THE PROBLEMS OF ION BEAMS MODELING IN INJECTORS AND RFQ LINACS

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Abstract

Problems of simulation of ion dynamics in injectors and RFQ linacs are discussed. Two methods of modeling of fields and particle dynamics in injection systems are considered. Ion optics as function of electrodes dimension in high gradient RFQ linacs are examined.

1.State-of-the-arts

Great progress made recently in Radio-frequency ion linacs have become possible due to the radio-frequency quadrupole focusing (RFQ), proposed by I.M.Kapchinsky and V.A.Teplyakov [Ref.1]. RFQ accelerators used as a low energy part of linac (LEBT) enable to provide a high ion trapping coefficient at a low injection energy and a small beam emittance at the inlet to the main part of an accelerator (HEBT). But to realise this it is necessary to fulfil quite exacting requirements for beam parameters at the inlet to the LEBT, especially at great phase current densities.The problems of matching a beam to the regular part of an accelerator were considered in a number of studies [e.g.Ref.2]. It has been revealed that the best matching of a beam to the regular channel will be obtained if the beam at the inlet to the bucher is convergent, symmetrical and with an optimal ratio of large and small semiaxes of phase ellipces in the planes XX^I and YY^I. The calculations of an ion injector with physical parameters providing the fulfilment of these conditions, is extremely labour-consuming and requires repeated modeling of the 3-dimensional ion dynamics in the injector chahhel. A standard scheme of a negative hydrogen ion injector with a plasma source is shown in Fig.1 (the same scheme may be used also to form a positive hydrogen ion beam).

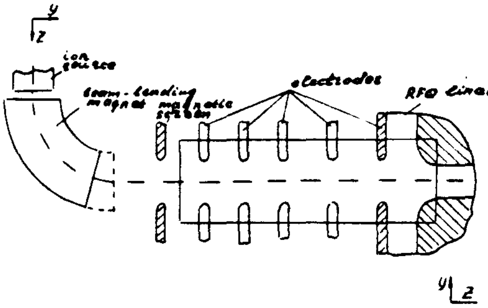

Fig1. Schematic configuration of ion injector of RFQ linac

The charged particle beam transport in such an injector is complicated by a considerable difference in the residual gas pressure (by 3 - 4 orders of magnitude) along the injector and the presence of a beam space-charge field. Near the source and in the bending magnet, which is used to remove heavy ions and caesium atoms from an H^- beam, the beam charge is compensated by ions arising during ionization of residual gas atoms or molecules. The density of the neutral atoms or molecules of residual gas and the density of a gas, entering the drift spase from the source, is usually such that the density of an ion plasma formed as a result of the ionization may be compared to or even considerably exceed the density of particles in a beam. As the mobility of ions and electrons of plasma being different, there appears a plasma ambipolar electric field, equilizing the fluxes of opposite charged particles in the radially limited systems (the injector length considerably exceeds its lateral dimension). This field may drastically affect the particle dynamics in the injector regions, where external elestromagnetic fields are absent or negligible. The external fields are of great importance in that part of the injector before the accelerator, where a beam volume chaarge is not compensated, and to match the beam emittance with the accelerator acceptance there is used a preaccelerating focusing system consisting of several electrodes.

Attempts to model the fields and particle dynamics in ion injection systems were made by J.H.Whealton and co-workers during 1978-1989, the problems of not only the transport(the region to the right of the source slit) but the ion extraction (the region to the left of the slit) having been considered. But the problem was not solved completely though up-to-date computers were made use of. The plasma density to the right of the source was suggested to be always sufficiently small. The results of these studies are reviewed by J.H.Whealton in [Ref.3]. His approach, consisting in the modeling of the Poisson equation and three kinetic Vlasov equations, is at present the only serious program allowing to model the process of an ion extraction from plasma sources of different types and to obtain results consistent with the experiment. But as for the modeling of ion transport processes in the preacceleration systems of different complexity more economical calculation methods are possible, which allow to obtain good results.

2. The model of the given field

To calculate a field potential and phase characterastacs of a beam in the region of high-to-low-pressure transition the pollowing system of equations must be solved: the equation for the potential φ

$$\Delta\varphi = -\frac{e}{\varepsilon_o}[n_i(\varphi)-n_b-n_e(\varphi)] \qquad (1)$$

plus the movement equations, that determine the distribution of the density of plasma ions and electrons, n_i and n_e, and beam ions, n_b.

But while carryng out prelliminary calculations, the problem may be simplified, considering the gas distribution in the injector as the given one, as it is mainly determined by the vacuum pumping system and a source operation mode. The experiments of M.D.Gabovich [Ref.4] showed that the dependence of beam potential on the pressure $\varphi_B = \varphi(p)$ near the volume charge compensation point is of a logarithmic character. Thus, knowing the function $\varphi_B=\varphi(p)$ and pressure distribution $P = P(z)$ it is possible to calculation $\varphi_B = \tilde{\varphi}(z)$. Such an approach in modeling the 3-dimensional ion dynamics in an injector with large pressure difference has been realized in the PL-codes [Ref.5]. The calculation of the proper field of a beam, taking into account the dependence $\varphi_B=\tilde{\varphi}(z)$, permitted to avoid the solution of a self-consistent problem. The dynamics of beam ions in the field of given forces is considered along the whole injector channel. The field of axial-symmetric electrostatic systems are calculated numerically by solving the Laplace equation with corresponding boundary conditions. The processes of an ion extraction from the source and the formation of a plasma boundary are not considered. The form and size of the phase beam volume of "large" particles are given in the point immediately after the extracting electrodes. As a rule, the initial phase volume is known from the experiment. The calculations of a negative hydrogen ion injector for a RFQ-accelerator have been made, with the help of this code, and the axial-symmetric electrostatic system of preacceleration, the bending magnet parameters being properly selected, have been shown to provide small losses of H^- ions in the injector channel and good matching of the beam emittance to the RFQ-structure acceptance [Ref.6].

3.The hydrodynamic model

A more strict approach to the modeling of processes in the injector channel includes the calculation of a self-consistent field in the plasma-beam system and further the calculation of the ion dynamics in the given field. This approach is justified, as one of the tasks of the injector design is to provide a small emittance growth of an acceleratted beam. To describe the behavior of electron and ion plasma components the equations of the two-fluid hydrodinamics are used, i.e. movement and continuity ones, as well as the Poisson or Gauss equations for a self-consistent beam-plasma field. These equations for a symmetrical plasma source (external fields are absent) may be written in a one-dimentional form, taking into account that the injector length considerably exceeds its lateral sizes, and supposing a weak nonuniformity of plasma and gas parameters along the injector ($\partial E/\partial r \gg \partial E/\partial z$ and $E_r \gg E_z$).Assuming that a beam ionized the gas only once the gas ionization by secondary electrons is negligible and only elastic collisions occur in the plasma itself. Under these assumptions the plasma-beam system may be modelled by five integro-differential equations [Ref.7]:

$$\int_V \frac{dn_\alpha}{dt} dV = \int_V \nu_H n_b dV - \oint_S n_\alpha u_\alpha dS,$$

$$\oint E_r dS = 4\pi e \int_V (n_i - n_b - n_e) dV, \qquad (2)$$

$$\frac{\partial u_\alpha}{\partial t} = -u_\alpha \frac{\partial u_\alpha}{\partial r} \pm \frac{eE_r}{m_\alpha} - \nu_H \frac{n_b}{n_\alpha} u_\alpha - \frac{T_\alpha}{m_\alpha n_\alpha} \times \frac{\partial n_\alpha}{\partial r} - \nu_{\alpha o} \frac{m_o}{m_o + m_\alpha} u_\alpha .$$

Here, the index α takes on values i, e (ions, electrons); n_α and u_α are the densities and directed velocities of plasma ions and electrons; n_b and v_b are the density and velocity of beam particles; ν_H and $\nu_{\alpha o}$ are the collision frequencies equal to $\nu_H = n_g(z)\sigma_i \nu_b$ and $\nu_{\alpha o} = n_g(z)\sigma_{\alpha o}\nu_\alpha$, respectively; n_g is the gas atom density; σ_i is the cross-section of a gas atom ionization by beam ions; $\sigma_{\alpha o}$ is the cross-section of elastic collisions of plasma components with gas neutrals ; T_α, ν_α, m_α are the temperature, thermal velocity and plasma particle mass; m_o is the gas atom mass. In system (2) the directed velocity of neutral gas atoms is accepted to be equal to zero without violating the generality. The boundary conditions are of the form:

$$\left.\frac{\partial u_\alpha}{\partial r}\right|_{r=0} = 0; \quad \left.\frac{\partial n_\alpha}{\partial r}\right|_{r=0} = 0; \quad u_i\Big|_{r=R} = \mathrm{const}\left(\frac{2T_e}{m_i}\right)^{\frac{1}{2}}. \qquad (3)$$

$$u_e\Big|_{r=R} = \left(\frac{3T_e}{m_e}\right)^{\frac{1}{2}}; \quad \left.\frac{\partial}{\partial r}\left(\frac{\partial n_\alpha}{\partial r}\right)\right|_{r=R} = 0; \quad \left.\frac{\partial}{\partial r}\left(\frac{\partial u_\alpha}{\partial r}\right)\right|_{r=R} = 0; \qquad (4)$$

They are discussed in detail in the paper of the same authors that in [Ref.7], which is to be published in JTP in the hearest future. Zero values of densities and directed velocities of plasma components correspond to the initial conditions of the problem. In case the space beam charge is not fully compensated by the plasma, when $n_i, n_e \ll n_b$, in order to calculate the field the beam movement equations ought to be added to equation system (2). With the external electrostatic fields the problem becomes the two-dimensional one. Fig.2 presents the curves of the resulting field in the plasma -beam system for three gas densities, $n_{g1} = 3,6 \times 10^{20}\ m^{-3}$, $n_{g2} = 3,6 \times 10^{19} m^{-3}$, $n_{g3} = 3,6 \times 10^{18} m^{-3}$, corresponding to three points of the injector along the longitudinal axis Z: $Z_1 < Z_2 < Z_3$. The maximum particle density on the system axis amounted to $n_b = 10^{13} m^{-3}$, the effective beam radius r_b= 3 cm, T_e= 3 eV, T_i= 0,03 eV, $\nu_b = 2 \times 10^8$m/s. To avoid the influence of boundary effects on the field near the beam the radius of the system wall was chosen considerably larder than that of the beam (20 cm). The case n_g=

n_{g2} corresponded to the full beam charge compensation ($n_i, n_e \geq n_b$). Under these conditions the plasma-beam system is consistent, and the dependence of an electric field potential on radius in the region 0...0.15 m corresponds to the one observed experimentally [Ref.8] (see Fig.3).

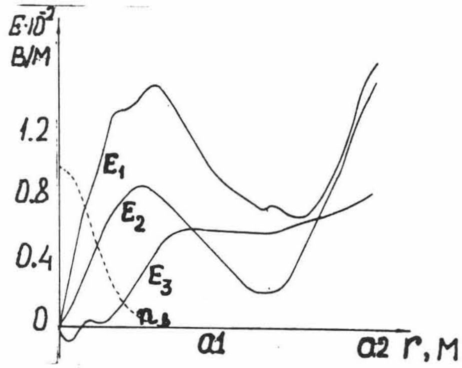

Fig2. A field distribution in the beam-plasma system
E_1-curve correspond to gas density n_{g1}; E_2- n_{g2}; E_3- n_{g3}.

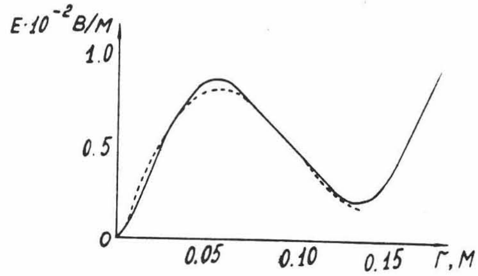

Fig3. Case of full charge compensation. Dependance of an electric field on the radius
—— Theory; ----- Experiment

4.Modeling of the ion dynamics in RFQ linacs

The calculation of the dynamics of charded particle beams with large density of a volume charge in RFQ accelerators is time-consuming, especially in carrying out multivariant calculations for optimization problems or in detecting the torerances for the manufacture of accelerating structures. Using different models of a particle beam considerably reduce the time for numerical modeling. There are another problems as taking into account the influence of heighbouring bunches on each other, the difference in calculation results for "ideal" and "real" electrodes of an RF resonator. In going from resonators with a 150 MHz operating frequency to those operating in a 400 - 500 MHz drequency range the number of bunches (ecxept the main one) to be taken into account in the model increases from two to four. Usually the account of only the terms of the first order, determining the acceleration and focusing effect, in the function of the potential dictribution corresponds to some ideal surface poles. In going to a real pole surface in resonators, operating with 400 MHz frequency and above, it results in considerable changes in the acceleration efficiency and ion trajectories, especially for the RFQ accelerating gradient($\Delta U/\Delta z$ > 1 MeV/m). The particle losses over the length for an accelerator with a 2 MeV finite energy for the "ideal"and "real"electrodes are shown in Fig.4. RFQ linac such as that must be built in D.V.Efremov Institute as LEBT for PET system, like one in [Ref.10].

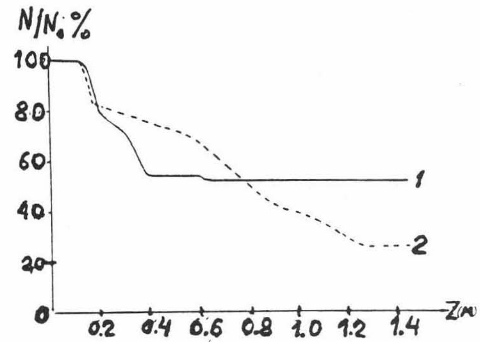

Fig4. The particle losses over the length for a accelerator
1- "ideal" electrodes;
2- "real" electrodes.

In going from the "ideal"to "real" electrodes current at the outlet is reduced by a factor of two. In this case the current was increased up to the former level by increasing a potential on the electrodes by 2 kV. But in generally case while calculating the particle dynamics in resonators with f>400 MHz the terms of higher orders of the potential expansion are to be taken into account.

Besides, for high-gradient structures the dependence of output beam characteristics on the parameters of initial phase ellipse becomes so sensitive that it is required to consider a common injector- accelerator system while modeling the ion dymamics.

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