UPDATE AND STATUS OF TEST RESULTS OF THE XFEL SERIES ACCELERATOR MODULES

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Abstract

The European X-ray Free Electron Laser is under construction at DESY, Hamburg. During preparation for tunnel installation 100 Cryomodules are tested in a dedicated facility on the DESY campus. Up to now around 50 cryomodules have been measured at 2K. This paper describes the current status of the measurements, especially single cavity limitations. In addition we present a comparison between the vertical test results of the individual cavities and the corresponding performance measurements of the cavities once assembled into the accelerator string inside the cryomodule.

INTRODUCTION

The linac part of the XFEL consists of 101 SRF cryomodules. Before installation into the linac tunnel all of the cryomodules are tested in a dedicated Hall AMTF (Accelerator Module Test Facility) on the DESY campus. The AMTF Hall is equipped with three horizontal test benches, which allows three cryomodule tests in parallel.

At the end of August 2015, more than 50 % of the cryomodules have been tested.

STATUS OF TESTED CRYOMODULES

Currently 52 cryomodules have been successfully tested. Some of the cryomodules delivered to the AMTF were not tested due to problems encountered before or during the test procedure.

The testing rate of the cryomodules was planned as one cryomodule leaving the AMTF test benches per week. With three test benches, the number of days foreseen for one cryomodule test is 21 calendar days. Within this time all necessary corrections have to be made as well. To be able to keep this schedule, works at AMTF are performed on two shifts. Current testing rate of the cryomodules is greater than planned (see Fig. 1). After improvements made to the existing testing procedure (see [1], [2]) after June 2015 the testing rate has significantly increased.

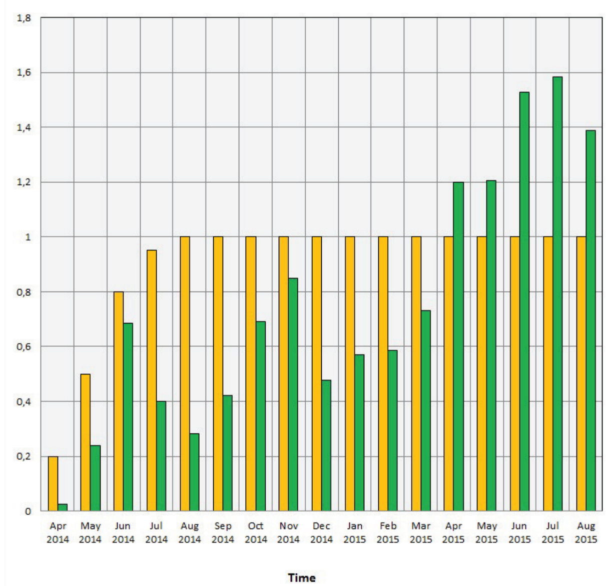

Figure 1: Cryomodule testing rate. Yellow bars represent planned quantity per week. Green one represents real quantity.

SINGLE CAVITIES PERFORMANCE IN THE CRYOMODULES

One of the most important cryomodule parameters measured at AMTF is the single cavity performance. During this so-called "flat - top" test, individual cavity limits are measured. There are two main threshold for the cavities: Maximum gradient and operating gradient.Maximum gradient is the gradient just below the cavity quench. However, at the AMTF with the given XFEL [3] pulse parameters, the maximum gradient which can be achieved is 31 MV/m. Infrastructure limitation causes a situation where some of the tested cavity have power limitation instead of real quench value of the accelerating field.

Operating gradient for a single cavity is a value of the usable acceleration field which is foreseen for the cavity during operation. It is defined as the minimum value of:

- BD (Break Down) Limit - Cavity gradient just before the quench reduced by 0.5 MV/m
- X-ray Limit - Gradient when the radiation level measured at one of the ends of the cryomodule is equal to 10^{-2} mGy/min
- PWR (Power) Limit - is equal to 31 MV/m.

XFEL specification for a single cavity operating gradient has been set to 23.6 MV/m . However, if some of the cavities do not fulfil this criteria, compensation by cavities with higher acceleration field is possible. As shown on Fig. 2, almost 25 % of the tested cavities have operating gradient below the XFEL goal. Despite this fact, the average operating gradient for all of the tested cavities is equal to 27.2 MV/m.

In the Fig. 3, the number of the cavities which did not meet XFEL goal in the cryomodules is shown. There is one of the cryomodules with 7 cavities below the XFEL specification

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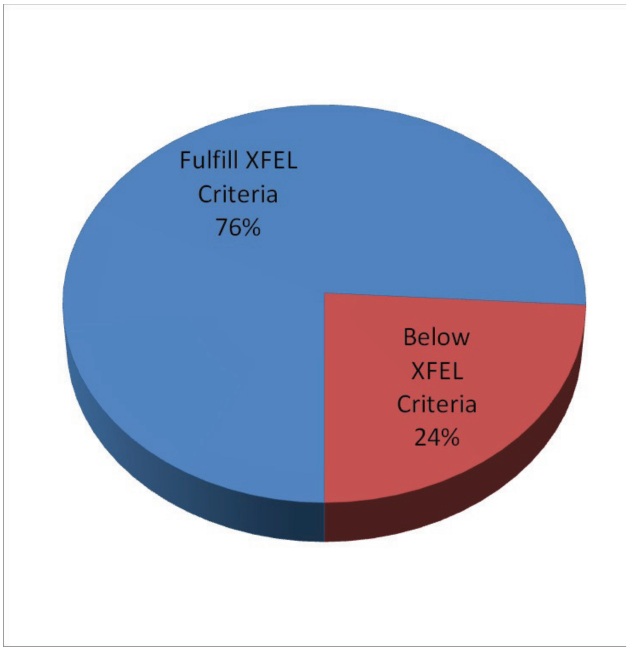

Figure 2: Number of cavities, which do not meet XFEL operating gradient criteria.

[3]. In this cryomodule cavities with bad performance in the vertical test have been grouped.

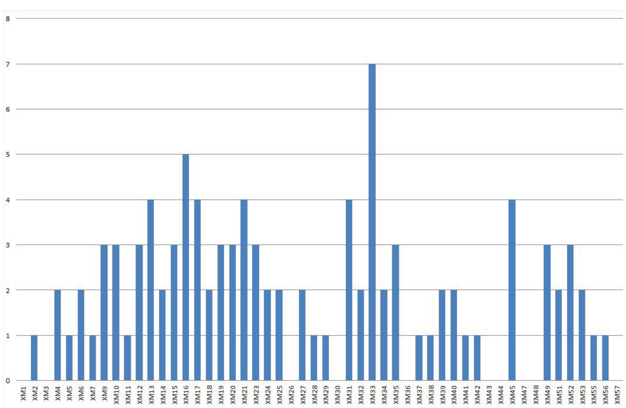

Figure 3: Number of cavities below XFEL goal in the cryomodules.

AVERAGED OPERATING GRADIENTS OF THE CRYOMODULES

The tunnel qualification is usually done by analysis of the average operating gradient of the whole cryomodule. To see the possible limitation other than quench and power limit, the cryomodule averaged maximum gradient is also taken into account.

In Fig. 4, average maximum and operating gradient for all tested cryomoduled are shown. Only two cryomodules have average operating gradient below the XFEL specification. One of those modules is XM33. To assemble this cryomodule 8 cavities with weak performance measured during vertical test have been chosen (average operating gradient of all cavities for XM33 during vertical measurement was only 22 MV/m). Another one is XM45. This cryomodule has an average operating gradient during vertical test at the level of 28 MV/m.

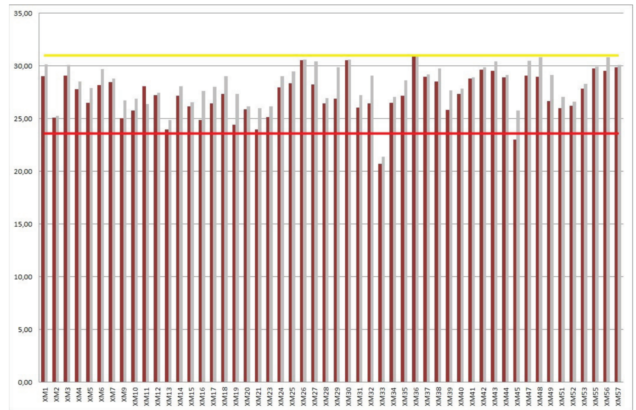

Figure 4: Averaged maximum (grey) and operating (red) gradients for all tested cryomodules. Red line represent XFEL goal. Yellow line is the power limitation.

AVERAGED CRYOMODULE QUALITY FACTOR

Another important parameter measured during AMTF test is a quality factor of the cryomodule. Obtaining the single cavity quality factor is not possible due to two main reasons. First is the time needed for such evaluation (Several hours for each individual cavity for each gradient). Second reason is a cryogenic resolution of the measurement system. During single cavity testing dynamic losses of the cavity are negligible in comparison to static losses. Because of this the quality factor for whole cryomodule is calculated from the dynamic cryogenic losses at 2K circuit. The XFEL specification requires the quality factor of the cryomodule to be above 1×10^{10}.

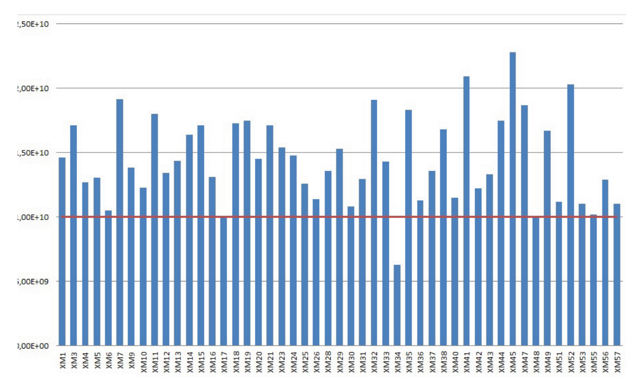

Figure 5: Average quality factor for all tested cryomodules. Red line corresponds to XFEL specification.

Only one of the tested cryomodules (see Fig. 5) did not fulfil this criteria. This cryomodule (XM34) has been equipped with cavities with operating gradient measured in vertical cryostat around 25 MV/m. 6 out of 8 cavities in this cryomodule had quality factor as a limitation.

SINGLE CAVITIES LIMITATIONS

As mentioned before few limitation have been introduced to describe the single cavity performance. As shown in Fig. 6 more than 50 % of tested cavities did not quench during cryomodule test (power limitation). One cavity has been limited by the problem with the coupler. Five cavities have the field emission limit exactly at the power-limit region. The rest are limited to below 31 MV/m by quench.

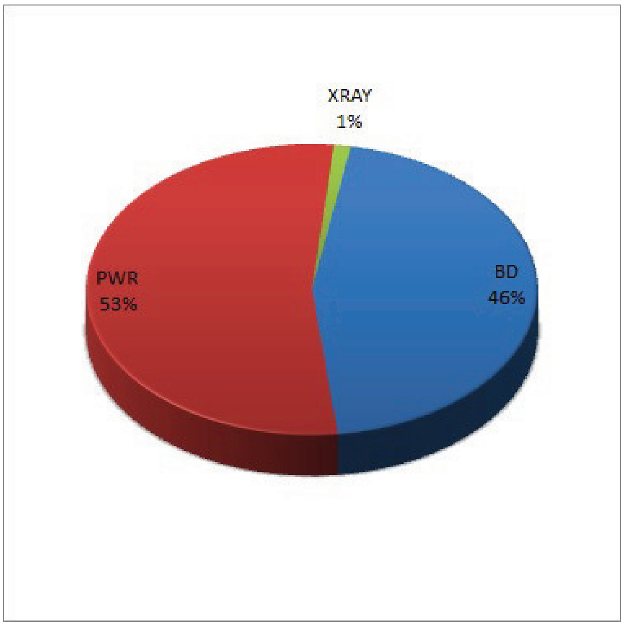

Figure 6: Limitation for singles cavity maximum accelerating field.

From the linac operation point of view the more important parameter is the operating gradient. In this case (see Fig. 7) more than 20 % of the cavities are limited by radiation. The number of cavities limited by infrastructure and by quench is almost equal.

COMPARISON BETWEEN VERTICAL TEST AND CROYOMODULE TEST

There is a fundamental difficulty in the comparison between vertical test results and the cavity in the cryomodule performance. Limitations given during vertical test are different from those used in cryomodule test The main difference is the quality factor of the cavity. As already mentioned, this value is not measurable during the XFEL cryomodule test for single cavities. However during the vertical test, the quality factor as a function of gradient is measured. Therefore, for the vertical test there is another gradient limitation, Q which

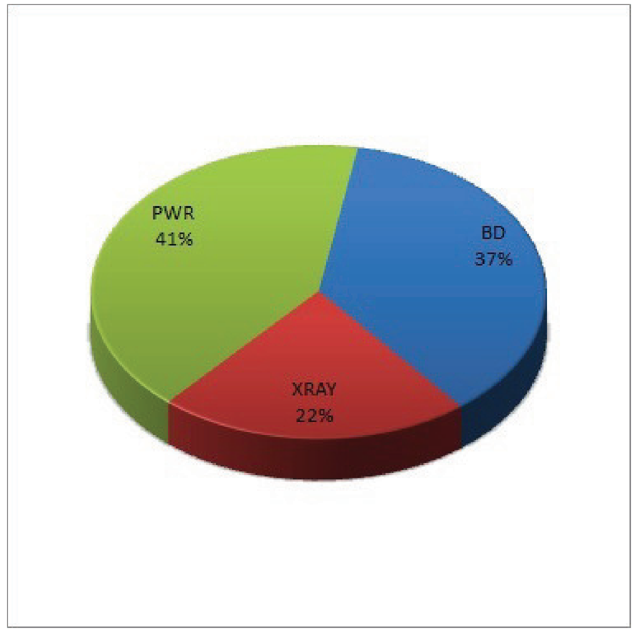

Figure 7: Single cavity maximum accelerating field limitation.

has to be above 1×10^{10}. Another problematic limitation is radiation. In the vertical test there are two X-rays detectors placed above and below cavities in the cryostat. In the horizontal test bench for the cryomodules there are two detectors placed on the beam axis outside of the cryomodule. Moreover, during the module test only one cavity is on resonance, which may cause a situation when a cavity is in the middle of the cryomodule string emits the radiation which is not visible by the detectors.

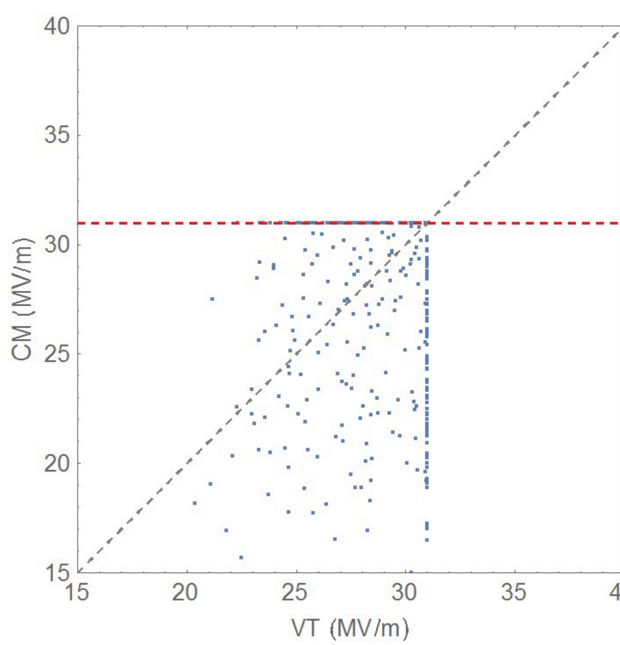

Figure 8: The cavities operating gradient comparison [MV/m] between vertical test and cryomodule measurement.

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Figure 8 shows the comparison between operating gradient measured in the cryomodule and during the vertical test. Vertical test results have been cut to 31 MV/m to provide a more fair comparison. Points above the diagonal show cavities which have either better performance in the cryomodule than in vertical test (this is very uncommon) or were limited during vertical test by quality factor of the cavity. All dots below the diagonal show some degradation between vertical test and the test in the Cryomodule.

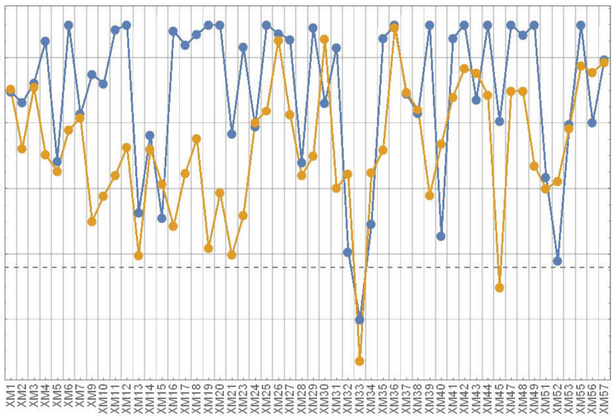

Figure 9: Comparison of the average operating gradients [MV/m] for whole cryomodules: blue plot shows vertical measurements, yellow shows the cryomodule test. Dashed line is the XFEL specification.

Figure 9 shows the comparison of the average operating gradient calculated from vertical test and those measured in the cryomodule test. Very good correlation could be seen especially for the cryomodules assembled from cavities with the performance around 25 MV/m or below.

The averaged values for all cavities tested up to now are shown in Table 1.

Table 1: Statistics of the operating gradient for all tested cavities in the vertical cryostat (VT) and in cryomodules (CM). (VT results are clipped at 31 Mv/m)

	VT	CM
Number of cavities	415	415
Averaged Eacc [MV/m]	28.9	27.2
RMS [MV/m]	2.5	4.6
Min Eacc [MV/m]	20.4	9.2
Max Eacc [MV/m]	31	31

POSITION OF THE CAVITY IN ACCELERATING STRING

After vertical test in AMTF cavities are grouped to be assembled into cryomodules. The main parameter taken into account is the operating accelerating field measured in vertical cryostat. Each cryomodule cavity string is planned as a grouping of cavities with similar results.

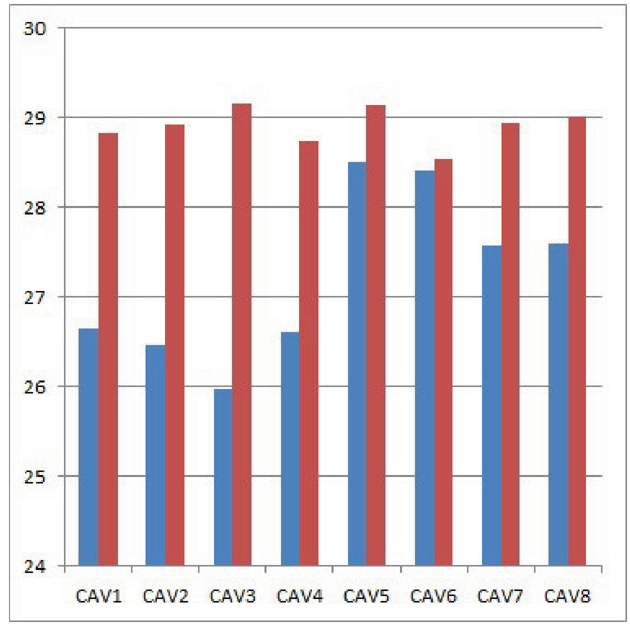

Figure 10: Average operating gradient [MV/m] for each position in the string. Blue bars represents cryomodule measurement while red ones vertical result.

Results of singles cavity performance in the cryomodule should be independent from the cavity position in the string. In Fig. 10 the average gradient for each of the position is shown. The average gradient taken from the vertical measurement is almost at the same level (fluctuating slightly around 29 MV/m). However, there is a significant difference between the first four and the second four cavities in the cryomodules.

Figure 11 shows number of cavities which do not fulfil XFEL specification for the accelerating field and their positions. In this comparison first four cavities show worse behaviour.

Figure 12 shows number of cavities with operating gradient power limitation. The number of cavities with power limit on first four positions is significantly lower than in second four. In addition, number of power limited cavities on position 5 to 8 are greater in the cryomodule than in vertical test. As mentioned before, due to differences in limitations between cryomodule test and vertical measurement, comparison is difficult. Despite this, it seems that cavities assembled on last four positions show better performance in general.

NOT TESTED CRYOMODULES

As of writing the last tested cryomodule at AMTF has serial number XM57. However, there were several cryomodules up to now which were not able to be tested. The following cryomodules were not tested up to now:

- XM8 - Not tested because of a leak in the 2K circuit
- XM22 - Not tested because of a leak in the beam line
- XM46 - Not yet delivered from IRFU

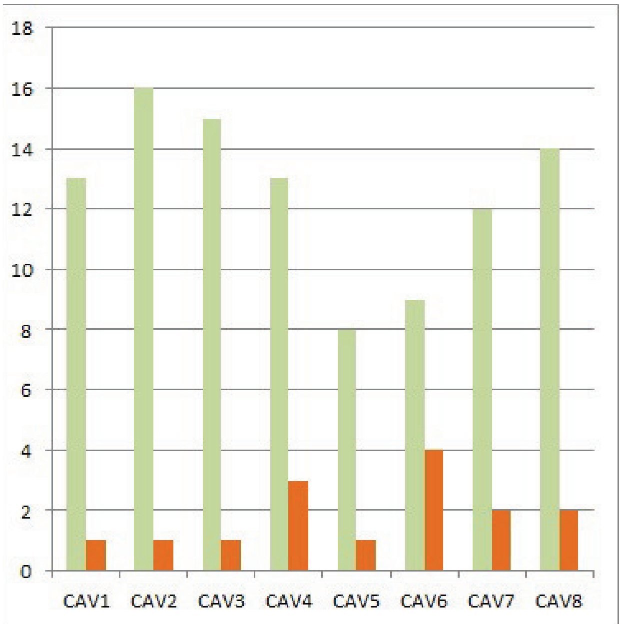

Figure 11: Number of cavities below XFEL specification versus cavity position. Cavities in the cryomodules are green. Orange bars shown results form vertical measurement.

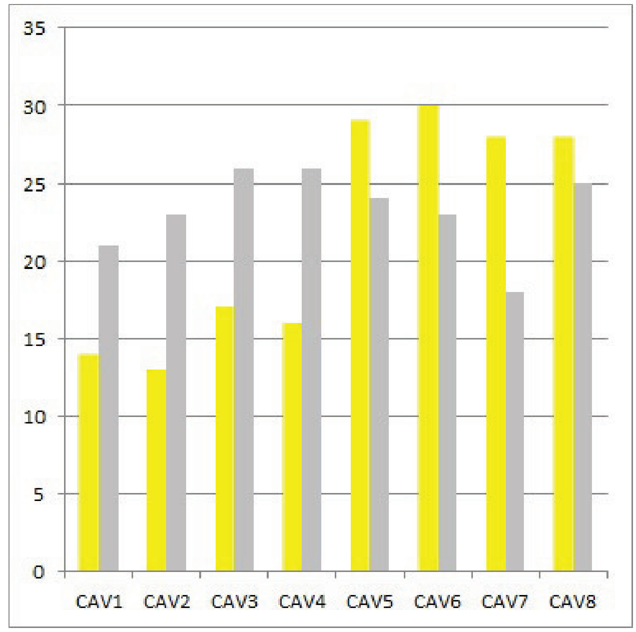

Figure 12: Number of cavities with power limitation versus position in cryomodules (yellow) and in the vertical (grey).

- XM50 - Not yet delivered from IRFU
- XM54 - Not tested due to leak in the beam line cold valve

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