INJECTION INTO RFQ USING BEAMS WITH DIFFERENT ENERGIES

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Abstract

An alternative way of beam injection into radio-frequency quadrupole (RFQ) linac is discussed. In the low energy part of an ion accelerator, a monochromatic beam extracted from ion source is transported to the entrance of RFQ by the low energy beam transport system (LEBT). RFQ has a high current limit. A beam current is often limited by LEBT or an ion source. A possible way to increase the beam current is to combine several beams at the entrance of RFQ. Beams can be generated by a set of ion sources or a multiple-beam ion source. A longitudinal acceptance of RFQ has a large energy spread (up to 30-40%), and can be filled by monochromatic beams with different energies. A total combined beam has a discrete energy spectrum within RFQ energy spread. Beams can be combined using a bending magnet acting as an inverse spectrometer. The injection scheme is studied for the HIMAC-RFQ. Simulation results are presented.

1 INTRODUCTION

RFQ linac has a high current limit. In heavy ion linacs, the beam current is often limited by LEBT or an ion source. A possible way to increase the beam current is to combine several beams at the entrance of RFQ. Beams can be generated by a set of identical ion sources or a multiple-beam ion source.

It is known that RFQ has the longitudinal acceptance with a large energy spread. This fact had been emphasized by I.M. Kapchinskii and V.A. Teplyakov in the paper [1], where features of longitudinal dynamics in RFQ linac were considered for the first time. To avoid bunch pulsations at an injection of a monochromatic beam, they had proposed to enhance an energy spread of the injected beam up to 30-40% using a one-gap microwave klystron-type resonator with wavelength of 10-30 cm. However, in existing RFQ linacs, the monochromatic injected beams are used.

The longitudinal acceptance of RFQ can be filled by monochromatic beams with different energies. A total combined beam has a discrete energy spectrum within RFQ energy spread. Several beams with different energies can be combined using a bending magnet acting as an inverse spectrometer [2,3].

In this paper, this injection scheme is studied for the HIMAC-RFQ [4]. Some simulation results are presented.

2 STUDY FOR HIMAC RFQ

2.1 Beam Currents of HIMAC Injector

In the low energy part of the HIMAC linac, a monochromatic beam extracted from ion source is transported to the entrance of RFQ by the low energy beam transport system (LEBT) using multiplets of electrostatic quadrupoles. The typical output currents of the NIRS-ECR ion source and the NIRS-HEC are 300 μA for C^{4+} and 1.1 mA for Ar^{18+}, respectively [5]. The LEBT intensity limit was estimated [6] to be several hundreds of μA, which agrees with experimental results.

The HIMAC-RFQ is essentially a copy of ‘TALL’-RFQ developed at INS, University of Tokyo [7,8]. Its estimated current limit is about 10 mA. A beam current in HIMAC injector is limited by both LEBT and ion sources.

2.2 Longitudinal Acceptance of HIMAC RFQ

To shorten cavity length compared with the design methods for a high-intensity RFQ [1], the TALL RFQ was designed by using a “rapid bunching process” proposed by S. Yamada [9]. The energy spread of the TALL RFQ is not so high as for a high-intensity RFQ. Experimentally measured values of the transmission [7,8] are 80 %, 70 % and 50 % for the injected beams with energy deviations of 0%, +5%, and -5%, respectively.

We have studied HIMAC-RFQ with the TALL data by using PARMTEQ code [10] for the charge to mass ratio 1/7. Table 1 presents the calculated values of the beam transmission, η_I versus different injection energies, $W_{\rm inj}$ at the zero injected beam current, $I_{\rm inj} = 0$.

Table 1: The transmission, η_I versus the injection energy, $W_{\rm inj}$ for the HIMAC-RFQ.

$W_{\rm inj}$, **keV**	52	54	56	58	60
η_I, **%**	43	77	84	76	42

If an injected beam will consist of five identical beamlets with slightly different energies as listed in Table 1, then, about 64% particles of such beam will be delivered to the RFQ end. In the case of the beam consisted of five beamlets (further called as the “5-beamlet-beam”), the total number of accelerated particles will be increased by the factor 3.8 ($5 \cdot 64\%/84\% = 3.8$) comparing to the conventional case of a single injected beam with nominal energy of 56 keV.

2.3 Phase Spaces at Multiple-Beam Injection

The conventional and “5-beamlet-beam” schemes of the beam injection have been compared by simulations with PARMTEQ code. Figure 1 shows the phase spaces occupied by these beams at injection. Number of the simulation particles is 360 and $1800 (= 5 \times 360)$, respectively. The projections of phase spaces on the transverse planes are the same. Only longitudinal phase spaces are different.

Figure 2 shows the phase spaces occupied by both considered beams at the end of RFQ. The injection beam current of the single beam, $I_{\text{inj}}^{(1)}$ is equal to 1 mA. The total injected beam current of the "5-beamlet-beam", $I_{\text{inj}}^{(5)}$ is equal to 5 mA. The phase space in the case of multiple beam is slightly increased without essential degradations.

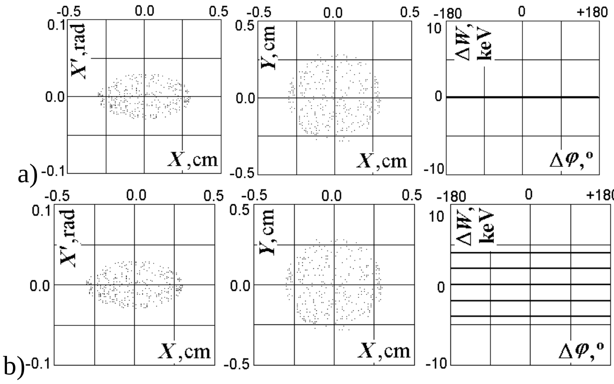

Figure 1: The phase spaces of the injected beam: a) the single beam; b) the "5-beamlet-beam".

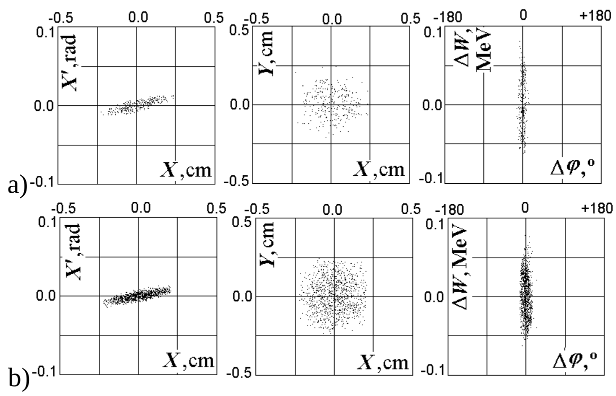

Figure 2: The phase spaces at the end of RFQ: a) the single beam; b) the "5-beamlet-beam".

2.4 Beam Transmission at Different Currents

Let's define the beam current transmissions for the single beam, $\eta_I^{(1)}$ and for the "5-beamlet-beam", $\eta_I^{(5)}$ as:

$$\eta_I^{(1)} = (I_{\text{out}}^{(1)} / I_{\text{inj}}^{(1)}) \cdot 100\% \,, \; \eta_I^{(5)} = (I_{\text{out}}^{(5)} / I_{\text{inj}}^{(5)}) \cdot 100\% \,, \quad (1)$$

where $I_{\text{inj}}^{(1)}$ and $I_{\text{inj}}^{(5)}$ are the injection currents of the single beam and the "5-beamlet-beam", respectively, $I_{\text{out}}^{(1)}$ and $I_{\text{out}}^{(5)}$ are the currents of accelerated beams at the RFQ end. The accelerated beam current of the "*N*-beamlet-beam" can be expressed via the injection current of the single beamlet, $I_{\text{inj}}^{(N)}$ according to the following relation:

$$I_{\text{out}}^{(N)} = \chi^{(N)} \cdot N \cdot I_{\text{inj}}^{(N)} \,, \quad (2)$$

where $\chi^{(N)} \leq 1$ is the coefficient of the beam current losses characterizing quality of the considered injection method.

Figure 3 shows the accelerated beam currents, $I_{\text{out}}^{(1)}$ and $I_{\text{out}}^{(5)}$, transmissions, $\eta_I^{(1)}$ and $\eta_I^{(5)}$, and the percent values of the coefficient, $\chi^{(5)}$ versus the values of the injected beam current of a single beam, $I_{\text{inj}}^{(1)}$, while $I_{\text{inj}}^{(5)} = 5 \cdot I_{\text{inj}}^{(1)}$.

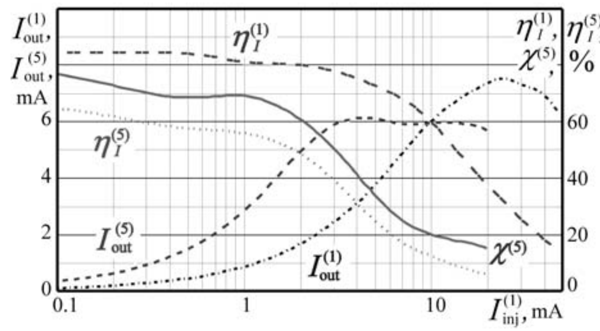

Figure 3: The beam currents, $I_{\text{out}}^{(1)}$ and $I_{\text{out}}^{(5)}$, transmissions, $\eta_I^{(1)}$ and $\eta_I^{(5)}$, and the coefficient, $\chi^{(5)}$ versus the injected beam current, $I_{\text{inj}}^{(1)}$.

The values of the accelerated beam current, $I_{\text{out}}^{(1)}$ are monotonically increased with the growth of the injection current, $I_{\text{inj}}^{(1)}$. The limiting value of beam current is about 6-7 mA. It is reached at the injection current more than 10 mA. The beam transmission for the conventional beam, $\eta_I^{(1)}$ monotonically decreases from its highest value, 84% at the zero value of $I_{\text{inj}}^{(1)}$. The beam transmission of the "5-beamlet-beam", $\eta_I^{(5)}$ is always less than the beam transmission of the single beam $\eta_I^{(1)}$.

The range of the injection beam currents, $I_{\text{inj}}^{(1)} = 0 \div 1\,\text{mA}$ corresponds to the currents achievable by HIMAC LEBT system. In this range, the coefficient $\chi^{(5)}$ is approximately constant $\chi^{(5)} \approx 70\%$, and the beam current is gained by the factor 3.5, i.e. $I_{\text{out}}^{(5)} = 3.5 \cdot I_{\text{inj}}^{(1)}$. Thus, in an exchange of an increasing the injection current by the factor 5 , the accelerated beam current will be increased by the factor 3.5.

3 BEAM COMBINING SYSTEM

The transformations between different projections of the phase-space occupied by the beam have been studied by V.V. Kushin and colleagues in 1970s [2]. These studies were also aimed to the particular tasks of the combining several beams. According to the one of the proposed combining schemes, several beams with different energies can be combined using a 180-degree bending magnet acting as an inverse spectrometer [3].

The beam-line arrangement with a 180-degree bending magnet seems to be inconvenient, because the LEBT becomes to be close to and parallel to the RFQ linac.

Instead of the 180-degree bending magnet, a 90-degree magnet with a circular boundary and uniform magnetic field can be used. This magnet is known as a broad-range magnetic spectrograph [11,12]. Figure 4 shows such magnet with circular pole pieces of radius R_0.

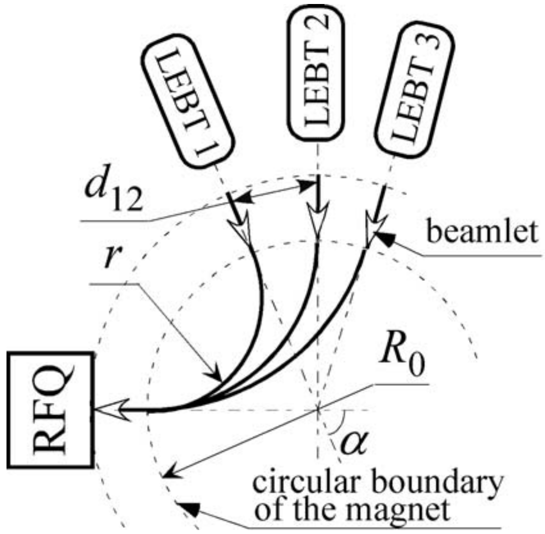

Figure 4: The beam line arrangement with the 90-degree bending magnet.

Let's consider the backward trajectories of ions of different momentum all directed along the same radial line from RFQ toward the center of an idealized magnet. Then for each momentum the backward trajectories exit from the idealized field along a radial line. So, for each momentum, all trajectories enter and exit normal to the field boundary [12]. The deflection of normal trajectory is 90º and its radius is equal to the pole radius, R_0. The angle α is defined by the equation [12]:

$$\cos\alpha = (R_0{}^2 - r^2)/(R_0{}^2 + r^2), \qquad (3)$$

where r is the bending radius for beam with an arbitrarily momentum. The distance between beamlets, d_{12} at a given distance from the magnet center can be calculated via the angle α.

Let's consider an example with a moderate magnetic field of 0.2 T. The magnet radius, R_0 is equal to 0.45 m. The beamlets energies are listed in Table 1. The distance between beamlets, d_{12} is about 0.019 m at the distance from the magnet center of 1.1 m. The length of trajectories is about 1 m and do not exceed the maximum length of the drift space in the HIMAC-LEBT, which is equal to 1.5 m. So, the combining magnet can be considered as an additional drift space for HIMAC-LEBT.

The considered above injection scheme uses a set of several beam lines having own LEBT and ion source. However, there can be a case of this injection scheme when a single ion source can be used. This is the case of the linac with a short-pulse operation. For example, an injector linac for a small synchrotron similar (e.g., "HIMAC S-ring" [13]) should provide the current pulses with duration of 10-30 μs. On the other hand, an ion source usually can provide a stable beam current during times of several hundreds μs.

A long-pulse beam of ion source can be cut to the set of short-pulse beams, which are stored on separated orbits of a supplementary ring (Fig. 5). Thus, this set of the short-pulse beamlets simulates a set of several beam lines considered above (Fig. 4). For the pulse duration of linac beam of $\tau_{\text{linac}} = 10\,\mu\text{s}$, the mean radius of the supplementary ring, R_{ring} is about 2 m.

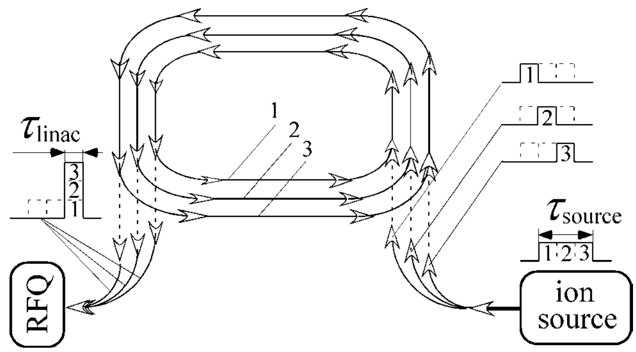

Figure 5: The injection scheme with a supplementary storage ring.

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