WAKEFIELDS STUDIES OF HIGH GRADIENT X-BAND ACCELERATING STRUCTURE AT SINAP*

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Abstract

Shanghai compact hard x-ray free electron laser (CHXFEL) is now proposed accompanied with a high-gradient accelerating structure, which is the trend of large scale and compact facility. This structure operated at X-band (11424 MHz) holds the promise to achieve high gradient up to 80MV/m. However, due to its particular property, a more serious wakefields will be generated, leading to worse beam instability effects. In this paper, the computation of this case will be carried out with simulation. Moreover, analysis and optimization will be adopted to suppress wakefields effects.

INTRODUCTION

Free electron lasers (FELs) [1] are famous for generating high brightness and ultra-short coherent x-ray radiation source. Under the consideration of construction cost and limited space, X-band accelerating structure with high-gradient becomes the trend of large scale and compact FEL facilities, such as the compact hard x-ray FEL (CHXFEL) facility [2] which will be located close to the Shanghai Synchrotron Radiation Facility (SSRF) [3] at the Zhangjiang campus in Shanghai Institute of Applied Physics (SINAP). The CHXFEL aims to generate 0.1 nm x-ray radiation, and its linac is made up of an injector, compression system and X-band accelerators, shown in Fig.1.

X-band accelerating structure should be designed with small iris radius to reduce the group velocity [3] and improve the RF power efficiency [4], which make the accelerating gradient extend to 80MV/m. However, larger short-range wakefields will be generated due to smaller iris radius a, which is given [5] by:

$$W_L(s)=\frac{Z_0 c}{\pi a^2}e^{-1.16(s/mm)^{0.55}}$$
$$W_T(s)=\frac{2Z_0 c}{\pi a^4}s_0\left(1-e^{-0.89(s/mm)^{0.87}}\right) \tag{1}$$

Where s is distance from the head of the bunch and Z_0=377Ω, s_0=0.46. The effect of wake function may result into beam loss or emittance growth when a moment of beam distribution exhibits an exponential growth. The stability requirement [6] is given by:

$$A=\int_0^L \frac{\beta}{2E}ds\langle W_T\rangle N_e^2 \tag{2}$$

Where A is a magnitude transmission parameters, determined by the performance of compact hard XFEL facility. Preliminary A=0.2 is selected for $\langle\beta\rangle$=10m, Charge=250pC, $\langle\sigma z\rangle$=20um, G=80MV/m, Ef=6.4GeV, E0=0.4GeV and average aperture radius should be 3.7 mm at least.

In this paper, we have investigated the short range wake fields at high gradient X-band accelerating structure and compared them with several analytical models. ABCI code [7] and CST simulation [8] have been also used to check the results. Alternatively, an optimized accelerating structure will be discussed in order to suppress the wakefields.

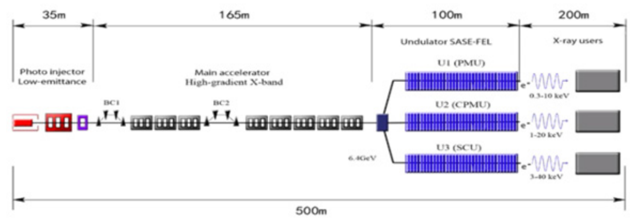

Figure 1: Layout of the CHXFEL facility.

WAKEFIELDS AND POTENTIAL

The wakefields in infinitely periodic structure shown in Fig.2 are investigated by many authors. Eq.1 presents the briefly approximate to Sessler-Vainsteyn model with the bunch traversing a sufficient number of cells [5]. Soon after, K. Yokoya and K. Bane [9, 10] put forward more precise models, as follows:

$$W_L(s)=\frac{Z_0 c}{\pi a^2}e^{-\sqrt{\frac{s}{s_1}}}$$
$$W_T(s)=\frac{4Z_0 c s_2}{\pi a^4}\left[1-\left(1+\sqrt{\frac{s}{s_2}}\right)\cdot e^{-\sqrt{\frac{s}{s_2}}}\right] \tag{3}$$
$$with \quad s_1=0.41\frac{a^{1.8}g^{1.6}}{L^{2.4}},\quad s_2=0.17\frac{a^{1.79}g^{0.38}}{L^{1.17}}$$

Where is valid over the parameter region as $s/L<0.15$, $0.34<a/L<0.69$, and $0.54<g/L<0.89$. Another model introduced the compliment error function with very short range wake, is given by:

$$W_L(s)=\frac{Z_0 c}{\pi a^2}\exp\left(\frac{2\pi\alpha^2 L^2 s}{a^2 g}\right)erfc\left(\frac{\alpha L}{a}\sqrt{\frac{2\pi s}{g}}\right)$$
$$with \quad \alpha\left(\frac{g}{L}\right)=1-0.4648\sqrt{\frac{g}{L}}-0.0708\frac{g}{L} \tag{4}$$

For example, analysis and simulation on one cell of X-band accelerating structures at CHXFEL linac, which cell period is fixed at L=10.497 mm, cavity radius is roughly

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b=10.585 mm, the iris radius a=3.775 mm, and the thickness t=1.5 mm. Note that the radio of a/L and g/L is satisfied the request of equations. The results of three models are illustrated in Fig.3 and Fig.4 with Gaussian current density.

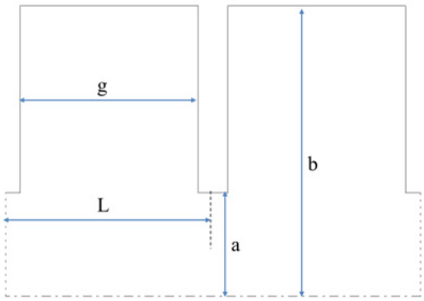

Figure 2: Two cells of the geometry under consideration.

It is point out in Fig. 3 that the longitudinal wake potential results at long bunches of all methods above except Eq.4, have the same shape when the distance from the head of bunch is below $10\sigma_z$. It is valid of Eq.4 for the distance range is very short. The error of maximum wake potential between each other methods are 32%, 11%, 51%, 2% under the standard of ABCI's results at long bunches. The wakefields calculated by ABCI and CST are oscillated owing to inverse Fourier transforming, meet the characteristic of Eq.3 well when the distance s is less than $10\sigma_z$ at the long bunch.

It is also easy to find out the effects displayed both the simulation on ABCI and CST are almost exactly the same, and the differences between them are negligible. Due to the 3D soft of CST calculates very slowly and is hard to compute the very short bunch about tens of micro meters, ABCI is usually used to calculate the wakefields.

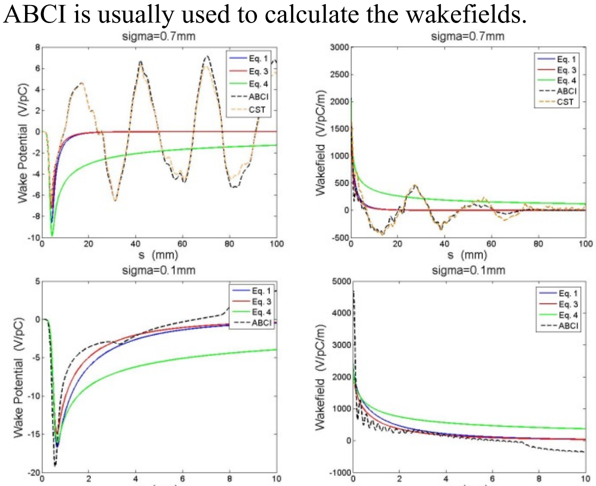

Figure 3: Longitudinal wake potential and wakefields of example cell at 0.7 mm and 0.1 mm rms bunch lengths.

However, at the short bunches, the maximum wake potential of Eq.4 is more approaching to results of ABCI than that of Eq.3. The error of maximum wake potential between each other methods are -13%, -22%, -16% under the standard of ABCI at short bunches. In addition, and as concluded from Fig.3, the analytical model of Eq.3 is perfectly valid for either long bunches which length is also far smaller than iris radius or short bunches. Note that the longitudinal wakefields of ABCI is larger relatively than these of other analysis models at short bunches. In fact, these analysis models of wakefields are the same in both long bunch and short bunch without the consideration of the length of bunch. The loss factor is about 6.5 V/pC or 13.8 V/pC in the two cases respectively, which means that shorter length of bunches lose bigger energy.

Let us consider the method of Eq.3 and ABCI code, transverse wakefields and potential are shown in Fig.4. From the picture, we find out that the wake potential is approximately different between each other. At short bunch, the analysis of Eq.3 is valid on the region of 10σ, but it is not applicable at long bunch. The transverse wake field is also oscillated along the distance due to inverse Fourier transforming, but the oscillation is strongly for long bunch. At short bunch, the wake potential calculated by Eq.3 is about 28% less than that of ABCI when the distance is 10σ, and the wakefields is about 18%. Moreover, the wake potential in Eq.3 is almost unchanged attributed to the saturation wakefields.

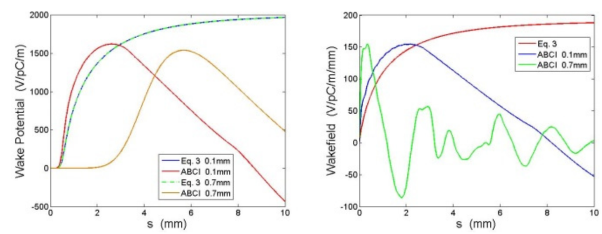

Figure 4: Transverse wake potential and wakefields of example cell at 0.1 mm rms bunch lengths.

WAKEFIELDS OPTIMIZATION

As mentioned above, one important factor of the beam instability is wakefields. Therefore, we should suppress the wakefields in the accelerating structures to keep the beam stability. For the same bunch, smaller wakefields lead to smaller wake potential correspondingly.

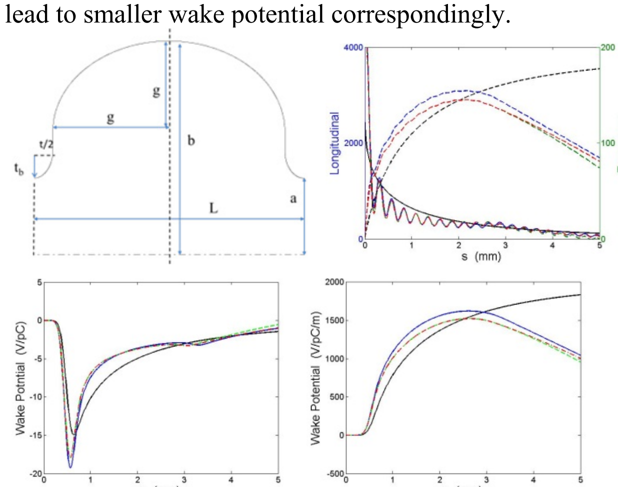

Figure 5: Optimized cavity and its wake function.

In the discussion, we use the simulation of ABCI, and the optimized accelerating cell and its results are shown in

Fig.5. Note that the analysis could not be applied directly without correction. The top left picture is layout of tested round cavity shape and top right is wakefield in several conditions, in which black line is analysis of Eq.3, blue line is the results of example cell in Fig.2, and green line and red line are the optimized shape with fixed cavity radius or operating frequency respectively. In addition, the bottom left is longitudinal wake potential and bottom right is transverse wake potential.

The error of last two cases (green and red) is less than 0.02%, which means the wakefields are mainly influenced by iris radius. The optimized results of maximum longitudinal wakefields, transverse wakefields, lose factor and kick factor are 4%, 6%, 6% and 5.5% less than rectangle model respectively for a Gaussian bunch with rms length of 0.1mm. It is demonstrated that the new accelerating structure is verified to suppress the wakefields in both longitudinal and transverse direction.

As to the accelerating structures, the constant impedance and constant gradient are usually adopted. The difference in these models shown in Fig.6, which are rectangle constant-impedance and rectangle constant-gradient structures. The error of the two cases is small, and the oscillation of constant-gradient structure is a little violent than the other, due to unequal cavity size.

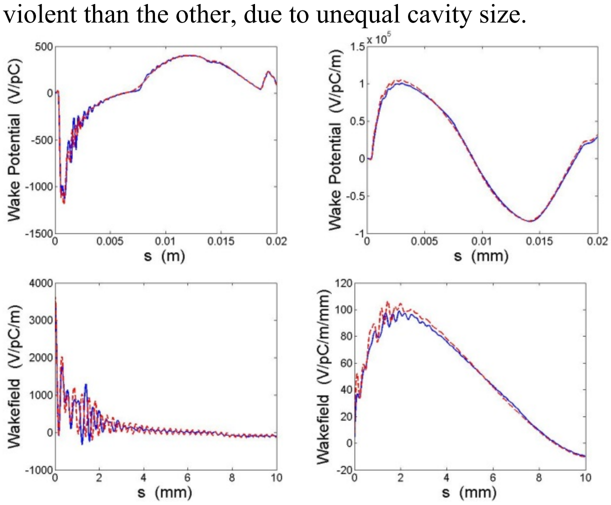

Figure 6: Wake potential and wakefields in three models: (blue line) rectangle constant-impedance, and (red line) rectangle constant-gradient.

For a real bunch distribution in the design of CHXFEL facility, the effects of accelerating structure's wakefields are illustrated in Fig.7. It is easy to obtain the information that constant-impedance structure is better. From the figure, the difference in longitudinal wake potential can be ignored, but transverse wake potential of red case is almost 50% larger than the blue one.

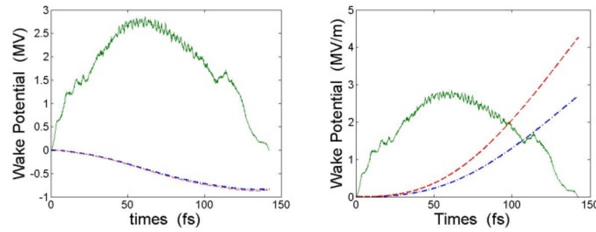

Figure 7: Longitudinal wake potential (left) and transverse wake potential (right) of peak current 3kA (green line). Blue line shows the results of rectangle constant-impedance structure, and red line shows the results of rectangle constant-gradient structure.

CONCLUSIONS

In this paper, we analyse the wakefields in several models, and compared them results. As mentioned above, the Eq.3 can be used to calculate the wake potential instead of ABCI at short bunches in an acceptable error. Round cavities and constant-impedance structures are confirmed to benefit on supressing the beam instability, which is mainly caused by transverse wakefields. Note that the simulation of ABCI is more accurate than the equations, especially in the non-standard structure, but it is not applicable to cylindrically asymmetric structures which should be calculated by 3D software. We have, in addition, performed numerical results between ABCI code and CST that the accuracy confirms to 2% in valid distance. We will also study the other factors that affect the beam stability in future and hope these conclusions to assist us for the construction of CHXFEL facility.

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