Pulsed fields influence on PIG ion source performance

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Abstract. The investigations of pulsed fields influence on PIG ion source performance preliminary results are presented. Fields are generated at the storage capacitance discharge through flat spiral antennas being cathodes of a Penning cell in H₂. Theoretical estimates of the ionization probability at different discharge regimes are given. The experimental unit designed to investigate these regimes at different electrode system configuration, electrophysical and geometrical parameters as well as an external constant magnetic field is described. The experimental results are shown in comparison with theorectic estimates.

1. Introduction
Penning ion sources (PIG IS) with self-sustained discharge have some disadvantages particularly expressed in pulsed or frequency regimes. It seems interesting to investigate the possibility of their characteristics pulsed magnetic field modulation by appropriate coils with rather large pulsed currents [1]. These fields may trigger the Penning discharge at its initial absence and vice versa. Besides, the discharge development at the magnetic field rising up instead of the electric one implies some new advantages, precisely the transition to low voltage – high current regime [2]. However, the attempt to simply place an ordinary PIG IS into a solenoid can hardly bring to success due to the field “skinning” and the conductors as well as magnetic materials availability inside the IS [3].

But if instead of coils plane spiral antennas playing roles of PIG IS cathodes are used the difficulties noted above disappear. At that the antenna metal may contact plasma and γ-processes are significant but may also be isolated from it and in this case the discharge excitation occurs only due to the volume ionization (α-processes). However, the initial discharge development stage is always α-regime due to the ion’s absence. Using different types of coils without contact with plasma one may get capacitively coupled plasma (CCP) instead of inductively coupled (ICP) and the decisive role will play just the curl electric field, not magnetic. In fact, both are significant but their mutual effect differs in different antennas and currents configurations.

In the absence of the characteristic PIG cell structure the discharge is a kind of pulsed ICP one characterized by different modes depending upon the plasma absorbed power and the antenna currents directions. The stationary regime of such H₂ discharge in the standard GEC (Gaseous Electronic Conference reference cell) is investigated in [4]. At relatively low pressures and powers the ICP discharge exists in E-mode if the pulse time is enough to ignite it. At pressures above 3 Pa and powers above 300 W inductively coupled plasma in H-mode with high density plasma and electron temperature is generated. At that the pulsed regime is possible. At lower pressures but greater powers the H-mode cannot be
realized in pulsed regime. At last with low pressures and powers a discharge ignition is generally impossible. However, the superposition of an auxiliary oscillating electrons discharge structure – the Penning cell – lifts pressure restrictions from below but the question of pulse durability enough to ignition lasts as before.

This question is not considered in [4] because of the discharge stationary regime but investigated in [5] where the ignition condition analogous to the Townsend’s one for the Penning cell is derived. It is based on the electron trajectories in a cell analysis. The extrapolation of this method on the case of supplementary pulsed exterior fields is possible because characteristic frequencies of Penning cell electron oscillations are of the 2–4 GHz order, much greater than pulsed RF fields ones – 2–4 MHz. However, the Penning discharge ignition time is 200–400 ns at best that is comparable with the RF pulse half-period. If one consider as “useful contribution” only the half-period when the generated magnetic field coincides in direction with the permanent one it is enough to consider the cell processes only during this time.

The question of the generator matching with such a specific load – the key one for any RF discharges particularly pulsed – is not less important. Thereupon one needs to understand to what extent the algorithm proposed in [4] is suitable for this combined discharge. A particular question in this calculation procedure is the question of the equivalent generator and plasma scheme used in [4] modification concerning the investigated structure and its (scheme) experimental verification.

2. Pulsed fields’ calculation
To estimate theoretically the pulsed fields influence on the PIG IS one has first of all to calculate these fields as space and time functions. It by-turn implies antenna currents knowledge in the plasma absence – zero approximation – and with the plasma in subsequent. The procedure implies the investigated discharge structure equivalent scheme composition and corresponding Kirchhoff equation system solution. This scheme is presented on figure 1. The ICP-discharge scheme given in [4] is used taking into account the CCP component for each of cathodes (cathode and anticathode) supplemented with PIG structure elements – anode and storage capacitance as well as variable resistances $R_{A1}$ and $R_{A2}$ characterizing currents “anode – cathode” and “anode – anticathode”. It is certainly the crude approximation of a PIG discharge equivalent scheme – see, for instance figure 3 in [6]. The ion collector chain was not included in the figure 1 scheme because discharge carried out in the “probe measurements” regime [6] that is collector potential didn’t influence cell’s plasma processes. At last, eddy currents induced in an anode by the azimuthal electric field [3] were not accounted because very slim (0.1 mm thick) or mesh anode was used. On the other hand, these currents may generate rather strong magnetic field [3] making the total field more uniform. That is why the question of these currents influence is to be investigated in addition.

Instead of the input RF voltage (as in [4]) the input signal $U_{\text{input}}(t)$ formed by the MathCad15 code approximation function “Genfit” of the experimental oscillogram (the 4-pulses averaged and “Excell” saved) was used in calculations – figure 2. In the ICP discharge the energy is introduced into plasma through “transformer” which chain consists of an antenna and plasma. Plasma serves as the transformer’s secondary winding. The ICP mechanism of capacitively coupling is equivalent to CCP that is why the equivalent schemes of corresponding chains are switched in parallel to this antenna-plasma transformer. In the description these inequalities from [4] are used: in the ICP chain $\omega L_1 > R_1$, $L_2 > L_2^{(6)}$, whereas in a CCP $R_{pl} << L_{pl}$, $R_s > 1/\omega C_s$. Plasma shields (near electrodes layers) have high resistance $R_{s1,2}$ and small capacitances $C_{s1,2} \approx A_{s1,2}/d_{s1,2} \approx 10 \text{cm} \approx 10 \text{pF}$, where $A, d$ are corresponding area and layer lengths. CCP discharges can glow either in $\alpha$-mode (initial state) or $\gamma$-mode, as well as a PIG discharge. The transition between these modes in hydrogen is very abrupt. In contrast to CCP discharge the plasma inductivity in the ICP discharge is determined mainly by the geometry of exited currents. The inductivity due to the electron’s inertia gives rather small contribution in the whole inductivity. The relation between $R_2, L_2$ depends upon many parameters and may change at the discharge parameters alteration.
Figure 1. Equivalent scheme of the combined RF (CCP-ICP) and PIG discharge with spiral cathodes. $R_1$ and $L_1$ are cathodes antennas resistance and inductivity. $R_2$, $L_2$ and $L_2^{(e)}$ are plasma resistance, its inductivity and inductivity due to the electron inertia. $L_{12}$ and $L_{21}$ are the mutual antenna and plasma inductivity coefficients taken equal for cathode and anticathode.

Figure 2. The experimental oscillogram $U_{inp}(t)$ (4 pulses averaged) and its approximation.

Estimating calculations were made for simple spiral antenna at the 20 nF storage capacitance charged to PIG IS anode voltage (3 kV) discharge in the series RLC contour. The antenna resistance $R = 0.2 \, \Omega$, its inductivity $L = 0.5 \, \mu\text{H}$ is estimated with the help of on-line calculator [7] at 8 turns, external diameter 19.8 mm, wire diameter – 1 mm and distance between turns 0.2 mm. (The experimental values of these parameters differ somehow from these ones – see the next section.)

Currents analytical expressions were used into fields calculation in the quasi-stationary approximation in accordance with common formula [4]. The examples of calculated magnetic and electric fields are given on figures 3 and 4. (They were calculated without possible eddy currents induced in an anode contribution. That is why real pulse fields were weaker despite of the anode design minimizing eddy currents.)
It is seen that the axial magnetic induction maximal value may sufficiently surpass ordinary used in PIG IS (less/about 100 mT). It means that the PIG cell discharge mostly effective in the “cutoff region [3]”, being initially far from it may be led in it during rather short time. The curl electric field is comparable with the radial constant cell’s field. Its force acting on an electron may be either added to the Lorentz one or subtracted depending upon the radial velocity component. It complicates electron trajectories that are no more spirals curled around magnetic field lines.

The fields analytical expressions were used in electron’s trajectories calculations in Penning cell (according to method presented in [5]) to determine time needed for discharge ignition either with external constant magnetic field or without it. However, instead of all electron’s behavior the ionization probability of the “representative” electron (starting from cathode at the 0.7R_{cell} apart from the cell axe) [5] was calculated during the pulse half-period. If this probability is more than 2 the discharge is switched on, in the opposite case – no. The maximal calculated probability was obtained at 18 mTorr
(or 2.4 Pa), $U_{an} = 3 \text{ kV}; U_{sp} = 1 \text{ kV}; L_{cell} = 2 \text{ cm}; H_{an} = 1.6 \text{ cm}; B_{const} = 40 \text{ mT}$ – figure 5. Without pulsed fields this probability during the quarter of pulse discharge – 80 ns – is equal to 1.535, whereas with opposite pulsed fields forming “monocasp trap” – 2.342 and with the same direction ones – 1.465. At 10 times lower pressure that is 1.8 mTorr the probability without pulsed fields during the same period is equal to 0.198. It means that the ignition time lays in the 400–800 ns diapason with account to $\gamma$-processes that correlates very well with the estimates given in [5]. The pulsed field “switching on” decreases this probability to 0.192 in the case of opposite fields and to 0.065 in the case of same direction fields. This small probability is explained simply by the electron fall on the anode at 40 ns (figure 5e).

![Figure 5](image1.png)

**Figure 5.** The “representative electron” starting from antinoida trajectories: a – without pulsed field, 0.24 Pa; b – without pulsed fields, 2.4 Pa; c – opposite currents, 0.24 Pa; d – opposite currents, 2.4 Pa; e – same direction antenna currents, 0.24 Pa; f – same direction antenna currents, 2.4 Pa.

It is clearly seen that the regular electron trajectory in the absence of pulsed fields at low pressure (a) is strongly disturbed while applying them (c, e). It is due to the strong pulsed curl azimuthal electric field. (Its “switching off” in the equations of motion returns the regular trajectory kind.) Whereas in the
case of opposite currents oppositely oriented electric fields damp each other and electron trajectories tighten to the cell axe as in every “monocasp trap”. At high pressures (b,d,f) the strong friction quickly ceases electron motion rising at the same time the ionization probability. This increase is mostly efficient in the “monocasp case”. So, at low pressures pulsed fields may be used to damp the glowing discharge whereas at high pressures – to trigger it in the case of oppositely directed currents or correspondingly azimuthal electric and radial magnetic fields.

3. Experimental stand

The modulating discharge antennas shown on figure 6 were investigated. The wire diameter was larger than used in preliminary calculations – 1.5 mm. Correspondingly cell’s geometric parameters were changed – $D = 40$ mm, $L = H_{an} = 14$ mm, $B_{z,\text{max}} = 40$ mT, $C_{st} = 35$ nF. This cell was mounted on the universal flange (ISO LF 160) of the research complex “Izolab-150” (figure 6).

![Figure 6](image)

Figure 6. The experimental Penning cell assembling sequence: cathodes spiral antennas mounting, anode with constant ring magnet mounting between two Teflon flanges, final fixing of the mesh collector.

This complex represents a high-vacuum stand equipped with gas inlet system and auxiliary diagnostics tools including mass-spectrometry, plasma parameters analyzer, optic spectrometry etc. These tools are not described in this paper. Antennas were mounted inside the vacuum chamber on the 10-pins glass-to-metal feedthroughs with a central gas inlet orifice. The storage capacitance and antennas were connected with pins by female jacks. Different configurations of discharge kinds were formed by bridge cross-connectors outside the chamber. The input pulse voltage was applied to one of the pins depending on the chosen configuration. This voltage (figure 2) was generated by the commutator block (BC) of the pulse neutron generator ING-01 (produced in VNIIA), whereas the charging voltage and pulse frequency...
were set up by the feeding and control block of this generator (BFC). The antennas high current measurements (block-scheme is shown on figure 7) were carried out with the Rogowski loop (12 A·V⁻¹), high-voltage pulses were registered with the high-voltage probe Tektronix TDS 2014B (1000x1). The power supply Spellman SL600 provided the anode voltage through current limiting resistance (12 kΩ, 25W). The pulsed discharge current was measured by the 10x1 probe from the grounded ohmic shunt (4.5 kΩ, 25 W) after separating capacity (100 nF, 30 kV). Produced ions were extracted by the mesh collector negatively biased relative to ground by the modified (output voltage regulation) ion pump power supply BP-10 (BP-10, -0.5–7 kV). Pulsed ion current was measured with the analogous R-C-R chain. To observe a discharge, the mirror (45° relative to the chamber axe) was mounted opposite the chamber window (figure 8). Hydrogen was generated by the high-purity generator GVCH-6D.

Figure 7. The block-scheme of the same direction currents measurements. Bridge cross-connectors are denoted by arc lines.

Figure 8. The discharge pulse photo (20Hz).

To observe reliably discharge modulation and compare it with theoretic estimates one has to sustain it in the Townsend’s regime [5] when plasma doesn’t screen yet pulsed fields or, better in the pre-ionization regime. Nevertheless, to qualitatively confirm the modulation effect it’s better to observe the glowing and its pulsation. Thus, high pressure regime is preferable from this point of view. Really at around 5 Pa this pulsation was clearly observable (see photo on figure 8) and often the power supply switched off due to “arcing” that is transition to the high-current regime ($I_{\text{disch}} > 85$ mA) as it was mentioned in the Introduction.

At low pressures practically interesting for some applications the stable regime was observed from $I_{\text{disch}} \geq 0.2$ mA. After chamber evacuation to about $10^{-6}$ Torr it was blowed out with H₂ and the pressure about 1 mTorr was established that corresponded to gas flow 5 cm³·min⁻¹. By applying the anode voltage
around the 1.35 kV the Penning discharge with \( I_{\text{disch}} = 0.2 \) mA was triggered. After that ING-01 had been switched on and pulse signal at \( U_{\text{sp}} = 1.5–3.5 \) kV was applied. Visible pulsation was observed beginning from \( U_{\text{sp}} = 2.5 \) kV and distinctively observed at 3 kV that is pulse energy (stored in capacitance) around 0.1 J. In the case of same direction currents inducing magnetic field opposite to the constant one at 100 Hz pulse frequency the average discharge current (Spellman SL600 display data) decreased to 0.1 mA that is twice as compared with the stationary one.

In the case of opposite pulse currents the discharge was enhanced but small plasma densities didn’t provide enough to the H-regime energy absorption. It is marginally confirmed by pulsed currents oscillograms at the plasma absence and with it – figure 9.

It is seen that plasma increase the damping decrement due to energy losses by moving charges. If without plasma it’s equal to \( 6.93 \times 10^4 \) Hz in plasma it rises up to \( 1.6 \times 10^5 \) that is more than 60%. It means in turn that though the effective inductivity is increased due to the “transformer coupling” (see figure 1) the effective resistance is increased more due to the plasma resistance \( R_2 \).

As for direct discharge and ion currents measurements one has to confess that they are strongly influenced and hardly quantitatively interpreted due to large breakthrough induced in all measurement chain elements as well as cell metal details themselves. Nevertheless, two experimental oscillograms of discharge and ion currents for the case of discharge ignition are shown on figure 10.

![Figure 9](image9.png)

**Figure 9.** The pulsed currents oscillograms without plasma – at left and with it. (The peak current of the left second half-wave is around 250 A).

At the left one the anode potential (yellow curve) and its current (violet curve) – discharge current – are shown. Neglecting the current limiting resistance in comparison with the plasma one the peak discharge current is around 0.7 mA. The peak ion current extracted at the collector potential – 4 kV is 20 times smaller that is around 30 \( \mu \)A. Evidently these estimates need more rigorous confirmation.

![Figure 10](image10.png)

**Figure 10.** The experimental oscillograms of anode potential, current and ion current.
4. Conclusion

The presented above theoretic estimations and preliminary experiments results of pulsed fields influence on PIG IS performance investigation allow one to draw such conclusions:

- the Penning cell is too perfect electron confinement device to be improved with external powerful pulsed fields, that is why it must be defended against them to sustain stable stationary regime;
- at the same time pulsed fields applying is a suitable mechanism of this stable discharge “chopping”, especially at low pressures and same direction fields regardless they orientation via constant magnetic field;
- at high pressures pulsed fields energy may be effectively absorbed by the initial pre-discharge electron cloud to ignite a discharge, especially in the case of opposite fields;
- the generation of pulsed ICP discharge in the H-mode is possible with constant magnetic field availability at the sufficient power and pressures above 2 Pa.

Further experiments are needed to answer definitely the question of discharge modulation by pulsed fields. Possible regimes optimization implies the significant breakthrough (inducing) damping, thorough equivalent scheme analysis and theoretic estimation upgrading.

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