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DESIGN AND EXPERIMENT OF A WINDOW-TYPE CW DEUTERON RFQ*

K. Zhu†, P. P. Gan, Q. Fu, H. P. Li, Q. Y. Tan, S. Liu, L. Tao, M. J. Easton, Z. Wang, Y. R. Lu
Peking University, Beijing, China
Y. He, Q. Wu, W. P. Dou, C. Wang, H.W. Zhao
Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou, China

Abstract

A deuteron CW RFQ was designed and fabricated in Peking University. It will accelerate 50 mA CW deuteron beam from 50 keV to 1M eV at 162.5 MHz. The novel structure of four-vane with magnetic coupling windows was used to separate the dipole mode from the accelerating mode. The field tuning of this RFQ was different from conventional four vane RFQ because that the four quadrants of the RFQ cavity were coupled. The beam dynamics of the RFQ was designed by equipartition and matching method, limiting current effect was considered at the same time. The voltage between electrodes is 60 kV, the transmission efficiency of RFQ is 98%. For the copper cavity, the measured Q_0 of the operating mode is 96% of the simulated value. Only 47 hours was spent to increase CW power of cavity from 0 to 55 kW in high power test and The RFQ can operate stable at the design voltage. The preliminary H_2^+ beam experiment has been done and 1.78 mA CW beam was obtained at exit of RFQ. This paper will introduce the design and experiment of the RFQ.

INTRODUCTION

High current CW RFQ accelerators are very useful in fusion material study, nuclear waste transmutation, high intensity neutron source, boron neutron capture therapy, etc. Many international laboratory are developing the technology of high current CW RFQ. A CW RFQ for accelerating heavy ion was built for FRIB project [1]; deuteron CW RFQ accelerators were built for SARAF and IFMIF/EVEDA project [2, 3]; a proton CW RFQ accelerators was constructed for CADS project [4]. The important problem of CW RFQ is deformation caused by high power consumption and discharge of the cavity, which can easily lead to unstable operation. In order to accumulate experience and technology in design, fabrication and operation of high current CW RFQs, a deuteron CW RFQ has been designed and fabricated in Peking University which is supported by the 973 program funding. New structure, four-vane with coupling magnetic windows, is used for the RFQ. This structure was used for RFQ of heavy ions in America and Russia [5, 6]. Our RFQ is the first high frequency window-type RFQ.

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† zhukun@pku.edu.cn

BEAM DYNAMICS DESIGN

In the beam dynamics design, we controlled the limiting current from the gentle bunching section to the end of the acceleration section, and adopted a matched and equipartitioned design method to reduce the radius of the transverse envelope, suppress the increase of the emittance, and reduce the beam loss at high-energy section. The detail of the beam dynamics design can be found in our previous publication [7]. Figure 1 shows the main parameters changing with RFQ cells after optimization. Table 1 lists our final RFQ design parameters.

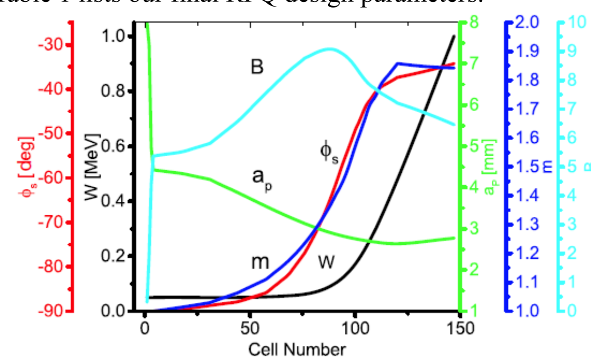

Figure 1: RFQ design parameters after optimization.

Table 1: Design Parameters of the RFQ

Parameter	Value
Current [mA]	50
Input energy [keV]	50
Output energy [MeV]	1.03
Inter-vane Voltage [kV]	60
Synchronous phase [Deg.]	-90 ~ -34
Kilpatrick coefficient	1.67
Modulation	1 ~ 1.86
Minimum aperture [mm]	2.63
Average aperture [mm]	3.88
Vane length [m]	1.81
Transmission [%]	98.2

COLD MODEL MEASUREMENT

The window-type RFQ RF structure design and the fabrication process can be found in Ref. [7]. In the beginning of 2018, we have completed the cavity fabrication and made low power RF test on the copper cavity. The measured RF characteristics of the RFQ cavity and the simulated ones are listed in Table 2. The operating frequency of the RFQ without tuning is 0.233 MHz below the simulated value. The measured Q_0 of the operating mode is 96% of the simulated value.

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Table 2: Comparison of the Simulated and Measured RF Parameters of the Cavity

Mode	Simulated		Measured					
	Frequency [MHz]	Intrinsic quality factor[a]	Frequency [MHz]	Intrinsic quality factor[a]	Loaded quality factor[a]	S_{21} [dB]	S_{11} [dB]	S_{22} [dB]
TE_{210}	161.930	9300	161.697	8962	7952	−18.68	−1.32	−0.89
$^{0}TE_{110}$	164.922	10427	164.664	10022	8654	−16.80	−1.51	−1.24
TE_{211}	177.840	5933	177.200	5916	5764	−31.84	−0.30	−0.15
$^{\pi}TE_{110}$	180.548	4298	182.645	4241	3896	−21.40	−0.85	−0.69
$^{0}TE_{111}$	183.273	4667	185.447	3349	3138	−23.73	−0.67	−0.50

[a] The electric conductivity of copper is adopted as: $\sigma=5.0\times10^{7}$ S/m.

Tuning of the RFQ includes adjusting the cavity frequency and the electric field distribution. Figure 2 illustrates the positions of the tuners relative to the coupling windows and the magnetic field distribution. The magnetic field varies periodically with the coupling windows, which indicates that the tuners in different longitudinal positions correspond to different tuning capability. Because of the half-window structure at the end of the horizontal electrodes, quadrants I and IV, and quadrants II and III are strongly coupled together, respectively. On the other hand, because of the windows in the vertical electrodes, quadrants I and II, and quadrants III and IV are weakly coupled together, respectively. To tune the asymmetry between the strongly coupled quadrants, tuner 3 and 4 are the most effective.

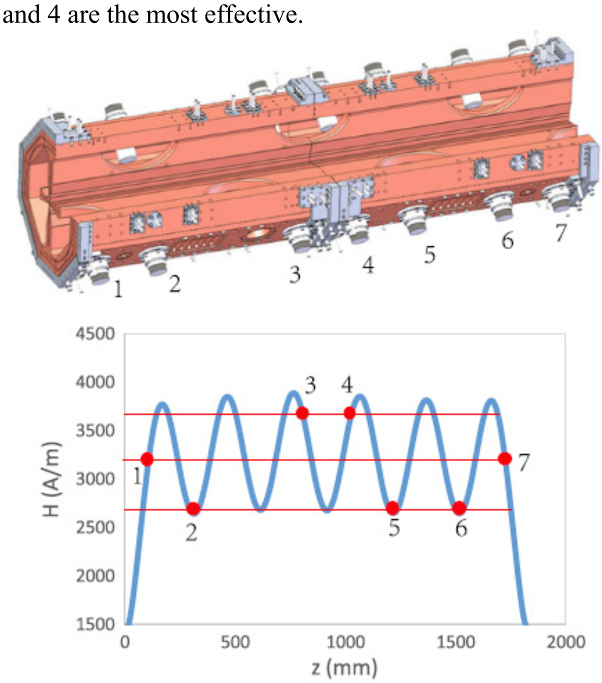

Figure 2: Positions of tuners relative to (top) the coupling windows and (bottom) the magnetic field distribution.

After tuning, we measured the frequency as 162.745 MHz. The electric field distribution of the four quadrants with simulated one is shown in Fig. 3. Excluding the electric field step, the maximum unflatness of the field in each quadrant ranges from +1.53% to −1.28%, and the asymmetry of the four quadrants ranges from +0.91% to −0.77%.

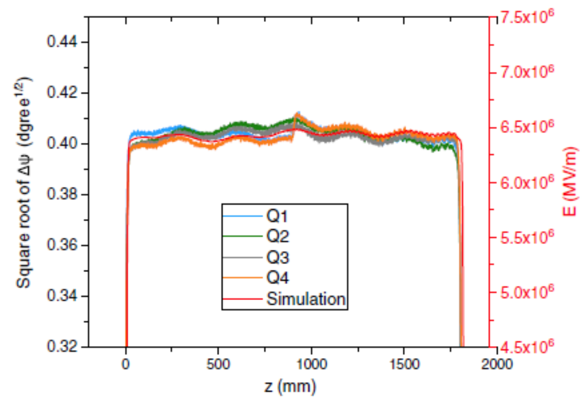

Figure 3: Measured and simulated electric field distributions after tuning.

HIGH POWER TEST

The RFQ is driven by two solid-state RF amplifiers of 80 kW through two couplers. After about 47 hours of conditioning, CW power up to 55 kW was transmitted into the RFQ. During the conditioning, the only problems triggered were occasional vacuum and power reflection protection trips, and no sparks were detected by the arc detectors. The RFQ had operated for 1 hour and 25 minutes in 55 kW CW mode before a spark occurred. Additionally, we recorded over 7 hours of uninterrupted (no-spark) operations at CW power of 50 kW, as shown in Fig. 4. These results indicate that the RFQ cavity design was successful and it can run stably in high power CW mode. We carried out the inter-vane voltage calibration using X-ray spectrum measurements. The results indicate that the RFQ needs around 50 kW to generate the inter-vane voltage of 60 kV.

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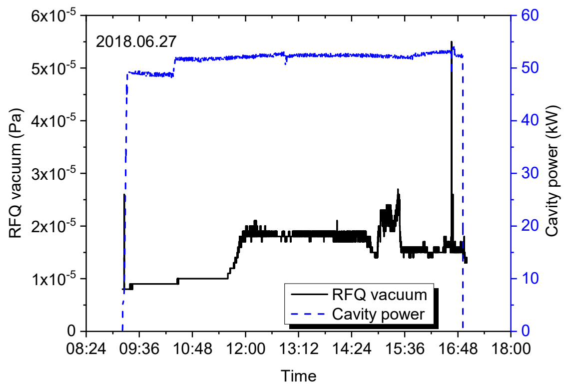

Figure 4: Uninterrupted (no-spark) operations at CW power of 50 kW recorded over 7 hours.

BEAM EXPERIMENT

The experimental setup for the beam experiment of the RFQ is shown in Fig. 5. It consists of an ECR ion source, an LEBT system based on three solenoids and a 32.5° bending magnet, the RFQ and an MEBT section. A fast current transformer (FCT) and a beam position monitor (BPM) were installed after the exit of the RFQ for beam energy measurement. Two water-cooled Faraday cups (FC) were used for transmission measurement.

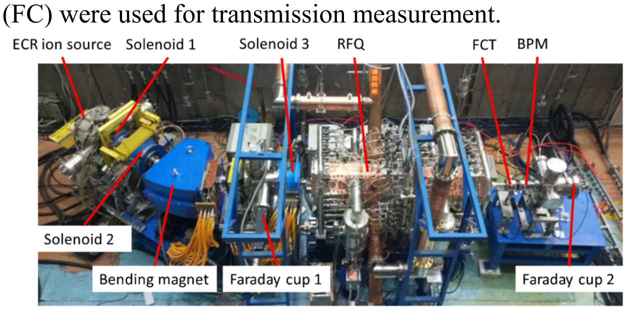

Figure 5: Overview of the RFQ test area.

We measured the beam energy of the RFQ using the time of-flight (TOF) method. Figure 6 shows the distance between the FCT and BPM, and the corresponding time signals. We made ten measurements, and the averaged output energy of the RFQ is 1.04 MeV ± 0.01 MeV, which is consistent with the simulated value of 1.03 MeV.

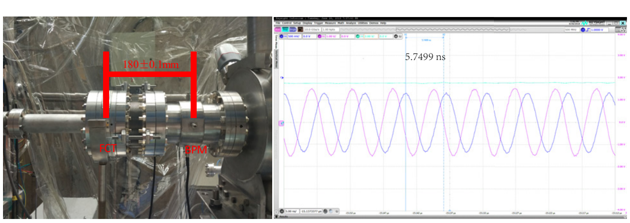

Figure 6: Measured distance and beam signals detected by the FCT and BPM (the FCT signal is blue, the BPM signal is pink).

Figure 7 shows the beam current at FC1 and FC2 during one hour of CW operation at a cavity power of 50 kW. Due to sparks in the ECR ion source, the FC2 beam current drops off three times. The RFQ vacuum is mostly stable at 8×10^{-6} Pa during the CW beam transmission. The transmission efficiency of the CW beam does not vary much in the range from 1.5 mA to 2 mA, with an average of over 90% transmission, as shown in Table 3. The reason that the measured transmission did not reach the designed 98% is mainly attributed to the mismatching between the LEBT and RFQ.

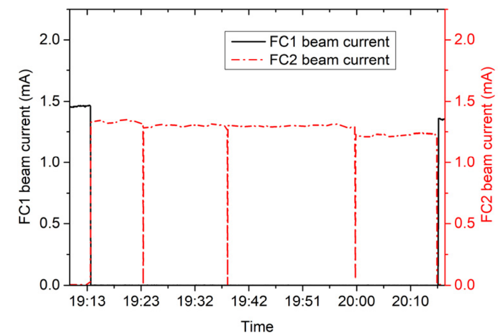

Figure 7: Change of FC1 and FC2 beam current during one hour of CW operation.

Table 3: CW Beam Transmission

FC1 beam current [mA]	FC2 beam current [mA]	Transmission [%]
1.53	1.38	90.2±1.8
1.65	1.48	89.7±1.8
1.67	1.51	90.4±1.8
1.95	1.78	91.3±1.8

CONCLUSION

We have constructed and tested the first high frequency window-type CW RFQ. For the low power test, the experimental and simulated results show good agreement. The RF conditioning results have indicated a successful RF structural design. For the beam commissioning, H_2^+ beam was accelerated to 1.04 MeV. One hour of stable CW operation has been successfully demonstrated. These results illustrate the great success of this CW RFQ. The experience of the design and fabrication can be applied to future CW RFQs.

ACKNOWLEDGEMENTS

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REFERENCES

[1] G. Pozdeyev, "FRIB Front End Construction and Commissioning", in *Proc. 9th Int. Particle Accelerator Conf. (IPAC'18)*, Vancouver, Canada, Apr.-May 2018, pp. 58-62. doi:10.18429/JACoW-IPAC2018-MOZGBF1

[2] P. Fischer,A. Schempp, and J. Hauser, "A cw RFQ accelerator for deuterons", in *Proceedings of the 21th Particle Ac-*

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celerator Conference, Knoxville, TN, 2005 (IEEE, Piscataway, NJ, 2005), pp. 794–795.

[3] J. Knaster, Y. Okumura, P. Cara, A. Kasughai, and M. Sugimoto, "Challenges of the High Current Prototype Accelerator of IFMIF/EVEDA", in *Proc. 7th Int. Particle Accelerator Conf. (IPAC'16)*, Busan, Korea, May 2016, pp. 52. doi:10.18429/JACoW-IPAC2016-MOZB02

[4] C. Meng *et al.*, "Beam Commissioning of C-ADS Injector-I RFQ Accelerator", in *Proc. 6th Int. Particle Accelerator Conf. (IPAC'15)*, Richmond, VA, USA, May 2015, pp. 3827-3829. doi:10.18429/JACoW-IPAC2015-THPF057

[5] P. N. Ostroumov *et al.*, "Development and beam test of a continuous wave radio frequency quadrupole accelerator", *Phys. Rev. Spec. Top. Accel. Beams*, vol. 15, pp. 110101, 2012.

[6] V. A. Koshelev *et al.*, "Design of 4-vane RFQ with Magnetic Coupling Windows for Nuclotron Injector Lu-20", in *Proc. 28th Linear Accelerator Conf. (LINAC'16)*, East Lansing, MI, USA, Sep. 2016, pp. 575-577. doi:10.18429/JACoW-LINAC2016-TUPLR050

[7] Fu Q., Zhu K., Lu Y. R. *et al.*, "Design and cold model experiment of a continuous-wave deuteron radio-frequency quadrupole", *Physical Review Accelerators and Beams,* vol. 20, p. 120101, 2017.