CAVITY AND OPTICS DESIGN OF THE ACCELERATOR FOR THE JAEA-ADS PROJECT *

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Abstract

The Accelerator Driven Subcritical System (ADS) becomes a prominent candidate for the transmutation of nuclear waste. To this end, the Japan Atomic Energy Agency (JAEA) is proposing the JAEA-ADS project which consists in a CW superconducting proton linac coupling with a subcritical core reactor, the accelerator will operate with a beam current of 20 mA and a final energy of 1.5 GeV. The first part of the work is focus in the design of five superconducting cavity models to accelerate the beam from 2.5 MeV to 1.5 GeV and the last one is dedicating to beam optic studies, with emphasis on the control of the emittance growth to reduce the beam halos and mitigate the beam loss, which is one of the main challenges for the successful operation of the ADS projects.

INTRODUCTION

The long-term and high level of radiotoxicity of the nuclear waste storage are some of the main challenges of nuclear energy. To deal with these problems, the scientific community is proposing Accelerator Driven Subcritical System (ADS) as a promising solution to these issues. Currently, several ADS demonstration projects are under commissioning around the world (MYRRHA [1] and Ci-ADS [2]). For its part, the Japan Atomic Energy Agency (JAEA) is designed and ADS to solve the challenges of the nuclear waste storage in Japan.

The JAEA-ADS project consists in high intensity accelerator coupling with a subcritical core reactor [3]. The requirements of high intensity accelerator with a beam power (some MW) together with the constrain to operate in Continuous Wave (CW) mode (compatible with the steady state of the reactor operation) points out that a CW superconducting proton linac is the favorable choice. Moreover, the requirements of the beam power (related to the thermal power of the reactor by the effective neutron multiplication (k_{eff})) and the efficient energy on the target (for the neutron production) were important to select the beam current of 20 mA and the final energy of 1.5 GeV for the JAEA-ADS linac.

The biggest challenges are the lower numbers of beam trips and its duration, MYRRHA has a limit of 10 trips longer than 3 s per 3 months of operation [4], that the linac can accepted to avoid thermal stress in the core reactor. These conditions demand a high operation stability in the linacs elements and a carefully design of the beam optics.

In particular, the JAEA-ADS linac presents the highest beam power linac so far (30 MW). The most relevant characteristics of the linac design are: 1) High beam current (20 mA), strong space charge which could induce the emittance growth, 2) The double frequency jump (162 MHz to 324 MHz to 648 MHz).

The first studies of the JAEA-ADS have been presented in others particle accelerators conference [5–7]. This report provides a summary of the Superconducting Radio Frequency Cavity (SRFC) models and a detailed discussion of the beam dynamics studies for the latest lattice model.

CAVITY MODEL

To achieve a highly efficient acceleration, the JAEA-ADS will use five types of families of SRFC (operating in a frequency of 162 MHz, 324 MHz and 648 MHz) to accelerate beam from 2.5 MeV to 1.5 GeV. By using this scheme, the numbers of cavity and its length can be reduced, the accelerating gradients (Eacc) and the cavity aperture can be increased. At the first step, the types of cavities, the geometrical beta, the number of cell and energy range of the JAEA-ADS SRFC were selected and the results are summarized in Table 1.

Table 1: Parameters of the SRFC

Cavity	Frequency [MHz]	β_g	Energy range [MeV]
Half Wave Resonator (HWR)	162	0.08	2.5-10
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 geometry of the SRFC were designed by using the programs SUPERFISH (SF) [8] for the two-dimensional models (only for the elliptical cavities) and CST Microwave Studio (CST) [9] for the three-dimensional ones. Figure 1 presents the three main types of cavities used for the JAEA-ADS.

For each of cavity a full geometry parametrization was implemented, the details can be found in somewhere else [5, 6]. The optimization process was done by making variable scan, the goals of the optimization process were the following:

- Lower $Epk/Eacc$ and $Bpk/Eacc$ (avoid electric breakdown, quench, etc.).
- Lower power dissipation (high value of R/Q and G).

Table 2 presents a summary of the most important figures of merit of the JAEA-ADS SRFC. The results presented were computed for an operation temperature of 2 K.

The results of the SRFC models were efficient in terms of lower electromagnetic peak ratio and power dissipation, how-

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Table 2: Figures of Merits of the JAEA-ADS Models

Parameters	HWR	SSR1	SSR2	EllipR1	EllipR2
Epk/Eacc	4.21	4.7	3.55	2.17	2.11
Bpk/Eacc [mT/MV/m]	3.41	6.68	5.13	4.22	4.07
R/Q [Ω]	285	212	285	443	619
G [Ω]	59	64	129	208	256

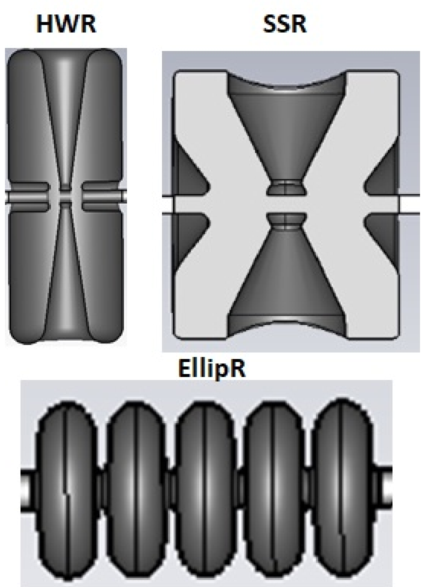

Figure 1: JAEA-ADS main types of SRFC: Half Wave Resonator (HWR), Single Spoke (SSR) and 5-cell Elliptical (EllipR).

ever, the SSR1 cavity performance was lower than HWR1 and SSR2.

BEAM OPTICS

The ADS has a high restriction in the numbers of beam trips and its duration. Thus, one of the main priorities in the linac design is an excellent control in the beam loss, which is the principal responsible of the beam trips. The beam loss has an strong correlation with the formation of beam halo and emittance growth in the linac. As a first step to achieve a robust lattice design, the beam optics will be focus to control the emittance growth. To this end, the following conditions were applied:

- 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).
- Epk ≤ 30 MV/m (to ensure the stable operation in the cavities by avoiding possible electric breakdown, quench, etc.).
- Continuity of the longitudinal acceptance (to reduce the emittance growth, specially in the region of frequency jump [10]).

This study used new emittance inputs obtained from preliminary studies of the RFQ for the JAEA-ADS [11]. Consequently, a new phase law was implemented to satisfy the equipartition condition. A summary of these changes and the comparison with the previous model [7] are presented in Table 3.

Table 3: Comparison of the emittance between previous and new studies. The unit of emittance is mm mrad.

Parameter	New studies	Previous study
Phase advance law	$k_z = 0.54k_{x/y}$	$k_z = 0.85k_{x/y}$
$\epsilon_{x/y,norm,rms}$	0.25	0.36
$\epsilon_{z,norm,rms}$	0.46	0.4

Another difference with the previous studies is the adoption of two new conditions: Epk ≤ 30 MV/m and continuity of the longitudinal acceptance. The first requirement comes for the operational experience of SRFC around the word, this limited could be recomputed and its side effect (reducing the Eacc) could be improved by the optimization of the SRFC electromagnetic peak ratios. The second new condition results in a change of the initial synchronous phase (ϕ_s) in all the SRFC sections. This has a decrease effect in the voltage gain for particle, which is translated as an increase in the numbers of cavities and the linac length.

Using the same the lattice layouts as the previous studies (See Fig. 2), two new models were created to evaluate the advantages of the continuity of the longitudinal acceptance. Table 4 presents a summary of the most important features of the two models.

Table 4: Summary of JAEA-ADS Schemes

Parameter	Model A	Model B
Epk = 30 MV/m	Yes	Yes
Continuity of the longitudinal acceptance	No	Yes
Number of cavities	278	374
Number of magnets	138	190
Linac length [m]	423	532

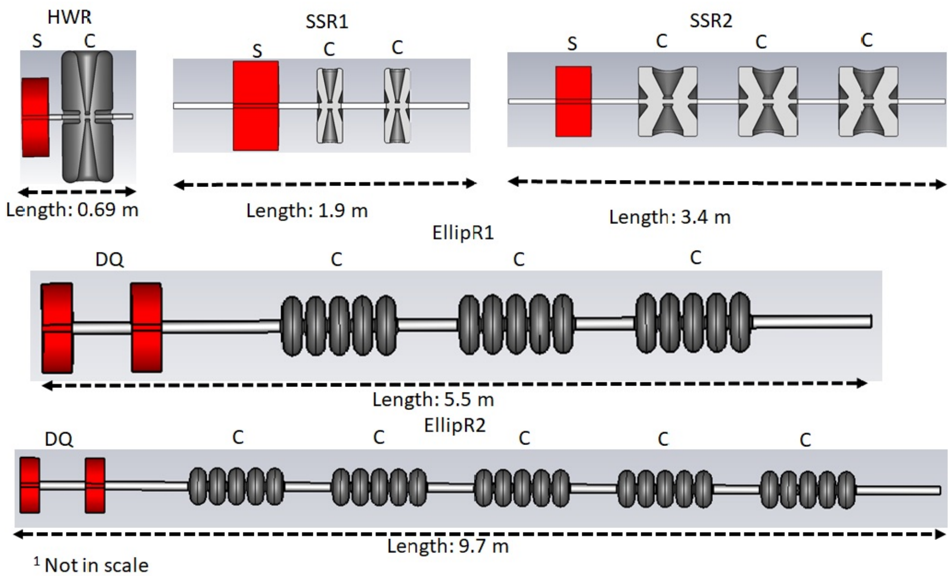

Figure 2: JAEA-ADS lattice layout. S= Solenoid, C = Cavity, DQ= Double Quadrupole.

The beam dynamics studies were developed by tracking 6-Dimensional Gaussian distributions (3σ cut) with 100,000 macro-particles. Figure 3 shows rms beam size envelopes along the linac for the model B, the horizontal (top red) and vertical (top blue) envelopes are bounded in a radius of 3 mm. The ratio between cavity radius and rms beam size are from 8 to 19, and the lattice presents quasi-periodic envelope. On the longitudinal plane, the rms phase is below 10 degree (Fig. 3 bottom).

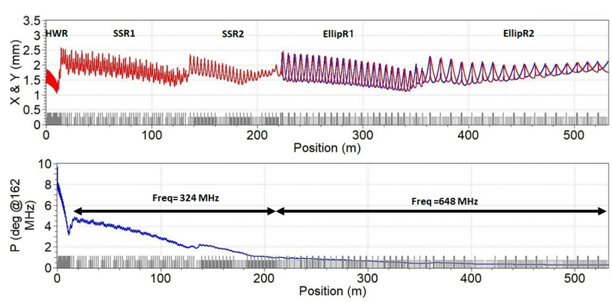

Figure 3: RMS beam size envelopes along the linac in the horizontal (top red) and vertical (top blue), and longitudinal plane (bottom).

The Hofmann charts (Fig. 4) shows that both models A (top) and B (bottom) operates near the equipartition region (dotted black line, where the growth rates of the emittance exchange is zero) and the two schemes have space charge dominant beams ($\frac{k_{x/y}}{k_{x/y0}} < 0.7$).

As a result of the continuity of the longitudinal acceptance, the longitudinal acceptance of the model B is almost 3 times larger than the one of A (See Fig. 5).

Model B presents a better control of the rms normalized emittance ratio ($\frac{\epsilon}{\epsilon_0}$) through linac than A (Fig. 6 top and middle). It can be seen a large longitudinal emittance growth

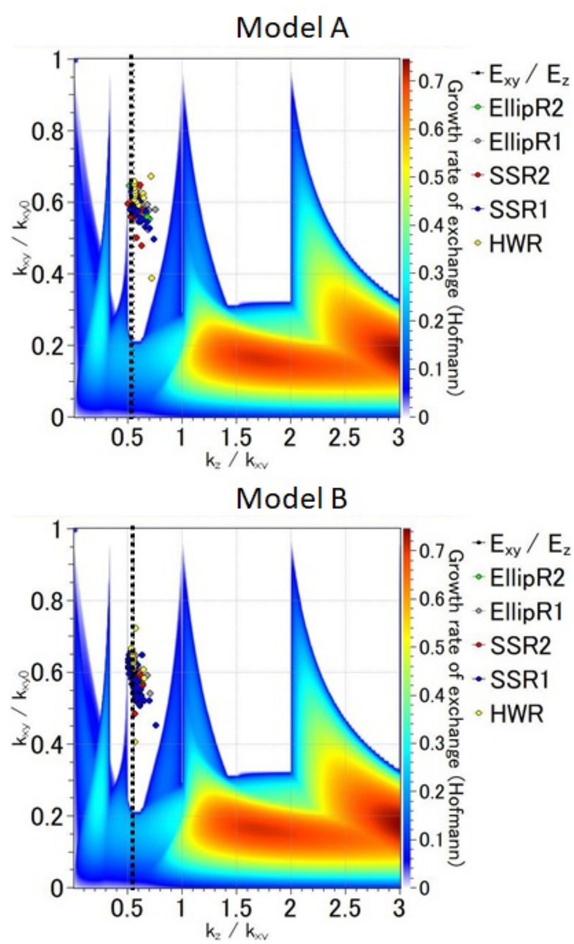

Figure 4: Stability chart (Hofmann chart) provides information of the growth rate regions for the models A (upper) and B (lower).

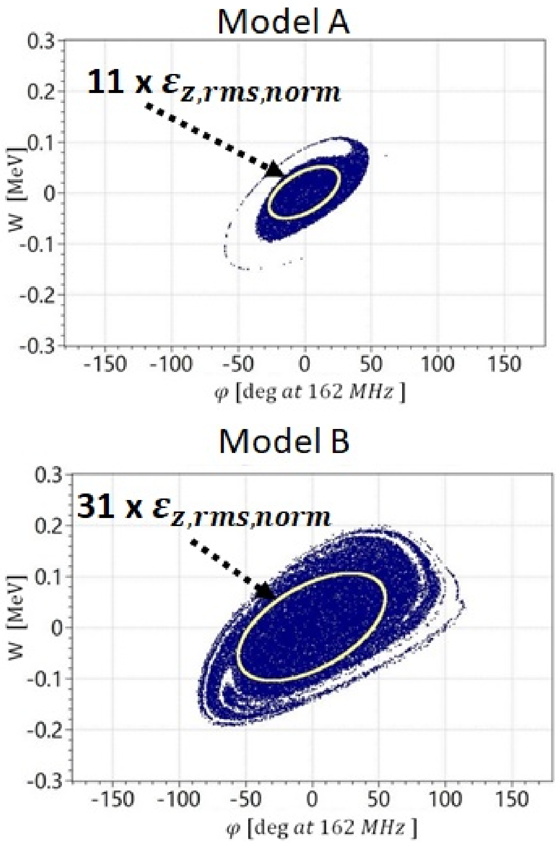

Figure 5: Longitudinal acceptance and the corresponding multiples of the initial longitudinal normalized rms emittance (yellow line) for the model A (top) and B (bottom).

oscillations (Fig. 6 bottom) at the beginning of the linac in special during the transition between HWR and SSR1.

CONCLUSIONS

The first electromagnetic designs of the JAEA-ADS SRFC were completed [1,2], these are an important advance for several reasons: 1) The SRFC is one of the key ingredients for the JAEA-ADS project and represent a significant part of the linac cost, 2) The SRFC results are critical for the beam optics design of the linac, 3) This work is the continuity and boost of the superconducting linac research and development in JAEA.

The SRFC models have an efficient performance in terms of the figures of merits and their values are close with the ones obtained by similar projects (PIP-II [12] and C-ADS [13]). The Epk/Eacc was under 2.2 for the high beta (elliptical) cavities and 4.8 for the rest of the cavities, similarly, Bpk/Eacc was under 7 in all the SRFC.

The JAEA-ADS linac is the highest beam power (30 MW) linac proposal. The control of the beam loss, halo and emittance growth are big challenges for the success of the project, specially in the ADS projects. This upgrade version adopted new emittance inputs in consequence a new phase law is used to achieve an equipartitioned beam. In addition, the

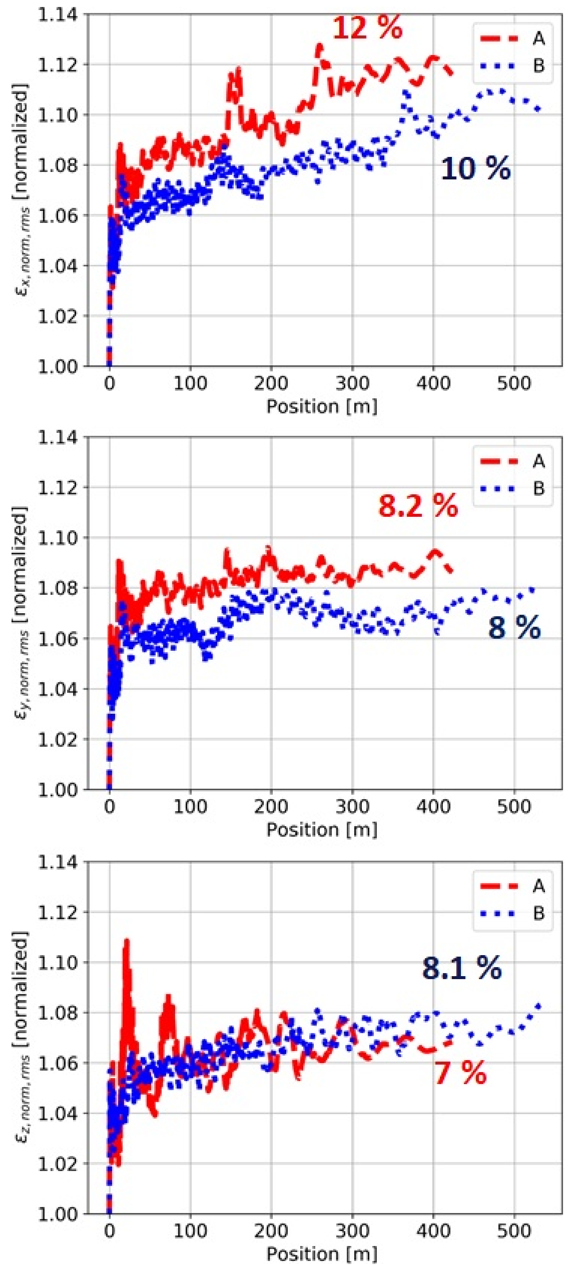

Figure 6: RMS normalized emittance ratio (ϵ/ϵ_0) along the length of the linac for the model A (dashed red line) and B (dotted blue line). Horizontal (top) and vertical (middle), and longitudinal planes (bottom).

Epk ≤ 30 MV/m, to operate the SRFC with high stability, decreases the Eacc gradients and the continuity of the longitudinal acceptance condition helps to control the emittance growth during the frequency jump.

Two models were developed: A (Epk limit, this scheme is similar as the previous model [7]), B (Epk limit and Continuity of the longitudinal acceptance). The beam dynamics studies showed that both models are space-charge dominant beams and theirs working points are near the equipartition region. Additionally, the two schemes have longer linac length (8% for A and 36% for B) and emittance growth (almost the double on the transverse plane and half on longitudinal one for A and half on all the planes for B) in comparison with previous model.

These increases in the emittance growth with respect to the previous study are consequence, principally, of the change of the $\frac{\epsilon_{x/y,norm,rms,0}}{\epsilon_{z,norm,rms,0}}$ from 0.85 to 0.54, the large difference in the emittance enhanced the energy transfer between transverse and longitudinal planes.

Model A and the previous scheme have similar longitudinal acceptance about $10 \times \epsilon_{z,norm,rms}$, on the contrary, B has almost 3 times that value. B has a better emittance growth control than A, specially on the transverse plane. This is due to the emittance interchange between the longitudinal plane and the transverse ones (See Fig. 6). The plots pointed out the advantage of the continuity of the longitudinal acceptance.

Finally, the study is a step forward in the robust design of the JAEA-ADS linac which is fundamental to the JAEA-ADS project and will help in the development of the future of the high intensity linacs around the world.

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