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SIMULATION OF ELECTRIC AND THERMAL BEHAVIOR OF CRYOGENIC THREE-CELL COPPER ACCELERATING CAVITY FOR HIGH GRADIENT EXPERIMENTS

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Abstract

A cryogenic C-band 3-cell π-mode accelerating cavity made of high purity copper has been designed for high power experiments aimed at an ultra-high accelerating gradient. The basic configuration of the cavity, consisting of the mode converter, the short circular waveguide and the accelerating cells with a rounded shape, is the same as that of the previous 2.6-cell photocathode electron gun cavity developed for cold tests. Due to replacement of the 0.6-cell end cavity with a full-cell cavity, the estimated total radio frequency (RF) power loss has been reduced by 7 % as compared with the 2.6-cell cavity. The input coupling coefficient of $\beta = 10$ at 20 K has been chosen by taking into account a significant decrease in the quality factor caused by the pulsed heating of the cavity surface. The result of the simulation on the input of high power RF pulse has shown similar behaviours of the electric field and the temperature on the cavity surface as those which were suggested for the 2.6-cell cavity.

INTRODUCTION

Normal-conducting copper accelerating structures have conventionally been operated at temperatures around 30 to 40 °C because of the high heat removal efficiency and temperature stability readily achieved by means of precisely controlled cooling water systems. However, it is well known that the operation at cryogenic temperatures is advantageous with respect to the RF power efficiency [1]. The authors have confirmed experimentally that the unloaded quality factor of a C-band copper cavity at 20 K can be increased to 5.4 times the value at room temperature [2]. Another advantage of a cryogenic copper cavity has been suggested with respect to the vacuum breakdown rate at very high RF electric field strengths [3, 4].

In order to study the possibility of realizing an ultra-high accelerating gradient of >100 MV/m by extension of conventional RF technologies, a C-band 3-cell accelerating cavity has been designed as a high power test model. The result of the electric design simulation by CST Studio [5] has been applied to the simulations of the electric and the thermal behaviours during the high power pulsed RF feeding up to 50 MW, where the same calculation method has been employed as described in the reports on a 2.6-cell photocathode RF electron gun cavity [6, 7].

DESIGN OF THE 3-CELL CAVITY

The basic configuration of the 3-cell π-mode cavity is the same as that employed in the cold model of the 2.6-cell photocathode RF electron gun. The resonant frequency of 5712 MHz has been chosen in consideration of the ready availability of a high power C-band pulse klystron. Figure 1 shows a 3D drawing of the inner surface of the entire cavity. The mode converter of the input RF from rectangular TE_{10} to circular TM_{01} has the same dimension that was optimized for the low insertion loss and reflection in the design of the 2.6-cell cavity.

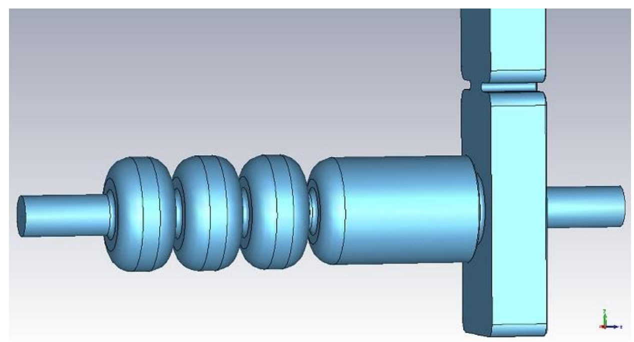

Figure 1: A 3D drawing of the 3-cell cavity designed for high-power and high-gradient experiments.

Table 1: The Properties of the 3-Cell Cryogenic C-band π-mode Accelerating Cavity at 20 K

Operating frequency	5712	MHz
Unloaded quality factor	77853	
Accelerating cell length	78.73	mm
Coupling coefficient	10	
Surface resistance	3.645×10^{-3}	Ω
Max. electric field on surface	*103	MV/m
Power loss in cavity	*0.331	MW
Max. current density on surface	*118	kA/m
Max. power loss per unit area	*2.56	kW/cm^2
Shunt impedance	680	MΩ/m
Transit time factor	0.731	
Accelerating gradient	*39.0	MV/m

*at an input RF power of 1 MW

The RF properties of the 3-cell cavity resulted from the design simulation is listed in Table 1. For high purity copper with RRR=3000 assumed as a cavity material, the surface resistance of 3.645×10^{-3} Ω at 5712 MHz was deduced from the theory of the anomalous skin effect [8]. The unloaded quality factor obtained from the simulation has been 77853, which is approximately 7 % higher than the experimental value in the previous 2.6-cell cavity. The coupling

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coefficient between the accelerating cells and the circular waveguide at 20 K was chosen to be 10 from the results of the simulations on the pulsed behaviours of the coupling coefficient and the electric field strength during the RF pulse for various combinations of the initial coupling coefficient and the peak input RF power [7]. In the design with CST Studio, the coupling coefficient has been adjusted by the thickness of the wall between the circular waveguide and the third accelerating cell.

The shunt impedance and the transit time factor have been evaluated from the electric field strength along the cavity central axis obtained by the CST Studio simulation. These values were deduced from the integration of the field over only the length of the 3 cells or just 1.5 times the free-space wavelength of the RF. Therefore, the effects of the fields at the end-pipes have not been reflected in the values. The result suggests that an energy gain of 39 MeV/m is possible for a relativistic electron beam at an RF power of 0.11 MW dissipated in each accelerating cell.

RF POWER LOSS ON THE SURFACE

Pulsed heating of the cavity surface with a high power RF causes a significant change in the RF efficiency, since the surface resistance of the high purity copper is strongly dependent on the surface temperature in the cryogenic region, which is apparent in the temperature dependence of the unloaded quality factor [2].

The cavity surface is heated by the surface current caused by the RF magnetic field. The heat or the RF power loss dP in a small area of surface dS is expressed as

$$\frac{dP}{dS} = \frac{1}{2} R_S J_{\parallel}^{2}, \tag{1}$$

where R_S is the surface resistance, and $J_{\parallel}$ is the current density parallel to the surface, respectively at a surface mesh point. The magnetic field and the current density on the cavity surface are calculated in the CST Studio simulation for every surface mesh point. Figure 2 shows the magnetic field distribution in the accelerating cells which resulted from the simulation: the magnetic field strength on the surface is rather homogeneous except for the positions close to the beam holes.

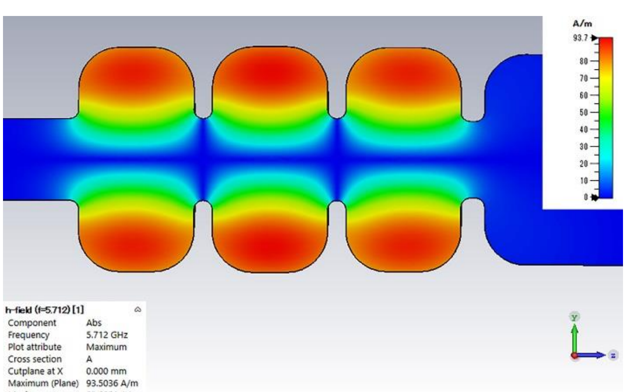

Figure 2: Magnetic field distribution in the accelerating cells which resulted from the CST Studio simulation.

The distribution of the surface area as a function of the RF power loss over the entire surface of the accelerating cells is shown in Fig. 3, where the loss per unit area was normalized to the maximum value and divided into 200 steps. Consistent with Fig. 2, the normalized loss larger than 0.88 /cm^2 is found distributed over 82 % of the entire surface area. Since we expect the area with a larger loss to contribute to the increase in the surface resistance, decrease in the quality factor and rise in the surface temperature more dominantly, a typical loss per unit area can be approximated by the average value in the large-loss area. Thus, in the simulation of the pulsed heating, an average loss of 0.936 /cm^2 over the large-loss area has been applied to the entire accelerating cell surface.

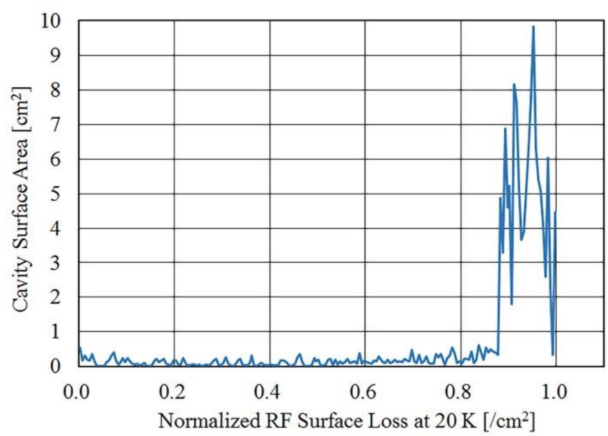

Figure 3: Distribution of the cavity surface area as a function of the normalized RF loss per unit area over the entire surface of the accelerating cells.

SIMULATION OF PULSED HEATING

Taking the heating of the cavity surface and the change in the surface resistance into account, the surface temperature rise, the RF power loss and the electric field strength during the input RF pulse of 2 μs have been obtained as a function of time. The temperature rise has been estimated using the one-dimensional thermal diffusion model [9]. In the differential equation for the calculation of the time evolution of the electric field in the cavity, the unloaded quality factor and the coupling coefficient have been involved as a function of the surface temperature and time as described elsewhere [7]. The temperature dependent thermal properties of high purity copper in the cryogenic region [10, 11] have been adopted in the calculation of the temperature rise.

Figure 4 shows the build-up of the electric field resulting from the simulation at an input peak RF power of 1 MW. The maximum temperature rise at the end of the RF pulse is 1.1 K. Since there is no significant change in the surface resistance, the behaviour of the build-up of the electric field strength in the cavity is similar to that at room temperature except for the very high efficiency and high accelerating gradient. The result suggests that a cryogenic copper cavity can simply work as a high efficiency accelerating structure at relatively low peak RF power.

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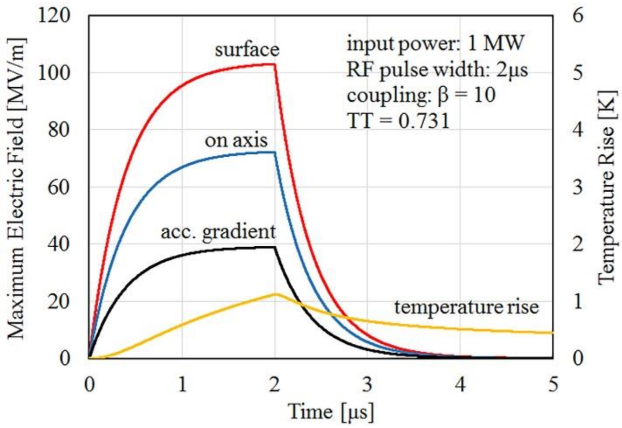

Figure 4: The build-up of the electric field and the temperature rise of the cavity surface resulting from the pulsed heating simulation at an input peak RF power of 1 MW for 2 μs.

Figure 5 shows the result of the simulation at an input peak RF power of 50 MW. In contrast to the result in the 1 MW input, the electric field strength is significantly enhanced toward the end of the RF pulse, as was also suggested in the simulation with the 2.6-cell cavity [6, 7]. The surface temperature rise during the RF pulse reduces the coupling coefficient and increases the transmission power into the cavity, which results in the enhancement of the electric field strength though the power loss is enhanced at the same time. If there are no other obstacles to the build-up, it will be possible to investigate the field emission, the vacuum breakdown and other related phenomena up to ultra-high RF electric fields greater than 1 GV/m.

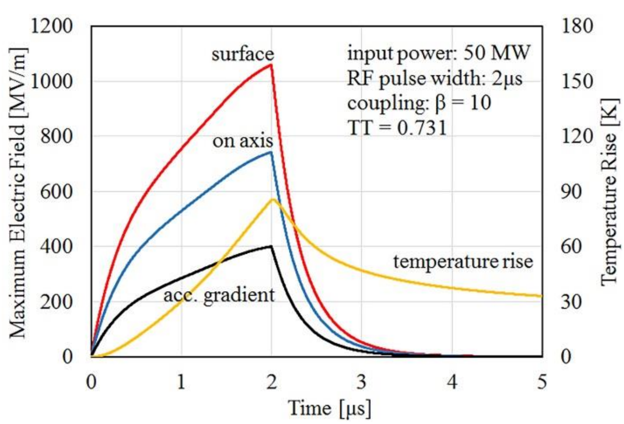

Figure 5: The build-up of the electric field and the temperature rise of the cavity surface resulting from the pulsed heating simulation at an input peak RF power of 50 MW for 2 μs.

CONCLUSIONS

A cryogenic C-band copper accelerating cavity has been designed for high power and high gradient experiments. The cavity consists of 3 round-shaped cells with rather homogeneous current density over the entire surface. Assuming the cavity is cooled down to 20 K, the simulation of the electric field build-up in the cavity taking the surface heating into account has suggested that the surface electric field strength up to greater than 1 GV/m will be within the scope of investigation at a maximum input peak RF power of 50 MW.

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