A New Vacuum Component: Fast Acting Puncture Valve

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Abstract. Generally, for proton induced X-ray emission (PIXE), external-PIXE, gamma ray spectrometry, charge particle spectrometry or ion beam irradiation in air using large vacuum system like particle accelerator, a thin Mylar or Kapton foil are used as a window material (chamber) for above beams to perform experiments. The problem arises when this thin Mylar or Kapton foil gets destroyed accidentally in mid-run. Air with high velocity rushes inside, which disturbs the inside vacuum of the chamber or beam lines and causes failure of the experimental system. In order to avoid this, one needs a sensitive arrangement, which can sense the rush of air and stop it entering in to the vacuum chamber or lines. The solution to the above problem is achieved by design a new fast acting puncture valve. The valve is working on the basis of differential pressure and the basic underlying principle to sense the rushing air is based on Bernoulli’s principle and Pascal’s law, which is different from commercially available fast acting valve. The new valve is installed in the External beam line of 3MV tandem pelletron accelerator at Institute of Physics, Bhubaneswar and working fine in both rough as well as high vacuum.

1. Introduction
External ion beam is used for investigating vacuum incompatible samples like biological objects, liquid specimens and large archaeological objects for multi-elemental analysis [1] and also for modification of materials like biological fluids, polymers [2,3] etc. by irradiating with ion beam in air for specific applications. Now a days, ion beam modification and ion beam analysis of materials using nuclear accelerator is a hot topic for material scientists. In the last few years, the study of the effects induced by irradiation in-air with heavy ions with energy of the order of MeV on materials has attracted attention, both for fundamental interest and for potential technological applications. Usually, materials are irradiated in vacuum for their modification in various aspects. Irradiation of materials in-air has its own merits over irradiation in vacuum because of various reasons, which are as follows: (i) Liquids, fibres and big objects like vacuum incompatible samples can be mounted and irradiated in air easily. Easy sample handling and positioning in air is possible in such cases, (ii) The advantage of this method is that the samples of almost any size and type can be irradiated ‘as such’, (iii) The risk of soft materials like polymers, papers, leafs etc damage due to radiation heating is considerably reduced because of efficient cooling by the air flow and (iv) Radiation irradiations are carried out only in-air so that in materials the recovery processes [4] can be finished by the time the sample gets ready. So the radicals disappear and only permanent changes can be observed.
An external ion beam facility was developed at Institute of Physics (IOP), Bhubaneswar, in India to carry out material modification by ion beam irradiation in air environment [2]. For the present work, ion beam was obtained from the 9SDH-2 (National Electrostatic Corporation, USA), which is a 3 MV horizontal, tandem-type pelletron accelerator. The details of the in-air irradiation technique are reported elsewhere [2]. In the external-beam line [1] setup at IOP, the beam is taken out of the vacuum chamber through a nozzle, whose end is closed by an 8micron Kapton foil. The problem arises when the Kapton foil gets destroyed accidentally in mid-run due to degradation or by heat generated in it when high-energy ion beam passes through it. Air with high velocity rushes inside which disturbs the inside vacuum (around 10^-7 mbar) of the beam line and causes machine shutdown. In order to avoid this, one needs a sensitive arrangement, which can sense the rush of air and stop it entering the vacuum lines. The solution to the above problem is achieved by fabricating a simple mechanical fast acting puncture valve (FAPV) using Nylon, rubber, and stainless steel materials. A portable FAPV for application on the external beam line of the accelerator has been developed. The most frequently used methods for this kind of protection in an accelerator are Fast-Acting Vacuum Valve (FAVV) and RF Waveguide Vacuum Valve, where the aperture of the beam path is 4 inch or more with heavy weight. Again, closing time of the FAVV is relatively high as compared to the new one and is expansive. These are the major drawbacks of FAVV as compared to FAPV.

2. Principle

The valve is working on the basis of differential pressure and the basic underlying principle to sense the rushing air is based on Bernoulli’s principle and Pascal’s law, which is different from commercially available fast acting valves [5]. Usually, the sensing mechanisms of the commercially available fast-acting valves are based on the ionization current of the gas molecules [6, 7]. The underlying physics of the FAPV defined below.

Breaking the foil of the nozzle air with high velocity rushes inside the vacuum chamber (around 10^-7 mbar) because of the differential pressure between the normal environment and vacuum chamber. The FAPV is modified Venturimeter with a special arrangement of a tongue and stopper fixed in the converge cone (merges throat) of the Venturimeter. This arrangement breaks the air flow into two parts. The first part of the air stops under the tongue (with stopper in closed position) because of closed path. According to the Pascal’s principle the pressure (P_{tong}) at a point in the gas (fluid) at rest under the tongue is the same in all direction and is equal to the air pressure (P_{air}), i.e, P_{air} = P_{tong}.

Again, the law of conservation of energy to the fluid flows in a system [8-10], one can have

\[ P_{air} + \frac{1}{2} \rho v_1^2 + \rho g h_1 = P_{stopp} + \frac{1}{2} \rho v_2^2 + \rho g h_2 \]  
\[ B \]  
\[ B = \frac{1}{2} \rho v^2 + \rho g h \]

Where \( P_{stopp} \) is the pressure on the stopper of the valve and other symbols have their usual meaning. Hence, in general

\[ P + \frac{1}{2} \rho v^2 + \rho g h = B \]  
\[ B \]  
\[ B = \frac{1}{2} \rho v^2 \]

From the above expression (3) one can see that, if there is an increase in velocity there must be a decrease of pressure and vice versa.

As the air flows over the stopper fixed on tongue near section of the valve opening, it entrains and removes air molecules between it and the upper part of the valve stopper, reducing the air pressure (because of high velocity of the air) \( P_{stopp} \) as discussed because of Bernoulli’s effect. The atmospheric
pressure $P_{\text{air}}$ below the valve stopper pushed the stopper up because of this pressure difference ($P_{\text{air}} - P_{\text{stop}}$). Hence, the valve stopper rises up. Again the dragging force pushes away towards the low pressure region (chamber), which close the path of the air flow (beam aperture).

3. Engineering Design

Applying the above said principles the FAPV is designed and shown in the Fig 1. The detailed engineering drawing of the FAPV was also shown in the Fig 2. A light weight, small and portable valve as shown in Fig.1 is designed (dia 20mm and length 30mm) to fit into the space available in a 50mm 25KF Nylon drift tube. In the present report the stopper of the valve is designed using 50 micron stainless steel sheet instead of rubber materials as reported earlier [5]. The beam is given a free path of 8mm and the rest part is blocked. Also the valve tongue is designed using the insulated material instead of aluminium to modify for the connection of an electronic circuit for the measurement of time period.

![Figure 2. Cross-section view of the FAPV](image)

![Figure 2. Design of the Fast-Acting Puncture Valve](image)
From the design point of view the valve closing time can be calculated as $t = \sqrt{\frac{2\varphi}{\omega}} = 0.759 \times 10^{-3}$ s $\approx 1$ millisecond, where angular acceleration of the valve, $\omega = \frac{\text{Torque}(T)}{\text{Moment of Inertia}(I)} = \frac{(40 \text{ N.mm})}{(8.8155 \text{ g.mm}^2)} = 4.54 \times 10^6 \text{ rad/s}^2$, angle to be turned, $\varphi = 75^\circ = 75\pi/180$ rad.

4. Conclusion
The FAPV was tested in both rough and high vacuum in the external beam line. The actual closing time found bit more then the theoretically calculated value due to the presence of opposing torque due to gravity acting on the stainless steel stopper. Experimental measure of the closing time of such a compact and portable valve is bit difficult. The work is under progress to measure the exact closing time. But in the existing system, the vacuum recovered after a puncture requires less than 5 minutes. The new valve is installed in the External and Nuclear beam line of 3MV Tandem Pelletron Accelerator Laboratory at Institute of Physics and working fine in both rough as well as high vacuum. The newly designed mechanical fast acting puncture valve will be useful for various external beam line experiments.

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