Conference Union of Compact Accelerator-Driven Neutron Sources I & II

Design of RFQ Accelerator Facility of PKUNIFTY

Xueqing Yan\textsuperscript{a}, Kun Zhu\textsuperscript{a}, Yuanrong Lu\textsuperscript{a}\* , Shixiang Peng\textsuperscript{a}, Shuli Gao\textsuperscript{a}, Jie Zhao\textsuperscript{a}, Chuan Zhang\textsuperscript{b}, Zhiyu Guo\textsuperscript{a}

\textsuperscript{a}State Key Laboratory of Nuclear Physics and Technology & School of Physics, Peking University, Beijing 100871, China
\textsuperscript{b}Institute for Applied Physics, Johann Wolfgang Goethe University, Frankfurt am Main, Germany.

Abstract

The Peking University Neutron Imaging Facility (PKUNIFTY) is being constructed, which is a compact accelerator-driven neutron source. The accelerator is a radio frequency quadrupole (RFQ) accelerator, which can deliver a 2 MeV deuteron beam. The neutrons are generated by deuterons bombarding beryllium target. The accelerator facility mainly consists of ECR (electron cyclotron resonance) ion source, LEBT (low energy beam transportation), RFQ cavity, HEBT (high energy beam transportation), RF transmitter and control system. This paper will introduce the requirements and design of that accelerator facility.

© 2012 Published by Elsevier B.V. Selection and/or peer-review under responsibility of UCANS

Keywords: RFQ; Beam dynamics; RFQ structure; ECR ion source.

1. Introduction

Varieties of small neutron sources based on the high current radio frequency linear accelerators such as RFQ and DTL have expanded widely around the world. Most of them are using high current proton or deuteron beam bombarding the beryllium or lithium target \cite{1}-\cite{3}. A 2 MeV 201.5 MHz 50 mA deuteron RFQ accelerator with duty factor of 10\% was proposed and constructed at Peking University in the last several years, which consists of an RFQ accelerator, 2.45 GHz ECR ion source, LEBT (low energy beam transportation), HEBT (high energy beam transportation) and water cooled beryllium target.

The Peking University neutron imaging facility (PKUNIFTY) is based on that RFQ accelerator, and will use 9Be (d,n) nuclear reaction to generate neutrons\cite{4}. Bombarding beryllium target with 2 MeV 40

* Yuanrong Lu. Tel.: +086-10-62755023; fax: +086-62751875.
E-mail address: yrlu@pku.edu.cn.
mA deuteron beam under 10% duty factor will produce neutron yield of $3 \times 10^{12}$ n/cm$^2$/s. Some specifications and constraints of this RFQ accelerator are as the follows:

(a) A 2.0 MeV deuteron beam with a peak current more than 40 mA and a duty factor of 10%.

(b) The beam transmission efficiency is as high as possible, and the kinetic energy of most lost particles should be less than 100 keV.

(c) The peak RF power is limited to less than 400 kW. A single THALES tetrode TH781 RF amplifier will deliver maximum 400 kW peak power with 10% duty factor and 1 ms of pulse duration. The operating frequency could be tuned from 198 to 203 MHz.

(d) The RFQ inter-electrode voltage is constrained to 70 kV throughout the RFQ, which is convenient for tuning.

(e) The deuteron injection energy to the RFQ is chosen as 0.05 MeV. A lower injection energy gives a shorter RFQ, this will minimize construction costs and rf dissipation power, but make it more difficult to minimize beam losses. For injected 50 mA deuteron beam current, a higher injection energy is preferred for depressing space charge forces, although the RFQ becomes longer, more expensive and needs more rf power.

(f) Based on the survey on the specific shunt impedance of some existing four-rod RFQs, the total deuteron RFQ electrode length is expected to be less than 3 m with respect to the available RF power and the required beam current and energy.

(g) The RFQ cavity design should use RAMI technology, which means all the system should have the high reliability, availability, maintainability and inspectability.

To fulfill the above goals the matched and equipartitioned beam dynamics design [5], mechanical structure design, RF system design, ECR ion source upgrade and extraction electrode optimization were carried out.

2. ECR ion source and LEBT

The ECR ion source and LEBT were designed and tested. PBGUN and Trace3D have been used to design the beam transportation from the extraction of 2.45 GHz ECR ion source to the entrance of RFQ. The selection of injection beam parameters of RFQ are based on the initial ion source test bench results. The first experiment was carried out with proton beam. More than 100 mA proton beam has been extracted at 50 kV; however, the extracted proton beam has too larger emission angle. After the electric field simulation and analysis in the extraction area, the plate extraction electrodes have been replaced by 90° cone electrodes. Then more than 100 mA proton beam with 0.13 mm-mrad normalized rms emittance has been extracted in the improved ion source [6]. Afterwards the further experiments for the deuteron beam extraction have been investigated in the last two years [7]. It shows that the deuteron beam up to 83 mA with 0.18 mm-mrad normalized rms emittance can be extracted from 2.45 GHz ECR ion source at 50 kV, which can fulfill the requirements of RFQ accelerator for the PKUNIFTY.

3. RFQ beam dynamics design

RFQ Linac can be divided into four sections: Radial Matching (RM), Shaper (SH), Gentle Buncher (GB) and Acceleration section (AC). The dynamics design of RFQ Linacs for high intensity beams had been extensively studied by LANL. Nowadays the most popular RFQ design codes are PARMTEQM [8], TOUTATIS [9], LIDOS [10] and pteqHI [11]. Every code has their speciality. We prefer the PARMTEQM 3.05 version for the deuteron RFQ beam dynamics design and optimization, meanwhile MATCHDESIGN code [12] are used to generate the input file of PARMTEQM, to verify our design strategy and simplify the design process. There are so many parameters that can be adjusted along the
RFQ accelerating cells, many different designs can reach quite good transmission by run of PARMTEQM. According to our strategy, the following three equations are important to keep the transverse oscillation energy not to go up, because the input mismatch is the source of emittance growth and beam halo formation. They are two envelope equations

\[
\frac{\mathcal{E}_n}{b\sigma_t} = a^2 \mathcal{E}_0 \sigma_t^2 / \lambda \\
\frac{\mathcal{E}_n}{b\sigma_l} = a^2 \mathcal{E}_0 \sigma_l^2 / \lambda
\]

and an equipartitioned equation

\[\frac{\mathcal{E}_n \sigma_t}{\left(\mathcal{E}_0 \sigma_t \right)} = 1 \quad \text{or} \quad \frac{a \sigma_t}{\sqrt{b \sigma_l}} = 1 \] (3)

where \(\sigma_t\) and \(\sigma_l\) are the transverse and longitudinal phase advance with beam current, \(\mathcal{E}_n\) and \(\mathcal{E}_n\) are the normalized transverse and longitudinal rms (root mean square) emittance, \(a\) and \(b\) are transverse and longitudinal rms beam radii (assuming an ellipsoidal distribution). Only above three controlling equations (1~3) are really available to solve the four beam parameters (\(\mathcal{E}_n\), \(\mathcal{E}_n\), \(a\), \(b\)) and the four design parameters for each cell of a RFQ accelerator \(B(n)\), \(\Phi_s(n)\), \(m(n)\) and \(V_0(n)\), where \(B\) is the focusing parameter for RFQ accelerator, \(n\) denotes cell number, \(\Phi_s\) is the synchronous phase, \(V_0\) is the intervane voltage and \(m\) is the modulation of the electrode. The voltage \(V_0\) is chosen and fixed as a constant.

The design results are shown in Table 1. The beam transmission along the accelerating cell is shown in Fig.1. The Fig.2 and Fig.3 show the particle distributions at the entrance and exit of RFQ, respectively.

Table 1. Main parameters of Deuteron RFQ

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (MHz)</td>
<td>201.5</td>
</tr>
<tr>
<td>Peak current (mA)</td>
<td>50</td>
</tr>
<tr>
<td>Intervane Voltage (kV)</td>
<td>70</td>
</tr>
<tr>
<td>Kilpatrick</td>
<td>1.86</td>
</tr>
<tr>
<td>Cell number</td>
<td>195</td>
</tr>
<tr>
<td>length (cm)</td>
<td>269.5</td>
</tr>
<tr>
<td>Cavity diameter (cm)</td>
<td>30.0</td>
</tr>
<tr>
<td>Average aperture (mm)</td>
<td>3.64</td>
</tr>
<tr>
<td>Minimum aperture (mm)</td>
<td>2.52</td>
</tr>
<tr>
<td>Electrode modulation (Max)</td>
<td>1.89</td>
</tr>
<tr>
<td>Synchronous phase [°] (deg)</td>
<td>-27.3</td>
</tr>
<tr>
<td>Input emittance (\epsilon_{\text{x,y,rms},\text{rramp}}) ((\mu\text{m} \cdot \text{mrad}))</td>
<td>0.2</td>
</tr>
<tr>
<td>Output emittance (\epsilon_{\text{x,rms},\text{rramp}}) ((\mu\text{m} \cdot \text{mrad}))</td>
<td>0.199</td>
</tr>
<tr>
<td>Output emittance (\epsilon_{\text{y,rms},\text{rramp}}) ((\mu\text{m} \cdot \text{mrad}))</td>
<td>0.193</td>
</tr>
<tr>
<td>Output emittance (\epsilon_{\text{z,rms}}) (MeV·deg)</td>
<td>0.134</td>
</tr>
<tr>
<td>Transmission Efficiency (%, elimit=0.5 MeV)</td>
<td>93.0</td>
</tr>
<tr>
<td>Estimated rf power loss (kW)</td>
<td>270</td>
</tr>
</tbody>
</table>
High current RFQs always have beam losses. Because of the risk of radiation, the beam dynamics analysis of the design scheme is necessary. Theoretically the first quality criterion of a design is the beam transmission efficiency. In practice, the following two points are more important: (1) the energy distribution of lost particles; (2) the sensitivity of the design scheme to variation of input beam parameters. Obviously, the beam loss is very small on the high-energy section, which helps to reduce D-D reaction and the difficulty of radiation shielding.

Fig. 1. Beam transmission along the accelerating cell.

Fig. 2. Particle distributions at entrance of RFQ
We can use the Matching and EP parameters to check the PKU deuteron RFQ designs. Fig. 4 shows that the transverse beam radius is nearly kept constant, which is of great benefit to decrease the beam loss later in the RFQ. Fig. 5 shows that in the case of short-length-requirements equipartitioning is unnecessary, and the equipartitioning state is realized only in the end.
4. Tolerance analysis of RFQ input parameters

The analysis was also focused on the influence of a non-ideal input beam. In the PARMTEQM 3.05 simulation the input beam was supposed to have a waterbag distribution, i.e. an evenly distribution in the four-dimensional transverse phase space and without energy spread in the longitudinal direction. In this design, the matched Twiss coefficients, \(a_x(a_y)\) and \(\beta_x(\beta_y)\) are 1.93 and 5.36 cm/rad; respectively. Since some input parameters will change and the non-ideal beam will affect the beam transmission, the studies on the sensitivity of the design scheme were started with the premise of fixing the designed electrode structure and varying only one input beam parameter at a time.

Firstly, \(a_x\) ranged from 1.43 to 2.43 and \(\beta_x\) ranged from 4.86 to 5.86 cm/rad for 10 values, respectively. Fig. 6 shows that: (1) the beam transmission is best when the value is matched; (2) the higher the matched value, the lower the beam transmission; (3) the beam transmission varies approximately between 5% and 3% over the scanned parameter range. Secondly, the influence of the input energy spread \(\Delta W/W\) and the input emittance \(\epsilon\) were explored. \(\Delta W/W\) was varied from 1% to 11% of the input energy and random distribution was applied. The emittance \(\epsilon\) was changed for 10 values around 0.0164 cm rad (the designed value). The maximum variations of the beam transmission are approximately 10% and 12% (see Fig. 7). Then the beam transmission as a function of the input beam current was plotted. In Fig. 8, it is smoothly decreasing with increasing beam current and the design point locates in a safe region.

All analyses show that a matched and quasi-equipartitioned beam leads to the best beam transmission. This design scheme is not sensitive to the deviations from the ideal input beam parameters which will happen in practical operation of the RFQ system.
**Fig. 6.** Beam transmission vs. beam input twiss parameters

**Fig. 7.** Beam transmission vs. input energy spread and input emittance
5. RFQ structure design

The RFQ inner structure design is composed of mini-vane electrodes, 32 supporting plate stems and mounting ground plate. They are all water-cooled. The electrodes will be divided to three segments and water-cooled separately. That is the reason why the supporting stems 11, 12, 21 and 22 are much thicker than the other stems. The water-cooling tubes are silver welded with connection copper blocks and pass through the supporting stem to the cavity outside. There is no water sealing and vacuum sealing o-ring inside the cavity. So the RF connection can be ensured to have RF power dissipation as less as possible.

The tuning of the cavity has been performed by the initial electromagnetic field simulation and bead pull measurement. The frequency can be adjusted by the mounting height h of the electrodes. There are also four stub tuners along the cavity, which can be adjusted based on both the field distribution along the axis and the cavity resonating frequency. The supporting stems 11, 12, 21 and 22 are also very useful to balance the field distribution along the axis, but it will make the field and the frequency go up. Another way to change the field and the frequency is putting some additional copper blocks between supporting stems. There are different results when the tuning is done in such a way. At both ends of the cavity, it will make the field at both ends of electrodes go down. But if it is put in the middle of the cavity, it will make the local field go up. The changing of frequency is similar to go up no matter where it is put. This is very sensitive tuning method but it increases additional RF power dissipation. So its RF contacting is very important.

From the field simulation, the RF power dissipation or power density distribution for the different components can be delivered to the code ANSYS to do the thermal analysis. The thermal analysis shows...
the water temperature rising at both ends of electrodes is only about 4.5°C, the deformation of the electrodes is very small. Because the supporting stems dissipate 69% of total RF dissipation power 270 kW, the deformation of the stem is about 20 μm.

400 kW amplifier with TH781 hypervaportron tetrode has been tested successfully with 1% up to 8% duty cycle and repetition frequency of 100 Hz [13]. The 80 kW water cooling system composed of two 40 kW refrigerators, 1.6 m³ de-mineral water container, three water pumps with maximum 8 m³/h water flowing has been completed and run nicely. It will provide the cooling water for the cavity and RF amplifier. The water inlet temperature could be handled in the room temperature ±2°C. The controlling of cooling water system is made of Siemens 200 PLC. The RF magnetic feeder for the deuteron cavity is also water cooled. The loop area is about 15 cm².

6. Conclusion

A 201.5 MHz 2 MeV deuteron RFQ with 10% duty cycle and 100 Hz repetition frequency has been designed and constructed in the last two years. The beam dynamics simulation and tolerance analysis with a matched and equipartitioned design method has been completed. The design makes the cavity length about 2.7 m, and the RF dissipation power is only about 270 kW. The beam transmission can be better than 93% for a 50 mA injection deuteron beam. The low level RFQ cavity measurements verify the electromagnetic field simulation and rf structure design. The initial ECR ion source and LEBT tests show that it is able to extract more than 50 mA deuteron beam at 50 kV with normalized rms emittance better than 0.2 mm-mrad. The RFQ system has been pumped to the vacuum of 2.3×10⁻⁵ Pa. The rf power commissioning will be carried out soon.

Acknowledgements

The authors would like to thank Prof. Dr. U. Ratzinger, H. Klein and A. Schempp at IAP in Frankfurt University for long term collaboration and valuable discussions on the RF accelerating structure, thank engineers in Shanghai Kelin Technology Limited Corporation for the RFQ manufacturing.

References

[4] Z.Y. Guo et al., This proceedings.