INJECTION OF ELECTRON BEAMS FROM A VACUUM INTO A GAS THROUGH A GASDYNAMIC WINDOW

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We shall consider the possibility of using capillaries pierced by the beam itself in a quartz wall for the purpose of extracting a low-power electron beam from a vacuum and injecting it into a high-pressure gas.

To extract high-power beams, differential gasdynamic windows are used where pumping is replaced by freezing out the working gas—carbon dioxide or water vapor. We shall consider two such devices with freezing inside and outside the window.
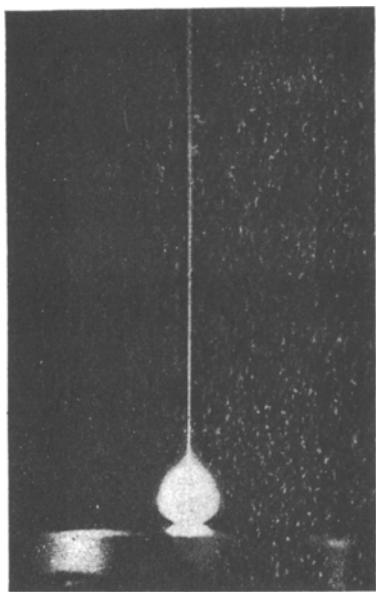

Fig. 1

When the required power is not too high and very thin beams having a diameter of a few tens of microns can be used, the beam may be extracted directly through a simple aperture of suitable diameter in the wall of the vacuum system, which is continuously evacuated. The amount of gas entering the vacuum system through such an aperture depends upon the dimensions of the aperture, the pressure, the type of gas. For air entering the vacuum from the atmosphere under normal conditions through a cylindrical capillary, the inleakage can be determined as follows [1]:

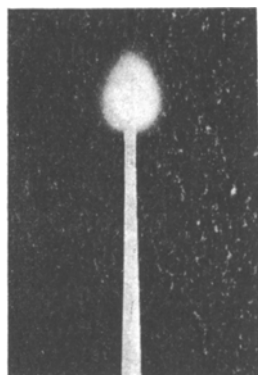$$I \approx 7600 \frac{d}{L}(1 + 7000d) \; [l \cdot mm \; Hg/sec]. \qquad (1)$$

Fig. 2

Here, d is the diameter of the capillary in cm, and L is its length in cm.

In order to maintain the vacuum we must compensate for this inleakage by continuously running a vacuum pump of corresponding capacity.

When a beam is extracted through a capillary, in order to obtain good focusing and very precise alignment one should use an aperture pierced in the wall by the beam itself. It is very interesting to use quartz for this purpose. In our experiments a 30 keV electron beam 0.8 mm in diameter impinged on a quartz plate 16 mm thick; the current density was on the order of 1 A/cm². The beam melted through the plate quite quickly (15–20 sec) forming a conical opening with a vertex half-angle of the order of 2° going over into a capillary of roughly constant diameter equal to 40–50 microns. Figure 1 shows the shape of the beam as it leaves the capillary and enters the gas. Where the beam leaves the plate there is a quite bright flame-like halo formed by slow electrons. The size of the halo decreases as the gas density increases. At air pressures greater than 100 mm Hg the halo completely disappears at room temperature. The boundaries of the halo are clearly defined. This indicates that the energy of the decelerated electrons is grouped around some particular value. However, a portion of the electrons passes through without noticeable deceleration and forms a narrow beam.
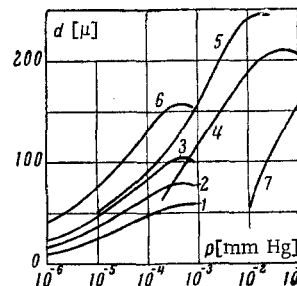

Fig. 3

A similar pattern also exists when electrons pass through quartz tubes. Figure 2 shows photographs of an electron beam passing through a conical tube 50 mm long and 0.5–0.3 mm in diameter. Here, the portion of electrons which passes through the tube without deceleration is small. Note that when the beam melts through the quartz, considerable thermal stresses appear near the opening. These, given rapid cooling, lead to the appearance of a large number of very fine cracks; as a result it is desirable to either anneal the plate or reduce its dimensions (cylinder 5–6 mm in diameter).

If the beam current is reduced by a factor of 2–3 after the aperture has been pierced, the capillary diameter will remain virtually constant with time. In our experiments, the capillaries operated for several hours at a beam exit current density of 2.5–3 A/cm⁻² and an accelerating voltage of 30 kV. This current density was roughly an order greater than the average current density of the beam striking the plate; this can be explained by the focusing effect of the surface charges which form on the inside surface of the aperture.

Beam extraction through a capillary melted through quartz makes it possible to simplify considerably the design of the electron gun, since there is no longer any need for alignment (two angular and two linear shifts), and to reduce its dimensions. The required pumping power is also decreased.

Figure 3 gives, as an example, the vacuum provided by various kinds of commercial pumps as a function of the diameter of a cylindrical capillary 5 mm long connecting the vacuum system with the atmosphere: 1) TsVL-100 pump; 2) N-5; 3) TsVL-15 m; 4) VN-3; 5) BN-1500; 6) N-8T; 7) VN-1. Calculations were performed using Eq. (1). As is clear from the graphs, it is quite realistic to use capillaries 30-50 microns in diameter even with relatively low-power pumps. However, larger diameters lead to a very sharp increase in the required evacuation rate.

To extract beams 0.1-2 mm in diameter and above, it is customary to use a differential gasdynamic window consisting of a system of coaxial wall openings, the spaces between which are evacuated with fore-vacuum pumps. The use of such a progressive pressure drop makes it possible to decrease the total volume of gas evacuated by the pumps by several orders and, as a result, to create open gasdynamic windows between the vacuum and high-pressure gas, whose diameter may reach several millimeters.
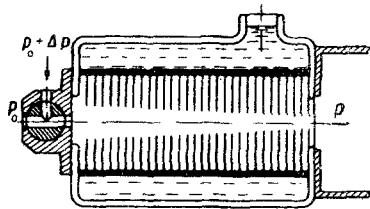

Fig. 4

Pauli [2] was the first to employ such a device. He used a two-stage window with an intermediate chamber evacuated by an auxiliary pump. A multistage gasdynamic window for extracting high-power electron beams was designed by S. T. Sinitsin [3, 4]. The modern theory of differential gasdynamic windows was worked out by Schumacher [3, 4]. Such windows are now quite widespread. However, it is not always possible to use high-power mechanical pumps which are quite clumsy and heavy, set up vibrations, and require the presence of a high-power electric drive, particularly when electron beams are used to measure gas and plasma flows. Progress in this direction can be made by replacing mechanical pumping with cryogenic evacuation. In fact, freezing permits one to eliminate the gas much more rapidly than by mechanical pumping. Moreover, the above shortcomings of mechanical pumps are eliminated. The freezing-out rate B is [1]

$$B = \frac{62}{\sqrt{M}} \left(1 - \frac{p}{p'} \right) S \ [l/\text{sec}]. \qquad (2)$$

Here M is the molecular weight of the frozen-out gas, p its pressure, p' the equilibrium gas pressure at the surface temperature, and S the area of the freezing surface in cm^2.

To condense gases such as nitrogen, oxygen, and argon, the temperature of liquid hydrogen (20.4° K) is required. At present, it is difficult to create these temperatures in small technical devices. However, there is no difficulty in obtaining the temperature of liquid nitrogen (78° K).

At the temperature of liquid nitrogen, the pressure of water vapor is 10^{-22} mm Hg, while that of carbon dioxide is $4 \cdot 10^{-6}$ mm Hg. Then, according to (2) the freezing-out rate (virtually independent of pressure) is 14.6 $l/\text{sec}^{-1}\text{cm}^{-2}$ for water and 9.4 $l/\text{sec}^{-1}\text{cm}^{-2}$ for carbon dioxide.

The following design for a gasdynamic window is of interest. There is an additional chamber between the high-pressure gas p_0 and the freezing system into which the gas to be frozen out is introduced (carbon dioxide or water vapor). The gas pressure in the chamber is somewhat greater than p_0 in order to prevent inleakage.

A diagram showing one variant of the device is given in Fig. 4. Here, freezing-out takes place at a series of diaphragms with coaxial apertures at the temperature of liquid nitrogen.

Fig. 5

In principle, such a device would permit one to avoid using pumps in general; however, unfrozen-out impurities, either initially present in the working-gas or formed by dissociation resulting from electron collisions, prevent this.

The gasdynamic window depicted in Fig. 4 can only be used for a limited time due to the restricted freezing capacity; however, the fact that it is compact and simple may be decisive in a number of cases.

In such a system the working gas is frozen out mainly at surfaces opposed to the flow. Figure 5 shows photographs of a section of a gasdynamic slit window with the carbon dioxide frozen out in it. Note that the freezing rate is virtually independent of gas pressure, whereas the amount of frozen-out gas is proportional to it; hence the working gas is mainly frozen out at the beginning of the window. We can make freezing more uniform by using apertures of different area, as shown in Fig. 4.

One drawback of this method is that the gas flowing into the freezing chamber may carry along individual crystals of carbon dioxide or water and cause them to enter the electron-gun chamber. To eliminate this, one can use the gasdynamic window shown in Fig. 6, where freezing-out takes place outside the window. This window can be used for an arbitrary amount of time either by increasing the volume of the freezing chambers or by doubling the number of chambers in a parallel arrangement and using each system alternately.

Comparing carbon dioxide and water vapor as working media, we note that, despite the complexity introduced by the necessity of using a preheater, water vapor has a number of advantages: 1) in view of the lower vapor pressure one can use thermoelectric freezing devices instead of liquid nitrogen; 2) the amount of working gas consumed in the case of water vapor is 1.5-2 times less and hence the size of the freezing unit is also reduced by the same amount; 3) the lower gas density leads to smaller energy losses as the electrons pass through the gasdynamic window.
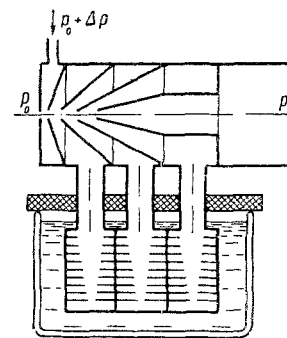

Fig. 6

Freezing-out the working gas, instead of using a vacuum pump, makes it possible to increase considerably the maximum diameter of the aperture between vacuum and gas. Whereas the maximum diameter of the window between atmosphere and vacuum when a pump is used is 3-4 mm, when freezing is used apertures of 15-20 mm in diameter are possible.

If it is not desirable for working gas (water vapor or carbon dioxide) to enter the high-pressure gas medium, one can add a chamber at the window inlet in which the pressure is below p_0.

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