THE RCNP ATOMIC BEAM SOURCE

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A new polarized ion source has been constructed at RCNP and is now operational. It employs cold (~ 30 K) atomic beam technology, permanent magnet sextupoles and an electron cyclotron resonance ionizer. Beam from the source was successfully injected into the AVF cyclotron through a new injection line at the end of September, 1994. The source has been used to deliver polarized protons for experiments since then. Results of the development of the source will be discussed.

1 Introduction

At the Research Center for Nuclear Physics, Osaka University, a large fraction of the experimental program is devoted to studies of spin degrees of freedom. The original atomic beam type polarized ion source was constructed in 1975, and extensive research has been performed since then with polarized protons and deuterons accelerated by the RCNP K140 AVF cyclotron. In 1991, a K400 ring cyclotron was completed as the post accelerator which can accelerate protons up to 400 MeV. In order to enhance the opportunities in spin physics research using intermediate energy beams from the ring cyclotron, the construction of a new high intensity polarized ion source was proposed as a two year project in 1993. Its design is based on sources in operation at PSI [1], TUNL [2], IUCF [3] and RIKEN [4], which employ cold ($\sim$ 30 K) atomic beam technology and an electron cyclotron resonance ionizer. Detailed features of the source were described elsewhere.[5] The source is coupled by a high-efficiency bunching system, a high-transmission injection line to the AVF cyclotron and a spiral inflector system.

2 Features of the Source

The new source built at RCNP is schematically illustrated in Fig. 1. The beam of H or D atoms is produced from H_2 or D_2 gas in a 13.6 MHz, 50~200 W discharge contained in a pyrex tube of 20 mm inner diameter. The discharge is cooled by water flowing between the dissociator tube and the second, surrounding pyrex tube of larger diameter, 30 mm. Atoms emerging from the discharge pass through a Macor section at the end of the tube and into a copper or an aluminum nozzle. The Macor serves to isolate the nozzle thermally at $\sim$30 K from the high temperature of the discharge. The nozzle is cooled by conduction to the cold head of a 9 W, closed-cycle helium refrigerator. Cooled atoms emerge as a directed jet from a 3 mm diameter nozzle orifice into the first vacuum chamber which is evacuated by a 2800 ℓ/sec turbomolecular pump with a magnetic suspension.
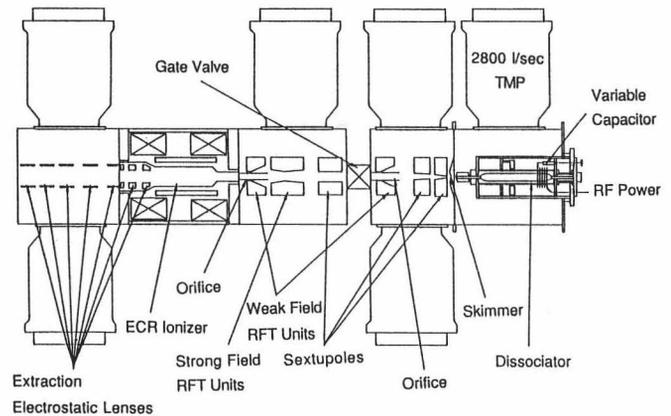

Figure 1: Schematic layout of the RCNP atomic beam source.

With 25 std-cc/min of H_2 flowing into the dissociator, the pressure in the first chamber is $< 6.5 \times 10^{-3}$ Pa.

An atomic beam is formed at the entrance to the second vacuum chamber when the beam passes through a skimmer aperture placed 25 mm from the end of the nozzle. This skimmer separates the first and second chambers. With other two 2800 ℓ/sec turbomolecular pumps on the second chamber, the pressure there is $< 1.1 \times 10^{-4}$ Pa. A third vacuum chamber follows where another 2800 ℓ/sec turbomolecular pump holds the pressure during operation $< 1.6 \times 10^{-5}$ Pa.

The atomic beam enters the first sextupole magnet system 25 mm beyond the skimmer orifice. The system consists of two sextupole magnets which are separated by 30 mm in order to efficiently evacuate the beam path. The first magnet is 50 mm long and has axially tapered pole tips with inner diameters of 16 mm at its entrance and 22 mm at its exit. The second one is 70 mm long and has inner diameters of 22 mm at its entrance and 30 mm at its exit. The atomic beam enters the third sextupole 272 mm beyond. The last sextupole is 100 mm long and has straight pole tips with a constant 30 mm

tip-to-tip diameter. The sextupole magnet is segmented in 24 pieses [6] of oriented Nd-Fe-B material, NEOMAX-35H, and the outer diameter is 120 mm. Each magnet is put in a vacuum tight container whose outer diameter is 170 mm. The remanent field B_r in the direction of the easy axis of the material was measured to be 1.245T, and the maximum energy product $(BH)_{max}$ 295 kJ/m^3. The size of sextupole magnets and their positions were optimized from calculations using a Monte-Carlo code for the atomic beam transport which was written at the University of Wisconsin [7]. In the calculation, the radius of the effective ionizing region was taken to be 10 mm.

The entrance of the ionizer is 375 mm downstream from the exit of the last sextupole magnet. The ECR ionizer was designed following Schmelzbach [1]. The inner diameter of solenoid coils is 180 mm. The current in the entrance and exit solenoid coils can be adjusted independently in order to optimize the shape of the axial mirror field. At the entrance of the ionizer, the solenoid coil has a 50 mm thick iron yoke with a hole of 36 mm in diameter to shield the rf transition units against the stray field from the ionizer. The sextupole magnet consists of six NEOMAX-35H bars which are 20 mm wide, 15 mm high and 210 mm long. They are magnetized in the width direction, and are assembled in a sextupole magnet with a 110 mm tip-to-tip diameter. The microwave frequency is 2.45 GHz at present, and the maximum power of the generator is 200 W. A quartz vessel is used as a discharge container, and the plasma potential is defined by the first electrode with an opning of 50 mm. The solenoidal coils have the ability to produce B_{min} of 230 mT for the axial mirror field. If the low magnetic field 87.5 mT deteriorates the proton polarization, we can increase the microwave frequency higher than 6 GHz.

The desired states of nuclear polarization for H and D atoms are produced by three sextupole magnets with one weak field radio-frequency transition (RFT) unit between the second and the third magnet, and the second weak field and one (1480 MHz for H) or two (455 MHz and 331 MHz for D) strong field units following the last sextupole. With this configuration, both the pure vector and the pure tensor states are produced for deuterons.

3 Injection Line to the AVF Cyclotron

A new injection line to the AVF cyclotron was designed and constructed. With the previous injection system, polarized protons and deuterons have been externally injected into the AVF cyclotron. On the other hand, unpolarized ions including light heavy ions have been produced by an internal ion source. When polarized ions were externally injected with a mirror system, structures in the central region of the cyclotron had to be changed from those used for the internal source. The vacuum chamber of the cyclotron was opened each time when
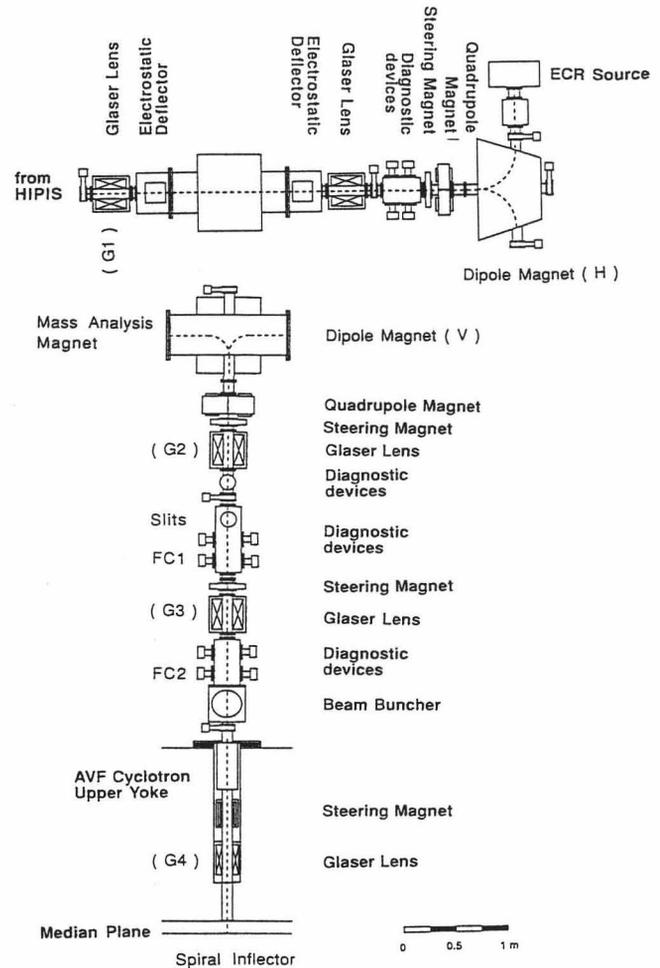

Figure 2: Injection line of the RCNP AVF cyclotron.

accelerated ions were changed from polarized protons/deuterons to unpolarized ions, and vice versa. In the new system, both polarized ions and unpolarized ions produced with an ECR source, NEOMAFIOS built by R. Geller at Grenoble, are injected through the common vertical injection line and the common inflection system. A schematic layout of the new injection line is shown in Fig. 2. At the exit of the source, protons and deuterons are longitudinally polarized. Protns are deflected by 96.7 degrees with a dipole magnet, and deuterons by 105 degrees, so that the beam remaines longitudinally polarized after the 90 degree deflection into the vertical beam line. For this purpose, small parts of pole pieces are added at the magnet entrance when deuterons are injected to the cyclotron. An electrostatic deflector is used to compensate the beam trajectory shifts. In the system, electromagnetic lenses are used instead of electrostatic ones used in the previous system. They ensure an efficient focusing and a good vacuum through the line. A beam

buncher is placed at 2.5 m upstream from the median plane of the cyclotron. It consists of two parallel mesh plates forming a single gap, and is excited by an RF voltage with a sawtooth-like waveform generated by combining RF sine waves with the first three higher harmonics.

A spiral inflector system was designed and fabricated. In the previous axial injection system, an electrostatic mirror system has been used to inflect polarized ions on the median plane of the cyclotron. A spiral inflector seems more suitable for high intensity beams than a mirror system, because there are no grids intersecting beams. A spiral inflector can be treated as a component of a beam transport system either analytically or numerically. The shape of electrodes was desinged based on the analytic solution of the Lorentz equation [8]. The electric radius was taken to be 24 mm, and the magnetic radius of the first cyclotron orbit 15.1 mm. For 65 MeV protons, the injection energy is 15 keV. These parameters were determined from the simulation of a particle orbit in the central region of the cyclotron. Numerical integrations of the equation of motion were performed with an impulse approximation assuming a Dee voltage of 70 kV. Parameters were optimized such that a beam should be accelerated on a well-centered orbit. In the present design, electrodes are set parallel, and are easily fabricated by a milling machine. The electrode spacing is 6 mm and the electrode width is 16 mm. Results of initial testing of the new system are summarized in Table 1. In the table, the efficiency is the ratio of the beam intensity extracted from the AVF cyclotron to the beam current measured after the mass analysis magnet in the axial injection line. The accelerated beam current was increased by a factor $3 \sim 6$ by using a buncher.

4 Development of the Source

4.1 Reliability

During initial off-line testing of the source, it was noticed that the ECR ionizer worked stably for periods of more than two months. On the other hand, the atomic beam intensity from the dissociator dropped by a factor of two or more after four day operation. A heat cycle

Table 1: Results of initial testing of the new injection system.

Ion Charge	Energy(MeV)	Efficiency(%)
^{1}H$^+$	65.0	14
^{2}H$^+$	43.5	10
^{3}He^{1+}	32.0	7
^{3}He^{2+}	92.6	22
^{4}He^{2+}	120.0	16
^{14}N^{4+}	130.0	8
^{14}N^{5+}	210.0	6

procedure, warming the copper nozzle to room temperature then cooling it under vacuum, could not recover the source. The accumulation of green spots was observed on the surface of the copper nozzle. The material of the nozzle was changed from copper to aluminum. In the beginning of the operation, the aluminum nozzle produced an atomic beam of similar intensity as the copper nozzle, and the source could be recovered by a heat cycle. It was found that the cold nozzle occluded with frozen ammonia. By reducing the N_2 gas flow rate to the cold nozzle, the dissociator now runs stably for periods of longer than one month before nozzle cleaning is required. With nominal source operating conditions, a proton current of $50 \sim 100$ μA was measured at 15 keV after the mass analysis magnet in the axial injection line. A maximum proton current of 8 μA was extracted from the AVF cyclotron at 65 MeV.

4.2 Polarization

When the source began to deliver beams for experiments last November, the proton polarization was much lower than expected. The beam line polarimeter measurements indicated an average polarization of p=0.55 or less. Extensive investigations have been performed to optimize source parameters in order to improve proton polarization. It was found there were two kinds of sources of unpolarized protons; one was residual hydrogen molecules and the other recombined molecules [1]. The former is now reduced by improved pumping of the plasma region. The latter was due to atoms from the dissociator which were not ionized in the ECR ionizer and recombined on the surface of the quartz vessel containing the plasma or on electrodes. In the RCNP source, since we use permanent magnet sextupoles to focus the atomic beam, there are no ways to adjust the hardware of the atomic beam transport system, so it had to be optimized by simulations using a Monte-Carlo code [7]. Diameters of the nozzle, the skimmer aperture, and the spacing between them were optimized to improve proton polarization. The optimum diameter of the nozzle orifice was 3 mm which is the same as that initially designed. The skimmer aperture diameter was reduced from the initially designed 6 mm to 4 mm. Additional orifices were installed at weak field RF transition units to reduce the undesired flow of molecules and atoms to the ionizer. Each orifice has a conductance of 6 ℓ/sec for air at room temperature. One of two turbomolecular pumps initially installed at the dissociator was moved to the exit chamber of the ECR ionizer for improved pumping of the plasma region. The pressure measured at the extraction chamber was improved to 3.5×10^{-5} Pa from 5.5×10^{-5} Pa. These modifications resulted in the average polarization of p ~ 0.75.

Proton polarization suffers from the low holding field of 87.5 mT in the ionizing volume [1]. The maximum achievable polarization is 93 % for a beam with substates

1+4 or 2+3, providing the Stern-Gerlach state separation and the RF transitions are perfect. In this model, proton polarization of 7 % is predicted even if all the RF transitions are turned off. In our source, measured proton polarization was about 5 %. Since our solenoidal coils have the ability to produce B_{min} of 230 mT for the axial mirror field, proton polarization will be improved by utilizing higher frequencies for the ECR ionizer.

In the new injection line, electromagnetic lenses are utilized to focus the beam. In glaser lenses, the off-axis particle feels the radial magnetic fields and the particle spin rotates around the field. This effect may cause depolarization. Tracking of the spin motion along the beam path in glaser lenses was performed to estimate the effects of radial magnetic fields on the polarization. It was found that depolarization was almost negligible when two successive glaser lenses are excited in opposite polarity to each other. An example of numerical spin tracking is shown in Fig. 3; a particle is assumed to be 20 mm off-axis at the entrance of the first lens. It can be seen that polarization, spin direction, is recovered after passing through two glaser lenses excited with opposite polarities. Similar effects should be expected in the mirror coil field at the ECR ionizer and in the hole lens region at the center of the AVF cyclotron. In the injection line shown in Fig. 2, mirror coils, glaser lenses, G1 ∼ G4, and the main coil of the cyclotron are powered to give the following magnetic field polarity along the beam path: mirror (S → N), G1 (N → S), G2(S → N), G3 (N → S), G4(S → N), the main coil (N → S). When the polarity of the mirror field was reversed, the proton polarization was reduced to 90 % of its initial value. The largest reduction to 70 % was observed as expected, when G2 was excited in the reversed polarity. It is interesting to note that the proton polarization was reduced to 81 % of its original value, when G4 was excited in reversed polarity. This may indicate that there is substantial depolarization at the hole lens. The larger the beam size is in the lens, the more important these effects are.

5   Conclusion

The RCNP atomic beam source was successfully constructed on schedule, and has delivered polarized protons for nuclear physics experiments at intermediate energies. It has operated stably for periods of longer than one month of continuous operation without maintenance. With nominal source operating conditions, a proton current of 50 ∼ 100 μA was measured at 15 keV. A maximum proton current of 8 μA was obtained from the AVF cyclotron at 65 MeV and a polarization is about 0.75. Future development will be devoted to improve the degree of polarization, and to get polarized deuterons.
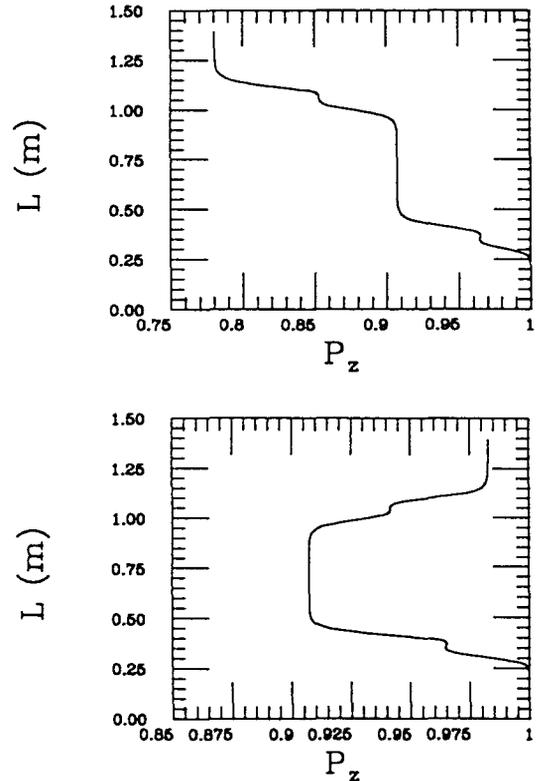

Figure 3: Spin tracking along two glaser lenses excited with the same (upper) and opposite (lower) polarities.

References

1. P. A. Schmelzbach, AIP Conference Proceedings **293**, 65 (1994).
2. T. B. Clegg, AIP Conference Proceedings **187**, 1227 (1989).
3. V. Derenchuk et al., AIP Conference Proceedings **293**, 72 (1994).
4. H. Okamura et al., AIP Conference Proceedings **293**, 84 (1994).
5. K. Hatanaka, Contribution to SPIN'94.
6. K. Halbach, *Nucl. Instrum. Methods* **169**, 1 (1980).
7. A. Roberts, private communication.
8. J. L. Belmont, Institut des Sciences Nucleaires de Grenoble, Rapport Interne ISN **86-106**, (1986).