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PERFORMANCE OF FIRST PROTOTYPE MULTI-CELL LOW-SURFACE-FIELD SHAPE CAVITY*

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Abstract

The first multi-cell LSF shape prototype cavity was built using the standard forming and welding techniques at JLAB. RF tests have been carried out at JLAB, following processing and treatment at KEK using the standard ILC TDR baseline recipe. Three out of five cells achieved B_{pk} values corresponding to E_{acc} 50 MV/m. The current limit is the field emission (FE) in end cells and several measures are being taken for its suppression. Instrumented testing with Kyoto University's sX-mapping system was carried out at JLAB for FE studies. We will present detailed experimental results and preparation procedures and next steps toward the first 9-cell LSF prototype cavity.

INTRODUCTION

The idea of cavity shaping for higher ultimate acceleration gradients has been proposed for some time, KEK's Low Loss/Ichiro and Cornell's Re-entrant being examples, both seeking a lower B_{pk}/E_{acc} at the expense of a higher E_{pk}/E_{acc} [1-4]. Experimental verification in 1-cell cavities of those shapes was very successful including record E_{acc} of 59 MV/m [5]. That success established a path forward for achieving higher E_{acc} well beyond 35 MV/m, and it was captured in the ILC TDR [6]. Pushing multi-cell cavities of those shapes was however blocked by FE - a bottle neck although not a fundamental limit. The best result achieved in a 9-cell ICHIRO shape cavity was 40 MV/m [7].

The Low-Surface-Field (LSF) shape, conceived at SLAC [8], seeks not only a lower B_{pk}/E_{acc} but also a lower E_{pk}/E_{acc}, therefore it has the advantage of raising ultimate E_{acc} at reduced FE.

Test results of LSF shape single-cell prototype cavities have been previously reported [9]. In this contribution, we present detailed experimental results and preparation procedures of the first multi-cell LSF shape cavity LSF5-1. We will also give an update on our next steps toward the first 9-cell LSF prototype cavity which was re-started now since the completion of its half-cells in 2012 [10].

DESIGN

As an intermediate step from single-cell to the first full-scale 9-cell LSF shape cavities, a 3-cell or 5-cell LSF cavity was considered a useful effort in addressing the unique challenge imposed by the small cell-to-cell coupling of the LSF shape. We ended up with a 5-cell cavity design as a compromise of several technical and financial factors.

For a multi-cell cavity, an important design feature is the cell wall stiffening scheme. In view of lessons learned from cavity shapes close to that of LSF, namely ICHIRO shape and CEBAF 12 GeV Upgrade LL shape, we put a premium on the cavity mechanical stability. This must be achieved without sacrificing the Lorentz detuning coefficient as is important for the goal gradient of 50 MV/m. Optimization work done by Zaplatin [11] and Posen [12] provided useful inputs. For the LSF shape multi-cell cavity, we choose a ratio of 0.64 for the stiffening radius to the equator radius. Another consideration is to control the cell shape deviation from welding of the stiffening pieces. We achieve this by selecting a three-arc-piece design as shown in Fig. 1, which differs from the ordinary two-half-ring design. This approach has the advantage of minimizing heat deposition from the electron beam welding of the stiffening components (by a factor of ~4) therefore greatly reducing shape deviations. Moreover, the arc piece location and partial penetration weld provide a further advantage. The key parameters for multi-cell LSF cavities are given in Table 1.

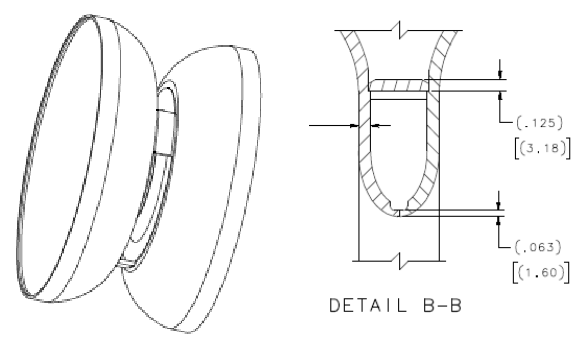

Figure 1: Three-arc-piece design for cell wall stiffening. Two pieces are visible in the 3D dumb-cell model (L). Location of each piece relative to cell walls is shown also (R).

Table 1: Key Parameters of Multi-Cell LSF Cavity

Parameter	Unit	5-cell	9-cell
Frequency	MHz	1300	1300
Iris radius	mm	30	30
Stiff. radius	mm	63	63
Eq. radius	mm	99	99
E_{pk}/E_{acc}	-	2.03	1.98
B_{pk}/E_{acc}	mT/(MV/m)	3.78	3.71
G	Ω	282	279
R/Q	Ω	628	1158
Cell-cell coupling	%	1.27	1.27

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FABRICATION AND PROCESSING

Fabrication

The 5-cell LSF shape cavity LSF5-1 was made from RRR 300 fine-grain niobium sheets supplied by Wah Chang. All fabrication steps were carried out with JLAB in-house machines. Half cells were deep drawn by using a 150-ton press. The equator and iris edges were milling machined to a wall thickness of 0.063 inch (1.66 mm) for butt welding at both places. The weld prep cleaning and stacking procedures, previously developed based on microscopic studies [13] and verified in building several single cell cavities, were used here as well. Iris-to-iris joints were electron beam welded from both inside and outside with partial penetration only. Stiffening pieces were electron beam welded with partial penetration as well. The finished dumb-bells were directly etched at equator edges, followed by equator-to-equator electron beam welding with full penetration from outside. No forced shape correction against dumb-bell or any additional equator edge machining were necessary. Figure 2 shows a photo of the completed cavity.

The field flatness of the completed cavity LSF5-1 was 33%. This was lower than expected and was attributed to the larger than expected weld shrinkage at the iris and at the stiffening pieces. High resolution optical inspection with a Kyoto camera was carried out. The overall impression of the electron beam weld at iris and equator regions was good. Notable features were documented.

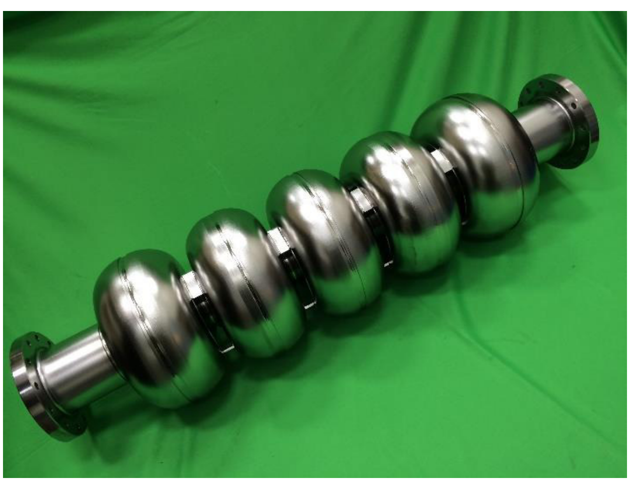

Figure 2: 5-cell LSF shape cavity LSF5-1 as completed electron beam weldment at JLAB.

Treatment, Processing, and Optical Inspection

The cavity was then shipped from JLAB to KEK for post-fabrication treatment and surface processing according to KEK's standard ILC TDR baseline style procedure and specification [6].

- Field flatness tuning to 95% using KEK's standard automatic tuning machine with modified tuning jaws and blades (Fig. 3).
- Pre-EP 5 µm with no acid circulation.
- Bulk EP 100 µm (Fig. 3).
- Ultrasonic cleaning with FM-20 detergent and HPR with ultra-pure water.
- Vacuum furnace annealing at 800 ºC for 3 hours.
- Field flatness tuning to 97%.
- Optical inspection of the inner surface at iris and equator weld regions.

The overall impression of the inner surface of the cavity after KEK treatment and processing was good. Some notable features documented initially at JLAB were still observable after treatment and processing at KEK. An example is given in Fig. 4, showing the survival of a twin spots close to the weld prep machining line in the equator region of the centre cell of LSF5-1.

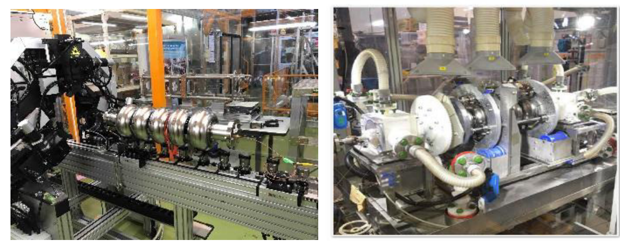

Figure 3: LSF5-1 tuning (L) and EP (R) at KEK STF.

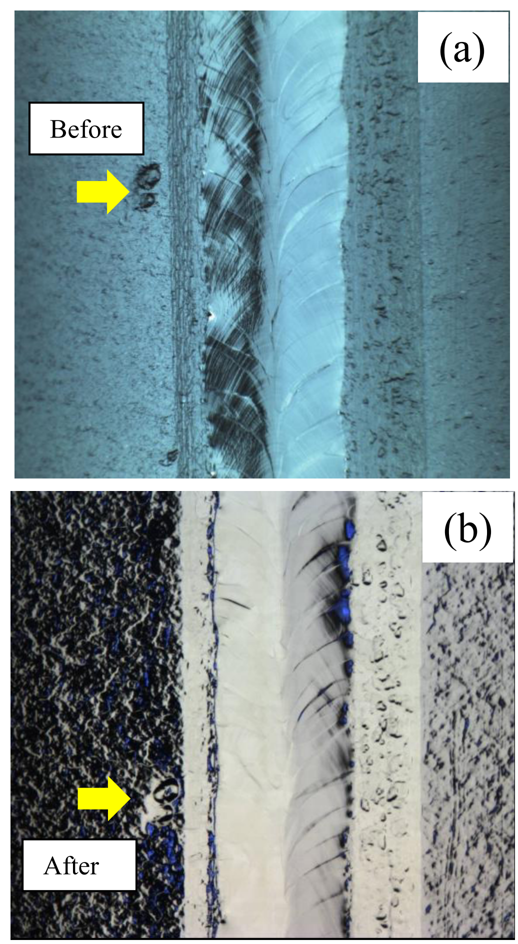

Figure 4: Comparison of optical inspection results at JLAB (a) and at KEK (b) of the same equator region of the center cell at 54º angle orientation.

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Final Surface Processing

After the cavity returned to JLAB in January 2018, the final surface processing was carried out for RF testing. The JLAB high gradient procedures [14] were optimized and verified with 122 9-cell cavity EP cycles and 187 9-cell cavity vertical tests over the period of 2006 – 2012. The key steps are final EP, post-EP cleaning and handling, and slow pump down. With their successful applications, JLAB demonstrated 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 [15].

Re-establishing these high gradient procedures at JLAB in present day has proven to be a challenge as a result of the Test Lab renovation project carried out in 2012. That project resulted in a major interruption to SRF facilities, including relocation of the EP machine, construction of a new clean room, and later on installation of a new high pressure rinsing machine etc. The initial high gradient cavity test results in using those new SRF facilities were mixed [10]. It was not until February 2014 when we were able to re-establish high gradient single-cell cavity test results [9]. Extension from single-cell thereafter to multi-cell was hampered by re-direction of JLAB priority to LCLS-II SRF production. Although large quantities of 9-cell cavities were still tested at JLAB for LCLS-II performance qualification, they were processed and assembled at vendor facilities instead of JLAB's and all were tested to gradients below the ILC specification. As a result, the capability of JLAB's new SRF facilities for high gradient multi-cell processing and handling remained an open question in February 2018 when the processing of cavity LSF5-1 began [16].

For reasons given above, re-establishing in-house high gradient multi-cell cavity processing and handling capability at JLAB has been a necessary part of our effort in advancing the cavity LSF5-1 toward the goal gradient of 50 MV/m. So far, 3 final EP cycles and 7 RF test cycles have been completed. Table 2 gives a summary of technical issues encountered and their subsequent resolutions.

A new advance beyond the standard procedure for cavity handling reported in Ref. [14] is an automated slow pump down device. Another new advance is the introduction of the solvent 3M Novec 7200 for iris and end-group wiping. A new HPR wand head has been made with a nozzle orifice selected for optimal "cleaning distance" tailored for radius from 30 – 35 mm, the proper range for a LSF shape cavity. The water jet angle is chosen to be 90 degree from the wand axis for maximum cleaning effect.

RESULTS

The best performance of cavity LSF5-1 was achieved in its 6th RF test as shown in Fig. 5, following a light EP of 20 μm according to the standard procedure [14] and a standard 48-hour low temperature bake at 120 ºC. It reached a maximum π–mode E_{acc} of 32 MV/m at 2K. The ordinary multipacting barrier ~ 20 MV/m was observed. The B_{pk} reached in 3 mid-cells was 189 mT as determined by passband mode measurements. This corresponds to an attainable E_{acc} of 50 MV/m in 3 out of 5 cells. The gradient limit was FE in the end cells (cell #1&5) at E_{pk} ~ 100 MV/m. The 7th RF test was carried out with Kyoto sX-mapping system aiming for studies of FE in the limiting end cells. Unfortunately, cavity and test stand were contaminated due to unexpected pump failures resulting in 61 g of air entered into the cavity. The cavity performance was severely degraded. The sX-mapping was tested successfully [17].

The measured Lorentz force detuning coefficient of LSF5-1 is -4.6 ± 0.2 Hz/(MV/m)^2. The field flatness was preserved within a few percent over various cavity handlings.

Table 2: Summary of RF Test Results and Issues

Test #	Max. E_{acc} [MV/m]	Issues met	Solutions & Actions
1	21	Ran out LHe, D6 too short	Pump and fill D6
2	24	Low Q_0, multipacting	EP 20μm, NbTi flange, Deeper dewar D3/4
3	30	FE, 4/5-Pi mode excitation	Re-HPR
4	8	Low Q_0, Slow pump down failure	Beam tube length addition, 3rd EP 20 μm, ethanol rinse
5	32	Small FE	Cavity low temperature bake at 120 ºCx48h
6	32	Test stand high AMU contamination	Iris wiping, HPR with new nozzle; Automatic slow pump down
7	7	Turbo pump loss to power, scroll pump failure	Re-clean cavity and re-clean test stand

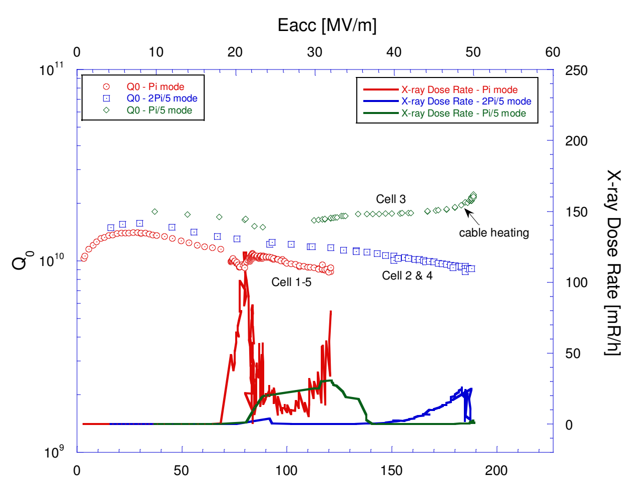

Figure 5: Best performance achieved so far by the cavity LSF5-1 at 2K.

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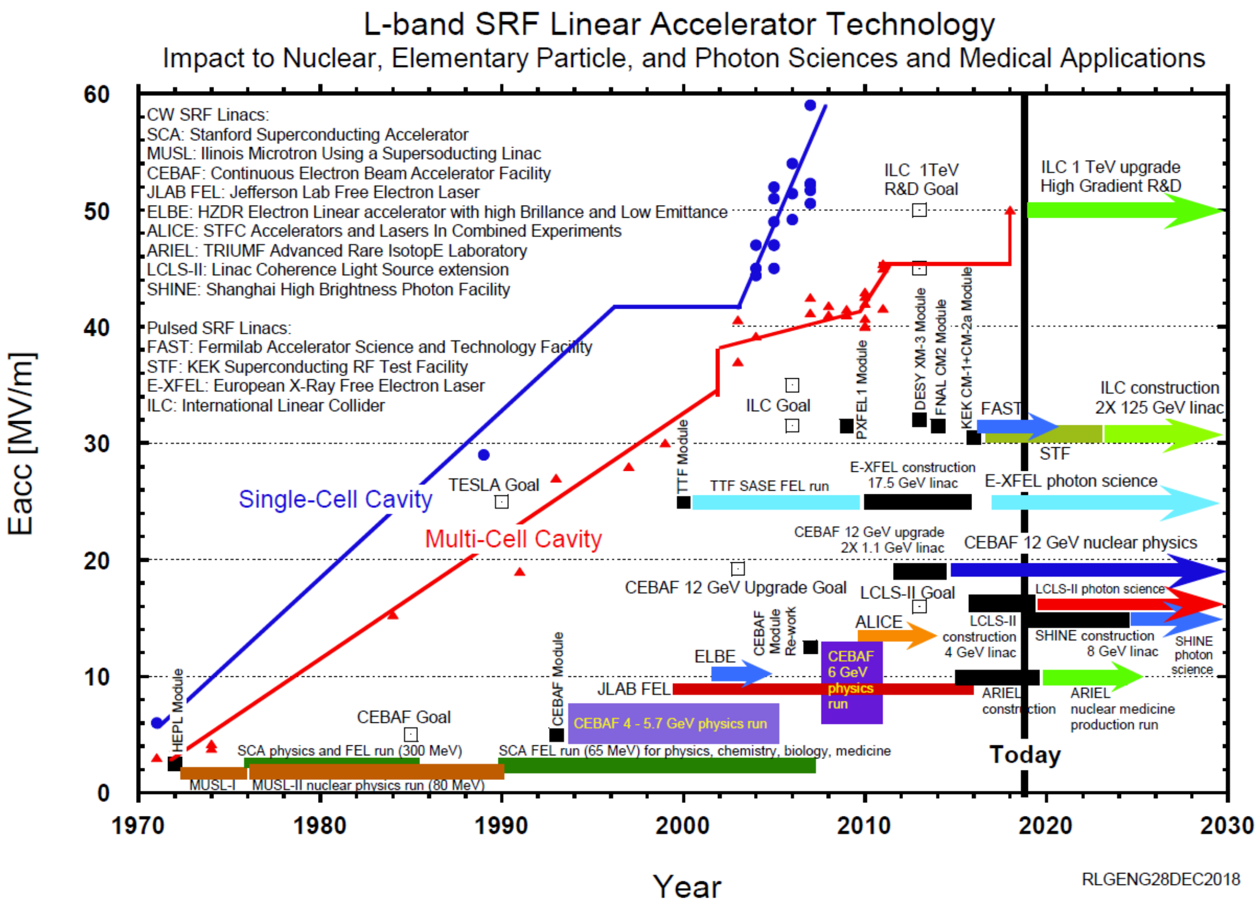

Figure 6: Today's landscape of gradient in SRF niobium cavities and the first sight of 50 MV/m in a multi-cell cavity.

CONCLUSION

The first multi-cell LSF shape prototype cavity was built using the standard forming and welding techniques at JLAB. RF tests have been carried out at JLAB, following processing and treatment at KEK using the standard ILC TDR baseline recipe. Three out of five cells achieved B_{pk} values corresponding to E_{acc} = 50 MV/m. The current limit is the FE in end cells and several measures are being taken for its suppression. Instrumented testing with Kyoto University's sX-mapping system was carried out at JLAB for pin-pointing the source of FE in the end cells at an E_{pk} of ~ 100 MV/m. The average Lorentz force detuning coefficient for LSF5-1 is -4.6 ± 0.2 Hz/(MV/m)^2. It is slightly (10%) better than that for ICHIRO shape cavity ICHRO7 which is -4.9 ± 0.2 Hz/(MV/m)^2 as measured previously at JLAB in a comparable configuration [7]. Moreover, the field flatness was preserved within a few percent over the course of various cavity handling processes. This confirmed our design in cell stiffening.

We are currently in the process of recovering from contamination due to pump failures. The plan is to re-test later this year for RF performance evaluation as well as for studies of FE using Kyoto's sX-mapping system.

In the meantime, the first 9-cell prototype LSF shape cavity LSF9-1 is in the process of in-house fabrication. The half cells were already made a few years ago [10] and by now we have essentially all the needed parts at hand. Our plan is to complete it in a couple of months and start processing and testing thereafter.

Although the cavity LSF5-1 has given us the first sight of E_{acc} = 50 MV/m in a multi-cell cavity in today's landscape of SRF gradients (Fig. 6), we face a challenge in FE suppression for reliable high gradient in multi-cell cavities. To that end, we continue to test new techniques such as iris wiping and remain open in seeking novel cleaning technologies beyond high pressure water rinsing.

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