

PERFORMANCE AND PRODUCTION STATUS OF HIGH-Q CRYOMODULES FOR THE SHINE PROJECT

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Abstract

The SHINE Linac was optimized to accelerate the beam to 8 GeV with 54 high-Q cryomodules (CMs), benefiting from the higher performance of the cavities and CMs. Currently, the mass production of SHINE cavities and CMs is ongoing. Up to now, around 350 high-Q cavities with mid-T baking or N-doping recipes have been fabricated and tested. Most of them have been assembled in CMs. More than 30 CMs have been tested. In this paper, we report the performance of high-Q CMs and lessons learned during the production.

INTRODUCTION

SHINE accelerator consists of an injector, and a Linac separated into four sections by three bunch compressors, designated as BC1 to BC3 [1, 2]. Due to performance improvements in SHINE 1.3 GHz high-Q cavities, the specifications for high-Q cavities and CMs were updated with the Q_0 of 3.0×10^{10} at a higher average gradient of 20 MV/m since 2024 [3]. Hence, the number of CMs can be reduced from the original 75 sets to reach the designed energy of 8 GeV. The distribution of the CMs in the four Linac sections is illustrated in Figure 1.

Similar to the CM designs for E-XFEL and LCLS-II projects [4, 5], each regular 1.3 GHz CM for SHINE includes 8 high-Q cavities, 8 fundamental power couplers (FPCs), 8 tuners, 8 cavity magnetic shields, 1 superconducting

magnet, 1 cold beam position monitor (BPM), 1 set of cryostat and cold mass, several vacuum tubes and valves, supports and other accessories. Some components are procured from mature international or domestic vendors, while many others are developed, verified and adopted for SHINE CMs.

As key components in CM, totally five vendors are involved for SHINE cavity production, including two European companies for both mechanical fabrication and surface treatment, and three domestic ones for mechanical fabrication [6]. All the surface treatment of domestic cavities is conducted by SHINE facilities in Wuxi [7]. The international cavities are treated with a modified 3/60 N-doping recipe, while almost all the domestic cavities are treated with mid-T baking [8-10].

Acceptance check of the main components is done before starting the assembly of each CM, which assures the quality for CMs. In principle, only qualified components are accepted, except a few ones with slight concession considering the tight time schedule.

All the CM assembly and horizontal tests are carried on the platforms dedicatedly built for SHINE project in SARI campus. Two cavity-string lines in ISO4 clean room enable the assembly of two CMs in quasi-parallel. Three horizontal test benches are used for CM tests.

Currently, 2~3 CMs per month can be guaranteed, considering the delivery of CM components, the capacity of CM assembly and horizontal test.

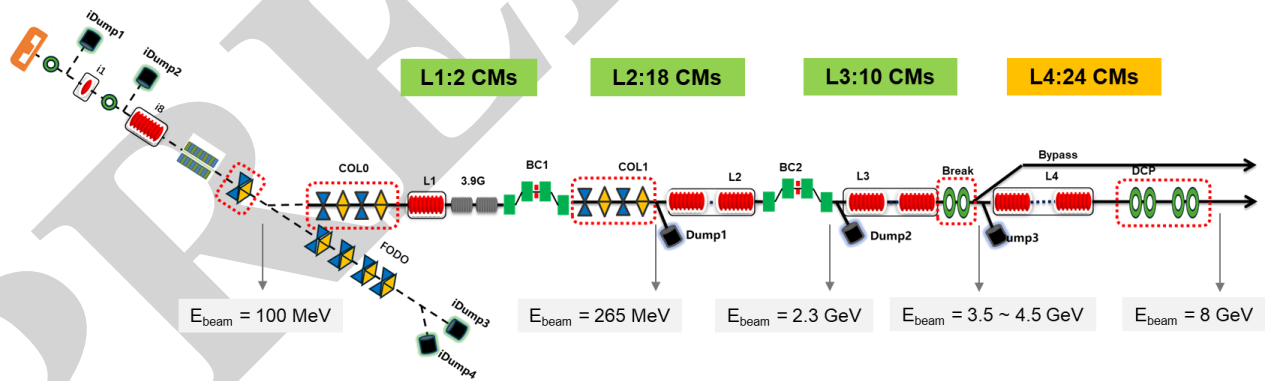


Figure 1: Layout of SHINE accelerator. High-Q CMs for L1-L3 have been installed tunnel, including HOM absorbers.

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PERFORMANCE OF HIGH-Q CAVITIES

So far, more than 350 dressed 1.3 GHz cavities have been machined, treated with high-Q recipes and tested at 2K [6]. Among them, 138 ones were treated with a modified 3/60 N-doping recipe, and the others with mid-T baking [8, 9]. The N-doped cavities are mainly fabricated by two established international vendors, while the other cavities, machined by domestic companies, are treated with mid-T baking recipe by SHINE facilities at Wuxi Creative [7].

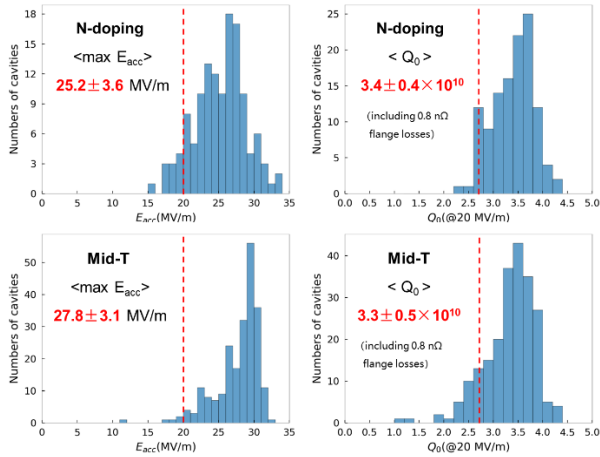


Figure 2: Performance of the 1.3 GHz high-Q dressed cavities in vertical test (0.8 nΩ losses of stainless steel flanges have not been deducted for Q_0). The upper figures show the N-doped results, and lower ones the mid-T baked.

Performances of the 356 dressed cavities in total are shown in Figure 2. For the 138 N-doped cavities, the average Q_0 is 3.4×10^{10} at 20 MV/m, with an average maximum gradient of 25.2 MV/m. And for the 218 mid-T baked ones, the average Q_0 is 3.3×10^{10} at 20 MV/m, with an average maximum gradient of 27.8 MV/m. According to the SHINE new specifications for dressed cavities in vertical test (VT) [3], namely, $Q_0 = 3.0 \times 10^{10}$ at 20 MV/m, and maximum $E_{acc} \geq 22$ MV/m, without field emission (FE) under 22 MV/m, approximately 80% are qualified by vertical test. Among these 285 qualified dressed cavities, 214 ones are qualified as dressed cavities received, including 60 repaired successfully during bare-cavity processing by Centrifugal Barrel Polishing (CBP), hand grinding or light BCP; and 59 ones qualified after HPR to eliminate FE, and 12 qualified after repair by CBP, re-treatment or light BCP.

Besides, 51 cavities (14%) are concessionally accepted for CM assembly, which may reach the gradient specification but with a slightly lower Q_0 ($> 2.5 \times 10^{10}$), or may reach the Q_0 specification but with a slightly lower gradient (> 18 MV/m).

Finally, the rest 20 cavities (6%) are unqualified yet, including 2 with FE awaiting further HPR, and 18 with too low gradient or Q_0 that are under or waiting for repair.

PERFORMANCE OF HIGH-Q CMS

Up to now, 32 high-Q cryomodules have been tested, among which 15 are equipped with N-doped cavities, and 17 with mid-T baked cavities, denoted as ND and MT, respectively. The CM03-MT, the first CM with 8 mid-T cavities, was tested to its maximum gradients [11]. Since CM04, an administrative limit of 26 MV/m was imposed on the subsequent CMs in horizontal test (HT), in order to speed up test as well as to reduce the risk of new FE in higher gradient.

Figure 3 shows the performances of all the CMs that have been tested, excluding the two reworked CMs (CM10, CM22) and an untested CM (CM33). The average usable voltage of the 32 CMs is 200.1 MV, corresponding to an average gradient of 24.1 MV/m, and the average Q_0 at 20 MV/m is 3.3×10^{10} .

Concerning the FE behaviour in CMs, 86 % of the cavities (219/256) showed no degradation in FE from VT to HT, including 84% FE-Free, and 2% with FE during VT at gradient larger than 22 MV/m. While the other 14% of the cavities experienced FE degradation in HT, among them around 13% with newly emerged FE and 1% with reduction in FE onset gradient. The average FE onset of these 14% cavities is 18.8 ± 4.4 MV/m. The summary of cavity gradients and FE information in CMs is shown in Figure 4.

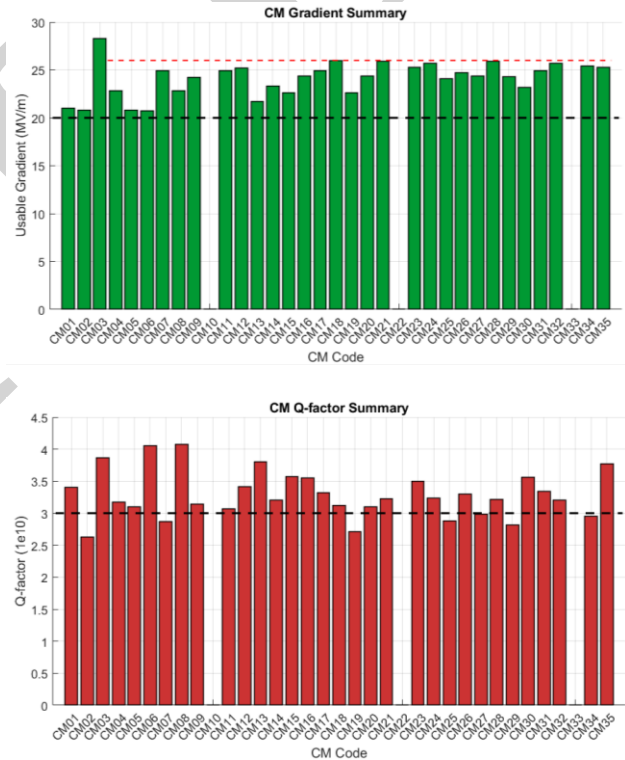


Figure 3: The average gradient and Q_0 performance of the tested high-Q CMs for SHINE.

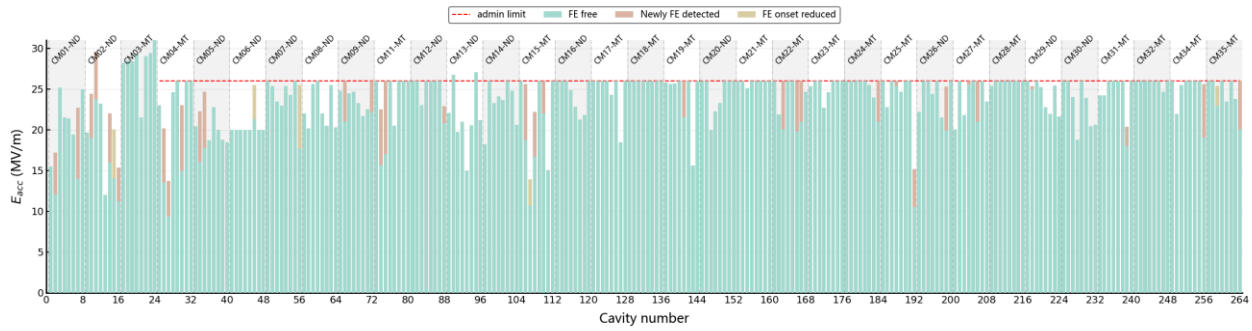


Figure 4: Summary of cavity gradient and field emission in cryomodules.

REWORKED CRYOMODULES

There were some CMs that experienced partial or full rework, including CM10-ND, CM12-ND, CM22-MT and CM32-MT.

The CM10 exhibited extremely low gradients for several cavities in horizontal test, was subsequently fully disassembled. All the eight N-doped cavities were cleaned by HPR and retested. Four of them were recovered, while the other four showed very poor performance and afterwards were recovered by light BCP. These cavities were likely contaminated in CM, but the cause remained unclear. Finally, all the eight cavities and the other components of CM10 were reused in the following CMs.

For CM12-ND, the beam vacuum degradation was found during its break of insulation vacuum after HT. In order to find the leakage, the CM12 was then partially disassembled. A leak rate of $1.8 \text{ E-}8 \text{ Pa.m}^3/\text{s}$ was found at the cold BPM flange due to some loose screws. The BPM flange was then retightened up, and the CM was repaired and retested. The performance in the 2nd test was similar to the 1st one, which showed no FE degradation. Therefore, the CM12 was successfully recovered.

For CM22-MT and CM32-MT, the beam vacuum degradation was found before installation in linac tunnel and during the warmup after HT, respectively. Both the CMs were partially disassembled to find leakage. In CM32, ceramic crack of the HOM-pu feedthrough on the #cav6 was found. The HOM feedthrough was afterwards replaced with a new one in an ISO4 clean booth, and the CM32 was retested. Same performance was achieved in the 2nd test for CM32, maintaining FE free, which illustrates a successful repair. In CM22, similar problem of the HOM-pu feedthrough on #cav3 was found, and solved with same way. The CM22 will be retested soon.

CONCLUSION

More than 350 high-Q dressed cavities have been delivered for SHINE CM assembly. 32 CMs have been tested, reaching an average Q_0 of 3.3×10^{10} at 20 MV/m, and an average usable gradient of 24.1 MV/m in horizontal test, which are well above SHINE specifications. All the CM production is expected to be completed within this year.

Among them, 30 CMs have been installed in linac tunnel from L1 to L3, and will be cooled down soon [12].

ACKNOWLEDGEMENTS

The authors thank all the members in SHINE cryomodule team for their great effort, and thank the cryogenic team and general technology team for their great support. We would like to thank Paolo Michelato (INFN-LASA) for his valuable suggestion during the design of Wuxi Platform, which makes it possible for high production capacity. We are grateful to Carlo Pagani (INFN-LASA), Hiroshi Sakai (KEK), Hans Weise and Detlef Reschke (DESY) for the advices on a reworked CM.

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