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A computer code for beam dynamics simulations in SFRFQ structure☆

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Abstract

A computer code (SFRFQCODEv1.0) is developed to analyze the beam dynamics of Separated Function Radio Frequency Quadruples (SFRFQ) structure. Calculations show that the transverse and longitudinal stability can be ensured by selecting proper dynamic and structure parameters. This paper describes the beam dynamical mechanism of SFRFQ, and presents a design example of SFRFQ cavity, which will be used as a post accelerator of a 26 MHz 1 MeV O^+ Integrated Split Ring (ISR) RFQ and accelerate O^+ from 1 to 1.5 MeV. Three electrostatic quadruples are adopted to realize the transverse beam matching from ISR RFQ to SFRFQ cavity. This setting is also useful for the beam size adjustment and its applications.

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Keywords: SFRFQ; ISR; Dynamic stability; Transmission

1. Introduction

The accelerating efficiency of RFQ will fall off when the beam energy exceeds several MeV. Many kinds of post-accelerating structures after RFQ have been developed in laboratories of USA, Russia and Germany, such as RFD [1], SPRFQ [2], finger-like structures and so on. These structures combine the radial focus and longitudinal accelerating together, and reduce the cost of focusing system. The SFRFQ is one of the new post -accelerating structures, it was proposed by the RFQ group of Institute of Heavy Ion Physics (IHIP) at Peking University [3], characterized by its higher accelerating and transmission efficiency. Fig. 1 is the cross-section of the structure; there are four diaphragms with two accelerating gaps in one cell, and also the ions will be focused outside the gaps. The code SFRFQCODEv1.0 has been developing for the beam dynamics simulation. As an example, a cavity with inter-electrode voltage 70 kV is designed to accelerate O^+ from 1 MeV up to about 1.5 MeV and scheduled to be manufactured at the end of the next year. The main results are presented in the subsequent sections.

2. Dynamics study of SFRFQ

The ions are accelerated and focused in the periodic accelerating structure at the same time. It includes two similar processes: on the one hand, the ions are focused by the traditional transverse RF quadruple field when they pass through the accelerating gaps; on the other hand they will be decelerated by a quite lower field when they pass through the region between two diaphragms that have the same potential polarity, this region is the main focusing area because the quadruples occupy about the 1/3 of a cell length. The bunched beam is assumed to be a uniformly charged ellipsoid, only one traveling wave harmonic and the space charge effect are taken into account, the equation of transverse motion can be written as following:

$$\frac{1}{\beta\gamma}\frac{d}{dz}\left(\beta\gamma\frac{dr}{dz}\right)+\left[\frac{B\sin(kz)}{\beta^2\lambda^2}+\frac{Ze\pi E_0T\sin\varphi}{m_0c^2\beta^3\gamma^3\lambda}-\frac{3I\lambda K[1-f(p)]}{a_t^2a_u\beta^2}\right]r=0. \quad (1)$$

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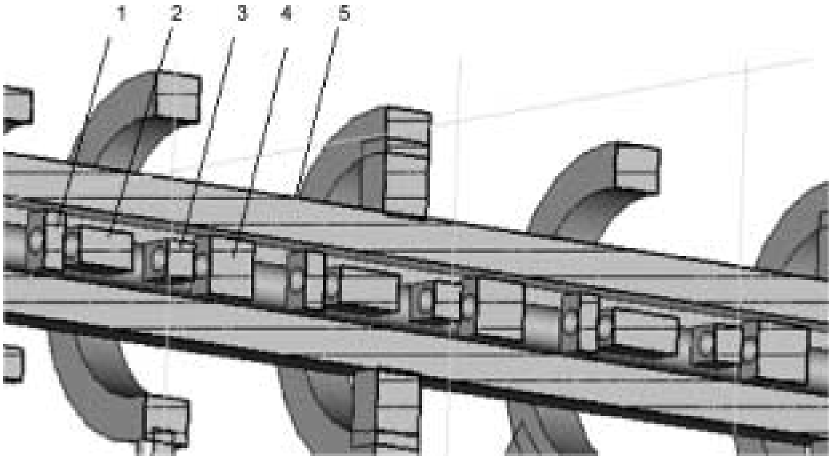

Fig. 1. Cross-section of the SFRFQ (1–4: diaphragms; 5: RFQ electrode).

If the velocity change is not so fast, we assume $\eta = z/\beta\lambda$ then Eq. (1) becomes

$$\frac{d^2r}{d\eta^2} + (\Delta + B\sin(2\pi\eta) - h)r = 0, \tag{2}$$

where

$$B = \frac{Ze\lambda^2V}{m_0c^2\gamma a^2}, \quad \varDelta = \frac{Ze\pi E_0T\lambda\sin\varphi}{m_0c^2\beta\gamma^3}, \quad h = \frac{3I\lambda^3K[1 - f(p)]}{a_t^2a_u},$$

r represents x or y coordinates, a is the radius of quadruples, Ze is the charge, λ is the RF wavelength, β is the normalized velocity, γ is the relativistic factor, φ is the current phase of ions, transit-time factor T is given by

$$T = \left[\int_{-L/2}^{L/2} E_z(0,z)\cos(kz)\,dz\right] \Bigg/ \left[[\int_{-L/2}^{L/2} E_z(0,z)\,dz\right].$$

a_t and a_u are the semi-axes of the ellipsoid, I is the average current over an RF period, $K = 3Ze/8\pi\varepsilon_0m_0c^3$, ε_0 and f(p) are the permittivity of the vacuum and the form factor of the bunch.

Eq. (2) is a Mathieu equation, so the transverse phase advance per period can be approximated as

$$\mu_r \approx \sqrt{\Delta - h + \frac{B^2}{8\pi^2}} = \sqrt{\frac{Ze\pi E_0T\lambda\sin\varphi}{m_0c^2\beta\gamma^3} - \frac{3I\lambda^3K[1 - f(p)]}{a_t^2a_u} + \frac{1}{8\pi^2}\left(\frac{Ze\lambda^2V}{m_0c^2\gamma a^2}\right)^2}. \tag{3}$$

Selecting proper structure parameters to let the solution of Eq. (2) within the stability region of Mathieu equation, the transverse stability is ensured.

The average field along the axes is regarded as the sum of the common field within accelerating gap and the decelerating field in the neighboring two diaphragms that were normally shielded in the traditional Wideroe or Alvarez drift tubes. If the decelerating field is approximately written as the form:

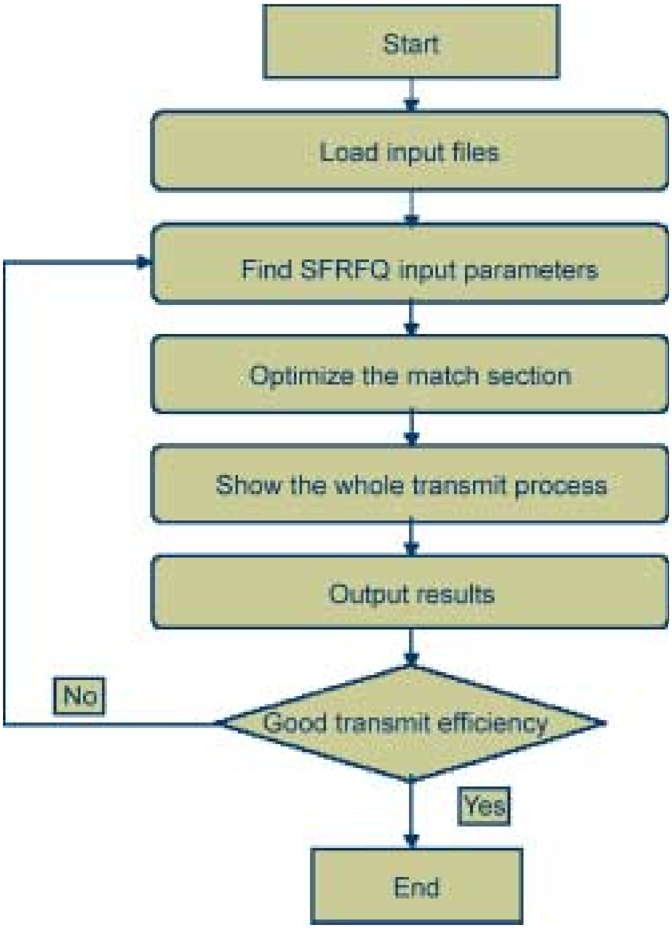

Fig. 2. Flow chart of SFRFQCODEV1.0.

$$E_{fs} = f(z)\cos(kz + \varphi_s), \quad E_f = f(z)\cos(kz + \varphi).$$

According to the same steps as the ordinary linac [4], the subscript s represents the synchronous particle, taking into