An ionization pressure gauge with LaB_6 emitter for long-term operation in strong magnetic fields

U. Wenzel, T.S. Pedersen, M. Marquardt, and M. Singer*

Max-Planck-Institut für Plasmaphysik (IPP), EURATOM Association,
Wendelsteinstr. 1, 17491 Greifswald, Germany

* Ernst-Moritz-Arndt Universität, Institut für Physik,
Felix-Hausdorffstr. 6, 17489 Greifswald

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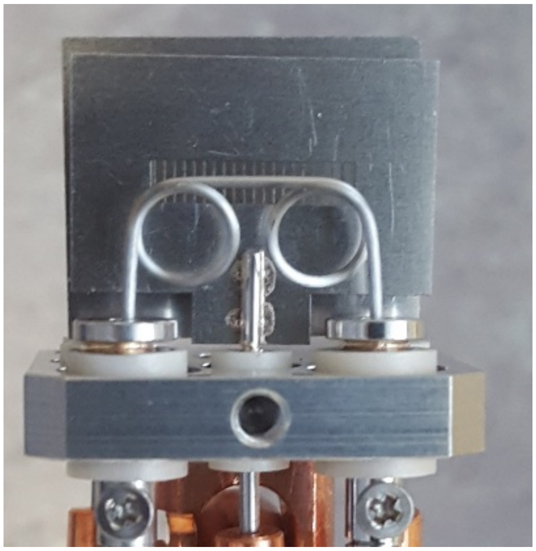
Abstract

We report here on a potentially significant improvement in the design of neutral pressure gauges of the so-called ASDEX-type which were first used in the Axially Symmetric Divertor EXperiment (ASDEX). Such gauges are considered state-of-the-art and are in wide use in fusion experiments, but they nonetheless suffer from a relatively high failure rate when operated at high magnetic field strengths for long times. This is therefore a significant concern for long-pulse, high-field experiments such as Wendelstein 7-X (W7-X) and ITER. The new design is much more robust. The improvement is to use a LaB_6 crystal instead of a tungsten wire as the thermionic emitter of electrons in the gauge. Such a LaB_6 prototype gauge was successfully operated for a total of 60 hours in B = 3.1 T, confirming the significantly improved robustness of the new design, and qualifying it for near-term operation in W7-X. With the LaB_6 crystal, an order of magnitude reduction in heating current is achieved, relative to the tungsten filament based gauges, from 15-20 A to 1-2 A. This reduces the Lorenz forces and the heating power by an order of magnitude also and is presumably the reason for the much improved robustness. The new gauge design, test environment setup at the superconducting magnet, and results from test operation are described.

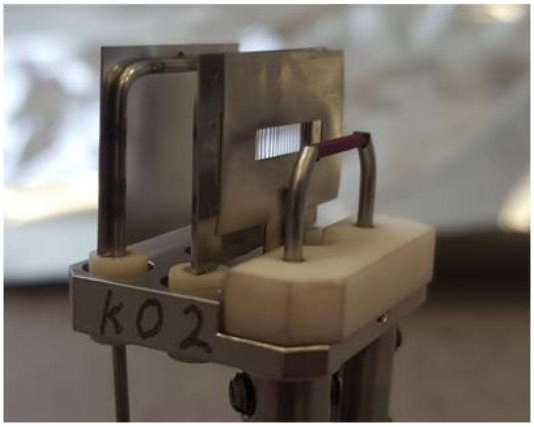
1 Introduction

For decades the ASDEX pressure gauge (APG) [1] has been used to measure the neutral pressure in strong magnetic fields. It is used in many leading nuclear fusion devices, tokamaks as e.g. ASDEX Upgrade [2] or DIII-D [3] and stellarators as e.g. W7-X [4]. APGs are also foreseen for the ITER facility [5]. They operate in various parts of the devices, including the divertor regions, at magnetic fields of several Teslas.

The APG is a hot cathode ionization manometer with a measuring range from 5×10^{-7} mbar up to 1×10^{-1} mbar. It makes use of four electrodes in a linear arrangement: cathode, control electrode, acceleration grid (anode), and ion collector. The cathode is made from a tungsten wire doped with thorium or lanthanum. Usually, the wire has two loops to allow for thermal expansion during heating (see Fig. 1(a)). The control electrode is used to modulate the electron source rate, allowing better background subtraction. APGs are normally operated in feedback mode: an electron emission current at the anode is set and the heating current is controlled by the electronics to reach this emission rate. For the tungsten filament gauges, currents between 15 and 20 A are needed for a typical anode current of 200 μA in a magnetic field of several Teslas.



(a) APG with a loop cathode from tungsten



(b) LaB_6 pressure gauge with a rodded cathode

Figure 1: Images of the APG with a tungsten cathode (top) and the new LaB_6 pressure gauge (bottom)

During operation of APGs in the Wendelstein 7-X stellarator it was observed that some cathodes were bent, some were even damaged to the point of fail-

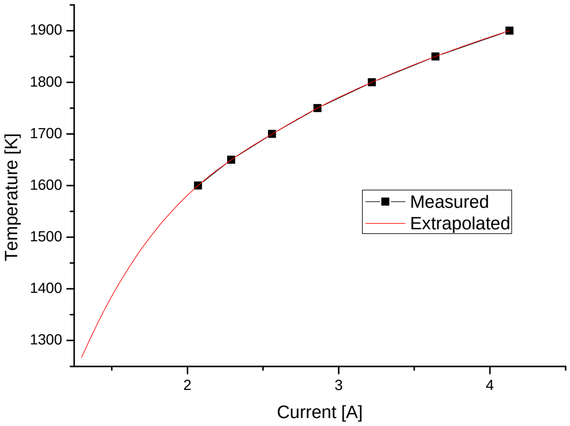


Figure 2: The temperature in the central region of the LaB_6 rod is plotted as a function of the heating current. Experimental points are used for the range 2-4 A (symbols) where temperature measurements were possible. An extrapolation is used for values below this range.

ure. The loops appear to be the cause of failure [4]. When the cathodes are deformed, a higher heating current is needed for the same electron current at the anode, increasing the Lorentz forces and the temperature of the filament, which can lead to further deformation. This way, the feedback scheme can become unstable and a failure of the gauge can result, for example by the bending causing a physical contact and a short between the filament and the control electrode.

Hoping to improve the reliability of the APGs, we replaced the tungsten wire by a cylindrical LaB_6 rod. LaB_6 is known to have a comparably lower work function and is widely used as a thermionic emitter in many situations, not only in vacuum (e.g. in electron guns or electron microscopes) but also in hydrogen for plasma or neutral beam generation [6, 7, 8, 9, 10]. For hydrogen, which is also used in nuclear fusion experiments, there is no cathode poisoning of LaB_6 emitters [11]. This is the first report of their successful use in a ionization pressure gauge, and as such it is important to establish whether the modified pressure gauge can be stably operated in the pressure ranges relevant for magnetic confinement fusion research (up to $5 * 10^{-1}$ mbar as predicted for the ITER experiment or $5 * 10^{-3}$ mbar as predicted for the Wendelstein 7-X). We present the new pressure gauge design in Sec. 2 which is based on the so called Vogel mounting [12]. Here we also describe the test set-up in a superconducting magnet. In Sec. 3 we describe the search of an operational point for the LaB_6 pressure gauge and the pressure calibration. We report on a long-time test over nearly 60 h at $5 * 10^{-3}$ mbar, which confirmed the mechanical and electrical stability. Finally, in Sec. 4 we discuss some physical effects which are observed when operating the LaB_6 pressure gauge.

2 Experimental set-up

2.1 The new LaB_6 pressure gauge

Fig. 1(b) shows the new electron emitter integrated into an APG. We used a LaB_6 crystal rod with a length of 8 mm and a diameter of 1 mm which is clamped by two molybdenum posts. It is a single crystal with (100) orientation along the rod axis. The rod is rotated in the base so one of the four side (100) planes faces the control electrode. The single plane (100) provides the majority of the current towards the LaB6 pressure gauge providing better emission stability.

Unlike the tungsten wire, the LaB_6 crystal cannot be efficiently heated by ohmic dissipation in the crystal itself, since it is strongly dependent on temperature - it decreases by an order of magnitude when heated. However, heating by heat conduction from another resistive component is possible. For this reason, between the posts and the crystal, two pyrolitic carbon blocks are mounted. These have sufficient ohmic resistance to provide the ohmic heating.

Fig. 2 shows the temperatures in the middle of the crystal for heating currents between 2 and 4 A. It was measured using a Mikron MCS640 infrared thermal imaging pyrometer at a wavelength of 650 nm. The temperature was measured directly in Kelvin corrected for the emissivity of LaB_6 (.77) and the loss for the vacuum window (7%). This curve was extrapolated to lower temperatures since the heating current at the operational point of the pressure gauge was below the measuring range.

First tests were made with the original potential distribution of the APGs without magnetic field [4]. Electron currents between 250 and 320 μA were measured at the anode, confirming that the LaB_6 rod was properly working in the pressure gauge.

2.2 Test environment

For the test of the LaB_6 pressure gauge, we used a horizontal superconducting magnet from Oxford Instruments. The LaB_6 pressure gauge was inserted into the magnet from one side together with the gas inlet. We used two gases for testing; helium and hydrogen. Helium was used for the initial tests. Later runs were always made with hydrogen. Pressure gauges, the vacuum pump and an optical window were mounted one the other side of the magnet. The vacuum pump was a 350 L/s turbo-molecular pump from Leybold. As described below, two gauges were used for the external pressure measurement: a baratron from MKS for the range from 10^{-5} to 0.1 mbar and a cold cathode gauge for the lower pressure range down to the base pressure of the chamber. Since the magnetic stray field at the baratron position was still relatively high - B_x = 2.2 mT, B_y = 11.1 mT (pointing to the ceiling), B_z= 9.4 mT (magnet axis direction), B_{total}= 15 mT) - the baratron and the cold cathode gauge were screened using mu-metal foil (Aaronia MagnoShield Flex). To obtain the hydrogen pressure, the cold cathode gauge readings were corrected by the mass factor of 2.2. After this correction we found a difference between baratron and cold cathode gauge hydrogen pressures of 1.46, with the baratron giving the higher values. The

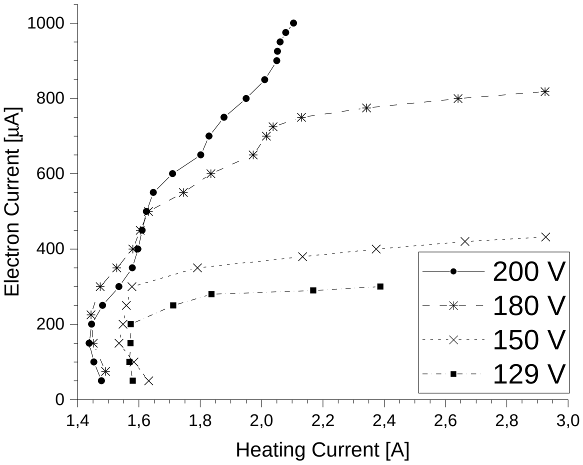


Figure 3: Electron emission current vs crystal heating current in the residual gas for various potentials at the control electrode. The higher the potential, the more electron current can be drawn from the $\mathrm{LaB_6}$ rod, indicating that the emission is more space-charge-limited than emission-limited.

cold cathode gauge readings were recalibrated accordingly to agree with the baratron readings. Bake-out of the chamber inside the bore of the magnet was restricted to 80 degrees C to avoid heating and potential quenching of the magnet. For this reason the base pressure could not be brought into the 10^{-7} mbar range (the base pressure was 2.2×10^{-6} mbar).
The magnet used for these tests was operated in persistent mode at 3.1 T, i.e. the magnet was not buffered by the power supply. Therefore, a test of the gauge in different magnetic fields was not completed, as it would have required a rather complicated and time-consuming procedure. All measurements presented here are with the coil activated and at a nominal magnetic field of 3.1 T at the $\mathrm{LaB_6}$ pressure gauge.

3 Operation of the $\mathrm{LaB_6}$ pressure gauge

3.1 Potential settings

For conditioning, the $\mathrm{LaB_6}$ pressure gauge was heated in the magnetic field over 30 min before operation. We observed a moderate pressure increase up to 7×10^{-6} mbar as measured by the Penning gauge. After conditioning, the $\mathrm{LaB_6}$ pressure gauge was operated in feedback mode with the standard APG potentials at the electrodes: cathode 20V, control grid 105 V and anode 250 V (see [4] for details of the potential settings). The heating current was hardware-limited to 3 A. A maximum electron current in the order of $100\mu A$ was obtained. Although the $\mathrm{LaB_6}$ pressure gauge could be operated with this current, for signal-to-noise reasons, and in order to operate our gauge as close as possible to the operating points used in the original APGs, we adjusted the voltage of the control electrode while leaving the other potentials at the cathode and anode

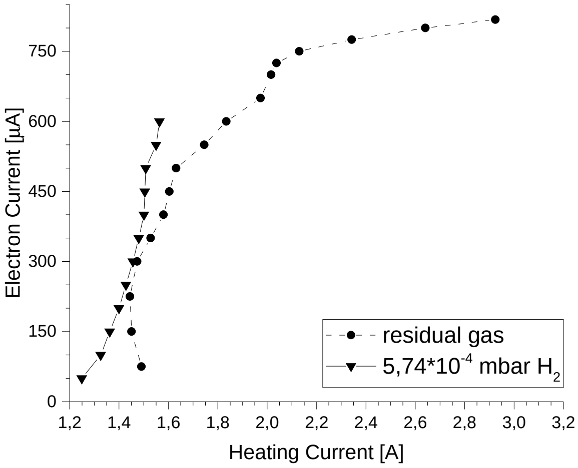


Figure 4: Electron emission vs crystal heating current for a potential of 180 V at the control electrode. With hydrogen the gauge cannot be operated in the space-charge limited region because of an unstable behaviour at $I_e = 650\mu A$.

unchanged.

Fig. 3 shows the results. With 129 V at the control electrode we see a saturation of the electron current as one would expect from space charge limited currents such as those described by Child and Langmuir [13]. With increasing potential we can draw more electron current from the source, and the saturation region is shifted to higher heating currents. At 200 V an electron current of 1mA was measured before saturation. This does not represent a physical limit, but rather the upper limit in our feedback electronics. It was decided to test the prototype in hydrogen with 180 V instead of the standard APG potential of 105 V at the control electrode. Fig. 4 compares two cases: residual pressure and hydrogen gas for a potential of 180 V at the control electrode. We found an upper limit to the operation in hydrogen. At $I_e = 650\mu A$ we observed unstable behaviour and did not observe a clear space charge saturation region. This limitation does not inhibit hydrogen operation because the gauge can be operated with electron currents between 200 and 300 μA in feedback mode without problems.

3.2 Pressure range

Fig. 5 shows a set of experiments in hydrogen with 6 pressure levels in the range 1.7×10^{-4} mbar to 4×10^{-3} mbar. The feedback electron current was set to 300μA. The heating current decreases with higher hydrogen pressure. The electron current shows various fluctuating phases depending on the hydrogen pressure. These are stabilised by the feedback system without any problems and are not visible in the ion current, but the response of the feedback system is visible in the heating current. Furthermore, two transitions to higher values of the heating current are observed: a smooth one at 2×10^{-3} mbar and a jump at 4×10^{-3} mbar. These effects will be discussed in Sec. 4 in more detail.

The response of the ion current is proportional to the neutral pressure, as

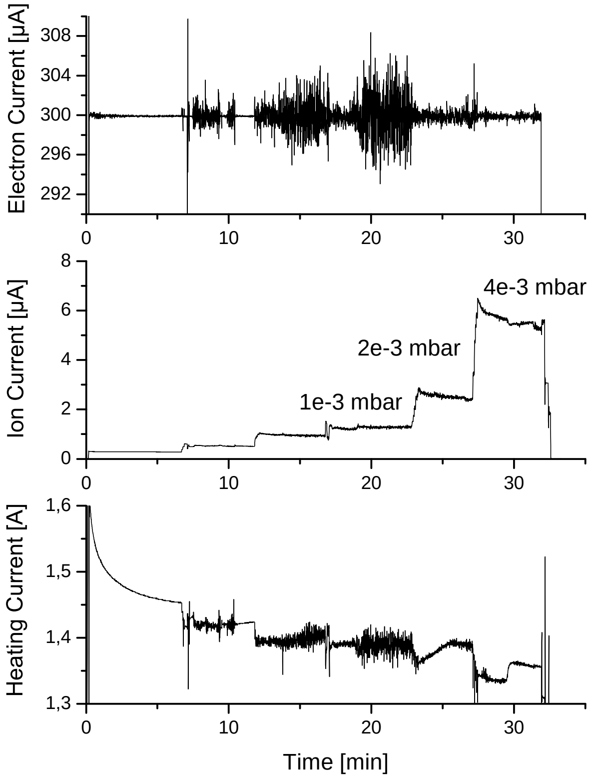


Figure 5: Example of a pressure variation (hydrogen) in the superconducting magnet measured by the LaB_6 pressure gauge. We realized 6 pressure levels up to 4×10^{-3} mbar (the last three are indicated in the Fig.). The gauge was operated in feedback mode with $I_e = 300\mu A$. The ion current response is proportional to the neutral pressure.

expected. The sensitivity of the gauge, defined as

$$S = \frac{I_i}{I_e * p}$$

is calculated from these experiments to be $S = 5 mbar^{-1}$. Without magnetic field, S is independent of I_e [14]. In a strong magnetic field, however, S is a function of B and I_e [1]. Fig. 6 shows the measured sensitivity as a function of the electron current (for B = 3.1 T). The higher the electron current, the lower the sensitivity. The maximum sensitivity is 9, the minimum is 2 mbar^{-1}.
Fig. 7 shows the calibration curve, i.e. the ion current vs. neutral pressure. Because of the higher sensitivity, we used an electron current of $200\mu A$ for the full range calibration. The pressure range spans three orders of magnitude from 1×10^{-5} to 1×10^{-2} mbar. In the upper range of pressures the relation $I_e >> I_i$ still holds, i.e. the electrons born in the ionization volume do not contribute significantly to the electron current. The lower limit of the interval is given by the base pressure in the vacuum chamber. It must be emphasized that the lower limit for these tests is given only by the test environment and not by the

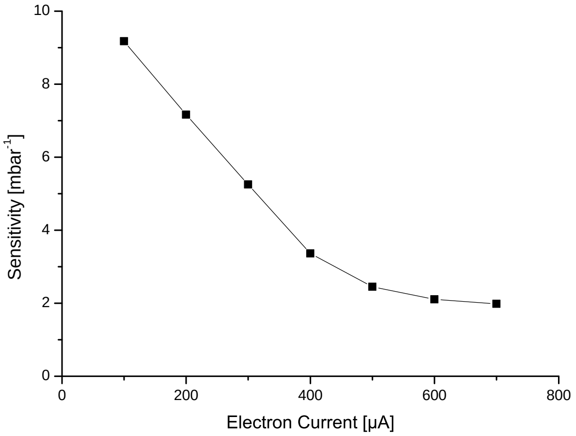


Figure 6: Sensitivity of the LaB_6 pressure gauge as a function of the electron current. The highest sensitivity is obtained at low electron currents. It falls linearly with the electron current and then stagnates at S = 2 mbar^{-1}.

LaB_6 electron emitter, which we believe can operate with good signal-to-noise at lower pressures. The sensitivity derived from the calibration curve is 7.4 mbar^{-1} which is in line with the results of Fig. 6.
We compare the sensitivity of the LaB_6 pressure gauge with that of other ionization gauges. For an original APG with tungsten filament, a sensitivity of 8 mbar^{-1} was measured (gauge 16 in ASDEX Upgrade at B= 2.0T and $200\mu A$) [15]. For the same electron current we found a very similar value S= 7.4 mbar^{-1} for the LaB_6 pressure gauge. Secondly, we compare it to other ionization gauges for general use without magnetic field [14]. Depending on the details of the design, sensitivities between 6 and 24 mbar^{-1} are reported, i.e. LaB_6 pressure gauges and APGs have sensitivities in a strong magnetic field in the same range.

3.3 Long-term experiment

In order to prove the mechanical and electrical stability of the LaB_6 pressure gauge, a long-term experiment was performed in the superconducting magnet. During 5 days of operation a total of 120 29-min-long experiments were performed, thereby accumulating almost 60 h of operation in the magnetic field. All runs were feedback-controlled with $200\mu A$ electron current. The pressure was set to 5×10^{-3} mbar of hydrogen for all 120 tests. For these settings the heating current was 1.33 A. In all experiments, the LaB_6 prototype gauge was operated without error, confirming the significantly improved robustness of the new design.

4 Physical effects observed

During operation we noticed two interesting effects when varying the hydrogen pressure. There were bifurcations of the heating current at some operating

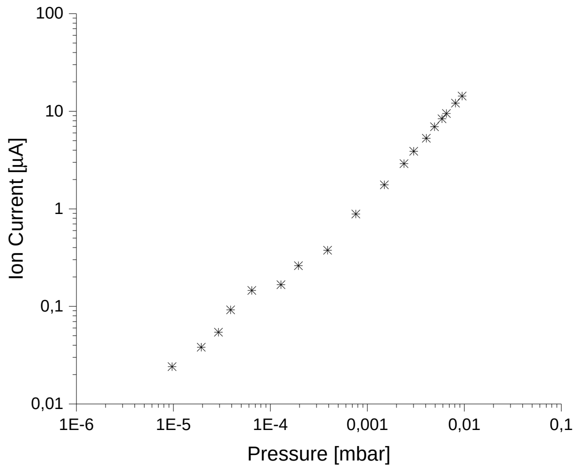


Figure 7: Calibration curve of the $\mathrm{LaB_6}$ pressure gauge for a feedback-controlled electron current of $200\mu A$ (ion current vs. hydrogen pressure). The gauge sensitivity is 7.4 mbar^{-1}.

points and the heating current decayed with rising pressure We will discuss these observations now in more detail.

4.1 Bifurcation of the electron current

Fig. 5 shows that pre-set feedback-controlled electron current can be sustained with two different values of heating current (see the last two pressure steps). To investigate this phenomenon further, we made a feedforward run with 1.472 A heating current (Fig. 8). We observe a spontaneous transition and later a transition back to the initial state. The electron current jumped between 400 (state 1) and 650 μA (state 2). Such cathode instabilities have been observed in many settings, including ones quite similar to ours [16]. For this reason, the $\mathrm{LaB_6}$ pressure gauge cannot be run in feedforward mode.

4.2 Decay of the heating current with rising hydrogen pressure

We observe that the heating current decreases with rising hydrogen pressure. To study this effect we performed a feedforward run with a fixed heating current of 1.472 A. By closing a leak valve, the hydrogen pressure drops from 5.7×10^{-4} mbar to the base pressure of about 2×10^{-6} mbar. Fig. 9 shows the associated reaction of the electron current onto the acceleration grid. The electron current is reduced from 425 to $375\mu A$, i.e. it depends on the neutral pressure. Such a reduction could be explained by either crystal surface emission of electrons due to bombardment of ions, or a contribution of electrons from the volumetric ionization region. Since the ion current ($I_i = 0.75\mu A$) is much smaller than the electron current ($I_e = 450\mu A$) we can exclude the latter effect. At this point we would like to refer to Gallagher [11], who found a 30 percent increase of the electron current at 2×10^{-4} mbar hydrogen relative to base pressure in their

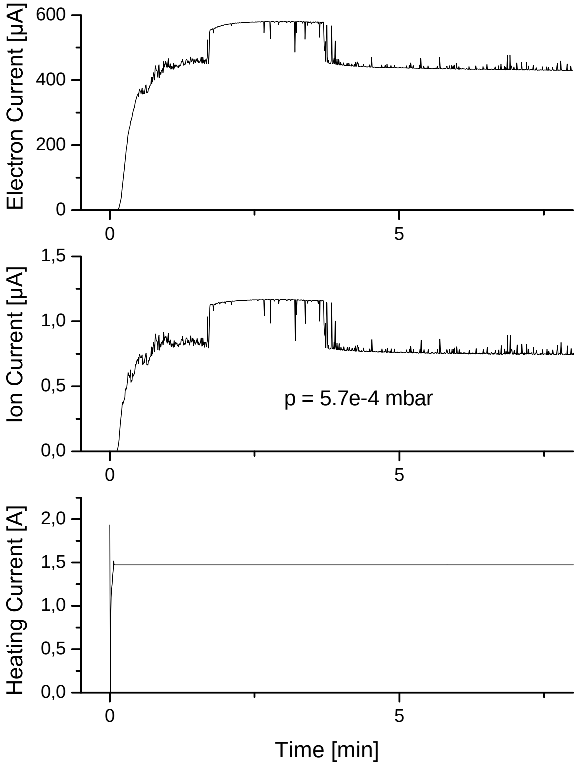


Figure 8: Feedforward run with a heating current of 1.472 A. There is a sponteanous transition between 2 values of the electron current. The hydrogen pressure was constant at 5.7×10^{-4} mbar.

device. These effects are not deleterious for the pressure range reported here, but one may need to develop a different feedback scheme for operation at very high neutral pressures, a topic of future work.

5 Summary

We described a hot cathode ionization pressure gauge with LaB_6 electron emitter for operation in strong magnetic fields. The great advantage compared to the APG with tungsten filament is the very low power consumption with heating currents between 1 and 2 A. A safe operational point with high sensitivity (7.4 mbar^{-1}) was defined and pressure measurements between 1×10^{-5} and 1×10^{-2} mbar hydrogen were demonstrated. A long-term test proved the electrical and mechanical stability over 60 h at 5×10^{-3} mbar hydrogen. The new pressure gauge has the potential to behave very robustly in magnetic fusion devices with field strengths of several Teslas and will be used in the Wendelstein 7-X stellarator.

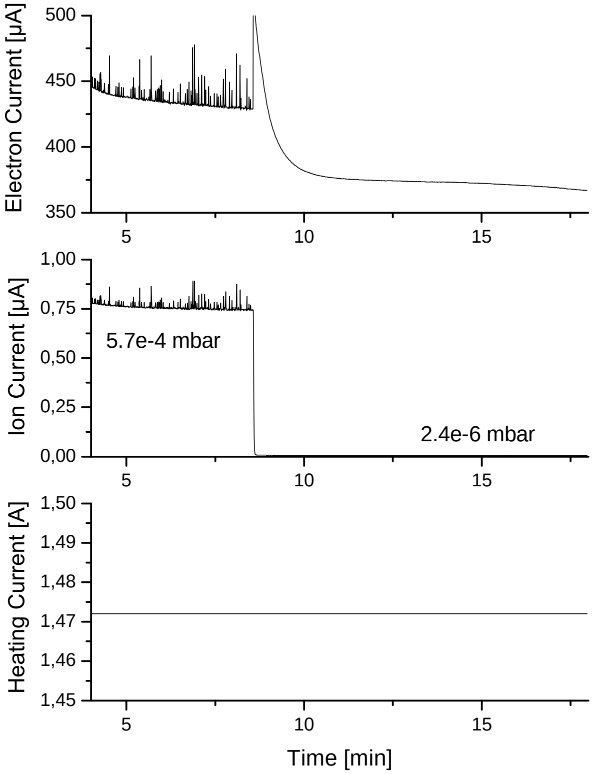


Figure 9: Feedforward run with a heating current of 1.472 A. When the gas valve is closed, the electron current is reduced from 425 to $375\mu A$.

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