PEFP LOW-BETA SRF CAVITY DESIGN*

Sun An#, C. Gao, Y. S. Cho and B. H. Choi
PEFP, Korea Atomic Energy Research Institute
P. O. Box 105, Yueong, Daejeon 305-353, Republic of Korea

Abstract

An elliptical superconducting RF cavity of 700 MHz with β_g=0.42 has been designed for the Linac of Proton Engineering Frontier Project (PEFP). A double-ring stiffening structure is used for a low-beta cavity for a Lorentz force detuning. The results of the electron multipacting analysis of the cavity are presented. A HOM analysis shows that the HOM coupler's Q_{ext} is lower than 3×10^5, thus reducing the influence of dangerous modes on the beam instabilities and the HOM-induced power.

INTRODUCTION

A superconducting RF (SRF) cavity is being considered to accelerate a proton beam after 80 MeV at 700 MHz in the PEFP Linac being built at Gyeongju [1, 2]. The first section of the PEFP SRF linac accelerates the proton beam from 80 MeV to 178.6 MeV, and is composed of nine low-beta cryomodules. Each low-beta cryomodule has three 5-cell cavities with geometrical beta β_g=0.42.

The PEFP low-beta SRF cavity is regarded as the lowest beta elliptical cavity operating at a pulse mode so far. Generally, lower beta cavities have a stronger Lorentz force detuning than higher beta cavities. For pulse SRF accelerators, a Lorentz force detuning is a more serious problem than that for CW accelerators. Therefore, a Lorentz force detuning control of a low-beta cavity is the most serious challenge in a cavity design.

This paper presents an optimized elliptical cavity shape of β_g=0.42 for the electromagnetic property for PEFP, and an optimum stiffening structure for a Lorentz force detuning for this cavity. The results of a multipacting simulation and a mechanical property analysis are presented. The results of the HOM analysis are also introduced.

CAVITY SHAPE OPTIMIZATION

In theory, the ultimate limit to the maximum achievable accelerating gradient E_{acc} of an elliptical cavity is the RF surface critical magnetic field $H_{rf,\ crit}$. In practice, in many cases, SRF cavities are limited by the onset of an electric field emission before their peak magnetic field H_{pk} up to $H_{rf,\ crit}$ due to cavity surface defects. Therefore a reduction in the ratio of E_{pk}/E_{acc} results in a higher accelerating gradient, even several cases have demonstrated that a good chemical treatment or mechanical grinding which can remove defects from a material can make the H_{pk} reach $H_{rf,\ crit}$. Based on the present SRF technology in PEFP, a reduction in the ratio of E_{pk}/E_{acc} should be a good choice for a PEFP cavity optimization.

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

In addition, a cavity with a higher cavity geometric shunt impedance *R/Q* has a lower RF loss at the same accelerating gradient, therefore, a realization of a higher *R/Q* is another rule for a cavity optimization design.

A ratio of the square of the cells number (*N*) to the product of a cell-to-cell coupling factor K_c and the cavity geometric beta β of a cavity is $S=N^2/\beta K_c$ [3], which is used to estimate the sensitivity of a field profile of an accelerating mode to the frequency errors of the individual cells. The previous practices have demonstrated that higher *S* cavities were not easy to tune for a field flatness. Lower *S* means a higher K_c or lower *N*. Increase in a coupling factor reduces the *R/Q* and raises the E_{pk}/E_{acc}. The design rule of the SRF linac was to maximize the cavity cell number, but the beam dynamics was also more favorable for a lower number of cells. In practice, its handling becomes more difficult with more cells, however this is trivial, but an important consideration, even though the real estate gradient increases. The APT cavities and the TRASCO cavity (all at 700 MHz and beta ~ 0.47) have 5 cells, the RIA 0.47 cavity at 805 MHz has 6 cells with *S*=5100 (maybe this is already a little bit high, but the cavity works). We can demonstrate that the cell-to-cell coupling is not an issue for a stored cavity energy filling, when the PEFP beam goes through the cavity. Considering a cavity field sensitivity and the production difficulty of a low-beta cavity, we chose a PEFP low beta cavity with 5 cells and a sensitivity *S* of 4220 that corresponds to a cell-to-cell coupling factor of 1.41%.

An individual cell of an elliptical cavity has a beam axial symmetry. A quarter cutaway view of a cell is schematically shown in Fig. 1 [4].

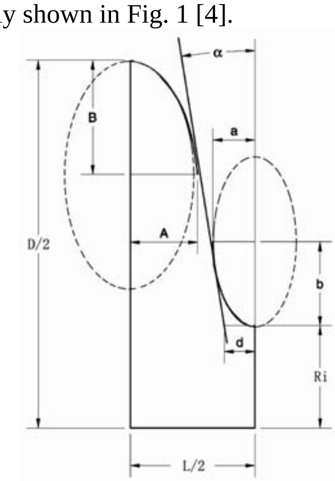

Figure 1: A quarter cutaway view of a cell and shape parameters:

L: cell length. For PEFP low beta cavity, *L*=90 mm.
Ri: cell iris radius.

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R=B/A: aspect ratio of equator ellipse.
r=b/a: aspect ratio of iris ellipse.
α: wall angle inclination.
a: distance of the cavity wall from the iris plane.
D: cell diameter.

A typical multi-cell cavity includes three building blocks: Field Probe (FP) end-cell, internal cells and Fundamental Power Coupler (FPC) end-cell, as shown in Fig. 2. A classical procedure for a cavity shape optimization is: first to optimize internal cell, then the FP end cell group and the FPC end cell group.

Internal cell shape optimization

The internal cell optimization is based on the method introduced by reference [4]. We optimized the iris ellipse aspect ratio **r**, the wall distance **d** and the wall angle **α**. An optimized result is listed in Table 1.

End cell shape optimization

The end cell design is based on the internal cell shape. A basic design rule of the end cell is the same as the internal cell design's. At the same time, the design should try to attain a lower E_{pk}/E_{acc} than that of the internal cell, and the end cell's beam pipes should have enough room to locate a stiffening structure and the couplers. FPC end cell with its beam pipe should offer a sufficient external quality factor Q_{ext} for the FPC.

A. Field Probe end cell group design

The Field Probe end cell group includes the FP end cell, the FP and HOM coupler beam pipe and the flange beam pipe. The inner half cell of the FP end cell is the same as internal half cell. The outer half cell is changed to compensate for the beam pipe. The radius of the FP and HOM coupler beam pipe is equal to the iris radius of the internal half cell. Its length is enough to locate an end cell stiffening structure, the FP and the HOM coupler etc. The size of the flange beam pipe is chosen to be the same as SNS cavity's. The reason that we chose this size is because the bellows pipe connected to the flange beam pipe is available in commerce and has the same cut-frequency for the HOM as the SNS cavity beam pipe. If it is necessary, the diameter of the flange beam pipe will be adjusted after the HOM analysis.

B. FPC end cell design

The FPC end cell group also includes three parts: FPC end cell, FPC and HOM coupler beam pipe and flange beam pipe. For the FPC end cell design, first we need to decide a size of the FPC and HOM coupler beam pipe, which should meet the FPC external quality factor's requirements.

According to the optimized results of the internal cell design and FP end cell group, the estimated cavity *R/Q* is about 112 Ohm. Based on the PEFP beam property and by considering the presence of a microphonics noise and a Lorentz force detuning, an optimum external Q (Q_{ext}) of the PEFP low-beta cavity FPC is about 8.0×10^5.

The value of the Q_{ext} strongly depends on the radius of the FPC and HOM coupler beam pipe and the inner conductor's penetration. We used **CST MicroWave Studio** to simulate the PEFP Q_{ext}, as shown in Fig. 2. For the PEFP low beta SRF cavity, the radius of 6.60 cm could meet its Q_{ext} requirement. Table 1 lists the optimized results of the PEFP low-bate SRF cavity.

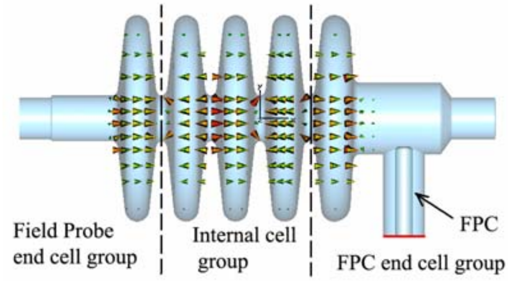

Figure 2: Building blocks of a PEFP low-bate cavity with FPC, its 3-D MWS mode and electric field distribution of the TM010 π mode.

Table 1: Parameters of the PEFP low-bate SRF cavity.

Frequency (MHz)	700		
Cavity type	TRASCO-ASH type		
Cavity geometrical β_g	0.42		
Cavity effective β	0.45		
Number of cell-die sets	3		
Half cell type	Internal	FP side	FPC side
Half cell length **L/2** (cm)	4.5	4.5	4.5
Iris radius **Ri** (cm)	4.18	4.18	6.60
Equator ellipse ratio **R**	1	1	1
Iris ellipse ratio **r**	1.50	1.30	1.80
Wall angle ***α*** (deg)	6.00	6.52	3.69
Cell-to-cell coupling (%)	1.41		
Cavity length (cm)	86.0		
Number of cells	5		
E_{pk}/E_{acc}	3.71		
B_{pk}/E_{acc} [mT/(MV/m)]	7.47		
R/Q (Ohm)	102.30		
G (Ohm)	121.68		

MULTIPACTING SIMULATION

Electron multipacting is an important limit to achieve a maximum cavity accelerating gradient. Here a multipacting simulation code **FishPact** [5] is used to estimate the multipacting risk for a whole cavity. The calculations indicate that the occurrence of a multipacting in the PEFP low-beta cavity is unlikely, because the electrons can not gain a sufficient energy to generate secondary electrons when impacting on the cavity's surface. Fig. 3 shows the simulation results.

HOM ANALYSIS

In order to understand the higher-order-mode (HOM) issues regarding the beam stabilities and the induced power in the PEFP low-beta SRF linac, we analyzed a normalized HOM-induced voltage, an induced power, and a time-averaged induced power, especially from the TM monopole modes. A HOM trapping possibility has been established by considering a manufacturing deviation of the HOM frequency and by studying the spectra of the monopole, the dipole, and the quadrupole modes in the low-beta SRF cavity. The HOM-induced power in the PEFP cavity has been calculated for different values of Q_{ext}. The discussions on beam instabilities show that beam instabilities are not issues in the PEFP low-beta SRF linac. For the PEFP low-beta cavities, the HOM coupler's Q_{ext} is lower than 3×10^5, thus reducing the influence of dangerous modes on the beam instabilities and the HOM-induced power [1]. In order to achieve the HOM damping requirements, a new type coaxial HOM coupler has been designed for the PEFP SRF cavities [6].

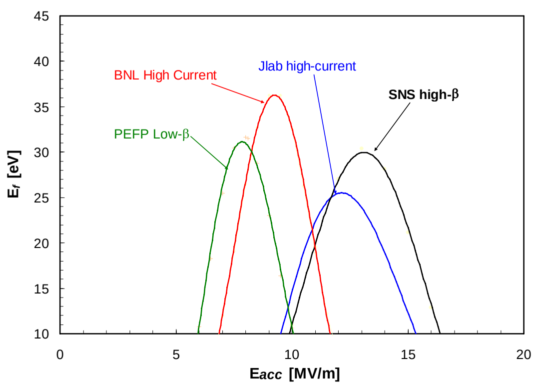

Figure 3: Electron's final energy compare of the multipacting electrons of the cavities, which include PEFP Low-β cavity, BNL High current cavity, SNS high-β cavity, JLab high-current cavity.

MECHANICAL ANALYSIS

Based on a basic design consideration for a stiffening structure to control a Lorentz force detuning, a double-ring stiffening structure has been designed for a low-beta cavity [7]. A cavity with this structure has a low Lorentz force detuning coefficient K_L, a reasonable cavity field flatness sensitivity, frequency sensitivity, tuning sensitivity and a stable mechanical property. Table 2 lists the mechanical parameters of the low-beta cavity. Fig. 4 shows the stiffening structure, and Fig. 5 shows a PEFP low-beta cavity with the stiffening structure, two HOM couplers and the accessories on the cavity ends.

Table 2: Mechanical parameters of the low-beta cavity with a double-ring stiffening structure.

Stiffening structure*	Double -ring
Min. K_L [Hz/(MV/m)^2]	-1.1
Field flatness sensitivity (%/MHz)	49.1
Frequency sensitivity (KHz/mm)	188
Tuning sensitivity (N/mm)	4498
Maximum Von Mises stress (MPa)	12.6

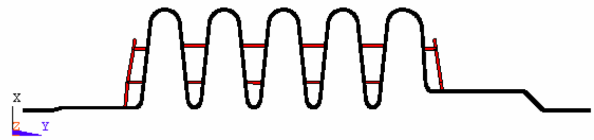

Figure 4: Stiffening structure of the PEFP low-beta SRF cavity: the double-rings between the inner cells and between the Field Probe end cell and end dish, and a single stiffening ring between the FPC end cell and end dish.

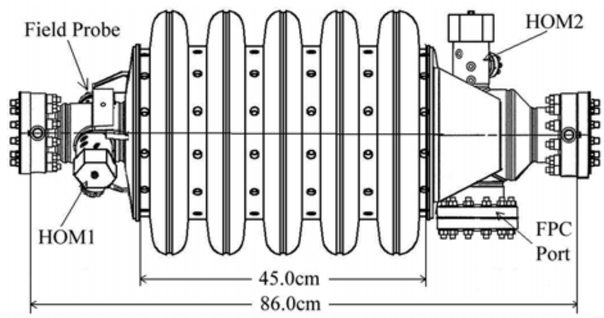

Figure 5: A PEFP low beta cavity with the stiffening structure and the accessories on the end sides.

CONCLUSIONS

A PEFP low-beta cavity has been successfully designed after a shape optimization for its electromagnetic property, a multipacting calculation, a HOM analysis and a mechanical analysis and design.

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