DEVELOPMENT OF ULTRA HIGH GRADIENT AND HIGH Q_0 SUPERCONDUCTING RADIO FREQUENCY CAVITIES*

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Abstract

We report on recent progress at Jefferson Lab in developing ultra high gradient and high Q_0 superconducting radio frequency (SRF) cavities for future SRF based machines. A technique has been developed for localizing active field emitters in a full scale 9-cell cavity. A new 1300 MHz 9-cell low surface field (LSF) shape prototype cavity is being fabricated. This cavity has an optimized shape in terms of the ratio of the peak surface field (both magnetic and electric) to the acceleration gradient, hence the name LSF. The goal of the effort is to demonstrate an acceleration gradient of 50 MV/m with Q_0 of 1E10 at 2 K in a 9-cell SRF cavity. Fine-grain niobium material is used. Conventional forming, machining and electron beam welding method are used for cavity fabrication. The completed cavity is to be first mechanically polished to a mirror-finish, a newly acquired in-house capability at JLab, followed by the proven ILC-style processing recipe established already at JLab. In parallel, new single-cell TESLA cavities made from large-grain niobium material are made to further advance the cavity treatment and processing procedures, aiming for the demonstration of an acceleration gradient of 45 MV/m with Q_0 of 2E10 at 1.8-2 K.

INTRODUCTION

The accelerating gradient choice has a significant impact to the energy reach and the project cost for the International Linear Collider (ILC). The baseline ILC design requires a cavity accelerating gradient of 31.5 MV/m in average with an allowable spread of < ±20% (TESLA-shape cavity) to achieve a center-of-mass energy of 500 GeV with two 11-km long main linacs. The vertical test acceptance specification is 35 MV/m at Q_0 8E9, with an allowable gradient spread of < ±20% [1]. In the past several years, a global cavity gradient R&D program was successfully carried out, leading to realization of the baseline design accelerating gradient and yield goals [1]. Jefferson Lab has been engaged in the ILC cavity gradient R&D program since 2006. A main initial focus is to improve cavity processing and handling procedure. This effort led to demonstration of a 90% yield at 38 MV/m gradient in the year of 2010, on the basis of ten full scale ILC baseline cavities fabricated by experienced industrial vendors [2].

Since October 2010, our effort in high gradient SRF R&D has evolved to raising the gradient beyond the ILC baseline design specification in a full scale cavity. Three major tasks are identified:

- Understand and reduce/eliminate field emission in full scale cavity in the regime of up to 100 MV/m peak surface electric field.
- Demonstrate ultra-high acceleration gradients in the regime of 50 MV/m in 9-cell cavities via the new Low-Surface-Field (LSF) shape.
- Demonstrate high Q_0 (2E10) at 45 MV/m gradient regime via large-grain material and further improved cavity treatment procedures.

These efforts aim for cavity performance demonstration in full scale cavities required for ILC upgrade to 1 TeV.

Our efforts, although driven by ILC, are expected to benefit other applications of SRF technology. For example, reliable and complete elimination of field emission in full scale multi-cell cavities (during vertical qualification test or in cryomodule operation) has not been achieved even in the medium gradient range of ~ 20 MV/m. It is important to reduce/eliminate field emission in CW machines such as CEBAF to limit activation of beam line components. A LSF cavity is intrinsically more energy efficient due to its optimized shape (higher G*R/Q). A 20% reduction in dynamic load to cryogenics can be expected as compared to the case of the ILC baseline cavity. This saving can be significant in CW applications such as NGLS.

UNDERSTANDING & REDUCING FIELD EMISSION IN FULL SCALE CAVITY

A procedure combining numerical simulations and experimental measurements has been developed for localization of active field emitters in a full scale 9-cell cavity [3].

The numerical simulation was done using the ACE 3P suites developed at SLAC. The energy spectrum of gamma-rays due to field emission was measured using a 4 in. dia. × 5 in. NaI(Tl) crystal detector placed on the top plate of the cavity vertical test insert (within the radiation shielding block). The spatial distribution of the gamma-rays was measured by placing Hamamatsu S1223-01

* Work supported by DOE. Authored by Jefferson Science Associates, LLC under U.S. DOE Contract No. DE-AC05-06OR23177. The U.S. Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce this manuscript for U.S. Government purposes.
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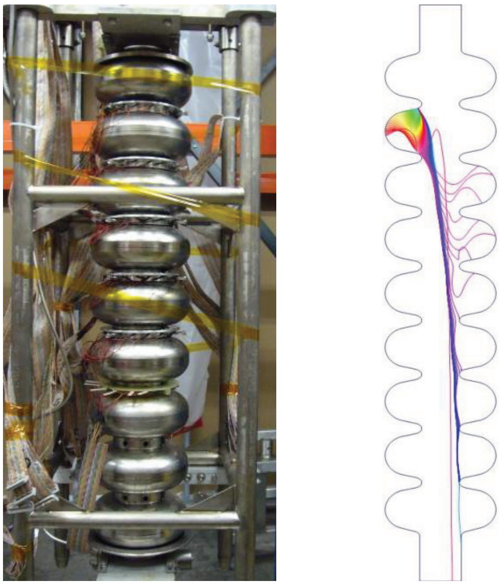
diodes at various locations around the cavity in liquid helium [4]. A 9-cell cavity with 96 mounted diodes ready for vertical test is shown in Fig. 1(a). The location of the dominant active field emitter was successfully identified. Trajectories of field emitted electrons originated from the predicted location are shown in Fig. 1(b).



(a) (b)

Figure 1: (a) A nine cell ILC cavity equipped with cryogenic radiation detection diodes for field emitter localization; (b) Trajectories of electrons emitted from the location as determined by the JLab procedure.

FABRICATION OF 9-CELL LSF CAVITY

The LSF cavity shape [5] has a reduced ratio of H_{pk}/E_{acc}, which is also the case for other alternative shapes such as Cornell re-entrant (RE) and KEK low-loss (LL). The advantage to the LSF shape is that it achieves a reduced H_{pk}/E_{acc} without sacrificing E_{pk}/E_{acc}. This feature makes the LSF shape very attractive for ultra-high gradient cavities. The disadvantage to the LSF shape is the lower cell-to-cell coupling. A comparison of RF parameters of the LSF shape against other shapes is given in Table 1.

Table 1: Comparison of RF parameters of various shapes. *TESLA: Original TESLA design, is ILC baseline; LL: KEK Ichiro Low-Loss; RE: Cornell Re-Entrant; LSF: SLAC Low-Surface-Field*

	Unit	TESLA	LL	RE	LSF
Aperture	mm	70	60	60	60
E_{pk}/E_{acc}	-	1.98	2.36	2.28	1.98
H_{pk}/E_{acc}	mT/(MV/m)	4.15	3.61	3.54	3.71
k	%	1.90	1.52	1.57	1.27
G*R/Q	Ω^2	30840	37970	41208	36995

E_{pk}: Peak electric field; E_{acc}: Acceleration gradient H_{pk}: Peak magnetic field; k: cell-to-cell coupling; G: Geometry factor; R/Q: Shunt impedance over quality factor

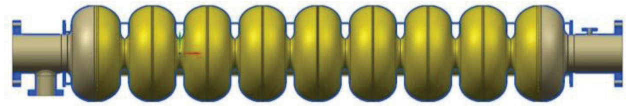


Figure 2: Model of the first 9-cell LSF shape cavity under in-house fabrication at Jefferson Lab.

Figure 3: Formed niobium cups for the first LSF 9-cell prototype cavity.

The fabrication of the first 1300 MHz prototype 9-cell niobium cavity is currently in progress. A model of the cavity is shown in Fig. 2.

Fine-grain niobium material is used. Conventional forming, machining and electron beam welding method are used for cavity fabrication. Some of the niobium cups for the LSF 9-cell are shown in Fig. 3. After initial deep drawing of niobium cups, a vacuum furnace heat treatment was applied for stress relief. The cups were re-formed using the original dies. The cups were then machined at the equator and iris to its final weld prep dimensions. This new technique ensures repeatable, accurate and inexpensive fabrication. All the niobium half cells needed for the first prototype 9-cell cavity have been completed. The CMM inspections of all the cups are also completed. All half cells showed highly repeatable dimensions. Currently, RF inspections of the finished half cells are on-going.

The completed cavity is to be first mechanically polished to a mirror-finish, a newly acquired in-house capability at JLab [6], followed by the proven ILC-style processing recipe established already at JLab [7]. To evaluate the effectiveness of the wall removal by mechanical polishing from the flat region of the LSF shape, a single-cell LSF copper cavity was fabricated and mechanically polished successfully to mirror-finish. The removal in the flat region is somehow less than that in equator region, but is sufficient.

VERY HIGH GRADIENT WITH HIGH Q_0

In order to operate the ILC at higher gradient efficiently, the quality factor Q_0 of the cavities need to be raised too as the cavity gradient is raised. To keep the dynamic heat load to the cryogenics the same, the Q_0 of a cavity needs to be doubled for 40% raise of gradient over

ISBN 978-3-95450-122-9

the ILC baseline operation gradient. The large-grain material has shown promising properties leading to lower surface resistance [8]. So far, the experience with large-grain niobium single-cell as well as multi-cell cavities at JLab has been favorable in achieving better Q_0 [9][10]. A 9-cell large grain TESLA shape cavity has achieved a gradient of 45 MV/m with a Q_0 of > 1E10 at DESY [11].

Aiming for the demonstration of an acceleration gradient of 45 MV/m with Q_0 of 2E10 at 1.8-2 K, two new single-cell cavities have been made from large-grain niobium material. The processing procedure of these two cavities consists of mirror-finish mechanical polishing, high temperature vacuum furnace heat treatment and electropolishing. Both cavities are currently under processing and testing. Fig. 4 show the visual impression of the mirror finish RF surface of the cavity G2 after mechanical polishing, heat treatment, electropolishing and initial high pressure water rinsing. The first test result of this cavity is given in Fig. 5.

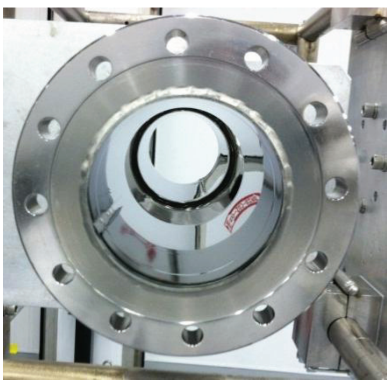


Figure 4: The view of a 1-cell 1300 MHz large grain niobium cavity mechanically polished to mirror finish. The red arc area at 4-5 o'clock is the reflection of a red tape on the clean room wall pointing a fire extinguisher.

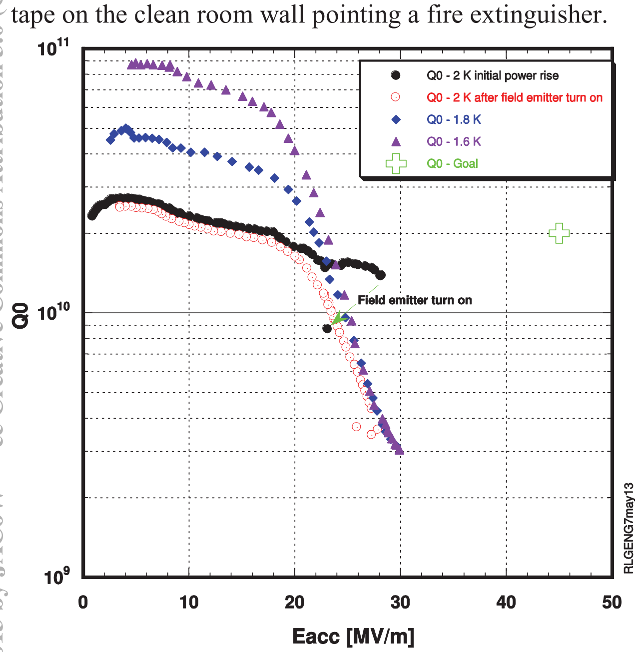


Figure 5: First test result of 1-cell 1300 MHz large-grain niobium cavity G2 processed with mirror-finish mechanical polishing, heat treatment and electropolishing.

CONCLUSION AND OUTLOOK

A technique has been developed for localizing active field emitters in a full scale 9-cell cavity. The goal of this effort is to systematically reduce field emission in real multi-cell cavities. A new 1300 MHz 9-cell prototype LSF cavity is being fabricated. The goal of the effort is to demonstrate an acceleration gradient of 50 MV/m with Q_0 of 1E10 at 2 K in a 9-cell cavity. Two new single-cell 1300 MHz cavities made from large-grain niobium are made and undergoing advanced treatment, processing and testing, aiming for the demonstration of an acceleration gradient of 45 MV/m with Q_0 of 2E10 at 1.8-2 K.

ACKNOWLEDGEMENTS

We thank Drew Weisenberger and the JLab Detector Group members for setting up the X-ray crystal detectors and the data acquisition system for 9-cell cavity field emission localization experiment. We are indebted to Kathryn Kuykendoll of NASA Langley Research Center for her help in CMM inspection of the cavity half-cells. We also highly appreciate Curtis Crawford of FNAL for electropolishing and cleaning of the mirror finish large grain single cell niobium cavity.

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