BEAM DYNAMICS STUDY OF A 400 kW D$^+$ LINEAR ACCELERATOR TO GENERATE FUSION-LIKE NEUTRONS FOR BREEDING BLANKET TESTS IN KOREA

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Abstract

Recently, a pre-conceptual design study was conducted in Korea for developing a dedicated linear accelerator (linac) for 400 kW (40 MeV, maximum 10 mA CW) deuteron (D+) beams to generate fusion-like neutrons. The accelerated beam hits a solid Beryllium target to produce fusion-like neutrons, which will be utilized for technical feasibility tests of the breeding blanket including tritium production and recovery. In this work, we present a detailed start-to-end simulation and machine imperfection studies with proper beam tuning, to access the target beam availability and validate the machine specifications. We have designed a 2.45 GHz ECR ion source and a 4-vane type 176 MHz RFQ by using IBSimu, Parmteq, and Toutatis simulation codes. We propose a super-conducting linac with HWR cavities and solenoid focusing magnets to accelerate the beam up to 40 MeV. In the HEBT line, we adopt two octupole magnets and subsequent quadrupoles to make a rectangular-shaped and uniform density beam with 20 cm × 20 cm footprint at the target. Extensive beam dynamics studies along the linac have been performed using the Tracewin simulation code.

FINAL LAYOUT

The Korea Institute of Fusion Energy (KFE) conducted a pre-conceptual design study for the Integrated Breeding Test Facility (IBTF), which serves as the central component of the Korea Fusion Engineering Advanced Test Complex (KFEAT) [1]. The primary objective of this facility is to assess the technical feasibility of a Breeding Blanket (BB), including tritium production and recovery. In order to generate neutrons suitable for these tests, we also performed a pre-conceptual design study of a linear accelerator (linac) aimed at delivering a 40 MeV deuteron beam (D$^+$) with a maximum average current of 10 mA [2].

The final layout of the pre-conceptual design of the 40 MeV D$^+$ linear accelerator in Korea is summarized in Fig. 1. In this study, we have mainly benchmarked the SARAF-PHASE2 facility [3] for the Superconducting RF (SRF) linac section to accelerate the beam up to 40 MeV. Additionally, we have optimized the High Energy Beam Transport (HEBT) line based on the IFMIF/IFMIF-DONES facility [4] to create a rectangular-shaped and uniform density beam cross-section in the transverse space at the target. The 40 MeV deuteron beam will impact a solid Beryllium (Be) target of 22 cm × 22 cm spot size under the continuous wave (CW) mode to produce fusion-like neutrons (14.1 MeV), which have similar characteristics to those generated by the D-T fusion reaction.

The detailed design structures of the Electron Cyclotron Resonance Ion Source (ECR IS), Low Energy Beam Transport (LEBT) line, and Radio Frequency Quadrupole (RFQ) are depicted in Fig. 2. A 2.45 GHz ECR IS generates over 12 mA of D$^+$ beam at a total output energy of 40 keV, for which the extraction has been simulated with IBSimu. For low-energy beam bunching and acceleration, we have designed the 4-vane type 176 MHz RFQ using Parmteq and Toutatis simulation codes, which accelerates the beam from 40 keV to 3 MeV.

BEAM DYNAMICS STUDY

The start-to-end simulation result along the Medium Energy Beam Transport (MEBT) line, SRF linac and HEBT line is shown in Fig. 3. It has been carried out by using TraceWin simulation code [5]. In the MEBT, the beam from the RFQ is matched to the SRF linac section by using two rebunchers (3-gap structure with an effective length of 280 mm and an aperture of 40 mm) and 7 quadrupoles, which focus the beam in the longitudinal and transverse directions, respectively. The effective voltages of the two rebunchers are 69 kV and 87 kV, respectively.

To achieve a beam power of 400 kW in CW mode, with the capability for long-term operation, we have adopted the SRF linac structure with Half-Wave Resonator (HWR) cavities and solenoid focusing magnets. This choice is motivated by the SARAF-PHASE2 design. The SRF linac is composed of 4 cryomodules; the first two are for low-beta (0.091) cavities (effective length: 0.155 m, maximum accelerating gradient: 6.1 MV/m) and the last two are for high-beta (0.181) cavities (effective length: 0.308 m, maximum accelerating gradient: 7.2 MV/m). The maximum solenoid magnetic field strength is 6.6 T. In this work, a design study of RF cavities in the MEBT and Superconducting linac has been conducted using the CST simulation code. The goal is to optimize machine specifications such as effective length and maximum electromagnetic field strength to meet the design requirements. We integrated the 3-dimensional field-map structures of the designed rebunchers and HWR cavities into the TraceWin simulation code to analyze beam dynamics and verify the target beam availability.

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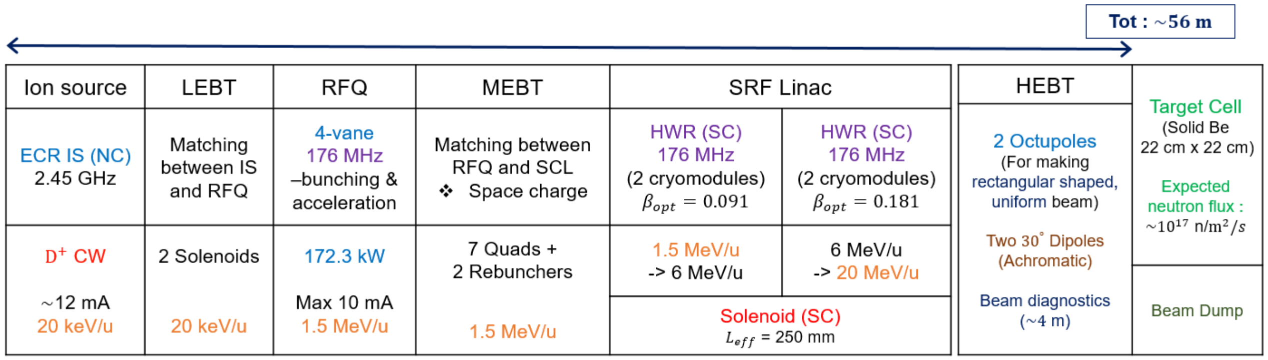

Ion source	LEBT	RFQ	MEBT	SRF Linac		HEBT	
ECR IS (NC) 2.45 GHz	Matching between IS and RFQ	4-vane 176 MHz –bunching & acceleration	Matching between RFQ and SCL ❖ Space charge	HWR (SC) 176 MHz (2 cryomodules) $\beta_{opt} = 0.091$	HWR (SC) 176 MHz (2 cryomodules) $\beta_{opt} = 0.181$	2 Octupoles (For making rectangular shaped, uniform beam)	Target Cell (Solid Be 22 cm x 22 cm) Expected neutron flux : ~10^{17} n/m^2/s
D^+ CW ~12 mA 20 keV/u	2 Solenoids 20 keV/u	172.3 kW Max 10 mA 1.5 MeV/u	7 Quads + 2 Rebunchers 1.5 MeV/u	1.5 MeV/u -> 6 MeV/u	6 MeV/u -> 20 MeV/u	Two 30° Dipoles (Achromatic) Beam diagnostics (~4 m)	Beam Dump
				Solenoid (SC) L_{eff} = 250 mm			

Figure 1: Layout of 40 MeV D^+ linear accelerator for a fusion-like neutron source in Korea. The total length is about 56 m long from ECR Ion source to target facility. The beam is accelerated up to 20 MeV/u passing through the Super-conducting RF (SRF) linac section with the RF frequency of 176 MHz.

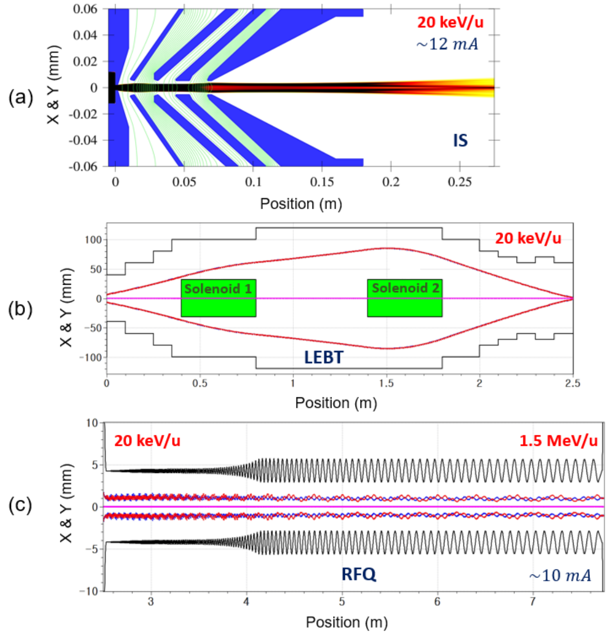

Figure 2: Pre-conceptual design structure of (a) ECR Ion Source, (b) LEBT, and (c) RFQ. The D^+ beam is extracted from ECR IS with the output energy of 20 keV/u and 12 mA of beam current. Two solenoids focus the beam in the transverse direction to match the beam into the RFQ. The beam is accelerated up to 1.5 MeV/u and the final beam current is 10 mA at the end of the RFQ.

In the HEBT line, there are two bending magnets of 30° angle to avoid back-scattered radiations affecting the upstream machine components, which are generated from the target cell. The bending section is designed to be achromatic in which the dispersion of the beam becomes zero after passing the two dipole magnets. It is highly required to have a rectangular-shaped flat top beam profile on the target, which results in generating uniform flux of neutrons on the breeding blanket component with the similar environment as a fusion reactor. The non-linear field strengths of octupole magnets and the arrangement of the subsequent quadrupole magnets are adjusted for achieving the required flat top uniformity of the beam [6]. The final long drift space expands the beam resulting in the 20 cm × 20 cm footprint on the target.

The final beam distributions on the x and y phase spaces are shown in Fig. 4. The final beam size falls within the acceptable range for the target of 22 cm × 22 cross section, and the required flat top uniformity of the particle distribution can be achieved within the tolerance range of the target facility, in accordance with the thermal deposition and cooling system.

So far, we have performed the start-to-end simulation studies by using multi-particle simulation codes to review the target beam availability and validate the machine specifications. Now, we carry out the machine imperfection studies to test whether the beam losses that occur from various static and dynamic errors are within the tolerance range of the facility. The beam corrections are made during the error study by applying steerers in each solenoid and Beam Position Monitors (BPMs) in front of the solenoids inside the cryomodules.

Figure 5 shows the results of the error study of the MEBT and SRF linac section. 1000 random error sets are used with 1,000,000 macro-particles for each simulation. The structural errors include displacement, rotating angle, and field gradient errors of focusing magnets and RF cavities in the MEBT and SRF linac. The following maximum error levels are applied to super-conducting section: 1 mm displacement, 0.5 deg of rotating angle in the x and y directions, and 1% error of electromagnetic field gradients from the design values. As shown in Figs. 5 (b) and (c), most of beam losses occur at the last cryomodule in the longitudinal direction. It is verified that the beam loss occurred under the structural errors are less than 1 W/m along the linac, which is within the maximum limitation of beam loss requirement.

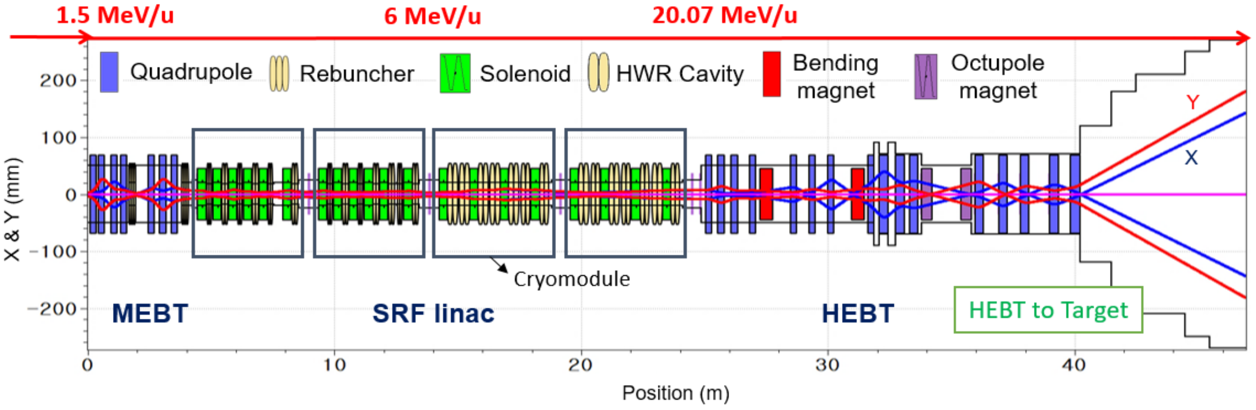

Figure 3: Start-to-end simulation result of D$^+$ beam along the MEBT, SRF linac, and HEBT line to the target. The beam is matched through the MEBT and goes into the SRF section in which the beam is accelerated up to 40 MeV after passing through the four cryomodules. The high-power beam is finally transported to the target via the HEBT.

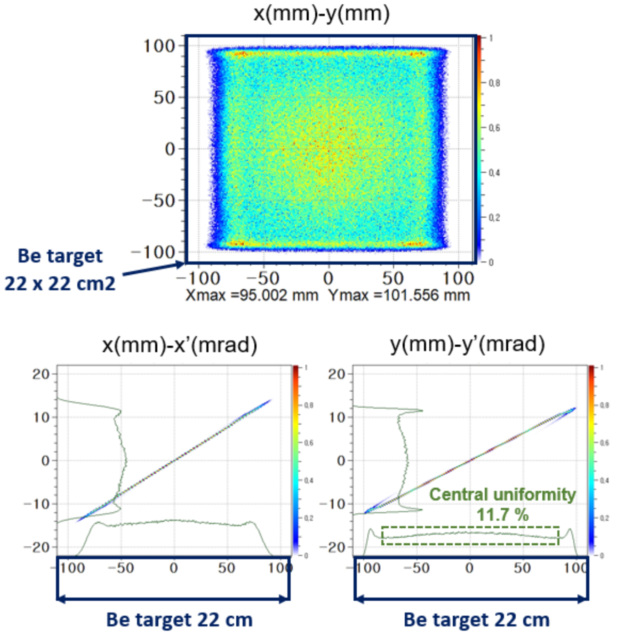

Figure 4: Beam distribution at the target with the spot size of 20 cm × 20 cm in transverse plane. Top: Beam distribution in $x - y$. Bottom: Beam phase spaces in $x - x'$ and $y - y'$.

CONCLUSION

In this paper, we overviewed the pre-conceptual design results of a dedicated D$^+$ linear accelerator for generating fusion-like neutrons (14.1 MeV) in Korea. We have performed the start-to-end simulation study from the ECR Ion source to the target facility. We have verified that the modest beam parameters (40 MeV, maximum 10 mA CW) can be provided under the design specifications, and the target beam distributions of rectangular-shaped and uniform density profile meet the requirements of the target facility for the breeding blanket component test. Finally, we have carried out the machine imperfection study and the beam loss from the structural errors along the linac was shown to be within the acceptable range of the high power accelerator facility. More detailed descriptions on the beam dynamics study and the final configuration of this facility will be reported later.

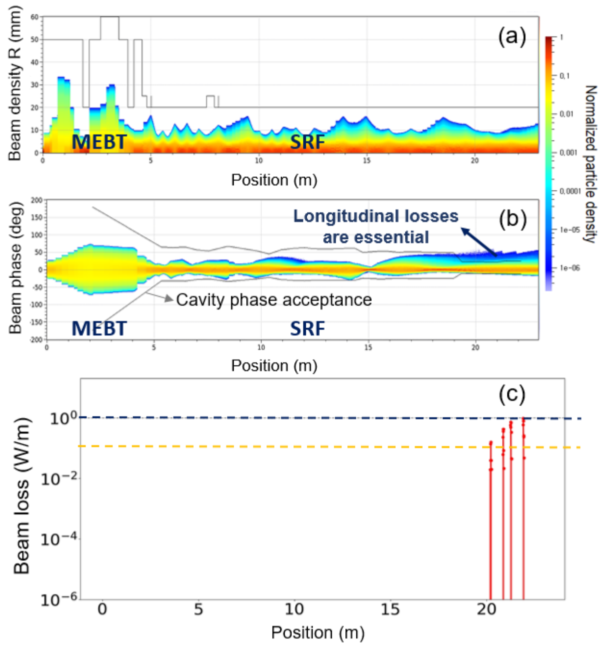

Figure 5: Results of the error study along the MEBT and SRF linac section. 1000 random error sets are used with 1,000,000 macro-particles for each simulation. (a) Beam radial density distribution, (b) Beam phase density distribution, and (c) Beam loss power. Beam loss is dominant in the longitudinal direction at the last cryomodule. The total beam loss is within 1 W/m.

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