

# DEVELOPMENT OF QWRS FOR THE FUTURE UPGRADE OF JAEA TANDEM SUPERCONDUCTING BOOSTER

Y. Kondo\*, H. Harada, H. Kabumoto, J. Kamiya, M. Matsuda, K. Moriya, J. Tamura,  
 JAEA, Tokai, Naka, Ibaraki, 319-1195, Japan  
 E. Kako, T. Dohmae, H. Sakai, K. Umemori,  
 KEK, Oho, Tsukuba, Ibaraki, 305-0801, Japan

## Abstract

The Japan Atomic Energy Agency (JAEA) tandem booster is one of the pioneering superconducting heavy ion linac in the world. It consists of 40 QWRs with an operation frequency of 130 MHz and  $\beta_{opt} = 0.1$ , and has potential to accelerate various ions up to Au to 10 MeV/u. The user operation was started in 1994, however, it has been suspended since the Great East Japan Earthquake in 2011. Recently, in addition to the efforts to restart the tandem booster, activities to develop new lower-beta cavities to improve the acceleration efficiency of heavier ions such as Uranium has been launched. In this work, the current status of the design study of the QWRS for the JAEA tandem facility is presented.

## INTRODUCTION

The JAEA tandem accelerator is a 20-MV tandem Van de Graaff accelerator which provides heavy ion beams for various kinds of studies such as low energy nuclear physics experiments and irradiation to reactor materials [1]. To obtain enough energy for the nuclear reaction of heavy ions with mass numbers of more than 70, the JAEA tandem facility is also equipped with a superconducting booster linac [2, 3]. Figure 1 shows the schematic layout of the JAEA tandem accelerator and the superconducting booster.

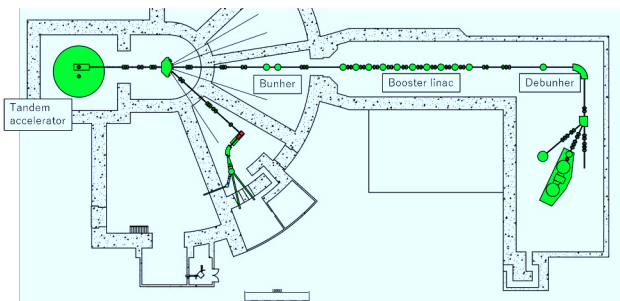


Figure 1: Schematic layout of the JAEA tandem accelerator and the superconducting booster.

With this booster, ions up to Au can be accelerated to 10 MeV/u. The tandem booster consists of 40 129.8 MHz quarter-wave resonators (QWRs) with an optimum  $\beta$  of 0.1. The total acceleration voltage is 30 MV. Since this QWR was developed at the very early stage of the low- $\beta$  superconducting resonator progress, it has unique structure. The outer conductor of this QWR is made of explosively

bonded niobium(Nb)-copper bi-metal sheets, which is indirectly chilled by the liquid helium filled at the top of the cavity. The drift tube made of pure Nb is suspended from the top plate bolted to the outer conductor via a flange. They are operated with 4.5 K, and the typical acceleration field  $E_{acc}$  is 4~5 MV/m, with input power of 4 W. Table 1 is main parameters of this QWR.

Table 1: Main Parameters of the JAEA Tandem Booster QWR.

Resonant frequency $f_0$	129.8 MHz
Duty	100%
Optimum beta $\beta_{opt}$	0.1
Inner diameter on beam axis	150 mm
Aperture	30 mm
Gap length	40 mm
$G = Q_0 \cdot R_s$	26 $\Omega$
$P_0$	4 W
$E_{acc}$	4~5 MV/m
$E_{pk}/E_{acc}$	4.6
$B_{pk}/E_{acc}$	7.5 (mT/(MV/m))

To improve the acceleration efficiency of heavier ions such as Uranium, development of lower  $\beta$  cavity had been proceeded [4], but unfortunately, the operation of the superconducting booster has been suspended since the Great East Japan Earthquake in 2011. The upgrade project was also postponed. Recently, we launched activities towards the restart of the tandem booster operation. The project is including the low energy extension of the booster, moreover, the future replacement of the tandem Van de Graaff accelerator with a superconducting linac is in the scope.

Using the same frequency as the existing booster is a natural choice for the low  $\beta$  extension of the booster. In the previous development, replacement of only the drift tube part of the existing cavity with a low- $\beta$  one was assumed. To this end, a twin drift tube (twin-DT) QWR had been developed [4] to obtain higher energy gain per cavity. The current R&D program is based on this development. However, more recent superconducting cavity technology using sheet-forming of pure Nb is assumed. Therefore, an ordinary single-DT resonator is also considered in addition to the twin-DT QWR. Assumed  $\beta$  range for these QWRs is from 0.048 (1.1 MeV/u) to 0.075 (2.7 MeV/c).

For the replacement of the tandem accelerator, acceleration of  $A/q=7$  particles such as  $^{238}\text{U}^{34+}$  is assumed. In this case, 130 MHz is too high because the focusing force

\* yasuihiro.kondo@j-parc.jp

Content from this work may be used under the terms of the CC BY 4.0 licence (© 2022). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI

of the radio frequency quadrupole (RFQ) at the first stage is not sufficient. Therefore, half frequency, namely 65 MHz is chosen. The requirement for this linac is to accelerate from 0.5 MeV/u to 4.5 MeV/u, which enables to accelerate  $A/q=7$  particle more than 8 MeV/u using the existing superconducting booster .

In this paper, the present status of the design work of both the 130-MHz and 65-MHz QWRs for the JAEA tandem superconducting booster is presented.

### 130 MHz QWR

The cavity design was conducted by using CST Micro Wave Studio [5]. Figure 2 shows the electro-magnetic field of the 130-MHz QWRs.

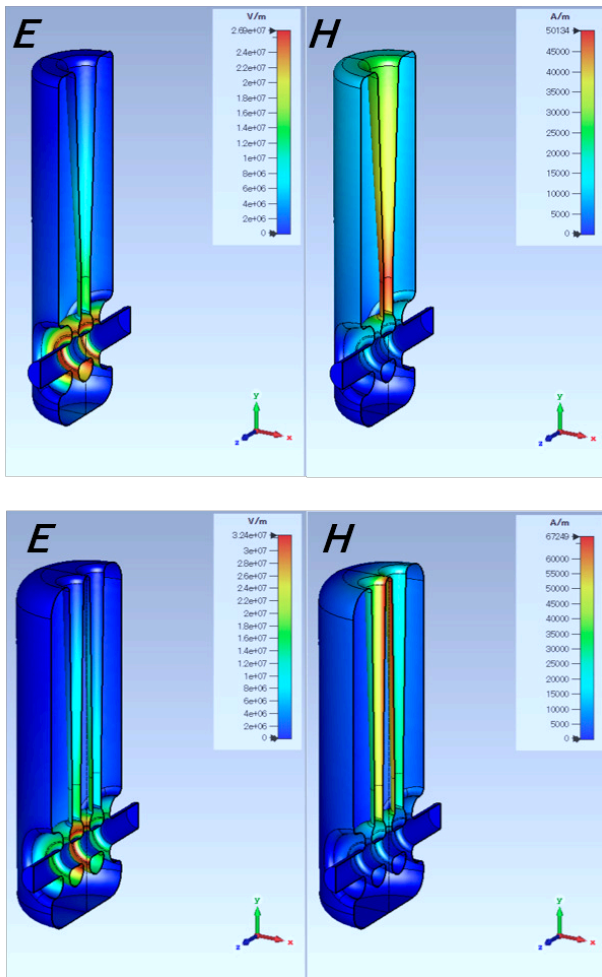


Figure 2: Electro-magnetic field of 130-MHz QWRs trial design. Upper figures are single-DT QWR, and lowers are twin-DT QWR. Left figures indicate the surface electric field and right ones are the surface magnetic field. The field is normalized to the stored energy of 1 J.

The inner diameters of the single-DT and twin-DT are 150 mm and 200 mm, respectively. Currently, no optimization was performed except for the frequency adjustment by changing the cavity height, and they are 515 mm and

510 mm, respectively. The cavities are rather compact because of their high frequency compared to that of usually used for QWRs.

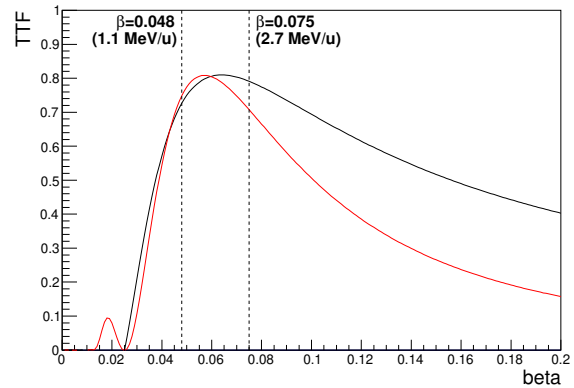


Figure 3: Transit time factors of the 130-MHz QWRs. The black line represents the TTF of the single DT, and the red one is for the twin DT.

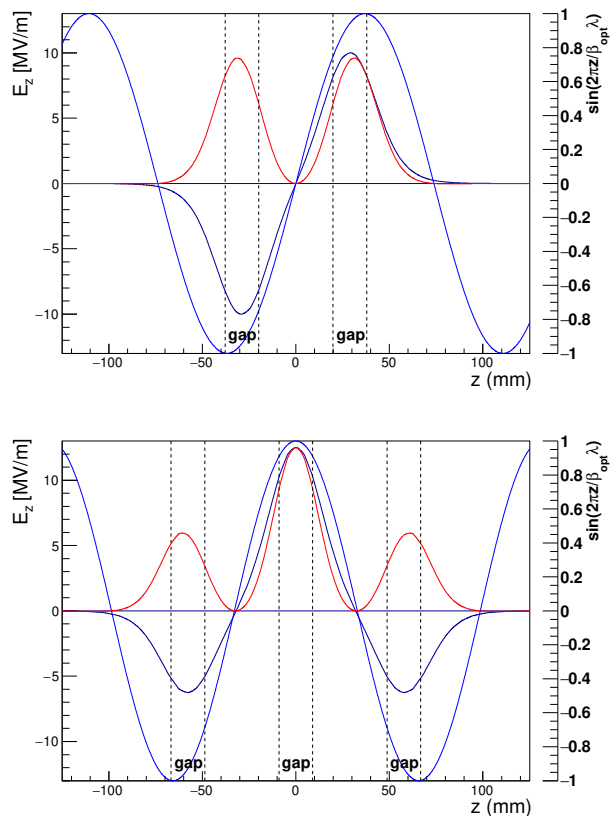


Figure 4: Electric-field distribution on the beam axis of the 130-MHz QWRs with stored energy of 1 J. Upper figure is the single-DT case, and the lower is for the twin DT.

The transit time factors (TTF) as functions of  $\beta$  of the are shown in Fig. 3. From this plot, the maximum TTF of the single DT is 0.81 at the  $\beta_{opt}$  of 0.064. The TTF of the

twin DT is the same as that of the single DT, but the band width is narrower and the  $\beta_{opt}$  is 0.057. The dotted lines represent the assumed beta range for these QWRs.

Figure 4 represents the electric field along the beam axis  $E_z$  of the 130-MHz QWRs. The black line shows the  $E_z$  obtained with MWS, and the blue one is the rf waveform  $\sin(2\pi z/\beta_{opt}\lambda)$ . The red line is the effective electric field interact with the particle  $E_z \sin(2\pi z/\beta_{opt}\lambda)$ . The dotted lines represents the gap position. The gap length is 18 mm for both the types. The lower figure indicates that the electric field in the twin-DT QWR is localized at the center gap.

The cavity parameters obtained with MWS are summarized in Table 2. The original concept of the twin-DT QWR assumed to use the outer conductor of the existing cavity. In this case, it was very effective, however, in case of the design from scratch, the gain of twin-QWR in accelerating efficiency is not so match in spite of its complex structure, compared to the ordinary single DT QWR.

Table 2: Simulation Results of the Trial Design of the 130-MHz QWRs for JAEA Tandem Booster

	single DT	twin DT
$f_0$ (MHz)		130
$\beta_g$		0.05
$\beta_{opt}$	0.064	0.057
Inner diameter (mm)	150	200
Height (mm)	515	510
Aperture (mm)		40
Number of gap $N_g$	2	3
Gap length (mm)	18	18
$L_{eff} = N_g \frac{\beta_{opt}\lambda}{2}$ (mm)	148	197
$G = Q_0 \cdot R_s$ ( $\Omega$ )	19.5	14.4
$R_{sh}/Q_0$	389	575
$E_{pk}/E_{acc}$	7.0	9.3
$B_{pk}/E_{acc}$ (mT/(MV/m))	16	24
$E_{acc}@E_{pk}=40$ MV/m (MV/m)	5.7	4.3

## 65 MHz QWR

As mentioned in introduction, 65-MHz QWR is suitable for the replacement of the tandem accelerator. For this frequency, only the ordinary single DT case was studied.

Figure 5 shows the electro-magnetic field of the 65-MHz QWR for the JAEA tandem successor, and Fig. 6 is the TTF. The maximum TTF is 0.86 at  $\beta_{opt} = 0.056$ , which is higher than the 130-MHz case. The electric field on the beam axis is shown in Fig. 7.

The obtained parameters of the 65-MHz QWR are summarized in Table 3. The energy gain per cavity is larger than that of the 130-MHz QWRs because of the longer  $L_{eff}$ . By using this QWR, 20 cavities are required to accelerate from 0.5 MeV/u to 4.5 MeV/u.

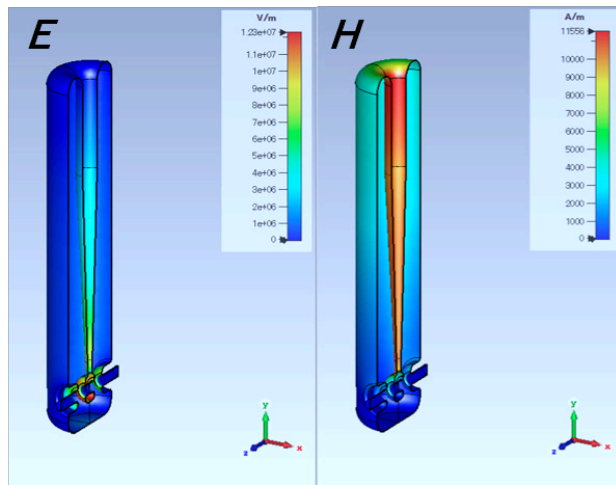


Figure 5: MWS model of the 65-MHz QWR trial design.

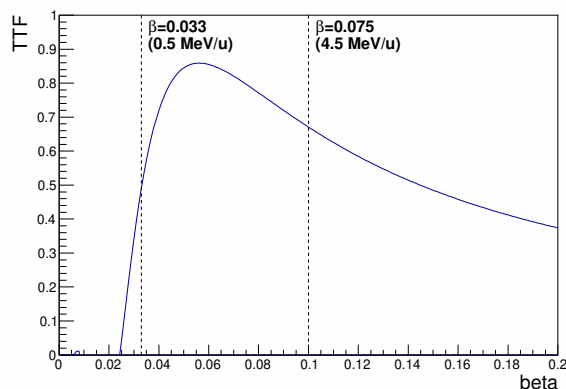


Figure 6: TTF of the 65-MHz QWR for the JAEA tandem successor.

## SUMMARY

For the upgrade of the JAEA superconducting tandem booster, simulation study of various types of the QWR was performed. For the low- $\beta$  extension, 130-MHz QWRs are considered. Assuming current standard sheet-forming method of pure Nb, ordinary single DT resonator is a safe choice than the twin-DT structure considered in the previous development by replacing only the DT part of the existing cavity. For the replacement of the Van de Graaff accelerator, the half frequency of the existing booster is a realistic choice from the requirement of the injector RFQ. As a next step, we are now proceeding the beam dynamics design of the superconducting linac which accelerate  $A/q=7$  particles up to 4.5 MeV/u as a successor of the JAEA tandem accelerator, in parallel with the effort to restart the existing tandem booster. The detailed design of the cryo-module for this accelerator is now also going on.

Content from this work may be used under the terms of the CC BY 4.0 licence (© 2022). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI

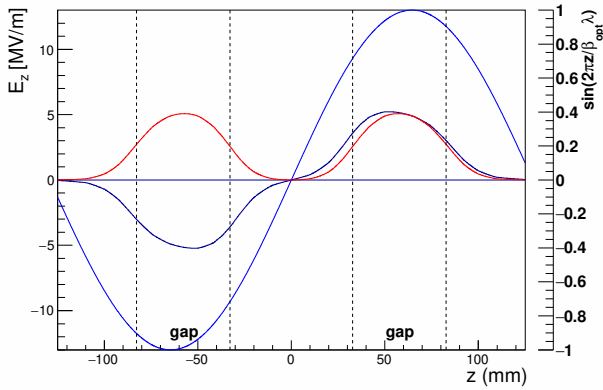


Figure 7:  $E_z$  of the 65-MHz QWR. Notation is the same as Fig. 4.

Table 3: Obtained Cavity Parameters of the 65-MHz QWR

$f_0$	65 MHz
$\beta_g$	0.05
$\beta_{opt}$	0.056
Inner diameter	300 mm
Height	1307 mm
Aperture	40 mm
Gap length	50 mm
$L_{eff} = 2 \times \frac{\beta_{opt} \lambda}{2}$	258 mm
$G$	20.0 $\Omega$
$R_{sh}/Q_0$	680 $\Omega$
$E_{pk}/E_{acc}$	6.0
$B_{pk}/E_{acc}$	7.1 mT/(MV/m)
$E_{acc}@E_{pk}=40$ MV/m	6.6 MV/m

## REFERENCES

- [1] S. Takeuchi *et al.*, “Status of the JAERI tandem ac-celerator and its booster,” *AIP Conference Proceedings*, vol. 473, no. 1, pp. 152–167, 1999. doi:10.1063/1.58982
- [2] S. Takeuchi *et al.*, “Acceleration of heavy ions by the JAERI tandem superconducting booster.” In: *Nucl. Instr. and Meth. A*, vol. 382, pp. 153–160, 1996.
- [3] S. Takeuchi *et al.*, “Operational Status of Superconducting Resonators of the JAERI Tandem-booster.” in *Proceedings SRF2001*, Tsukuba, Japan, 2001, pp. 591–593.
- [4] H. Kabumoto *et al.*, “Superconducting twin quarter wave resonator for acceleration of low velocity heavy ions.” In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 612, no. 2, pp. 221–224, 2010. doi:10.1016/j.nima.2009.09.130 <https://www.sciencedirect.com/science/article/pii/S0168900209019159>
- [5] Dassault Systems, *CST Studio Suite*, <http://www.cst.com>