Study of separated function radio frequency quadrupoles accelerator *

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Abstract SFRFQ (Separated Function Radio Frequency Quadrupoles) accelerator is a new post accelerator of RFQ (Radio Frequency Quadrupoles) type, which has been developed since the beginning of the 1990s at Peking University. In order to demonstrate the possibility of the SFRFQ, a prototype cavity has been designed. A special dynamics design method has been proposed to avoid the sparking problem and decrease the energy spread at the exit of SFRFQ. It consists of two aspects: the asymmetry structure design for transverse focusing and the inner buncher design for longitudinal bunching. This allows the improvement of the beam properties without increasing the cavity length. The simulation results show that the energy spread can be substantially reduced by using the inner buncher in the SFRFQ structure.

Key words SFRFQ, beam dynamics, energy spread

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1 Introduction

An RFQ (Radio Frequency Quadrupoles) is considered to be the most suitable linear accelerator for the acceleration of low energy beams due to the merits of simultaneous transverse focusing and longitudinal bunching in a cavity [1, 2]. The RFQ accelerator can accept continuous beam from an ion source then accelerate the ions to the next accelerator, such as Alvarez-DTL, H-type structure [3, 4]. However, the DTL cavity often requires a rather higher input beam energy because the focusing elements must be installed inside the drift tubes, so people have to improve the output energy of the RFQ accelerator. It generally needs a long RFQ cavity which will make the efficiency of RF power decrease rapidly [5]. The SFRFQ structure combines the characters of conventional RFQ and DTL, it is composed of a series of accelerating gaps and standard quadrupoles, and so the accelerating and focusing are separated in a cavity. The feasibility of SFRFQ being using as a post accelerator of RFQ has been discussed in Ref. [6]. A completed SFRFQ system contains four sections: an injector ECR ion source, an ISR-RFQ 1000 (Integral Split Ring RFQ) accelerator, a magnetic quadrupole triplet which is installed as the transverse matching section and an SFRFQ cavity.

With the support of the National Natural Science Foundation project "Study of Separated Function RFQ", a prototype cavity has been built. An improved asymmetry structure is proposed in this paper in order to improve the focusing strength and to reduce the peak surface field. The longitudinal beam properties deteriorate as it passes through a 1-meter-long transverse matching section after RFQ, an inner bunching section at the entrance of the SFRFQ accelerator is needed to reduce the energy spread. A SFRFQ cavity with the synchronous phase near −90 degree is chosen to bunch the beam at the first three cells, and then the beam is accelerated to the designed energy with synchronous phase at about −30 degrees. The simulations with the special code SFRFQCODEV1.0 [7] indicate that this method can realize the needed output energy gain and the energy spread (FWHM) being less than 3%.

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2 Beam dynamics study of SFRFQ

In the RFQ accelerator, the quadrupole focusing field is spatially continuous along the z-axis, in every period the quadrupole radius varies from a to ma (a is the radius, $m>1$ is the radius modulation parameter) in both the x-z plane and y-z plane [8]. The structure of SFRFQ is somehow different from that of RFQ by a series of diaphragms loaded inside the quadrupole electrodes, so the radius of SFRFQ must be large enough to contain diaphragms [9]. For example, the maximal electric field is about 7.2 MV/m when the frequency is 26 MHz according to the empirical formula in Ref. [10], considering the inter-vane voltage is 70 kV, the minimal distance in the structure shouldn't be less than 7 mm. It is hard to machine and install the diaphragms in the quadrupoles, if we keep enough focusing strength. It means the average radius must be reduced. This may lead to the increase of surface electric field. The simulation indicates that the maximal electric field may exceed 18.8 MV/m, so it is hard to load the designed inter-voltage in the electrode. To avoid the sparking problems, the "asymmetry" structure has been proposed. The quadrupole radius in the x-plane and y-plane is respectively a and ma ($m>1$), but not as in the RFQ accelerator, where a and m are kept constant along z-axis, so it is also a kind of spatially periodic structure.

The focusing strength mainly includes two terms in the transverse plane, one is the quadrupole focusing and the other is the RF defocusing. The quadrupole terms have a dominative effect in the transverse focusing (assuming low or zero current, the space charge effects can be neglected). The axial field distribution of asymmetry structure also satisfies the LAPALCE equation. Suppose that the maximal and minimal radius are respectively ma and a, we can write the equation in cylindrical coordinate system as follows:

$$\frac{\partial^2 V}{\partial r^2}+\frac{1}{r}\frac{\partial V}{\partial r}+\frac{1}{r^2}\frac{\partial^2 V}{\partial \theta^2}+\frac{\partial^2 V}{\partial z^2}=0 , \quad (1)$$

where V is the function of r, θ, z,

$$V(r,\theta,z) = \sum_{p=0}^{\infty}A_{02p+1}r^{2(2p+1)}\cos 2(2p+1)\theta+\sum_{m=1}^{\infty}\left[\sum_{n=0}^{\infty}A_{mn}I_{2n}(mkr)\cos(2n\theta)\right]\times\cos(mkz) , \quad (2)$$

where I_{2n} is the Bessel function, $m=2q+1$ ($q=0,1,2,\cdots$); $k=2\pi/\beta_s\lambda$ is the wave number, β_s is the relative velocity of synchronous particle, and λ is the wave length. The first-order approximation of V is:

$$V(r,\theta,z)=A_{01}r^2\cos 2\theta+A_{10}I_0(kr)\cos kz . \quad (3)$$

Taking into account that $V(a,0,0)=-V(ma,\pi/2,0)$, we can get:

$$A_{01}=\frac{V_0}{2a^2}F , \quad (4)$$

$$A_{10}=\frac{V_0}{2}A , \quad (5)$$

where parameters A and F are given by the following expressions:

$$A=(m^2-1)/[m^2I_0(ka)+I_0(mka)], \quad (6)$$

$$F=(I_0(ka)+I_0(mka))/[m^2I_0(ka)+I_0(mka)]. \quad (7)$$

Formula (6) and (7) are usually used in RFQ accelerator, m is a modulation factor, and it means m is a variable along z-coordinate, but m is a constant in the whole cavity of SFRFQ structure. Assuming the

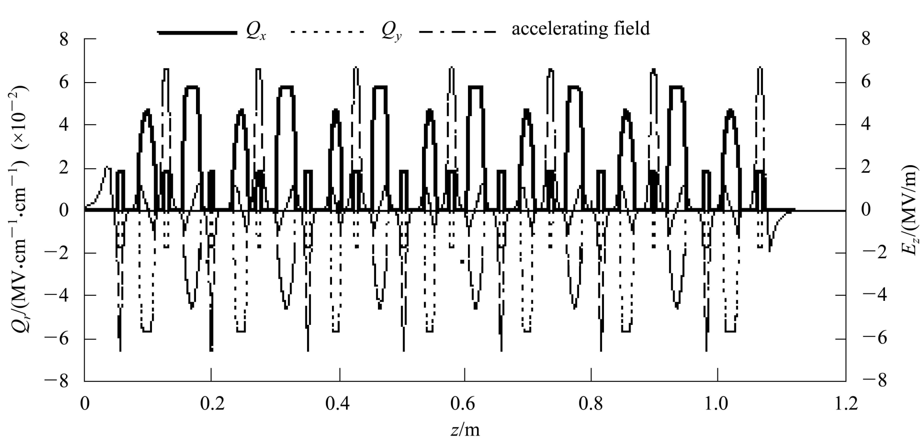

Fig. 1. The transverse focusing and accelerating field distribution.

electrode radius is r, we can get the average radius:

$$R=\sqrt{\frac{ra}{F}}\ . \tag{8}$$

R is an important parameter in the dynamics design. We can evaluate the approximate transverse focusing strength, supposing $m=2$, $a=14$ mm, $V_0=70$ kV.

The field distribution which is shown in Fig. 1 calculated by SFRFQCODEV1.0, where Q_x and Q_y mean the transverse focusing parameters respectively in x-plane and y-plane.

3 Matching design method of SFRFQ

The matching between RFQ and SFRFQ is an important problem. It includes two aspects: in the transverse plane, the beam size that comes from RFQ may exceed the radius of SFRFQ after a drift space and lead to the decrease of capture efficiency; in the longitudinal plane, the phase expansion may lead to large output energy spread. To realize the beam matching from ISR RFQ-1000 [11] to SFRFQ cavity, a matching section with a magnetic quadrupole triplet has been designed. The total length of the triplet is about 1 meter long. When the beam reaches at the entrance of SFRFQ, the longitudinal phase width exceeds 125 degree (Fig. 2). The simulation show that the output energy spread is very large (Fig. 3) if we adopt the same synchronous phase along z-direction (no inner buncher design), where W_{i} is the start energy of counts and W_{p} is the energy which contains the most particles.

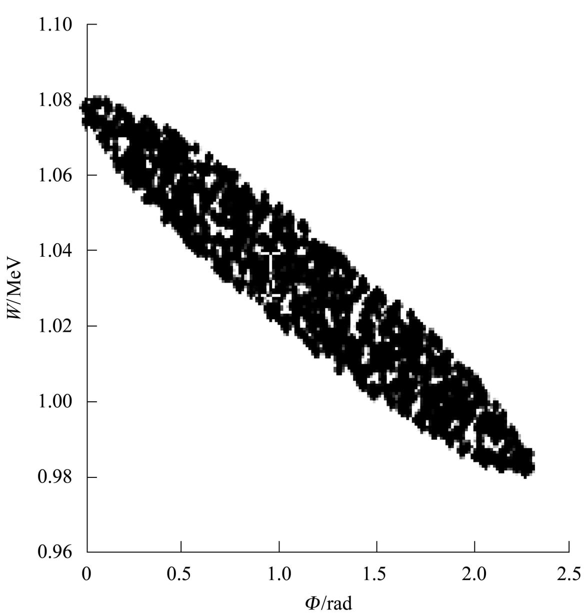

Fig. 2. Input phase-energy distribution.

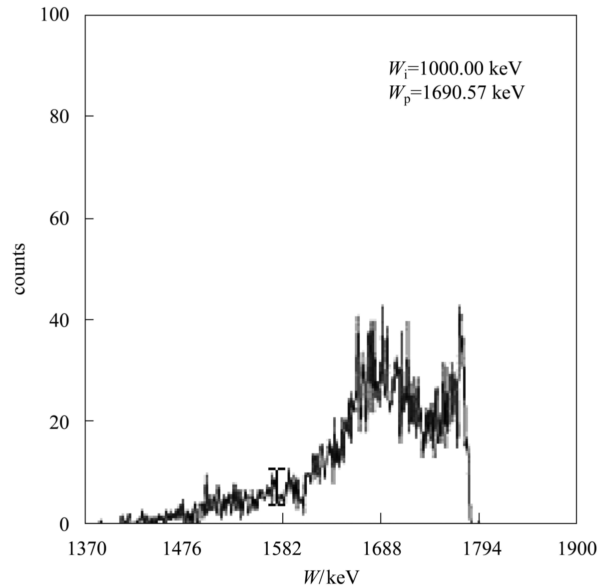

Fig. 3. Energy spread (no inner buncher).

In most cases longitudinal pre-bunching is accomplished by an external buncher [12, 13], but it will make the transport line become much complicated and the cost increases accordingly. So it is better to use the first two or three accelerating gaps to act as the buncher by adjusting the synchronous phase just as in RFQ accelerator, for example, the synchronous phase may change from −90 degrees to −30 degrees along the longitudinal direction (Fig. 4). The problem is how to achieve the balance between acceleration and bunching. A major effort was devoted to optimizing the synchronous phase array. The simulation results show that 3 gaps can achieve the required energy spread (Fig. 5) and the energy gain can be ensured as well.

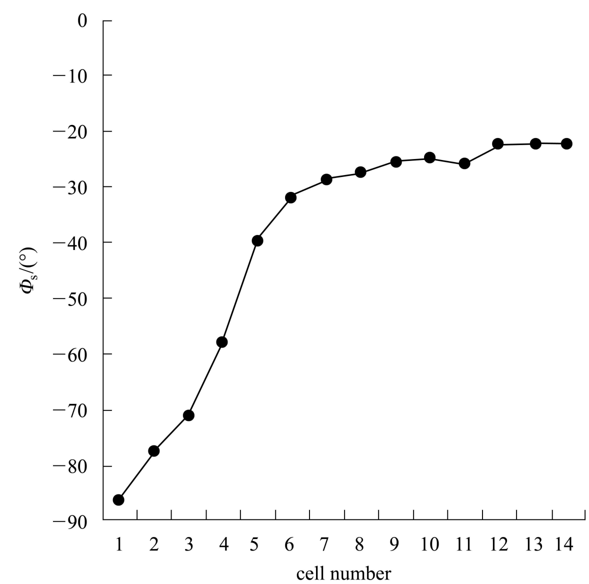

Fig. 4. Synchronous phase curve.

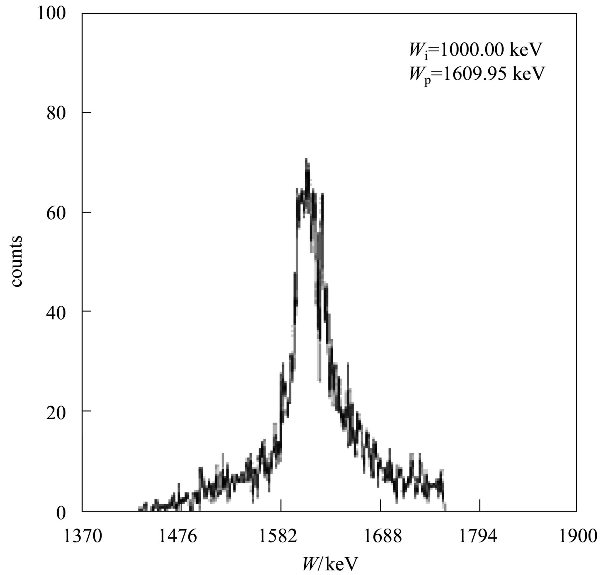

Fig. 5. Energy spread (inner buncher).

Although this would result in the decrease of the energy gain, the total efficiency is still much higher than the RFQ accelerator. The corresponding parameters are listed in Table 1.

4 Conclusions

We have developed a simulation code SFRFQ-CODEV1.0 especially for the design of SFRFQ accelerator based on the beam dynamics study. Unlike the conventional RFQ, on the one hand, SFRFQ introduces the gap accelerating to the quadrupoles; on the other hand, an asymmetry structure is proposed to avoid the sparking problem. In order to reduce the energy spread at the exit of SFRFQ, the author proposed the inner buncher method. The simulation results show that the output energy spread can be decreased substantially without increasing the cavity length. SFRFQ is a new structure which combines the characters of conventional RFQ and DTL, it can be utilized as a connecting section between the low velocity structures and the medium velocity structures due to its higher accelerating efficiency than a conventional RFQ accelerator.

Table 1. The comparison of simulated parameters for O^+.

	RFQ	SFRFQ (inter buncher)	SFRFQ
input energy/MeV	1.00	1.00	1.00
output energy/MeV	1.60	1.62	1.71
input ε_z/deg·keV	1.46	1.46	1.46
output ε_z/deg·keV	5.49	5.10	6.31
maximal synchronous phase/deg	−22.4	−25.6	−30.0
inter-vane voltage/kV	70	70	70
length/m	1.513	1.024	1.124
transmission(%)	97.2	94.9	95.6

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