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Author(s)	Yee-Rendon B., Kondo Yasuhiro, Maekawa Fujio, Meigo Shinichiro, Tamura Jun
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Beam optics design of the superconducting region of the JAEA ADS

B Yee-Rendon, Y Kondo, F Maekawa, S Meigo, and J Tamura
J-PARC Center, Japan Atomic Energy Agency, Tokai, Naka, Ibaraki, 319-1195 Japan
E-mail: byee@post.j-parc.jp

Abstract. The Japan Atomic Energy Agency (JAEA) is proposing an Accelerator Driven Subcritical System (ADS) for the transmutation of the nuclear waste. ADS will consist of a superconducting CW proton linear accelerator of 30 MW and a subcritical nuclear reactor core. The main part of the acceleration will take part in the superconducting region using five types of radio frequency cavities. The ADS operation demands a high intensity and reliability of the beam. Therefore, the beam optics design plays a fundamental role to reduce the beam loss, control emittance growth and beam halo.

1. Introduction

The Accelerator Driven Subcritical System (ADS) is a promising solution to deal with nuclear waste problem. Thus, the Japan Atomic Energy Agency (JAEA) is designing a linear accelerator for this purpose[1]. The ADS needs an accelerator with a beam power of tenths of MW working in a Continuous Wave (CW) mode. This requirement indicates that superconducting CW proton linac is the best choice. In addition, a severe restriction on the duration and the numbers of beam trips requires an excellent control in the beam loss. Consequently, it is necessary to develop a beam optics which allows to operate beams with high stability.

The JAEA CW proton linac will operate with a beam current of 20 mA and a final energy of 1.5 GeV. The linac will use superconducting cavities to accelerate the beam from 2 MeV to 1.5 GeV, a summary of the cavities is presented in Table 1 [2, 3].

Table 1. Parameters of the superconducting cavities.

Cavity	Frequency [MHz]	β_g	Energy range [MeV]
Half Wave Resonator (HWR)	162	0.08	2-10
Single Spoke 1 (SSR1)	324	0.16	10-35
Single Spoke 2 (SSR2)	324	0.43	35-180
5-cell Elliptical 1 (EllipR1)	648	0.68	180-500
5-cell Elliptical 2 (EllipR2)	648	0.89	500-1500

The lattice design and the studies of the beam dynamics for the superconducting region of the JAEA-ADS were developed using the programs GenLinWin and TRACEWIN [4].

2. Linac design

One of the main problems for the stable operation of the high intensity proton linacs is the emittance growth. Thus, in order to control the emittance growth, the next conditions were used during the lattice design:

- The phase advance (k) in all the planes is kept lower than 90 degree to avoid parametric resonances.
- The beam must satisfy the equipartitioning condition,

$$\frac{T_{x/y}}{T_z} = \frac{k_{x/y}\epsilon_{norm,x/y}}{k_z\epsilon_{norm,z}} \tag{1}$$

  where T is the rms kinetic energy on the plane, k is phase advance and ϵ_{norm} is the normalized emittance. This is to prevent emittance exchange between the planes.
- Smooth envelope (an excellent beam matching between different cavity sections, especially in the regions where frequency jump occurred).

Similar requirements were used for other high beam power machines [5, 6, 7]. In addition, the lattice structures were also inspired by those projects. Table 2 presents a description of the section layouts using the following notation: C= cavity, S= solenoid, DQ= doublet quadrupole.

Table 2. Lattice of the superconducting sections.

Section	HWR	SSR1	SSR2	EllipR1	EllipR2
Layout	S-C	S-C^2	S-C^3	DQ-C^3	DQ-C^5
Period length [m]	0.7	1.9	3.4	5.5	9.7

Two models were developed to explore different phase advance law and investigated which configuration was more suitable in terms of beam reliability, numbers of elements and linac length.

Table 3. Summary of the JAEA-ADS models.

Parameters	Model A	Model B
Phase advance law	$k_{x/y} = 0.83k_z$	$k_z = 0.85k_{x/y}$
$\epsilon_{norm,rms,x/y}$ [π mm mrad]	0.48	0.36
$\epsilon_{norm,rms,z}$ [π mm mrad]	0.4	0.4
Number of cavities	247	248
Number of magnets	119	121
Linac length [m]	381.9	386.6

Table 3 shows the summary of the models, additional magnets were required to do the beam matching, a solenoid between HWR and SSR1 sections and a doublet quadrupole between SSR2 and EllipR1 sections, in both models.

3. Results

Figure 1 shows the rms envelope of the model B. It is easy to identify the matching regions due to change of envelope periodicity, in particular, the sections where the frequency jump occurred (HWR-SSR1 and SSR2-EllipR1).

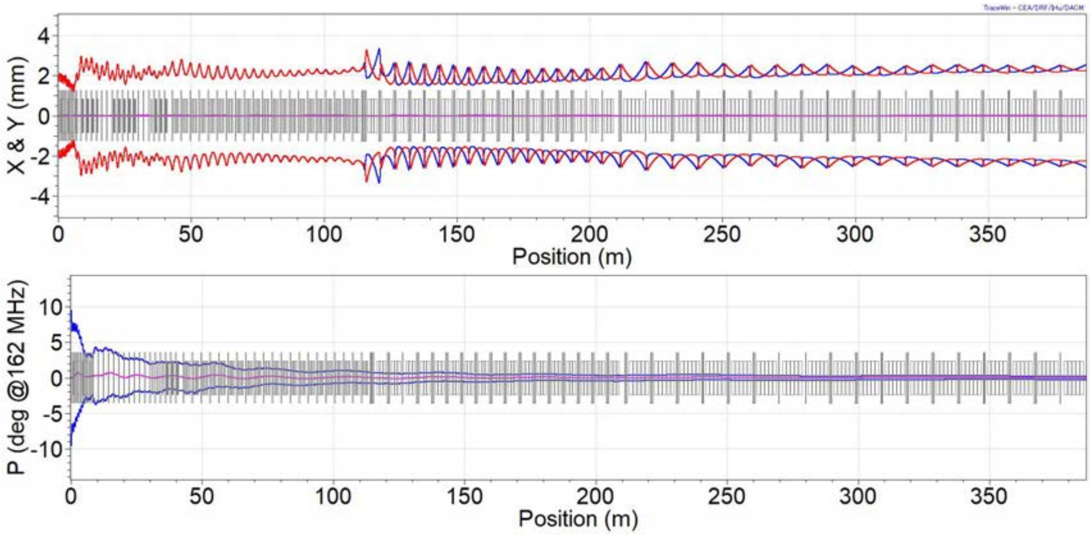

Figure 1. The model B rms envelopes: transverse plane (x in red, y in blue on the top) and longitudinal (bottom).

Model A and B use opposite phase advance laws, nevertheless, both cases operate close to the equipartitioning region (dotted line) as in shown in Fig. 2.

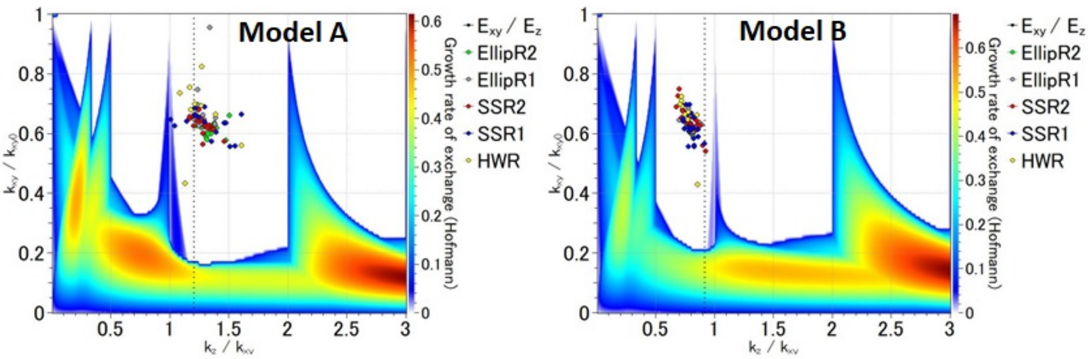

Figure 2. Stability chart (Hofmann chart) provides information of the growth rate regions for the models A (left) and B (right).

The performance of the models was tested by computing the evolution of the rms emittance along the linac. To this end, multiparticle simulations were done by tracking a 6D water-bag distribution with 100,000 macroparticles, the results are in Fig. 3. As it was expected from the stability chart, the emittance growths were not severe, the emittance increase on the transverse plane was below 3% and 12% for the longitudinal one, most of the increase took place in the first part of the linac.

The high control of the beam loss required for the ADS's accelerator is one of the biggest challenges of the project. It is well known that beam halo is one of the main source of the beam

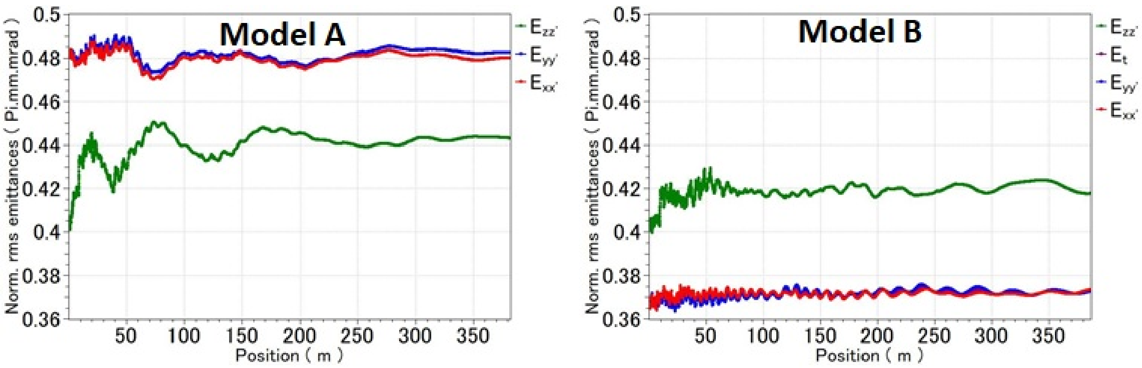

Figure 3. The normalized rms emittance in the linac: horizontal (red), vertical (blue) and longitudinal (green).

loss. Thus, it becomes relevant to study beam halo formation in our linac. The studies consisted in computing the evolution of emittance growth in the linac, for different beam fractions as it was done in similar projects [6, 7]. Model B was chosen for the studies of beam halos instead of A because it has a better control of the emittance growth (mainly in the longitudinal plane). In addition, two different beam distributions were used: 6D water-bag and 6D Gaussian with 3σ. The reason is that at low energy the beams present a more uniform density profile (6D water-bag), on the contrary, at high energy, the beam distributions look Gaussian [8]. Consequently, a lower and higher limit of the emittance growth is estimated. Figure 4 shows that the emittance growths was confined between 50% to 130% in the three planes. No beam loss was recorded for these ideal (no error) cases.

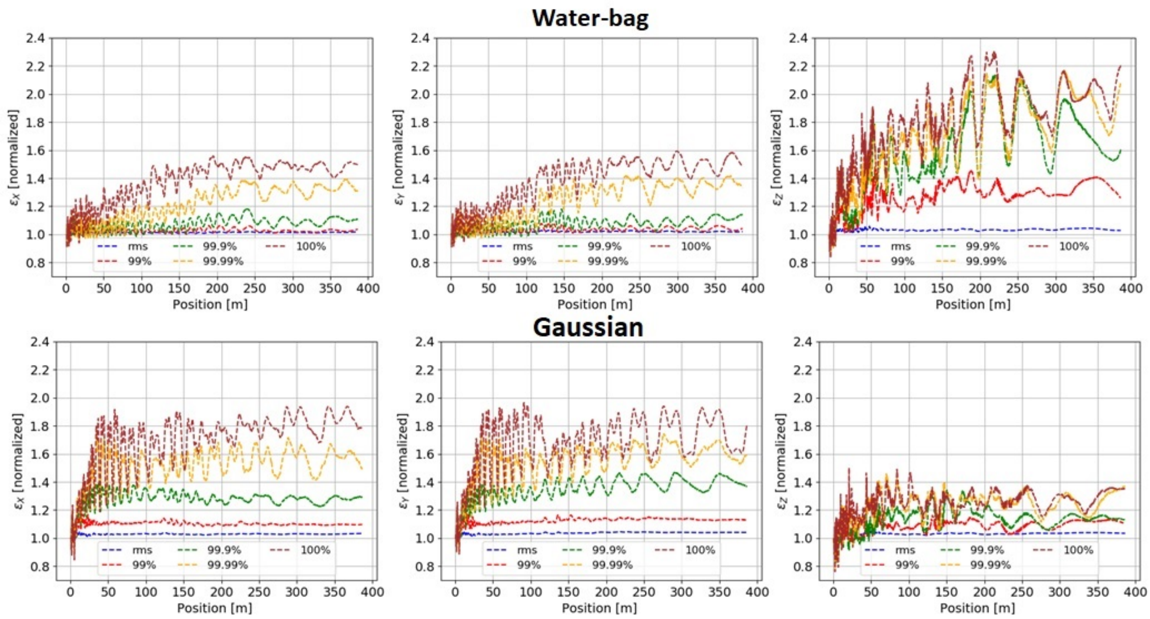

Figure 4. Halo formation on the linac for different emittance fractions. On the top plots the results for 6D water-bag distribution and on the bottom plots for the Gaussian ones. The horizontal, vertical and longitudinal emittances are on the left, middle and right plots, respectively.

4. Conclusions

The models operate near the equipartitioning region and far from the high emittance growth areas. Nevertheless, both models generate space-charge dominant beams. This has a large impact on the emittance growth at the beginning of the linac. The normalized rms emittance growths for model A were in the range of 1% on the transverse plane and 12% on the longitudinal one. Similar results were obtained for model B, in that case the emittance growths were 2.3% and 5.7% for the transverse and longitudinal plane, respectively.

Model B was used for the studies of halo formation instead of the model A, the main reasons were: large transverse emittance value of model A (a possible constraint for the transverse aperture), some of the operations points of the model A laid in the region of emittance growth higher than zero (SSR1). The beam halo development estimates a minimum emittance growth of 50% and a maximum one of 130% in all the planes for the full emittance.

Finally, no beam loss was registered in these studies, however, only cases without errors were simulated. The future work will simulate the cases with errors to estimate the beam loss in a more realistic situation. Additionally, most of the emittance growth took place in the first part of the lattice. This was the result of space-charge effect and the imperfect matching between HWR and SSR1 region. Therefore, the next work will also include the re-design of the two initial sections of the linac to control and reduce the emittance growth, and the beam mismatch. This will help in the minimization of the beam halo, and as a consequence, the potential reduction of the beam loss.

5. Acknowledgments

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