Simulation of charged particle beam dynamics extracted from a plasma source

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Abstract. This paper presents the results of computer simulation in COMSOL Multiphysics of the hydrogen isotopes beam dynamics extracted from a plasma source of small linear accelerator. The beam energy was 100 keV. The simulation was carried out taking into account the charge exchange of ions on neutral gas molecules in the accelerating system. At the same time, the calculations took into account the process of secondary ion-electron emission from the surfaces of the accelerating system that are bombarded with both fast and slow ions. Consideration of this process made it possible to determine that the value of the electronic load is at least 50% of the main beam current of 100 µA. The inclusion in the trajectory analysis the magnetic field simulation in the secondary electrons generation area made it possible to determine the magnetic field strength, which effectively blocks secondary electrons on the target (3000 Gauss). Then it has been experimentally demonstrated that the discharge current in a plasma source automatically increases by 20% when using the magnetic suppression system on the target node (magnetic field strength is 3000 Gauss).

1. Introduction
The Penning-type plasma source is one of the nodes of a small linear ion accelerator (SLA) designed for neutron generation [1-3]. In this source plasma is generated in a pulsed mode in a medium of hydrogen isotopes, from which hydrogen isotope ions are extracted by applying a constant negative potential relative to the earth to the electrodes of the accelerating system (AS). Then its accelerated to an energy of 90-100 keV and bombard the target, where nuclear reactions occur with the formation of neutrons [4]: T(d,n)4He, D(d,n)3He, T(t,2n)4He. The SLA scheme is shown in figure 1.

When the beam is transported to the AS, it is recharged on neutral gas molecules with the formation of slow ions and fast neutrals, which leads to a loss of the main beam current, which is usually about 100-150 µA. In addition, the generation of secondary electrons due to the process of secondary ion-electron emission (SIEE) in the SLA target node leads to a decrease in the proportion of the ion current in the beam due to the presence of a reverse electron current in it. A decrease the ion component in the main beam current leads to a drop in the neutron flux generated by the SLA. This is due to the fact that during the operation of the SLA, a given beam current is controlled and automatically maintained. Beam current is the sum of the current of ions and secondary electrons knocked out by them i.e. $I_\text{beam} = I_i + I_e$.

In the case of an involuntary increase in the electronic component of the beam current, the SLA automation system reduces the discharge current in the Penning plasma source to maintain its fixed...
value. It leads to a decrease in the ionic component $I_i$ of the beam current, and, accordingly, to a decrease in the neutron flux [5].

![Figure 1. Scheme of SLA for neutron generation: 1 - Penning plasma source with $D_2+T_2$, 2 - grounded electrode of acceleration system, 3 - acceleration system high-voltage insulator, 4 - high voltage electrode of acceleration system, 5 - neutron target.](image)

In this paper, the influence of such secondary processes as the charge exchange of the beam transported to the AS and the generation of secondary electrons on the beam current is studied. The calculation of the main beam trajectories and secondary particles, as well as their currents, was carried out in the COMSOL Multiphysics environment. The simulation of the magnetic field locking the secondary electrons in the target node was also carried out in this software package. To verify the calculations, a physical experiment was carried out. It consisted in studying the influence of the magnetic field value in the target node on the value of the neutron flux generated by the SLA.

2. Technique and initial data for beam dynamics numerical simulation

2.1. Starting parameters of the ion beam

Trajectory analysis is began by creating a three-dimensional model of the AS structure (for example, using automated design tools). After further loading it into the modeling environment and specifying the calculated areas materials (metal, dielectric), two physical problems are solved sequentially. The first is electrostatic problem, which determines the electric potential distribution in the consideration AS structure. When solving the electrostatic problem, the voltage on the high-voltage electrode of the AS (figure 1) was set to minus 100 kV. After that, taking into account the parameters of the AS modeled structure, the emittance $\varepsilon$ and $\alpha$, $\beta$ -Twiss parameters are determined [6]. As shown in [6], emittance and Twiss-parameters are the starting conditions for the beam dynamics. The plane of the ion start is the plane of the AS grounded electrode output aperture (figure 1). According to [6], the emittance of the beam in the plane of the output aperture of the AS grounded electrode was $\varepsilon = 1.31 \, \pi \, \text{mm}$-$\text{rad}$ and Twiss-parameters $\alpha = 2.4$, $\beta = 38 \, \text{mm/rad}$. Next, the second problem is solved – tracing charged particles in the previously obtained electrostatic field. As a result particle trajectories are calculated and the spatial and current characteristics of the beam are determined.

The initial number of particles in the simulation was $10^6$. The maximum cell size of the computational grid was 0.3 mm, the maximum counting time was 500 ns with a time step of 5 ns. The pressure in the AS was taken to be 5 mTorr, which corresponds to the operating pressure of the SLA plasma source. The ion beam current was 100 μA.

2.2. Secondary processes taken into account when simulating the dynamics of an ion beam
The simulation took into account the resonant charge exchange of an accelerated molecular ion on a molecular neutral with the formation of a fast molecular neutral and a slow molecular ion 
\[
\text{H}_2^+ + \text{H}_2^0 = \text{H}_2^0 + \text{H}_2^+,
\]
as well as charge exchange with subsequent dissociation of the molecular neutral into atoms 
\[
\text{H}_2^+ + \text{H}_2^0 = 2\text{H}_1^+ + \text{H}_1^+.
\]
The characteristics of the processes of interaction of particles were the cross sections of these processes, the approximations of the dependences of which on the ion velocity \(V\) [cm/s] for the first reaction look like [7]:
\[
\sigma = \begin{cases} 
11.28 \cdot 10^{-16}, & V < 3 \cdot 10^6, \\
2.8 \cdot 10^{-17} \cdot (17 - 0.715 \cdot \ln(V))^2, & 3 \cdot 10^6 \leq V \leq 1.55 \cdot 10^8,
\end{cases}
\]
and for the second reaction [7]:
\[
\sigma = \begin{cases} 
7.6 \cdot 10^{-17}, & 0 < V < 1 \cdot 10^7, \\
1.022 \cdot 10^{-23} \cdot V^{0.9836}, & 1 \cdot 10^7 \leq V < 1.1 \cdot 10^8, \\
8 \cdot 10^{-16}, & 1.1 \cdot 10^8 \leq V < 1.7 \cdot 10^9,
\end{cases}
\]
where
\[
V = 1.4 \cdot 10^6 \cdot (W / m)^{0.5},
\]
\(W\) [eV] – ion energy, \(m\) [a.m.u.] – ion mass.

At the same time, the calculations took into account the process of SIEE from the surfaces of the AS, which are bombarded by both fast and slow ions (the surface of the high-voltage electrode and the target of the AS). To calculate the SIEE coefficient \(\gamma_s\), an approximation of the coefficient for molecular ions and hydrogen neutrals \((\text{H}_2^+ \text{ и } \text{H}_2^0)\) velocity \(V\) [cm/s], bombarding stainless steel, previously degassed at a temperature of 800 K for 10 hours, was used. This approximation, obtained by the authors [7], is valid for gas pressure values from \(10^{-3}\) to \(10^{-2}\) Torr and can be represented as:
\[
\gamma_s = \begin{cases} 
0, & V < 1.3 \cdot 10^7, \\
3.88 + 10^{-8} \cdot (V - 1.3 \cdot 10^7), & 1.3 \cdot 10^7 \leq V < 7 \cdot 10^7, \\
2.21 + 1.64 \cdot 10^{-8} \cdot (V - 7 \cdot 10^7), & V \geq 7 \cdot 10^7.
\end{cases}
\]

These conditions most closely describe the working conditions of SLA. The transformation of the given SIEE coefficient depending on the angle of incidence of the ion on the surface was carried out programmaticaly in COMSOL Multiphysics according to the cosecant law [8]. Simultaneously, the magnetic field of the system for suppressing secondary electrons from the target unit, which consisted of two permanent magnets in the form of half rings, was simulated.

### 3. Results of modeling the beam dynamics in the accelerating system

Figure 2 shows the result of modeling the trajectories of the ion beam and slow ions in the AS, as well as the calculated trajectories of neutrals against the background of the main ion beam in the AS. It can be seen from the figure that the main ion beam completely reaches the target surface without interacting with the inner surface of the AS high-voltage electrode. However, the slow ions and neutral atoms formed as a result of recharging bombard the surface of the high-voltage electrode, which explains the current losses of the main beam. In particular, according to the simulation results, it was found that at a given beam current of 100 \(\mu\)A, only 95 \(\mu\)A ion current falls on the target and 5 \(\mu\)A falls on the inner surface of the high-voltage electrode. Moreover, the current of 5 \(\mu\)A is slow ions current,
which is registered only after switching on the process of recharging the ion beam extracted from the plasma source.

**Figure 2.** Calculated trajectories of the main ion beam (1) and slow ions (2) in the AS (a) and the calculated trajectories of neutrals (3) against the background of the main ion beam (b).

**Figure 3.** Calculated trajectories of the main ion beam and slow ions (a), as well as secondary electrons from the target in the absence of a system for their suppression (b). Arrows indicate the directions of movement of ions (a) and electrons (b).

Figure 3 shows the result of modeling the trajectories of corpuscular fluxes in the AS, taking into account the SIEE process. It can be seen from the presented figure that slow ions falling on the inner surface of the high-voltage electrode have an energy of about 10 keV, while the energy of the beam reaching the target is 100 keV (figure 3a). Based on the approximation for $\gamma_k$, the SIEE coefficient for slow ions is at least 2 times lower than the coefficient for accelerated ions, while the current of slow ions is only 2% of the current of accelerated ions. Therefore, secondary electrons are generated mainly on the target, and not on the surface of the high-voltage electrode, bombarded only by slow ions. Figure 4 shows the dynamics of secondary electrons formation and their filling of the AS volume. In the absence of a magnetic suppression system field, electrons knocked out of the target are reflected from the inner surface of the high-voltage electrode and accumulate near the target until an accelerating field acts on them (figure 4d).

After that, a stream of secondary electrons is formed, moving towards the SLA plasma source (figure 4c and figure 4d), creating a current of approximately 60 µA. Thus, the presence of an
electronic component of this value in a given beam current of 100 µA allows us to have only on 40 µA of the ion current interacting with the target and leading to the neutron radiation generation of the SLA.

Figure 4. Dynamics of secondary electrons formation in the target node of the AS and their filling of its volume in the absence of a magnetic suppression system: 1 – high voltage electrode of acceleration system, 2 – neutron target. The time corresponding to each frame: a – 26 ns; b – 28 ns; c – 30 ns; d – 32 ns (the time origin corresponds to the moment of ion injection).

In SLA, electrostatic and magnetic suppression systems are used to suppress secondary electrons on the target [5, 9]. Therefore, further, in order to reduce the electron load in the main ion beam, the simulation of charged particles dynamic in the AS was supplemented by modeling the magnetic field in the target region. For this, two permanent magnets in the form of half-rings were placed on target end side (which does not interact with the ion beam, see figure 5a). The magnetic field strength on the target surface created by such a system was equal to 3000 Gauss. The SLA target node equipped with a magnetic suppression system and the magnetic field lines are shown in figure 5b. Based on the simulation results, it was found that such a value of the magnetic field strength is sufficient to effectively block secondary electrons on the target (figure 5c).

4. Experimental verification of the performed calculations
For experimental verification of the performed calculations, which consisted in identifying the causes of reverse electron current formation in the SLA AS, the following experiment was performed. The discharge current in the plasma source and the generated neutron flux in the SLA were measured without a secondary electron suppression system on the target, and then with a magnetic electron suppression system installed. The value of the accelerating voltage was minus 100 kV, and the ion beam current was set equal to 100 µA, as in numerical modeling. The magnetic field strength on the target surface was 3000 Gauss. Figure 6 shows the results of the experiments described above.
Figure 5. Calculated trajectories of the main ion beam and slow ions (a), as well as secondary electrons from the target equipped with magnetic suppression system (c). Arrows indicate the direction of the magnetic field lines (b).

Figure 6. The values of the discharge current in the plasma source and the neutron flux in the absence of a secondary electron suppression system and in its presence.

It can be seen from the figure that in the case when there is no system for suppressing electrons from the target, the measured neutron flux reaches a value of \(2.2 \times 10^8\) neutron/s, the discharge current in this case is 500 μA. When installing a magnetic system for suppressing electrons, the neutron flux increases to a value of \(3.2 \times 10^8\) neutron/s. An increase in the neutron flux indicates an increase in the ionic component at a fixed beam current of 100 μA. An increase in the ionic component is due to an
increase in the discharge current in the plasma source to 650 μA (see figure 6). The discharge current was increased by the SLA automation system in order to maintain a fixed value of the beam current at a level of 100 μA, which tended to decrease with a decrease in the electronic component due to the use of a magnetic suppression system.

5. Conclusion
The paper presents the results of computer modeling of the dynamics of corpuscular flows in the SLA AS. Shown are the trajectories of neutrals and slow ions formed as a result of charge exchange on neutral gas molecules of the ion beam extracted from the plasma source. In the simulation, the current of the extracted beam was 100 μA, and the voltage accelerating the ions was equal to minus 100 kV. It was found that the bombardment of a neutron target with fast ions leads to the occurrence of SIEE processes, which result in the appearance of an electron current of at least 50% of the main beam current. Based on the simulation results, it has been shown that a decrease in the electronic load in the SLA AS can be achieved through the use of a magnetic system for suppressing secondary electrons from the target. It has been experimentally demonstrated that the discharge current in a plasma source automatically increases by 20% when using the magnetic suppression system on the target node. This leads to an increase in the ionic component in the beam current and a 45% increase in the neutron flux generated by the SLA.

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