An RF Beam Sweeper for Purifying In-Flight Produced Secondary Ion Beams at ATLAS

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Abstract

A new large-acceptance RF beam sweeper was designed, constructed and put into operation with the goal to remove the energy-degraded primary beams tails from radioactive beams (RIB) produced by in-flight transfer or charge-exchange reactions. The system makes use of the velocity difference between the RIB beam of interest and the remaining tails of the primary beam after momentum selection by a bending magnet. The time-delayed primary beam components are deflected vertically out of the beam path by the RF sweeper, significantly reducing the stable beam background. Beam purity for the in-flight radioactive ion beams as high as 96% has been achieved with this system.

Keywords: radioactive beam, in-flight production, RF sweeper, beam optics

1. Introduction and Technical Approach

The ATLAS facility^j at Argonne National Laboratory is a national user facility for low-energy nuclear physics research. Primarily, ATLAS is a ‘stable’ beam facility that provides beams of any species at energies as high as 22 MeV/u, but for the past 18 years ATLAS has also provided in-flight near-to-stability radioactive ion beams (RIB) produced by charge-exchange or few-nucleon transfer reactions. The radioactive beams are momentum analyzed by a beamline switching magnet and delivered to the experimenter’s target to study the reaction of interest.

The geometry of the ATLAS RIB production target and the subsequent beam transport system is shown in figure 1. The in-flight RIB production facility was designed for the mass range of $6 < A \leq 40$. The ion energy requested by users to date spans the range of $4 \leq E/A \leq 20$ MeV/u. This corresponds to a velocity range of $0.08 \leq \beta < 0.2$. After traversing the production target (either a gas cell with metal windows or a low-Z foil), the primary beam is energy degraded and acquires a long low-intensity energy tail from the multiple-scattering processes in the target material as well as a charge state distribution. After magnetic analysis, a portion of this energy tail will inevitably have the same magnetic rigidity as the RIB beam of interest and will be transported by the beam transport system to the experiment. For such low intensity RIB beams (10^4 to $2\text{--}3 \times 10^6$ ions/s), these tails of the primary beam can easily dominate the total delivered beam. Thus another selection criterion is needed to separate the remaining primary beam tail from the RIBs.

To better handle the large divergence and energy spread of the in-flight beam and to improve the transport efficiency, the secondary beam is first refocused immediately after production with a superconducting solenoid. The energy spread is then reduced using a superconducting RF resonator (see Figure 1) operating in a ‘debunching’ mode to rotate the longitudinal phase ellipse to a ‘parallel’ orientation and thereby minimize the energy spread. This manipulation is shown in calculations with the program TRACKⁱⁱ in figure 2.

Velocity or time-of-flight generally can provide additional discrimination for removal of the primary beam tail. Both depend on the slight velocity difference between the two beam components. There are two possible techniques for acting on this velocity difference. One is to develop a device that is sensitive to velocity such as a Wien filterⁱⁱⁱ. A Wien filter works for a DC beam as well as for bunched beams which are used at the ATLAS accelerator. The other technique, for a bunched beam, makes use of the time difference that eventually develops between the two beam components due to the velocity difference, by utilizing a transverse dependent electric field generated by a RF sweeper located downstream of the production target. This technique, well suited for the bunched beams, was chosen for our application at ATLAS instead of the Wien filter. For either to work effectively, the velocity difference between the primary beam tail and the RIB beam must be greater than the velocity distribution within each bunch.

After refocusing the RIB beam and reducing the energy spread, the beam is momentum analyzed with a typical momentum acceptance of +/- 5%. This selection around the central momentum of the RIB beam of interest removes the entire primary beam except for this small momentum acceptance window. Thus the remaining tail of the primary beam has a velocity compared to that of the RIB beam of:

$$v_T/v_R = \left(\frac{M_R}{M_T}\right)\left(\frac{Q_T}{Q_R}\right) \quad (1)$$

where v_T , M_T , and Q_T are the velocity, mass and charge of the beam tail (T subscript) and the RIB ions (R subscript), respectively.

One benefit of a Wien filter is that the position of the filter is rather flexible since no time separation between the beam components at the filter is required. The disadvantage is that to achieve a significant deflection of the unwanted components requires a rather large device and/or a very high electric field. If the beam optics and the large emittance of the beam require a significant gap between the electrodes, then the necessary plate voltage may be difficult to achieve.

A beam sweeper, on the other hand, requires a drift distance after the ion creation point to generate a time difference at the sweeper plates as well as an additional drift distance to the beam removal slits. In addition, a sine wave sweeper will create some additional transverse emittance growth due to the finite transit time through the plates and the finite beam width which experiences a time dependent deflection. Therefore it is important to keep the time width for the RIB beams as narrow as possible both to maximize the bunch time separation and to avoid creating additional transverse distortions. This is achieved by the use of two superconducting resonators in the beamline. The first resonator is used to produce a time focus on the production target thereby minimizing the longitudinal emittance growth from the reaction kinematics and straggling effects. This first rebunching resonator is located approximately 11 meters upstream of the production target, to the left and out of the view shown in Figure 1. The second resonator 'debunches' the RIB beam to reduce the energy spread created in the production target and from the kinematics of the reaction process. Both are superconducting split-ring resonators^{iv} with a matched velocity of 0.1c used throughout the ATLAS facility. This will also minimize the time width at the RF sweeper which is dominated by the beam energy spread at that point. Some example cases of in-flight RIB production that span the mass range used at ATLAS are shown in Table 1

along with relevant parameters. For the available geometry, the sweeper position was selected to be approximately 7.5 meters from the production target.

Table 1. Examples of In-flight RIB beams produced with the ATLAS In-flight facility. In the “Delta Time” column, both the time separation in nanoseconds and the RF phase difference for a 6 MHz frequency is given for the beam tail component corresponding to the charge state shown in column 2.

RIB Beam & Energy (MeV)	Reaction and RIB produced	RIB velocity (v/c)	Beam tail central velocity (v/c)	Maximum RIB beam divergence (mr)	Delta Time at Sweeper (ns/deg.) (distance =7.5m)	Plate voltage (kV)
⁶ He (80)	d(⁷ Li ²⁺ , ⁶ He ²⁺) ³ He	0.1692	0.1450	335	24.6/54°	59
¹¹ C (105)	p(¹¹ B ⁵⁺ , ¹¹ C ⁵⁺)n	0.1432	0.1193	76	34.8/76°	21
¹⁵ C (205)	d(¹⁴ C ⁶⁺ , ¹⁵ C ⁵⁺)p	0.1713	0.1675	96	3.3/7.2°	399
¹⁵ C (65)	d(¹⁴ C ⁶⁺ , ¹⁵ C ⁵⁺)p	0.0965	0.0943	93	5.8/13°	61
¹⁷ F (90)	p(¹⁷ O ⁸⁺ , ¹⁷ F ⁹⁺)n	0.1066	0.1055	48	14/32°	28
²⁵ Al (180)	p(²⁵ Mg ¹²⁺ , ²⁵ Al ¹³⁺)n	0.1243	0.1148	21	17/37°	30
³⁷ K (275)	d(³⁶ Ar ¹⁸⁺ , ³⁷ K ¹⁹⁺)n	0.1263	0.1230	39	5/11°	98

Figure 1. a) Layout of the ATLAS In-flight RIB facility showing the production region and the beamline to one of the target stations. The distance from the production target to the RF sweeper is approximately 7.5 m. b) Expanded view of the In-flight production region showing the relationship between the production gas cell, the refocusing solenoid and the de-bunching superconducting resonator.

Figure 2 Rotation of the RIB longitudinal beam emittance by the second debuncher (see Fig. 1) to minimize the beam energy spread for ¹⁷F produced by the ¹⁷O(p,n) reaction, as calculated by TRACK. The total time width is approximately ±3 ns for ~90% of the beam.

2. The RF Beam Sweeper Design

The beam from the ATLAS linac is a ‘continuous wave’ train of beam pulses with a repetition frequency of 12.125 MHz. Thus the time separation between pulses is 82.4 ns. A properly phased RF sweeper, with a vertically directed electric field, running at half the beam frequency, 6.0625 MHz, will alternately sweep beam tails out of the beam either up, or down. For beam components with enough time difference with respect to the beam of interest, the deflection will be sufficient to stop these particles on a set of slits approximately 3 meters downstream from the sweeper plates. The sweeper voltage, V , required to deflect the primary beam tail (energy U , velocity v , and charge q) by a vertical distance y , and to remove particles coming at a delta time measured in RF phase, ϕ , relative to the tuned central RIB particle is:

$$V = \left[\frac{2gUy}{lLq} \right] * \left[\frac{\frac{\omega l}{2v}}{\sin\left(\frac{\omega l}{2v}\right)} \right] / \sin\phi \quad (2)$$

for a sweeper with gap g , plate length l , sweeper frequency f , ($\omega = 2\pi f$), when the slits are at a distance 'L' meters downstream from the deflector center.

Typically for RIB beams, the bunch width at the sweeper will be around 3 - 4 ns FWHM. Thus for tail components separated in time from the RIB beam of interest by more than the bunch width it is possible to get excellent selectivity from the RF sweeper. Therefore when designing the bunching system an acceptance window for the sweeper of ~5 ns and a desired deflection at the sweeper slit of 2 cm was used in estimating the maximum voltage required.

As can be seen from Table 1, there are a few cases for which it is difficult to achieve a clean separation with the RF sweeper due to insufficient velocity differences. An example is the case of $d(^{14}\text{C}^{6+}, ^{15}\text{C}^{5+})p$ at 205 MeV where the necessary plate voltage cannot be achieved. For most other cases of interest at ATLAS, a maximum sweeper voltage of 55 kV is sufficient for a clean separation with 1 meter long sweeper plates and a 10 cm gap. These parameters were chosen as the design parameters for this project.

The sweeper plates, 1 m long by 10 cm wide and 2 mm thick, were manufactured from OFHC copper mounted on ceramic standoffs in a large vacuum vessel. The plates together with the associated resonant circuit components are mounted in a vacuum chamber shown in figure 3. The vacuum vessel has inner dimensions of 0.72 m x 1.28 m x 0.85 m. Access is provided through a removable top plate. After approximately 2 months pumping and a low-temperature bake-out, a base vacuum of approximately 2×10^{-7} Torr is routinely achieved. The completed unit is shown in figure 4 installed in the Enge spectrograph beamline at ATLAS.

Figure 3 RF sweeper deflecting plates (left) and the associated inductors forming the resonant circuit (right) in the sweeper vacuum chamber.

Figure 4 RF sweeper assembled and installed in the beamline to the ATLAS Spectrograph area. This is one of two beamlines which have been used in the in-flight RIB program at ATLAS.

3. Discussion of RF Circuit and RF Electronics

The RF circuitry of the RIB sweeper is based on a parallel resonant tank circuit which develops 55 kilovolts of deflection from one kilowatt of RF drive. To keep the RF drive power low, it is necessary to minimize the resonating capacitance and maximize the resonant Q. The dipole deflection electrode provides 42% of the total resonating capacitance. Figure 5 is a diagram of the RF tank circuit, the capacitive tuning system, and the impedance matching to the 1 kW RF drive amplifier.

A commercial Emtron DX-2SP^v 2.0 kW RF amplifier is located close to the vacuum vessel and provides sufficient power for 55 kV sweeping. Inside the vacuum vessel, the sweeper resonant frequency is controlled by a moveable capacitive vane. Proximity to the resonating inductance is controlled by a

threaded, rotatable drive shaft. The vane is attached to a precision linear potentiometer which provides position information. Vane position is set by a stepper motor located outside the vacuum vessel.

Figure 5 Schematic drawing of the RF sweeper tank circuit.

Performance of the sweeper is dependent on proper impedance matching to the RF drive amplifier. To this end, the RF coupling coil shown in Figure 5 is adjusted for minimum reflected RF power. This is accomplished by rotating the “RF coupling” control.

4. Sweeper RF Parameters

Accurate measurement of the tank circuit Q is important for calculating the sweeper deflection voltage. First, critical RF coupling must be achieved for the Q measurements. Figure 6 shows the RF tank response when the excitation frequency is varied above and below resonance. Three data points establish the Q as shown in Equation 3.

Figure 6 Resonant circuit response as a function of frequency referenced to the nominal circuit eigenfrequency.

$$Q = \frac{f_0}{f_2 - f_1} \quad (3)$$

For the beam sweeper the measured values are: $f_0 = 6.06250 \times 10^6$ HZ, $f_1 = 6.05776 \times 10^6$ HZ and $f_2 = 6.06723 \times 10^6$ HZ corresponding to a loaded Q = 640 for the RF sweeper circuit.

The deflection voltage achieved as a function of RF drive power is given by:

$$V_p = \sqrt{\frac{P Q_0}{\pi f_0 C_T}} \quad (4)$$

Where: V_p = Peak Deflection (volts), P = RF Drive (watts), f_0 = Tank Circuit Resonant Frequency (6.06250×10^6 HZ), C_T = Resonating Capacitance (2.223×10^{-11} Farad), and $Q_0 = 2Q = 1280$. Q_0 represents the unloaded value before critically coupling the RF drive.

Operational measurements yielded the data shown in Table 2. The measured peak deflection is compared to calculated values from Equation 4. Significant heat is generated during beam sweeper operation. The beam sweeper uses water cooling for tank circuit coils, deflection electrodes, and interconnections to avoid overheating these components. The resonant tank inductance is comprised of two, large nine turn coils. These are connected in series with a grounded center point, as shown in

Figures 5. Copper tubing, 3/8" diameter, is used throughout the resonant tank circuit with an internal 1/4" copper tubing inserted. This coaxial arrangement facilitates water cooling without the need for insulated hoses at high voltage points. Figure 7 shows the cooling water flow path.

Table 2. Measured vs calculated peak deflection voltage.

RF Drive (W)	Measured V_p (kV)	Calculated V_p (kV)
1000	55.0	55.0
850	46.9	50.7
750	43.9	47.6
600	40.7	42.6

The RF sweeper is controlled through the main ATLAS accelerator control system^{vi} as any other beam resonator device giving complete control of plate voltage as well as RF phase.

Figure 7. RF cooling water circuits for the RF tank circuit and plates. Note the use of an interior coaxial copper tube to create a coaxial flow for the cooling channels.

5. RF Sweeper Performance Example

A typical example of the use of the RF sweeper for cleaning in-flight RIB beams is the production of ^{37}K from the reaction $d(^{36}\text{Ar}, ^{37}\text{K})n$ at an incident primary beam energy of 360 MeV. This is the heaviest in-flight radioactive beam produced by ATLAS so far. The ^{36}Ar impinges on a 3.7 cm long D_2 gas cell with 1.9 mg/cm^2 Havar windows. The ^{37}K atoms produced emerge with an energy of $\sim 275 \text{ MeV}$ ($\beta=0.13$) and are refocused transversely with the superconducting solenoid magnet while the energy spread of the emerging beam is reduced with the superconducting split-ring resonator. The beam is then momentum selected with the beamline bending magnet and refocused with quadrupole magnets onto the final target as shown in figure 1. The resulting beam components are shown in Figure 8 (top) with the RF sweeper off. The ^{37}K portion of the beam is approximately 3% of the total beam. The energies of the different components shown in figure 8 are defined by the momentum slice acceptance of the beamline bending magnet which was set for the RIB beam of interest. Thus the energy of the primary beam tail components for the various possible charge states is given by:

$$E_p = \left[\frac{M_{RI} E_{RI}}{Q_{RI}^2} \right] * \left[\frac{Q_P^2}{M_P} \right] \quad (5)$$

where M_{RI} is the mass of the radioactive beam or the primary stable beam, M_P , and Q_x is the charge state of the corresponding species.

Figure 8(bottom) shows the remaining beam components after turning on the RF sweeper and re-optimizing the rebunching resonators to minimize the time spread of the ^{37}K beam in the RF sweeper. With this optimization, the ^{37}K now constitutes $\sim 65\%$ of the beam arriving at the final reaction target. The time separation between the $^{37}\text{K}^{19+}$ and the $^{36}\text{Ar}^{18+}$ was approximately 5 ns and the RF voltage

required for this case was 104kV. Since the maximum sweeper voltage is approximately 55kV there is not sufficient voltage to completely remove the beam tail in this case. The other charge states have lower energy and larger time differences from the ^{37}K beam and are completely removed by the sweeper. The rebunching resonators are used to reduce the energy spread of the ^{37}K and thereby reduce the time width at the sweeper plates. This effect is an important part of the optimization process. Thus the combination of the rebunching resonator and the RF sweeper is necessary to make optimal use of the sweeper.

Alternate beam pulses will be swept up, then down. Due to the finite length of the sweeper plates, and thus the time spent in the electric field, even precisely phased particles will experience some vertical offset due to the finite time in the sweeper electric field. For a finite longitudinal emittance beam, there will be both a displacement of the beam pulse center and a slight increase in the beam divergence. In the case of ^{17}F at 63 MeV that centroid shift is approximately 0.5 mm vertically compared to a beam has a half height of approximately 2 mm. Some of this deflection can be restored by shifting the sweeper phase by a small amount to bring the beam back toward the center at the final target. In this case the emittance growth is approximately 10-20% in the vertical plane. For these in-flight produced RIB beams, this small emittance growth does not cause a measureable loss of intensity at the target location.

6. Conclusion

A large acceptance RF beam sweeper has been constructed and put into operation at the ATLAS facility to remove primary beam tails from the in-flight produced secondary beams. Purities as high as 96% have been achieved on target without measurable losses of the RIB beam of interest. At this time the sweeper can only serve one target station, but plans to upgrade the in-flight facility will move the sweeper to a location where it can be used for cleanup of beams delivered to multiple experimental stations.

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Figure 8. In-flight RIB production of ^{37}K via the $d(^{36}\text{Ar}, ^{37}\text{K})n$ reaction with a 360 MeV primary ^{36}Ar beam bombarding a deuterium-filled gas cell. (top) Mixed beam at the final target without the RF sweeper. Visible is the desired $^{37}\text{K}^{19+}$ as well as tails from the $^{36}\text{Ar}^{18+, 17+, 16+}$ primary beam with energy which matches the magnetic rigidity of the desired ^{37}K . The ^{37}K ions constitute about 3% of the beam. (bottom) The distribution of particles arriving at the final target with the RF sweeper on. The percentage of the beam in the ^{37}K peak is now ~65%. The time separation at the RF sweeper plates for the $^{36}\text{Ar}^{18+}$ and the $^{37}\text{K}^{19+}$ is only 5 ns. Thus the two species are not fully separated in time and some residual primary beam in the 18+ charge state remains.

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Figure 1b

Superconducting Solenoid
(movable)

Superconducting De-buncher/
Accelerator

Gas Cell

Figure 2

Figure 4

Figure 5

Figure 6

Figure 7 Beam Sweeper Resonant Tank
Water Cooling Detail