Study on shunt impedance and voltage distribution of 4-rod RFQ cavity

ZHANG Zhou-Li(张周礼)[1,2;1)] R.A. Jameson[3] ZHAO Hong-Wei(赵红卫)[1] XU Zhe(许哲)[1]
ZHANG Sheng-Hu(张生虎)[1] ZHANG Cong(张聪)[1,2] SUN Lie-Peng(孙列鹏)[1,2]
MEI Li-Rong(梅立荣)[1,2] SHEN Xiao-Kang(申晓康)[1,2]

[1] Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China
[2] Graduate University of Chinese Academy of Sciences, Beijing 100049, China
[3] Inst. Angewandte Physik Goethe Uni. Frankfurt, Max-von-Laue-Str. 1, D60438, Frankfurt-am-Main, Germany

Abstract A high current RFQ (radio frequency quadrupole) is being studied at the Institute of Modern Physics, CAS for the direct plasma injection scheme. Shunt impedance is an important parameter when designing a 4-rod RFQ cavity, it reflects the RF efficiency of the cavity, and has a direct influence on the cost of the structure. Voltage distribution of a RFQ cavity has an effect on beam transmission, and particles would be lost if the actual voltage distribution is not as what it should be. The influence of cell length, stem thickness and height on shunt impedance and voltage distribution have been studied, in particular the effect of projecting electrodes has been investigated in detail.

Key words 4-rod RFQ, shunt impedance, voltage distribution

PACS 29.20.Ej, 41.75.Ak

1 Introduction

A RFQ (radio frequency quadrupole) accelerator working at a low 100 MHz frequency with a high current of 20 mA $^{12}C^{6+}$ is being studied at the IMP (Institute of Modern Physics) for the direct plasma injection scheme (DPIS), in which a laser ion source (LIS) and a RFQ are joined without the LEBT [1]. As a R&D (research and development) program the DPIS-RFQ is dedicated to researches of a compact carbon ion cancer therapy machine and intense heavy ion beam injection for the Cooling Storage Ring of the Heavy Ion Research Facility in Lanzhou (HIRFL-CSR) [2]. LIS is the most intense ion source capable of producing highly charged ion beams with a current of 10–100 mA and pulse duration of 1–10 μs. Taking advantages of LIS and DPIS-RFQ, we can propose a compact and cost-effective carbon cancer therapy synchrotron by using a single-turn and single-pulse injection. On the other hand, if we use DPIS-RFQ-IH (interdigital-H) Linac as an injector of HIRFL-CSR, we can achieve much more intense beam by multi-turn injection. Due to its advantages at low frequency such as nice reliability, stability and simplicity, the 4-rod structure has been chosen for the RFQ. The total length of the RFQ is two meters.

Shunt impedance reflects the RF efficiency of a RFQ cavity. High shunt impedance means low power loss in the cavity which involves small input power to maintain the required voltage and can simplify the cooling system, and consequently reduces the cost of the structure. Electric field distribution is assumed to be perfectly flat in the beam dynamics design, otherwise, particle losses would happen where the voltage is low and focusing is insufficient [3], which could result in maintenance difficulties. Almost all the existing 4-rod RFQs in the world are loaded with tuning plates to make the electric field flat, which causes an extra power loss of the cavity and reduces the shunt impedance.

Parameters of the cavity, for example, stem thickness and height, cell length and electrode projecting length, influence the properties of it duo to the capacitances and inductances of electrodes and stems.

Received 3 April 2009

1) E-mail: jolly@impcas.ac.cn

Therefore, attention is paid to the influence of these parameters during the process of the IMP RFQ cavity design in an attempt to maximize the shunt impedance of the structure and make the electric field flat only by adjusting the cavity parameters, method which has never been tried before.

The design study has been carried out with MAFIA [4], and the number of mesh points used by the MAFIA calculation has been optimized to ensure the accuracy of calculation. The frequency 100 MHz has been kept unchanged during the process of calculation.

2 Study on shunt impedance of 4-rod RFQ

The shunt impedance of the 4-rod RFQ, as shown in Fig. 1, is defined as the following

$$R_s = \frac{V_P^2}{(2P/L_{tot})} , \tag{1}$$

where V_P is the inter electrode peak voltage, P the power loss and L_{tot} the cavity length [5]. There are many parameters which affect the shunt impedance, and the most important ones are the ratio of the electrodes curvature radius ρ to the average beam aperture r_0, the stem thickness d and the stem height h, and finally the basic cell length L (this basic cell is different from the cell in beam dynamics). The ratio ρ/r_0 and r_0 have been set to 0.75 and 7.1 mm respectively in this study, and attention has been focused on dependence of the shunt impedance on the stem thickness d, the stem height h and the basic cell length L. The width w of the stems is set at 100 mm during the calculation.

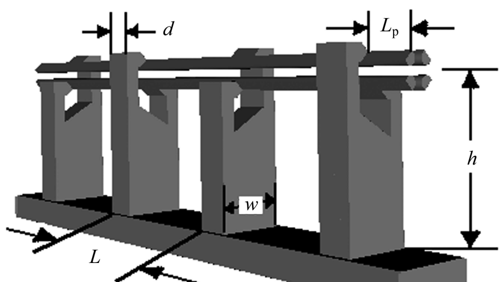

Fig. 1. 4-rod RFQ cavity of 3-basic-cells, L_p is the electrode projecting length.

A 3-basic-cell structure has been chosen for calculation because of the periodicity of the 4-rod RFQ, as the structure shown in Fig. 1, and the electrode projecting length L_p is kept at 10 mm. In the calculation the following strategy is adopted: first the stem thickness d is fixed when changing the basic cell length L, and next d is changed, and then the first step is repeated. Results of calculation are plotted in Figs. 2, 3.

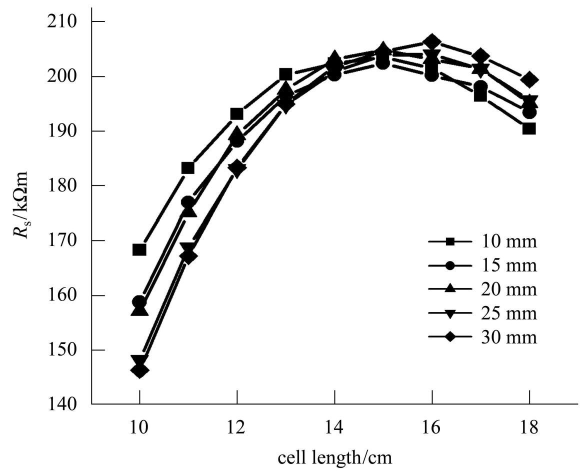

Fig. 2. The shunt impedance as a function of cell length L and stem thickness d.

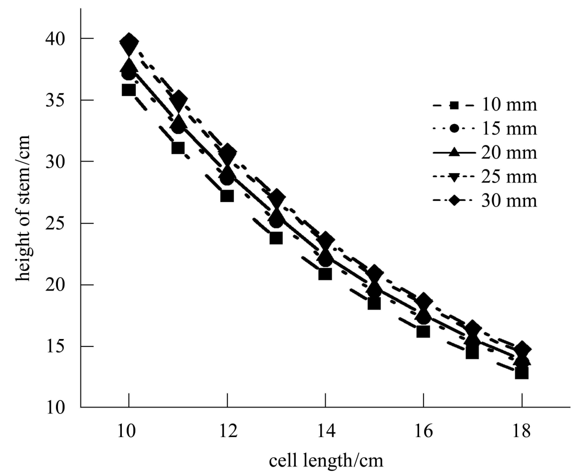

Fig. 3. The stem height as a function of cell length L and stem thickness d.

Figure 2 shows that there is an optimal cell length which creates a maximum of the shunt impedance R_s for each stem thickness, and the thicker the stem is, the bigger the maximum shunt impedance is. Also we can find that the shunt impedance changes quicker when the stem is thicker. Fig. 3 illustrates that the stem height is decreasing with the cell length increasing to keep the frequency fixed for each stem thickness, and the stem height is decreasing with its thickness decreasing at a certain cell length, too.

The surface current of the cavity is mainly distributed at the stems and the electrode tips. The influence of capacitance between the stems is important, the current density becomes high and the power losses on the stems increases when the cell length is short, consequently the shunt impedance is reduced [6, 7]. The capacitance between the electrodes is dominant and the power loss on electrodes is high when the cell length is long, which reduces the shunt impedance, too. Thus there is an optimal cell length for the best shunt impedance.

For thicker stems the magnetic field is more homogeneous around them, which reduces the surface resistance where the stems are welded with the ground plate [8]. Hence thicker stem reduces power loss and leads to high shunt impedance.

3 Study on voltage distribution of 4-rod RFQ

Besides high shunt impedance, voltage distribution is another important parameter for high current 4-rod RFQ cavity, and it is expressed by flatness.

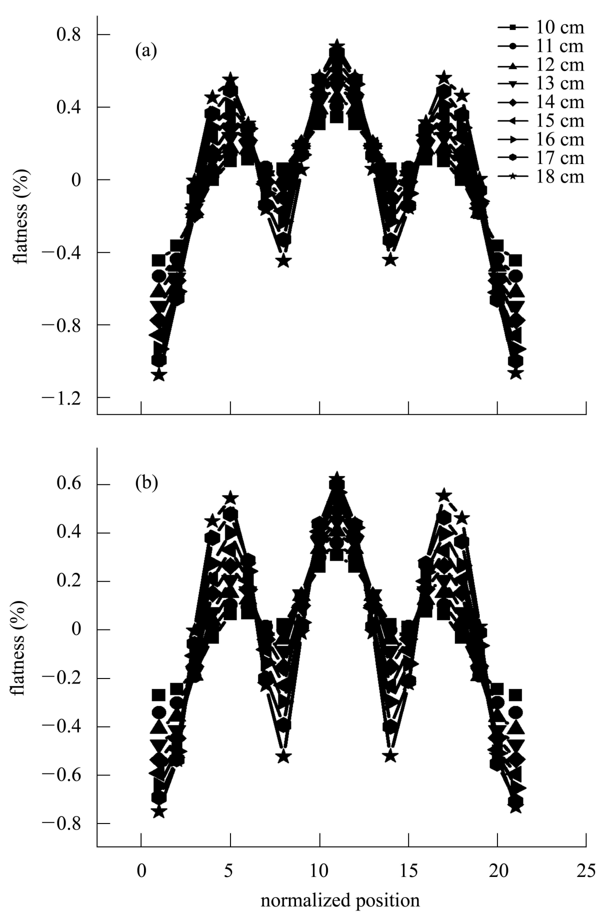

Fig. 4. Voltage distribution of 3-basic-cell structure with stem thickness of 10 mm (a) and 20 mm (b).

3.1 Voltage distribution of 3-basic-cell structure

Figure 4 shows the voltage distribution of a 3-basic-cell structure of different cell length with fixed electrode projecting length L_p of 10 mm.

Voltage distribution with stem thickness of 15 mm, 25 mm, and 30 mm have been calculated, too. And we find that the curves of voltage are distributed from convex to concave with increasing stem thickness, and with shorter cell length the voltage distribution becomes more flat. The ration of the cell frequencies and coupling strength has been changed when altering the stem thickness and cell length[1)], which causes the shift of voltage distribution.

3.2 Influence of projecting electrodes on voltage distribution

To represent the voltage distribution of a real cavity more accurately, the 9-basic-cell structure is studied. In this calculation the cell length L and stem thickness d are fixed at 16 cm and 30 mm respectively. The calculation results are shown in Fig. 5 and listed in Table 1.

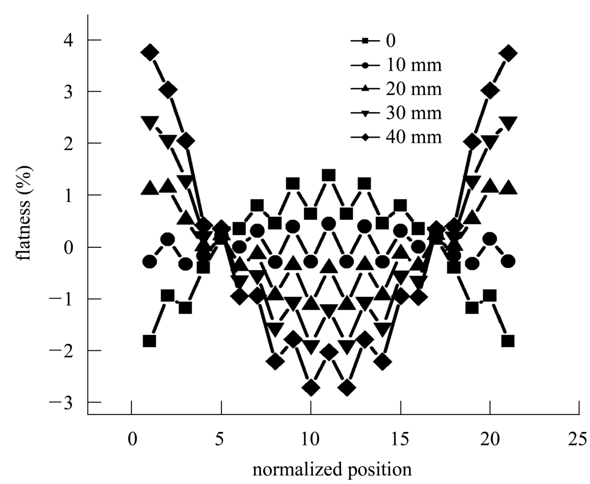

Fig. 5. Voltage distribution of 9-basic-cell with different electrodes projecting length L_p.

In Fig. 5 the electrode projecting length L_p varies from 0 to 40 mm with spacing 10 mm. We can see that there is an optimal electrode projecting length (L_p=10 mm) which makes the voltage distribution the flattest. Also from Table 1 we know that there is another optimal electrode projecting length (L_p =20 mm) which produces the biggest shunt impedance.

1) Schempp A, E-mail: a.schempp@em.uni-frankfurt.de

Table 1. Shunt impedance of different electrodes projecting length.

L_p/mm	R_s/kΩm
0	2.094×10^2
10	2.125×10^2
20	2.126×10^2
30	2.113×10^2
40	2.094×10^2

4 Conclusion

The results of calculation indicate that every parameter of the cavity will affect the shunt impedance and voltage distribution. Besides, the total length L_{tot} of the cavity can be expressed as the following formula:

$$L_{tot} = n \times L + d + 2 \times L_p, \quad (2)$$

where n is the number of basic cell. The formula shows that all the parameters influence each other, too, when the total length of the cavity is set. Therefore, the design of a 4-rod RFQ cavity is a complicated procedure, but the results turn out that to maximize the shunt impedance and to make the electric field flat only by adjusting the cavity parameters can be realized if the parameters are chosen carefully. A model cavity is planned to be built according to the method mentioned here.

References

1 ZHANG Z L, Jameson R A, ZHAO Hong-Wei et al. Nuclear Instruments and Methods in Physics Research A, 2008, **592**(3): 197

2 XIA J W et al. Nucl. Instrum. Methods A, 2002, **488**(1-2): 11

3 Fischer P, Schempp A. Tuning a CW 4-rod RFQ. Proceedings of LINAC 2006. Knoxville, Tennessee USA. 728–730

4 Corlett J N. Experience with Cavity Design Programs. Proceedings of CERN Accelerator School on RF Engineering for Particle Accelerators. Oxford, UK, 1992, 2. 307–317

5 Bricault P G et al. Simulation of the TRIUMF Split-ring 4-rod RFQ with MAFIA. Proc. of PAC 95. Dallas, Texas USA. 1125–1127

6 Podlech H et al. Electromagnetic Design of an 80.5 MHz RFQ for the RIA Driver Linac. Proceedings of EPAC 2002. Paris, France. 942–944

7 Lombardi A et al. Comparison Study of RFQ Structures for the Lead Ion LINAC at CREN. EPAC'92. Berlin, Germany: 1992. 557–559

8 ZHANG Chuan. Research on High Current Radio Frequency Quadrupole Accelerators for Neutron Production. Doctoral Dissertation of Peking University, 2004. 65 (in Chinese)