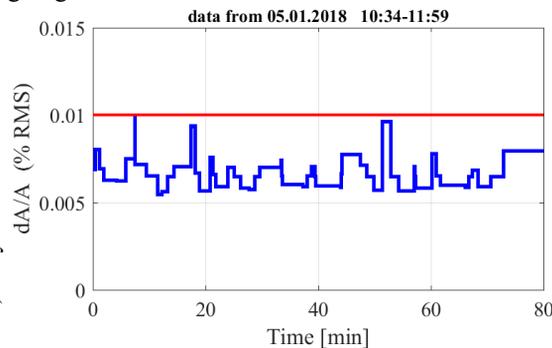
Figure 4: VS signal amplitude regulation dA/A (RMS). XFEL specifications are shown in red.

The vector sum field stability was guaranteed by the RF feedback, while the resonance control of individual cavities was achieved using an integral feedback together with ANC filters acting on the cavity piezos (set to suppress 31 Hz oscillations).

Single Cavity Operation

Single cavity studies were pursuing two objectives. The first goal was to push towards higher gradients (above 20 MV/m) for a constant Q_L. The second goal was to push towards higher Q_L for a gradient set point of 16 MV/m. Due to its high gradient capability (above 40 MV/m), cavity 3 in XM-3 was used for the first goal. An amplitude and phase regulation of dA/A = 0.019% and dP = 0.014° respectively was achieved for a maximum gradient of 23.5 MV/m in CW, still a factor of 2 away from the target specifications. RF and piezo feedback along with ANC set to suppress 31 Hz and 49 Hz were used. For the second goal, cavity 4 was chosen due to its high Q_L tuning range. In this study, Q_L was set to 8.2E7 (corresponding to a half bandwidth ~8 Hz). The achieved RMS performance was dA/A = 0.015% and dP = 0.017°.

CONCLUSION

Some very encouraging results have been obtained at CMTB during CW tests of XFEL prototype cryomodules. The high Q_0 observed on large grain cavities might be an indication to pursue this approach when upgrading the front end cryomodules in the XFEL CW upgrade scenario. Furthermore, RF stability compliant with the XFEL specifications could be achieved in amplitude and phase at a Q_L =1.5E7 and partially in amplitude and phase at Q_L above 6E7. For a given RF power source, increasing Q_L for the cryomodules of the main linac directly translates into higher final beam energy. Since the XFEL cryomodules are equipped with remote tunable couplers, it is interesting to see how high Q_L can be set, while still meeting the RF field stability and heat load specifications. With the next 2 cryomodules to be investigated in CW (XM46 and XM50), we will see how these results translate to series XFEL cryomodules. More work is required on the LLRF system, to improve the robustness of the piezo feedback and automate the optimization of ANC parameters (frequency detection, learning rate…). A better understanding of the cavity mechanical modes and their dependency on gradient and Q_L is currently under investigation as part of the R&D effort towards CW operation of the XFEL [7]. More work is also required to understand the current limitation of the RF feedback preventing to reach the XFEL specifications. In particular, a more sophisticated controller (MIMO-based) is in preparation, and should help run at higher gain by increasing the decoupling between the in-loop and quadrature components of the feedback control signal, providing better amplitude and phase stability.

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