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DESIGN CONSIDERATIONS OF A BALLOON-SHAPED SSR SUPERCONDUCTING CAVITY

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Abstract

We introduce a balloon-shaped SSR superconducting cavity for multipacting mitigation. The electromagnetic modeling of the SSR was made based on the RF parameter optimization. The simulation results show much narrower multipacting bandwidth, compared to those for the traditional spoke cavity. Mechanical analyses with stiffening structure indicate acceptable stresses at the cavity wall.

INTRODUCTION

A single spoke resonator (SSR) having flat or round end walls has broad multipacting (MP) ranges in acceleration gradient, sometimes including operation region. In order to overcome such MP barriers, quite long radio frequency (RF) conditioning is required, which is not cost-effective and disadvantageous for mass production of the superconducting cavities. An alternative cavity with a resonant frequency f of 325 MHz and an optimum beta β_o of 0.3 has been being developed at TRIUMF [1, 2].

An SSR with $f = 325$ MHz and $\beta_o = 0.51$ has been studied at Korea University. Especially, this spoke cavity may be applied to the high-energy superconducting linac sections for a heavy ion accelerator such as RAON [3]. In this study, we introduce a balloon variant of the superconducting SSR which makes the MP mitigation possible due to its structural simplicity, based on its electromagnetic (EM), MP, and mechanical analyses.

ELECTROMAGNETIC SIMULATIONS

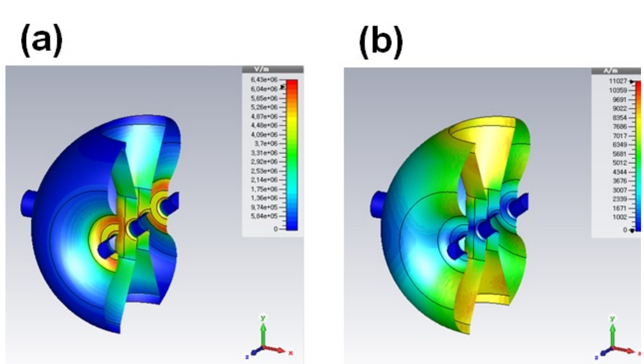

Figure 1: (a) Electric and (b) magnetic field distributions of the balloon-shaped SSR.

Figure 1 shows EM field distributions of the balloon-shaped SSR. The electric fields are mostly distributed at near a beam tunnel and the magnetic fields at loft and base parts of the spoke for the cavity with a transverse electromagnetic (TEM) mode. The horizontal geometric parameters of an EM modeling for the balloon-shaped SSR are based on the definitions from beam dynamics and transit time factor (TTF) studies that an iris-to-iris length L_{iris} is $(2/3)\beta_g\lambda$ and a gap-to-gap length L_{gap} is $\beta_g\lambda/2$, where β_g is a geometric beta ($\approx \beta_o$ of 0.51) and λ a wavelength (~923 mm for 325 MHz). Two (upper and lower) ellipses in a *y-z* plane were adopted for the balloon-shaped modeling. A view of the balloon-shaped SSR in a *x-y* plane is nearly circular.

It is well-known that a superconducting cavity should be designed to lower the peak electric field E_{peak} and the peak magnetic field B_{peak} as possible with keeping good RF properties because their increases can limit the acceleration performance by field emission and quench, respectively. In the EM design of the balloon-shaped SSR, we aim the B_{peak} under 80 mT when the E_{peak} is 35 MV/m. The resultant RF parameters are also normalized by 35 MV/m. As the geometric parameters change, we focus on the decrease of E_{peak}/E_{acc} and B_{peak}/E_{acc} and the increase of $G{\cdot}R_{sh}/Q_0$, where E_{acc} is the acceleration gradient, G the geometry factor, R_{sh} the shunt impedance, and Q_0 the unloaded quality factor of the cavity. The surface resistance R_s used for calculating the G (= Q_0R_{sh}) is ~10.64 nΩ from BCS resistance R_{BCS} of 0.64 nΩ at a frequency of 325 MHz and a temperature of 2 K with an assumption of the residual resistance R_{res} of 10 nΩ ($R_s = R_{res} + R_{BCS}$). From proper compromises among simulation results with the geometric parameter sweeps, the final geometry of the balloon-shaped SSR were determined and its RF parameters are summarized in Table 1.

Table 1: EM Simulation Results for the Balloon-shaped SSR.

RF Parameter	Value
Q_0 (× 10^9)	10.7
R_{sh}/Q_0 (Ω)	296
G (Ω)	118
E_{peak} (MV/m)	35
B_{peak} (mT)	75
V_{acc} (MV)	4.2
E_{acc} (MV/m)	9
E_{peak}/E_{acc}	3.9
B_{peak}/E_{acc} (mT/MV/m)	8.4
Stored energy (J)	29.6
Dissipated power (W)	5.6

MULTIPACTING SIMULATIONS

A main advantage of the balloon-shaped SSR is MP suppression due to its simple structure. A traditional spoke

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cavity has an end wall structure, where blending parts exist for convenient e-beam welding with a main cylindrical body. The larger the blending area, the smaller the higher-order MP [4]. The balloon-shaped SSR is an assembly of two half bodies with a spoke and has no end walls. The balloon shape corresponding to maximization of the blending areas gives an effect to eliminate the secondary-electron emission areas. Furthermore, the blending parts at the spoke bases which are the origins of the first order MP [4] were removed in the balloon-shaped SSR.

Figure 2 shows an example of the MP simulation results for the balloon-shaped SSR, where the numbers of secondary electrons vary with time as the E_{acc} increases. The two-point MP shown in the electron trajectories of Fig. 2 is mostly caused by the cyclotronic electron motion by magnetic fields near the spoke base. Figure 3 shows a growth rate α vs. E_{acc} curve calculated for the balloon-shaped SSR. The MP for the balloon-shaped SSR occurs at a very narrow acceleration zone from ~0.8 MV/m to 1.8 MV/m, which is far from the operating E_{acc} of 9 MV/m.

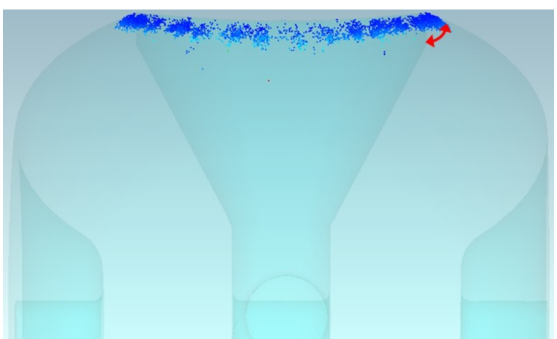

Figure 2: A simulation result on electron trajectories near a spoke base of the balloon-shaped SSR. The red arrow indicates two-point MP.

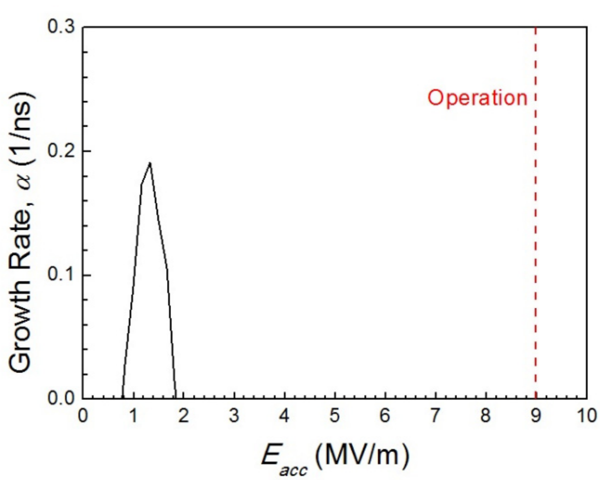

Figure 3: Simulation results on variation of the growth rate with respect to the acceleration gradient for the balloon-shaped SSR.

MECHANICAL SIMULATIONS

After analyzing the mechanical stresses of the balloon-shaped SSR, which is uniformly composed of 3-mm-thick Nb sheets, with an external atmospheric pressure, two kinds of stiffening structures were added to the cavity. We consider two boundary conditions that both beam pipes are fixed and free, respectively. For the former case, most of mechanical stresses are distributed near the beam port surroundings, where the electric field is dominant and the frequency sensitivity by the deformation is very critical. Thus, we adopted two Nb bulks at the beam port surroundings for structural rigidity with avoiding the complicated daisy ribs [5]. With the latter boundary condition, most of stresses are distributed near the equators of the cavity, which can cause the frequency shift by deformation at the magnetic field dominant region. For this reason, we added two ring stiffeners at both equators.

Figure 4 shows a plane view of the balloon-shaped SSR with the stiffening structure. We aim the mechanical stresses less than the maximum allowable stress of 32 MPa at 300 K and 171 MPa at 2 K in the following environments:

Case-1 (Leak check): External pressure of 1 bar, room temperature (293 K), free beam pipes.

Case-2 (Cool-down): External pressure of 5 bar, cryogenic temperature (5 K), fixed beam pipes.

A simulation result on the Case-1 is shown in Fig. 5. The leak-check state means that the cavity inside is maintained with vacuum and the outside with atmospheric pressure. Under such conditions, the mechanical stresses around the equators transfer to the ring stiffeners. The Von Mises stresses in the cavity were around or under 32 MPa. The maximum stresses of ~48 MPa are discretely distributed at the joint parts between the cavity and the ring stiffeners, but it is tolerable compared to the yield strength of 70 MPa. In the Case-2, the maximum allowable working pressure (MAWP) of 5 bar is supposed at 5 K. The corresponding simulation result is shown in Fig. 6. The mechanical stresses uniformly distributed in the cavity are under 100 MPa at cryogenic temperature. The maximum stresses at the beam-port cross-sections are negligible because the areas were used for the fixed boundary condition.

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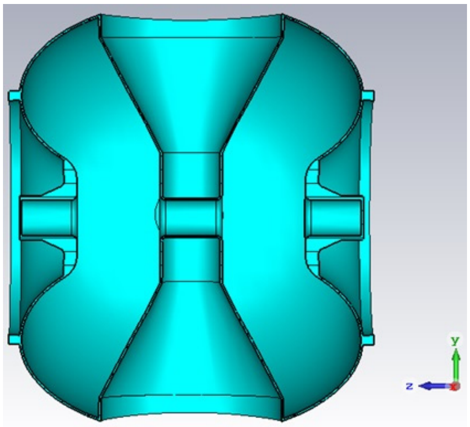

Figure 4: A balloon-shaped SSR and its stiffening structure.

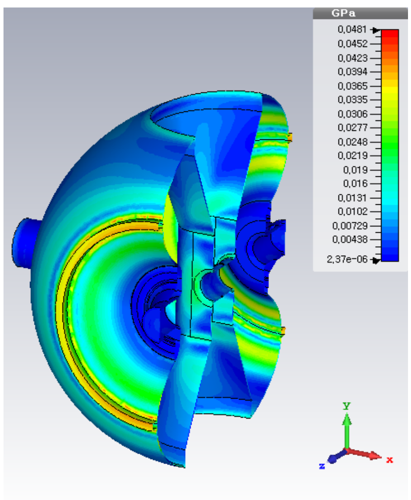

Figure 5: Mechanical simulation results on Case-1 of 1 bar, 293 K, and free beam pipes.

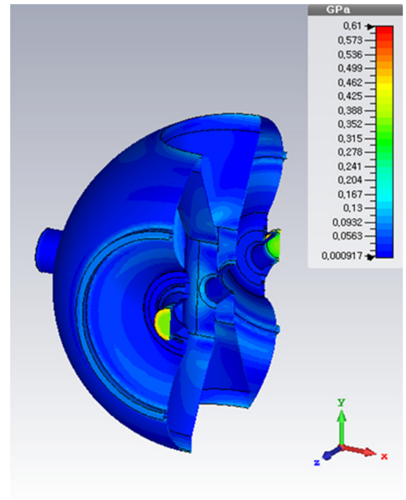

Figure 6: Mechanical simulation results on Case-2 of 5 bar, 5 K, and fixed beam pipes.

CONCLUSION

We proposed a 325 MHz and $\beta_o = 0.51$ balloon-shaped SSR for a proton/heavy-ion superconducting linac. The simulation results showed that its structural simplicity made it possible to effectively suppress the MP phenomena, compared to traditional spoke cavities. The balloon-shaped SSR also has a minimal number of stiffeners for mitigating the mechanical stresses at various environments. Pressure vessel studies with a liquid helium jacket design will be followed.

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