PERFORMANCE ANALYSIS OF THE EUROPEAN XFEL SRF CAVITIES, FROM VERTICAL TEST TO OPERATION IN MODULES

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Abstract

More than 800 resonators have been fabricated, vertically qualified and operated in module tests before the accelerating module installation in the linac, which will be completed before the conference. An analysis of this experience, with correlation of the final cavity performances with production, preparation and assembly stages, is underway and at the time of the conference a summary of the activities will be available.

INTRODUCTION

The construction of the 17.5-GeV SRF linac for the European XFEL (EXFEL) [1] is now complete. A total of 102 cryomodules (100 series modules and 2 pre-series) have been successfully constructed in a period of three years from 816 1.3-GHz nine-cell Tesla cavities entirely produced by industry and tested at DESY. The completed cryomodules were returned to DESY for testing before installation in the tunnel. Finally 97 of the total 102 cryomodules have been installed; the last four cryomodules were not installed due to schedule constraints.

All individual cavities (cold vertical test) and completed cryomodules (module test) were tested at the purpose-built Accelerator Module Test Facility (AMTF) at DESY [2,3,4]. All testing was performed by a team from IFJ-PAN Krakow, as part of an in-kind contribution to EXFEL. A peak cryomodule production rate of 1.25 cryomodules per week was achieved from the beginning of 2015, successfully matched by AMTF testing rates.

In this paper we present the final production statistics of the cavity cold vertical tests and cryomodule tests. For the cavity production, we present both an analysis of the factors limiting the gradient performance, as well as steps taken to acceptably recover low-performance cavities. The high-power pulsed RF results from the cryomodule tests will then be presented, and a rough comparison of the observed performance in both the vertical and module tests made. Finally the expected installed linac performance will be discussed.

CAVITY PRODUCTION

Industrial Cavity Production

A comprehensive review of the cavity production for the EXFEL can be found in [5]. Here we briefly summarise the key points by way of introduction to the latter sections of this report.

The total cavity production for EXFEL was split equally between two vendors (E. Zanon Spa. (EZ), Italy, and Research Instruments GmbH (RI), Germany), and included both the mechanical fabrication and the surface-polishing chemical treatments. Cavity production followed the so-called “build to print” concept [6], with no cold RF performance requirement of the vendors. DESY accepted the responsibility for recovering low performance cavities. The niobium material was purchased by DESY and after quality control sent to the vendors [7,8].

The cavities were delivered to DESY fully equipped with helium tank, flanges, HOM antennae, pick-up probe, and a fixed-coupling high-Q input coupler antenna, ready for cold vertical testing (see Fig. 1).

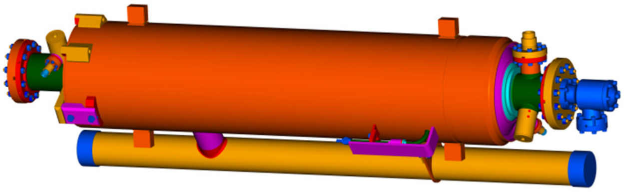

Figure 1: 3-D model of a fully-equipped XFEL cavity as delivered to DESY:

Cavity production differed at the two vendors in the choice of the final chemical surface polishing. 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 (“Final EP”).

Cavity production began in in early 2013 and ramped up to an average total production rate of approximately 30 cavities per month at the end of that year. Production then continued through to the end of 2016. Of the total of 844 cavities successfully produced, 816 were used for the construction of cryomodules. The remainder were special cavities used for infrastructure commissioning and testing, as well as the so-called HiGrade cavities [9], delivered without helium tank and used throughout production for QA and also R&D.

COLD VERTICAL TEST PERFORMANCE

Overview of Cold Vertical Testing

As previously noted, the cavities were delivered to DESY from the vendor ready for cold vertical testing at AMTF. The extensive QA/QC checks performed before and after the vertical test are described here [10]. All of the 816 sent for cryomodule assembly and the 16 remaining HiGrade cavities underwent at least one cold vertical

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test. To assure the required testing rates of (at least) eight cavities per week, two independent cryostats were used, each capable of taking an insert containing up to four cavities (Fig. 2). Details of the test procedure can be found in [10, 11, 12]. During production a peak testing rate of 15 cavities in one week was achieved.

Figure 2: Inserts for the AMTF vertical tests. (Left) 3D schematic of an insert. (Right) inserts in the preparation area.

The vertical test was heavily automated and followed a standard procedure, which included multiple measurements of the unloaded Q-value (Q_0) as a function of accelerating field (E). Typical RMS measurement errors were 3.3% and 6.6% for E and Q_0 respectively [13]. The total uncertainty including systematic effects was assumed to be closer to ~10% and up to ~20% respectively. Field emission was monitored by two X-ray detectors placed inside the concrete shielding, above and below the cryostats. No "administrative limit" was applied during the tests and cavities were measured up their maximum gradient performance (in general limited by quench, the maximum 200W forward power available, HOM coupler heating, or excessive X-rays). Once successfully completed, the data were analysed and the key RF parameters transferred to the XFEL Database [14], on which the results presented here are based.

The cold vertical test was primarily used as an RF acceptance test and to facilitate sorting of like-performance cavities for subsequent cryomodule assembly. The key measured RF parameter was the so-called *usable gradient* which reflected the accelerator requirements on Q_0 ($\geq 10^{10}$) and permissible field emission (as determined by threshold limits on the X-ray monitors), as well as the maximum achieved gradient described above.

"As Received" Cold Vertical Test Performance

Figure 3 shows the distribution and yield of the "as received" maximum and usable gradients, in general corresponding to the first test after acceptance of the cavity from the vendors.

The overall performance of the cavities was excellent: the maximum gradient of over half the cavities exceeded ~30 MV/m, with a significant number achieving over 40 MV/m –a strong indication of the successful industrialisation of the complete cavity production process. The inclusion of the Q_0 and field-emission requirements (usable gradient) reduces the mean by approximately 4 MV/m (~13%).

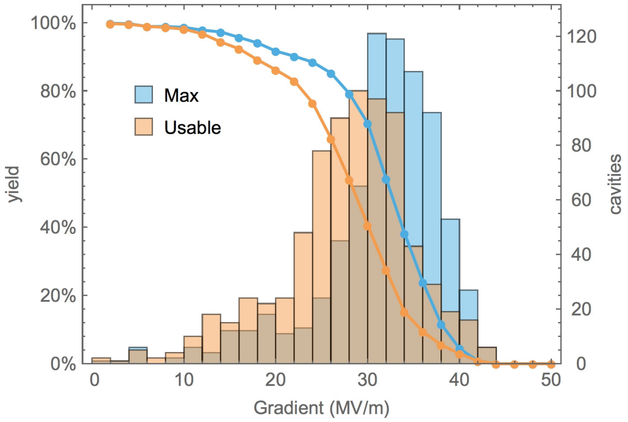

Figure 3: "As received" maximum and usable gradient distributions and yield. The darker colour represents the overlap of the two histograms.

Table 1: Key statistics for the "as received" gradient distributions shown in Figure 3.

		Max	Usable
Average	MV/m	31.4	27.7
RMS	MV/m	6.8	7.2
Median (50%)	MV/m	32.5	28.7
Yield ≥20 MV/m		92%	86%
Yield ≥26 MV/m		85%	66%

Figure 4 shows the fractions of "as received" cavities limited in the usable gradient by quench (BD), Q_0 (Q0) and field emission (FE). Figure 5 shows the stacked distributions in usable gradient for the same categories. FE tends to dominate below ~24 MV/m, above which low Q_0 performance is the main limiting factor, which was generally attributed to the so-called high-gradient Q-slope [15].

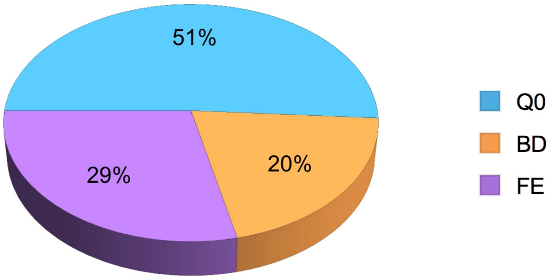

Figure 4: Breakdown of limiting factor (quench "BD", Q_0 "Q0" or field emission "FE") for the "as received" usable gradient.

Figure 6 shows the distribution for the "as received" Q_0 performance, measured at 4 MV/m and the EXFEL nominal design gradient of 23.6 MV/m. The clear shift in centroid is an indication of the typical negative Q-slope with gradient. However, even the Q_0 values at 23.6 MV/m mostly exceed the 10^{10} requirement; the small tail below

10^{10} will have limited the usable gradient to below 23.6 MV/m in these cases.

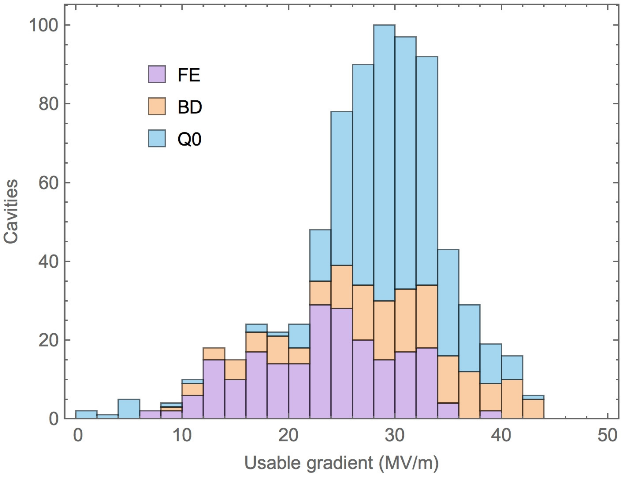

Figure 5: Stacked histograms of the usable gradient limited by quench (BD), Q_0 (Q0) or field emission (FE).

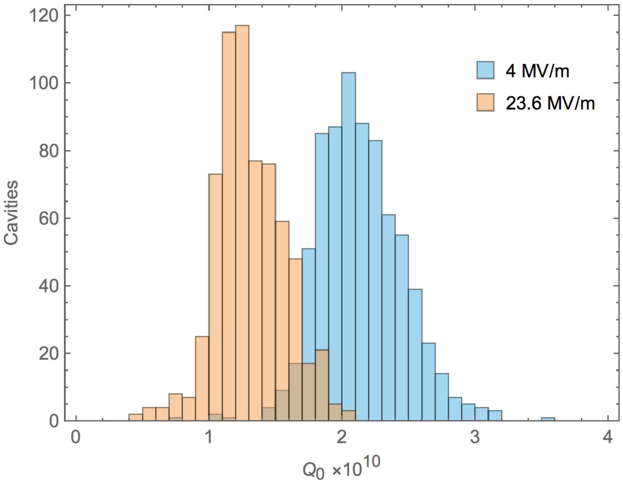

Figure 6: Q_0 distributions for the "as received" cold vertical tests, measured at 4 MV/m and 23.6 MV/m.

Acceptance Criteria and Impact of Retreatment

At the beginning of series testing, the threshold for acceptance for cryomodule assembly was set at 26 MV/m (approximately the EXFEL nominal accelerator gradient plus 10%). After some production experience, it was possible to relax this to 20 MV/m while still maintaining an acceptable average performance, thus reducing the overhead of retesting the cavities after treatment.

Approximately 15% of the total cavity production was rejected due to below-acceptance usable gradient performance, and subsequently sent for surface retreatment at the DESY infrastructure or in a few cases at the vendors. A similar fraction of the cavities underwent a retreatment for other, non-performance-related reasons; these were mostly due to vacuum related non-conformities before or during the tests. The choice of retreatment was considered on a case-by-case basis, but in general a relatively simple application of the standard High Pressure Rinse (HPR) was first applied. This proved to be particular effective in recovering the performance of cavities limited by FE. A fewer cases were chemically polished using BCP (followed by a 120°C bake), mostly (but not exclusively) as a second retreatment when the initial HPR proved insufficient. Figure 7 gives the breakdown of the reasons for the first retreatment at DESY; 68% of the retreatments were performance driven, with over half being due to FE.

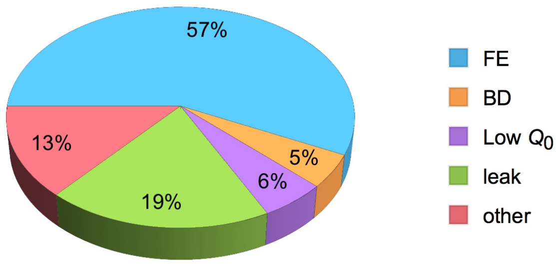

Figure 7: Breakdown of the reasons for the first retreatment at DESY. The first three categories (FE, BD and Low Q$_0$) are performance driven.

Figure 8 shows the usable gradient performance before and after HPR (for cavities initialling achieving ≤20 MV/m). Over 70% of these cavities could be successfully recovered, with over half achieving ≥26 MV/m. The remaining ~30% were in general sent for a further retreatment.

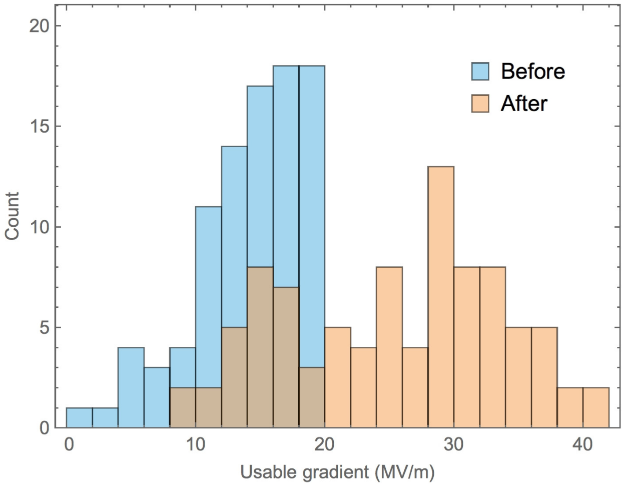

Figure 8: Improvement in the usable gradient distribution after the application of HPR.

Final Performance

Figure 9 gives the distribution of the usable gradient for the final "accepted" performance of the cavities used for cryomodule assembly, compared to the "as received" performance. The reduction of the low-performance tail as a result of retreatment is clearly visible. The few low-gradient cavities below the acceptance threshold (< 20 MV/m) could either not be recovered or retreatment was not attempted due to schedule constraints. The average usable gradient (±RMS) of the cavities sent for cryomodule assembly was 29.8±5.1 MV/m.

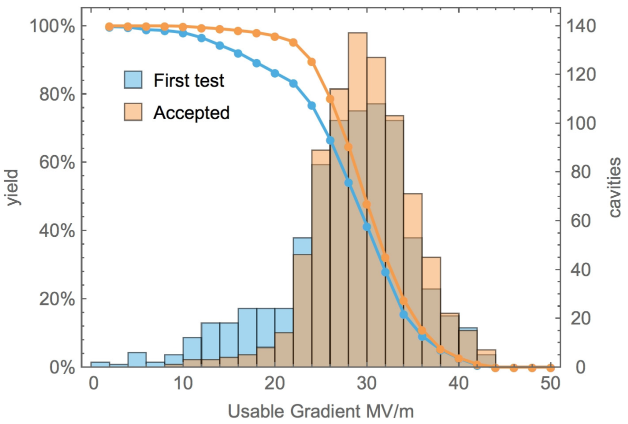

Figure 9: Comparison of the first ("as received") and final accepted usable gradient distributions.

CRYOMODULE PERFORMANCE

A total of 102 cryomodules (100 series plus two pre-series[1]) were assembled in a purpose built plant at CEA, Saclay [16]. All modules underwent a cold high-power pulsed RF test at AMTF. As with the cold vertical tests described above, the test suite followed a well-defined and heavily automated procedure, developed and run by the team from IFJ-PAN [2,3,4]. Key results were again transferred to the XFEL database. Figure 10 shows a photograph of one of the three cryomodule test stands.

More comprehensive detailed information on the cryomodule assembly experience can be found for example here [17,18,19]. In the remainder of this section only the RF performance of the cryomodules will be summarised.

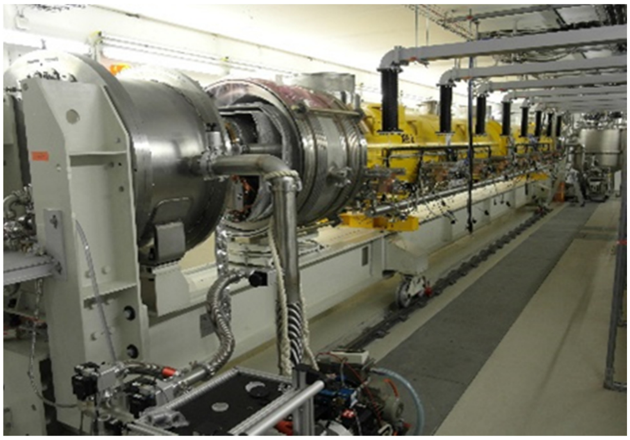

Figure 10: Cryomodule test-stand installation at AMTF.

The cryomodule tests included the measurement of the maximum gradient performance of each individual cavity in the cryomodule. As with the cold vertical tests, a distinction was made between maximum and usable gradient (referred to as operational gradient for the cryomodule tests). However, unlike the vertical tests, the maximum gradient was administratively limited to 31 MV/m, primarily due to concerns of the high-power waveguide distribution. Furthermore, field emission ("dark current") was again monitored by X-ray monitors, but the geometry and setup was significantly different, with a monitor located on the beam axis at either end of the cryomodule. Finally, no individual cavity Q_0 measurements were possible (the cryogenic heat loads were only measured with all eight cavities of the cryomodule on resonance). As a result, a direct and unambiguous comparison between vertical and cryomodule test is very difficult at best. Nonetheless, in order to attempt to quantify "performance degradation" due to string assemble, a rough comparison can be made.

Figure 11 shows the average cavity operational gradient for all the series cryomodules (XM1-100) and the two pre-series modules XM-2 and XM-1. For comparison, the expected performance from the vertical cold tests, capped at 31 MV/m is shown.

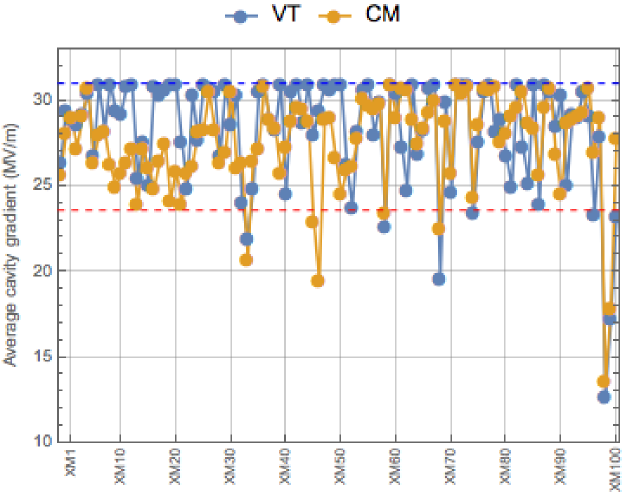

Figure 11: Average operational gradient for all EXFEL cryomodules (CM, orange data points). The blue data points are the average expected performance from the vertical tests (VT, blue data points, assumed capped at 31 MV/m). The red and blue dashed lines represent the nominal EXFEL gradient (23.6 MV/m) and the administrative limit in the cryomodule test (31 MV/m) respectively.

With a few exceptions, all cryomodules achieved or exceeded the nominal EXFEL gradient specification (23.6 MV/m). The average performance across all modules is 27.5 MV/m (with an RMS of 4.8 MV/m). Several modules achieved (and possibly would have exceeded) 31 MV/m on average –the maximum allowed by the power limitations of the test stand. By comparison, the average comparable performance expected from the vertical test results is 28.3 MV/m, corresponding to an overall reduction of less than 3%. Closer inspection of Figure 11 shows that individual cryomodule performance exhibited large relative degradation in many cryomodules at the start of production but that the latter production performed much better. This has been attributed to overall better practises during clean room assembly (see [17,18] for more details). The degradation quantified in this way is essentially zero for a large fraction of the modules in

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[1] This does not include the first pre-series module (XM-3) which was not constructed from EXFEL series production cavities.

the latter production period. Several instances where the module showed improvement over the expected performance from the vertical test is mostly due to the lack of a Q_0 limit in the cryomodule test, or in some cases improved FE performance.

For the measured cryomodule operational gradient, approximately 18% of the cavities were limited by X-rays (FE), 36% by quench, with the remaining cavities being administratively limited at 31 MV/m (46%).

Figure 12 shows the cryomodule average cavity Q_0 as measured at AMTF (CM, orange data points). With the exception of three cases, all cryomodules exceeded the specification of 10^{10}. The orange data points show an estimate based on the Q_0 values of the cavities as measured in the cold vertical test (VT). While the average over all modules is approximately the same for CM and VT at ~$1.4{\times}10^{10}$, the spread is higher from the VT estimates and there appears little correlation. Given the very different nature of the measurements (CW single-cavity RF versus pulsed cryomodule cryogenic heat load measurement for VT and CM respectively), as well as the expected large uncertainty in both (up to 20%), there is little that can be inferred over a change in Q_0 between vertical test cryomodule test.

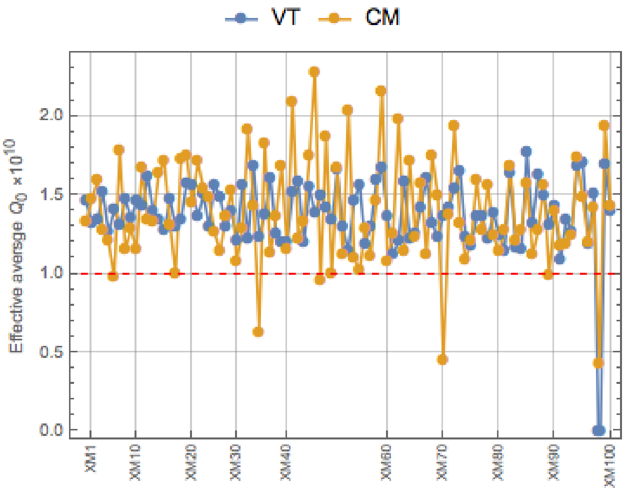

Figure 12: Effective cavity Q_0 for EXFEL cryomodules (MT, orange data points). The blue data points are the estimate from the vertical tests (VT). The red dashed line represent the EXFEL specification (10^{10}). Note that heat-load measurements were not available for all cryomodules.

EXPECTED LINAC PERFORMANCE

Figure 11 represents the maximum available module gradient based on the performance of each of the individual cavities. Operationally, four cryomodules (one RF station, 32 cavities) are driven by a common 10 MW multi-beam klystron, which requires relatively complex waveguide distribution (WD) system [20]. To accommodate the rather large spread in the gradients, the WD systems were individually tailored (within constraints) to match as far as possible the measured maximum performance of the individual cavities. The energy gain has been further optimised by sorting the cryomodules for installation into the RF stations. It is projected that the loss of maximum available operational gradient due the WD system will only 5%. Table 2 gives a summary of the average gradient performance for the 97 cryomodules installed in the linac.

Table 2: Summary of the average gradient performance for the 97 cryomodules installed in the linac (±RMS).

Vertical test	29.8 ± 4.6 MV/m
Vertical test (capped at 31 MV/m)	28.4 ± 3.1 MV/m
Cryomodule	27.7 ± 2.7 MV/m
Installed linac	26.3 ± 3.0 MV/m
Expected maximum linac energy	~20 GeV

The projected maximum energy of the EXFEL linac is approximately 20 GeV, exceeding the design requirement of 17.5 GeV, despite the currently missing last RF station. The actual operational performance of the main linac RF stations will be measured with beam during commissioning towards the end of this year.

FURTHER STUDIES

Although the construction phase of the EXFEL is now complete, there is still much that can be learnt from the experience. One important legacy is the large amount of data that has been amassed during the industrial cavity manufacturing, cryomodule assembly at CEA, Saclay, and the associated testing at DESY. Despite the overwhelming success of the cryomodule production, there still remains possible “room for improvement”. For example, despite the very impressive average performance of the cavities delivered by industry, the spread in that performance is very large (ranging from 10 MV/m up to 40 MV/m). This is an indication that the production process was still not well enough understood, and tighter controls of key parameters could lead to more consistent results in the future. Searching for correlation between the vertical test performance and the many parameters measured and recorded during manufacture and surface chemistry is one possible way to understand the process. Unfortunately, attempts made so far to correlate final performance with key production figures of merit have provided no clear indication of where the problem lies. However, this avenue of study has certainly not been exhausted, and further studies along these lines are planned for the future.

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