A NEW ATLAS EFFICIENCY AND INTENSITY UPGRADE PROJECT*

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Abstract

The ATLAS facility provides beams of essentially all stable isotopes at energies above the Coulomb barrier for nuclear physics research. We have developed a two-stage ATLAS upgrade plan which includes the replacement of aging split-ring cavities by high-performance quarter-wave resonators (QWR) capable of accelerating ~100 pμA ion beams. The first stage of the upgrade project funded through the American Recovery and Reinvestment Act includes an accelerator efficiency increase by adding a new RFQ injector, development and construction of a new cryomodule containing up to 4 SC solenoids and 7 QWRs. A new 72.75 MHz resonator is designed for an optimum ion velocity β=0.075. To achieve a record high accelerating voltage of ~ 2.5 MV at this very low velocity range, the EM properties of the resonator are highly optimized to reduce peak surface fields. The vast experience gained during the development, commissioning and operation of the ATLAS energy upgrade cryomodule [1,2] will be applied to the design of the new cryomodule.

INTRODUCTION

The efficiency and intensity upgrade of ATLAS is motivated by the need to increase intensities for both stable and exotic beams to address the most pressing scientific issues defined in the most recent NSAC Long Range Plan. The factor of two intensity increase for exotic beams from Californium Radioactive Ion Beam Upgrade (CARIBU) project provides, for example, the opportunity to (i) investigate the single-particle structure of neutron-rich nuclei in the ^{132}Sn region further from stability, and (ii) to probe new collective modes in neutron-rich Zr and Pd nuclei. It will also provide access to nuclei required to study reactions close to the astrophysical r-process path. An increase in the intensity of stable beams is an essential component of research programs investigating the structural properties of the heaviest elements, shell structure in N=Z nuclei near ^{100}Sn, reaction yields of astrophysical importance (rp-, αp-, νp-, CNO-processes). In addition, high-intensity stable beams will be used to produce beams of rare isotopes by the in-flight technique for both structure and nuclear synthesis investigations. They are also required to provide the large quantities of specific isotopes needed for high-precision measurements of fundamental symmetries in atomic and ion traps.

The replacement of the first two Booster cryomodules, as shown in Figure 1, is essential to increase the intensity of ATLAS. These modules contain aging split ring cavities which are the most responsible for the present intensity limitations. The new cryomodule will provide beams up to ~ 5 MeV/u. While the biggest gain will be in the increased intensity of stable beams (less beam steering and losses), the improved transmission will also increase the intensity of CARIBU re-accelerated beams.

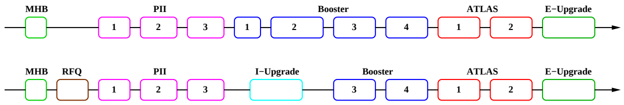

Figure 1: Layout of the existing ATLAS (top) and the proposed efficiency and intensity upgrade (bottom).

The new cryomodule with seven β_G=0.075 QWRs and four SC solenoids takes advantage of the recent ATLAS Energy Upgrade (AEU) cryomodule developments and superior technology of fabrication and surface treatment of superconducting cavities at Argonne [3]. Currently, extensive beam dynamics studies are being performed to optimize the accelerating and focusing lattice of the new cryomodule incorporated into the ATLAS structure. Preliminary studies show that larger beam apertures for both solenoids and cavities, together with corrective beam steering implemented into the cavity design, provide a transverse acceptance four times larger than in the existing Booster section. The previously-used resonator Voltage Controlled Reactance (VCX) phase control system for this velocity range limits the accelerating gradients to ~8.3 MV/m. Therefore newly developed fast piezoelectric tuners will be used to operate SC cavities at higher gradients. The new resonators will provide accelerating gradients a factor of three higher, on average, than in the existing ATLAS. The resonators will be equipped with capacitive couplers to handle about 2 kW RF power.

CAVITY AND CRYOMODULE SPECIFICATIONS

The fundamental frequency of the ATLAS linac is 12.125 MHz. The proposed RFQ for the intensity upgrade project will operate at the 5th harmonic (60.625 MHz). The natural choice of the frequency for the upgrade cryomodule would be also 60.625 MHz, however, to reduce the resonator frequency jitter due to micro-phonics we choose a frequency of 72.75 MHz. At 72.75 MHz, the cavity is shorter by about 20 cm.

The choice of the design β was optimized based on the beam dynamics and the actual performance of ATLAS cavities, especially the PII injector which is operating at more than 50 % higher voltage of its original design. It was found that a β of ~ 0.075 is most appropriate.

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Figure 2 shows the effective voltage per cavity as a function of β for a 1/7 charge-to-mass ratio. The 7 points at ~ 2.5 MV corresponds to the proposed intensity upgrade cryomodule and the last 7 points to the newly installed energy upgrade cryomodule. The focusing period will consist of 2 cavities and 1 solenoid.

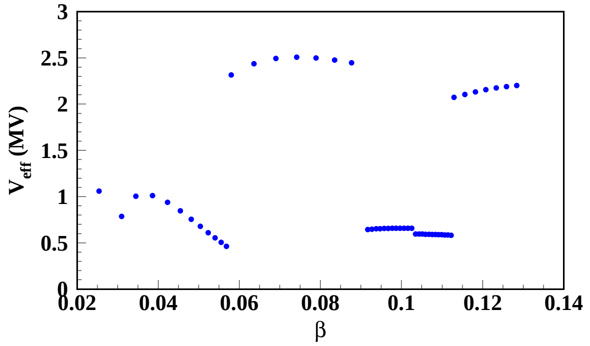

Figure 2: Effective voltage as function of β for existing ATLAS cavities and the proposed cryomodule for ATLAS intensity upgrade project (7 points at ~ 2.5 MV).

ELECTROMAGNETIC OPTIMIZATION

To reach a record high accelerating voltage of 2.5 MV per cavity, the EM design was carefully optimized. The main goal of the optimization was to minimize the peak magnetic and electric fields while still keeping good values for the stored energy, the shunt impedance (R/Q) and the geometric factor ($R_S \times Q$). The cavity height was also another important parameter as mentioned above. Starting from a 25 cm diameter cylindrical shape and gradually increasing to a 30 cm diameter with the same cavity geometrical β, we notice a significant improvement in all the parameters of interest (see Figure 3). Beyond 30 cm we begin to sacrifice real-estate gradient. We clearly notice a ~ 15 % reduction in peak magnetic field.

In a second step of the optimization we varied the top cylinder diameter while keeping the same diameter for the bottom section of the cavity at 30 cm. The cavity now has a cylindrical shape on the bottom and a conic shape on the top as shown in Figure 4. We have clearly noticed an improvement in almost all the important parameters with a larger diameter on the top. More importantly, the cavity height is reduced by about 6% (from ~ 122 cm to ~ 116 cm) for a top cylinder diameter of 40 cm. At 40 cm, the effect on the real-estate gradient is not significant because we take advantage of the space required for cavity interconnections and solenoids. More detailed optimizations were performed to reach the final design parameters given in table 1. The optimization also included the internal drift tube face angle required for beam steering correction. An angle of 2.5 deg was found appropriate to correct the beam centroid.

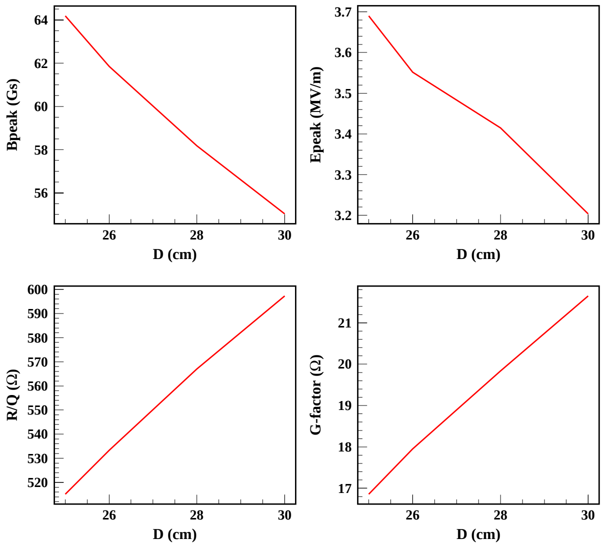

Figure 3: Cavity parameters normalized for 1 MV/m accelerating field as functions of the cavity diameter.

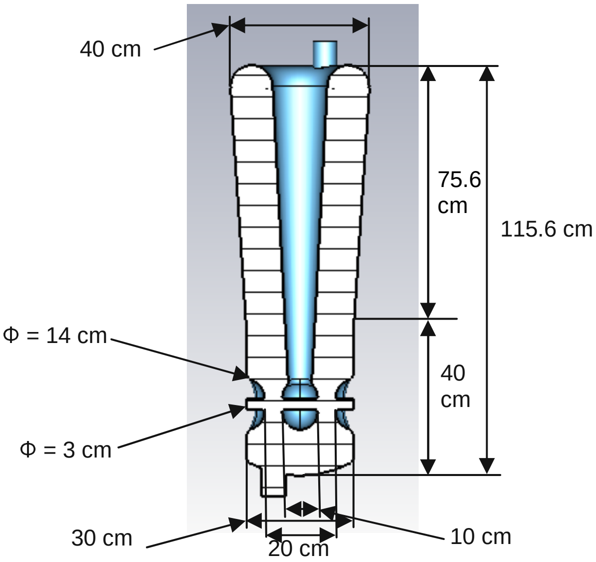

Figure 4: Resonator main dimensions.

MECHANICAL DESIGN

Cavities

Recently we have commissioned a new cryomodule containing seven 109 MHz β=0.15 quarter-wave superconducting cavities [1,2]. All cavities tested in the cryomodule have shown outstanding performance which resulted in an average quench-limited gradient of 12 MV/m. Therefore, our intention is to apply all design features of the 109 MHz QWR except for slight modifications. Namely, the VCX fast tuner is not part of the new cavity design. A fast phase control in the new cavities will be provided by over-coupled operation. In addition, a piezoelectric tuner will be developed and

Table 1: Final design parameters of the new QWR

Parameter	Value	Units
Frequency	72.75	MHz
β value	0.077	
Stored energy @ 1 MV/m	0.152	J
B_{PEAK} @ 1 MV/m	48.0	Gs
E_{PEAK} @ 1 MV/m	3.25	
R/Q	575	Ohm
R_SQ	26.4	Ohm
Design voltage	2.5	MV
Design Q_0 @2.5 MV	2×10^9	
Dynamic cryogenics load @2.5 MV	5.4	W

installed to control low frequency micro-phonics noise below ~100 Hz if required.

The new cavity will have longer stem compared to the 109 MHz QWR and, consequently, more risk of micro-phonics. Significant engineering studies using ANSYS multi-physics software are being performed to:

a) Minimize the resonator frequency sensitivity to fluctuations in helium pressure;
b) Move eigen-frequencies of mechanical oscillations above ~100 Hz by appropriate stiffening of the cavity body and stems;
c) Provide acceptable level of stresses;
d) Evaluate slow tuner range and stresses;
e) Find the best location for the fast tuner and perform modal analysis of the cavity including piezoelectric tuner system.

Based on our recent experience and as a result of new developments, substantially higher accelerating fields and cavity voltages are expected compared to other TEM cavities being used or developed worldwide in this velocity range.

Cryomodule

The cryomodule design is very similar to the recently commissioned AEU cryomodule [1,2]. Features include separation of the cavity and the cryogenic vacuum systems, and top-loading of the cavity-string subassembly which enables assembly and hermetic sealing of the cavity string in the clean room. Based on our experience with AEU cryomodule, slight design modifications are being implemented mostly related to the cryostat bottom, coupler penetration and vacuum manifold. Figure 5 shows a section view of the cryomodule containing 6 cavities and 3 solenoids. Recently we have received additional funds to include one more cavity and a solenoid. Figure 6 shows a conceptual 3D view of the cavity string. The seven-cavity cryomodule will provide 17.5 MV total voltage which is comparable to the total voltage provided by all four existing Booster cryomodules.

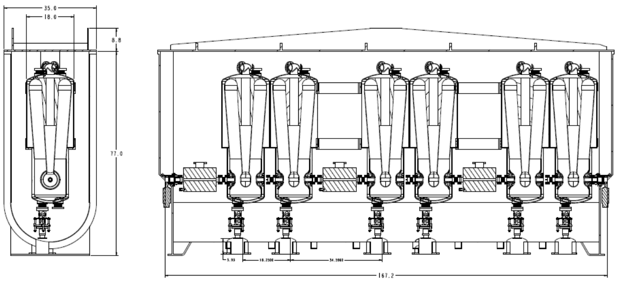

Figure 5: Section view of the cryomodule.

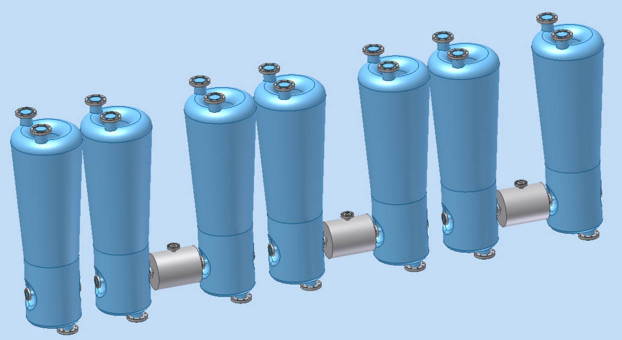

Figure 6: Conceptual 3D model of the cavity-solenoid string.

RF Coupler

A capacitive coupler is a good option for QWRs due to suitability for bottom mounting and low RF losses. An adjustable coupler offers several advantages compared to a fixed one. Our experience shows that using an adjustable coupler for RF pulsed conditioning can result in higher accelerating gradients. In addition, the adjustable coupler will minimize the required RF power in future upgrades of ATLAS. The design of a 2 kW adjustable capacitive coupler matching to 1-5/6″ coaxial cable is in progress. A 3D engineering model of the coupler is shown in Fig. 7. The cavity vacuum space is isolated by an 8-mm-thick ceramic disk window which will be actively cooled by liquid nitrogen. An additional warm window to isolate the cryostat vacuum is foreseen. A copper plated SS bellow to enable 30 dB coupling range will be used between the conflat flange shown in Figure 7 and the cavity flange.

The recently commissioned 109 MHz cavities have RMS micro-phonics of 1-2 Hz [4]. Based on this data we expect that the micro-phonics noise for the 72.75 MHz cavities should be within a ~ 25 Hz window. Therefore, over-coupling a 2 kW RF power to the cavity operating at design accelerating gradient of 12.5 MV/m is sufficient to control microphonic noise with peak-to-peak amplitude of 24 Hz as shown in Figure 8. The optimal Q_{EXT} is $2{\cdot}10^6$ and can be achieved at the coupler location shown in Figure 9.

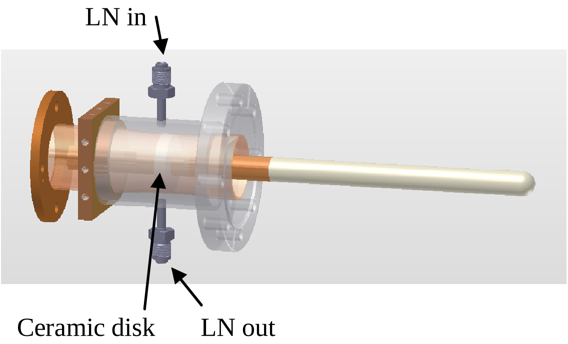

Figure 7: 3D engineering model of the coupler.

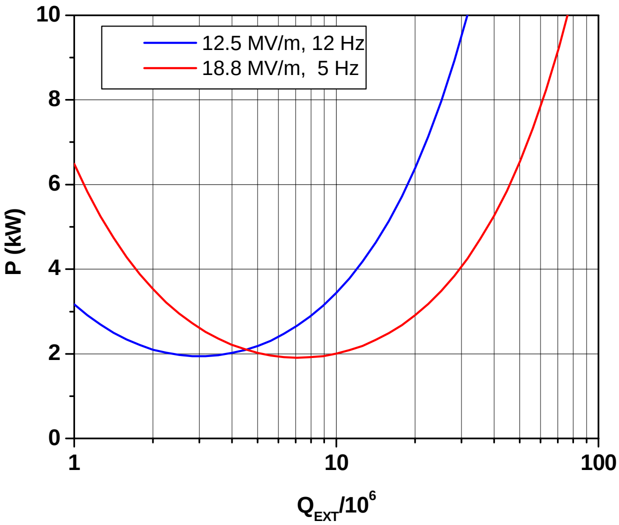

Figure 8: RF power as a function of the external Q to accelerate 100 μA beam at synchronous phase 25°. The blue and red curves correspond to 12.5 MV/m and 18.8 MV/m accelerating field respectively.

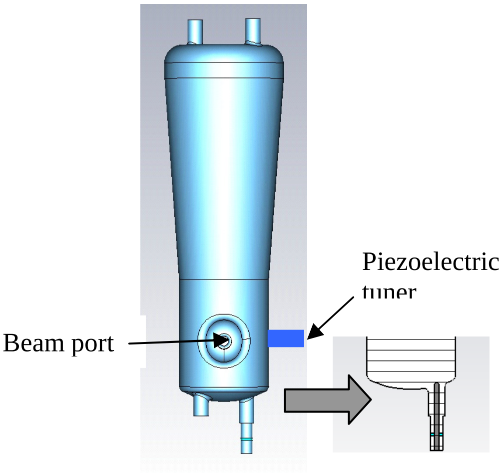

Figure 9: Correct position of the coupler minimizing required RF power.

Fast Tuner

A fast piezoelectric tuner will be installed on the cavity (Fig. 9) to supplement micro-phonics control. As is seen from Figure 8, a 2 kW RF power may be sufficient to operate at the design voltage of 2.5 MV. However, for given RF power, operation at higher voltages reduces the controllable frequency window (Fig. 8). Therefore, a fast tuner will be necessary to compensate the frequency jitter at higher level of cavity voltage. The combination of over-coupling and fast tuner should allow us to operate the new cavities as high as 20 MV/m which corresponds to 4 MV voltage gain per cavity.

Slow Tuner

This system will be the same pneumatic tuner as was used in the previous 109 MHz QWRs. These tuners are capable of operating with very high slew rate ~1.2 kHz/sec [5] and have shown excellent reliability during ATLAS operations.

PROJECT STATUS

The cavity electromagnetic design is complete. Currently several components of the cavity sub-systems such as the coupler and its components and the piezoelectric tuner are being developed and fabricated. We are working with several vendors on the technology of copper plating of SS bellows. Previously we had negative experience with copper plated bellows in the coupler assembly. In particular, the copper film had flaked off after HPR.

SC coils for the solenoid will be purchased from a vendor and a cryostat satisfying the pressure vessel code will be built. This solenoid will be tested together with the new 72.75 MHz SC cavity. All cold tests will be performed in the new TC3 test cryostat [6] located near the ATLAS front end.

Currently we are procuring RRR250 Nb for seven cavities. Our plan is to build the first fully-dressed cavity and cold test in TC3 by the end of next year.

CONCLUSION

A new 72.75 MHz quarter wave resonator is being developed for an optimum ion velocity of β=0.077. Thanks to highly optimized design including all cavity sub-systems, each cavity should provide a nominal voltage of 2.5 MV. The first fully-dressed cavity will be tested by the end of next year while the construction of the 7-cavity cryomodule and following installation, commissioning is planed in three years.

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