PROCESS OF FORMATION OF ATOMIC HYDROGEN BEAM AND INTENSITY LIMITATIONS OF ATOMIC BEAM-TYPE POLARIZED ION SOURCES AND GASEOUS TARGETS

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Results of experimental investigation of a pulsed atomic hydrogen beam are considered. It is concluded that effects of intensity limitations observed are connected with process of formation of atomic hydrogen beam. A model is proposed for explanation of the experimental results. It is assumed that a shock-like gaseous cloud is formed close to a skimmer orifice and the atomic hydrogen beam is attenuated during passage through the gaseous cloud. Possibilities to reduce the atomic hydrogen beam attenuation are discussed.

1. Introduction

Development and improvements of atomic beam-type polarized ion sources and gaseous targets have resulted to production of polarized atomic hydrogen and deuterium beams with intensity of ~ 10^{17} cm^{-2} s^{-1} [1, 2].

Further increase of polarized atomic beam intensity is limited by several restricting processes including scattering and recombination of atoms. Scattering problem reveals itself as saturation or decrease of forward hydrogen beam intensity vs gas flow from a dissociator even for molecular hydrogen (in this case recombination problem does not exist). To eliminate the scattering problem modern polarized atomic beam-type sources (ABS) have powerful differential vacuum pumping systems. However, it was noted (see for example, [1]) that for modern ABS scattering is not defined by nonsufficient vacuum pumping because further increase of pumping speed of vacuum pumps and respective decrease of residual gas pressure does not produce notable increase of maximum achievable polarized atomic hydrogen beam intensity.

The scattering problem becomes more violent for cold atomic hydrogen beams. A.I. Hershcovitch with coauthors [3] found that for temperature of a dissociator accommodator of 6 K focusing factor for the cold atomic hydrogen beam (focusing factor was defined as ratio of densities for the beam with sextupole magnets "on" and "off") drops with increase of the atomic hydrogen beam density from value of ~ 12.8 for low density to value of ~ 2.3 for high density of the initial unfocused atomic hydrogen beam. It was supposed that this effect is explained by intra-beam scattering of hydrogen atoms during their passage through sextupole magnets [3].

E. Steffens estimated [4] that only moderate losses due to intra-beam scattering can be expected for achieved intensities of ~ 10^{17} atoms/cm^2s in present ABS's even for very large value of scattering cross-section of 1.5 10^{-14} cm^2 accepted for the estimation.

D.K. Toporkov [5] suggested that observed saturation of molecular hydrogen beam intensity and intensity limitations of ABS may be explained by "screening skimmer effect" which is connected with increase of hydrogen atoms source radial size with increase of gas flux due to increase of radius of a "freezing surface".

Experimental study of a pulsed ABS had been performed at INR, Moscow [6, 7]. Peak intensity of a polarized atomic hydrogen beam of this ABS is $2{\cdot}10^{17}$ $cm^{-2}s^{-1}$. A pulsed mode of operation of this source allows to eliminate a problem of scattering of atoms by residual gas molecules. Nevertheless, it was found that intensity of the pulsed atomic hydrogen beam is limited similar to ABS working in continuous mode of operation. It has been suggested that observed limitation of the pulsed atomic hydrogen beam intensity is connected with attenuation of the atomic beam on gas "cloud" formed inside the skimmer.

In chapter 2 of this paper results obtained in [6, 7] will be discussed in more detail. In chapter 3 a model of ABS intensity limitation connected with formation of a gaseous cloud at a skimmer will be considered. In chapter 4 possibilities to reduce the intensity limitation are discussed.

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2. Study of the Pulsed ABS of INR RAS

2.1. *Characteristics of the INR RAS polarized ion source*

Atomic beam-type polarized ion of INR RAS has resonant charge exchange plasma ionizer and produces pulsed beam of polarized protons with current up to 11 mA and polarization of 80 % or polarized negative hydrogen ion beam with peak current up to 4 mA and polarization of 90 % [7].

The hydrogen dissociator of the polarized ion source has pulsed mode of operation for RF discharge and for gas injection. RF discharge pulse duration is ~ 1 ms and repetition rate of 1-10 Hz. A characteristic time for hydrogen gas going out the dissociator tube is ~ 1 ms. Effective pumping speed for pumping out gas from the dissociator and sextupole magnet vacuum chambers is about 2500 l/s and 5000 l/s respectively. Characteristic times for pumping out the vacuum chambers are about 50 ms. For operation with repetition rate of 1 Hz residual gas pressure in the source vacuum chambers is improved during time between pulses to level about 10^{-6} mbar, and scattering of the atomic beam in the source in collisions with residual gas molecules is negligible.

For ABS operating with rep. rate of 1 Hz atomic hydrogen beam density has been measured by a time-of-flight mass spectrometer installed 35 cm downstream the sextupole magnets.

2.2. *Beam density vs. gas flux*

Typical dependencies of atomic hydrogen beam density vs. number of hydrogen molecules injected into the dissociator tube per pulse for the ABS with the sextupole magnets “on” and “off” are shown in Figure 1.

For the sextupole magnets “on” the density of the pulsed atomic hydrogen beam reaches maximum at $\sim 2.5{\cdot}10^{17}$ mol/pulse (volume of the dissociator tube is 15 cm^3). For larger fluxes the atomic hydrogen beam density decreases with increase of the gas flux.

For the sextupole magnets “off” the atomic beam density in forward direction has saturation vs. gas flux.

This means that focusing factor decreases vs. gas flux similar to behavior of polarized atomic hydrogen beam cooled to 6 K [3].

For data shown in Figure 1 the focusing factor drops from value of ~ 45 for gas flux of $2{\cdot}10^{17}$ mol/pulse to value of ~ 10 for gas flux of $8{\cdot}10^{17}$ mol/pulse.

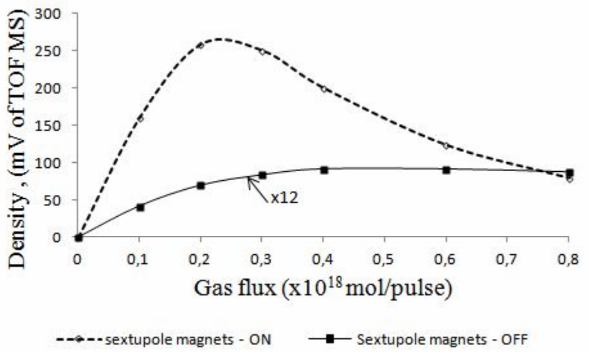

Figure 1. Polarized atomic hydrogen beam density (recorded in a middle of each pulse) vs. gas flux (number of molecules injected into the dissociator tube per pulse) for sextupole magnets “on” and “off” (sensitivity of the mass – spectrometer was increased 12 times for the sextupole magnets “off”).

2.3. *Beam density vs. the nozzle-skimmer distance*

Results of measurement of pulsed polarized atomic hydrogen beam density vs. the nozzle – skimmer distance are shown in Figure 2.

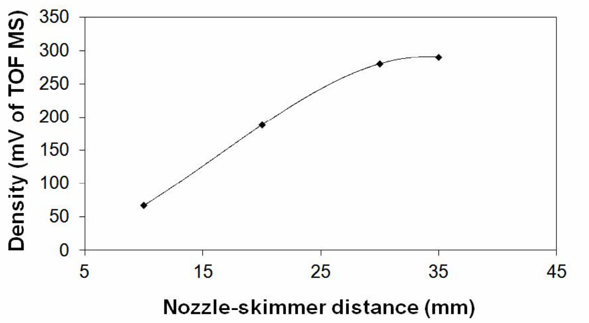

Figure 2. Polarized atomic hydrogen beam density vs. the nozzle-skimmer distance. The beam density was recorded at middle of the atomic hydrogen beam pulses.

It follows from the data of the Figure 2 that decrease of the nozzle-skimmer distance results to sharp decrease of polarized atomic hydrogen beam density downstream the sextupole magnets. The dissociator parameters were fixed for different nozzle-skimmer distances.

The polarized atomic hydrogen beam pulses for distances between the dissociator nozzle and the skimmer orifice of 10 mm and 35 mm are shown in Figure 3. The pulses have overshoot with duration of ~ 300 µs. For the nozzle-skimmer distance of 10 mm the atomic hydrogen pulse is shortening to the initial overshoot with duration of ~ 300 µs, during remaining pulse its intensity drops almost one order of magnitude.

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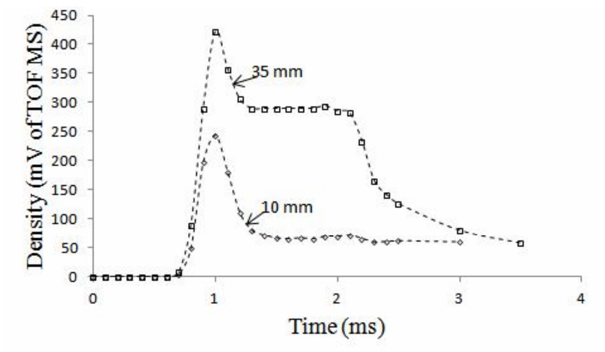

Figure 3. Polarized atomic hydrogen beam pulses for different distances (10 mm and 35 mm) between the dissociator nozzle and the skimmer orifice.

The sharp change of the polarized atomic hydrogen beam density vs nozzle-skimmer distance cannot be explained by intra-beam scattering in the sextupole magnets because acceptance angle for focusing of hydrogen atoms by sextupole magnets only weekly depends on the distance between the atoms source and the sextupole magnet entrance.

"Screening skimmer effect" also cannot be responsible for the dependence observed because decrease of distance between "freezing surface" and the skimmer orifice produces little effect on number of atoms starting from the "freezing surface" and passing through the skimmer orifice with angles 0-60 mrad accepted by the sextupole magnets of the ABS.

It was supposed in ref. [6, 7] that the effects observed are connected with attenuation of the beam in collisions with molecules of a gas "cloud" formed in the region inside the skimmer and between the skimmer and sextupole magnet. It has been shown in [7] that "beam-cloud" instability can arise for passage of molecular beam through a region which has restricted vacuum conductance for pumping. This process can lead to formation of a dense gaseous "cloud" in the region and to strong attenuation of the molecular beam due to scattering during passage the beam through the gas "cloud".

The model check has been performed with measurements of radial size of hydrogen atoms source at test bench of a pulsed ABS at COSY Juelich [8]. It was found that radial distribution of density of hydrogen atoms source has tails with size larger than diameter of a skimmer. This means that some hydrogen atoms trajectories start from region downstream the skimmer orifice indicating existence of "gas cloud" consisting from hydrogen atoms inside the skimmer. The gas cloud size (~ 10 mm) indicates that the gas cloud is situated close to the skimmer orifice.

These results of the tests lead to a model of intensity limitation of the pulsed atomic hydrogen beam which will be considered in the next section.

3. Mechanism of Intensity Limitation of Atomic Hydrogen Beam

A mechanism of intensity limitation of atomic hydrogen beam which is responsible for the experimental data described above seems to look qualitatively as follows (see illustration in Figure 4):

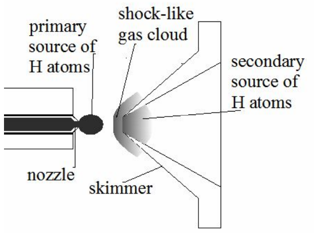

Figure 4. Picture illustrating formation of a gaseous cloud at the skimmer orifice. The primary atomic hydrogen beam is attenuated during passage through the gaseous cloud, while the gaseous cloud becomes by a secondary source of hydrogen atoms.

- atomic hydrogen beam passing through the skimmer orifice is attenuated in collisions with particles of a shock-like gaseous cloud which is originated due to interaction of atomic hydrogen jet from a dissociator nozzle with the skimmer.
- Characteristic time for origination of the gas cloud is ~ few hundreds of microseconds.
- The gaseous cloud is located near the skimmer orifice and, presumably, situated inside and outside the skimmer cone.
- The gaseous cloud becomes by a secondary source of hydrogen atoms and molecules.
- Radial size of the secondary source is significantly larger in comparison with radial size of the primary source.

Character of dependencies of atomic hydrogen beam density vs. gas flux (Figure 1) are explained in the considered model by attenuation of primary atomic hydrogen beam in the gaseous cloud and by large size of the secondary source of hydrogen atoms. With the sextupole magnets "on" the primary atomic hydrogen

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beam is attenuated in collisions with particles of the gaseous cloud while hydrogen atoms emitted by the secondary source are focused by the sextupole magnets worse due to large size of the secondary source. So, the density dependence vs. gas flux for the focused beam has form typical for attenuation due to scattering with gas molecules supplied by the beam [9]. With the sextupole magnets “off” both primary and secondary sources produce input to forward beam intensity. This leads to different character of dependencies of atomic beam density vs. gas flux for sextupole magnets “on” and “off” and to decrease of focusing factor with increase of the gas flux.

Dependence of polarized atomic hydrogen beam density vs. distance between the nozzle and the skimmer (Figure 2) is naturally explained by increase of thickness of the gas cloud for smaller nozzle-skimmer distances.

Time dependence of atomic hydrogen beam pulses (see Figure 3) evidently is determined by dynamic of formation of the gas cloud.

The model should be valid for dc ABS’s as well. In particular, it forecasts qualitatively experimentally observed [9] linear dependence of gas flux coming through a skimmer vs. nozzle flux and nonlinear dependence for molecular beam density recorded downstream a collimator because scattering takes place on gaseous cloud close to a skimmer orifice.

Similar effects including decrease of a molecular beam intensity and change of velocity distribution for small nozzle-skimmer distances or for high gas fluxes were observed in experiments with supersonic molecular beams in vacuum. The effects were explained by a beam-skimmer interference which was supposed to be formation of gaseous cloud due to interaction of supersonic molecular jet with a skimmer [10, 11].

4. Possibilities to Reduce Atomic Beam Attenuation

An efficient way to eliminate the beam-skimmer interference is increase of the nozzle-skimmer distance. From experiments with the pulsed ABS described above it follows that the optimal nozzle-skimmer distance should be larger than 35 mm (Figure 2). For higher gas fluxes even larger nozzle-skimmer distance can be necessary. Direct Simulation Monte-Carlo method [12] can be used for optimization of parameters of the beam formation system such as nozzle-skimmer distance, skimmer dimensions, etc. For the large nozzle-skimmer distance parameters of sextupole magnets should be optimized also.

5. Conclusion

Experimental data obtained from study of the pulsed ABS show that observed intensity limitation of the ABS can be connected with formation of a shock-like gaseous cloud at the skimmer orifice. Attenuation of the polarized atomic hydrogen beam is reduced with increase of the nozzle-skimmer distance. Further study is necessary for optimization of the beam forming and sextupole magnet systems.

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