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RF DESIGN STUDIES OF A 1.3 GHz NORMAL CONDUCTING CW BUNCHER FOR THE EUROPEAN XFEL

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Abstract

A CW upgrade of the European XFEL is under consideration, and CW electron injectors are under R&D at DESY. One of the CW injector solutions is a LCLS-II like injector based on a normal conducting VHF-band gun and an L-band buncher. RF design of the 1.3 GHz normal conducting buncher structure with a cavity voltage of ~400 kV, is carried out at DESY, Zeuthen site. The buncher structure with different geometrical shapes and number of cells is studied. The cavity RF designs are optimized to have higher shunt impedance, higher mode separation and lower RF power for CW operation. In this paper RF design and multipacting analysis of the buncher are discussed.

INTRODUCTION

The European XFEL operates in pulsed mode with a duty factor of 0.65% with an L-band normal conducting (NC) pulsed photocathode RF gun based injector system [1, 2]. For a future upgrade to operate in CW mode it requires a CW injector system. One of the possible injectors would be based on a NC VHF gun similar to APEX at LBNL [3]. An injector system based on a 217 MHz, NC, photo cathode gun followed by a 1.3 GHz buncher is being studied at DESY, Zeuthen site [4]. Preliminary beam dynamics studies with beam energy of 860 keV from the gun require a buncher voltage of ~ 400 kV to achieve the desired beam quality. The APEX buncher has a re-entrant geometry with 2-cells and operates at 240 kV with an input RF power of 7.8 kW [3]. Employing the APEX buncher for voltage of a 400 kV requires 20 kW RF power which needs a complex cooling scheme. Another limitation of the APEX buncher is its small mode separation of ~ 1 MHz [3]. In-order to relax the RF power requirement and increase the mode separation, the RF design of a 1.3 GHz buncher with different geometries and number of cells is studied at DESY, Zeuthen site. In the following section details of the RF design and multipacting analysis of the 1.3 GHz buncher are presented.

RF DESIGN OF TWO-CELL BUNCHER

In literature, along with the APEX design two more single cell buncher designs are reported: (1) Cornell and (2) KEK with shunt impedances of 4.2 and 5.3 MΩ, respectively [5, 6]. Although the shunt impedance per cell is highest for the KEK design, the RF power required for a voltage of 400 kV is ~ 30 kW. Since shunt impedance increases with number of cells, we studied multi-cell structures with KEK type geometry, a two-cell buncher is designed using CST Microwave Studio® (CST MWS) [7]. The main constraint of design is to have a beam pipe diameter 36 mm as required by beam dynamics simulations. The electric field array and magnetic field distribution for π mode is shown in Fig.1, while major RF parameters are summarized in Table 1. The structure has a shunt impedance of 9.9 MΩ and requires RF power of ~ 17 kW for a voltage of 400 kV. Although this design has higher shunt impedance, the power dissipation is significantly higher, mode separation is very small (~1 MHz) and maximum heating is near the inter-cell coupling iris which is difficult to remove due to mechanical constraints.

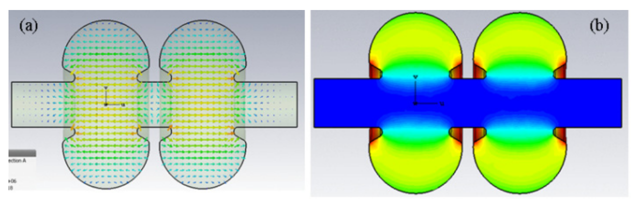

Figure 1: Two-cell buncher (a) electric field array plot and (b) magnetic field distribution for π mode predicted by CST MWS.

Table 1: RF Parameters of Two-Cell Buncher

RF parameters	KEK type	DESY design 1	DESY design 2
Frequency f_π (GHz)	1.3	1.3	1.3
Quality factor Q_0	25316	27206	27819
Shunt Impedance R (MΩ)	9.9	8.36	9.19
Mode Separation $f_\pi - f_{\pi/2}$ (MHz) [8]	1.03	2.75	3.02
Power dissipation P_c (kW) for 400 kV	17	19	18

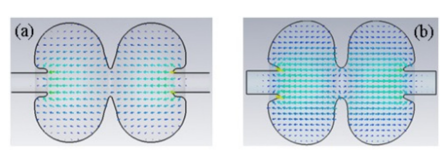

Figure 2: Shape of (a) tapered (DESY design 1) and (b) elliptical (DESY design 2) inter-cell coupling iris.

Considering the operational difficulties and to simplify the cooling scheme the geometry of the two-cell buncher is modified to increase the mode separation and shift the peak power density away from the inter-cell coupling iris.

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The inter-cell iris is modified from nose- cone shape to (1) tapered (DESY design 1) and (2) TESLA type elliptical (DESY design 2) as shown in Fig. 2.

The geometrical dimensions are optimized to obtain the π mode at 1.3 GHz with equal amplitude of the on-axis accelerating field in both cells. The important RF parameters of the new structures are given in Table 1. Both structures have similar mode separation however, the structure with TESLA type elliptical inter-cell coupling iris has slightly higher shunt impedance hence is preferred. The variation of the on-axis accelerating field along the structure length is shown in Fig. 3.

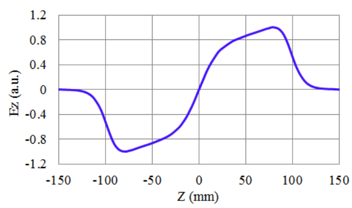

Figure 3: Variation in on-axis accelerating field for the two-cell buncher with elliptical inter-cell coupling iris.

RF DESIGN OF THREE-CELL BUNCHER

Since we want to keep water cooling scheme as simple as possible, we limit the RF power dissipation per cell to 5 kW. To reach this, a three-cell buncher is studied. The three-cell structure is modeled with elliptical inter-cell coupling irises with re-entrent shape as shown in Fig.4. Since the three-cell coupled structure supports three Eigen modes viz. 'π/3' '2π/3' and 'π' [8], the separation of π mode from the nearest mode (2π/3) reduces for the same inter-cell coupling iris. In-order to have higher mode separation between π and 2π/3 mode the inter-cell coupling iris is enlarged from 42 mm to 56 mm. Electric field array plot and variation in on-axis accelerating field for π mode in the three-cell buncher predicted by CST MWS is shown in Fig. 4. The RF parameters of the three-cell buncher are given in Table 2.

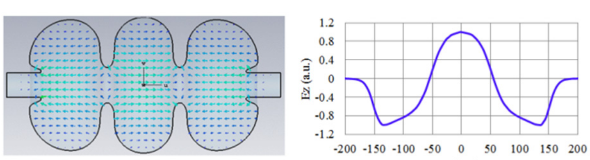

Figure 4: Electric field array plot and variation in on-axis accelerating of π mode in three-cell buncher predicted by CST MWS.

MULTIPACTING SIMULATIONS

The multipacting simulations (MP) are carried out using CST Particle Studio® tracking solver [7]. Since in elliptical or 'Ω' shape cavities the magnetic field distribution near cavity surface is such that the motion of electrons is in r-Φ plane [9], hence in order to reduce the simulation time the 1/8th model is simulated as shown in Fig. 5.

Table 2: RF Parameters of Three-Cell Buncher

RF parameters	Values
Resonance frequency f_π (GHz)	1.3
Quality Factor Q_0	27639
Shunt Impedance R (MΩ)	12.5
Mode Separation f_π-$f_{2\pi/3}$ (MHz)	3.18
Power dissipation P_c (kW) for 400 kV	12.8

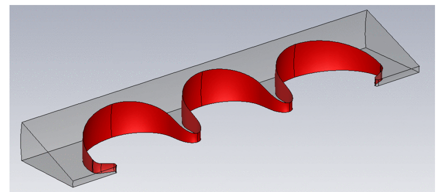

Figure 5: The 1/8th model three-cell buncher used for multipacting simulations.

In order to further reduce the simulation time, the electromagnetic field distribution is imported form Eigen mode solver and scaled accordingly. For multipacting simulations CST utilizes a hexahedral mesh, which has poor accuracy as compared to a tetrahedral mesh and is unable to accurately represent the small features of the structure such as the nose cone or inter-cell coupling iris etc. [10]. Although the accuracy of the model with hexahedral mesh can be improved by increasing the mesh numbers, however it also increases the simulation time.

To have good accuracy as well as reasonable simulation time, we adopted a different approach, where the RF fields from Eigen mode solver with tetrahedral mesh are saved as ASCII file and then imported for multipacting simulations with scaling. Since multipacting occurs near the surfaces hence to improve the accuracy of simulations the mesh density is enhanced near surfaces. To create this mesh refinement the cavity model in CST MWS is made of two vacuum solids as discussed in detail in reference [11].

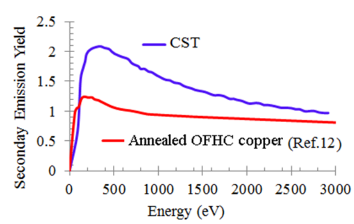

Figure 6: Comparison of SEY of copper given in CST and in reference [12].

The MP strongly depends upon the SEY properties of the material which depends upon the material composition and processing. The SEY of copper given in CST material library is significantly higher compared to the data reported in reference [12] for annealed copper as shown in Fig.6. Though it is more practical to use SEY data from reference [12], as the cavity has to be brazed which means the copper is annealed, however to be on safer side we also checked MP using CST SEY data. The MP is determined by exponential growth of particles (electrons) with time fitting $N(t) = N_0 e^{\alpha t}$, where N_0 is

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the number of primary electrons, and α is the growth rate expressed as ns^{-1}. The positive (negative) value of α indicate the presence (absence) of MP.

The multipacting simulations of the three-cell buncher predict a strong exponential growth of secondary electrons for voltages > 300 kV as shown in Fig. 7. Simulations predict stable trajectories of electrons near the inter-cell coupling irises and particle vs time curve shows that multipacting is of 1st order single point.

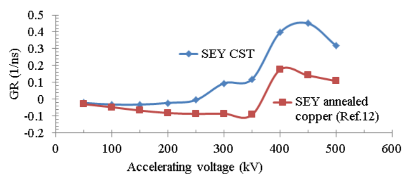

Figure 7: Exponential growth rate as a function of voltage in the three-cell buncher predicted by CST PS tracking solver.

Mitigation of Multipacting

In order to mitigate the MP, the resonance motion of electrons with the electromagnetic fields has to be broken. To break the resonance we modified the inter-cell coupling iris by increasing its x-radius 'a' as shown in Fig. 8, from 10 mm to 12 mm.

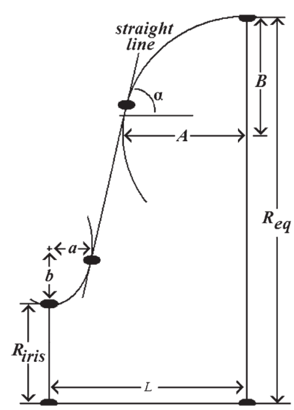

Figure 8: Schematic diagram of half of central cell, picture taken from [9].

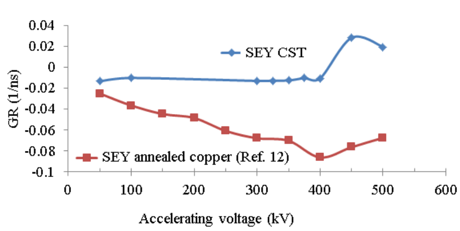

Figure 9: Exponential growth rate as a function of voltage in the three-cell buncher predicted by CST PS tracking solver.

The modified geometry shows no MP for voltage up to ~500 kV for annealed copper SEY data while a very mild MP (GR<0.03/ns) for CST SEY data, as shown in Fig. 9. Though the increase in thickness of inter-cell coupling iris mitigated the multipacting, this also reduced the shunt impedance from 12.5 MΩ to 11.5 MΩ while the mode separation is the same. The reduction in shunt impedance requires RF power of ~14 kW to achieve the voltage of 400kV.

CONCLUSION

The RF design of normal conducting CW buncher cavities with two and three cells were carried out using CST MWS. Geometrical dimensions were optimized to achieve higher mode separation as well as higher shunt impedance compared to the APEX buncher design. Multipacting simulations were performed and suitable modifications are made in geometry to mitigate the multipacting. Compared to the two cell design, the three cell design with a lower RF power per cell is preferred to relax the cooling design complexity.

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