REDUCED-BETA CAVITIES FOR HIGH-INTENSITY COMPACT ACCELERATORS*

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Abstract

This paper reports on the development and testing of a superconducting quarter-wave and a superconducting half-wave resonator. The quarter-wave resonator is designed for beta = 0.077 ions, operates at 72 MHz and can provide more than 7.4 MV of accelerating voltage at the design beta, with peak surface fields of 165 mT and 117 MV/m. Operation was limited to this level not by RF surface defects but by our administrative limits on x-ray production. A similar goal is being pursued in the development of a half-wave resonator designed for beta = 0.29 ions and operating at 325 MHz.

INTRODUCTION

The length and cost of the low-velocity portion (β = v/c < 0.6) of superconducting proton and heavy-ion linacs are dominated by the accelerator cavity performance. Accelerator cavities used in this velocity region, reduced-beta cavities, have not performed at the same peak-surface fields which are regularly achieved in elliptical-cell cavities optimized for velocity-of-light electrons [1], 160 mT and 80 MV/m peak surface fields. This performance disparity has been blamed on the greater complexity of the reduced-beta cavity fabrication and processing. Several advances at Argonne National Laboratory in cavity design [2]; fabrication and processing have disproved this hypothesis.

First, the results locating a defect which limited the performance of a prototype 72 MHz quarter-wave cavity (QWR) optimized for β = 0.077 ions for the ATLAS intensity upgrade will be presented. Second, the fabrication and processing of a subsequent geometrically identical quarter-wave cavity will be outlined. Finally, the impact of these results and future plans for a similarly constructed half-wave cavity will be discussed.

INITIAL PROTOTYPE PERFORMANCE

The QWR prototype fabrication and test results were presented in [3]. Since these papers were published we have refined our electromagnetic simulations of the cavity surface fields and the results used in this paper are given in table 1. This cavity was limited to peak surface fields of 96 mT and 70 MV/m by a surface defect which initiated a cavity quench. Figure 1, shows the cavity with the location of the defect highlighted in red along with a single channel record of the quench.

The defect was located by measuring the time-of-flight of second sound waves propagating from the cavity quenching defect to an array of oscillating superleak transducers [4]. The distance the second sound wave travelled was calculated with the wave velocity. This combined with the known location of the detectors allowed us to determine the defect location. Our detector array was 1-dimensional in nature and located the height of the defect in the quarter-wave cavity center conductor.

This defect was located at the same height as an electron beam weld blow-out which occurred during final welding of the center conductor. The center conductor is formed from two halves which are welded together. The center conductor halves were tack welded, but the final electron beam welds could not be finished within the desired 24-hour etch window between pre-weld etching and welding. The parts were etched again after tacking and the very small-gap joint between the two parts could not be properly cleaned. Some foreign debris was trapped in this joint which caused a blow-out during the final electron beam welding which was repaired.

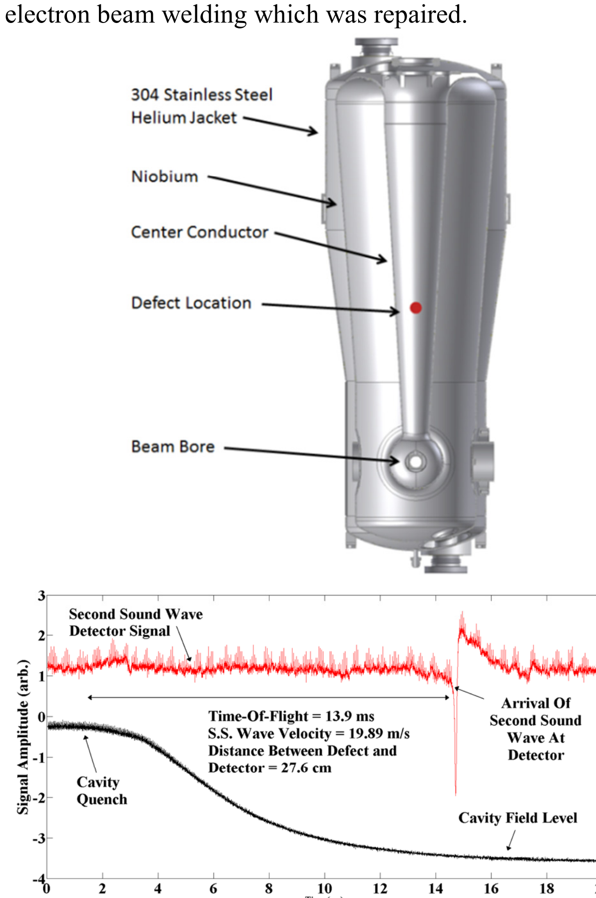

Figure 1: (Top) The cavity with a red dot placed at the height of the defect in the center conductor, the cavity is 53 inches from top to bottom . (Bottom) A single quench event with an oscillating superleak transducer signal and the cavity transmitted power.

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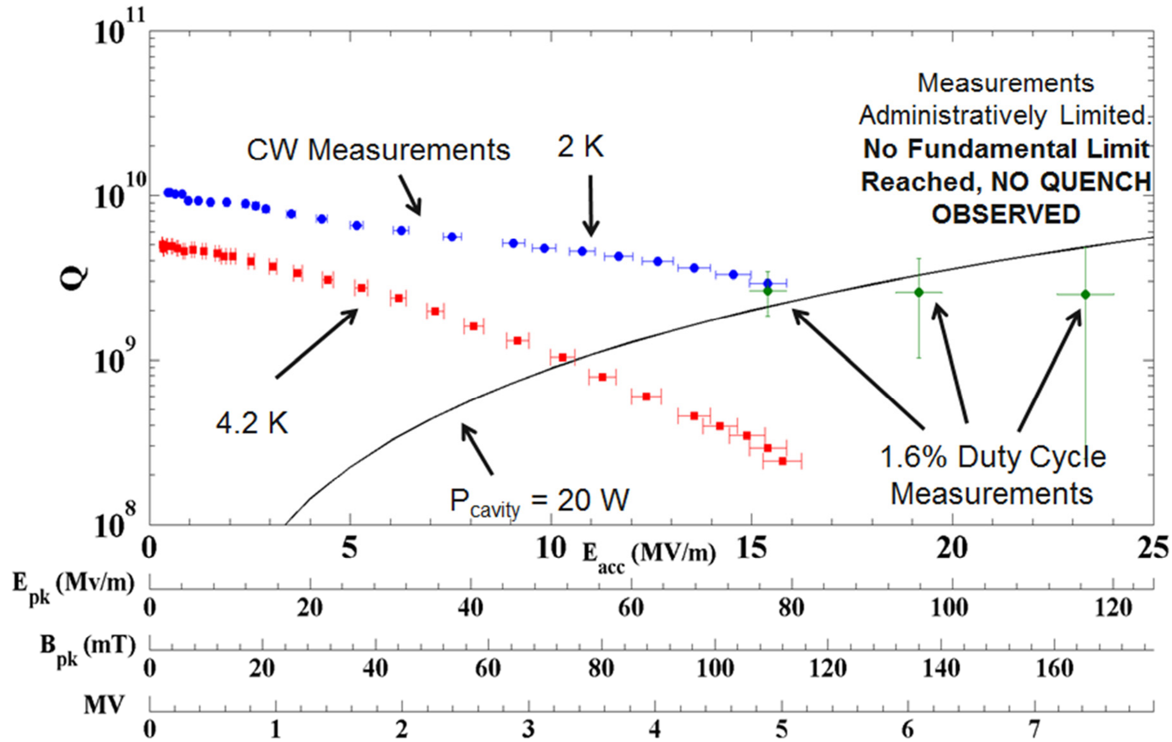

Figure 2: The measured performance of the QWR. There are 4 horizontal axes corresponding to the accelerating gradient, peak surface electric and magnetic fields, and the voltage gain of a synchronous β = 0.077 ion. The vertical axis corresponds to the cavity quality factor. The blue data points were measured at 2 K and the red data points were measured at 4.2 K in the cw mode, the green points were measured at 2 K with a 1.6% duty cycle, and the solid black line corresponds to 20 W of RF power dissipated in the cavity. No fundamental limit to the cavity performance was encountered and the cavity could have reached higher fields with appropriate radiation shielding

Table 1: Electromagnetic Properties of the QWR

Freq. (MHz)	72.75
β	0.077
l_{eff} (cm, βλ)	31.75
E_{pk}/E_{acc}	5.0
B_{pk}/E_{acc} (mT/(MV/m))	7.1
QR_s (Ω)	25.9
R_{sh}/Q (Ω)	568

FABRICATION AND PROCESSING

Here the fabrication details which differ from what was presented in [3] for the prototype QWR are listed:

1) Very careful attention was paid to the status of the weld joints and their preparation prior to electron beam welding. All components were soaked in DI water after every handling/machining step to look for inclusions.
2) Significantly more surface inspection and QA. The cavity RF surface was carefully hand-polished with 220 grit sandpaper to avoid fold-over and deep polishing marks. All pits, orange-peel, and scratches were polishing in this manner in the high field regions.
3) The temperature of the pre-weld etches were limited to T < 16^{0}C to limit hydrogen uptake. The bulk electropolish procedure (~120 µm removal) temperature was reduced to 25 < T < 30^{0}C. The final light (~20 µm removal) electropolish temperature was 20 < T < 25^{0}C.
4) The cavity was baked at 625^{0}C for 24 hours to degas the hydrogen dissolved in the bulk niobium. This prevents Q-disease and improves the 2 K performance of the cavity.

After fabrication was complete the electropolishing, baking, and cleaning proceeded. Recent tests of similar cavities have found that the Q may be improved by about a factor of 2 by reducing the 625^{0}C bake duration to 12 hours [5].

TEST RESULTS

The cavity vacuum was allowed to pump for 72 hours reaching a pressure < 1 e-7 torr prior to cooldown. The cavity was cooled to 4.2 K with care taken to limit the time spent between 50 and 165 K to about 45 minutes even with the hydrogen degassing. The cavity was conditioned using up to 10 watts of RF power to remove the low-level multipacting barriers over ~2 hours and then 5 minutes of pulsed power processing at 4.6 K with 4 kW

Figure 3: The niobium subassemblies which will be welded together to make the HWR. The parts clockwise from top left are outer-conductor halves, toroids, inner-conductor, and re-entrant noses.

of forward power. Following this conditioning the performance given in figure 2 was observed. Note that the residual resistance of the cavity at low-fields is less than 4.5 nΩ at 4.2 K and 2.5 nΩ at 2.0 K. The gradients presented in figure 2 were not limited by any fundamental phenomena, e.g., defect-initiated quench or field emission. The results were limited administratively to avoid exceeding the ANL limits on x-ray production. The cavity is only partially shielded behind a high-density concrete wall and is not in a complete cave-like enclosure. This allows considerable x-ray shine to reach experimenters. To reduce the average x-ray production the cavity was operated with a 1.6% duty cycle to safely comply with the ANL guidelines. The data points measured in this manner are highlighted in green and are the three highest gradient 2 K measured data points. Please note that the cavity dissipated power measurement accuracy decreased due to measuring these data points in the over-coupled limit but the relative accuracy of the field amplitude is unchanged. The highest data point measured was repeatable and corresponded to a voltage gain of 7.4 MV and peak surface fields of 165 mT and 117 MV/m. At no point was the QWR tested here quenched. The high field data points do not represent a fundamental limit on the cavity performance. With additional radiation shielding the maximum performance of this cavity can be determined.

The best 9-elliptical cell cavity built for the ILC program reached 175 mT and 84 MV/m. The quarter-wave cavity tested here reached comparable peak surface magnetic fields relative to the best 9-cell cavity and exceeds the peak surface electric field by 40% [1]. The previous best reduced beta cavity was a spoke cavity tested at FNAL which reached 127 mT and 85 MV/m after extensive conditioning [6].

IMPACT AND FUTURE WORK

The test results presented here characterize the world's highest peak-field performance in a reduced-beta cavity designed for heavy-ion particle accelerators. The results approach the theoretical maximum of performance of any niobium resonator and allow for the proposal of future accelerators with higher base line gradients, shortening and reducing the cost of these installations.

We are now in the final stages of fabricating a half-wave resonator (HWR) designed to operate at 325 MHz and optimized for $\beta = 0.29$ ions [7]. This cavity builds upon the success of the conical geometries developed at ANL for quarter-wave cavities which optimize the cavity field distributions maximizing accelerator performance. The HWR is being fabricated in a manner identical to the record setting QWR. Figure 3 shows the subassemblies which will be combined to make the niobium cavity in the next several weeks. We expect to finish fabrication of this cavity in October 2012 with cold testing sometime in late November or early December. Results will be published once available.

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