COMPLETION OF EFFICIENCY AND INTENSITY UPGRADE OF THE ATLAS FACILITY*

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Abstract

The ANL Physics Division has completed a major upgrade of the ATLAS National User Facility by successfully installing a new RFQ and cryomodule. The new normal conducting CW RFQ, capable of providing 295 keV/u beams of any ion with m/q ≤7, was fully integrated into ATLAS and has been in routine operation for more than a year. The RFQ doubled the efficiency of beam delivery to experiment targets and opened the possibility to accelerate much higher intensity beams. Recently, the new cryomodule containing 7 high-performance 72.75 MHz superconducting quarter-wave resonators and 4 superconducting solenoids was successfully commissioned with beam. New design and fabrication techniques for these resonators resulted in record accelerating voltages during the beam commissioning. From the very beginning, the new cryomodule provided 17.5 MV accelerating voltage which has been gradually raised by increasing the available input RF power and improving LLRF system. The new cryomodule, which replaced 3 old split-ring cryomodules, is also essential for high intensity stable beams. Results of beam commissioning and operation of ATLAS with the new RFQ and cryomodule are presented.

INTRODUCTION

Starting in the 1990's, the ATLAS heavy ion linac included 48 MHz SC resonators capable of accelerating pre-bunched ions with an initial velocity of 0.008c. Due to the high velocity gain in the first 4 SC resonators, a significant distortion of both transverse and longitudinal emittance occurred and resulted in low beam transmission through the linac. To address this issue, we have developed and built a CW RFQ capable of accelerating any ion from proton to uranium from 30 keV/u to 295 keV/u. The first cryomodule of ATLAS's Positive Ion Injector (PII) was significantly modified for operation with the new RFQ: the first three SC resonators were removed and the fourth is operated in a re-bunching mode.

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 planning to replace all ATLAS split-ring resonators with QWRs. Five years ago we commissioned a new cryomodule containing seven 109 MHz β_{OPT}=0.15 QWRs to provide an additional 15 MV of voltage. Now, we have developed, built and commissioned a new cryomodule consisting of seven SC β_{OPT}=0.077 QWRs operating at 72.75 MHz and four 9-Tesla SC solenoids. The SC solenoids include return coils to minimize stray magnetic fields. As a result of this innovative design, no extra magnetic shielding is required inside the cryomodule. The new high-performance cryomodule replaced three existing split-ring cryomodules increasing the intensities of accelerated ion beams available for experiments.

LEBT AND MEBT

The Low Energy Beam Transport (LEBT) is composed of electromagnetic quadrupoles and two 90° bending magnets to provide a small beam size (≤20 mm in diameter) in the multi-harmonic buncher (MHB). In conjunction with the installation of the RFQ, we have decided to build a new beam matching section between the MHB and RFQ using 3 electrostatic doublets and a triplet. The latter is directly attached to the front flange of the RFQ resonator. Fig. 1 shows matched beam envelopes in the MHB-RFQ section.

The RFQ is connected to the first PII cryomodule through a short bellows section. The Medium Energy Beam Transport (MEBT) is situated within the available space inside the cryomodule where the first three SC cavities were removed. The MEBT includes four SC solenoids, electrostatic X-, Y-steerers and a SC cavity operating as a re-buncher. The RFQ forms an axially-symmetric beam, and the transverse matching with SC solenoids is straightforward.

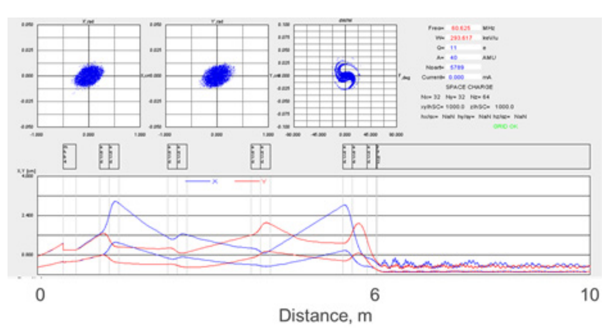

Figure 1: TRACK screenshot with the beam phase space plots after the RFQ and beam full, rms envelopes in the MHB and RFQ section.

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CW RFQ

The CW RFQ designed and built for the ATLAS Facility was commissioned off-line [1] and installed at the ATLAS front end in October 2012. Fig. 2 displays the current view of the ATLAS front end. 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 [2]. A novel trapezoidal vane tip modulation is used in the acceleration section of the RFQ which resulted in an increased shunt impedance. To form an axially symmetric beam at the RFQ exit, a very short output radial matcher, only 0.75βλ long, was developed.

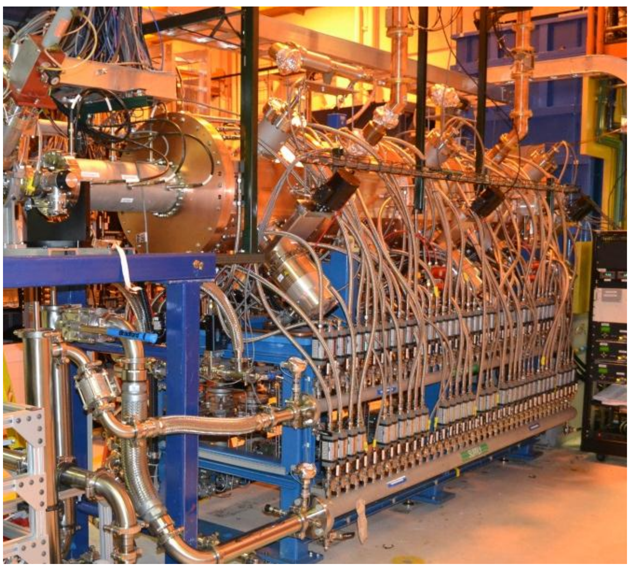

Figure 2: ATLAS front end with the RFQ in position.

In December 2012 the entire PII was tuned for the acceleration of an $^{40}Ar^{11+}$ beam. The RFQ inter-vane voltage was set to 36.4 kV, the design value for this specific beam. The optimal setting of the MHB was obtained by using a Fast Faraday Cup upstream of the RFQ and by measuring the transmission of the beam accelerated by the RFQ through the entire PII. The first SC cavity in the PII was set for bunching mode. The tuning of the remaining 14 accelerating cavities in PII was carried out successfully, based on the standard phase scan routine. The $^{40}Ar^{11+}$ beam was accelerated to the expected total kinetic energy of 69 MeV.

The beam energy spectrum and the bunch time profile were measured after each accelerating cavity. Fig. 3 provides the energy spectrum of the 69-MeV $^{40}Ar^{11+}$ beam. The transmission through the entire RFQ + PII system was determined to be 81% from the ratio of a beam intensity measurement after the PII to that measured upstream of the MHB. During the commissioning, the system was operated with beam intensities up to 3.6 eμA. Later, significantly higher argon beam intensities up to 80 eμA through the PII were demonstrated. This is a factor of 5 higher beam intensity than the typical intensities available prior to the installation of the new RFQ.

Since its inception, the RFQ has provided the acceleration of various ion species spanning the full range of the design charge-to-mass ratio. In addition, the transmission from the Positive Ion Injector (PII) to the experiments is now 100% due to the high quality of the RFQ beams. The overall reliability of the RFQ system is 97%, which is primarily defined by trips of the RF amplifiers. Further improvements are planned for the RF system. Particularly, RF circulators will be installed in the RF transmission line for each of the two amplifiers.

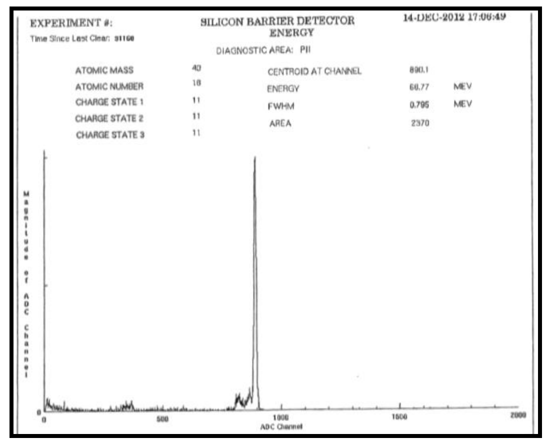

Figure 3: Energy (top) profile (bottom) of 69 MeV 40Ar11+ bunch at the exit of PII. The lower energy beam is scattering from the foil holder. The small secondary peak left of the main peaks is beam scattered from the carbon backing used in the target foil construction.

QWR CRYOMODULE

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 was discussed in previous publications [3, 4]. The beam steering compensation is provided by the internal drift tube face angle [3].

During the fabrication of the niobium components, a wire EDM technique instead of traditional machining was used to reduce the likelihood of inclusions 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 [4].

Overall, the innovative design of the cavities and solenoids has resulted in exceptional performance. The clean assembly of the cavity-solenoid string was completed in January 2013 as shown in Fig. 4. The assembly of the cold mass attached to the cryostat lid (Fig. 5) and alignment of the resonators and solenoids [5] was continued outside of the clean room and completed by June 2013. After off-line cold and RF testing, the cryomodule was installed into the ATLAS tunnel. To handle higher intensity beams at ATLAS, significant modifications of the beamline and the Booster area were undertaken: new concrete shielding in the Booster area has been installed. The cryomodule was cooled down in December 2013. The static heat load was measured to be just 12 Watts [6]. Beam commissioning of the new beam-lines and new cryomodule was completed in March 2014. Fig. 6 shows $^{45}Sc^{11+}$ beam energy measurements after each SC cavity when the synchronous phase was set in the range from 36° to 30°. The effective cavity voltage was calculated by fitting TRACK simulations to the measured energy gain. Table 1 lists effective voltages for each cavity. The total effective voltage of the cryomodule is 17.5 MV. As discussed in ref. [7], all cavities are capable of providing more than 4 MV voltage with E_{PEAK}>70 MV/m and B_{PEAK}>100 mT.

Currently, the available cavity voltage is limited by the LLRF system. Lorentz detuning effects on the stability of the LLRF system at even higher fields will be investigated.

Figure 4: String of seven superconducting resonators and four solenoid magnets after completion of clean assembly.

Figure 5: Cold mass assembly is ready to load into the cryostat vacuum vessel.

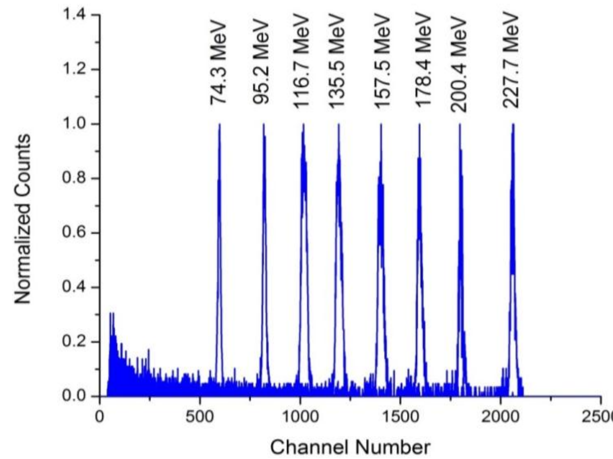

Figure 6: Beam energy profile measurements after sequential acceleration by each SC cavity.

Table 1: Energy Gain and Cavity Voltage

Resonator	$^{45}Sc^{11+}$ energy gain (φ_S=0), MeV	V_{EFF}, MV
R211	25.7	2.45
R212	26.86	2.47
R213	23.51	2.14
R214	26.38	2.41
R215	25.18	2.35
R216	26.77	2.55
R217	31.48	3.05

SUMMARY

We have successfully completed efficiency and intensity upgrade of the ATLAS facility at Argonne. All project goals have been achieved. The project included development, construction, installation and beam commissioning of a 60.625 MHz CW RFQ and a cryomodule with seven 72.75 MHz QWRs and four 9-Tesla solenoids. Both RFQ and new cryomodule are in routine operation and provide high-quality, high-intensity beams. The performance of the QWRs is especially remarkable and sets a new world record both in terms real world accelerating gradients and residual resistance.

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