Conceptual design studies of ionization gauges for the measurement of neutral gas density at high pressures and high magnetic fields

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Time resolved information about the neutral gas density at various positions inside fusion reactors is essential for machine control and for the understanding of physical processes at the plasma edge. The ASDEX pressure gauge [1] is a specially designed ionization manometer that is able to measure the density of neutral gas in the presence of strong magnetic fields and with high time resolution in present-day fusion machines. The requirements in terms of accessible pressure range and magnetic field strength increase drastically along with more powerful reactors in the future. While pressure gauges at ASDEX Upgrade operate in magnetic fields of up to 3 T, manometers in ITER will have to cope with fields of 8 T. Similarly, the neutral gas pressure in the divertor of ITER is expected to reach considerably higher values of up to 0.2 mbar in partially detached states [2]. Going even further towards fully detached plasma scenarios which are required for the DEMO reactor, the neutral gas pressure is expected to reach considerably higher values. The aim of this contribution is to assess the suitability of ionization gauges that are based on the so-called Schulz-Phelps design to cope with thus high neutral gas pressures and magnetic fields.

Schulz and Phelps proposed already in 1957 an ionization manometer that relies on a linear scheme of plane electrodes [3]: a hot filament releases electrons in between two plane-parallel electrodes. One is charged to high potential (called anode or electron collector) and the other one is kept at low potential (called ion collector). The electrons are accelerated in the monotonic electric field, possibly ionize neutral gas along their trajectory and finally impinge on the anode. The ions are directed into the opposite direction. The current at the ion collector over the anode current I_{ic}/I_e is an almost linear function of the pressure. However, in the presence of a strong magnetic field, it is expected that ions are prevented from reaching the ion collector since charged particles are forced to follow the lines of force and the ions are accordingly directed onto the filament where the electrons originate from. The effect becomes significant when the gyroradius of the ions is of the same order of magnitude than the radius of the filament. This consideration seems to make the application of the Schulz-Phelps gauge concept inappropriate for fusion devices. A possible way to circumvent this shadowing effect is to introduce a certain angle α between the gauge axis and the magnetic field. In this case, the electrons and ions experience a drift $v_{drift} = \frac{|E|}{|B|} * \sin\alpha$ perpendicular to the electric and magnetic field direction. Thus, the ions will leave their original field line and increase their chance to miss the filament and finally reach the ion collector. A magnetic field component in parallel to the filament is essential. The distance from the filament to the anode has to be large in order to increase the time of flight for the ions. However, ions that will be produced in close vicinity to the filament are hindered to reach the electrode. The fraction of those ions has to be small. On the other hand, the distance should not be too large so that the number of produced secondary electrons does not dominate the number of primary electrons. This translates into a maximal distance that is comparable to the mean free path of electrons at high pressures. Assuming an ionization cross section of 10^{-16} cm^2 for hydrogen, the mean free path of electrons is approximately 2 cm at a pressure of 0.2 mbar.

To assess the performance of such a gauge more quantitatively, a numerical tool based on the Monte-Carlo method has been applied. Originally, the code was constructed to investigate the physical effects leading to saturation at high pressures in ASDEX gauges [4]. The simulation considers ionizing collisions of electrons with neutrals as well as several elastic and inelastic collisions of charged particles with neutrals. It also accounts for secondary electrons from ionizations. Electron-electron, electron-ion interaction and neutral particle motions are neglected. For our purpose, the gauge geometry was adapted and a simplified potential distribution like in an ideal parallel-plate capacitor was assumed. The normalized ion current $I_{ic}/(I_e - I_{ic})$ in dependence of the neutral gas pressure was computed for different angles of the gauge axis with respect to the magnetic field and for various magnetic field strengths up to 8 T. Figure 1 represents the results for an angle of 30°. The output increases largely linear with increasing pressure and no saturation effect is visible up to a pressure of 30 Pa. In fact, the signal depends on the magnetic field strength and roughly halves if B increases from 2 T to 8 T. The ion collector current also depends crucially on the angle of the B-field; a variation of ±10° causes a change in the signal of a factor of roughly ±50 % (not shown here). The impact of these effects on the sensitivity has to be taken into account during calibration. Moreover, the gauge can be oriented in such a way that changes of the field line angle due to variations of the poloidal field component provoke an ion drift in parallel to the filament, which does not affect the sensitivity.

Complementary to the simulations, a gauge head prototype has been built and tested in the laboratory. The dimensions and the potential distribution are shown in figure 2.

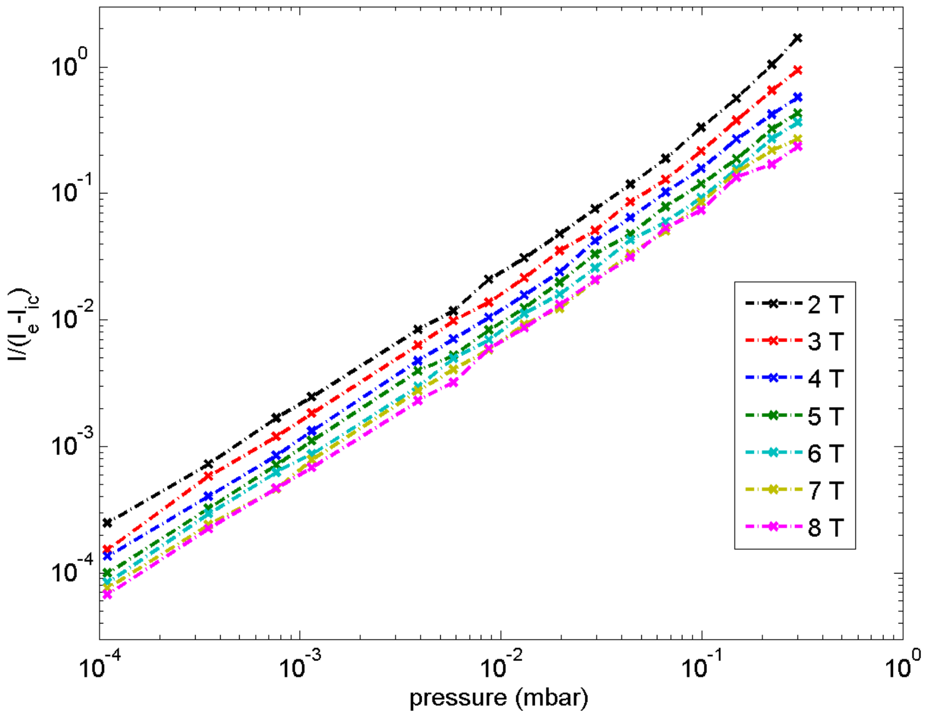

Figure 1: Simulated gauge signals as function of pressure for different magnetic field strengths. The angle between the magnetic field and the gauge axis is 30°.

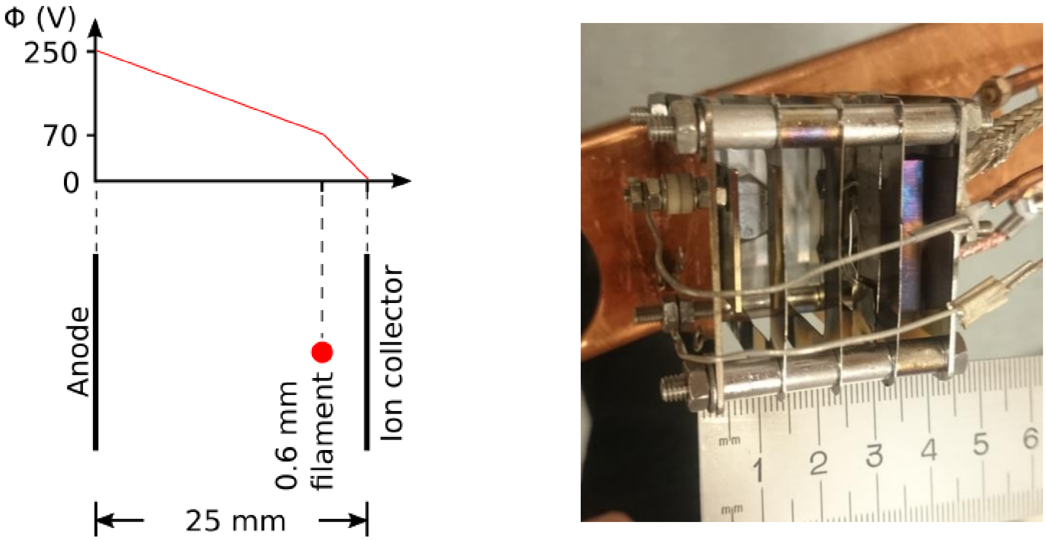

Figure 2: Dimensions and potentials (left) and photograph of the gauge head prototype

A photograph illustrates how the assembly is fixed to a copper rail which is then introduced in a cylindrical vacuum vessel surrounded by a solenoid. The gauge head can be rotated to adjust the angle between the gauge axis and B. The rotation axis is perpendicular to the emitting part of the filament. Tests were performed in the pressure range from 10^{-3} to 0.3 mbar. The magnetic field was varied from 0 to 0.75 T and the axis of the gauge with respect to the B-field was 0° and ±15°. The results are directly compared with numerical simulations for the same parameter regime, see figure 3. The sensitivity of the gauge prototype in the experiment is significantly smaller than predicted by simulations and the deviation increases with pressure. Most surprisingly, the measured characteristics are non-linear even without magnetic field. Also, the shadowing effect with B in parallel is hardly observable in the measurements. The great discrepancy suggests that physical effects remain unconsidered in the simulations. Shielding effects of electrons probably play a role: the Debye length is estimated to be of the same magnitude than the gauge dimensions. Experiments with lower electron emission currents may deliver insight here. Also, a more realistic model of the electrostatic field of the gauge may be appropriate to be implemented into the simulations.

Experiments in the future will be carried out at much higher magnetic fields of at least 6 T. In addition it seems to be worthwhile to construct a gauge with a more straightforward design, avoiding the implications of nested structures in vicinity of the ionization volume.

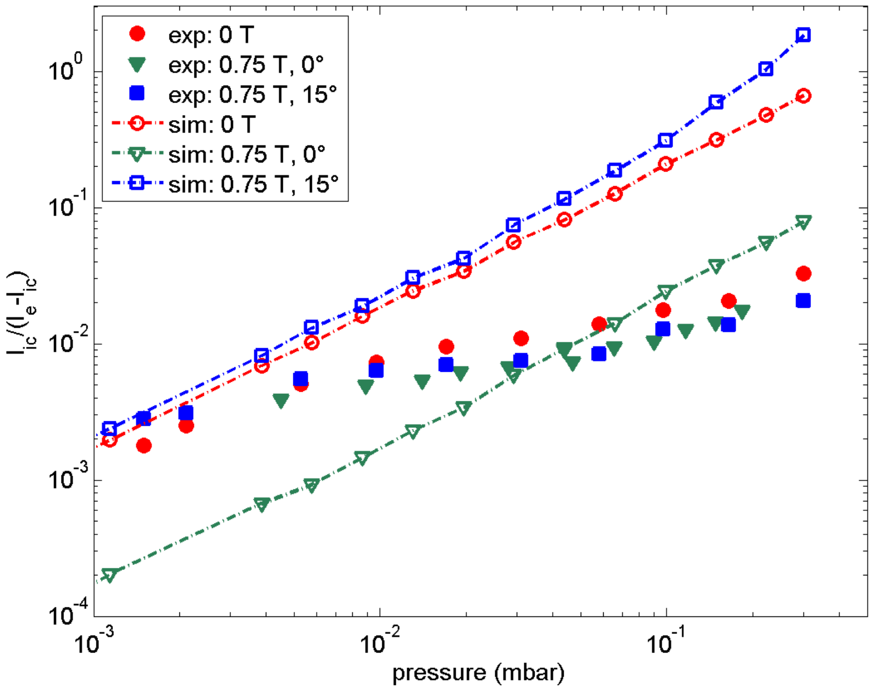

Figure 3: Comparison of experimental results (closed symbols) with numerical simulations (open symbols)

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