RF FOCUSING OF LOW-CHARGE-TO-MASS-RATIO HEAVY-IONS IN A SUPERCONDUCTING LINAC*

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Abstract

A post-accelerator of radioactive ions (RIB linac) must produce high-quality beams over the full mass range, including uranium, with high transmission and efficiency [1]. The initial section of the proposed linac consists of many 4-gap quarter wave cavities operating at –20° with respect to the maximum energy gain and focusing is provided by 15 Tesla superconducting (SC) solenoids following each cavity. A possible alternative focusing method based on the combination of low-field SC solenoids and rf focusing is discussed in this paper.

INTRODUCTION

The initial section of the RIB linac is a low-charge-to-mass-ratio superconducting rf linac (SRF) which will accelerate any ion with q/A≥1/66 to ~1 MeV/u or higher. The low-energy RIB linac will be based on 4-gap quarter wave SC cavities, which can provide typically 1 MV of accelerating potential per cavity in the velocity range 0.011c<v<0.06 c. The initial section of the linac consists of four groups of those cavities designed for different geometrical beta.

The input beam is formed by upstream RFQs operating at room temperature. The initial normalized transverse emittance is ε_T=0.1 π·mm·mrad and the longitudinal emittance is ε_L=0.3 π·keV/u·nsec.

For ions with charge-to-mass ratio *Z/A*=1/66 a proper focusing can be reached with the help of strong SC solenoid lenses with magnetic fields up to 15 T. These state-of-the-art solenoids are expensive. A possible lower cost alternative focusing method based on a combination of low-field SC solenoids (up to 9 Tesla) and rf focusing is discussed in this paper.

SOLENOID FOCUSING IN SC LINAC

In the initial section of the RIB linac the focusing is provided by SC solenoids following each SC cavity forming a focusing period with length *L*. Prior to 3D ion dynamics simulations, it is useful to analyze the ion motion in a linear approximation on the basis of transfer matrices. The reference particle velocity β can be represented as a sum of a smooth motion term β_c and a fast oscillation term of period *L*. The fast oscillation term can be neglected if the particle velocity β is close to β_G in each group of identical cavities. In this case the transfer matrix calculations can be used for analysis of the beam dynamics in a periodical accelerating structure.

For an ion moving inside a cavity the phase, $\tau = \omega t$, can be replaced by $\pi z/D_i + \varphi_c$, where ω is the rf frequency, φ_c is the phase of the rf field when the reference particle (centre of the bunch) arrives at the beginning of the cavity, and $D_i = \beta_G \lambda/2$. The dimensionless time-of-flight of the reference particle is $\tau_c = 2\pi \int dz/\lambda\beta_c$. The normalized energy of the reference particle on the axis of the accelerator can be determined from the following expression:

$$d\gamma_c/dz = eZE(z)\cos(\tau_c + \varphi)/Amc^2 , \quad (1)$$

where *E*(*z*) is the spatial part of the on-axis accelerating electrical field. The phase of an arbitrary particle relative to the reference-particle phase, φ_c, is $\zeta = \tau - \tau_c$. The normalized energy deviation with respect to the reference particle is $\Delta\gamma = \gamma_c - \gamma$.

The energy and phase deviations at the entrance and exit of one structure period are coupled through the matrix M_z: $\begin{pmatrix}\zeta \\ \Delta\gamma\end{pmatrix}_{out} = M_z \begin{pmatrix}\zeta \\ \Delta\gamma\end{pmatrix}_{in}$. A similar matrix M_r applies to the transverse phase space:

$$\begin{pmatrix} r \\ dr/dz \end{pmatrix}_{out} = M_r \begin{pmatrix} r \\ dr/dz \end{pmatrix}_{in} . \quad (2)$$

For longitudinal motion, the transfer matrix is:

$$M_z = \begin{pmatrix} C_z - 4\alpha \frac{L_1}{L} S_z \sin\varphi_c & (L_1 C_z + L_{res} S_z)/L_v \\ \overline{U} S_z \sin\varphi_c & C_z \end{pmatrix}, \quad (3)$$

where $\overline{U} = eZU/Amc^2$ is a dimensionless amplitude of accelerating potential per cavity, $\alpha = L\overline{U}/4L_v$, $L_v = \lambda\beta^3\gamma^3/2\pi$, $L = L_{res} + 2L_d + L_{sol}$ is a period length, L_{sol} is the length of a solenoid, $L_1 = L - L_{res}$ is the distance between two cavities, and L_d is the distance between the cavity and the solenoid. The coefficients C_z and S_z depend on the advanced phase of the longitudinal oscillation per one cavity, χ_z, and are equal

$$C_z = \cos\chi_z , \; S_z = \sin\chi_z/\chi_z , \; \chi_z = \sqrt{-4\alpha L_{res}\sin\varphi/L} \quad (4)$$

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The transfer matrix for the transverse motion is described by the multiplication of two matrices and can be written as:

$$M_r = M_{sol} M_{res} \tag{5}$$

$$M_{sol} = \begin{pmatrix} C_\theta - \theta^2 \dfrac{L_d}{L_{sol}} S_\theta & L_{sol} S_\theta + L_d C_\theta \\ -\dfrac{\theta^2}{L_{sol}} S_\theta & C_\theta \end{pmatrix} \tag{5a}$$

$$M_{res} = \begin{pmatrix} C_r - 2\alpha \dfrac{L_d}{L} S_r \sin\varphi & L_d C_r + L_{res} S_r \\ -2\dfrac{\alpha}{L} S_r \sin\varphi & C_r \end{pmatrix}. \tag{5b}$$

The first matrix, M_{sol}, is obtained by multiplying the matrices of the focusing solenoid and drift space. The second matrix, M_{res}, is obtained by multiplying the matrices of the defocusing resonator and drift space. The solenoid matrix is defined by the coefficients:

$$C_\theta = \cos\theta \ , \ S_\theta = \sin\theta/\theta \ , \tag{6}$$

where $\theta = eZBL_{sol}/2Amc\beta\gamma$, and B is the solenoid magnetic field. The focal length of the solenoid is $F = L_{sol}/\theta^2 S_\theta$. The coefficients $C_r = \cos\chi_r$ and $S_r = \sin\chi_r/\chi_r$ in the cavity matrix depend on the parameter $\chi_r = \sqrt{2\alpha L_{res}\sin\varphi/L}$. The defocusing force in the accelerating cavity is determined by the value of $\alpha \cdot \sin\varphi$, and quickly drops as $1/\beta_c^3$ (see Fig. 1). The focal length of the solenoid increases with velocity as β_c^2. The matrices (3) and (5) allow us to compute the phase advances per period as a function of $\alpha \cdot \sin\varphi$ and *L/F*:

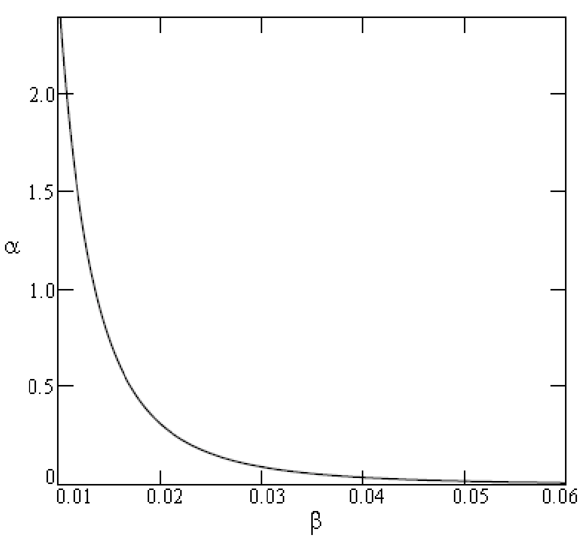

Figure 1: The parameter α as a function of the particle velocity.

$$\cos\mu_z = C_z + 2\alpha(L - L_{res}) S_z \sin\varphi/L \tag{7}$$

$$\cos\mu_r = C_\theta C_r + \alpha S_r \left(L_d^2/2F - L_{sol} S_\theta - 2L_d C_\theta\right) \sin\varphi/L - -\left(L_{res} S_r + 2L_d C_r\right)/2F \tag{8}$$

The choice of μ_z and μ_r is limited by the bunch size. In the case considered, the solenoid magnetic field *B* determines μ_r, the beta function and the extreme values of the beam envelope. The value of *B* as function of β_c for $\mu_z=20^0$, $\varphi_c=-20^0$ and different μ_r is shown in Fig. 2. For a charge-to-mass ratio *Z/A*=1/66 and beam velocity range $0.01<\beta_c<0.02$ a proper focusing can be reached with magnetic fields up to 15 T, if $\mu_r<25^0$. For beam velocities between 0.05-0.06c, the solenoid magnetic field *B* must be increased to obtain $\mu_r \approx 25^0$.

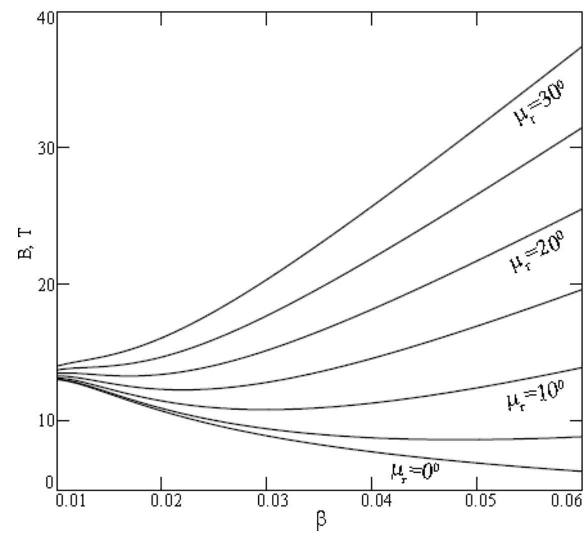

Figure 2: The magnetic field of SC solenoid as the function of the beam velocity.

SOLENOID AND APF FOCUSING

The alternating phase focusing (APF) [3-6] can be effectively applied for focusing of low velocity ions. Below we present our studies of the APF application in the RIB linac based on transfer matrix formalism.

Let's consider a simple case of the focusing period containing two SC cavities. By adjusting the phases φ_1 and φ_2 of each cavity individually, we can provide both acceleration and focusing. The phase advances per period, μ_z and μ_r, can be found from two transfer matrices M_z and M_r. The stability diagrams on φ_1, φ_2-plane for α=0.25, α=0.75 and the different μ_z and μ_r are shown in Fig. 3. For the charge-to-mass ratio *Z/A*=1/66 the parameter $\alpha \approx 1$, when the beam velocity $0.01< \beta_c<0.02$. In this case a large area of the stability on a plane (φ_1,φ_2) is available when $\mu_r > 20^0$. If the velocity $\beta_c >0.03$, the parameter α becomes less than 0.1 (see Fig.1). For small α, the area of stability tapers abruptly and the phase advances per period, μ_z and μ_r, quickly decrease, implying that the matched beam size becomes larger. The area of stability can be extended by adding a solenoid focusing which will also provide a separate control of transverse and longitudinal beam dynamics. For a beam velocity range of $0.03<\beta_c<0.04$ it is sufficient to add one superconducting solenoid per accelerating period. The stability diagram for different values of *B* is shown in Fig. 4a. If one solenoid with magnetic field 9 Tesla is added, there is a large area of stability and a wide range of cavity phases φ_1 and φ_2 are possible. For the beam velocity range 0.05-0.06 the accelerating period must consist of two superconducting solenoids and two superconducting rf cavities. The stability diagram is shown in Fig. 4b for this case. A value of the magnetic field, 9 Tesla, is sufficient to ensure beam focusing in the accelerator.

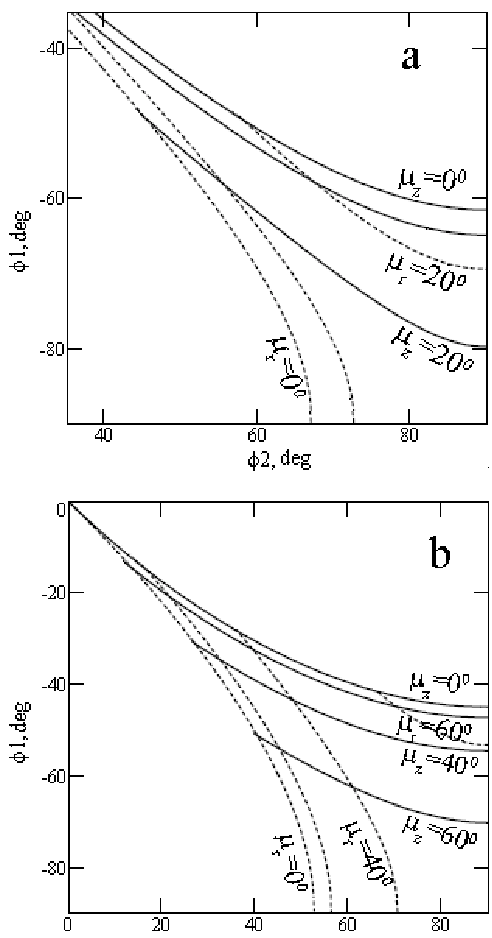

Figure 3: Stability diagram for APF focusing:
a) $\alpha=0.25$; b) $\alpha=0.75$.

CONCLUSION

A possible alternative focusing method based on the combination of low-field SC solenoids and rf focusing is proposed and discussed. For ions with charge-to-mass ratio *Z/A*=1/66, proper focusing can be reached with the help of APF if the beam velocity β_c is lower than 0.02. For higher beam velocities a focusing 9-Tesla SC solenoid must be added to provide focusing for beam velocities $\beta_c \geq 0.02$. Practical application of APF in the RIB linac requires more detailed beam dynamics studies in order to verify the linear transformations of the emittance in both transverse and longitudinal phase space.

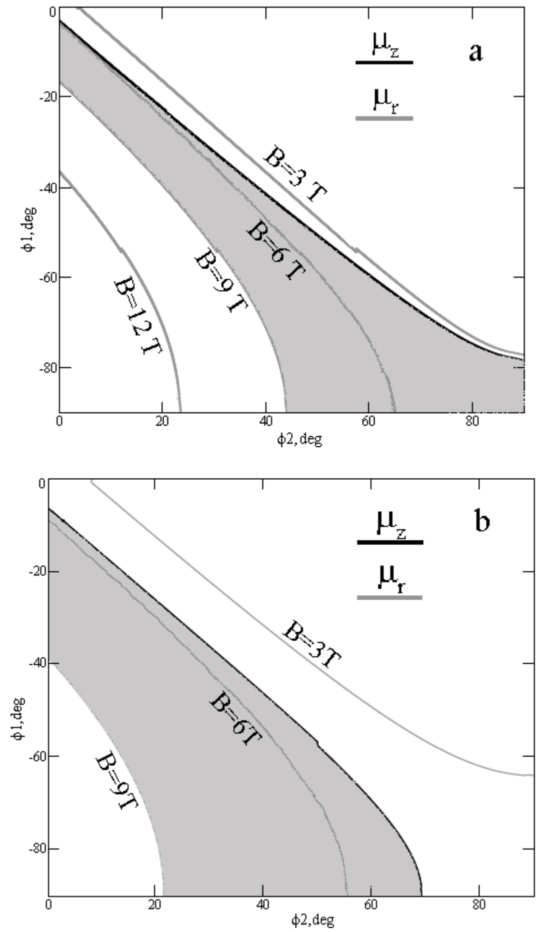

Figure 4: Stability diagram for a solenoid and APF focusing: a) one solenoid per accelerating period, $\beta_c=0.03$; b) two solenoids per accelerating period, $\beta_c=0.05$.

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