ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-TUPA116

DEVELOPMENT OF POLARIZED H AND D ATOMIC BEAM SOURCE AT IMP*

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Abstract

Polarized beam is an effective tool in basic research. An Electron-ion collider in China (EicC), as a future high energy nuclear physics project, has been proposed. EicC can provide good research conditions for precision measurements of the partonic structure of nucleon or nuclei and the study on the interactions between nucleons and so on. High quality polarized beam is helpful to the accurate measurement of the relevant experiment date. Polarized proton and deuterium (H&D) beam source are one of the key technologies for EicC. Based on the atomic beam polarized ion source (ABPIS) scheme, a polarized H&D ion source with polarization more than 0.8 and beam current more than 1mA is under construction at the Institute of Modern Physics (IMP), providing theoretical and technical support for the design and construction of EicC polarized source. In the ABPIS, the separating magnet ensures the electron polarization and the effective transmission of the atomic beam; the radiofrequency transition (RFT) unit ensures that the electronic polarization is converted into deserved nuclear polarization. In order to generate high intensity and high polarization H&D atomic beam, these assemblies need to be precisely designed and optimized. In the paper, key issues such as electron polarization, nuclear polarization and atom transmission is studied.

INTRODUCTION

Polarization ion sources have been extensively researched and developed for several decades, which is used for the study of nuclear structure. Institute of Modern Physics (IMP) is currently actively researching polarized ion sources to prepare for EicC [1]. The origins of polarized ion source can be traced back to the 1960s, when the first experiments on polarized atomic beams were conducted [2]. The polarized ion source which is being developed in IMP, is an atomic beam polarized ion sources scheme with a charge exchange plasma ionizer, and it is expected to produce 1 mA, 25 keV pulsed H^+ and D^+ ions with the pulse width of 100 μs, repetition frequency 5 Hz and polarization of 80%. The polarized atomic beam source has been designed to achieve these parameter indicators.

The polarized atomic beam source (Fig. 1), consists of dissociator, skimmer, the first set of sextupole magnet, medium field transition unit, the second set of sextupole magnet, strong field transition unit and weak field transition unit from left to right.

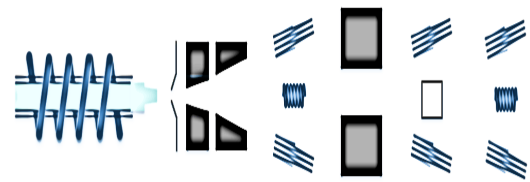

Figure 1: Sketch of atomic beam polarized ion source in IMP.

The generation process of polarized atoms is briefly introduced here. The beam for hydrogen (H) or deuterium (D) molecules enters the dissociator, then the molecules gas dissociates into neutral atoms via electron impact in a cold plasma provided by the action of an electrodeless RF discharge in the dissociator. The dissociated atoms gas then expands through a carefully designed cryogenically cooled nozzle at thermal speed into a vacuum supported by a powerful pumping system, so an intense beam of hydrogen or deuterium atoms is produced. A hydrogen atomic beam is then formed using a skimmer.

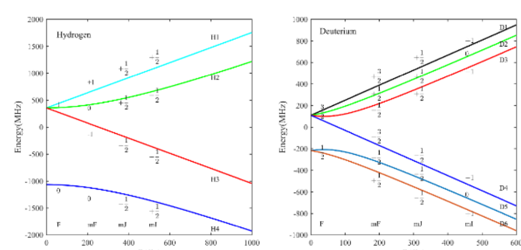

Figure 2: The Breit-Rabi energy level diagram of hydrogen and deuterium.

The sextupole magnets produce the electron polarized atomic beam by separating atoms passing the magnets for their electron spin states. The hydrogen (deuterium) atoms ground state splits up into four (six) hyperfine states in the magnetic field (Fig. 2). The atomic magnetic moment μ is mainly determined by the electronic magnetic moment. The force acting on the atoms is purely radial in the multipole magnetic field B:

$$F = -\nabla(\mu \cdot B)$$

which selectively focuses atoms with electron spin $m_J = +1/2$ into the ionizer cell, and defocuses atoms with electron spin $m_J = -1/2$ away from the atomic beam axis. After the sextupole magnet, theoretically only the atoms in hyperfine states $|1\rangle$ and $|2\rangle$ for hydrogen ($|1\rangle$, $|2\rangle$ and $|3\rangle$ for deuterium) are in the atom beam.

* Work supported by National Key R&D Program of China during the 9th Five-Year Plan Period (NO.2020YFE0202004).
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Then the electron-polarized atomic beam drifts downstream through the radiofrequency (RF) transition unit. Depending on the desired final polarization states of protons or deuterons, one or more R.F. transition units are chosen in operation. In these processes, electron polarization is transferred to nuclear polarization. More kind of nuclear polarization can be obtained by the high-frequency (HF) transitions in combination with the second separating magnet system. In addition, the second sextupole magnet system is also help focus the atomic beam into the subsequent ionizer.

SEXTUPOLE SEPARATING MAGNET

The multipole separating magnet is helpful for the electron polarization, and at the same time, a higher atom beam intensity can be achieved by a carefully designation of the magnet size.

The force on the hydrogen atom is based on the gradient of the multipole magnet field. Among multipole magnets, sextupole magnet seems work well. Although on the axis (in an infinitesimal volume) in a sextupole there is no spin-state separation whereas in a quadrupole the separation force is constant over the entire volume. It seems in principle this should guarantee a somewhat higher beam polarization than from a sextupole. But the trajectory simulation has shown a sextupole magnet can realize more than 99% electronic polarization when the drift distance is long enough. Our finding on the focusing effects of different multipole magnet at least hints that only sextupole magnet fields focus the parallel atom beam like an optical lens (Fig.3).

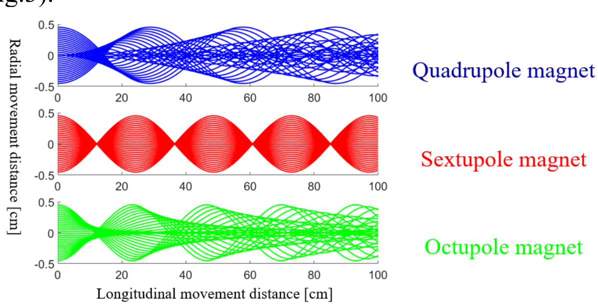

Figure 3: 2D trajectory of hydrogen atom in hyperfine state $|1\rangle$.

The primary magnet configuration has referred to the RHIC on [3]. The first three magnets of the first set are tapered to have the largest possible acceptance of the diverging atomic beam and to provide achromatic focusing. The fourth magnet of the first group is parallel to the parallel atomic beam to the second sextupole magnet system. The fourth magnet of the first set is parallel to the beam axis, which is expected to form a quasi-parallel atomic beam. The second set of sextupole magnets focuses the atomic beam into the entrance tube of the ionizer storage cell. In order to make the sextupole magnet configuration more suitable for the IMP polarized atom beam source, the magnet was optimized based on the simulation of atomic motion in the magnet.

Within the magnet, the evolution of the track is calculated by the ode45 solver based on the software MATLAB. When the movement equation and limited parameters are put in the procedure, the atom is either rejected or used in the further track calculation. In the calculation, the atoms crossing the magnet boundary are all "rejected". Velocity distribution of the atoms in the supersonic beam from the nozzle measured by Belov [4] is used in simulation. The system transmission Tr is determined as ratio of atoms number focusing into the ionizing storage tube to the initial atoms number of the same type (passing the front face of the first sextupole magnet.).

The final system geometry after optimization by 2-dimensional(2D) trajectories simulation is illustrated in Fig.4. The magnet is made by the high-quality permanent material NdFeB with the remanence of 1.43T. The distance between the two sets of sextupole magnet is 300mm. The four short gaps between magnets were fixed at 12mm. A further novel finding is that atomic transport is not sensitive to the gap in the current simulation where atomic scattering is not considered.

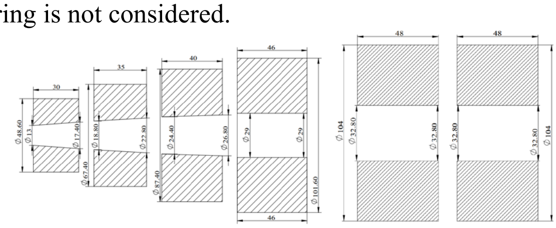

Figure 4: Optimal configuration of the sextupole magnet by 2D simulation.

The present calculation result (Fig. 5), just like those of other groups [5], confirms the expectation that the transmission as function of the atom velocity should present two maxima, in which one is corresponding to the most probable velocity and another is smaller.

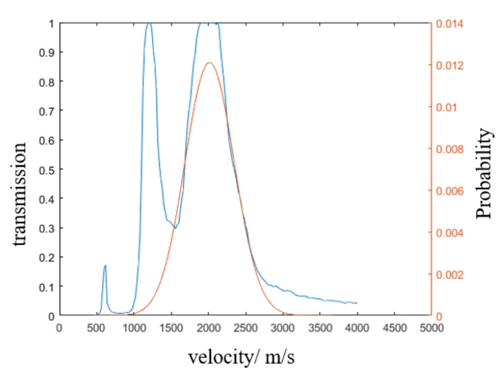

Figure 5: The transmission of $m_J = +1/2$ atoms (2D simulation) with different velocities with the optimal magnet structure and the corresponding velocity probability distribution.

Hydrogen atoms with the most probable velocity of 2015m/s all enter the entrance of the storage cell in this configuration (Fig. 6). The average transmission of m_J=+1/2 atoms is about 71%, when the velocity weighting is considered.

14th International Particle Accelerator Conference,Venice, Italy JACoW Publishing
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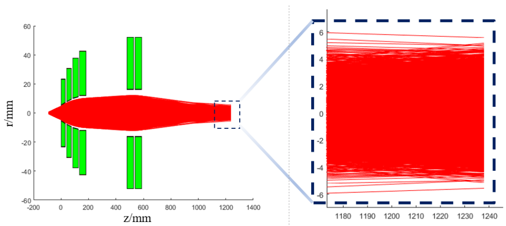

Figure 6: 2-dimensional trajectories of $m_J = +1/2$ atoms. The atom velocity used is 2015m/s.

RADIO FREQUENCY TRANSITION UNIT

Radio frequency transition (RFT) unit is used to get transfer of polarization from electron to nuclear via the method of adiabatic passage, which was proposed by Abragam and Winter [6]. The radio frequency transitions are typically three basic types depending on the strength of the magnetic field: Weak field transition (WFT), Medium field transition (MFT) and Strong field transition (SFT).

The best and earliest introductions to the theory of the adiabatic passage for atomic beam sources are those of Beurtey and Haeberli [7], [8]. The RFT happens when the atom passes through a RF magnet field whose central magnet field strength is B_r with the frequency ω, and there also is a static magnet field (Bs, background magnet field) whose central magnet field strength is B_0 with a gradient dB_0/dz (where z represents the beam direction). A magnet field gradient dB_0/dz of 2 G/cm seems work well for the MFT transition unit [9]. For WFT (INR ABS) the static magnetic field gradient is about 1.2 G/cm. The magnetic field gradient can be generated concurrently with the B_0 field by the inclined iron yoke [10], or alternatively, by utilizing the gradient coil [11]. The static magnet field direction is perpendicular to the atom movement direction. The RF magnet field direction is depended on the type of RFT.

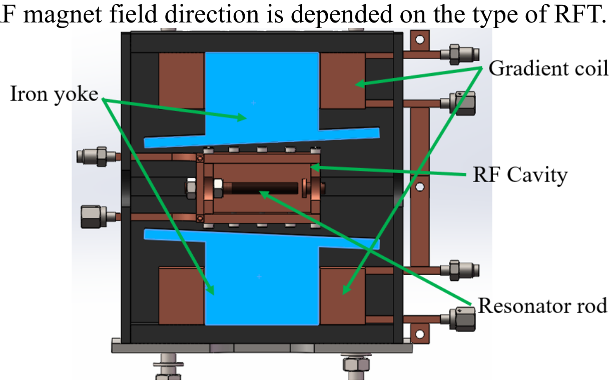

Figure 7: Schematic diagram of SFT unit with an inclined iron yoke.

RF coils provide the RF magnet field Br in both WFT and MFT units, while in SFT, the high-frequency field is generated by a strip-line resonator due to the much higher RF frequency (Fig. 7). The resonator consists of two rods. Ideally, the length of the resonator rods should be one quarter of the wavelength, but in practice, they are shortened to less than λ/4 by inserting a capacitive load at the free end. This allows for shorter high-frequency transition units and tuning of the resonator to a suitable frequency by adjusting the distance between rod[11].

For the polarized ion source in IMP, SFT H 2↔4 (1430MHz) and WFT H1↔3 (13.56MHz) is used for hydrogen, for deuterium, SFT D2↔6 (430MHz), D3↔5, MFT D1↔4 (27.12MHz), D3↔4 and WFT D1↔4, D2↔3, D5↔6 (6.78MHz) is used. MFT is located between two sets of sextupole magnets, while SFT and WFT are sequentially located behind the second set of sextupole magnets. These RF transitions can realize the pure vector polarization of hydrogen atom, and also help to generate pure vector polarization, pure tensor polarization or other types of deuterium atom.

RFT simulation for hydrogen has referred the work of Beijers [12]. Fig. 8 shows the time evolution of the state populations for WFT 1↔3, and the transition efficiency is clearly 100%.

By the simulation analysis of MFT. It is founded that the gradient part of background static magnet field provided by gradient coil is more advantageous than that of the inclined pole. And by adjusting the background static magnetic field (B0 and dB/dz) and RF magnetic field intensity Br, the transition efficiency of the three currently designed RF transition units has reached 100%

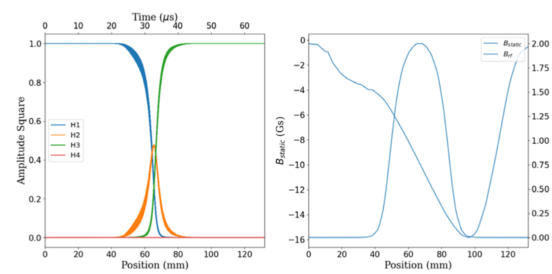

Figure 8: Time evolution of the state populations of WFT H 1↔3. The initial state is N1(z=0) = 1; B_0 is 10G, dB_0/dz is -2G/cm, B_r is 2G, the atom velocity is 2015m/s, the RF frequency is 13.56MHz. The WFT cavity is 120mm in length.

CONCLUSION

A polarized hydrogen/deuterium atomic source based on the atomic beam polarization ion source scheme is being developed by the Institute of Modern Physics for generating pulsed H^+ and D^+ ion beams. Simulations have been conducted on key physical issues, and the design of sextupole magnets and RF transition units has been completed. Currently, various components of the polarized atomic source are being manufactured, and testing is expected to be completed within a year. The successful development of this polarized atomic source will have significant implications for future particle physics research and will contribute to the ongoing efforts to advance our understanding of the fundamental nature of matter.

ACKNOWLEDGMENTS

The authors are grateful to A. S. Belov for the fruitful discussions and their insightful suggestions on the design of the polarized ion source.

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