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Gas Injection And Fast Pressure-Rise Measurements For The Linac4 H^- Source

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Abstract. In the era of the Large Hadron Collider, the CERN injector complex comprising the 34 years old Linac2 with its primary proton source, is presently upgraded with a new linear accelerator for H^- (Linac4). The design, construction, and test of volume production and cesiated RF-driven H^- ion sources is presently ongoing with the final goal of producing an H^- beam with 80 mA beam current, 45 keV beam energy, 500 μs pulse length, and a repetition rate of 2 Hz. In order to have quantitative information of the hydrogen gas density at the moment of plasma ignition the dynamic vacuum properties of the plasma generator were studied experimentally. We describe the experimental setup and present fast pressure-rise measurements for different parameters of the gas injection system, such as gas species (H_2, He, N_2, Ar), piezo valve voltage pulse length (200 - 500 μs), and injection pressure (400 - 2800 mbar). The obtained data are compared with a conductance model of the plasma generator.

Keywords: Ion source, negative ions, dynamic vacuum.
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INTRODUCTION

The replacement of the ageing Linac2, CERN's 50 MeV proton accelerator, with Linac4, a 160 MeV H^- accelerator, is an important step towards a general upgrade of the beam brightness available from the Proton Synchrotron Booster, and the consolidation of the entire LHC injector complex. The installation and commissioning of a new volume production RF-driven H^- ion source is presently ongoing in a dedicated test stand at CERN used for the commissioning of different ion source prototypes, the Low Energy Beam Transport (LEBT), and the 3 MeV Radio Frequency Quadrupole (RFQ). An overview of the planned H^- ion source prototypes for Linac4 can be found in [1]. For optimized operation of an H^- ion source it is interesting to obtain quantitative information of the hydrogen gas density at the moment of plasma ignition, especially when the gas is pulsed into the source. The pressure response in the source is very useful to understand at which time after the initiation of the gas pulse the ignition of the source with either a spark gap, or the RF pulse, should be made. Therefore, we have systematically studied the dynamic vacuum properties of the plasma generator. We describe the experimental setup and present fast pressure-rise measurements, which are compared with dedicated vacuum simulations of the Linac4 ion source.

EXPERIMENTAL SETUP

The experiments were performed with the CERN SPL plasma generator (PG) test stand, which is described in detail elsewhere [2]. This test stand was modified for fast pressure-rise measurements. The plasma chamber of the PG was replaced with a stainless steel tube of the same inner diameter, which included a port allowing a pressure gauge to be mounted. Figure 1 shows the cross sections of a full plasma generator, and the test setup used for the pressure measurements; a photograph of the new experimental layout is also displayed.

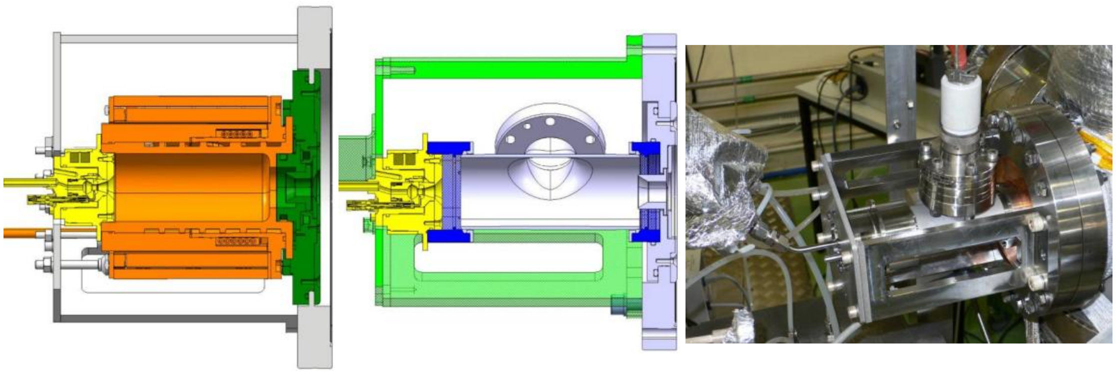

FIGURE 1. Cross sections of the CERN SPL plasma generator with installed plasma chamber (left) and a stainless steel test chamber (middle) equipped with a port for a high-pressure vacuum gauge. Both images show the upstream ignition element (yellow part) and the downstream plasma chamber collar. Photograph of the experimental setup used for fast Linac4 ion source pressure-rise measurements (right). The stainless steel chamber, equipped with a high-pressure ionization gauge, is connected to the main vacuum chamber of the CERN SPL plasma generator test stand. On the left side parts of the gas injection system comprising the temperature stabilized gas injection piezo valve are visible.

For the experiments presented here, the AlN plasma chamber was replaced by a T-shaped stainless steel vacuum chamber, comprising a high-pressure ionisation gauge (Balzers IMR 312) for fast pressure readings. Gas was injected through a temperature stabilized piezo valve (Maxtech MV-112) mounted to the variable pressure gas supply line. This assembly was mounted onto the DN 160 CF vacuum cross of the SPL PG test stand, equipped with a 500 l/s turbo molecular pump and a 12 m^3/h backing pump, vacuum gauges (Balzers IMR 312, PKR 261), and other diagnostics.

The IMR 312 hot-cathode ionization gauge allows vacuum measurements between 10^{-6} and 1 mbar. Special care was taken for the fast pressure-rise experiments. The quantity measured is the pressure-dependent ion current of the IMR 312 gauge. The electrons emitted by the cathode (+30 V) ionize the gas molecules on their trajectory to the positive (+170 V) electron collector. The created positively charged ions are measured with the ion collector (0 V). The measured pressure of the gauge depends on the gas type, a calibration factor of 1.0 relates to nitrogen (N_2). For other gases (H_2, He, Ar) the corresponding calibration factors were used. Within the entire measuring range the ion current is proportional to the pressure. The measured ion current is converted to a voltage by the electrometer amplifier of the gauge controller.

The gauge controller provides the voltages to the gauge and the circuit to measure the ion current and convert it into a pressure reading. The voltage supplies to the gauge were left unmodified. The ion current signal from the gauge was disconnected at the input to the controller's measurement board and connected to a rear panel mounted switch. The switch diverts the ion current either to an external measurement circuit or the gauge controller's own measurement circuit. By disconnecting the gauge controller's measurement circuit the full ion current can be sent to the external circuit to avoid signal filtering of the internal circuit thus maximizing time resolution.

The external measurement circuit consists of a BNC connector mounted on the rear panel with a spark gap in parallel to prevent charging to high voltages. The ion current signal is then fed via a BNC cable to a resistor in parallel with an oscilloscope's input resistance to convert the ion current into a voltage for direct display on the oscilloscope. Different resistor values were used giving different measurement sensitivities. To minimize the time constant of the circuit (Fig. 2), the capacitance of the measurement circuit was kept as low as possible by shortening the coax cable between the gauge and controller and between the controller and oscilloscope. A spark gap was chosen for its low capacitance compared to semiconductor devices.

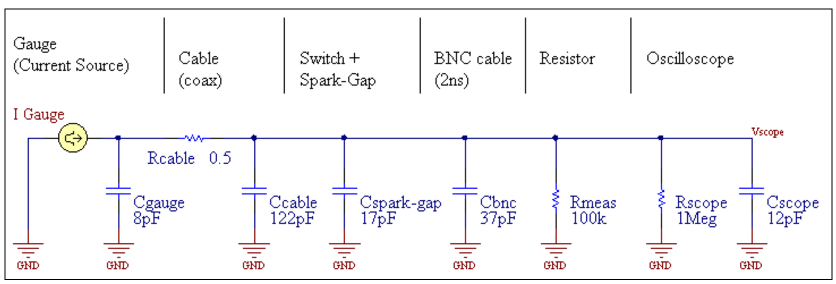

FIGURE 2. Schematic layout of the measurement circuit used for fast pressure-rise experiments.

Dynamic Pressure Simulations

The Linac4 H^- ion source gas dynamics have been studied via the electrical network - vacuum analogy. This technique allows the evaluation of the time dependent one-dimensional pressure profile along the source as a function of the pulsed gas injection, the geometry of the vacuum chambers, as well as the chosen pumping groups. The parallelism between the laws governing electrical variables (current, voltage, resistance) and the laws governing vacuum variables (gas load, pressure, conductance) is the basis of vacuum engineering. By translating each component of the vacuum line in an electrical component, it is possible to create a network that can be solved in dedicated programs, *e.g.* LTspice or PSpice.

In addition, having to deal with complex geometries, a Monte Carlo simulation was carried out with Molflow, in order to estimate the transmission probability, therefore the conductance, of the source components. A detailed description of the simulation technique and the results obtained for the Linac4 H^- ion source vacuum system can be found elsewhere [3].

Dynamic Pressure Measurements

Systematic fast pressure-rise measurements have been performed for different parameters of the gas injection system. The piezo valve voltage pulse length was varied between 200 µs and 500 µs at a repetition rate of 2 Hz, while keeping the injection pressure applied onto the piezo valve at 1300 mbar. The experimental pressure-rise curves obtained for H_2 and N_2 are displayed in Fig. 3 and compared with simulations. Similar curves were measured for the injection of He and Ar gas.

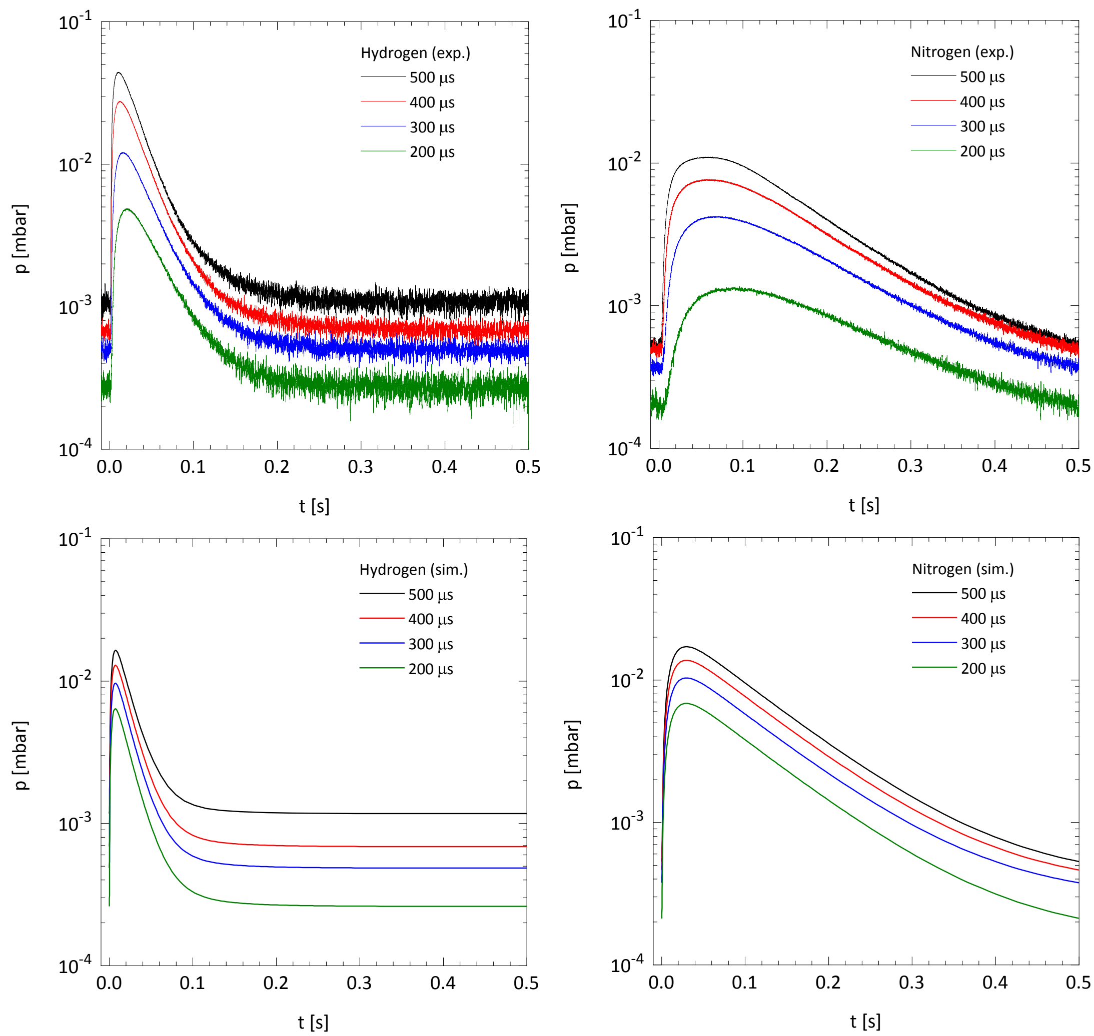

FIGURE 3. Pressure-rise curves for H_2 and N_2 gas injections into the plasma chamber using piezo valve voltage pulse lengths between 200 µs and 500 µs, 1300 mbar gas pressure on the piezo valve, and a repetition rate of 2 Hz. The measured curves (top) are compared with simulation data (bottom).

From such type of experimentally measured pressure-rise curves one can obtain a set of interesting parameters, which are potentially useful for an optimized operation of our ion source. In addition, these measurements can be used to benchmark the obtained simulation results. We have determined the pressure rise time (10-90% value) t_{rise} , the maximum pressure p_{max}, and the pumping speed S. The pumping speed is derived by fitting the pressure decay curve. Since the plasma chamber and the main vacuum chamber are separated by the so-called "collar", this introduces a conductance of 14.6 l/s for H_2 and 3.9 l/s for N_2. The above mentioned parameters are listed in Table 1, which compares the experimental results with simulations.

TABLE 1. Summary of measured and simulated pressure-rise times t_{rise}, maximum pressures p_{max}, and derived pumping speeds S, obtained for H_2 and N_2 gas injections with different pulse lengths at a repetition rate of 2 Hz. The measured values are compared with simulation data, which are listed in brackets.

H_2 gas injection			
Pulse length [μs]	**t_{rise} [ms]**	**p_{max} [10^{-2} mbar]**	**S [l/s]**
500	4.9 (6.6)	4.4 (1.5)	9.6 (12.6)
400	5.8 (6.5)	2.8 (1.2)	8.9 (12.1)
300	7.9 (6.5)	1.2 (0.9)	7.8 (12.4)
200	10.7 (6.5)	0.5 (0.6)	7.0 (12.3)
N_2 gas injection			
Pulse length [μs]	**t_{rise} [ms]**	**p_{max} [10^{-2} mbar]**	**S [l/s]**
500	23.2 (24.0)	1.1 (1.7)	2.3 (2.3)
400	26.6 (23.4)	0.8 (1.4)	2.1 (2.2)
300	32.6 (27.0)	0.4 (1.0)	1.9 (2.3)
200	46 (24.5)	0.1 (0.7)	1.6 (2.3)

We observe that the simulated pressure-rise times t_{rise} and pumping speeds S are pulse length independent and change as expected with gas type. These theoretical results can be understood because the dynamic pressure simulations for the Linac4 vacuum system, comprising the H^- ion source, were done in the molecular flow regime in which any conductance is pressure independent. Therefore, the conductance of the collar, which separates the test chamber from the main vacuum chamber, does not vary in the simulations. As expected, the maximum pressure increases with pulse length because more molecules are injected into the system.

From the quantitative point of view the experimental results reveal a slightly different picture (see Table 1). The maximum pressure increases up to the range of 10^{-2} to 10^{-1} mbar (see Fig. 3). Here we are in the transitional flow regime and pressure simulations are much more complicated since any conductance becomes pressure and geometry dependent. In contrast to the simulation results, the measured H_2 pressure-rise times in the test chamber decrease with increasing gas pulse length (see Table 1) and the determined pumping speeds S increase with longer pulses. The same trend was observed for N_2 and the other two gases (He, Ar) we studied. These experimental results confirm our expectation because the conductance of the orifice (collar) is expected to increase between 10^{-2} and 10^{-1} mbar due to the change to the transition flow regime [4]. This has been experimentally verified with the same test setup by steady state H_2 gas injection experiments.

Despite these quantitative differences between simulations and experiments we conclude that the measured pressure rise curves for the test chamber are qualitatively well described by simulations. A deeper understanding of the identified differences would require much more complicated simulations, which is beyond the scope of this study.

The dynamic pressure rises were further measured as a function of the backing pressure on the piezo valve, which was varied from 400 mbar to 2800 mbar; 500 μs long piezo valve voltage pulses were applied with a 2 Hz repetition rate into the test chamber. The results obtained for H_2 and N_2 are displayed in Fig. 4. Similar curves were measured for the two other studied gases He and Ar.

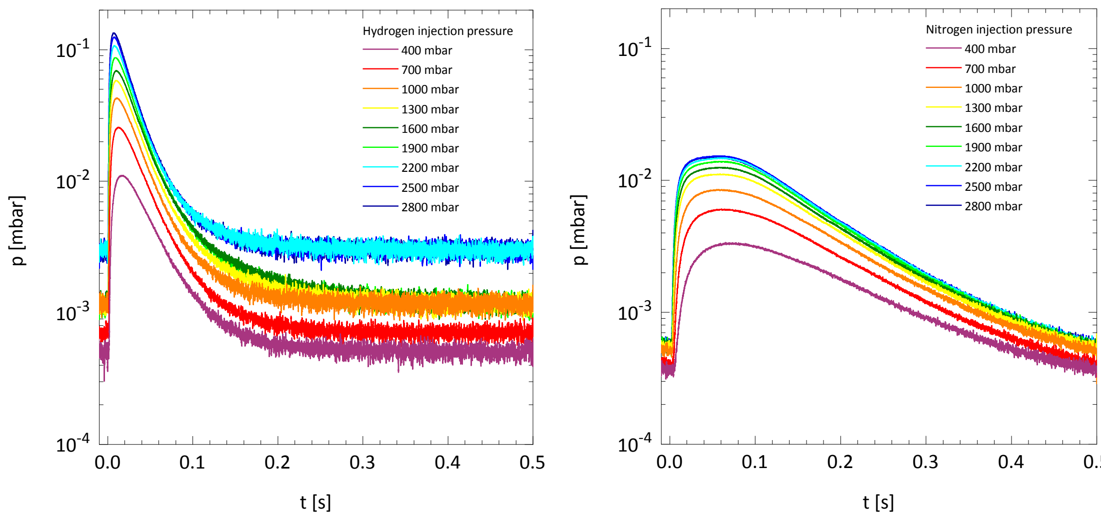

FIGURE 4. Pressure-rise curves as a function of gas pressure on the piezo valve measured for 500 μs long H_2 (left) and N_2 (right) piezo valve voltage pulses injected with a 2 Hz repetition rate into the test chamber.

We observe for a constant piezo valve voltage pulse length of 500 μs that the maximum pressure, measured with the IMR 312 gauge, increases with increasing gas pressure applied to the piezo valve. The results obtained for N_2 gas show the same trend but smaller pressure rise values.

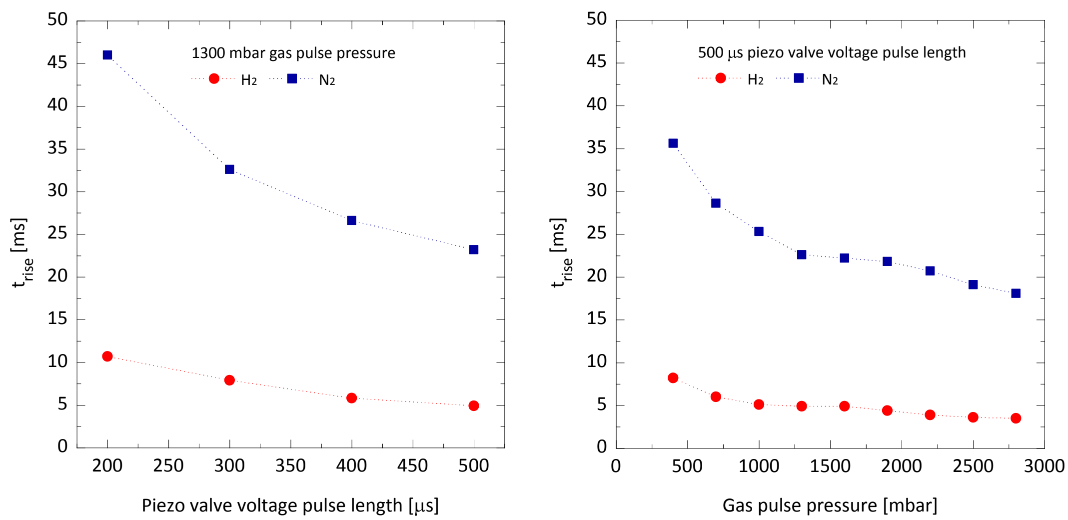

FIGURE 5. Pressure-rise time measurements for pulsed (2 Hz) gas injections into the test chamber. The results obtained for different piezo valve voltage pulse lengths (left) and various gas pulse pressures (right) are compared for H_2 and N_2.

For the operation of the Linac4 H^- ion source the time behaviour of the hydrogen pressure-rise inside the plasma chamber is important to know in order to achieve optimum source performance. Figure 5 summarizes the measured H_2 pressure-rise times as a function of piezo valve voltage pulse length and gas pressure on the piezo valve, the results are compared with N_2.

For the nominal Linac4 ion source piezo valve voltage pulse length of 500 μs the hydrogen pressure-rise time in the stainless steel test chamber is about 4.9 ms, measured with a gas pulse pressure of 1300 mbar. A reduction of pulse length from 500 μs to 200 μs yields to an increase of the rise time up to 10.7 ms. A change in gas pressure applied to the piezo gas injection valve also influences the H_2 pressure-rise time. At 2800 mbar the measured rise time decreased to 3.5 ms, while we obtain 8.2 ms at 400 mbar.

During operation of the Linac4 ion source no direct online vacuum monitoring will be possible on the plasma chamber. Therefore, we have performed comparative experiments with two different vacuum gauges (IMR 312, PKR 261) installed downstream of the test vacuum chamber. Both gauges were mounted on the vacuum cross of the PG test stand, which was pumped with a 500 l/s turbo molecular pump. The pressure rise of the test chamber was recorded simultaneously with one of the two gauges on the main vacuum chamber. For the PKR 261 gauge, the 0-10 V analog output signal of its power supply was recorded. The results obtained for three different H_2 piezo valve voltage pulse lengths, injected with a 2 Hz repetition rate, are compared in Fig. 6.

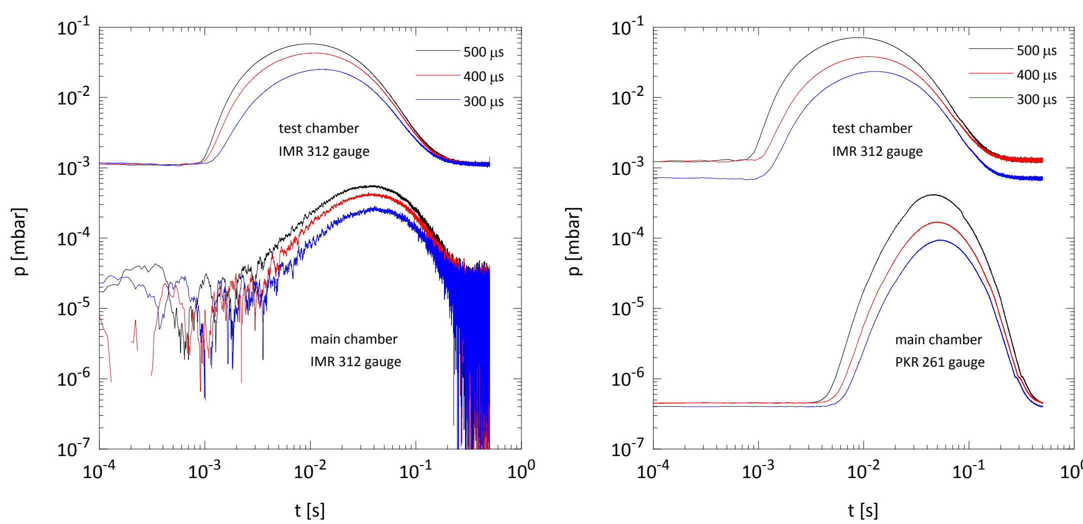

FIGURE 6. Comparison of H_2 pressure-rise curves measured with different vacuum gauge configurations on the test and the main vacuum chamber. Hydrogen gas pulses (500 μs, 400 μs, 300 μs) were injected with a 2 Hz repetition rate (1300 mbar gas pressure on the piezo valve) into the test chamber. The vacuum gauge configuration IMR 312/IMR 312 (left) is compared with the IMR 312/PKR 261 setup (right).

For the experiments performed with two IMR 312 gauges, one installed on the test chamber and the second one on the main vacuum chamber, we observe fast pressure-rises after H_2 injections with 500 μs, 400 μs, and 300 μs. The pressure-rise time t_{10}, defined as the time after which the pressure has reached 10% of the maximum pressure, was evaluated for all experiments. For the hydrogen 500 μs gas pulse injection we obtain t_{10} = 1.3 ms (IMR 312) on the test chamber compared to 4 ms (IMR 312) and 12.8 ms (PKR 261) on the main vacuum chamber. The absolute error of these numbers is in the order of ± 0.1 ms. Since the main vacuum chamber is pumped with a turbo molecular pump, the measured pressures are of course much lower than in the test chamber. Although the time response of the IMR 312 gauge (main chamber) is faster than the PKR 361 gauge, its signal is noisier below 10^{-4} mbar.

We conclude that even without any special efforts on the electronics side of its controller, the PKR 261 gauge is suited for such kind of studies. Since we have measured the pressure-rise time delay between the main vacuum chamber and the test chamber it looks very promising to use the PKR 261 gauge for online vacuum monitoring of the Linac4 H^- ion source plasma chamber.

It should be noted that the long-term behaviour (weeks/months) of both vacuum gauges under the above described vacuum conditions is not known in detail. A potential reaction of the IMR 312 and PKR 261 gauges with hydrogen gas has not yet been studied systematically; this should be done in the future.

CONCLUSIONS

Systematic fast pressure-rise measurements were presented to study the dynamic vacuum behaviour of the Linac4 H^- ion source. Within the investigated H_2 gas injection parameters, the pressure rise Δp increases with longer piezo valve pulse lengths (200 - 500 μs) and higher gas pressures (400 - 2800 mbar) applied onto the piezo valve.

For the highest pressure peak of Δp_{max} = 1.3 x 10^{-1} mbar (500 μs, 2800 mbar) the shortest rise time of t_{rise} = 3.5 ms with $t_{10\%}$ = 1.1 ms was measured. For the lowest pressure peak of Δp_{min} = 4.9 x 10^{-3} mbar (200 μs, 1300 mbar) the longest rise time of t_{rise} = 10.7 ms with $t_{10\%}$ = 3.1 ms was measured. The conductance of the source outlet aperture, which provides the pumping of the source, was seen to depend on the amount of injected gas. Near-future gas injection experiments with the Linac4 H^- ion source prototype (IS-01), presently installed at the 3 MeV test stand, will be performed to find the best H_2 injection parameters for optimum ion source performance.

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