WORLD RECORD ACCELERATING GRADIENT ACHIEVED IN A SUPERCONDUCTING NIOBIUM RF CAVITY*

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Abstract

On November 16, 2004, a CW accelerating gradient of 46 MV/m was achieved in a superconducting niobium cavity with an unloaded quality factor (Q_0) over 1×10^{10} at a temperature of 1.9 °K. In pulsed mode, 47 MV/m was achieved. This represents a world record gradient in a niobium RF resonator. At a reduced temperature of 1.5-1.6 °K, an enhanced Q_0 was measured, ranging from 7×10^{10} at 5 MV/m to 2×10^{10} at 45 MV/m. The 1.3 GHz single-cell cavity has a reduced ratio of Hpk/Eacc, ensured by a reentrant geometry. The maximum peak surface electric and magnetic field exceeded 100 MV/m and 1750 Oe respectively. A soft multipacting barrier (predicted by calculations) was observed near 25 MV/m gradient and was easily processed through. Field emission in the cavity was negligibly small, and the highest field was limited by thermal breakdown. The cavity was built, processed, and tested with LEPP facilities at Cornell University. New techniques included half-cell heat treatment with yttrium for post-purification to RRR = 500, and vertical electropolishing the finished cavity.

INTRODUCTION

The accelerating gradient E_{acc} (see [1] for definition) in RF superconducting niobium resonators has been raised remarkably in the past decades. In 1.3 GHz *single-cell* niobium cavities, an accelerating gradient in excess of 40 MV/m has been reliably achieved [2] with the best result being 42-43 MV/m [3].

The ultimate gradient limit E_{acc}^{max} for a given cavity geometry is set by breakdown of superconductivity when the peak magnetic field H_{pk} on the RF surface of a resonator reaches the critical RF magnetic field $H_{crit,RF}$,

$$E_{acc}^{max} = \frac{H_{crit,RF}}{H_{pk}/E_{acc}}. \qquad (1)$$

$H_{crit,RF}$ is a material property and H_{pk}/E_{acc} is solely determined by the cavity geometry. The super-heating theory [4] predicts that $H_{crit,RF} = 1.2H_c$ for niobium at microwave frequencies, H_c being the DC thermo-dynamic critical field. Despite the prediction of a $H_{crit,RF}$ value close to 2300 Oe at 2 °K, the maximum achieved experimental H_{pk} value is still below 1900 Oe. Over the past 10 years, the 1.3 GHz niobium cavities in the 40 MV/m class were limited by quench at $H_{pk} = 1750 \pm 100$ Oe [5].

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Advancing E_{acc} beyond the state-of-the-art can be realized through two avenues: (1) Develop new technologies for niobium material production and cavity surface processing so as to bring H_{pk} to the intrinsic limit $H_{crit,RF}$ of niobium or explore alternative material possessing a higher $H_{crit,RF}$, such as Nb_3Sn; (2) Reduce H_{pk}/E_{acc} by changing the cavity geometry.

REENTRANT CAVITY

The concept and RF optimization of reentrant cavity has been published in Ref. [6]. Here only a brief summary is given. Our optimization is referenced against the center-cell shape of the 1.3 GHz 9-cell TESLA cavity. Driven by the wakefield effect consideration, the bore hole diameter at iris is kept identical to that of the reference geometry (70 mm). This prerequisite has the following consequence: a reduced H_{pk}/E_{acc} is obtained only at the cost of an increased E_{pk}/E_{acc}. An elevated peak surface electric field (E_{pk}) is dis-advantageous in terms of field emission and voltage breakdown. Nevertheless, there are convincing experimental data [7][8][9] to show that a surface electric field of 100-200 MV/m imposes no fundamental limit to superconducting niobium.

The reentrant geometry we have chosen to evaluate experimentally is shown in Fig.1. For comparison, the reference geometry of the original TESLA shape is given as well. Relevant RF parameters are compared in Table1.

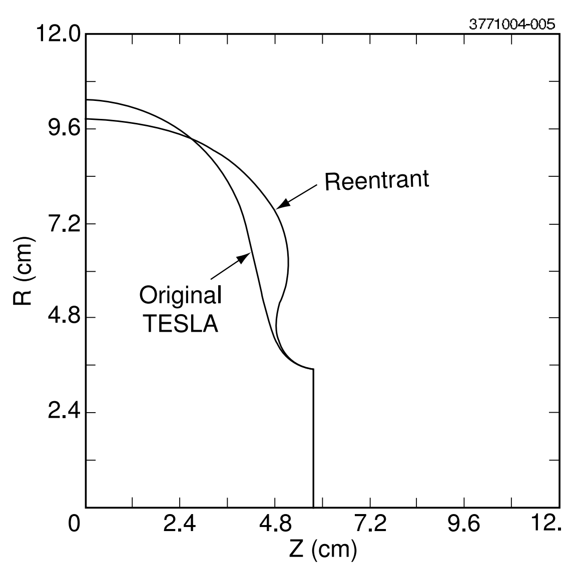

Figure 1: Half-cell contours of reentrant and original TESLA shape.

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Table 1: RF parameters: reentrant vs. reference shape. f: resonant frequency; k: cell-cell coupling factor.

Shape	$f[MHz]$	$\frac{H_{pk}}{E_{acc}}[\frac{Oe}{MV/m}]$	$\frac{E_{pk}}{E_{acc}}$	$k[\%]$
Reentrant	1300	37.8	2.4	2.4
TESLA-type	1300	42.0	2.0	1.9

For understandable reasons, a single-cell cavity was fabricated for the first experimental evaluation of the concept. RF parameters of the single-cell cavity are slightly modified, as compared to that of the center cell of a multi-cell cavity, because of beam tubes. Ultimately, the calculated RF parameters of the single-cell reentrant cavity are given in Table 2.

Table 2: RF parameters of single-cell reentrant cavity

Frequency	1284	MHz
H_{pk}/E_{acc}	37.9	$\frac{Oe}{MV/m}$
E_{pk}/E_{acc}	2.2	-

FABRICATION AND SURFACE TREATMENT

The reentrant cavity was fabricated by using the regular method. Cups were formed by deep-drawing 3 mm thick sheet material. The reentrant contour was obtained by multiple stamping steps using additional dies. Stacked cups with interleaving yttrium foils were heat treated in a furnace at 1200 °C for 4 hours. The residual resistance ratio (RRR) was increased to about 500 from the starting value of 250. A layer of 20 μm was removed by chemical etch (BCP1:1:2) from both in- and out-side surface of the cups. Half-cells were joined to beam tubes (reactor grade niobium) by electron beam welding. The inner surface of half-cell/beam tube sub-assemblies was electropolished with a vertical set-up [10], removing material by about 50 μm. The equator end of sub-assemblies was immersed in BCP1:1:2 for 5 minutes. The final fabrication step was to join sub-assembly equators by electron beam welding (butt weld).

The surface preparation of the single-cell cavity, prior to each RF test, typically consists of chemical etch (BCP1:1:2 at temperatures below 10°C or vertical electropolish), followed by high pressure water rinsing (pump pressure 1000-1200 PSI), clean room assembly and low temperature bake-out (90-120 °C) under vacuum. Vertical electropolishing of a single-cell cavity (Fig.) is conceptually identical to that of a half-cell [10], except the fashion of acid agitation[1]. In any case, electropolish was performed in the continuous current oscillation mode.

[1]For a half-cell, a magnetically driven spin bar alone provides sufficient agitation; whereas for a single-cell, acid agitation inside the cell must be provided directly by two flexible arms inserted into the cell space. The rotation movement of arms is provided by a coupled spin bar.

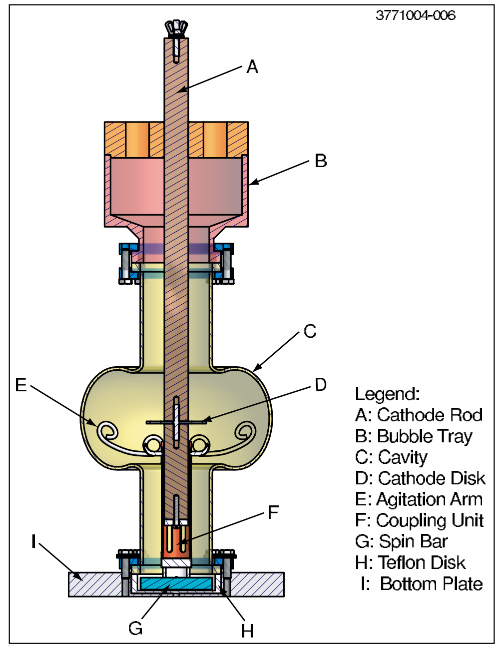

Figure 2: Vertical Electropolish of a single-cell niobium cavity.

RF TEST AND CAVITY PERFORMANCE

RF tests were conducted for a temperature range of 1.5-2.0 °K. $Q(E_{acc})$ curves were measured when the RF was operated in the CW mode. RF processing (CW or pulsed) was applied often. Sometimes, gas helium processing was performed with a best improvement from 37 to 43 MV/m (16%) in the accelerating gradient.

A summary of RF test results is given in Table 3. With an accumulated surface removal of 18 μm by BCP1:1:2 for the welded single-cell cavity, an accelerating gradient of 27 MV/m was already reached during the second test at a Q_0 of 6×10^9. No field emission was observed. This result shows that gradients in excess of 25 MV/m can be obtained at a high Q_0 by performing heat treatment and primary electropolish at the half-cell stage.

The highest CW accelerating gradient reached 46.3 MV/m at 1.9 °K with a Q_0 of over 1×10^{10} (Fig. 3) after the cavity was further electropolished. This corresponds to a peak surface electric and magnetic field of 101 MV/m and 1755 Oe respectively. At a reduced temperature of 1.5-1.6°K, an enhanced Q_0 was measured, ranging from 7×10^{10} at 5 MV/m to 2×10^{10} at 45 MV/m. Field emission in the cavity was negligibly small. The highest accelerating gradient reached in the pulsed mode was 47 MV/m and was limited by thermal breakdown.

A soft barrier was observed reproducibly at $E_{acc} \sim$ 25 MV/m, in excellent agreement with calculated multi-

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Table 3: Accelerating gradient history of the single-cell reentrant cavity at 2 K.

Test	E^m_{acc}	$Q_0(E^m_{acc})$	Limit
1	25.0	5×10^9	Quench
2	27.1	6×10^9	Quench
3	26.9	7×10^8	Quench
4	18.4	2×10^8	Power
5	37.1	8×10^8	Power
6	42.6	1×10^9	Power
7	44.4	1×10^9	Quench
8	44.3	8×10^8	Quench
9	42.5	9×10^8	Power
10	46.3	1×10^{10}	Quench
11	39.2	4×10^9	Quench

pacting barrier (first order two-sided multipacting at equator [6]). It was easily processed through by exercising some RF processing. Similar multipacting barrier of comparable hardness is observable also in TESLA type single-cell cavities, as well as nine-cell cavities. Based on these results, it is expected that a multi-cell reentrant cavity will have also, but not be limited by, a soft multipacting barrier.

CONCLUSIONS

The results of these experiments demonstrate that the accelerating gradient can be improved by reducing the H_{pk}/E_{acc} ratio, despite an increased E_{pk}/E_{acc}. Exploration in this direction is thus warranted. A new RF design has already shown that H_{pk}/E_{acc} can be further reduced to 35 Oe/(MV/m) by reducing the iris diameter to 60 mm [11]. A single-cell 60 mm beam tube reentrant cavity has been fabricated and RF test is under preparation. An accelerating gradient of 50 MV/m is expected by applying the same surface treatment established from the present reentrant cavity studies.

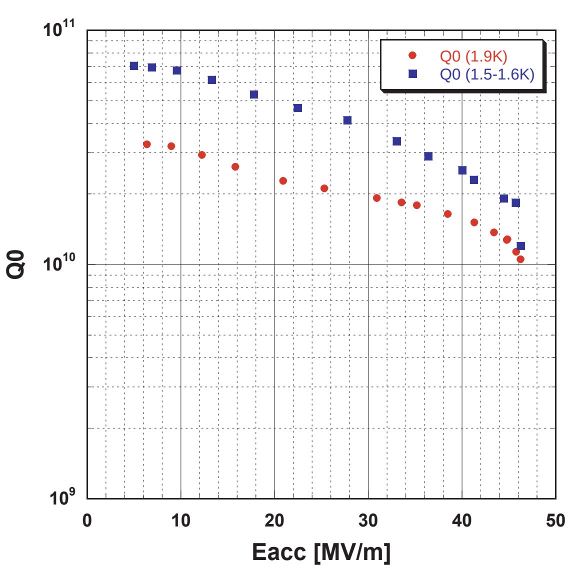

Figure 3: Performance of Cornell reentrant cavity LR1-2.

The achieved 46.3 MV/m represents the highest CW accelerating gradient ever realized in a niobium RF resonator. At 1.5-1.6 °K, Q_0 is 7×10^{10} at low field and remains 2×10^{10} at 45 MV/m. Measurements of $Q_0(T)$ show that the residual resistance is 3 nΩ.

The successful demonstration of a peak surface electric field in excess of 100 MV/m over the broad iris surface area of the reentrant cavity confirms that there is no fundamental limit due to the surface electric field. However a high surface electric field imposes challenges for control of field emission and surface damage. It has been observed that surface damage in the iris region occurs when a contaminated cavity is operated at high gradient [12]. The robustness of a broad niobium surface under a peak RF field of >100 MV/m must be examined and demonstrated to warrant the practical use of reentrant cavities in accelerators.

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