

# 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  $1 \times 10^{10}$  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  $7 \times 10^{10}$  at 5 MV/m to  $2 \times 10^{10}$  at 45 MV/m. The 1.3 GHz single-cell cavity has a reduced ratio of  $H_{pk}/E_{acc}$ , 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  $H_{crit,RF}$ ,

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

$H_{crit,RF}$  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].

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 disadvantageous 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.

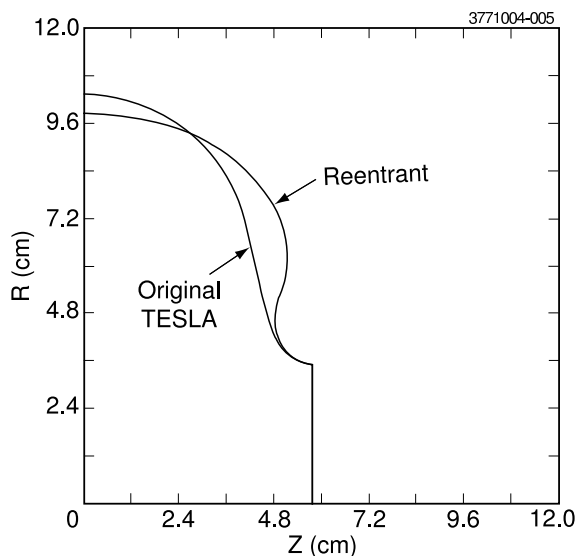


Figure 1: Half-cell contours of reentrant and original TESLA shape.

\* Work supported by NSF and by DOE

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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  $\mu\text{m}$  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  $\mu\text{m}$ . 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<sup>1</sup>. In any

<sup>1</sup>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.

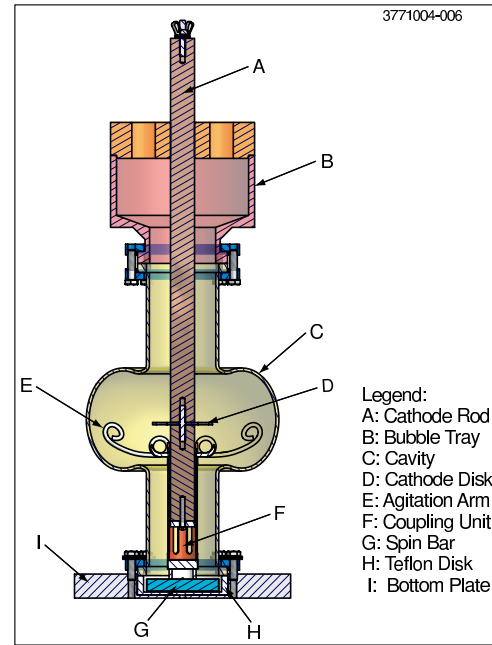


Figure 2: Vertical Electropolish of a single-cell niobium cavity.

case, electropolish was performed in the continuous current oscillation mode.

## 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  $\mu\text{m}$  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  $6 \times 10^9$ . 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  $1 \times 10^{10}$  (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  $7 \times 10^{10}$  at 5 MV/m to  $2 \times 10^{10}$  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-

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

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

packing 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 accel-

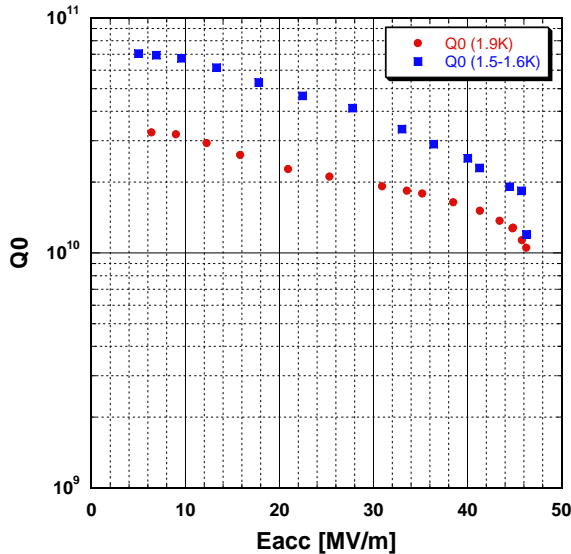


Figure 3: Performance of Cornell reentrant cavity LR1-2.

erating gradient of 50 MV/m is expected by applying the same surface treatment established from the present reentrant cavity studies.

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  $7 \times 10^{10}$  at low field and remains  $2 \times 10^{10}$  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.

## REFERENCES

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