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A HIGH-PASS, MECHANICAL VELOCITY FILTER FOR FAST NEUTRAL MOLECULAR BEAMS

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16. Abstract

The transmission characteristics of a mechanical velocity filter are analyzed, and a design is described in which mean velocity of transmitted beam divided by rotor speed is equal to 5.99×10^{3} centimeters per revolution. Preliminary results for operation of the velocity filter with a fast cesium atom beam are presented.

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A HIGH-PASS, MECHANICAL VELOCITY FILTER FOR FAST NEUTRAL MOLECULAR BEAMS

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SUMMARY

The transmission characteristics of a mechanical velocity filter are analyzed for time-independent particle beams. Results are presented for a monochromatic beam of particles of velocity v_0 and for a rectangular velocity distribution centered at v_0 with a full width of $2\Delta v$. The problem arising from a slight misalinement of the filter axis and the beam is also discussed.

A design is described in which the ratio of the cutoff velocity to the rotor speed is equal to 5.99×10^3 centimeters per revolution. Results of the operation of the filter in analyzing the velocity distribution of a fast cesium atom beam are presented.

INTRODUCTION

The use of rotating helical slots to select velocities from atomic and molecular beams has become a standard technique. In practice the rotor is constructed of slotted disks placed in careful angular alinement with axial spacings chosen to provide a unique helical path through the slot configuration (Hostettler and Bernstein, ref. 1; Kinsey, ref. 2). Velocity resolutions of 3 to 5 percent are typical, and molecular speeds up to 6×10^5 centimeters per second have been measured when the rotor speed is extended to 40 000 rpm (Trujillo, Rol, and Rothe, ref. 3). The need for measuring considerably higher velocities in some molecular beam studies is anticipated, as for example in the analysis of the neutral products arising in ion, molecule reactions. This report describes the design and preliminary tests of a mechanical velocity filter which is capable of yielding information about a molecular velocity distribution centered about a high mean velocity without resorting to high rotor speeds. With the filter a molecular

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velocity of 1.5×10^6 centimeters per second can be measured with a rotor speed of 15 000 rpm.

TRANSMISSION CHARACTERISTICS

The filter described is essentially a modified slotted disk velocity selector of the Hostettler and Bernstein type with zero pitch; that is, all pass channels are alined parallel to the axis of rotation. Hence, for open shutter times that are long compared to the transit time down the axis of the rotor, the channels operate as a standard beam chopper. However, as the open shutter time approaches the axial transit time, the probability of transmitting a particle of velocity v depends both on the time of its admittance relative to the opening of the channel and on the angular velocity of the rotor.

The transmission of a finite beam where the width is comparable to the pass channel slot width can be easily constructed from the results for a narrow line beam. Thus, we consider the case of a line beam of unit intensity and velocity distribution $I(v)$ incident on the structure shown in figure 1.

For a narrow, time-independent source of particles alined with the axis of the discriminator the time-averaged transmission $\overline{T}$ is defined by

$$\overline{T} = \frac{2\pi R\Omega}{l_1 + l_2} \int_0^{(l_1+l_2)/2\pi R\Omega} \int_0^{\infty} P(v,t)I(v)\, dv\, dt \tag{1}$$

where $P(v,t)$ is the probability that at time t a particle with velocity v will be transmitted. The time axis origin has been chosen to be coincident with the opening of the pass channel slot. The remaining symbols are defined in figure 1.

A beam particle will be transmitted through the velocity filter only if the axial transit time is less than or equal to the time remaining in the shutter. This condition is given by

$$v_{min} \geq \frac{2\pi R\Omega L}{l_1\left(1 - \frac{2\pi R\Omega t}{l_1}\right)} \qquad \text{for} \quad 0 \leq t \leq \frac{l_1}{2\pi R\Omega} \tag{2a}$$

$$v_m = \frac{2\pi R\Omega L}{l_1} \tag{2b}$$

$$v_{min} \geq \frac{v_m}{1 - \frac{v_m t}{L}} \tag{2c}$$

where v_m is the minimum velocity capable of transmission at a rotor speed of Ω. The axial spacing of the six disks shown in figure 1 is chosen to interrupt particle trajectories with pitch greater than l_1/L (velocity less than v_m).

The form of $P(v,t)$ is shown in figure 2. The limiting values of $P(v,t)$ are $P(v,t) = 0$ for $l_1/2\pi R\Omega < t < (l_1 + l_2)/2\pi R\Omega$ and all v, since the tooth of width l_2 blocks the beam; $P(v,t) = 1$ for $0 \leq t \leq l_1/2\pi R\Omega$ and $v \to \infty$, since the rotor operates as a standard beam chopper; and $P(v,t) = 1$ for only a fraction of the total open shutter time of $l_1/2\pi R\Omega$ for velocities $v \geq v_m$ and $t \geq 0$. This last condition is given by

$$t(v) = \frac{l_1}{2\pi R\Omega}\left(1 - \frac{v_m}{v}\right) \quad \text{for } v \geq v_m \tag{3}$$

The time-averaged transmission $\overline{T}$ then becomes

$$\overline{T} = \frac{2\pi R\Omega}{l_1 + l_2} \int_0^{l_1/2\pi R\Omega} \int_{v_m/\left[1-(2\pi R\Omega t/l_1)\right]}^{\infty} P(v,t)I(v)\, dv\, dt \tag{4}$$

since $P(v,t) = 0$ for $l_1/2\pi R\Omega \leq t \leq (l_1 + l_2)/2\pi R\Omega$. When the relations among v_{min}, v_m, t, and $P(v,t)$ are used to interchange the order of the double integration in the (v,t) plane, they yield

$$\overline{T} = \frac{2\pi R\Omega}{l_1 + l_2} \int_0^{(l_1/2\pi R\Omega)\left[1-(v_m/v)\right]} dt \int_{v_m}^{\infty} I(v)\, dv \tag{5a}$$

$$\overline{T} = \frac{l_1}{l_1 + l_2} \int_{v_m}^{\infty} \left(1 - \frac{v_m}{v}\right) I(v)\, dv \quad \text{for } v \geq v_m \tag{5b}$$

$$\overline{T} = 0 \quad \text{for } v < v_m \tag{5c}$$

To illustrate the operation of the filter, we consider the transmission of a beam of particles with velocity v_o and also the transmission of a beam of particles with a mean velocity of v_o and a full width of $2\Delta v$.

The result for particles of unit intensity and velocity v_o is obtainable at once from equation (5), since $I(v) = \delta\,(v - v_o)$.

$$\left.\begin{aligned} \overline{T} &= \frac{l_1}{l_1 + l_2}\left(1 - \frac{v_m}{v_o}\right) && \text{for } v_o \geq v_m \\ \overline{T} &= 0 && \text{for } v_o < v_m \end{aligned}\right\} \tag{6}$$

Equation (6) shows that, as the rotor speed is increased, the transmission falls linearly towards cutoff at $v_m = v_o$.

The transmission of a unit intensity rectangular beam of full width $2\Delta v$ centered at v_o is given by

$$\left.\begin{aligned} \overline{T} &= \frac{l_1}{l_1 + l_2}\left[1 - \frac{v_m}{2\Delta v}\ln\left(\frac{v_o + \Delta v}{v_o - \Delta v}\right)\right] && \text{for } v_o - v \geq v_m \geq 0 \\ \overline{T} &= \frac{l_1}{l_1 + l_2}\left[\frac{v_o + \Delta v - v_m}{2\Delta v} - \frac{v_m}{2\Delta v}\ln\left(\frac{v_o + \Delta v}{v_m}\right)\right] && \text{for } v_o + \Delta v \geq v_m \geq v_o - v \\ \overline{T} &= 0 && \text{for } v_m \geq v_o + \Delta v \end{aligned}\right\} \tag{7}$$

Equation (7) shows that this transmission decreases linearly with increasing v_m for $0 \leq v_m \leq v_o - \Delta v$. The linearly extrapolated intercept v_{mo} at $\overline{T} = 0$ is given by

$$v_{mo} = \frac{2\Delta v}{\ln\left(\dfrac{v_o + \Delta v}{v_o - \Delta v}\right)} \simeq v_o \tag{8}$$

where the approximation is for $(\Delta v/v_o)^2 << 1$. Hence, an extrapolation of the experimental transmission curve to zero transmission will yield the mean velocity of the beam particles. Analysis of the region of the transmission curve near cutoff yields information about the velocity spread in the incident beam.

If the beam axis is misalined with respect to the rotor axis by a few degrees, extrapolation of the linear portion of the transmission curve does not give $v_{mo} \simeq v_o$. It can easily be shown that, if the misalinement is by an angle α (taken as positive in the direction of rotation), extrapolation yields

$$v_{mo} = v_o\left(1 + \frac{L}{l_1}\tan\alpha\right) \tag{9}$$

Essentially the open shutter time for a velocity is increased or decreased by $L \tan\alpha$ depending upon the sign of α. Therefore, if transmission curves are recorded for both directions of rotation (at constant beam velocity distribution conditions) and each is extrapolated to zero transmission, the larger value of v_{mo} is the result of rotation in the direction of misalinement. When the beam and rotor axes are in perfect alinement, the transmission and the extrapolated intercepts are independent of the direction of rotation. This property can be used to aline the beam with the rotor axis.

EXPERIMENTAL TEST OF THE FILTER

The filter disks were machined for use in a velocity selector of the Hostettler and Bernstein design. The rotor assembly, mounting-frame, and drive-motor, as well as other details of the overall facility have been described elsewhere (Manista and Sheldon, ref. 4). The rotor dimensions inserted in equation (2b) give the relation $v_m/\Omega = 5.99\times10^3$ centimeters per revolution. The angular speed of the rotor is monitored by a light pulse tachometer system.

Preliminary tests of the filter have been conducted by operating it in conjunction with a fast cesium atom source designed after that of Rubin, Dittner, and Bederson (ref. 5). A schematic of the apparatus is shown in figure 3. Cesium vapor from the charge-exchange chamber is ionized upon striking the surface of the tantalum cathode, which is heated by an electron gun. Ions are extracted and accelerated toward the grid by the 90-volt potential difference between the target and the grid. The overall ion acceleration is determined by the voltage between the cathode and the grounded charge-exchange chamber. Ions which fail to be neutralized in the chamber are removed from the beam by 600 volts applied across parallel plates along the beam path. The neutral beam is detected by a surface ionization technique.

Typical operating conditions are cesium reservoir temperature, 95° C; charge-exchange chamber temperature, 200° C; and background pressure in the vacuum envelope, 3×10^{-7} torr.

In the present apparatus, alinement of the fast beam, the rotor axis, and the detector is facilitated during operation by the adjustment of the collimating slit and detector with push rods which pass through the vacuum chamber wall. Extrapolated intercepts were obtained from experimental transmission curves for both directions of rotation and several detector positions. The beam was considered alined when the difference between the extrapolated intercepts for both directions of rotation was a few rps. The collimating slit was then centered at this detector position.

After alinement the velocity filter was used to determine the mean velocity of the fast neutral cesium atoms for various ion accelerating voltages applied to the source. Typical data are presented in figure 4. The transmission of thermal cesium atoms from the charge-exchange chamber was negligible for rotor speeds above 20 rps. The linear extrapolation (dashed line) to zero transmission indicates $v_0 = 1.18\times10^6$ centimeters per second. The solid curve is a plot of equation (7) for this value of v_0 and $\Delta V = 0.3\times10^6$ centimeters per second. The velocity $v_0 + \Delta v$ corresponds to an energy of 152 electron volts, which compares favorably with the applied acceleration voltage of 150 volts.

CONCLUDING REMARKS

The transmission characteristics of the velocity filter were derived for a beam of particles of velocity v_0 and for a beam of particles with a rectangular velocity distribution centered at v_0 with a full width of $2\Delta v$. The filter was used to analyze a fast cesium atom beam produced by the charge-exchange mechanism. Good agreement was found between the maximum expected atom energy and the maximum ion energy.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, May 13, 1971,
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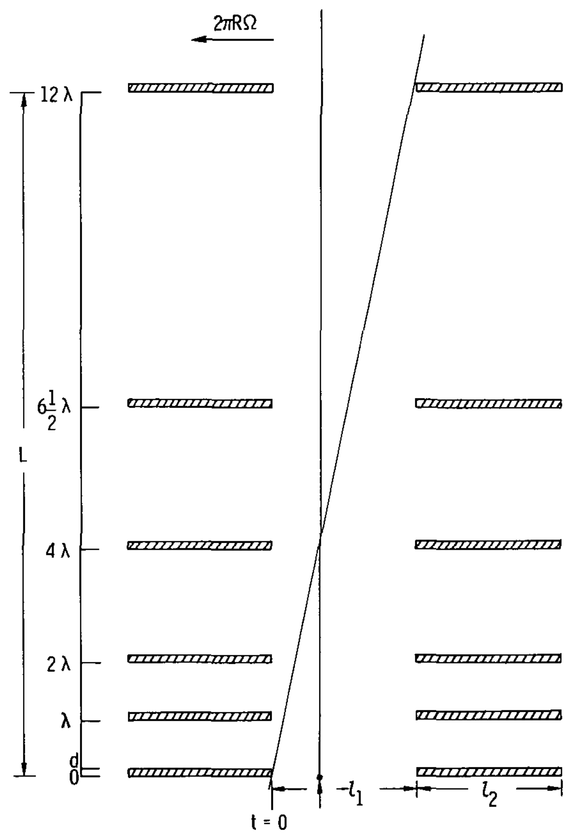

Figure 1. - Velocity discriminator design. Spacing unit λ, 0.833 centimeter; disk thickness d, 0.16 centimeter; slot width, l_1, 0.081 centimeter; tooth width l_2, 0.091 centimeter; mean rotor radius R, 7.6 centimeters; overall length L, 10.16 centimeters; number of slits per disk, 278.

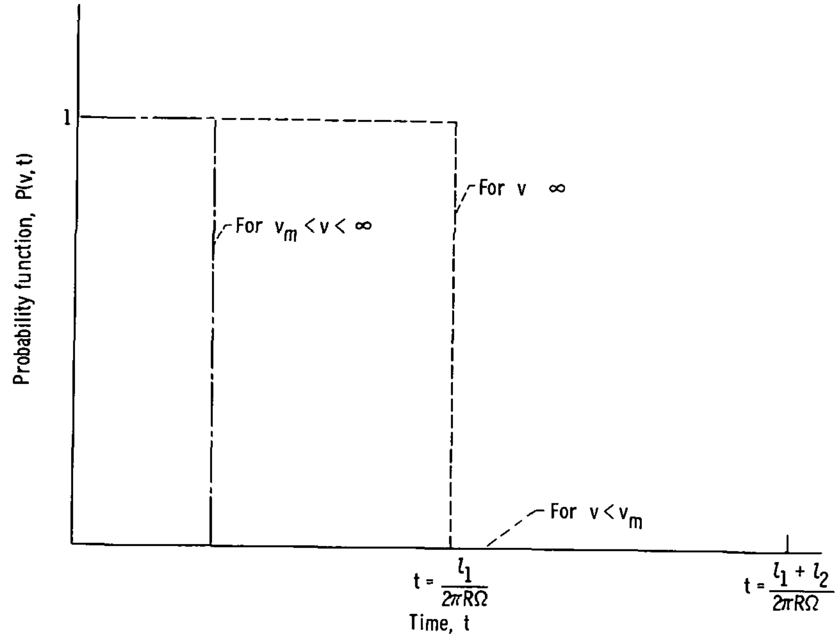

Figure 2. - Probability function P(v, t) for $0 \leq t \leq (l_1 + l_2)\ 2\pi R\Omega$ and various velocities v.

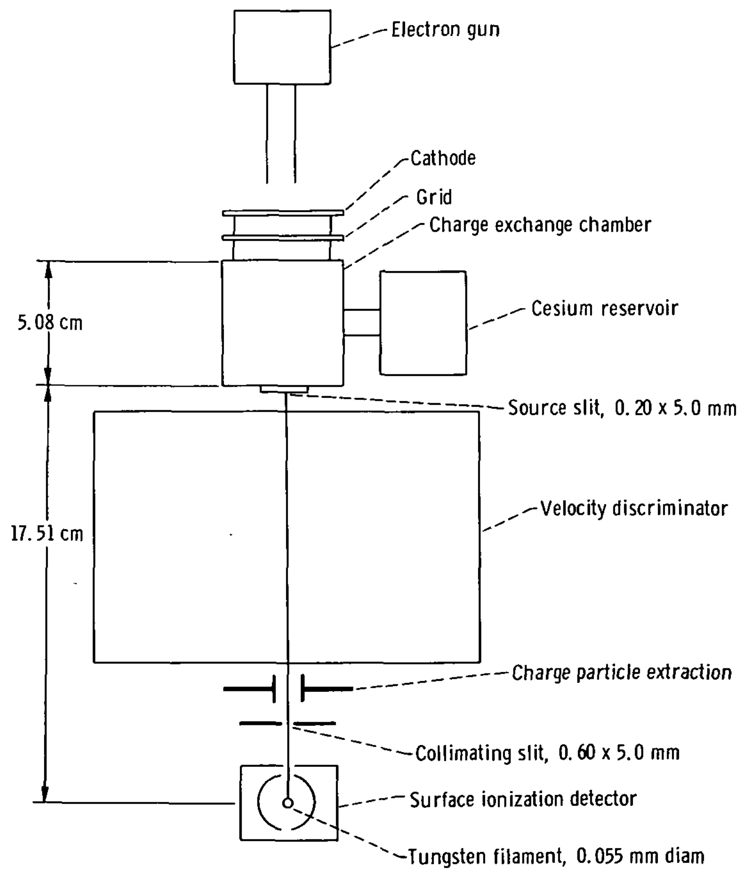

Figure 3. - Fast cesium beam apparatus.

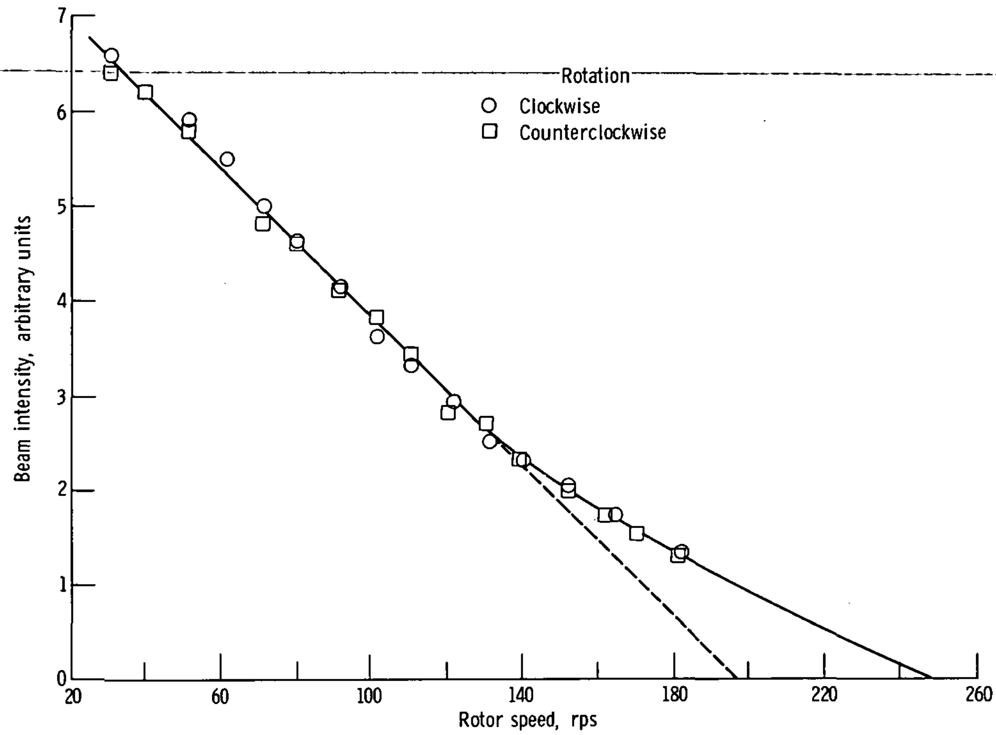

Figure 4. - Velocity discriminator transmission.

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