PERFORMANCE OF SUPERCONDUCTING CAVITIES FOR THE EUROPEAN XFEL

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for the European XFEL Accelerator Consortium

Abstract

The superconducting accelerator of the European XFEL consists of the injector part and the main linac. The injector includes one 1.3 GHz accelerator module and one 3.9 GHz third-harmonic module, while the main linac consists of 100 accelerator modules, each housing eight 1.3 GHz TESLA-type cavities, operated at an average design gradient of 23.6 MV/m. The fabrication and surface treatment by industry as well as the vertical and cryomodule RF tests of the required 808 superconducting 1.3 GHz cavities are analysed and presented.

INTRODUCTION

The 17.5 GeV SRF linac for the European XFEL is currently under construction by a consortium consisting of several European institutes [1]. At the beginning of 2015 the cryomodule production and testing rate was increased from an average of 1 to 1.25 eight-cavity-modules per week, in order to meet the expected tunnel closure date of September 30, 2016. Testing of both individual cavities and cryomodules is performed in a dedicated test facility at DESY (AMTF) [2,3,4]. In early 2016 all of the 816 series EU-XFEL TESLA-type 1.3 GHz SRF cavities have been produced, and have each undergone at least one vertical acceptance test in AMTF. As of April 15, 2016 87 of the 102 EU-XFEL cryomodules (101 for installation + 1 spare) have been tested at AMTF. Vertical and module testing is performed by a team from IFJ-PAN Krakow as an in-kind contribution. The installation of cryomodules and first steps of commission for the main linac are in full swing. The injector commissioning started successfully in December 2015.

XFEL CAVITIES AND VERTICAL ACCEPTANCE TEST

Production Overview

Series production of the 1.3 GHz TESLA cavities was equally divided between E. Zanon Spa. (EZ), Italy, and Research Instruments GmbH (RI), Germany. Production included both mechanical fabrication and surface preparation [5] together with required extensive documentation [6]. Details about the niobium and niobium-titanium material used can be found in [7]. The RF measurements for quality assurance during the cavity production are described in [8]. 804 XFEL series cavities (401 by EZ; 403 by RI) were delivered complete with helium tank (Fig. 1), ready for vertical testing at DESY in AMTF. Each vendor also produced additional 12 cavities without helium tank for the ILC-HiGrade programme [9], which have been used as a quality control tool as well as for further R&D. For 8 of these 24 cavities a subsequent assembly of the He-tank was made. In addition 4 of the additional 16 cavities used for infrastructure set-up and commissioning have since been fitted with a He-tank for use in the assembly of the 102 cryomodules.

Both vendors must exactly follow well-defined specifications for the mechanical fabrication and surface treatments, but no cold RF performance guarantee is required. The surface preparation at both vendors started with a bulk electro-polishing (EP) followed by 800° annealing, but for the final surface treatment two alternative recipes have been used: EZ applied a final chemical surface removal (“Flash-BCP”), while RI applied a final EP. All cavities were fully equipped with their HOM antennas, pick-up probe and a High-Q input coupler antenna with a fixed coupling. All cavity transports took place horizontally in a dedicated transport box [10] under UHV conditions by truck. No performance degradation after transport has been observed. The procedures before and after the vertical acceptance test at 2K are described in [10]. Once received at DESY, an initial incoming inspection was performed (mechanical, electrical, warm RF and vacuum checks). While originally intended to check for transport damages, the incoming inspection proved necessary to identify unexpected non-conformities, with the result that 54 cavities were sent back to the vendors before vertical testing.

All 832 tested cavities have clearly demonstrated that the chosen scheme for mechanical production and surface preparation was successful implemented at both vendors.

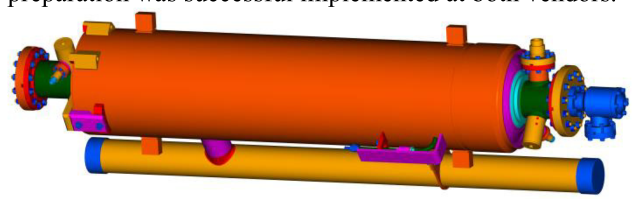

Figure 1: 3-D model of the series XFEL cavity equipped for delivery to DESY.

Vertical Testing Scheme

The vertical acceptance tests of up to 10 cavities per week have been made using two independent test systems, each consisting of an independent bath cryostat and RF test stand. Each test cryostat accepts an “insert” which supports up to four cavities (Fig. 2), greatly increasing the efficiency of cool-down / warm-up cycles. All 1,225 vertical acceptance tests of the 832 cavities are now complete (except of potentially few non-conform returns from string assembly). Each vertical test was categorized ac-

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cording to well-defined “test reasons”. Depending on the result a categorized “decision” was taken and documented in the cavity and cryomodule managing system [11] of the AMTF as well as in the XFEL cavity data base [12,13]. Cavities without non-conformities (see below) and with acceptable performance usual have only one vertical acceptance test (“as received”) after which they receive the decision “send to string assembly”. In case of non-conformities (e.g. insufficient cavity performance, RF problem, vacuum leak, mechanical deviation, etc.) the cavity was retested, retreated or sent back to the vendor eventually resulting in additional vertical tests [14].

Figure 2: Test inserts for vertical testing at AMTF.

The vertical acceptance tests followed a standardised procedure, which included the measurement of the unloaded Q-value (Q_0) versus the accelerating gradient E_{acc} at 2 K, as well as the frequencies of the fundamental modes. For each point of the $Q_0(E_{acc})$-curve, X-rays were measured inside the concrete shielding above and below the cryostat. No general administrative gradient limit was applied. The average measurement error is calculated to be 3.3 % for E_{acc} and 6.6 % for Q_0 [15]. In general the systematic error of the RF measurement is about ~10% for E_{acc} and up to ~20 % for Q_0.

In addition to the $Q_0(E_{acc})$ curves many cavities had the higher-order mode frequencies of the TE111, TM110 and TM011 modes measured [16], depending on the fabrication process.

After a successfully completed test, selected key data were transferred to the XFEL Cavity Data Base, which forms the basis of the analyses report here.

Definition of “Usable Gradient” and Acceptance Criteria

Although all cavities are tested to their maximum achievable gradient ($E_{acc,max}$), of greater importance for accelerator operation is the “Usable Gradient” ($E_{acc,us}$), which takes Q_0 as well as field-emission performance into account. It is defined [17] as the <u>lowest value</u> of:

- quench gradient (quench limited);
- gradient at which Q_0 drops *below* 10^{10} (Q_0 limited);
- gradient at which either X-ray detector *exceeds* the threshold (field-emission limited).

At the beginning of production, the criterion for acceptance for module assembly was specified as $E_{acc,us} \geq 26$ MV/m. In May 2014 it was reduced to $E_{acc,us} \geq 20$ MV/m, in order to optimise the number of vertical tests while still maintaining an average module gradient of 23.6 MV/m [17].

Cavities with $E_{acc,us} < 20$ MV/m were considered for further processing or re-treatment. The exact nature of the handling of low-performance cavities was judged on a case-by-case basis. As there was no vendor performance guarantee, retreatments were in general the responsibility of DESY. Nevertheless both vendors did agree to perform several retreatments depending on the case.

VERTICAL TEST RESULTS

‘As received’ from Vendor

Figure 3 shows histograms and yield curves for the vertical test performance for usable gradient “as received” from the vendors. The final analysis is based on 743 vertical tests (EZ: 368; RI: 375). Table 1 summarises the average of the distributions shown in Fig. 3. The average usable gradients for both vendors are above the required operational gradient for XFEL. The usable gradient is reduced from the maximum performance by 3.7 MV/m on average, predominantly due to the Q_0-value dropping below 10^{10}. The effect can be seen in Fig. 3 as an increase (top to bottom plot) in the numbers of cavities with performance less than 30 MV/m. For both vendors ~13% of the cavity tests “as received” result in a necessary retreatment due to field emission.

There is also a statistically significant difference in the average performance of the two vendors (~3 MV/m for the maximum and usable gradient), and gradients above 40 MV/m have mainly been observed with RI cavities. The better performance is attributed to the use by RI of electro-polishing as the final surface preparation scheme as described above, but also to the fact that RI cavities showed less quenches at low gradients.

The percentage (“yield”) of cavities above 26 MV/m (20 MV/m) usable gradient is 59% (83%) for EZ and 73% (89%) for RI, with a total yield of 66% (86%).

Table 1: Average (±1.std.dev) of the Maximum and Usable Gradient “As received”

	Tests	Maximum E_{acc} [MV/m]	Usable E_{acc} [MV/m]
Total	743	31.4 ± 6.8	27.7 ± 7.2
EZ	368	29.8 ± 6.6	26.3 ± 6.8
RI	375	33.0 ± 6.6	29.0 ± 7.4

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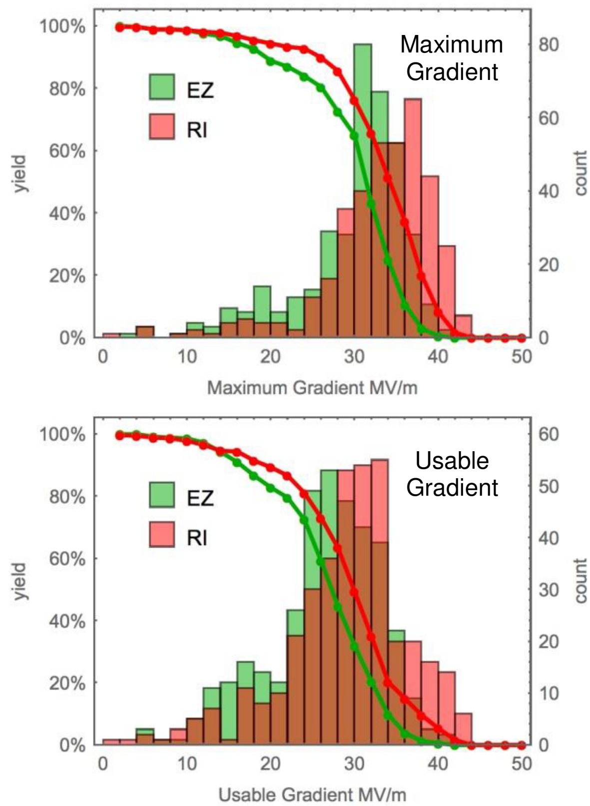

Figure 3: Comparison of performance distribution and yield for maximum gradient (top) and usable gradient (bottom) "As received" from RI (red) and EZ (green).

The trend in average usable gradient over the production until August 2015 is described in [17]. For the final months of production both Q-value and usable gradient remained constant compared to the previous production.

Impact of "Retreatment"

Three categories for retreatments have been identified:

- Non-conformities after delivery from vendor. About 90 cavities showed a mechanical, vacuum, electrical or other non-conformity, which required a retreatment at DESY or the vendor before the first vertical test. These do not have an "as received" test.
- Performance. As described above, most cavities with usable gradients below 20 MV/m underwent retreatment [18, 19] with a goal of increasing their performance. Often a high-resolution optical inspection was performed before the retreatment in order to localize the limiting defect [20]. Approximately 18% of all cavities have been retreated and retested due to insufficient performance. In general, high-pressure ultra-pure water rinsing (HPR) is applied as a first retreatment. This is particular effective since most low-performance cavities are dominated by field emission, which is likely associated with a removable surface emitter (e.g. particles). The average usable gradient increased from 19 MV/m to 26 MV/m, while the Q_0(4MV/m) increased from $2.1 \cdot 10^{10}$ to $2.4 \cdot 10^{10}$.
- Non-conformity during string assembly (e.g. during power coupler assembly), in which case the cavity was shipped back to DESY and in general a HPR applied.

Performance "Send to string assembly"

The average usable gradient of the last vertical test before transport to the string assembly facility at CEA Saclay is about 30 MV/m (Fig.4). The percentage ("yield") of cavities above 26 MV/m (20 MV/m) usable gradient is 79% (97%). As the cavities have been assigned to cryomodules by their performance, three cryomodules will have a gradient below 20 MV/m.

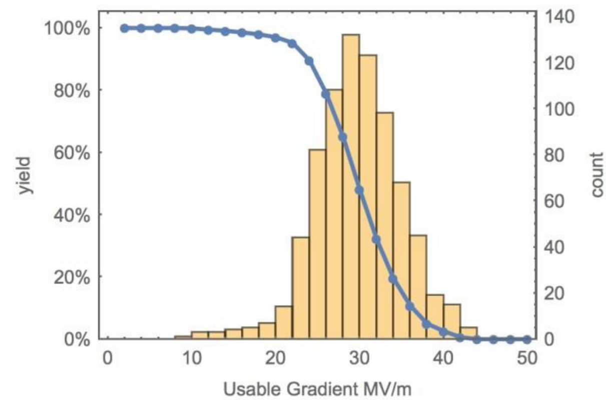

Figure 4: Performance distribution and yield for usable gradient "Send to String assembly".

CRYOMODULE TEST RESULTS

The string and module assembly at CEA Saclay is described in [21, 22]. As of April 27, 2016 93 cryomodules have been assembled, of which 87 have been RF tested [3,4,24] at the AMTF (Fig. 5). This includes the pre-series modules XM-1 and XM-2, which are equipped with EU-XFEL series cavities.

Figure 5: Cryomodule test-stand installation at AMTF.

Comparability of "Usable and Operational Gradient" in vertical vs. cryomodule test

A direct comparison between the VT usable gradient as defined above and the operational gradient in the cryomodule test (CT) is difficult: First, no individual cavity Q_0 performance data is available for the CT; second, the geometry of the x-ray monitors in the CT are significantly different; and third, the individual cavity measurements in the CT are limited to 31 MV/m by the RF power system. Only cavities observed quench limits in both tests can be strictly compared (see [21] for details).

Table 2: Averages (±1.std.dev) of VT and CT measured performance (maximum and usable/operational) of all cavities assembled into cryomodules. IMPORTANT: For comparison the VT gradients are clipped to the CT limit of 31 MV/m before averaging.

	Tests	Maximum E_{acc} [MV/m]	Operational E_{acc} [MV/m]
VT	695	30.3 ± 1.8	28.7 ± 2.9
CT	695	28.7 ± 3.9	27.6 ± 4.5

"Maximum gradient" in CT vs. VT

Figure 6 shows the maximum achieved CT gradients for all individual tested cavities in comparison to their VT test results. The horizontal dashed red line indicates the RF power limit in the CT (31 MV/m). In an ideal case all results should scatter around a line with a slope = 1. A number of cavities clearly show a reduced performance in the CT after a good to excellent behaviour in the VT (lower right section of the plot). The third column of Table 2 gives the means for the maximum gradients for the VT and CT respectively. The average systematic RF measurement error in VT and CT is discussed in [15]. More details and possible correlations of the performance to non-conformities during the module assembly process are given in [22].

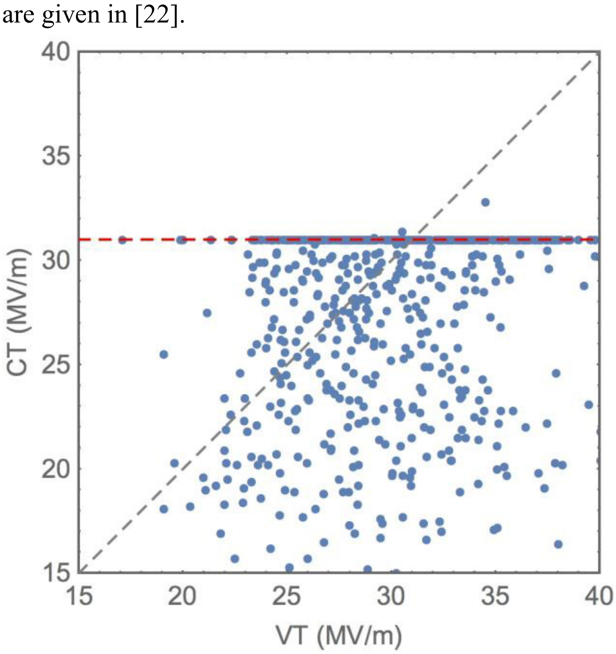

Figure 6: Individual CT – VT comparison for the maximum gradient. The horizontal red dashed line indicates the power limit in the CT (note some early tested were allowed to exceed this value).

"Usable / Operational Gradient" in CT vs. VT

In Fig. 7 the average operational gradients for all cryomodules tested so far are presented and compared to the respective average vertical test results. For a fairer comparison all vertical test gradients above 31 MV/m are clipped before averaging. Table 2 shows the mean operational gradients over all cryomodules with the CT gradient meeting the VT gradients within 4%.

Except for XM26 the order of assembly is in agreement with ascending cryomodule numbering. An average gradient loss can be observed in about the first third of assembled cryomodules, which then improved significantly for more recently assembled modules. This is due to improvements in the cleanroom procedures and additional operator training, which are described in detail in [22, 23]. XM20, XM33, XM45, XM58 and XM68 show the lowest performance. As XM33, XM58 and XM68 are equipped with cavities showing VT gradients of 22 MV/m, 23 MV/m and 21MV/m, respectively, no higher gradients can be expected in CT. The strong degradation of XM45 can be correlated with an accidental loss of electricity in the cleanroom during string assembly.

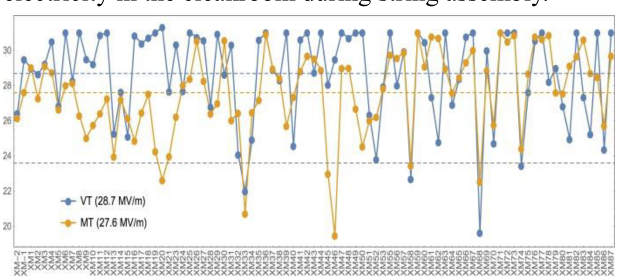

Figure 7: Average cryomodule operational gradients (orange) compared to the respective average vertical test results (blue). IMPORTANT: For comparison the VT gradients are clipped to the CT limit of 31 MV/m before averaging.

Quality Factor at Operational Gradient in CT vs. VT

The dynamic cryogenic heat load at 2K of a module is dominated by the Q_0-values (i.e. their surface resistance) of the cavities at their operational gradient. Figure 8 shows the CT effective average Q_0-values at (20-23.6) MV/m calculated from the cryo losses in comparison to the expected average Q_0-values from the vertical tests. As a main result all cryomodules except of XM34 and XM70 meet the EU-XFEL design goal of $\geq 1{\cdot}10^{10}$. The mean Q_0-values for CT and VT are equal at $1.4{\times}10^{10}$, despite the large scatter in both. Exceptions where there is a significantly higher CT Q_0-value were either caused by an enhanced measurement error at low heat loads due to a poor "signal to background" ratio, or may have been caused by a dependence of the RF losses on the cooldown procedure.

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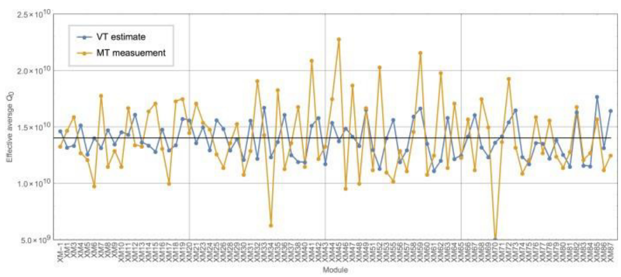

Figure 8: Average cryomodule Q_0-values measured by cryogenic heat load measurement at an operational gradient of (20-23) MV/m.

INJECTOR CRYOMODULE OPERATION

The EU-XFEL injector and its commissioning progress are described in detail in [25]. Since the end of 2015 both the 1.3 GHz cryomodule and the 3.9 GHz third-harmonic system (Fig. 9) are in operation at 2 K.

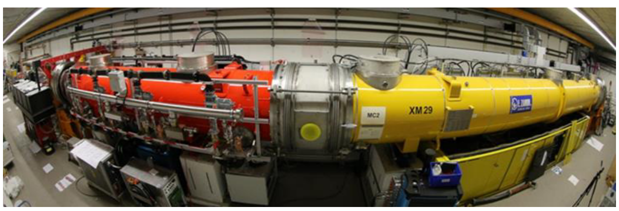

Figure 9: 3.9 GHz third-harmonic cryomodule (red) and 1.3 GHz cryomodule in the injector.

1.3 GHz Injector Cryomodule

The cryomodule XM29 in the injector is routinely operated at 2 K accelerating a beam up to a maximum energy of 160 MeV. The cavities have been operated up to an average gradient of 21.3 MV/m without any performance limitation. As no higher energy is necessary for a stable injector operation it was not attempted to reach the average usable gradient of 27 MV/m achieved in the AMTF module test.

3.9 GHz Third-Harmonic System

The third-harmonic system at 3.9 GHz of the EU-XFEL injector section is a joint INFN-DESY contribution and consists of a single module housing eight SRF cavities and a quadrupole magnet package. Ten cavities have been vertically tested and qualified for module assembly, reaching at least 18 MV/m with an average gradient of 20.8 MV/m and Q_0 above 10^9 at this field level [26,27]. In contrast to the 1.3 GHz cryomodules, only a system test of a single "cavity package" [28] consisting of a horizontal cavity equipped with power coupler, tuner and wave guide tuners was successfully performed before the module assembly [29] and its installation into the injector.

In routine operation the 3.9 GHz module runs with moderate acceleration voltages up to 30 MV. Voltages up to 45 MV have been achieved without cavity limitation. At present about 15% lower gradient is observed in the injector operation as compared to the VT; this may be an effect of the less accurate tunnel RF infrastructure, and further calibration measurements are planned.

A spare 3.9 GHz module is already under fabrication with plans for cw tests [30].

CW R&D ON EUROPEAN XFEL CRYOMODULES

The design operation of the European XFEL is a short pulse mode with a maximum RF pulse length of 1400 µs (including rise time) and a repetition rate of 10 Hz (a duty factor of 1.4%). Reducing the average gradients of the cryomodules, the technology has the potential for much larger duty factors up to 100% (limited by the tolerable heat load) which will make the facility even more attractive for users. A series cryomodule XM4 has been tested extensively in the separate cryomodule test bench (CMTB) at different operation temperatures and after two different cooldown procedures. A summary of the excellent results is given in Table 3 and more details can be found in [31]. In all conducted tests no cavity quench was observed for long-pulse and cw operation. The maximum demonstrated heat load was 71 W in cw mode at about 15 MV/m and stable operation. The cw activities at DESY will be continued and expanded in the near future.

Table 3: Demonstrated maximum gradients and Q_0-values at maximum achieved gradient for the applied operation modes on XM4.

Mode	Short pulse DF=1.4%	Long pulse DF=20%	CW DF=100%
Max E_{acc} [MV/m]	31.8	19	15
Q_o-value@ max E_{acc}	-	$2.0 \cdot 10^{10}$ (2 K)	$2.3 \cdot 10^{10}$ (2 K) $3.5 \cdot 10^{10}$ (1.8 K)

SUMMARY

The accelerator cavity production and treatment at both vendors has been successfully finished. The 1.3 GHz cryomodule assembly at CEA Saclay and subsequent testing at DESY is close to being finished and is highly successful. The installation of cryomodules into the EU-XFEL is in full swing. Cold commissioning of the injector started at the end of 2015 with the successful operation of both the 1.3 GHz cryomodule as well as the 3.9 GHz third-harmonic system. In preparation for possible future cw operation, one series 1.3 GHz cryomodule has been tested in cw and long-pulse mode with excellent results.

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