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THE ION-OPTICAL CHANNEL OF 2.5 MeV 10 mA TANDEM ACCELERATOR

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The ion-optical channel of 2.5 MeV 10 mA tandem accelerator

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The ion-optical channel of vacuum insulation tandem accelerator for 2.5 MeV proton energy and up to 40 mA current is studied by numerical simulation technique. Different ways of transporting high current negative ion beam with the initial energy of 25 keV from the source to the accelerator are considered. Possible schemes of coordinated injection of this beam to accelerator are also considered, which allow to accelerate it with minimum losses and transport it through the charge-exchange tube. Basing in the carried out research two constructions of ion-optical channel of 2.5 MeV 10 mA tandem accelerator are proposed.

Within the project of building the source of neutrons for the neutron capture cancer therapy [1, 2] the BINP staff is developing the electrostatic tandem accelerator with vacuum insulation of the protons energy up to 2.5 MeV and direct current up to 40 mA. Fig. 1 displays the scheme of the accelerator.

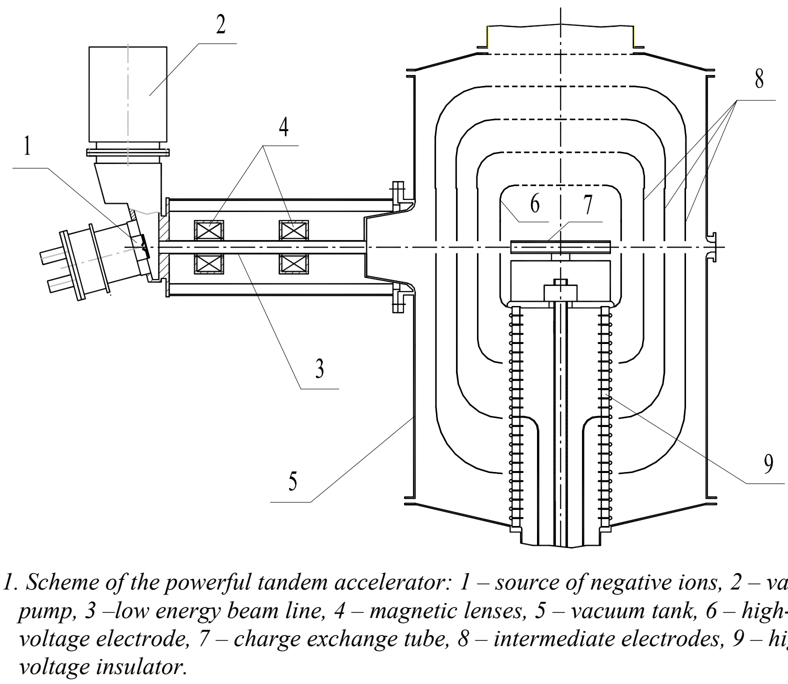


Fig.1. Scheme of the powerful tandem accelerator: 1 – source of negative ions, 2 – vacuum pump, 3 –low energy beam line, 4 – magnetic lenses, 5 – vacuum tank, 6 – high-voltage electrode, 7 – charge exchange tube, 8 – intermediate electrodes, 9 – high-voltage insulator.

One of the parts of tandem accelerator is ion-optical channel, which should have the following functionality:

1. Transportation of the negative ion beam from the source to the accelerator.
2. Acceleration of negative ions in the first accelerating gap up to the energy of 1.25 MeV with minimal precipitation of the beam on intermediate electrodes.
3. Maximum passing of ion beam through the charge-exchange tube.
4. Acceleration of the proton beam in the second accelerating gap to the energy of 2.5 MeV with minimal precipitation of the beam on intermediate electrodes.

By numerical simulation this work examines different ways of transferring the negative ion beam with the energy of 25 keV and current of up to 40 mA from its source to the accelerator. It also considers various ways of coordinated leading this beam in the accelerator, allowing its acceleration and transfer through the charge exchange tube with minimal loss. Basing in the carried out research we offer two possible structures of the ion-optical path of the tandem accelerator for transferring the beam with a current of 10 mA. The results of calculations of the beam transit from its source to the accelerator exit within these structures are states further.

I. Ion beam parameters at the outlet from the source

While designing the ion-optical channel two negative ion beams were examined: with 10 and 40 mA of amperage. The experimentally obtained parameters of the dc 5 mA negative ion beam [3] were used as initial parameters for 10 mA beam. At the outlet from the ion-optical system (IOS) 5 mA beam had homogeneous density distribution and diameter of 3 mm. The measured opening angle of the beam at the outlet from the source was equal to 50 mrad. The obtained transverse temperature of the ions with the energy of 20 keV at the outlet from the source was equal to 0.7 eV.

It is intended to increase the diameter of the ion source outlet to 5 mm, raise the current to 10 mA and energy of ions to 25 keV in future. So the initial energy of the ions for the design of transportation and acceleration was chosen to be 25 keV, the initial diameter of the beam – 5 mm, the initial opening angle – 50 mrad and the initial transverse temperature of the ions – 1 eV.

The new ion source [4] is being developed for the 40 mA dc negative ion beam generation. Since the beam parameters at the outlet from this source are still undefined, they were obtained during the computation of its transportation just by recalculation the 10 mA beam parameters: by doubling its initial diameter and opening angle. Transverse temperature of the ion beam was still assumed 1 eV.

II. Requirements for the beam in the charge-exchange target and at the outlet from the accelerator

One of the most difficult tasks in the design of the ion-optical channel of the tandem accelerator is a transportation of the dc ion beam with 1.25 MeV energy and current up to 40 mA (with power up to 50 kW) through 500 mm length charge-exchange tube with inner diameter of no more than 12 mm [5]. There are a lot of requirements to avoid the precipitation of the beam on the charge-exchange tube.

First of all the diameter of the beam, considering its thermal halo, has to be smaller than the inner diameter of the tube all over it. Therefore the slope of the beam's trajectory in the tube cannot exceed the following value:

$$\alpha_{\max} \approx \frac{D}{L} , \qquad (1)$$

where D and L are the diameter and length of the charge-exchange tube respectively. This estimation corresponds to the case when the beam and the tube it is coming through have the same radius and the beam is focused to the middle of the tube. In this case $\alpha_{\max} = 24$ mrad. If the beam needs to occupy only half of the tube's aperture, this angle has to be twice as small.

Secondly, it is possible to estimate the maximum acceptance of the charge-exchange tube, if the beam is focused at the outlet from the tube:

$$A_{\max} \approx \frac{D^2}{4L} . \qquad (2)$$

This estimates the maximum acceptable transverse temperature of the negative ion beam. If the beam has the same diameter as the charge-exchange tube, it corresponds the transverse temperature $T_{\perp\max} \approx W_i\,(2\,A_{\max}/D)^2$, where $W_i = 1.25$ MeV is the energy of the ions in the charge-exchange tube. In this case $T_{\perp\max} = 180$ eV.

The formula (2) overestimates the value very much because at the outlet from the tandem accelerator there are additional requirements made for the beam. After acceleration it is intended to transmit the continuous proton beam with the energy of 2.5 MeV and current of up to 40 mA (with power of up to 100 kW) through the 3 meters long channel to the neutron producing target with diameter of $3 \div 5$ cm. For the beam transmission from the accelerator to the target with minimal amount of intermediate focusing elements it is required for the beam to have minimal diameter and opening angle. It means that the beam's focusing is required not at the outlet from the charge-exchange tube, but at the outlet from the accelerator. The distance between the entrance to the charge-exchange tube and the accelerator outlet is approximately twice as big as the tube's length, therefore the acceptance of this part of the ion-optical channel is two times smaller than the estimation, obtained with formula (2). So for the negative ion beam with diameter equal to diameter of the charge-exchange tube the obtained maximum acceptable transverse temperature is 45 eV.

III. The approximations and software used for the design of the ion-optical channel of the accelerator

When it comes to choosing the way of transporting the ion beam from its source to the accelerator, the beam dynamics calculations were carried out using the program ExtraSam [6], which considers both transversal and longitudinal field of the space charge of the ion beam. The set of rectangular nets covering only the suppositional path of the beam was used to describe space distributions of space charge, potential and electric field. Calculations of beam dynamics in axial electrostatic lenses with strong deceleration of the ions require complete consideration of the space charge field.

The actual size and opening angle of the ion beam at the outlet from the ion source was defined by the size and shape of the effective emitter. The current density distribution at the emitter in ExtraSam can be defined as constant or as Gaussian distribution. The program can also consider thermal dispersion of ions transverse velocity (radial and azimuth) at the outlet from the ion source. The magnitude of the dispersion is defined as transverse temperature of the ions on the emitter. Furthermore, it is required to define the amount of radial and azimuth layers, describing the Maxwell distribution of ions thermal transverse velocity. Several particles with different transverse velocity start simultaneously from each point of the emitter. This allows designing the thermal emittance of the ion beam.

Since magnetic lenses were chosen for the beam transportation, the necessity of consideration of the influence of the longitudinal electric field of the space charge disappeared because of its inferiority in comparison with the transverse field. So, further calculations were carried out using the program BEAM [7], which describes only transverse field of the space charge of the beam, using the 1-dimensional PIC model. The external fields of the accelerator and magnetic lenses were calculated in BEAM with paraxial approximation of the fifth order. The longitudinal distributions of the field and of all their derivatives up to the fifth order were precisely calculated using a program SAM [8]. The usage of BEAM allowed to greatly shorten the time of calculations in comparison with using ExtraSAM.

When using BEAM it is possible to define the initial radius and the opening angle of the ion beam in any initial section. The current density distribution in this section can be defined either as a constant or random by points. It is also possible to define the initial thermal dispersion of the ions transverse velocity as a transverse temperature of the ions in the current section. The Maxwell distribution of the ions thermal transverse velocities is modeled using a random numbers generator. Every particle of the PIC model gets its own transverse velocity, random in value and direction. The large amount of those particles helps describing the actual thermal emittance of the ion beam.

Both programs ExtraSAM and BEAM provide an opportunity to define several areas of compensation of the space charge of the ion beam. Each area is described by the initial and final coordinates on the axes and the compensation coefficient. When modeling the transportation of the negative ion beam using the electrostatic decelerating lenses one area was defined with full compensation of the beam space charge: from the source to the closest lens (to the point of raising the decelerating potential higher than the beam temperature). There are two such areas when magnetic lenses are used: the first is from the source to the accelerator entrance (to the point of raising the accelerating potential higher than the beam temperature) and the second is inside the charge-exchange tube.

IV. Possible ways of transporting the beam from its source to the accelerator

When designing the ion-optical path two ways of transporting the ion beam from its source to the accelerator were examined: a) using the axial electrostatic lenses with deceleration of the beam; b) using the axial magnetic lenses.

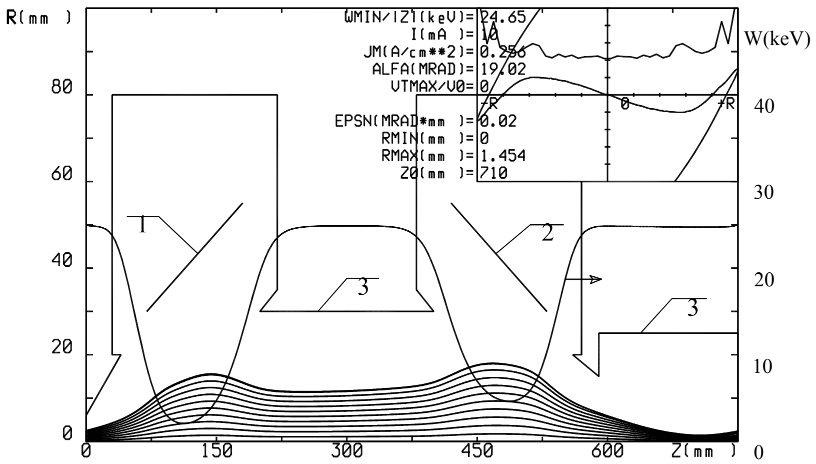
Each of foregoing ways has its advantages and disadvantages. The obvious advantage of the electrostatic lenses is their low power consumption. However, in order to provide the required focusing of the ion beam it has to be decelerated in the lens from 25 keV to 1 ÷ 2 keV. The beam with current of 10 mA and higher greatly expands under the influence of the space charge forces and can occupy up to 80% of the lens aperture (which depends on the beam current). It leads to big aberrations and distortion of radial current density distribution and phase-plane portrait of the beam after its passing the lens. Finally, it becomes difficult to perform a coordinated transportation of such a beam into the accelerator and transfer it through a narrow charge-exchange tube, especially using several electrostatic lenses.

Besides, the use of electrostatic lenses after the first one causes disappearance of such an important feature of continuous negative ion beam as ability to compensate a space charge due to ionization of residual gas. Thus, it requires additional beam focusing in order to compensate beam space charge forces**.** Note that a complete compensation in this case is impossible because of heterogeneous distribution of the charge density after passing the strong decelerating electrostatic lens. These effects develop especially when the current of the beam is stronger than 10 mA.

Fig. 2 shows the results of calculations of transportation of 25 keV negative hydrogen ion beam with current of 10 mA and 40 mA from its source to the accelerator using two axial electrostatic lenses. In order to minimize aberrations the decelerating electrodes have conical shape. Both beams examined had potentials on the first decelerating electrode equal to –23.5 kV and –21 kV on the second one. Both illustrations show the longitudinal distribution of the ions energy considering the influence of the beam space charge, calculated trajectories of the beam ions in the lens; the insert in top right corner shows radial distribution of the current density and the beam phase-plane portrait in the focal point of the second lens.

Magnetic lenses allow transporting of completely compensated negative ion beam with constant energy. As a result the maximum size of the beam and the channel's optical properties have a weak dependence on the beam current. This dependence can be caused only by change of the beam size and angle of its entrance into the accelerator. Furthermore, magnetic lenses have such an important advantage over electrostatic lenses as their ability to choose the optimal position without changes in the channel design.

a



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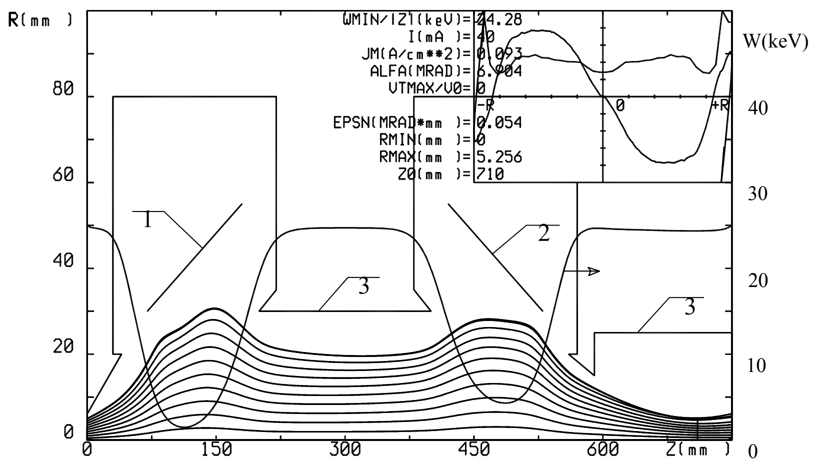
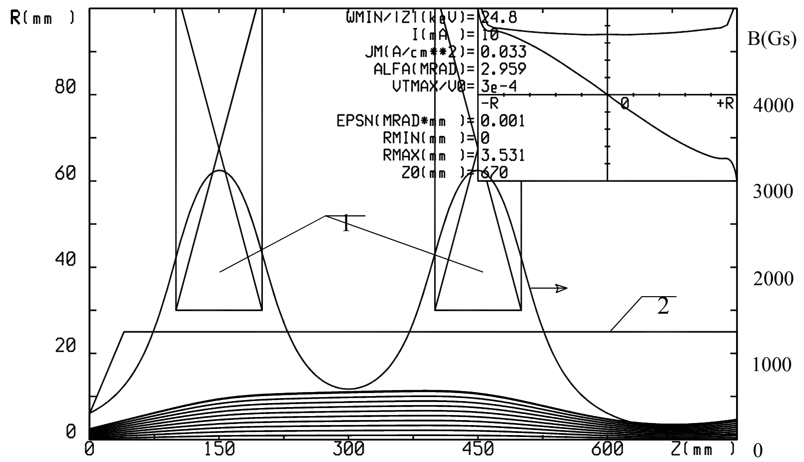


Fig.2. Results of calculations of the transportation the 25 keV H^- beam with a current of 10 mA (a) and 40 mA (b) using two electrostatic lenses: 1 – the first decelerating electrode, 2 – the second decelerating electrode, 3 – contour of the drift tube. On the insert in the top right corner there are the radial distribution of the current density and the phase-plane portrait of the beam in the focal point of the second lens.

a



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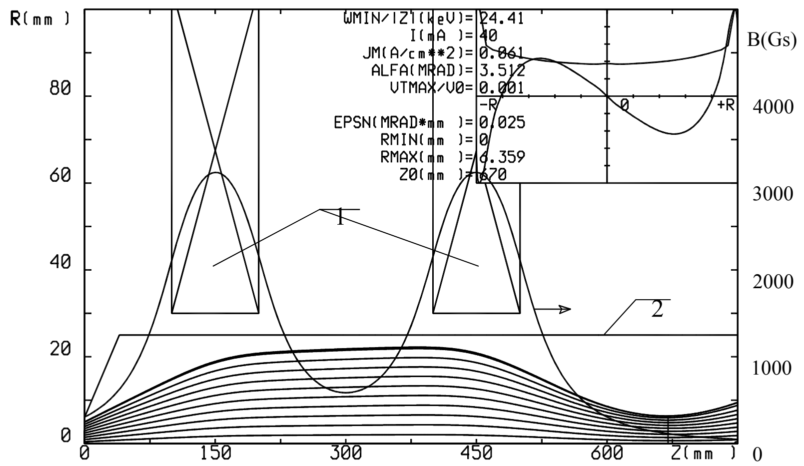


Fig. 3. Results of calculations of the transportation of 25 keV H^- beam with current of 10 mA (a) and 40 mA (b) using two magnetic lenses: 1 – current coils, 2 – contour of the drift tube. On the insert in the top right corner, there are the radial distribution of the current density and the phase-plane portrait of the beam in the focal point of the second lens.

Fig. 3 shows the calculations results of transportation of 25 keV negative hydrogen ion beam with current of 10 mA and 40 mA from its source to the accelerator using two axial magnetostatic lenses. These calculations supposed fully compensated beams from the ions source to the outlet of the second lens, after which it was supposed the beam to enter the electric field of the accelerator. The lenses are two coils with average diameter much bigger than the maximum beam size in order to minimize aberrations inside the lens. Fig. 3 also displays the geometry and position of the coils, calculated longitudinal distribution of the magnetic field, ions' trajectories inside the lens and radial distribution of current density and a phase-plane portrait of the beam in the focal point of the second lens (top right corner). The full current in both coils was supposed to be equal to 40 kA for both beams.

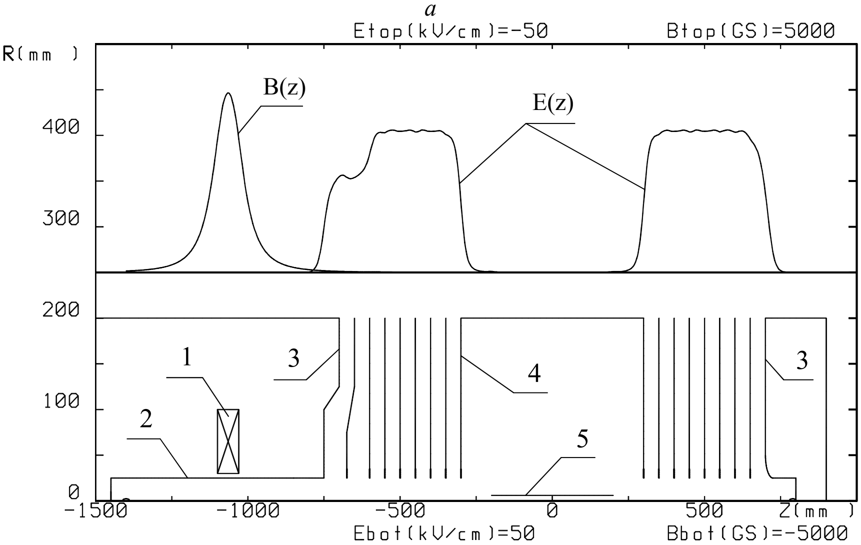
Due to such advantages as the ability to transport high current compensated ion beams and to choose the optimal position of the focusing elements without changes in channel design, it is proposed to use magnetic lenses to transport the beam from its source to the accelerator.

V. Schemes of coordinated beam transport in the accelerator

If the protons energy is 2.5 MeV, the electric field in the tandem accelerator in each of two main 40 cm accelerating gaps reaches the value of 32 kV/cm. In this field the estimation of the focal distance of an electrostatic focusing lens appearing at the entrance to the accelerator for the ions with the initial energy of 25 keV is approximately 3.5 cm, which is much less than the first main accelerating gap of the accelerator. Therefore, in order to provide the beam transfer through the accelerator it is required to reduce the focusing influence of the electrostatic entrance lens and to generate a parallel beam at the outlet from the first main accelerating gap with diameter less than the diameter of the charge-exchange tube. There were two schemes of such coordinated beam transport in the accelerator using magnetic lenses examined: “strong” and “weak” focusing of the beam by the accelerator electric field.

In the scheme with “strong” focusing the compensation of focusing influence of the electrostatic entrance lens is achieved due to inputting of small radius strongly divergent beam into the accelerator. Such a beam can be generated only by its overfocusing, using the magnetic lens before the entrance to the accelerator. Fig. 4,a displays geometry of ion-optical channel of tandem accelerator and longitudinal field distributions according to “strong” beam focusing scheme (charge-exchange effect was not considered in calculations, therefore it was proposed that fields in both main accelerating gaps have the same sign). The number of intermediate gaps was 8. One can see that in this case in order to weaken the influence of the first electrostatic lens field in the first two accelerating gaps had to be reduced by 1.5 times by enlarging the gaps. Fig. 4, b shows the calculated envelopes of 25 keV ion beams with currents of 1 mA, 10 mA and 40 mA according to “strong” focusing scheme. The density distribution at the entrance to the magnetic lens was defined as Gaussian distribution with equal-sized beams and the initial opening angle was proposed zero. In order to provide the optimal transfer of the beam through the charge-exchange tube 12 mm in diameter 400 mm length the necessary longitudinal position and current of the lens were matched for each value of the beam current.

a



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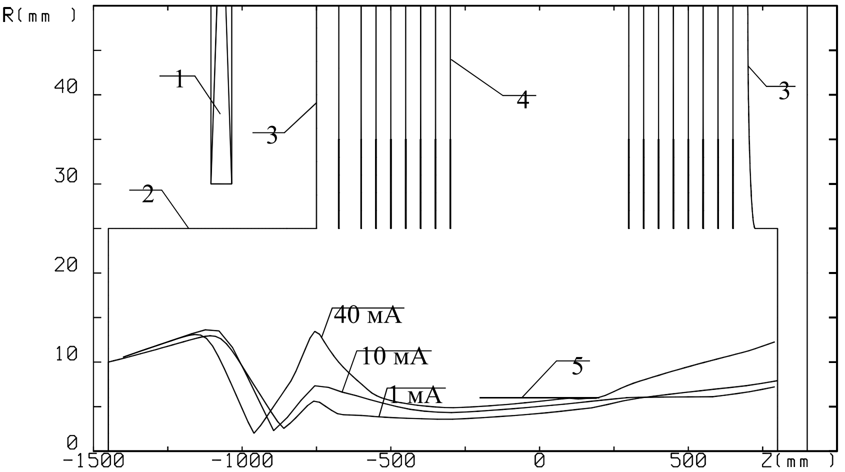


Fig. 4. Coordinated transport of 25 keV H^- beam in the tandem accelerator according to "strong" focusing scheme: the ion-optical path geometry, calculated longitudinal field distributions (a) and the envelopes of ion beams with current of 1 mA, 10 mA and 40 mA (b). The numbers mark: 1 – current coil, 2 – drift tube, 3 - vacuum tank, 4 – high-voltage electrode, 5 – stripping tube.

The disadvantages of this scheme are evident increase of the beam emittance at the entrance to the accelerator due to the nonlinear influence of space charge forces and high sensitivity of its passing coefficient and output parameters to the opening angle as well as to the longitudinal coordinate of the beam refocusing point at the entrance to the accelerator. On the other hand, the advantage of this scheme is a week dependence of the beam's radius in the charge-exchange tube and its passing coefficient on the beam current. It allows transferring beams with different currents through the accelerator easily.

As for the "weak" focusing scheme, the effect of the first lens is weakened significantly due to the gradual increase of the electric field at the entrance to the accelerator. Here the slope of the envelope of the beam at the entrance to the accelerator is close to zero and the beam radius is specially matched in order to mostly compensate the focusing influence of the weak electrostatic entrance lens by pushing effect of transverse field of a beam space charge (equilibrium radius). However, the disadvantage of such a scheme is a strong dependence of the beam equilibrium radius at the entrance (and, therefore, the beam radius in the charge-exchange tube as well) on the beam current. At the same time, the advantages of this scheme in comparison with the one with a "strong" focusing are: a much less increase of a beam emittance on the entrance to the accelerator due to weakening of space charge forces and a smaller sensitivity of passing coefficient and of the output parameters of the beam to the convergence angle of the beam on the entrance to the accelerator. It allows to use a weaker lens for the coordinated beam transport as well as transferring through the accelerator and getting at the outlet a more qualitative beam of the given intensity.

It is possible to find analytical distributions of potential and field for high current beam with initial energy W_0 and homogeneous current density distribution, which provide acceleration if radius is constant. For the potential it is defined as:

$$U(\xi)=\left[\left(\sqrt{\xi^2+1}+\xi\right)^{2/3}+\left(\sqrt{\xi^2+1}-\xi\right)^{2/3}-1\right]^2, \qquad (3)$$

where $U(\xi) = 1 + V(\xi)/V_0$ is a non-dimensional potential, $V(\xi)$ − the actual potential, and $V_0 = W_0/e$ − is an initial potential of the ion beam; $\xi = \dfrac{Z}{2d_0}$ is a non-dimensional longitudinal coordinate, d_0 and V_0 are connected to the density of the ion beam by the following relation:

$$j_0=\frac{1}{9\pi}\cdot\sqrt{\frac{2e}{m}}\cdot\frac{V_0^{3/2}}{d_0^2}, \qquad (4)$$

where e and m are charge and mass of the ions. Fig. 5 shows curves of potential and the field longitudinal distribution for 10 mA negative hydrogen ion beam with initial energy of 25 keV and equilibrium diameter of 10 mm. They were calculated using the formulas (3) and (4).

Initially the required distribution of the potential was examined for realization by expanding the first intermediate gap of the accelerator near the axis of the ion beam and putting in this area two additional electrodes (Fig. 6, a) with potentials calculated by the formula (3). Resulting curves of electric and magnetic fields distributions on the ion-optical path axis are also shown on Fig. 6, a. Six intermediate gaps has been chosen for this case and further. Fig. 6, b displays calculated envelopes of 25 keV beams with currents of 1 mA, 10 mA and 40 mA, covering 95% of the current, calculated for the given geometry. At the entrance to the magnetic lens the current density distribution was defined as Gaussian one and the initial opening angle of the beams was proposed zero. The initial size and current of each beam in the lens was matched in the way to provide the maximum beam passing through the charge-exchange tube with inner diameter of 12 mm and 400 mm length with minimal slope of the beam envelope.

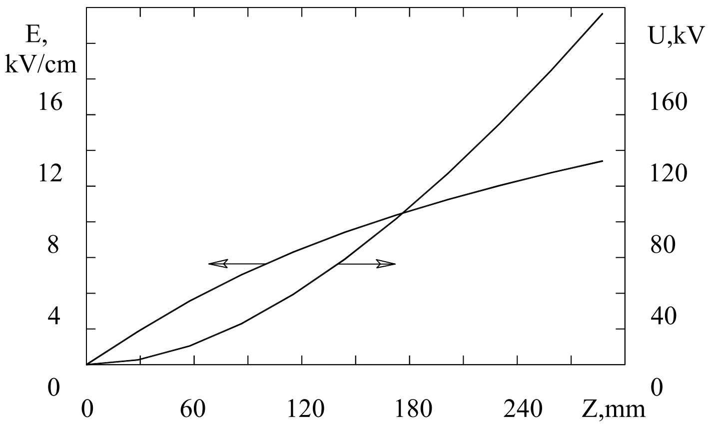
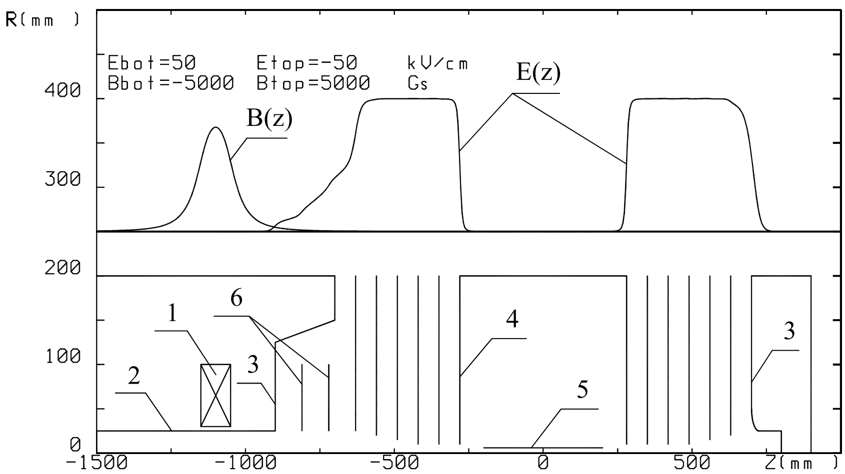


Fig. 5. Analytic distribution of the potential and the field, which provides acceleration of the negative hydrogen ion beam with initial energy of 25 keV and current of 10 mA with a constant diameter of 10 mm.

Later on, it was found that the longitudinal distribution of the electric field, close to the required one, can be achieved without additional electrodes. It is sufficient just to expand the first intermediate accelerating gap near the point of beam path in the accelerator (Fig. 7, a). Resulting curves of electric and magnetic fields distributions on the ion-optical path axis are also shown on Fig. 7, a. The initial size of the first intermediate gap is increased from 67 mm to 267 mm; maximum diameter of the conical area, where the gap is changed, is 300 mm and minimum is 250 mm. The magnetic lens is represented here as a coil in the magnetic shield.

a



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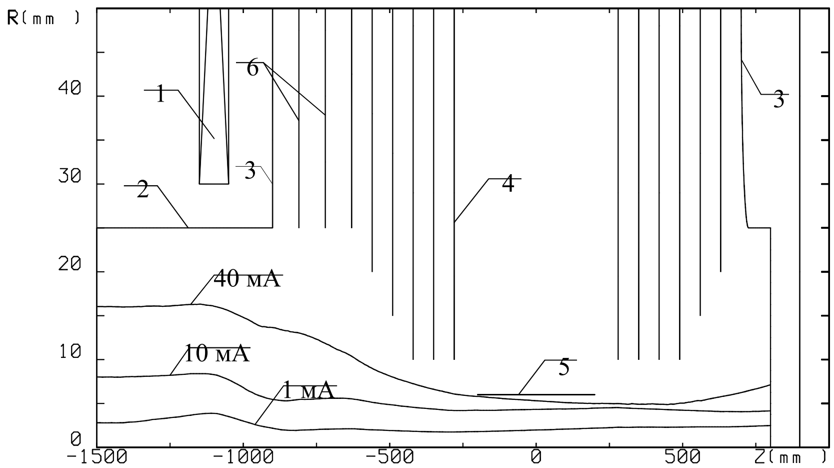


Fig. 6. Coordinated transport of 25 keV H^- beam through tandem accelerator according to "weak" focusing scheme: the ion-optical path geometry, calculated longitudinal distributions of the field (a) and the calculated envelopes of ion beams with current of 1 mA, 10 mA and 40 mA, spanning 95% of the current (b). The numbers mark: 1 – current coil, 2 – drift tube, 3 - vacuum tank, 4 – high-voltage electrode, 5 – charge-exchange tube, 6 – additional electrodes.

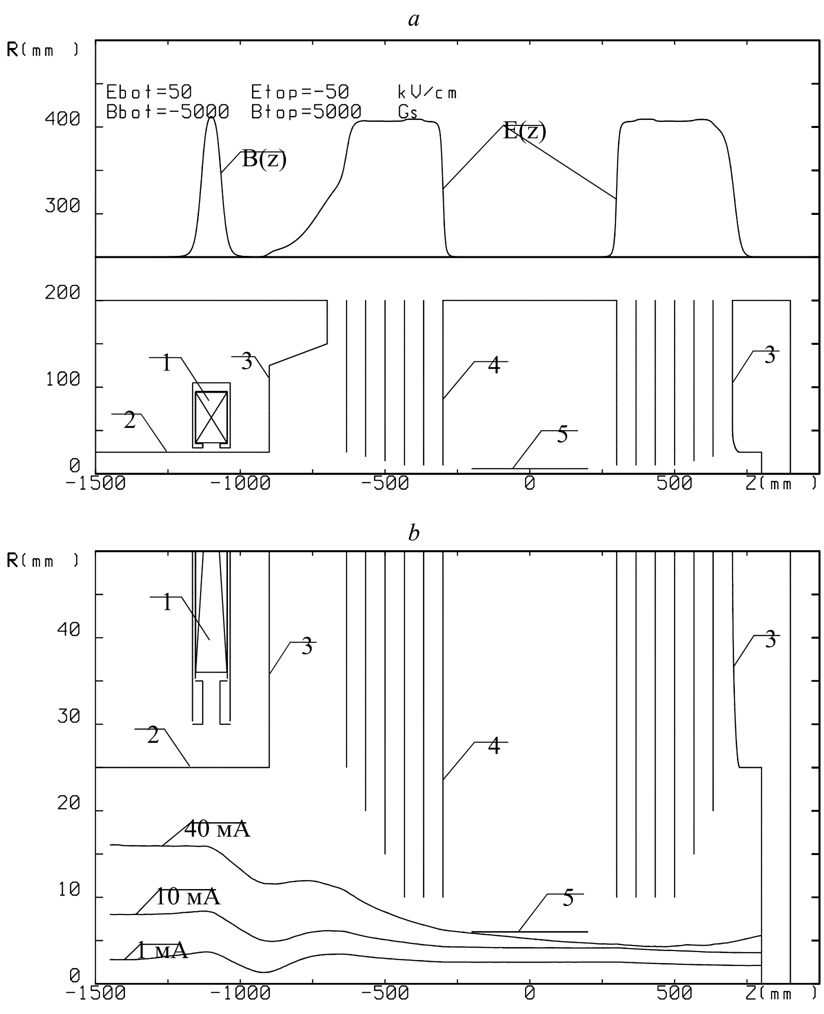


Fig. 7. Coordinated transport of 25 keV H- beam throughtandem accelerator according to simplified "weak" focusing scheme: the ion-optical path geometry, calculation longitudinal distributions of the field (a) and the envelopes of ion beams with current of 1 mA, 10 mA and 40 mA, spanning 95% of the current (b). The numbers mark: 1 – the magnetic lens, 2 – drift tube, 3 - vacuum tank, 4 – high-voltage electrode, 5 – charge-exchange tube.

Fig. 7, b displays the calculated envelopes of 1 mA, 10 mA and 40 mA ion beams, spanning 95% of the current in the given geometry. The initial conditions were defined the same as in the previous calculations and the lens current was again matched in order to provide the beams maximum passing through the charge-exchange tube with minimum slope of their envelopes. The comparison of Fig. 6 and Fig. 7 indicates that the "weak" focusing scheme can be realized without additional electrodes.

As a whole, both schemes of transporting the negative ion beam in the tandem accelerator with "weak" and "strong" beam focusing, described above, supplement each other, though having slight differences in their ion-optical channel geometries. So the decision was to provide the opportunity during the design of the final ion-optical path geometry to check both "soft" and "strong" beam focusings experimentally and to make a final choice of the beam transport scheme after comparing the results of these experiments.

VI. Final geometry and parameters of the ion-optical channel

During the first stage of development of geometry of the ion-optical channel of the 2.5 MeV tandem accelerator, the optimal geometry of the magnetic shield was found and parameters for two magnetic lenses, which are intended to be used for transporting and coordinated leading/inputting of 10 mA ion beam into/through the accelerator, were calculated. The lenses were designed basing on the existing modules of the winding of solenoid with external water cooling.

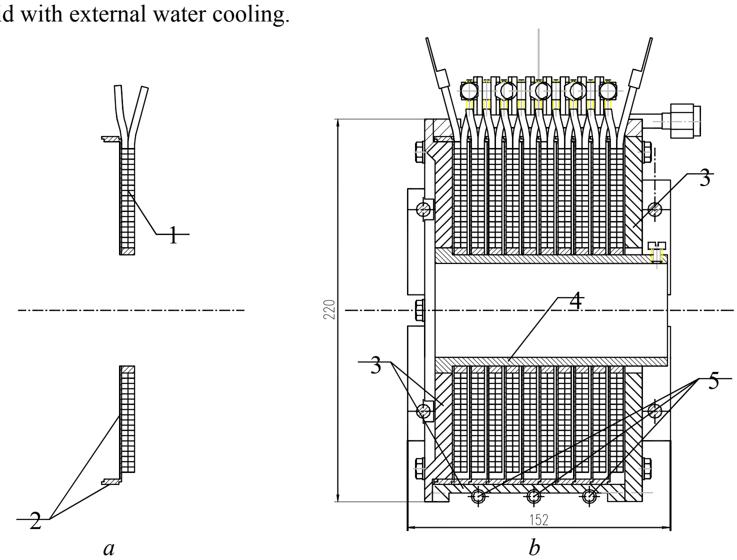


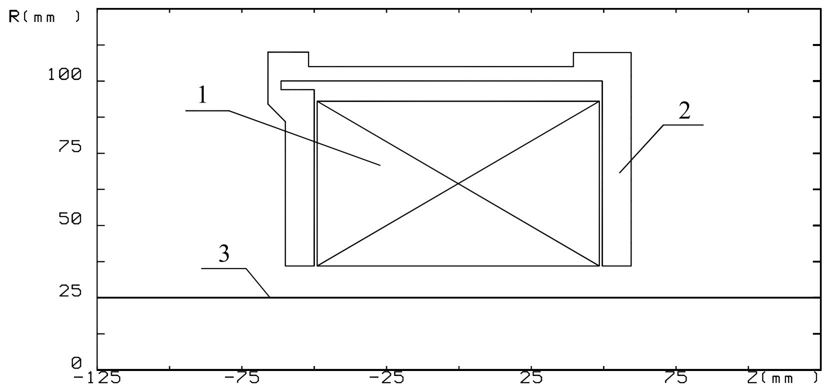
Fig. 8. Magnetic lens draft: base winding module (a) and a ready-assembled magnetic lens (b). The numbers mark: 1 – a current bus-bar, 2 – aluminum disc, 3 – magnetic shield, 4 – lens frame (stainless steel), 5 – pipes of cooling system.

The draft of such a module is shown on Fig. 8, a. It contains the heat-eliminating aluminum disc, which has 39 turns of current bus-bar with cross-section of 2.8×4 mm^2 glued to it. The inner hole of the disc has diameter of 64 mm and the external diameter of the disc is 200 mm, the period of module structure is 10.25 mm. The winding of each lens consists of 10 such modules. Fig. 8, b displays the draft of the whole ready-assembled lens including the winding, magnetic shield, frame and a cooling system. The maximum current in the lens winding is 29.25 kA·turns. It can be achieved when the current in the bus is 75 A and the full voltage on the lens winding is 25 V.

During the calculations, the optimal geometry for the magnetic shield was found. It provides minimal aberrations of lens and absence of saturation effects. The drift tube of the ion-optical channel, which the lens is fixed on, has inner diameter of 50 mm. Fig. 9 displays the contour of the drift tube, c calculated geometry of the magnetic lens and longitudinal distribution of magnetic field for the maximum current in the lens winding. The maximum value of magnetic field here is 3350 G and the active length of the lens is 83 mm.

The next stage of development of the ion-optical path was devoted to matching the optimal distance between the ion source and the center of the tandem accelerator tank, position and current of both lenses and geometry of the entrance part of the accelerator for “weak” and ”strong” beam focusing schemes. The ion source was proposed to generate a beam with current of 10 mA, initial ions energy of 25 keV, transverse energy of 1 eV, initial diameter of 5 mm and initial opening angle of 50 mrad. The distance between the source and the center of the first magnetic lens is physically limited and cannot exceed 200 mm. The tube of the ion beam transportation system, which the magnetic lenses are fixed on, has inner diameter of 50 mm. The inner diameter of charge-exchange tube is 12 mm and its length is 500 mm. The optimality test was the minimal beam radius in the charge-exchange tube and minimal opening angle and emittance of the beam at the outlet from the accelerator with minimal power, consumed by the windings of both magnetic lenses.

a



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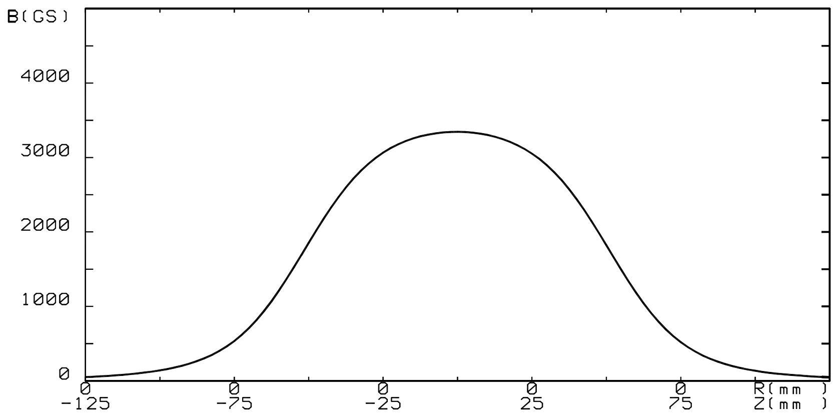

Fig. 9. Calculated geometry of the magnetic lens (a) and longitudinal distribution of magnetic field for maximum current 29,25 kA·turns in the lens winding (b). The numbers mark: 1 – current coil, 2 – magnetic field, 3 – contour of the drift tube.

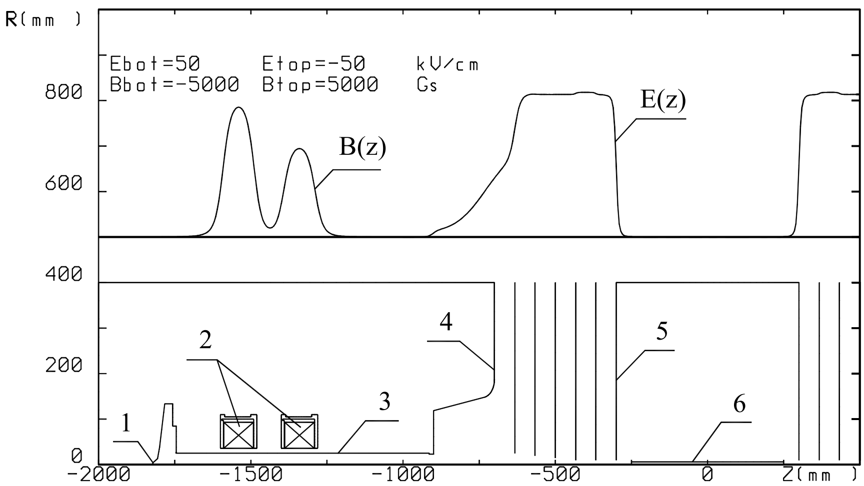

Fig. 10. Geometry of the ion-optical channel of a tandem accelerator and calculation longitudinal distribution of the field for the scheme with "weak" focusing of a H^- beam with current of 10 mA and initial energy of 25 keV. The numbers mark: 1- the ion source, 2 – magnetic lenses, 3 – drift tube, 4 – vacuum tank, 5 – high-voltage electrode, 6 – charge-exchange tube.

The calculated geometry of the ion-optical path of tandem accelerator for the scheme with "weak" beam focusing is displayed in Fig. 10. The maximum diameter of the conical funnel at the entrance to the accelerator is 300 mm, its length is 200 mm. The picture also shows position of the ion source and magnetic lenses as well as calculated distribution of the magnetic shield of the focusing lenses and electric field of the accelerator along the axis. Here current in the closest to the ion source lens is 25 kA and in the second one it is 17 kA.

Results of calculation in this geometry are displayed on Fig. 11. Fig. 11,a shows contours of the electrodes, the charge-exchange tube and the magnetic lens, and also the envelopes of 25% and 95% of the beam current. Fig. 11, b shows radial current density distribution and a phase-plane portrait of the beam at the outlet from the accelerator. It also displays the calculated values of the radius, maximum opening angle and normalized r.m.s. emittance of the beam at the outlet from the accelerator.

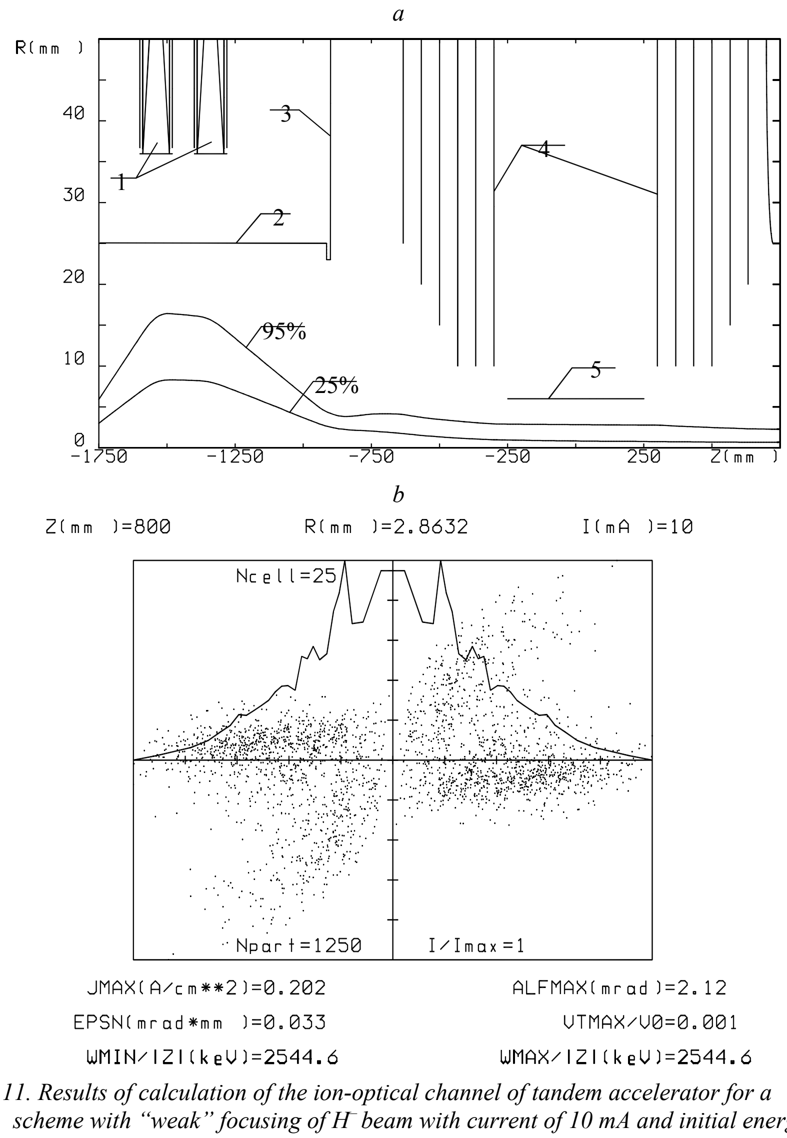

Fig. 11. Results of calculation of the ion-optical channel of tandem accelerator for a scheme with "weak" focusing of H^- beam with current of 10 mA and initial energy of 25 keV: a – envelopes of 25% and 95% of the beam current; b – radial current density distribution and beam emittance at the outlet from the accelerator. The numbers mark: 1 – magnetic lenses, 2 – drift tube, 3 – vacuum tank, 4 – high-voltage electrode, 5 – charge-exchange tube.

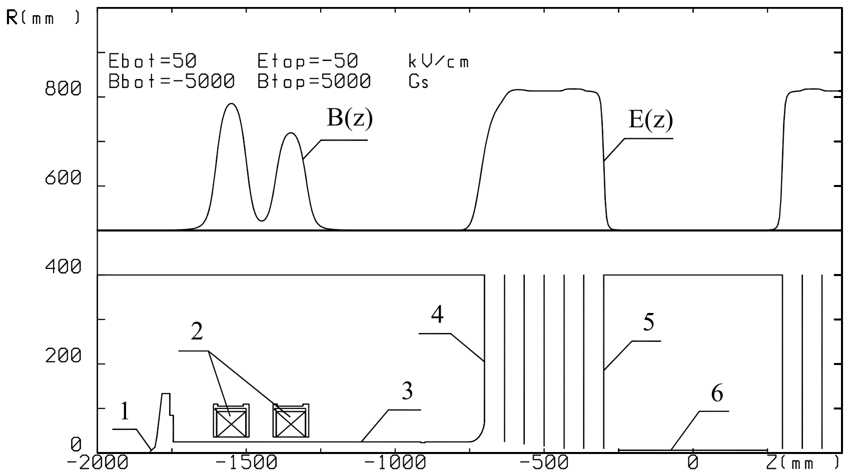

Fig. 12. Geometry of the ion-optical channel of tandem accelerator and calculated longitudinal distribution of the field for the scheme with "strong" focusing of H^- beam with current of 10 mA and initial energy of 25 keV. The numbers mark: 1- the ion source, 2 – magnetic lenses, 3 – drift tube, 4 – vacuum tank, 5 – high-voltage electrode, 6 – charge-exchange tube.

The geometry of the ion-optical path of a tandem accelerator for leading in a "firmly"-focused beam is displayed in Fig. 12. Position of the ion source and two magnetic lenses matches the one in the case with "weak" focusing. Note that the first intermediate gap was not changed, but the tube of transportation channel with inner diameter of 50 mm was smoothly docked with accelerator tank using toroidal surface with radius of curvature of 50 mm. Fig. 12 also displays calculated distribution of magnetic field of the focusing lenses and electric field of the accelerator along the axis of the ion-optical path. Here current in the closest to the ion source lens is 25 kA and in the second one it is 19.2 kA.

Results of calculation of such a geometry are presented in Fig. 13. Fig. 13, a displays contours of the electrodes, the charge-exchange tube and the magnetic lens, and also envelopes of 25% and 95% of the beam's current. Fig. 13, b shows the radial current density distribution and phase-plane beam portrait at the outlet from the accelerator. It also displays the calculated values of the radius, maximum opening angle and normalized r.m.s. emittance of the beam at the outlet from the accelerator.

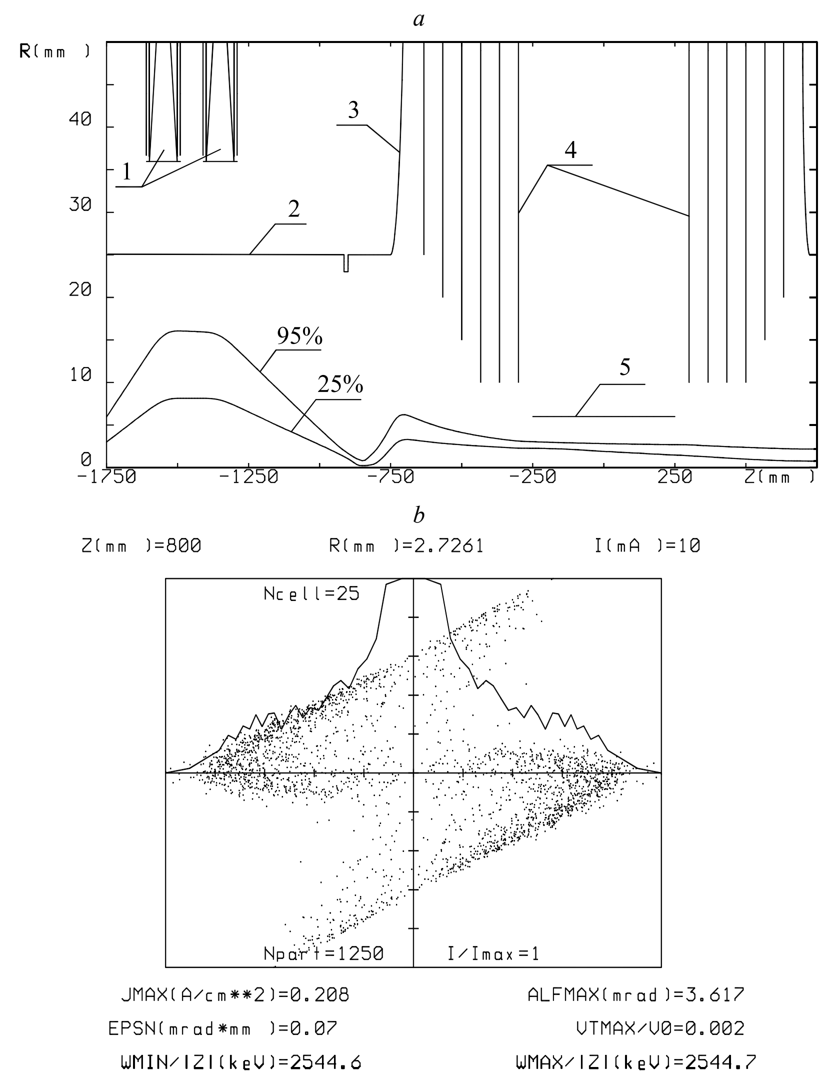

Fig. 13. Results of calculation of the ion-optical path of tandem accelerator for a scheme with "weak" focusing of a H^- beam with current of 10 mA and initial energy of 25 keV: a – envelopes of 25% and 95% of the beam's current; b – radial current density distribution and beam emittance at the outlet from the accelerator. The numbers mark: 1 – magnetic lenses, 2 – drift tube, 3 – vacuum tank, 4 – high-voltage electrode, 5 – charge-exchange tube.

The comparison of Fig. 11, a and Fig. 13, a indicates that diameters of the beam in the charge-exchange tube and at the outlet from the accelerator are almost the same in different focusing schemes. At the same time the comparison of Fig. 11, b and Fig. 13, b indicates that a “firm” focusing scheme leads to a big increase of normalized r.m.s. emittance of the beam at the outlet from the accelerator (it increases approximately 2.5 times in comparison to the initial thermal beam r.m.s. emittance equal to 0.028 π mm mrad). More detailed analysis of the beam dynamics shows that most of the emittance increase takes place at the entrance to the accelerator due to the nonlinear nature of a space charge forces, which have a great influence on the dynamics of the beam because of its small radius at the entrance. Note that the sign of strong nonlinear effects, caused by a space charge forces, coincides with the sign of weak nonlinear effects, emerging inside the magnetic lenses.

A “weak” focusing scheme allows transferring and accelerating the ion beam without any increase of its emittance. The weak nonlinear effects, emerging in magnetic lenses cancel with ones, caused by the forces of a space charge.

Fig. 14 displays the curves of dependence of maximal radius of 95% beam’s current envelope in the charge-exchange tube on the full current in the second magnetic lens for the described above schemes with “weak” and ”strong” beam focusing. Note that minimal radius of the beam in the charge-exchange tube means non-optimal radius and opening angle at the outlet from the accelerator. However, “weak” focusing allows achieving smaller radius of the beam with smaller current in the lens. Moreover, this scheme allows to transport the beam through the charge-exchange tube with much more different values of current in the second lens than the scheme with “strong” focusing. It makes the ion-optical path setup easier and lowers requirements to current stabilization in the lens.

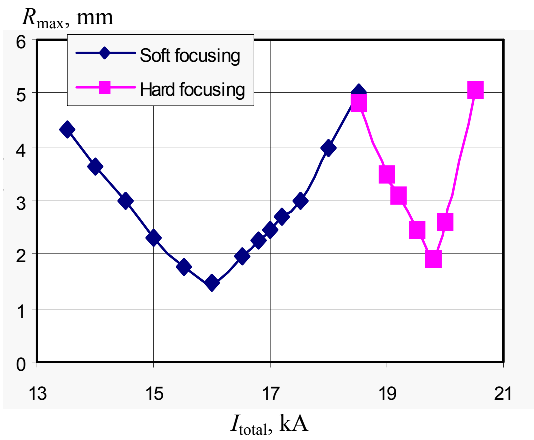

Fig. 14. Calculated dependence of maximum radius of the envelope of 95% of the H^- beam’s current in the charge-exchange tube on the full current in the second magnetic lens for the schemes with “weak” and ”strong” beam focusing.

Summary

Numerical simulation of dense H^- beam transport from the source through the charge-exchange target up to outlet of the accelerator in electric and magnetic fields was carried out taking into account beam space charge and emittance. Optical focusing system was optimized for transporting negative hydrogen ion beam without significant increase of the beam emittance. The minimization of effect of space charge compensation was desirable.

Two ways of transporting the dc high current beam of negative hydrogen ions from ion source to the accelerator were considered: the one using axisymmetric lens and another using magnetic lens. Despite big power consumption it was recommended to use magnetic lenses for realization, because they allow transportation of fully compensated beam of negative hydrogen ions; and since it was possible to choose their position without changing the channel construction.

Two schemes of coordinated transportation of negative 25 keV hydrogen ion beam of in the tandem accelerator were examined; they are the “strong” scheme with the use of strong magnetic lens and beam overfocusing at the entrance to accelerator, and "weak" introduction without beam overfocusing with increased first gap and more smooth increase of electric field intensity in tandem. Since both of the schemes have advantages and disadvantages and both of them have only slight difference in the ion-optical path designs, the recommended solution is to provide the possibility to check both "weak” and “strong” beam focusing experimentally.

The optimal geometry of magnetic screen providing minimum aberrations introduced by the lens and the absence of saturation effects was determined. Magnetic lens like a folding solenoid with outer water cooling was designed and manufactured.

As a result, there are two constructions of the ion-optical channel of tandem accelerator for the H^- beam with the initial ions energy of 25 keV and current of 10 mA: with “weak” and “strong” beam focusing.

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