SRF CAVITIES FOR FUTURE ION LINACS*

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Abstract

There is considerable interest worldwide in the applications of high-intensity (>5 mA) high-energy (> 200 MeV) ion accelerators and the research which could be done with these machines. This presentation will present results of the three year ANL study funded specifically to make possible substantial reductions in the size and cost for future ion linacs in the region beta < 0.5. Applications include basic research, medical isotope production, and accelerator driven systems. High-performance low-beta resonators are key components of all of these machines. Recent 72.75 MHz, beta = 0.077, quarter-wave resonator cold test results, designs and their impact on next generation ion accelerators are discussed. Peak fields in excess of 166 mT and 117 MV/m have been achieved and future work to improve upon this will be discussed.

INTRODUCTION

There is a growing demand for heavy-ion/proton linear accelerators which require substantial investment in the low-velocity front ends ($\beta = v/c < 0.5$). For example, at Argonne National Laboratory (ANL) alone work is on-going for an in-house accelerator upgrade, the ATLAS Efficiency and Intensity Upgrade [1], the first superconducting cryomodule for FNAL's Project-X driver linac [2] and the development of a 40 MeV, 5 mA proton/deuteron accelerator for the phase-II of SARAF at Soreq-NRC [3]. This list does not include the on-going efforts of laboratories worldwide which include: the construction of the Facility for Rare Isotope Beams at Michigan State University [4]; the construction of Spiral2 in France [5]; the development and prototyping for IFMF [6]; the development of SRF technology in support of accelerator driven systems in Asia and Europe [7]; and work on a rare isotope production facility in Korea [8]. For all of these projects the length and cost of the low-beta superconducting proton and heavy-ion linacs are dominated by the SRF resonator performance. Accelerator cavities used in this velocity region, low-beta cavities, have not performed at the same peak-surface fields which are regularly achieved in elliptical-cell resonators optimized for velocity-of-light electrons [9], 145 mT and 70 MV/m peak surface magnetic and electric fields respectively for $E_{acc} = 35$ MV/m. 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 [10], fabrication and processing [11] have disproved this hypothesis.

First, the results of a three ANL study funded specifically to make possible substantial reductions in the size and cost for future ion linacs will be presented. Second, the impact of these results and work applying these results to future low-beta accelerators at ANL will be discussed.

DEVELOPMENT OF HIGH-GRADIENT LOW-BETA SRF CAVITIES

The purpose of the ANL study was to demonstrate that low-beta cavities could attain the peak surface fields realized in velocity-of-light elliptical cell cavities, 145 mT and 70 MV/m peak surface magnetic and electric fields respectively. This is the crucial first step toward constructing a compact proton linac.

To this end, we fabricated a 72.75 MHz, $\beta = 0.077$, quarter-wave cavity structurally identical to those built for our in-house ATLAS Intensity Upgrade [1]. We have also built a 325 MHz, $\beta = 0.300$, half-wave resonator which remains to be tested, see Figure 1.

Figure 1: The 72 MHz quarter-wave (back) and the 325 MHz half-wave (front) resonators recently built at ANL.

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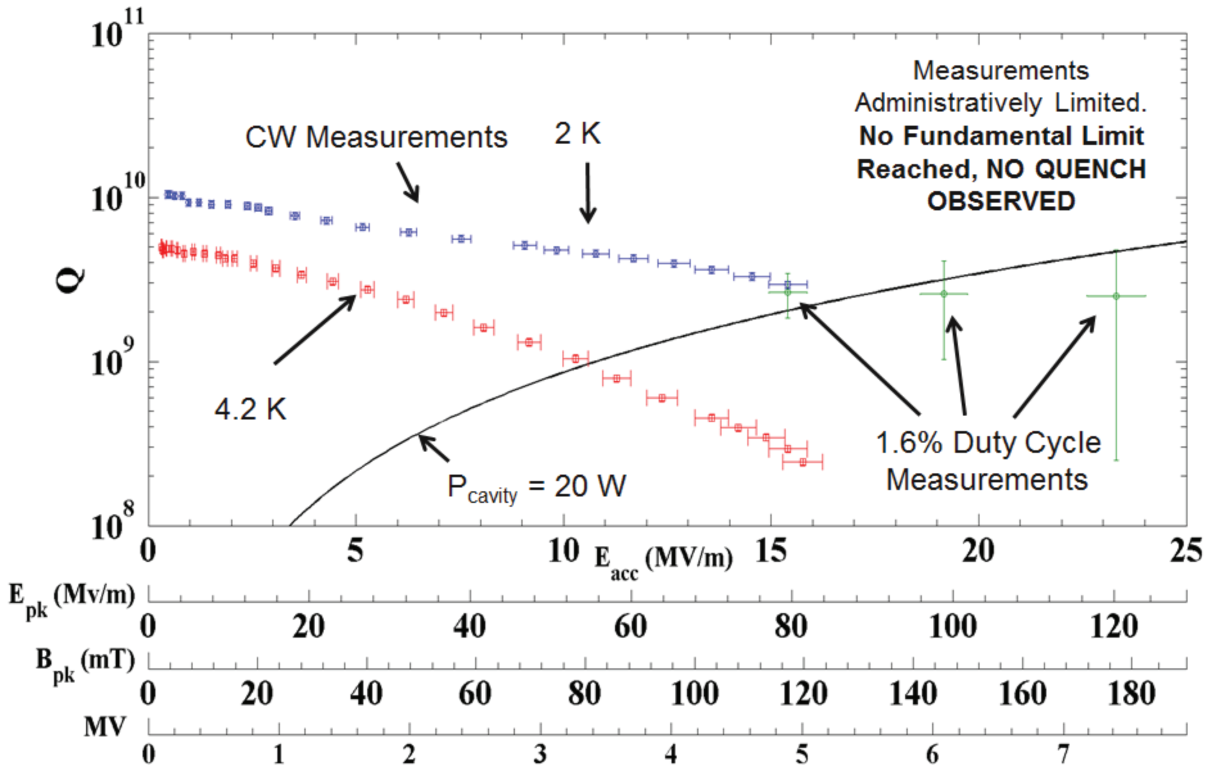

Figure 2: The measured performance of the QWR. There are 4 horizontal axes corresponding to the accelerating gradient, peak surface electric and magnetic fields, and the voltage gain of a synchronous β = 0.077 ion. The vertical axis corresponds to the cavity quality factor. The blue data points were 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.

Our work builds upon the substantial progress made for elliptical-cell cavities over the past 2 decades with several new innovations.

1) A unique low-beta electropolish tool developed at ANL which processes the finished cavity [12].
2) Improved pre-electron beam weld quality control using electrostatic discharge machining of the areas to be welded preventing tooling inclusions [11].
3) Significantly more surface inspection. The cavity RF surface was carefully hand-polished with 220 then 320 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.

Many of the other fabrication details are very similar to the processing steps of ILC cavities [13]. 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 cavity was baked at 625^{0}C to degas hydrogen dissolved in the bulk Nb and the final light (~20 μm removal) electropolish temperature was 20 < T < 25^{0}C. No 125^{0}C bake was performed on this cavity, and future improvements in the high-field Q-slope may be possible with the addition of this bake.

Test Results

After the final light electropolish the cavity was cleaned and prepared for testing. Prior to cooldown the cavity vacuum was allowed to pump for 72 hours reaching a pressure of 8.6 e-8 torr. 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 of forward power. Following this conditioning the performance given in figure 2 was observed with no measurable field emission up to E_{acc} = 13.5 MV/m.

Note that the residual resistance of the cavity at low-fields is less than 4.5 nΩ at 4.6 K and 2.5 nΩ at 2 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 ANL radiation safety 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 166 mT and 117 MV/m. The best 9-elliptical cell cavities built for the ILC program reach surface fields of 175 mT and 84 MV/m [9]. 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%. The previous best low-beta cavity was a spoke cavity tested at FNAL which reached 127 mT and 85 MV/m at 2 K and many of the spoke cavities which followed performed very well in their own right [14, 15].

At no point was the QWR tested here quenched. The high field data points do not represent a fundamental limit on the cavity performance.

FUTURE APPLICATIONS

Low-beta cavities have served their applications very well for over 3 decades. However, future large heavy-ion/proton accelerators will benefit from cost reductions due to the improved design and performance of the front ends. High-performance low-beta cavities can significantly reduce the front-end cost of the accelerator by reducing component count and linac lengths.

At ANL we are developing compact cryomodules for two separate projects: one for Project-X at FNAL and two for SARAF Phase-II at Soreq-NRC. The cryomodules for these projects will house superconducting half-wave resonators which require similar layouts but differ in operation modes and dimensions. To reduce risk and optimize the cost of the cryomodule fabrication we are developing the three designs together. All designs are modifications and improvements on box-cryomodules fabricated at ANL in the past 5 years [16]. Our most recent cryomodule houses seven 72 MHz, β = 0.077, quarter-wave resonators identical to the one discussed earlier. The test results of these cavities are presented in [11] and exceed expectations. This cryomodule was designed, conservatively, to provide 17.5 MV of voltage gain over 5.2 meters giving a 3.4 MV/m real-estate gradient, with current results suggesting that we may reach 4 MV/m real-estate gradient. Building upon this we have developed several new cryomodule designs for Project-X and SARAF Phase-II.

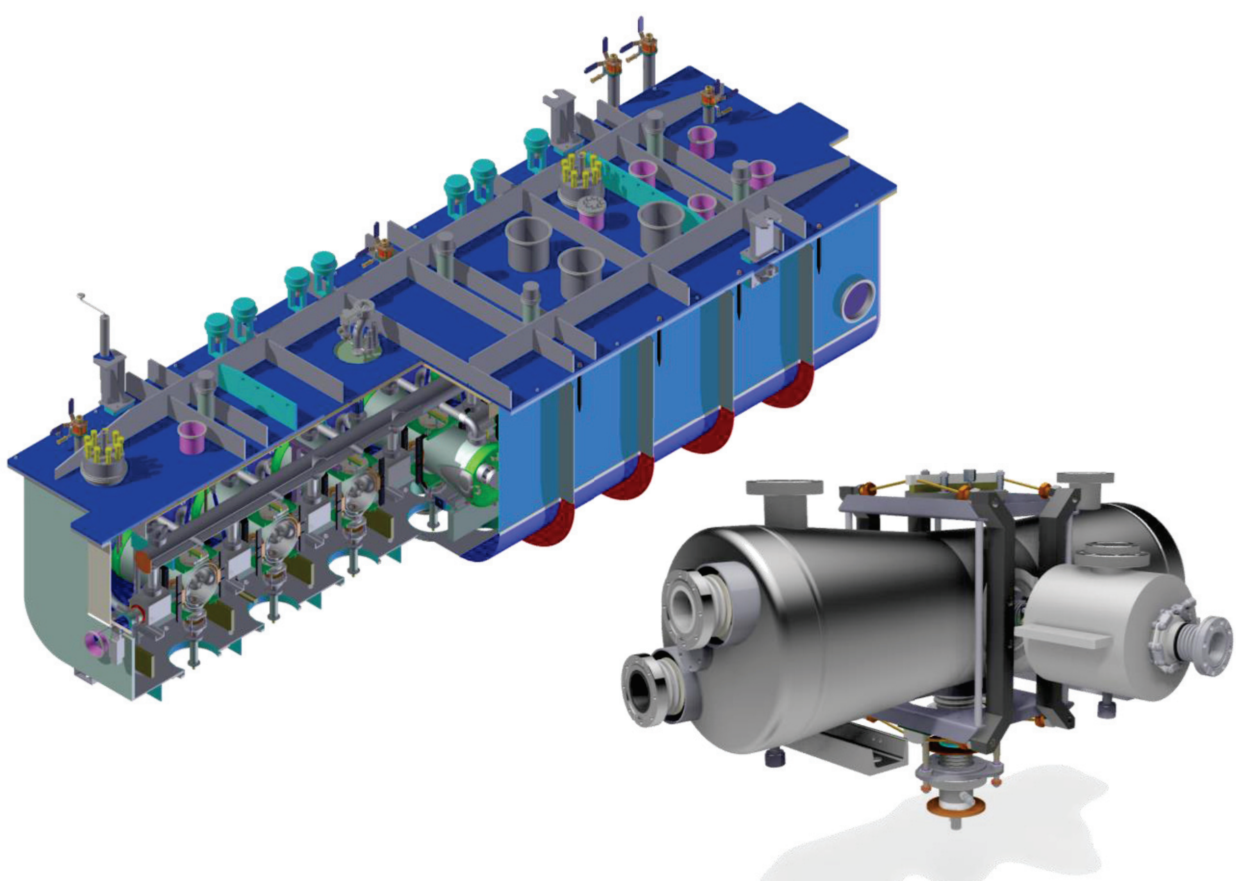

Figure 3: Project-X half-wave resonator cryomodule model. The cryomodule contains 8 superconducting 162.5 MHz, β = 0.112, half-wave resonators and 8 superconducting solenoids with beam position monitors rigidly attached to each solenoid. (Top) The cryomodule with a section cut out to show the inside. (Bottom) A single focusing period containing a solenoid, beam position monitor and half-wave resonator.

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Project-X is a high intensity, 1 mA, H^- linear accelerator facility being developed at FNAL. A single half-wave resonator cryomodule will house 8 β = 0.11 162.5 MHz superconducting cavities, 8 superconducting magnets and will operate at 2 K. A model of this cryomodule is shown in figure 3. The cryomodule accelerator lattice comprises 8 cavity/solenoid/beam-position monitor units each of which occupies 63 cm along the beam axis.

The SARAF Phase-II project is an upgrade of the current SARAF accelerator to accelerate >5 mA, 40 MeV/u, proton/deuteron beams. Four cryomodules are required of two types, all of which will operate at 4 K. The first type, the low-beta cryomodule, contains 7 β = 0.09 176 MHz superconducting cavities and 7 superconducting magnets. The second type, three high-beta cryomodules, each housing 7 β = 0.16 176 MHz superconducting cavities and 4 superconducting magnets. These cryomodules are identical to the Project-X cryomodule with slight differences for 4 K operation, e.g., no J-T valve and sub-cooled heat exchanger.

CONCLUSIONS

There is no fundamental reason why low-β resonators should not perform at the limits of niobium. The front-end of future ion linacs can benefit substantially by investing the time and cost required to optimize the linac lattice and to build it using high performance SRF cavities arranged in compact lattice geometries. This can enable new SRF applications where SC linac technology was too expensive to support in the past. Examples of this include accelerators for basic science (e.g., isotope production driver linacs, neutron sources, high-intensity machines for high energy physics research), national security, accelerator driven systems, and nuclear medicine.

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