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DEVELOPMENT OF 3.9 GHz 9-CELL CAVITIES AT SHINE

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Abstract

The Shanghai high-repetition-rate XFEL and extreme light facility (SHINE) Linac requires two 3.9 GHz crymodules to linearize energy distribution before the bunch compressor. As a key component to the project, studies of 3.9 GHz cavities were conducted in the past few years. The first 3.9 GHz 9-cell prototype cavity has been fabricated, tested, and qualified. It reached Q_0=3.5×10^9 at 13.1 MV/m and a maximum accelerating gradient of 25.0 MV/m during the vertical test of the bare cavity. The prototype has been helium tank integrated and reached Q_0=2.9×10^9 at 13.1 MV/m in the vertical test, with a large margin with respect to the SHINE specification. The second prototype has been fabricated and is planned to be tested in 2023. This paper will cover the fabrication, surface treatment, and RF test of the 3.9 GHz cavities.

INTRODUCTION

The main part of the SHINE Linac is an 8 GeV superconducting accelerator operating in continuous wave (CW) mode. It consists of seventy-five 1.3 GHz cryomodules and two 3.9 GHz cryomodules [1–4]. The third harmonic cavities compensate the nonlinear longitudinal phase space distortion due to the accelerating field curvature in the 1.3 GHz cavities prior to bunch compression [5, 6].

As a key component to maintain low emittance beam for the production of FEL light to the experimental users, 3.9 GHz cryomodules 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]. The rf design of the 3.9 GHz 9-cell cavity has been optimized for SHINE project [16]. Two prototypes of 3.9 GHz 9-cell cavities have been fabricated and one of them has been vertical tested. Mass production of the 3.9 GHz SHINE cavity series has been started. This paper presents the results of the prototypes achieved so far, and the status of the SHINE 3.9 GHz cavities.

RF DESIGN OF THE CAVITY

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. Beam pipe and end half-cell of the SHINE 3.9 GHz cavity was modified compared with the other designs. Inner cell was kept the same. The radius of the beam pipe was decreased to 38.0 mm to shift the lowest dipole mode to 4165 MHz. This is to avoid difficulties for fundamental mode operation and HOM notch tuning [14, 15]. Details of the rf design could be found in Ref. [16].

FABRICATION OF THE PROTOTYPES

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]. The fabrication of the first prototype started from the beginning of 2021 and the second one started from the end of 2022.

Bare Cavity Fabrication

The production of the SHINE 3.9 GHz prototypes adopted standard fabrication procedures [10]. The components of 3.9 GHz 9-cell cavity including half-cells, dumbbells, and end groups were characterized both in mechanical measurements and rf tests during the processing.

The half-cells were prepared with an additional length at both iris and equator area which accounts for the welding shrinkages and trimming procedures. Inner shape of the half-cells and dumbbells were checked by the coordinate measuring machine. Figure 1 shows all the components of the prototype before final welding.

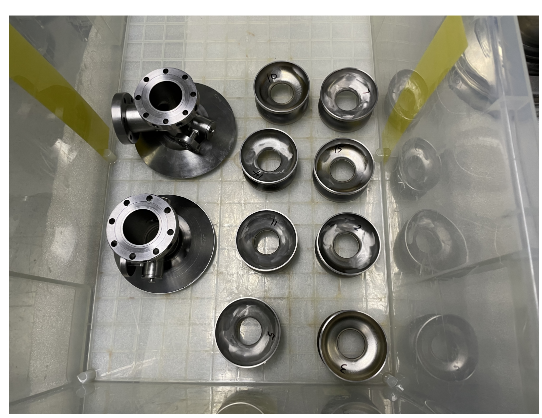

Figure 1: Components of the prototype before welding.

The dumbbells were trimmed to meet the designed frequency and length at the same time before integrating together. The sensitivity coefficients applied in the trimming

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were derived from the simulation and the experimental studies during the single-cell cavity production. Then the dumbbells and the end groups were welded into the cavity structure. Figure 2 presents the picture of the first 3.9 GHz prototype.

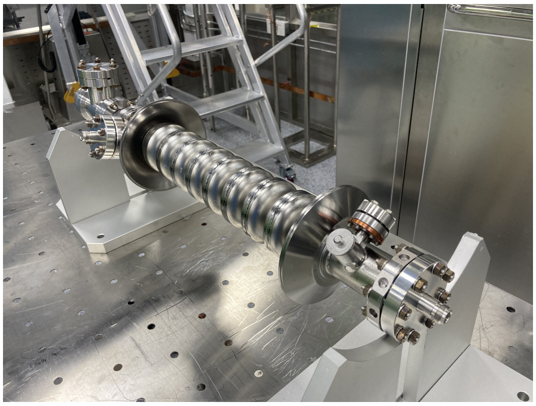

Figure 2: Bare cavity of the first prototype.

The measurement results of the two prototypes were summarized in Table 1. The results were measured at room temperature and atmospheric pressure. Note that the eccentricity of the second prototype was improved by the lip-weld geometry at the iris of the half-cell.

Table 1: Results of the Prototype Production

Quantity	**1_{st} proto.**	**2_{nd} proto.**	**Goal**
Length [mm]	508.7	509.5	506.0^{+4}_{-4}
Frequency [MHz]	3903.0	3902.8	3898.5^{+5}_{-5}
Eccentricity [mm]	1.0	0.46	<1.0
Field flatness [%]	89.0	86.6	>50

Surface Treatment

Buffered chemical polishing (BCP) treatment was applied to the surface preparation of the 3.9 GHz 9-cell prototype. Firstly a heavy BCP of 120 µm was performed to remove damaged layers, pollutants, and defects on the surface of the cavity caused by processing and manufacturing. The polishing process parameters and acid ratio was optimized in SHINE project. The polished surface was flat, smooth, and bright without obvious defects, as shown in Fig. 3.

Heat treatment at 900 °C was then applied in an ultra-high vacuum furnace for 3 hours to remove H_2 from bulk niobium, as shown in Fig. 4. A light BCP of 20 µm was performed afterwards to remove high loss layers formed on the surface during the heat treatment.

Field Flatness Tuning

A frequency and field flatness tuning was performed between the processing of the heat treatment and the light BCP. The field flatness is required to be better than 95%. A tuning machine was developed for the SHINE 3.9 GHz cavities, as shown in Fig. 5. The middle cells were squeezed or stretched by the translation of two movable clamping plates. The end cell was tuned by shifting the clamping plate and fixing the side of the cavity.

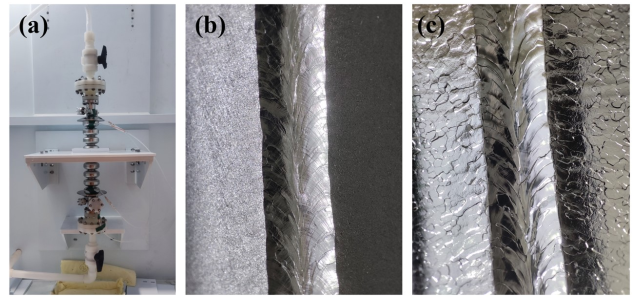

Figure 3: (a) BCP treatment of the 3.9 GHz prototype; Inner surface of the prototype before (b) and after (c) 120 µm BCP.

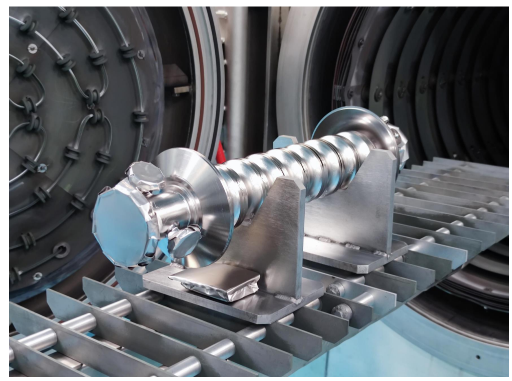

Figure 4: Heat treatment of the 3.9 GHz prototype inside the vacuum furnace.

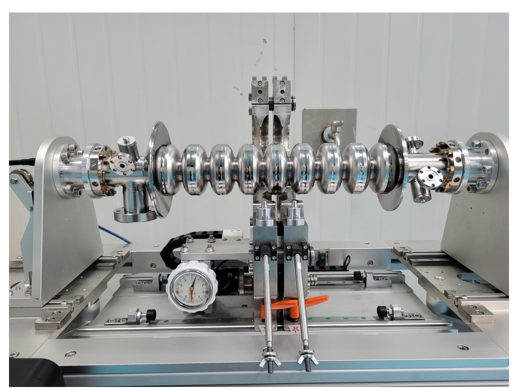

Figure 5: Field flatness tuning of the 3.9 GHz prototype.

The field distribution of the cavity was obtained by bead-pull measurement. The tuning quantity of each cell was calculated based on the field flatness result and the frequency deviation from the target. Frequency and field flatness would be re-evaluated after operating the clamping plates. After iterating the operations as described above, the frequency of the first prototype was adjusted to 3892.84 MHz at room temperature and atmospheric pressure. The field flatness was tuned to 95.9% at the same time.

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Optical Inspection

The optical inspection was conducted to monitor the inner surface of the cavity. It is an important processing to improve the electron beam welding and the surface treatment of the cavity. A self-made borescope system was developed to inspect the inner surface of the 3.9 GHz cavity, as shown in Fig. 6. The system consisted of a movable support, a insertion probe, and a macro camera module. The prototype was horizontally placed on the support which allowed the cavity to be rotated. The rotating angle information was recorded by the maker placed on the beam pipe flange. The insertion probe, which was equipped with the macro camera module and the light source composed of multiple LEDs, was inserted into the cavity. The support could be moved by a stepper motor along the beam direction to adjust the cells to be observed.

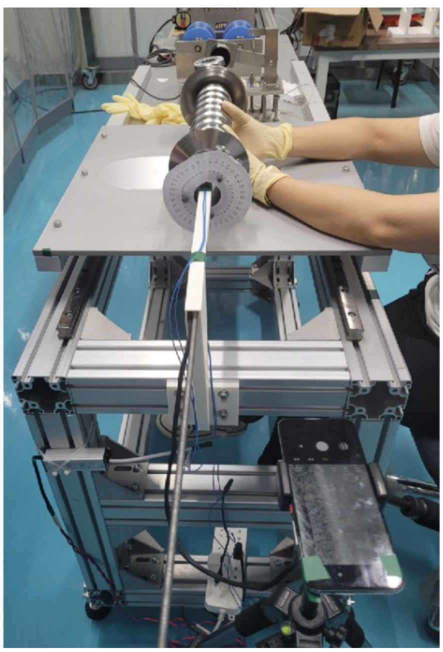

Figure 6: Borescope system of the 3.9 GHz prototype.

Helium Tank Integration

Helium tank was TIG welded to the bare cavity. The bare cavity was sealed with 1050 mbar nitrogen before the welding. An inner magnetic shield was designed and installed before the integration [18]. Mechanical test and helium tank pressure test were performed before the vertical test. The dressed cavity is shown in Fig. 7.

TESTS OF THE PROTOTYPE

The specification of SHINE 3.9 GHz cavity is $Q_0 > 2.0{\times}10^9$ at 13.1 MV/m and maximum $E_{acc} \geq 16.5$ MV/m. The bare cavity and dressed cavity of the first prototype were vertical tested at SHINE testing facility.

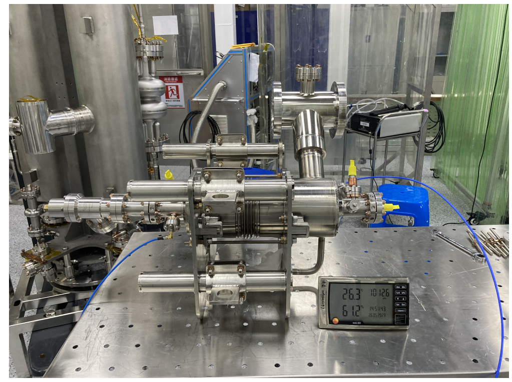

Figure 7: Dressed cavity of the first prototype.

Vertical Tests

The vertical test results of the bare cavity is shown in Fig. 8. A 75/120 °C baking was performed to the bare cavity after the first vertical test [19]. Q_0 was increased from $3.1{\times}10^9$ to $3.6{\times}10^9$ at 13.1 MV/m after the 75/120 °C baking. The maximum accelerating gradient was slightly increased from 24.1 MV/m to 25.2 MV/m. A Q_0 of $4.0{\times}10^9$ was obtained at 19.0 MV/m. However, a degradation of both Q_0 and maximum E_{acc} was observed after the helium tank integration. Q_0 was reduced to $2.9{\times}10^9$ at 13.1 MV/m and the maximum accelerating gradient was 20.3 MV/m. The performance achieved by the first prototype has a large margin with respect to SHINE specification. The dressed cavity will be vertical tested again soon after high pressure rinsing (HPR) and re-assembling. Then the horizontal test will be conducted together with an 1.3 GHz cavity in a small cryostat.

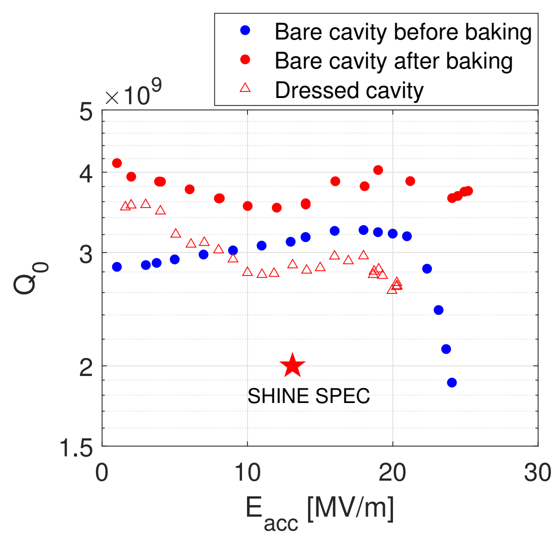

Figure 8: Vertical test results of the first prototype.

PRODUCTION OF THE 3.9 GHz SHINE CAVITY SERIES

Based on the fabrication experience and vertical tests of the prototypes, mass production of the 3.9 GHz SHINE cavity series has been started. A first batch of ten cavities was under fabrication for the first 3.9 GHz cryomodule.

SUMMARY

SHINE Linac requires two 3.9 GHz crymodules to linearize energy distribution. Two prototypes have been fabricated and one of them has been helium tank integrated. Optical inspection indicated a smooth inner surface achieved by the surface treatment. The frequency and field flatness met the SHINE requirements after the tuning. The first prototype reached 3.6×10^9 at 13.1 MV/m with a maximum accelerating gradient of 25.2 MV/m in the vertical test of the bare cavity. The dressed cavity achieved 2.9×10^9 at 13.1 MV/m with a maximum accelerating gradient of 20.3 MV/m. It will be vertical tested again followed by the horizontal test in a small cryostat. The second prototype is under surface treatment and will be tested soon. Fabrication of the SHINE cavity series has been started based on the promising results of the prototype.

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