Proposal of a 1 ampere class deuteron single-cell linac for nuclear transmutation

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Abstract

A 1 ampere class high-intenisty deuteron linac (ImPACT2017 model) is proposed for the mitigation of the long-lived fission products (LLFPs) by nuclear transmutation. This accelerator consists of single-cell rf cavities with magnetic focusing elements to accelerate deuterons beyond 1 A up to 200 MeV/u.

1 Introduction

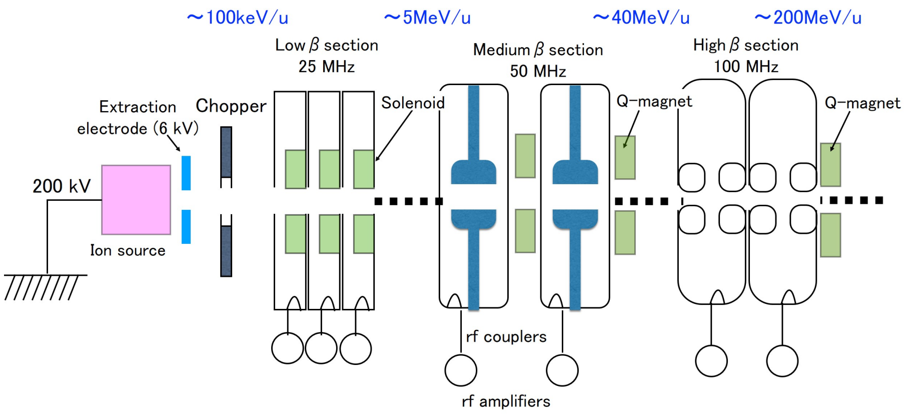

Figure 1: Schematic of a single-cell linac, model ImPACT2017.

High-level radioactive waste from nuclear power plants has caused notable social problems. To address these social problems, research and development of partitioning and transmutation technologies are essentially important to determine the most efficient methods for the reduction of radioactivity in waste material [1]. We hereby propose a reasonably feasible transmutation scheme with high-energy neutrons produced by a deuteron beam, where liquid lithium is utilized for the production target [2]. To realize the transmutation scheme, design of a 100-200 MeV/u deuteron accelerator with an intensity of 1 A is highly desired for the transmutation of LLFP nuclides.

We consider a linac that can accelerate deuterons to such a high current. Most modern high-power linacs [2, 3, 4, 5] use a radio frequency quadrupole (RFQ) as a front-end accelerator, which performs adiabatic rf capture of a direct current (DC) beam from an ion source, transverse focusing, and acceleration. The typical aperture of an RFQ is 1 cm. However, the expected size of the 1-A beam from an ion source amounts up over 10 cm in diameter. It is therefore evident that an RFQ cannot accommodate such large beams with 1 A. In this study, we propose a novel linac that consists of single-cell cavities with magnetic focusing elements to accept a 1-A beam with a large bore. The single-cell linac (SCL) has the following advantages for the acceleration of high-intensity beams:

- Low-frequency rf cavities with a large bore can be used to mitigate strong space charge forces owing to lower beam current density.
- Voltage and phase of each cell can be independently selected to compensate for the space charge effects, and also to implement an efficient bunching function for a DC beam like an RFQ entrance section.

Table 1: Basic parameters of the single-cell linac ImPACT2017. QWR stands for quarter wave resonator.

Ion Source and LEBT	
Energy range (MeV/u)	0.1
Type of IS	Cusp ion source
Particle	deuteron
Beam current (A)	1
Emittance (normalized)	25π mm·mrad
Low-βsection	
Energy range (MeV/u)	0.1-5
Number of cell	90
Cell length (m)	0.25
rf cavity	Normal conducting
	Single gap
Focusing	Solenoid
Medium-β section	
Energy range (MeV/u)	5-40
Number of cell	44
Cell length (m)	1.38
rf cavity	Superconducting
	QWR, Double gaps
Focusing	Quadrupole magnet
High-β section	
Energy range (MeV/u)	40-200
Number of cell	200
Cell length (m)	0.8
rf cavity	Superconducting
	Single gap
Focusing	Quadrupole magnet

2 Scheme

The 1-A deuteron SCL (ImPACT2017 model) consists of four sections: (1) the ion source section, (2) the low-β section, (3) the medium-β section, and (4) the high-β section. Figure 1 shows a schematic layout of this system and the typical parameters of each section are presented in Table 1. In this scheme, a large transverse normalized RMS emittance of 25π mm·mrad is assumed at the injection of the SCL, which is sufficient for relaxing the space charge effect in the beam dynamics. A relatively low rf frequency acceleration system is suitable for a large bore.

In the SCL, the fundamental mode of the longitudinal space charge force could be compensated cell by cell through individual fine rf detuning to beam bunches. The SCL also facilitates individual strong beam focusing against the transverse space charge force with external magnetic focusing elements, such as solenoids and quadrupole magnets.

The ion source produces a current of deuterons, with a magnitude above 1 A. A cusp-field-confinement-type ion source with a large extraction area was chosen because a multi-hole beam extraction system is inevitable for the extraction of such large beam currents. Such ion sources are used for NBI (neutral beam injector) in Tokamak fusion reactors. The structure of the ion source can be seen, for example, in [6]. The Child-Langmuir law estimates that a current of 20 mA/cm^2 can be extracted at maximum through one hole with a diameter of 14 mm when an extraction voltage of 6 kV is applied to the gap of 3 mm. At least 37 holes are required to extract 1 A assuming that the ratio of D^+ to the total current including D_2^+, etc. is 85%. The low-energy beam transport (LEBT) section consists of a series of beam focusing solenoids as shown in Fig. **??**.

The low-β section is composed of approximately 90 single cells, and each cell includes a single rf cavity with a 25 MHz resonant frequency and a focusing solenoid. The rf cavity has a capacitive plate to maintain the outer diameter under ~2 m and the maximal rf voltage is approximately 300 kV, which is approximately 1.2 K_L, where K_L is discharge limit given as a function of the frequency by Kilpatrick [7]. The transit time factor at 5 MeV/u exceeds 0.95. The rf power except the beam power dissipated by the entire single-cell cavity system is approximately 5 MW.

The rf voltage and phase of every single cavity were appropriately selected to optimize the beam capture and acceleration. The optimization was performed by evaluating the adiabatic parameter, as shown in the following [8] [9] [10]:

$$\Omega_s >> \frac{1}{A}\left|\frac{dA}{dt}\right|, \tag{1}$$

where A is a rf bucket area and Ω_s is the phase (synchrotron) oscillation frequency., and from this criterion, an adiabatic parameter is defined as,

$$n_a = \frac{\Omega_s T_s}{1-[V_i/(V_i+\Delta V)]^{1/2}}. \tag{2}$$

Here, V_i is rf voltage, ΔV increment of rf voltage per cell and T_s transit time per cell.

Good adiabaticity is achieved when the value of the adiabatic parameter n_a exceeds 10 and the DC beam from the ion source can be well-captured by the rf bucket and consequently accelerated. The phase and rf voltage variations should be appropriately optimized to preserve the adiabaticity of the beam capture and acceleration, following the condition shown in eq.(1). The longitudinal beam behavior was simulated for these conditions and the results are plotted in Fig. 2. Evidently, the beam is well captured and is accelerated adiabatically. This rf capture of the DC beam was successfully simulated by a 3D PIC code.

The deuteron beam from the low-β section is accelerated up to 40 MeV/u via the medium-β section that consists of 44 superconducting quarter wave resonators (QWRs) at 50 MHz and

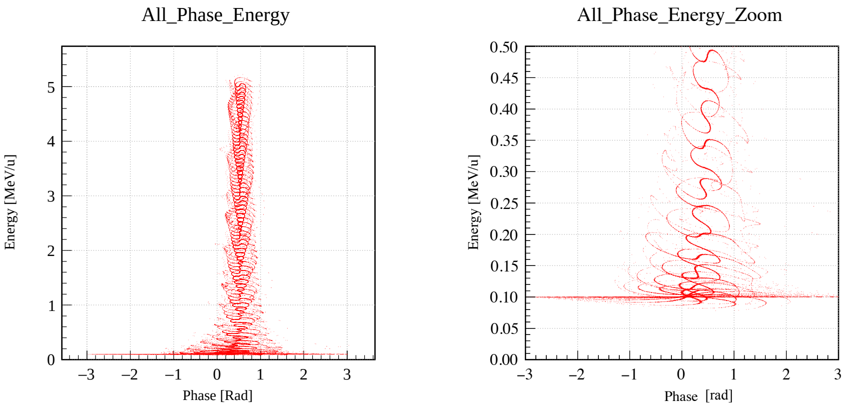

Figure 2: Beam capture and acceleration: left panel shows the entire longitudinal beam motion in the low-β section, while right plot shows the initial phase of the beam capture and acceleration.

quadruple magnets between the resonators. The superconducting and/or permanent magnets act as the quadrupole magnet. The schematic layout of the QWR is shown in Fig. 3. The height and diameter of the outer cylinder are 1.62 m and 1.16 m, respectively and the maximal rf voltage is 1.24 MV. The transit time factor is approximately 0.74 at 40 MeV/u and the gap distance is 0.58 m, which corresponds to $\beta\lambda/2$ at 18 MeV/u.

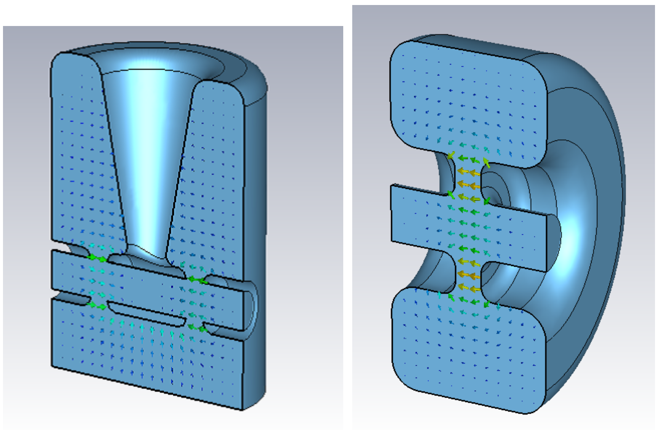

Figure 3: Structure of QWR (left) for the medium β and Reentrant cavity(right) for the high β section.

The deuteron beam from the medium-β section is accelerated up to 100–200 MeV/u through the high-β section that consisted of 200 superconducting reentrant cavities at 100 MHz and quadruple magnets between the resonators. The superconducting and/or permanent magnets serve as the quadrupole magnet. The schematic layout of the reentrant resonator is shown in Fig. 3. The diameter and the length of the cavity are 1.25 m and 0.6 m, respectively and the maximal rf voltage is 2.3 MV. The transit time factor is approximately 0.96 at 200 MeV/u.

2.1 Summary

A 1 ampere class deuteron linac (ImPACT2017 model) was proposed for the mitigation of the long-lived fission product (LLFP) by nuclear transmutation. This model consists of single-cell rf cavities with magnetic focusing elements to accelerate deuterons beyond 1 A. The beam dynamics and conceptual design for each section were presented and discussed.

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