F. Levrero, R. Parodi and S. Terrenti:
Polarized Hydrogen Beam Target
POLARIZED HYDROGEN BEAM TARGET

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1. INTRODUCTION

A polarized hydrogen beam target to be used in high energy particle accelerators is presented

Fig. 1 - The whole apparatus.
A schematic view of the apparatus is shown in Fig.1: the atomic hydrogen beam produced by a microwave discharge in the source S passes through the hexapole magnet EX which focuses in the interaction region the atoms with the electronic spin antiparallel to the local magnetic field.

The spin–flip stage SF destroys the electron spin polarization and produces a beam with polarized nuclear spin (1).

The source, hexapole and spin–flip chambers C1, C2, C3 are evacuated by turbomolecular pumps LÉYBOLD–HERAEUS TURBOVAC 1000 (T1 and T2 in Fig.1) and TURBOVAC 360 (T3 in Fig.1) with conventional rough pumps LÉYBOLD–HERAEUS RUVAC WA 251 and TRIVAC D60A (RT and R in Fig.1).

In this note we present the first two stages of the apparatus: the atomic hydrogen source, described in section 1, and the hexapolar magnet focusing system, described in section 2, which were tested by monitoring the beam density with the quadrupolar mass spectrometer QMS. The experimental results are reported in section 3.

2. ATOMIC HYDROGEN SOURCE

Fig.2 shows a schematic drawing of the beam production system.

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Fig. 2 - The beam production system.

The A and B bottles contain respectively hydrogen and oxygen. The oxygen has an accessory function: it is mixed in amount of few percent to Hydrogen in order to improve the dissociation efficiency.

The hydrogen–oxygen mixture is supplied to the quartz tube Q which is ended by the nozzle N. The tipical nozzle throat diameter is .5 mm. The quartz tube is located in a high impedance region of a transmission line which acts as an electric field transformer (2).

The RF power for the H2 dissociation is supplied by the magnetron M. L is a RF load (NARDA 50Ω, 175 W).
The pressure upstream the capillary SC is set at values ranging from 1 to 4 abs. atm. The capillary SC has impedance much higher than the nozzle in order to set the pressure inside the quartz tube at values of a few mbar.

The \( H_2 \) throughput is measured by reading the pressure \( p_1 \) in the \( C_1 \) chamber as \( \frac{\phi_{H_2}}{1000 \text{ l/sec}} \) is the pumping speed in \( C_1 \) and the numerical factor accounts for the ionization efficiency of \( H_2 \).

The \( O_2 \) gas supply line is similar to \( H_2 \) line but the impedance of its capillary is a factor 100 higher.

The \( O_2/H_2 \) pressure ratio in the quartz tube is obtained from the measurement of the ratio \( \frac{\phi_{O_2}}{\phi_{H_2}} \), taking into account the different thermal velocities of the two species.

The magnetron M (EMS MICROTRON 200) supplies to the broad band field transformer a maximum RF power of 200 W on an output impedance of 50\( \Omega \) at a frequency of 2450 kHz.

The transmission line is ended by a 50\( \Omega \) RF load L which match the impedance of the field transformer at the output impedance of the magnetron avoiding microwave power reflection.

**Fig. 3** - The atomic hydrogen beam source.

Fig. 3 shows a sketch of the source: the quartz tube crosses the microwave transmission line in the high impedance region where the electric field is high enough to maintain the discharge in a stationary regime but not enough in order to start the discharge which has to be started by means of a H.F. sparck produced by a Tesla coil.
The discharge can be sustained at pressure values ranging from about 0.1 torr to 20 torr. Only about the 10% of the power adsorbed by the discharge is carried by the dissociated beam, while the remaining 90% is transferred to the quartz tube wall by surface and volume H recombination.

The discharge tube is cooled by a forced flow of pressurized air or cold nitrogen vapours as shown in Fig.3.

3. FOCALIZATION SYSTEM

The magnetic hexapole located in the C, chamber focuses in the interaction region the atoms with spin antiparallel to the local magnetic field.

Table 1 reports the main hexapole constructive features.

<table>
<thead>
<tr>
<th>Feature</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>external cylinder dimensions</td>
<td>190 x 100 mm</td>
</tr>
<tr>
<td>expansions dimensions</td>
<td>14 x 78 x 200 mm</td>
</tr>
<tr>
<td>number of coil winding</td>
<td>272</td>
</tr>
<tr>
<td>winding wire diameter</td>
<td>1.2 mm</td>
</tr>
<tr>
<td>coil resistance</td>
<td>2350</td>
</tr>
<tr>
<td>expansions field (50V 3A)</td>
<td>7 K Gauss</td>
</tr>
</tbody>
</table>

**TABLE 1 - Magnetic hexapole construction features**

The hexapole acts on the beam atoms as a chromatic lens, focusing in different axial points atoms having different velocities.

The system has been designed in order that atoms having velocities between 2000 m/s and 3500 m/s enter the final collimator.

3.1 Spin selection

The magnetic field inside the hexapolar magnet has cylindrical symmetry and modulus given by (4)

\[ B = B_0 \left( \frac{r}{r_0} \right)^2 \]

where \( r \) is the radius of the cylinder tangent to the magnetic expansions and \( B_0 \) is the magnetic field modulus at this cylinder. Inside the hexapole the H atoms energy levels are splitted according to the hyperfine levels diagram of Fig.4, where the single arrows refer to the electronic spin states (\( \uparrow \Rightarrow m_s = +1/2 \)) and the arrows with a bar to the nuclear spin states (\( \uparrow \Rightarrow m_n = +1/2 \)).

Only \( |b\rangle \) and \( |d\rangle \) are pure states for every field value, while \( |a\rangle \) and \( |c\rangle \) are in general mixed states. The mixing parameter \( \Theta \) in high field approaches zero asymptotically (\( \Theta \rightarrow 0 \)) according to

\[ \sin \Theta = \frac{a}{2 \alpha^{+} B} \]

where \( a \) is the energy gap in zero magnetic field, \( \mu_{e,N} = g_e e + g_n k_N \) (\( k_e, k_n \) electronic and nuclear magneton, \( g_e, g_n \) electronic and nuclear \( g \)-factors) and \( B \) the magnetic field.
Fig. 4 - Hyperfine levels of a hydrogen atom.

The force acting on the atoms in the magnetic field is radial and its modulus is

\[ F = 2\mu B \frac{r}{r_o} \]

Atoms lying in the two upper hyperfine levels have positive \( \mu \) and are focalized. On the contrary atoms lying in the lower levels are defocalized.

So the beam is electronically polarized, except for the small depolarized part present in the mixed state \( |c\rangle \).

The magnetic field must be kept at the highest possible value in order to obtain the highest beam polarization. In our apparatus we have chose a magnetic field strength of 0.7 Tesla in order to avoid the worsening of the vacuum, due to the coil outgassing, in the C\(_2\) chamber.

3.2 - Velocity selection

In magnetic fields higher than 100 Gauss the H atom motion may be described by means of the adiabatic approximation which assumes the conservation of the magnetic moment along the local direction of the field.

The atomic motion inside the hexapole is the superposition of an axial uniform motion and of a radial motion which, in the adiabatic approximation, is harmonic with frequency

\[ \omega = \frac{2\mu B}{r_o m} \approx 2 \cdot 10^6 \text{ s}^{-1} \]

where \( \mu \) is the \( \mu \) component parallel to the local field and \( m \) is the H mass.

The typical situation is shown in Fig. 5.
The detailed calculations of the trajectories was performed by using the transfer matrix method in the paraxial approximation.

The focal point of the magnetic system is given by the solution of the following equation (5):

\[
\cotg \frac{\omega}{V} L_0 = \frac{\omega}{V} \frac{L_1}{L_0} \frac{L_2 - V^2/\omega^2}{L_1 + L_2}
\]

where \( V \) is the atom velocity, \( \omega \) the harmonic radial motion frequency and \( L_0, L_1, L_2 \) the distances shown in Fig. 5.

The acceptance \( \Omega \) of the system i.e. the solid angle, centered on the nozzle, inside which atoms are transmitted is

\[
\Omega = \pi \frac{r_0^2 \omega^2}{v^2 + \omega L_1 L_2}
\]

if the final collimator (of radius \( r_0 \)) does not causes atom losses, and is

\[
\Omega = \pi \left[ \cos \frac{\omega}{V} L_0 - \frac{\omega}{V} L_2 \sin \frac{\omega}{V} L_0 \right]^2 \frac{r_0^2}{d^2}
\]

in the opposite case.

We have computed focal distances and acceptance for different velocities and for some values of geometrical parameters \( L_0, L_1 \) and \( L_2 \).

Typical results are reported in Table 2.

A plot of the system acceptance versus the velocity is shown in Fig. 6 while Fig. 7 shows the velocity distribution of the beam entering the final collimator calculated as product of the acceptance by the maxwellian distribution of the atoms emerging from the nozzle.
Fig. 6 - System acceptance versus velocity

Fig. 7 - Velocity distribution of the beam entering the final collimator.
$L_1 = 5 \text{ cm}$  \hspace{1cm} $L_c = 20 \text{ cm}$

<table>
<thead>
<tr>
<th>VELOCITY (m/s)</th>
<th>FOCAL (cm)</th>
<th>ACCEPT. (sterad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2284</td>
<td>10</td>
<td>$3.8 \times 10^{-3}$</td>
</tr>
<tr>
<td>2360</td>
<td>12</td>
<td>$3.6 \times 10^{-3}$</td>
</tr>
<tr>
<td>2427</td>
<td>14</td>
<td>$3.4 \times 10^{-3}$</td>
</tr>
<tr>
<td>2487</td>
<td>16</td>
<td>$3.3 \times 10^{-3}$</td>
</tr>
<tr>
<td>2540</td>
<td>18</td>
<td>$3.2 \times 10^{-3}$</td>
</tr>
<tr>
<td>2588</td>
<td>20</td>
<td>$3.1 \times 10^{-3}$</td>
</tr>
<tr>
<td>2670</td>
<td>24</td>
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</tr>
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<tr>
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<td>2972</td>
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<td>$2.4 \times 10^{-3}$</td>
</tr>
<tr>
<td>3036</td>
<td>60</td>
<td>$2.3 \times 10^{-3}$</td>
</tr>
<tr>
<td>3085</td>
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<td>3185</td>
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<td>100</td>
<td>$2.1 \times 10^{-3}$</td>
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<td>3226</td>
<td>120</td>
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<tr>
<td>3258</td>
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<td>$2.1 \times 10^{-3}$</td>
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<td>3283</td>
<td>160</td>
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<tr>
<td>3302</td>
<td>180</td>
<td>$2.0 \times 10^{-3}$</td>
</tr>
<tr>
<td>3318</td>
<td>200</td>
<td>$2.0 \times 10^{-3}$</td>
</tr>
</tbody>
</table>

**Table 2** - Focalization distances and acceptance for various velocities of atoms.

4. EXPERIMENTAL RESULTS

We have measured the H and $H_2$ signals on the mass spectrometer for a few different nozzle diameters and for various pressures in the quartz tube.

![Signal and Background](image)

**Fig. 8** - The QMS signal
The chopped signal in Fig.8 is due to the beam both for H and H₂.

The background H signal is negligible and is mainly due to the H₂O dissociation in the ionization region of the detector. The H₂ background signal is proportional to the H₂ density in the detector chamber due to the randomization of the H₂ beam molecules and to the recombination followed by randomization of the H beam atoms.

We have calibrated the QMS signal in absolute density accounting that the H₂ background signal corresponds to the density

\[ n_{H_2} = \frac{\Delta p}{kT} \]

where \( \Delta p \) is the pressure rise measured in the detector chamber due to the beam. For the chopped H signal the ratio of the ionization efficiency for H and H₂, which is 0.67, was taken into account.

One set of measurements is reported in Table 1.

<table>
<thead>
<tr>
<th>Nozzle (torr/sec)</th>
<th>P (mbar)</th>
<th>( n_{H_2} ) backg (molecules/cm³)</th>
<th>( n_{H_2} ) beam (molecules/cm³)</th>
<th>( n_{H} ) beam HEX OFF (atoms/cm³)</th>
<th>( n_{H} ) beam HEX ON (atoms/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.16</td>
<td>9 \times 10⁻⁷</td>
<td>2.2 \times 10¹⁰</td>
<td>3.6 \times 10⁹</td>
<td>3.1 \times 10⁹</td>
<td>9.4 \times 10⁹</td>
</tr>
</tbody>
</table>

The dissociation degree of the beam is

\[ D = \frac{n_{H}^{OFF}}{n_{H}^{OFF} + 2n_{H_2}} = 30\% \]

The polarization degree of the beam is

\[ P = \frac{n_{H}^{ON} + n_{H_2}}{n_{H}^{ON} + 2n_{H_2}} = 79\% \]

5. ACKNOWLEDGEMENTS

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6. REFERENCES

(5) F. Levrero, "Realizzazione di un bersaglio di idrogeno gassoso polarizzato per esperimenti di fisica subnucleare", tesi di laurea, Genova.