ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-WEPGW037

DEVELOPMENT OF A DENSE GAS SHEET TARGET FOR A 2D BEAM PROFILE MONITOR

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Abstract

We are developing a dense gas-sheet target to realize a non-destructive and fast-response beam profile monitor for the accelerators in the J-PARC. The beaming effect in vacuum science and technology has been employed for making a gas sheet. This time, we have developed a new gas sheet generator with the density of 10^{-2} Pa using a thin concentric circular slit with a large aperture.

INTRODUCTION

In order to supply continuously the beam of 1 MW in J-PARC it is important to reduce the beam loss thoroughly. Otherwise, the loss of even a small fraction of the beam generates secondary radiation such as neutrons and beta and gamma rays, which cause the components such as beam ducts to be radioactive. Thus the non-destructive and fast-response beam-diagnostic tools for extensive researches have been strongly required. An idea to realize the fast and non-disruptive beam profile detection is to introduce a gas target so as to increase the interactions with the beam [1,2,3]. The beaming effect in vacuum science and technology has been employed for making a gas sheet [4-6]. The gas sheet with a thickness of less than 1 mm and the density of 2×10^{-4} Pa was successfully obtained. Then, the profiles of the 400 MeV H^- ion beam in J-PARC linac was successfully obtained by detecting the ions generated through the collision of this gas sheet to the H^- beam. This time, we have developed a new gas sheet generator with the density of 10^{-2} Pa using a thin concentric circular slit with a large aperture. Gas is introduced from the outside toward the center, leading to the appearance of a large-scale of gas sheet around the center. The details of the new gas sheet generator are shown below.

MONTE CARLO SIMULATIONS

The test-particle Monte Carlo method in a molecular flow regime is used to determine the angular and density distributions [6]. The thin concentric circular slit with a large aperture is modeled as shown in Fig. 1. The letters r_1 and r_2 represent the radii of the aperture and the disk, respectively. The gap between the two disks is shown as d. Origin of Cartesian coordinates (x,y,z) is placed on the center of the plane B and the azimuth λ is also defined as shown in Fig. 1. The molecules are assumed to be distributed uniformly and to impinge over the entry plane A. Then the molecules are reflected according to the cosine law from the inner wall of the circular slit. The test molecules are generated until the number N_0 of outgoing molecules from the exit B amounts over than 1×10^5.

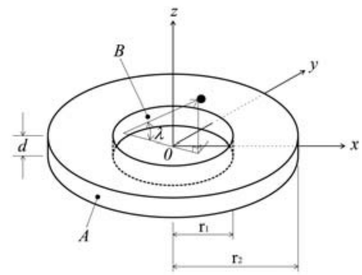

Figure 1: Calculation model.

Angular Distribution

The number N_i of outgoing molecules whose trajectories are between λ_i and $\lambda_i + \Delta\lambda$ is counted. Then the angular distribution function $n_a(\lambda)$ is defined as the ratio of N_i to the total emitted molecules N_0. That is:

$$n_a(\lambda_i)\ \Delta\lambda \equiv N_i/N_0, \quad (1)$$

here, the $\Delta\lambda$ is $\pi/300$ and $\lambda_i = (i - 1/2)\ \Delta\lambda$ ($i= -150, -149, , 150$).

The dependence of $n_a(\lambda)$ on the gap "d" is shown in Fig. 2a). Here r_1 and r_2 values are maintained as 65 and 145 (mm), respectively. As the value of "d" decreases, the distribution $n_a(\lambda)$ is inclined to have a sharp peak at λ=0.

With the parameter set of (r_1,r_2,d)=(100,200,0.1) (mm), the full width at half maximum (FWHM) of the function $n_a(\lambda)$ becomes less than 0.0025 rad. After all, only the molecules with the smaller velocity parallel to the z axis can come out. Thus, the molecules emitted from the circular slit can be shaped into a sheet when the following is satisfied: $(r_2 - r_1)/d >> 1$.

Density Distribution

As the molecules emitted from the exit are found to converge on the xy plane, the depth of gas-sheet is evaluated directly using the density distribution. In this paper, we ignore the reflection of the emitted molecules on the chamber wall and the other components in a vacuum for simplicity.

Thus, we can calculate the density distribution function $n_d(x,y,z)$ from the ratio $\eta(x,y,z)$ of the number of molecules transmitted through the virtual small object with the volume V to the total number N_0 of molecules emitted from the slit per second. The center of the object is assumed to be located at $P(x,y,z)$. That is;

$$n_d(x,y,z) = \eta(x,y,z)\ \tau\ /V. \quad (2)$$

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Here, the τ is the mean residence time of the molecules which come into the virtual object. The thin and small cylinder whose rotational axis is parallel to the z axis is selected as the virtual object, because both the precise thickness of the gas sheet and the accurate $\eta(x,y,z)$ should be obtained. Here, the mean residence time τ is well approximated with the following equation;

$$\tau = (\pi r/2) /\langle 1/v\rangle = 2r/\langle v\rangle. \quad (3)$$

Where, the cylinder has a radius of r and a thickness of t, and $\langle v\rangle$ is the mean velocity of the molecules. From the above equations, the density distribution n_d is expressed by the following;

$$n_d(x,y,z) = 2\,\eta(x,y,z) /(\pi\, r\, t \langle v\rangle). \quad (4)$$

In this study, the radius r and the thickness t of the virtual cylinder is selected to be 5 mm and 0.2 mm, respectively. Then the mean velocity $\langle v\rangle$ is calculated for N_2 molecules at 300K. Furthermore, instead of the above distribution function per outgoing molecule per second, the density distribution per unit flow rate (Pam^3/s) $p_d(x,y,z)$ will be displayed as pressure. In conversion, we use that nitrogen gas molecules of 1 Pam^3 correspond to 10^{20} molecules at 300 K.

Typical results of the density distribution per unit flow $p_d(x,y,z)$ are shown in Fig. 2b). These are for the slit with the parameter set of (r_1,r_2,d) = (100,200,0.1) (mm), which has the sharpest $n_a(\lambda)$ in Fig. 2a). These distribution functions $p_d(x,y,z)$ are plotted as a function of the z coordinate for several parameter sets of (x,y). First of all, it is clear that all the curves have the peaks at z=0. This is equivalent to the peaking of $n_a(\lambda)$ at λ=0, and directly shows that the emitted molecules gather on the xy plane.

In the case of the circular slit, with inner and outer diameters of 200 and 400 mm, respectively, and a gap of 0.1 mm, the generated gas sheet had a diameter of 130 mm and the thickness of less than 0.4 mm. In this area, the uniformity of the gas density was more than 85%.

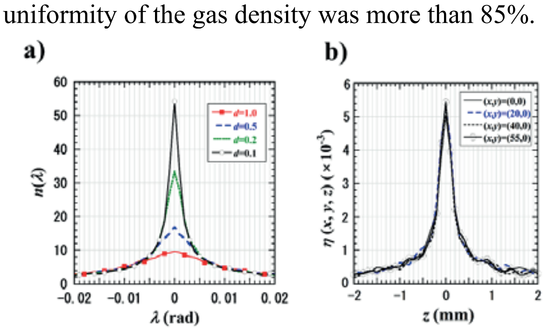

Figure 2: Simulation results; a) angular distribution, and b) density distribution for a circular slit with the parameter set (L, a, b) = (100, 50, 0.1).

PROTOTYPE OF THE GAS-SHEET GENERATOR WITH A CIRCULAR SLIT

Construction

According to the above, prototype of the gas-sheet generator was constructed as shown in Fig. 3. Main parts of the generator are a circular slit for producing a gas sheet and an auxiliary slit for differential pumping. The circular slit, which is formed between 2 metal cylindrical plates, has inner and outer diameters of 130 mm and 290 mm, respectively, and a gap of 0.08 (mm). A pit for a gas reservoir is also digged right outside of the thin drain for the circular slit on one of the plates.

On the other hand, the auxiliary slit in front of the exit plane is placed on the cover for the differential pumping. The dimensions are as follows; a diameter of 100 mm, and a gap of 0.3 mm. Of course, the circular and auxiliary slits share the center and rotating axis. Only the emitted molecules with a small angle of $|\lambda|$ are introduced into the main chamber through this slit, and the other molecules are evacuated to keep the vacuum in a good condition. In addition, this slit is useful to control the thickness of the gas sheet.

From here onwards, we introduce the same coordinates O-xyz as shown in Fig.1 to describe the experimental data of the gas sheet. The origin, O, is placed at the center of the exit plane of the circular slit.

Experimental Evaluation of the Gas Sheet

First of all, the thickness of the gas sheet was investigated. In a molecular flow regime the generated gas sheet is found to have a thickness of ~ 0.6 mm, which is consistent of the simulation results.

Then the distribution of the gas density is examined on the xy plane. Typical results are shown in Fig. 4a). When the inlet pressure is less than ~70 Pa, the gas-sheet density is found to be almost uniform over the area with a diameter of ~60 mm around the center. Then, the area gradually decreases with the inlet pressure Pin, however, even at Pin of ~1500 Pa the uniform density is maintained over the area with a diameter of ~40 mm.

Furthermore, the dependence of the sheet density on the inlet pressure was examined. As shown in Fig. 4b), the density increases linearly with the pressure Pin until ~100 Pa. The density increase rate decreases with the inlet pressure above ~100 Pa, however, the density of $\sim 10^{-2}$ Pa is finally realized with the Pin of ~4000 Pa.

As shown above, the circular slit is effective to generate a high density gas sheet over a large area around the center.

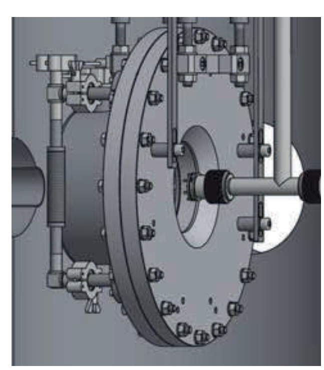

Figure 3: Bird-eye view of the gas sheet generator.

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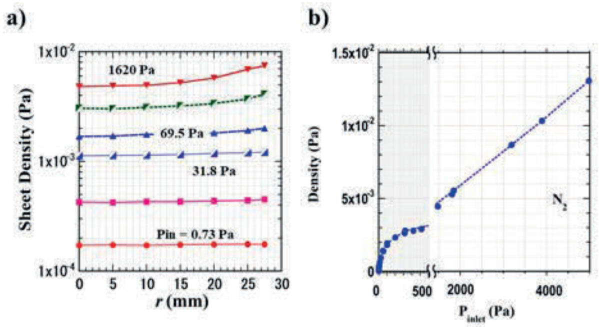

Figure 4: Change in sheet density; (a) dependence on r value, and (b) on inlet pressure.

DEMONSTRATION EXPERIMENTS

Detection System

The experimental layout is very simple. The gas sheet, which is generated by the circular slit, is orthogonal to the electron beam. The electron beam crosses with the rotating axis of the light receiving surface of the image intensifier (I.I.) near the center of the gas sheet. In addition, the angle between the axis and the beam is set to be 45°. The distance from the intersection to the light receiving surface of the I.I. is ~250 mm. Image of the light (mainly N_2^+ negative band (391.4 nm)) generated by the collision of the beam and the N_2 gas sheet is focused on the light receiving surface of the I.I., and amplified. Thus the light image is directly observed on the CCD camera.

Electron Beam Detection

In this experiment, the electron beam is supplied by a commercially available electron gun.

First of all, we observed the 30 keV electron beam with a current of 10 μA and a diameter of ~ 0.35 mm in a uniform N_2 atmosphere of 1×10^{-3} Pa. As shown in Fig. 5a), photons are in a straight line. It refers to the orbit of the electron beam.

Then, we observed the same electron beam under the following conditions; 1) There is a N_2 gas sheet with the density of ~2×10^{-3} Pa and the thickness of ~0.6 mm, and 2) the ambient pressure in the chamber is ~5×10^{-5} Pa. As shown in Fig. 5b), the bright light spot is clearly observed near the center of the gas sheet. The bright light spot is found to move in conjunction with the beam position. In addition, the light intensity of the spot is correlated with the density of gas sheet as well as the beam current. By the way, thin trace near the bright spot is due to the photons generated by the collision of the beam with the uniformly distributed ambient gas.

SUMMARY

We have been developing a gas-sheet generator to realize the non-destructive profile monitor. This time, we have developed a new type of gas sheet generator using a concentric circular slit.

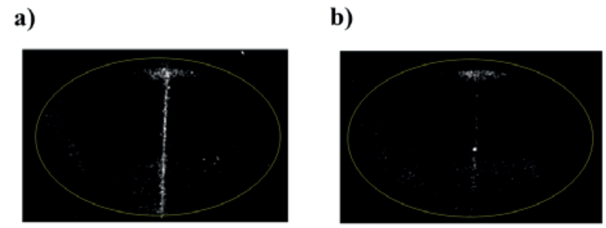

Figure 5: Light image on I.I.; a) in a uniform N2 atmosphere, and b) with a gas sheet.

1) Using the test-particle Monte Carlo method the basic characteristics of the emitted molecules through the circular slit were examined. When the slit has a ratio of the flow length (r_2-r_1) to the gap (d) much larger than 1, a large-scale of gas sheet is appeared around the center.

2) Then a prototype of the circular slit was made, and the generated gas sheet was experimentally examined. The inner and outer radii of the circular slit are r_1=65 mm, and r_2=145 mm, respectively, and the gap d is 0.08 mm. In a molecular flow regime, the generated gas sheet has a thickness of ~ 0.6 mm. The density is almost uniform over a diameter of 60 mm from the center. In addition, with the higher inlet pressure (≥ 4000 Pa) the gas-sheet density exceeds 10^{-2} Pa.

3) For the electron beam of 30 keV with a diameter of ~ 0.35 mm, the position and the two-dimensional profiles were measured using fluorescent light which was generated by the collision of the gas sheet and the electron beam.

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