In-Beam Production and Transport of Radioactive ^{17}F at ATLAS

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Beam currents of radioactive ^{17}F($T_{1/2}$ = 65s) as high as 2×10^6 s^{-1} have been produced at the ATLAS facility and delivered to target for nuclear physics research. The d(^{16}O,^{17}F)n and p(^{17}O, ^{17}F)n reaction were used to produce the ^{17}F in the energy range of 65-110 MeV with ^{17}F intensities of up to 250 pnA. The target employed is a liquid nitrogen cooled H_2 gas cell, with HAVAR windows, operating at up to 8X10^4 Pa pressure. A new beam optics geometry consisting of a superconducting solenoid immediately after the production target followed by a single superconducting resonator has significantly improved the total capture efficiency of the transport system. The superconducting solenoid captures the highly divergent secondary beam and refocuses it to improve the beam match into the remainder of the transport system. A single superconducting resonator then 'debunches' the beam, reducing the energy spread by a factor of four. The beam energy can also be varied, using the resonant cavity, without changing the primary beam energy. Detailed discussion of the results, comparison to calculations, and further possible improvements will be presented.

INTRODUCTION

The interest in beams of radioactive isotopes for a wide variety of research in nuclear physics continues to grow. At the ATLAS facility more than 15% of all beam time in the past year was devoted to not naturally occurring radioactive species. The development of a ^{17}F beam ($T_{1/2}$=65 s) has been in progress for a number of years and the first successful experiments with such a beam were reported earlier(1,2,3).

For the production of ^{17}F, we use an in-flight technique exploiting the features of inverse kinematics to produce a well-defined secondary beam. Primary beams of either ^{16}O or ^{17}O bombard a gas cell containing correspondingly either deuterium or hydrogen. The ^{17}F beams are produced via either the d(^{16}O,^{17}F)n or p(^{17}O,^{17}F)n reactions in the energy range of 65-110 MeV. The beam properties are determined by the reaction kinematics and effects of straggling in the gas and the windows of the gas cell.

By normal accelerator standards, these beams are of very poor quality with large energy and angular spreads. The beam emittance can be minimized by using a good transverse and time focus of the primary beam on the production target, but the effect is limited by the significant thickness of the target gas cell. In this paper we report the performance of a new beam optics configuration which improves our ability to capture and transport the secondary beam produced in these inverse reactions and achieves a significant reduction in the energy spread of the secondary beam.

PRODUCTION AND TRANSPORT

Primary Gas Target

In order to achieve high secondary beam intensities, a high pressure gas cell with metal windows is used as the production target which can withstand primary beam intensities up to 250pnA. The gas cell consists of a double-walled 2.5 cm inner diameter cylinder 7.5 cm long. The chamber between the walls can be filled with a circulating cooling liquid such as liquid nitrogen which both stabilizes the target thickness and increases the effective thickness at a given pressure. The windows are 1.9 mg/cm^2 HAVAR™ (a cobalt chromium nickel alloy) foils soldered to a stainless steel ring with an inner diameter of 1.3 cm and mounted on the gas cell using an indium gasket. The pressure used in the gas cell ranged up to 8.5X10^4 Pa. The lifetime of the HAVAR foils was up to 80 hours depending on the beam current, spot size, and cooling. Cooling the cells to liquid nitrogen temperature is critical to optain the longest window lifetimes. In order to eliminate the need for opening the beam line system after a window failure, two assemblies of three gas cells each were stacked together on linear translator stages.

First Production and Transport Geometry

The gas cell was initially installed in front of a bending magnet leading to the Enge split-pole spectrograph at the ATLAS accelerator at Argonne National Laboratory. The optics of the spectrograph beamline was modified by the addition of a second quadrupole doublet (see Fig. 1) to improve the transport efficiency for the ^{17}F beam which is estimated to have a total normalized emittance ($e_n=\gamma\beta\varepsilon$) of 11.3$\pi$ mm·mr. Even with the addition of a second quadrupole the beamline angular acceptance is approximately 0.55° for a beam with no energy spread. The acceptance was further reduced due to the energy spread of the reaction products.

In this configuration, ^{17}F beams with energies between 55-100 MeV have been produced. The average reduced ^{17}F beam intensity was 700 (s·pnA)$^{-1}$ and corresponded to a beam transport efficiency of approximately 1.5%. With a primary ^{17}O beam of up to 250 pnA, rates of 2×10^5 ^{17}F/s on the secondary target were achieved into a 1 cm diameter beam spot.

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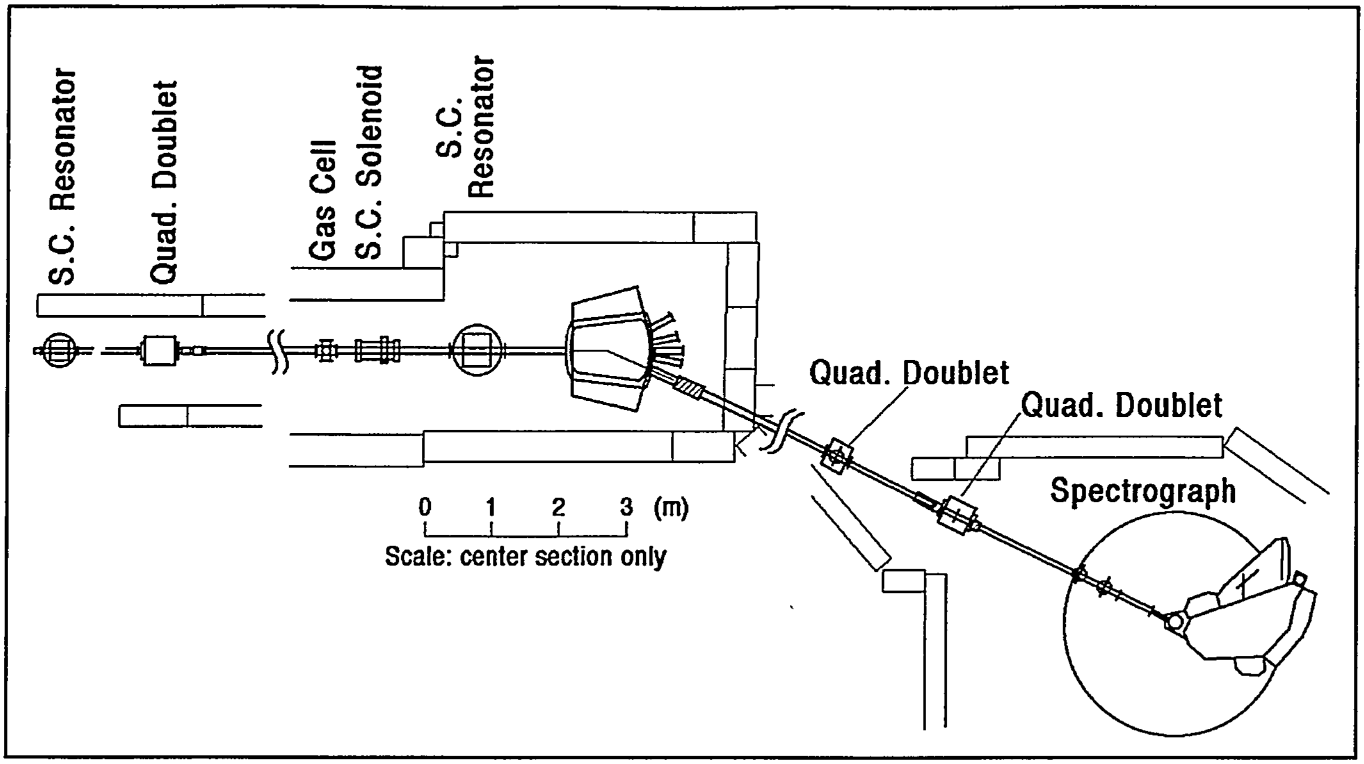


Figure 1. Floor plan of the ATLAS radioactive beam in-flight production facility.

New Production and Transport Geometry

The beam matrix optics code TRANSPORT (4) and a locally developed beam ray-tracing code LINRAY(5), used in the design of ATLAS, were used to developed an improved production and transport system for the ^{17}F beam. LINRAY was modified to include the correct particle distributions and correlations in the reaction process as well as straggling effects in the gas cell windows. LINRAY is a cylindrically symmetric code and therefore does not treat beam transport through quadrupoles correctly, nor the small dispersion induced by the beamline switching magnet. The output from LINRAY through the gas cell, solenoid, and resonator then served as the starting point for TRANSPORT in modeling the remainder of the beam line.

The results of the beam optics studies showed that improved capture and transmission of the ^{17}F ions was possible by the installation of additional focusing elements in the transport system, especially close to the target and the use of RF cavities before and after the target to minimize the longitudinal emittance growth and reduce the energy spread of the outgoing ^{17}F. The addition of a transverse focusing lens near the production target reduces the beam divergence before particles strike an aperture and also controls the size of the beam through the second RF cavity. Due to the large transverse emittance of the secondary beam the optimum transmission achieved is the result of compromises at the various constrictions in the beamline leading to the spectrograph.

The new production and transport configuration developed is shown in Fig. 1. The production target has been moved upstream approximately 5 meters. In this position, the gas cell is between two existing ATLAS superconducting rebuncher resonators and just ahead of a newly installed 2.4T superconducting solenoid. The solenoid is mounted in such a way as to be easily moveable over a 0.63 meter distance for best placement depending on the reaction kinematics. The superconducting solenoid forms a transverse waist after the second resonator. This optics design is a compromise between the need for a sufficiently small ^{17}F beam envelope through the 2.5 cm. diameter aperture of the resonator and the need to minimize the divergence of the beam so that as much beam as possible can be captured and refocused by the two quadrupoles on the spectrograph beamline.

By placing the production target between two RF cavities, it is possible to reduce the longitudinal emittance of the secondary beam and then use the energy-time correlation of the beam to reduce the energy spread with the second resonator. The RF cavity upstream from the production target refocuses the primary beam to a small time width on the production target which minimizes the longitudinal emittance of the secondary beam and maximizes the energy-time correlation necessary to reduce the ^{17}F energy spread. The RF cavity after the production target then 'debunches' the beam, significantly reducing the energy width of the secondary beam.

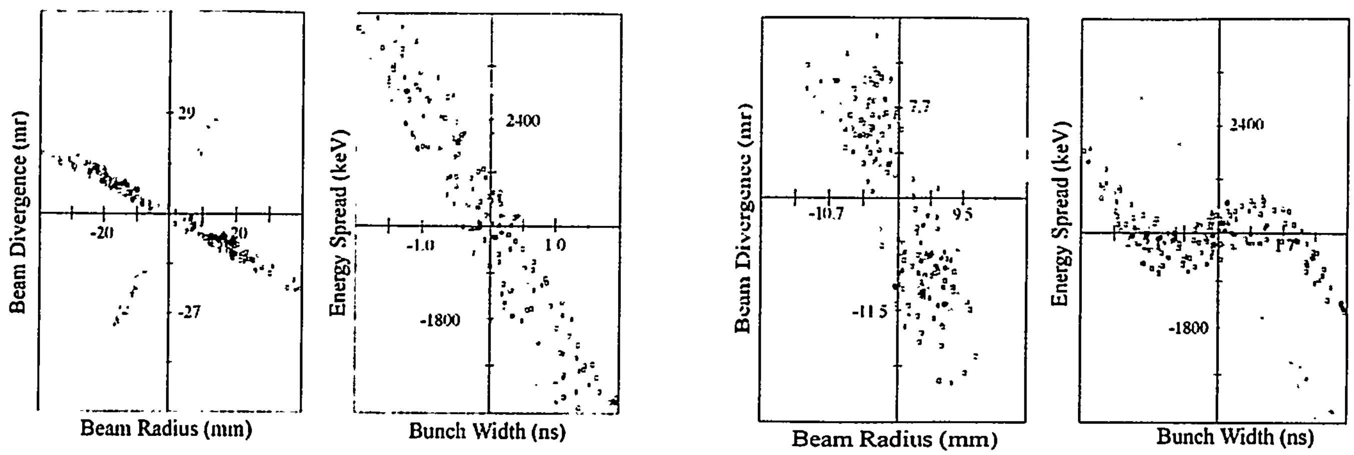


Fig 2a.

Fig 2b.

Figure 2. Calculated ^{17}F phase space (a) at the superconducting solenoid and (b) at the second rebunching resonator. The light '+' symbols represent particle coordinates entering the devices while the darker squares represent particles leaving the devices. Note the bimodal transverse distributions and the nonlinear effects of the RF on the longitudinal emittance.

The phase of the second RF cavity can also be adjusted to change the ^{17}F beam energy over a range, in this case, of approximately ±4 MeV while still maintaining a small energy spread. This feature allows the choice of production energy to be chosen partially based on secondary beam yield while allowing excitation functions to be more easily mapped out using the energy variability from the second RF cavity.

Calculations with the program LINRAY allowed the optimum relative position of the gas cell, solenoid, and resonator to be determined. An example of the calculated effects of the new solenoid and resonators on the transverse and longitudinal phase space for the p(^{17}O,^{17}F)n reaction is shown in Fig. 2.

The calculations demonstrate that the use of a 'rebunching' resonator in front of the gas cell to produce a minimum time width at the target for the primary beam is crucial for the best use of the second resonator. The primary beam bunch width without rebunching is approximately 3 ns FWHM. Using only the resonator after the gas cell to reduce the energy spread of the secondary beam reduces that energy spread from ±4 MeV to ±1.7 MeV. When a rebunching resonator is used to refocus the primary beam to a bunch width of ±0.5 ns, the secondary beam's longitudinal emittance is reduced, the energy-time correlation is improved and an energy width of ±0.7 MeV for the ^{17}F beam is predicted for the full beam.

This effect was easily observed in the experiment where we found that using only the second rebunching resonator increased the transmitted beam by only 10-20%, but that using both resonators yielded a 50% increase in beam current compared to optimization with only the superconducting solenoid.

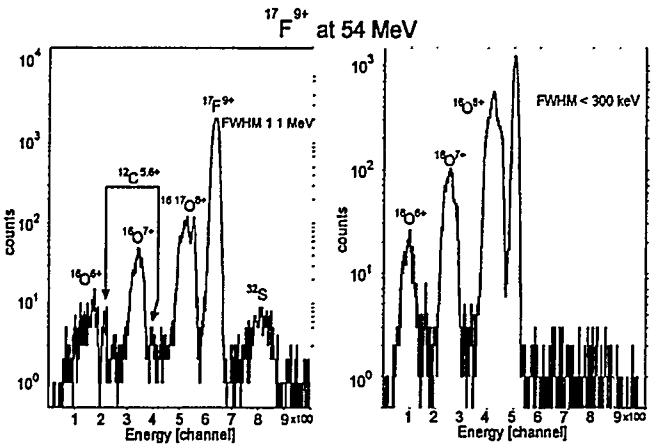
The improvement in the energy width of the ^{17}F beam was also easily observable. The energy spread of the beam arriving at the secondary target without any resonator is approximately 1.6 MeV which is essentially a measure of the acceptance of the beam transport system. With increasing experience in tuning the secondary beam and improved diagnostic information as this project progressed it was possible to reduce the energy spread at the spectrograph target to as little as 0.3 MeV FWHM and routinely to a little less than 1 MeV FWHM. This is consistent with the modeling calculations noting that we have been able to transmit to target only about 25% of the total expected beam, as discussed below.

The gas cell is now significantly closer to the final primary beam quadrupole which produces a waist at the gas cell. If the target where 'thin' one would expect a reduction of the transverse emittance which is effectively a product of the beam spot size and the maximum emission angle for the ^{17}F from the reaction kinematics. Unfortunately because we are forced to use a gas cell in order to accept reasonable primary beams on the production target, the finite extent of the interaction region means that the beneficial effect of a smaller primary beam waist is largely lost. The problem is exacerbated further by the multiple scattering of the primary and secondary beams in the HAVAR windows of the gas cell. Therefore we believe that the transverse emittance of the beam is little changed from that estimated above for the first production geometry used.

Two examples of the secondary beam delivered to the spectrograph are shown in Fig. 3. Components from the primary beam which scatter from the gas cell window frames and other areas constitute the dominant source of tails from the primary beam. Any primary beam degraded in energy sufficiently to match the magnetic rigidity of the desired ^{17}F will be transmitted to target and those components are seen in Fig 3. The best ^{17}F beam purity achieved has been approximately 90%, with 75% a more typical value.

TRANSMISSION RESULTS

The transport of this 'reprocessed' secondary beam to the reaction target at the spectrograph by the remaining beam is now significantly improved. With the new configuration a LINRAY calculations predict a total transport efficiency of 52% or 26% including the stripping fraction. Instead the best efficiency achieved so far is approximately 6%.



(a) (b)

Figure 3. Two examples of beam components arriving at the secondary target. In (a) the energy spread is approximately 1 MeV FWHM and approximately 88% of the beam is ^{17}F. In (b) only 44% of the ions delivered are ^{17}F but the energy spread is less than 300 keV.

A number of factors may contribute to the discrepancy between the observed transmission and the predicted value. First the apertures of the two quadrupoles continue to be significant constraints to the transport efficiency. LINRAY's cylindrical symmetry assumptions cannot properly model a quadrupole. Second, the beam spot at the spectrograph target is significantly larger than for the earlier geometry (12 mm X 8 mm compared to 3 mm X 5 mm.). Such a large size cannot fully be accepted by the spectrograph detector and this reduces our useable efficiency by 50%. These problems could be improved with larger aperture quadrupoles moved to locations reducing the beamline magnification. Unfortunately such quadrupoles are not available to us at this time. Finally realizing the optimum optics calculated in a real experiment is a difficult process and our learning curve may yet yield further improvements in overall transmission.

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REFERENCES

1. B. Harss, et al., Proc. of 1996 Lin. Accel. Conf, Geneva, Switzerland, CERN 96-07, 496(1996).
2. B. Harss, et al., Proc. of 1997 Part. Acel. Conf., Vancouver, Canada, 2696(1998).
3. K.E. Rehm, et al, Phys. Rev. Lett., in print.
4. K.L. Brown, Advances Particle Physics., 1, 71(1967).
5. R. Pardo, LINRAY Operating Manual, unpublished.