OBSERVATION OF STABLE LOW SURFACE RESISTANCE IN LARGE-GRAIN NIOBIUM SRF CAVITIES*

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Abstract

Low surface resistance, or high unloaded quality factor (Q_0), superconducting radio frequency (SRF) cavities are being pursued actively nowadays as their application in large-scale CW SRF accelerators can save capital and operational cost in cryogenics. There are different options in realization of such cavities. One of them is the large-grain (LG) niobium cavity. In this contribution, we present new experimental results in evaluation of LG niobium cavities cooled down in the presence of an external magnetic field. High Q_0 values are achieved even with an ambient magnetic field of up to 100 mG. More over, it is observed that these high Q_0 values are super-robust against repeated quench, literally not affected at all after the cavity being deliberately quenched for hundreds of times in the presence of an ambient magnetic field of up to 200 mG.

INTRODUCTION

Low surface resistance, or high Q_0, superconducting radio frequency (SRF) cavities are being pursued actively nowadays as their application in large-scale CW SRF accelerators can save capital and operational cost in cryogenics. There are different options in realization of such cavities. One of them is the LG niobium cavity.

The strength of a LG niobium cavity lies in its capability of reaching higher Q_0 at medium and high gradients as compared to its fine grain (FG) niobium counterpart. Many 9-cell LG niobium TESLA shape cavities achieved a large Q_0 in the range of $3\text{-}5\times10^{10}$ at 1.8K for medium gradient of 15-20 MV/m and large Q_0 of $> 2\times10^{10}$ at 1.8K for high gradient of > 35 MV/m [1,2].

As will be shown in this contribution, a new property of high Q_0 LG niobium cavity has been observed: stability of its low surface resistance against repeated quench. Such a property is interesting in its own right and begs for understanding. Practically, a highly robust low surface resistance cavity is valuable as it allows realization of low loss cavities in cryomoudles without stringent magnetic shielding configurations.

ADDED SURFACE RESISTANCE DUE TO REPEATED QUENCH

It is well documented that the Q_0 of an ordinary FG niobium SRF cavity is degraded when it is repeatedly quenched in a typical testing dewar with an ordinary magnetic environment. Quenching can be triggered by soft multipacting occurring near the inner surface of the equator region in an elliptically shaped cavity [3] or by thermal instability near a permanent defect on the inner surface of a cavity [4]. The resultant increase of the effective surface resistance averaged over the entire cavity surface area can be quite significant. For example, as much as 10 nΩ is estimated for a 9-cell cavity [3]. Thermometry data revealed a non-uniform augmentation in surface resistance, with an increase near the quench site. Such an observation led to the trapped flux explanation. One model links the added flux to a thermal current around the quench site when it recovers rapidly from normal state back to superconducting state [4].

Recent experimental results measured from nitrogen-doped niobium cavities at FNAL indicate that the Q_0 degradation after repeated quench is a result of trapping external fluxes, therefore an extrinsic effect [5]. In this case, Q_0 degradation is avoidable as long as a ultra-low magnetic environment around a cavity (< 2 mG) is provided.

STABLE HIGH Q_0 IN TYPICAL VTA MAGNETIC ENVIRONMENT

The main subject of our studies is high Q_0 LG high-purity niobium cavities. The reference high Q_0 cavity (RDT-5) is a nitrogen-doped cavity fabricated and processed at JLab [6]. It is a single-cell 1.3GHz TESLA end-cell shape cavity made from high purity FG niobium. The surface processing of RDT-5 consisted of typical buffered chemical polishing (BCP1:1:2) at 15 ºC, vacuum furnace heat treatment with nitrogen doping (800 ºC for 3 hours, 2 minute nitrogen exposure at 40 mTorr, 6 minute annealing) followed by 5 µm surface electropolishing.

Two single-cell LG niobium cavities are studied. The first cavity (PJ1-2) is a 1.5 GHz CEBAF upgrade end-cell shape cavity made from high-purity LG niobium. The surface processing of PJ1-2 consisted of 160 µm buffered chemical polishing (BCP1:1:1) at room temperature, vacuum furnace outgassing at 800 ºC for 3 hours, 40 µm electropolishing and in-situ baking at 120 ºC for 18 hours. The second cavity (G2) is a 1.3 GHz TESLA end-cell shape cavity made of high-purity LG niobium. Initial surface processing of G2 consisted of "mirror-finish" 180 µm mechanical polishing, vacuum furnace outgassing at 800 ºC for 3 hours, 30 µm electropolishing and in-situ baking at 120 ºC for 48 hours. Later on this cavity was nitrogen doped (800 ºC for 3 hours, 2 minute nitrogen exposure at ~ 20 mTorr, 30 minutes annealing at 800 ºC with nitrogen pumped out of the furnace chamber), and electropolishing for 10 micron removal in equator region.

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Testing of these cavities was carried out in the VTA facility at JLab. Magnetic shielding in the VTA dewars is achieved by a combination of passive shielding cylinders and active compensation coils. Under regular conditions, the residual magnetic field around a single-cell cavity is typically ~ 5 mG oriented in the vertical direction. The cavity axis is approximately in the vertical direction.

The baseline performances of these high Q_0 cavities prior to endured quench events are shown in Table 1.

Table 1: Baseline Cavity Performance

Cavity	Nb	Nitrogen -doping?	Q_0, 2K, 16 MV/m [10^{10}]	Q_0, 1.8K, 16 MV/m [10^{10}]	Max. Eacc [MV/m]
PJ1-2	LG	No	2.0	3.3	49
G2	LG	No	2.4	4.0	38
G2+N	LG	Yes	4.1	7.1	25
RDT-5	FG	Yes	5 3 .	-	20

The effective average surface resistance of a cavity is computed by G/Q_0, where G is the geometric factor. The added average surface resistance due to multiple quench events is shown in Fig. 1. It can be seen that the amount of added effective surface resistance due to repeated quench events can be very different depending on the cavity. The rate of surface resistance addition seems to be the highest during initial quench events and is slowed down as the accumulated quench events increases.

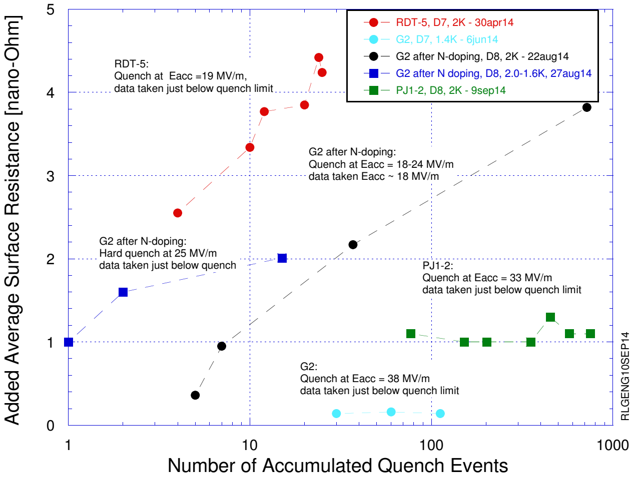

Figure 1: Added average surface resistance as a cavity endured quench events during vertical testing with an ambient magnetic field of ~ 5 mG. Typical uncertainty in surface resistance is ~10%.

The reference cavity RDT-5 shows the largest effect among the cavities tested in the regular JLab VTA magnetic environment (circa 2014) with 4 nΩ was added after ~ 20 accumulated quench events.

The LG cavity G2 shows a dramatically different behavior before and after nitrogen doping. Following the baseline processing, it was literally immune from any an added surface resistance due to repeated quench. In contrast, after nitrogen doping, 2 nΩ was added after 10-20 accumulated quench events (nearly 4 nΩ was added after ~700 accumulated quench events).

The other LG cavity PJ1-2 shows a larger effect as compared to the LG cavity G2. Approximately 1 nΩ was added after ~1000 accumulated quench events.

LG CAVITY TESTING IN ELEVATED MAGNETIC ENVIRONMENT

Further tests of LG cavities in an elevated magnetic environment by applying an external magnetic field were carried out. The external magnetic field was generated in the vertical direction by a coil wound around the cavity. The external magnetic field was applied before cooling down and remained on over the entire course of testing. Systematic studies of controlled applied field and varied cool down process were conducted. A comprehensive analysis of these results will be published elsewhere.

The cavity PJ1-2 had been maintained under vacuum since previous tests. Baseline tests were carried out immediately before the field cooled testing. Additional electropolishing was applied to the cavity G2 for a surface removal of 45 μm. The degraded limiting gradient due to nitrogen doping was fully recovered to its pre-nitrogen-doping performance level.

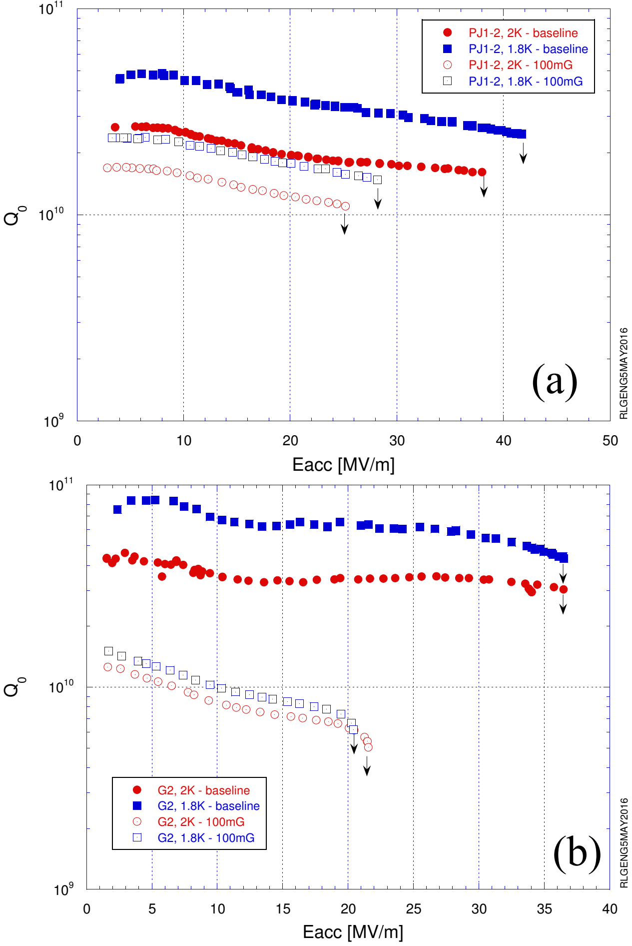

Figure 2: $Q(E_{acc})$ of the cavity PJ1-2 (a) and G2 (b) tested at 2 K and 1.8 K in regular VTA magnetic environment and in 100 mG externally applied magnetic field.

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Figure 2(a) and (b) shows the baseline as well as field cooled (100 mG) test results of cavity PJ1-2 and G2, respectively, at 2 K and 1.8 K. High Q_0 values in the regime of 2×10^{10} were realized by PJ1-2 at 1.8 K and E_{acc} = 15 MV/m with an applied magnetic field of 100 mG.

A new repetitive quench limit was met during testing of both cavities PJ1-2 and G2, when cooled with an externally applied magnetic field. This limit is significantly lower that the originally observed quench limit with cavity cooled down in the regular VTA magnetic environment. This can be seen in Fig. 2. The initial gradient quench limit of cavity PJ1-2 was ~ 40 MV/m. With 100 mG field cooling, the gradient limit degraded to < 28 MV/m. The initial gradient quench limit of cavity G2 was ~ 37 MV/m. With 100 mG field cooling, the gradient limit degraded to 20 MV/m. No X-ray was detectable during the quench events. Diode thermometers attached to the cavity outer surface in the equator region detected sporadic temperature spikes.

STABLE HIGH Q_0 IN ELEVATED MAGNETIC ENVIRONMENT

As shown previously, high Q_0 values are still achievable in the cavity PJ1-2 cooled down in an elevated magnetic environment as high as 100 mG (similar high Q_0 values were achieved at 50 mG). These high Q_0 values are extremely robust against the effect of added surface resistance due to repeated quench in the presence of the externally applied field. The change in the surface resistance after accumulated quench events up to ~1000 was measured to be within ±1 nΩ.

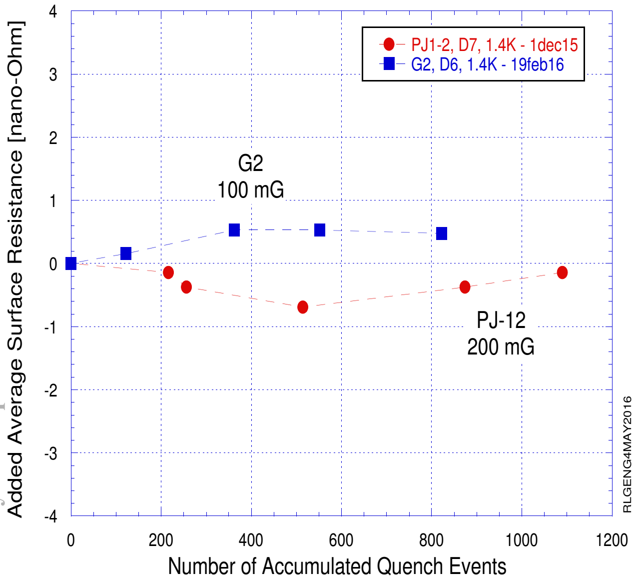

Figure 3: Change in the average effective surface resistance as a LG niobium cavity endured quench events with an externally applied magnetic field.

This Q_0 stability against repeated quench was found both in cavity PJ1-2 and cavity G2 at any applied field (from 50 to 200 mG) and any temperature (from 1.4 to 2.0 K) as shown for example in Fig. 3, despite the fact that the Q_0 values were dependent on the magnitude of the applied field, temperature gradient at Tc crossing, and bath temperature. The cavity PJ1-2 was repetitively quenched at Eacc = 23 MV/m with an applied field of 200 mG. The Q_0 data was taken at 1.4 K and Eacc = 10 MV/m with an increasing number of accumulated quench events. The cavity G2 was repetitively quenched at 20 MV/m with an applied field of 100 mG. The Q_0 data was taken at 1.4 K and Eacc = 15 MV/m with an increasing number of accumulated quench events.

DISCUSSION

It is not clear why the added surface resistance of nitrogen-doped niobium cavities tends to saturate with increasing number of accumulated quench events. For cavity testing of nitrogen-doped G2 on August 22, 2014, the cavity quench field was in the gradient range of 18-24 MV/m, coinciding the known multipacting barrier. The continued increase of added surface resistance might be a result of quench location moving to a new place after one region is processed through. For cavity testing of G2 on August 27, 2014, the quench gradient was 25 MV/m, which is outside of multipacting barrier. Yet a continued increase in added surface resistance is still observed. This may suggest that (a) the nitrogen doped surface has a large capacity to trap flux; or (b) the quench location moves progressively to new places after one site is saturated with trapped flux. Similar saturation behavior was observed in a 1.3 GHz seamless niobium-copper clad cavity after repeated quenching at 40 MV/m [7].

The new barriers met by the cavity PJ1-2 and G2 when field cooled with an external magnetic field were not expected. The origin of these barriers is unknown. The coincidence with the known multipacting barrier in cavity G2 may indicate these barriers are the two-point multipacting, enhanced by the DC magnetic field near the inner surface of the equator due to frozen flux effect. Another possibility is thermal quench ignited by overheated trapped fluxoids.

CONCLUSION

In summary, several high Q_0 superconducting RF cavities, including two LG niobium cavities, have been tested to assess their properties in added surface resistance due to repeated quench events. Both LG niobium cavities are shown to be immune from the effect. This newly found property might be usable in attaining stable high Q_0 superconducting RF cavities under practically achievable magnetic environments. A new gradient limit has been observed when a superconducting niobium cavity is cooled with an externally applied field between 50 – 200 mG. The origin of the highly stable low surface resistance of LG cavities and the new quench limit in a field cooled SRF cavity is unknown and their understanding has to wait till future studies.

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