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HIGH Q AND HIGH GRADIENT PERFORMANCE OF THE FIRST MEDIUM-TEMPERATURE BAKING 1.3 GHz CRYOMODULE

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Abstract

World's first 1.3 GHz cryomodule containing eight 9-cell superconducting radio-frequency (RF) cavities treated by medium-temperature furnace baking (mid-T bake) was developed at the Institute of High Energy Physics (IHEP), Chinese Academy of Sciences. The 9-cell cavities in the cryomodule achieved an unprecedented high average intrinsic quality factor (Q_0) of 3.8×10^{10} at 16 MV/m and 3.6×10^{10} at 21 MV/m in the horizontal test. The cryomodule can operate stably up to a total continuous wave (CW) RF voltage greater than 193 MV, with an average cavity usable accelerating gradient of more than 23 MV/m. The results significantly exceed the specifications of Circular Electron Positron Collider (CEPC) and Dalian Advanced Light Source (DALS) and the other high repetition rate free electron laser facilities (LCLS-II, LCLS-II-HE, SHINE, S^3FEL etc.). This contribution reviews the cryomodule performance and discusses some important issues in cryomodule assembly and testing.

INTRODUCTION

High Q_0 1.3 GHz cryomodules operating in the CW mode are critical technology for several major scientific projects under construction or being planned in the world. For example, Shanghai High Repetition Rate X-ray FEL and Extreme Light Facility (SHINE) [1], Shenzhen Superconducting Soft X-Ray Free Electron Laser (S^3FEL) [2], and high duty cycle upgrade of the European XFEL [3]. High Q_0 will save a large part of the construction and operational cost of the cryogenic system for these projects.

The successful commissioning and operation of Linac Coherent Light Source II (LCLS-II) at SLAC first time demonstrated high Q_0 cavity in a CW superconducting RF linac [4] with nitrogen-doping (N-doping) technology [5]. Fermilab and JLAB has achieved even ambitious performance goals in LCLS-II-HE prototype and production cavities and cryomodules by improving the nitrogen doping technology [6-8].

Medium-temperature baking (mid-T bake) is a novel high Q_0 recipe discovered in 2019 [9-11] by Fermilab. KEK simplified the implementation of the recipe by mid-T baking of the unassembled cavity in a normal vacuum furnace (so called mid-T furnace baking) [12], which is more accessible than the original in-situ mid-T bake. KEK's systematic investigations showed that 300 C bake has the highest Q_0 [13].

Based on Fermilab and KEK's experience on single cell cavities, IHEP further simplified mid-T furnace bake procedure to only one bulk EP (without light EP) and successfully applied it first time to 1.3 GHz 9-cell cavities in October 2020 [14, 15]. Since then, fourteen mid-T 9-cell cavities have been tested with high reliability by industrial vendors. Researches from other labs [16-19] also confirmed the mid-T furnace bake a reproducible and stable recipe for high Q_0 cavities. In June 2023, a 1.3 GHz cryomodule with eight mid-T furnace baked 9-cell cavities was assembled and tested at IHEP and achieved world leading high Q_0 and high gradient.

There are some distinct advantages of mid-T bake compared to nitrogen doping [20]. Mid-T bake has been widely applied successfully to large grain cavities [21, 22], other frequencies and shapes [23, 24] and even carried out without furnace [25]. In particular, mid-T furnace bake high Q_0 recipe was recently adopted for the low-beta 650 MHz 5-cell cavities for Fermilab's PIP-II project [26]. The ongoing and future high repetition rate FEL and ERL projects (e.g. SHINE, S^3FEL, DALS, PERLE and high duty cycle upgrade of European XFEL etc.), as well as the energy frontier circular lepton colliders (CEPC, FCC-ee) are all considering to use mid-T furnace bake treatment for their large number of cavities.

Therefore, demonstration of mid-T bake cavity performance in a real cryomodule is becoming essential for the development and practical application of this novel high Q_0 technology. In this contribution, we report the performance of the world's first mid-T bake cryomodule.

CRYOMODULE ASSEMBLY AND INSTRUMENTATION

The cryomodule structure and assembly procedure are similar to LCLS-II cryomodules which is modified from Euro-XFEL design. The 12 m long cryomodule (Fig. 1) contains eight 1.3 GHz 9-cell cavities, eight power input couplers, eight tuners with piezos, one conduction-cooled superconducting magnet and one BPM. Measures to reduce microphonics were adopted according to LCLS-II experience [27]. To avoid contamination risk, the cavity string was kept in vacuum after leak check all through to the horizontal test. To reduce the multipacting processing time, the cavity string was also pumped by a turbo molecular pump whenever possible during the cold mass

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assembly outside the clean room for better cavity vacuum [28].

Figure 1: 1.3 GHz cryomodule with eight mid-T bake 9-cell cavities in the horizontal test stand at IHEP's Platform of Advanced Photon Source (PAPS), Huairou, Beijing.

Temperature sensors were mounted on the top and bottom of cell#1 and cell#9 of cavities#1, #5, and #8 to monitor the temperature difference at the critical temperature. Flux gates were mounted on the outside of the cavity wall inside the helium vessel in different directions to monitor the magnetic field. Six radiation detectors around the cryomodule and two Faraday cups in the upstream and downstream end of the beam pipes were used to detect the field emission and dark current.

Temperatures of all the 16 HOM coupler feedthroughs and 8 input coupler cold windows were also monitored. These thermal sensors were critical to find the overheating of the HOM couplers and input couplers.

MULTIPACTING PROCESSING AND GRADIENT PERFORMANCE

TESLA-shape cavities treated with high Q_0 recipe (e.g. N-doping, no low temperature bake after high pressure rinsing) sometimes need more multipacting processing than EP baseline recipe (120 C bake after high pressure rinsing), especially in the cryomodule [6, 29]. This poses a particular challenge to the relevant machines whose nominal operation gradient lies within the range of multipacting band at 17-24 MV/m of the TESLA-shape cavity.

For the mid-T cryomodule, it took two days' processing to increase the gradient of the eight 9-cell cavities to their maximum gradient. Two of the cavities (cavity#2 and cavity#8) showed repetitive quenching during the processing, while the other cavities had nearly no multipacting quench. Cavity#2 took four hours to reach 19 MV/m (14 quenches at < 14 MV/m, 12 quenches at 17-19 MV/m). Cavity#8 took five hours to reach 26 MV/m (57 quenches at 17-24 MV/m).

Cavity#2 quenched below 20 MV/m due to overheating of the HOM coupler feedthrough on the field pick-up side. It is necessary to further improve the thread and bolt structure of the thermal anchor of the HOM coupler feedthroughs to avoid large gradient drop in the cryomodule, especially for long distance transportation. Cavity#5 had severe outgassing in the warm part of the input coupler, and pulsed RF conditioning was carried out to solve the problem.

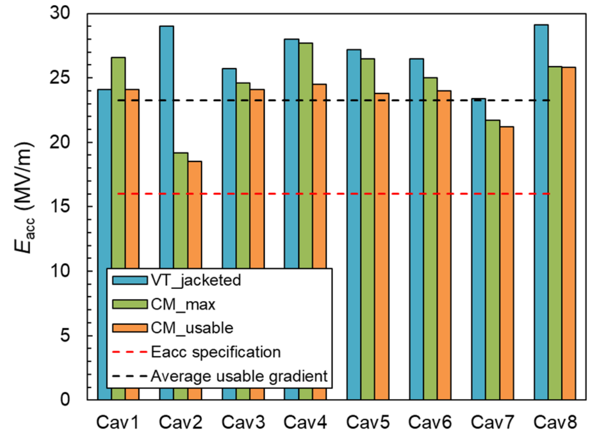

Figure 2: Comparison of vertical test gradient, cryomodule maximum gradient and cryomodule usable gradient for each cavity in the mid-T bake cryomodule.

Figure 2 shows the vertical test gradient, cryomodule maximum gradient and usable gradient for each cavity. The usable gradient is defined as the maximum gradient at which the following three conditions are met: (1) radiation level is below 0.5 mSv/h. (2) the cavity can run stably for one hour. (3) 0.5 MV/m below the quench field. The cryomodule maximum gradient of Cavity#8 is limited by the available RF power instead of quench. The reason that Cavity#1's cryomodule maximum gradient is higher than vertical test is probably due to not enough processing during the vertical test.

When all eight cavities were operating at 16 MV/m, the maximum radiation dose of the six detectors was 0.08 mSv/h, below the specification of 0.5 mSv/h. The field emission control results verified the clean assembly procedure of the cavity string as well as the end beam pipes connections.

Dark current was measured by Faraday cups at each end of the beam pipe outside of the cryomodule when all the eight cavities operating at 16 MV/m. The dark current was always below the background by RF phase scanning, and fulfiled the specification of 1 nA.

The cryomodule stably reached to a total CW RF voltage of 193.5 MV when all eight cavities and the superconducting magnet were powered on. The average cavity CW gradient is 23.3 MV/m, which is higher than the average gradient of the LCLS-II cavities in the cryomodule (18.2 MV/m) [4] and comparable to the average gradient of the LCLS-II-HE cryomodules (24.3 MV/m) [8]. The cryomodule performed continuous operation for 12 hours at 133 MV (all cavities working at 16.0 MV/m) without any trip. The temperatures of the input couplers' cold windows reached 65-88 K and were near saturation, which were lower than the specification of 100 K.

Q_0 PERFORMANCE

After all the cavities were processed to the maximum gradient with multiple quenches, the cryomodule was

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warmed up to 40 K and cooled down to 2 K again. The static and dynamic 2 K heat load of the cryomodule were measured using the mass flow rate method [30]. A heater in the liquid level tank at the end of the two-phase pipe was used to calibrate the mass flow. The static heat load of this cryomodule is 25.8 W [30].

Total 2 K heat load of the cryomodule at 133 MV (16 MV/m average gradient) is 83.5 W, which fulfils the specification of DALS (130 W) as well as LCLS-II and SHINE (93 W). Total 2 K heat load of the cryomodule at 173 MV (21 MV/m average gradient) is 133 W, which fulfils the specification of LCLS-II-HE (137 W). The average Q_0 of eight cavities was calculated from the total 2 K dynamic heat load of the cryomodule. The heat load of the input couplers was very small, so it was included in the cavity dynamic heat load. The average Q_0 at 2 K is 3.8×10^{10} at 16 MV/m and 3.6×10^{10} at 21 MV/m, which are far beyond the specifications of the related 1.3 GHz CW superconducting accelerators. The Q_0 of the individual cavities at 2 K was measured at 16 MV/m and 21 MV/m (Fig. 3).

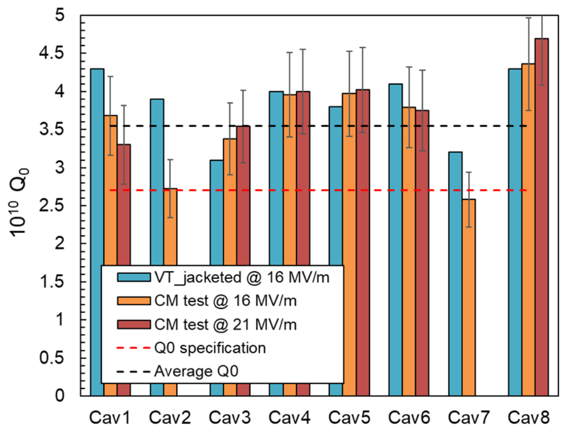

Figure 3: Comparison of cavity Q_0 in vertical test at 16 MV/m, Q_0 in the cryomodule at 16 MV/m and 21 MV/m.

The remnant magnetic fields on the cavity walls at 2 K were all less than 5 mG. Preliminary studies showed that the average cavity Q_0 values in the cryomodule were similar for slow (8~12 g/s) cool down and fast cool down (> 40 g/s), and the top to bottom cavity temperature differences at the critical temperature were all near or larger than 4 K in these two cases, which was enough for the flux expulsion [31].

SUMMARY AND OUTLOOK

The world's first medium-temperature baked (mid-T) high Q_0 1.3 GHz cryomodule is developed at IHEP. Main performance of the cryomodule including the total RF voltage, cryogenic heat load and radiation dose meets the requirement of DALS, S^3FEL and SHINE, and is beyond LCLS-II-HE and CEPC specification. The module can operate stably up to a total RF voltage greater than 193 MV with an average usable gradient of more than 23 MV/m, and has unprecedented 2 K high average Q_0 of 3.8×10^{10} at 16 MV/m and 3.6×10^{10} at 21 MV/m. Mid-T bake is expected to be a feasible and promising technical approach for future high Q_0 superconducting accelerators.

More mid-T bake 1.3 GHz cavities and cryomodules will be built for China's FEL projects in next few years for further investigations and improvements

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