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Bench Test Results of the Pulsed Gas Jet and the Differential Vacuum System

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Abstract.
we studied the characteristics of the pulsed gas jet and the differential vacuum system with a bench test setup. Integrated mass flow per pulsed gas jet were measured as functions of the backing gas pressure and the pulse duration, with hydrogen and nitrogen, as well as the fluctuation of the pulse-by-pulse integrated mass flow. Effectiveness of the differential vacuum system has been studied with schemes of the gas jet collector tube and the scheme of the separating windows between vacuum chambers. Measurement on the vibration of the vacuum chambers has been performed.

The integrated mass flow of the gas jets of the hydrogen and nitrogen are 2.6×10^{-4} mol/jet and 7.0×10^{-5} mol/jet respectively with the backing pressure of 1000 psia with the pulse duration of 800 μs. The integrated mass flow of the gas jet is proportional to the pulse duration and to the backing gas pressure. The fluctuation of the integrated mass flow of the gas jet, RMS/MEAN, was measured to be 1 - 2 % with hydrogen and nitrogen with the backing pressure of 100 - 1100 psia, with the pulse duration of 800 μs.

We obtained the average vacuum pressure of 0.6×10^{-6} torr in the 2nd vacuum chamber with double windows with holes of 2 mm in diameter in the center, with the hydrogen gas jet with the backing pressure of 1000 psia with the pulse duration of 800 μs at the frequency of 1 Hz. The vacuum pressure in the second vacuum chamber increases and decreases with the same frequency as that of the gas jet emission. Gas jet collector tube scheme was effective only if the distance between the gas jet nozzle and the opening of the gas jet collector tube was below 2 mm or less. Double separating window with 2 mm diameter holes were shown to be effective to reduce the vacuum level of the second vacuum chamber.

The horizontal and the vertical movement of the vacuum chamber due to the vibration were measured to be 0.48 μm and 0.14 μm respectively in the bench test, which were caused by the vibration of the roots pump, turbomolecular pumps, mechanical vacuum pumps, and the pulsed solenoid valve of the gas jet. Those movement is expected to be smaller with the heavier beam test vacuum chamber and with more solid supporting at the SLAC FFTB.

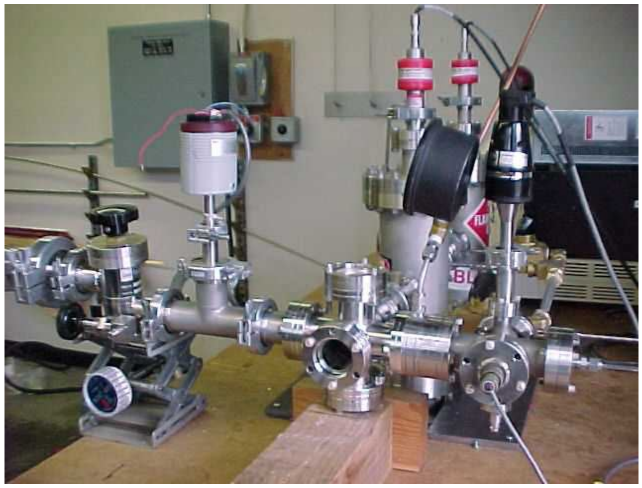


FIGURE 1. Overview of the Vacuum Chambers and vacuum gauges

I GOALS

The major goals of this bench test are the following:

- study on the stability of the total mass flow of the gas jets with hydrogen and nitrogen,
- measure the dependence of the total mass flow of the hydrogen and nitrogen on the backing pressure and on the pulse duration of the gas jet,
- achieve the vacuum level of 1.0×10^{-6} torr or less with the hydrogen gas jet in the second vacuum chamber of the differential vacuum system, including the optimization of the collection scheme of the gas jet into the roots pump.
- demonstrate that the amount of movement of the vacuum chambers due to the vibration by vacuum pumps and the gas jet solenoid can be suppressed below the level of around 0.5 μm in vertical and horizontal direction. The movement of the chamber smears the beam width measurement by the wire scanner.

II SETUP

Figure 1 shows the overview of the vacuum chambers and the vacuum gauges. The vacuum chambers consist of the gas jet chamber which has a gas jet solenoid, and the first and the second vacuum chamber which are located on top of the turbomolecular pumps. Vacuum level of the gas jet chamber is monitored by a capacitance manometer(mechanical) and a Pirani(thermal conductivity) vacuum

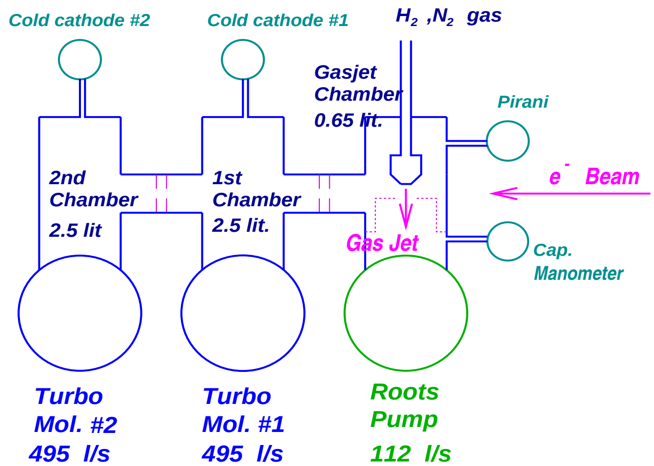


FIGURE 2. Schematic diagram of the vacuum chambers and vacuum pumps

gauges. Vacuum level of the first and second vacuum chambers are monitored by Cold Cathode(ionization) vacuum gauges.

Figure 2 shows the schematic diagram of the layout of the vacuum chambers and the vacuum pumps. The gas jet chamber and the first vacuum chamber, the first vacuum chamber and the second vacuum chamber are separated by a set of two thin metal windows with 2 mm diameter holes in the center with a separation gap of 8 mm. The figure also shows the temporary setup of a collector tube of the gas jet which is separated from gas jet nozzle with a variable gap. The diameter of the holes of the (gas exhaust) collector tubes are 3.0 mm and 7.0 mm. Collector tubes are made of steel pipes with inner diameter of 29.4 mm and the outer diameter of 31.8 mm which are tightly fit into the downstream half of the gas jet chamber with two rubber O-rings.

The schematic diagram of the gas flow is shown in Figure 3. The procedure to execute the measurement of the mass flow rate and the vacuum level with nitrogen and hydrogen gas is listed in the *Appendix A*. We have to keep the gas jet chamber and the vacuum chambers in good vacuum throughout the procedure, and we have to purge the gas volume of the vacuum pumps and their exhaust pipes with nitrogen before and after using the hydrogen gas jet. Table 1 lists the parameters of vacuum pumps, and the vacuum gauges.

The solenoid valve of the gas jet (model number 91-222) is a product of Parker Hannifin Corporation with the orifice diameter of 0.78 mm. The power supply of the pulsed solenoid is the IOTA ONE Pulse Driver with a product number 060-0001-900. Figure 4 shows the electron beams view of the gas jet nozzle and the body of the pulsed solenoid valve. A drawing of the cross section is attached in *Appendix B*.

The orifice is located at 2.0 mm from the center of the axis of the vacuum chambers. The inner diameter of the gas jet vacuum chamber in the picture is 34.8 mm. An energized solenoid coil pulls an iron armature which then pulls a teflon

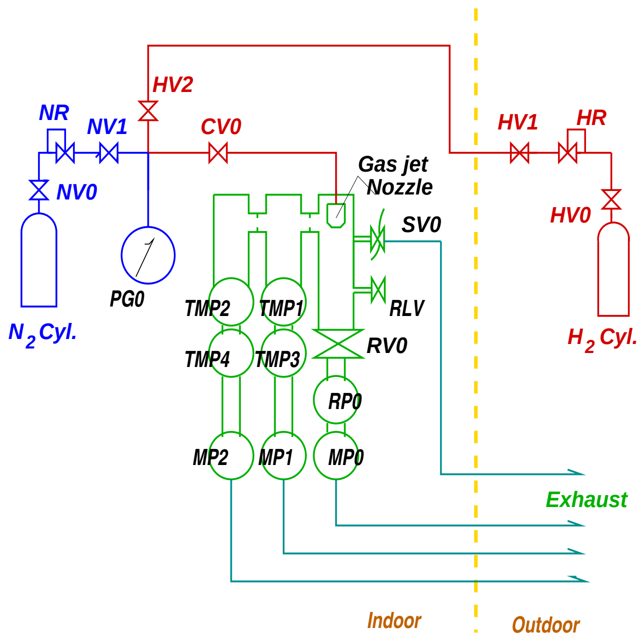


FIGURE 3. Schematic diagram of the gas flow

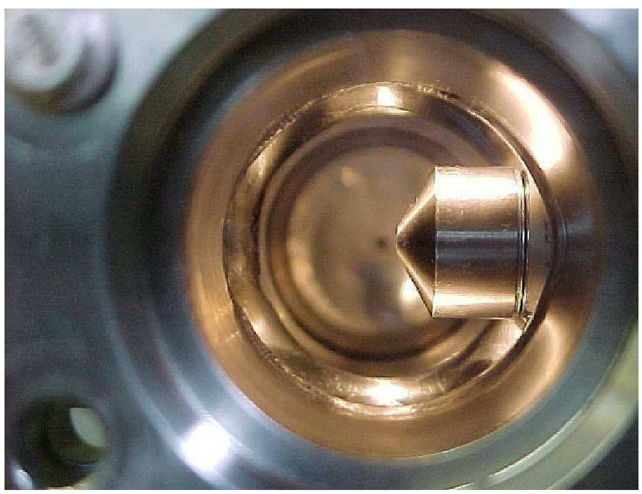


FIGURE 4. Gas jet nozzle of the pulsed solenoid valve

poppet, which opens the gas channel through a straight-through hole in the nozzle. The power supply provides linearly increasing voltage across the solenoid coil up to 280 V within 340 μs then switches to supply 5V holding voltage to keep the channel open completely with the preset duration time. Figure 5 shows the scope pictures of the current (left hand picture) and the voltage (right hand picture) across the solenoid for a single gas jet pulse.

The vacuum chambers are the following:

- gas jet chamber: 0.65 litter,

TABLE 1. parameters of the vacuum pumps and the vacuum gauges

Vacuum Pumps	Model	pump speed(l/s)	range(torr)
roots pump	WA500	110	10^{-3} - 1
turbomol. pump	V450 TMPC874 P.S.	490	10^{-8} -10^{-3}
turbomol. pump	V60 TMPC878 P.S.	60	10^{-8} -10^{-3}
mechanical pump	SD300	11	10^{-3} - 1
mechanical pump	D16A	7	10^{-3} - 1
mechanical pump	E150	47	10^{-3} - 1

Vacuum gauges	Model	detection	vacuum range(torr)
capacitance manometer	622A11TDD L8350301	mechanical	10^{-3} -10^{3}
Pirani	TR901KF CC3 Vacuum Gauge	thermal conductivity	10^{-3} -10^{3}
Cold cathode	850-610-G2 CC3 Vacuum Gauge	ionization	10^{-7} -10^{-3}

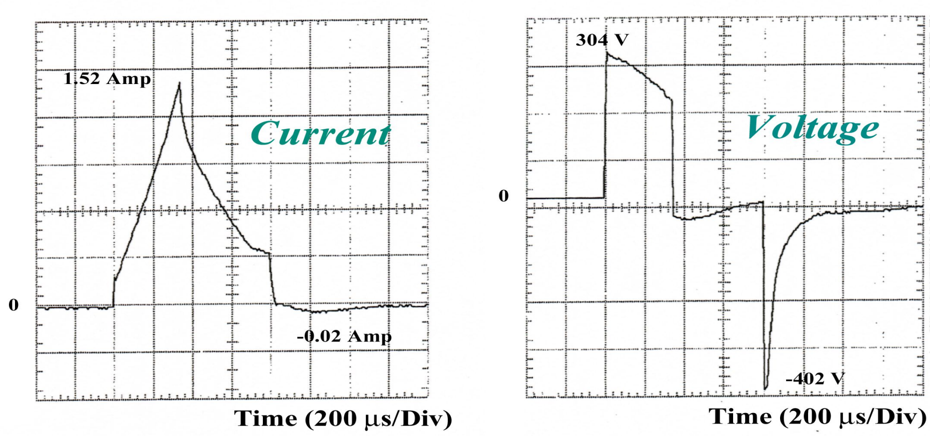


FIGURE 5. current and voltage across the pulsed solenoid

is connected to a Roots Vacuum pump(RUVAC WA500) with the pumping speed of 110 litter/s which is backed up by a mechanical pump(E150). A PIRANI(thermal conductance vacuum gauge) and a Capacitance manometer(mechanical vacuum gauge) monitors the vacuum of the chamber.

- the first vacuum chamber: 2.5 litter
  sits on top of a turbomolecular pump(V450) with the pump speed of 490 litter/s which is connected to another smaller turbomolecular pump(V60) which

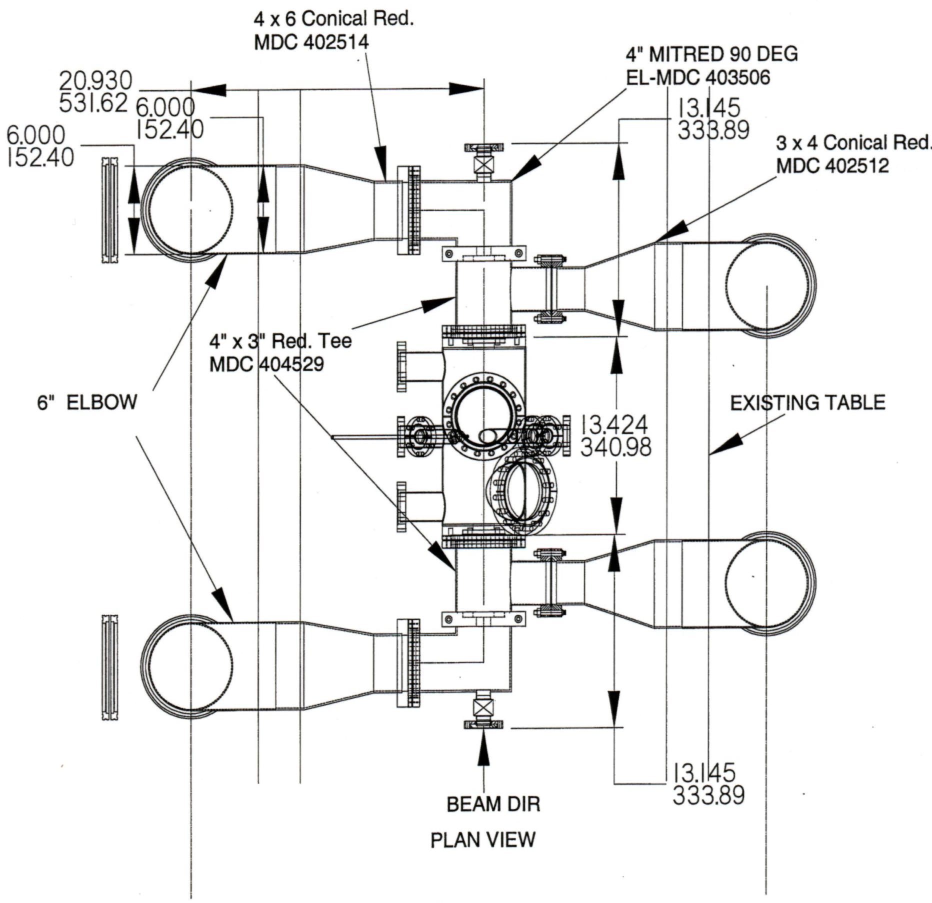


FIGURE 6. plan view of the test beam vacuum chamber(by Dieter Walz)

is backed by a mechanical pump(SD300). A cold cathode ionization vacuum gauge is used to monitor the vacuum level of the chamber.

- the second vacuum chamber: 2.5 litter
  sits on top of another turbomolecular pump(V450) with the pump speed of 490 litter/s which is connected to another smaller turbomolecular pump(V60) which is backed by a mechanical pump(D16A) in order to improve compression ratio with the hydrogen gas jet. A cold cathode ionization vacuum gauge is used to monitor the vacuum of the chamber.

The test beam model of the vacuum chamber has the differential vacuum system both upstream end and the down stream end of the gas jet chamber as shown in Figure 6. The volume of the gas jet chamber will be 5.8 litter which is much larger than the one in the bench test which volume is 0.65 litter. The volume of the first and the second vacuum chambers of the differential pumping system are as large as the those we have in the bench test.

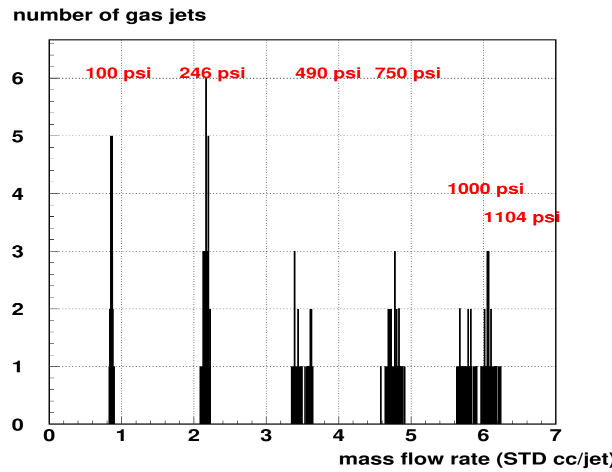


FIGURE 7. hydrogen mass flow rate at 100 - 1104 psia

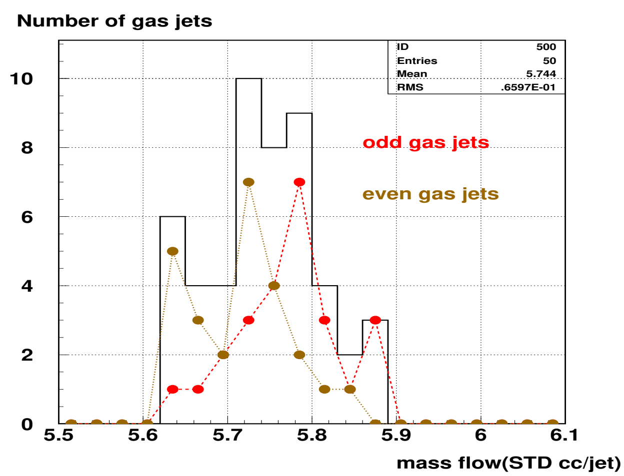


FIGURE 8. hydrogen mass flow rate at 1000 psia

III MASS FLOW RATE

Mass flow rate of the gas jet was measured by using the disconnected gas jet chamber and the two vacuum gauges, a capacitance manometer and a Pirani thermal vacuum gauge. The volume of the gas jet chamber is 0.65 litter. We measured the pressure increase of the vacuum chamber after each gas jet with hydrogen gas and with nitrogen gas, with backing pressure range of 50 - 1100 psia (with the pulse duration of 800 μs), and with the pulse duration range of 500 - 2500 μs(with the backing pressure of 1000 psia).

Figure 7 shows the mass flow rate per gas jet pulse in the unit of the Standard gas cm^3 with hydrogen with the backing pressure of 100, 246, 490, 750, 1000, and 1104 psia. Figure 8 shows the mass flow rate per gas jet pulse with hydrogen with the backing pressure of 1000 psia. The broken lines shows the mass flow rate per gas jet

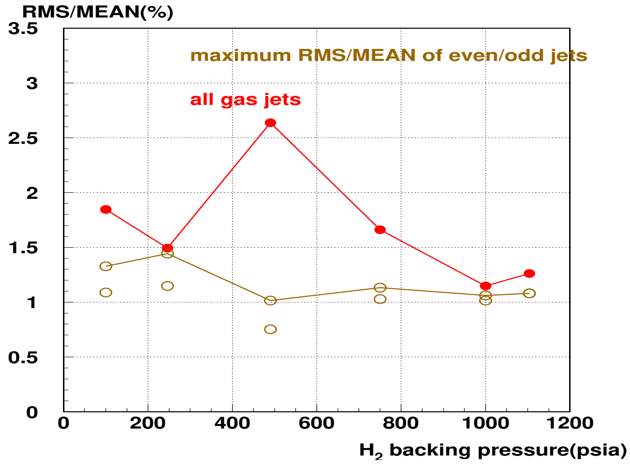


FIGURE 9. RMS/Mean of the hydrogen mass flow rate vs. backing pressure

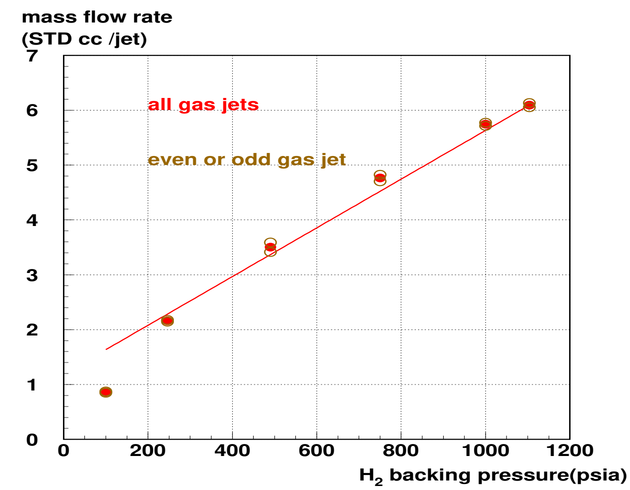


FIGURE 10. hydrogen mass flow rate vs. backing pressure

pulse in the even and odd sequential gas jets. Because the power supply alternates the power transformer channels in generating the 280V initial driving pulse, we observed the systematic difference in the average of the integrated mass flow rate between the even and odd sequential gas jets. Figure 9 shows the RMS/Mean of the mass flow rate per gas jet pulse with hydrogen as a function of the backing pressure. The blue line shows the maximum of the RMS/Mean of the mass flow rate of the even or odd sequential gas jet, which is between 1.0 and 1.5 %. Figure 10 shows the mass flow rate per gas jet pulse with hydrogen as a function of the backing pressure.

Figure 11 shows the nitrogen mass flow rate per gas jet with the backing pressure at 100 - 1104 psia. Figure 12 shows the RMS/Mean of the nitrogen mass flow rate as a function of the backing pressure. Figure 13 shows the nitrogen mass flow rate

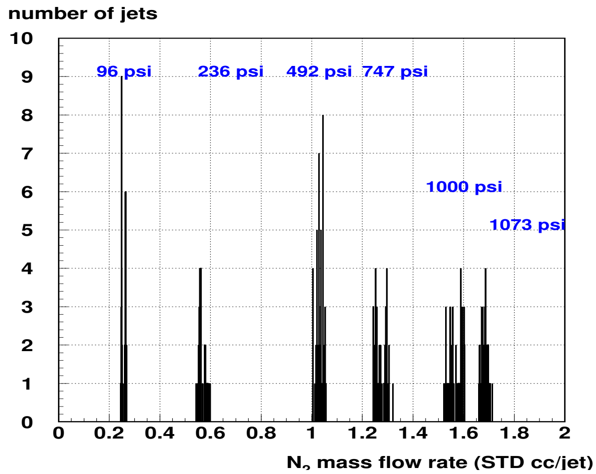


FIGURE 11. nitrogen mass flow rate at 100 - 1104 psia

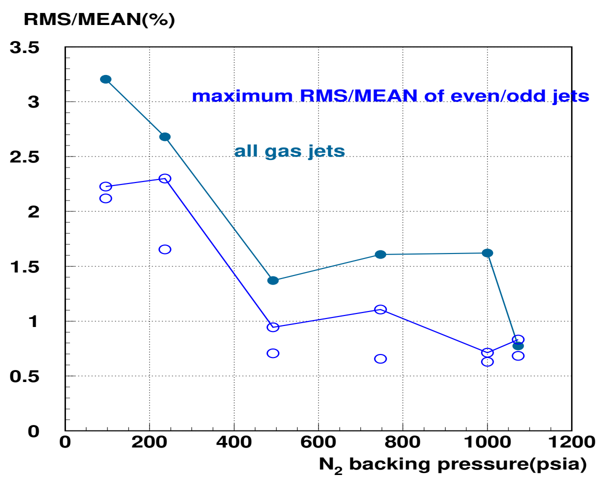


FIGURE 12. RMS/Mean of the nitrogen mass flow rate vs. backing pressure

per gas jet as a function of the backing pressure.

Figure 14 shows the hydrogen mass flow rate per gas jet as functions of the backing pressure with more measured pressure points. Figure 15 shows the hydrogen mass flow rate per gas jet as functions of the pulse duration with more measured pressure points.

IV DIFFERENTIAL PUMPING SYSTEM

As shown in Figures 2, The gas jet vacuum chamber, the first vacuum chamber, and the second vacuum chamber are separated by a set of two metal sheet windows with a gap of 8 mm, where each window has 2.0 mm diameter hole in the middle to clear the electron beam. Typical vacuum pressure of those three chambers are

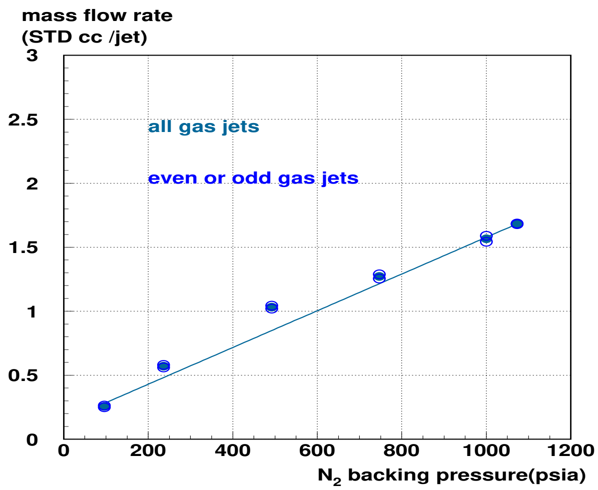


FIGURE 13. nitrogen mass flow rate vs. backing pressure

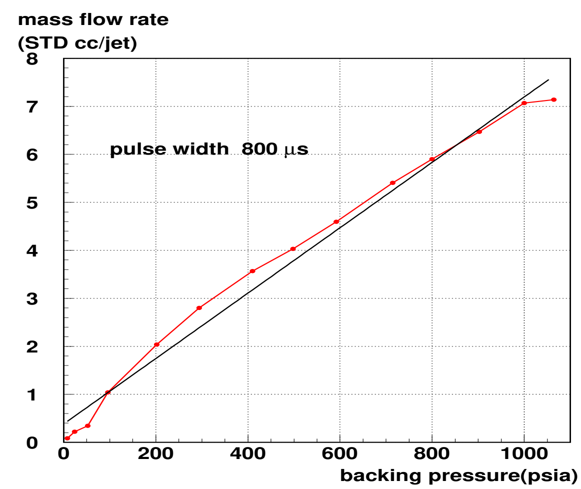


FIGURE 14. hydrogen mass flow rate vs. backing pressure

10^{-2} - 10^{-1}, 10^{-5} - 10^{-3}, and 10^{-7} - 10^{-5} torr in the upstream to the downstream order, with the hydrogen gas jet frequency of 1.0 Hz with the backing pressure of 1000 psia.

Figures 16 shows the maximum and the minimum vacuum pressure of the second chamber as a function of the gap length between the gas jet nozzle and the collector tube hole with diameters of 3.0 mm and 7.0 mm. As shown in the figure, in order to get any improvement in the vacuum pressure of the second vacuum chamber, we have to place the collector tube less than 2 mm from the gas jet nozzle in the case of using the 7 mm diameter hole, and less than 1 mm in the case of using the 3 mm hole, comparing with the vacuum pressure of the second vacuum chamber in the case without a collector tube in the gas jet chamber. In this test, the separator window between chambers had only one layer of the metal sheet with a hole in the

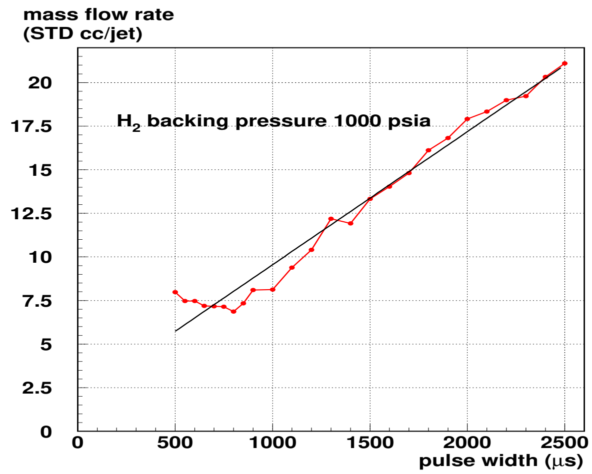


FIGURE 15. hydrogen mass flow rate vs. pulse duration

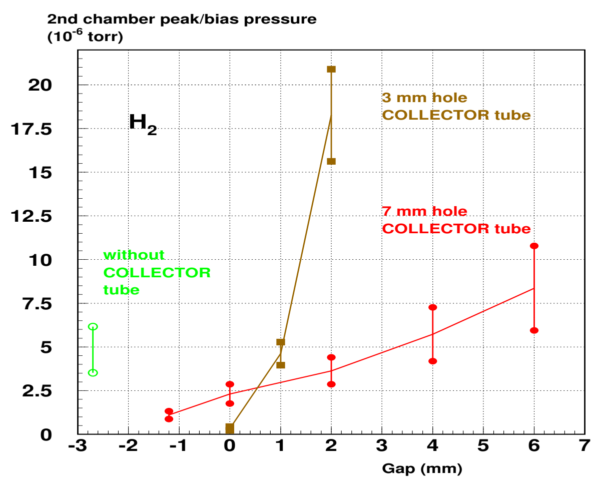


FIGURE 16. 2nd chamber pressure vs. gap to collector tubes

middle, and the additional turbomolecular vacuum pumps, V60, were not used. By using two sets of the double windows instead of two single window between vacuum chambers, we obtained the reduction of a factor 3 in the vacuum pressure of the second vacuum chamber with the hydrogen gas jet with 800 μs pulse duration with the frequency at 1.0 Hz.

V VIBRATION MEASUREMENT

Figure 17 shows the setup of the horizontal and vertical geophones which were placed on an Aluminum plate which was tied securely to the gasjet vacuum chamber. Geophones are devices which measure the velocity of the object with a pickup coil surrounding a heavy solid iron. Figure 18 shows the integrated movement of

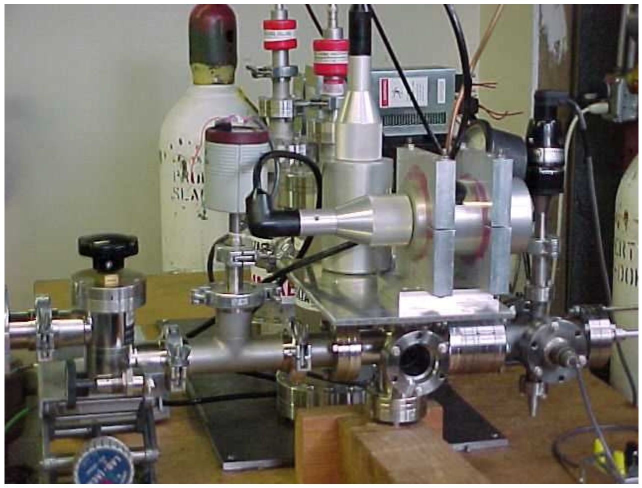


FIGURE 17. Geophones setup on the gasjet vacuum chamber

the gasjet chamber as a function of the frequency of the vibration in horizontal direction (bottom plot) and in vertical direction(top plot) with the gas jet and all the vacuum pumps turned on. The major part of the horizontal motion of the vacuum chamber is due to the vibration by the turbomolecular vacuum pumps and the backing mechanical pumps, which contribution in the horizontal motion is 0.42 μm. The horizontal motion is 0.48 μm with all the vacuum pumps and the gas jet turned on, as shown in the figure, where the horizontal motion is 0.14 μm with the same condition. Because the test beam module of the vacuum chambers are significantly larger and heavier and they will be supported more solidly onto the supporting structure at the FFTB, we expect much smaller integrated motion of the test beam vacuum chambers in horizontal and vertical direction.

VI ITEMS TO BE TESTED FURTHER

The following is a list of items to be tested in the future.

- measure the instantaneous gas density of a gas jet with the plasma producing laser by observing the backward Raman scattered light, and the forward blue shift of the laser light at the LLNL and at the SLAC FFTB.
- use the laser interferometer and the shadow graph to monitor the neutral gas jet density and the general shape of the gas jet.
- durability test of the pulsed solenoid coil
  run the solenoid valve at 1.0 Hz with 1000 psia nitrogen backing pressure for a few to ten weeks. Monitor the average and RMS/Mean of the mass flow rate.
- try the harder material poppet in replacing the teflon poppet.

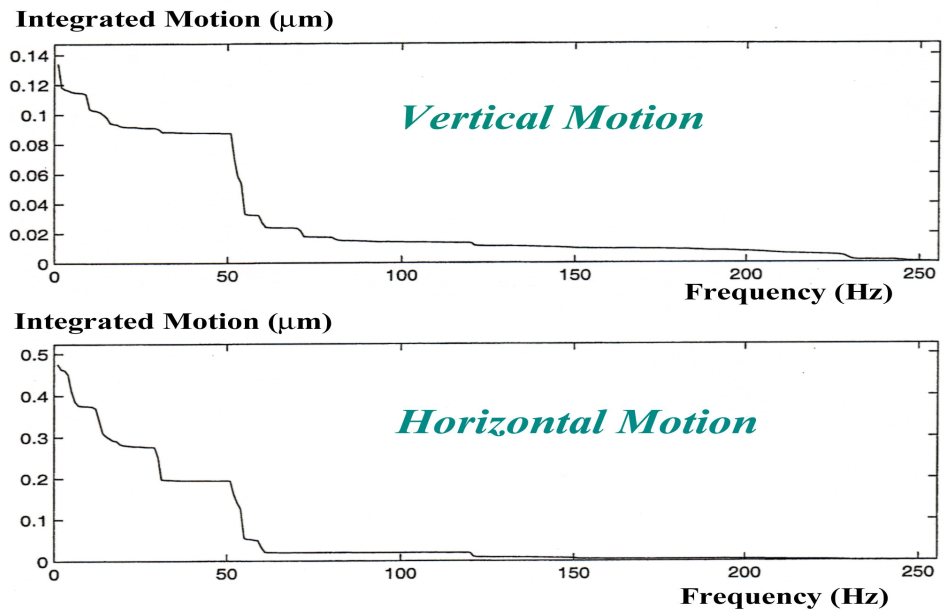


FIGURE 18. Integrated motion as a function of the frequency(by Tim Slaton)

VII CONCLUSION

The gas jet system and the differential vacuum system are good enough to be tested at the LLNL to measure the instantaneous gas density with the plasma producing laser by observing the backward Raman scattered light, and the forward blue shift of the laser light.

The integrated mass flow of the gas jets of the hydrogen and nitrogen are 2.6×10^{-4} mol/jet and 7.0×10^{-5} mol/jet respectively with the backing pressure of 1000 psia with valve opening time width of 800 μs. The integrated mass flow of the gas jet is proportional to the valve opening time width and to the backing gas pressure. The fluctuation of the integrated mass flow of the gas jet, RMS/MEAN, was measured to be 1 - 2 % with hydrogen and nitrogen with the backing pressure of 100 - 1100 psia, with pulse duration of 800 μs.

We obtained the vacuum pressure of 0.6×10^{-6} torr in the 2nd vacuum chamber with double windows with holes of 2 mm in diameter in the center, with the hydrogen gas jet with the backing pressure of 1000 psia with the valve opening time width of 800 μs at the frequency of 1 Hz. The vacuum pressure in the second vacuum chamber increases and decreases with the same frequency as that of the gas jet emission. Gas jet collector tube scheme was effective only if the distance between the gas jet nozzle and the opening of the gas jet collector tube was below 2 mm or less. Double separating window with 2 mm diameter holes were shown to be effective to reduce the vacuum level of the second vacuum chamber.

The horizontal and the vertical movement of the vacuum chamber due to the vibration were 0.48 μm and 0.14 μm respectively in the bench test, which were caused by the vibration of the roots pump, turbomolecular pumps, mechanical vacuum pumps, and the solenoid valve of the gas jet nozzle. Those movement is expected to be smaller with the heavier beam test vacuum chamber and with more solid supporting at the SLAC FFTB.

The authors thank David Cline, Patrick Kwok, and Pisin Chen for their help on the initial design of the bench test. We also thank the members of the cryogenic group around the building 104 at SLAC for their help in getting the hardware setup and in operating the system in the building. Wesley Muffet spent significant amount of time in constructing the bench test setup. Thomas Knight helped us in converting the NT picture data into UNIX ps files. We thank Wim Leemans and Pavel Volfbeyn of the LBNL for their design work on the gas jet nozzle and their comments on this bench test measurement. This research was supported by the Department of Energy on the E150 experiment at SLAC.

1. make sure that the release valve, RLV, and the roots pump valve, RV0, are closed.

2. turn on mechanical pumps, MP1 and MP2.

3. turn on the power switch of a receptacle which supply power to the turbomolecular pumps and the vacuum gauge readout modules.

4. turn on V60(smaller) turbomolecular pumps TMP3 and TMP4. It takes a few minutes to get the operational rotational speed(RPM) of the turbomolecular pumps.

5. turn on V450(larger) turbomolecular pumps TMP1 and TMP2. It takes a few minutes to get the operational rotational speed(RPM) of the turbomolecular pumps.

6. turn on a mechanical pump MP0(under the roots pump).

7. turn on the roots pump, RP0, and open a valve, RV0.

8. make sure that the valve, HV2, is CLOSED, and the pressure gauge PG0 shows lass than 14 psia.

9. set the duration time at 800 μs, and the frequency at 1.0 Hz, and START the gas jet(to vacuum the gas in the tube between the gas jet nozzle and the nitrogen cylinder.

10. open the valves, NV1 and NV0, and adjust the backing pressure at 1000 psia at the pressure gauge, PG0.

11. set the duration time at 10 ms, and keep the nitrogen gas jet for 5 minutes to purge the vacuum pumps and exhaust pipes.

12. close the valve, NV0, and keep the valve, NV1 open. And vacuum the nitrogen gas in the pipe between the gasjet nozzle and the nitrogen cylinder. Adjust the duration time of the gas jet accordingly, and get the vacuum level of 1 psia or less.

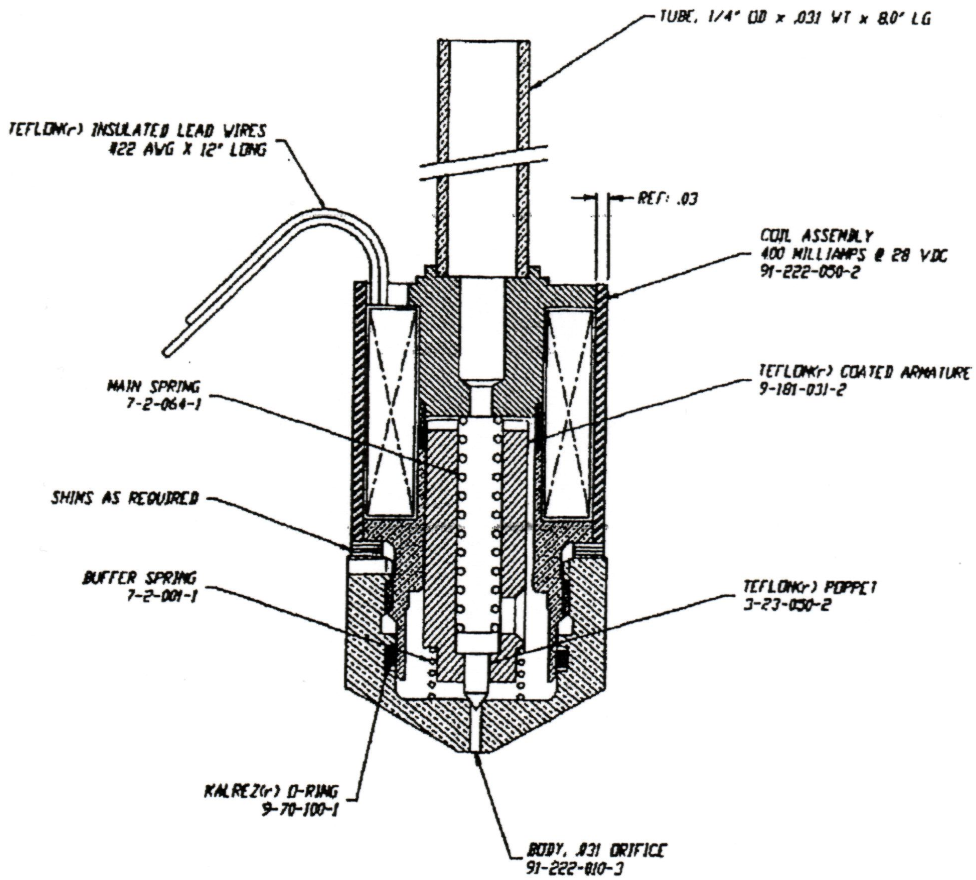
13. make sure that the delivery side of the pressure gauge of the regulator, HR, shows 0 psia, and the valve, HV1, is OPEN.

14. OPEN the valve, HV2, and keep the gas jet running to get the vacuum level below 0.5 psia.

15. close the valve, NV1, and open the valve.

16. make sure that the regulator delivery pressure is set at 0 psia. (Pressure adjustment handle should be fully turned counter-clock-wise.)

17. make sure that the duration of the gas jet is set at 800 μs and the frequency at 1.0 Hz.
18. open the valve HV0, and then adjust the backing pressure at 1000 psia.
19. start the *hydrogen gas jet*.
20. keep watching that the roots pump RV0, and the three mechanical pumps, MP0, MP1, and the MP2 are running while using the hydrogen gas jet.
21. —– Finishing routine —————–
22. close the valve, HV0, and keep the valve, HV1 open.
23. vacuum the pipe between the gas jet nozzle and the hydrogen cylinder below 0.5 psia. Be careful not to trip the roots pump RP0 in adjusting the gas jet duration time.
24. close the valve HV2.
25. open the valve NV0, and then open the valve NV1, and adjust the nitrogen pressure at 1000 psia.
26. set the gas jet duration time at 10 ms, and start the gas jet.
27. keep the gasjet for 5 minutes to purge the vacuum pumps and the exhaust pipes.
28. close the valve NV0, and keep the valve, NV1 open.
29. vacuum the pipe between the gas jet nozzle and the nitrogen cylinder, till the vacuum level reaches to below 1 psia.
30. stop the gas jet, and close the roots pump valve, RV0.
31. turn off the mechanical pump MP0, the roots pump, RP0, and the mechanical pumps MP1 and MP2.
32. turn off turbomolecular pumps TM3 and TMP4.
33. turn off turbomolecular pumps TM1 and TMP2.
34. slowly open the release valve RLV to put the air into the vacuum chambers.



APPENDIX B Pulsed Solenoid Drawing