MECHANICAL ANALYSIS AND DESIGN OF THE PEFP LOW BETA CAVITY*

Sun An#, Y. S. Cho and B. H. Choi
PEFP, KAERI, Daejeon 305-353, Korea

Abstract

The PEFP low beta superconducting RF cavity is the lowest beta elliptical cavity operating at pulse mode so far, the Lorentz force detuning control of the PEFP low beta cavity is a big challenge in cavity design. In this paper, a basic design consideration in the stiffening structure for Lorentz force detuning control has been presented. Based on this consideration, a new stiffening structure has been designed for the PEFP low beta cavity. The PEFP low beta cavity with this structure has low Lorentz force detuning coefficient K_L, reasonable cavity field flatness sensitivity, frequency sensitivity, tuning sensitivity and stable mechanical property.

INTRODUCTION

Superconducting RF (SRF) cavity is considered to accelerate a proton beam with repetition rate of 60 Hz at 700 MHz in the PEFP Linac being built at Gyeongju [1, 2]. The first section of the SRF linac is composed of 9 low beta cryomodules with three 5-cell elliptical cavities of β_g=0.42, and will accelerate a proton beam from 80 MeV to 178.6 MeV [3,4]. Table 1 lists the primary parameters of the PEFP Low beta cavity.

Table 1: Primary parameters of the PEFP Low beta cavity.

Parameters	Value
Frequency (MHz)	700
Geometrical beta β_g	0.42
E_{acc} (MV/m)	8.0
E_{pk}/E_{acc}	3.71
B_{pk}/E_{acc} [mT/(MV/m)]	7.47
R/Q (Ω)	102.30
Cell to cell coupling (%)	1.41
Geometrical Factor (Ω)	121.68

The cavity is deformed by the Lorentz radiation pressure, the tuner, the helium liquid pressure and the atmosphere pressure after pump-down. This deformation induces resonant frequency shift, field flatness change, ununiform stress distribution of the cavity. Therefore, mechanical stability of the SRF cavity is a fundamental consideration in the cavity design.

Generally, the lower beta cavities have stronger Lorentz force detuning than that of the higher beta cavities. For pulse SRF accelerators, the Lorentz force detuning is a more serious issue than that of CW accelerators. The PEFP low beta cavity is the lowest beta elliptical cavity operating at pulse mode so far. Its Lorentz force detuning control is a big challenge in the cavity design. In order to control Lorentz force detuning, a optimized stiffening structure is installed on the cavity normally. In this paper, a basic consideration to optimize the stiffening structure is presented. The stiffening structure design of the PEFP low beta cavity is introduced.

* Work supported by the 21C Frontier R&D program in Ministry of Science and Technology of the Korean Government.
#sunan@kaeri.re.kr

STIFFENING STRUCTURE DESIGN

The function of the stiffening structure is to control Lorentz force detuning and protect cavity. A good stiffening structure should:

- Effectively control the Lorentz force detuning.
- Have low cavity field flatness sensitivity.
- Have low tuning sensitivity.
- Have low peak stress in the cavity.

The PEFP stiffening structure design follows above rule.

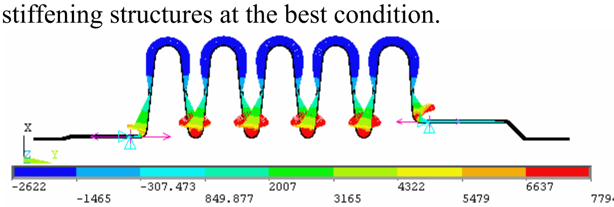
In the superconducting RF cavity, the RF power produces radiation pressures on the inside cavity wall [5]. The pressures deform the cavity wall, that produces the cavity resonant frequency shift. RF system needs to supply a surplus RF power to compensate the cavity frequency shift for keepping the cavity voltage constant. It can be demonstrated the cavity frequency shift is negative, and can be expressed as:

$$\Delta f = -K_L E_{acc}^2 . \quad (1)$$

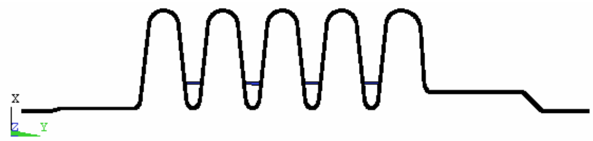
Here E_{acc} is the cavity accelerating gradient. K_L is the Lorentz force detuning coefficient, which strongly depends on the cavity shape and cavity wall's thickness. In order to reduce the RF system costs, usually a stiffining structure is used to control the Lorentz force detuning.

Stiffening structure design

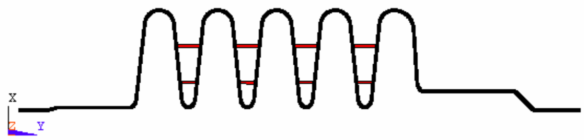
The simulation method of combining Poisson Superfish with ANSYS is used to analyze PEFP cavity mechanical property [6]. The different stiffening structures have been simulated for PEFP low beta cavity, as shown in Fig. 1. Table 2 lists the Lorentz force detuning coefficient K_L with the cavity wall thickness of 4.3 mm for different stiffening structures at the best condition.



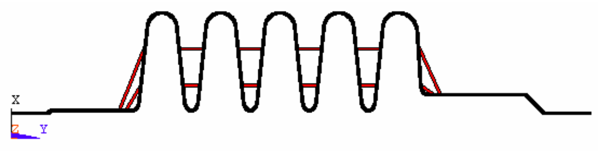
A. A PEFP low beta cavity without stiffening structure and the Lorentz pressure distribution on it.



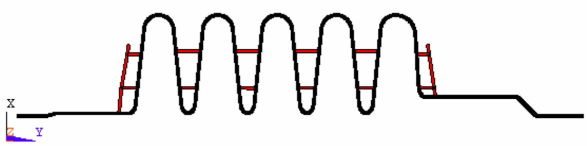
B. Single stiffening ring between inner cells.



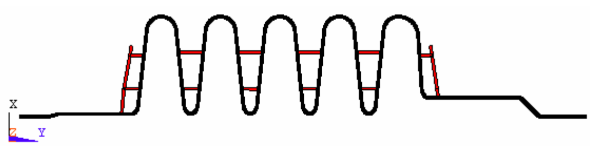
C. Double stiffening ring between inner cells.



D. Double stiffening ring between inner cells and double stiffening cone on end cells.



E. Double stiffening ring between inner cells and between end cell and end dish.



F. Double stiffening ring between inner cells and between Field Probe end cell and end dish, and single stiffening ring between FPC end cell and end dish.

Figure 1: Lorentz radiation pressure distribution and different stiffening structures of the PEFP low beta cavity.

Cavity field flatness sensitivity

The field flatness affects not only the accelerating voltage maximization and the peak surface electro-magnetic field minimization, but also the K_L and the external quality factors Q_{ext} of Field Probe and FPC [7]. Simulation shows that Lorentz pressures do not change cavity field flatness. PEFP cavity frequency tuning strucuture is a SNS type tuner located on the cavity Field Probe side to strecth or press the cavity in logitudinal direction. Measurements have indicated that the tuner's motion changes the cavity field flatness linearly when changing cavity frequency [7].

The cavity field flatness sensitivity due to tuner's motion depends on the cavity structure. Table 2 lists the field flatness sensitivity of a PEFP low beta cavity for different stiffening structures. Other parameters in the Table 2 will be obtained in following sections.

Table 2: Lorentz force detuning coefficient K_L, cavity field flatness sensitivity, frequency sensitivity and tuning sensitivity for different stiffening structures

Stiffening structure*	A	B	C	D	E	F
Min. K_L [Hz/(MV/m)^2]	25.90	19.20	7.60	0.4	0.1	-1.1
Field flatness sensitivity (%/MHz)	2.5	9.4	108	18.5	54.7	49.1
Frequency sensitivity (KHz/mm)	353	369	263	190	184	188
Tuning sensitivity (N/mm)	834	1123	2522	11766	4507	4498
Maximum Von Mises stress (MPa)	77.6	88.5	108	45	12.1	12.6

*Note: The stiffening structure A, B, C, D, E, F correspond to the structure in Fig. 1, respectively.

Cavity frequency sensitivity

The cavity frequency sensitivity is used to specify the tuner movement range and preload the tuner before cool-down. Low frequency sensitivity means a low tuner step resolution and a big tuner movement range for a given frequency range, which needs a heavy tuner-load. An ideal situation is low tuner load and low tuner step resolution. Because the cavity frequency sensitivity is strongly dependent on the mechanical prperty of the cavity and its stiffening structure, the cavity frequency sensitivity must be considered in the stiffening structure design. Table 2 lists the frequency sensitivity of a PEFP low beta cavity for different stiffening structures.

Cavity tuning sensitivity

Cavity tuning sensitivty stronly decides a specification of the tuner load. Higher tuning sensitivity means the heavier tuner load, which needs the biger-size tuner aims and thicker helium vesel wall. The tuning sensitivity depends on the cavity and cavity stiffening structure. Table 2 lists the cavity tuning sensitivity of a PEFP low beta cavity for different stiffining structures.

Cavity stress distribution

After pump-down in the production, the cavity is deformed by the atmosphere pressure at the room temperature, and also deformed by the helium liquid pressure at the low temperature. Because the helium liquid pressure is much lower than the atmosphere pressure, and the niobium's yield strength at low temperature is higher than it at the room temperature, we only consider the inluence of the the atmosphere. Fig. 2 shows the cavity deformation and Von Mises stress distribution of a PEFP low beta cavity. The maximum Von Mises stress values in the cavity wall for different stiffening structures are listed in Table 2.

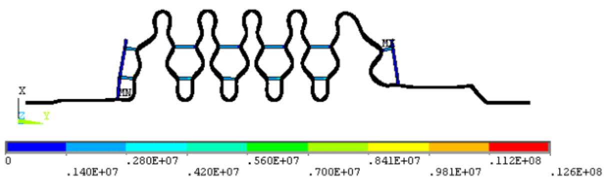


Figure 2: Cavity deformation and Von Mises stress distribution under atmosphere after pumped down.

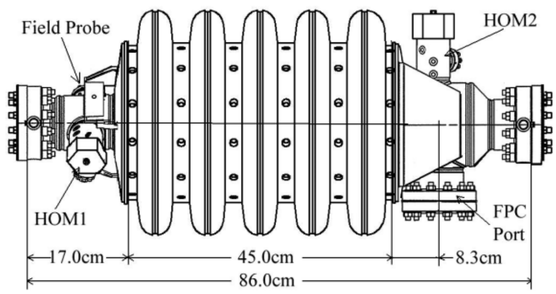


Figure 3: PEFP low beta cavity with the stiffening structure F and the support structures on the end sides.

Discussion

According to above discussions and simulations, structure C, D, E and F can get low Lorentz force detuning coefficient K_L. But structure C could induce very high stress in the cavity, the niobium yield strength is about 70 MPa, therefore, the cavity with structure C is not stable during pumping down. The cavity with th structure D has the highest tuning sensitivity, which increases the tuner design difficulty. The cavity with structure E or F has low stress, and its field flatness sensitivity is little higher, but it is acceptable. The structure F is easier to fabricate than structure E. Therefore, the best stiffening structure for the PEFP low beta cavity should be structure F. Fig. 3 shows a PEFP cavity with the stiffening structure F and the support structures on the cavity end sides.

MECHANICAL MODE ANALYSIS

For PEFP SRF cavities, the pulse repetition rate of 60 Hz means the Lorentz force shakes the cavities to vibrate with 60 Hz, and the cavity's mechanical mode, whose frequency is near the 60 Hz could be dangerous. Here the cavity's mechanical modes are calculated by using the ANSYS 2-D model and 3-D model.

The simulation results show that the mechanical mode with the lowest frequency is a longitudinal mode of 152 Hz, and the lowest frequency of the transverse mode is about 306 Hz. Normally the Dynamic Amplification Factor η is used to judge the resonance risk. The Dynamic Amplification Factor η of the first longitudinal and transverse modes is 1.0 approximately, as shown in Fig. 4. This means that PEFP Low Beta Cavity has no dangerous mechanical modes for 60 Hz pulse repetition.

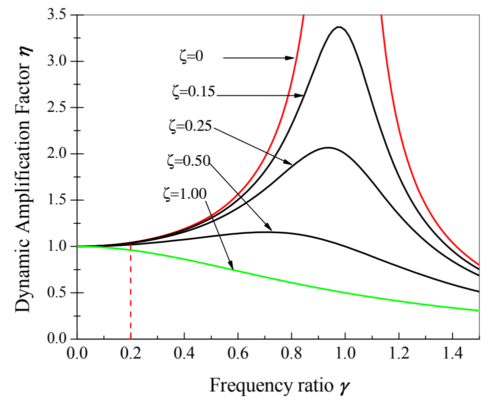


Figure 4: Dynamic Amplification Factor η curves of the frequency ratio γ. Here $\gamma = f_d/f_n$ (f_d is the driving frequency, for PEFP Cavity f_d =60 Hz; fn is the cavity mode's frequency). ζ is the damping ratio of the cavity.

CONCLUSION

The PEFP low beta cavity with the stiffening structure of double stiffening ring between inner cells and between Field Probe end cell and end dish, and single stiffening ring between FPC end cell and end dish has low Lorentz force detuning coefficient K_L, reasonable cavity field flatness sensitivity, frequency sensitivity, tuning sensitivity and stable mechanical property.

ACKNOWLEDGEMENT

The authors would like to thank H. Wang, E. Daly from JLab for their technical review, and all the PEFP members for discussing and support. This work is supported by the 21C Frontier R&D program in Ministry of Science and Technology of the Korean Government.

REFERENCES

[1] Y. S. Cho and K. Y. Kim, J. Korean Phys. Soc. 48, 721(2006).
[2] H. J. Kwon, H. S. Kim, K. T. Seol and Y. S. Cho, J. Korean Phys. Soc. 48, 726(2006)
[3] Sun An, Y. S. Cho, B. H. Choi and J. H. Jang, J. Korean Phys. Soc. 59, (2007).
[4] Sun An, Y. S. Cho and B. H. Choi, *Design of the PEFP Low Beta Cryomodule*, Proceedings of APAC2007 in Indore, January 29 to February 2, 2007, 2007, WEPMA127.
[5] R. Mitchell et al., *Lorentz Force Detuning Analysis of the SNS Accelerating Cavities*, Proceedings of SRF2001, SA010.
[6] Sun An, *Superconducting RF Cavity Frequency and Field Distribution Sensitivity Simulation*, Proceedings of PAC 2005, p4194.
[7] Sun An, H. Wang, G. Wu, Effect of the Tuner on the Field Flatness of SNS Superconducting RF cavities, Proceedings of LINAC 2004, p815.