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Current Status of ATLAS and Proposed Expansion to an Exotic Beam Facility

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Abstract

The Argonne Tandem Linear Accelerator System (ATLAS) has been operating on a twenty-four hour, seven days a week schedule since the beginning of Fiscal Year 1994. Twenty-six different ion species ran during this period in 71 separate experiments. During the past year, there have been many projects undertaken to improve operation efficiency and upgrade various accelerator systems. There is also a new ECR ion source construction project underway. This paper covers, linac operation and new tuning techniques, the second generation ECR source construction project, the refrigerator system upgrade, an upgrade to the control system. Also described is a future expansion of ATLAS as an Exotic Beam Facility. ATLAS is a world class heavy ion accelerator with an estimated value of approximately \$80 million. A concept that would utilize ATLAS as the foundation for a facility to generate and accelerate radioactive beams is briefly discussed.

1. INTRODUCTION

ATLAS is a niobium superconducting heavy-ion accelerator at Argonne National Laboratory. It is a tool for research in nuclear physics, atomic physics, and occasionally some

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other areas of science. The accelerator is a two-fold system consisting of an injector followed by a superconducting linac. There are two injectors available, a 9 MV electrostatic accelerator with a negative-ion source (TANDEM) and a positive-ion injector (PII). PII is an ECR source on a high voltage platform coupled with a superconducting low-velocity linac. ATLAS is capable of delivering beam to three separate target areas. Figure 1 is a floor plan of ATLAS.

2. Operating History

ATLAS has been in operation, in various configurations, since 1978. The accelerator originally consisted of a 9 MV tandem and twenty-four split-ring superconducting resonators in four cryostat modules. In 1985 a section of three more cryostats, for a total of forty-two resonators, and a new target hall were added. In the summer of 1992 the PII injector consisting of 18 interdigital superconducting resonators in 3 cryostats became operational. At present, the total number of niobium superconducting resonant structures on-line is sixty-four.

In the beginning of fiscal year (FY) 1994, ATLAS started a 24 hour, seven days a week schedule. The goal of this change was to increase the amount of beam time available for research. This was accomplished in two ways: first, by having more staffed hours per week, and secondly, by not turning the machine off on the weekends. Not shutting down for the weekends is beneficial in several respects:

1. The operating efficiency was improved.
2. There was a reduction in down-time caused by electronic failures.
3. The start-up time previously required on Monday mornings was eliminated.

Table 1 shows statistics for operating hours for FY 1994 and for the first 10 months of FY 1995.

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3. Machine Development

There have been some significant developments in the area of beam production at ATLAS. In the ECR source, direct plasma sputtering was observed during laser ablation studies¹. The sputter method involves placing a negatively biased solid sample just outside the ECR plasma. Plasma ions, supplied by the support gas, accelerate toward the sample, impact upon its surface, and sputter solid material into the plasma. This technique proved to be very valuable in a ^{48}Ca run. Using the ECR sputter method, a 20% enriched sample of ^{48}Ca was used to deliver 1-2 pA on target, with a source target consumption rate of 100 $\mu\text{gm/hr}$. A second significant ion beam development involved the negative ion source and the Tandem accelerator. The measurement of the $^{18}\text{F}(\text{p},\alpha)^{15}\text{O}$ reaction was carried out with a ^{18}F beam of a few pA at ATLAS². Because of the relatively long half-life of ^{18}F ($T_{1/2} = 100 \text{ min.}$) it was possible to use a two-step procedure for the beam production. ^{18}F is generated at the medical cyclotron of the University of Wisconsin. Chemical processing was done at the University, details of which will be published later³. The end product is a copper cathode with ^{18}F ready for insertion into a National Electrostatics Corp. SNICS ion source. The cathode is transported by air to Argonne National Laboratory and installed into the source. With an activity at the end of the chemical process of 530 mCi, the experiment starting activity, after 2 hours (transportation time), was 250 mCi, corresponding to a total number of ^{18}F atoms of 8.8×10^{13} . Figure 2 displays the results of this experiment.

In FY 1994 there was a total of 71 separate experiments run with a total of 26 different ion species. Similarly, as of August FY 1995, there were 48 separate experiments run with a total of 25 different ion species. Because of the number of different experiments, which require separate accelerator tunes, and because of the fact that the charge to mass ratios vary widely, a new tuning technique is being developed. A library of tunes is kept. When beams are tuned with the same q/m as a previous run, the appropriate archived tune table is loaded into the

accelerator tables. When there is not an exact match however, the most similar tune is loaded, then the resonator field levels are scaled to match the velocity profile of a previous tune with a slightly different q/m . There was a technical challenge with this technique. Due to the physical layout of ATLAS the three accelerator sections are in three different rooms. We found that because of small differences in the time-of-arrival (TOA) at the entrance of each accelerating section, the correct velocity profile through a given section was not properly preserved. To fix this problem a TOA phase monitor was installed.⁴ Along with the TOA, a modification to the Master Oscillator System was made. The Master Oscillator modification gives each section of the accelerator an its own phase shifter that changes the phase of all resonators in that section independently of the other sections. The new tuning method records the TOA phase of the archived tune and then matches that phase, using the independent phase shifter, for the new scaled tune. The hardware required is installed in all three sections but at the present time, the electronics necessary to read the phase is only installed in the PII section. The use of this method in PII has worked exceedingly well and the translation to the other parts of the machine is expected to work as well.

Figures 3 & 4 demonstrates the number of different ion species and the percentage of time each species was run. It is clear from these charts that most demand is for beams heavier than mass 58.

3. Linac Performance

The resonator performance necessary to achieve so many hours of beam on target must be very reliable. Resonator levels are set conservatively so as not to cause unacceptable down time. Therefore, the operating levels given below are not the maximum achievable fields, but rather the daily operating levels. For the PII interdigital structures the average accelerating field level is 3.65 MV/m. For the low beta (0.06c) structure the average accelerating field level is 3.20 MV/m, the high beta (0.1c) structures the average is 2.90MV/m. Given the above

accelerating fields, for an optimum velocity particle, the total linac voltage is 42.3 MV. Figure 3 shows a graph of ion mass verses beam energies typically available at ATLAS. The ATLAS accelerator has excellent beam quality. Typical longitudinal emittances of 10-20p keV-nsec permits beam timing resolution in the 100 psec range simultaneously with energy resolution of $\delta E/E < 10^{-3}$. ATLAS can presently accelerate ions of charge state $q/m > 0.15$.

4. New ECR Source Construction

ATLAS supports research programs in many areas of nuclear physics. The user demand has increased considerably since the completion of PII with its capability for delivering high quality beams from the entire periodic table. Many of the programs at ATLAS would benefit greatly from the capabilities that will be made possible with the addition of a second generation ECR ion source. Such an ion source is now the highest priority accelerator improvement project at ATLAS.

The second ECR source is a collaborative project between Argonne National Laboratory and Lawrence Berkeley Laboratory. The source is an evolutionary design based on the highly successful 14 Ghz Advanced ECR ion source^{5,6} now in operation at the LBL 88 inch Cyclotron Laboratory. Some improvements include enhancements in the solenoid and hexapole magnetic fields. These changes were made because of the recent understanding that a high mirror-ratio solenoid field design and a strong hexapole field are important parameters in the performance of high-charge state ECR ion sources. The new source will also possess an all aluminum hexapole housing and other components to make use of the large secondary electron yield from aluminum oxide.

With the present ECR ion source, the charge state distribution is such that it is necessary to strip heavy beams, such as uranium and lead, to reach 6 MeV per nucleon with the ATLAS linac. Existing second generation ECR sources are producing analyzed currents of 1.5 - 2 euA of 34+ bismuth and lead ions. Figure 6 compares the charge state distribution, for

uranium, achieved with the LBL AERC ion source verses the first generation PII ECR ion source. With such high charge states available from the new source, even the heaviest beams, such as uranium, can be accelerated to energies above the Coulomb barrier without subsequent stripping. This new capability will result in three important benefits. Both beam emittance and stability would be improved, beam intensity delivered on target will be increased, and the beam intensity will not be dependent on stripper foil lifetime.

All phases of construction on the new ECR source project are moving along at a good pace. The new building is expected to be occupied by November 1995. Figure 7 shows the status of the construction on August 22, 1995. The source design is complete, and construction of the source components is approximately 70% complete. Initial source operation is scheduled for the late spring of 1996. The new source is expected to be used with ATLAS in 1997.

5. Refrigerator Improvements

The majority of the 693 hours of scheduled down time this year was for the installation of two wet engine expanders on the helium refrigeration system. The wet engines were added to the output of two, model 2800 CTI refrigerators, replacing the Joule-Thomson valves. The goal of this upgrade was to increase the refrigerator efficiency and capacity. Before the installation of the wet engines, the ratio of the power input (300 kW) to the cooling power output (300 W) was 1000 Watts/Watt. Preliminary measurements made after the installation indicate an improvement of that ratio depending on the quantity of compressed helium gas delivered to the refrigerator (power input). After the upgrade, the ratio was measure to be 822 Watts/Watt. However, with a lower power input of 250 kW, the resulting power ratio is 718 Watts/Watt. There are still more ways to improve these figures. Further improvement to the refrigerator efficiency will be investigated. Figure 8 shows one of the two wet engines.

6. Control System Upgrades

The ATLAS control system is presently in the third and final phase of a major upgrade project. Before the start of the computer upgrade project, the control and monitoring of the accelerator was accomplished with three DEC PDP-11 computer systems. The operating system for the PDP-11 was RSX-11. All the software was written in-house, and subsequently had to be supported by only a single in-house staff member. A CAMAC serial highway subsystem was used as the primary interface between the computer systems and the various accelerator components. Control of the accelerator was from the control room, although the operator interfaces included a variety of touch screens, monitors, terminals, knobs, keypads, and switches that were geographically removed from each other. Having a spread out variety of controls proved to be very cumbersome and confusing.

The upgrade will replace all the PDP-11 computers with a DEC MicroVAX using the VMS operating system. Graphic workstations are provided, which are capable of using the "X" windowing system as an operator interface. Control and monitoring, from various locations throughout the machine, are accomplished using "X" terminals, or PCs used as "X" terminal emulators. Figure 9 shows a PC terminal emulator at the entrance of the PII linac.

All the systems are linked by Ethernet into a local area network configuration. The new system uses a commercial software package marketed under the name "Vsystem" by Vista Control Systems, Inc. Due to a large investment in CAMAC components the CAMAC I/O subsystem has been retained.

The process of removing tasks from the PDP-11s and replacing them with the VAX control system has been done mostly while the machine is in operation. Many painful steps had to be taken to insure that the operation of the machine was not compromised. Indeed, some of the processes have proved to be very difficult to remove from the last remaining PDP-11. So the few remaining tasks are being worked on, and soon the final phase will be complete. When

this is done, the MicroVAX will be replaced by a machine using the latest RISC technology, thus completing all the goals of the upgrade project.

As a result of this upgrade, virtually all operator interface with the accelerator is accomplished from two workstations in the control room. Figure 10 shows the two workstations and the multiple screen capabilities.

7. Exotic Beam Facility

There is much enthusiasm in the nuclear physics community for the opportunity to study reactions and spectroscopy using radioactive beams. These opportunities could be provided by an advanced, high intensity accelerated radioactive beam facility based on the isotope-separator on-line (ISOL) method. There are recent reports on this subject from both North American and European study groups^{7,8}. Since ATLAS is an ideal post-accelerator for beams of all nuclei, a group of ANL Physics Division staff and ATLAS outside users have discussed the research possibilities with radioactive beams and prepared a working paper entitled 'Concepts for an Advanced Exotic Beam Facility Based on ATLAS'.⁹

A schematic layout of a possible facility is shown in Figure 11. The existing ATLAS accelerator and experimental facilities are in the lower part of the figure, and the proposed addition for an Exotic Beam Laboratory is in the upper part. In this new facility, radionuclides are produced by irradiating targets with light ion beams from a normally-conducting drift tube linac. The present plan is for the primary linac and production targets to be located below grade level to assist shielding prompt neutron radiation. Using standard ISOL target ion source techniques the radionuclides are extracted and ionized, mass separated, and then sent either directly to an experimental area for research with ion or atom traps, or sent to a low-charge-state superconducting linac¹⁰ to be accelerated for injection into ATLAS.

Production Methods

The basic concept is to use a conventional drift-tube driver linac with 100 kW beam power available for a variety of light ions as indicated in Figure 12. Also in this figure are specifications for the linac. The driver linac would have a fixed velocity profile, but can accommodate beams of several different ions and charge states and could provide up to 215 MV to acceleration. Fully stripped ions with a $q/m = 1/2$, such as ^2H , ^4He , and ^{12}C will be accelerated to 100 MeV per nucleon. Protons at 100 MeV per nucleon and 300 MeV ^3He will also be available. With the method of using deuterons to make neutrons, target heating problems are alleviated for production of neutron-rich radioactive nuclei. Also with this method only a modest linac of 200 MV is required as compared to the 1 GeV proton machine required in several other recent proposals. The driver linac can be used for several other ion species to provide good yields of a wide variety of unstable nuclei. A 30 MV RFQ/Linac injector for $q/m = 1/6$ permits the pre-acceleration of heavier beams. These heavy ions will be accelerated through an injector as $^{18}\text{O}^{3+}$ or $^{36}\text{Ar}^{6+}$, stripped at 5 MeV per nucleon to $^{18}\text{O}^{8+}$ and $^{36}\text{Ar}^{16+}$ respectively; then they will be accelerated to 100 MeV per nucleon in the 215 MV driver linac. As for the sources, light ions will be available, in the required intensities, from a conventional multicusp ion source. The heavier ions will require an ECR ion source optimized for very high currents at relatively low charge states. The specifications of this driver linac and its injectors closely match the capabilities of a commercial supplier, AccSys Technology, Inc. in Pleasanton, California.

Production Targets and Ion Sources

Since the production linac described above can deliver up to 100 kW of a variety of light heavy-ion beams, the production targets will have to be designed to deal with very high power densities. This is a problem of concern to a number of radioactive beam facilities concepts currently under consideration at various laboratories worldwide. One effective solution to this problem is to decouple the heat dissipation issue from that of nuclide production and release to

the ion source. This can be accomplished by stopping a deuteron beam in a rotating uranium wheel to produce an intense flux of secondary neutrons to irradiate a second target located behind the wheel. This is just one proposed method. Continued R & D on high power targets and associated ion sources is important for advanced radioactive beam facilities worldwide.

The production method described in above has been investigated for this facility. Quantitative yields from such a geometry were measured recently by an ANL/MSU (Michigan State University) collaboration using low intensity, 200 MeV deuteron beam at the NSCL. Yields of a variety of short-lived fission products, including ^{132}Sn , were determined. Figure 13 shows the results of this study. Scaling the measured yields to a 0.5 mA deuteron beam and a 100 g/cm² secondary uranium target gives 10^{13} ^{132}Sn /sec produced in the ion source/target system.

Secondary Beam Accelerator

The secondary beam accelerator is based on the existing ATLAS superconducting linac. This technology can accelerate ions from protons through uranium to the energy range from 6 to 15 MeV per nucleon. For an exotic beam facility, a new 30 MV injector section would be needed to accelerate low charge state (typically 1⁺) ions to the energies necessary for stripping to the higher charge states required by the existing ATLAS. The technical challenge in developing the low charge state injector is maintaining excellent beam quality in both longitudinal and transverse phase space.

Figure 14 is a block diagram showing the elements of a possible low-charge state injector linac. The first section of the secondary-beam accelerator consists of a 12 Mhz normal-conducting RFQ operating on a high-voltage platform. With the ion source at 100 kV and a 300 kV platform, mass 132 ions, for example, enter the RFQ at a velocity of 0.002c. Prebunching with a gridded-gap 4 harmonic buncher is done on the platform. With 1 MV of energy gain in the RFQ and deceleration from the platform, the ions are at velocity 0.004c. This velocity is matched for acceleration by the 24 Mhz linac that follows.

The second accelerating component is a short linac section covering the velocity range from $0.004c$ to $0.008c$. To cover this lower velocity regime with superconducting structures requires a small extension of currently working components. One design being studied is a folded coaxial line structure operating at 24 Mhz. Such a structure should have mechanical and frequency stability comparable to our present 48 Mhz structures that are operating reliably.

The third section, which constitutes 90% of the new injector, is a 30 MV, $q/m > 1/70$ superconducting linac. This section is based totally on existing 4-gap superconducting RF structures in operation on the PII injector at ATLAS. Using this technology, the exceptional beam quality available at ATLAS will also be obtained from this new injector. Because of the unique modularity of superconducting structures, the machine velocity profile can be easily changed. The present PII design must be upgraded. Because the beams in this section have 6 times lower q/m than in PII, but cover the same velocity range, the 8 Tesla superconducting solenoids that are used in PII cannot be used here. For good transverse acceptance, they must be replaced with a stronger focusing element. A preliminary design of a small, high-gradient superconducting quadrupole triplet is complete and a prototype is being constructed. The design goal for this quadrupole is 350 T/m over a 3cm diameter bore. The same quadrupoles would be used in the 24 Mhz section described above.

Performance

A worksheet based on measured/scaled yields from the ANL/MSU collaboration is presented in Figure 15 . It studies the case of ^{132}Sn from the production target and details the expected efficiencies of various ionization, bunching, acceleration, and stripping stages of the ISOL and secondary beam accelerator to estimate the beam intensities to be expected at the proposed facility.

8. Conclusion

The performance and reliability of ATLAS have been enhanced over the past several years as shown in recent operational statistics. A further enhancement will be realized with the addition of a second ECR ion source, scheduled for operation in 1997.

ATLAS can provide a cost-effective starting point for the construction of an Exotic Beam Facility that can satisfy nearly all the specifications of the benchmark facility discussed in the white paper by the North American Steering Committee for an Isospin Laboratory. We are actively developing the technology required for such a facility.

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Figure 1. A floor plan of the ATLAS facility.

Figure 2. Results of a measurement on the $^{18}\text{F}(p, \alpha)^{15}\text{O}$ reaction carried out with a radioactive ^{18}F beam produced at the ATLAS facility.

Beams at ATLAS for Fiscal Year 1994

Figure 3

Beams at ATLAS for Fiscal Year 1995

Figure 4

	Fiscal Year 1994	Fiscal Year 1995 *
Total Staffed Hours	7757.62	6015.58
Total Research Hours	5276.60	3993.67
New Experiment Start-up Time	1273.82	865.64
Scheduled Down Time	687.69	693.40
Unscheduled Down Time	519.91	462.87

Fiscal Year starts October 1

* These hours are valid through August 1995. (a 10 month period)

Table 1

Figure 5. Typical beam energy and intensity presently available at ATLAS.

Figure 6. A comparison of the LBL ACER Source and the first generation ANL ECR source for uranium.

Figure 7. Construction of the new ECR ion source building as of August 1995.

Figure 8. One of the two wet engines installed in 1995.

Figure 9. A remote PC terminal emulator at the entrance of PII.

Figure 10. Two new workstations in the ATLAS control room.

Argonne Exotic Beam Laboratory

Fig. 11. A layout of the conceived Exotic Beam Laboratory. The lower section shows the existing ATLAS facility.

Heavy Ion Production Linac

Concept for exotic isotope production

Parameters of the Production Linac

Max Output Beam Energy:	100 MeV per nucleon
Max Output Beam Power:	100 kW
Typical Light Ions (multicusp ion source):	^1H , ^2H , ^4He
Typical Heavy Ions (pulsed ECR ion source):	$^{12}\text{C}^{2+,6+}$, $^{16,18}\text{O}^{3+,8+}$, $^{20,22}\text{Ne}^{4+,10+}$, $^{36}\text{Ar}^{6+,16+}$
Typical Max. Light Ion Currents @ 100 kW:	^1H , 1000 μA ; ^2H , 500 μA ; ^4He , 250 μA
Typical Max. Heavy Ion Currents @ 100 kW:	$^{18}\text{O}^{8+}$, 55 μA ; $^{36}\text{Ar}^{16+}$, 28 μA
Typical Heavy Ion Source/Stripping Limits:	$^{18}\text{O}^{8+}$, 20 μA ; $^{36}\text{Ar}^{16+}$, 3 μA

Linac Specifications:

Injector RFQ/Linac	5 MeV/u output @ $q/m = 1/6$, (30 MV)
Main Linac	100 MeV/u output @ $q/m = 8/18$, (215 MV)
Duty Cycle	2% @ 120 Hz
Input Power	1 MW
Output Energy Variability	15% increments
Controls	Pulse-pulse ion source and energy variation possible

Figure 12. Conceptual layout of the Production Linac, its ion sources and injector, and a simplified target cell. General specifications, typical beams and currents, and some linac parameters are listed under the figure.

Experiment at MSU

Off-line Gamma-spectra

Figure 13. Portions of off-line gamma-ray spectra of a thin ^{238}U disc irradiated with neutrons produced from a 200 MeV d beam stopping in a 2.5 cm thick U piece. The spectra were measured with a 100% Ge detector and the time intervals were chosen to maximize the yields of ^{132}Sn , which has a 40 s half-life.

Figure 14. Block diagram showing the elements of the low-charge-state injector linac. 1^+ ions at 100 kV are accelerated to energies of 1.2 MeV per nucleon before entering the existing ATLAS heavy-ion accelerator system. The positions of the two stripping stages are indicated. Ions with mass less than ~ 70 do not require the first stripping.

Worksheet for the Secondary Beam Accelerator for the Argonne Exotic Beam Laboratory										
Driver Accelerator:			200 MV Linac, q/m=0.5, 100 kW beam power, 120 Hz							
Radioactive Beam Accelerator:			¹³² Sn Example				A= 132			
Voltage				Accel.						
gain	q	T/A	velocity	length	efficiency	efficiency	intensity	intensity	Device:	Comments:
(MV)		(MeV/A)	(v/c)	(m)	(this step)	(cumulat.)	(ions/sec)	(part. na)		
							1.0E+13		primary production rate	100 g/cm ² UC target
0.1	1	0.0008	0.0013		0.03	0.030	3.0E+11	50.0	ion source & release	4π mm-mr
					0.80	0.024	2.4E+11	40.0	isobar separation	resolution ~30,000.
0.3	1	0.003	0.003	1.0	1.00	0.024	2.4E+11	40.0	onto HV platform	
					0.65	0.016	1.6E+11	26.0	prebunch/rebunch	
1.0	1	0.011	0.005	2.0	0.95	0.015	1.5E+11	24.7	RFQ on HV platform	12 MHz RFQ
-0.3	1	0.008	0.004	1.0	1.00	0.015	1.5E+11	24.7	leave HV platform	
0.0	2	0.008	0.004		0.40	0.006	5.9E+10	9.9	strip and rebunch	Gas stripper
2.0	2	0.039	0.009	2.0	0.95	0.006	5.6E+10	9.4	24 MHz linac	SC folded resonator
30.0	2	0.493	0.033	15.0	0.95	0.005	5.4E+10	8.9	48 MHz linac	PII-type, 4 gap
	20	0.493	0.033	1.0	0.20	0.0011	1.1E+10	1.8	strip to q/m=0.15	Foil stripper
	20	0.493	0.033	2.0	1.00	0.0011	1.1E+10	1.8	rebunch	
4.0	20	1.099	0.049	3.0	0.95	0.0010	1.0E+10	1.7	72 MHz matching linac	PII-type, 4-gap
40.0	20	7.160	0.123	25.0	0.90	0.0009	9.1E+09	1.5	out of ATLAS	existing accelerator

Fig. 15. Worksheet illustrating a scenario for post-acceleration of ¹³²Sn.