AN O_2 SHEET BEAM GENERATOR FOR A NON-DESTRUCTIVE BEAM PROFILE MONITOR

T. Fujisawa. NIRS, Chiba, Japan
Y. Hashimoto and T. Morimoto, KEK, Tsukuba, Japan

Abstract

An oxygen molecular sheet beam was generated by using a nozzle beam method and focused with a multi-pole magnet. The principle and calculations of the focusing effect are discussed and the preliminary experimental results are shown.

1. INTRODUCTION

A highly dense neutral gas beam is required as a target of a non-destructive beam profile monitor whose schematic view is shown in Fig. 1[1]. An oxygen molecular sheet beam is obtained in the gas jet chamber by using the nozzle beam method [2]. The sheet beam runs to the detector chamber through the slit chamber and the magnet chamber. In the slit chamber, the diverged molecules are rejected and in the magnet chamber parts of the beam are focused at the median plane with the multi-pole magnet. In the monitor chamber the sheet beam collides with an ion beam to detect the beam profile.

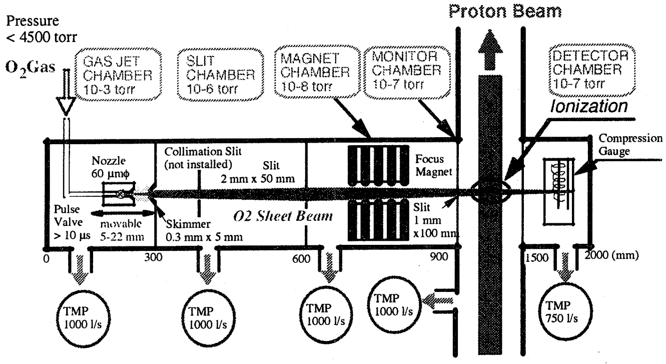


Fig. 1. Schematic view of a beam profile monitor

The method to focus the sheet beam with the multi-pole magnet is based on the fact that an oxygen molecule has a magnetic moment of as large as 2 Bohr magnetons and a spin of 1. The similar method is applied in an atomic beam type polarized proton ion source [3]. In a polarized proton ion source, hydrogen atoms pass through along a center axis of a six-pole separation magnet. In a present case, however, since a molecular oxygen beam is not cylindrical but a sheet beam, the gradient of the inhomogeneous magnetic field has to be up-down symmetry and uniform along the beam width.

The beam profile monitor has been fabricated and studied by using an 8 Mev proton beam extracted from the NIRS cyclotron. A clear beam profile has been observed[4].

2. PRINCIPLES AND BASIC CALCULATION

2-1 Estimation of Focusing Force

In terms of the classical mechanics, a particle having a magnetic moment associated with a spin(s) precesses about the orientation of an external magnetic field (H) with the Larmor frequency (ν) given by

$$\nu = g\mu sH/h, \qquad (1)$$

where g, μ, and h are the gyro-magnetic ratio, the Bohr magneton, and the Plank constant, respectively. On the other hand, the product of hν is interpreted quantum -mechanically as an energy shift caused by an external magnetic field. Thus, a particle having a magnetic moment associated with a spin acquires an extra energy (W) in an external magnetic field as expressed

$$W = g\mu mH \qquad (2),$$

where m is the z component of the spin.

From Eq. (2), the force acting on the particle in an inhomogeneous magnetic field is given by

$$F = -\,\mathrm{grad}\,(g\mu mH). \qquad (3).$$

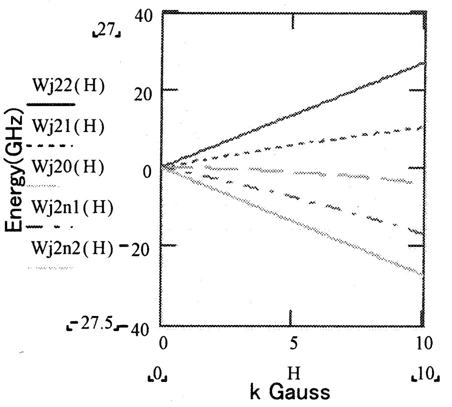
This force is familiar in the Stern-Gerlach experiment. If the g and m are independent of a magnetic field, Eq. (3) is rewritten as

$$F = -g\mu m \cdot \mathrm{grad}(H) \qquad (4).$$

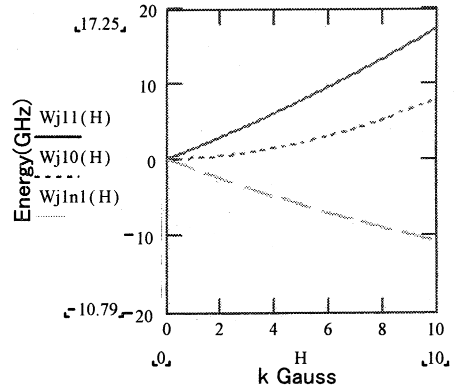
The magnitude of F for m=1 is calculated to be 5.6×10^{-16} dyne when the magnitude of grad(H) is 30 k gauss/cm which is realized in a usual polarized proton ion source [5,6]. The strength of this force corresponds to the acceleration of 1.04×10^{7} cm/sec^2 for a particle whose mass is 32 atomic mass units. The mean velocity of O_2 molecules is expected to be 73000 cm/s in the nozzle beam. On the above-mentioned conditions, if the field length along the beam path is 5cm, a focal length of the beam having a width of 5 mm is estimated to be 25 cm. It, however, is noteworthy that if particles on the m=1 state are converged, those on the m=-1 are diverged and particles on the m=0 state are not deflected.

2-2 Rotational Levels of an Oxygen Molecule

An oxygen molecule is not spherical, and normally rotating. Thus, it is necessary to take account of the coupling between the rotational angular momentum (K) and the spin (s) [7,8] in the calculations of the focusing effect. Figure 2 shows energy levels of K=1 given by Tinkham[9]. The other levels are not discussed here because the temperature of the nozzle beam gas is assumed to be several °K and the level energy of K=3 is 27 °K higher than that of K=1 in no magnetic field. The symbols J and M are quantum numbers of a total angular momentum (J=K+s) and of its magnetic sub state. The energy shift of M=2 (-2) is nearly same to that of m=1(-1) discussed in Section 2-1.



J = 2 (M= 2, 1, 0, −1, −2,)



J = 1 (M= 1, 0, −1)

Fig.2. Levels of an oxygen molecule for K=1 in a magnetic field.[9] The other states are shown in Ref. 9.

2-3 Adiabatic Passage

A magnetic moment of a particle is not polarized in space but with respect to the orientation of the external magnetic field, provided the field direction changes slowly (adiabatic change). However, the polarization is disturbed by a rapid change of the magnetic field comparable or faster than the Lamar frequency(ν). From Eq. (1), the Lamar frequency is calculated to be 2.8 GHz at the magnetic field of 1 k gauss.

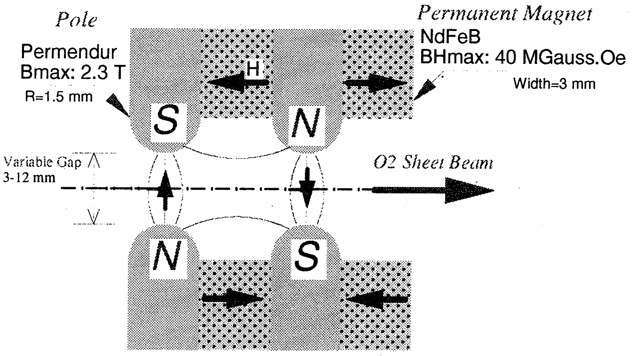


Fig.3. Cross-sectional view of the focusing magnet. The magnetic field gradient is up-down symmetry. The fabricated magnet consists of 26 pairs of poles.

In the arrangement of magnets as shown in Fig. 3, the direction of the magnetic field changes from 90 to -90 degree in the distance of 6 mm. If the velocity of the particle in the nozzle beam is 700 m/sec , it takes 8.6 μ sec for a particle to pass through the distance of 6 mm. During the period of 8.6 μ sec, the direction of magnetic moment precesses 24000 times in the magnetic field of 1 k gauss. Since the magnetic field is higher than 1 k gauss in the most of the focusing area, the direction of the magnetic moment is expected to follow the orientation of the magnetic field[6].

2-4 Velocity Distributions

To estimate the focusing effect it is necessary to take account of the velocity distribution of particles in the gas. The velocity distribution f(v) of particles in the nozzle beam is given by[2]

$$f(v)=av^2\exp(-m_p(v-u_0)^2/2k_bT_1),$$

where a, m_p, u_0, k_b, and T_1 are a normalization constant, the mass of particle, the mean velocity of the gas, the Boltzmann constant and the temperature of the gas, respectively. Figure 4 shows an example of $T_1=10^\circ$ K. Thus the beam intensity distribution is given by the equation of $vf(v)= av^3\exp(-m_p(v-u_0)^2/2k_bT_1)$. From Fig. 4, it seems that the aberration due to the velocity distribution is not so serious if the gas is cooled at the temperature of 10 °K .

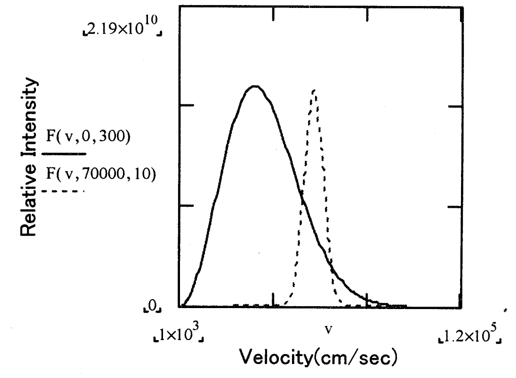


Fig. 4. Velocity distributions of the nozzle beam gas (dotted line) and Maxwell Boltzmann distribution (solid line).

3. FOCUSING MAGNET

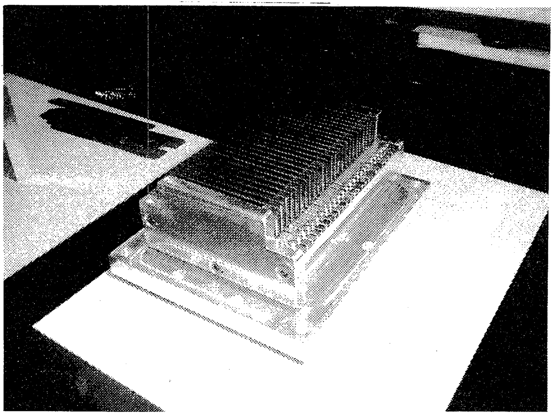


Fig.5. Upper poles of the focusing magnet.

The cross-sectional view of the focusing magnet fabricated is shown in Fig. 3 (1) and the picture is shown in Fig.5. Material of permanent magnets is NdBFe and the poles are made of Permendur (high permeability material). The width of the magnet is 70 mm and the length 150 mm. The pole gap is variable in a range of 3 to 14 mm to adjust the field strength. The magnetic fields are measured with a hole unit whose sensitive area is 70 μm×70 μm. In a case of 5 mm pole gap, the magnetic field is shown in Fig. 6.

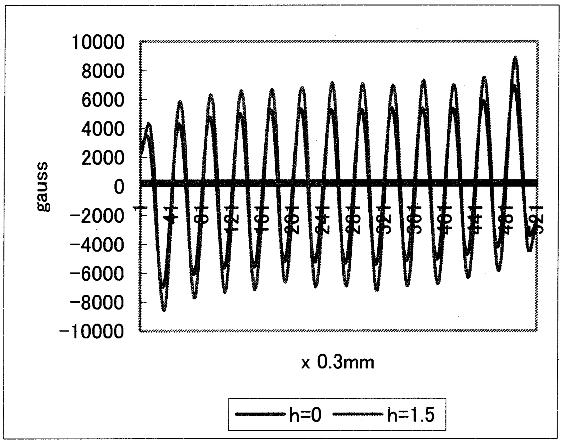


Fig. 6. Magnetic field distribution along the beam path. The gap between the poles is 5 mm and the parameters are distance from the median plane.

4. FOCUSING EFFECT

The distance between the skimmer (beam source) and the magnet center is 56 cm, and the ion beam profile is measured at the colliding position of 50 cm distance from the magnet. The intensity distribution of the O_2 sheet beam on the colliding position is calculated assuming that the temperature of the nozzle beam is 10 °K, the mean velocity is 730m/sec, the rotational quantum number (K) is 1, the populations of magnetic sub-states (M) are even, and the focal length of the M=0 sub-state is infinite. The results are shown in Fig.7.

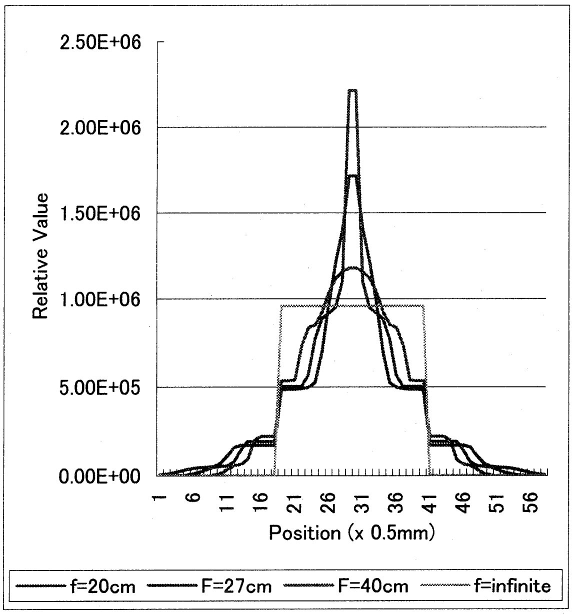


Fig. 7. Calculated vertical intensity distributions of an O_2 sheet beam. The parameters of F are focal lengths of the velocity of 730 m/sec.

The intensity distribution on the focal plane is measured with the compression gauge method. The compression chamber has a small slit (0.5(h) x 14(w) mm (1)) and a B-A gauge is installed in it. Moving the gauge along the focal plane, the spatial intensity distribution was measured. Figure 8 shows the vertical intensity distribution measured on the colliding position. The best focusing is obtained at the gap of 7 mm and the focusing effect is observed at the gap of even 14 mm. It seems that the intensity at the median plane increases up to two times of that without the magnet. From the calculation as shown in Fig.7, the gap of 7 mm corresponds to the focal length of 20 cm.

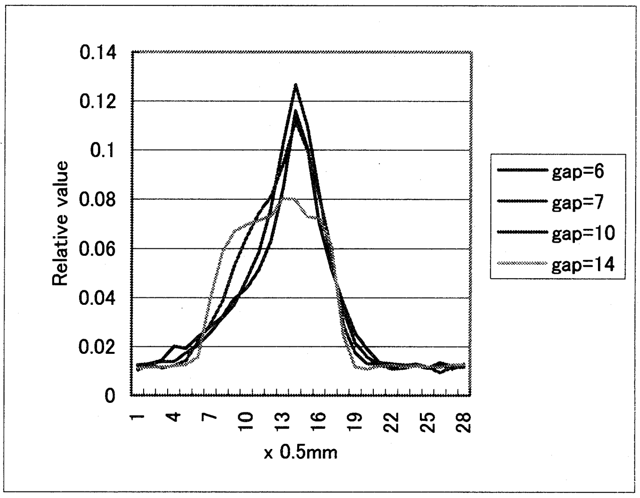


Fig. 8. Measured vertical intensity distribution of an O_2 sheet beam. The parameters are the pole gaps.

5. CONCLUSION

The focusing effects of inhomogeneous magnetic fields for an O_2 sheet beam have been proved. The intensity at the median plane increases up to about two times.

References

1) Y. Hashimoto et al. Proc. 7th Euro. Particle Accel. Conf.(2000)1729.
2) A. Kantrowitz and J. Grey, Rev. Sci. Instr. 2, 328 (1951).
3) G. Clausnitzer, et al, Z. Physik, 144, (1956) 336.
4) Y. Hashimoto, et al, PAC(2001)(Chicago).
5) T. Fujisawa, Scientific Paper of I.P.C.R. 77, (1983) 117.
6) W. Haeberli, Annual Rev. Nucl. Sci. 17(1967)373.
7) M. Tinkham and M. W.P. Strandberg, Phys. Rev. 97, No.4 (1954) 937 and 951.
8) J.M. Hendrie and Kusch, Phys. Rev. 107, No.3 (1957) 716.
9) M. Tinkham, MIT, PhD thesis(1954).