SIMULTANEOUS ACCELERATION OF RADIOACTIVE AND STABLE BEAMS IN THE ATLAS LINAC*

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Abstract

ATLAS is now the only US DOE National User Facility for low-energy heavy-ion stable beams. With the recent commissioning of the Californium Rare Isotope Breeder Upgrade (CARIBU), ATLAS is now also used to accelerate radioactive beams. The demand for both stable and radioactive beam time is already exceeding two to three times the 5500 hours delivered by ATLAS every year. The time structure of the EBIS charge breeder to be installed next year for CARIBU beams is such that less than 3% of the ATLAS duty cycle will be used for radioactive beams. Being a CW machine, ~ 97% of the ATLAS cycle will be available for the injection and acceleration of stable beams without retuning. This simultaneous acceleration is possible for stable and radioactive beams with charge-to-mass ratios within 3%. We have developed a plan to upgrade ATLAS for this purpose to be implemented over the next few years, where two to three beams could be delivered simultaneously to different experimental areas. The upgrade concept will be presented along with the recent studies and developments done in this direction.

THE ATLAS FACILITY AND RECENT UPGRADES

The Argonne Tandem Linear Accelerator System (ATLAS) was the first superconducting linac for ion beams in the world [1]. It has been operating and delivering ion beams for over thirty years at different capacities. Over the same period, ATLAS has undergone several upgrades [2]. The most recent are CARIBU [3] and the Efficiency and Intensity upgrade [4].

CARIBU uses a Californium fission source to produce radioactive daughter nuclei which are collected, separated and then cooled to form a beam. An ECR charge breeder [5] is used to increase the charge state of these beams for injection and acceleration in ATLAS.

The Efficiency and Intensity upgrade consisted of a new RFQ [6] and a new superconducting module [7]. The RFQ replaced the first three superconducting cavities of the Positive Ion Injector (PII) to avoid deterioration of the beam quality due to fast acceleration of low energy beams. The RFQ uses the existing multi-harmonic buncher (MHB) as a pre-buncher. Two notable features of the ATLAS RFQ are trapezoidal modulations in the accelerating section and a compact output matcher to produce an axis symmetric beam for direct beam injection into PII which uses solenoidal focusing [8]. The new cryomodule replaced three old modules with split-ring resonators [9]. The split-ring cavities are known to cause beam steering which results in beam loss and the subsequent quench of solenoids. The new cryomodule is made of 7 quarter-wave resonators (QWR) and 4 superconducting solenoids. The QWRs were designed and built with steering correction [10]. The new module should be able to accelerate 10 to 100 times higher intensity stable beams without significant beam loss.

Both the new RFQ and cryomodule have been recently commissioned and are now being used for routine ATLAS operations. Following this upgrade, the transmission has improved by 50 to 100% for all beams accelerated in ATLAS [11]. The overall transmission is now routinely over 80%, which is dictated by the MHB used to produce a small longitudinal emittance for more efficient beam transport and acceleration in ATLAS [12]. Figure 1 shows the current layout of ATLAS after the recent upgrades.

THE NEED FOR MULTI-USER CAPABILITIES AT ATLAS

ATLAS is now the only US DOE National User Facility for low-energy heavy-ion stable beams delivering upward of 5500 hours of beam-on-target every year. With CARIBU online, ATLAS is also being used for the acceleration of radioactive beams, which often require longer beam time for experiments due to their lower intensity. In the past two years, the demand for ATLAS beam time has more than doubled and with longer radioactive beam run periods, less and less users will be served, especially stable beam users. Therefore the need for a multi-user capability is significant at ATLAS in order to satisfy more users and maximize the scientific output of the ATLAS facility.

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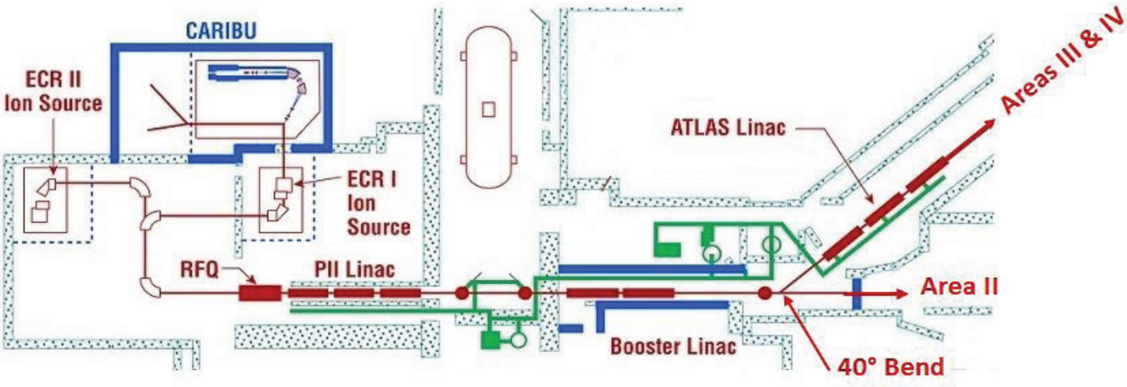

Figure 1: Current layout of the ATLAS facility showing CARIBU, the ECRs, the RFQ and the three linac sections; PII, Booster and ATLAS. It also shows the beam lines leading to the different experimental areas II, III and IV.

THE EBIS CHARGE BREEDER AND SIMULTANEOUS ACCELERATION OF RADIOACTIVE AND STABLE BEAMS

With the installation of the recently commissioned CARIBU EBIS charge breeder [13] in 2015, it will be possible to simultaneously accelerate one radioactive and one stable beam in ATLAS. The EBIS produces a 10 µs to 1 ms beam pulse up to a 30 Hz repetition rate, that is about 3% of the duty cycle. ATLAS, being a CW machine, enables the possibility of injecting stable beams during the remaining 97% of the duty cycle. Considering the fact that a stable beam with a charge-to-mass ratio close to that of the CARIBU beam is usually used as a guide beam to tune the linac, it would be straightforward to inject any stable beam with a charge-to-mass ratio within 3% without retuning the machine. Figure 2 shows the proposed time structure of the ATLAS beam for the simultaneous acceleration of one radioactive beam from CARIBU EBIS and one stable beam from the ECR ion source. The proposed operation scheme is 3% for radioactive beam, 96% for stable beam and 1% for switching between the two beams.

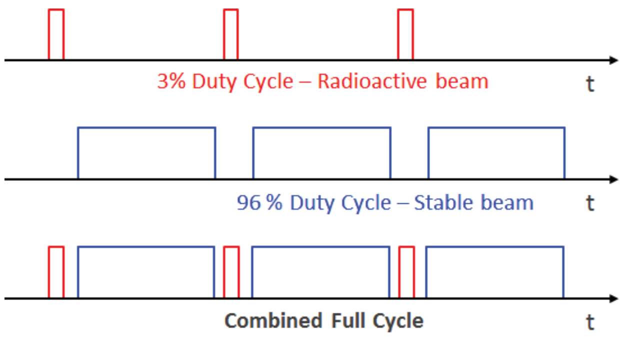

Figure 2: Time structure for the proposed simultaneous acceleration of radioactive and stable beams in ATLAS. 3% duty cycle for the radioactive beam (top), 96% for the stable beam (middle) and 1% for switching between beams to combine them into the full cycle (bottom).

The CARIBU beam mass numbers range from 80 to 170 with atomic numbers from 30 to 70. The highest charge-to-mass ratio that they could be ionised to is ¼. Considering that ATLAS accelerates beams with charge-to-mass ratios equal to or higher than 1/7, the useful range for the multi-user capability is 1/7 < q/A < ¼. Higher q/A (~ 1/3) could be achieved by operating the EBIS with longer breeding times and a 10 Hz repetition rate, which would also lead to a 10% (radioactive beam)-90% (stable beam) operation scheme.

A MODIFIED LEBT FOR TWO BEAM INJECTION

Figure 3 shows a preliminary layout for a modified low-energy beam transport (LEBT) line for the injection of two beams; one radioactive from the CARIBU EBIS and one stable from the ECR [14]. As shown on the figure, both the EBIS and ECR have their own high-voltage platform which could be adjusted independently to match the required RFQ injection velocity. The main components of the new LEBT are a pulsed electrostatic deflector and an achromat. The deflector is turned off when injecting the beam from EBIS and turned on when injecting from the ECR. When the deflector is off, the DC beam from the ECR is stopped. The proposed achromat is made of four 45° bending magnets with a dispersive middle plane for further purification of the EBIS beam. An option with two 90° magnets is being considered for higher resolution. The achromatic property is essential for the transport of beams with different charge-to-mass ratios and to minimize any emittance growth from the energy spread.

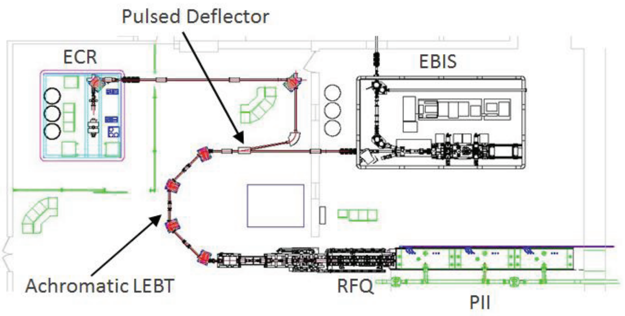

Figure 3: Layout for a new LEBT including a pulsed electrostatic deflector to inject either an EBIS or an ECR beam, and an achromat made of four 45° magnets.

EXTRACTION OF ONE BEAM AFTER THE BOOSTER

Following the injection, the two beams are accelerated in the RFQ, PII and Booster in different time periods of the duty cycle as shown in Figure 2. After the Booster, a beam could be either injected into ATLAS for further acceleration using the 40-degree bend area to serve the experimental areas III and IV as shown in Figure 1, or sent straight through to experimental area II at the Booster energy. At this time, the 40-degree bend area is made of DC magnets and it is not achromatic. We propose to modify it for pulsed extraction of one of the beams to experimental area II while the second beam is injected in the ATLAS section of the linac for further acceleration. At the same time, the injection line could be made achromatic. Figure 4 shows the Booster-to-ATLAS injection line modified to be achromatic, while Figure 5 shows a pulsed achromatic chicane to be placed under the ATLAS main beam line for the extraction of one of the beams to experimental area II. The two main components of the extraction line are a 5° pulsed kicker magnet and a 15° septum magnet for a total of 20° beam deflection under the ATLAS line. The rest of the chicane is made of three 20° regular magnets. An option using a Lambertson magnet instead of the septum is being investigated.

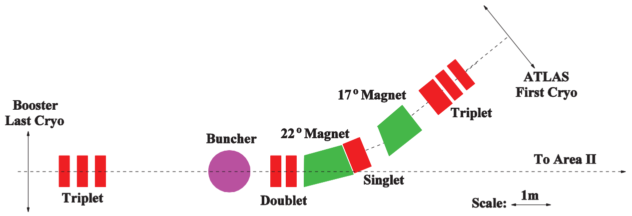

Figure 4: Top view of the 40-degree bend area modified to be achromatic for the transport of beams with different charge-to-mass ratios.

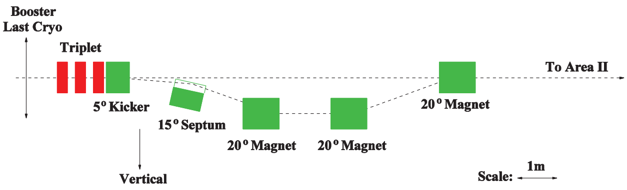

Figure 5: Side view of the vertical chicane to be placed under the ATLAS main line for the extraction of one of the beams after the Booster to send to experimental area II. The achromatic chicane is made of a kicker and a septum magnet followed by three 20° regular magnets.

EXAMPLES OF SIMULATNEOUS RADIOACTIVE AND STABLE BEAMS

Simultaneous multiple charge state acceleration was first demonstrated at ATLAS [15]. The acceptance in the charge-to-mass ratio is about 3%. Figure 6 shows an example of simultaneous two-beam injection and acceleration in ATLAS. In this case, the radioactive beam is ^{132}Sn^{27+} from the CARIBU EBIS and the stable beam is ^{48}Ca^{10+} commonly produced in an ECR source. The figure shows combined phase space plots for the two beams at different stages of injection and acceleration ending at the Booster with an energy of 5.9 MeV/u, where one of the beams will be extracted. In this case, the ^{48}Ca beam is extracted to send to experimental area II while the ^{132}Sn beam is injected for further acceleration into the ATLAS section of the linac up to an energy of 10 MeV/u for experimental area III or IV [14].

Similar examples of possible simultaneous stable and radioactive beams are listed on Table 1. The table shows that for every stable beam, multiple candidates for the radioactive beams could be accelerated simultaneously and vice versa, which adds a much needed flexibility in the scheduling of beam time. It is also important to note that by adjusting the breeding time of the EBIS, the charge state distribution of any radioactive beam could be adjusted to match the closest stable beam of interest.

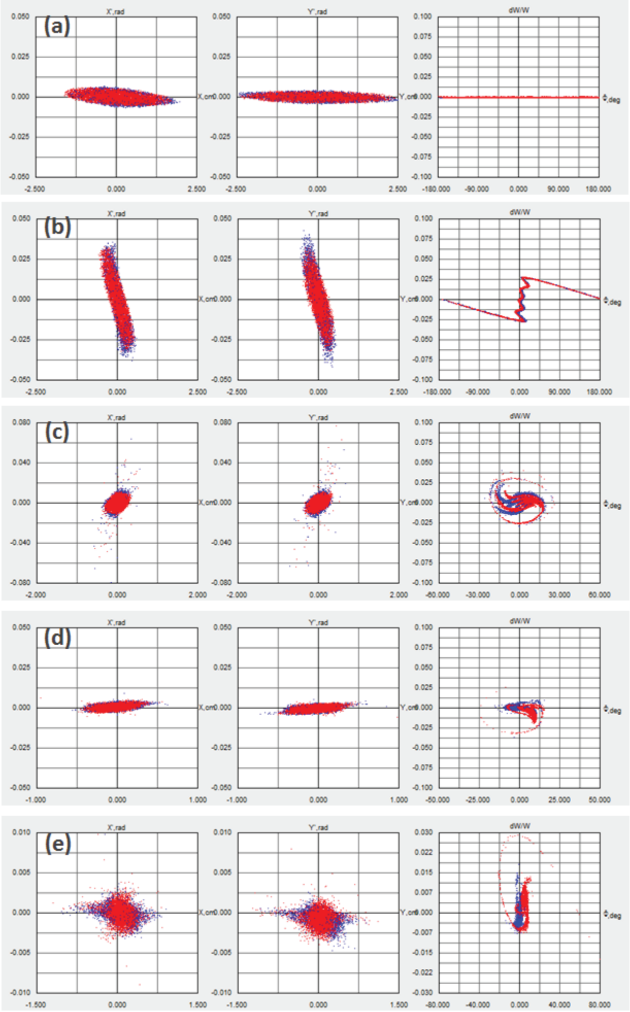

Figure 6: Phase space plots for the simultaneous injection and acceleration of the radioactive beam $^{132}Sn^{27+}$ (red) and the stable beam $^{48}Ca^{10+}$ (blue) at the LEBT (a), in front of the RFQ (b), at the RFQ exit (c), at the end of PII (d) and Booster (e).

Table 1: Examples of radioactive and stable beams that could be simultaneously accelerated in ATLAS.

q/A	Stable beams	Radioactive beams
0.25	$^{20}Ne^{5+}$, $^{28}Si^{7+}$, $^{36}Ar^{9+}$	$^{84}Se^{21+}$,$^{88}Kr^{22+}$,$^{92}Sr^{23+}$
0.24	$^{50}Ti^{12+}$	$^{101}Zr^{24+}$,$^{105}Ru^{25+}$,$^{117}Cd^{28+}$
0.23	$^{48}Ti^{11+}$,$^{56}Fe^{13+}$,$^{74}Ge^{17+}$	$^{92}Kr^{21+}$,$^{105}Nb^{24+}$,$^{109}Tc^{25+}$
0.22	$^{40}Ca^{9+}$,$^{102}Ru^{23+}$,$^{120}Sn^{27+}$	$^{89}Br^{20+}$,$^{112}Rh^{25+}$,$^{139}Xe^{31+}$
0.20	$^{40}Ar^{8+}$,$^{60}Ni^{12+}$, $^{90}Zr^{18+}$	$^{85}Se^{17+}$,$^{110}Mo^{22+}$,$^{124}In^{25+}$
0.19	$^{132}Xe^{25+}$	$^{137}I^{26+}$, $^{153}Pr^{29+}$, $^{165}Tb^{31+}$
0.17	$^{80}Se^{14+}$	$^{91}Kr^{16+}$, $^{97}Zr^{17+}$, $^{109}Ru^{19+}$
0.15	$^{180}Hf^{27+}$,$^{197}Au^{29+}$,$^{238}U^{37+}$	$^{100}Sr^{15+}$, $^{101}Y^{15+}$, $^{107}Nb^{16+}$

STAGING OF THE PROPOSED ATLAS MULTI-USER UPGRADE

The proposed ATLAS multi-user upgrade could be implemented in three stages starting with two beams at different energies and ending with three beams with more flexible output energies serving three different experiments simultaneously. The last stage would also deliver much higher intensity stable beams with the possibility of accelerating multiple charge state radioactive beams to increase their intensities. The different stages of the proposed upgrade are described below.

Stage I

This stage is essentially the one described above. It will allow the simultaneous acceleration of two beams; one radioactive from CARIBU EBIS and the other stable from the ATLAS ECR. Both beams are accelerated simultaneously up to the Booster energy. Then one of the beams is extracted to be sent to experimental area II while the second is injected for further acceleration in the ATLAS section of the linac up to the full ATLAS energy for delivery to experimental area III or IV. This first stage will require the installation of:

- The CARIBU EBIS charge breeder, which will happen independently next year.
- A pulsed electrostatic deflector to inject the EBIS and ECR beams in different time periods of the ATLAS cycle as shown in Figure 2.
- A new achromatic LEBT for the transport of beams with different charge-to-mass ratios without emittance growth.
- A pulsed switchyard after the Booster for the extraction of one beam while the second is injected into the ATLAS section of the linac. A kicker and septum magnets are required for an achromatic vertical chicane to be placed under the main ATLAS beam line to serve experimental area II.
- Eventually, a new transport line to deliver the beam extracted at the Booster to experimental areas III and IV in addition to area II.

In this first stage, it will not be possible to accelerate the two beams to the full ATLAS energy for two main reasons: first because the 40-degree bend area is not achromatic and thus not suited for multiple beam injection, and second because the ATLAS section of the linac still have split-ring resonators which can cause significant beam steering and beam loss especially when injecting beams with different charge-to-mass ratios.

Stage II

This second stage will allow the simultaneous acceleration of two beams, one radioactive and one stable, to the full energy of ATLAS. It will also allow for the acceleration of high-intensity stable beams to the full energy in the ATLAS section of the linac which was limited by the steering in the split-ring resonators. High-intensity stable beams are much needed for the production of a different class of radioactive beams using the future

Argonne Inflight Radioactive Isotope Separator (AIRIS) [16]. This stage will require:

- The modification of the 40-degree bend area to be achromatic for the transport and injection of beams with different charge-to-mass ratios.
- Replacing the three remaining split-ring resonator cryomodules with at least one new QWR module, similar to the one installed recently. Adding a second QWR module similar to the energy-upgrade cryomodule is also recommended.
- Pulsed switchyards downstream of ATLAS to send the beams to different experimental areas
- Reconfiguring and adding new shielding to accommodate higher intensity beams in ATLAS.

It is important to note, that the first 72 MHz - $\beta \sim 0.77$ QWR cryomodule replacing the split-ring resonators would produce the same beam energies available now at ATLAS while enhancing their intensity for the production of radioactive beams in AIRIS. A second 109 MHz – $\beta \sim 0.15$ QWR cryomodule similar to the energy-upgrade cryomodule [17], would boost the energy of ATLAS beams up to 20 MeV/u for the heavier ions and 30 MeV/u for the lighter ones, which would further enhance the production of radioactive beams in AIRIS from higher cross sections of several production channels [18].

Stage III

This last stage will allow the simultaneous acceleration of three beams, one radioactive and two stable, to either the Booster energy or the full ATLAS energy to serve three experimental areas simultaneously. Higher intensity stable beams will be produced in a new superconducting (SC) ECR ion source and multiple charge states of radioactive beams will be combined to at least double their intensity. This last stage will require:

- Replacing one of the existing ECRs with a new high-performance SC ECR source.
- Developing and installing a beam chopper system in the LEBT to inject two stable beams with close q/A ratios into two separate RF buckets.
- Modifying the injection for multiple-charge-state radioactive beams from CARIBU EBIS.
- Developing and installing two RF switchyards for areas II and III.
- Modifying the experimental beam lines to allow the transport of multiple-charge-state and larger emittance beams.

SUMMARY

With the CARIBU EBIS installation next year, it will be possible to simultaneously accelerate radioactive and stable beams in ATLAS. This could significantly increase the available beam time to satisfy the increasing demand from the users. The overlap in charge-to-mass ratio between stable and radioactive beams is significant and should allow for a much needed flexibility in beam scheduling.

We have presented a detailed plan to upgrade ATLAS with multi-user capabilities which could be implemented in three stages. The first stage is at low cost by adding a pulsed injection and extraction for simultaneous two- beam acceleration, which could be implemented in two years. The second stage will replace the remaining split-ring resonators with one or two QWR cryomodule and adds a pulsed switchyard after ATLAS, allowing two- beam acceleration to the full ATLAS energy. The third and last stage will install a new SC ECR for higher intensity stable beams and the simultaneous multiple-charge-state acceleration of radioactive beams. With the completion of this upgrade, three beams could be accelerated and delivered to three different experimental areas simultaneously.

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