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STATUS OF THE BNL COLD ATOMIC BEAM AND ITS FOCUSING MAGNETS*

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Abstract - Since the last workshop in Montana, Switzerland, output of the BNL cold atomic beam has improved by more than an order of magnitude to a flux of over 10^{20} H°/sr/s. Spin selection and focusing by three different magnets: a superconducting solenoid lens, a long permanent magnet sextupole, and a system consisting of two short permanent and electromagnet sextupoles, have been tried. Results indicate that the latter scheme is best for our particular needs.

INTRODUCTION

One aspect of the BNL program to develop an intense source of polarized H^- is the production of very cold polarized H° beams. The production of cold unpolarized H° beams has been reported[1]. Nuclear polarization of the latter is achieved by a combination of magnetic focusing (the Stern-Gerlach effect), and rf induced transitions. The original plan was to use a superconducting solenoid as the magnetic lens, and beyond it, a set of rf transition units to produce the nuclear polarization. The beam will then be ionized by a ring magnetron ionizer. A review of the entire program is given by J. Alessi in this workshop. This report deals only with the H° beam and its focusing.

Cold Atomic Beam

In Ref. 1, the setup and results are described for our first attempt to produce a high flux, low velocity H° beam by passage of the atoms through a 6 K copper accommodator section at the exit of an rf dissociator. At 6 K, time-of-flight measurements of the velocity distribution showed that the beam had a most probable velocity of 680 m/s, a FWHM of approximately 200 m/s, and a forward flux of 9.4×10^{18} H°/sr/s. (Recently, we have had strong indication, after reexamining the old data and comparing it with magnetic focusing results, that the most probable velocity is most likely about 500 m/sec). Operation of the source was

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with pulsed gas and rf for the dissociator. The source repetition rate was typically 0.5 Hz, and the H° pulse was flat for much more than 0.5 ms we require. The atomic beam stage has since been further improved, and the present configuration is shown schematically in Fig. 1. It differs from the setup in Ref. 1 in several ways. The volume of the Pyrex dissociator was reduced, allowing us to operate with a higher rf power density in the dissociator. The exit of the dissociator tube is cooled via a liquid nitrogen cooled copper clamp around the outside of the Pyrex.

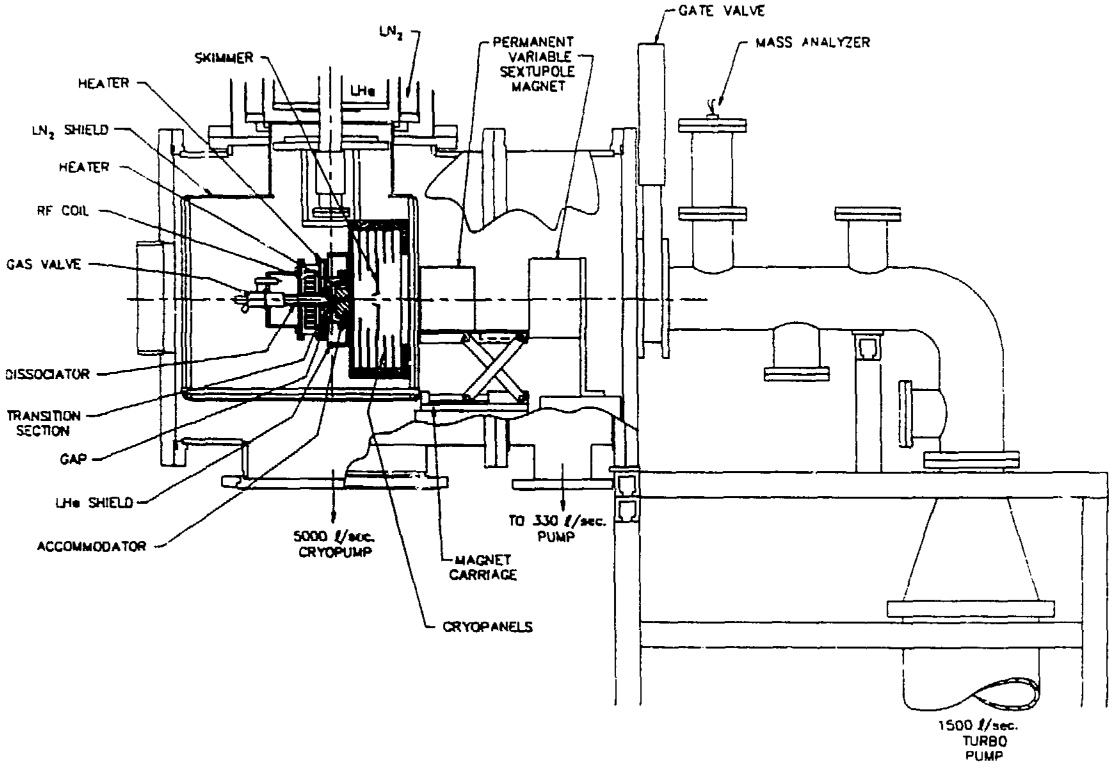

FIGURE 1 Schematic of the setup for the cold atomic beam focusing experiments.

Following this, there is a 0.3 mm gap, and then the liquid helium cooled copper accommodator. The accommodator channel has a 25 mm long, 5 mm diameter nearly straight section, followed by a 10 mm long section which tapers out to a final diameter of 10 mm. The first 70% of the accommodator channel is designed to result in frictionally choked flow, which ensures that the outlet Mach Number is independent of density. Therefore, subsequent to supersonic expansion, the final beam velocity distribution depends only on outlet Mach Number and accommodator temperature.[2] This design is based on the excellent agreement[1] between theory and experiment. The flared section followed from a suggestion of T. Niinikoski,[3] and is based on the desire to keep the H° density in the accommodator below the point where one begins to lose significant flux due to three-body recombination, while the H° velocity is decreasing.

As in the previous atomic beam source, there is a skimmer following the accommodator which is coated with charcoal and kept at 2.5 K to cryopump H_2. Now however, there is in addition, a stack of 5 charcoal coating cryopanels, (also at 2.5 K), having a combined area of about 3000 cm^2. This tremendous pumping (about 27,000 ℓ/s for the H_2 at these temperatures) ensures that scattering by any gas other than H° is insignificant.

With this new atomic beam stage, and an accommodator temperature of 6 K, a pulsed H° density of $6 \times 10^{11}/cm^3$ was measured 90.5 cm away. This density, measured via a quadrupole mass spectrometer and without any focusing of the atoms, was an improvement by a factor of 34 over the density measured with the atomic beam in Ref. 1. It should be noted that these results were obtained earlier[4] with one difference: the accommodator was followed by 10 cryopanels with a combined area of about 4500 cm^2 and a corresponding pumping speed of 40,000 ℓ/s. The 5 cryopanels were removed only very recently, and the RGA was placed closer, at a distance of 70 cm from the accommodator exit.

Magnetic Focusing

Focusing the neutral hydrogen beam with a superconducting solenoid was not successful at peak beam intensity due, we believe, to intrabeam scattering in the solenoid. This conclusion is based on the observation that focusing decreased with increasing beam density. On the basis of this observation, the H° - H° scattering cross section has been inferred[4] to be 100 Å^2, somewhat higher than values previously reported in the literature.

Modifying the solenoid to give it a more open geometry for improved pumping was not practical, hence we decided to build a 20 cm long permanent magnet sextupole having a 4 cm bore diameter and a pole-tip field of 7 kG.[5] This individual magnet from which the poles were assembled were made from Nd-Fe and specially coated to resist attack by atomic hydrogen. Azimuthally machined slots in the yoke allowed for additional (radial) pumping of the bore.

No significant focusing was observed with this magnet, and our inability to vary the magnetic field, was a serious drawback since subsequent simulations showed that the focusing was very sensitive to beam velocity. We have established that the strength of the magnet did not match the 680 m/s velocity, based on which the magnet was designed. Furthermore, correlating simulations with experimental results indicated a beam velocity in the 500 m/s range.

A TWO-MAGNET SYSTEM

The permanent magnet has now been reduced to a length of 10 cm. This will be used in conjunction with a conventional electromagnet sextupole which is also 10 cm long, has a 3.6 cm diameter aperture, and is capable of 6.3 kG pole-tip field in dc operation (cooling being the limitation) and higher, if it is pulsed. This arrangement is shown in Fig. 1. The permanent magnet will be nearer to the nozzle because its slightly larger bore and pole-tip field give it a larger acceptance. The field of the second magnet will be varied to focus the beam to the detector. The permanent magnet may also be moved axially up to 4 cm, giving us another degree of freedom in optimizing beam focus at the detector.

Simulations

We used computer simulations to determine a suitable configuration of the two magnet system. The simulations involved tracking individual atoms from the nozzle to the detector, which was placed at the position where the ring magnetron ionizer will eventually be located. The Monte Carlo technique was used to launch the atoms. The parameters which were randomly selected are (1) the speed of the atom - according to the measured supersonic velocity distribution, (2) the radial position at the tip of the nozzle - we assumed uniform flux density across the nozzle aperture, (3) the angle of elevation - we assumed a $\cos^5 \theta$ distribution but the results are not sensitive to the value of the exponent, and (4) the electron spin state - either 1/2 or - 1/2. Azimuthal motion and beam attenuation by scattering were ignored. If the detector was assumed to have a circular aperture, then particles reaching the aperture were weighted with their distances from the axis there. The focusing factor, FF, defined as the ratio

$$\frac{\text{Weighted counts at detector with magnets on}}{\text{Weighted counts at detector with magnets off}}$$

was used as the figure-of-merit to compare the efficacies of different sets of operating conditions. Results of these simulations are plotted in the figures of Ref. 6. We see that the two-magnet system we should be able to observe focusing[6] over a wide range of beam velocities, by adjusting the field of the variable magnet.

Experimental Results

Prior to this workshop, only two experimental runs were performed. In the first set of measurements, a problem developed with the accommodator cooling system. Consequently, the accommodator temperature could not be reduced below 25 K. This set of measurements was performed with the accommodator channel reduce to a 3 mm aperture (with a copper insert in the flared section), i.e., the operating conditions were identical to the "second peak" of Ref. 1. The second set of measurements was done with a 6 mm accommodator aperture, i.e., at higher H° outputs. Table 1 displays the focusing factor of the leading edge of the H° pulse, with the permanent magnet in line and the electromagnet at its maximum field, as a function of the unfocused leading edge density N_u and the accommodator temperature T_{acc}. The density values are based on RGA readings and comparison with previous data obtained at similar operating conditions (the last RGA calibration was about two years ago).

From Table I, it is obvious that the scattering problem still exists (although it is substantially reduced): The focusing factor decreases with increase in density, and it increases with the increase in accommodator temperature (forward beam velocity). Some additional characteristics of this focusing system are (1) FF kept on increasing with increasing magnetic field strength of the electromagnet sextupole.

(2) FF changed very little with axial motion of the permanent magnet sextupole. (3) Vertical position of the permanent magnet sextupole had a substantial effect on the focusing: FF reduced to 60% of its peak value when this sextupole was moved 3 mm off axis.

TABLE I Peak focusing factor versus unfocused density and accommodator temperature

T_{acc}	4.6 K	25 K
N_u		
10^{10} cm^{-3}		10.4
9.8 x 10^{10} cm^{-3}		8.8
1.6 x 10^{11} cm^{-3}	5.75	
3.5 x 10^{11}	3.6	8.29
4 x 10^{11} cm^{-3}	2.3	6.29

In conclusion, these preliminary results indicate that, although scattering still exists, this two magnet system can deliver a $\vec{H}^{\circ}$ density in excess of 10^{12} cm^{-3} into the ionizer region. With some modifications (better differential pumping, a tapered permanent sextupole, and a higher field electromagnet sextupole), $\vec{H}^{\circ}$ densities of about 10^{13} cm^{-3} are possible.

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