# Beam dynamics and RF design of trapezoidal IH-RFQ with low energy spread*

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**Abstract** Beam dynamics and RF design have been performed of a new type trapezoidal IH-RFQ operating at 104 MHz for acceleration of $^{14}C^{+}$ in the framework of RFQ based $^{14}C$ AMS facility at Peking University. Low energy spread RFQ beam dynamics design was approached by the method of internal discrete bunching. $^{14}C^{+}$ will be accelerated from 40 keV to 500 keV with the length of about 1.1 m. The designed transmission efficiency is better than 95% and the energy spread is as low as 0.6%. Combining the beam dynamics design, a trapezoidal IH-RFQ structure was proposed, which can be cooled more easily and has better mechanical performance than traditional RFQ. Electromagnetic field distribution was simulated by using CST Microwave Studio (MWS). The specific shunt impedance and the quality factor were optimized primarily.

**Key words** low energy spread, beam dynamics, RF design, trapezoidal IH-RFQ

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## 1 Introduction

RFQ, proposed by I. M. Kapchinsky and V. A. Teplyakov in 1970[1], has been used widely as injectors, neutron sources and so on. It can simultaneously focus, bunch and accelerate the low energy beams, extracted from ion sources directly, over a mass range from proton to heavy ions based on the RF electrical field of a modulated quadruple transport channel[2]. RFQ was used in $^{3}H$ Accelerator Mass Spectroscopy (AMS) firstly by LLNL in USA because of its inherent compact size[3]. RFQ based $^{14}C$ AMS application has been studied 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 200 μA, which is so low that the space charge effects can be ignored. Non-adiabatic bunching method should be used to make the 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 expected to be easily cooled and performed well mechanically. More-

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over, it should have higher resonant frequency than traditional IH-RFQ[7] due to different modes excited in the cavity in order to make accelerating frequency higher for heavy ions such as $^{14}C^{+}$. Simulations of the electromagnetic fields have been completed by CST Microwave Studio (MWS). RF characteristic is investigated, and geometrical parameters were optimized to make the shunt impedance and the quality factor as large as possible.

## 2 Beam dynamics design

According to the Staples' distribution, 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 with the modulation parameter $m$ ramps from zero to a maximum and then back down to zero, which perform the function of bunching as a non-adiabatic buncher. The following several unmodulated cells make up 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 $-90°$ to its final value $-30°$. The final energy is reached by the acceleration section. Significantly lowered longitudinal output emittance and slightly lowered transverse emittance can be obtained by this new design technique compared with the previous methods, which has been proved by PARMTEQM.

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

$$\Delta w_{\max} = [2A\xi V_0 e w_{\mathrm{s}} (\varphi_{\mathrm{s}} \cos\varphi_{\mathrm{s}} - \sin\varphi_{\mathrm{s}})]^{1/2}\ , \qquad (1)$$

where $\Delta w_{\max}$ is the separatrix height that indicates the maximum beam energy spread, $\xi$ is the charge-to-mass ratio of the ion, $e$ is the charge of an electron, and $w_{\mathrm{s}}$ the kinetic energy of the synchronous particle. The formula shows that energy spread can be lowered by reducing the acceleration coefficient $A$, electrode voltage $V_0$ and $\varphi_{\mathrm{s}}$, where lower $A$ means lower $m$.

From what is mentioned above we can see apparently that $\varphi_{\mathrm{s}}$ should be as large as possible in order to obtain low energy spread, but not to be kept at $-30°$. 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 and minimize the emittance growth and related beam loss[9]. The two aspects can be realized by MATCHDESIGN[10], a code developed at IHIP by 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 the 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 60 kV, 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 Fig. 1 and listed in Table 1. Energy spectrum of ion beam output from this RFQ is shown as Fig. 2.

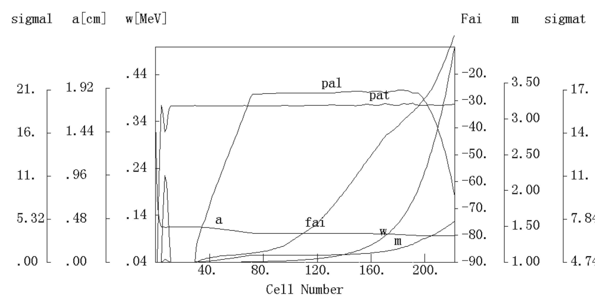


Fig. 1. The main dynamics parameters (sigmal is longitudinal phase advance, sigmat is transverse phase advance, Fai is synchronous phase, a is aperture radius, w is ion energy and m is modulation respectively).

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 $W_{\mathrm{i}}$/keV | 40 |
| output energy $Wo$/keV | 500 |
| modulation $m$ | 1.0—1.57 |
| minimum aperture radius $a$/mm | 2.93 |
| maximum focusing factor $B$ | 3.44 |
| synchronous phase $\varphi_{\mathrm{s}}$/(°) | −90 to −6 |
| electrode length $L$/mm | 1091.3 |
| transmission $T$ (%) | 97.6 |
| energy spread (%) | 0.6 |

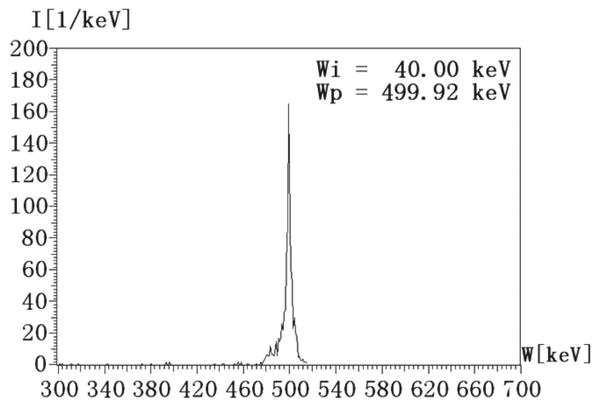


Fig. 2. Output beam energy spectum.

The total length of the RFQ is about 1.1 m, and further more $m$ is small to make particles be focused sufficiently 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 comparison with the external non-adiabatic bunching. The maximum surface field is about 25 MV/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 the external bunch design.

## 3 RF design

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

Fig. 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, 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 the 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%.

In order to reduce the 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 104 MHz to keep the tuning margin, and the conductivity is set to $5.0\times10^{7}$ s/m. Considering the cavity is relatively short, the whole cavity is simulated. The distance between the neighboring two support boards is almost equivalent to the amount of support boards since the total length has been confirmed by the 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 115 mm. Finally, the simulated quality factor is around 5192, and the specific shunt impedance is optimized to reach about 110 kΩ·m, which means the designed RF power is 36 kW. 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 |
| spacing 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 |

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

## 4 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 satisfactory beam dynamics design was obtained, we proposed the trapezoidal IH-RFQ operating at $H_{21(n)}$ mode illustrated by MWS simulations. It has a higher resonant frequency and a 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 the RF design to decrease the power consumption. A trapezoidal real IH-RFQ power cavity will be constructed with the support of NSFC (19775009) and tested next year.

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