Magnetic field influence on the Penning discharge characteristics

N V Mamedov¹,², A S Rohmanenkov¹ and A A Solodovnikov¹

¹Dukhov Research Institute of Automatics (VNIIA), 22SushchevskayaSt., Moscow, 127055, Russia
²National Research Nuclear University MEPhI, 31KashirskoeSt.,Moscow, 1154092, Russia

E-mail: M_nikitos@mail.ru

Abstract. In this work characteristics of pulsed penning ion source for miniature linear accelerators was investigated by experimental measurements and PIC (Particle-In-Cell) simulations. The paper presents dependences of the discharge current and extracted current on intensities of the uniform magnetic field for different pressure. Also, typical examples of the current pulse waveforms obtained by PIC simulation and experiment for different magnetic field are presented. The simulated electron and ion distributions inside discharge gap give qualitative explanation of the experimentally observed fluctuations in current pulses. These current fluctuations arise as a result of the violation of the electric field axial symmetry due to the electron spoke movement of the towards the anode.

1. Introduction

The Penning discharge (discharge in crossed $E\times H$ fields) is widely used in ion sources for miniature linear accelerators (MLA) of a neutron generator [1]. As it’s known, in 1937 F M Penning and J Moubis used this discharge for the first time as an ion source in a small linear accelerator for D–D or D-T reactions and the production of neutrons [2]. Such widespread use is due to several characteristic such as the simple power supply system, simple design, reliable operation at low working-gas pressures. The structure of the Penning discharge cell is simple; it consists of two cathodes and cylinder (or ring) anode. Cathodes have negative potential relative to the anode. And all electrodes are placed in a longitudinal magnetic field directed parallel to the system axis. In magnetic field the electron trajectories become distorted, which leads to a lengthening of the electron paths and an increase in the efficiency of the working gas ionization inside the discharge cell.

Nowadays, Penning ion source (PIS) for the sealed-tube neutron generators continue to be studied actively [3-7] to this day. The neutron tubes with PIS still play important role in borehole logging [8]. For this kind of an application, stable PIS operation requires linear dependence of the discharge ($I_d$) and the extracted ion ($I_{ex}$) currents on the gas pressure. Also, the extraction coefficient (the ratio of the extracted ion current to the discharge current $I_{ex}/I_d$) should be the maximum. There are three main time characteristics of extracted current, which should be known precisely: Turn on time (or time delay $t_d$), leading and trailing edge times. Turn on time (or time delay $t_d$) is a time between the initiation of the anode voltage pulse and the registration of the extracted current. Leading edge time is...
gas ionization time $t_f$ and trailing edge time is turn off time. Also shape of the extracted current pulse should be rectangular with short leading and trailing edges. PIS current pulses should be stable and reproducible through the given pressure range.

In this paper, experimental and numerical studies of the current pulses depending on the magnitude of the magnetic field and pressure (the working gas is deuterium) were done.

2. Experimental & Simulation details

Miniature pulse PIS geometry used is described in [9]. Discharge cell consists of two cathodes (distance between it ~ 20 mm) and one cylindrical anode (approximately 15xØ12 mm) with axial magnetic field. Details of electrical and vacuum experimental scheme are described in [9,10]. Typical experimental conditions are as follows: voltage pulses frequency $f = 10$ kHz, the pulse duration $t_{\text{pulse}} = 30$ µs, the voltage anode amplitude $U_a = 2.0$ kV, gas pressure range (working gas is deuterium) $P = 0.1-10$ mTorr. Solenoid is used to create an axially symmetric and homogenous magnetic field of different magnitude ($B_z = 60-120$ mT) [10]. The details of the physical measurements are published in the articles [9-11].

For the Penning discharge simulations numerical model based on 2D/3D electrostatic PIC-MCC method was used. This model utilizes the structured rectangular grids and is implemented in the VSim [12] software package. The Monte-Carlo collision (MCC) method is used in this code [13] to simulate the kinetic processes in gas-discharge plasma. The numerical simulation parameters are: the time step ~ 10 ps, initial particles ~ 100000 macro-electrons and ~ 100000 H$_2^+$ ions, which correspond charged particles density $2\times10^{14}$ m$^{-3}$. Initial particles are placed in the anode cylindrical region. Initial velocities of the macro-particles are sampled using Maxwell distribution at temperature 300 K. The realistic geometry of the PIS and experimentally measured distribution of the magnetic field are used in simulations.

3. Experimental results

Typical examples of the discharge and extraction currents pulse waveforms obtained for different magnetic field are shown in figure 1.

![Figure 1](image.png)

The shape of discharge and extraction current pulses dependence change significantly with an increase magnitude of the magnetic field. As can be seen, at magnetic field 65-75 mT the discharge and
extraction current pulses had triangular periodic spikes. At magnetic field 65-75 mT and at pressures above 5-6 mTorr or at pressures above 3-4 mTorr and at magnetic field 80-90 mT trapezoid current pulses were observed. In the experimentally measured range of 65-90 mT $I_d$ decreases, whereas the discharge current increases with increasing $B_z$. There is a delay between the discharge and extracted current pulses at magnetic field more than 95-100 mT. As can be seen, the extraction ion current is extremely small compared to the discharge current. This means that the efficiency of ion extraction ($I_{ex}/I_d$) from the PIS goes down. Experiments show, that with increasing $B_z$ value, discharge ignition pressure threshold becomes lower region. Discharge value $<I_d>$ increase with increasing $B_z$ value in the range 70-100mT, and then it tends to decrease as the magnetic field increases (see figure 2). The dependence of the extracted current has two characteristic maxima (see figure 2). Moreover, the gap between the maxima is formed by a rectangular form of a current pulse (see figure 1 (c)).

4. PIC simulation results

Figure 3 shows typical examples of the current pulse waveforms obtained by PIC simulation. As can be seen from figure 1 and 3 general view simulated waveforms is similar to the experimentally observed ones. Whereas the simulated current levels are much higher, also there is no delay time between anode voltage pulse and current pulse. It can be explained by three reasons: the computational grid roughness, small particle total number and big number of initial particles. Nevertheless, the simulated electron distribution inside discharge gap gives qualitative explanation of the experimentally observed fluctuations in current pulses. In figures 4 and 5 electron and $D_2^+$ distributions at different time moments are shown for various magnitudes of magnetic field and for gas pressure $P = 4$ mTorr. For clarity of the simulation results, the charge particles distribution is shown in the transverse plane passing through the middle of the anode. White rings in figure 4 indicate positions of the ion source external body (1) and anode of ion source (2). The obtained simulation results show two (stable and unstable) discharge modes, which are realized depending on the $B_z$ value and pressure level. At low pressure (0.5-4 mTorr) and low magnetic field (65-70 mT) the current oscillations obtained in the simulations indicate the plasma instability development in the Penning discharge. Discharge current rise with the electron density growth, which creates the electron spoke in the centre of discharge cell. Over time electron density increases above $2 \times 10^{16} m^{-3}$ which lead to increase the spoke size. Electron spoke takes up all the space and after this moment discharge turns off.
Figure 3. Typical examples of the current pulse waveforms obtained by PIC simulation for different magnetic field and for $P = 4$ mTorr. a) 70 mT, b) 80 mT, c) 90 mT, d) 100 mT.

For an unstable discharge mode (for $B_z = 70$ mT), the following stages can be detected (figure 4):

1. Gradual accumulation of volume charge. The electrons are distributed fairly evenly. Electron concentration slight increases in the anode central part. Ions are distributed mainly in the anode center in the cylinder form with rather vague edges.

2. The rapid growth of the particle number and the sharp accumulation of the volume charge. The electrons occupy almost the entire anode volume. In this case, the electron concentration increases in the cylinder at a small radius from the system axis. The electron distribution in this cylinder is uneven and constantly changes. Almost all ions are located in the same cylinder with clear boundaries.

3. Chaotic mixing of plasma. The electron-neutral plasma spots fall on the anode. After that, the particle concentration drops rapidly.

4. Redistribution of the remaining charged particles by the PIS volume. In this case, the distribution of charged particles returns to the case of gradual volume charge accumulation. The process is then repeated.

It can be seen from figure 5 (for $B_z = 80$ mT), that spokes in the electron distribution are also observed, but these spokes continuously rotate in time. Figures 5 shows quasi-stationary operation discharge mode, as can be seen in the figures 1 (c) and 3 (b). This discharge process has a strict periodicity. In this case, the period may vary depending on the geometry and physical parameters of the penning discharge (see figure 5).
Figure 4. Electron (a) and D₂ (b) distributions at different time moments for various magnitudes of magnetic field \( B_z = 70 \) mT and for gas pressure \( P = 4 \) mTorr. The right scale shows the concentration of particles (m⁻³). I – 1 \( \mu \)s, II – 2 \( \mu \)s, III – 2.35 \( \mu \)s, IV – 2.5 \( \mu \)s, V – 3 \( \mu \)s, VI – 3.5 \( \mu \)s. Indicated by 1 – Ion source external body and 2 – Anode of ion source.

Also, conditionally, the "stationary" discharge mode stages can be described:

1. The charge accumulation stage. The electrons are not evenly distributed and occupy only part of the anode. In this case, the rotation of the electron cloud around the anode axis is observed over time. Ions are distributed mainly in the anode center in the cylinder form with rather vague edges.

2. The stage of establishing a stationary mode. Due to the particle concentration increase, their redistribution occurs. Part of the charged particles goes to the anode. The electronic cloud becomes more concentrated with fairly clear boundaries, but smaller in volume. Almost all the ions are evenly distributed over a cylinder with clear boundaries.

3. The stationary mode stage. Here, the main part of the electrons forms a stable cloud rotating around the PIS axis. Ions are evenly distributed throughout the cylinder. This charge distribution picture does not change over time in the future.
(a)
5. Conclusion
The paper presents the results of experiments and PIC (Particle-In-Cell) simulations of the dependence of the discharge and extraction currents on the gas pressure and magnetic field of pulsed penning ion source. Experiments and simulations results show two (stable and unstable) discharge modes which realized depending on the magnetic field value, the working gas pressure range. At low pressure (0.5-4 mTorr) and low magnetic field (65-70 mT) discharge mode is unstable, the current pulses have oscillations or triangular periodic spikes. At low pressure (4-6 mTorr) and low magnetic field (80-90 mT) discharge mode is stable, the rectangular shape of the current pulses observe. Electron and ion density (in the transverse plane passing through the middle of the anode) depending on $B_z$ value and pressure level was shown. The simulation results indicate that the discharge the experimentally observed current fluctuations result from the disturbance of the axial symmetry of the electric field due to the electron spoke movement to anode.

References
[1] Valkovic V 2015 14 MeV Neutrons - Physics and Applications (London: CRC Press)
[2] Penning F M and Moubis J H A 1937 Physica 4 1190–9
[3] Zhou X, Lu J, Liu Y and Ouyang X 2021 Nucl. Instrum. Meth. A 987 164836
[4] Zhoua X, En Y, Lu J, Liu Ya, Li K, Lei Z, Wang Z and Ouyang X 2020 Instrum. Exp. Tech. 63 595–9
[5] Rachkov R S, Maslennikov S P and Yurkov D I 2019 Atom. Energy 127 45–50
[6] Yan F, Jin D, Chen L and Xiao K 2018 Nucl. Instrum. Meth. A 906 110–3
[7] Maslennikov S P and Shkol’nikov E Ya 2017 Atom. Energy 121 360–4
[8] Shope L A, Berg R S, O’Neal M L and Barnaby B E 1983 Int. J. Appl. Radiat. Is. 34 269–72
[9] Mamedov N V, Maslennikov S P, Presnyakov Yu K, Solodovnikov A A and Yurkov D I 2019 Tech. Phys. 64 1290–7
[10] Mamedov N V, Maslennikov S P, Solodovnikov A A and Yurkov D I 2020 Plasma Phys. Rep. 46 217–29
[11] Mamedov N V, Gubarev A V, Zverev V I, Maslennikov S P, Solodovnikov A A, Uzvolok A A and Yurkov D I 2020 Plasma Sources Sci. T. 29 025001
[12] Nieter C and Cary J R 2004 J. Comput. Phys. 196 448–73
[13] Rokhmanenkov A S and Kuratov S E 2019 J. Phys. Conf. Ser. 1250 012036