

# EFFICIENCY AND INTENSITY UPGRADE OF THE ATLAS FACILITY\*

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## Abstract

The ANL Physics Division is pursuing a major upgrade of the ATLAS National User Facility. The overall project will dramatically increase the beam current available for the stable ion beam research program, increase the beam intensity for neutron-rich beams from the Californium Rare Isotope Breeder Upgrade (CARIBU) and improve the intensity and purity of the existing in-flight rare isotope beam (RIB) program. The project will take place in two phases. The first phase is fully funded and focused on increasing the intensity of stable beams by a factor of 10. This will be done using a new normal conducting, CW Radio Frequency Quadrupole (RFQ) accelerator and replacing three cryostats of split-ring resonators with a single new cryostat of high-performance quarter-wave resonators. To further increase the intensity for neutron-rich beams, we have started development of a high-efficiency charge breeder for CARIBU based on an Electron Beam Ion Source (EBIS). The goal of the proposed second phase will be to further increase the energies and intensities of stable beams, as well as, increase the efficiency and beam current for CARIBU and in-flight RIB beams. The focus of this paper is on innovative developments for Phase I of the project.

## ATLAS LAYOUT

Figure 1 shows the layout of the ATLAS facility after the completion of Phase I of the project. The current Electron Cyclotron Resonance (ECR) charge breeder will be replaced with a more efficient EBIS charge breeder. A normal conducting RFQ will be installed in front of the SC linac and a new high-performance cryomodule will replace three existing cryomodules with split-ring cavities.

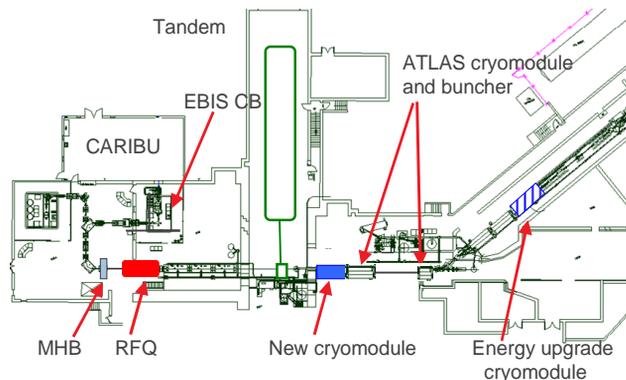


Figure 1: Layout of the ATLAS after Phase I.

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## CW RFQ

The new CW RFQ will deliver 295 keV/u ion beams to the ATLAS Positive Ion Injector linac (PII). The first cryomodule of the PII will be modified to match the RFQ beams to the SC section. By replacing three of the aging Booster cryomodules with one new cryomodule of low-beta cavities, a 10-fold higher current may be accelerated to Coulomb barrier energies. These modifications will improve the transport efficiency throughout the ATLAS system, while limiting the emittance growth for high-intensity beams and also, double the CARIBU re-accelerated beam intensities because the RFQ and associated bunching systems will capture more of the ions for subsequent acceleration.

In our application, the RFQ must provide stable operation over a wide range of RF power levels to allow acceleration of ion species from protons up to uranium. The new design incorporates developments that came out of the successful Rare Isotope Accelerator (RIA) RFQ prototype tested in 2006. The resonator is a pseudo split coaxial structure which reduces the maximum transverse dimension to 18 inches at an operating frequency of 60.625 MHz. The cavity is designed as a 100% OFE copper structure and fabrication is based on a two-step furnace brazing process. The cavity consists of five nearly identical longitudinal segments. The central segment consists of two driving loops located in opposite quadrants as shown in Fig. 2. The main parameters of the RFQ are listed in Table 1.

The effective shunt impedance is increased by 40% by introducing a trapezoidal shape to the vane modulation in the accelerating section instead of a traditional sinusoidal modulation. Typical accelerating field distributions for both types of vane shape modulation are shown in Fig. 3. Notice that the trapezoidal modulation modifies the field distribution significantly and increases the transit-time factor. Another feature of the RFQ is the formation of an axially-symmetric beam exiting the RFQ. This feature is

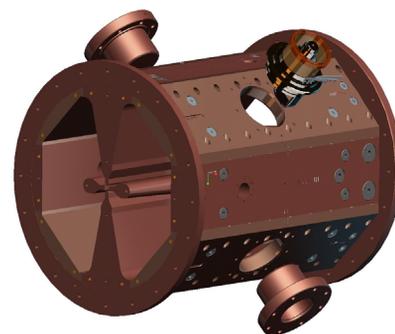


Figure 2: One of five segments of the RFQ.

Table 1: Basic Parameters of the RFQ.

Parameter	Value
1 Input Energy	30 keV/u
2 Output Energy	295 keV/u
3 Average radius	7.2 mm
4 Vane Length	3.81 m
5 Inter-Vane Voltage	70 kV
6 RF power consumption	60 kW

required for matching into a cryomodule with SC solenoidal focusing. A more detailed RFQ design is discussed elsewhere [1]. Currently, we are in the process of fabricating the RFQ parts to prepare for brazing in the spring of 2011.

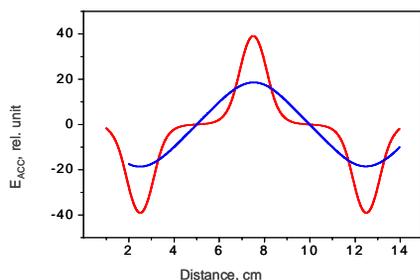


Figure 3: Accelerating field distribution in the RFQ with sinusoidal (blue) and trapezoidal (red) modulations.

## CRYOMODULE

The replacement of three existing ATLAS cryomodules will allow a 10-fold increase in stable ion beam intensities. The new cryomodule takes advantage of the recent ATLAS Energy Upgrade (AEU) cryomodule developments [2], in addition to innovative superconducting cavity fabrication and surface treatment technologies developed at ANL. The new cryomodule consists of seven highly optimized  $\beta_G=0.075$  QWRs at 72.75 MHz and four 9 Tesla SC solenoids. The engineering 3D model of the cavity string suspended from the cryostat lid is shown in Fig. 4. New cryomodule features include the separation of the cavity and the cryogenic vacuum systems, and top-loading of the cleaned and sealed cavity-string subassembly. Based on our experience with the AEU cryomodule, minor design modifications are being implemented. These included a simplified coupler penetration port and bottom mounted cavity vacuum manifold.

Beam dynamics studies show that larger 30-mm beam apertures for both solenoids and cavities, together with corrective beam steering implemented directly into the cavity design [3], provide a factor of four larger transverse acceptance than the existing Booster linac section. The new QWRs will create accelerating gradients a factor of three higher, on average, than in the existing ATLAS and will provide a total voltage of

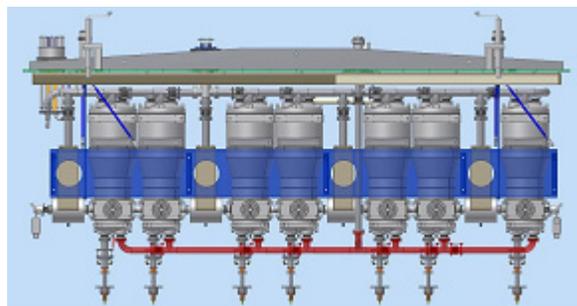


Figure 4: Cryomodule engineering model.

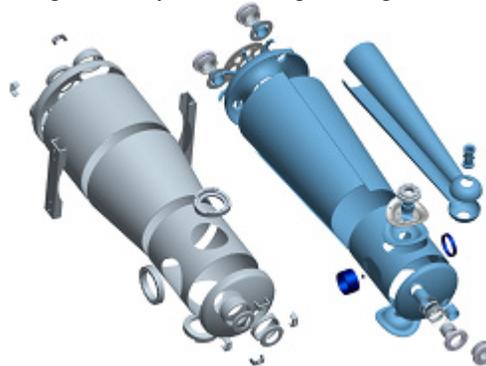


Figure 5: Exploded view of the 72.75 MHz QWR. Niobium parts are shown on the right and stainless steel parts on the left.



Figure 6: Various cavity niobium parts as die forming complete.

17.5 MV. Cavity design parameters are reported in [4,5]. An exploded 3D view of the cavity niobium parts and stainless steel helium vessel is shown in Fig. 5. Fabrication of the cavity niobium parts is complete (see Fig. 6) and electron-beam welding (EBW) is in progress with the aim to complete the first fully-dressed cavity by the end of the year and to start cold RF field tests.

The two most critical components of the cavity sub-system include an adjustable coupler and fast piezoelectric tuner already successfully developed, fabricated and undergoing testing. The 4 kW adjustable capacitive coupler matching to a 1-5/8" coaxial drive line and the fast tuner have been installed on the existing 170 MHz HWR and operated in the test cryostat as we report at this conference [6].

## EBIS CHARGE BREEDER

At relatively low intensities ( $<10^9$  ions per second) of radioactive beams, the EBIS charge breeder has demonstrated a factor of 3–4 higher efficiency depending on ion species, shorter breeding times, and better ion beam quality regarding emittance and the superposition of impurities as compared to present ECRIS performance. Due to limited intensities ( $\sim 10^7$  ions per second) of CARIBU radioactive ion beams, an EBIS combined with RFQ-buncher preceding the EBIS is an excellent choice as a charge breeder. The EBIS project for CARIBU will utilize heavily state-of-the-art technology recently developed at BNL [7]. The efficiency of EBIS-CB in the pulsed injection mode will be significantly higher than in the continuous (DC) injection mode. An RFQ Cooler-Buncher (RFQ-CB) will be used to collect ions downstream of the mass separator. To avoid limitations due to space charge, the collection time will be limited to about 33 ms. The breeding takes about 33 ms while another bunch of ions is being collected in the RFQ-CB. This procedure is repeated at a frequency of 30 Hz. The expected total efficiency of the RFQ-CB defined as a ratio of the number of extracted ions in a bunch to the number of injected ions in a single cycle is above 80%. The collected and cooled ion bunch is extracted from the RFQ-CB within  $\sim 10 \mu\text{s}$  and injected into the EBIS-CB. Ion beams with charge-to-mass ratios  $\geq 1/7$  will be extracted within  $\sim 10 \mu\text{s}$  after charge breeding. High efficiency for the whole process, up to about 20%–25%, is possible due to the absence of space charge effects.

The electron beam current density inside the SC solenoid will be similar to that in the BNL EBIS, allowing suitably fast charge breeding of the radioactive ion beams. Two different electron guns will be designed and built for the CARIBU EBIS-CB: (1) high-current ( $\sim 2$  A) e-gun and (2) low-current ( $\sim 0.2$  A) e-gun. The high-current e-gun will allow for the operation of the CARIBU EBIS-CB's in the experimentally proven regime as of the BNL EBIS. We are going to develop a low-current e-gun to test the ionization process involving the so-called "shell closures" effect. A low-energy electron beam ( $\sim 2$  keV) must be used for the "shell closures" operation of the EBIS-CB in the case of moderate charge states. The electron beam current of the e-gun is limited by perveance and formation of the virtual cathode and should be reduced to 0.2 A for an  $\sim 2$  keV electron beam inside the ion trap. One should note that the switch between high and low current regimes requires only the replacement of the e-gun which can be isolated by a vacuum valve; no other parts of the CARIBU EBIS-CB need to be modified. The layout of the proposed EBIS-CB for the CARIBU intensity upgrade is presented in Fig. 7. Engineering development of the EBIS trap region and electron beam collector are in progress. The high-perveance electron gun and 6-Tesla 15-cm bore SC solenoid are being procured. Fig. 8 shows a 3D view of the solenoid with the ion trap region which is isolated by vacuum valves both from the e-gun and electron collector.

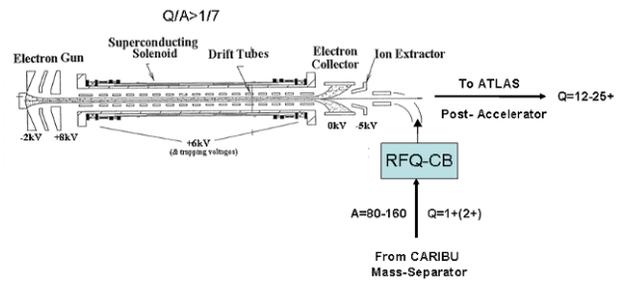


Figure 7: Layout of the proposed EBIS charge breeder for the CARIBU intensity upgrade (RFQ-CB – Radio Frequency Quadruple Cooler-Buncher).

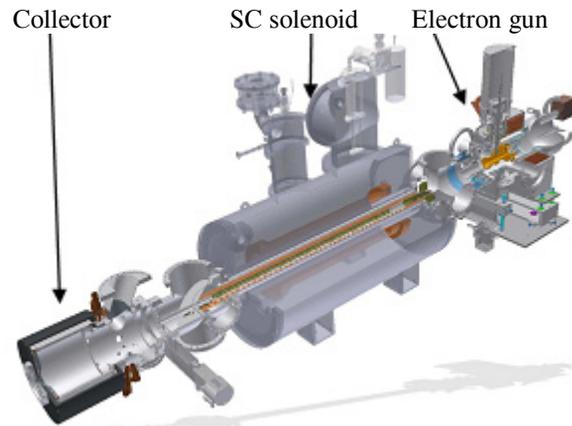


Figure 8: Engineering model of the CARIBU EBIS charge breeder. The e-gun and electron collector are identical to the BNL EBIS design.

## PROJECT STATUS

The RFQ design is complete and OFE parts of the RFQ are being fabricated in local shops. Prototyping of the frequency control system based on the adjustment of the cooling water temperature is under way. Fabrication of the first SC cavity is nearly complete. The frequency tuning of the cavity and final electron beam welding will take place in about a month. The cold RF test of the cavity with all subsystems is planned in the beginning of 2011. The cryostat vessel and remaining 7 cavities are in production in US industry. A 9-Tesla SC solenoid for the cryomodule has been purchased from industry and cold tested. While long-lead components of the EBIS are being procured from industry, we continue the engineering design of the trap area and the electron beam collector.

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