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Testing the First 1300 MHz Reentrant Cavity

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Abstract. We report the first test results of a superconducting niobium cavity of reentrant geometry, suitable for acceleration of β=1 charged particles in future superconducting machines such as a TeV scale superconducting linear collider. The reentrant geometry offers a reduced ratio of H_{pk}/E_{acc}. It hence has the potential to reach a higher accelerating gradient (E_{acc}) before the peak surface magnetic field (H_{pk}) hits the physical breakdown limit of superconductivity. A CW accelerating gradient of 44-45 MV/m was achieved at a peak surface magnetic field of 1683 Oe in a 1.3 GHz single-cell niobium cavity of reentrant geometry. As the critical RF magnetic field of niobium is still beyond 1683 Oe, further improvement in E_{acc} into the regime of 50 MV/m can be anticipated. New fabrication techniques were also adopted, such as half-cell post purification, half-cell electropolish and single-cell vertical electropolish.

INTRODUCTION

The accelerating gradient[1], E_{acc}, 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 [1] with the best result being 42-43 MV/m [2].

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 $H_{crit,RF}$,

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

$H_{crit,RF}$ is a material property and H_{pk}/E_{acc} is solely determined by the cavity geometry. The super-heating theory [3] 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 2K, 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 [4].

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. The two approaches have different advantages: The first one has a higher potential premium; and the second one offers immediate benefit. Further more, these two approaches are totally independent and improvement realized through either one can be multiplied with that realized through the other. The present work has adopted the reducing H_{pk}/E_{acc} approach.

REENTRANT CAVITY AND RF OPTIMIZATION

The concept and RF optimization of reentrant cavity has been published in Ref. [5]. 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

[1] The accelerating gradient is defined as the maximum voltage a $\beta = 1$ particle can possibly gain during the transit of the resonator divided by the active length of the accelerating gap. The choice of the active gap length is not unique. In this paper, we take it as the half wavelength in vacuum of the microwave at the resonating frequency of the cavity.

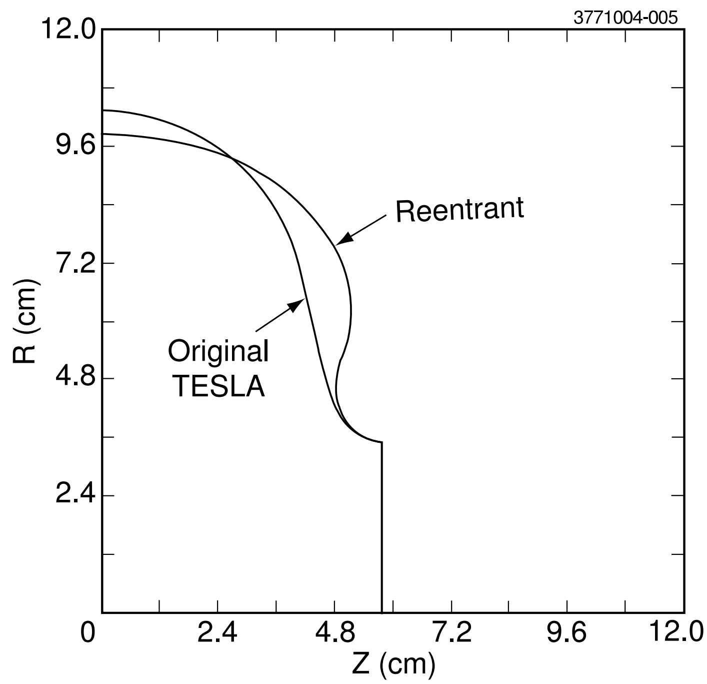

FIGURE 1. Half-cell contours of reentrant and original TESLA shape.

TABLE 1. RF parameters: reentrant vs. reference shape

Shape	$f[MHz]^{*}$	$\frac{H_{pk}}{E_{acc}}[\frac{Oe}{MV/m}]$	$\frac{E_{pk}}{E_{acc}}$	$k[\%]^{\dagger}$
Reentrant	1300	37.8	2.4	2.4
Original TESLA	1300	42.0	2.0	2.0

* Resonating frequency
† Cell-cell coupling factor

(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}) in turn is disadvantageous in terms of field emission and voltage breakdown[2]. Nevertheless, there are convincing experimental data [6][7][8] 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.

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	-

[2] The conventional wisdom in cavity shape optimization is to reduce E_{pk}/E_{acc} for field emission concerns.

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 [9], 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.2) is conceptually identical to that of a half-cell [9], except the fashion of acid agitation [3]. In any case, electropolish was performed in the continuous current oscillation mode.

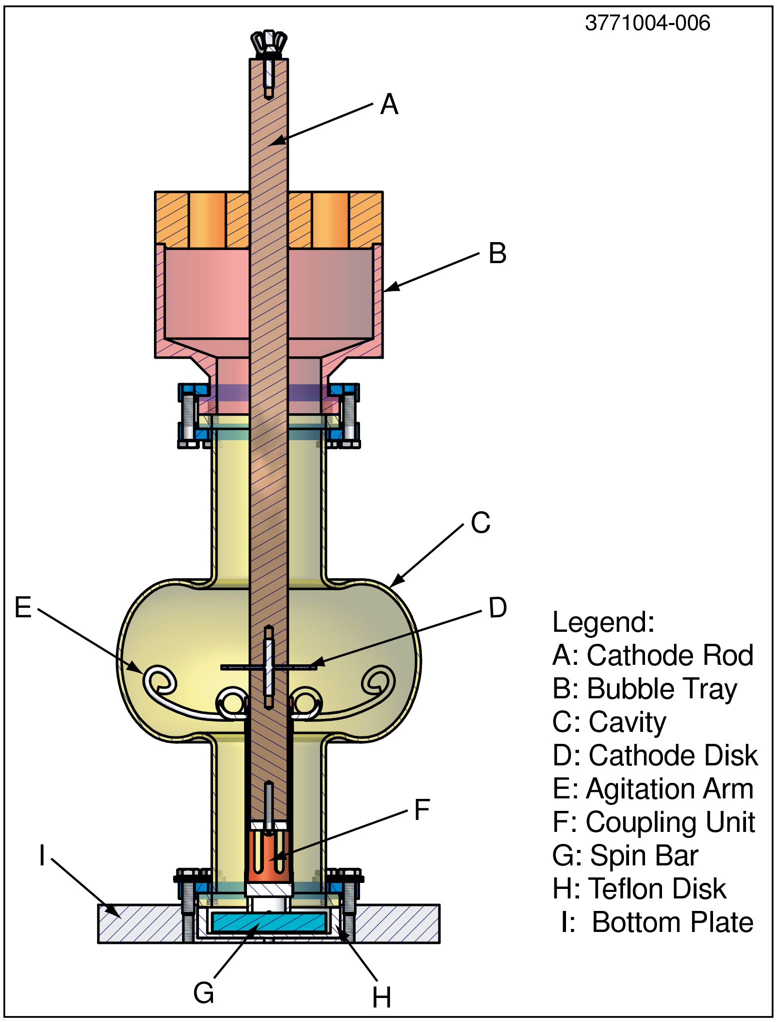

FIGURE 2. Vertical Electropolish of a single-cell niobium cavity.

[3] 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.

RF TEST AND CAVITY PERFORMANCE

RF tests were conducted at a nominal temperature of 2 °K. Bremsstrahlung x-rays were monitored by a probe placed outside the liquid helium cryostat. The x-ray dose rate serves as an indicator for the intensity of field emission inside the cavity. $Q(E_{acc})$ curves were measured when the RF was operated in CW mode. RF processing (CW or pulsed) was applied often. Sometimes, gas helium processing was performed.

A summary of the results of the first eight RF tests is given in Table 3. After an accumulated surface removal of 18 μm by BCP1:1:2, 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. For large-scale cavity production, the fabrication cost can be saved appreciably if high temperature heat treatment and primary surface etch are done with half-cells.

The best result was obtained after the cavity was further electropolished (vertical electropolish and 50 μm surface removal) followed by additional etch with BCP1:1:2 (7 μm). Gas helium processing reduced field emission and boosted the accelerating gradient from 37 to 43 MV/m, a 16% gain. The highest gradient reached 44.4 MV/m at a Q_0 of 1×10^9 (Fig. 3) after the cavity was partially warmed up to an intermediate temperature (the exact value was not monitored). This corresponds to a peak surface magnetic field of 1683 Oe. A second gas helium processing somehow enhanced field emission. Nevertheless, it was able to re-establish the quench field at 44.3 MV/m despite the increased field emission. These data suggest that the high field quench is caused by the niobium material instead of field emission.

A soft barrier was observed reproducibly at $E_{acc}\sim 25$ MV/m, in excellent agreement with calculated multipacting barrier (first order two-sided multipacting at equator [5]). 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. 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.

The achieved 44.4 MV/m represents the highest accelerating gradient ever realized in a niobium RF resonator although field emission is strong. Q_0 remains $> 10^{10}$ up to $E_{acc} = 35$ MV/m. Further improvement into the regime of 50 MV/m can be anticipated by additional surface treatment.

The current optimization prerequisite of maintaining a large iris diameter results a penalizing higher E_{pk}/E_{acc}. Not surprisingly, excessive field emission was observed. But field emission was found to be not responsible for the gradient limit. The high peak surface electric field ($\sim$ 100 MV/m) on a broad area in CW mode is believed to impose no fundamental limit, but further tests are needed to carefully examine its effect.

TABLE 3. Surface treatments after final equator welding and test results of the single-cell reentrant cavity

Test	Etch*	HPR†	Vacuum bake	E_{acc}^{m} **	$Q_0(E_{acc}^{m})$	Limit	FE?	Comments
1	BCP 10μm	2×50 min	19 hr at 90°C	25.0	5×10^9	Quench	Yes	
2	BCP 8μm	4×50 min	48 hr at 90°C	27.1	6×10^9	Quench	No	
3	VEP 50μm‡	4×60 min	48 hr at 110°C	26.9	7×10^8	Quench	Yes	
4	BCP 5μm	2×120 min	48 hr at 100°C	18.4	2×10^8	Power	Yes	Test stand contaminated
5	BCP 2μm	2×60 min	-	37.1	8×10^8	Power	Yes	No bake out
6	-	-	54 hr at 100 °C	42.6	1×10^9	Power	Yes	After He processing
7	-	-	-	44.4	1×10^9	Quench	Yes	After partial warm up
8	-	-	-	44.3	8×10^8	Quench	Yes	After 2nd He processing

* BCP 10μm = BCP1:1:2 etch to remove 10 μm from both inside and outside surface
† 2×50 min = 2 cycles, 50 minutes each
** Maximum E_{acc} achieved during test
‡ Single-cell vertical electropolish

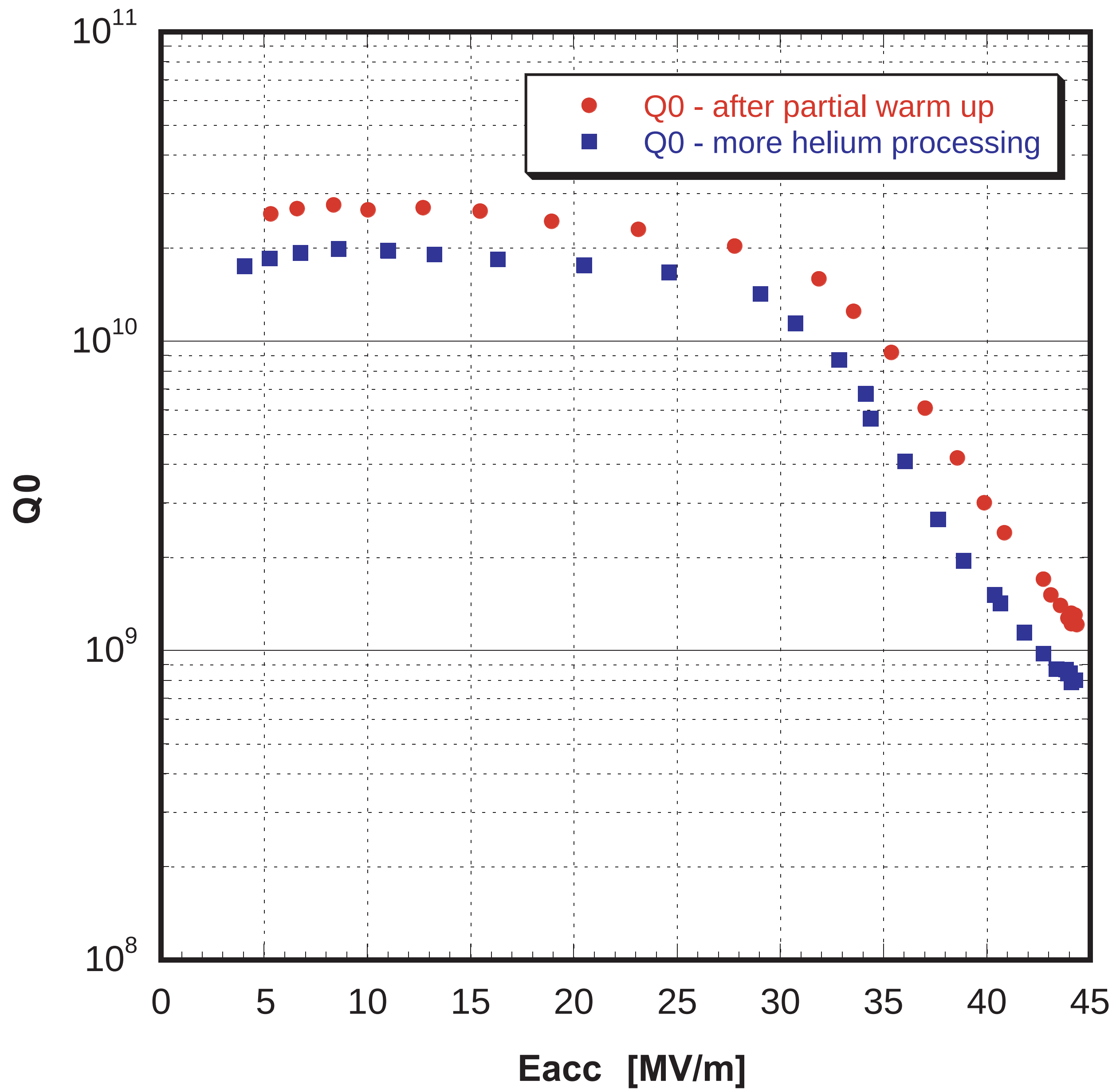

FIGURE 3. Dependence of the unloaded quality factor Q_0 on the accelerating gradient E_{acc} of the single-cell niobium cavity of reentrant geometry. Solid circle: after first helium processing and partial warm up. Solid square: after second helium processing.

These experiments also demonstrate that high-gradient (25 MV/m) cavities can be fabricated by doing high temperature post-purification heat treatment and primary chemical etch of RF surfaces at the half-cell stage. For large-scale production of niobium cavities, fabrication cost can be saved by using the half-cell method.

ACKNOWLEDGMENTS

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