REVIEW OF NEW SHAPES FOR HIGHER GRADIENTS*

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Abstract

High gradient superconducting RF (SRF) cavities are needed for energy frontier superconducting accelerators. Progress has been made over the past decades and the accelerating gradient E_{acc} has been increased from a few MV/m to ∼ 42 MV/m in SRF niobium cavities. The corresponding peak RF magnetic field H_{pk} on the niobium cavity surface is approaching the intrinsic RF critical magnetic field $H_{crit,RF}$, a hard physical limit at which superconductivity breaks down. Pushing the gradient envelope further by adopting new cavity shapes with a lower ratio of H_{pk}/E_{acc} has been recently proposed. For a reduced H_{pk}/E_{acc}, a higher ultimate E_{acc} is sustained when H_{pk} finally strikes $H_{crit,RF}$. The new cavity geometry include the re-entrant shape conceived at Cornell University and the so-called "Low-Loss" shape proposed by a DESY/JLAB/KEK collaboration. Experimental work is being pursued at Cornell, KEK and JLAB. Results of single-cell cavities are encouraging. A record gradient of 47 MV/m was first demonstrated in a 1.3 GHz re-entrant niobium cavity at Cornell University. At the time of writing, a new record of 52 MV/m has been realized with another 1.3 GHz re-entrant cavity, designed and built at Cornell and processed and tested at KEK. Single-cell low-loss cavities have reached equally high gradients in the range of 45-51 MV/m at KEK and JLAB. Owing to their higher gradient potential and the encouraging single-cell cavity results, the new cavity shapes are becoming attractive for their possible use in the International Linear Collider (ILC). Experimental work on multi-cell niobium cavities of new shapes is currently under active exploration.

INTRODUCTION

High-gradient SRF cavities are imperative for energy frontier accelerators such as the International Linear Collider (ILC). Progress has been made over the past decades owing to the effort of the TESLA collaboration. The accelerating gradient (E_{acc}) in SRF niobium cavities has been increased from 10 MV/m to ∼ 42 MV/m. Understanding of gradient-limiting mechanisms played a crucial role [1]. The new insight was often gained through studies of single-cell cavities and performance improving technologies accompanied. The successful application of suitable technologies to multi-cell cavities has led to a shrinking gap between the cavity operation gradient and the best gradient, as defined by the single-cell cavities. The past ten years saw a continuous increase in the practical gradient in multi-cell niobium cavities. But it seems the gradient envelope has reached saturation near 42 MV/m since this was first demonstrated in 1995 [2].

As well known, it is the peak surface electric (E_{pk}) and magnetic (H_{pk}) field that decide the achievable accelerating gradient [3]. Both E_{pk} and H_{pk} increase proportionally as E_{acc} is raised. The ratios of E_{pk}/E_{acc} and H_{pk}/E_{acc} are constants and determined solely by the cavity geometry. Traditional wisdom was to optimize the cavity shape, among other things, for a minimal E_{pk}/E_{acc} because of field emission, which increases exponentially with E_{pk}. An example is the TESLA/TTF cavity shape designed in 1992 [4].

Although field emission control is a practical challenge, there is no known fundamental limit to the electric field up to 100-200 MV/m on the superconducting niobium surface [5]-[7]. In many cavities, a E_{pk} of 70-80 MV/m has been achieved with little field emission, the control of which is realized by a reduced surface particulate contamination by using the high pressure water rinsing technology [8] and by a smoother cavity surface by using the electropolishing technology [9].

As to the H_{pk}, there is an intrinsic limit referred to as the RF critical magnetic field $H_{crit,RF}$. When the H_{pk} is raised to $H_{crit,RF}$, super-conductivity breaks down. The maximum allowable gradient E_{acc}^{max} can be written as,

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

$H_{crit,RF}$ is a material property. 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. For many high-gradient niobium cavities tested at 2 °K, the H_{pk} value falls in the range of 1650-1850 Oe [10], which is not far away from the predicted $H_{crit,RF}$ value of 2300 Oe. It is suspected that a hard barrier due to H_{pk} is responsible for the flat gradient envelope in the past ten years. In this context, pushing the gradient limit has attracted some attention as reflected by the talks presented at a recent workshop at ANL [11].

From Eq.1, it is obvious that there are two solutions to further improve the accelerating gradient: (1) Increase $H_{crit,RF}$ by using better material such as Nb_3Sn; (2) Reduce H_{pk}/E_{acc} by changing the cavity geometry. In this paper, we will review the recent developments on the work of pushing the gradient envelope by cavity shapes optimized for a reduced H_{pk}/E_{acc}.

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NEW SHAPES AND RF DESIGN

The discussion of reducing H_{pk}/E_{acc} by cavity shape optimization for a higher potential gradient was published in 2002 [12][13]. A re-entrant shape consisted of two conjugated elliptical arcs was proposed. The reference shape is that of the center cells of the TTF cavity [4]. A group of 1.3 GHz re-entrant shapes with a reduction in H_{pk}/E_{acc} of up to $\sim$ 13% were given. A graphical comparison of the re-entrant shape, which has a 10% reduction in H_{pk}/E_{acc}, and the reference TTF shape is given in Fig. 1. The iris aperture of the re-entrant shape is 70 mm, identical to that of the TTF shape. This keeps the wakefield the same. Simulation studies predicted the existence of a soft two-point multipacting barrier, very similar to that of the TTF shape. There is another re-entrant shape design which has a smaller aperture of 60 mm [14]. The H_{pk}/E_{acc} is 35.4 Oe/(MV/m), which is 15% lower than that of the reference TTF shape.

The so-called "low-loss" shape was initially proposed in 2002 for the 1.5 GHz cavities for CEBAF 12 GeV upgrade [15]. It was originally optimized for a higher shunt impedance (R/Q) and geometry factor (G), which means a lower power dissipation on the cavity surface for the same cavity voltage and hence a lower cryogenic loss (reason for dubbing the shape low-loss). The low-loss shape was re-examined in 2004 as a geometry for higher gradients because of its lower H_{pk}/E_{acc} [10]. The design of the 1.3 GHz low-loss cavity (see Fig.2) was reported shortly at the first ILC workshop in 2004 [16]. A more comprehensive report was published in 2005 [17]. Like the TTF shape, the low-loss contour is consisted of two elliptical/circular arcs (one at equator and the other at iris) and a straight line segment in between. Compared to the TTF shape, the low-loss shape has a smaller (60 mm) aperture and the straight line segment is more perpendicular to the beam axis.

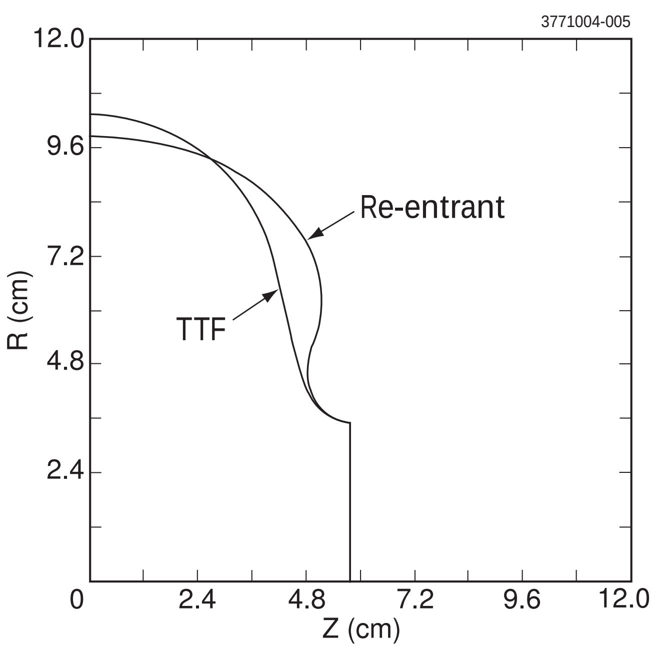

Figure 1: Half-cell geometry comparison of a re-entrant shape and the TTF shape. H_{pk}/E_{acc} of the re-entrant shape is 10% lower.

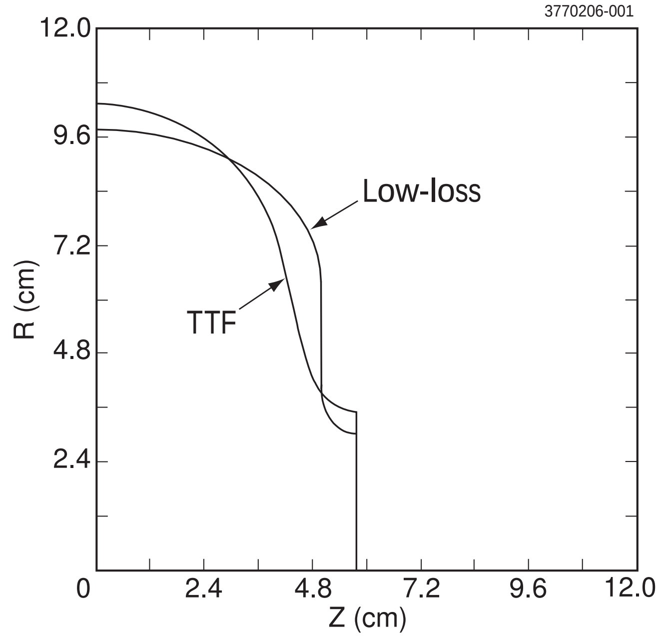

Figure 2: Half-cell geometry comparison of the low-loss shape and TTF shape.

There is a re-entrant variant called "half re-entrant" shape [18] [19]. In this case, the single cell is composed of two asymmetric half cells, one being the TTF/low-loss type and the other being the re-entrant type. Two half re-entrant shape designs were proposed, one has a 70mm aperture and the other 58 mm. The half re-entrant shape has an improved technical advantage of easing the fluid flow and avoiding gas pockets during the cavity processing, as compared to the re-entrant shape.

RF parameters of the TTF shape and the new shapes are summarized in Table 1. In summary, as compared to the TTF shape, the new shapes lower the H_{pk}/E_{acc} by 9-15% at the price of a 10-35% higher E_{pk}/E_{acc}.

SINGLE-CELL CAVITY EXPERIMENTAL RESULTS

Single-cell re-entrant cavity

Cornell University has been conducting experimental studies of single-cell re-entrant cavities since 2003 [20]. The first 70 mm aperture single cell cavity was built by using the regular fabrication methods. Deep-drawn cups were post purified (boosting the residual resistance ratio of the niobium from 250 to about 500). Trimmed half cells and beam tubes were joined at the equator and irises by electron beam welding. The cavity RF surface was processed by electropolishing, which is followed immediately by high pressure water rinsing (HPR). HPR was repeated typically

Table 1: Comparison of RF parameters of the TTF shape and the new shapes.

Parameter	**Unit**	**TTF**	**Re-entrant 70mm aperture**	**Low-loss**	**Re-entrant 60mm aperture**	**Half re-entrant**
Frequency	MHz	1300	1300	1300	1300	1300
Aperture	mm	70	70	60	60	58
$H_{pk}/Eacc$	Oe/(MV/m)	41.5	37.8	36.1	35.4	35.1
E_{pk}/E_{acc}	-	1.98	2.40	2.36	2.28	2.40
$G \cdot R/Q$	Ω^2	30840	33762	37970	41208	39363
k_c(§)	%	1.90	2.38	1.52	1.57	1.52
$k_{\|}$(†)	V/pC	1.46	1.45	1.72	-	-
$k_{\perp}$(‡)	V/pC/cm^2	0.23	0.23	0.38	-	-
K_L(¶)	Hz/(MV/m)^2	-0.74	-0.81	-0.83	-	-

(§) Cell-to-cell coupling factor.
(†) Longitudinal HOM loss factor (assuming bunch length $\sigma_z = 1mm$).
(‡) Transverse HOM loss factor (assuming bunch length $\sigma_z = 1mm$).
(¶) Lorentz force detuning coefficient (assuming 2.8 mm cavity wall thickness and optimal stiffening ring location).

four cycles (one hour for each cycle) with the cavity orientation flipped once. After the trapped water in the re-entrant pocket was spelled out by shaking, the cavity was dried in a class-10 clean space. The cavity was normally baked for 48 hours at 90-120 °C under vacuum prior to the cold test. In November 2004, the first 1.3 GHz re-entrant cavity reached a record gradient of 46 MV/m in the CW mode and 47 MV/m in the long (a few ms) pulsed mode [21]. There was little field emission. Q_0 remained over 1×10^{10} at 46 MV/m at a bath temperature of 1.9 °K. At a reduced temperature of 1.5-1.6 °K, Q_0 reached 2×10^{10} at 45 MV/m. The integrated inner surface material removal was 300 μm. The 47 MV/m gradient corresponds to a E_{pk} of 103 MV/m and a H_{pk} of 1781 Oe, respectively. Thermal breakdown was the gradient limit.

The second 1.3 GHz re-entrant cavity was built at Cornell University in the same way as for the first re-entrant cavity, except that it was post-purified after the whole cavity was electron beam welded. The processing and cold test was done at KEK. The cavity was mechanically polished (centrifugal barrel polishing) initially, followed by a light chemical etch. It was then annealed at 750 °C for 3 hours and further electropolished. Following a one hour high pressure water rinsing, vacuum pump down was usually started right way (when the surface was still wet). In September 2005, the second re-entrant cavity reached a new record gradient of 51 MV/m [22]. Some field emission was present. At 2 °K, Q_0 was 6×10^9 at the highest gradient. The integrated inner surface material removal was 200 μm. In a following test for which the cavity was further high pressure water rinsed, 52 MV/m was reached with a Q_0 of 1×10^{10} at 2K [23]. Field emission was little. The cavity was limited by quench. The 52 MV/m gradient corresponds to a E_{pk} of 114 MV/m and a H_{pk} of 1971 Oe, respectively. This represents today's record RF electric and magnetic field reached in the CW mode on a large niobium surface.

Single-cell low-loss cavity

JLAB built and tested a 2.3 GHz low-loss cavity from the special single-crystal niobium [24]. Niobium sheets were sliced from a large grain ingot by wire electro-discharge machining. The starting residual resistance ratio of the niobium was about 280. Post-purification at 1250 °C was applied improving the RRR by about 10%. The standard deep-drawing, machining, electron beam welding method were used for fabrication. The RF surface was etched initially for 100 μm with BCP1:1:1 at room temperature. 800 °C annealing was performed for 3 hours for hydrogen degassing. A second room temperature BCP1:1:1 etch removed another 100 μm from the RF surface (total removal 200 μm). After high pressure water rinsing for 30 minutes, the cavity was dried in a class 10 clean room for 2 hours and vacuum pump down then started. Vacuum bake out at 120°C was performed for for 24 hours. This cavity reached an accelerating gradient of 45 MV/m. At 2 °K, the Q_0 was 7×10^9 at the highest gradient. The 45 MV/m gradient corresponds to a E_{pk} of 93 MV/m and a H_{pk} of 1602 Oe, respectively.

KEK has been conducting experimental studies of 1.3 GHz single cell cavities since 2004 [25]. First 1.3 GHz low-loss cavities have been built by using the regular fabrication methods (deep drawing, machining and electron beam welding). The starting RRR of the sheet niobium is 300. No titanium post-purification was applied. The KEK cavity processing method has been already mentioned in previous section. In September 2005, the first 1.3 GHz low-loss cavity reached 47 MV/m with a Q_0 of 1.2×10^{10} at 2 °K [23]. Field emission was little. The integrated surface material removal was 400 μm. At a reduced temperature of 1.7 °K, a higher Q_0 of 1.7×10^{10} was obtained. The highest gradient remained 47 MV/m. The gradient limit was quench. Soon after this successful demonstration, two more single cell low-loss cavities reached 45 MV/m and 49 MV/m, respectively. Q_0 was about 1×10^{10} in both cases.

Field emission was little. The 49 MV/m cavity was later further high pressure water rinsed for 2 more times (1 hour each) and a gradient of 51 MV/m was reached with a Q_0 of 8×10^9 at 2K [22]. The integrated surface removal was 260 μm. The 51 MV/m gradient corresponds to a E_{pk} of 95 MV/m and a H_{pk} of 1892 Oe, respectively.

Fig. 3 illustrates $H_{pk}(E_{acc})$ and $E_{pk}(E_{acc})$ of the best TTF single cell cavities and the single cell re-entrant and low-loss cavities.

In summary, six single cell cavities (two 1.3 GHz re-entrant shape, one 2.3 GHz low-loss shape and three 1.3 GHz low-loss shape) reached gradients $\geq$ 45 MV/m. Gradients $\geq$ 50 MV/m were demonstrated in both the re-entrant and low-loss shape. Similar as in the TTF shape, a soft multipacting barrier around 20 MV/m is observed (as predicted by simulations) in both cavity shapes. It can be passed by RF processing. E_{pk} reached 95-115 MV/m. Controlling of field emission at such a high E_{pk} was proven possible.

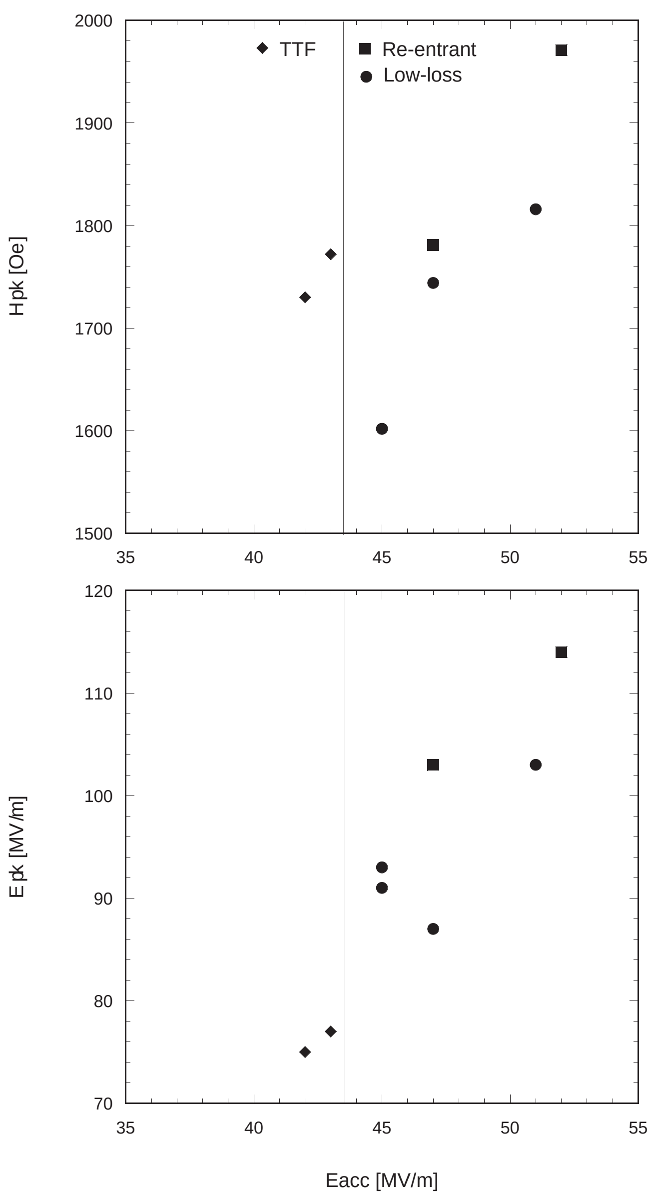

Figure 3: E_{acc} and corresponding H_{pk} and E_{pk} achieved in various single cell niobium cavities. TTF: diamond; Re-entrant: square; Low-loss: Circle. Gradients $\geq$ 45 MV/m are made available by new shapes.

MULTI-CELL CAVITY EXPERIMENTAL WORK

Experimental work of multi-cell cavities of new shapes is currently pursued.

KEK has an aggressive 1.3 GHz 9-cell low-loss cavity program for ILC. First four 9-cell low-loss cavities have been built and cold test is on-going [25]. Fig. 4 shows a photo of this type of cavity which was named ICHIRO after a Japanese baseball player who's number is 51, the goal gradient for the 9-cell low-loss cavity. ICHIRO cavity has suitably designed end-cells and TTF type HOM couplers. 20 MV/m was reached so far in ICHIRO and the limit was quench. Strong multipacting was observed at this gradient. The heat produced by the bombardment of multipacting electrons was suspected to be responsible for quenching.

Cornell University is fabricating a 1.3 GHz 9-cell re-entrant cavity for ILC in collaboration with industry.

JLAB 1.5 GHz 7-cell low-loss cavities for CEBAF upgrade have reached 25 MV/m [26]. JLAB has also built a 1.3 GHz 5-cell and a 7-cell low-loss cavity with large grain niobium.

DISCUSSION

Advantages and disadvantages of new shapes

Besides the primary advantage of a lower H_{pk}/E_{acc}, the new shapes discussed in this paper have another beneficial feature, *i.e.* a higher $G \cdot R/Q$. It means lower dynamic losses on the cavity surface and less cryogenic need for the same beam voltage. This is the very reason the low-loss shape was developed in the first place. For example, as compared to the TTF shape, the low-loss shape offers a 23% saving in cryogenic requirement. The 60 mm aperture re-entrant shape even offers a 34% saving.

The higher E_{pk}/E_{acc} is a disadvantage for all new shapes discussed in this paper.

Some new shapes have smaller aperture sizes. This reduces the cell-to-cell coupling and increases the field flatness sensitivity due to the frequency error in individual

Figure 4: ICHIRO: KEK 9-cell low-loss cavity. (Photo courtesy: K. Saito)

cells in a multi-cell cavity. Smaller aperture increases the loss factor of longitudinal ($k_{\parallel}$) and transverse ($k\perp$) wakefields. For example, the low-loss shape has a 18% higher $k_{\parallel}$ and a 65% higher $k_{\perp}$ (for a bunch length of σ_z=1mm), as compared to that of the TTF shape [17]. This demands more stringent cavity alignment in order to preserve the beam emittance. For these reasons, there is probably a lower limit to the aperture size set by the requirement of beam dynamics. The impact of the smaller aperture size needs to be examined numerically and experimentally.

Preliminary numerical calculations show that the Lorentz force detuning factor (K_L) of new shape cavities are slightly higher that that of the TTF cavity for the same wall thickness [27]. However, a minor increase in the wall thickness restores K_L to the level of the TTF cavity.

Changes in the cavity geometry may also open up the possibility of multipacting. Experimental work with single cell cavities of new shapes confirmed the existence of two-point multipacting barriers, as predicted by numerical simulations. Like in the TTF shape cavity, these barriers are soft and can be passed by performing modest RF processing.

Cavity fabrication and treatment considerations

We want to make a few comments on the cavity fabrication, treatment and processing, although they are not specific to cavities of new shapes. Eq. 1 describes the theoretical maximum gradient obtainable in an ideal cavity. However, a more general form of the equation should be written as the following,

$$E_{acc}^{max} = \frac{r \cdot H_{crit,RF}}{\beta_{MAG} \cdot (H_{pk}/E_{acc})}. \quad (2)$$

Here r, a dimensionless factor ≤ 1, represents the reduction of the RF critical field from its theoretical value of niobium due to impurities, lattice defects etc. in the RF penetration depth. β_{MAG}, a dimensionless factor ≥ 1, represents the enhancement of H_{pk} due to local geometric imperfections.

In an ideal cavity made from ideal niobium with a perfectly smooth inner surface, $r = 1$ and $\beta_{MAG} = 1$ and Eq.2 reduces to Eq.1.

A real world cavity is much more complicated. on the one hand, depending on the choice of the starting sheet niobium, cold work of half cells, surface removal, high temperature treatment (for hydrogen outgassing or for post-purification), and low (~ 100 °C) temperature bake-out, the critical RF magnetic field of the end cavity surface may be smaller than $H_{crit,RF}$, or $r < 1$. On the other hand, local geometric imperfections, such as the under-bead at the equator EBW joint, the grain boundaries exposed by differential chemical etching, can not be avoided and hence $\beta_{MAG} > 1$. Overall, the maximum attainable gradient is reduced by a factor of $\frac{r}{\beta_{MAG}}$. Starting niobium, fabrication and treatment methods must be carefully controlled in building cavities of new shapes so that the benefit of the lower H_{pk}/E_{acc} is not eroded.

Use of new-shape cavities

New shape cavities have two uses. One is for energy frontier accelerators taking advantage of the higher gradient capability. The re-entrant shape and low-loss shape are both considered as alternative cavity shapes for ILC upgrade [28]. The other use takes advantage of the lower loss nature. The 12 GeV upgrade of CEBAF at JLAB uses a low-loss shape. 1.5 GHz prototype 7-cell low-loss cavities have been tested [26]. The low loss feature is also attracting to the future CW superconducting accelerators for x-ray light sources, such as the Cornell ERL.

CONCLUSIONS

The argument of lower H_{pk}/E_{acc} for higher gradient made in the year of 2002 has been proven experimentally to be a valid one. The 47 MV/m breakthrough was realized in a 1.3 GHz single cell re-entrant cavity in the year of 2004. Today several single cell cavities have reached gradients $\geq$ 45 MV/m, the record being 52 MV/m. Both the re-entrant and low-loss shape single cell cavities have demonstrated gradients in the neighborhood of 50 MV/m.

Experimental work with single cell cavities of new shapes has proven that it is possible to sustain a CW RF field of $E_{pk} \geq 100$ MV/m over a broad surface area with little field emission. This is achieved by using existing technologies. With improvements of these technologies and inventions of future new technologies for field emission control, one can expect reliable cavity performances with little or no field emission in multi-cell cavities operated at the ultimate gradient determined intrinsically by $H_{crit,RF}$.

No hard multipacting barrier was observed in neither the re-entrant nor the low-loss single cell cavities.

The successful single cell cavity results have made the re-entrant and low-loss shape alternative choices for ILC upgrade which requires 9-cell cavities. Four 9-cell low-loss cavities are under testing. A 9-cell re-entrant cavity is being fabricated.

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