Present Status of Ion Sources at the RCNP

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Abstract

The RCNP polarized ion source employs cold (~ 30 K) atomic beam technology and an electron cyclotron resonance ionizer. The source has been intensively operational since fall in 1994 to provide polarized protons to experimental researches at 200 - 400 MeV. Developments have been continued to increase the long term stability of the source and to improve the beam polarization. The source works for two months before cleaning the dissociator. Proton beam intensity from the source is 50 - 100 μA and the polarization is 70 % or better after acceleration with the K400 RCNP ring cyclotron.

1 INTRODUCTION

The Research Center for Nuclear Physics (RCNP), Osaka University, was established in 1971 as the national research center of nuclear physics in Japan. Recently the RCNP facility was upgraded by bringing the new ring cyclotron with K = 400 MeV into operation [1]. The existing AVF cyclotron is used as the injector. Frequencies of accelerating voltage at the ring cyclotron are 3 or 5 times of those at the AVF cyclotron depending on the accelerated particle and energy. A flat topping system [2] is introduced to accelerate beams with small energy spreads in order to perform precise and ultra high resolution studies at the intermediate energy region. For this purpose, it is inevitable to inject high quality beams from the injector cyclotron to the ring cyclotron, especially with narrower pulse width than 1 ns for 65 MeV protons which are accelerated to 400 MeV by the ring cyclotron. In general, AVF cyclotrons have a large phase acceptance, and the beam burst width is usually observed as wide as 3 - 5 ns with the RCNP AVF cyclotron. A narrow beam pulse width such as 1 ns can be attained by reducing the RF phase acceptance by slits in the central region of the AVF cyclotron, but it largely sacrifices the beam intensity. The energy spread of the extracted beam from the ring cyclotron becomes about twice of the injected beam energy spread due to a phase compression process which results from the radial distribution of the accelerating RF voltage. This effect requires the energy spreads of the injected beams as small as possible, and we have to cut beams with unacceptable energy spreads by energy defining slits in spite of reducing beams intensity. The acceptance of the ring cyclotron in the transverse phase space is estimated around 3π mm-mrad and is a half of the measured nominal beam emittance from the AVF cyclotron [3]. It is necessary again to reduce the beam spreads in the transverse phase space as well as in the longitudinal phase space to match the injected beam to the acceptance of the ring cyclotron. Consequently, the intensity of the 400 MeV polarized proton beam was restricted to around 10 nA on target with the previous polarized ion source.

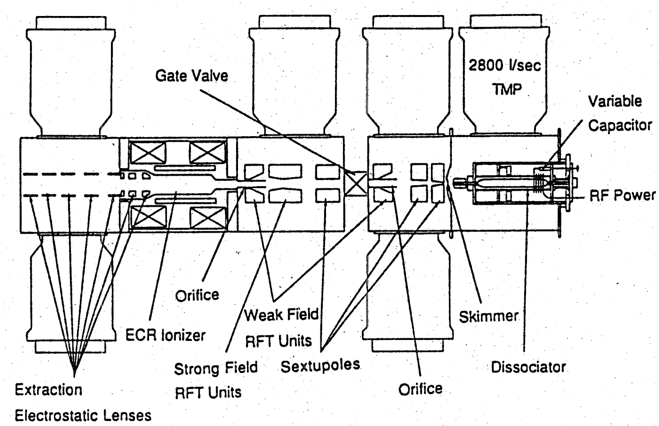

Fig. 1 General Layout of RCNP High Intensity Polarized Ion Source.

A large fraction of the experimental program at the RCNP is concentrated on studies of spin degrees of freedom. More than 60 % of the approved beam time is performed with polarized protons. In order to enhance the opportunities in spin physics research at intermediate energies by the ring cyclotron, the construction of a new high intensity polarized ion source was started in 1993. The new source built at the RCNP is schematically illustrated in Fig.1. Its design is based on sources in operation at PSI [4], TUNL [5], IUCF [6] and RIKEN [7], which employ the cold (~ 30K) atomic beam technology and an electron cyclotron resonance (ECR) ionizer. The source was completed in 1994 and has been intensively operated since then to produce polarized protons to perform researches at 200 - 400 MeV.

In this paper, performances of the source, developments and results will be described.

2 DEVELOPMENTS OF THE SOURCE

The source was assembled in February 1994 and connected to the AVF cyclotron in the beginning of September after half a year performance tests off line. The source has been intensively operated since then to provide polarized protons for experimental researches at 200 - 400 MeV. Although the available time was limited, some performance tests and developments have been continued to realize the stable operation of the source.

2.1 Dissociator

The material of the nozzle was changed from copper in the original design to aluminum. The aluminum nozzle produces the atomic beam of the same intensity as the copper nozzle. Usually the dissociator works for two months by reducing the N_2 gas flow rate. Even if

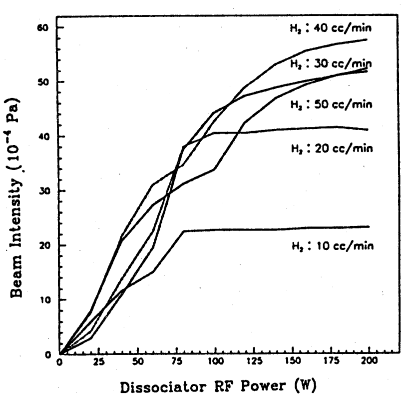

Fig. 2 Measured atomic beam intensities at the ionizer position.

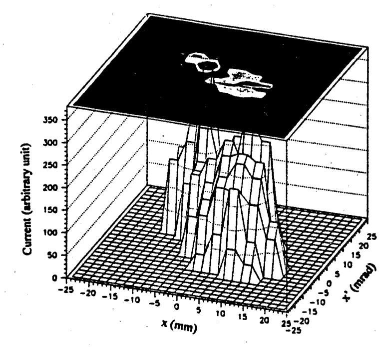

Fig. 3 Beam emittance measured at the vertical injection line to the AVF cyclotron.

the nozzle is occluded with frozen ammonia, the dissociator is easily recovered by a heat cycle. The life time of the dissociator seems to be determined by a subtle characteristic of a pyrex tube which depends on the production lot [10]. We also tested quartz tubes in place of pyrex tubes, and found the more stable operation was obtained with quartz tubes than with pyrex tubes.

Atomic beam intensity was measured with a compression tube which was installed in place of the ionizer. The size of the compression tube is the same as that of the ionizer vessel. Fig.2 shows the pressure difference measured with a hot cathode ion gauge as a function of the microwave power fed to the dissociator.

Since the compression tube has not been calibrated, those data are only relative. In the measurements, N_2 gas was fed at the rate of 0.02 std-cc/min near the nozzle through the Macor section. In the usual operational condition where the microwave power is 100 W, the optimum gas flow rate was 30 std-cc/min. For the gas flow rate of 40 std-cc/min, higher atomic beam intensity was achieved with higher microwave power, but the shorter life time is anticipated for the dissociator tube. When the gas flow rate was increased up to 50 std-cc/min, atomic beam intensities decreased. This fact may come from the effect of intrabeam scattering in the beam path.

2.2 Atomic beam section

When the source began to deliver polarized protons for experiments in November 1994, the beam polarization was much lower than expected. The beam line polarimeter measurements [11] indicated an average polarization of $p = 0.55$ or less. Extensive investigations have been performed to optimize source parameters in order to improve the polarization. It was found there were two kinds of sources of unpolarized protons; one was due to residual hydrogen molecules and the other recombined molecules. The former is now reduced by an 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 our source, since we use permanent magnet sextupoles to focus the atomic beam, there are no easily adjustable parameters for the atomic beam transport system. Diameters of the nozzle, the skimmer aperture, and the spacing between them were searched to improve proton polarization without sacrificing beam intensities. The optimized diameter of the nozzle orifice was 3 mm which was the same as the original design. The skimmer aperture diameter was reduced from 6 mm to 4 mm. Additional orifices were installed at locations two 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 turbo-molecular pumps originally installed at the dissociator chamber was moved to the extraction chamber downstream the ECR ionizer to improve the vacuum at the plasma region. These modifications improved the average polarization to 70 % or better.

2.3 The ECR ionizer

The correlation between atomic beam intensities and proton intensities were measured [8]. Atomic beam intensity was measured with a compression tube which was installed in place of the strong field RF transition units after the last sextupole magnet (Fig.1). Proton beam intensity was also measured after a 90-degree analyzing magnet. The beam intensities for 30 std-cc/min are three times larger than those for 15 std-cc/min. It was observed that beam intensities were nearly same when the hydrogen gas flow rate was larger than 25 std-cc/min. It can be seen that atomic beam intensities measured with the compression tube show a saturation effect as a function of the microwave power compared with proton currents. At higher microwave power than 160 W, proton currents begin to saturate.

Fig.3 shows the beam emittance measured at the vertical injection line to the AVF cyclotron. 100 % of the beam were found within an emittance of 300 mm mrad at 15 keV.

Even if the Stern-Gerlach state separation and the RF transition are perfect, the proton polarization is not always 100 %. When the hydrogen atoms are ionized at the magnetic field B mT, the maximum achievable polarization for the beam with substrates $1+4$ or $2+3$ is given by [9].

$$P = \frac{1}{2}(1+\delta) \tag{1}$$

where

$$\delta = \frac{x}{\sqrt{1+x^2}}, \qquad \text{and} \qquad x = \frac{B}{50.7}$$

The ECR condition at the frequency 2.45 GHz requires the magnetic field of 87.5 mT and this field strength predicts the maximum beam polarization of 93 % from eq.1. In this model, proton polarization of 7 % is predicted even if all the RF transitions are turned off. At the RCNP source, the measured proton polarization was about 5 % without any RF transitions. For this reason, several laboratories have selected higher frequency microwave sources which operate between 3 and 4 GHz [12]. Since our solenoidal coils have the ability to produce B_{min} of 230 mT for the axial mirror field, operational tests were performed at 3.5 GHz. An appreciable increase in the proton polarization was not observed, although the beam current was 1.3 to 2.0 times larger than at 2.45 GHz. Most probable reason is the larger radial extent of the ECR plasma at 3.5 GHz than at 2.45 GHz, because the sextupole field was not increased. Background gas in the ionizer, coming from unpolarized hydrogen atoms lost from the beam and recombined into molecules, can thus more easily re-enter the plasma, become ionized and extracted, and dilute the emerging beam polarization. For the present design of the ECR ionizer, the resonance surface is originally extended rather in the radial direction than in the longitudinal direction [4]. The higher beam intensity at 3.5 GHz shows that the denser ECR plasma is attained when the microwave frequency is increased [13]. In usual operation, the full proton intensity from the source is 50 - 100 μA after the analyzing magnet.

3 SUMMARY

Features and performances of the newly constructed polarized ion source at the RCNP was described. It employs cold ($\sim$ 30K) atomic beam technology and an electron cyclotron resonance ionizer. After the commissioning of the source, many developments were performed to increase the long term stability and the beam polarization. With an aluminum nozzle, the source works for two months before cleaning the dissociator. Beam polarization was improved by optimizing the geometry of the atomic beam section to preventing unwanted molecules or atoms from entering the ECR ionizer. Higher frequency for the ECR microwave did not improve the beam polarization appreciably, although the beam intensity was increased. It may be necessary to increase the sextupole field strength at the ionizer to get a radially smaller extent of the ECR plasma. The beam emittance was measured at the vertical injection line to the AVF cyclotron, and 100 % of the beam found within an emittance of 300 mm mrad at 15 keV.

During the past three years the source has been used to perform experimental researches with 200 - 400 MeV protons from the ring cyclotron. In usual operation, the proton current is 50 - 100 μA from the source and the beam polarization is 70 % or better after acceleration.

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