NEGATIVE ION BEAM FORMING IN LINAC INJECTOR

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Abstract

A negative ion of hydrogen passing through a gas ionizes the gas, and the electron and iones so produced collect in the vicinity of the beam to form plasma with number density that can be much greater the density of the beam. A two-dimensional static theory (a second coordinate is a parameter) gives the plasma density and ambipolar field distribution in the space. The other method of solution of problem is considered. Simulation of dynamic of negative ions gives possibility to determine parameters of optical systems of injector. Ion optics as function of electrode dimensions are examined.

1. Principle of Ion Beam Forming for RFQ or alternating-phase focussing accelerators.

Injector is a necessary part of a linear ion accelerator with a plasma source and is a system of generation, transportation and preacceleration of a beam. Value of particle energy at injector output depends on a type of accelerating structure in which acceleration of particles up to high energies takes place. At last time RFQ accelerators proposed by I.M.Kapchinsky and V.A.Teplyakov [1], gained currency. These accelerators can accept a high current, low-velocity beam, bunch it with high efficiency, but RFQ linac imposes exacting requirements on a shape and value of a phase volume of a beam at the injector output. As it is shown in [2], the best matching of a beam with the accelerating channel will be achieved, if a beam at the accelerator input is convergent and symmetrical and has an optimal relationship of large and small semi-axes of ellipses, representing a beam in two-dimensional phase spaces XX' and YY'. Accelerator with drift tubes and alternating-phase focussing, considered for example in papers of KhPhTI specialists [3] is the other possible type of accelerator with a relatively low energy of injection. Converging and axially symmetrical beam is also desired here for a good putting into acceleration and bunching. Realization of these requirements is concerned with solution of complex problems as ion injector is not a device with high vacuum, and a surface-plasma H^- source (see, for example [4]) produces not axially symmetric, but a ribbon-shaped beam. Transport of the beam of charged particles in the injector is made difficult by a substantial change of pressure residual gas along the length of the injector (by 2-3 orders) and by presence of the beam space-charge field. Typical scheme of injector is shown in fig.1. Near the source and in the bending magnet (which is used for extraction of heavy ions and caesium atoms from the beam H^-) beam charge is compensated by ions, forming in ionization of atoms and molecules of the residual gas.

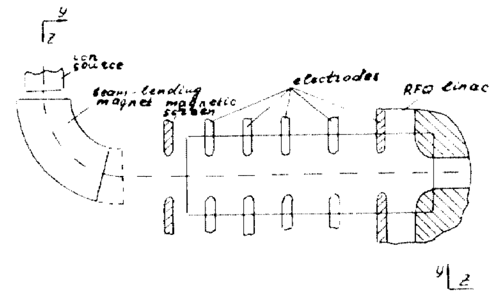


Fig.1. Schematic configuration of ion injector of RFQ linac

Density of neutral atoms and molecules of the residual gas and gas, coming to the drift space from the source, has usually such a value, that density of plasma, formed as a result of ionization, may be equal to density of particles in the beam or even exceed it considerably. As mobility of plasma ions and electrons is different, then in the systems, limited in the radial direction, (injector length considerably exceeds transverse dimensions of the injector), plasma ambipolar electric field, flattening fluxes of the unlike-charged particles, arises. This field can seriously influence on the particle dynamics in these regions of the injector, where external electromagnetic fields [6] are absent or small. There are three regions in the injector, beam dynamics on which differs qualitatively.

The first region is extraction of ions from the source, where gas density is very high ($10^{-1} \div 10^{-2}$ mm of mercury) and inelastic scattering of beam ions on gas ions may be substantial.

The second region is movement of the beam in the field of the bending magnet and in the field of "plasma" lens. In this region gas pressure is rather considerable ($\sim 10^{-4}$ mm of mercury), spatial charge of the beam is overcompensated.

In the third region - from the point with pressure $P = P_c$, corresponding to full compensation of beam charge - before the accelerator input a pressure drop by two orders (from $\sim 10^{-4}$ down to $\sim 10^{-6}$ mm of mercury), takes place as well as change of the potential sign in the beam and increase of the phase volume of its particles under the action of the own space charge, a value of which increases with vacuum increase. In order to prevent an excessive expansion of the beam and ensure correlation of its emittance with the accelerator acceptance, it is possible to place gaps of acceleration, magnetic and electrostatic focusing lenses.

Injector for RFQ accelerator with focussing, magnetic quadrupole lenses in the injector channel and compensation of the space charge along all the injector is considered in paper [4]. This method has a disadvantage: it is practically impossible to implement a sufficiently good compensation of the space charge of the beam on a length of tens of centimetres at alternating pressure. Undercompensation and overcompensation of the space charge by 1% leads to a strong mismatch of beam emittance and accelerator acceptance. Ion injector with electrostatic system of focussing and acceleration of the beam is studied in this paper. Questions of numerical simulation of a beam of negative hydrogen ions in such injector, forces, acting on the particles, and of equations of motion are stated in the paper [5]

For symmetrization of a beam and limitation of emittance growth in the regions 1-3 of the injector there is a number of physical parameters, which may be changed in the known limits: for example, field index in the bending magnet; intensity of ambipolar electric field of plasma, depending on a residual gas pressure and electron temperature, and length of the particle path in the bending magnet. However, it is difficult to implement control of the last parameter in practice. In the region 3 beam dynamics is determined by a number of electrodes of the preacceleration system, arrangement of them and potential values on them. Results of numerical simulation of passage of a beam of negative hydrogen ions through the injector in varying of the mentioned characteristics and assessment of sensitivity of beam parameters to their change are represented under.

2. Numerical Simulation of Particle Dynamics in the Injection System

Scheme of injector, shown in fig.1 with the source of V.G.Dudnikov type [7], producing 100 mA H^- current with 20 keV energy of particles near the slot of the source, has been chosen for investigation. Dimensions of the source slot are 0.5 mm x 10 mm radius of the bending magnet is 8 cm. Electrostatic system of preacceleration of ions up to 150 keV ensures effective injection both into RFQ and alternating phase focussing accelerators. Influence of change of a field index on a degree of symmetrization of the beam is seen from fig.2,3 Beam envelopes in the planes XZ and YZ for two initial phase volumes of the beam with emittances: $\varepsilon_{x1}, \varepsilon_{y1}, \varepsilon_{x2}, \varepsilon_{y2}$ and two different field indices in the bending magnet n =0.8 and n = 0.9 are shown there. It is seen, that in the case $\varepsilon = \varepsilon_2$ the beam may be symmetrized at n = 0.9 (fig.2), that agrees with the experimental data, stated in paper [8] well enough. Possibility of symmetrization depends appreciably on a shape and value of beam emittance near the source slot. Therefore, relationship of a width and length of the source slot is also a parameter, which allows to optimize beam characteristics. As for the ambipolar field, stipulated by radial drift of electrons and ions, in the bend magnet this field can arrize only in XZ plane, since a drift of charged particles along the force lines of the magnetic field is possible in this plane. Calculation of intensity of the electric ambipolar field was produced in accordance with [6] by the formula:

$$E_x = \frac{4\gamma}{(\gamma+1)^2}\frac{T_e}{e x_\ell}\frac{2}{\sqrt{\pi}}\, e^{-\frac{x^2}{x_\ell^2}}\frac{\mathrm{erf}\,\xi}{\mathrm{erf}\,\xi_w}\left\{1-\frac{4\gamma}{(\gamma+1)^2}\frac{\mathrm{erf}^2\xi}{\mathrm{erf}^2\xi_w}+\left[1-\frac{4\,\mathrm{erf}^2\xi}{(\gamma^2+1)\,\mathrm{erf}^2\xi_w}\right]^{-\frac{1}{2}}\right\}^{-1}$$

where $\xi = \frac{x}{x_\ell}$; $\xi_w = \frac{x_w}{x_\ell}$

x_ℓ - is effective halfwidth of the beam on x axis.

x_w - is the distance to the metallic surface.

γ - is exponent of adiabat, which is a term of the formula for "ion sound" velocity.

T_e - is temperature of plasma electrons.

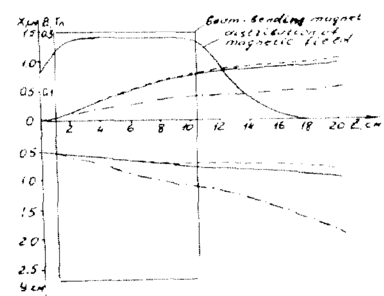


Fig.2. A variation of the field along bending magnet axis: Beam envelopes in the planes XZ and YZ

—— $\varepsilon_{x2}, \varepsilon_{y2}$, n = 0.9 - - - -, ε_{x2}, ε_{y2} n = 0.8

—·—·— $\varepsilon_{x1}, \varepsilon_{y1}$ n = 0.9

Beam envelopes without account and with account of the ambipolar field influence are shown in fig.3. It is seen, that influence of this effect is not great in this case. It is clear, if we take into account, that ambipolar field intensity does not exceed (10-20) Volt/cm and at the same time it is less by an order than a value of the focusing forces.

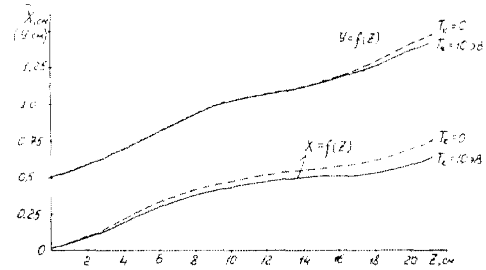
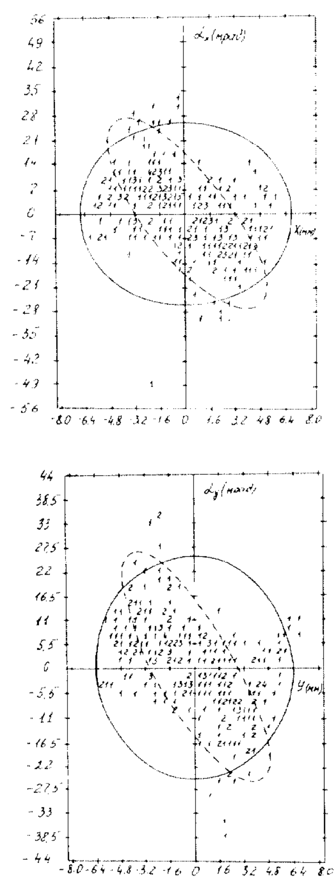


Fig.3. Beam envelopes without account (---) and with account of the ambipolar field (——) influence

However, focusing effect due to action of the ambipolar force may be used for correction of the phase space of the beam in XX' plane. Ion-optic system of preacceleration and focussing consisted of 5 electrodes, the last of which was the input flange of the accelerator. Low growth of emittance and maximum passage of current was reached due to the use of the system of single lenses and appropriate choice of internal radii of the electrodes and distances between them. The last two parameters were varied. Electrode displacement by 8÷10 mm from the optimal position leads to decrease of passing of particles into acceptance in the transverse plane by 15÷20%. Change of the internal radius by the value $\delta R/R = \pm 10\%$ leads to decrease of reaching the acceptance by 25-30%. (Acceptance for particles with synchronous phase with respect to high--frequency field is meant here).

Phase patterns of a beam of particles at the input of the acceleration structure in the planes XX' and YY' are shown in fig.4a, 4b. This case corresponds to the field index $n = 0.9$ and linear accelerator with the operating 2 m wavelength. Possible acceptance of RFQ-focussing accelerator is shown by the dotted line, acceptance of the alternating phase focussing accelerator is shown by continuous line.



a

b

Fig.4. Phase patterns of a beam at the input of the acceleration structure
—— acceptance of APF-structure
- - - -acceptance of RFQ-structure

Conclusions

1. Numerical simulation of dynamics of particles in the injector with ionoptical system, discussed in the paper, showed, that axially symmetrical electrostatic system of preacceleration at the correct choice of bending magnet parameters allows to ensure high current-passage in the injector channel and good agreement of the beam emittance with acceptances of RFQ- and alternating phase focussing accelerators.

2. Variation calculations showed, that change of internal radii of ion-optical system electrodes influences on the dynamics of ions much stronger than change of distances between electrodes.

3. In the numeric simulation of H^- ion beams dynamics with high phase density in addition to the external rf and focussing fields it is necessary to take account of the influence of the electrostatic ambipolar field, arrising in the beam-plasma system.

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