FINE GROOVING OF CONDUCTOR SURFACES OF RF INPUT COUPLER TO SUPPRESS MULTIPACTORING

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Abstract

An rf input coupler for accelerating cavities with heavy beam loading undergoes many multipactoring zones due to the wide range of the input rf power. Furthermore, a regular coaxial line is more subject to multipactoring than a rectangular waveguide because of the uniformity of the electromagnetic field. Grooving the conductor surfaces of the coaxial line is a promising method to suppress multipactoring under any conditions expected in the above cases. This paper reports results of the multipactoring simulation study and the status of the development of input coupler with a grooved coaxial line for SuperKEKB and other high beam current storage rings.

INTRODUCTION

An rf input coupler is one of the most important components for high-power rf systems. In the normal-conducting accelerating cavity system ARES [1] for KEK B-factory (KEKB), coaxial-line input couplers are used to feed high power into accelerating cavities with heavy beam loading. The schematic drawing is shown in Fig. 1. The coaxial line is made of oxygen free copper, and there is a loop at the end for coupling to the magnetic field of the TE_{013} mode in the energy-storage cavity of the ARES three-cavity system.

We had a serious problem caused by multipactoring in the coaxial line on two of the 32 ARES input couplers used in the KEKB operations, and *temporarily* solved it by applying the multipactoring zone map, where the cavities suffering from multipactoring were operated in a multipactoring-free region of the map [2]. The study reported in this paper aims at a multipactoring-free coaxial-line coupler as a *decisive measure* for SuperKEKB [3] and other high beam current storage rings, by fine grooving of the conductor surfaces of the coaxial line.

MULTIPACTORING SIMULATION

Although the basic method is the same as in [2], where cylindrical coordinates (r, θ, z) are used, and electron motion is calculated by numerically solving the relativistic equation of motion, there are three differences on (i) the electromagnetic field calculation, (ii) the representation of multipactoring, and (iii) the superposition of input and reflected waves.

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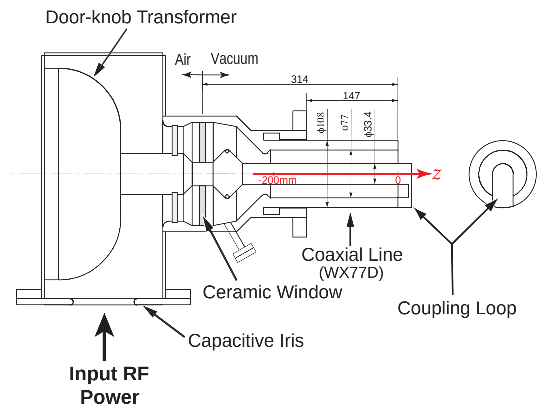

Figure 1: Schematic drawing of the ARES input coupler.

Electromagnetic Field of the Quasi-TEM

The electromagnetic field of the *quasi*-TEM wave in the grooved coaxial line was obtained by using a 3D electromagnetic-field simulator `GdfidL` [4], where the default mesh size was $0.1\,\mathrm{mm}$. In this simulation, a sinusoidal input wave was generated at time $t = 0$, then the electromagnetic fields in the region of $-18.5\,\mathrm{mm} < z < -2.5\,\mathrm{mm}$ at $t = 3 \times 2\pi/\omega$ and $t = 3.25 \times 2\pi/\omega$ were stored as $\Re\left(\mathbf{E_r^{(0)}}, \mathbf{E_z^{(0)}}, \mathbf{B}_\theta^{(0)}\right)$ and $\Im\left(\mathbf{E_r^{(0)}}, \mathbf{E_z^{(0)}}, \mathbf{B}_\theta^{(0)}\right)$, respectively, where ω indicates the rf angular frequency of KEKB ($2\pi \times 508.9\,\mathrm{MHz}$). In Fig. 2, an example of the geometries for the grooved coaxial line is shown. It should be noted that fine grooving in the azimuthal direction is performed only for the outer conductor because multipactoring is almost single-sided on the outer conductor in the case of ARES.

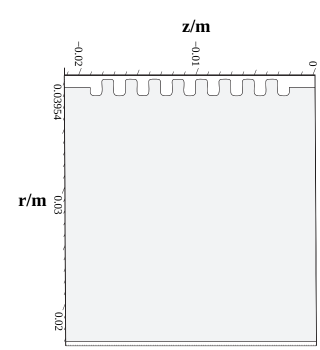

Figure 2: Geometry for the grooved coaxial line, used in `GdfidL`, which is a body of revolution around the z axis. This is the case for the groove depth of $1.4\,\mathrm{mm}$.

Modified Representation of Multipactoring

The definition of the quantity to represent multipactoring in [2] is modified for the unsmooth grooved surface as follows,

$$
\begin{aligned}
\tilde{\mathcal{M}}(P_{\rm in},\Gamma) &= \frac{1}{\tilde{N}_{\rm p}^{(z)} N_{\rm p}^{(\phi_0^{\rm (I)})} N_{\rm p}^{(\phi_0^{\rm (R)})}} \\
&\quad \times \sum_{l=1}^{N_{\rm p}^{(z)}} \sum_{k_i=1}^{N_{\rm p}^{(\phi_0^{\rm (I)})}} \sum_{k_r=1}^{N_{\rm p}^{(\phi_0^{\rm (R)})}} \sum_{j=1}^{2} \frac{r_j}{r_{\rm in}+r_{\rm out}} \\
&\quad \times f\Big[N_{\rm imp}\left(P_{\rm in},\Gamma;j,k_i,k_r,l\right),10\Big], \quad (1)
\end{aligned}
$$

where $N_{\rm p}^{(z)}$ is the number of sampling points uniformly distributed along the conductor surface in the z direction with a step size ($\Delta_{\rm ini}$) of about 0.2 mm, l is an index for the initial position, k_i and k_r indexes for the initial phases for input and reflected waves, respectively, $r_{\rm in}$ ($r_{\rm out}$) the radius of the inner (outer) conductor, $j=1$ ($j=2$) means start from the inner (outer) conductor, $r_1 = r_{\rm in}$, $r_2 = r_{\rm out}$, $r_j/(r_{\rm in}+r_{\rm out})$ is a weight concerning the surface areas of the inner and outer conductors in the case of no groove, $N_{\rm imp}$ is number of impacts of the multipactoring electron, and the function f is defined as

$$
f(x,a) = \begin{cases} x & (x \geq a) \\ 0 & (x < a) \end{cases} . \quad (2)
$$

The first difference from the definition in [2] is the normalization factor on the initial position, which is $\tilde{N}_{\rm p}^{(z)}$ defined as $(z_{\rm max}-z_{\rm min})/\Delta_{\rm ini}+1$, where $[z_{\rm min}, z_{\rm max}] = [-18.5{\rm mm}, -2.5{\rm mm}]$ is a z region for the multipactoring simulation in this study. $\tilde{N}_{\rm p}^{(z)} = N_{\rm p}^{(z)}$ holds for the coaxial line with no groove. The second difference is the two independent initial-phase parameters: $\phi_0^{\rm (I)} = 2\pi \times (k_i-1)/N_{\rm p}^{(\phi_0^{\rm (I)})}$ and $\phi_0^{\rm (R)} = 2\pi \times (k_r-1)/N_{\rm p}^{(\phi_0^{\rm (R)})}$, which will be used in the following Eqs. (3)-(5). $N_{\rm p}^{(\phi_0^{\rm (I)})}$ and $N_{\rm p}^{(\phi_0^{\rm (R)})}$ are numbers of sampling points uniformly distributed in the region of $[0, 2\pi]$ for the input and reflected waves, respectively.

Superposition of Input and Reflected Waves

With the electromagnetic field of the quasi-TEM wave $\left(\mathbf{E_r^{(0)}}, \mathbf{E_z^{(0)}}, \mathbf{B}_\theta^{(0)}\right)(r,z)$ obtained using `GdfidL`, the electromagnetic field at space-time (r,z,t) for the multipactoring simulation is calculated as

$$
\begin{aligned}
E_r(r,z,t) &= \Re\Big\{\mathbf{E_r^{(0)}}(r,z)\,e^{-i(\omega t+\phi_0^{\rm (I)})} \\
&\quad +\Gamma\,\mathbf{E_r^{(0)}}(r,\tilde{z})\,e^{-i(\omega t+\phi_0^{\rm (R)})}\Big\}, \quad (3) \\
E_z(r,z,t) &= \Re\Big\{\mathbf{E_z^{(0)}}(r,z)\,e^{-i(\omega t+\phi_0^{\rm (I)})} \\
&\quad +\Gamma\Big[-\mathbf{E_z^{(0)}}(r,\tilde{z})\Big]\,e^{-i(\omega t+\phi_0^{\rm (R)})}\Big\}, \quad (4) \\
B_\theta(r,z,t) &= \Re\Big\{\mathbf{B}_\theta^{(0)}(r,z)\,e^{-i(\omega t+\phi_0^{\rm (I)})} \\
&\quad -\Gamma\Big[-\mathbf{B}_\theta^{(0)}(r,\tilde{z})\Big]\,e^{-i(\omega t+\phi_0^{\rm (R)})}\Big\}, \quad (5) \\
E_\theta &= B_r = B_z = 0, \quad (6)
\end{aligned}
$$

where $\tilde{z} = z_{\rm max} - z + z_{\rm min}$, and Γ indicates the real reflection coefficient. In the above calculation, the reflection plane is set to be at $z=0$. Using the two independent initial phases ($\phi_0^{\rm (I)}$ and $\phi_0^{\rm (R)}$) corresponds to multipactoring simulation for a coaxial line with the infinite length, so that we calculate Eq. (1) only for the overcoupling region because the multipactoring zone map is symmetric between the overcoupling and undercoupling regions for a infinite-length coaxial line.

Multipactoring Zone Maps

Multipactoring zone maps, showing the quantity $\tilde{\mathcal{M}}$ defined in Eq. (1), for different groove depths are shown in Fig. 3, where the groove width and pitch are fixed at 1.0 mm and 2.0 mm, respectively. These groove width and pitch were determined from the following facts;

- less multipactoring suppression was obtained for groove widths larger than 1.0 mm and/or pitch larger than 2.0 mm;
- the mean value of the maximum movement distances in the z direction for $N_{\rm imp} < 10$ in the typical operating regions was calculated to be about 1 mm;
- 1.0 mm in groove width and 2.0 mm in pitch were the smallest from a point of view of reliable machining.

Figure 4 shows integrated $\tilde{\mathcal{M}}$ over the $(P_{\rm in},\Gamma)$ space in the map as a function of the groove depth. It is clear that fine grooving of the conductor surface of the coaxial line is very effective against multipactoring. From Fig. 4, we have adopted the depth of 1.4 mm, where the depth should be as small as possible since there are water cooling channels in the outer conductor. The maximum peak electric field for 1 MW input power (CW) has been checked using `GdfidL`, which is 0.565 MV/m as shown in Fig. 5. This value is lower than that on the inner conductor of the coaxial line with no groove (0.717 MV/m).

PROTOTYPE PRODUCTION

We have constructed a prototype input coupler in order to verify the suppression effect of the fine grooving in high power tests. The main shape of the grooves was made using a metal slitting saw, and then finish machining was done using a diamond bit. Figure 6 shows pictures of the grooved coaxial line for the first prototype. We have checked the result of the machining of grooves by making a replica, as shown in Fig. 7.

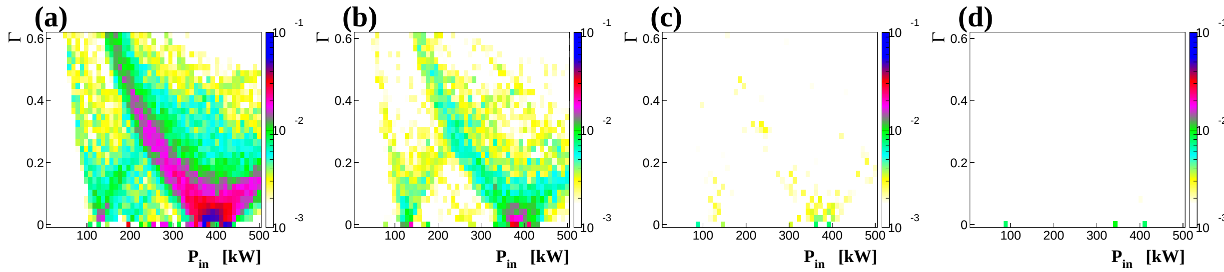

Figure 3: Multipactoring zone maps for groove depths of (a) 0.8 mm, (b) 1.0 mm, (c) 1.2 mm and (d) 1.4 mm.

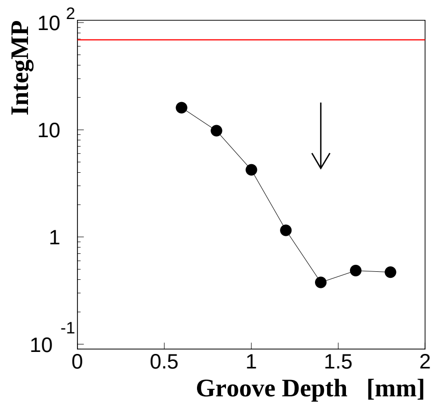

Figure 4: Integrated $\tilde{\mathcal{M}}$ (IntegM) over the $(P_{\rm in}, \Gamma)$ space in the multipactoring zone map as a function of the groove depth. The horizontal line indicates the level for the coaxial line with no groove. The vertical arrow indicates the groove depth adopted for the prototype production.

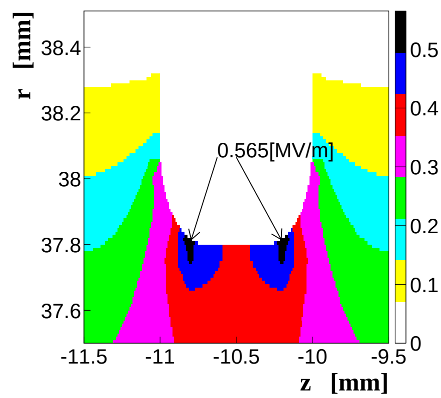

Figure 5: Peak electric field [MV/m] as functions of z and r around the groove in the case of the groove depth of 1.4 mm for the input power of 1 MW (CW), obtained using `GdfidL`. The maximum field value is 0.565 MV/m.

High power test is going to be performed soon in the upgraded coupler teststand [5], where the maximum input power available is 1 MW (CW).

SUMMARY

We have performed a simulation study based on the method developed in the multipactoring study for the KEKB/ARES input couplers [2]. It has been found that fine grooving of the conductor surfaces of the coaxial line is very effective against multipactoring all over the $(P_{\rm in}, \Gamma)$ region for the KEKB/ARES operations. We have constructed a first prototype of input coupler with a grooved coaxial line. High power test is going to be performed soon to verify the suppression effect of the fine grooving.

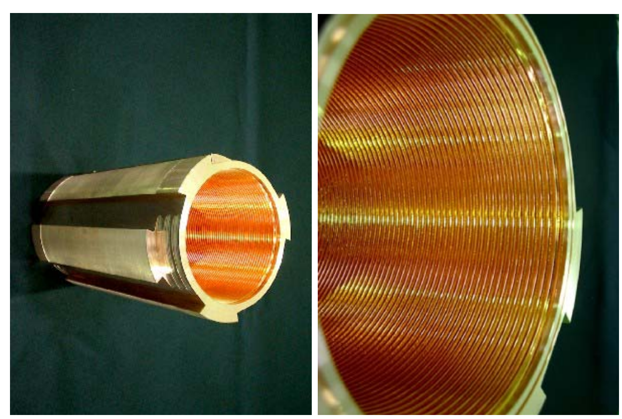

Figure 6: Grooved outer conductor of the coaxial line, made of oxygen free copper, for the first prototype.

Figure 7: Replica of the grooves of the outer conductor of the coaxial line for the first prototype.

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