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STATUS OF THE ESS MEDIUM BETA CAVITIES AT INFN LASA

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Abstract

The INFN LASA's contribution to the ESS Medium Beta Superconducting Linac consists of 36 cavities that raise the proton beam energy from 216 MeV to 571 MeV. Out of the 36 cavities, 28 have been successfully qualified and delivered for assembly into a cryomodule at CEA Saclay. The remaining cavities have been reprocessed in order to bring them up to ESS specifications. To mitigate further delays in the delivery of the cavities, four new ones are currently under construction. We are reporting on the current status of both the recovery actions we have developed so far and the performance of the newly produced resonators.

INTRODUCTION

INFN Milano - LASA is responsible for the Italian In-Kind contribution to the European Spallation Source (ESS) ERIC of the Superconducting (SC) Medium Beta Cavities. For these cavities, we developed the electromagnetic design and the we optimized it taking into account mechanical requirements, their feasibility in industry and their compliance to the ESS interface requests. This last point has been proven to be of critical importance to ensure the smooth assembly of the cavities in their cryomodule at CEA Saclay. Table 1 summarizes the key parameters of the INFN Medium Beta cavities.

Once operated in the SC linac, the Medium Beta (β=0.67) cavities will capture the 62.5 mA proton beam from the Spoke section (256 MeV) and accelerate it up to 571 MeV for its further injection in the High Beta cryomodules that will bring the beam to its final energy of 2 GeV.

The 5 MW average power proton beam will be pulsed at 14 Hz, each pulse being 2.86 ms long. This long beam pulses operation has been one of the driving reasons for using superconducting cavities. This choice allows achieving the project parameters while preserving in cost. Moreover, there is the additional need to operate the cavities at high accelerating gradient to reach the needed energy in the foreseen accelerator footprint.

The proton beam will then be delivered to the target station for producing the neutron beam by the spallation process [1]. The European Spallation Source (ESS) ERIC will be, once in operation, the most intense neutron source in the world [2].

This paper presents an update on the cavity production status with dedicated emphasis on the recovery actions we have performed so far to qualify low performance cavities. Moreover, to mitigate possible delay in completing our In-Kind contribution we are providing new resonators with updated surface treatments as learnt during the recovery activity.

Table 1: ESS Medium Beta Cavities Main Parameters

Parameter	Value
R_{iris}	50 mm
Geometrical β	0.67
π-mode Frequency	704.42 MHz
Acc. length	0.855 m
Cell-to-cell coupling k	1.55%
π-$5\pi/6$ mode sep.	0.70 MHz
Geometrical factor G	198.8 Ω
Optimum beta, β_{opt}	0.705
Max R/Q at β_{opt}	374 Ω
E_{acc} at β_{opt}	16.7 MV/m
E_{peak}/E_{acc}	2.55
E_{peak}	42.6 MV/m
B_{peak}/E_{acc}	4.95 $\frac{mT}{MV/m}$
Q_0 at nominal gradient	>5 × 10^9
Q_{ext}	7.8 × 10^5

ESS MEDIUM BETA CAVITIES STATUS

The production of ESS Medium Beta cavities is based on a scheme inherited from our previous work in industrial production of European XFEL SRF cavities. To ensure high quality, INFN has developed strict guidelines for cavity production and implemented a comprehensive Quality Control and Quality Assurance plan that encompasses the entire cavity production process [3].

In line with the objectives of the ESS project, we have chosen to treat the cavities using a Buffered Chemical Polishing (BCP) process, both in bulk and as a final treatment. The final treatment, known as the "Final BCP", is part of the cavity preparation necessary to assemble the cavity before the Vertical Test at cryogenic temperatures, required for cavity qualification. To accommodate the high cavity delivery rate required by the project, most of the qualification tests were conducted at DESY, utilizing the AMTF infrastructure [4].

However, for specific cavities, we utilized the LASA infrastructure, which is not able to sustain the series test rate but is equipped with advanced diagnostic tools capable of identifying quench and field emission sources that could potentially limit the cavity performance.

A total of twenty-eight cavities successfully met the ESS specifications and were subsequently assembled into cryomodules at CEA Saclay and, few of the, there tested. These cryomodules were then transferred to ESS for further testing

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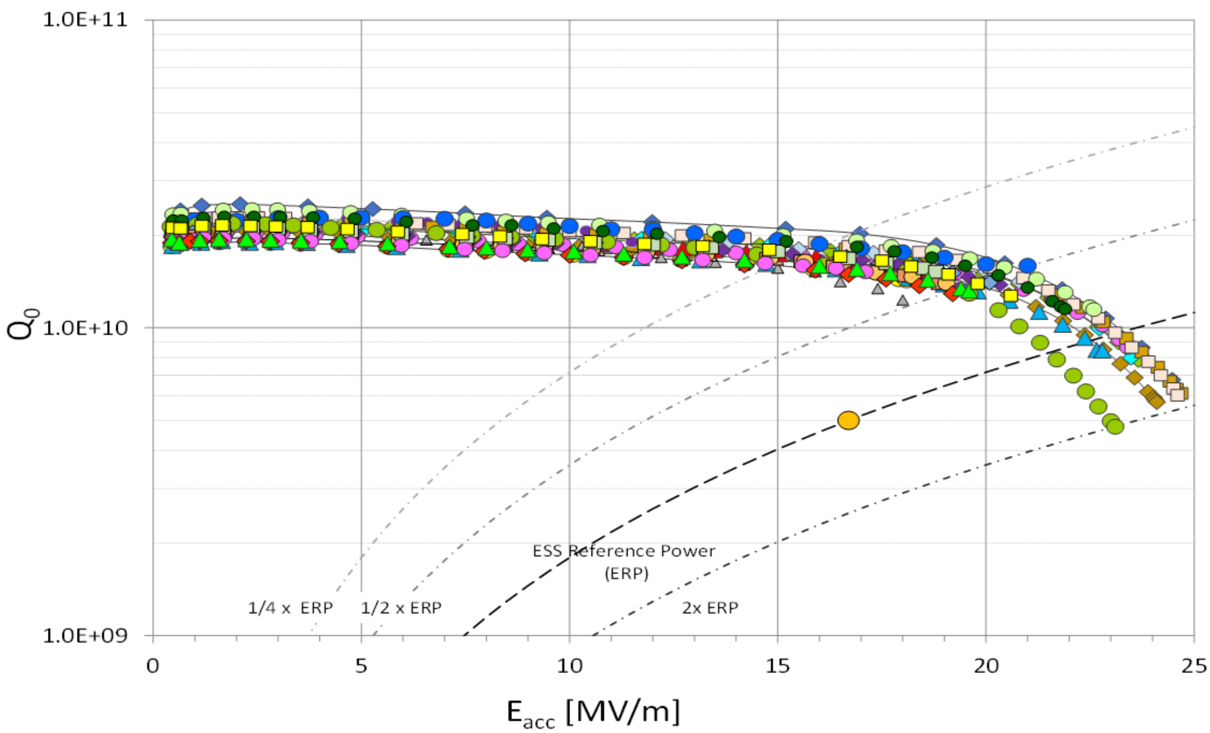

Figure 1: ESS Medium Beta Cavities qualification power rise at 2 K, the nominal working temperature. ERP corresponds to the cryogenic power consumption at the ESS goal of 5×10^9 at 16.7 MV/m.

and qualification in preparation for installation in the Linac [5, 6].

Figure 1 illustrates the power rises (Q_0 vs E_{acc}) for these cavities, as measured at 2 K at DESY. All of the cavities exhibited quality factors (Q_0) at the ESS E_{acc} goal well above the project required value (E_{acc} = 16.7 MV/m at Q_0 = 5×10^9).

In fact, when considering the delivered cavities, the measured Q_0 values are between two and four times higher than the ESS specification, indicating significantly reduced cryogenic consumption during machine operation.

CAVITY REPROCESSING

Over the past two years, our primary focus has been on qualifying the remaining cavities required to complete the Italian In-Kind contribution to the Medium Beta section of the ESS linac.

As previously mentioned [7], we conducted a thorough review of the entire production process, identifying two areas for improvement: High Pressure Rinsing and BCP treatment.

The High Pressure Rinsing process was optimized to effectively cover the large cell of the ESS cavities with its steep walls resulting from the low beta geometry. This improvement allowed recovering cavity M006. Indeed this cavity showed strong multipacting and, after new HPR, this was cured and the cavity qualified for installation.

On the other hand, we conducted a more detailed investigation into the BCP treatment because some cavities did not meet the ESS requirements due to a drop in quality factor (Q_0) already at low accelerating gradient without any field emission measurable both inside and outside the cryostat by standard radiation diagnostic tools.

During our observations, we noticed deep grooves on the inner surface of the cell, particularly in the region starting from the equator towards the inclined wall of the cell (see Fig. 2). In-depth fluid dynamics simulations [8] revealed that these grooves may have been caused by bubbles generated during the BCP process due to the low fluid speed in that specific region of the cavity. Indeed, the simulations show a main BCP stream in the cavity center from bottom to top (direction of the BCP flow from the plant), a second stream in the opposite direction. This second stream is then responsible to induce the low velocity circulation of the fluid inside each single cell. The simulations have been verified by a scaled model of a cavity that confirmed the results obtained by the fluid dynamics simulations.

The presence of the grooves is a possible cause of the low performance of the cavities. Two possible effects can be attributed to them, namely dissipation by improper cleaning make it difficult by the grooves and/or dissipation induced by enhancement of magnetic field at the sharp peak of the grooves themselves. This latter interpretation of the effect of the grooves has been reported in [9, 10].

Based on this information, we made the decision to further investigate the possible impact of the grooves on the cavity performance. Having identified the BCP process parameters as the source of the grooves, we applied a different BCP process. The process, using the verified fluid model,

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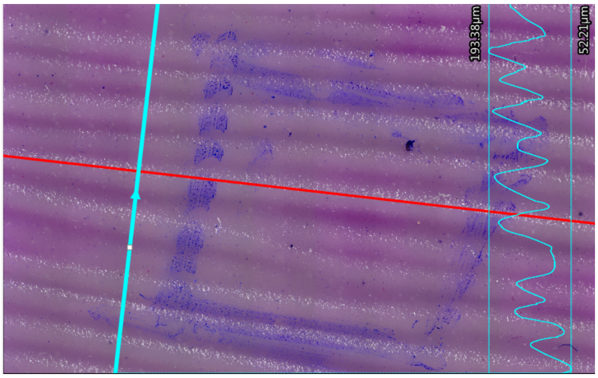

Figure 2: Grooves observed on inner cavity wall by means of replica. Analysis with 3D microscope is shown on the side with height extension of the grooves.

was studied to improve the BCP speed in the cell, aiming to smoothing the grooves. Higher speed was achieved by modifying the BCP circuit with larger tubes to increase the inlet BCP speed. Cavity M037 was process with this new layout and indeed, as shown in Fig. 3, the cavity performance lightly improves supporting our thesis that, the drop of Q_0 was related to the presence of the grooves on the inner surface of the cavity cells.

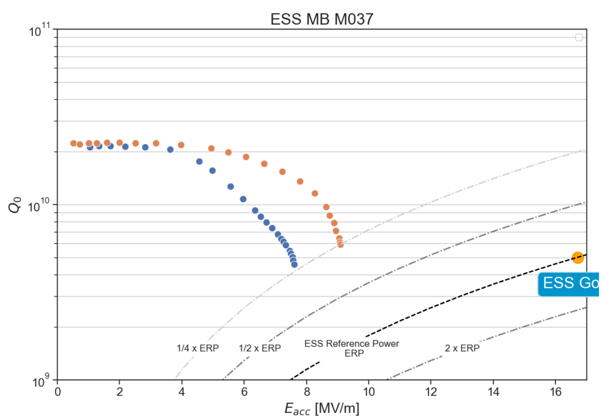

Figure 3: M037 power rise before (blue dots) and after (orange dots) the "High Speed BCP" process. A clear improvement in the performance is observable in particular the maximum E_{acc} has increased by nearly 2 MV/m and the Q slope is noticeably improved. No radiation was observed in both tests.

The encouraging results of the "High Speed BCP" process presented before motivated a further exploration of possible processes to reduce or remove the grooves.

However, we had to reprocess both cavities not yet integrated (unjacketed) into the Helium tank (He-Tank) and cavity already integrated (jacketed). The substantial difference between the two types of cavity is that the jacketed cavity are already tuned to their final frequency and field flatness and hence the possible material removal is limited to a couple of tens of micrometers.

To cope with this limitation, we opted to process with Electropolishing the unjacketed cavities while we explored the features of rotational BCP for the jacketed cavities.

Electropolishing

The EP process was tailored by the cavity vendor, drawing upon their expertise gained from the European XFEL and LCLS-II projects large scale productions, as well as our collaborative work on prototypes within the PIP-II project [11].

M024 Cavity M024 was unjacketed and experienced a significant Q-drop. It was the first to be processed with EP [7]. We removed about 100 µm of bulk EP, heat treated, tuned the cavity and did 10 µm final cold EP. The results obtained after the initial Vertical Test (VT) were highly promising, achieving an E_{acc} of 17 MV/m.

However, during a subsequent inspection conducted by the vendor prior to He-tank integration, the cavity exhibited geometrical deformation and a Field Flatness of 85%. Fortunately, the vendor was able to rectify these issues, bringing the cavity back within the specified requirements and successfully integrating it into the He-tank. Unfortunately, the notification of the deformation was done only after the integration process was started. We could not identify where, along the overall EP process, the cavity was deformed. Vertical Test subsequent to He-Tank integration produced results as shown in Fig. 4, where a quench occurred at E_{acc} = 13.7 MV/m (green dots). The analysis of the Field Flatness at the incoming inspection and of the modes during VT test reveals that the quenching cell was the cell with lower electric field before FF tuning. Once the cavity was appropriately tuned and the field flatness adjusted, this cell became the limiting factor affecting the overall cavity performance.

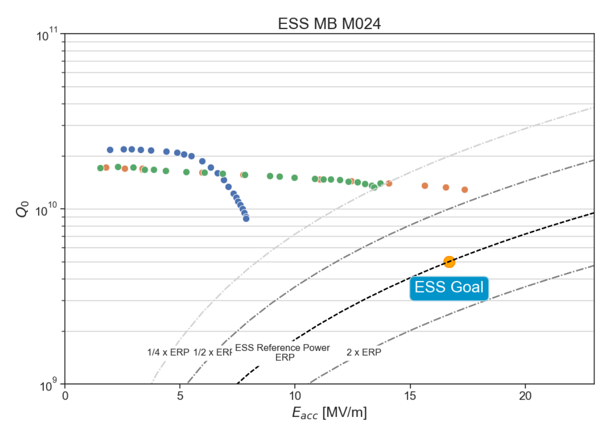

Figure 4: M024 Vertical Test power rises comparison after BCP (blu dots), after EP unjacketed (orange dots) and once jacketed into the He-Tank (green dots). To be noticed that before the He-Tank integration, the Field Flatness was 85%.

However, the EP process successfully recovered the substantial Q slope observed at low field in the cavity, resulting in an impressive improvement of approximately 80% in the maximum accelerating gradient.

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This outcome strongly suggests that the presence of grooves on the inner wall of the cell, which served as a dissipating mechanism, was indeed one of the probable factors contributing to the cavity's subpar performance. As a result, we decided to apply EP treatment to the remaining two unjacketed cavities as well.

The outcomes of these treatments are detailed in the subsequent two subsections.

M017 Cavity M017 was initially treated with BCP and reached a quench at 7.4 MV/m. The cavity was then processed with 110 µm of bulk EP and prepared for test with additional 10 µm of final cold EP. The performance of the cavity after EP retreatment is reported in Fig. 5 and represented by the orange dots. Additional 50 µm cold EP were removed to attempt further improving the final E_{acc} . The increase was limited to less than 1 MV/m (green dots) and hence we decided to proceed to integrate the cavity. Red dots represent the performance of the cavity once integrated: the effect of multipacting are visible around 11 MV/m, with also some radiation. It is worthwhile here to remind that jackted cavities receive a final BCP (typically 20 µm) and not EP due to the installed He-Tank.

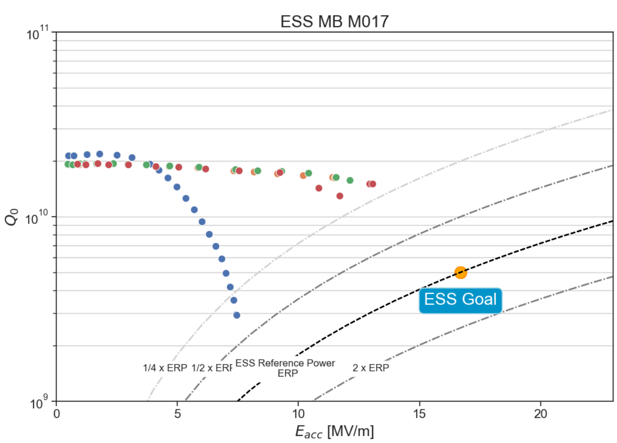

Figure 5: M017 power rises. Blue dots report data after BCP. Orange dots refer to the power rise after the first EP while green dots report the cavity performance after additional 50 µm. Finally, data after He-Tank integration are represented by red dots.

As for cavity M024, we notice a significant recovery of the Q slope. The cavity is now integrated and limited by quench at E_{acc} = 13.1 MV/m, with an improvement of about 80% of the maximum accelerating gradient.

M037 We have already reported on the first attempt to improve cavity M037 in a previous section. Here, we focus on the EP processing and the following integration into the He-Tank.

As for cavity M017, also cavity M037 was processed with 110 µm of bulk EP, heat treated, tuned and prepared for Vertical Test with additional 10 µm of cold EP. After the successful test, the cavity was integrated into the He-Tank and tested once more to monitor possible performance changes. The summary of the cavity performance change with EP is reported in Fig. 6.

As for previous two cavities, the EP processing significantly recover the Q slope and improve the final E_{acc} . In case of cavity M037, the integration into He-Tank slightly reduce the maximum E_{acc} while preserving the Q_0 .

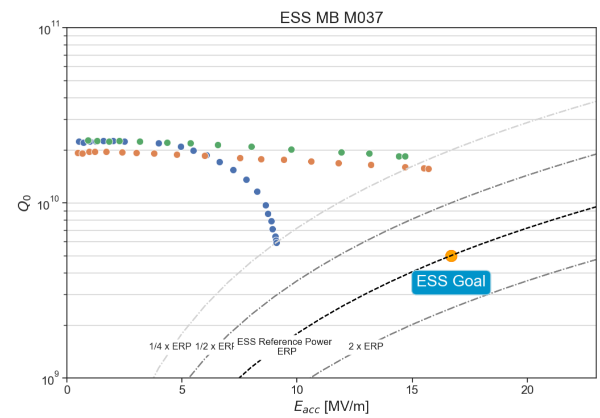

Figure 6: M037 power rises. Blue dots report data of power rise after "High Speed BCP" as reported in "Cavity Processing" section. The power rise after EP is represented by the orange dot. Finally the green dots show data after He-Tank integration.

Rotational BCP

The process selected for jacketed cavities needs to take into account the limitations given by the presence of the tank. While EP was used on integrated cavities, we selected rotational BCP since this process is less sensitive to possible temperature variation and it should guarantee more uniform removal, beneficial for preserving the field flatness of the cavity.

M028 We selected cavity M028 to be processed with rotational BCP. The process was done at Argonne National Laboratory in a framework of a joint collaboration.

M028 has a peculiar process history. The cavity was prepared as a series cavity, i.e. equipped with He-Tank. At the Vertical test it showed a quench at 11.2 MV/m with a minimal field emission. To cure the field emission, we reprocessed the cavity with additional 20 µm of BCP. Unexpectedly, the maximum E_{acc} dropped to 9 MV/m with a start of the Q_0 decrease shifted to 5 MV/m, as shown in Fig. 7 (orange dots). The new power rise showed no radiation at all. Interpreting this results as an increase of the groove depth due to the additional BCP process, we decided to treat this cavity with the rotational BCP in view of a possible application of this process to all the jacketed cavities.

Cavity M028 was shipped to ANL e processed with about 25 µm rotational BCP. Afterwards, it was rinsed, cleaned and pumped down before shipping it back. It was then prepared for the vertical test only by HPR, to not alter the surface

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finishing. The test was limited by huge field emission that required an additional HPR process and preparation for a new test. The data of this latest VT are reported in Fig. 7 (green dots) that shows a clear improvement of the Q_0 decrease as well as of the final E_{acc} . It is worthwhile to mention that the field flatness was unchanged after the rotational BCP process, meaning a uniform material removal on the inner cavity surface.

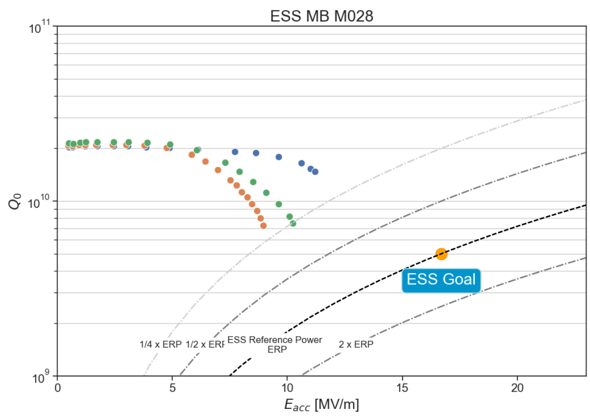

Figure 7: M028 power rises. Blue dots report data of power rise after series process. The power rise after additional 20 µm is represented by the orange dot. Finally the green dots show data after rotational BCP performed at ANL.

NEW CAVITIES PRODUCTION

To mitigate potential delays and potentially replace underperforming cavities, four new cavities were manufactured. The mechanical preparation of these cavities followed a similar process to the series production. Building on our experience with BCP treatments, we opted for EP as the bulk treatment method (160 µm), while the final treatment, since the cavity was already integrated, involved a flash BCP process. Additionally, we introduced an intermediate vertical test for the bare cavities after the primary EP treatment, along with an additional final EP (10 µm) before He-Tank integration, allowing us to implement any necessary corrective measures if needed.

All four cavities were mechanically fabricated and underwent EP treatment. Two cavities proceeded directly to the Vertical Test without any issues, while the remaining two showed defects in the equator area, requiring a grinding operation. Figure 8 illustrates the power rise of these two cavities prior to integration.

Significantly surpassing the ESS specifications, these two cavities underwent the integration process and are scheduled for testing by July of this year at DESY. As for the other two cavities, they are ready for the intermediate VT test, which is also foreseen in July. Upon successful testing, these two cavities will also proceed to integration. We anticipate being ready for the final test after integration by fall of '23 and aim to deliver the complete package by the end of 2023.

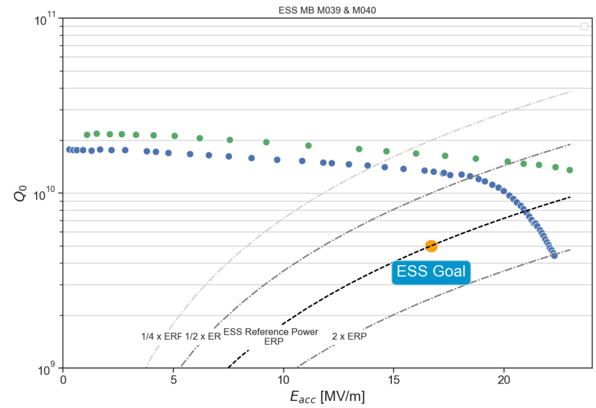

Figure 8: Cavities M039 (blue dots) and M040 (green dots) power rises in the intermediate phase (bare cavities). 160 µm of bulk EP for both cavities, followed by 10 µm of final EP, warm for M039 and cold for M040 respectively.

CONCLUSION

The Italian In-Kind contribution to the Medium Beta Section of the ESS Superconducting linac is making steady progress towards fulfilling the delivery requirement of 36 cavities. So far, 28 cavities have been qualified and delivered for installation in the cryomodule. Excitingly, the intermediate results of the production of four new cavities are displaying excellent performances.

The successful recovery of the previously underperforming cavities through EP treatment has led to significant improvements. This suggests that these cavities could potentially be utilized in the initial cryomodules of the Medium Beta section, where the matching conditions from the spoke section necessitate lower accelerating fields. Additionally, the four new cavities, which have undergone EP treatment, are exhibiting outstanding performance, providing strong motivation for a potential additional contribution of four spare cavities to the ESS project. Discussions regarding this contribution are currently underway.

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