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

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Abstract: A 1-ampere-class high-intensity deuteron linac (ImPACT2017 model) is proposed for mitigating 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.

Keywords: SCL (single cell linac), LLFP (long-lived fission product), nuclear transmutation

1. Introduction

High-level radioactive waste from nuclear power plants has caused notable social problems. Deep geological disposal has been a policy of several governments, however, the identification of appropriate locations for the disposal station is seriously challenging. To address these social problems, the 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.

With respect to transmutation, two schemes have been proposed and discussed; fast-breeder reactor-based and accelerator-based transmutation. In the former scheme, the transmutation of mainly long-lived minor actinides has been investigated in terms of utilizing fast neutrons in the reactors. On the other hand, the transmutation of long-lived fission products (LLFPs) in waste material is also crucial for reducing the risk of their diffusion into the geosphere and hydrosphere. The transmutation cross sections of LLFPs by thermal and fast neutrons are regrettably low. As such, an alternative scheme using a high-energy, high-intensity accelerator that can produce much faster neutrons to make the transmutation efficient for any LLFP nuclear species has been investigated.

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. Concerning the major LLFP nuclides (93Zr, 99Tc, 107Pd, 129I and 135Cs), the transmutation throughput with high-energy neutrons is higher than that with direct irradiation of a primary deuteron beam at 100–200 MeV/u. This is because thick LLFP materials can be used owing to the long mean free path of neutrons in the materials. The required beam intensity for the deuteron beam is estimated to be 1 A, which results in a transmutation throughput of LLFP at the same level as that of the Rokkasho reprocessing facility. The highest beam intensity among all accelerators worldwide is on the order of 1 mA. The construction cost of an accelerator is scaled as the square root of the beam power. Therefore, the total cost of one thousand 1-mA accelerators is about 30-times higher than that of one 1-A accelerator. Thus, the 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(3)-(7) use a radio-frequency quadrupole (RFQ) as a front-end accelerator, which performs the 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 size of the 1-A beam from an ion source

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is expected to be 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 a lower beam current density.
- The 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.

2. Scheme

2.1. Outline. 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.

2.2. Ion source and LEBT. 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 ref. 8. The Child-Langmuir law estimates that a current of 20 mA/cm² can be extracted at maximum through one hole with a diameter of 14 mm when an extraction voltage of 6 kV is applied to a gap of 3 mm. At least 37 holes are required to extract 1 A, assuming that the ratio of D² to the total current, including D² + 2, etc., is 85%, as shown in Fig. 2. The beam extracted from the ion source was electrostatically accelerated to 100 keV/u for injection into the low-β section. The normalized RMS emittance of the accelerated beam was determined to be 12.1 mm·mrad, as shown in Fig. 2. For the design of the succeeding linac, the normalized RMS emittance was set to be 25 mm·mrad, thereby maintaining a safety margin.

The low-energy beam transport (LEBT) section consists of a series of beam-focusing solenoids, a line beam chopper, and an achromatic bending system, as shown in Fig. 3. The beam size and the dispersion function for the LEBT are shown in the top and bottom panels in Fig. 4. We assumed no neutralization of the space-charge force in calculating the beam size. The dispersion function exhibited no chromaticity at the exit from the LEBT. The magnetic-field intensity of the beam-focusing solenoid was approximately 1 T, which is sufficient for suppressing the space-charge forces and for matching the beam optical parameters to those of the following low-β linac. A line-type beam chopper, as in a reference 9), can be used to match a longitudinal beam size to the rf bucket of the following low-β section by chopping off a less than 30% portion of the DC beam non-acceptable in the rf bucket.

2.3. Low-β section. 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. A schematic of a single-cell unit of the low-β section is shown in Fig. 5. The rf cavity has a capacitive plate to maintain the outer diameter of under ~2 m, and the maximal rf voltage is approximately 300 kV, which is approximately 1.2 K_L, where K_L is the discharge limit, given as a function of the frequency by Kilpatrick. The transit time factor at 5 MeV/u exceeds 0.95. The rf power, except for the beam power dissipated by the entire single-cell cavity system, is approximately 5 MW. The basic parameters of the rf cavity are given in Table 2.

The rf voltage and the 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: 11–13
where $A$ is an rf bucket area and $\Omega_s$ is the phase (synchrotron) oscillation frequency; from this criterion, an adiabatic parameter is defined as

$$n_a = \frac{\Omega_s T_s}{1 - [V_0/(V_0 + \Delta V)]^{1/2}}. \quad [2]$$

Here, $V_0$ is the rf voltage, $\Delta V$ the increment of rf voltage per cell and $T_s$ the 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 expressed by Eq. [1]. The longitudinal beam behavior was simulated for these conditions and the results are plotted in Fig. 6. Evidently, the beam is well captured and is accelerated adiabatically.

An enormous deuteron beam current in excess of 1 A is projected in this model, and the compensation of large space-charge forces is an issue of significant interest in beam dynamics. Obviously, space-charge effects are significant in the low-energy region; thus, methods for suppressing and managing the transverse and longitudinal space-charge forces are important in the low-β section of this SCL.

In the transverse direction, two defocusing forces should be managed; one is caused by the rf gap field, while the other one is due to the space-charge effect. Both are axial symmetric forces; thus, solenoid focusing is used. The transverse beam size (analyzed using an envelope equation\(^{14-16}\)) is shown in Fig. 7. The length of the solenoid is 18 cm for each of the first 15 cells and 34 cm for the remainders. The maximum magnetic field of the solenoid is approximately 5 T, which could be realized to use a high-temperature superconductor with the maximum critical magnetic field of more than 10 T.\(^{17}\) It is evident in Fig. 7 that the beam size becomes relatively small after reaching 5 m away from the injection, so that further optimization of the cavity design (length, bore size, etc.) may be required.

The longitudinal beam emittance deteriorates owing to the rf bucket deformation associated with the space-charge force and the beam-loading effect, which can be overcome with an rf feedback and/or detuning of the rf cavity of each cell. The fundamental

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**Fig. 5.** Schematic of a single-cell unit of the low-β section (left: outline, right: cross section).

**Fig. 6.** Beam capture and acceleration: the left panel shows the entire longitudinal beam motion in the low-β section, while the right plot shows the initial phase of the beam capture and acceleration.

**Table 2.** Basic parameters of the rf cavity of the low-β section

| Structure                       | Reentrant with capacitive plate |
|---------------------------------|---------------------------------|
| Frequency (MHz)                 | 25                              |
| Cavity diameter (m)             | 2                               |
| Aperture radius (cm)            | 15                              |
| Cell length (m)                 | 0.25–0.4                        |
| Maximum rf voltage per cell (kV)| 300                             |
| Shunt impedance (MR)            | 0.775                           |
| $Q_0$                           | 20066                           |
| Transit time factor (5/5MeV/u)  | 0.966                           |
mode of the longitudinal force (space-charge impedance) can be compensated using ordinary methods, such as cavity detuning\cite{18,19} and feedback and/or feedforward beam loading compensation. At a relatively low beam current, the beam loss can be suppressed only if a proper rf feedback system is utilized for the fundamental mode. However, it is necessary to implement a higher-mode rf compensation system because the nonlinear higher-order modes become stronger as the beam current increases.

We estimated the beam losses caused by the rf bucket distortion that is induced by the space-charge impedance of the second and third-order higher harmonics. Figure 8 shows the calculated longitudinal beam emittance, which is affected by the higher order harmonics of the nonlinear space-charge forces. The emittance growth is more than twice as large as when the beam current is 1 A. However, if the space-charge field of the second harmonic is compensated, it largely suppresses the emittance growth, as shown in Fig. 8.

It is expected that beam losses should occur owing to the rf bucket distortion caused by the higher harmonics of the nonlinear space-charge forces. Figure 9 shows the relative beam survival along the position of each cell in the low-$\beta$ section of the SCL. According to the calculations, beam losses of more than 10\% are unavoidable if there is no compensation for higher-order harmonics when the beam current exceeds more than 1 A. However, if the second-harmonic field is compensated by using an appropriate feedback system invoked by impedance tuning, the beam loss could be significantly reduced, as shown in Fig. 9. Although the beam losses take place mostly at low energy ($\sim 500$ keV), the higher harmonic field compensation seems to be preferable for stable beam operation.

Three-dimensional beam envelope simulations in the low-$\beta$ section were performed using TRACK\cite{20}, a code that includes the space-charge effect and nonlinear phenomena owing to this effect. No actions of the wake field from the rf cavities and beam pipes on the beams were included in these simulations. The initial distribution of the beam is a water bag distribution. Two cases were compared: the first one (Case I) fully included longitudinal space-charge effects, while the second case (Case II) did not include these effects. Case II corresponds to a situation in which the longitudinal space-charge forces are fully compensated. Figure 10 shows the beam envelopes in the transverse direction and the longitudinal phase plots for the cells for which the beams are adiabatically captured. Although the
Phase plots indicate that the DC beams were successfully captured in both cases, the phase plots for Case I indicates that strong space-charge forces distort the beam distribution. The survival rate was 98.0% and 98.2% in Cases I & II, respectively. Approximately 1.4% of the total number of particles is widely distributed in the phase plot for Case I, apart from the center of the beam. These particles will be lost in the succeeding medium and high-\( \beta \) sections, which suggests that space-charge compensation of the longitudinal space-charge forces is important in suppressing of uncontrolled beam loss not only in the low-\( \beta \) section, but also in the succeeding sections.

**2.4. Medium-\( \beta \) section.** The deuteron beam from the low-\( \beta \) section is accelerated up to 40 MeV/u via the medium-\( \beta \) section, which consists of 44 superconducting quarter-wave resonators (QWRs) at 50 MHz and quadruple magnets between the resonators. The superconducting and/or permanent magnets act as a quadrupole magnet. The schematic layout of the QWR is shown in Fig. 11. The height and diameter of the outer cylinder are 1.62 m and
The beam dynamics in the section was studied using TRACK\textsuperscript{20} in the case of a 1 A current, where the space-charge forces are dominant. Normalized RMS emittance values of the initial distribution of the beams were acquired from the values at the exit of the low-\(\beta\) section. A stronger quadrupole field can compensate for the transverse space-charge forces. To compensate for the longitudinal space-charge force, the cavity voltage and the phase were changed to yield stronger focusing forces and to maintain the same acceleration gain as that for 0 A. For example, the synchronous phase was changed from 60 to 45 degrees, and the voltage was changed from \(V_0\) to \(V_0\sin(60^\circ)/\sin(45^\circ)\). Figure 12 shows the envelope and the longitudinal phase plot at the exit. The ratio of the inner radius of the cavities and the beam pipes to the RMS of the beam envelope is approximately 4 at the entrance and 5 at the exit, resulting in beam losses of approximately less than 1 kW, assuming a Gaussian distribution of the beam. To achieve acceptable beam losses, beam scrapers are placed between the low-\(\beta\) and the medium-\(\beta\) sections and further study will be made to suppress the beam halo.

2.5. High-\(\beta\) section. The deuteron beam from the medium-\(\beta\) section is accelerated up to 100–200 MeV/u through the high-\(\beta\) section, consisting of 200 superconducting reentrant cavities at 100 MHz and quadrupole 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. 13. 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. Typical specifications of the rf cavities are listed in Table 4.

The beam dynamics in this section was studied using TRACK\textsuperscript{20} in the case of a 1 A current in which the space-charge forces are dominant. Normalized RMS emittance values of the initial distribution of the beams were acquired from the values at the exit of the medium-\(\beta\) section. A stronger quadrupole field can compensate for the transverse space-charge forces. To compensate for the longitudinal space-charge force, the cavity voltage and the phase were changed to yield stronger focusing forces and to maintain the same acceleration gain as that for 0 A. For example, the synchronous phase was changed from 60 to 45 degrees and the voltage was changed from \(V_0\) to \(V_0\sin(60^\circ)/\sin(45^\circ)\). Figure 14 shows the envelope and the phase plot at the exit. The ratio of the inner radius of the cavities and beam pipes to

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. The typical specifications of the rf cavities are listed in Table 3. The beam-steering effect due to the asymmetry of the QWR is estimated to be 0.5 mm of the displacement and having an angle of 0.7 mrad, after passing through one cavity. This is not negligible; thus, some measures are necessary. Tilting of the drift tube faces may be one solution for suppressing the aforementioned vertical kick.\textsuperscript{21)
RMS of the beam envelope can be estimated to be approximately 4 at the entrance and 6 at the exit, resulting in beam losses of approximately less than 1 kW, assuming a Gaussian distribution of the beam.

To achieve acceptable beam losses, beam scrapers are placed between the medium-β and high-β sections, and further study will be made to suppress beam halo.

### 3. Discussion and summary

A high-intensity deuteron linac with a single-cell cavity system (SCL; ImPACT2017 model) was proposed for the mitigation of LLFPs by nuclear transmutations. Deuterons with a current in excess of 1 A can be accelerated up to 200 MeV/u. A large transverse-normalized RMS beam emittance of 25 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 in the case of a large acceptance.
The accelerator consists of the ion source and three different types of rf acceleration structures: (1) the low-\(\beta\) section, (2) the medium-\(\beta\) section, and (3) the high-\(\beta\) section. Each section is based on a different type of single-cell rf cavity with magnetic focusing elements. In the low-\(\beta\) section, a low-frequency normal conducting cavity of 25 MHz is used for every single cell and the beam from the ion source is well-captured and accelerated adiabatically by appropriately manipulating the rf phase and voltage of each cavity properly. The beam is focused transversely with the superconducting solenoids placed at each cell. The medium-\(\beta\) section accelerates the beam up to 40 MeV/u and in each cell, a quarter wave resonator (QWR) type of \(\pi\)-mode superconducting rf cavity is used. Variable-field permanent quadrupole magnets were placed between each cell for proper beam focusing. The high-\(\beta\) section was also composed of many single cells, and accelerates the beam up to 200 MeV/u. In each cell, reentrant-type superconducting rf cavities were used, and variable-field permanent quadrupole magnets were also placed at the end of each cell for transverse beam focusing.

The blow-up of the beam owing to transverse space-charge forces can be compensated for by tuning the strength of the quadrupole fields. Longitudinal space-charge forces can also be compensated for by tuning the synchronous phase and cavity voltage, to obtain larger focusing forces. Resonators in the medium-\(\beta\) and high-\(\beta\) section have large sizes compared with that of superconducting cavities, that are made of Nb bulk sheets in the existing linear accelerators. Alternative methods, such as sputtering Nb on the Cu structure, may be applied to large cavities in these sections.

The electric power requirements for the rf and focusing elements are summarized in Table 5. The rf power requirements are divided into three parts: beam power and wall loss in the rf cavities (Wall loss) and heat loads into the magnet cryostats and rf cryomodules (Heat load).

| Section         | Beam  | Wall loss | Heat load |
|-----------------|-------|-----------|-----------|
| IS and LEBT     | 0.2   | —         | —         |
| Low-\(\beta\)   | 9.8   | 6         | 2         |
| Medium-\(\beta\)| 70    | 0.47      | 0.3       |
| High-\(\beta\)  | 320   | 4.3       | 1.3       |
| **Total**       | **400** | **10.8**  | **3.6**   |

Table 5. Electrical power (MW) consumed by beam power loading (Beam), wall current ohmic loss in the rf cavities (Wall loss) and heat loads into the magnet cryostats and rf cryomodules (Heat load).
throughputs of \( \sim 100 \text{kg/year} \). This corresponds to \( ^{239}\text{Pu} \) production from approximately twenty 1-GW reactors. The total electric power of 400 MW for the 1-A deuteron accelerator is \( \sim 2\% \) of the total power produced by 20 reactors.

In summary a 1-ampere-class deuteron linac (ImPACT2017 model) was proposed for mitigating produced by 20 reactors. The total electric power of 400 MW for the this interesting project.

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References

1) International Atomic Energy Agency (2004) Implication of Partitioning and Transmutation in Radioactive Waste Management (Technical Reports Series, No. 435). International Atomic Energy Agency, Vienna.
2) Knaster, J. (2017) Overview of the IFMIF/EVEDA project. Nucl. Fusion 57, 102016.
3) Furutachi, N., Okuno, H. and Sakurai, H., in preparation.
4) Shiltsev, V. (2014) A phenomenological cost model for high energy particle accelerators. J. Inst. 9, T07002.
5) Henderson, S., Abraham, W., Aleksandrov, A., Allen, C., Alonso, J., Anderson, D. et al. (2014) The Spallation Neutron Source accelerator system design. Nucl. Instrum. Methods Phys. Res., Sect. A 763, 610–673.
6) Peggs, S. (2013) ESS Technical Design Report, ESS-doc-274-v15.
7) Pan, W.M., Chi, Y.L., Fu, S.N., Sha, P. and Xing, Q.Z. (2012) Chinese ADS project and proton accelerator development. In Proc. of 26th International Linear Accelerator Conference 2012 (LINAC2012) (Tel Aviv, 2012). Soreq Nuclear Research Center, Yavne, pp. 412–416 (T1A03).
8) Kuriyama, M., Akiba, M., Akino, N., Araki, M., Dairaku, M., Ebisawa, N. et al. (1987) The Design Research and Development of JT-60 Neutral Beam Injector (Report No. JAERI-M 87-169). Japan Atomic Energy Research Institute, Tokai, Ibaraki (in Japanese).
9) Duperrier, R., Ferdinando, R., Gros, P., Lagniel, J.-M., Pichoff, N., Uriot, A. et al. (2000) Design of the ESS RFQs and chopping line. In Proc. of 20th International Linac Conference LINAC2000 (Monterey, CA, 2000). Stanford Linear Accelerator Center, Stanford, CA, pp. 548–550 (TUD03).
10) Kilpatrick, W.D. (1957) Criterion for vacuum sparking designed to include both rf and dc. Rev. Sci. Instrum. 28, 824–826.
11) Montague, B.W. (1977) Single-particle dynamics — RF acceleration (Report No. CERN-77-13). In Proc. of the First Course of the Int. School of Particle Accelerators (Erice, 1976). CERN, Geneva, pp. 63–81.
12) Lilleequis, C.G. and Symon, K.R. (1959) Deviations from Adiabatic Behavior during Capture of Particles into an R. F. Bucket (Report No. MURA-491). MURA, Madison, WI.
13) Ng, K.Y. (2012) Adiabatic Capture and Debunching (Report No. FERMILAB-FN-0943-APC). Fermi National Accelerator Laboratory (FNAL), Batavia, IL.
14) Sacherer, F.J. (1971) RMS envelope equations with space charge. IEEE Trans. Nucl. Sci. 18, 1105–1107.
15) Lee, S.Y. (1999) Accelerator Physics. World Scientific, Singapore.
16) Okamoto, H. (1989) Beam dynamics of alternating phase focused linacs. Nucl. Instrum. Methods Phys. Res., Sect. A 284, 233–247.
17) Takayama, S., Koyanagi, K., Tosa, T., Tasaki, K., Kuros, T., Yoshiyuki, T. et al. (2012) Fabrication of YBCO coils for accelerator magnet development (1) YBCO negative-bend coil. In The 2012 Annual Meeting Record, I.E.E. Japan. The Institute of Electrical Engineers of Japan, Tokyo, p. 179.
18) Koba, K., Arakawa, D., Fujieda, M., Iegami, K., Ishi, Y., Kanai, Y. et al. (1999) Longitudinal impedance tuner using high permeability material. In Proceedings of the 1999 Particle Accelerator Conference, Vol. 3. New York, NY, pp. 1653–1655.
19) Phum, M.A., Fitzgerald, D.H., Langenbrunner, J., Macek, R.J., Merrill, F.E., Neri, F. et al. (1999) Experimental study of passive compensation of space charge at the Los Alamos National Laboratory Proton Storage Ring. Phys. Rev. Spec. Top. Accel. Beams 2, 064201.
20) Assev, V.N., Ostromov, P.N., Lessner, E.S. and Mustapha, B. (2005) TRACK: The new beam dynamics code. In Proceedings of the 2005 Particle Accelerator Conference. Knoxville, TN, pp. 2053–2055.
21) Ostromov, P.N. and Shepard, K.W. (2001) Correction of beam-steering effects in low-velocity superconducting quarter-wave cavities. Phys. Rev. Spec. Top. Accel. Beams 4, 110101.
22) Okuno, H., Furutachi, N., Mori, Y. and Sakurai, H., in preparation.

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