ANALYSIS OF THE RF TEST RESULTS FROM THE ON-GOING CAVITY PRODUCTION FOR THE EUROPEAN XFEL*

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Abstract

The main Linac of the European XFEL will consist of 100 superconducting accelerator modules, operated at an average design gradient of 23.6 MV/m. The fabrication by industry (which includes chemical surface preparation) of the required 800 superconducting cavities is now in full swing, with approximately 400 cavities having been delivered to date. In this interim report, we present an analysis of the RF acceptance tests amassed so far.

INTRODUCTION

The 17.5 GeV SRF linac for the European XFEL is currently under construction by a consortium consisting of several European institutes [1]. A cryomodule production rate of one eight-cavity-module per week requires an average cavity production and vertical acceptance testing rate of at least eight per week. Testing is performed in a dedicated facility at DESY (AMTF) [2,3]. As of July 31, 2014, approximately 380 of the 800 series XFEL TESLA-type 1.3 GHz SRF cavities have been produced, and have each undergone at least one vertical acceptance test at AMTF. Vertical and module testing is performed by a team from IFJ-PAN Krakow as an in-kind contribution. This report presents the current statistics of the cavity results at this half-way stage in the production, including the performance of the cavities as received from industry and the impact of retreatment cycles performed in the DESY infrastructure. Finally, the first complete module test results will be reported.

XFEL CAVITIES AND VERTICAL ACCEPTANCE TEST AT AMTF

Production Overview

Series production of the 1.3 GHz TESLA cavities is equally divided between E. Zanon Spa. (EZ), Italy, and Research Instruments GmbH (RI), Germany. Production includes both mechanical fabrication and surface preparation [4]. The 800 series cavities required for XFEL (400 per vendor) are delivered complete with a helium tank, ready for vertical testing in AMTF at DESY. Each vendor also produces an additional 12 cavities without helium tank for the ILC-HiGrade programme [5], which are used as a quality control tool as well as for further R&D. Both vendors must exactly follow well-defined specifications for the mechanical fabrication and surface treatments, but no RF performance guarantee is required. The surface preparation at both vendors starts with a bulk EP followed by 800° annealing, but for the final surface treatment two alternative recipes are in use: EZ applies a final chemical surface removal ("Flash-BCP"); RI applies a final electrochemical surface removal (EP). All cavities are fully equipped with their HOM antennas, pick-up probe and a High-Q input coupler antenna with fixed coupling. The procedures before and after the vertical acceptance test are described in [6].

Vertical Testing Rates

In order to achieve the desired testing rate of at least eight cavities per week, the vertical acceptance tests are 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, greatly increasing the efficiency of cool-down / warm-up cycles. The test infrastructure has been in full operation since October 2013 and has achieved an average greater than 9 vertical tests per week (see Fig. 1). Assuming realistic rates for necessary retesting of cavities (e.g. after retreatment, see below), all vertical acceptance tests of the 824 cavities will be finished within the current project schedule (end of 2015).

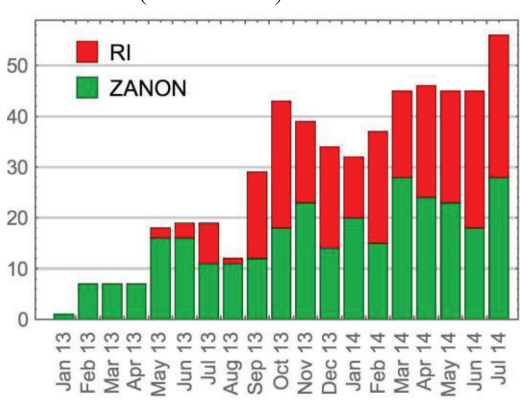

Figure 1: Trend of the vertical test rate

The vertical acceptance tests follow a standardised procedure, which includes 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 are measured inside the concrete shielding above and below the cryostat. No general administrative gradient limit is

*The research leading to these results has received funding from the European Union Seventh Framework Programme (FP7/2007-2013) under grant agreement no 283745 (CRISP)
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ISBN 978-3-95450-142-7

applied. The average measurement error is calculated to be ~4 % for E_{acc} and ~7 % for Q_0. A few cases with test-to-test comparisons showing larger deviations than the estimated errors are under investigation.

After a successfully completed test, selected key data are transferred to the XFEL Cavity Data Base [7], 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 as the lowest value 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).

For the field-emission limit, the acceptable X-ray thresholds are set to 0.01 mGy/min and 0.12 mGy/min for the top and bottom detector respectively. The threshold 0.01 mGy/min is based on experience of the FLASH cavity testing. The higher limit for the lower detector is a geometrical effect.

At the beginning of production, the criterion for acceptance for module assembly was specified as $E_{acc,us} \geq 26$ MV/m, chosen to give a margin of ~10% compared to the required average design operation gradient (23.6 MV/m at $Q_0 \geq 10^{10}$). Based on an analysis of about 270 cavities tested up to May 2014, including the necessary retreatments and retests, the acceptance criteria 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.

Cavities with $E_{acc,us} < 20$ MV/m are considered for further processing or re-treatment. The exact nature of the handling of low-performance cavities is judged on a case by case basis. As there are no vendor performance guarantees, retreatments are in general the responsibility of DESY.

VERTICAL TEST RESULTS

'As received' from Vendor (1st Acceptance Test)

Figure 2 shows histograms and yield curves for the vertical test performance for both maximum and usable gradient, as received from the vendors. The analysis is based on 339 vertical acceptance tests (EZ: 185; RI: 154). Table 1 summarises the average of the distributions shown in Fig. 2. 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 ~4 MV/m on average, predominantly due to field emission. The effect can be seen in Fig. 2 as a increase (top to bottom plot) in the numbers of cavities with performance less than ~28 MV/m. For both vendors ~20% of the cavities require a retreatment due to field emission.

There is also a statistically significant difference in the average performance of the two vendors (~6 MV/m and ~4 MV/m for the maximum and usable gradients respectively), and gradients above 40 MV/m have only been observed with RI cavities. The better performance is attributed to the use by RI of electropolishing as the final surface preparation scheme as described above, but also to the fact that RI cavities show less quenches at low gradients.

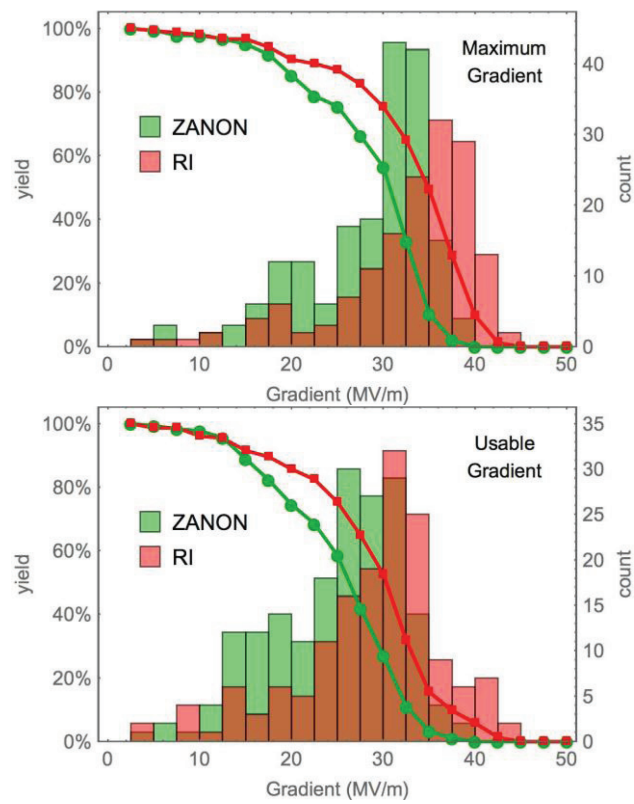

Figure 2: Comparison of performance distribution and yield for maximum gradient (top) and usable gradient (bottom) "As received" from RI (red) and EZ (green).

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	339	30.4 ± 7.6	26.6 ± 7.6
EZ	185	28.4 ± 7.1	24.8 ± 7.0
RI	154	32.4 ± 7.6	28.6 ± 7.9

The percentage ("yield") of cavities above 26 MV/m (20 MV/m) usable gradient is 51% (75%) for EZ and 71% (80%) for RI, with a total yield of 60% (80%). As described above, cavities with usable gradients below 20 MV/m undergo re-treatment with a goal of increasing their performance (see below); based on the current statistics this will result in retreating and retesting approximately 20% of the remaining cavity production.

Impact of "Retreatment"

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).

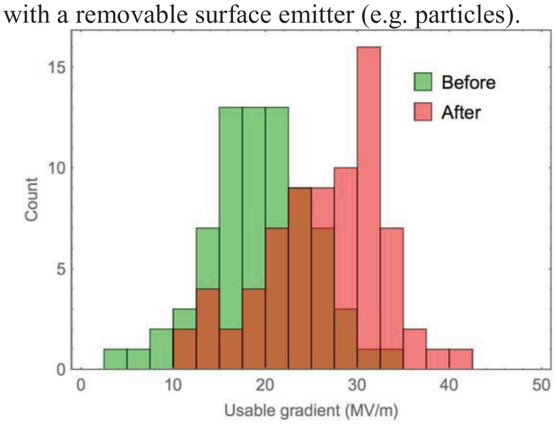

Figure 3: Comparison of usable gradient performance for cavities undergoing retreatment at DESY (74 retreatments).

Figure 3 shows the distributions of 74 test results before and after retreatment (this include cavities whose initial performance was above 20 MV/m, but which still underwent a retreatment). The average usable gradient before and after retreatment for cavities with initial (before) performance < 20 MV/m (40 test results) is 15.3 MV/m and 26.4 MV/m respectively, an average gain of ~11 MV/m, with 80% of those cavities achieving ≥ 20 MV/m. The remaining ~20% in general undergo a second retreatment with HPR or possibly BCP.

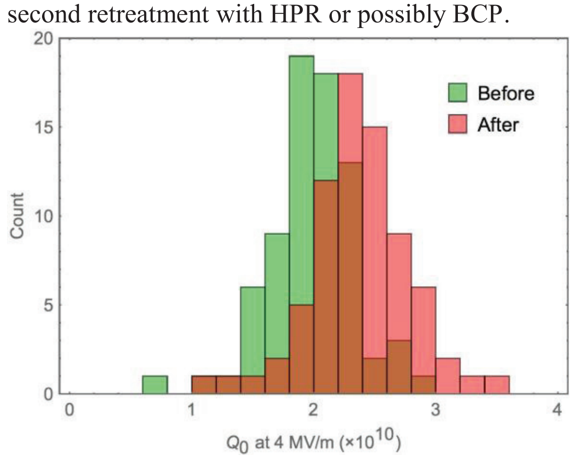

Figure 4: Comparison of low-field (4 MV/m) Q_0 for cavities undergoing retreatment at DESY (74 retreatments).

Figure 4 shows the impact of retreatment on the low-field (4 MV/m) Q_0 performance. This is of particular interest since there is no field emission at these low fields. The results indicate an average improvement of 20% due to retreatment (predominantly HPR), increasing the average Q_0 from 2.0×10^{10} to 2.4×10^{10}.

FIRST MODULE TEST RESULTS

The string and module assembly at CEA Saclay is described in [8]. The first 7 modules have been tested with encouraging results above the XFEL design value. Table 2 summarises the average gradient performance for the first 7 modules (2 pre-series and 5 series).

Table 2: Module gradient performance (average over the 8 installed cavities) with the equivalent vertical test results for comparison (Units are MV/m).

	Module Test		Vertical Test	
	max	operational	max	usable
XM-2	27.2	24.5	28.1	26.5
XM-1	28.2	25.1	30.8	29.4
XM1	30.3	27.6	32.5	29.0
XM2	27.7	25.5	32.7	28.6
XM3	30.4	28.8	32.0	29.3
XM4	28.6	23.8	33.3	30.5
XM5	27.8	24.9	28.9	26.9

The first data column in table 2 shows the average values for the maximum gradient of the 8 cavities in each module; this can be compared with the equivalent maximum gradient from the vertical test (third data column). The second data column gives the average operational gradient of the cavities in the module, which is lower than the maximum, since it includes operational margins, and reflects limits set on field emission (detected as X-rays) as well as the effect of the XFEL "paired" rf power distribution. In a few cases significant degradation of cavity performance due to string assembly as compared to the vertical tests is seen [3]. The forth data column gives the usable gradient of the corresponding vertical test for comparison. The results for these first seven modules show an overall reduction in operational gradient of ~10% on average, as compared to the value predicted based on the vertical test usable gradient. Further more detailed analyses will be the subject of future reports.

ISBN 978-3-95450-142-7

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