ISBN: 978-3-95450-211-0 doi:10.18429/JACoW-SRF2019-MOP049

PROTOTYPES FABRICATION of 1.3 GHz SUPERCONDUCTING RF COMPONENTS FOR SHINE PROJECT*

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Abstract

Aiming to high repetition rate hard X-ray facility, construction of Shanghai HIgh repetition rate XFEL aNd Extreme light facility (SHINE) project has been approved. During the R & D phase, prototypes fabrication of key components of 1.3GHz superconducting rf system have been proposed, especially 1.3 GHz 9-cell niobium cavities. Here the paper will present the progress of the fabrication status and performance of the prototypes, together with the analysis of not only the quality factor and gradient of the cavities. Consideration of HOM feedthroughs and absorbers are also reported.

INTRODUCTION

The SHINE project is a high repetition rate hard XFEL facility driven by a superconducting RF linear accelerator with energy higher than 8.0 GeV [1]. The LINAC mainly includes sixteen 3.9 GHz 9-cell niobium cavities for linearization and six hundreds of 1.3 GHz 9-cell cavities for acceleration. As the operating repetition can be up to 1.0 MHz, the SRF cavities will be operated at continuous wave mode which brings the challenge of higher quality factor performance for the purpose of decreasing dynamic power and thus reduce the cost of cryoplant. The specification of 1.3 GHz cavities is defined to have Q_0=(2~3) $\times 10^{10}$ at E_{acc} = 14~18 MV/m.

The TESLA type 1.3 GHz 9-cell cavities have been already adopted in European XFEL [2,3] and SLAC LCLS-II [4,5] facilities which prove the cavity type to be successful. Because industrial production of TESLA type cavity has been accomplished for EXFEL and LCLSII, it is also decided to adopt the cavities based on TESLA type in SHINE project. As the required high Q-factor performance, SHINE started the prototype fabrication in China in order to obtain the fabrication techniques and the surface treatment procedures especially the nitrogen doping recipes, to condition the test infrastructures and to train the technicians.

For EXFEL and LCLS-II, the cavities is made of fine grain material but with different surface treatment procedures. EXFEL adopts the bulk EP together with low temperature baking (120°C) [2] and LCLS-II adopts the bulk EP together with N2 doping [4, 6]. The N2 doped cavities can have high quality factor in the medium accelerating gradient which can fulfill the SHINE cavities specification.

Therefore, the baseline of SHINE 1.3GHz 9-cell cavities' surface treatment is bulk EP with N2-doping. In the same time, as the large grain (LG) cavities always show higher Q performance [7,8] than the fine grain (FG) cavities, we decided to start the LG cavities fabrication during SHINE R&D phase.

In this paper, we present the recent results of SHINE prototypes of cavities made of FG and LG material in detail. Considerations of HOM absorbers are reported, too.

CAVITY SPECIFICATION AND PROTOTYPE R&D SCHEME

TESLA type 1.3GHz 9-cell cavity has been widely installed in several accelerator facilities and its parameters such as the dimensions, r/Q value, geometry factor can be found in many papers [9] we will not present all of them in detail in this paper. Because of the high Q-factor requirement, some related parameters defined as SHINE specification can be seen in Table 1. The inner diameter of 2-phase line is enlarged from 76 mm to be around 98 mm [10] for better conduction and for improving the mass flow. The Q_0 factor is in the range of $(2.0 \sim 3.0)\times 10^{10}$ at 16 MV/m gradient, while the average Q0 is defined to be higher than 2.7×10^{10}, which means the dynamic power is 10 W. The gradient at vertical test should be larger than 19 MV/m without field emission.

Table 1: Specification of SHINE 1.3 GHz 9-cell Cavity

Cavity type	TESLA
Operation freq.	1300.2 +/- 0.1 MHz
Operation mode	CW
Cavity length	1283.4 +/- 3.0 mm
Q_0 @ E_{acc}=16 MV/m	2.7×10^{10} (average)
Dynamics load	10 W
E_{acc} @ vertical test	> 19 MV/m
Field flatness	> 95% (bare cavity)
Field flatness	> 90% (dressed)
Ambient Magnetic.	< 5 mGauss
cooldown/warmup	two lines
ID. of 2-phase	98 mm
Optimal FPC Q_e	4.12×10^7

Several 1.3 GHz 9-cell cavities were fabricated and vertical tested in China before SHINE project was approved. In order to ensure a successful prototype fabrication, we find a wide collaboration in China to take the advantage of

* Work supported by SHINE project
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their experience from PKU, IHEP and HIT. The cavity prototype RD scheme find three groups collaboration for twenty-four 1.3 GHz 9-cell cavities fabrication, together with the studies of EP treatment and N2-doping recipe. This scheme includes almost all the companies and institutes which have the 1.3 GHz 9-cell cavities fabrication experience.

- Group-1: HE-Racing Technology (HERT) and Institute of High Energy Physics (IHEP), CAS. This group will mainly fabricate the fine grain cavities.
- Group-2: Peking University (PKU), which will mainly concentrate on large grain cavities fabrication.
- Group-3: Harbin Institute of Technology (HIT) and Shanghai Institute of Applied Physics (SINAP), CAS. This group will also mainly fabricate the fine grain cavities, too.

Our prototype R&D in China is divided into two steps. At first phase, each group will fabricate eight cavities using different acid polishing: four BCP cavities and four EP cavities. The fine grain cavities will be N2 doped. At the second phase, we will select two of the three groups to fabricate sixteen more cavities to fix our fabrication and surface treatment procedures. Besides the prototype RD in China, SHINE will collaborate with DESY on research of large grain cavities.

NIOBIUM MATERIAL

During prototype R&D, the niobium material will be supplied by SHINE. We chose the same niobium suppliers as EXFEL and LCLS-II: NingXia OTIC (NX) and Tokyo Denkai (TD). Both NX and TD supplied SHINE the RRR300 FG sheets with almost the same specification of EXFEL. LG Nb material was supplied by NingXia OTIC.

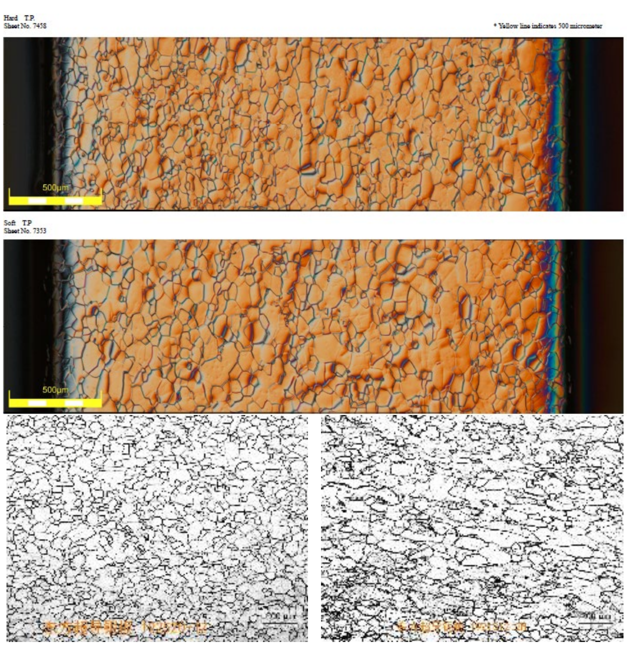

Figure 1: Micrograph of niobium material. Up: TD material. Bottom: NX material.

As the niobium material quality such as the grain size is one concern for N2 doping [11], we asked NX to change the processing parameters in order not to have too fine grain. The main grain size is defined to be ASTM 6 and in the range of ASTM 7 to ASTM 4. Figure 1 shows the samples of NX and TD niobium material, respectively. From the inspection document, grain size of NX material is from ASTM 4.5 to ASTM 5.5, and grain size of TD material is from ASTM 5 to ASTM 6. As lack of eddy current machine, the niobium sheets were accepted only by eye inspection. The single cell cavities have been made of both NX and TD material for N2 doping recipes.

1.3GHz 9-CELL CAVITIES FABRICATION

The baseline of SHINE 1.3 GHz 9-cell cavities is to be fabricated using FG material, electropolished and N2-doped because of the high Q0 factor requirement. Firstly, four BCP-ed cavities will be fabricated, surface treated ad vertical tested in order to verify all the fabrication procedures including deep drawing, electron beam wielding, surface treatment procedures, clean assembly techniques and to test and improve the function of SRF infrastructures and vertical testing stand. The Q_0 is required to be in the range of (1.0 ~ 1.5) $\times 10^{10}$ at 16 MV/m while the gradient shall still be higher than 19 MV/m in vertical test. Secondly, four EP-ed cavities will be N2-doped once the doping recipes are obtained from single cell experiments. The Q_0 is required to be in the range of (2.0 ~ 3.0) $\times 10^{10}$ at 16 MV/m. Up to now, four FG bare cavities have been fabricated by Group-1, and two LG bare cavities by Group-2. All these six cavities were carried out with about 150 µm heavy BCP, 750°C annealed, pre-tuned, HPR and about 25 µm light BCP. Low temperature baking at 120°C is carried out to FG cavities for 48 hours. The first fabricated FG bare cavity by Group-1 and two LG bare cavities by Group-2 are shown in Fig. 2. Some parameters such as cavity length, field flatness, frequency can be seen in Table 2.

Figure 2: First FG cavity fabricated by Group-1 in the shipping box and two LG cavities fabricated by Goup-2 after 750°C annealing.

In Table 2, regarding to FG cavities, after pre-tuning and field flatness adjusted, cavity length (flange to flange) meets the specification. Frequency at 2.0K, too. The cavities' length of the two LG cavities are waiting for measurement after vertical testing. The field flatness of all the bare cavities is better than 95% which meets SHINE specification.

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Table 2: Performance of Fabricated FG and LG Cavities

Cavity number	FG#1	FG#2	LG#1	LG#2
Cavity length @ RT & 1.0 bar (mm)	1284.55	1283.59	Not measured	Not measured
Field flatness (%)	95.0	98.0	98.4	97.4
Freq. @ RT & 1.0 bar (MHz)	1298.22	1298.17	1298.11	1298.07
Freq. @ 2K vacuum (MHz)	1300.25	1300.20	1300.38	1300.44
Q_0 @ 16 MV/m @ 2.0K	1.50×10^{10}	1.15×10^{10}	1.75×10^{10}	1.89×10^{10}
Q_0 @ 16 MV/m @ 1.8K	/	1.31×10^{10}	3.0×10^{10}	3.20×10^{10}
Maximum gradient (MV/m)	20.0	19.6	25.3	26.0
Gradient limited by	N-connector broken	quench	LHe	quench

The Q_0~E_{acc} performance of BCP polished cavities have all fulfilled the specification, however, the maximum gradient is lower compared to the world level limited by quench. It is hard to distinguish if it is a real quench without temperature mapping system or second sound detectors. One FG cavity has been welded with helium vessel and vertical tested which turns out to be no performance degradation by helium vessel weldment. The Q_0~E_{acc} curve can be seen in Fig. 3.

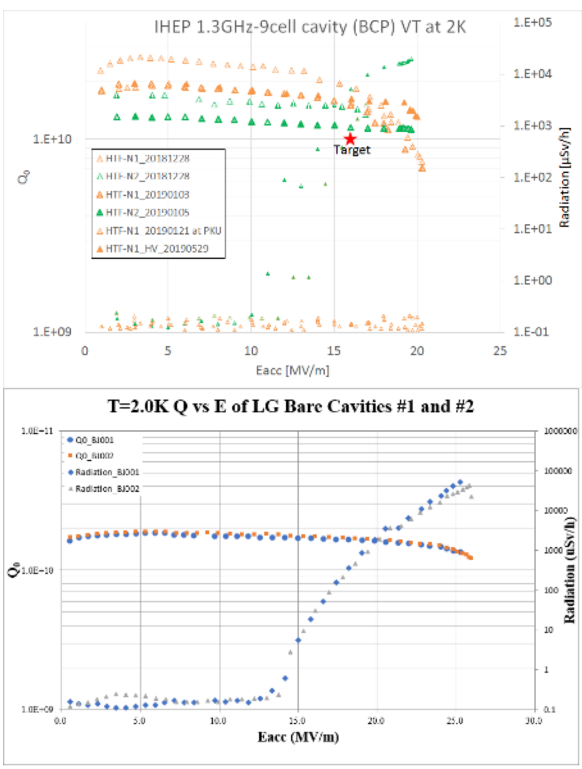

Figure 3: vertical testing results of SHINE 1.3 GHz prototype cavities at 2K. Up: FG cavities by Group-1. Bottom: LG cavities by Group-2.

Regarding to the LG cavities, from Table 2, the ratio of Q0 at 2.0 K and 1.8 K is about 1.7, which shows LG material can be a good candidate for high Q performance and CW operation. In Figure 3, we can see field emission arises around 10 MV/m for FG #2 cavity, and it arises around 13.3 MV/m and 14.4 MV/m for two LG cavities, respectively. We suspect the time of HPR maybe not enough.

In order to find out if the performance of FG cavities are limited by weld joints, one Kyoto type camera was used to inspect the inner surface of FG #3 and #4 cavities, which will be clean assembled and vertical test. From the photos, it turns out no defects around the joints area, however, the performance still needs vertical testing. Figure 4 shows one photo of FG #3 cavity at one position of equator as an example.

Figure 4: Photo of inner surface at one equator of FG #3 cavity, which shows no defects.

CONSIDERATIONS OF OTHER RF COMPONENTS

SHINE machine will be operated at high repetition rate up to 1.0 MHz and SRF cavities will be operated at CW mode, which will not only bring challenge for high Q performance, but the HOM feedthroughs, pickup feedthroughs and HOM absorbers. The XFEL design has been specified for HOM and pickup feedthroughs for SHINE cavities. With 300 pC charge and 1.0 MHz repetition rate,

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when the bunch length is 21 μm at L3 section, the HOM power generated by the beam at the first four crymodules are 34.4 W, 15.9 W, 14.7 W and 14.6 W, respectively. According to the HOM absorber design and its thermal connection, the thermal connection area should be optimized, which is similar with the results of LCLS-II [12]. Figure 5 shows the temperature distribution of a simplified absorber model cooled by 45 K with 35 W dissipated power. The thermal connection is selected to be 16 mm × 50 mm which can ensure the highest temperature at the bottom of the ceramics to be 118 K. Further simulation of the absorber including thermal stress will be carried out soon.

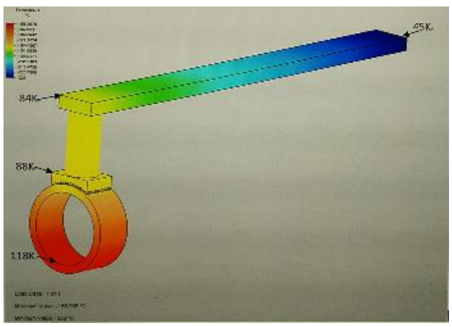

Figure 5: Temperature distribution of absorber with 35 W dissipated power.

SUMMARY

The 1.3 GHz 9-cell cavities prototype R&D have been started and two FG cavities and two LG cavities have been fabricated and vertical tested. The performance has been reported and analyzed. The BCP treated cavities have met SHINE prototype specification, however, it needs more diagnostic tools to tell which limits the performance. Field emission was found which requires more tests to judge the problem is from HPR or clean assembly.

ACKNOWLEDEMENT

The authors would like to thank many partners from OSTEC, PKU, IHEP, KEK and SARI for their great help.

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