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MASS PRODUCTION OF 3.9 GHz 9-CELL CAVITIES AT SHINE

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Abstract

Two 3.9 GHz cryomodules of sixteen cavities are required in the Shanghai high-repetition-rate XFEL and extreme light facility (SHINE) linac. They are placed before the first bunch compressor to linearize energy distribution. A total of twenty-one 3.9 GHz 9-cell cavities including two prototypes were fabricated and partly tested. The first two prototypes have been fabricated, tested, and qualified in the vertical tests, having a large margin with respect to the SHINE specification. The first prototype was integrated into a small cryostat and qualified in the horizontal test. Mass production of the cavity series was launched after the prototype qualification. Ten bare cavities of the first batch were qualified in the vertical tests. An average Q_0 of 3.2×10^9 at 13.1 MV/m and maximum accelerating gradient of 22.6 MV/m were achieved. Bare cavity fabrication of the second batch of nine cavities has been finished and the cavities are now under surface treatment. This paper will cover the experience of the prototype development and mass production of the 3.9 GHz cavities.

INTRODUCTION

SHINE linac is an 8 GeV superconducting accelerator in continuous wave (CW) mode which consists of seventy-five 1.3 GHz cryomodules and two 3.9 GHz cryomodules [1–4]. The 3.9 GHz cryomodules, located before the first bunch compressor, compensate the nonlinear longitudinal phase space distortion due to the accelerating field curvature in the 1.3 GHz cavities [5, 6]. It plays an important role to maintain low emittance beam for the production of FEL light to the experimental users and has been successfully applied in the FLASH VUV facility, the European X-ray Free Electron Laser (EXFEL), and the Linac Coherent Light Source-II (LCLS-II) [7–15]. Each 3.9 GHz cryomodules consist of eight 3.9 GHz 9-cell cavities. A total of 21 cavities, two prototypes and two batches of 10 and 9, have been realized and partly tested up to specifications. The status and results of the SHINE 3.9 GHz cavities are presented in this paper.

FABRICATION OF THE CAVITY SERIES

The rf design of the SHINE 3.9 GHz 9-cell cavity was optimized based on the design and experience of 3.9 GHz cavities in the EXFEL and the LCLS-II projects. Details of the rf design could be found in Ref. [16]. The production of two 3.9 GHz 9-cell prototypes was tendered to a domestic company which fabricated several 3.9 GHz single-cell cavities as a starting step [17]. Two prototypes have been fabricated and helium tank integrated. The fabrication of the first batch started from the beginning of 2023 and the second batch started from the end of 2023.

Cavity Prototypes

A set of two preseries cavities was ordered to a domestic industrial vendor (OSTEC, Ningxia), which was responsible for the mechanical production. The production of the SHINE 3.9 GHz prototypes adopted standard fabrication procedures [10]. Details of the prototype fabrication could be found in Ref. [18]. The surface treatment, optical inspection, field flatness tuning, and clean assembly were conducted in SHINE facilities at the Wuxi platform. Then the cavity was vertical tested in SHINE facilities at the Shanghai platform, described in later part of this paper. A great experience was gained and various technologies were developed with the construction and preparation [18].

Development of the Cavity Preparation Strategy

The 3.9 GHz cavity, with a small size compared with the 1.3 GHz TESLA-shape cavity [19], is sensitive to geometry variations and preparation processed [10]. Based on the prototype experience, the main steps of SHINE 3.9 GHz cavity to achieve the rf goals are summarized in Table 1.

Production of the Series Cavities

Two additional batches of 10 and 9 cavities were then ordered to the same vendor in order to provide components for the SHINE third harmonic cryomodules. With these two batches a total of twenty-one 3.9 GHz cavities have been produced. The bare cavities of the first batch have been vertical tested. The second batch are now under surface processing. The consistencies of mechanical fabrication, treatment processing, and frequency control were improved in the mass production. The bare cavities of the second batch and the second dressed prototype cavity are shown in Fig. 1.

The cavity series were delivered to SHINE facilities at the Wuxi platform for surface treatment once the fabrication acceptance goal was met. The cavities were processed with

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Table 1: Main Cavity Preparation Steps

a	Forming of half-cells by deep drawing
b	Iris welding of half-cells into dumb bells (DB)
c	Measurements and trimming of DBs, with the defined individual frequency/length
d	Preparation of end groups (EG)
e	Measurements and trimming of EGs, with the defined individual frequency/length
f	Equatorial welding of the DBs to form two-DBs (2D), four-DBs (4D), and eight-DBs (8D)
g	Equatorial welding of the 8D and the EGs to form single cavity
h	Optical inspections of the inner cavity surface before buffered chemical polishing (BCP)
i	Bulk BCP of cavity (approx. 130 µm)
j	3 hours 900 °C heat treatment for hydrogen removal
k	Optical inspections of the inner cavity surface after BCP
l	Final BCP of inner surface (approx. 20 µm)
m	RF Field flatness and frequency tuning and cells runout adjustment
n	High pressure rinsing (HPR), installation of testing antennas, and cleaning assembly
o	2-step baking under vacuum pumping
p	Preparation for rf testing

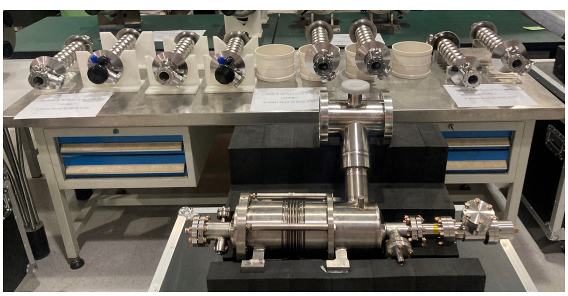

Figure 1: Bare cavities of the second batch (top) and the second prototype (bottom).

BCP recipe pulse 2-step vacuum baking [20]. Frequency, field flatness and cell runout were tuned after BCP and heat treatment by special tools developed by SHINE. All the cavities reached a field flatness over 95 % and an eccentricity less than 0.4 mm.

Optical inspection is an effective method for monitoring internal surface conditions of the cavity. SHINE has developed a device dedicated to the 3.9 GHz 9-cell cavity [18]. Two times of optical inspections were performed before the surface treatment processing and after BCP respectively. No obvious defects were observed on the inner surface of the series cavities during the first inspection before BCP, while several cavities had stains which were eliminated by BCP.

2-step baking is applied to improve the performance of 3.9 GHz cavity. Temperature sensors were placed on the cavity surface during the vacuum baking. The baking temperature is set at 75 °C for 4 hours and 120 °C for 48 hours, with temperature rising time around 30 minutes each. Argon gas flow is passed outside the cavity to protect the outer surface from oxidation.

Table 2: Performance Specifications for SHINE 3.9 GHz Cavities

Quantity	**Value**
Nominal E_{acc} in linac [MV/m]	13.1
Maximum E_{acc} in linac [MV/m]	15.0
Maximum E_{acc} in vertical test [MV/m]	>16.5
Q_0 [10^9] at 13.1 MV/m	>2.0

Figure 2: 3.9 GHz small cryomodule under horizontal test.

QUALIFICATION OF THE PROTOTYPES

The nominal operating gradient of the SHINE 3.9 GHz cryomodules is 13.1 MV/m [16]. The maximum gradient of the potential operating mode is 15.0 MV/m. The acceptance limit for the gradient in the vertical test was set at 16.5 MV/m with a 10 % margin to the maximum operating gradient by taking the potential degradation and measurement uncertainties into account. The quality factor Q_0 has to surpass $2.0{\times}10^9$ at 13.1 MV/m. The performance requirements are summarized in Table 2.

Vertical Tests

The two prototype were qualified in the vertical test. The performance of the first prototype has a large margin with respect to SHINE specifications [18]. Same processing procedure was conducted on the second prototype. Field emission (FE) occurred from 14.0 MV/m during the test of the second prototype.

Horizontal Test

The first prototype was installed in a small cryostat together with an 1.3 GHz TESLA-shape cavity [18], as shown in Fig. 2. The cavity was equipped with outer magnetic shield and blade tuner during the cryomodule assembly.

The prototype was tuned to 3900.00 MHz and the two piezo actuators were engaged during the operation. The slow tuner sensitivity was 9.7 Hz/step in the measurement. The piezo actuators detuned the cavity by 13.7 kHz, having a large margin to the specification of 1 kHz. Resolution of the fast tuner was 0.8 Hz.

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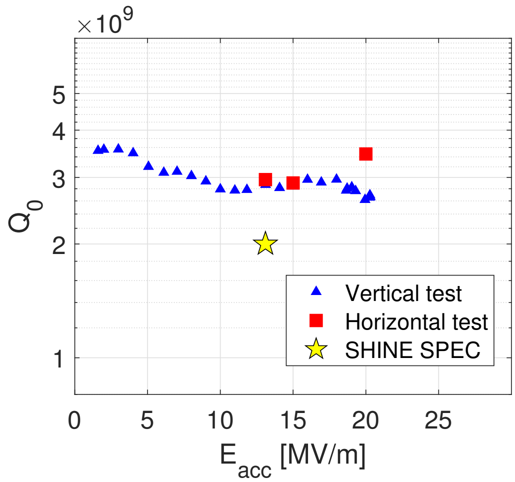

Figure 3: Horizontal test results and vertical test results of the first prototype.

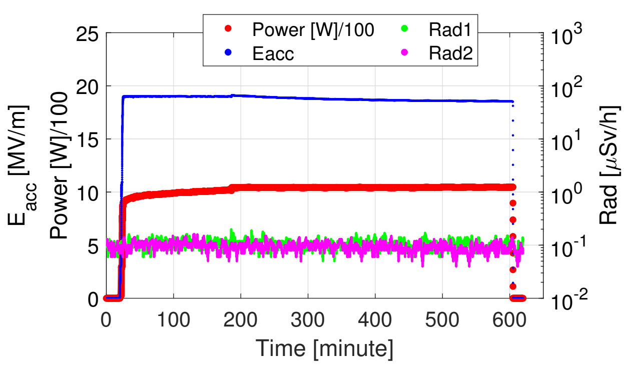

Figure 4: Stable operation of the first prototype in the horizontal test.

The maximum gradient of the cavity in the horizontal test reached 20.3 MV/m, which is same as the vertical test. Q_0 was measured by liquid level method, having a good consistence with the vertical test, as shown in Fig. 3.

Stable operation was kept at 18.9 MV/m for 580 minutes in CW mode, as shown in Fig. 4. The horizontal test was terminated due to an interlock triggered by an overpressure of helium caused by the overfilled liquid level. No field emission was detected in the horizontal test.

VERTICAL ACCEPTANCE TESTS OF THE FIRST BATCH

The vertical acceptance test of the batch bare cavities has been finished. The performance curves of the 10 bare cavities are shown in Fig. 5 and Table 3 summarizes the results. The average Q_0 at 13.1 MV/m is 3.2×10^9 and the maximum E_{acc} is 22.6 MV/m.

Field emission was observed in most cavities of the first batch. The HPR setup and clean room of 3.9 GHz cavity assembly are now under investigation. The first batch will be helium vessel integrated and re-HPR before testing.

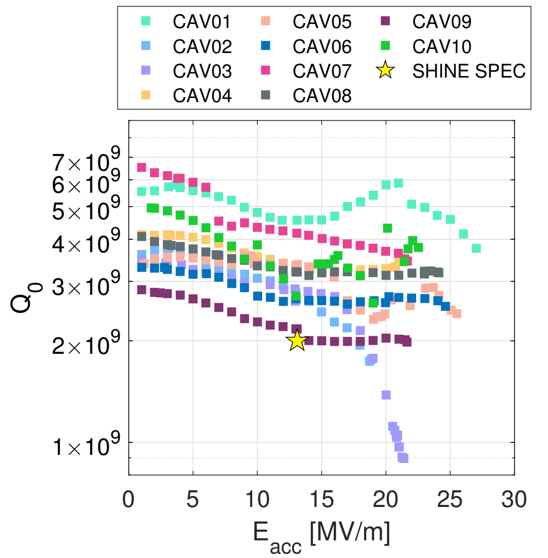

Figure 5: Vertical test results of the first batch of the SHINE 3.9 GHz bare cavities at 2 K.

Table 3: Summary of the first batch of SHINE 3.9 GHz bare cavities' vertical test performances. The uncertainties are the standard deviations of the measured values.

Quantity	Value
E_{acc} [MV/m]	22.6 ± 2.9
Q_0 [10^9] at 4.5 MV/m	4.0 ± 1.1
Q_0 [10^9] at 13.1 MV/m	3.2 ± 0.7
Q_0 [10^9] at 15.0 MV/m	3.1 ± 0.8

CONCLUSION

As a key component to the SHINE linac, 3.9 GHz cavities have been studied and developed in the past few years. Twenty-one 3.9 GHz 9-cell cavities including two prototypes were fabricated in total. The prototypes were qualified in the vertical tests and one was installed in a small cryostat and horizontal tested. A maximum gradient of 20.3 MV/m was achieved in both of the vertical and horizontal tests. Stable operation was also conducted in the horizontal test. Two batches of series cavities were fabricated based on the successful results of the prototypes. The first batch of 10 bare cavities was qualified in the vertical tests. The average Q_0 at 13.1 MV/m is 3.2×10^9 and the maximum E_{acc} is 22.6 MV/m. The first SHINE 3.9 GHz 8-cavity cryomodule is expected to be tested in late 2024.

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