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ECR3 COMMISSIONING AND PLANNING FOR C-14 ION BEAMS AT THE ARGONNE TANDEM LINAC ACCELERATOR SYSTEM*

R.H. Scott†, R.C. Vondrasek,
Argonne National Laboratory, Lemont, IL, USA

Abstract

The Electron Cyclotron Resonance Ion Source ECR3 has recently been commissioned at the Argonne Tandem Linac Accelerator System (ATLAS) at Argonne National Laboratory. While ECR3 can provide many of the stable ATLAS beams, its other intended purpose is the production of C-14 ion beams which were previously produced by a now-retired negative ion source. This paper will discuss the final installation and commissioning of the ion source as well as the preparations for running C-14. A stable C-13 ethylene gas was used as a surrogate to determine the expected level of N-14 contamination when running C-14 since they are inseparable at ATLAS. We were also able to confirm consumption rates and charge state efficiencies under different C-13 running conditions in order to optimize the upcoming C-14 beam production.

INTRODUCTION

The BIE100 [1] Electron Cyclotron Resonance Ion Source (ECRIS), configured with permanent magnets for both axial and radial plasma confinement, was originally conceived by Berkeley Ion Equipment [2]. After use by the Argonne National Laboratory (ANL) Physics Division for off-line research, the ECRIS and a new low energy beam transport (LEBT) section have been incorporated into the Argonne Tandem Linac Accelerator System (ATLAS) [3]. The BIE100, named chronologically as ECR3 within ATLAS, is intended to provide carbon-14 (C-14) ion beams thereby limiting radioactive contamination at ECR2. ECR3 will also lessen the burden of ECR2 which has essentially been the sole provider of stable ion beams at ATLAS since 2015.

INSTALLATION AT ATLAS

The planning, installation and commissioning schedule of ECR3, concurrent with ATLAS operation, was stretched over several years to accommodate personnel and equipment conflicts. In mid-2017 construction began. Electrical service for the area was installed. Relay racks were populated, beamline stands and a high voltage (HV) platform were placed as well (see Fig. 1). Milestones in 2018 included installation of vacuum components, safety systems, air, cooling water and electrical service to the HV platform. Early 2019 was dedicated to installation of the ECRIS onto the HV platform, interlock verifications on the vacuum, high voltage and x-ray protection systems, and the incorporation of all devices into the ATLAS control system.

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† rscott@anl.gov

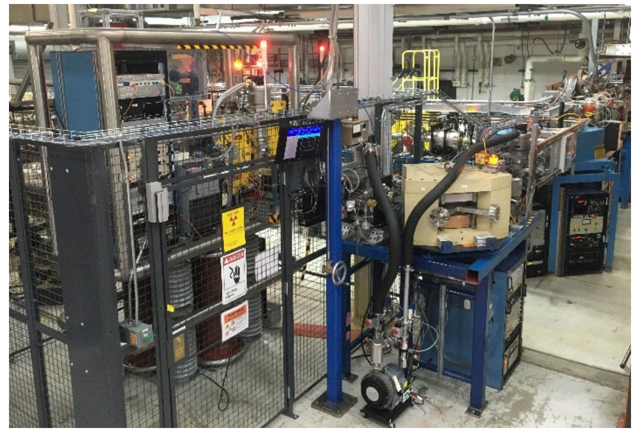

Figure 1: ECR3 ion source on platform inside fenced enclosure (left) and LEBT with m/q selecting dipole (right).

ECR3 Commissioning

Approval for ECR3 operation at ATLAS was obtained in June 2019. At this time RF conditioning was started, and beam identification and transport studies soon followed. Helium, oxygen, neon, argon and krypton production were verified. In October, the first ECR3 beam for the ATLAS experimental program, $^{14}N^{6+}$ using background gas was delivered to target. This was followed by $^{12}C^{4+}$ using methane in December. Ion beam transmission for these experiments ranged from 21% to 38% from the first faraday cup of m/q analysis to the last faraday cup before target, with room for improvement mostly in the ECR3 LEBT. For comparison, transmission from ECR2 is typically near 55% and has been as high as 64% in the last two years.

C-14 PREPARATIONS

C-14 production paused at ATLAS upon retirement of the ATLAS Tandem Van de Graaff in 2013, and the ECR3 ion source was envisioned as the subsequent producer. To eliminate radiocarbon transmission into the facility, the source and beamline pump exhaust is channeled to the CARIBU exhaust stack. Procedures have been written for use of C-14 at ECR3, and a Dual Alpha and Beta Radioactive Assay System has been moved to the adjacent work area to assist radiation protection technicians in field measurements during ion source and beamline entry.

The most stringent requirements of two currently approved ATLAS experiments are an energy of 210 MeV, target intensity of 100 pnA, and ratio of C-14 to N-14 contaminant ≥ 4:1. We have set out to verify that these requirements can be met in a way that minimizes consumption of C-14. It is planned to deliver ethylene gas (C_2H_4) saturated in C-14 supplied by ViTrax, Inc. [4] using a Varian Model 951 variable leak valve. Preliminary tests were performed with ethylene gas enriched with 99% C-13 as a substitute,

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C-12 was not used due to large m/q contaminants in $^{12}C^{3+}$ and $^{12}C^{6+}$.

Energy Verification

Achievable energy was predicted using in-house software that takes into account active accelerating components and their maximum energy gain. ATLAS is divided into three accelerating sections with stripping available after the first and second section. It was determined ≥ 210 MeV can be achieved with various accelerator configurations. The first is with ECR3 producing $^{14}C^{6+}$ and accelerating to target. The other option would be to start with charge state (C.S.) 3+ (or 4+) and strip to 6+ using a 50 μg/cm^2 carbon foil after the first accelerating section with a calculated stripping fraction of 40%. Resultant predicted energies are shown in Table 1 for the different configurations available.

Table 1: C-14 Beam Energy Calculations

Source		Stripping		Maximum
	Energy		Fraction	Energy
q	[MeV]	q		[MeV]
3+	25.7	3+	-	122.2
3+	25.7	6+	0.4	210.8
4+	27.9	4+	-	156.3
4+	27.9	6+	0.4	212.3
5+		5+	-	186.4
6+	30.6	6+	-	214.3

Intensity Verification

In Table 2, we determine source intensity requirements for 100 pnA at target assuming a minimum 20% transmission of unstripped beam from source to target and 8% transmission accounting for the additional stripping fraction. Tests were performed with C-13 ethylene gas to determine if a target intensity of 100 pnA is achievable. Maximum stable beam current for $^{13}C^{6+}$ was found to be 13 pnA with 100 W of RF input at 11.49 GHz. $^{13}C^{6+}$ output was limited by a combination of gas and RF input levels causing discharges in a downstream focusing lens. For $^{13}C^{3+}$, stable beam of greater than 7000 pnA was easily produced with 50W RF input power at the same frequency.

Table 2: C-14 Beam Intensity Calculations

Source		Transmission	Target	
q	I [pnA]	[%]	q	I [pnA]
3+	1250	8	6+	100
4+	1250	8	6+	100
6+	500	20	6+	100

From an intensity perspective, the $^{14}C^{3+}$ or $^{14}C^{4+}$stripped to $^{14}C^{6+}$ options are immediately viable. If at all possible, shifting the charge state distribution higher so that $^{14}C^{6+}$ out of the source could be used would make set-up and tuning of the accelerator simpler.

Nitrogen Contamination Levels

Given the concentration of nitrogen in air, it is not surprising an ECRIS produces some level of N-14 ion beams. These beams are inseparable from C-14 of the same charge state at ATLAS. For the upcoming ATLAS experiment a ratio of C-14:N-14 ≥ 4:1 is requested. We were able to look at C-13 and background N-14 beam intensities to determine what the expected ratio might be during a C-14 run under various conditions. The C:N ratio measured for $^{13}C^{6+}$ at 13pnA was 1:1. The ratio improved at lower RF input, with a cost to beam current. Increased RF power resulted in unstable beam dropouts, however overall 6+ output increased, while C:N ratio worsened. Helium gas mixing also improved $^{13}C^{6+}$ current, but did not favor carbon over nitrogen.

Figure 2 shows the relationship of C:N ratio to beam intensity. C:N ratios ≥4:1 were seen at beam intensities >1000 pnA for $^{13}C^{3+}$ and 500 pnA for $^{13}C^{4+}$ at the ion source. Measurements were taken for best intensity with RF input ranging from 13 to 50 W. This information confirms the argument for stripping downstream of ECR3.

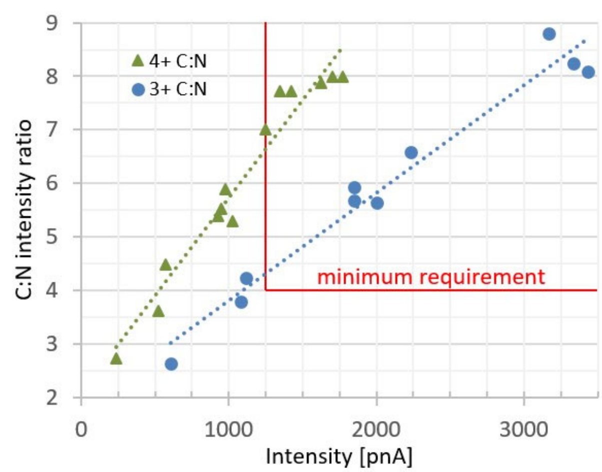

Figure 2: Ratio of C:N intensities vs. ^{13}C intensity at two different charge states (3+,4+).

One further consideration for C:N ratio is that less favorable stripping for carbon occurs than for nitrogen into the 6+ charge state. We calculate the fraction for carbon at 42.6% and nitrogen at 52.9%. This reduces C:N measured at the source by ~20% after stripping. Ratio data shown in Fig. 2 is corrected for this reduction

Ethylene gas pressure upstream of the leak valve had an effect on the C:N ratio as well. This should be noted as we intend to use a small amount of gas (25 ml at STP) that will slowly drop in pressure throughout an experiment. Figure 3 shows the beam current relationship to C:N ratio (corrected for C and N stripping efficiency differences) of $^{13}C^{4+}$ for line pressures of 0.3 atm and 2.2 atm as an example. Since the ECR charge distribution favors 3+ in the range of tested operation, we infer source intensity and C:N are also maintained for $^{13}C^{3+}$ even at low backing pressure.

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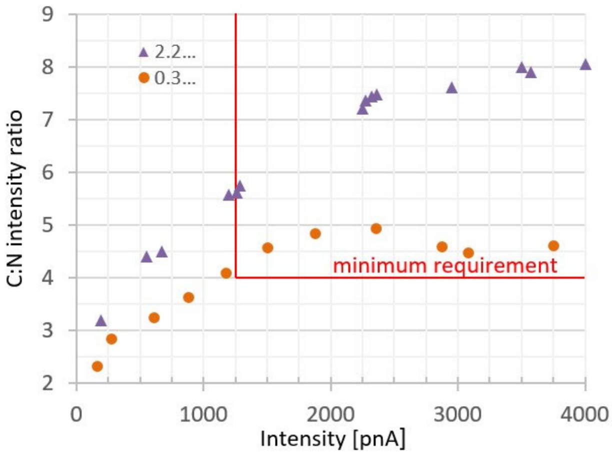

Figure 3: C:N ratio vs. $^{13}C^{4+}$ intensity with ethylene gas feed line before leak valve at 2.2 atm and 0.3 atm.

Carbon Consumption Rates

It is important to consider the consumption of C-14 on two bases. First is to limit the amount of radioactive contamination in the source, downstream beamline and exhaust. We also prefer to conserve the material as a cost savings to facility operation. A measured volume of 8.25 ml was filled with C-13 ethylene during the intensity and contamination tests. Pressure of the volume was measured before and after a test run using an Omega model DPG2001B digital pressure gauge. Ideal gas law was used to calculate number of moles at the start and end of a test run, which was then converted to mg of C-13. From there a consumption rate in mg/hour was derived.

Beam current improvements were obtained by adding ethylene gas, thereby increasing consumption rate and the C:N ratio making the three parameters interrelated. The minimum carbon consumption rate in which required $^{13}C^{3+}$ intensity and C:N ratio (corrected for stripping differences) are met is ~.04 mg/hr (see Fig. 4). This rate would yield ~30 days of continued experiment time for 25 ml of C-14 ethylene gas at STP.

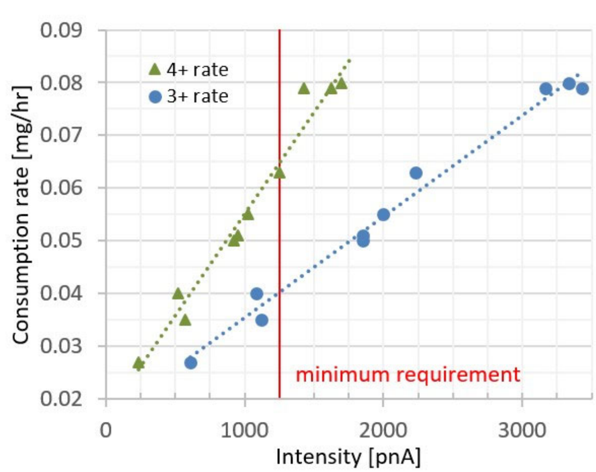

Figure 4: Consumption rate vs. intensity for C-13 3+ and 4+ with ethylene gas feed.

Ion Source Efficiency

Efficiency into a single charge state at the ion source was also examined during these test runs by dividing number of ions intercepting the m/q analysis faraday cup by the number of atoms introduced to the ECRIS over the same time period. For simplicity Table 3 shows the range of efficiencies seen over a variety of gas feed, RF power and frequency conditions used. Under any single condition, 3+ efficiency exceeded that of 4+.

Table 3: C-13 Charge State Efficiencies

q	Source Efficiency
3+	1.0% - 2.1%
4+	0.5% - 1.5%
5+	0.05% - 0.17%

CONCLUSION

An ECR ion source has been installed at the ANL ATLAS facility and will fulfill two needs: the returned production of C-14 after seven year hiatus, and added flexibility as a second ion source for the delivery of stable beams for the experimental program. The source has completed its commissioning phase and is in use at ATLAS. We plan to address the limitations involving the discharging lens with further investigation into root cause and by increasing the gap between electrode and ground. If the discharges are resolved, we can further examine production of $^{13}C^{6+}$ at the source. We are also looking at beam optics in the LEBT to see if transmission can be improved. Even with limitations to overall performance noted above, ECR3 has demonstrated the ability to produce stable C-14 ion beams at the energy, intensity and ratio of carbon to nitrogen required for approved experiments at ATLAS with 3+ out of the source stripped to 6+ downstream.

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