UPDATE AND STATUS OF VERTICAL TEST RESULTS OF THE EUROPEAN XFEL SERIES CAVITIES

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Abstract

The series production by two industrial vendors of the 808 1.3-GHz superconducting cavities for the European XFEL has been on-going since the beginning of 2013 and will conclude towards the end of this year. As of publication some 740 cavities (~93%) have been produced at an average rate of ~7 cavities per week. As part of the acceptance testing, all cavities have undergone at least one vertical RF test at 2K at the AMTF facility at DESY. The acceptance criterion for module assembly is based on the concept of a "usable gradient", which is defined as the maximum field taking into account Q_0 performance and allowed thresholds for field emission, as well as breakdown limits. Approximately 18% of the cavities have undergone further surface treatment in the DESY infrastructure to improve their usable gradient performance. In this paper we present the performance statistics of the vertical test results, as well as an analysis of the limiting criteria for the usable gradient, and finally the impact of the surface retreatment on both usable gradient and Q_0.

INTRODUCTION

The 17.5 GeV superconducting linac for the European XFEL is currently under construction at DESY by a European consortium [1]. The linac consists of 101 cryomodules each containing eight 1.3-GHz TESLA-shape niobium cavities, with a design average operational gradient of 23.6 GeV with $Q_0 \geq 10^{10}$. The 808 cavities are being entirely manufactured by industry. Performance testing (vertical test at 2K) is performed at DESY [2]. After vertical testing, accepted cavities are sent to the string and cryomodule assembly facility at CEA Saclay [3], while low-performing cavities are retreated using the DESY infrastructure.

As of publication, the production and testing of the cavities has been in full swing for over 20 months and is now almost complete. This report presents an update of [4] which presented the vertical test results of the first half of the production. In addition to the overall statistics for the "as received" performance, further analysis of the limiting criteria for the usable gradient are reported. Finally the impact of surface retreatment (at DESY) for the low performance cavities (approximately 18% of the total) on both usable gradient and low-field Q_0 will be given.

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CAVITY PRODUCTION AND TESTING OVERVIEW

Industrial Cavity Production

The series production of 808 TESLA-type cavities is equally divided between two vendors: E. Zanon Spa. (EZ) in Italy, and Research Instruments GmbH (RI) in Germany. The cavities are delivered to DESY complete with helium tank, pick-up probe, High-Q input coupler (fixed coupling), and are ready for vertical testing. The achieved average production rate is 6.6 cavities per week (slightly lower than the original target of 8 per week). DESY provides the niobium material (semi-finished products). The vendors perform the mechanically fabrication and subsequent surface treatment, both of which must confirm to strict specifications provided by DESY (so-called "build to print"). No final performance guarantee is required, for which DESY accepts the risk: hence DESY is responsible for any remedial action required should the cavity fail to meet gradient and/or Q_0 performance goals.

The cavities produced by EZ and RI differ in the final chemical treatment (final polishing), with EZ applying a final chemical surface removal ("Flash-BCP"), while RI have opted to use a light electro-polishing (EP), both treatments being within the specification. Flash-BCP has the advantage that it can be applied with the cavity already mounted in the helium tank, while for EP, the tank must be mounted post treatment.

Vertical Acceptance Testing

Once delivered to DESY, the cavity undergoes acceptance testing at the purpose built Accelerator Module Test Facility (AMTF), which includes a full performance RF test suite at 2K [5]. To achieve the relatively high testing rates (~10–15 tests per week including retests) two vertical cryostats are employed, each capable of simultaneously cooling down four cavities. The test infrastructure has been in full operation since October 2013 (see Fig. 1). The vertical acceptance tests follow a standardised and automated 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. Cavities are always tested to their limiting gradient, generally

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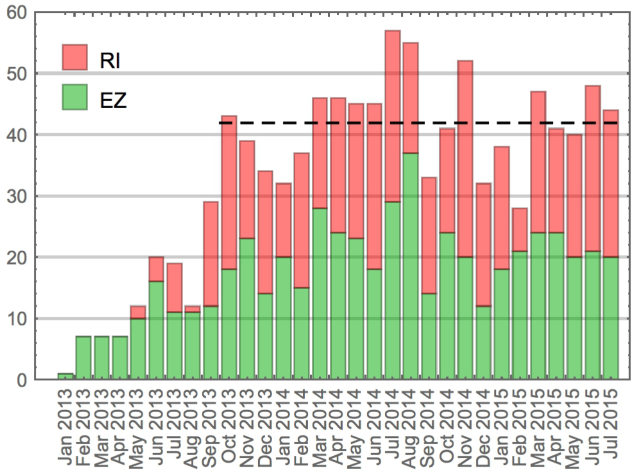

Figure 1: Vertical testing rates per month in AMTF. The dashed line indicates the average per month since October 2013 (approximately 42 tests per month, or ~10 per week).

given by breakdown (quench) or in some cases X-ray limits (FE) or limitations in the available forward power. Once the vertical test is successfully completed, all important data are transferred to the XFEL database [6], which is the source of the analyses reported in later sections of this report.

Retreatment

If the performance of the cavity is considered unacceptable, then the cavity is (in general) retreated in the DESY infrastructure, and in some cases returned to the vendor. As a rule, the first retreatment is an application of high-pressure rinse (HPR), which has proven extremely effective in improving poor performing cavities ($G < 20$ MV/m). Should the performance still be unacceptable after the second test, the cavity undergoes an additional BCP, 120º C bake and HPR.

BASIC ACCOUNTING

Table 1: Basic Numbers for Cavity Production and Testing

Number of cavities with at least one VT	738
EZ	398
RI	340
Total number of VT	1037
Average VT per cavity	1.4

Table 1 gives the cavity and VT numbers (with VT dates up to and including 31st July 2015). Figure 2 shows the status breakdown of the 738 cavities. Here "accepted" means accepted for string assembly. Fractions are relative to the total number of cavities, rounded to the nearest per cent. A total of ~18% of the cavities have undergone one or more retreatment at DESY (of which 15% have since been accepted –see Fig. 2). 10% of the cavities have undergone an additional retreatment at a vendor.

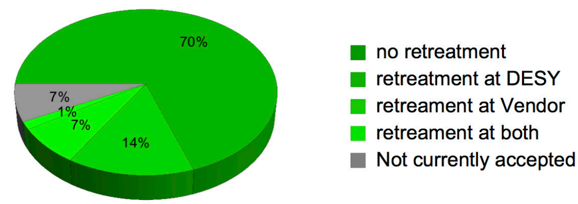

Figure 2: Breakdown of cavity status. Green shades are formally accepted (~93%), while the remaining ~7% (grey) are still being handled.

Most (~90%) of the 1037 vertical tests are associated with either the first acceptance test ("as received") or a test after retreatment. The remaining 10% of the VT are for retests due to RF problems, early infrastructure commissioning, and for cavities returned from Saclay[1]. (See [7] for more details.)

AS RECEIVED PERFORMANCE

Definition of Maximum and Usable Gradient

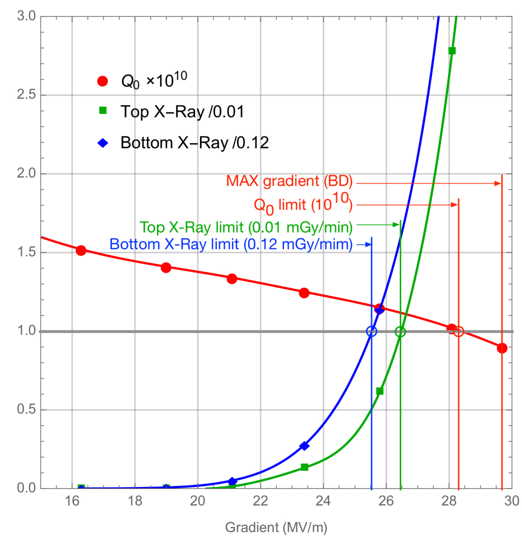

Figure 3: Definition of *Usable Gradient*. The limiting field for each threshold is indicated. See text for details.

All cavities are vertically tested to their *maximum* achievable gradient, defined as either the quench limit (breakdown, BD), excessive field emission (FE, as measured by the X-ray monitors), limits on the forward power, or problems with the HOM coupler. In general, testing the cavities to the maximum gradient has not degraded or damaged them, although a few cavities have exhibited a reduced performance after the first power rise.

The definition of *Usable Gradient* also includes additional operationally important criteria, namely X-ray (FE) and Q_0 performance. Figure 3 explains the definition. The usable gradient is defined as the gradient which has (i) $Q_0 \geq 10^{10}$ and (ii) X-ray signals $\leq$0.01 mGy/min and $\leq$0.12 mGy/min for the Top and Bottom X-ray monitor respectively, or ultimately the

[1] Cavities returned from Saclay are not included in the reported analyses.

maximum gradient. In Fig. 2, the cavity shows FE and is limited to a usable gradient of 25.5 MV/m by the Bottom X-ray signal (as compared to maximum BD value which is close to 30 MV/m). In the following discussions, we will no longer explicitly refer to Top or Bottom signals, but rather treat these limiting criteria as a single FE limit.

VT Performance Statistics

We first consider the performance of the cavities "as received" from industry (the first test of a cavity which has been manufactured according to the specifications, without any additional retreatments).

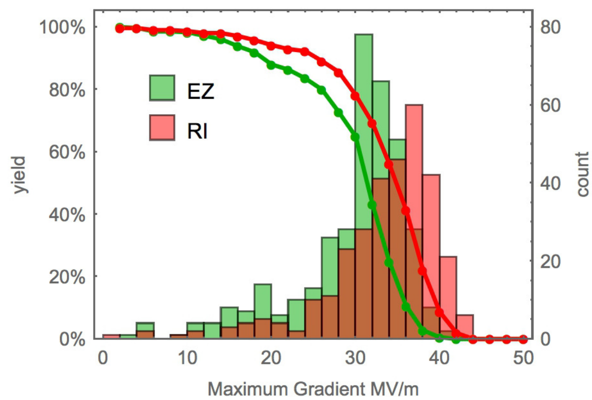

Figure 4: Histograms and yield lots of the *Maximum Gradient* in the "as received" test for EZ (green) and RI (red).

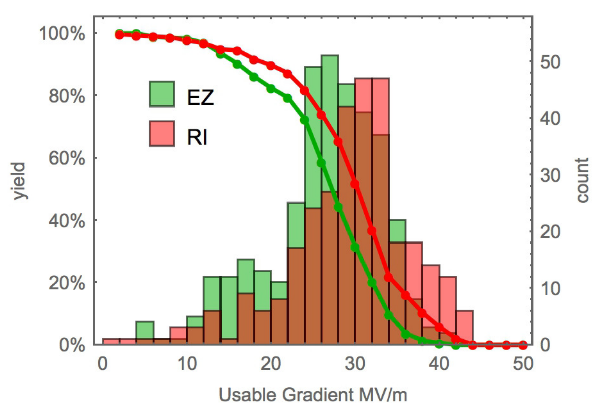

Figure 5: Histograms and yield plots of the *Usable Gradient* in the "as received" test for EZ (green) and RI (red) cavities.

Figures 4 and 5 summarise the results of the vertical "as received" tests for the maximum and usable gradients respectively. The plots show the distributions of measured gradients, as well as the yield (defined as the fraction of the total number of cavities equal to or exceeding the specified gradient) for both EZ and RI. Table 2 gives the summary statistics.

Table 2: Summary statistics for "as received" vertical tests. (Column C gives the combined results).

		Max. Gradient			Usable Gradient		
		RI	EZ	C	RI	EZ	C
$\langle G \rangle$ (MV/m)		33.4	29.6	31.4	29.4	26.3	27.7
G_{RMS} (MV/m)		6.6	6.8	7.0	7.4	6.8	7.2
Yield	20 MV/m	94%	88%	91%	90%	82%	86%
Yield	26 MV/m	90%	80%	84%	75%	59%	66%
Yield	28 MV/m	86%	73%	79%	66%	44%	54%

Figures 4 and 5 show significant numbers of high-performing cavities, with many cavities above 30 MV/m (and tens of cavities exceeding 40 MV/m). However, this is more than compensated in the average performance by a low-performing tail. Nonetheless, Table 2 shows that the average performance comfortably exceeds the operational requirement for the XFEL (23.6 MV/m). The loss of usable gradient due to FE or poor Q_0 performance is approximately 4 MV/m on average (a reduction of ~12% of the average maximum gradient).

Comparing the performance of the two vendors, we can see that the RI cavities are on averaging performing slightly better than EZ cavities, by ~4 MV/m and ~3 MV/m for the maximum and usable gradient respectively. This is attributed in part to the use of light EP for the final surface polishing at RI (which effectively removes the low-gradient quenches seen in some of the EZ cavities) [8]. The RMS spread for both vendors is about the same.

The yield curves are important as they give an indication of the number of cavities that would require retreatment, given the choice of cut-off for the acceptable gradient performance. Originally the acceptance criteria was set at ≥ 26 MV/m. During the early production, the usable gradient yield at this value was ~60%, requiring nearly 40% of the cavities to be retreated and then retested at DESY. However, because of the relatively high average performance (due to the high performing cavities), a decision was made to drop the threshold to ≥20 MV/m, which at that time had a yield of ~80%, thus halving the projected number of retreatments and (more importantly) vertical tests. Table 2 shows that the cavity performance has improved significantly since [4], with the yield at 20 MV/m now at 86% for the entire production. Figure 6 shows the production history of the usable gradient (binned by month). The improved performance can be seen in the last year. Figure 7 shows the associated yield history, where each set of stacked bars covers a three-month production, split into three gradient bins. The fraction of cavities with $G < 20$ MV/m has been around 10% (equivalent to a yield of 90%) for the last year, as opposed to 20% the previous year, indicating that the current retreatment and retest rates are now down to about 10% of the as received tested cavities.

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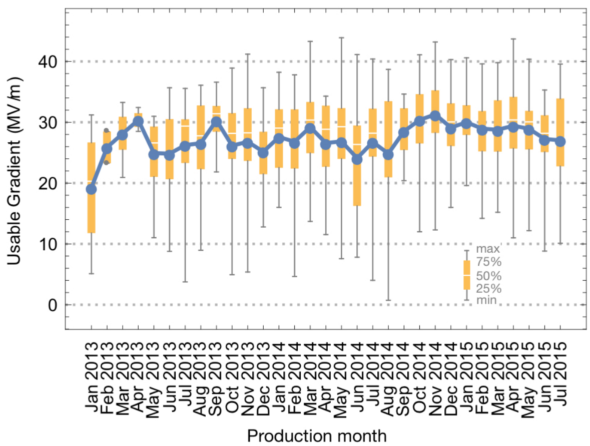

Figure 6: As received usable gradient production history. The box-whisker indicates the distribution of performance for cavities delivered to DESY that calendar month, while the blue data points are the monthly averages.

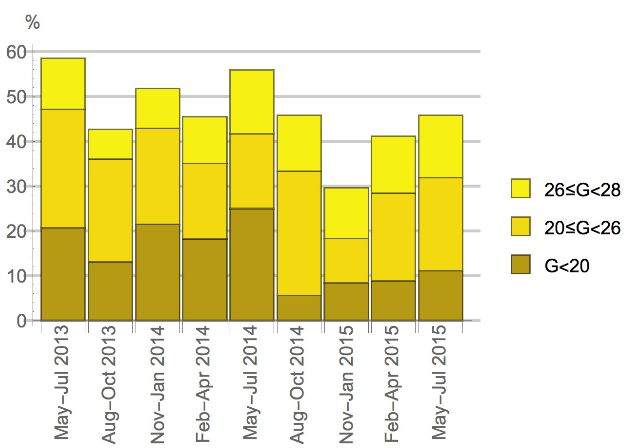

Figure 7: As received usable gradient distributions for three bins (quarterly production). The reduction in low-performing cavities (G < 20 MV/m, darker colour) has dramatically reduced during the last year of production.

ANALYSIS OF USABLE GRADIENT LIMITING CRITERIA

As previous mentioned, the usable gradient is determined taking into account FE (X-Ray measurements) and Q_0 performance (in addition to the physical breakdown limit of the cavity). Figure 8 Shows the breakdown of the limiting criteria for the as received cavities.

We have separated the Q_0 limited tests into those with and without FE; this is important since there is a strong correlation between the FE limited gradient and the Q_0 limited gradient, when FE is present. The very high fraction of cavities limited by Q_0 in the case of no FE (52%) is due to the large number of cavities with very high maximum gradient performance (>30 MV/m), where the Q_0 tends to drop below the threshold of 10^{10}. FE limited gradients are in generally lower.

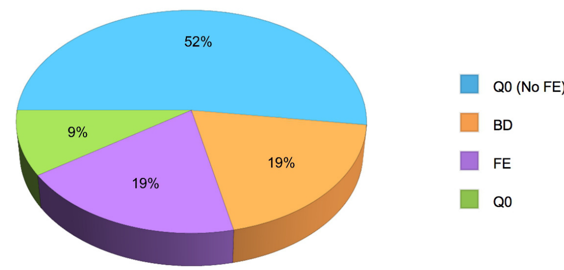

Figure 8: Breakdown of usable gradient limiting criteria for as received tests.

Figure 9 shows the distributions of as-received usable gradients with and without FE (defined by the usable gradient acceptance limit). While the spread (RMS) of the distributions is approximately the same (~7 MV/m), the mean of the FE distribution is clearly shifted down as compared to distribution with no FE (24.4 MV/m compared to 29.7 MV/m respectively). Figure 9 also indicates that the cavities with G < 20 MV/m requiring retreatment are mostly FE limited, although there is still a fraction limited by poor Q_0 performance or early breakdown. Above ~24 MV/m Q_0 and BD begin to dominate.

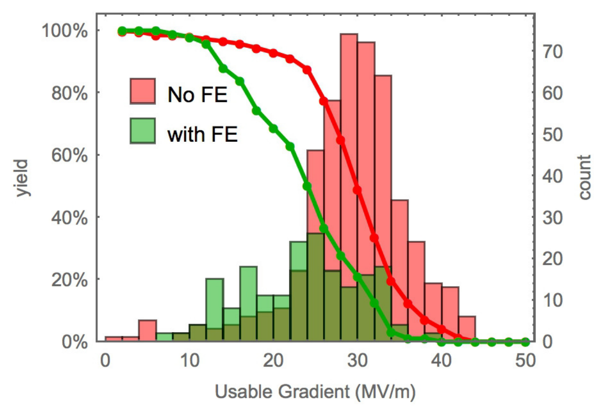

Figure 9: Usable gradient distribution for (red) no FE and (green) with FE. The two distributions are clearly distinguishable.

IMPACT OF RETREATMENT AT DESY

Of the cavities tested, approximately 18% have undergone one or more retreatment at DESY[2] [9], the average number being ~1.2 retreatments per cavity. Figure 10 shows the breakdown by limiting criteria of the first retreatment. The predominant reason is FE, consistent with Figure 9 taking into account the G < 20 MV/m retreatment threshold. Figures 11 and 12 show the "before" and "after" impact of retreatment at DESY on the usable gradient for the same cavities. Figure 11 shows all retreatment types (HPR, BCP) while Fig. 12 shows only HPR for initial gradients that are below

[2] 10% of cavities have also undergone an additional retreatment a the vendor.

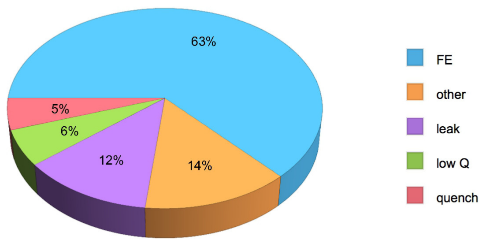

Figure 10: Breakdown by cavity number of the reason for the first retreatment. FE, low Q and quench are all performance related. Leak and other are in general due to problems during testing, which have then required an additional high pressure rinse before retesting.

20 MV/m (the current retreatment threshold). Multiple retreatments of the same cavity are included. The impact on HPR on low-performing cavities ($G < 20$ MV/m) is quite dramatic, with the average usable gradient increasing form 14.3 MV/m to 25.8 MV/m.

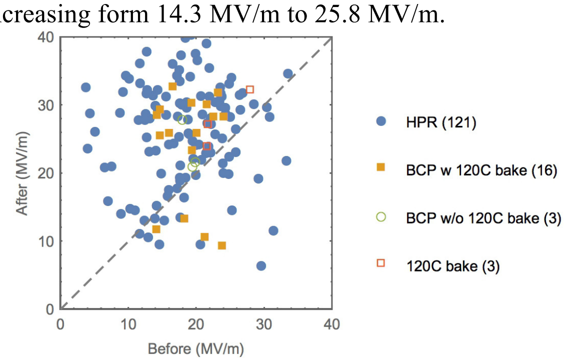

Figure 11: Usable gradient before and after retreatment at DESY, divided by the type of retreatment (number of comparable retreatments given in parenthesis).

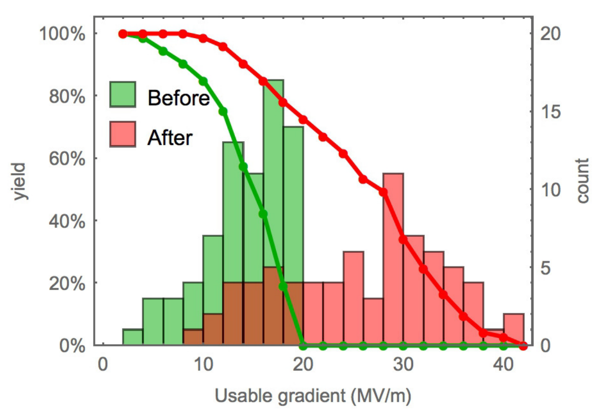

Figure 12: Distribution (and yields) for the usable gradient before (green) and after (red) HPR treatment at DESY, for cavities with initial (before) gradients less than 20 MV/m.

The post-treatment yield at 20 MV/m is 73%, a figure which shows a *decrease* from the 80% retreatment yield quoted in [4] for the first half of the cavity production, although the total number of retreatments for the second half of the production is less. The 16% of retreated cavities with $G < 20$ MV/m (~2% of the total cavity production) require further retreatment (in general BCP).

Given the observed beneficial impact of a relatively simple HPR at DESY, an attempt to analyse cavities which had undergone additional HPR at the vendors (as well as at DESY) was undertaken to see if the same overall statistical improvement was visible. The results were inconclusive, but there appeared to be no apparent "improved performance" due to additional HPRs at the vendor.

Finally, Fig. 13 shows the impact of HPR on the Q_0 performance at low gradients where there is in general no FE (4 MV/m). The average Q_0 increases from 2.1×10^{10} to 2.4×10^{10}, a gain of 14%, again somewhat less than the ~20% reported in [4] for the first-half production.

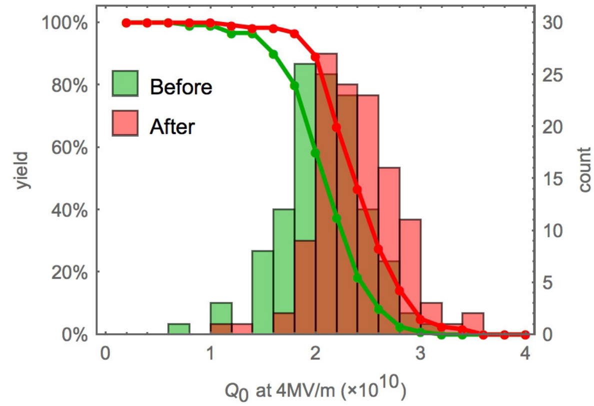

Figure 13: Influence of HPR on the low-gradient Q_0.

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