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EVALUATION OF A HIGH PERFORMANCE LARGE GRAIN MEDIUM PURITY SRF CAVITY FROM KEK*

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Abstract

We present the RF measurement results for a 1.3 GHz single-cell cavity fabricated at KEK made from large grain ingot niobium with RRR=107. The cavity reached ~35 MV/m with a $Q_0 \sim 2.0\times10^{10}$ at 2.0 K, which is a record performance for a cavity made from medium purity ingot niobium. The cavity was cooled down with different temperature gradients along its axis in order to understand the flux expulsion mechanism when the cavity goes through the superconducting transition, and to investigate the effect of trapped magnetic fields on the residual resistance. The measurements revealed excellent flux expulsion with a flux trapping sensitivity of 0.29 nΩ/mG for an electro-polished surface and 0.4 nΩ/mG for the cavity followed by a low temperature baking at 120 ºC for 24 hours.

INTRODUCTION

Superconducting niobium (Nb) has been the material of choice for modern particle accelerators to accelerate charged particles given the lower power dissipation in the superconducting state compared to normal conductor counterparts. The performance of SRF cavities is described by the dependence of its quality factor Q_0 on the accelerating gradient or peak magnetic field on the surface of a cavity at the operating temperature, usually 2.0 K. One of the requirements from the operation point of view is to lower the power dissipation at the desired accelerating gradient, the optimal value of which also depends whether the machine is operating in continuous wave or pulsed mode. Most of the accelerators currently in operation and under construction are relying on cavities made from high purity fine grain (ASTM grain size ~ 5-7) Nb. Research and development in the last decade demonstrated that cavities made from large grain (LG) ingot Nb showed a performance as good as FG counterparts if not better [1].

In the past the push for high purity Nb for SRF cavities resulted as the requirement for high thermal conductivity in the Nb in order to provide the thermal stability against localized defects dissipating higher rf power and driving the cavity to a premature quench with reduced Q_0 [2]. The LG ingot niobium is considered as an alternative to the high purity FG Nb owing to its higher thermal conductivity at ~2.0 K due to an enhanced phonon peak [3], while the material costs are reduced simultaneously since the production of ingot Nb is much simpler [4]. Recently, cavities made from medium purity (residual resistivity ratio ~ 100) ingot Nb achieved accelerating gradients higher than 30 MV/m with $Q_0 > 10^{10}$ at 2.0 K [5,6]. In this paper, we present the result of rf measurements done for a single-cell cavity fabricated at KEK (referred to as LG-4 in Ref. [6]) applying differing cool down procedures at different residual magnetic fields in order to demonstrate the high performance of the cavity made form medium purity ingot Nb under various conditions.

EXPERIMENTAL METHOD

The single-cell TESLA-type cavity LG-4 (B_p/E_{acc}=4.2 mT/(MV/m), f = 1.3 GHz) was fabricated at KEK from Nb ingot provided by CBMM with RRR ~ 107 and with 1034 ppm Ta content. The details of the fabrication can be found in Ref. [6]. The cavity was delivered to JLab and standard procedures were applied to clean the cavity surface in preparation for an rf test: degreasing in ultrapure water with a detergent and ultrasonic agitation, high pressure rinsing with ultrapure water, drying in the ISO4/5 cleanroom, assembling flanges with rf feedthroughs and pump out ports and evacuation.

A pair of Helmholtz coils with ~12” diameter was used to create a uniform magnetic field at the cavity surface. Several Cernox temperature sensors were mounted on the irises and equator of the cavity to measure the cooldown rate during the cooldown process. To measure the residual magnetic flux density on the cavity surface during the cooldown, three Bartington single-axis magnetic sensors were mounted on the cavity surfaces. Two magnetic sensors were placed on the equator of the cavity, whereas one sensor was placed on the beam tube to ensure the uniformity of the magnetic flux density before the cooldown. The magnetic field uniformity within the cavity enclosure is ~ ±1 mG. The cavity was inserted in a vertical cryostat and cooled to 4.5 K with liquid helium using the standard JLab cooldown procedure. The cavity cooldown process is as follows: (i) the magnetic field was set < 2 mG using the compensation coil in the Dewar without any current flowing yet in the Helmholtz coils. The cavity was then cooled down applying the standard procedure to generates ~4 K temperature difference between the top and bottom iris oc the cavity equivalent to a temperature gradient of ~0.2 K/cm. (ii) The temperature and magnetic field were recorded until the vertical Dewar was completely filled and a uniform temperature of ~4.3 K was achieved. (iii) An rf test was conducted to measure Q_0(T) at a low rf field ($B_p \sim$ 10 mT) from 4.3-1.5 K using the phase lock system. (iv) The cavity was warmed up above the superconducting transition temperature (~9.2 K) and cooled down to 4.3 K while keeping the temperature gradient between the cavity irises below 0.1 K. (v) Again, an rf test was carried out to determine Q_0(T) from 4.3-1.5 K using the phase lock system. (vi) The current in the Helmholtz coils was set at a certain value and steps (ii) – (v) were repeated with three different values for the magnetic field. Furthermore, the temperature and magnetic field were measured to extract

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the flux expulsion ratio (B_{SC}/B_{NC}) for different cooldown conditions as described in Ref. [7].

After the rf measurements were completed for the cavity in the as-received state, the cavity was subjected to a low temperature baking (LTB) at 120 ºC for 24 hours in a UHV environment, and the measurement was repeated with different cooldown procedures and residual magnetic fields in the Dewar. After this first set of measurements the cavity was heat treated at 1000 ºC for 3 hours followed by a surface removal of ~40 µm by electropolishing (EP). The Q_0 vs. E_{acc} curve was measured again after EP to investigate the effect of the annealing temperature on the cavity performance.

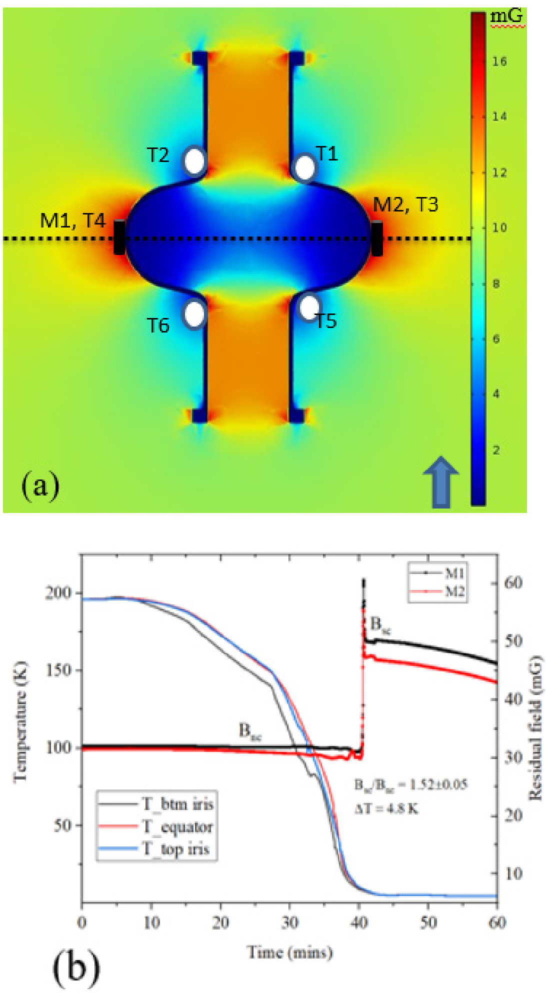

Figure 1: (a) Complete Meissner effect during cooldown showing the schematic of a single-cell cavity with flux-gate magnetometers (M1, M2) and Cernox sensors (T1,…T6) and (b) Temperature and magnetic field during transition from normal to superconducting state measured during a cooldown cycle of the cavity.

CAVITY TEST RESULTS

Cool-Down and Flux Expulsion

The ratio of the residual dc magnetic field measured after (B_{SC}) and before (B_{NC}) the superconducting transition qualitatively explains the effectiveness of the flux expulsion during the transition. As shown in Fig. 1 (b) a sharp jump in the measured flux is observed during the superconducting transition. Experimentally, the ratio B_{SC}/B_{NC} depends on the Nb material and on the temperature gradient along the cavity axis during the cool-down. For a larger temperature gradient the value approaches to the ideal value of B_{SC}/B_{NV} ~ 1.7 for that cavity. Figure 2 shows the flux expulsion ratio as a function of the spatial temperature difference (iris-iris) on a cavity after EP and LBT.

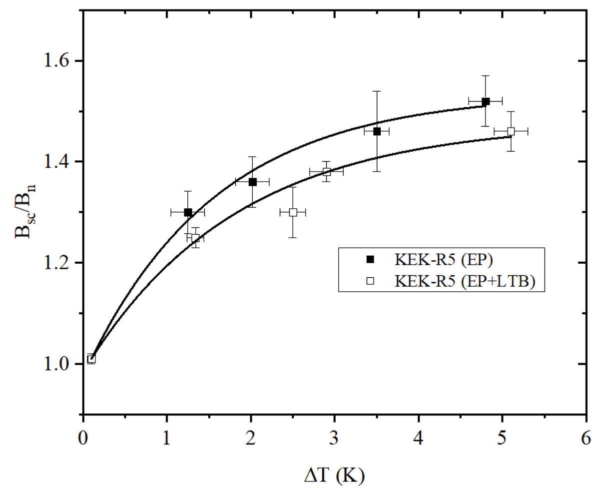

Figure 2: Flux expulsion ratio as a function of spatial temperature difference (iris-to-iris) for the cavity after EP and LTB. Solid lines are fits with a sigmoidal curve.

Rf Measurements

The following sequence of rf tests was done:

- RF test #1: cavity as received from KEK
- RF test #2: LBT at 120ºC for 24 hours
- RF test #3: multiple cooldowns with different residual magnetic fields in Dewar with non-uniform and uniform cooldown
- RF test #4: 800ºC heat treatment followed by ~ 40 µm EP
- RF test #5: multiple cooldowns with different residual magnetic field in Dewar with non-uniform and uniform cooldown
- RF test #6: LBT at 120ºC for 24 hours
- RF test #7: 1000ºC heat treatment followed by ~ 40 µm EP
- RF test #8: LBT at 120ºC for 24 hours

During the rf test #3 and #5, the average surface resistance was obtained from the measurement of $Q_0(T)$ at low rf field (B_p~10 mT) for two different conditions; one with uniform temperature gradient (ΔT < 0.1 K) and one with larger gradient (ΔT > 4 K). The measurements were repeated with different values of applied dc magnetic field prior to each cooldown. The data were fitted with the following equation:

$$R_s(T) = R_{BCS}(T, l, \Delta/k_BT_c) + R_{res} \quad (1)$$

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where R_{BCS} is the surface resistance computed numerically from the MB theory and R_{res} is the temperature independent residual resistance. The mean free path, l, and the ratio of the energy gap at 0 K, Δ, divided by the product of the Boltzmann's constant, k_B, and T_c are considered fit parameters. T_c= 9.2 K, coherence length, ξ_0 = 39 nm, and London penetration depth, λ_L = 32 nm, were considered as material constants.

Figure 3 shows R_{res} vs the residual field in the Dewar when the cavity transitioned to the superconducting state at two different conditions, i.e. ΔT < 0.1 K and ΔT > 4.0 K. The intrinsic residual resistance was measured to be 0.7 ±0.2 nΩ after EP and increased to 3.6 ±0.3 nΩ after 120ºC/24 hours LBT. There is also an increase of the residual resistance measuered due to trapped residual flux by ~40% from 0.29 nΩ/mG to 0.4 nΩ/mG as a result of the LBT. Details concerning the flux expulsion and trapping sensitivity measurements were presented in Ref. [8].

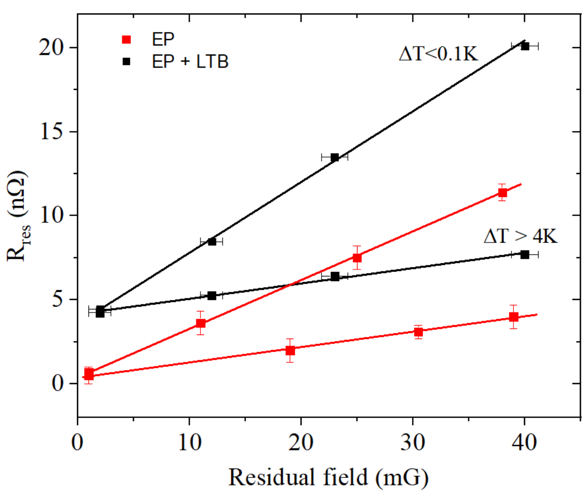

Figure 3: Residual resistance as a function of applied dc magnetic field measured for ΔT<0.1 K and ΔT> 4.0K after EP and followed by LTB, respectively.

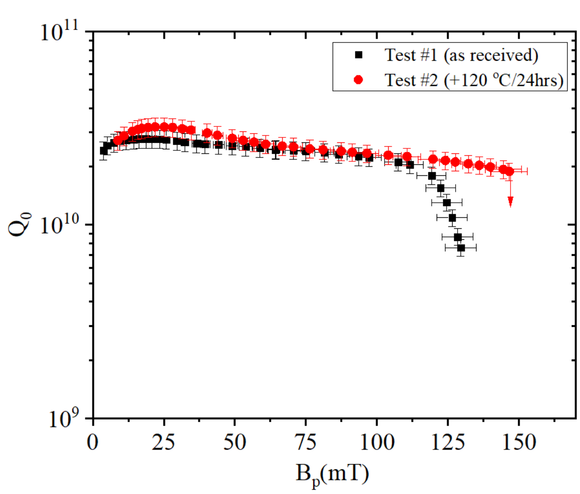

Figure 4: $Q_0(B_p)$ at 2.0 K measured of the cavity in the as-received state and after LTB at 120ºC for 24 hours. The cavity in the as-received state was limited by a Q-slope, whereas the cavity was limited by a quench after LTB.

Figure 4 shows $Q_0(B_p)$ at 2.0 K of the cavity as-received from KEK and after the LBT at 120 ºC for 24 hours. The cavity reached B_p = 130 ±5 mT and was limited by a Q-slope in the as- received state, whereas the cavity reached B_p = 147 ±7 mT corresponding to E_{acc} = 35 ±1 MV/m with Q_0 = (1.9 ±0.2)×10^{10} before it quenched.

Note that the cavity was heat treated at 750 ºC at KEK before it was received at JLab. To further explore the effect of the high temperature heat treatment, the cavity was heat treated at 800 ºC for 3 hours followed by ~40 µm EP. The cavity then reached 135 ±5 mT before it quenched. After 120 ºC LTB for 24 hours, the quench field remained unchanged. The summary of rf tests at 2 K is shown in Fig. 5.

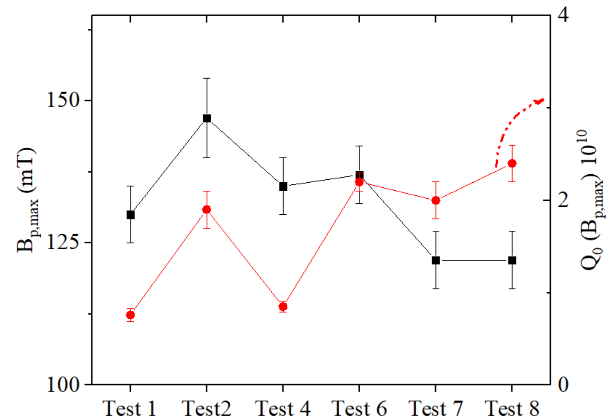

Figure 5: Summary of rf test results at 2.0 K.

Subsequently the cavity was heat treated again but at 1000ºC for 3 hours followed by ~40 µm EP and 120ºC LTB for 24 hours. In this case the cavity quench field degraded to B_p = 122 ± 5 mT, which corresponds to E_{acc} = 29±1 MV/m with $Q_0(B_{p,max})$ = (2.4 ± 0.2)×10^{10} after LTB.

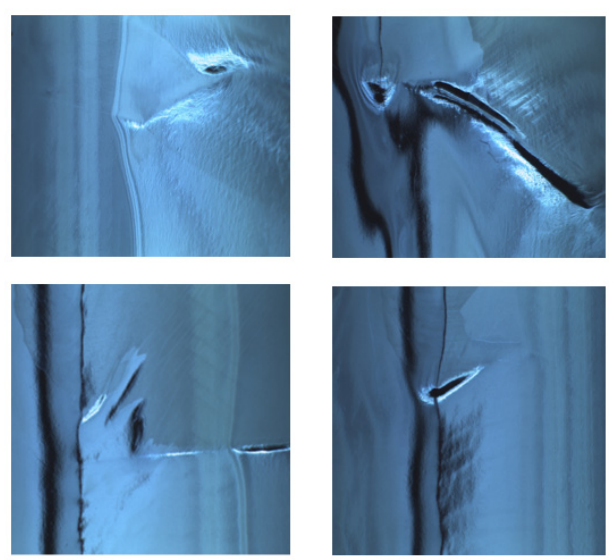

Figure 6: Optical photographs on the inner cavity surface near the equator.

The cavity was optically inspected after the last test and some features were observed (see Fig. 6), although no conclusion can be made based on the optical images to what

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extent the features would degrade the quench field. As mentioned in ref. [6], the cavity originally had fabrication defects and it was repaired by applying a grinding technique. It is possible that after a total of ~ 80 µm EP some defects may reappear causing the cavity to quench.

CONCLUSION

A cavity made from medium purity large grain niobium reached a record quench field corresponding to an accelerating gradient of 35 MV/m with a quality factor Q_0 ~ 2×10^{10} at 2.0 K. The cavity showed an excellent flux expulsion during cooldown, and the flux trapping sensitivity is 0.29 nΩ/mG after applying EP, which increased to 0.4 nΩ/mG after LTB at 120 ºC for 24 hours. This value is comparable to that measured for high purity Nb cavities [8]. The medium purity Nb may be beneficial particularly for reaching high quality factors since the BCS resistance is lower compared to the case when using high purity Nb. The demonstrated performance of the cavity made form medium purity ingot Nb reaching high Q and high gradient is of great interest for high energy accelerators such as the proposed Linear Collider [9], while it allows lower material costs apart from reducing the cryogenic heat load.

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