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Pulsed Optically-Pumped Polarized H^- Ion Source Development

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Abstract

Results are presented of pulsed optically-pumped polarized H^- ion source (OPPIS) development for high energy accelerators. An atomic hydrogen beam intensity of 2×10^{18} atoms/s within the polarizer acceptance was obtained with an atomic H injector at BINP. A pulsed polarized H^- ion current of about 10–20 mA should be obtainable using this injector. Limitations on beam characteristics due to space-charge were studied. A polarization scheme to avoid space-charge limitations is considered, in which charge-exchange and spin-exchange are combined.

I. Introduction

Future polarization facilities at high energy-accelerators and colliders require polarized beam intensities similar to unpolarized beam values. Typical currents for unpolarized H^- ion sources are in the 20–50 mA range. With a lower current polarized beam the use of multi-turn charge exchange injections into a booster ring should help to store sufficient current for subsequent injection into the high-energy ring, but only a 10–20 mA source will completely solve the problem. A 1.6 mA dc polarized H- ion current was recently obtained at the TRIUMF OPPIS with a promise of further increases to the 2–3 mA range[1]. However, the ECR-type primary proton source used at the TRIUMF OPPIS has a comparatively low emission current density and high beam divergence which further limits current increases and gives rise to inefficient use of the available laser power for optical pumping.

In a pulsed source operation, suitable for application at high energy accelerators, the ECR source limitations have been overcome by using a high- brightness proton source outside the magnetic field[2]. In this paper the status of the pulsed OPPIS development is presented.

II. Polarization Technique

An advantage of OPPIS in comparison with the competing atomic beam source technique is the use of fast beams (of several keV energy). Therefore ionization to an H^- ion beam can be easily done by passing the atomic beam through a sodium ionizer cell[3]. Polarization in the OPPIS is produced via charge-exchange or spin-exchange collisions between the primary proton or atomic H beam and optically-pumped alkali-metal vapor. The acceptance of the OPPIS polarizer section is limited by the optically-pumped cell diameter (especially in dc operation due to a shortage of laser power) and by the ionizer cell diameter. The latter also determines the polarized beam emittance. Therefore the OPPIS current is completely determined by the primary beam quality. The optically-pumped cell must be situated in a high (about 25 kG) magnetic field. The closely coupled ECR proton source operating in the same field is a quite efficient configuration, but still has the above mentioned limitations.

In the proposal of high-current pulsed source development for high energy accelerators, we examined the possibilities of increasing the current in the INR-type OPPIS with a pulsed high brightness primary proton source situated outside the magnetic field[4]. In this scheme the proton beam is focussed by a solenoidal magnetic lens and neutralized in a pulsed hydrogen cell. That type of atomic H injector was primarily developed at BINP Novosibirsk for fusion plasma diagnostics applications[5]. It produces atomic H beams of 1–10 keV energies with equivalent normalized brightness up to 3 A/(mm mrad)^2. The focussed atomic hydrogen beam is then injected into a solenoid where it is first ionized in a pulsed He gas cell. Further polarization processes are the same as in the OPPIS with the ECR proton source. Due to the small initial beam divergence and the focussing, almost all the beam passing through the optically-pumped cell is within the ionizer cell acceptance. Therefore for a current density in the cell similar to the ECR-based OPPIS, the resulting polarized current will be at least 5 mA. A much higher current density was obtained in experiments on a test-bench at BINP and a resulting atomic H intensity equivalent to 360 mA was measured within a 2 cm ionizer diameter. The general pulsed OPPIS layout is presented in Fig. 1. The atomic H injector consists of a pulsed plasma generator, proton extraction system, solenoidal focussing lens and pulsed neutralizing hydrogen cell. The pulsed helium ionizing cell is biased to -1 kV, thus separating in energy protons produced in the cell from neutral atoms passing through the cell. A proton polarization of 65% was obtained with a 12 kG Rb cell magnetic field, downstream of a bending magnet that separates the unpolarized higher energy beam[2]. The cell biasing partially destroys the space-charge compensation, and leads to about 40% beam current losses. The space-charge compensation can be improved by fine grids at the cell ends.

A combined charge-exchange and spin-exchange polarization technique was recently proposed[6] to avoid the limitations of each technique and hopefully to keep the advantages of both. In this scheme, charge-exchange collisions are used for polarization of protons produced in the unbiased helium ionizer cell, and spin-exchange collisions in the high thickness optically-pumped Rb cell enhance H electron polarization to over 90%. The optically-pumped vapor thickness required for this scheme is not as high as for pure spin-exchange polarization and the optimal atomic H beam energy is 3–4 keV.

III. Atomic Hydrogen Injector Development

A BINP-type pulsed proton source schematic is presented in Fig. 2. The arc discharge is sustained between a copper cold cathode (4) and a copper anode (6). The discharge current is 400-600 A and the discharge voltage is 50–80 V. The molybdenum floating diaphragms collimate the arc-discharge channel. A short high voltage ignition pulse is applied between the triggering electrode (3) and the cathode synchronously with gas injection. The electromagnetic valve (2) produces gas pulses with a short (about 100 μs) rise time. The ion generation efficiency is increased by using anode magnetic isolation (of about 1 kG) produced by solenoid (1). The discharge produces a quasipoint plasma emitter near the anode having a density of about 10^{15} cm^{-3} and an electron temperature of about 5 eV. The full proton current is about 20 A. The plasma freely expands in vacuum and its density drops rapidly. Beyond a distance

of about r_0 = 1 cm the flow of the ion component becomes collisionless and we can consider it in terms of ion beam optics. In that way expansion is a rotation in phase-space (see Fig. 3). At a distance Z from the emitter, the ion flux has a regular radial velocity: $V(R)=V_i \times R/Z$ (R is the distance from the beam axis, V_i is the initial thermal ion velocity), and a radial velocity spread: $dV=V_i \times r_0/Z$. The current density is reduced to 0.5-1.0 A/cm^2 at a distance greater than 5 cm from the plasma generator. At that point an efficient ion extraction system can be installed which will utilize the highest possible current density beam with the low radial velocity spread. The regular radial velocity doesn't contribute to the beam emittance and can be compensated by a focussing lens for production of a low divergence beam. Only the central homogeneous part of the plasma stream, 4 cm in diameter, is used for production of the highest brightness proton beam and the extracted current is 3 A.

To take full advantage of the low plasma temperature requires a high quality ion extraction system. A high current, low energy beam can be obtained only by using a multi-aperture ion extraction system. A four-electrode multi-slit extraction system was used in the experiments. It consists of three multi-wire grids and a fourth cylindrical grounded electrode (7). The grids are made of 0.2 mm molybdenum wire. The spacing between wires is 1.0 mm. The wires are positioned on the mounting electrodes by precisely cut grooves and fastened by point-welding. The mutual grid alignment accuracy is better than 0.02 mm. For U=5–8 keV beam energy the optimal extraction is obtained by using an accel-accel extraction system with a potential distribution as follows: U-first grid, 0.85U-second grid, −0.07U-third grid and fourth electrode grounded. The gap between the first and second grids is 1.0 mm, the second and third grids −2.0 mm, the third and fourth −2.0 mm. That system gives a substantial improvement of the beam divergence, in the direction perpendicular to the wire, in comparison with a three-electrode system. The ion extraction system together with plasma expansion cup is adjustable by four screws (5) to provide the required accuracy of the low divergence beam alignment through the long polarizer.

In the experiments at BINP the optimal pulsed OPPIS geometry was closely reproduced. The OPPIS polarizing section is quite long, about 140 cm. It includes a 30 cm long He ionizer cell, a 50 cm long Rb optically-pumped cell, a 30 cm distance between the high field solenoid and ionizer solenoid for the Sona- transition, and a 30 cm long Na ionizer cell. The sodium ionizer cell is 2 cm in diameter, in order to keep the polarized beam emittance within the specified 2.0π mm mrad normalized emittance. After extraction the proton beam is focussed by the solenoidal magnetic lens (see Fig. 1) and immediately neutralized in a pulsed hydrogen cell. Precautions should be taken to provide very good space-charge compensation during beam transport and focussing. Usually ionization of residual gas and secondary emission from the cell walls provide a sufficient number of electrons for space-charge compensation. The beam should be well screened from the electric fields of the extraction system electrodes.

The atomic beam profiles measured by secondary emission detectors for the two directions corresponding to parallel and perpendicular to the wires are presented in Fig. 4. The measured profiles are Gaussian with fair accuracy: $(X,Y) = j_{max} \times \exp(-X^2/X_0^2 - Y^2/Y_0^2)$, where j_{max} = 135 mA/cm^2, X_0=1.8 cm and Y_0=3.5 cm. The 360 mA equivalent current of the atomic beam passing through a 2.0 cm diameter ionizer cell was measured with a calibrated calorimeter. This is in agreement with profile measurements.

A lower energy beam is required for the spin-exchange polarization technique and the combined spin-exchange and charge-exchange technique[6]. Experiments on beam formation at energies 1–8 keV were performed. It was found that at 1 keV energy the magnetic lens focussing does not work well because of incomplete space-charge compensation. The energy dependence of the beam profile width is presented in Fig. 5. Below 3 keV beam energy the poor space-charge compensation causes the profile width energy dependence to deviate from its expected proportionality to $1/\sqrt{E}$. 1 keV beam focussing was substantially improved by

placing a negatively biased mesh inside the lens. More experiments are required to study space-charge compensation of low energy beams. An atomic beam energy of 3–4 keV is optimal for the very promising combined polarization technique, and fortunately at this energy the beam focussing works well. Experiments on beam formation optimization for those energies are continuing.

IV. Conclusions

Experiments on atomic beam formation for pulsed OPPIS applications were performed. A 360 mA equivalent of atomic H beam intensity was obtained within a specified ionizer acceptance. A BINP-type atomic beam injector has been built for polarization tests at TRIUMF. A pulsed flashlamp-pumped Ti:sapphire laser was tested. It produces a pulsed power of several kW in a 150 μs duration pulse. We plan a 10–20 mA polarized H^- current demonstration at the operational TRIUMF OPPIS in the near future. We rely on help from the high-energy spin- physics community to push for the completion of this development in 1996.

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Figure Captions

Fig. 1. General layout for pulsed OPPIS test at the operational TRIUMF OPPIS: 1) proton source; 2) focussing solenoid; 3) hydrogen neutralizing cell; 4) super- conducting solenoid; 5) helium gas ionizing cell; 6) optically-pumped Rb vapor cell; 7) deflecting plates; 8) Sona-transition region; 9) sodium ionizer cell; 10) pumping lasers; PV-pulsed gas valves.

Fig. 2. The BINP-type high brightness proton source: 1) solenoid; 2) pulsed valve; 3) triggering electrode; 4) cathode; 5) adjusting screw; 6) anode; 7) ion extraction system.

Fig. 3. Phase-space diagram of expanding plasma: r_0 = 1 cm - a collisionless plasma range; Vimax- maximum ion velocity corresponding to 5 eV plasma temperature; dVi- radial velocity spread; 2R = 4 cm - diameter of the ion extraction system.

Fig. 4. Atomic H beam profiles at a distance 2 m from the source. X - perpendicular to the wires direction; Y - parallel to the wires direction.

Fig. 5. Dependence of the focussed beam width (parallel to the wires direction) on the beam energy. The dotted line is the expected width proportionality to $1/\sqrt{E}$.

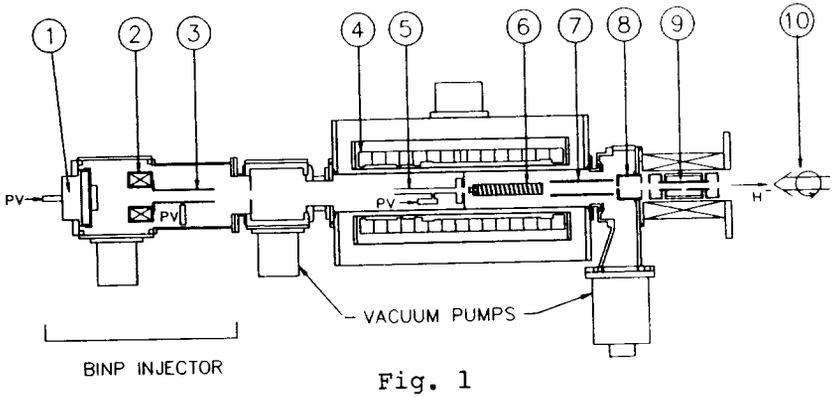

Fig. 1

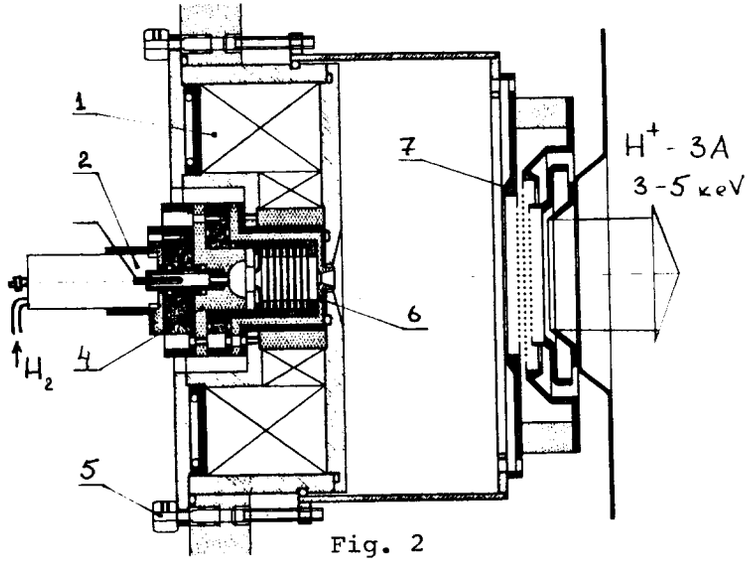

Fig. 2

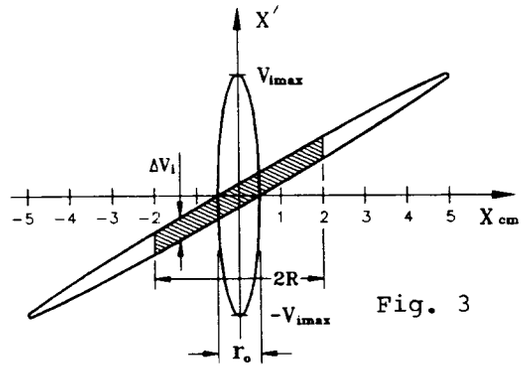

Fig. 3

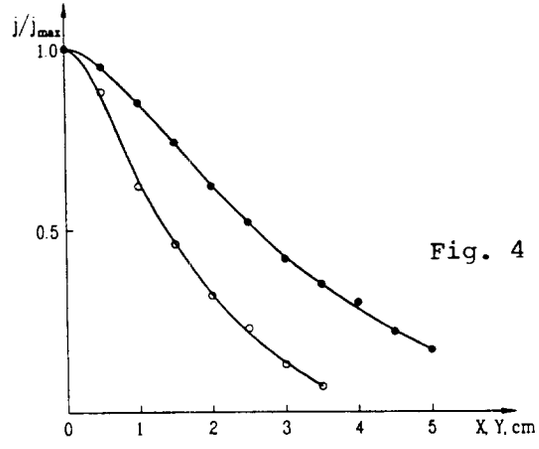

Fig. 4

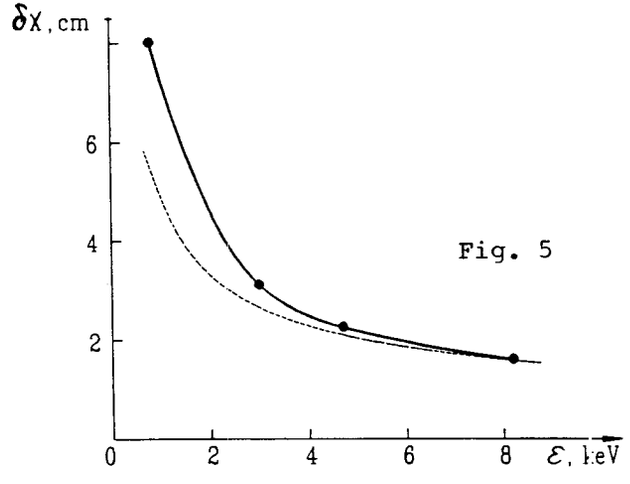

Fig. 5