# A new compact structure for a high intensity low-energy heavy-ion accelerator*

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**Abstract:** A new compact accelerating structure named Hybrid RFQ is proposed to accelerate a high-intensity low-energy heavy ion beam in HISCL (High Intensive heavy ion SuperConducting Linear accelerator), which is an injector of HIAF (Heavy Ion Advanced Research Facility). It is combined by an alternative series of acceleration gaps and RFQ sections. The proposed structure has a high accelerating ability compared with a conventional RFQ and is more compact than traditional DTLs. A Hybrid RFQ is designed to accelerate $^{238}U^{34+}$ from 0.38 MeV/u to 1.33 MeV/u. The operation frequency is described to be 81.25 MHz at CW (continuous wave) mode. The design beam current is 1.0 mA. The results of beam dynamics and RF simulation of the Hybrid RFQ show that the structure has a good performance at the energy range for ion acceleration. The emittance growth is less than 5% in both directions and the RF power is less than 150 kW. In this paper, the results of beam dynamics and RF simulation of the Hybrid RFQ are presented.

**Key words:** Hybrid RFQ, high intensity, heavy ion linac, compact structure

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## 1 Introduction

HIAF (Heavy Ion Advanced Research Facility), which is a multi-function, full ion species, national user accelerator facility, is proposed by IMP (Institute of Modern Physics), CAS (Chinese Academy of Sciences). HISCL (High Intensive heavy ion SuperConducting Linear accelerator) as the injector of HIAF consists of ECRs, LEBT, RFQ and superconducting section. The layout of the primary design is shown in Fig. 1. As shown in Fig. 1, low $\beta$ superconducting DTLs are placed just after RFQ, which is an alternative choice for the energy range.

Usually after the conventional RFQ, IH-DTL structures or superconducting cavities are widely used for the acceleration of heavy ion beams. However for IH-DTLs, it is hard to offer the required transverse focusing strength in the case of high intensity beam current at low energy. Use of magnetic focusing elements outside the DTLs always causes an increase of longitudinal emittance growth, while placing them inside of the DTLs will

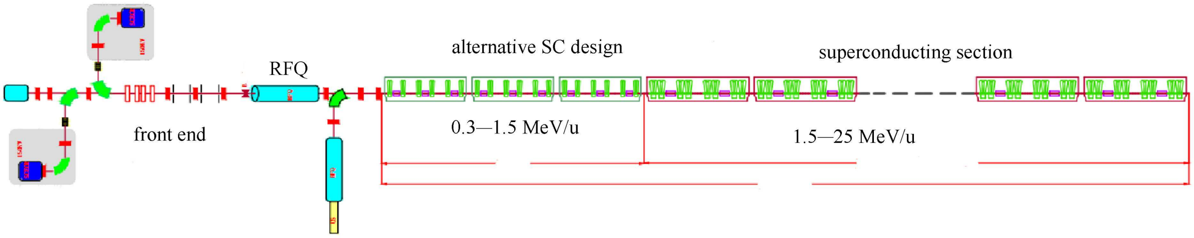

Fig. 1. (color online) The general layout of HISCL.

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cause external RF power. For superconducting cavities, which is adopted by FRIB [1] and RAON [2], it is a low efficiency, high price solution.

The Hybrid RFQ, which is first proposed by Argome National Laboratory [3], as one alternative solution to accelerate the beam from 0.38 MeV/u to 1.33 MeV/u with 1.0 mA beam current is investigated. The beam dynamic simulations with TRANSIT [4] which is particle tracking code in time domain and preliminary RF simulation with three-dimensional finite element code MWS (Micro Wave Studio) [5] have been done. The results show that the beam can be accelerated to the final energy with good beam quality and RF parameters meet the requirement.

In this paper, the simulation results of the structure will be presented.

## 2 Introduction of the Hybrid RFQ structure

The Hybrid RFQ which is depicted in Fig. 2 is composed of a series of acceleration gaps and RFQ sections. As shown in Fig. 2, the IH (Inter-digital H mode) DTL structure is used to accelerate the beam and to provide focusing force in the longitudinal direction. At 81.25 MHz, the IH structure was chosen for its high shunt impedance and high acceleration efficiency [6]. The RFQ cells can produce a quadrupole electric field to focus the beam in the transverse direction. The transverse focusing force in RFQ is usually characterized by the parameter $X$, which is expressed in Eq. (1).

$$X=\frac{I_0(ka)+I_0(kma)}{m^2I_0(ka)+I_0(kma)}, \tag{1}$$

where $k$ is the wave number, the $a$ is the minimum radius of the electrode tips, and the $m$ is the modulation parameters. From Eq. (1), it is shown that when $m=1$, there is maximum focusing factor. The RFQ cell with the length of $(\beta\lambda)/2$ at $m=1$ acts like a quadrupole, each two-cell RFQ section acts as a “Doublet”.

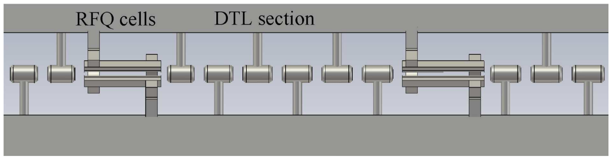

Fig. 2. The configuration of Hybrid RFQ structure formed by alternating series of RFQ cells and DTL sections.

The focusing effect of RFQ cell is equivalent to a magnetic quadrupole with effective length $(\beta\lambda)/2$ when

$$R_0=\sqrt{\frac{2U_1}{\pi\beta cG_{\rm m}}}, \tag{2}$$

where $R_0$ is the average radius of RFQ cells, $U_1$ is the electric potential on the RFQ electrodes and $G_{\rm m}$ is the equal magnetic gradient of quadrupole, $\beta$ is the velocity of particles. For particles with kinetic energy between 0.35 MeV/u and 1.33 MeV/u, the strength of quadrupole is 0.5 T to 1.0 T with the same length of RFQ cell and 15 mm radius. This means at the energy region, the RFQ and quadrupole has no obvious advantage, while RFQ focusing is more compact and simpler than quadrupoles.

To eliminate the influence of the fringe field of the RFQ section, the drift length between DTL and RFQ should be optimized to make the transverse electric field at the edges of the RFQ electrodes be zero when the beam enters the RFQ section.

For the acceleration of ions with different $Q/A$, the Hybrid RFQ structure can provide suitable acceleration and focusing force linear with $Q/A$. So the structure can be used to accelerate ions with different $Q/A$.

## 3 Beam dynamics simulation of the Hybrid RFQ

The Hybrid RFQ is composed of seven DTL sections and six RFQ sections with length $\beta\lambda$. Basic beam parameters are listed in Table 1.

Table 1. Basic simulation parameters of Hybrid RFQ

| parameters | value |
|---|---|
| operation frequency/MHz | 81.25 |
| ion species | $^{238}$U$^{34+}$ |
| beam energy/(MeV/u) | 0.38–1.33 |
| total length/m | 4.12 |
| beam current/mA | 1.0 |
| drift tube radius/mm | 10 |
| gap length/mm | 20 |
| voltage between gaps/kV | 200 |
| voltage between RFQ electrodes/kV | 200 |
| transmission(%) | 100 |
| $\epsilon_{xy}$/(mm·mrad) | 0.243 |
| energy spread(%) | 1.5 |
| phase spread/(°) | 15 |

In Table 1, $\epsilon_{xy}$ is the initial normalized RMS emittance in the transverse direction. The voltage between gaps was chosen to be 200 kV to keep RF power loss as low as possible considering CW operation mode. The total length is about 4.12 meters long, which is a moderate length for fabrication. The initial beam emittance values were obtained from the output of the conventional RFQ upstream.

TRANSIT code was applied for beam dynamics simulation. The code can provide calculation of a 3-D electrical field map in the gaps between DTLs and transverse electric fields between RFQ electrodes. The focusing force was adjusted by the appropriate choice of average radius of RFQ cells. 40000 macro particles initialized with the parameters in Table 1 were transported through the structure with 1.0 mA beam current. The particles distribution in the phase space at the end of the Hybrid RFQ was plotted in Fig. 3. From the simulation, there is no nonlinear distortion in the transverse phase space. The normalized RMS emittance growth in the transverse is lower than 5%. While for the longitudinal phase space, there is little distortion, it is also in the acceptance of downstream superconducting section.

As shown in Fig. 3, there is no beam loss in the simulation, the final $\beta$ of beam is 0.0532, which was corresponding to beam energy 1.33 MeV/u.

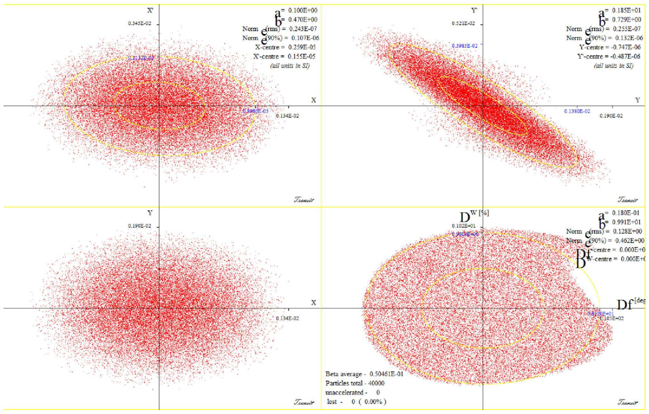

Fig. 3. (color on line) The particles distribution in the phase space at the end of the Hybrid RFQ.

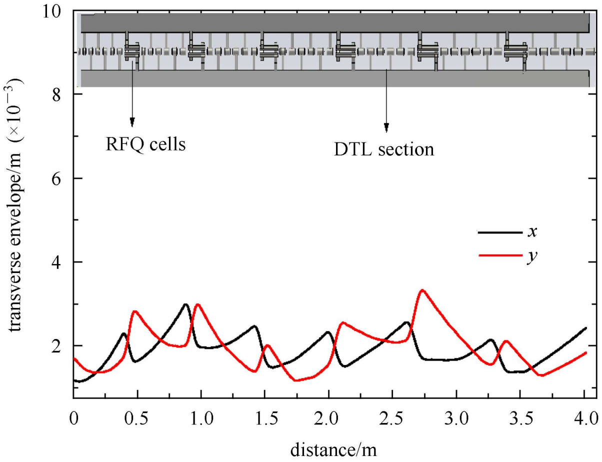

Fig. 4. (color on line) The simulated transverse envelopes along the Hybrid RFQ.

The simulated beam envelope in the transverse direction was plotted in Fig. 4. In the Fig. 4, the radius of beam pipe is 10 mm, the transverse beam envelope is lower than 5.0 mm, so there is a large traverse acceptance. There are seven DTL sections and six two-cells RFQ sections.

In the Table 2, the parameters comparison between Hybrid RFQ and SC cavities [7] are listed.

Table 2. Comparison between Hybrid RFQ and SC cavities acceleration option.

| parameters | Hybrid RFQ | SC cavities |
|---|---|---|
| total length/m | 4.12 | 16.38 |
| input energy/(MeV/u) | 0.38 | 0.3 |
| output energy/(MeV/u) | 1.33 | 1.54 |
| $\epsilon_{xy}$ growth(%) | 4.6 | 4 |
| cavity number | 1 | 16 |
| solenoids number | 0 | 8 |
| operation temperature/K | normal | 4.5 |
| acceleration gradient/(MeV/u/m) | 0.23 | 0.075 |

From Table 2, the acceleration gradient of Hybrid RFQ is more than three times compared with SC cavities scheme. The beam quality from both schemes is almost the same.

As follows from the results of beam dynamics simulation, the Hybrid RFQ has a high acceleration efficiency and strong enough transverse focusing. The beam quality is well controlled, so the structure can work well with the high beam current, low energy ion beam. For HISCL project, this structure will be a good option for acceleration between RFQ and SC cavities.

## 4 RF simulation of the Hybrid RFQ

For the Hybrid RFQ structure, the RF simulation should be done to check the following issues: one is about the RF properties, such as frequency, field distribution along the beam axis. The field distribution should be as flat as possible in DTL sections which is close to the beam dynamics design situation. There should be no longitudinal electric field and just transverse RF electric field. More attention should be paid to the field map between RFQ and DTL, for geometric structure of this part is complicated and it has a large influence on the frequency. The distance between the two sections should be optimized to meet both requirements of the beam dynamics and RF properties.

The strictest limitation for Hybrid design is about RF dissipation power. This is very important for the CW normal conducting machine for the thermal problem.

The simulations of the resonant structure have been performed using MWS code. A 1.5 meters long section, which includes three DTL sections and two RFQ sections, was simulated to check the RF properties because optimizing the full model is time consuming. The most difficult problem in the RF design of the structure is the balance of local frequency between DTL sections and RFQ sections for the different capacitance in the two geometric structure.

From the simulation, we find that the capacitance in the RFQ section is larger than the DTL section, so larger

RFQ aperture radius should be applied to increase the local frequency, also to provide large transverse acceptance for beam dynamics.

The optimized results are acquired after adjusting the RFQ aperture radius and the distance between RFQ and DTL. The geometry structure of the Hybrid RFQ and the longitudinal electric field distribution along the beam axis are shown in Fig. 5. As shown in the figure, the longitudinal electric field distribution is almost flat along the DTL section. In the RFQ section, the required configuration of the transverse electric field has been achieved along the path located at the center of the two adjacent electrodes. The transverse field is the same sign in the mean time, the field will change direction with time to produce focusing and defocusing force when particles pass through. The field between the DTL section and the RFQ section is almost half the value of the normal acceleration gaps. The maximum surface electric field is located at the RFQ electrode.

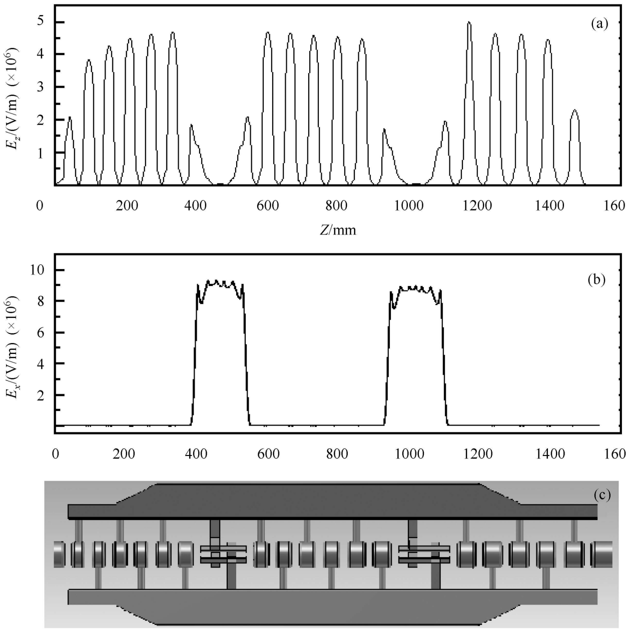

Fig. 5. The field distribution along the $Z$ direction. Fig.(a) is the longitudinal field distribution along the $Z$ axis, Fig.(b) is the transverse electric field along the path located at the center of two adjacent RFQ electrodes, Fig.(c) is the layout of the Hybrid RFQ structure.

The main RF parameters of the structure are listed in Table 3.

Table 3. The main RF parameters of the Hybrid RFQ.

| parameters | value |
|---|---|
| RF frequency/MHz | 81.0 |
| length of the model/m | 1.54 |
| RFQ aperture radius/mm | 15 |
| $U_z$/MV | 2.78 |
| inter-electrode voltage/MV | 0.15 |
| RF power/kW | 30 |

In Table 2, $U_z$ is the voltage integrated along the $Z$ axis, the electric field is 10 MV/m between electrodes corresponding to the $K_\mathrm{p}$ value 1.0. The RF power from the CST simulation is 30 kW, which means the nominal total dissipation power is 145 kW for the whole Hybrid RFQ.

## 5 Summary

In this paper, a new structure is proposed to accelerate a heavy ion beam at the low energy part of HISCL. The beam dynamics simulation results showed that the structure can offer good beam quality at 1.0 mA, the emittance growth is lower than 5%. Compared to the SC acceleration option, the Hybrid RFQ has a high accelerator efficiency and similar beam quality. Also from the RF simulation, the field distribution in the RFQ and DTL sections agrees with the beam dynamics. The total RF power is less than 150 kW which is a reasonable value for a CW machine.

From the simulation results, the Hybrid RFQ will be a good choice for high-intensity low-energy heavy ion linac. More optimization work will be done on the structure, and the model cavity should be done in the future.

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