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DESIGN AND OPTIMIZATION OF A PROTON SOURCE EXTRACTION SYSTEM FOR THE JAEA-ADS LINAC

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Abstract

The Japan Atomic Energy Agency (JAEA) is designing a 30 MW continuous wave (cw) superconducting proton linear accelerator (linac) for the Accelerator Driven Subcritical System (ADS) proposal. The JAEA-ADS linac's ion source must provide a proton beam over 20 mA with an energy of 35 keV and a normalized rms emittance of less than 0.1 mmmrad. As the extraction system determines the beam properties and quality, systematic optimizations in the geometry and input values of the extraction system design were conducted using the AXCEL-INP 2-D simulation program to satisfy the goal requirements. This work describes the extraction system design and reports the beam dynamics results of the first study for the proton source of the JAEA-ADS linac.

INTRODUCTION

The Accelerator Driven Subcritical System is a viable solution to the challenges caused by nuclear waste. Consequently, the Japan Atomic Energy Agency (JAEA) endeavors to design a continuous wave (cw) linear accelerator (linac) to accelerate a 20 mA proton beam up to an energy of 1.5 GeV. The JAEA-ADS linac begins with a normal conducting segment, up to 2.5 MeV, then transitions to a superconducting section [1]. During the last years, a great effort was put into the linac design from the RFQ to the end of the linac [1–3]. Now, we focus on the design of the initial part of the linac: the ion source. The ion source is a basic element for particle accelerators because it provides the particles that are accelerated for the downstream part of the machine. Generally speaking, ion sources are composed of two components: a plasma generator and an extraction system. The plasma generator generates enough of the desired ions, and the extraction system shapes the beam with the required size and orientation for the following sections [4].

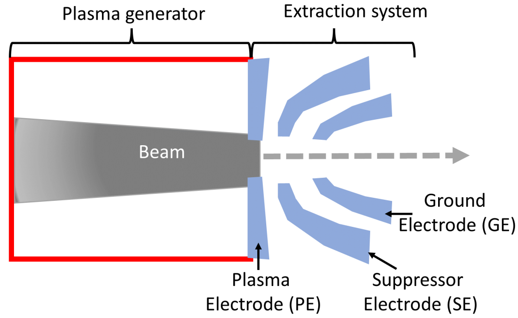

Figure 1: Schematic of the proton source for the JAEA-ADS linac. The extraction system has a triode configuration.

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Table 1: JAEA-ADS Proton Source Parameters

Parameters	**Value**	
	Goal	**This work**
Energy (keV)	35 ± 0.35	34.96
Current (mA)	25 ± 0.25	25.06
$\epsilon_{norm,rms}$ (π mm mrad)	≤ 0.1	0.09
Emission current density (Am^{-2})	≤ 1000	900
Strength field (kV/mm)	< 6	4.37

Figure 1 shows a simple configuration of a proton source for the JAEA-ADS linac and Table 1 provides a list of its major requirements. The beam parameters are based on the JAEA-ADS linac [1]. The demanded emittance is half of the required for the RFQ entrance [2, 3], presuming 100% emittance growth at the low-energy beam transport line. The others parameters were decided for long-stable operation. This study concentrated on the optimization of the extraction system by utilizing the AXCEL-INP 2-D simulation program [5]. This work presents the design strategy and outlines the simulation results.

DESIGN STRATEGY

The simplest extraction system is the diode configuration: plasma electrode (PE) and ground electrode (GE) [4]. A more advanced version is the triode scheme. The triode configuration has the advantage of preserving the space-charge compensation by adding a suppressor electrode (SE), with an opposite potential as the PE, to keep away the extra opposite charged ions that disturb the space-charge compensation, see Fig. 1. Other extraction systems that have more electrodes, i.e., the five-electrode (pentode system), are also available.

For ADS linacs, high availability is a priority for its proper operation. Thus, the JAEA-ADS linac will operate under moderated conditions to reduce the probability of beam trips. For example, to reduce the chances of arc discharge in the electrodes, the strength field for the proton source must be under 6 kV/mm. In addition, an uncomplicated design is also preferable for operation and optimization; therefore, a triode configuration was selected as a compromise of performance and simplicity.

The extraction system was simulated using AXCEL-INP 2-D, a Vlasov solver with axis-symmetric properties that has been utilized by other extraction systems [6, 7]. We began the process by parametrizing the geometry of a triode system, as represented in Fig. 2. The radial and longitudinal dimensions of the simulated area are represented by the variables r and s, respectively. Additionally, Ls represent length distances, Φs indicate the apertures of the electrodes, and θs are the angles of the electrodes relative to the horizontal.

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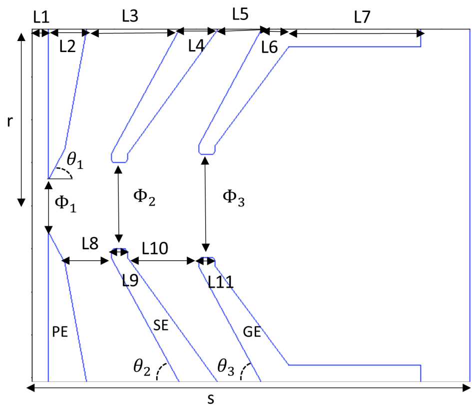

Figure 2: Parametrization of the geometry of the triode configuration.

The parameters were optimized to reach the desired performance, taking into account the following:

- The plasma boundary, also called the plasma meniscus, must have a proper concave shape to reduce beam divergence
- The voltage of PE was fixed for the desired beam energy, and the voltage of SE was scanned to reduce the beam divergence, i.e., achieve the required plasma meniscus shape.
- 19 mm > L8 > 6 mm. The upper limit was to guarantee the emission current density > 1000 $\mathrm{Am^{-2}}$ according to the Child-Langmuir law [8], and the lower limit was to achieve a strength field of < 6 kV/mm.
- For large values of Φ_1, the extracted current increased but also the emittance.

SIMULATION RESULTS

Taking into account the conditions already mentioned, the parameters were scanned and the beam performance was evaluated to optimize the model. To ensure that the design was feasible, we used some conservative values, such as the ion temperature of 0.8 eV. The main inputs for the simulations are outlined in Table 2.

Table 2: Input Parameters for the Computer Simulations

Parameters	Value
Ion fraction	85% protons, 10% H_2^+, and 5% H_3^+
Electron temperature	5 eV
Ion temperature	0.8 eV

As an example of the optimization, Fig. 3 shows the scan of θ_1 parameter to achieve the required beam current. The blue area indicates the acceptable value of the current. Table 3 reports the optimized values.

Figure 4 displays the beam trajectories and the potential of the optimized design. The model exhibits an effective reduction of aberrations, resulting in a small emittance growth. The θ parameters had a considerable contribution to this

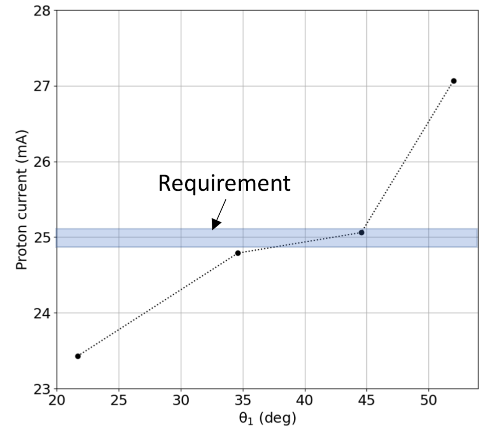

Figure 3: Optimization of the θ_1 parameter.

Table 3: Optimized Triode Model Parameters

Parameters	Value
r	20 mm
s	80 mm
L1	3 mm
L2	7 mm
L3	17 mm
L4	5 mm
L5	8 mm
L6	4 mm
L7	25 mm
L8	8 mm
L9	3 mm
L10	12 mm
L11	4 mm
Φ_1	6.5 mm
Φ_2	10 mm
Φ_3	12 mm
θ_1	44 deg
θ_2	45 deg
θ_3	45 deg
Voltage of the PE	35 kV
Voltage of the SE	−2 kV

performance; θ_2 and θ_3 have the same value, with θ_1 being slightly different because, among θ values, only θ_1 influences the extracted beam current.

Figure 5 shows the final emittance for the proton beam on the $x - x'$ plane. The proton beam presents a slightly smaller, ≈10%, emittance than the other high-charge ions, please see Table 1. The Twiss parameters were basically the same for all the ions, α = -1.7 and β = 0.17 mm/mrad. Table 1 reports the beam performance of the model and compares it against the requirements. The beam parameters fulfill the demanded values; additionally, the emission current density of the model is 10% lower than the maximum allowed, and the strength field is 27% below the limit. Thus, the results

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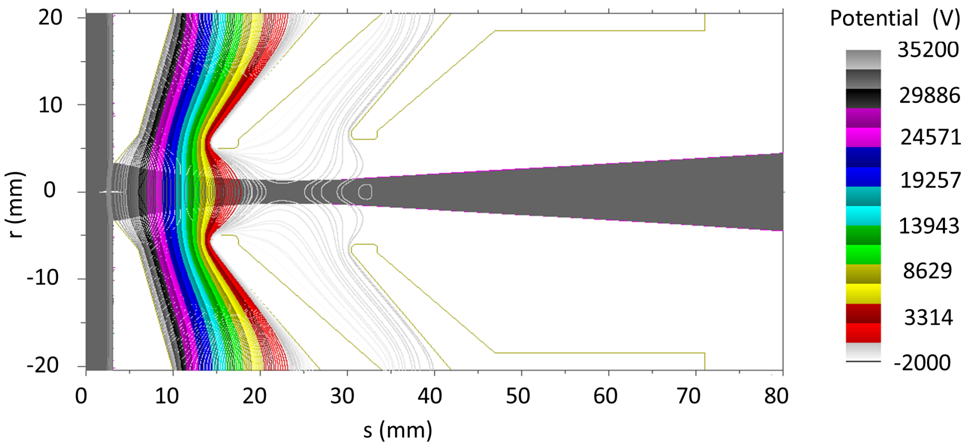

Figure 4: Trajectory and potential plot for the optimized triode system.

confirm the suitability of this triode extraction system for the JAEA-ADS linac.

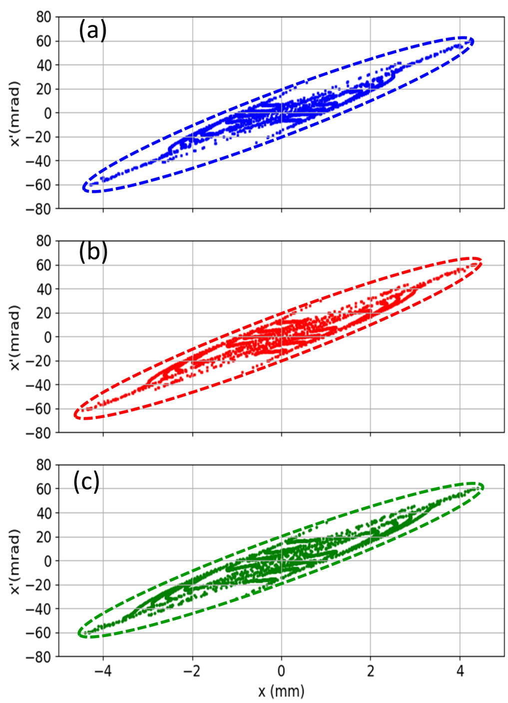

Figure 5: Final horizontal emittance for the extracted proton beam.

CONCLUSION

This study presents the design of a triode extraction system for the JAEA-ADS linac. The work focused on geometry optimization subjected to restrictions and conservative input conditions to ensure a long-stable operation. The extraction model has a simple shape and compact length, less than 80 mm, but secure enough space to facilitate its realization. In addition, it operates with a low-strength field, 4.7 kV/mm, between the plasma and the ground electrode, reducing the likelihood of arc discharge. Furthermore, the simulations show that the triode extraction system can deliver a proton beam with the required beam current, energy, and emittances for the JAEA-ADS linac.

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