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LEAK PROPAGATION DYNAMICS FOR THE HIE-ISOLDE SUPERCONDUCTING LINAC

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Abstract

In order to cope with space limitations of existing infrastructure, the cryomodules of the HIE-ISOLDE superconducting linac feature a common insulation and beam vacuum, imposing the severe cleanliness standard of RF cavities to the whole cryostat. Protection of the linac vacuum against air-inrush from the three experimental stations through the HEBT (High Energy Beam Transport) lines relies on fast valves, triggered by fast cold cathode gauges. To evaluate the leak propagation velocity as a function of leak size and geometry of the lines, a computational and experimental investigation is being carried out at CERN. A 28 m long tube is equipped with cold-cathode gauges. A leak is opened by the effect of a cutting pendulum, equipped with an accelerometer for data acquisition triggering, on a thin aluminium window. The air inrush dynamics is simulated by Finite Elements fluid dynamics in the viscous regime.

INTRODUCTION

The protection of beam vacuum against an accidental vacuum hazard in an experimental station is crucial in the beam lines of synchrotron light sources. The issue is present also in superconducting linacs and even more so in those with common beam and insulation vacuum in the cavity cryomodules. Indeed, vacuum rupture results in a propagating air front, transporting air and dust towards the clean cavities, causing loss of beam time and requiring a lengthy reconditioning or even cleaning of the cavities. Usually, protection is obtained by a fast acting valve along the beam line, together with air propagation delaying devices, so called Acoustic Delay Lines (ADL), first proposed in [1].

The problem of sudden opening of a membrane separating two regions of high and low pressure is well known in continuous fluid dynamics: it is the vacuum shock tube problem [2]. This problem is solved analytically starting from energy and momentum conservation. The most startling feature in this treatment is the shock wave, travelling at constant speed

$$u_{max} = \frac{2}{\gamma - 1} c_0$$

into vacuum, but carrying vanishing density. Here, c_o is the local speed of sound, while γ is the specific heat ratio. For air, γ=1.4 and c_o=331m/s, so the shock wave speed is 1655m/s, or Mach=5. The particular case of constricted flow, i.e., where an orifice of diameter d separates a cylindrical tube of diameter D at initial pressure p_1 from a region at (higher) pressure p_4, is developed in [3], in relation to the sudden opening of a leak at the extremity of a vacuum beam line. Similarly to the shock tube problem, the propagation of a pressure wave inside vacuum results in a shock wave travelling at speed Mach=6.7, while the contact surface between gas and vacuum follows at a constant speed ~1800m/s.

Several experimental studies have been performed on the issue of expansion of air into vacuum through an orifice. Parameters like initial base pressure [3] and initial pressure ratio across the orifice [4], ratio between the orifice size and the tube diameter β [3,5], and gas species [4] were widely explored. Results vary considerably, with propagation speed of the fastest pressure front between 50m/s and 1100 m/s.

For an efficient protection in a real machine, detecting the shock wave permits to anticipate the closure of a fast valve. Yet, the damaging element is the density wave which travels at lower speed behind the shock wave.

In HIE-ISOLDE, the compact layout of the beam transfer line system does not permit the insertion of a delay device. A fast valve, triggered by fast Penning gauges, reacts within 15ms to the pressure signal rise; this time includes the initial pressure rise, the delay induced by the Penning gauge, cables, electronic cards, up to the movement onset of the valve and until complete hermeticity is obtained. However, the overall distance between the nearest experimental station and the last cryomodule is shorter than 6m: a shock wave travelling at 1000m/s will reach the cryomodule before the fast valve has completely closed.

To benchmark calculation, characterize the complete protection chain and eventually evaluate the efficiency of very short delay devices, we have set up an experimental station aiming at measuring the propagation speed of pressure waves in an Ultra High Vacuum (UHV) tube. This paper describes the facility and presents preliminary experimental results for complete rupture of vacuum.

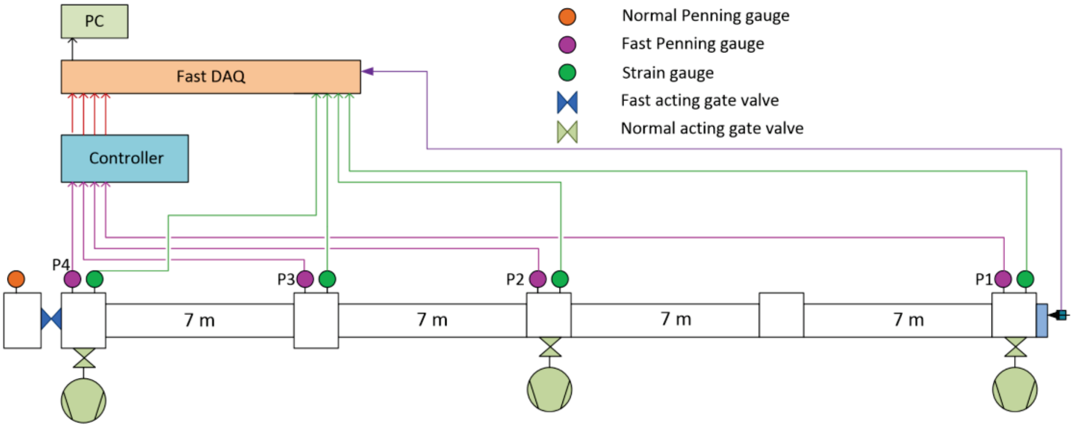

Figure 1: Schematic view of the experimental set-up.

EXPERIMENTAL SET-UP

The experimental set-up is presented schematically on Fig. 1. It consists in a 28 m long, 80 mm diameter tube, with intercalated 100 mm crosses on which pumps and instrumentation are installed. The system is evacuated by 3 turbomolecular pumping groups of nominal pumping speed 100 l/s. Pressure gauges are commercial fast Penning gauges. High sensitivity (20µm) strain gauges are installed on blank flanges, whose thickness has been reduced to 0.1mm. The crosses have a free port on which fast glow discharge gauges are planned to be installed.

At one extremity, the tube is closed by a thin vacuum window of a diameter 35mm, obtained by clamping a pure aluminium foil (100-200µm) between two copper gaskets. A pendulum armed with a sharp tip and a shock-recorder accelerometer is attached to the flange. At the other extremity, a fast valve (VAT, DN40) separates the main tube from a 3 litre volume vacuum chamber. This model is the only perfectly leak tight fast valve in the supplier's catalogue. Vacuum in the secondary chamber is monitored by a normal, calibrated Penning gauge; this will allow measuring the gas that passes the valve before its full closure in future test runs.

The fast gauges signal is recuperated from the analog output modules (0-10V) of the VAT fast valve controller and sent to an 8-channel high frequency (19.2 kHz) 24bit A/D converter and amplifier (QuantumX MX840A by HBM). The amplifier sends data to a PC via an Ethernet bus. Data processing software is provided by the amplifier's supplier.

Before starting a new test, the tube is pumped down for several hours until a base pressure $1x10^{-5}$ Pa is reached. The gate valves isolating the turbomolecular pumps from the tube are then closed and pressure stabilized for some minutes. At time t_0, the window is broken.

RESULTS AND DISCUSSION

In a set of preliminary measurements, gauge P1 is used for time stamp. A time delay of 2.6 ms was recorded between the onset of pressure rise on this gauge and the accelerometer on the cutting tip. A typical measurement is shown on Fig. 2.

The onset of a pressure rise is taken as an increase in pressure of a factor 3 of the high frequency noise above the average pressure level before t_0.

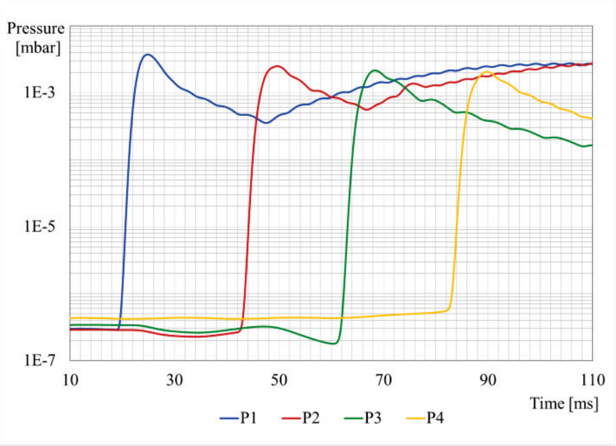

Figure 2: Typical recording of gauges P1, P2, P3 and P4 upon breaking the vacuum window.

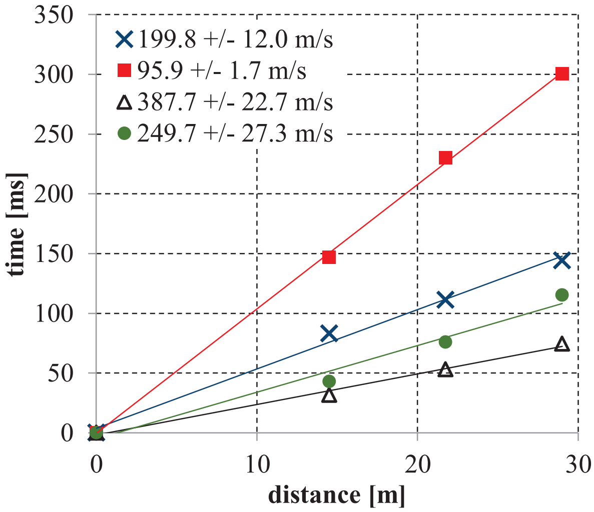

Figure 3: time delay of onset of pressure rise on P2, P3 and P4 with respect to pressure rise on P1. In abscissa, the longitudinal distance of the three gauges P2, P3 and P4 from the window.

Figure 3 shows the time of the onset of a pressure rise versus the longitudinal position of the three gauges P2, P3 and P4, for four measurements. The slope and standard error on the slope are displayed on the graph. The three experiments differ in the size of the opened hole. The area of the hole is determined a posteriori from a numerical picture of the window by applying graphical analysis software.

As the hole has an irregular shape, we have computed a β value as the square root of the area ratio between the hole and the cross section of the tube. Figure 4 shows the relation between the speed computed from the linear regression on the time/distance data and this β value. Even if a trend appears, with velocity increasing with β, we are still far from the values stated in [3] for pressure ratios comparable to ours.

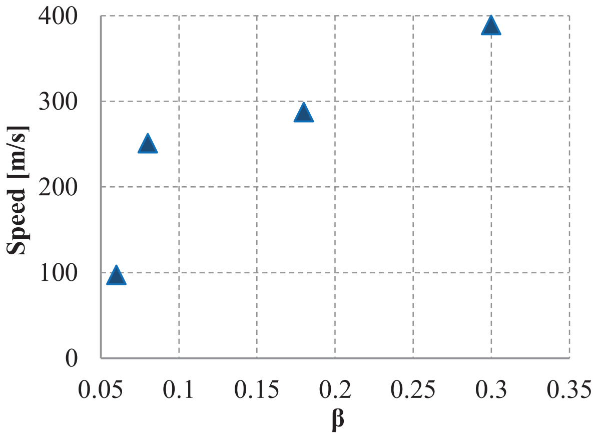

Figure 4: velocity of the pressure front versus β, the ratio between hole diameter and tube diameter.

We therefore need to question whether we are really sensing the shock wave. Since molecules travelling with high velocity don't have line-of-sight access to the Penning gauges positioned off-axis, we can improve the setup by positioning the gauge at the extremity of the tube and at its centre. This planned modification will allow us to precisely quantify preliminary molecules arriving before the high density wave. Delayed closure of the fast valve at the end of the main tube should also permit to quantify the gas having reached the extremity of the tube in a well-defined time.

NUMERICAL SIMULATIONS

We have used the COMSOL High Mach Number Flow module to simulate gas inrush through an orifice. Since this module doesn't support simulating multiple flow regimes, we had to accept the limitation that instead of UHV, base pressure in the vacuum chamber prior to opening of the orifice is 1000 Pa. The high pressure region is at 10^5 Pa. With this value of base pressure, the simulation (Fig. 5) predicts a shockwave propagation speed of 620 m/s with β=0.125.

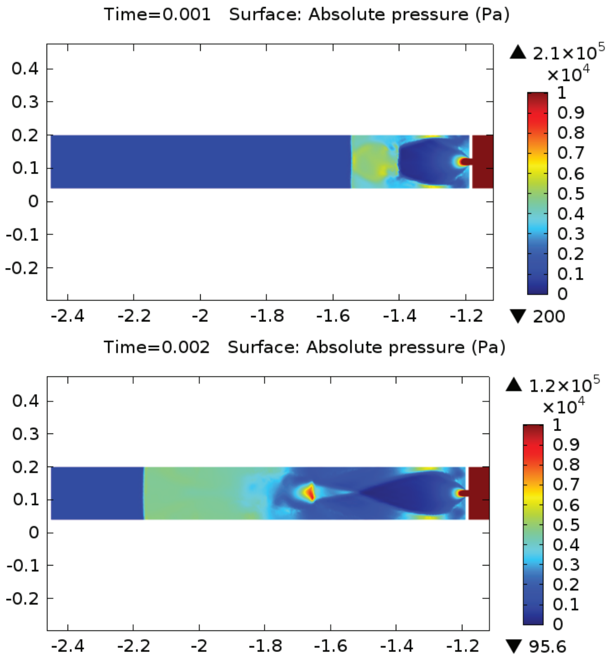

Figure 5: COMSOL simulation of pressure evolution in a tube at times 0.001s and 0.002s after opening a hole between two regions at 10^5 Pa and 10^3 Pa, with β=0.125.

CONCLUSION

First data shows that the propagation speed increases with the ratio of the square roots of hole surface and cross section of the tube. We can observe the trend that larger holes increase the propagation speed, but more data is required to establish a clear relation linking pressure-front velocity and the ratio β between the constriction orifice and the tube. Measurement of the size of the opening in the window will be completed by steady conductance determination across a pressure difference. Future measurements will also concentrate on the determination of the amount of gas reaching the volume after the fast valve, with variable time delay.

A preliminary conclusion of our study is that the cryomodules of HIE-ISOLDE will be protected by fast valves only in the event of a small leak, i.e. if the incoming shock wave has a low speed.

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