Studies on RFQ accelerators and its applications*

CHEN Jia-Er(陈佳洱)[1] GUO Zhi-Yu(郭之虞)[1;1)] FU Shi-Nian(傅世年)[2]
FANG Jia-Xun(方家驯)[1] LU Yuan-Rong(陆元荣)[1] YAN Xue-Qing(颜学庆)[1]

1 (State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, China)
2 (Institute of High Energy Physics, CAS, Beijing 100049, China)

Abstract Development activities of Radio Frequency Quadrupole (RFQ) accelerators in China are presented. A 1 MeV O^+ RFQ and a 3.5 MeV ADS proton RFQ have been constructed. A novel separated function RFQ is under beam test, a 2 MeV D^+ RFQ is under construction and a CSNS RFQ is going to be constructed. The RFQ dynamics and the simultaneous dual beam acceleration with positive and negative ions were investigated and related codes were developed. The applications of RFQ will be further promoted in China.

Key words RFQ, integral split ring RFQ, mini-vane RFQ, separated function RFQ, four-vane RFQ

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1 Introduction

A Radio Frequency Quadrupole (RFQ) accelerator has many advantages, such as the simultaneous realization of the focusing and acceleration by electrode tip modulation. It is suitable for accelerating low β particles, so it was usually used directly after the ion source. A high beam transmission can be obtained because of its bunching ability when a DC beam is directly injected. It can handle the intense beam of up to 100 mA. Hence RFQs have been widely used in many applications during the past decades[1, 2]. However, the RFQ's longitudinal shunt impedance decreases with the increasing particle energy during its acceleration, so the accelerating efficiency drops. In order to improve the accelerating efficiency within an energy interval of a few MeV, some ideas to insert accelerating gaps into the RFQ structure were suggested and tested[3, 4]. The studies on various RFQ and post-RFQ structures for accelerating protons, deuterons and heavy ions at Peking University (PKU) and the Institute of High Energy Physics (IHEP) in China will be presented.

2 Development of RFQ accelerators in China

2.1 Heavy ion RFQs

A 26 MHz RFQ for O^+ and O^- ions was constructed at PKU, which adopted an integral split ring (ISR) and a mini-vane structure (Fig. 1)[5]. The O^+ ions can be accelerated to 1 MeV with a peak current of more than 2 mA and a duty factor of 1/6 after upgrade[6]. The RFQ cavity is 2.6 m long and the RF power consumption is less than 30 kW at an inter-vane voltage of 70 kV.

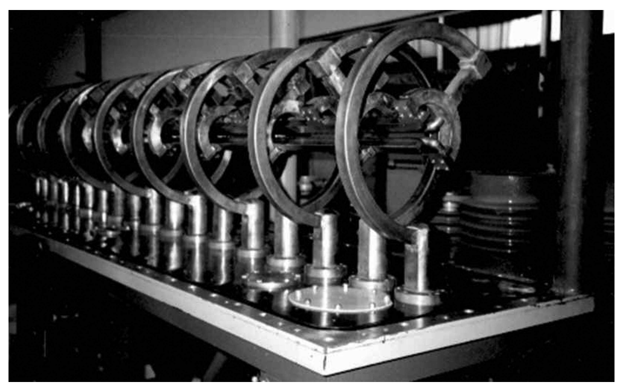

Fig. 1. Structure of 1 MeV O^+ ISR RFQ.

2.2 Separated function RFQ

To accelerate ion beams more efficiently in a higher energy range, a novel acceleration structure called a separated function RFQ (SFRFQ) has been proposed and developed at PKU[7]. A series of diaphragms are inserted into the two pairs of electrodes,

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1) E-mail: zhyguo@pku.edu.cn

as shown in Fig. 2, so the ions can be accelerated in the gaps of paired diaphragms 1 and 2, 3 and 4 etc., and can be focused outside the gaps, i.e. between the diaphragms 2 and 3, and so on. A SFRFQ is suitable to work between RFQ and DTL (Drift Tube Linac) with $\beta = 0.01$—0.1.

A 26 MHz SFRFQ prototype cavity was designed and constructed, which is to be running after the upgraded 1 MeV ISR RFQ as a post-accelerator to accelerate the O^+ ions to 1.6 MeV. To reduce the deceleration effect generated by the longitudinal reverse electrical field, the thickness of the second diaphragm in a pair is extended to about $\beta\lambda/4$. To enhance the transverse focus and to avoid the RF breakdown, the quadrupole bore is designed as an alternatively asymmetrical structure as shown in Fig. 2. The RF power test indicates that the designed inter-vane voltage of 70 kV can be safely reached with a RF power of about 19 kW[8].

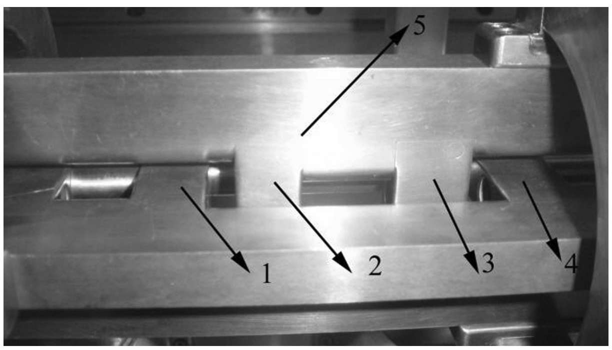

Fig. 2. Structure of SFRFQ electrodes. 1 and 2 are one pair of diaphragms, 3 and 4 are another pair. 5 is the electrode with asymmetrical quadrupole.

2.3 Proton RFQ

The major parameters of the ADS RFQ are listed in Table 1. To address the longitudinal field stability, this 3.5 MeV RFQ is separated into two resonantly coupled segments. Each segment consists of two technological modules of nearly 1.2 m in length. The ADS RFQ assembly is shown in Fig. 3. More detailed information about the design and development of the RFQ can be found in Ref. [9]. The duty factor is from 6% to 100%, which means the RFQ is designed with 100% duty in terms of the cavity and RF power source, but, as the first step, it was commissioned at 6% duty factor. In fact, the high power RF conditioning at 15% duty factor has been successfully performed.

In 2006 the beam commissioning at a low duty factor was carried out at IHEP. The duty factor gradually reached 7% with 1.43 ms pulse length at 50 Hz. An output beam current of 46 mA was obtained with an input beam current of 49 mA, resulting in a beam transmission of more than 93%. During the operation, the cooling water temperature was tightly controlled for fine tuning of the RFQ cavity resonant frequency. A digital RF control system based on FPGA was developed at IHEP and added to the RF system, which was provided by CERN. With this new feedback system the operation stability became better in the case of long pulses and heavy beam loading. The RF amplitude and phase stability reached ±0.4% and ±0.5°, respectively.

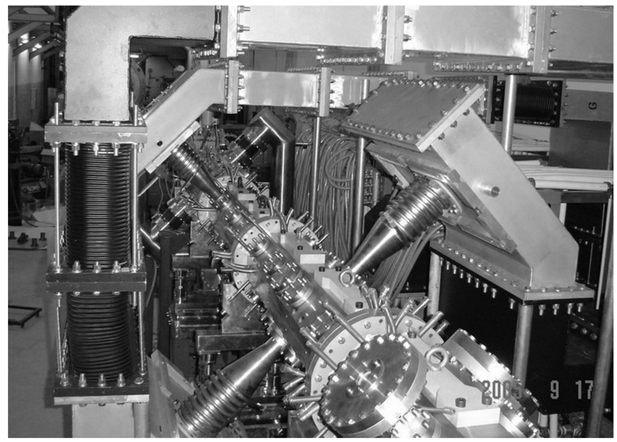

Fig. 3. ADS RFQ assembly.

Table 1. ADS RFQ major design parameters.

input energy/keV	75
output energy/MeV	3.5
peak current/mA	50
structure type	4 vane
duty factor(%)	6—100
RF frequency/MHz	352.2
maximum E_s/(MV/m)	33
beam power/kW	170
structure power/kW	420
total power/kW	590
total length/m	4.75

2.4 Deuteron RFQ

A 201.5 MHz 2 MeV deuteron RFQ accelerator is being constructed at PKU for neutron generation[10]. The designed output peak current is 40 mA with 10% duty factor. To suppress the emittance growth due to space charge effects and the energy transfer between the longitudinal and transverse motion, the matched and equipartitioned method was applied in the beam dynamics design. Considering the radiation safety and easy maintenance, the RFQ must have a high transmission and the energy of most of the lost particles should be controlled below 100 keV. In addition, the output RF power of the transmitter is limited by its final amplifier tetrode TH781. So the total length of the cavity should be less than 3 m and the inter-vane voltage should be lower than 80 kV. The beam dynamics design met all above requirements. The input energy is 50 keV, the average radius of the aperture is 3.64 mm, the maximum electrode modulation is 1.89, the maximum surface field is 27.67 MV/m, the corresponding Kilpatrick coefficient is 1.86, the electrode length is 2.695 m, and the inter-vane voltage is 70 kV.

In addition the RF structure design and the thermal design have also been carried out. The mini-vane electrodes are supported with 32 stems as shown in Fig. 4. The simulation indicates that the RF power consumed by the structure is about 250 kW at an inter-vane voltage of 70 kV. The maximum stem deformation due to temperature rise is 27 μm.

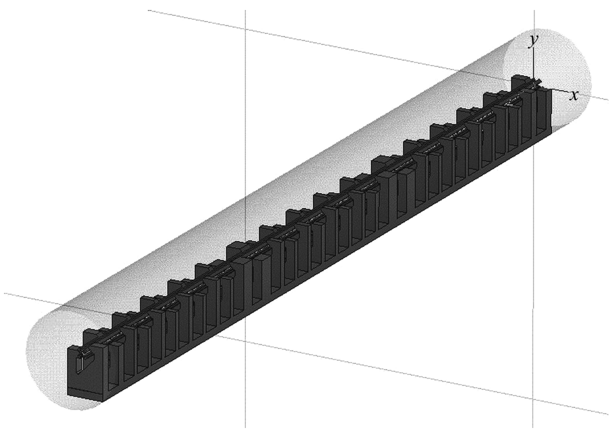

Fig. 4. RF Structure of D^+ RFQ.

2.5 RFQ particle dynamics design

For the RFQ particle dynamics design the international common simulation codes PARMTEQM and LIDOS are usually used. But for some special situations they are not so convenient. A code RFQDYN was developed at PKU, which can simulate the beam transmission with different ions and parameters for a fixed RFQ structure. We have studied the feasibility to use RFQ to construct an accelerator mass spectrometry (AMS). When the structure is optimized with ^{14}C, we can study the ^{13}C and ^{12}C transmission for the same structure[11].

In order to optimize the high current beam transmission through RFQ, the "match - equipartition method" was studied extensively at PKU[12, 13]. A RFQ design code MATCHDESIGN was developed which can realize the optimization automatically and generate the input file for the simulation.

The dynamics design of SFRFQ cannot use either PARMTEQM or PARMILA, so a code SFRFQCODE was developed at PKU for the SFRFQ design[14]. The code is based on the dynamics equation of SFRFQ, which considers the space charge effect. The code consists of a design module and a simulation module. The error tolerance analysis can be performed with the code.

2.6 Simultaneous acceleration of positive and negative ions in a RFQ

The advantage of simultaneous acceleration of positive and negative ions in a RFQ is that the space charge can be effectively neutralized in the LEBT and the beginning section of RFQ as well as at the target. Secondly, the charge of each beam bunch can only be half of the total charge as compared with single beam acceleration, which is helpful to reduce the space charge effect too.

The experiments and simulation of the dual beam simultaneous acceleration were carried out at PKU[15, 16]. The positive and negative oxygen ions were injected into an 1 MeV ISR RFQ, and the simultaneous acceleration of the dual beams was observed (Fig. 5). The simulation indicates that the transmission efficiency for dual beams is a bit lower than single beam, and the energy spread and emittance growth are also larger than the single beam situation.

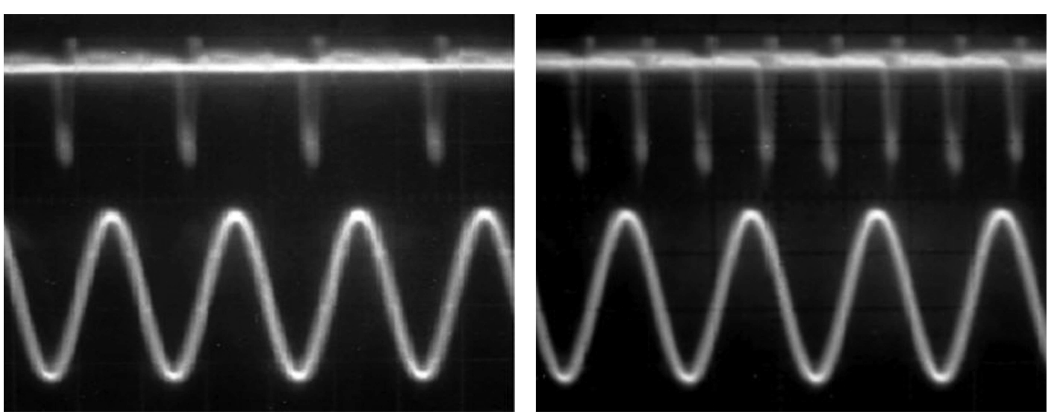

Fig. 5. Micropulses of O^+ beam (left) and O^+ & O^- beams (right).

Tsinghua University and IHEP also performed the simulation of the dual beam acceleration[17]. It is found that there is the phenomenon of capturing the particles with opposite charge during the bunch formation, which is the main cause of the increasing longitudinal loss.

3 Applications of RFQ

The RFQ accelerators are commonly used as injectors for linacs or synchrotrons, as ion implanters, and as neutron generators.

3.1 Injector for linac and synchrotron

RFQs have been widely used as injector for high-energy proton synchrotrons (LHC, DESY, J-PARC etc.), heavy ion and radioactive beam experimental facilities (ISAC, UNILAC, FAIR, RIA etc.), proton and heavy ion therapy facilities (HITACHI, IUCF, HIMAC, HICAT etc.), spallation neutron sources (ISIS, SNS, CSNS etc.), and other high power proton accelerators (HPPA), such as the designed ADS and IFMIF[1, 9].

Table 2. CSNS RFQ major design parameters.

RF frequency/MHz	324
structure type	4 vane
injection energy/keV	50
output energy/MeV	3.0
peak current/mA	40
duty factor(%)	1.05—2.1
input n. rms emittance/(πmm·mrad)	0.2
vane length/m	3.603
average bore radius/mm	3.565
inter-vane voltage/kV	80
total power/kW	410

The China Spallation Neutron Sources (CSNS) will use a 324 MHz proton RFQ as its injector. The design has been fulfilled at IHEP and the major RFQ parameters are listed in Table 2.

3.2 Intense neutron generator

RFQs are suitable to accelerate intense proton or deuteron beams up to several MeV. Intense neutrons can be obtained using such a beam to bombard D, T, Li and Be targets. This kind of neutron generator is a powerful candidate for BNCT and neutron radiography[2]. Hitachi uses a combined accelerator system, which includes a 4 MeV RFQ and a 7 MeV DTL, to construct a BNCT and a radioisotope production facility. In Italy, INFN-LNL is planning to use the 5 MeV TRASCO RFQ for BNCT.

Neutron radiography and tomography has wide applications in science and industry. The accelerator-based thermal neutron radiography system has advantages for the inspection of explosive devices, turbine blades, composite and aircraft maintenance etc. In such a case, the source must provide a thermal neutron flux of 10^5 n/(cm^2·s) or more at a collimation ratio $L/D = 30$[18]. A thermal neutron radiography facility based on the 2 MeV deuteron RFQ is being developed at PKU[19]. A thick Be target is used and the expected thermal neutron flux is (2—4)×10^5 n/(cm^2·s) at an $L/D = 50$.

4 Conclusions

The RFQ technology has been studied extensively in China. Both mini-vane and four-vane RFQs have been constructed and the beam tests have been performed. A novel SFRFQ structure was investigated and it may play an important role in extending the energy range of RFQ. It is anticipated that the CSNS RFQ and 2 MeV deuteron RFQ are to be set up and put into operation in the near future.

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