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TEST RESULTS OF THE EUROPEAN XFEL SERIAL-PRODUCTION ACCELERATOR MODULES

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Abstract

The serial-production tests of 100 cryomodules for the European XFEL have been finished. In this paper the statistics of the cold RF measurements in the AMTF (Accelerator Module Test Facility) are reported for all the modules. In addition comparison between the cavity vertical test results and module test results are presented.

INTRODUCTION

In August 2016 measurements of serial-production accelerating components for the European XFEL project was finished. The main element of the accelerator (linac) is called the cryomodule and it consists of 8 SRF TESLA type cavities. Each one was examined in the dedicated test infrastructure called AMTF at DESY during the 4 year production period. Tests were performed on two shifts by the team of the engineers from the IFJ PAN, Krakow, Poland [1]. The measurements resulted in information about operating parameters, namely: maximum gradient, quality factor of the RF cavities, as well as cryo-losses and control parameters. After testing, 97 modules have been installed in the European XFEL tunnel. Finally, since April 2017 the accelerator has been successfully commissioned [2].

In this paper an analysis of the final measurement results for serial production cryomodules (from XM1 to XM100) is presented. Based on the AMTF test results there are several ways, in which to quantify the production [3]. Here the emphasis is put on the difference between cryomodule and the vertical test results taking into account the production order and cavity position in the cryomodule. Investigated are data obtained during the pulsed high power RF test and heat-loads measurements. The aim of the pulsed high power RF measurement is to study operating gradients and cavity limits. The data are also compared to those obtained during the vertical measurements. An analysis of the heat-load measurements, which aim to quantify the thermal cryogenic load during operation, is also presented.

CAVITIES PULSED HIGH POWER RF TEST: PERFORMANCE MEASUREMENT OF THE CAVITIES INSTALLED IN THE CRYOMODULES

In order to measure the performance of the European XFEL cavities, the pulsed high power RF test was performed [4]. The maximum and operating accelerating gradients [MV/m] were obtained.

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The operational limits on the cavity gradients were chosen as the minimum value of:

- (X-RAY) the gradient when radiation exceeds 10^{-2} mGy/min one or other end of the module,
- (BD) the gradient before the quench limit (0.5 MV less),
- (PWR) limit of the ATMF infrastructure (31 MV/m),
- (CPL) cavity operation limit caused by a fundamental power coupler having not conditionable RF discharge or strong overheating (overtemperature) problem.

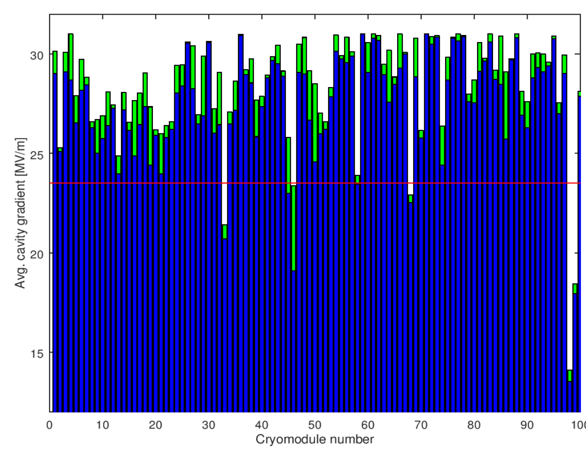

Figure 1: Average of the operating (blue) and maximum (green) gradient for cavities in each serial-production cryomodule. European XFEL Specification is marked by a red line.

The maximum gradient was defined as the highest of the above, taking into account a radiation safety limit of 10 mGy/min for the X-ray measurements.

The European XFEL design operating gradient [5] for a single cavity is specified as 23.6 MV/m, sufficient to achieve the design energy goal of 17.5 GeV with some margin.

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ANALYSIS OF THE OPERATING GRADIENTS IN THE CRYOMODULES

On the Figure 1 the average cavity maximum and average operating gradient for each cryomodule is presented. It is clearly visible that only a few of the cryomodules are below the European XFEL acceptance threshold (marked by a red line).

Actually, only 7 out of 100 serial-production cryomodules did not fulfil the acceptance criteria. For 5 out of these 7 the expected averaged gradients after the vertical measurements were lower than 23.6 MV/m. However only 7 issued cryomodules do not cause a problem due to the fact that the average gradient of all cavities is higher, that the expected threshold (see Table 1).

Vertical vs. Cryomodule Test

Only two cryomodules (XM45 and XM46) shows gradients considerably decreased between vertical and cryomodule measurements (see Figure 1) - their averaged operating gradients after the vertical test were higher than European XFEL threshold, but during the cryomodule test the results were below the 23.6 MV/m.

In Table 1 the average results are presented. For comparison the vertical test data are also clipped to 31 MV for these and all other analyses presented data in this paper.

Table 1: Average Gadient [MV/m] for 100 Serial-Production Cryomodules

	MAXIMUM clipped at 31.0	**OPERATING** specified to 23.6
Cryomodule	28.5	27.5
Vertical	30.1	28.6

In Figure 2 a comparison between operating gradients in the cryomodule and during the vertical test is presented. Points below the diagonal represent data when vertical results are lower than obtained in the cryomodule. There are two reasons of this unclear issue: the additional parameter for the operation limit during the vertical measurement - the quality factor (limit 10^{10}) and the second is a relatively high measurement error for cryomodule test (~ 10%) [3, 6, 8].

The same results are plotted in Figure 3 including the cryomodule number, so in production order. It shows significant decrease between the XM1 and XM20. After the approximately 1/5 of the cryomodule assembly and treatment the degradation of the RF cavities between the vertical and cryomodule test is not observed anymore (except the two cryomodules - XM45 and XM46).

Limits in the Cryomodule Tests

The results of the cryomodule pulsed high power RF measurements can be also analysed by the reason for the RF cavity limits. The Figure 4 shows that 56% of the cryomodules during AMTF tests did not quench below the AMTF power limit (blue area). 43% of the cavities quenched below

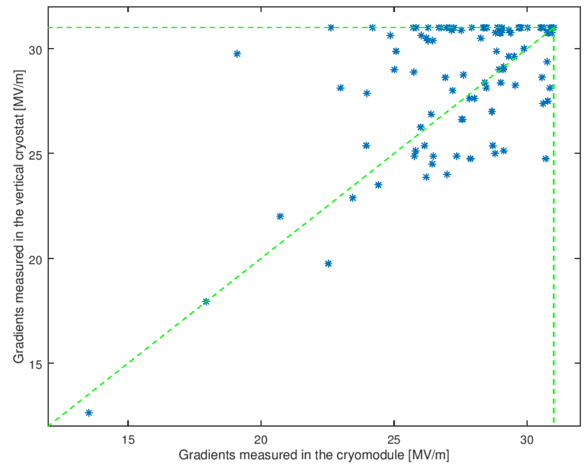

Figure 2: The comparison between the average of the operating gradients obtained during the vertical and cryomodule test.

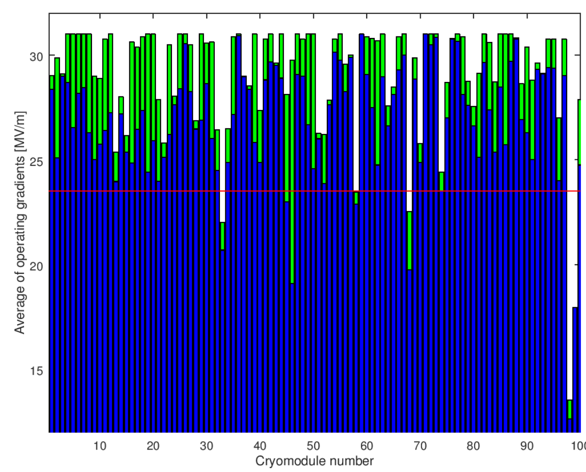

Figure 3: The comparison between the average of the operating gradients for cavities obtained during the vertical (green) and cryomodule (blue) tests for each cryomodule number (assembly order).

31 MV/m. Furthermore 9 measurements were limited due to the radiation (yellow) exceeding the safety limits. One cavity is limited by an unconditionable coupler during the final measurement (black), which when used caused significant loss of the coupler vacuum. Several other couplers limited measurements, but after correction action at DESY issues were fixed [7] not limiting the cavity during the test any more.

The operating limitations are presented in Figure 5. Almost half of the cavities reached the power limit (46%). Furthermore 17.9% reached the field emission limit. The one coupler issue (black) is also presented in the plot. What is more, out of the quenched cavities 84% did not change their behaviour after the vertical measurement. They quenched

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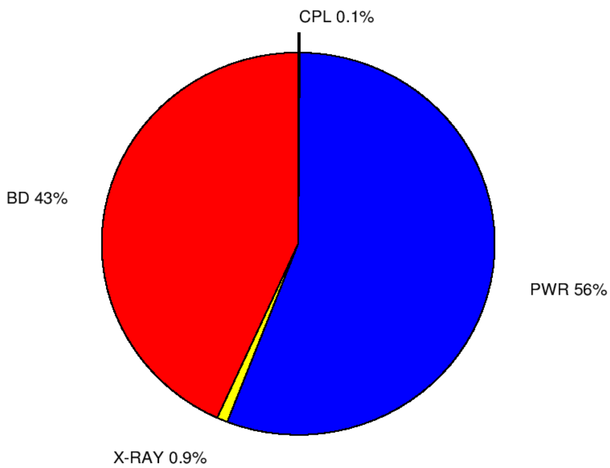

Figure 4: Cavities maximum gradient limitation.

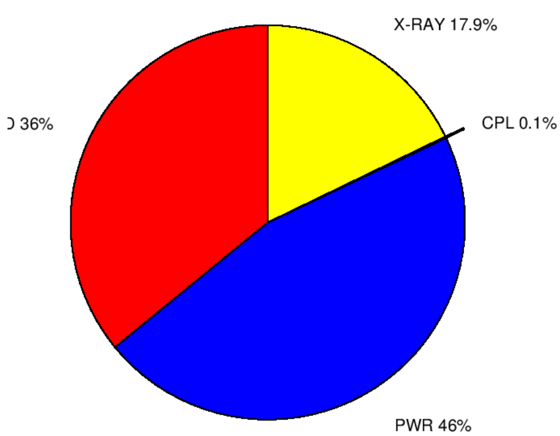

Figure 5: Cavities operating gradient limitation.

below the power limitation, but no influence after integration into string was observed. Only 16% decreased their behaviour from gradients above 23.6 MV/m to values below the European XFEL specification.

Position of the RF Cavity in the Cryomodule

Maximum gradient In order to analyse the data of the measured cavities, their position in the cryomodule is also taken into account. As shown in the Figure 6 the highest gradients have been obtained for cavities 5 and 6. However the averaged values on these positions shows that the best cavities from the vertical test were assembled there. On contrary the worst cavities behaviour with respect to the maximum gradient have been noticed on positions 3 and 4.

As shown in Figure 7 the biggest number of cavities with the limitation PWR influenced the average maximum gradient on positions 5 and 6. Only few cavities are limited by the high radiation (positions 1,2,5,7). One important remark must be here made: if a cavity is limited by the maximum gradient with the high 10 mGy/min radiation safety limitation, then the neighbour cavities were also spoiled: either by significant reduce of the operating gradient or by the X-ray limitation for the operating field!

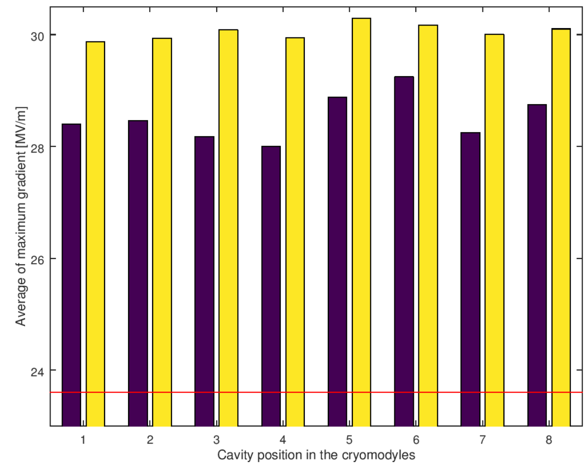

Figure 6: Average of the maximum gradients for the each cavity measured in the vertical cryostat (yellow) and in the cryomodule (violet) with respect to the position in the cryomodule.

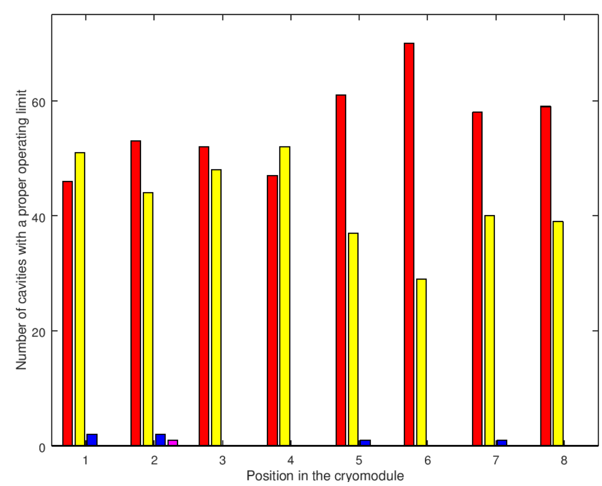

Figure 7: Number of cavities with the maximum limitation stored as PWR (red), BD (yellow), X-ray (blue), CPL (pink) versus the position in cryomodule.

Operating gradient As expected from Figure 6 the numbers of cavities with the operating power limit should by the highest on positions 5 and 6 as well. The results confirms this expectations (see Figure 8). On the other hand the worst operating limits in comparison to the vertical measurements is observed on positions 2 and 4. Further, a significant difference between positions 1-4 and 5-8 is visible before [8], but except the 7th cavity.

Figure 9 shows the operating limit reasons in numbers for each position in the cryomodules. A clear difference in the

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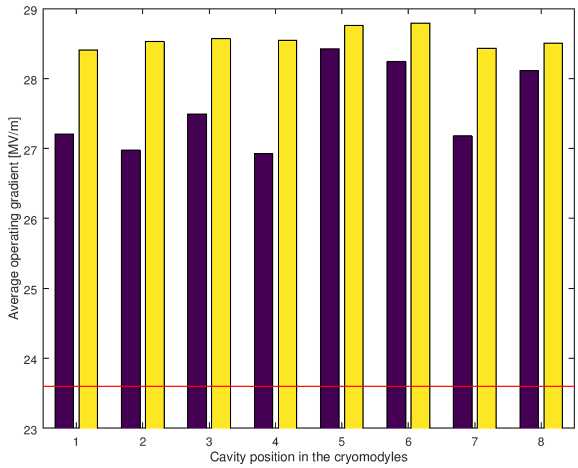

Figure 8: Average of the operation gradient for the each cavity measured in the vertical cryostat (yellow) and in the cryomodule (violet) with respect to the position in the cryomodule.

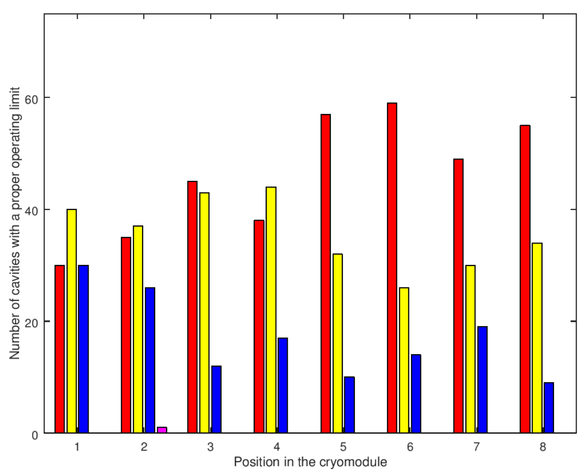

Figure 9: Number of cavities with the operating limitation: PWR (red), BD (yellow), X-ray (blue), CPL (pink) versus the position in cryomodule.

numbers of the power limit for cavities 5-8 in comparison to the 1-4 is visible.

HEAT-LOADS: PERFORMANCE MEASUREMENT OF THE CAVITIES INSTALLED IN THE CRYOMODULES

The parameter not taken into account for analysis during the pulsed high power RF measurement is the quality factor. To obtain it the heat-loads test was performed, the aim of wich is to evaluate thermal loads during normal European XFEL cryomodule operation. The measurement is performed driving all the cavities at 23.6 MV/m, unless they previously determined limit is less. In order to do that the waveguide distribution is changed to apply different powers to different pairs of the cavities. The restriction is only the paired distribution in the AMTF infrastructure: i.e. it means that the same power is set to the neighbouring cavities. This determines the chosen gradient for the test as the weakest from the cavity pair (1-2, 3-4, 5-6, 7-8). Finally after a period of stable operation from the thermal loads an average quality factor is calculated.

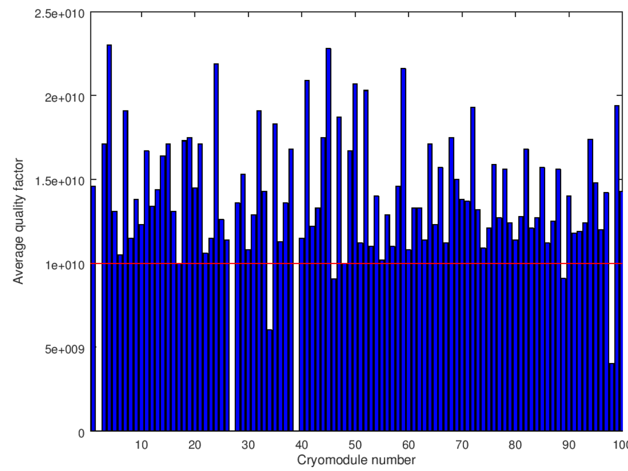

Figure 10: Estimated average quality factor for all serial-production cryomodules. European XFEL Specification is marked by a red line.

ANALYSIS: QUALITY FACTOR

In Figure 10 the average quality factor obtained during the heat-loads test for each cryomodule is presented in the cryomodule (assembly) order. Three cryomodules were not measured due to cold-leaks of cavity strings. Four have quality factors below the European XFEL threshold, which is 10^{10}. For cryomodules XM46 and XM98 the behaviour is also combined with the low results of the pulsed high power RF measurements. In the case of two other cryomodules the reasons are unclear.

In Figure 11 the averaged quality factors are plotted in comparison to the averaged operating gradients during the heat-loads measurements. On the right hand side the measurement is limited to the 23.6 MV/m, which makes results difficult to analyse. No correlation of the results is observed. It has to be taken into account that for the heat-loads measurement, the cavities were not supplied in the same way as they are in the accelerator. Firstly the distribution in the AMTF decreased the better cavity in pairs. Secondly supplying of the cavities in the tunnel is not limited to the 23.6 MV/m, but it is the proportion of the power needed to supply the operating gradient for each cavity in the RF-station (4 cryomodules). The average value of the quality factor is $1.42 * 10^{10}$, which is above the acceptance criteria.

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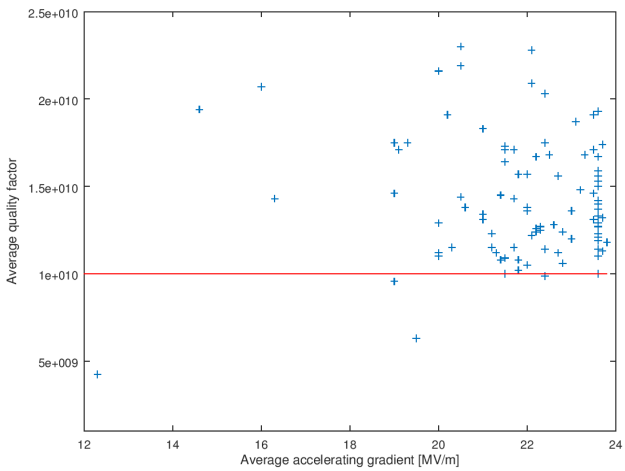

Figure 11: Estimated average cavity quality factor for all serial-production cryomodules versus average of the gradients.

CONCLUSION

Some conclusions from the results can be summarized below:

- Only two cryomodules show excessive gradients degradation during cryomodule measurements: for them the averaged gradients are below the European XFEL specification, although their averaged values for vertical measurements were above this threshold.
- Cavity behaviour is the best for position 5 and 6 in the cryomodule, which might be related to the assembly process.
- Number of cavities with the power limit is much higher for positions 5-8 than in positions 1-4.
- About 50% of the cavities in the European XFEL have operating gradients above or equal the ATMF infrastructure limit (31 MV/m).
- Only one coupler during the final measurement in the AMTF was unconditionable.
- The process of the assembly and testing of the cryomodules between the vertical measurement and the cryomodule test was well understood after the 20 out of 100 cryomodules.
- European XFEL cavities behaviour is better than expected: 23.6 MV/m was the specification, but the measured average is 27.5 MV/m.
- The averaged quality factor of the cryomodules is above the European XFEL specification.

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