New Folder Name Pressure Pulses

Abstr.#: 256

Program#: VT-WEM1

Detection of small pressure pulses in an ion pumped UHV-system

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Contribution to 40th AVS Symposium

Abstract

Pressure stability in the UHV-system of a gravitational wave detector is a crucial point for its sensitivity limit. We carried out an investigation in order to detect presssure fluctuations in an UHV system pumped with an ion pump. The expected charcacteristics of pressure pulses caused by desorption were simulated with Monte-Carlo methods. A test equipment was developed with a sensitivity limit for relative pressure changes of 10^{-3} at a base pressure of 10^{-6} Pa in the range up to one kHz, and of 10^{-4} below 40 Hz. Pressure fluctuations in the 10^{-4} range of working pressure were found in the frequency range < 40 Hz and larger pressure pulses in the percent range with a frequency of about 1 in 4 h.

1. Introduction

For the realization of highly sensitive gravitational wave detectors long baseline optical interferometers are being planned or already under construction[1-4]. These interferometers with arm lengths of several kilometers will operate under ultra high vacuum (UHV) conditions at pressures of typically 10^{-6} Pa. Stability of pressure in the vacuum system is an important factor for the detection limit of gravitational waves. A millisecond pressure pulse of $1\cdot10^{-10}$ Pa at a working pressure of $1\cdot10^{-6}$ Pa in a 1 m segment of the tank may cause optical fringe shifts like a gravitational wave[4], the frequencies of which are expected in the audio-frequency range. Ion pumps for example may cause pulses when a discharge at a whisker causes abrupt desorption from the cathode surface.

The following investigation was made to detect small pressure fluctuations and pulses in an UHV system in the interesting audio-frequency range in order to estimate the effects which may happen in a gravitational wave detector vacuum system. Pressure pulses so far have been investigated by some authors for diffusion pumps[5] and turbomolecular pumps[6], however at a much lower frequency range. Ion pumps are known to generate electromagnetic noise in the high frequency region[7,8] (> 1MHz up to Ghz), for pressure fluctuations < 1 kHz, however, we have found no reports in the literature.

2. Expected characteristics of pressure pulses

When gas of the amount q_{pV} is desorbed in the volume V and expands in zero time interval $\Delta t=0$, it will cause a pressure rise of $(\Delta p)_0 = q_{pV}/V$. If the volume is pumped with the effectice pumping speed S, the time dependence of the decrease of Δp is given by

$$\Delta p = (\Delta p)_0 \exp(-t / \tau_1) \tag{1}$$

where $\tau_1 = V/S$. It should be noted that V is the total volume including the pump volume. Erraneous results will be received, if only the volume above the pump inlet area is inserted in V.

When we give up the assumption of an expansion in zero time interval, the following model gives an adequate description of the time dependence of the pressure rise: Let us assume that gas will be expanded from a small volume V_1 into a large volume V_2. At time $t_0 = 0$ we will remove a virtual membrane between the two volumes and observe the pressure rise in V_2. Then, under molecular flow conditions the number of particles dN_1/dt leaving V_1 into V_2 is given by $dN_1(t)/dt = n_1(t)\cdot c\cdot A/4$, where n_1 is the particle density per unit volume in V_1, c the mean thermal velocity and A the open area between V_1 and V_2. The number of particles leaving V_2 into V_1 is given by $dN_2(t)/dt = n_2(t)\cdot c\cdot A/4$, where n_2 is the particle density per unit volume in V_2. Since the total number of particles in V_1 and V_2 shall remain constant (no pumping during pressure rise) and $-dN_1(t)/dt = dN_2(t)/dt$ we get the following two coupled differential equations:

$$\begin{aligned} V_2\frac{dn_2(t)}{dt} &= \frac{Ac}{4}\Big(n_1(t) - n_2(t)\Big) \\ V_1\frac{dn_1(t)}{dt} &= \frac{Ac}{4}\Big(n_2(t) - n_1(t)\Big) \end{aligned} \tag{2}$$

These are solved with the two boundary conditions $n_2(0) = 0$ and $n_1(0) = N_1/V_1$ as

$$\begin{aligned} n_2(t) &= n_1(0)\frac{V_1}{V_1+V_2}\Big(1 - \exp(-t/\tau_2)\Big) \\ n_1(t) &= n_1(0)\left(\frac{V_1}{V_1+V_2} + \frac{V_2}{V_1+V_2}\exp(-t/\tau_2)\right) \end{aligned} \tag{3}$$

with

$$\tau_2 = \frac{4}{Ac}\left(\frac{V_1V_2}{V_1+V_2}\right) \tag{4}$$

If $V_1 << V_2$ we simply get $n_2(t) = n_1(0)\,(V_1/V_2)\,(1-\exp(-t/\tau_2))$ and $\tau_2 = 4V_1/(Ac)$. While τ_1 is given by the ratio of volume to effective pumping speed, τ_2 is given by the ratio of (the smaller) volume to ideal pumping speed. To get some typical numbers for τ_1 and τ_2, we assume $V = V_2 = 785$ l, which is the volume of a cylindrical segment of 1 m length and 1 m diameter (typical for gravitational wave detectors), $V_1 = 50$ l, which is a typical volume of an ion pump, S = 1000 l/s, A = 0.0177 m^2, corresponding to an inner diameter of 150 mm, and c for hydrogen at 20°C. Then τ_1 = 785 ms and τ_2 = 6.5 ms. It is typical for most vacuum systems that $\tau_2 << \tau_1$ and justifies the assumption that no pumping occurs during pressure rise.

Leaving this modelled situation, we have to consider that it was assumed that the particle distribution in each of the volumes is instantenous, so that homogeneous n_1 and n_2 can be assumed. This seems justified, because the mean velocity is large enough that a particle can reach arbitrary points in typical volumes as above in a time interval much shorter than τ_2. If, however, a pressure pulse is caused by sudden desorbing particles from a microscopic area, no volume V_1 is defined. For this reason we carried out Monte-Carlo simulations to estimate τ_2 more accurately. The result is shown in Figure 1. The inset shows the geometrical configuration, desorption point, and detection area, where the number of particles per unit time $n(t)$ crossing it in the direction of the arrow is counted. V_1 corresponds to the volume and adapter flange of an ion pump, V_2 to a cylindrical segment of the gravitational wave detector tube. Desorption of hydrogen molecules at half height of the pump (arrow) is assumed. As seen in Figure 1, the results could be fitted very well with the equations derived above:

$$n(t) = const \cdot \left(1 - \exp(-t / \tau_2)\right) \exp(-t / \tau_1) \tag{5}$$

τ_1 = 841 ms was very close to $(V_1+V_2)/S$, where V_1 = 50 l and V_2 = 785 l as above and S = 933 l/s at cross sectional area A. τ_2 = 10 ms was larger than $4V_1/(Ac)$ = 6.5 ms, which is reasonable, since it takes also time to distribute the particles in V_1. Changing the position of the detection area in the large volume did not alter $n(t)$, which verifies the assumption of instanteneous random distribution.

In conclusion it can be expected that a pressure pulse from a "catastrophic" desorption event will have the characteristic of $n(t)$ in equation (5). The time constant τ_1 can be estimated from V/S and the lower limit of τ_2 may be estimated from equation (4). Since τ_1 scales with the volume, oscillations of frequencies > S/V start to damp out in a volume of size V.

3. Experimental

Since the pressure rise $(\Delta p)_0$ is inversely proportional to V, it is advantageous for increasing sensitivity to gas desorbed in the pump to measure pressure stability with a relative small volume additional to the pump volume. The triode ion pump to be tested was flanged to a stainless steel cylindrical tube with a volume of about 8.5 l , while the volume in the ion pump was about 43 l. Nominal pump speed S_n was 1000 l/s for hydrogen (400 l/s for nitrogen). A gas inlet on the opposite side of the cylinder was installed such, that gas could be injected symmetrically from either a leak valve or a piezo-driven valve. Two ionization gauges of Bayard-Alpert-type were arranged on the cylinder, symmetrically to both the ion pump and the gas inlet for coincidence measurements. The two gauges were 75 cm apart. Gas analysis was performed with a quadrupole mass spectrometer.

With moderate baking at 120°C an ultimate pressure of 10^{-7} Pa was achieved. By continuously injecting H_2 through the leak valve, simulating higher outgassing from stainless steel walls, we established a working pressure of 10^{-6} Pa. With the piezo-driven valve with a typical opening time of a few ms it was possible to generate pulses of 1% height at the working pressure of 10^{-6} Pa.

It was found that the available controllers for ion gauges had noise levels of typically 5% in the audio-frequency range, mainly because of mains hum. Therefore the potentials of the ion gauges were applied with stabilized power supplies. The emission currents were generated by supplying the filaments with two independent, highly stable, biased current sources. With these stabilized supplies the noise level could be reduced to 0.1%.

The ion current of the ionization gauges was measured with shielded and battery powered low noise amplifiers (3 db reduction at 50 kHz) directly mounted on the gauge heads. The amplified voltage signals were fed into a fast (100 kHz) 2 channel digital voltmeter with a memory of 30000 data per channel. The memory was read into a workstation via a IEEE interface.

Data were recorded once per millisecond. After reading from the memory they were checked for events, i.e. the mean value of 10 consecutive points deviate from the overall mean (30000 data) by more than 0.5% in one channel. If an event is detected, data are stored for detailed analysis. The dead time for transfer of data, preanalysis and storage is 13 s, compared to 30 s of measurement.

For further decreasing the noise level to values of $1\cdot10^{-4}$ low-pass filtering by means of Fast-Fourier analysis was performed.

4. Results and discussion

Figure 2 shows a typical pulse in the UHV-system, which happened with a frequency of about once in 4 h, registered by both ion gauges at the same time with the same characteristics. The measured pulse could be fitted as expected from equation 5. The rise time τ_2 was 7 ms, the decay time τ_1 110 ms, the puls height 7% of working pressure. This pulse corresponds to a particle burst of $4.5\cdot10^{-6}$ Pa l (10^{12} particles). The measured pulse heights ranged from 0.1% up to 10% of working pressure. For a similar pulse as shown in Figure 2 it was found with the mass spectrometer that at least 90% of the particles in the pulse are hydrogen molecules. Sometimes considerably higher pulse heights of about > 100% were observed. The precise height is unknown, since the amplifier run out of its range.

While τ_2 was consistent with Monte-Carlo simulations, τ_1 is about a factor of two higher than expected from V/S_n = 50 ms. This is, because the pump speed decreases with pressure and is typically about 40% lower at 10^{-6} Pa than the nominal (maximum) speed[7,9] S_n at about 10^{-4} Pa. Also it has to be taken into account that a pump with a long elapsed run time and less remaining capacity had been used for the experiments.

The origin of pulses as shown in Figure 2 may be short instabilities in the leak valve, desorption from the walls, desorption caused by the ionization gauges or desorption events in the pump:

If the gas supply through the leak valve would be unstable in the ms range, also negative pulses can be expected, which were not observed.

On the other hand, pulses of this size by desorption from the stainless steel walls can be excluded: The surface area was about 3500 cm^2 and the highest outgassing rate could be assumed as $3 \cdot 10^{-8}$ Pa l/s cm^2. Hence, $3 \cdot 10^{10}$ particles are outgassed in each millisecond and the number of particles in a measured pulse as shown in Figure 2 would be reached only after 35 ms from the whole surface area. This means that a puls of this height and time characteristic cannot be explained by fluctuations of outgassing.

Small gas bursts in the ion gauge heads could be observed sometimes, revealing itsself by a large pressure rise in one of the gauges while considerably damped in the other. These events could be clearly identified.

Hence, it could be concluded that electrical instabilities in the ion pump causing desorption are the most probable source of pressure pulses.

To further support this conclusion, we changed three parameters of the pump: previous history immediate before experiment, gas load, and the high voltage in the pump.

History: After 1 h pumping with a rate of 10^{-1} Pa l/s , corresponding to pumping at 10^{-4} Pa and returning to the working pressure of $1 \cdot 10^{-6}$ Pa, the frequency of pulses increased considerably.

Gas load: At longer run times at ultimate pressure (leak valve closed) we found that the frequency of pressure pulses considerably reduced. The frequency did not significantly depend, however, on the size of the working pressure up to 10^{-5} Pa, when the pump was not in an overloaded condition.

High voltage: When the high voltage was reduced to 1 kV, the frequency of pressure pulses also greatly reduced. No single puls was observed in a period of 20 h.

Gas bursts could also be initiated by mechanical shocks causing vibrations in the pump system.

Figure 3 shows the typical signals from the two ionization gauges at 10^{-6} Pa when no pressure pulse occurs. Data were low pass filtered with the cut-off at 4 Hz. Fluctuations coincide to a very large level at the two gauges and have a maximum value of about $5 \cdot 10^{-4}$ from the working pressure. Coincidence of fluctuations got lost at frequencies above about 40 Hz, leading to the conclusion that noise of higher frequency was not caused by pressure fluctuations but by electrical noise. Again, statistical fluctuations of the outgassing rate in the 100 ms range are only of the order of 10^{-7} at the working pressure of 10^{-6} Pa, orders of magnitudes smaller than the observed fluctuations.

To track down the reason for these fluctuations we turned off the emission of both gauges and recognized that the resulting voltage fluctuations were of a height of $1 \cdot 10^{-4}$ and uncorrelated. This excludes the effect of stray fields from external electrical sources below 40 Hz and supports the conclusion that indeed the particle density was fluctuating. When the high voltage in the ion pump was reduced from 5 kV to 1 kV, the fluctuations < 4 Hz decreased by 30%. This suggests that also the small pressure fluctuations stem from small gas bursts in the ion pump, possibly by point discharges at small clusters or tips in the pump.

5. Conclusions

From the investigation above it can be concluded that, if operated with low gas load, an ion pump produces a pressure pulse of up to a few % (volume of 50 l) about once in 4 h run time on the average. The time charcacteristics of it scales with the volumes involved. Even small volumes of 50 l show well defined time characteristics of these pulses with a time scale which should allow to distinguish them from the characteristics of a gravitational wave.

Also it was found that small pressure fluctations < 40 Hz occur in a smaller ion pumped system dependent on the voltage in the pump. These fluctuations, however, will be considerably damped in the large tubes of gravitational wave detectors. An ion pump should, however, be mounted not too close to the tube or inside of it.

This investigation will be extended to various pump types as NEG, titanium sublimation pumps, and turbomolecular pumps.

References

[1] D. G. Blair, "The detection of gravitational waves", Cambridge University Press (1991).

[2] D. G. Blair, L. Ju, and M. Notcutt, Rev. Sci. Instr. **64,** 1899 (1993).

[3] A. Abramovici et al., Science **256,** 325 (1992).

[4] J.R.J. Bennet and R.J. Elsey, Vacuum **43,** 35 (1992).

[5] J. Flexman et al. Vacuum **40,** 381 (1990).

[6] S. Danziger, B.R.F. Kendall, and J. Dormer, J. Vac. Sci. Technol. **21,** 893 (1982).

[7] K.M. Welch, "Capture Pumping Technology", Pergamon Press, (1991).

[8] P.A. Redhead, Vacuum **38,** 901 (1988).

[9] Ion pump manufacturer's manual.

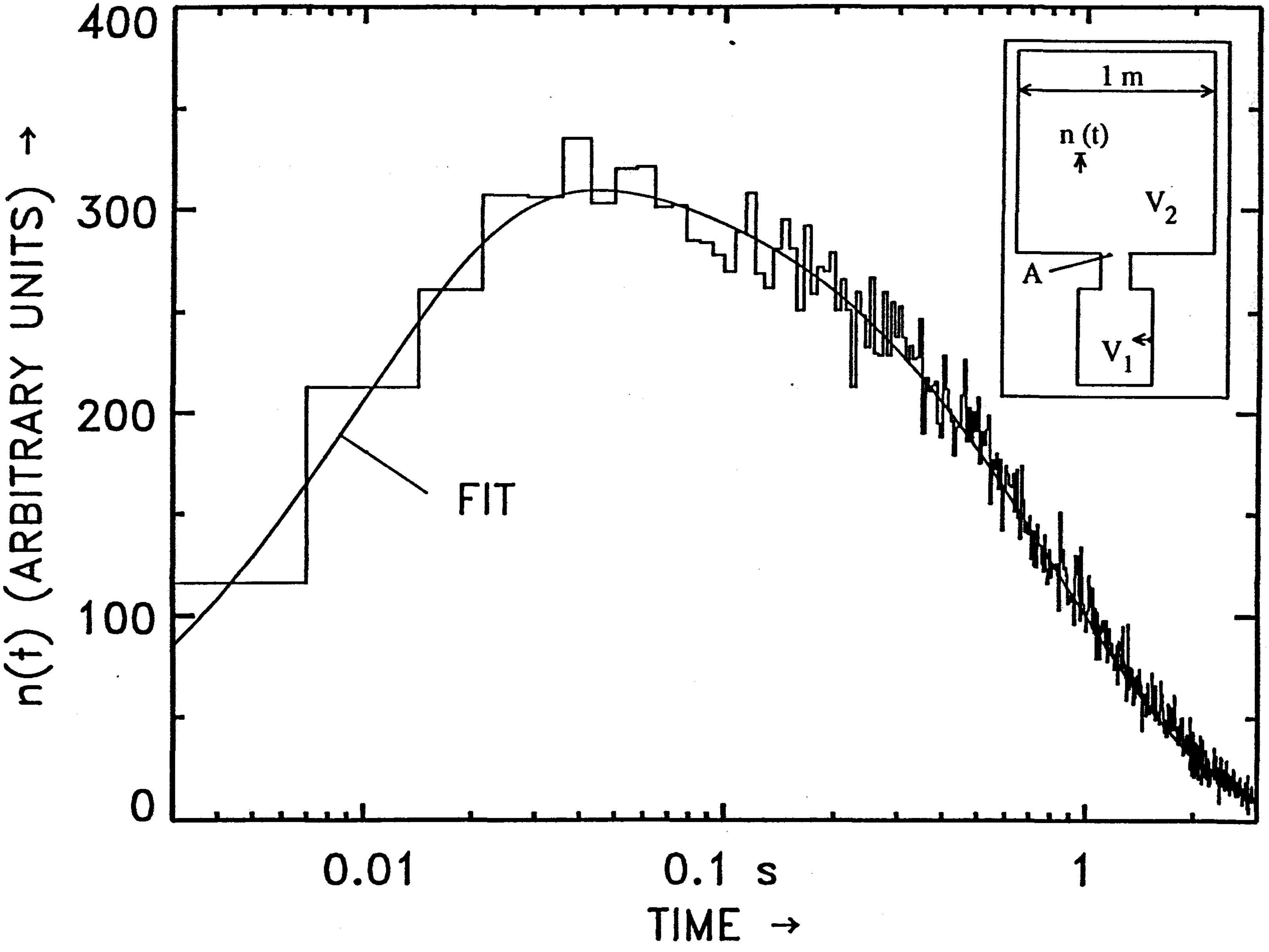
Figure Captions

Fig.1.: The number of hydrogen particles *n(t)* passing in the marked direction through the area in volume V_2 (shown on inset) in a time interval of 7.15 ms, calculated by Monte-Carlo methods. $1.2 \cdot 10^5$ particles were desorbed with cosine distribution in the direction of the arrow marked in volume V_1. The solid line depicts a fit curve according to equation (5) with $\tau_1 = 841$ ms and $\tau_2 = 10$ ms.

Fig.2.: Typical pressure pulse at $1 \cdot 10^{-6}$ Pa, simultaneously measured with the two ionization gauges. The signal of one ionization gauge has been shifted for better showing. The smooth line depicts a fit curve from equation (5) with $\tau_1 = 110$ ms and $\tau_2 = 7$ ms.

Fig.3.: Typical pressure fluctuations at $1 \cdot 10^{-6}$ Pa. Frequencies > 4 Hz have been low pass filtered by means of FFT. The signals are highly correlated.

Fig.4.: Fluctuations of the signals at the Voltmeter in mVolt, when emission is turned off. Frequencies > 35 Hz have been low pass filtered by means of FFT. For comparison with amplitudes in Figure 3 the fluctuations have to be related to a dc signal of 3 Volt.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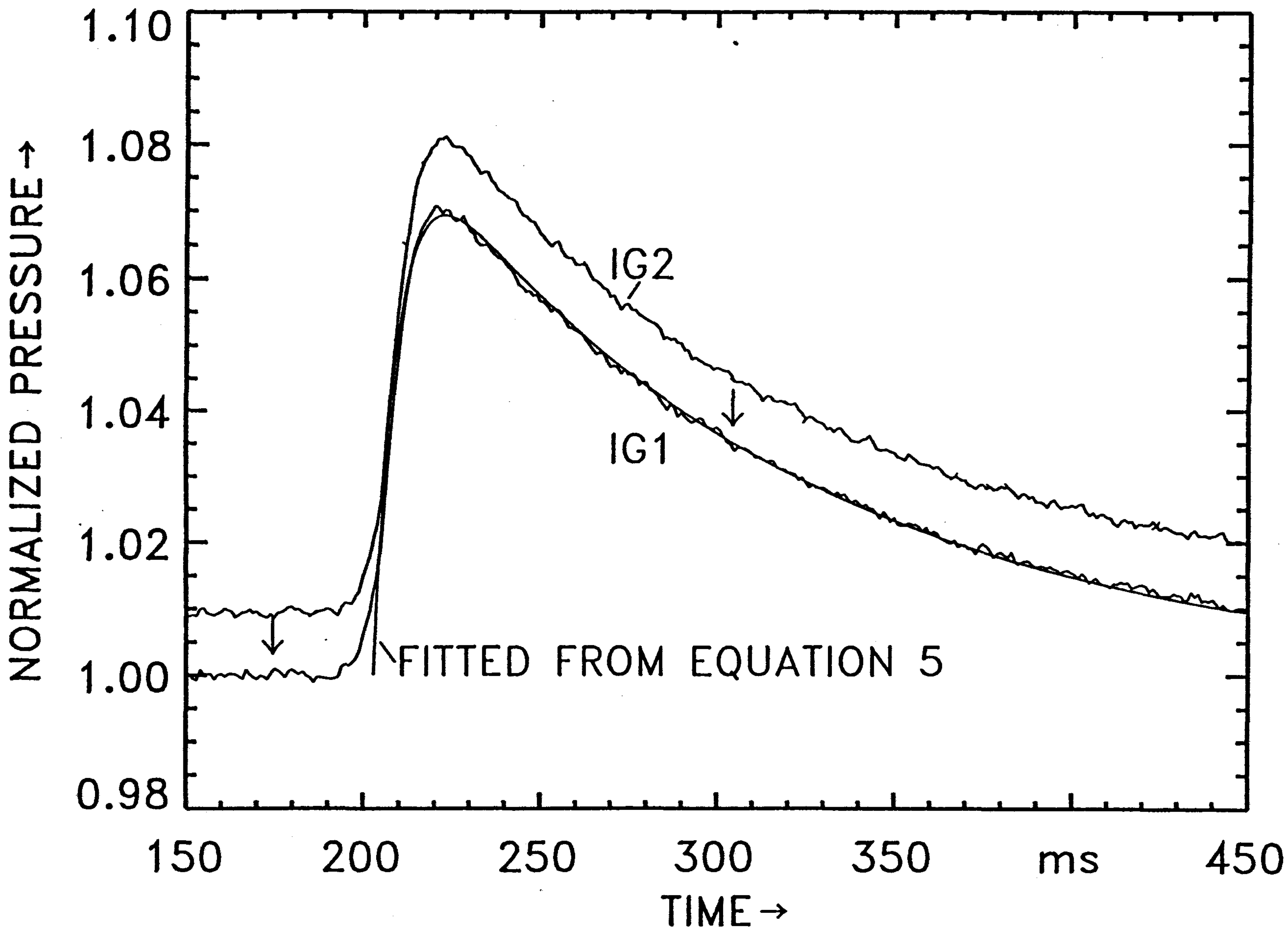

1.10
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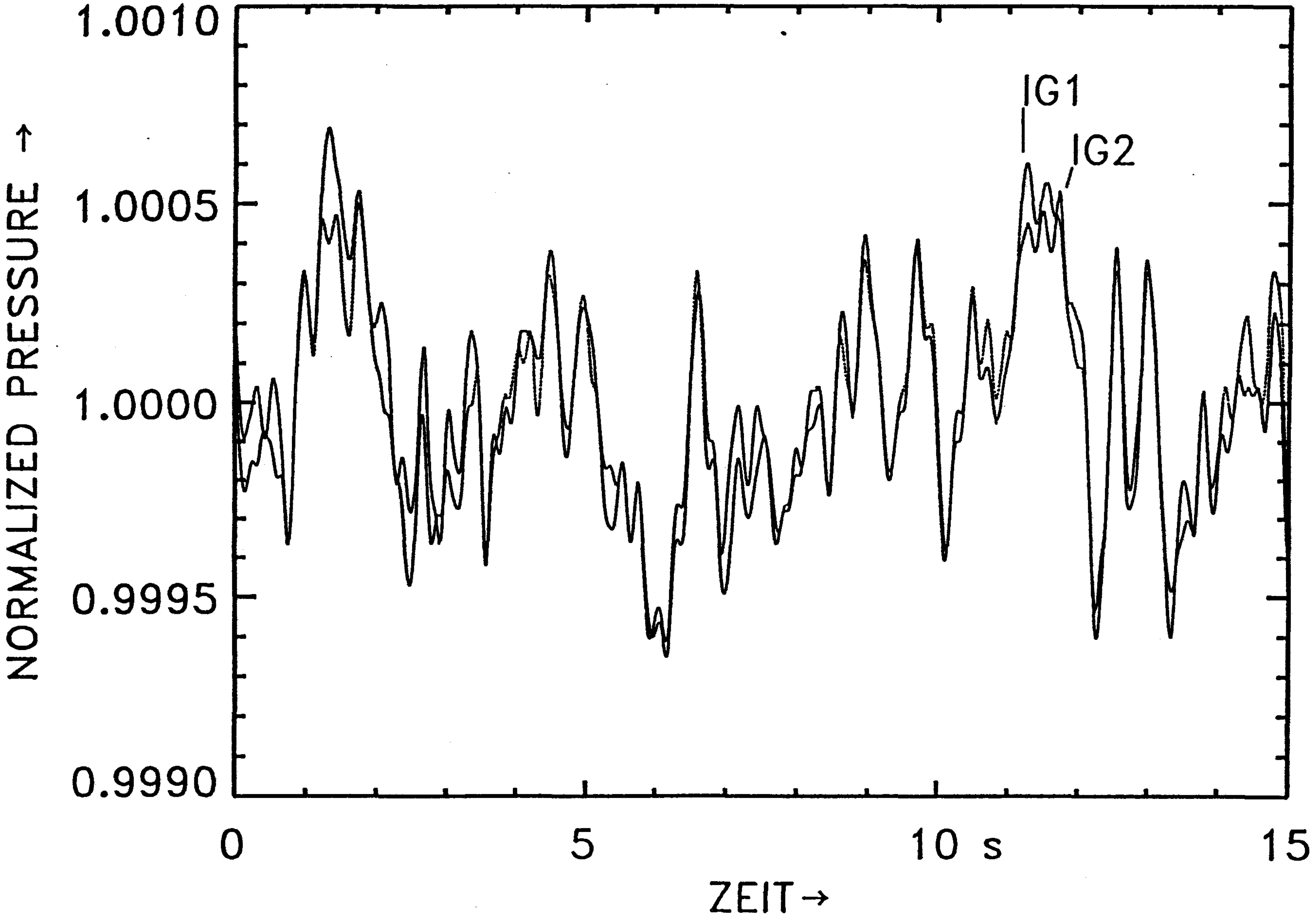

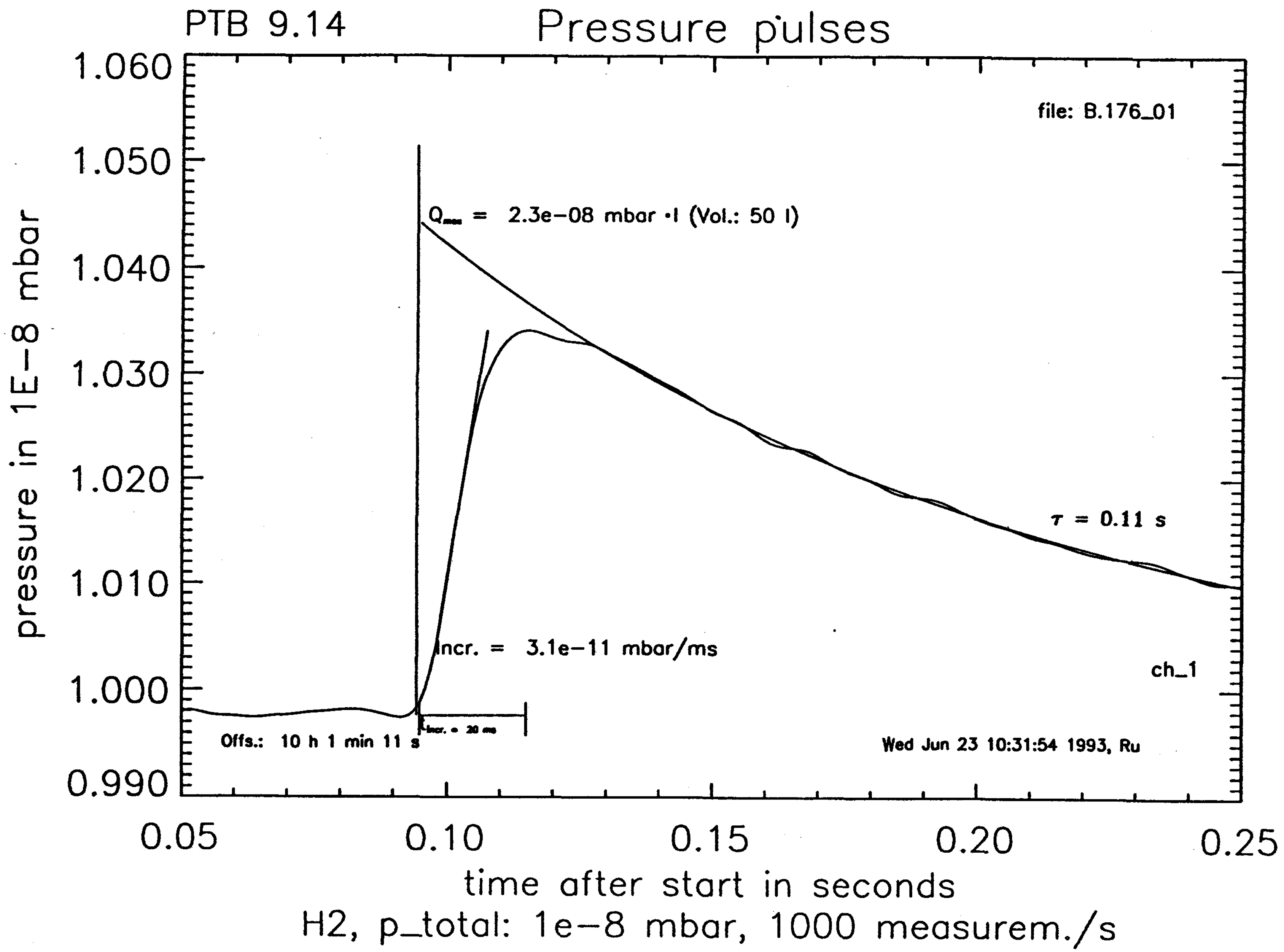

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