BEAM COMMISSIONING AND NEUTRON RADIOGRAPHY ON A HIGH CURRENT DEUTERON RFQ*

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Abstract

The high current deuteron RFQ has been developed and widely used in many projects, especially for accelerator based neutron source and its applications. This paper presents the beam dynamics, structure design, RF full power test and beam commissioning of PKUNIFTY (Peking University Neutron Imaging Facility), which consists of a high current compact ECR source, a 201.5 MHz four-rod deuteron RFQ, thick beryllium target, moderator, collimator and neutron radiography system. RF and beam commissioning with duty cycle of 4% show the RFQ inter-vane voltage reaches 70 kV at about 240 kW, the delivered peak current of deuteron beam is about 12 mA at 300 kW with the beam transmission of about 60%. The improvement of transmission is going on. The initial neutron radiography test has been carried out. The results will promote the future development of small accelerator based neutron source.

INTRODUCTION

Radio frequency quadruple (RFQ) accelerators have been widely used not only as injectors in many large scale accelerators such as SNS, ISIS, LHC, but also as small high flux fast neutron generators. A high current deuteron RFQ was developed at the State Key Lab of Nuclear Physics and Technology at Peking University in the last several years for neutron radiography and other applications. It accelerates deuterons from 50keV to 2.0MeV with peak beam current up to 50 mA. The repetition frequency is 100 Hz or 160 Hz, and duty cycle can be adjusted from 1% to 10%. The beam dynamics design was completed in 2006. The PKUNIFTY design had passed international review and the project was funded in 2008. The manufacturing of RFQ cavity was finished at the end of 2010. RF commissioning of RFQ cavity was carried out in 2011. The PKUNIFTY was completed at the beginning of 2012. The RFQ beam commissioning, first neutron beam and first neutron radiography were main achievements at 2012. All these results will be presented in this paper.

PKUNIFTY DESIGN

PKUNIFTY, shown in Fig.1, consists of ECR ion source, LEBT, RFQ accelerator, HEBT, Beryllium target and neutron imaging system. ECR ion source can provide deuteron beam 83 mA with its emittance of about 0.18π mm mrad at extraction voltage of 50 kV [1]. The LEBT has two solenoids and X,Y steers. The basic parameters of this RFQ are listed in Table 1. The target is made of beryllium with thickness of 2 mm, which is clamped on an aluminum alloy frame and cooled by water.

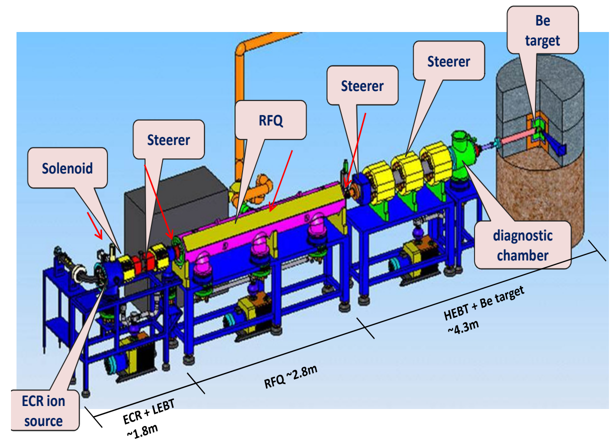

Figure 1: Schematic diagram of PKUNIFTY.

Table 1: Main Parameters of Deuteron RFQ [2]

Parameters	Values
Fequency (MHz)	201.5
Peak current (mA)	50
Duty factor	1%-10%
Repetition frequency (Hz)	100,160
Intervane Voltage (kV)	70
Kilpatrick	1.86
Cell number	195
length (cm)	269.5
Cavity diameter (cm)	30.0
Average aperture (mm)	3.64
Minimum aperture (mm)	2.52
Electrode modulation(Max)	1.89
Synchronous phase [°] (deg)	-27.3
Input emittance, x,y,norm,rms (π mm·mrad)	0.2
Output emittance, x,norm, rms (π mm·mrad)	0.199
Output emittance, y,norm, rms (π mm·mrad)	0.193

RF COMMISSIONING OF RFQ

The RFQ cavity is shown in Fig. 2a. The dedicated 400 kW RF transmitter with operating frequency range from 199 MHz to 203 MHz has been manufactured and tested successfully [3]. A 201.5 MHz, 1 mW CW signal generated by HP 8656B signal generator is transmitted to solid amplifier. A 1 kW solid amplifier operating in

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pulsed mode is used as an exciter for a 20 kW IPA (Intermediate Power Amplifier). The 20 kW IPA (Intermediate Power Amplifier) is consisted of tetrode FU-113F. The 400 kW FPA (Final Power Amplifier) is also a tube amplifier equipped with a TH781 tetrode. The typical rating for tetrode TH781 is 200 kW in CW mode with frequency at 200 MHz. For the pulse mode, it is suitable to operate up to 250 MHz, and can deliver pulse peak power 400 kW with the duration up to 1.4 ms and the duty cycle up to 16%. Its Maximum rating of output power at 200 MHz is 450 kW meanwhile plate dissipation power is about 250 kW in peak [4]. The output RF power is delivered by a 4-1/8" coaxial transmission line and fed into the RFQ cavity by loop coupler with high vacuum porcelain sealed RF windows. The loop coupler of about 15 cm^2 between two neighbouring stems can be rotated slightly to achieve proper impedance matching between the RFQ cavity and the RF transmitter, and the structure of the loop coupler is shown in Fig. 2b. The input impedance of RF coupling loop comes out to be 49.2 ohms, i.e. S11 for impedance matching is -40.1 dB at operating frequency 201.52 MHz. The measured Q_0 value is about 3117, a bit less than the CST simulated value 3886.

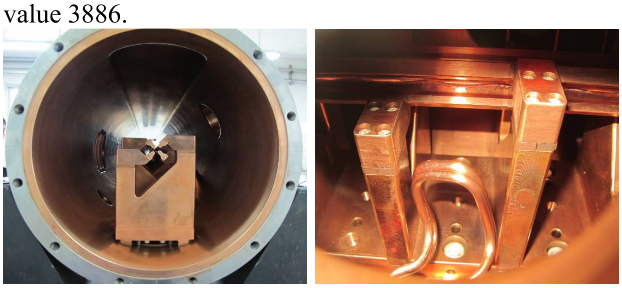

Figure 2: RFQ inner structure (above left), Magnetic coupler (above right).

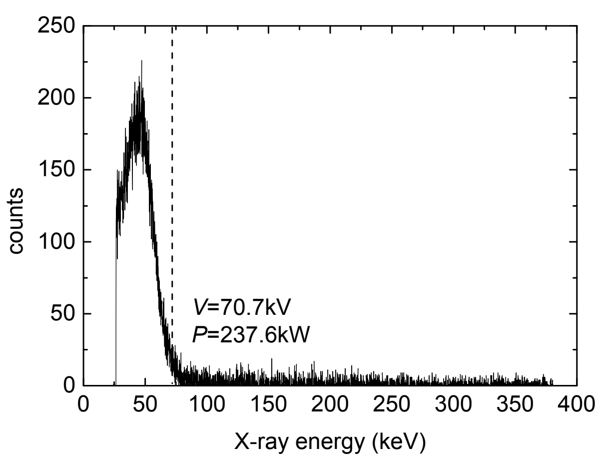

Figure 3: Roentgen spectrum at 237.6kW.

When RF power and cooling water were applied, the cavity was operated with vacuum ~ 10^{-6} Pa. The RF power up to 280 kW was fed into the RFQ cavity at 4% duty cycle. The bremsstrahlung spectrum of X-ray method provides a precise technique for measuring inter-electrode voltage. To obtain the inter-electrode voltage, a high purity Ge detector cooled by liquid nitrogen was placed opposite to the observation window made by lead glass to measure the energy spectrum of x-rays. An ORTEC computer multi-channel system was employed to deal with the signal, which consists of a preamplifier, a master amplifier, a PCI computer multi-channel card and a notebook PC. The system was calibrated by using standard radiation sources ^{152}Eu. After adjusting the amplification factor properly, setting the 344.31 keV x-ray peak of ^{152}Eu at channel 3705, then another two peaks appeared at channels 1310 and 2633 corresponding to ^{152}Eu 121.78 keV and ^{152}Eu 244.697 keV, respectively. The above 3 points fit a good linearity, which means that the measuring system calibration is successful，and the conversion factor is 0.093 keV/channel.

From the measured Roentgen spectrum at RF power 237.6 kW shown in Fig. 3, the inter-electrode voltage reaches 70.7 kV, which is higher than the designed value 70 kV. The specific shunt impedance is defined as $R_s = (V^2/P)L = R_pL$, where L=2699.6 mm is the length of the RFQ. so the corresponding specific shunt impedance is about 52.7 kΩ•m [4].

BEAM COMMISSIONING

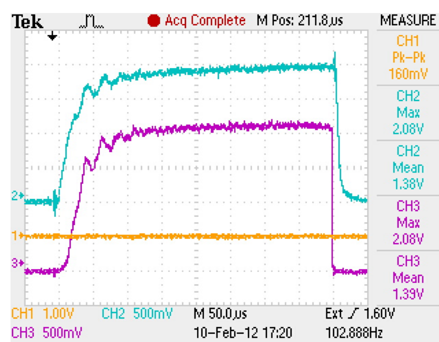

Figure 4: Input and output current waveform.

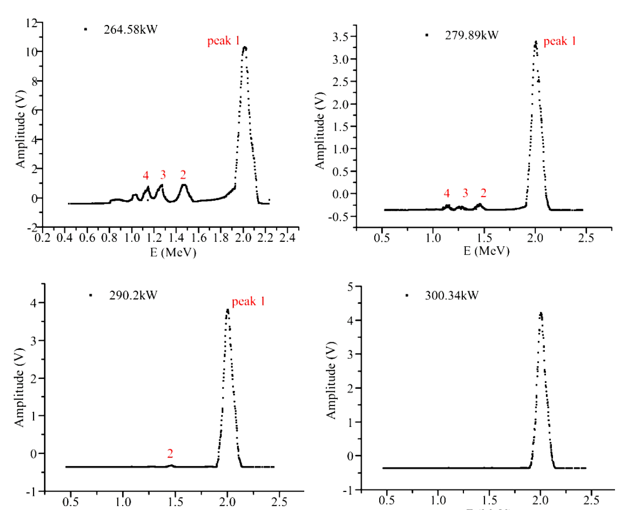

Figure 5: Output deuteron energy spectrum at different RF power.

Beam commissioning operated from duty cycle 1% with repetition frequency 100 Hz. Although the ECR can deliver very high deuteron current, the discharging chamber for lower current output less than 20 mA is not so stable for short pulse duration. We really don't hope so many particles will possibly be lost in the RFQ cavity to bombard on the RFQ electrodes. Finally we use 4% at 100 Hz to measure the beam transmission and output deuteron kinetic energy. Figure 4 shows the measured beam waveforms, which were measured by ACCT at 290 kW RF power and 4% duty cycle at the entrance and exit of RFQ, respectively. After the calibration, the output (pink) beam current is only half of input one (blue). This will be improved in the near future.

The output deuteron beam energy was analysed by a analysing magnet and recorded by computer automatically (shown in Fig. 5). When input RF power is less than 290 kW, there are many particles not to be accelerated to 2.0 MeV, one can see several peaks with less energy. When the RF power is higher than 300 kW, the output energy spectrum is very clean and the corresponding deuteron kinetic energy is exactly 2.0 MeV with energy spread of about 2.5%.

Up to now, the beam experiment doesn't go up to higher duty cycle because the transmission wasn't improved so well although the cooling water temperature difference from the inlet and outlet water is less than 3°C after system balance. The water cooling system didn't operate at fixed water temperature mode because the refrigerator worked in running/stop mode not in faster /slow mode.

NEUTRON RADIOGRAPHY

Because of the RFQ transmission, we limit the input beam current at nearly 20 mA, the maximum of output beam current goes up to 12 mA, transmission efficiency is about 60% after the realignment of inner RFQ accelerating structures. For the neutron imaging experiments, the output peak beam current is kept as 10 mA. The averaged beam current on the beryllium target is about 330 μA. The thermal neutron flux was measured by means of gold activation, and the spatial resolution was measured using the line-pair card of Gd. The current performance PKUNIFTY was listed in Table 2.

Table 2: Current Performance of PKUNIFTY [5]

Parameters	Unit	Value
Fast neutron yield	n/s	2.4×10^{11}
Thermal neutron flux on the imaging plane with *L*/*D* = 50	n/cm^2/s	2.35×10^4
Collimation ratio (*L*/*D*)		50 – 200
Field of view	cm^2	21 × 21
Spatial resolution	mm	0.33
Dynamic range of gray level		195:1
Contrast sensitivity of thickness		<5%

Figure 6 shows some examples of neutron radiographs taken on PKUNIFTY. If we didn't melt the candle to cover the gap of Chinese writing to enhance the contrast, we couldn't distinguish the Chinese carving so well. One can also see the thickness difference clearly by the thickness sensibility experiments.

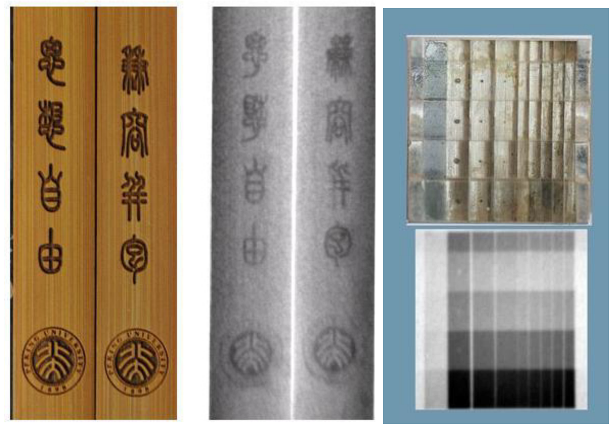

Figure 6: Examples of neutron radiography.

CONCLUSIONS

The four rod 201.5MHz deuteron RFQ with duty cycle of 10% has been manufactured and tested at 4% in the past years. The output deuteron energy is 2.0 MeV at 300 kW with energy spread of 2.5%. the fast neutron yield achieves 2.4×10^{11}/s at average beam current of 330 μA (peak current of 10 mA). Some neutron radiography experiments have been carried out. Several images got from neutron radiography experiments show good spatial resolution. It shows good potential in industrial applications.

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