INVESTIGATION OF SYSTEM FOR EXTERNAL INJECTION OF H$^-$ION BEAM ON CYCLOTRONS

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The article presents results of experimental studies carried out at an installation (“SVITS”) simulating a system for external injection of H$^-$ions with the beam current of up to 2 mA and energy up to 30 keV for cyclotrons. The beam characteristics (current, current density distribution over cross-section, phase diagrams) as well as gas pressure were measured in three points along the beam axis. The influence of the compensation and de-compensation of the beam space charge on the beam dynamics in the plasma produced under beam transportation was studied.

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INTRODUCTION

The system for external injection of negative H$^-$ ions into a cyclotron-type accelerator is intended for forming a beam with a current of more than 1mA and energy of 10-30 keV and its transport for a distance of several meters. The system contains: a plasma source of ions, electrostatic beam-forming optics, a beam-transportation channel with elements of magnet focusing system and an inflector required to bend the beam to the cyclotron median plane.

The “SVITS” installation (the system of H$^-$ beam external injection into cyclotron) was constructed at the D.V. Efremov Institute, NIIEFA in the middle 90-ies. [1]. The facility is intended for try-out and optimization of separate elements of the external injection system and production of output H$^-$ beam with specified parameters optimal for injection to the central area of cyclotron.

The problem of negative ion beam transportation under gas leaking from the ion source to the transportation channel is highly topical but it is rather far from being solved. There is a series of works on this problem [2-5]. Collective processes causing excitation of a spectrum of plasma oscillations result in heating of fast ions and dynamic de-compensation of the space beam charge. The effect of strong de-compensation of negative ion beam with a current density of 50 mA/cm^2 was discovered by the authors [6]. In ref. [5] is suggested a theoretical model describing the process of dynamic de-compensation of space charge of ion beam due to developing ion beam-plasma instability; analytic expressions for plasma ion density and stationary electric field distribution in partially compensated beam are obtained. Numerical solution of the equation of beam motion in self electric field and external magnetic field allowed us to determine the effect of plasma charged particles on the transportation of the 30 mA, 30 keV negative ion beam through the cyclotron injector (ref. [5]).

This report presents results of numerical simulation of ion beam dynamics in the channel of external injection in comparison with results obtained on the “SVITS” installation with the H$^-$beam of ≈1.5 mA and energies of 12 and 24 keV.

EXPERIMENTAL EQUIPMENT

Fig.1 presents a schematic of the “SVITS” installation.

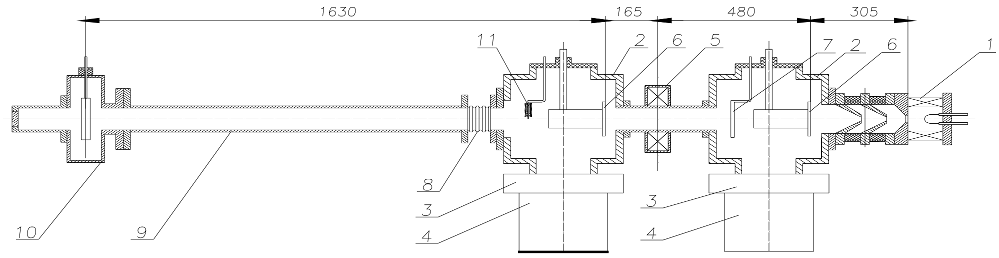


Fig.1. Schematic of the “SVITS” installation: 1-ion source; 2-vacuum chamber; 3-vacuum gate valve; 4-turbomolecular pump (750 l/s); 5-solenoid magnetic lens; 6- beam emittance, current and current density distribution sensor; 7--“pepper-pot” current collector; 8-bellows; 9-ion channel; 10-diagnostic chamber of ion beam; 11-capacity probe

The “cusp”-type volume-plasma ion source (1) with transverse magnetic filter is described in ref. [7]. At discharge current of 20 A this source (with the emission electrode aperture 5mm in diameter) produced an H^- ion beam with a current of more than 2 mA, energy of 30 keV and normalized emittance of 0.3 π mm mrad. The 80 mm long solenoidal magnetic lens (5) provides maximum induction of axial magnetic field up to 0.4 T.

The emittance scanner (6) also functions as a beam total current meter and meter of radial current density distribution. The method of the beam emittance determination is based on measuring the divergence of elementary sheet beams cut off from the main beam with a narrow slit diaphragm. The measurements being completed, the emittance scanner sensor is removed out of the beam.

The “pepper-pot” type current collector (7) is fixed in vacuum chambers for the period of the beam alignment. Behind the current collector, there is placed a quartz glass, which provides visual information about the beam structure and sizes.

The chamber of ion beam diagnostics (10) is located at the output of the ion channel. It is equipped with a moving sensor, which serves to measure the beam total current, current density distribution over the radius and beam emittance.

The capacitive probe (11), of the design similar to that in [6], serves to measure the potential distribution in the beam cross-section.

All vacuum chambers, including the diagnostic chamber, are equipped with vacuum pressure gauges.

RESULTS OF MEASUREMENTS AND CALCULATIONS

When measuring the beam characteristics, we kept constant the operating mode of the ion source with the following parameters: discharge current-15 A; discharge voltage-100 V; extraction voltage-2.8 kV; current of extracting electrode-50mA, H_2 pressure in the source-10^{-2} torr, pressure in the first chamber- 1.2×10^{-4} torr, pressure in the second chamber-3.5×10^{-5} torr, pressure in the diagnostic chamber-4.0×10^{-5} torr.

The beam parameters in the first chamber were measured to form a beam with matched phase volume at the magnetic lens input. In this case at an energy of W_b=24 kev the current of H^-beam was I_b=1.7 mA, radius-R_b=7 mm, divergence–R’=20 mrad and normalized emittance-ε_n=0.32 π mm·mrad.

Fig.2 (“a” and “b”) demonstrate measured distributions of current density and diagrams of the beam emittance in the second chamber for two versions: 1) W_b=24 keV, I_b=1.5 mA, induction in the center of the lens - B_{max}=0.26 T; 2) W_b=12 keV, I_b=1.35 mA, B_{max}=0.18 T. In the second case the beam was initially accelerated up to 19 keV and then decelerated down to 12 keV. The lens field induction was chosen in such a way as to minimize the beam sizes at the system output.

In ref. [5] we obtained an expression for critical gas density at which the de-compensation of the ion beam occurs. In this expression transverse ion-plasma oscillations were taken into account: $n_{gs} \approx v_s/3\sigma_i v_b x_b$, where: v_b and x_b are the beam longitudinal velocity and beam transverse dimension, respectively, σ_i is the cross-section of a gas molecule ionized with a beam ion, $v_s=(T_e/m_i)^{1/2}$ is the ion sound velocity.

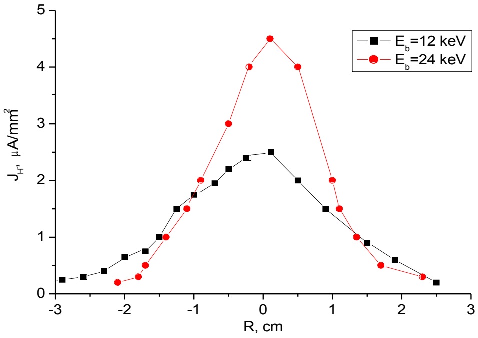


Fig.2a. Distribution of the beam current density in the second chamber

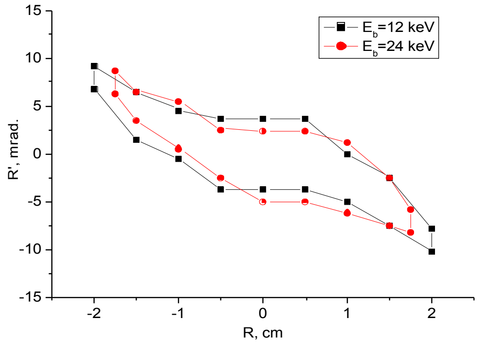


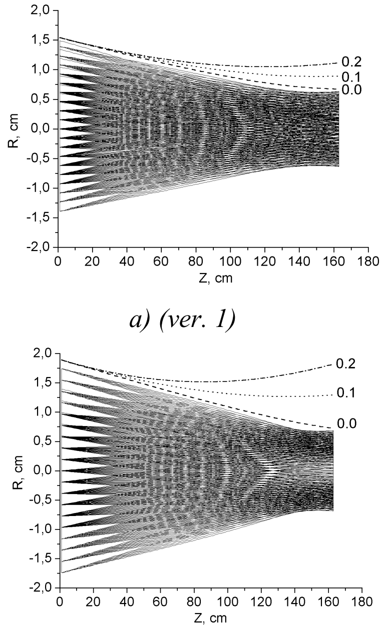
Fig.2b. Diagram of the beam emittance in the second chamber

Values of H_2 critical pressure, which can be derived from this expression, are: 8.4×10^{-5} torr (for 24 keV) and 6×10^{-5} torr (for 12 keV). Thus, in compliance with the theory, conditions for de-compensation of the beam space discharge in the second vacuum chamber are provided in both the cases. However, increment and amplitude of oscillations are rather small and the degree of de-compensation is close to zero due to large (~2cm) radius of the beam. Further, as the beam moves to the diagnostic chamber, the beam radius is decreased and negative potential near the beam axis should be increased due to larger amplitude of plasma transverse ion oscillations and larger ejection of positive ions to the walls of the ion guide. Under these conditions the mode of the space charge weak overcompensation is maintained at the beam periphery. In [8] the positively and negatively charged areas in the H^-beam cross-section at $n_g < n_{gc}$ were experimentally discovered.

Fig.3 (a,d) demonstrate calculated beam trajectories for two versions: W_b=24 keV, I_b=1.5 mA, B_{max}=0.26 T, ε_n=0.4 π mm mrad. 2) W_b=12 keV, I_b=1.35 mA, B_{max}=0.18 T, ε_n=0.25 π mm mrad. Envelopes calculated in the approximation of uniformly charged beam with a de-compensation degree of 0.0, 0.1 and 0.2 are also shown on the same figures.

Fig.3 (b,e) shows calculated diagrams of emittance at the system output for versions1 and 2, respectively.

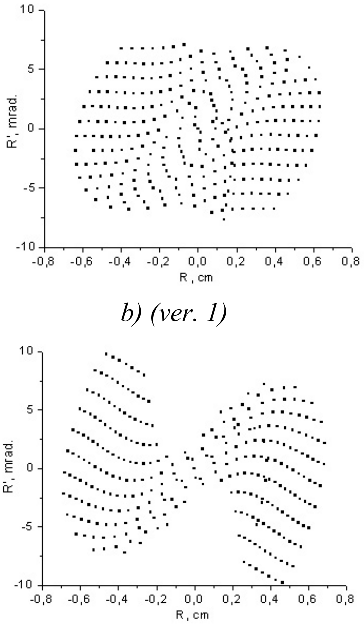
Fig.3 (c,f) shows photos of the beam cross-section in the diagnostic chamber for the same two versions.



a) (ver. 1)

d) (ver. 2)

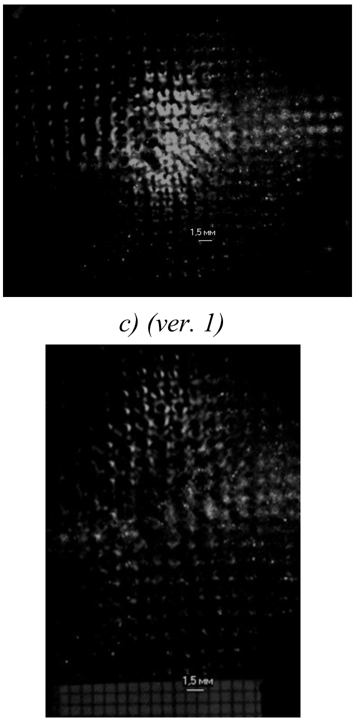
Fig.3(a,d). Calculated beam trajectories and envelopes with different de-compensation degree



b) (ver. 1)

e) (ver. 2)

Fig.3(b,e). Calculated diagram of beam emittance at the injector output



c) (ver. 1)

f) (ver. 2)

Fig.3(c,f).Photos of the beam at the injector output.

In the calculations we assumed that the beam space charge was fully compensated at the section from the ion source to the emittance scanner in the second chamber. Trajectories (z=0) were started from this emittance scanner and ended in the diagnostic chamber (the drift part was 163 cm long). 300 trajectories were involved in the calculation. Initial distribution of particles in the 4-dimensional phase space was specified uniform. In the point z=0, the amplitude of plasma potential oscillations was assumed to be 1 V.

From Fig.3 it is seen that for the version with W_b=24 keV the de-compensation effect is rather weak and at a given emittance practically is not seen. With twice reduction of the beam energy (W_b=12 keV) and with constant current magnitude, the de-compensation effect is appreciably heightened. Distribution of particles over the beam cross-section at the output of the system becomes non-uniform. The effective emittance is more than 1.5 times increased.

Results of probe measurements in the second chamber at beam energy of 12 keV have demonstrated the following. The n_e/n_i ratio (where n_e, ni are the electron and ion concentrations in plasma), obtained as a result of the analysis of probe characteristics, was in the range of $(2\text{-}5)\cdot 10^{-3}$. Such a low concentration of electrons is indicative of the de-compensated state of the beam. Potential fluctuations with an amplitude of 0.2-0.5 V and frequency of~ϖ_{pi} (ϖ_{pi} is the Langmuir frequency of ions) were observed in the beam. Floating potential of the capacitive probe on the beam axis was 0.45 V. When the probe is moved from the beam axis to the chamber wall, its potential smoothly rises up to 0.82 V and then drops. The potential has its maximum at a distance of 1.7 cm from the axis that corresponds to the beam effective radius. With 1.5 times higher induction of the magnetic field of the lens, the beam effective radius is reduced to 0.5 cm. In this case the potential on the beam axis is 0.68 V and the potential on the beam radius is 1,3 V, respectively. The capacitive probe potential is higher than that of the beam by an average energy of secondary electrons knocked out of the probe under the beam action. If the probe is made of tungsten with 0,5% of Tho, the average energy of secondary electrons is lower than 1 eV. Thus, in the area near the beam axis, the potential is minimum and can acquire negative values. On the beam periphery, weak overcompensation of the space charge and positive potential are observed.

CONCLUSIONS

The experimentally obtained results confirm that compensation and partial de-compensation of the space charge of the beam of negative ions occurs under gas leaking to the transportation channel from the ion source. These results agree with experimental data of other authors[6-8] as well as with analytical studies of potential distribution in a partially de-compensated beam [5].

The dynamics of the beam moving under plasma ion oscillations was calculated by the method of large particles by solving the motion equation. The results were compared with the results obtained by the method of envelopes with different degrees of compensation.

Differences in the beam dynamics of these two models have been observed, which are due to non-linear character of the stationary electric field distribution over the beam radius in the first case.

Experimentally found positively and negatively charged areas in the cross-section of H^- beam affect its dynamics and results in an increase of its effective emittance.

We should note that in a low current beam ($I_b \leq$ 1 mA) the effect of the space charge de-compensation and changes in the beam dynamics are weak. With higher beam current, they will have increased their importance.

The carried out investigations are aimed at the construction of H^- ion injector for new-generation cyclotrons intended for production of medical isotopes nowadays designed in the D.V. Efremov Institute, NIIEFA.

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ИССЛЕДОВАНИЕ СИСТЕМЫ ВНЕШНЕЙ ИНЖЕКЦИИ ПУЧКА ИОНОВ H^- ДЛЯ ЦИКЛОТРОНА

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Приводятся результаты экспериментальных исследований, выполненных на установке, моделирующей систему внешней инжекции H^- с током пучка до 2 мА и энергией до 30 кэВ для циклотрона. Измерение характеристик пучка (тока, распределения плотности тока по сечению, фазовых диаграмм), а также давления газа производится в трех точках вдоль оси пучка. Отмечено влияние на динамику пучка в инжекторе эффекта компенсации собственного пространственного заряда пучка ионами плазмы, нарабатываемой при движении пучка в остаточном газе.

ДОСЛІДЖЕННЯ СИСТЕМИ ЗОВНІШНЬОЇ ІНЖЕКЦІЇ ПУЧКА ІОНІВ H^- ДЛЯ ЦИКЛОТРОНУ

О.Л. Вересов, С.В. Григоренко, Ю.В. Зуєв, А.П. Строкач, С.Ю. Удовиченко, С.С. Циганков

Приводяться результати експериментальних досліджень, виконаних на установці, що моделює систему зовнішньої інжекції H^- зі струмом пучка до 2 мА й енергією до 30 кеВ для циклотрону. Вимір характеристик пучка (струму, розподілу густини струму по перетині, фазових діаграм), а також тиску газу провадиться в

трьох точках уздовж осі пучка. Відзначено вплив на динаміку пучка в інжекторі ефекту компенсації власного просторового заряду пучка іонами плазми, що напрацьовується при русі пучка в залишковому газі.