PERFORMANCE EVALUATION OF FAST CLOSING SHUTTER SYSTEM AT THE SPring-8 FRONT-END

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Abstract

The fast closing shutter (FCS) system plays an important role in protecting the ultra-high vacuum in the SPring-8 storage ring from an accidental vacuum hazard in the beamlines. In order to predict the transit time of the shock wave and the following pressure increase, a shock tube system with an inner diameter of 35 mm and a total length of 10 m was prepared to measure the shock Mach number. Experiments have been conducted that simulated an inrush of the atmosphere into the high-vacuum (~10^{-3} Pa) pipe by using a trigger system that combines a thin cellophane diaphragm with a plunger. Special ionization gauges with a high-speed amplifier were distributed about every 1 m to detect the transit time of the shock wave and to measure the pressure in the low-pressure chamber (LPC) after the actuation of the FCS system. By inserting larger pipes (inner diameter=390 mm) with various lengths into the shock tube, the attenuation in the shock wave was systematically investigated. The results of the experiment confirmed that the pressure increase in the LPC exhibits a close relationship with the total internal volume of the shock tube.

INTRODUCTION

More than 55 beamlines, which are arranged radially from the SPring-8 storage ring (circumference: ~1.5 km), are now in operation for various experiments. Maintaining the ultra-high vacuum (UHV; 10^{-8}–10^{-9} Pa) in the storage ring is indispensable for avoiding any decrease in beam lifetime and the generation of Bremsstrahlung radiation. Therefore, when a severe vacuum accident occurs in a beamline, it becomes possible for the UHV of the storage ring to break due to an air inrush, which would be followed by the long-term suspension of the user experiments. To prevent such a situation from occurring, a commercially available fast closing shutter (FCS) system (VAT Series 773 linear actuator type) was prepared in each front-end. This system works to detect rapid vacuum deteriorations and is capable of immediately closing the shutter main body, which is installed at the most upstream side of the beamline front end. The shutter does not have an airtight, UHV-compatible vacuum at the seat; that is because typical sealing materials, such as VITON (a type of fluorocarbon rubber), cannot be used because of the severe radiation environment in the 8 GeV ring tunnel. In this way, the FCS system primarily aims to prevent the inrush of a shock wave into the storage ring without delay. Accordingly, a general all-metal gate valve (GV) that is radiation resistant and interlocked with the FCS must also be installed at the upstream side of the FCS in order to prevent further vacuum deterioration.

EXPERIMENTAL SETUP

As shown in Fig. 1, the shock tube system, which has a total length of about 10 m, is mainly composed of vacuum pipes with electro-polishing treatment on the inner surface, a window part with a thin diaphragm made of moisture-proof cellophane and an HV sensor for the trigger, low-pressure and high-pressure chambers at both ends of the pipe, and miniature ionization gauges (MIGs) with a sampling time of 0.1 ms. We defined the low-pressure chamber (LPC) and high-pressure chamber (HPC) as the upstream side and downstream side, respectively. The inner diameter of the vacuum pipe is 35 mm. This corresponds to the standard 2.75-inch ConFlat flange, which has the same nominal aperture size of actual front-end components for the SPring-8 standard undulator beamline. Both the FCS and GV, which are installed just downstream from the LPC, are used with the 2.75-inch ConFlat flange. The window part can simulate momentary fracture of the beryllium window by breaking the cellophane diaphragm using a plunger connected to a pneumatic driving cylinder. The aperture size of the window is 10 mm (diameter), in accordance with the actual component. The MIG measurement spans three orders of magnitude in the range from 10^{-4} to 10 Pa (typically 10^{-3}–1 Pa) by fixing the emission current. Fast pressure measurement with a sampling time of 0.1 ms can be achieved by combining a high-speed amplifier with a generic vacuum controller.

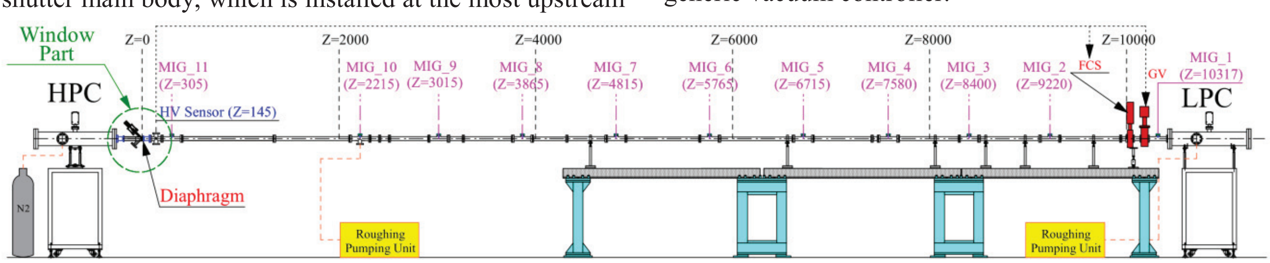

Figure 1: Schematic layout of the shock tube basic system with a total length of 10 m.

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The MIGs were mounted at ~1 m intervals to detect rapid increases in pressure, and the transit time of the shock wave at each MIG is represented by the time when the rapid increase in pressure is detected at each MIG. In addition to analog output from the MIGs, the following signals were recorded with a high-speed data logger synchronized with the operating command of the plunger as a trigger: "HV sensor" (output INRUSH), "FCS closed" (close output external), and "GV closed".

ADVANCED PREPARERATION

Measuring Rupture Time of Diaphragm

To determine the exact time when the diaphragm was broken, we prepared a high-speed video camera system. By synchronizing the starting time of the photographing with the triggering of the operating command of the plunger, the delay time between the moment of the diaphragm fracture and the rapid increase in pressure at MIG_11 in Fig. 1 (the closest MIG to the diaphragm) was estimated to be 0.2 ms on average.

Measuring Closing Time of FCS

The signal of "FCS closed" is output at the moment when the latch is just released – namely, the starting time of the closing operation. An off-line experimental setup, which consisted of the FCS, a pin photodiode, and a laser system, was prepared to measure the actual driving time of the FCS. The laser emitted inside the FCS aperture through view glass windows was detected by the pin photodiode, which was located on the opposite side of the FCS from the laser. We monitored the temporal relationship between the output of the "FCS closed" signal and the signal of the pin photodiode being interrupted. By varying the height level of the laser, the driving speed from the open position to the close position was estimated to be 8.32 mm/ms. As the result, the actual driving time of the FCS with an aperture size of 35 mm was calculated to be 4.2 ms.

EXPERIMENTS

The LPC and vacuum pipes were evacuated to a pressure on the order of 10^{-3} Pa by two roughing pump units. A nitrogen gas container was connected to the HPC to maintain atmospheric pressure, resulting in a pressure differential that spanned eight orders of magnitude. Then, we actuated the plunger to break the diaphragm immediately after isolating the pumping units by valves. Besides the basic configuration shown in Fig. 1, (which was constituted only by 35 mm inner-diameter plain pipe (35PP)), experiments were carried out for some configurations with 16" plain pipe (16"PP) inserted into the tube. Three kinds of the 16"PP (inner diameter=390 mm) with lengths of 0.25 m, 0.5 m, and 1 m were prepared. For each configuration, measurements were carried out four times in the cases of both FCS/ACT and FCS/NON-ACT; the mean value was used in the evaluation. FCS/NON-ACT means that only the GV was actuated by a signal of the HV sensor.

RESULTS AND DISCUSSIONS

The blue-circled closed symbols (Basic_35PP) in Fig. 2 show the transit times of the shock wave as a function of the distance from the diaphragm in the case where only 35PP is present. The shock wave velocity gradually decreased with the propagation of the wave owing to the pipe friction. The transit time when the shock wave reached MIG_1, which was located about 10.32 m from the diaphragm, was 15.7 ms. Figure 3 shows a flow chart for the series of events accompanying the FCS action with actual values measured in the case of 35PP as an example. Immediately after the diaphragm was broken, the HV sensor detected the abnormality and sent a command to close the FCS in 3.4 ms, which was followed by the start of the FCS closing action after 21.6 ms has elapsed, which is thought to depend on the cable length between the controller and the FCS body. We utilized a 50 m long cable in this experiment that is identical to that actually used in SPring-8. The FCS completely closed in 25.8 ms, which was derived by adding the FCS driving time of 4.2 ms to 21.6 ms. On the other hand, the shock wave propagation reached MIG_1 in 15.7 ms, so that in this configuration the FCS could not prevent the inrush of the shock wave into the LPC. After that, the vacuum leak continued through the FCS to the LPC until the GV closed after 619 ms had elapsed.

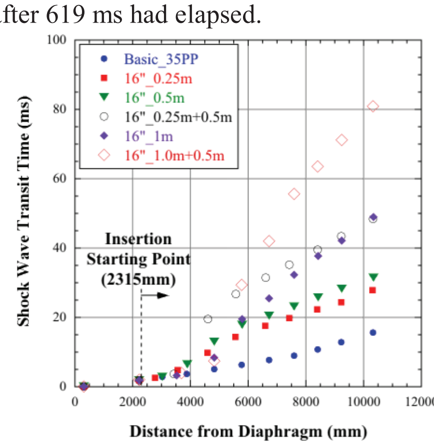

Figure 2: Transit times of the shock wave as a function of the distance from the diaphragm in the case of plain pipe (Basic_35PP) and in the case of inserting various 16"PPs.

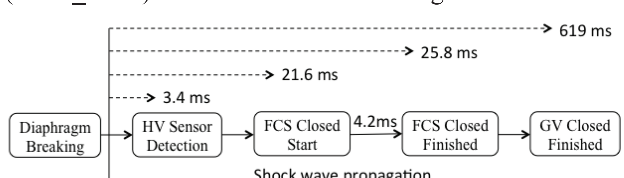

Figure 3: Flow chart for a series of event accompanying the FCS action, along with typical actual values in the case of basic configuration (35PP only) as an example.

The transit times of the shock wave in the case of inserting various 16"PPs into the tube are also shown in Fig. 2. In all cases, the 16"PP was inserted from the same starting point, which was located 2315 mm from the diaphragm. The case of "0.25 m + 0.5 m" implies that a 0.25 m long 16"PP and a 0.5 m long 16"PP were installed in tandem. The velocity of the shock wave began to drop sharply after exiting from the inserted pipe; this means that the insertion of an expanding pipe delays the shock wave propagation. To evaluate this effect quantitatively, we organized the data by using the Mach number (M_a), which indicates the intensity of the shock wave, and can be represented by the following equation:

$$M_a = \frac{(Z_i / t_i)}{c}. \quad (1)$$

where Z_i is the distance from the diaphragm at the measuring point (i), t_i is the transit time of the shock wave at the measuring point (i), and c is the speed of sound. As shown in Fig. 4, which depicts the relationship between the M_a and the distance from the diaphragm, the value of M_a in the case of only 35PP decreased gradually from 3 to 2. On the other hand, in the case of inserting the 16"PP, M_a dropped sharply after exiting the insertion component and became almost constant at 0.6–1.1 when the distance from the diaphragm exceeded about 8 m. This means that the transit time should be proportional to the distance after 8 m. Moreover, the larger pipe (16"PP) should be installed within at least 4 m of the diaphragm so that the sufficient delay time could be gained.

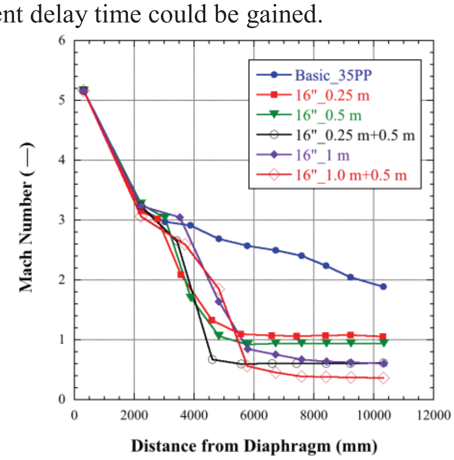

Figure 4: Relationship between the Mach number and the distance from the diaphragm in the case of inserting various 16"PP.

Figure 5 shows M_{ave} as a function of the total internal volume of the shock tube. Here, M_{ave} represents the value of M_a averaged over three points at locations further than 8 m. With an increase in the total internal volume, the attenuation effect of the shock wave increased, which resulted in a decrease in M_{ave}. It was found that M_{ave} became subsonic when the total internal volume exceeded 0.05 m^3. Figure 6 shows the final pressure in the LPC for FCS/ACT (right Y-axis with open symbols) and FCS/NON-ACT (left Y-axis with closed symbols) as a function of the total internal volume. Roughly speaking, the former is about four orders of magnitude lower than the latter for every configuration, which is a direct consequence of the FCS system. It should also be noted that the final pressures exhibited an almost linear relationship with the total internal volume.

CONCLUSIONS

The performance of the FCS system was successfully evaluated by using a shock tube system with a total length of about 10 m, which was able to simulate an air inrush into the rarefied gas dynamics region. The experiments were carried out for not only the plain pipe configuration but also for many configurations with larger pipes having various lengths into the shock tube. In the case of only plain pipe with an inner diameter of 35 mm, which corresponded to the standard 2.75-inch ConFlat flange, the shock wave propagation would reach a distance of 10.32 m in 15.7 ms. The insertion of the larger pipe resulting in the rapid cross-sectional change is effective for delaying the transit time of the shock wave, and the total internal volume of the shock tube is the primary factor in the delay time and the following pressure increase. The FCS system could suppress the pressure increase by about four orders of magnitude compared with the case of only the GV.

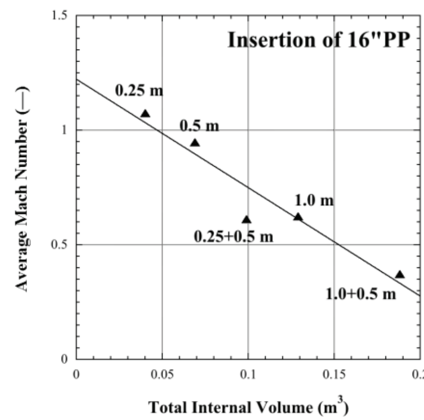

Figure 5: Average Mach number as a function of the total internal volume in the shock tube in the case of inserting various 16"PPs.

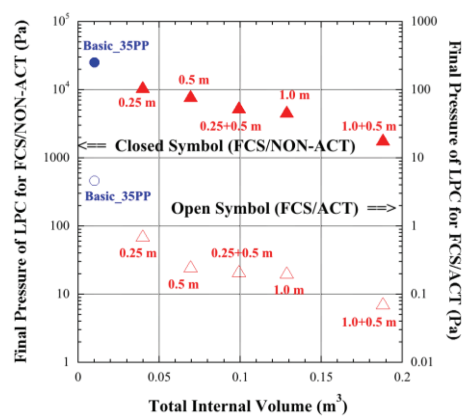

Figure 6: Final pressures in the LPC after closing the GV as a function of the total internal volume. The right Y-axis with open symbols and the left Y-axis with closed symbols correspond to FCS/ACT and FCS/NON-ACT, respectively.

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