BASELINE DESIGN OF A PROTON LINAC FOR BNCT AT OIST

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Abstract

A new facility to develop a proton linac-based neutron source for boron neutron capture therapy (BNCT) and various neutron science is planned at Okinawa institute of science and technology (OIST). This facility aims to develop a prototype system of the mass production model of BNCT systems as medical apparatus. The linac consists of an ECR ion source, a two-solenoid-magnet LEBT, a four-vane RFQ, and an Alvarez DTL, which are very conventional as components of proton linac. As a medical apparatus, it is required that the linac system is stable and operated easily without experts of accelerator. In this paper, the baseline design of this OIST BNCT linac is described.

INTRODUCTION

To carry out the boron neutron capture therapy (BNCT), 2×10^9 n/cm^2/s epi-thermal (0.5 eV to 10 keV) neutrons are required. The yield of the epi-thermal neutron itself is larger at higher proton beam energy. However, with high energy protons, fast neutrons, they are harmful to the patients and cause the strong residual radiation around the neutron production target, are also intensively generated. Therefore, the proton energy should be as low as necessary neutrons are achievable. The BNCT accelerator planned at Okinawa institute of science and technology (OIST) is based on that of Ibaraki neutron medical research center. It consists of a 3-MeV radio frequency quadrupole (RFQ) linac and an 8-MeV Alvarez-type drift tube linac (DTL), and is using a beryllium target. The peak beam current is 50 mA, the duty factor is 20%, thus, the beam power is 80 kW. According to the design study of this BNCT machine, 4×10^9 n/cm^2/s epi-thermal neutrons are expected at 8 MeV [1]. This expected yield is two times larger than the required 2×10^9 n/cm^2/s, therefore, we can relax the beam power to 1/2. Taking into account the reliability as a medical machine, it is better to relax the duty factor as low as possible.

At lower energy, for example at 3 MeV, the neutron-production cross section is decreased to less than 1/10, therefore, for BNCT, CW operation is required. On the other hand, for many industrial applications, such as neutron radiography, the 5-kW beam power is enough. In addition, pulse operation is important feature because it enable the energy measurement of the transmitted neutron by using time of flight method. This kind of neutron source is of course very useful for the imaging device study. This beam power can be easily achieved for example with a peak current of 55 mA and a duty factor of 5%. This parameter is similar to the specification of the J-PARC RFQ [2] [3], thus can be achieved without additional development. We had constructed a test stand for J-PARC RFQ in the J-PARC linac building [3] (Figure 1), and the potential of this accelerator is 50 mA with 3% duty factor.

Figure 1: J-PARC RFQ test stand at J-PARC linac building.

This accelerator is, in a sense, already a compact neutron source if an appropriate neutron production target is installed. This means that a very compact 5kW pulsed neutron source can be immediately realized with established technologies. At much lower energy, for example at 2.5 MeV, the neutron yield from the Be target is too small, but this energy is suitable for lithium target. However, more intensive development is needed to realize easy to use Li targets for neutron sources.

From the above discussions, we decided that the baseline of the OIST BNCT accelerator is a 10-MeV, 50-mA pulsed linac. The linac based system enables the very flexible operation with the repetition frequency from the single shot to 200 Hz, and the pulse length from 50 μs to 1 ms (up to 20% duty factor). As for the beam energy, there is almost no impact to the DTL design whether the 8 MeV or 10 MeV is adopted. Final energy should be optimized to maximum the fraction of epi-thermal neutrons and minimize the fast neutrons and gamma-rays.

PARAMETER CONSIDERATIONS

In modern high intensity proton linac, the maximum surface electric fields of RFQs are typically a few times higher than those of other cavities, thus the RFQs tend to easily discharge. To improve the discharge hardness, decreasing the surface field is very effective. However, if the surface field is decreased, the RFQ become longer and difficult to

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keep the field flatness due to the mixing of the higher order modes. To prevent this and keep the RFQ length short, reduction of the RFQ energy is effective. On the other hand, a 3-MeV RFQ can be an individual neutron source even using a Be target.

The second consideration is the tank structure of the DTL. Many DTL tanks are made of steel cylinders and coated with copper by plating or electro-forming technique. However, making thick and uniform copper layer is a quite difficult technique, thus manufacturers those who can make the copper layer satisfying required quality are very limited. In addition, because the cooling water channels are grooved on the steel, separated cooling-water system is necessary. Therefore, by making the DTL tank from the bulk copper, it is expected that both the fabrication and operation cost can be reduced. However, mechanical strength of the copper is much lower than that of the steel, thus it is difficult to make large copper cylinder. From this point of view, high frequency and compact cavity has advantage.

Based on the above discussion, in the next section, resonant frequency of the RFQ with the output energy of 2.5 MeV and 3 MeV is surveyed in the 300 to 400 MHz band.

RFQ PARAMETERS

For the parameter survey, trial designs of RFQs are conducted using LINACSrfq [4] [5]. Table 1 shows the input parameters for this design study.

Table 1: Design Parameters of the RFQ Input

Beam species	proton
Injection energy	50 keV
Input peak current	70 mA
Input transverse emittance	0.2 π mm mrad, normalized, rms

To newly design the high-power components such as circulators needs extra cost, thus it is better to adopt already widely used frequency. Therefore, RFQs of four frequencies are designed. The other parameter of this study is the maximum electric field E_{max}. Typically, E_{max} of RFQs is designed to be 1.8 E_k, here, E_k is the Kilpatrick's discharge limit [6]. We also designed the RFQs of 1.7 E_k and 1.6 E_k. The result shows that the RFQ length L does not depend on the frequency f. However, the parameter related to the strength of the higher-order mode mixing is the normalized length by the free-space wave length L/λ. Therefore, we use this value as a criterion. The results are summarized in Figure 2.

The normalized lengths of J-PARC RFQ II and III are 3.5 λ and 3.9 λ, respectively. From the tuning experience of these RFQs, it is better not to exceed these values very much. From Figure 2, even though E_{max} is limited lower than 1.7 E_k, the frequency can be raised to 400 MHz in the 2.5 MeV case, otherwise, for the 3 MeV case, 352 MHz is appropriate. Especially, the absolute length of the 2.5-MeV 400-MHz RFQ is about three meters. In this case, the RFQ

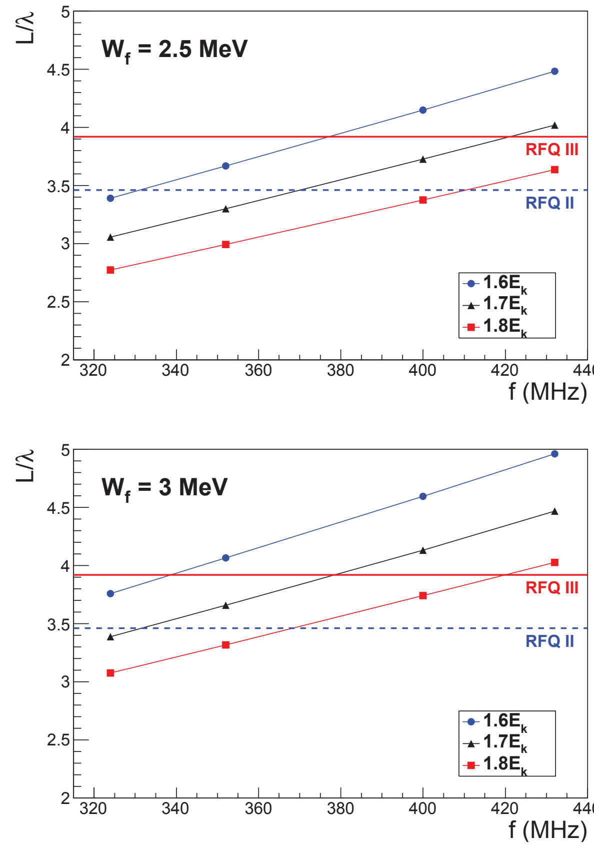

Figure 2: Normalized lengths of RFQs as functions of the resonant frequency.

can be composed by two modules (J-PARC RFQ consists of three modules). This would drastically reduce the fabrication cost of the RFQ.

The power dissipation is also estimated for 2.5-MeV and 3-MeV RFQs. The cross sectional shapes of the RFQs are tuned to be the target frequency using RFQFISH [7]. The power dissipation is 320 kW for 2.5-MeV 400-MHz case, and that of 3-MeV 352-MHz RFQ is 360 kW. In both cases, the maximum surface field is 1.6 E_k and including the empirical degradation factor of Q-value, 0.8.

DTL DESIGN

Trial designs of the 400-MHz and 352-MHz DTL are carried out. The input energy of the 400-MHz DTL is 2.5 MeV, and that of the 352-Mz DTL is 3 MeV. The beam-dynamics design is conducted using PARMILA [8], and the transit-time factors necessary in PARMILA calculation is evaluated using DTLFISH [7]. Acceleration field E_0 is set to 2.5 MV/m, which is same as the J-PARC DTL's. At present, the geometrical parameters are scaled from the J-PARC DTL by the frequency. Figure 3 shows the electric field of the J-PARC DTL and the 352-MHz DTL.

The power dissipation is calculated using MDTFISH [7]. Input parameters and design results are summarized in Table 2.

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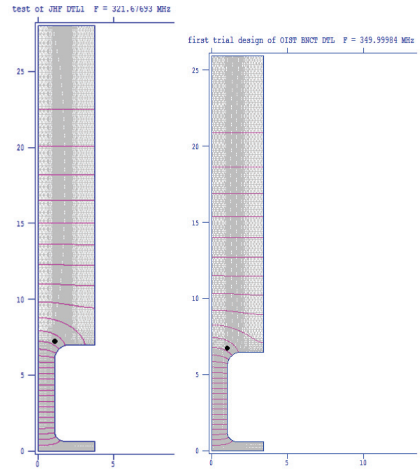

Figure 3: SUPERFISH models of β=0.8 cells of 324 MHz (J-PARC DTL:left) and 352 MHz (right) DTLs.

Table 2: Design Parameters of DTLs

Frequency (MHz)	352	400
Input energy (MeV)	3.0	2.5
Output energy (MeV)	10	10
Energy gain (MeV)	7.0	7.5
Acceleration field E_0 (MV/m)	2.5	
Number of cells	45	57
Total length (m)	4.3	4.7
Power dissipation (kW)	360	360

The power dissipation per one cell for the 400-MHz DTL is smaller than that of the 352-MH DTL, however, the length is longer because the required energy gain is high. Therefore, they are canceled out, and the power dissipation of both cases is 360 kW.

RF SOURCE REQUIREMENT

As demonstrated in the J-PARC linac, the digital low-level RF system employing feedback technique is essential for the stable and flexible operation of high intensity proton linacs. The RF feedback provides dynamic beam-loading compensation for wide range of the beam current. To this end, the different type of cavities must be driven individual RF sources. Therefore, we are planning to use compact multi-beam klystrons (MBK) [9] as RF sources. In addition, the feedback is applied using proportional-integral control method, therefore, the RF source must be used in proportional range, which is typically less than 80% of nominal power in case of using klystrons. Required power of the 10-MeV linac is listed in Table 3.

In case of 400-MHz, the required power is distributed to the RFQ and DTL with better balance. Because assuming power of the MBK is 600 kW, the RFQ and the DTL can be driven with one and two MBKs, respectively. On the other hand, in the 352-MHz case, there is no margin of the RFQ power for one 600-kW MBK. In this case, it is better to use two klystrons for the RFQ for nominal operation, but can be operated with a little bit reduced voltage or peak beam current.

Table 3: RF Power Requirement

Frequency (MHz)	352	
	RFQ	DTL
Energy (MeV)	0.05 to 3.0	3.0 to 10
Energy gain (MeV)	3.0	7
Peak beam current (mA)	50	
Cavity power (kW)	360	360
Beam power (kW)	150	350
Total power of each cavity (kW)	510	710
Total power of accelerator (kW)	1220	
Frequency (MHz)	400	
	RFQ	DTL
Energy (MeV)	0.05 to 2.5	2.5 to 10
Energy gain (MeV)	2.5	7.5
Peak beam current (mA)	50	
Cavity power (kW)	320	360
Beam power (kW)	120	380
Total power of each cavity (kW)	440	740
Total power of accelerator (kW)	1180	

SUMMARY

As discussed in previous sections, for a 10-MeV linac, the 400-MHz and 2.5-MeV RFQ looks better because of its compactness and low fabrication cost. However, the 3-MeV RFQ is a very attractive choice because a 3-MeV RFQ can be an individual neutron source for the industrial applications. Therefore, possible strategy is as follows: The goal is 10-MeV linac based pulse neutron source, however, we will start up the facility with only a 3-MeV RFQ as the first step. In this case, 352-MHz frequency is better than the higher frequency as shown in figure 2, and this RFQ can be driven with one 600-W MBK by reducing the operation power or peak beam current. Even with this condition and using Be target, it can provide enough neutron flux for the development of imaging devices and many industrial applications. Simultaneously, we can develop a solid lithium target for more neutron yield. If this development will success, there is a possibility to construct a BNCT machine only with an RFQ. According to the progress of the development, we will decide to add a DTL to increase the energy to 10 MeV or so. The energy should be optimized to maximize the yield of necessary neutrons.

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