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DESIGN OF IH-DTL TO ACCELERATE INTENSE LITHIUM-ION BEAM FOR COMPACT NEUTRON SOURCE

S. Ikeda, T. Kanesue, and M. Okamura
Collider-Accelerator Department, Brookhaven National Laboratory, Upton, NY, USA

Abstract

We are studying feasibility of a compact neutron source with a lithium-ion beam driver. The neutron source comprises a laser ion source, an RFQ linac, and an IH-DTL. Recently, we demonstrated 35-mA $^7Li^{3+}$ ion beam acceleration by an RFQ linac with a laser ion source. Based on the result, we performed beam dynamic design of an IH-DTL to accelerate the lithium-ion beam to the energy required for the neutron production, 14 MeV. To obtain a realistic field distribution, we made a rough model of the IH-DTL cavity with Microwave studio. It was confirmed with GPT 3D beam simulation that 1.7-m and 200-kW IH-DTL with two triplets can accelerate 30-mA $^7Li^{3+}$ beam.

INTRODUCTION

Accelerator-driven compact neutron sources have attracted great attention because of the wide range of the applications, such as non-destructive inspection for defects of buildings and explosive material in cargo[1]. They are composed of an MeV-class accelerator and a neutron conversion target. The availability coming from the compactness and the relatively low cost is also desirable for industrial and educational users. Recently, even portable neutron source has been developed for the purpose of inspection of infrastructures. They are also interested as alternative for small neutron reactors.

For the moderate range of neutron flux, proton accelerators with lithium or beryllium targets are used. Especially for lithium target, the neutrons are generated by the nuclear reaction.

$$7\text{Li} + \text{p} \rightarrow 7\text{Be} + \text{n} - 1.64\ \text{MeV} \quad (1)$$

The proton energy is slightly higher than the threshold value, typically 2.4 MeV. Because this reaction is endothermic, the energy distribution of the neutrons is narrow. Meanwhile, the neutrons are produced in all direction due to the small velocity of the center of mass. Only the part in the forward direction is used for the applications. In contrast to the conventional neutron sources, we are proposing a lithium-ion beam driver with a laser ion source[2]. It is composed of a laser ion source, an RFQ linac, and an IH-DTL. The features of the use of the laser ion source are lithium projectile 1) and a pulsed beam with high peak current and short width 2). The type of ion is $^7Li^{3+}$. The peak current, the pulse width, the repetition rate will be 30 mA, 0.1 to 10 μs, and 1 to 1 kHz, respectively. With a lithium projectile, the velocity of the center of mass is larger than with a proton projectile. This leads to a narrow angular distribution of the neutrons. This effect is called kinematic focusing demonstrated with simulation and experiments[3]. The generated neutrons are in forward direction and can be used at downstream. The enhancement factor compared with proton injection can be factor of ten[3]. Furthermore, the background neutrons are less and the shielding can be lighter, which leads to lower cost and better portability. Regarding the pulse and peak current, laser ion sources are known with the ability to produce intense pulsed beam. The beam current is several orders of magnitudes higher than conventional heavy ion sources. The pulse width can be adjusted to 1 μs or shorter. The beam with the high peak current and short width is advantageous for pulsed neutron beam applications since the short pulse neutron beam will enable users to separate the background neutrons from the probe beam, resulting in a good signal-to-noise ratio.

The advantage of the lithium projection is obvious, but it was not practical because the beam current of conventional heavy ion machines is low. Meanwhile, it was proved that a combination of a laser ion source and an RFQ linac can produce large beam current by using Direct Plasma Injection Scheme[4]. By applying this scheme, the intense lithium driver will be able to be used to neutron sources.

In previous study, we recently succeeded to accelerate 35 mA of 7Li3+ ion beam by an RFQ linac[5]. As a next step, we designed an IH-DTL to accelerate the beam to the nuclear reaction threshold, 14 MeV[3]. We are considering IH-DTL as the second accelerator after the RFQ linac because of the high efficiency for the energy range. We checked the feasibility and the specification of the IH-DTL for the intense beam. The design was mainly about the beam dynamics. An RF simulation with a rough model was done with CST studio to obtain the electric field distribution for particle tracking. More practical cavity design will be next step.

IH-DTL DESIGN

The parameters of the input beams were from the beam parameters from the existing RFQ linac. The input energy is 1.43 Me, the transverse and longitudinal 90 % normalized emittances are 3 pi mm mrad and 0.54 MeV-deg, respectively. The beam current was set to 40 mA to have some margin to accelerate the 35 mA from the RFQ linac. The longitudinal emittance was the calculated value by Parmteq in design. To estimate the transverse emittance, trace3D simulation was performed for the analyzing line in the previous study to compare with the experimental result. The simulation revealed that the maximum emittance to propagate the dipole is 3 pi mm mrad containing 90 % of ions. In other word, with larger emittance than 3, the transmission was worse than the previous experiments. So, 3 pi mm mrad was selected as the input parameter for the IH-DTL.

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It was assumed that the ratio of the gap voltage and the gap width of the drift tubes (V_{gap} / w_{gap}) is smaller than 450 kV / 30 mm = 15 MV/m. In the upstream section, w_{gap} was set to the half of the cell length. The voltage was determined to have 15 MV/m. w_{gap} was fixed to 30 mm after the central section. V_{gap} was assumed to be the half when the gap was next to the cavity wall or triplet housings. The inner diameter of the drift tubes was assumed to be 20 mm because of the short cell length in the upstream section. The resonant frequency was 100 MHz, which is the same as for the RFQ linac. Quadrupoles were used inside of the cavity. This method was established by researchers[6]. Namely, the quadruples are packed in a housing at ground potential, and the adjacent drift tubes have opposite polarity of voltage. This requires the length of the housing is about N beta lambda. Based on the conditions, the cell lengths were calculated by formula for drift and thin gap model. The transit time factor was estimated based on the analytical expression of Einzel lens field[7]. Then the envelope was checked with Trace3D. The twiss parameters were optimized for maximum transmission. In addition, the longitudinal dynamics was checked with a 1D simulation. The electric field distribution was calculated using the Einzel lens formula and the space charge force was calculated with the formula for a uniform ellipsoid. After some iterations, the design was determined. It was found that the total length is 1.67 m, the number of gaps should be 17, and two triplets are needed to transport the beam. The lengths of the outer and the inner quads of the triplets are 70 mm and 140 mm, respectively. The synchronized ion gained energy as illustrated in Fig. 1.

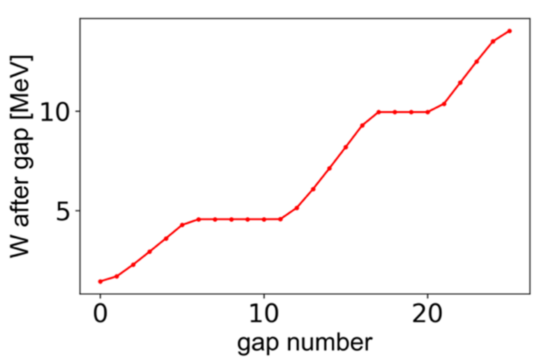

Figure 1: Designed ion energy at each gap.

To check the validity of the design, the electric field distribution was calculated by making a rough 3D model of the cavity with CST studio. Figure 2 is the cross-sectional view of the IH-DTL model. The undercuts were adjusted to have the similar field peak at each gap. The unloaded Q was calculated to be 20000.

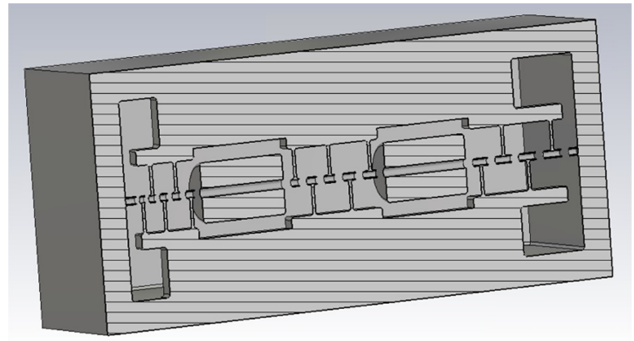

Figure 2: CST model of IH-DTL

The field distribution on the beam axis and the calculated voltage distribution are shown in Figs. 3 and 4.

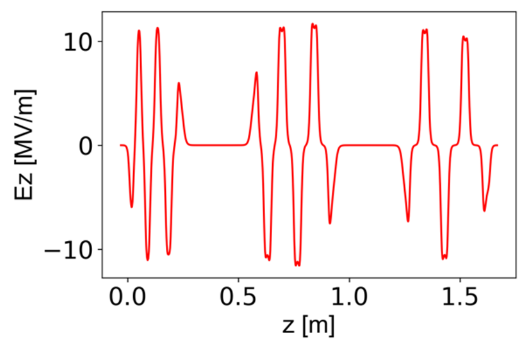

Figure 3: Distribution of longitudinal component of electric field, *Ez*, on beam axis.

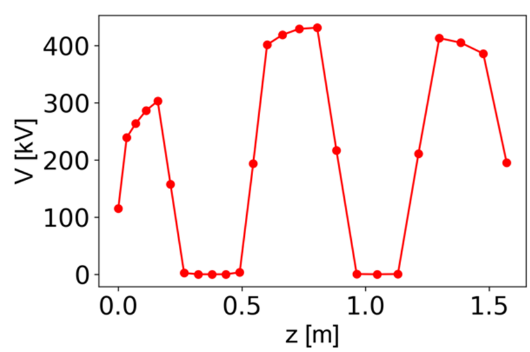

Figure 4: Voltage distribution at each gap.

The field distribution was imported into a particle simulation code, General Particle Tracer (GPT). 10000 macro particles were generated as 6-D waterbag with Twiss parameters optimized in the design process. Figure 5 shows the distributions. The quadrupole fields were generated with the function prepared in GPT in which the fringe field is described by Enge function[8]. The space charge effect was calculated by solving Poisson equation with Particle in Cell method. The optimization was done about the multiplication factor for electric field, the initial RF phase, the quadrupole strengths, and the converging angle of the initial beam. The optimized trajectories are shown in Fig. 6. The significant effect of the dipole components was not observed.

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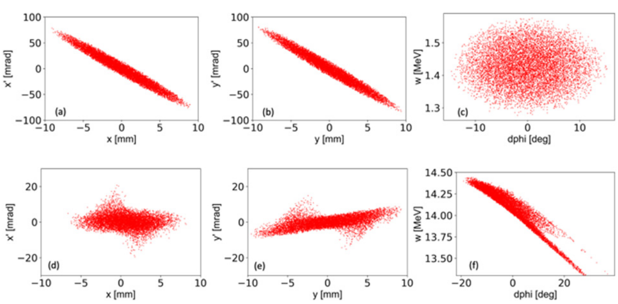

Figure 5: Phase space plot at entrance (a, b, c) and exit (e, f, g) of IH-DTL.

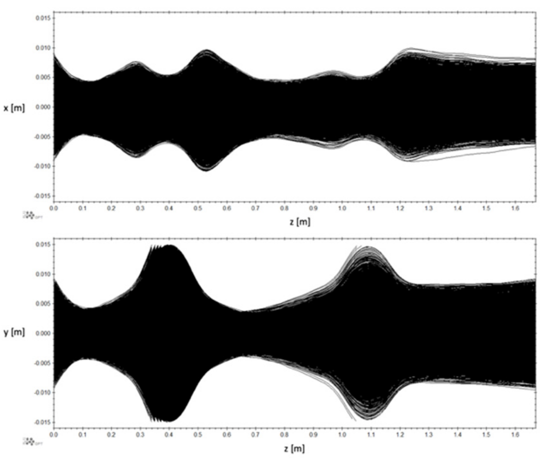

Figure 6: Ion trajectories in IH-DTL calculated with GPT in z-x and z-y planes.

The transmission was 96.6 % in which the energy of the ions are within +- 5% of the average energy, 14.2 MeV. The maximum strengths were 42 T/m in the first triplet and 38 T/m in the second one. The particle distribution at the exit is shown in the lower part of Fig. 5. The transverse and longitudinal emittances (norm. rms) are 0.57 pi mm mrad and 0.63 MeV-deg, respectively.

With the optimized field, the maximum gap voltage was 440 kV and the effective shunt impedance is 74 MΩ/m. From the unloaded Q value, the required RF input power was estimated to be 160 kW. The unloaded Q is usually estimated high compared with a real cavity. As a result, the estimated power becomes smaller. Q can be 70 % or 80 % of the calculated value. So, the RF power can be 200 kW or 230 kW. This is within typical value. The beam loading was also estimated. If a beam pulse with 1 us width is accelerated, 0.17 J out of 2.5 J was removed from the stored energy. So, the gap voltages drop by 4 %. This should be acceptable. If the repetition rate is 1 kHz, the average loading is 170 W. This can be compensated. The effective shunt impedance is lower than other IH DTL machines. The use of two triplets is one of the reason due to the high current. Even though, the impedance is still larger than the other structures. So, IH-DTL is still the best choice. If one wants to improve the specification, one way may be to increase the beam energy at the RFQ exit and reduce the number of the triplets. Next step will be more practical design of the IH cavity and the triplets.

CONCLUSION

For a compact neutron source with a lithium-ion beam driver, an IH-DTL was designed especially in terms of the beam dynamics. It was found that 1.7-m and 200 kW IH-DTL can accelerate 30 mA of $^{7}Li^{3+}$ beam to 14 MeV. The input beam parameters are determined from the existing RFQ linac which required two strong triplets to transport the low energy and high current beam. It is believed that the design is not far from the typical IH-DTL machines, and the feasibility was shown.

ACKNOWLEDGEMENT

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