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ELECTROMAGNETIC DESIGN OF THE LOW BETA CAVITIES FOR THE JAEA ADS*

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Abstract

The Japan Atomic Energy Agency (JAEA) is designing a superconducting CW proton linear accelerator for the ADS project. The superconducting region will use five types of radio frequency cavities. In the region from 2 to 180 MeV the acceleration will be done using Half Wave Resonator (HWR) and Single Spokes (SS) cavities. HWR cavities will accelerate the beam from 2 to 10 MeV with a geometrical beta of 0.08 and the SS ones will do from 10 to 180 MeV using two cavity families with geometrical betas of 0.16 and 0.43. The results of electromagnetic model design are presented and the comparison with similar cavities from other projects are included.

INTRODUCTION

The Accelerator Driven Subcritical System (ADS) designed by Japan Atomic Energy Agency (JAEA) will require a superconducting CW proton linac to achieve a final energy of 1.5 GeV with a beam current of 20 mA [1]. In the last part of the acceleration, the so-called high beta region, is clear that the use of elliptical cavity is the best candidate for that task. However, for the low energy (low beta) exits several candidates: Quarter-wave resonators (QWR), Half-wave resonators (HWR), Single Spoke (SS) [2, 3].

JAEA linac staff has a large experience with 324 MHz cavities, thus, it was decided to operate with multiples and submultiples of that frequency [4]. The initial operation frequency of 162 MHz was chosen to mitigate the transverse RF defocusing [5]. Consequently, HWR cavity (operating at 162 MHz) was selected to start the superconducting section, after that SS cavities with a frequency of 324 MHz and finally Elliptical cavities at 648 MHz. Table 1 shows a summary of the superconducting cavities families selected for the JAEA-ADS project, the details of the cavity selection are discussed elsewhere [6].

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

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SIMULATIONS

The low beta cavity models were developed using as a baseline the literature suggestions as well the designs of similar projects [2,3,7–11]. Based on the works presented by Mustapha [8], HWR and SS model share common features in the geometry, the parametrization of the low beta cavity geometries are presented on left side of Fig1. Additionally, other work from Mustapha [9] pointed out the importance of inner center conductor geometry for the cavity performance, thus, an elliptical torus shape was adopted to this end by all the models (See right side of Fig1).

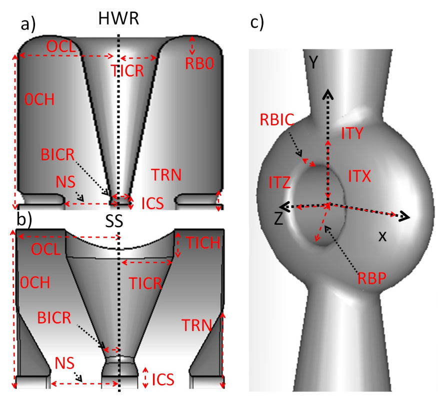

Figure 1: Parametrization of the low beta cavity geometries. On the left: a) HWR and b) SS. On the right, the inner center conductor geometry. Table 2 gives a definition of the acronyms and the final geometries values.

In addition, Facco provided excellent guidelines for the design of low beta cavities [3] which helps us to setup the performance goals for the cavities. The conditions are:

- The Transit Time Factor (TTF) described by

$$TTF(\beta) = \frac{Sin(\frac{\pi g_{eff}}{\beta\lambda})}{\frac{\pi g_{eff}}{\beta\lambda}} \frac{2\pi ITZ}{\beta\lambda} \quad (1)$$

$$g_{eff} = \sqrt{(NS - ITZ)^2 + (2RBP)^2} \quad (2)$$

  where g_{eff} is the effective gap, Nose Start (NS), Radius Beam Pipe (RBP), Internal Torus Z (ITZ) is the distance from the center of the cavity to the gap , λ is the ratio of the speed of the light and the cavity frequency [3, 10]. TTF must be higher than 0.7.

- The maximum electric peak in the surface of 60 MV/m and a maximum surface magnetic field of 120 mT.

The TTF condition provides relations between the gap length of the cavity (NS-ITZ), the beam pipe radius and the frequency. In particular this defines ITZ, NS, RBP, the

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rest of the variables will be used to achieve the condition of the electromagnetic peak limits. The 3D program CST Microwave Studio (CST) [12] was used to build the geometry and to compute the RF parameters of the cavities for an operating temperature of 2 K.

RESULTS

CST models were optimized by using a tetrahedral mesh type, which is more suitable to complex geometry (inner conductor center shape) than hexahedral mesh and the number of mesh cells of the order of 10^5. The optimization process was done by scanning all the variables and the final geometry values are presented in Table 2.

Table 2: Optimized Geometry Values for the JAEA-ADS Low Beta Cavities

Parameters [mm]	HWR	SSR1	SSR2
Outer Conductor Height (OCH)	499.1	283.4	299.5
Outer Conductor Length (OCL)	192	200	500
Top Inner Conductor Radius (TICR)	80	70	140
Bottom Inner Conductor Radius (BICR)	15	10	140
Radius Beam Pipe (RBP)		20	
Inner Conductor Start (ICS)	25	30	45
Nose Start (NS)	54.7	53.8	151.5
Inner Torus X (ITX)	22	16	40
Inner Torus X (ITY)	26	16	40
Inner Torus X (ITZ)	20	16.1	43.4
Top Radius Nose (TRN)	50	110	150
Radius Bending Outer (RB0)	56	1	15
Radius Bending Inner Center (RBIC)	1	10	4
Radius Bending Inner Nose (RBIN)	10	10	4
Radius Bending Outer Nose (RBON)	15	15	50

The inner conductor geometry plays a fundamental role to control the ratio of the electric peak and the accelerating gradient (Epk/Eacc) as well as the magnetic peak and accelerating gradient ratio (Hpk/Eacc) values (See Fig. 2).

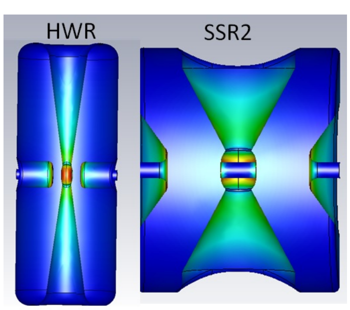

Figure 2: The electric field surface distribution for the HWR (left) and SSR2 (right). It can be seen that the higher electric fields are located in the inner center conductor (brilliant color surface).

Figure 3 shows the electromagnetic ratio peaks as a function of the transverse dimensions of the inner center conductor between the ring shape and the elliptical torus geometry of the HWR cavity. Table 3 shows the figures of merit values of the HWR models for the PIP-II [7] model and JAEA-ADS.

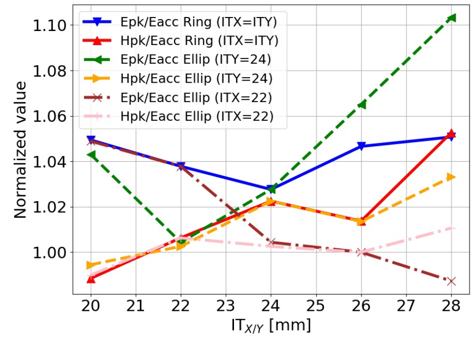

Figure 3: The values of Hpk/Eacc and Epk/Eacc as a function the transverse dimensions of the inner conductor shape. The ring shape cases (solid blue and red lines) both values were changed, and for the elliptical cases: in one ITY was fixed to 24 mm (dashed green and orange lines) and the other case ITX had a value of 22 mm (dashed-dotted brown and pink lines).

Table 3: Figures of Merits of the PIP-II and JAEA-ADS HWR Models

Parameters	PIP-II	JAEA-ADS
β_g	0.11	0.08
Frequency [MHz]	162.5	162
Eacc [MV/m]	9.7	
Epk/Eacc	4.62	4.21
Hpk/Eacc [mT/MV/m]	4.97	3.41
R/Q [Ω]	275	285.39
G [Ω]	48	59.15
TTF	-	0.77

Table 4: Figures of Merits of the PIP-II, C-ADS and JAEA-ADS SS Low Beta Models

Parameters	PIP-II	C-ADS	JAEA-ADS
β_g	0.22	0.12	0.16
Frequency [MHz]	325		324
Eacc [MV/m]	10	–	10
Epk/Eacc	3.84	4.5	4.7
Hpk/Eacc [mT/MV/m]	5.81	6.40	6.68
R/Q [Ω]	242	142	212.72
G [Ω]	84	63	64.78
TTF	-	-	0.75

For the SS cavities the ring shape provided enough performance in Epk/Eacc and Hpk/Eacc. Figure 4 presents the figures of merits (Hpk/Eacc, Epk/Eacc, R/Q and G) of SSR2 as a function of the transverse size of the inner conductor center. Finally, Tables 4 and 5 presents the relevant RF

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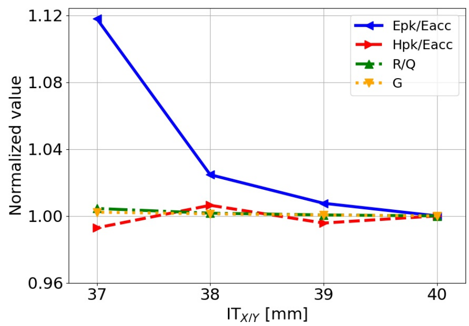

Figure 4: The figures of merits as a function the transverse dimensions of the inner conductor shape. Epk/Eacc (solid blue line), Hpk/Eacc (dashed red line), R/Q (dashed-dotted green line) and G (dotted orange line).

Table 5: Figures of Merits of PIP-II and JAEA-ADS SS High Beta Models

Parameters	PIP-II	JAEA-ADS
β_g	0,47	0.43
Frequency [MHz]	325	324
Eacc [MV/m]	11.4	
Epk/Eacc	3.50	3.55
Hpk/Eacc [mT/MV/m]	5.65	5.13
R/Q [Ω]	296	285.80
G [Ω]	115	129.20
TTF	-	0.77

parameters of SSR1 and SSR2, respectively. Additionally, the single spoke cavity values of similar projects [7, 11] are included in the Tables.

CONCLUSION

The JAEA-ADS low beta cavities were designed to operate with the same accelerating gradient of 9.7, 10 and 11.4 MV/m for HWR, SSR1 and SSR2, respectively (same values as PIP-II [7]), thus, the electric peaks are 40.88, 47.31 and 40.49 MV/m and the magnetic ones are 33.07, 66.80 and 58.48 mT, for the same order of cavities. These values achieved the design target to obtain a maximum surface electric field lower than 60 MV/m and a maximum surface magnetic field lower than 120 mT. In addition, the transit time factor was higher than 0.75 for all the models.

The inner conductor center geometry was fundamental to achieve the performance goal, the implementation of the elliptical torus shape of HWR model helps to reach low values of electric and magnetic peak for a low geometrical beta. In the cases of the SS cavities, the ring shape (same horizontal and vertical dimensions of the inner conductor center) was enough to achieve the target design. However, the SSR1 model presents high electromagnetic peak values in comparison with PIP-II, CADS and the others JAEA-ADS low beta cavities. The possible explanation is that for a low geometrical beta cavity, elliptical torus geometry in the inner conductor center is preferable than the ring shape, as in the case of HWR. Thus, two solutions to improve the results are: adopt an elliptical torus shape for the inner conductor center or select a higher geometrical beta.

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