High-intensity pulsed source of polarized protons with an atomic beam

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A source of polarized protons with a beam current up to 2.5 mA in the pulse, a degree of polarization 0.78 ± 0.01, a current pulse length of 120 μs, and a repetition frequency of 1 Hz is described. This is the first source of polarized protons which makes use of the charge exchange of polarized hydrogen atoms with ions of a deuterium plasma.

Increasing the intensity of pulsed sources of polarized protons is important for accelerating polarized protons in pulsed accelerators with a high duty factor of the injected beam and for research with polarized protons at high energies. Among the continuous-action sources of polarized protons which are presently available, those which offer the highest intensity (above 100 μA; Ref. 1) use an atomic beam. They operate by virtue of a spatial separation of thermal atoms in different hyperfine states in a highly nonuniform magnetic field, followed by ionization of the polarized atoms (see, for example, the review by Plis and Soroko[2]). Beams of polarized ions with currents up to 200 μA have been produced in pulsed sources of this type.[3]

In the present letter we describe a pulsed source of polarized protons with a beam current up to 2.5 mA. The source is shown schematically in Fig. 1. Atomic hydrogen

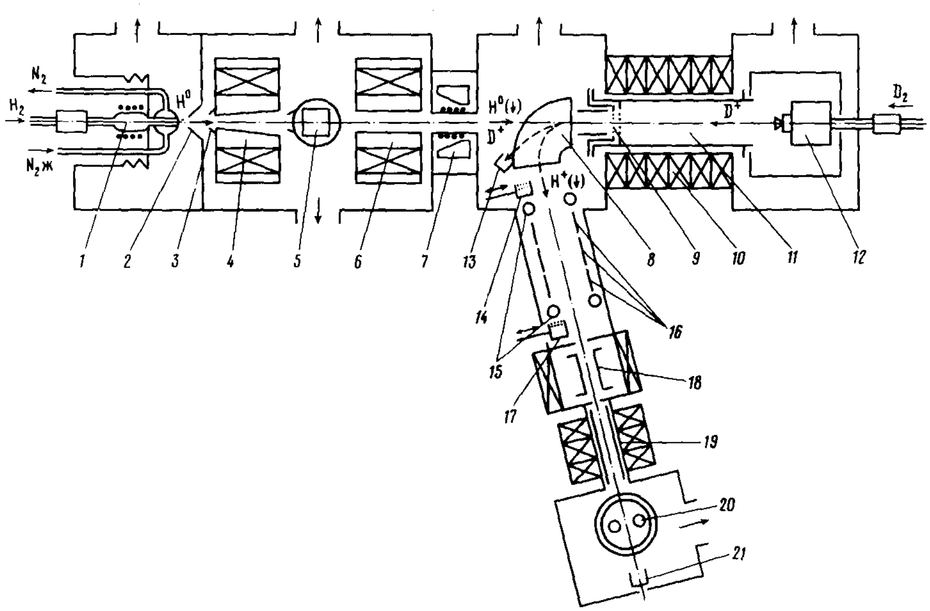

FIG. 1. The source of polarized protons and the polarimeter.

is formed in the source in a pulsed dissociator 1 with an rf discharge.[4,5] As the gas flows out of the dissociator through an acoustic nozzle 2 mm in diameter into a vacuum, a supersonic flow of atomic hydrogen is formed. In this hydrogen the most probable particle velocity is 2×10^5 cm/s, the Mach number is above 4, and the intensity is about 2.8×10^{20} atoms/(sr·s). The atomic beam is formed with the help of a skimmer 5 mm in diameter (2) and a collimator 9 mm in diameter (3).

To produce a beam of polarized hydrogen atoms, we used a combination of two hexapole magnets 4 and 6 and a unit for an rf transition in a weak field (7). At the exit from a polarization system of this sort, after the rf transition, the atoms are known[2] to be in hyperfine-structure states with $F=1$, $m_F=-1$, and $F=1$, $m_F=0$, and the polarization of the protons in the atoms (in a strong magnetic field with $B\gg507$ G) is approximately -1. The dimensions of the magnets are optimized on the basis of calculations of the paths traced out by atoms with the measured velocity distribution. The distance between the opposite pole tips in the first hexapole magnet increases from 11 mm at the entrance to 27 mm at the exit from the magnet. In the second magnet, the aperture is constant along the length of the magnet ($L=23$ cm), equal to 31 mm. The magnets are placed 35 cm apart. The maximum magnetic induction at the pole tips of the magnets is 9 kG. The time-of-flight mass spectrometer 5 is used to measure the composition and density of the hydrogen beam.

The polarized protons are produced in the source in the charge exchange of polarized atoms and deuterium ions: $H^0(\uparrow)+D^+\rightarrow H^+(\uparrow)+D^0$. To the best of our knowledge, this is the first source of polarized protons to make use of charge exchange of hydrogen atoms with ions of a deuterium plasma. This method has the fundamental advantage of a high probability for charge-exchange of the atoms, because of the large cross section for the charge-exchange process. When the velocity of the relative motion of the particles is $\sim2\times10^6$ cm/s (when the energy of the deuterium ions in the plasma is ~5 eV), the charge-exchange cross section is $\sim4\times10^{-15}$ cm^2. The charge exchange occurs in a magnetic field of about 1.2 kG, produced by a multisection solenoid 10. A deuterium plasma produced in an arc source[6] 12 is injected in pulses into the solenoid in the direction opposite the motion of the atoms. The deuterium ion current density in the plasma reaches 100 mA/cm^2 in the charge-exchange region. The polarized protons that are formed in charge-exchange region 11 are confined radially by the magnetic field of the solenoid, and they undergo an accelerated motion in the weak electric fields in the plasma toward accelerating-electrode system 9, in which the deuterium ions and the polarized protons are accelerated simultaneously. Deflecting magnet 8 spatially separates the $H^+(\uparrow)$ and D^+ beams. The currents of the ion beams are measured with Faraday cups 13, 14, and 17, which have an aperture 34 mm in diameter and in which secondary electrons are suppressed. Figure 2 shows the current of the polarized-proton beam, measured by Faraday cup 17 at a point 55 cm from the accelerating electrodes, and the current of the deuteron beam (Faraday cup 13) versus the energy to which the ions are accelerated (the density of the deuterium plasma was varied at each accelerating voltage to minimize the beam divergence). At an ion energy of 9.0 keV, we obtain a beam of polarized protons with a current of 2.5 mA.

The polarization of the proton beam is measured with a low-energy beam polarimeter.[7,8] This polarimeter consists of a gaseous sodium target 18, in which the polar-

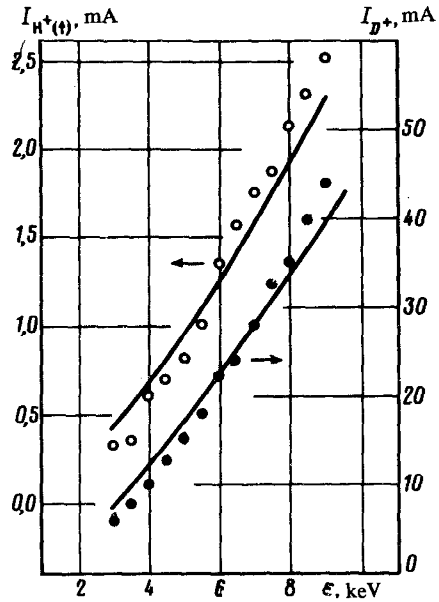

FIG. 2. The current of the beams of polarized protons and deuterium ions extracted from the source versus the ion energy. Solid line—Approximation of the experimental results by $I \propto \epsilon^{3/2}$; points—peak values of the pulsed current of $H^+(\uparrow)$ (O) and D^+ (●) ions.

ized protons undergo a partial charge exchange into metastable hydrogen atoms, $H(2S_{1/2})$; a spin filter 19, to suppress the β states of $H(2S_{1/2})$; a metastable-atom detector 20; and also an electrostatic lens for beam focusing (16), beam correctors (15), and a Faraday cup (21) to monitor the passage of the beam through the polarimeter. The polarization of the proton beam is calculated from the measured ratio of the flux densities of metastable atoms in the α state with the rf transition turned on (I_{α_1}) and off[8] (I_{α_2}): $P = 2/[1 - x/(1+x^2)^{1/2}](I_{\alpha_1}/I_{\alpha_2} - 1)$, where $x = B/B_0$, B is the magnetic induction at the sodium target (in our case, $B = 5.5$ G), and $B_0 = 63.4$ G is the critical field for $H(2S_{1/2})$. At a beam energy of 9.0 keV and a beam current of 2.5 mA, the measured degree of polarization of the protons is 0.78 ± 0.01. The reduced intensity in this source is $P^2I = 1.5$ mA—more than an order of magnitude greater than the value of P^2I which has been achieved previously in pulsed sources of this type ($P^2I = 0.07$ mA; Ref. 3). The intensity of this source could probably be increased severalfold, in particular, by increasing the plasma density in the charge-exchange region and by correspondingly increasing the proton energy.

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