DESIGN AND CONSTRUCTION OF THE BPL-RFQ

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Abstract

BPL-RFQ is a four-rod type linac structure, currently under construction, that will be operated at a radio frequency of 201.25 MHz. According to the design, it can accelerate protons from 40 keV to 750 keV with a pulse beam current of 60 mA. BPL-RFQ is planned as the Beijing Proton Linac's injector instead of the present bulky Cockroft-Walton accelerator. This paper describes the general layout, dynamics design features, four-rod structure, field distribution measurements, and recent status of the BPL-RFQ.

1 INTRODUCTION

In August 1993, it was considered to construct an RFQ system as BPL's injector. Since then the design of beam dynamics, the design and the manufacture of a cold model had been done. The cold model of four-rod structure had been measured and tested. The mechanical design of RFQ structure, the construction of rf power supply, the reconstruction of the ion source have been done also. The formal electrode modules and the cavity is being assembled and tested. The control subsystem, emittance measurement devices, and solenoids have been tested also.

2 GENERAL LAYOUT AND DESIGN FEATURE

The construction of BPL-RFQ is based on the consideration for replacement of the present Cockroft-Walton accelerator, which has been used for BPL's injector near two decades. In order to meet the need as BPL's injector, some performance requirements for the BPL-RFQ had been proposed as follows: frequency of 201.25 MHz, output energy of 750 keV, pulse beam current of 60 mA, maximum repetition rate of 12.5 Hz, output transverse normalized emittance of less than 3 π-mm-mrad and the output energy spread of ±25keV.

BPL-RFQ system is composed of three sections:[1,2] including of RFQ section, IS-RFQ match section, and RFQ-DTL match section as shown in Fig.1.

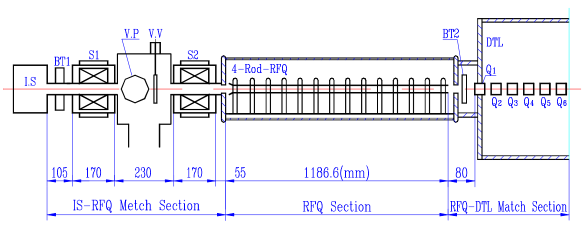

Fig.1: Scheme of the BPL-RFQ system

The RFQ is chosen to be a four-rod structure, because it has the advantages of easy manufacture and tuning, and the other features on feasibility of circular rods as electrodes giving very good mechanical as well as very good beam dynamic properties. Also four-rod RFQ has been successfully tested and used[3-5].

The RFQ beam dynamics design consists of four segments: the radial matcher, the shaper, the buncher and the acceleration. The first four cells is the radial matching segment , where the protons are gradually matched to the time dependent transverse focusing system. The next 51 cells is the shaper segment where the bunching process is initiated with a slow decrease of the stable phase from -90°to -77.2°and with a slow increase of the modulation parameter of m from 1 to 1.150. In the next 52 cells, the stable phase is reduced to -30°, the parameter of m is increased to 1.824, the protons are brought to 417 keV and fully bunched. The final 8 cells is the acceleration segment, the stable phase and parameter of m are kept constants of -30°and 1.824 respectively, the protons are accelerated to 750 keV by the end of RFQ. BPL-RFQ has a total of 115 cells and is 118.7 cm long. The main parameters of BPL-RFQ are listed in Table 1.

Table 1: Main Parameters of the BPL-RFQ

Particle	proton
Input energy	40keV
Output energy	750keV
Input pulse beam current	>100mA
Output pulse beam current	>60mA
Pulse length	180 micro-sec.
Input r.m.s. emittance:	
(x,x′)	<0.34 π-mm-mrad
(y,y′)	<0.32 π -mm-mrad
Output r.m.s. emittance:	
(x,x′)	<0.56 π -mm-mrad
(y,y′)	<0.54 π -mm-mrad
Frequency	201.25 MHz
Repetition rate	1-12.5 Hz
Maximum surface field (Es.max)	24.9MV/m
Inter-electrode voltage (V)	130.2kV
Characteristic radius	0.708 cm
Aperture radius (a)	1.962 - 0.492 cm
The length of electrode	~120 cm
Number of modules	13
Number of stems	14
Total number of cells (N_T)	115
Modulation parameter (m)	1-1.824
Trans. focu. parameter (B)	0.8-6.136
Stable phase	-90°— -30°

In the front of RFQ , there is an IS-RFQ matching section which consists of two solenoids and a beam transformer. Two solenoids are used for focusing and matching the beam into RFQ. Behind the RFQ there is an RFQ-DTL matching section which is composed of first six quadrupoles of DTL. In order to reduce the beam longitudinal mismatch, our RFQ is located very close to the DTL entrance. The distance between RFQ's electrode and first quadrupole of DTL is 8 cm only. The computer simulation for the 100 mA of beam motion from the exit of RFQ to the end of DTL had been done by PARMILA code. The simulation indicates that more than 98 mA of beam can be accelerated to the end of DTL.

The BPL-RFQ has some design features as follows:

- High transmission efficiency of 97% and 92% for the input beam current of 0 mA and 100 mA respectively.
- Low input energy of 40 keV even for an input beam current of 100 mA.
- The initinal focusing parameter of B_i and the radial matching cell number of N_{rm} have been chosen 0.8 and 4 respectively.
- The length of BPL-RFQ is short (~ 120 cm) . And the inter-electrode voltage is high (~130 kV).

3 FOUR-ROD STRUCTURE AND THE FIELD DISTRIBUTION MEASUREMENT

3.1 Four-Rod Structure

We chose a simplified structure (see Photo 1). The RFQ is brazed on a massive rail and can be aligned and tuned outside the cavity on a bench and then screwed into the cavity. The cylindrical electrodes with cones and cylinders of variable diameter have been used for our four-rod-RFQ.

Two pairs of the electrode rods form RFQ fields, each pair being held by seven stems. There are fourteen stems in total. The stems are equally spaced. Each electrode pair is supported by a common leg. The module geometry dimensions of our RFQ had been calculated by MAFIA.

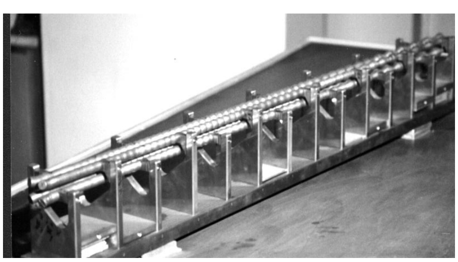

Photo 1: Electrodes and stems and substrate of the BPL-RFQ's model on the bench

3.2 Field Distribution Measurement

A cold model with full scale had been constructed for the field measurement and adjustment. Two kinds of electrodes, which are un-modulated and modulated, had been made and respectively assembled into the model. The field distribution had been measured by using bead pull perturbation method. When a bead is pulled into the cavity, the resonant frequency of the cavity will be shifted by a Δ f which satisfies the formula

$$\frac{\Delta f}{f} = -\left[\frac{\varepsilon}{\mu}\int_{v_b} E^2 dv - \int_{v_b} H^2 dv\right] / (2\int_{v_c} H^2 dv) \tag{1}$$

where v_b and v_c are volumes of the bead and cavity respectively .

If the measurement is done at near beam axis where H apprixiates zero, so

$$(\Delta f / f) \propto \int_{v_b} E^2 dv \tag{2}$$

The $\Delta f / f$ can be got by measuring the $\Delta\phi$ which satisfies $\Delta\phi = tg^{-1}\left[\frac{2\Delta f}{f} Q_L\right]$. We expect to look for a method to calculate the theoretical design values of $\int_{v_b} E^2 dv$ for the RFQ. For a RFQ, the electrical field components can be expressed by formula [6]

$$\left.\begin{aligned} E_z &= \frac{kAV}{2} I_0(kr)\sin kz.\sin(\omega t+\varphi) \\ E_r &= -\left[\frac{GV}{a^2} r\cos 2\theta + \frac{kAV}{2} I_1(kr)\cos kz\right].\sin(\omega t+\varphi) \\ E_\theta &= \frac{GV}{a^2} r\sin 2\theta.\sin(\omega t+\varphi) \end{aligned}\right\} \tag{3}$$

where V–inter-electrode voltage, I_0 and I_1–modified Bessel functions

$$\left.\begin{aligned} k &= 2\pi / \beta\lambda \\ A &= (m^2 - 1) / \left[m^2 I_0(ka) + I_0(mka)\right] \\ G &= 1 - A I_0(ka) \end{aligned}\right\} \tag{4}$$

According to the (3), the electrical field amplitude of E_m is given by

$$E_m^2 = E_{zm}^2 + E_{\theta m}^2 + E_{rm}^2 = L_{(r,\theta,Z,G,k,A)} V^2 \tag{5}$$

where

$$L_{(r,\theta,z,G,k,A)} = \left[\frac{G}{a^2} r\cos 2\theta + \frac{kA}{2} I_1(kr)\cos kz\right]^2 + \\ + (\frac{G}{a^2} r\sin 2\theta)^2 + \left[\frac{1}{2} kAI_0(kr)\sin kz\right]^2 \tag{6}$$

The L depends on the r,z,θ and the RFQ parameters of G,k,A. We are interested in field amplitude, so let's put (6) into the (2) and consider that V is constant for our RFQ, then

$$\frac{\Delta f}{f} \propto \int_{v_b} L_{(r,\theta,z,G,k,A)} dv \tag{7}$$

Define
$$\eta = \int_{v_b} L_{(r,\theta,z,G,k,A)} dv \tag{8}$$

which indicates the field distribution at the position appointed and usually it is not constant. η is called the field distribution factor by us.

In the BPL-RFQ, the cell length is short and the variations of field near beam axis are very sharp. Therefore when we calculate the integration of the formula (8), the variation of field in the range of bead size can not be neglected. We do the measurement at the $\theta = \pm 45$ ° and $\theta = \pm 135$°, because the calculations of η

are easy there.

For each cell of RFQ, there are maximum and minimum η at the positions of Z where coskz=1, sinkz=0 and coskz=0, sinkz=1 respectively. So

$$\eta_{\min} \approx 4\pi . r_b^3 \left[\frac{G^2}{a^4} (\frac{1}{3} r_a^2 + \frac{2}{15} r_b^2) + k^4 A^2 (\frac{r_a^2}{48} + \frac{r_b^2}{40}) \right] \tag{9}$$

$$\eta_{\max} \approx 4\pi . r_b^3 \left[\frac{1}{12} k^2 A^2 + \left(\frac{G^2}{a^4} + \frac{1}{8} k^4 A^2 \right) \left(\frac{1}{3} r_a^2 + \frac{2}{15} r_b^2 \right) + \frac{k^6 A^2 r_a^2}{48} (r_a^2 + \frac{r_b^2}{5}) \right] \tag{10}$$

where r_b is the bead radius and r_a is the radial distance from bead center to the beam axis. The average of η, $\eta_{Av} = (\eta_{\min} + \eta_{\max}) / 2$, can be calculated also for each cell of RFQ. We like to use a relative normalized $\eta_{N,AV}$, because the calculated and measured field distribution are relative. The $\eta_{N,AV}$ can be as theoretical design values of field distribution, and it is shown in the Fig.3 for the BPL-RFQ.

In order to obtain a good result and to get a stronger signal for avoiding the noise perturbation and to reduce the image effect, it is important to choose an appropriate bead position, size, and material. We do measurement at the position off beam axis and use a dielectrical bead with a radius of 2mm . The measurement results are shown in the Fig.2 and Fig.3.

In the case of un-modulated electrodes, the results were: the field distribution unblance is less than ±1.5% azimuthally and the field flatness is less than ±4.0% longitudinally. In the case of modulated electrodes, the results were not so good as in the case of un-modulated one, but the measurement values correspondingly agree with theoretical values.

Fig.4 shows the measured field distribution of three modes in the case of un-modulated electrodes and without cavity shell. The nearest mode spacing is about 30 MHz.

4 OTHERS

4.1 RF Power Supply

There was a 50 KW rf power supply, which was initially used for a buncher supply of the BPL. We decided to upgrade it to satisfy the need of rf power for our RFQ by adding a new final power amplifier, which uses a TH-116 triode. Therefore the upgraded rf power supply system can provide the power output of more than 300 KW.

4.2 Ion Source

A dualplasma type ion source has been chosen for our RFQ system. A beam current of 140 mA has been reached under 40 kV.

4.3 Emittance Device

The emittance device is of "a slit and multi - wires" type. It is temporarily located behind of second solenoid for measuring the emittance at the entrance of RFQ.

4.4 Solenoids

Two pulsed solenoids had been made. The coil of the solenoid consists of 12 "cakes" with different inner diameters to obtain the wanted magnetic field shape. Two solenoids had been tested under the maximum magnetic field of 7.5 KGass. The measured effective magnetic length is 12.9 cm.

4.5 Status

The mechanical engineering for the BPL-RFQ is almost completed. It is being installed and commissioned.

5 ACKNOWLEDGMENT

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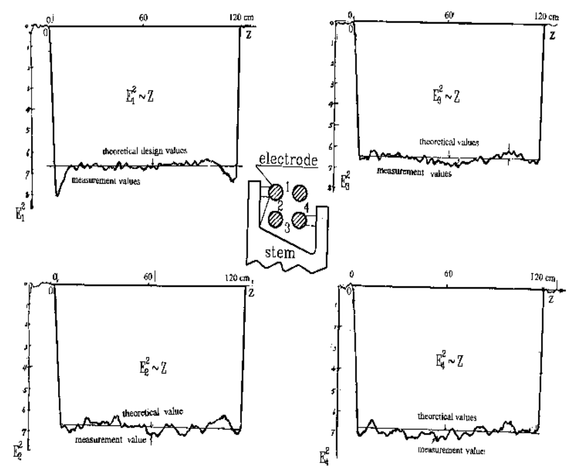

Fig.2: E^2 Vs Z at four quadrants(with unmodulated electrodes and 9mm of bead center to beam axis)

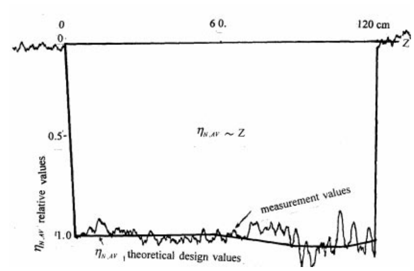

Fig.3: $\eta_{N,AV}$ Vs Z at a quadrant (with modulated electrodes and 5mm of bead center to beam axis)

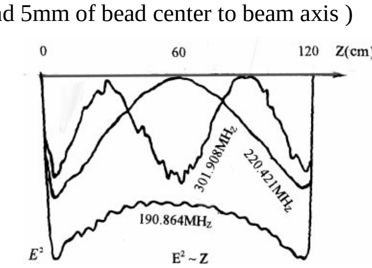

Fig.4: E^2 Vs Z for three modes