Design of an RFQ for direct plasma injection scheme

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Abstract A high current radio frequency quadrupole (RFQ) is being studied at the Institute of Modern Physics, Chinese Academy of Sciences (IMP, CAS) for the direct plasma injection scheme (DPIS). Because of the strong space charge of beams from laser ion source, the beam dynamics design of the RFQ has been carried out with a new code, which can deal with space charge effectively. The design of the RFQ structure is performed with an electromagnetic simulation code and the determination of parameters of the structure has been done to maximize the shunt impedance when the frequency is kept fixed. The influences of dipole mode effect and flatness on beams were also discussed.

Key words LINACSrfq code; 4-rod structure, Dipole mode effect, Flatness

1 Introduction

An RFQ (Radio Frequency Quadrupole) accelerator with high current (20 mA) $^{12}C^{6+}$ is being studied at Institute of Modern Physics for the direct plasma injection scheme (DPIS), in which a laser ion source (LIS) and an RFQ are joined together without the low energy beam transport line. The sketch map of DPIS is shown in Fig.1. As an R&D program, the DPIS-RFQ is dedicated to researches of a compact carbon ion therapy machine and intense heavy ion beam injection for Cooling Storage Ring of the Heavy Ion Research Facility in Lanzhou (HIRFL-CSR)[1].

LIS is the most intense ion source capable of producing highly charged ion beams with 10–100 mA current and 1–10 μs pulse duration. The parameters well meet the requirements of single-turn injection into synchrotrons[2,3]. Taking advantages of LIS and DPIS-RFQ, we can propose a compact and cost-effective carbon ion therapy synchrotron by using a single-turn and single-pulse injection. On the other hand, with a DPIS-RFQ-IH linac as an injector of HIRFL-CSR, much more intense beam can be achieved by multi-turn injection. However, an important issue for the LIS and the DPIS in above applications are long-term reliability, stability and reproducibility, which are among the main goals for our research program. An LIS has been set up and a DPIS-RFQ has been designed at Institute of Modern Physics.

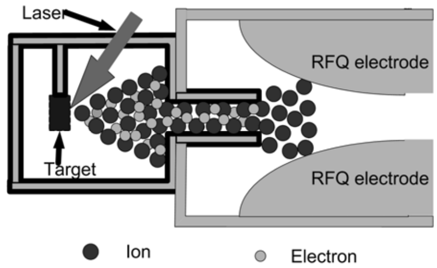

Fig.1 Sketch map of direct plasma injection scheme.

2 Beam dynamics design of the RFQ

The beam dynamics design was carried out with LINACSrfq code[1], which was proved effective in the IFMIF RFQ design. The most distinct feature of the code is that it requires an equipartitioned condition at the end-of-shaper (EOS), in which there is no free

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Received date: 2009-05-27

energy in the degrees of freedom that can drive emittance growth and which can treat space charge effectively for heavy ions especially. For the acceleration section of the RFQ, we could use the code to make choices between matched-only design strategy and equipartitioning design strategy. This helped us to find the best beam dynamics design. Both the design strategies are good. But in terms of the transmission efficiency, output energy in two meters and emittance growth[1], the equipartition design strategy does not seem as good as the matched-only design strategy, which was chosen as the final design strategy. Results of the calculation are shown in Table 1 and main parameters of beam dynamics are plotted in Fig.2.

Table 1 Basic parameters of IMP RFQ for DPIS

Ion	$^{12}C^{6+}$
Frequency / MHz	100
Input/Output Energy / MeV	0.36/7.12
Peak Beam Current / mA	20
Voltage / MV	0.12
Minimum aperture / cm	0.71
Modulation	1–2.1
Sync. Phase	–90.0–20.0
Trans. Efficiency	94.8%
Length /m/cell number	2.0/100
Input/Output Trans. Norm. RMS Emittance	0.2/0.3479
Input/Output Long. Norm. RMS Emittance	0.4/1.023

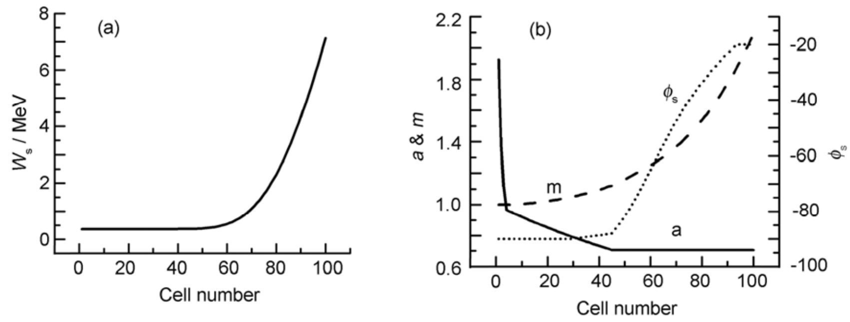

Fig.2 Dynamics parameters *vs*. cell number: (a) sync. energy; (b) aperture, modulation and sync.

3 Cavity design of the RFQ

The 4-rod structure was chosen as the RFQ cavity structure (Fig.3), because the RFQ will work at a low frequency (100 MHz), and the 4-rod structure, with a more complex cooling system, though, is more suitable for accelerating heavy ions in that situation than a 4-vane system. The 4-rod structure has the following advantages over the 4-vane structure: (1) at low frequencies, it is smaller in size and mechanically simpler, hence the convenience in construction; (2) the opposing rods are connected to each other by stems, and this eliminates the dipole mode, an unavoidable problem for 4-vane structures[4]. To determine parameters of the structure, many calculations were done with the electromagnetic simulation code MAFIA[5], and the number of mesh points was optimized to ensure the accuracy of calculations. All the calculations were aimed at maximizing the shunt impedance of the structure to reduce power loss for the complex cooling system.

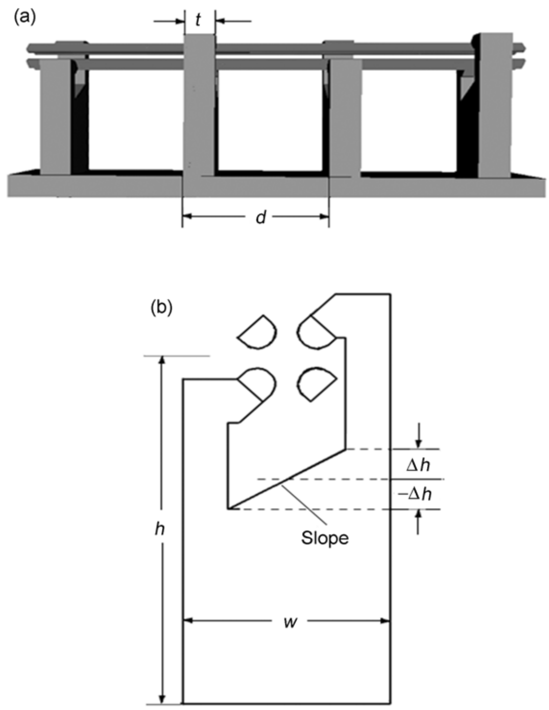

Fig.3 The 4-rod RFQ structure: (a)side view (b) front view.

3.1 Electrodes of the structure

For a 4-rod RFQ structure, most of the capacitance is distributed between the electrodes, and the capacitance affects properties of the structure strongly. A structure loaded with a big capacitance usually has small shunt impedance[6]. To have a high shunt impedance of the structure, the electrode shape was optimized with different shapes of the electrodes on stems of fixed shape. The optimized electrode shape was shown in Fig.3(b). The curvature radius of the electrodes is set at 0.53 cm to reduce the impact of higher-order harmonics on the beams.

3.2 Stems of the structure

The frequency of 100 MHz was kept during the process of optimizing the stems. The main optimized parameters were mainly (Fig.3) the stem thickness *t*, the stem height *h*, and the distance *d* between adjacent stems. The width *w* of the stems is fixed at 100 mm, because its influence on properties of the structure is very small.

A four-stem basic structure was chosen for calculation because of the periodicity of the 4-rod RFQ (Fig.3a). In the calculation the following strategy was adopted: change the distance *d* first and then the stem thickness *t*. Results of the calculation are plotted in Fig.4 and Fig.5.

From Fig.4, one sees that for each stem thickness there is an optimal distance between adjacent stems with a maximum shunt impedance R_s, and the thicker the stem is, the bigger the maximum shunt impedance is. Also one can find that the shunt impedance changes more quickly for a thicker stem. Fig.5 illustrates that

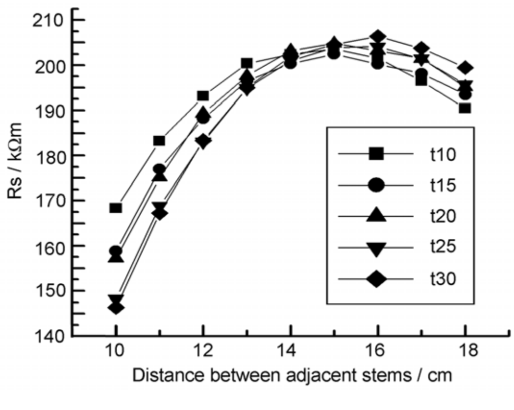

Fig.4 Shunt impedance as a function of stem thickness (mm) and distance between adjacent stems.

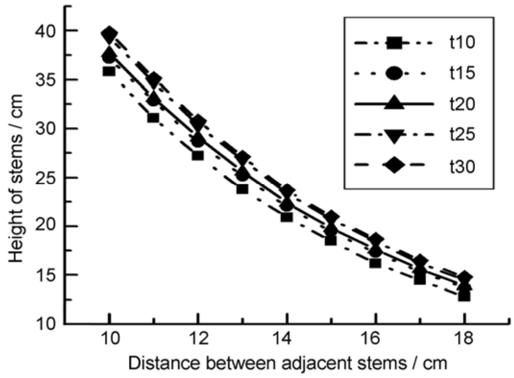

Fig. 5 Stem height as a function of stem thickness (mm) and distance between adjacent stems.

the stem height decreases with increasing distance between adjacent stems, so as to keep the frequency fixed for each stem thickness, and the stem height decreases with its thickness decreasing at a certain distance between adjacent stems, too.

The surface current of the cavity is mainly distributed on the stems and the electrode tips. The influence of capacitance between the stems is important, the current density becomes higher and the power losses on the stems increases with shorter distance between adjacent stems, hence the reduced shunt impedance is reduced[7]. The capacitance between the electrodes is dominant and the power loss on electrodes is higher when the distance is longer. This reduces the shunt impedance, too. Thus there is an optimal distance for the best shunt impedance. For thicker stems, the magnetic field around them is more homogeneous, and this reduces the surface resistance where the stems are welded with the ground plate[8]. Therefore, a thicker stem reduces power loss and leads to higher shunt impedance.

Since an RFQ with a bigger *d* needs larger amount of cooling water for the electrodes, we decided that *d*=14 cm (even though the maximum shunt impedance occurs at *d*=16 cm) and *t*=20 mm, because of the bigger shunt impedance and convenience in inserting cooling tube into the stems of 20 mm thick.

3.3 Dipole mode effect

Dipole mode contributions in the electrode fields correspond to differences in the potential of the electrodes, e.g. the potential on the beam axis is not zero. It can be a reason for beam losses depending on its strength and beam emittances. However, dipole components of the electrode-voltage can be reduced by shaping the stems with a slope as shown in Fig.3(b)[9]. Dipole factor, which is the voltage ratio of the upper and low electrodes was calculated as 1.09, 1.06, 1.04, and 1.02 for 0, 10, 20, and 30 mm of the Δh in Fig.3(b), respectively. It is also found that big Δh can reduce the shunt impedance. As compromise between dipole mode effect and shunt impedance, a Δh of 20 mm was chosen.

3.4 Flatness

Flatness represents voltage distribution on the electrodes. The voltage distribution was assumed perfectly flat in the beam dynamics design. Otherwise, particle losses would happen where the voltage is low and focusing is insufficient. Usually, adjustment of voltage distribution is a must in cavities to get perfect flatness and is realized by a frequency tuning in cells[10]. During the process of commissioning, voltage distribution can be adjusted conveniently by inserting tuning plates of different height into cells as shown in Fig.6.

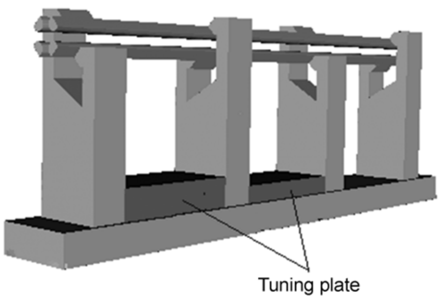

Fig.6 4-rod RFQ structure with tuning plates.

4 Conclusion

The beam dynamics design of the IMP RFQ has been performed with LINACSrfq code which adopts the equipartitioned design strategy at the end-of-shaper (EOS).The 4-rod structure is chosen for the RFQ due to the advantages of it. The shape of the electrodes and stems has been optimized to maximize the shunt impedance of the structure. Results indicate that there is a maximum of shunt impedance at a certain distance between adjacent stems when the frequency is unchanged, but a shorter distance is adopted to simplify the cooling system. Method of reducing the dipole mode effect has been studied, too. The RFQ is being built now and is planned to be commissioned in July 2009.

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