ATLAS Beam Properties: Some Implications for Target Making

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Abstract

The expansion of the tandem-linac booster into the Argonne Tandem-Linac Accelerator System, ATLAS, is approximately 40% complete. When completed, the facility will provide beams of heavy ions from lithium to tin with energies eventually, to 25 MeV/amu. The existing facility continues to provide beams for the experimental program in nuclear and atomic physics during the construction phase. The booster system is capable of accelerating ions as heavy as selenium to energies of 10 MeV/amu for the lighter ions.

The good beam quality provided by the linac means that multiple scattering, energy straggling, and target inhomogeneities are major factors in the resolution attainable in experiments. The beam properties that can be expected from ATLAS will be discussed and the present state of high resolution experiments will be reported.

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In this talk I would like to first describe the heavy ion tandem-linac accelerator that will soon become known as ATLAS. Then I will discuss some of the areas that target making is critical for the proper functioning of this accelerator. Finally, I will discuss some results that we've had with the accelerator in terms of attempting to make use of the rather unique beam properties possessed by this accelerator.

The accelerator that is in existence today first accelerated a beam in 1977. Since its birth, it has grown, like any baby, at a rather rapid pace starting out with only a couple of resonators and then expanding on to four, ten, twelve, finally to the present configuration of twenty-four accelerating resonators. In addition to the superconducting linear accelerator, the complete accelerator consists of an inverted sputter ion source, a three-element bunching system that produces beam pulses of approximately 100 ps into the linac, and a Tandem Van de Graaff that operates in a linac injection mode with a terminal voltage of 8.5 megavolts. The linac operates today with eleven "low beta" resonators which provide optimum acceleration to particles that have a velocity of .06c - the "matched velocity". Following those eleven, are thirteen additional "high beta" resonators that have a matched velocity of 0.1c.

The ATLAS expansion of this system consists of an additional eighteen resonators in three cryostats, a new building housing the expanded linac and a much larger experimental hall, and some other items such as a new, high voltage ion source. The new resonators will consist of twelve additional high beta (0.1c) resonators and six resonators of a new class. This new class of resonators, known as "super high beta", will have a matched velocity of 0.16c. The ability of this machine to make optimal use of the accelerating fields for heavy ion acceleration is the fact that the phase of each resonator
is independently adjustable. This feature allows a variable velocity profile through the accelerator as opposed to facilities of a more conventional design, such as the Berkeley HILAC, which has a fixed velocity profile and therefore fixed maximum energy per nucleon.

Figure 1 shows the superconducting split ring resonator. The resonator housing is of a composite material of niobium, the superconductor, on the interior which has been explosively bonded to a copper outer skin. Copper provides cooling of the housing by thermal conduction to the base where the liquid helium system is attached. The loading arm and drift tube assembly for the resonator consists of pure niobium. The loading arm and drift tubes are hollow. Liquid helium flows into the base of the loading arms and serially through each drift tube providing the cooling which maintains the resonator temperature near the liquid helium boiling point of 4.5°K. The on-line effective accelerating fields achieved are generally 2.5 to 3 MV/m. Accelerating fields in off-line tests of over 8 MV/m have been achieved. The resonators and superconducting solenoids are mounted on a skeletal "ladder" assembly which provides structural support as well as a pathway for the helium cooling and mounted into cryostats shown in Figure 2. Pairs of these independently phased resonators are separated by superconducting solenoids which provide the transverse focusing properties of the accelerator.

The overall floorplan of the facility is shown in Figure 3. The existing facility is shown in white background and the ATLAS construction area is shown in cross hatched area. The building which is nearing completion, will provide a second large experimental hall and a new data acquisition room.

In addition to one of the first successful applications of superconductivity for acceleration, another feature that is somewhat unique to this accelerator is its computer control system. The linac is completely
under the control of a PDP-11/34. An example of the level of automation that
the computer control system provides is the tuning of the linac for a new
beam. Since these resonators are independently phased, one has to determine
the proper operating phase angles. The procedure for measuring the maximum
energy gain of each resonator and determining the proper operating phase angle
of each resonator is completely automated. This task would take many hours
without the use of a computer-control system but is generally accomplished in
one to two hours at present. Once tuned, those results are stored. These
parameters can be recalled and the linac can be set to the old values in just
a few seconds. Once the linac has been tuned, the experimenter, to a large
degree, takes over the operation of the accelerator. The computer allows the
experimenters to change energies by just requesting the desired energy. If a
resonator deconditions and can no longer operate at a previous setting, the
computer will calculate the new parameters for the accelerator with that
resonator operating at a new level and set the accelerator to those values.
As ATLAS becomes operational, the list of automatic and computer controlled
functions will greatly expand.

The beams that have been accelerated at the Tandem-Linac during the
past year is shown in Figure 4. Lithium is the lightest ion that we
accelerate, mostly due to the problems of radiation shielding for light
ions. Also ions such as helium are not at all well suited for acceleration
because the velocities are too high to efficiently match to our resonators.
Heavy ions which can presently be provided for the experimental programs cover
the periodic table from lithium to selenium. Beam energies available range
from about 11 MeV/amu for $^{12}\text{C}$ and $^{16}\text{O}$ down to about 7.5 MeV/amu for $^{58}\text{Ni}$.
When ATLAS is fully operational, heavy ions through tin will be provided.
An important design requirement for ATLAS was that this accelerator should provide tandem-like beam properties. The accelerator should provide good energy resolution, good phase space, and easy energy variability as well as a wide selection of heavy ions at the design energies. In order to achieve these properties using a linear accelerator, the injected beam must be bunched to a time width which is a small fraction of the total RF period. For ATLAS, this requires that the beam must be bunched to approximately 100 ps FWHM prior to injection into the linac. This is accomplished with a 3-stage bunching system which consists of a pre-tandem harmonic buncher, an rf beam chopper, and a superconducting resonator buncher. The beam is bunched at 48.5 Mhz yielding a pulse period of 20.6 nanoseconds. We are presently developing a new bunching system that will continue to allow operation at 20.6 ns but will provide pulse periods of 82.4 ns with only a small degradation in bunching efficiency. The longitudinal emittance of the beam, that is the beam's energy spread times the time spread, for oxygen is 20 keV-ns and for nickel is approximately 40 keV-ns. The transverse emittance for this beam is approximately $19\pi$ mm-mrad. This transverse emittance allows possible spot sizes on target of approximately 2 millimeters diameter.

For bunched beams, the time resolution and the energy resolution are coupled in such a way that the two dimensional area of $\Delta E \Delta t$ must be conserved. It is possible, using a separate superconducting resonator, to manipulate the phase space of the beam in order to achieve either the best energy resolution or the best timing resolution for a particular situation. We have conducted a number of tests to measure the performance of the rebuncher/debuncher in achieving either good timing or good energy resolution on target. The results of the tests are indicated in Table I. These results are obtained in elastic scattering on gold at forward angles. The timing
results are consistent with the geometry of our experimental area and the assumed phase space of the beam from the linac. In energy resolution tests using the Enge split-pole spectrograph, we have obtained energy resolution for 107 MeV $^{12}$C of 150 keV in elastic scattering experiments.

Heavy-ion accelerators such as ATLAS have requirements which involve the art of target makers in at least three areas. First the beam currents and variety of isotopes being requested by experimenters place a high premium on the performance of the ion source used. A very important aspect of beam development is understanding the optimum chemical form for a particular element and any special preparation techniques which can enhance beam currents from the source. We have found that target purity and surface preparation can be critical for certain elements in determining source output. The proper technique of hydrogen loading for certain elements, such as calcium and titanium, in order to optimize the yield of the negative hydride of these elements has been shown to be critical for acceptable beams. Finally, the use of expensive isotopic materials means that one wants to be very efficient in their usage. All of these issues involving the ion source can benefit from the expertise of a trained target maker.

The next area that is most critical is the charge changing carbon stripper foils employed by the tandem preaccelerator and at other locations in the linac. The most critical stripper foil location is the terminal of the tandem because that is the one that intercepts the beam at very low velocity and therefore produces large multiple scattering and beam straggling as well as the shortest lifetime. The requirements placed on these foils are first long lifetimes and, second, good thickness uniformity. For heavy ions, the foil lifetime is largely limited by the decrease in transmission through the accelerator due to increasing foil thickness and degradation in foil
uniformity. For ATLAS, the above properties are needed for very thin foils whose thickness is generally 2-5 \( \mu g/cm^2 \).

The tandem stripper foils in normal use at Argonne are 2 \( \mu g/cm^2 \) thick carbon arc evaporated foils. These foils are mounted on a foil holder that is then reduced in diameter to produce a slackening of the foil. We find that slackening gives approximately an order of magnitude increase in the foil lifetime. The lifetime that we currently experience for nickel is of the order of 8 pna-hours on target. This corresponds to approximately 40 pna-hours of beam on the foil because of beam attenuation due to double stripping and other transmission losses.

Other carbon foil production methods have been tried including the ethylene cracked glow discharge methods. Although a number of these methods seem to provide improved lifetimes when compared to arc evaporated foils when the foil thickness is 10-15 \( \mu g/cm^2 \), for foil thickness in the 2-5 \( \mu g/cm^2 \) range, no method seems superior to the arc evaporated foil. In fact, all seem to produce about the same foil lifetimes for these very thin foils.

The energy loss of heavy ions in the energy range of 2-25 MeV/AMU is large compared to the desired experimental energy resolution. The energy-loss straggling of heavy ions in these targets soon becomes a significant problem and can dominate the energy spread in the beam for these heavy ions. This effect is shown in Table II where the best possible resolution is given assuming only the intrinsic beam energy spread and energy-loss straggling contribute to the resolution. For light ions such as oxygen, the beam energy spread is the dominant effect, but for nickel and heavier ions the energy loss straggling dominates. Therefore thin, uniform targets must be used when high resolution is demanded.
In order to approach the resolution indicated in Table II targets must be highly uniform. Nonuniformity of targets is an effect which adds linearly to the resolution quoted in Table II. A 250 µgm/cm² gold target which is uniform to ±10% over the beam region would have an expected resolution of 770 keV for nickel ions at 400 MeV and nearly 2 MeV for tin ions at 1000 MeV. The target must not only be produced with a high degree of uniformity but must be resistant to beam induced non-uniformity and changes in total thickness over the course of the data acquisition. These stringent requirements have caused an increase in efforts to develop gas targets of various types and present a real challenge to the maker of solid targets in an effort to reduce the effects of non-uniform target thickness.

To conclude, ATLAS and other heavy-ion accelerators that are coming on line such as Stonybrook and Oak Ridge are providing beams of extremely high quality that require the maximum of ingenuity from the target makers and the experimenters in order to make full use of the beam quality being provided. This challenge will require the development of new target production methods and target designs which have not been contemplated up to now.
Table I. Results of timing and energy resolution tests with the superconducting linac system. Elastic scattering on gold $\theta_{\text{lab}} = 20^\circ$.

<table>
<thead>
<tr>
<th>Ion</th>
<th>Linac Energy (MeV)</th>
<th>Pre-tandem buncher timing (ns)</th>
<th>Measured timing resolution on target (psec)</th>
<th>Measured energy resolution (KeV)</th>
<th>Beam timing resolution (corrected) (psec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{12}$C$^{5+}$</td>
<td>104.0</td>
<td>0.80</td>
<td>107</td>
<td></td>
<td>94</td>
</tr>
<tr>
<td>$^{16}$O$^{6+,8+}$</td>
<td>108.7</td>
<td>1.0</td>
<td>105</td>
<td></td>
<td>93</td>
</tr>
<tr>
<td>$^{16}$O$^{6+,8+}$</td>
<td>140.0</td>
<td></td>
<td></td>
<td></td>
<td>295</td>
</tr>
<tr>
<td>$^{28}$Si$^{8+,13+}$</td>
<td>229.0</td>
<td>1.1</td>
<td>118</td>
<td></td>
<td>117</td>
</tr>
<tr>
<td>$^{34}$S$^{8+,13+}$</td>
<td>163.0</td>
<td>1.3</td>
<td>210</td>
<td></td>
<td>194</td>
</tr>
<tr>
<td>$^{37}$Cl$^{8+,13+}$</td>
<td>260.0</td>
<td></td>
<td></td>
<td></td>
<td>620</td>
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</tbody>
</table>
Table II. "Best possible resolution" for various heavy ion beams on a 250 μgm/cm² target

<table>
<thead>
<tr>
<th>Energy (MeV)</th>
<th>Energy Straggling (KeV)</th>
<th>Energy Scattering (KeV)</th>
<th>Total Energy (KeV)</th>
<th>Target Energy Loss (KeV)</th>
<th>Potential Beam Energy Spread (KeV)</th>
<th>&quot;Best&quot; Resolution Possible (KeV)</th>
<th>&quot;Best&quot; Resolution including 10% target nonuniformity (KeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>197Au(16O,16O)</td>
<td>200</td>
<td>72</td>
<td>80</td>
<td>107</td>
<td>240</td>
<td>120</td>
<td>160</td>
</tr>
<tr>
<td>197Au(58Ni,58Ni)</td>
<td>400</td>
<td>433</td>
<td>268</td>
<td>509</td>
<td>2500</td>
<td>120</td>
<td>523</td>
</tr>
<tr>
<td>197Au(120Sn,120Sn)</td>
<td>1000</td>
<td>1300</td>
<td>460</td>
<td>1379</td>
<td>6225</td>
<td>120</td>
<td>1384</td>
</tr>
</tbody>
</table>

*include Total σₑ and beam spread, only.
Fig. 1
END VIEW OF LINAC CRYOSTAT

HELIUM TRANSFER LINE

LIQUID NITROGEN COOLED HEAT SHIELDS

OUTER VACUUM WALL

INSTRUMENTATION AND RF LEADS

RESONATOR

HELIUM IN

HELIUM OUT

ROLLER SUPPORT

Fig. 2
Fig. 3