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PRELIMINARY CRYOGENIC COLD TEST RESULTS OF THE FIRST 9-CELL LSF SHAPE CAVITY*

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Abstract

Following successful prototyping and testing of single- & 5-cell LSF shape cavities, the first 9-cell LSF shape cavity LSF9-1 was successfully constructed in-house with an improved process at JLab. The cavity was shipped to KEK for mechanical adjustment, treatment and surface processing. Cold testing was carried out at JLab VTA facility instrumented with a suite of Kyoto instruments. The favourable measured values of the bath pressure detuning sensitivity and Lorentz force detuning coefficient validate our in-cell stiffener design. Pass-band measurements indicate 4 out of 9 cells are capable of reaching a gradient > 45 MV/m, up to 51 MV/m in 2 cells. Cornell OST detectors identified the current quench source. Multipacting-like barriers observed in end cells are investigated both analytically and numerically. The cavity has now received a light EP of 40 micron surface removal at the joint ANL/FNAL facility and further cold testing at JLab is underway. Two new 9-cell LSF shape cavities are being constructed including one made of large-grain niobium material.

INTRODUCTION

The idea of cavity shaping for higher E_{acc} has been proposed for some time, such as Low Loss/ICHIRO and Reentrant, realizing a lower B_{pk}/E_{acc} at the expense of a higher E_{pk}/E_{acc} [1-4]. Experimental verification was successful including record E_{acc} 59 MV/m in 1-cell [5], setting a path forward for E_{acc} well beyond 35 MV/m as captured in the ILC TDR [6]. Pushing multi-cell cavities of those shapes was however blocked by FE. 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 and 5-cell prototype cavities have been previously reported [9, 10]. In this contribution, we present the fabrication, processing and preliminary testing results of the first 9-cell LSF shape cavity LSF9-1. We will also give an update on the fabrication status of two new 9-cell LSF prototype cavities, including one made of large-grain niobium material. Table 1 gives the key parameters of LSF9-1.

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Table 1: Key Parameters of 9-Cell LSF Cavity LSF9-1

Parameter	Unit	Value
Frequency	MHz	1300
Iris radius	mm	30
Stiffener radius	mm	63
Equator radius	mm	99
E_{pk}/E_{acc}	-	1.98
B_{pk}/E_{acc}	mT/(MV/m)	3.71
G	Ω	279
R/Q	Ω	1158
Cell-cell coupling	%	1.27

FABRICATION AND PROCESSING

Fabrication

Standard sheet metal stamping and electron beam welding methods were used for in-house cavity fabrication at JLab. The niobium material was supplied by Ningxia/OSTEC as per JLab specification (RRR >300, thickness 1/8 inch nominal). To achieve the desired half-cell shape accuracy, the formed cup was degreased, lightly BCP etched, annealed in a vacuum furnace, re-stamped, and milling machined at its equator and iris edges into a half-cell arriving at its final dimensions. The half cells are inspected with a FARO laser scanner for their shape accuracy. Figure 1 gives a typical example. Statistics of 18 half-cells are given in Fig. 2. The average RMS shape deviation is 0.082 mm. The shape accuracy was re-measured in the dumb-bell (DB) with an average value of 0.083 mm.

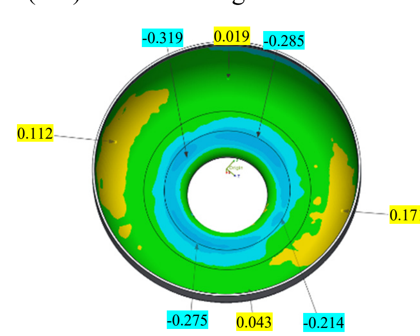

Figure 1. Half-cell C5 shape accuracy measured with a FARO laser scanner. Point deviation in mm.

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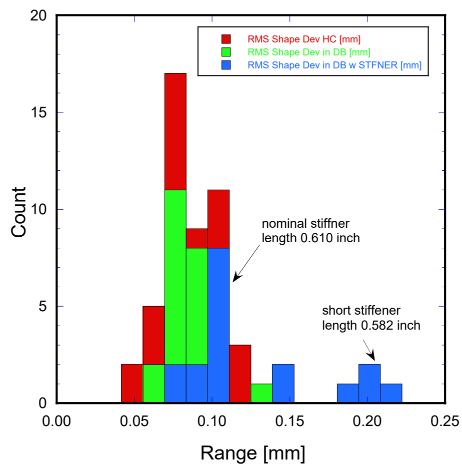

Figure 2. Half-cell shape accuracy statistics.

The DB wall stiffening scheme for this first 9-cell LSF cavity follows what was developed for the first 5-cell cavity LSF5-1 [10]. It is characterized by three salient characteristics: (1) a ratio of 0.64 for the stiffening radius to the equator radius; (2) three uniformly distributed arc pieces; (3) partial penetration welding. For the first two DB's of LSF9-1, the stiffener width was customized for light interference fit into the actual gap across half cells (0.582 inch). However, FARO laser scanning revealed large (~ 0.2 mm) shape distortion after the stiffeners were welded. By using a pair of niobium strips pivoted over a thin cylinder, a stiffener piece of the nominal width (0.610 inch) was easily mounted in place, resulting a very tight fit with the cell walls. The resulting post-stiffener-welding shape accuracy was significantly improved (see Fig. 2). The average RMS shape deviation after stiffener welding is 0.104 mm.

In summary, systematic and progressive laser scanning of the half-cell shape established that our current fabrication technique is capable of achieving the RMS shape deviation of 0.08 mm at the individual half-cell stage and 0.1 mm at the DB stage with stiffeners welded. It appears that there is further room for improvement in DB shape accuracy by using slightly wider stiffener pieces. This positive first data plus the low-cost fact of our much simpler DB stiffener welding process, relative to the standard one where post stiffener welding equator edge machining and aggressive cell deforming with complicated fixtures are required, give us confidence that a cost-effective method capable of delivering predictable DB cell shape accuracy, needed for mass production, is within reach. Figure 3 shows a photo of LSF9-1 as completed on August 30, 2019.

Figure 3. Completed first 9-cell LSF cavity LSF9-1.

Welding seams were inspected using the JLab optical inspection machine. The welding quality is quite satisfactory and is on par with that we observed in best industrially fabricated 9-cell cavities.

The cavity straightness was inspected using a CMM machine. The centre of the middle cell was found to deviate from the mechanical axis (defined by the line connecting the centres of end flanges) by 2 mm. The source of this error is attributable to the horizontal orientation for the final weld at the middle cell equator, a constrain imposed by the existing electron beam welding machine at JLab. Nevertheless, this issue does not seriously impact our research goal and a known solution exists, namely welding the cavity sub-assembly in vertical orientation, as being done in many facilities where large chamber size is available.

The π-mode RF frequency of the as-built cavity is 1300.305 MHz with a decent field flatness across the five mid-cells consisting DB's made with 0.061 inch stiffeners. The other two mid-cells end up with a poor field flatness due to the cell shape distortion originated from the short (0.582 inch) stiffener used during the initial process.

Treatment and Processing

In November 2019, the cavity was 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], consisting of (1) Cavity straightness adjustment arriving at a cell-center deviation from the mechanical axis within ±0.7 mm for all cells; (2) Pre-EP 5 µm with no acid circulation; (3) Bulk EP at 100 µm removal (Fig. 4); (4) Ultrasonic cleaning with FM-20 detergent and HPR with ultra-pure water; (5) Vacuum furnace annealing at 800 ºC for 2 hours; (6) Optical inspection of the inner surface at iris and equator weld regions; (7) Field flatness tuning to 93%; (8) Local grinding for removal major defects in the cell equator region (3 each); (9) Final EP at 50 µm removal; (10) End group brushing and iris brushing (Fig. 4); (11) HPR with ultra-pure water; (12) Drying in clean room for 3 days, then packing and shipping back to JLab.

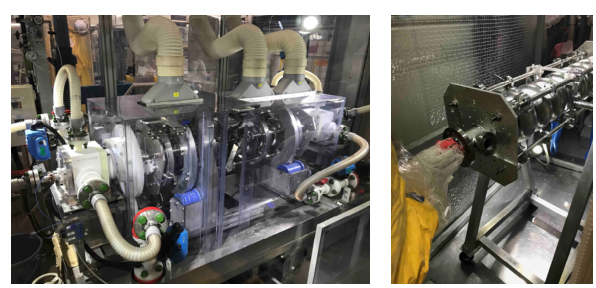

Figure 4: LSF9-1 EP processing (left) and iris brushing (right) at KEK STF.

PRELIMINARY TEST RESULTS

In January 2020, the cavity returned to JLab for final HPR cleaning followed by in-situ baking under vacuum at 120 °C for 48 hours and the first RF test at 2K. Prior to the test, the vacuum components of the test stand was taken apart completely and re-cleaned to recover from the contamination [10].

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The cavity was instrumented with 1622 sensors (1600 Kyoto U and 22 JLab) for detection of field emission, quench and flux expulsion (see Fig. 5a). Of particular interest for LSF9-1 testing is localizing the source of field emission using Kyoto sX-mapping system [11]. During the initial power rise with the π mode excited, sX-mapping revealed transient local "X-ray hot spots" at strip sX6 & sX5 attached to irises in mid-cells that are attributable to activation and processing of local field emitters (see Fig. 5b). Interestingly, when the cavity was excited in the 4/9-π mode, repeatable hot spots appeared at sX1 & sX2 attached to the end cell irises right before the cavity ran into the quench limit at a field of 18.6 MV/m in the end cells (see Fig. 5c). We were observing multipacting induced X-rays in the end cell (Cell#9 counted from the RF input power coupler).

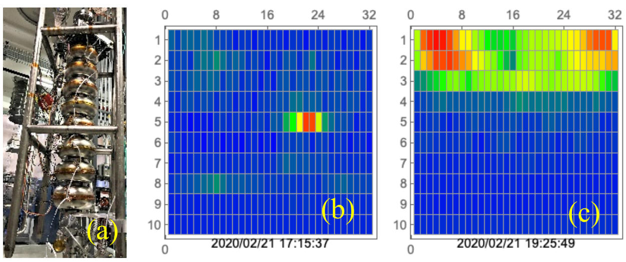

Figure 5: 1622 sensors attached to LSF9-1 (a) and X-ray hot spots captured by Kyoto U sX-mapping system (b, c).

The best gradient performance in π-mode achieved so far is 25 MV/m in the 4th RF test as shown in Fig. 6. An "explosive" event struck later on, degrading the performance to 21 MV/m.

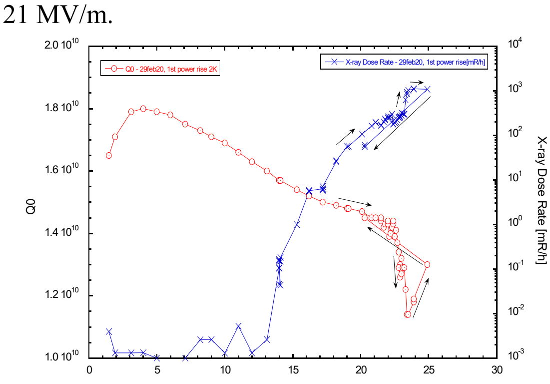

Figure 6: Best π-mode performance achieved so far by the cavity LSF9-1 at 2 K.

After six RF test cycles with successful systematic data taking with sX-mapping, XTX-mapping and B-mapping systems, the cavity was partially disassembled and HPR'ed for 3 cycles. This re-processing effectively cured the field emission problem encountered during the first test cycles. The π-mode gradient was however limited to 21-22 MV/m, which persisted even after extend processing. Pass-band mode measurement data indicate that 4 (#2/8, #4/6) out of 9 cells are capable of reaching a gradient of > 45 MV/m with 2 (#4/6) capable of 51 MV/m (see Fig. 7). Second sound quench detection data point at cell#3 being the limiting cell with a quench limit of 27 MV/m.

With regard to the current limit at 21-22 MV/m in the π-mode, systematic analysis of the end-cell and mid-cell including the details of the weld prep undercut has been carried out using the same procedure published in [12], ruling out hard multipacting barrier in cell equator regions. We notice the cavity was accidentally soaked in hot water over night before re-HPR and speculate the SEY of the cavity RF surface being raised, leading difficulty in processing through the 2-sided multipacting in the end cell equator region. Regarding to the quench limit in cell#3, we observed unusual surface roughness on the corresponding location (see Fig. 7 inset). With these evidence, we decided to EP the cavity surface for another 40 µm, which has been done at the joint ANL/FNAL facility (see Fig. 8).

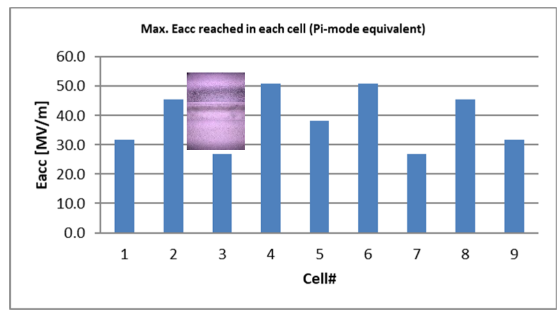

Figure 7: Gradient capability of each cell of LSF9-1. Inset shows the RF surface image of quench location in Cell#3.

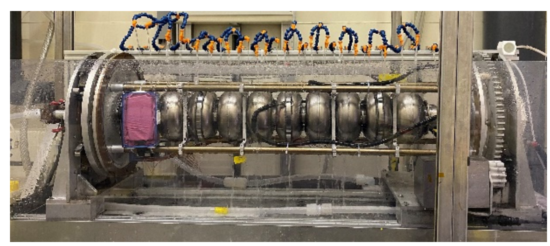
Figure 8: LSF9-1 EP 40 µm at joint ANL/FNAL facility.

In summary, the first 9-cell LSF shape cavity has been successfully fabricated and tested in a joint international effort. The highest gradient attained is 25 MV/m so far. Four of 9 cells demonstrated capability of reaching a gradient of > 45 MV/m including 2 capable of 51 MV/m. Test results confirmed our stiffener scheme with an average df/dp of -138 Hz/Torr and Lorentz for detuning of -2.7 Hz/(MV/m)^2, on par with the values measured in the standard TESLA 9-cell cavities tested in the similar configuration at JLab.

Presently, continued testing of LSF9-1 is on-going. Two new 9-cell LSF shape cavities including one made of large-grain niobium material are being fabricated.

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