HIGH-PERFORMANCE SC CRYOMODULES FOR CW ION ACCELERATORS

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Abstract

New superconducting (SC) cavities and cryomodules required for various low- and medium beta- CW ion accelerator projects are under development at laboratories and institutions around the world. To date, development in this area has been mostly for basic science applications, however, the trend in new and proposed projects demands compact high-power CW linacs for applications in applied science and technology such as medicine, national defense, and accelerator driven systems. An overview of significant recent developments in the low- and mid-beta cavity and cryomodule design and fabrication is presented, together with, a more detailed look at the ANL approach to the design and fabrication for the next generation of cryomodules for CW ion accelerators. The outlook for these machines and particular requirements driving ongoing R&D will be discussed.

INTRODUCTION

A major technical development for ion accelerators in the last decade was the demonstration of new SC TEM cavity geometries to span the velocity range $0.01 < \beta < 0.6$ [1]. Together with elliptical-cell structures, SC cavities span the full velocity range up to $\beta = 1$. At the same time, a dramatic increase in real estate gradient even for $\beta \sim 0.1$, from 1 MV/m up to ~3 MV/m or more has been achieved due primarily to clean room techniques during fabrication and assembly and improved electromagnetic designs based on three dimension simulation tools. R&D for upgrades of existing CW heavy-ion linacs and for planned ion linacs such as FRIB [2], Project-X [3] and EURISOL [4] will continue to advance these techniques. At the same time, planned or proposed CW light-ion drivers for new applications is pushing the technology toward higher power CW operation requiring very low beam losses.

RECENT DEVELOPMENTS

Cryomodule Performance

The first demonstration of high-pressure water rinsing and clean assembly techniques, developed successfully for elliptical-cell (e-cell) SC cavities, was performed on a low-beta (SC spoke) cavity only ten years ago. As for e-cell cavities, factors of 2-3 in field performance gain were achieved and were consistent and repeatable if the cavities remained clean.

The first use of these techniques in an operational low-beta SC ion linac was at TRIUMF in 2006 for ISAC-II commissioning [5] where each cryomodule was fully assembled inside a clean room. A total of forty 80 MHz SC cavities in eight cryomodules have now been installed in ISAC-II providing ~40 MV of accelerating potential.
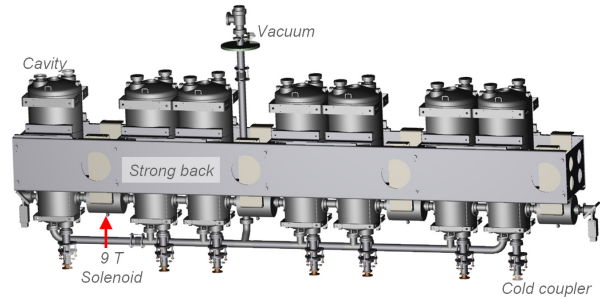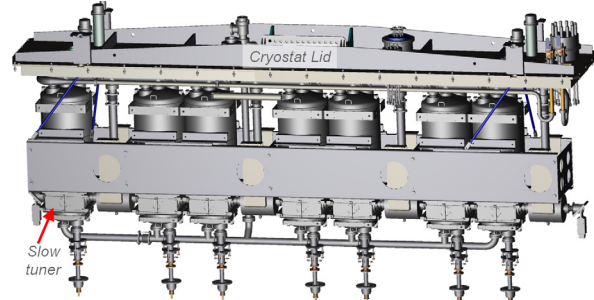

Figure 1: Clean room-assembled cavity string.

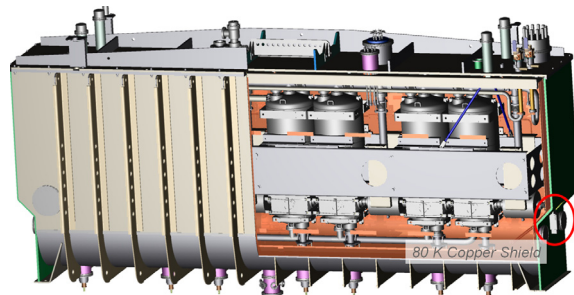Figure 2: Cavity string with tuners, cryogenics and lid.

Figure 3: Complete cryomodule assembly.

At the ATLAS SC heavy-ion linac at Argonne, a new cryomodule of seven 109 MHz $\beta = 0.15$ SC cavities was installed in 2009 [6]. The approach uses a clean cavity string with separate cavity and insulating vacuum as illustrated in Fig. 1. A feature this approach is that tuners, cryogenic plumbing, copper and magnetic shields, pictured in Figs. 2-3, are all assembled outside the clean room. A similar approach has also been adopted for ion linac cryomodules at SARAF [7], FRIB[2], SPIRAL2[8]. The most recent, ANL upgrade cryomodule is providing 14.5 MV of accelerating voltage in 4.6 meters, presently the highest real-estate gradient for any section of SC linac in this range of beta. A new ATLAS upgrade, with new cavities and cryomodule shown in Figs. 1-3, now in fabrication have a design goal of $V_{acc} = 17.5$ MV in a 5-meter length [9].
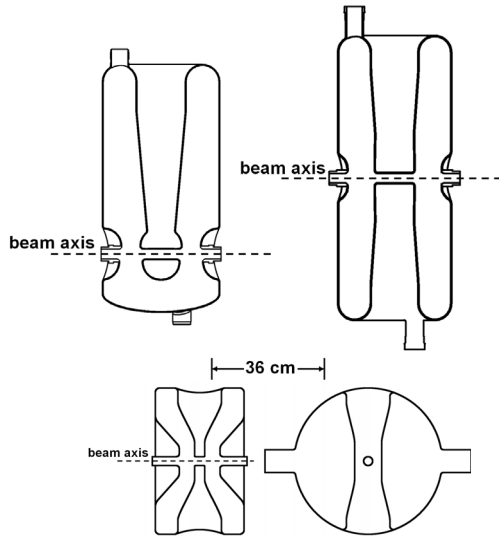
Figure 4: Typical geometries for quarter-wave (top left), half-wave (top right) and spoke (bottom) cavities.

Figure 5: ANL EM design showing the electric field (left) and magnetic field (right) for a β=0.077, 72.5 MHz quarter-wave cavity. E_{peak}/E_{ACC}=4.7 and B_{peak}/E_{ACC}=6.9 mT/(MV/m), where ℓ_{ACC}=$\beta\lambda$.

Electromagnetic Design

Existing TEM-class cavity types are either quarter-wave ($\lambda/4$) or half-wave structures ($\lambda/2$) operated in the lowest TEM mode with fundamental frequencies ranging from ~50-800 MHz. Physical dimensions are $0.1 < \ell < 1$ meter. Examples of typical modern geometries are shown in Fig. 4. Spoke cavities, a type of $\lambda/2$ structure, have one or more central conductors oriented perpendicularly to a cylindrical outer housing and may be naturally extended to multiple cells per cavity. Other low velocity cavity geometries such as helices, re-entrant cavities and split-rings have been operated in useful linacs, however, performance is generally superceded by more recent designs.

The ANL approach to the EM design for SC cavities is as follows; use of modern forming and deep drawing techniques, fine grained 3 mm-thick RRR 250-300 niobium sheet, and 3D simulation codes to optimize cavity geometries for minimum surface electric and magnetic fields. Of course, fabrication, processing and cleaning requirements should be incorporated for the outset. Reasonable values for shunt impedance, geometrical factor cavity stored energy result with little or no additional optimization. The primary reason for this approach is economic, where the cost of sophisticated cavities is substantially outweighed by the performance benefits and decreased cavity count especially when sub-systems, manpower and tunnel length are considered.

Figure 5 shows an ANL design for a β_G=0.077, 72.75 MHz quarter-wave resonator [10] performed with CST Microwave Studio. The peak surface magnetic field has been optimized by (1) using the inter-cavity space already required to connect the beam ports to expand the outer housing in the high magnetic field region and (2) by v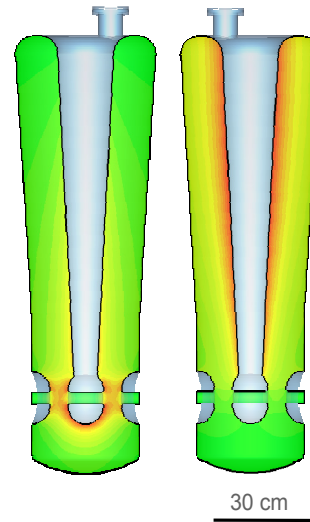arying the inner conductor taper in order produce a nearly uniform magnetic field profile along the inner conductor surface. Peak electric fields are minimized by adjusting the overall size and aspect ratio of the racetrack shaped drift tube (horizontal plane) to produce a nearly uniform profile around the drift-tube. The magnitude of the peak electric field on the drift-tube and on the two re-entrant noses is, likewise, nearly equal.

Mechanical Design

The problem of microphonics and/or helium pressure induced frequency deviations in TEM cavities can be largely mitigated in design using FEA simulation tools. Uncompensated, the sensitivity to helium pressure fluctuations ($|\Delta f/\Delta p|$) may be ~100 Hz/Torr or higher, however, with proper design the effect may be essentially eliminated. One example was simulated and then verified in a prototype spoke cavity [11]. The quarter-wave cavity in Fig. 5 has modest niobium stiffeners on the outside of the torus of the magnetic field region and in the electric field region at an angle of 90° to the beam axis. The simulated value of $\Delta f/\Delta p$ is -1.6 Hz/Torr (Advanced Energy Systems). This value will be verified in a prototype presently under construction. It is noted that the stiffeners on the torus also increase the center conductor pendulum vibrational mode to 68 Hz.

Surface Processing

Preparation of the RF surface using chemistry and cleaning is required to achieve good niobium cavity performance. Electropolishing to remove at least 100 μm of material from the rf surface is, statistically, the best demonstrated chemical procedure to achieve high gradients in velocity-of-light structures and is the only technique that has been used at several laboratories to produce niobium cavities approaching the RF critical field, B_{peak}~180 mT. Many of the best performing TEM
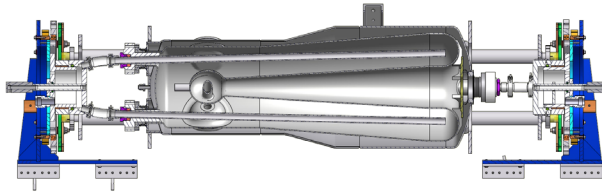
Figure 6: ANL engineering design for a new horizontal electropolishing system under construction in the joint ANL/FNAL cavity processing facility.

cavities have also been prepared using electropolishing [12] and certainly, there is no fundamental reason to expect a difference between low- and high-beta cavities.

ANL is installing the first electropolishing system designed for a completed low-beta niobium SC cavity with integral liquid helium vessel. The design is based on that used for electropolishing 1.3 GHz nine-cell elliptical cavities for the global ILC development effort. Finally, unlike buffered chemical polishing, electropolishing may be repeated, if necessary, without producing a progressively rougher surface.

A fully engineered model, shown in Fig. 6, has the EP system along with the 72 MHz β=0.077 quarter-wave cavity. Fundamentally, the process is the same of for e-cell cavities, that is, the cavity is filled to roughly 50% with standard 9:1 H_2SO_4:HF mixture and rotated about the long axis at a rate of 1 rpm. Rather than a single cathode, a set of four aluminum cathodes projects into the cavity interior through coupling ports at the end of the cavity. The cathodes also provide a means to circulate acid through the cavity. Direct water cooling of the niobium, by means of circulated chilled water through the helium jacket, also permits the acid flow rate to be optimized independently of the cavity temperature. This is not possible with present elliptical cell EP systems. The system will be installed in the joint ANL/FNAL cavity facility at Argonne in time for the first quarter-wave prototype of the ATLAS Intensity Upgrade project [9].

OUTLOOK

Cavity Performance

Advances in SC cavity performance achieved using clean processing and assembly techniques in the early 1990's at laboratories such as KEK, DESY and JLab for elliptical cavities are being adapted, to various degrees, for low-β TEM-cavities. TEM cavity field performance with B_{peak}~100 mT is common in prototypes, however, operational surface fields lag those for intensely developed 1.3 GHz e-cell geometries.

However, evidence suggests that large improvements can still be made. Excellent test results for a prototype β=0.2 SC spoke resonator (see Fig. 7) have been demonstrated recently at Fermilab as shown in Fig. 8 [13]. The cavity was fabricated using well known forming, machining and electron beam welding techniques from high RRR 3 mm niobium at Roark.
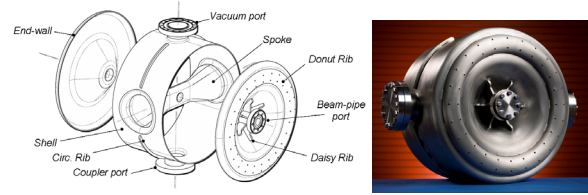

Figure 7: Optimized single spoke cavity from FNAL with E_{PEAK}/E_{ACC}=2.56 and B_{PEAK}/E_{ACC} =3.87 mT/(MV/m), leff=2/3$\beta\lambda$.
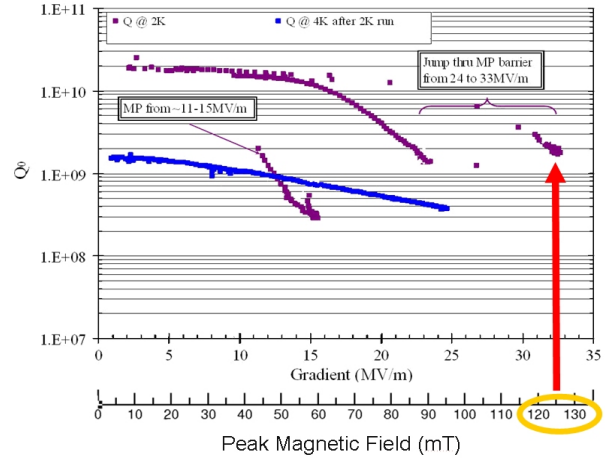

Figure 8: Fermilab/Roark single spoke cavity with E_{ACC}=33 MV/m. V_{ACC}=4.5 MV, physical length = 0.33 m.

Buffered chemical polishing (BCP) was performed with 1:1:2 BCP at T~15-17°C. Final surface preparation was performed using high-pressure de-ionized water for rinsing and clean room assembly at Argonne before transfer to Fermilab for testing.

This highly optimized EM design also operates with a peak magnetic field of B_{PEAK}~125 mT and would provide 4.5 MV of accelerating potential over a length of only 1/3 meter along the beam axis at this gradient. RF losses (Q-slope) in 4 Kelvin operation requires further study and may be reduced by techniques such hydrogen degassing, or in future designs, by electropolishing the completed cavity.

CONCLUSION

Improvements in cavity and cryomodule technology for SRF linacs include the sophisticated cavity rf designs and the adaptation of clean techniques for low-beta cryomodules. Many of these techniques are being used in upgrade of existing ion linacs for basic science. The ANL approach to cryomodule design is to use low frequency SC cavities with optimized geometries to achieve a large voltage gain per cavity and (2) a long (top loading) cryomodule with high packing factor in order to achieve a high overall real estate gradient. Continued improvement in these techniques for β<1 SC cavities and cryomodules will position this technology well for the next generation of high-intensity CW ion linacs for basic and applied science.

ACKNOWLEDGEMENTS

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