LOW ENERGY SPREAD BEAM DYNAMICS AND RF DESIGN OF A TRAPEZOIDAL IH-RFQ *

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Abstract

The methodology for a low energy spread RFQ beam dynamics design has been studied for C^{14+} AMS application This paper will present a low energy spread beam dynamics and RF design for a trapezoidal IH-RFQ (abbreviated T-IH-RFQ) operating at 104MHz at Peking University. $^{14}C^{+}$ will be accelerated from 40keV to 500keV with the length of about 1.1m. The designed transmission efficiency is better than 95% and the energy spread is as low as 0.6%. Combining the beam dynamics design, a T-IH-RFQ structure was proposed, which can be cooled more easily and has better mechanical performance than traditional RFQ. The electromagnetic field distribution was simulated by CST Microwave Studio (MWS). The simulation results show such T-IH-RFQ has higher operating frequency than normal four rods RFQ and/or IH-RFQs. The specific shunt impedance and the quality factor were also compared to these RFQ structures.

INTRODUCTION

RFQ, proposed by I.M.Kapchinsky and V.A.Teplyakov in 1970[1], has been used widely for many applications. It can focus, bunch and accelerate low energy beam, extracted from ion sources directly, over a mass range from proton to heavy ions such as uranium based on the RF electrical field of a modulated quadruple transport channel [2]. RFQ was used to ^{3}H Accelerator Mass Spectroscopy (AMS) firstly by LLNL in USA because of its inherent compact size [3]. RFQ based ^{14}C AMS application has been studying in recent years at the Institute of Heavy Ion Physics (IHIP), Peking University [4, 5]. The most critical problem is that the energy spread of full width at half magnitude (FWHM) for traditional RFQ is usually larger than 2% because of the process of adiabatic bunching and phase oscillation, which is too high for the particle identification in an AMS detector. So, ways must be found to reduce the energy spread of the output ^{14}C beam. The highest beam current of RFQ used for AMS ^{14}C facility is lower than 200μA, which is such low that the space charge effects can be ignored. Non-adiabatic bunching method should be used to make output beam energy spread low. A physical design of RFQ with 0.6% energy spread has been obtained through external bunching method by previous work at IHIP. A pre-buncher will be necessary in the injection system before RFQ to bunch beam length in the range of [-20°, 20°]. However, the bunching efficiency of a pre-buncher can only be 70~80%. As a result, the total transmission will be lower than most tandems based AMS facility even though no particle is lost in RFQ. An internal discrete bunching proposed by J.W.Staples at LBNL [6] is used to save additional RF power supply and buncher cavity. The low energy spread beam dynamics design for $^{14}C^{+}$ RFQ will be presented in this paper.

On the other hand, an IH-RFQ acceleration structure was proposed and studied. The four electrodes are supported by erect boards connected to the external cavity up and down. This new structure was named trapezoidal IH-RFQ according to its appearance. The trapezoidal IH-RFQ is easily cooled and will have good mechanical performance. Moreover, it will have higher resonant frequency than traditional IH-RFQ [7]. Simulations of the electromagnetic fields have been completed by CST Microwave Studio (MWS). RF characteristics is investigated, and geometrical parameters are optimised initially to make the shunt impedance and the quality factor as large as possible.

BEAM DYNAMICS DESIGN

According to Staples' method, the whole RFQ beam dynamics design is divided into five sections, radial matcher, buncher section, drift section, transition section and accelerator section. The radial matcher is similar to that of four-step method developed at LANL [8], which matches DC input beam to the time-varying transverse envelope at the entrance of RFQ. The buncher section is distributed over several cells while the modulation parameter m ramps from zero to a maximum and then back down to zero, which performs the function of bunching as a non-adiabatic buncher. The following several unmodulated cells make up of the drift section which allows the ideal beam bunch to form. In the transition section, the beam is accelerated slowly as the synchronous phase varies from -90º to its final value -30º. Finally, the designed energy is reached in the acceleration section. Significantly lowered longitudinal output emittance and slightly lowered transverse emittance can be obtained by this new design technique compared to previous methods, which has been proved by PARMTEQM.

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There is another approach to reduce the RFQ energy spread further more, which can be shown by

$$\Delta w_{\max} = \left[2A\xi V_0 e w_s \left(\varphi_s \cos\varphi_s - \sin\varphi_s\right)\right]^{1/2} \quad (1)$$

Where $\Delta w_{\max}$ is the separatrix height that indicates the maximum beam energy spread, ξ is the charge-to-mass ratio of the ion, e is the charge of an electron, and w_s the energy per nucleon of the synchronous particle. The formula shows that energy spread can be decreased by reducing acceleration coefficient A, inter-vane voltage V_0 and synchronous φ_s, where lower A means lower m.

From above we can see apparently that φ_s should be as large as possible in order to obtain low energy spread, but not be kept at -30º. On the other hand, the focus parameter B should increase during the first stage of the transition section and then keep constant, whereas at the acceleration section it should decrease slowly in order to receive the constant transverse phase advance to keep the beam matched, minimize the emittance growth and related beam loss [9]. The above two aspects can be realized by MATCHDESIGN [10], a code developed at IHIP taking matching equations, equipartition condition and constant transverse beam size into account to avoid emittance growth and beam loss.

Integrating all the above points, we are capable of performing beam dynamics design in pursuit of low energy spread. The design parameters were given by MATCHDESIGN, and then the internal non-adiabatic buncher was designed by the code of J.W.Staples. On one hand V_0 should be as low as possible to reduce power consumption; on the other hand V_0 should be large enough to achieve sufficient focusing. Finally V_0 was chosen to be 60kV, meanwhile m should be increased very slowly, otherwise particles will not be focused effectively and some of them will then be lost. The main dynamics parameters of the RFQ are plotted in figure 1 and listed in Table 1. Energy spectrum of ion beam output from this RFQ is shown as figure 2.

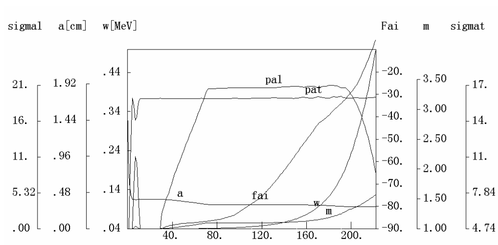

Figure 1: The main dynamics parameters (sigmal is longitudinal phase advance, sigmat is transverse phase advance, Fai is synchronous phase, a is aperture radius, w is ion kinetic energy and m is modulation respectively).

Table 1: The Main Dynamics Parameters

Ion	^{14}C
Charge number q	1
Operating frequency f (MHz)	104
Electrode voltage V_0 (kV)	60
Input energy W_i (keV)	40
Output energy W_o (keV)	500
Modulation m	1.0–1.57
Minimum aperture radius a (mm)	2.93
Maximum focusing factor B	3.44
Synchronous phase φ_s (degree)	-90 to -6
Electrode length L (mm)	1091.3
Transmission T (%)	97.6
Energy spread (%)	0.6

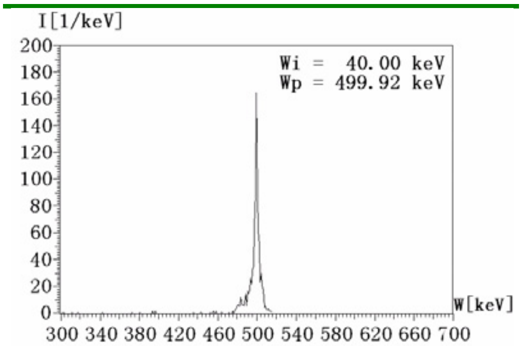

Figure 2: Output beam energy spectum.

The total length of the RFQ is about 1.1m, and further more m is small to make particles be focused sufficient in the whole acceleration process and to obtain low energy spread. However, the low energy spread beam dynamics design method introduced in this paper will undoubtedly simplify the RFQ based AMS in compare to external non-adiabatic bunching. The maximum surface field is about 25MV/m, so the Kilpatrick coefficient is about 2.1 which can be accepted in the case of weak beam current. The transmission efficiency is about 97.6%, which is much better than that of external bunch design.

RF DESIGN

A cavity model was built using MWS, given by figure 3. Intuitively, a trapezoidal IH-RFQ has great mechanical capability and will simplify the cooling system very much.

Figure 3: Model of trapezoidal IH-RFQ

The RF design includes resonance frequency, electromagnetic field distribution and RF efficiency. The field distribution illustrated that the trapezoidal IH-RFQ structure was a cavity operated at $H_{21(n)}$ mode shown in figure 4, not $H_{11(n)}$ mode like classical IH-RFQ. As a result, the trapezoidal IH-RFQ has higher resonant frequency than traditional RFQ and IH-RFQ when they have same transverse dimension. It is suitable for not only light particles such as proton and deuteron but also heavier ions such as $^{14}C^{+}$. The longitudinal field distribution un-flatness is less than 5%.

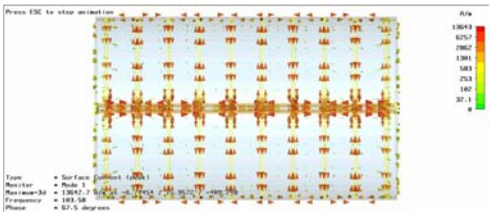

Figure 4: Current flow for T-IH-RFQ.

In order to reduce RF power loss, the specific shunt impedance and quality factor were optimized for different geometric parameters, such as shape of electrode, width and thickness of the support boards, spacing between support boards and cavity diameter. The simulated cavity frequency is a bit lower than 104MHz to keep the tuning margin, and the conductivity is set to 5.0×10^{7}s/m. Considering the cavity is relatively short, the whole cavity was simulated. The distance between neighbouring two support boards is almost equivalent to the amount of support boards since the total length has been confirmed by beam dynamics design. If it is large, the electrode length per module increases which leads to large capacitance, whereas a small distance means significant capacitive loading between the support boards [11]. Taking mechanical factor into account, 10 support boards were used and the distance was chosen to be 115mm. Finally, the simulated quality factor is around 5192, and the specific shunt impedance is optimized to reach about 110kΩ•m, which means the designed RF power is 36kW. The optimized structure parameters are listed in table 2.

Table 2: The Optimized Structure Parameters

RF frequency f (MHz)	103.6
Cavity length L (mm)	1111.3
Number of support boards	10
Distance between support boards (mm)	115
Width of support boards (mm)	112
Thickness of support boards (mm)	13.5
Cavity diameter (mm)	680
Quality factor	5192
Specific shunt impedance (kΩ•m)	110
RF power (kW)	36

Comparing T-IH-RFQ to traditional four rods RFQ and IH-RFQ with the same mechanical dimensions, T-IH-RFQ has the highest frequency and lowest RF shunt impedance. Their performances are shown in Table 3.

Table 3: Comparing Three Different RFQs

	T-IH-RFQ	IH-RFQ	Four Rod RFQ
Frequency/MHz	103.6	46.5	77.9
Shunt impedance /kΩ•m	110	300	170.9
Quality Factor	5192	5934	5077

Cold model cavity will not be necessary because good agreement between simulation results and the cavity measurements. The real trapezoidal IH-RFQ power cavity will be manufactured directly based on MWS design.

CONCLUSION

Internal discrete bunching method was used to simplify the RFQ based ^{14}C AMS and improve the transmission. The non-adiabatic buncher section functioned as the pre-buncher before RFQ. All dynamics parameters were designed and modified repeatedly by MATCHDESIGN, the code of Staples and PARMTEQM. After a satisfying beam dynamics design was obtained, we proposed the trapezoidal IH-RFQ operating at $H_{21(n)}$ mode illustrated by MWS simulations. It has higher resonant frequency and great mechanical performance. After optimization, the quality factor and the specific shunt impedance for the trapezoidal IH-RFQ are initially satisfied.

Further optimization will be carried out for RF design mainly aimed to decrease power consumption. A trapezoidal real IH-RFQ power cavity will be constructed under the support of NSFC (19775009) and be tested next year.

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