DESIGN AND BEAM DYNAMICS STUDIES OF AN ADS RFQ BASED ON AN EQUIPARTITIONED BEAM SCHEME

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Abstract

The Japan Atomic Energy Agency (JAEA) is designing a 30-MW proton linear accelerator (linac) for the accelerator-driven subcritical system (ADS) project. The radio frequency quadrupole (RFQ) is an essential component for the performance of high-intensity linac, especially in ADS projects where stringent reliability is demanded. The JAEA-ADS RFQ will capture a 20 mA proton beam and accelerate from the energy of 35 keV to 2.5 MeV, where the space-charge effects are severe. The JAEA-ADS RFQ's design employs the equipartitioning (EP) beam scheme to control the emittance growth and compactness. As a result, the beam halo formation was minimized and allowed the optimization of the superconducting linac downstream part. A remarkable feature of this RFQ is the low Kilpatrick factor of 1.2 adopted to achieve high stability by reducing the probability of surface sparking on the vane. This work presents and discusses the results of this RFQ design.

INTRODUCTION

The Japan Atomic Energy Agency (JAEA) is developing a 30-MW cw superconducting proton linear accelerator (linac) for the accelerator-driven subcritical system (ADS) project [1]. Figure 1 displays a simplified version of the JAEA-ADS linac.

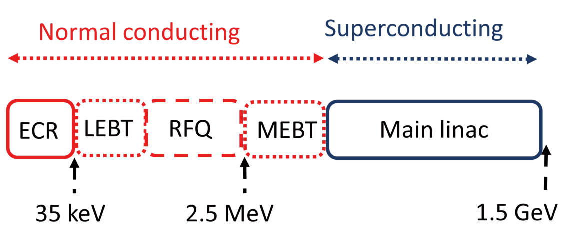

Figure 1: Simplified scheme of the JAEA-ADS linac.

The linac has a normal conducting part and a superconducting one, where most of the acceleration occurs [2]. The Main linac, superconducting part, adopted an equipartitioned (EP) beam scheme [3]. EP condition balances the internal energy between planes, minimizing the emittance exchange by removing free energy between transverse and longitudinal planes that could drive parametric resonances. Thus, it provides low emittances, tight beams, and low beam loss. The EP condition is represented as:

$$\frac{\varepsilon_{n,r,l}}{\varepsilon_{n,r,t}}\frac{\sigma_l}{\sigma_t} = 1, \tag{1}$$

where $\varepsilon_{n,r}$ is the normalized root-mean-square emittance, σ is phase advance, and the sub-indexes t and l stand for transverse and longitudinal, respectively. Hereinafter $\frac{\varepsilon_{n,r,l}}{\varepsilon_{n,r,t}}\frac{\sigma_l}{\sigma_t}$ is refer as EP condition.

Table 1: Specification for the JAEA-ADS RFQ

Parameter	
Particle	Proton
Beam current (mA)	20
Frequency (MHz)	162
Initial energy (keV)	35
Final energy (MeV)	2.5
RF duty factor	100% (CW)
KP factor	≤ 1.2
Beam transmission (%)	≥ 97
Final $\epsilon_{n,r,l}$ (π mm mrad)	≤ 0.39
$\epsilon_{n,r,l}/\epsilon_{n,r,t}$	≤ 1.5
Particle outside the acceleration band [6](%)	≤ 1
Length (m)	≈ 7

However, by fulfilling EP condition, Eq. 1, the values of the phase advance per period (σ/L_{period}) are restricted. Moreover, σ_l/L_{period} is related to the accelerating gradient (E_{acc}) of the cavities by the following relation:

$$\sigma_l/L_{period} \propto \sqrt{E_{acc}}. \tag{2}$$

Combined Eq.1 and 2, we obtain:

$$E_{acc} \propto (\frac{\sigma_t/L_{period}}{\varepsilon_{n,r,t}/\varepsilon_{n,r,l}})^2. \tag{3}$$

A reference design of JAEA-ADS RFQ [4] employed a conventional RFQ design [5]. Beam transmission was over 97%, with final $\varepsilon_{n,r}$s of 0.22 and 0.39 π mm mrad on the transverse and longitudinal plane, respectively. The reference RFQ design had an output $\varepsilon_{n,r,l}/\varepsilon_{n,r,t}$ equal to 1.77; consequently, $E_{acc} \propto ((\sigma_t/L_{period})/1.77)^2$ in the Main linac. By decreasing the final ratio to 1.5, Eq. 3 shows that E_{acc} of the cavities of the Main linac could be increased by 18% regarding the ratio of 1.77, which will help to reduce the number of required cavities. Therefore, to improve the beam quality provided by the RFQ and increase the acceleration efficiency at the Main linac, an intermediate RFQ design based on the EP beam scheme is developed to satisfy

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the requirements listed in Table 1. This manuscript presents and discusses the results of the EP JAEA-ADS RFQ design.

RFQ DESIGN STRATEGY

The design and the beam dynamics studies were done in the LINACS framework developed by Jameson [7], LINACSrfqDES and LINACSrfqSIM provide full control of all RFQ design and simulations parameters, including beam-driven design, fully 3D simulation using correct quadrupolar symmetry and carefully connected Poisson solution for external and space charge fields, and extensive analysis techniques. In LINACS, the RFQ parameter adjusting is done by solving beam equations or by specifying rules for the evolution of the beam parameters. The RFQ parameters are tuned to provide the required external fields that allow the specific beam target characteristics.

EP JAEA-ADS RFQ adopted a similar procedure as other EP RFQs [8, 9]. The RFQ is divided into three sections: radial matching, Shaper, and Main RFQ. The radial matching comprises a few cells, usually four, that accept the beam from the upstream part. Shaper is where the beam begins to bunch and where the beam is brought to the EP condition. Main RFQ is where the beam is finally bunched and accelerated to its target energy. The design strategy consisted of adjusting the RFQ parameters to satisfy the two matching equations along the RFQ and the EP equation from the end of the Shaper until the end of the RFQ. The end of the Shaper is a key point for the RFQ design because there the beam is close to the design size; thus, it is a robust and convenient location to bring the beam to the EP condition. Furthermore, the bunching process starts at the Shaper; therefore, it has a crucial role in the longitudinal beam emittance. The transverse and longitudinal sizes are used to satisfy the matching equation, and the vane modulation (m) is tuned to achieve the EP condition. Thus, the rest of the variables were adjusted according to the rules to achieve the required beam performance.

BEAM DYNAMICS STUDIES

The optimization of the RFQ was carried out using beam dynamics analysis, which comprised the tracking of 100,000 macroparticles using the LINACSrfqSIM program. As an example of the optimization process for the RFQ parameters, we discussed the selection of the synchronous phase (ϕ_s) at the end of the Shaper. Figures 2 and 3 summarize the important results of this scan. For ϕ_s target values close to −90 deg, the beam bunching becomes adiabatic; thus, the longitudinal emittance growth is reduced but increases the RFQ length, see Fig. 3(c).

Figures 2(a) and (b) show that the five models stay close to the EP condition and are below the limit of the $\varepsilon_{n,r,l}/\varepsilon_{n,r,t}$, respectively. Figure 2(c) presents a spike in the longitudinal emittance after the Shaper, which position is slightly different for each model, where some particles escaped from the longitudinal acceptance and eventually lost, thus reducing the emittance. At the entrance of the Main RFQ section,

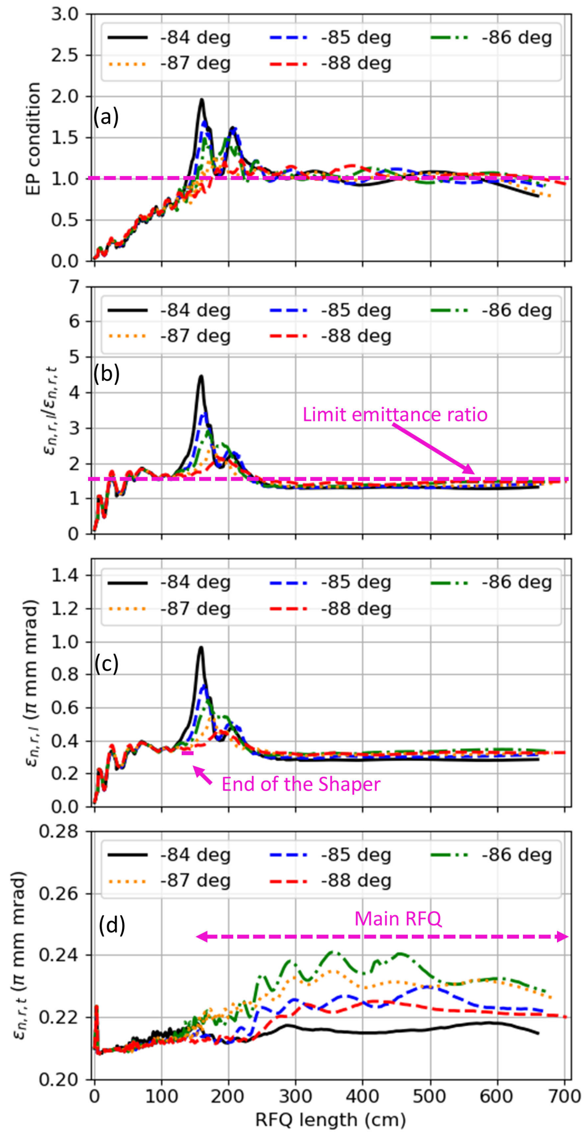

Figure 2: EP condition (a), longitudinal to transverse emittance ration (b), and the longitudinal (c) and transverse (d) normalized rms emittance along the RFQ for different ϕ_s target at the end of the Shaper. The magenta dotted line shows an EP condition value of 1 for subplot (a) and an emittance ratio of 1.5 for subplot (b).

the beam characteristics for each model were different: the −84 deg ϕ_s target model was almost unaffected by resonances resulting in a smooth beam envelope, but -85 and −86 deg cases suffered from harmful resonances, ending in a significant transverse emittance growth, as shown in Fig. 2(d).

−84 deg ϕ_s target case provides the best performance in terms of emittance growth and shortest length, but Fig. 3(b) reveals that it has a fraction of out energy particles beyond the acceptable limit presented in Table 1. −88 deg ϕ_s target model has the higher transmission and the smallest beam fraction of out energy particles, as shown in Figs. 3(a) and (b). The emittance growth control, and the EP and emittance ratios are acceptable, but it has the longest length. However, the length still fulfills the specification; furthermore, the length could be reduced by applying other parameter optimizations. Thus, we chose the −88 deg as the ϕ_s target at the end of the Shaper.

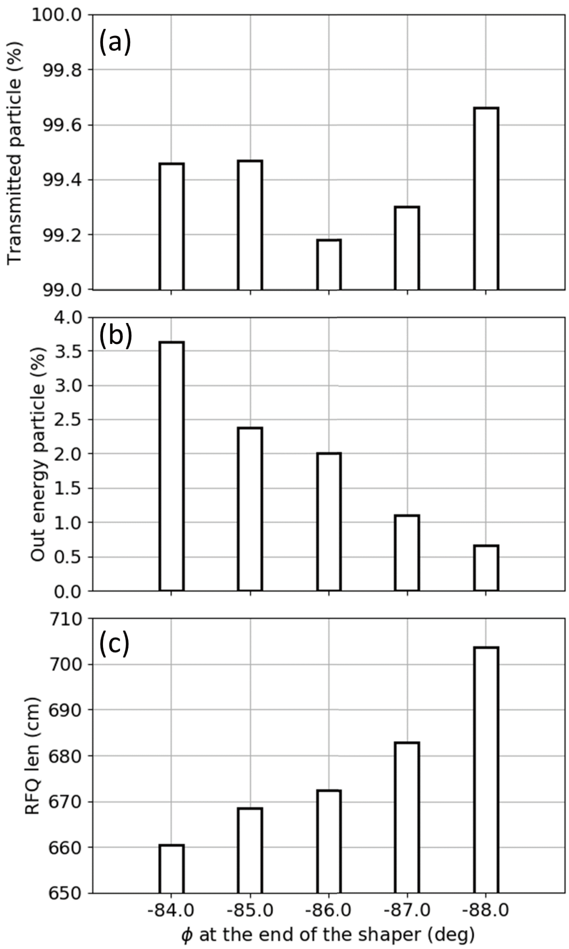

Figure 3: Transmission (a), out energy particles (b), and RFQ length (c) as a function of the ϕ_s target at the end of the Shaper.

Figure 4 shows the cell parameters for the optimized RFQ design, where a is the minimum radius of the electrode tip, r_0 is the average bore radius, B is the dimensionless focusing parameter, Ws is the design energy, and V is the inter-vane voltage. One distinct feature of this RFQ is its long Shaper section, essentially the first 1.3 m of the RFQ. 80% of the Shaper is composed of a "porch" section, i.e., a fraction of the length where the ϕ_s remains −90 deg, which helps to achieve a smooth bunching process. Table 2 summarizes the principal parameters of the design.

Figure 5 shows the evolution of the EP condition, $\varepsilon_{n,r,l}/\varepsilon_{n,r,t}$, and the normalized rms emittance along the RFQ. The EP condition, red dashed line in Fig. 5 (a), approaches one at the end of the Shaper, then increases over one

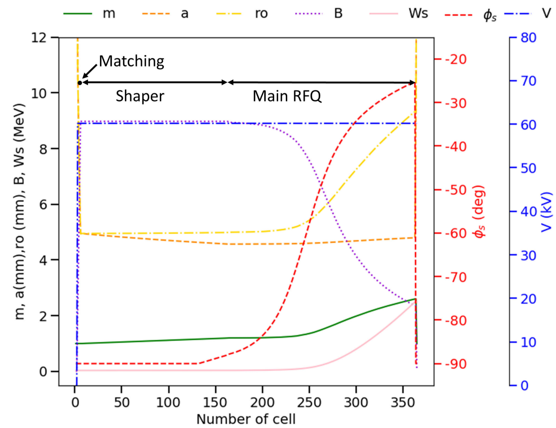

Figure 4: Vane parameter for the EP JAEA-ADS RFQ.

Table 2: Design parameter of the EP JAEA-ADS RFQ

Parameter	
Inter-vane voltage (V)	60.2
ρ_t/r_0	0.75
m_{max}	2.6
a_{min}(mm)	4.5
r_0(mm)	4.9 - 9.3
$\phi_{s,max}$ (deg)	-25.3
B_{max}	8.9
Number of cells	365
Length (m)	6.9

at the beginning of the Main section, and finally smoothly converges near the EP condition. The model indicates that the $\varepsilon_{n,r,l}/\varepsilon_{n,r,t}$, blue dotted line in Fig. 5 (top), is mainly affected by the longitudinal emittance performance because the transverse emittance remains almost constant, Fig. 5(b). Figure 6 presents the transverse distribution (a) and the longitudinal phase space (bottom) at the end of the RFQ. The distribution exhibits a tight beam in the transverse plane with less dense tails. The longitudinal phase space is contained ± 40 deg in phase and ± 75 keV, $\Delta W/W_0$ = 3%, in energy. Table 3 confirms that the model satisfies the specification of the RFQ design.

Table 3: Beam dynamics results of the EP JAEA-ADS RFQ

Parameter	
Initial transverse distribution	water bag
Initial $\epsilon_{n,r,t}$ (π mm mrad)	0.2
Initial longitudinal distribution	uniform phase
Final $\epsilon_{n,r,t}$ (π mm mrad)	0.22
Final $\epsilon_{n,r,l}$ (π mm mrad)	0.32
$\epsilon_{n,r,l}/\epsilon_{n,r,t}$	1.45
Beam transmission (%)	99.7
Particle outside the acceleration band (%)	0.85
Length (m)	6.9

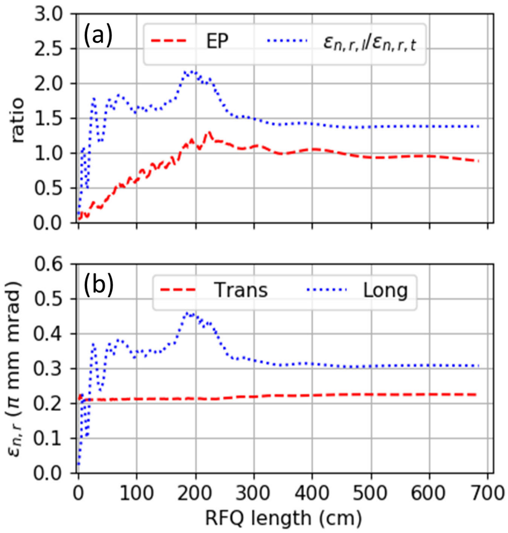

Figure 5: EP and emittance ratios (a) and normalized rms emittance (b) obtained from beam dynamics studies.

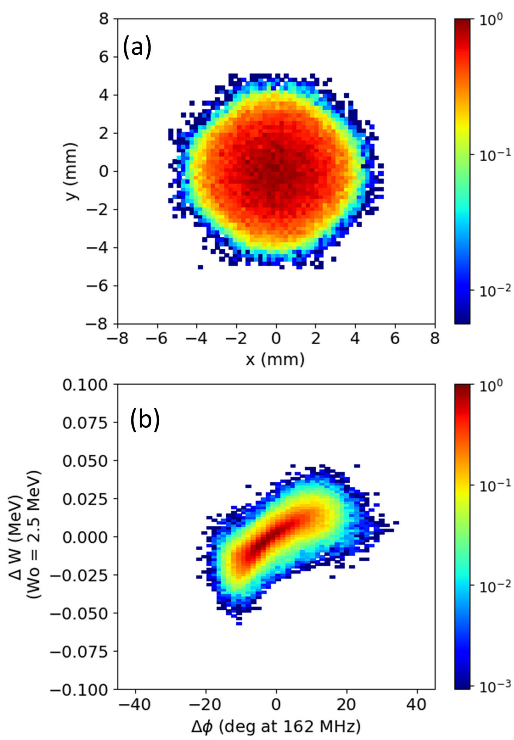

Figure 6: Transverse distribution (a) and longitudinal phase space (b) at the end of the RFQ.

CONCLUSIONS

An alternative RFQ design based on the equipartitioned beam scheme has been developed for the JAEA-ADS linac. The EP JAEA-ADS RFQ design was optimized by adjusting its parameters to provide the required external fields to achieve the desired beam performance. In particular, the vane modulation was tuned to achieve an equipartitioned beam scheme. The design applied a smooth bunching process to control the longitudinal emittance growth and reduce the number of particles outside the energy band, which is a potential source of beam loss in the downstream sections. In addition, the model exhibits a high beam transmission with appropriate control of the transverse size. The $\varepsilon_{n,r,l}/\varepsilon_{n,r,t}$ of 1.45 raises the accessible longitudinal phase; consequently, increasing the available accelerating gradient in cavities at the main linac of the JAEA-ADS. The design satisfies the requirements for the JAEA-ADS linac; thus, it is another viable choice that offers extra control over the beam performance and high acceleration efficiency for the JAEA-ADS linac.

ACKNOWLEDGMENTS

The authors would like to thank to the members of the JAEA-ADS group for their comments and suggestions. This work was supported by the Subsidy for Research and Development on Nuclear Transmutation Technology.

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