R&D TOWARDS CW ION LINACS AT ANL*

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Abstract

The accelerator development group in ANL's Physics Division has engaged in substantial R&D related to CW proton and ion accelerators. Particularly, a 4-meter long 60.625-MHz CW RFQ has been developed, built and commissioned with beam. Development and fabrication of a cryomodule with seven 72.75-MHz quarter-wave resonators (QWR) is complete and it is being assembled. Off-line testing of several QWRs has demonstrated outstanding performance in terms of both accelerating voltage and surface resistance. Both the RFQ and cryomodule were developed and built to upgrade ATLAS to higher efficiency and beam intensities. Another cryomodule with eight 162.5-MHz SC HWRs and eight superconducting SC solenoids is being developed and built for Project X at FNAL. We are also developing both an RFQ and cryomodules (housing 176-MHz HWRs) for proton & deuteron acceleration at SNRC (Soreq, Israel). In this paper we discuss ANL-developed technologies for normal-conducting and SC accelerating structures for medium- and high-power CW accelerators, including the projects mentioned above and other developments for applications such as transmutation of spent reactor fuel.

INTRODUCTION

Technologies for CW RFQ and SC RF successfully developed for ATLAS upgrade for higher efficiency and beam intensities [1,2] can be applied in future high-power CW accelerators. Particularly, we are developing a CW RFQ and two cryomodules with different β_{OPT} for the SARAF accelerator facility at SNRC [3]. Similar SC RF technology is being used for the development and construction of the HWR cryomodule for Project X [4]. Below we discuss beam commissioning of the RFQ and results of QWRs testing and cryomodule assembly for the ATLAS upgrade project. Status of the SARAF and PXIE cryomodule development is presented.

CW RFQ

This summer we commissioned a CW RFQ designed and built for the ATLAS Facility [5]. Several innovative ideas were implemented in this CW RFQ. By selecting a multi-segment split-coaxial structure we have achieved moderate transverse dimensions for a 60.625 MHz resonator. For the design of the RFQ resonator and vane tip modulations we have developed a full 3D approach which includes MW-Studio and TRACK simulations of the entire structure. A novel trapezoidal vane tip modulation is used in the acceleration section of the RFQ which resulted in increased shunt impedance. To form an axially symmetric beam exiting the RFQ, a very short output radial matcher, only $0.75\beta\lambda$ long, was developed.

An advanced fabrication technology was applied for the construction of the RFQ which includes precise machining and two-step high temperature brazing. Thanks to the high accuracy of the overall fabrication, the assembly of the 5-segment RFQ was straightforward and resulted in excellent alignment. The resonance frequency control system based on water temperature regulation showed excellent performance. The RF measurements show excellent RF properties for the resonator, with a measured intrinsic Q equal to 94% of the simulated value for OFE copper. The multi-segment split-coaxial structure creates strong coupling between the quadrants and individual RFQ segments which reduces the effect of local frequency deviations on electromagnetic field distortions. Therefore, no bead-pull measurements were required for tuning of the accelerating field. Figure 1 shows the complete RFQ assembly after installation of

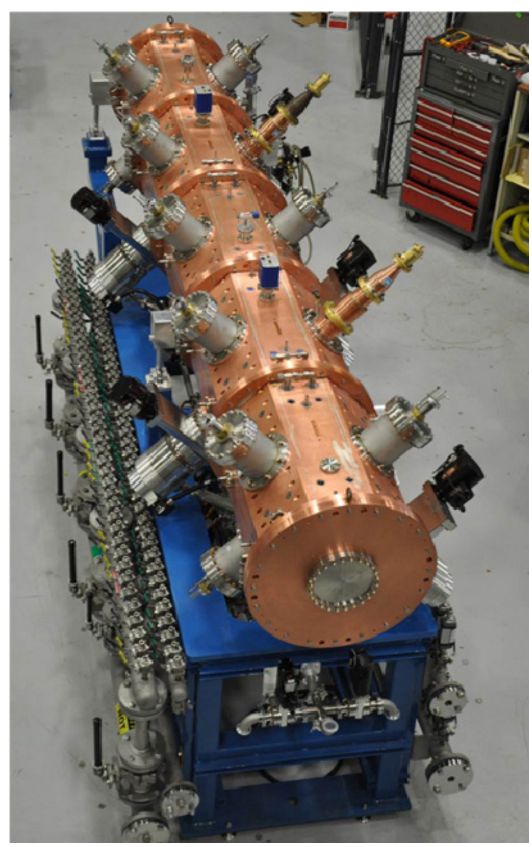

Figure 1: Completed RFQ assembly.

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the tuners, vacuum pumps, vacuum gauges, RF couplers, and pick-up loops.

An O^{5+} ion beam extracted from an Electron Cyclotron Resonance (ECR) ion source was used for the RFQ commissioning. In off-line beam testing, we found excellent agreement of the measured beam parameters with the results of beam dynamics simulations. For example, the beam energy spread was determined by scanning the magnetic field level in the 70° bending magnet located downstream of the RFQ. The results of these measurements are shown in Fig. 2.

The great success of this advanced design and fabrication technology is reflected in the measured beam parameters after the RFQ which are nearly identical to the simulated data. Currently we are developing the design for a 4-vane RFQ operating at 176 MHz for acceleration of protons or deuterons up to 1.5 MeV/u. This design takes full advantage of the ATLAS RFQ experience.

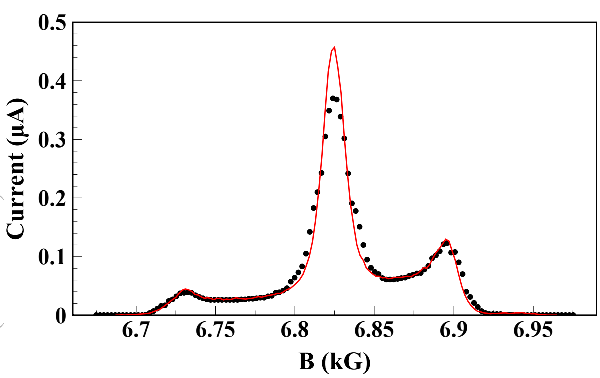

Figure 2: Measured (dots) and simulated (red curve) beam intensity as a function of the magnetic field.

QWR CRYOMODULE

While split-ring resonators are successfully operated at ATLAS with low-intensity ion beams, they exhibit a fundamental limit in the acceleration of high-intensity beams due to RF steering. Therefore we are replacing all ATLAS split-ring resonators with QWRs. Three years ago we commissioned a new cryomodule containing seven 109 MHz β_{OPT}=0.15 QWRs to provide an additional 15 MV voltage. Now, we have developed and built a new cryomodule which consists of seven β_G=0.077 QWRs at 72.75 MHz SC cavities and four 9-Tesla SC solenoids. The new high-performance cryomodule will replace three existing ATLAS cryomodules with split-ring cavities to increase the intensities of accelerated ion beams.

Compared to the previous generation of quarter-wave resonators, several innovations were implemented into the cavity design, fabrication and RF surface treatment. The cavity geometry is highly optimized to reduce both electric and magnetic peak fields: both outer and inner conductors are conical as shown in Fig. 3. During the fabrication of the niobium components, a wire EDM technique instead of machining was used to maintain clean surfaces prior to electron-beam welding. Electropolishing of the cavities was performed for a completed cavity with the integral helium vessel installed. The cavity is equipped with a double-window 4-kW adjustable RF coupler with a nitrogen cooled cold window. The new QWRs will create accelerating gradients a factor of three higher, on average, than in the existing split-ring cavities, and are designed to provide an accelerating voltage of 2.5 MV per cavity. Four 72.75 MHz QWRs were cold tested in the test cryostat and all of them provided more than 4 MV voltage, E_{PEAK}>70 MV/m and B_{PEAK}>105 mT [6,7]. The fabrication of the cryomodule, all the 72.75-MHz QWRs and SC solenoids is complete. Figure 4 shows the assembled cavities being loaded into the box cryostat during a trial fitting. The new cryomodule was designed to produce 17.5 MV total voltage but will provide up to 21 MV which will be limited only by the available cryogenic capacity.

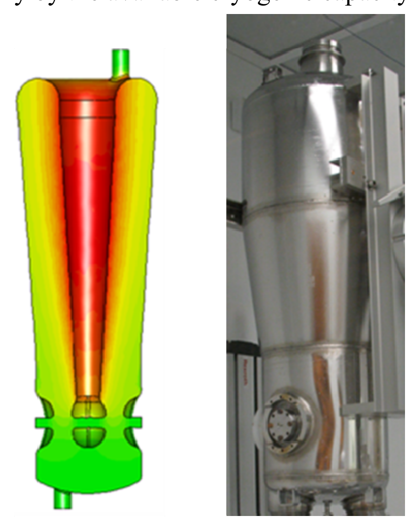

Figure 3: Cavity MWS model showing magnetic field distribution (left) and completed cavity assembly in the HPR apparatus (right).

Figure 4: Cavity string is being lowered into the box vacuum vessel during mock assembly.

HWR CRYOMODULES

In high-intensity light ion accelerators, to reduce space charge effects, the fundamental frequency should be high as compared to heavy-ion linacs. SC HWRs are superior to QWRs at operational frequencies above ~150 MHz and optimal beta $\beta_{OPT} \geq 0.1$. The fundamental frequency of Project-X is 162.5 MHz which is defined by the RFQ. Therefore we are developing a cryomodule with 8 HWRs for the acceleration of H-minus ions from 2.1 MeV to 11 MeV [8]. Similar HWRs operating at 176 MHz are designed for the SARAF Phase II 5-mA proton and deuteron linac. To increase the available accelerating voltage, the HWR shape is highly optimized reducing both B_{PEAK}/E_{ACC} and E_{PEAK}/E_{ACC} [9]. Optimization of the cavity shape was performed taking into account die-forming fabrication technology available from industry [10,11]. The final cavity shape has tapered central and outer conductors as shown in Fig. 5. The confidence in the proposed HWR design and predicted performance is based on the very successful design, construction and testing of a conical QWRs for the ATLAS upgrade. The results of the EM optimization are summarized in Table 1.

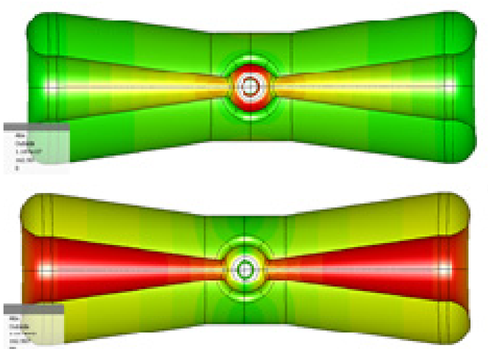

Figure 5: A half-wave resonator model in MWS. The electric (top) and magnetic field (bottom) distributions on the surface are shown.

Table 1: HWR main parameters

Parameter	PXIE	SARAF	
Frequency, MHz	162.5	176	
Operating temperature, K	2	4	
Optimal beta, β_{OPT}	0.11	0.089	0.16
$L_{EEF}= \beta_{OPT}\lambda$, cm	20.7	15.2	27.3
Aperture, mm	33	33	36
Accelerating voltage, MV	1.7	1.0	2.1
E_{PEAK}/E_{ACC}	4.7	5.3	4.7
B_{PEAK}/E_{ACC}, mT/(MV/m)	5.0	5.6	5.6
$G = Q_0R_S$, Ω	48	40	60
R/Q_0, Ω	272	231	296

Both PXIE and SARAF HWR cryomodule designs are an evolution of the top-loaded box cryomodule design used successfully for the ATLAS Upgrade. The PXIE and the first HWR SARAF cryomodules layout were determined with careful beam-dynamics simulations and estimates of recent cavity performance. As a result of these studies, a focusing period contains a solenoid-BPM-HWR sequence. Each solenoid is equipped with dipole coils for beam steering in both planes. The cryomodule design is developed around these requirements. The cryomodule beam-line assembly along with the strong-back, vacuum and helium manifolds, and cavity subsystems is shown in Figure 6.

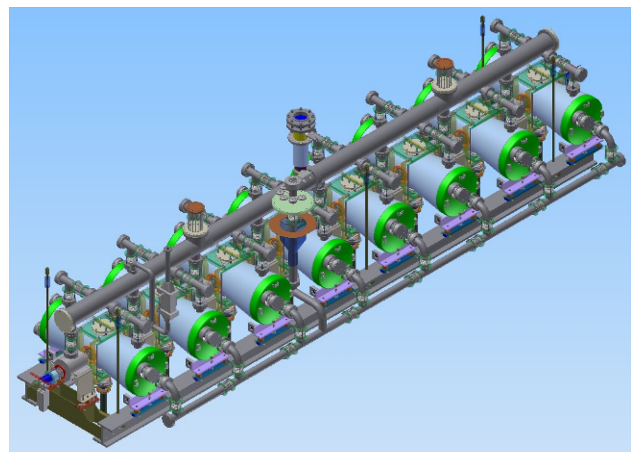

Figure 6: PXIE HWR cryomodule design

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