SIMULATION AND MEASUREMENT OF THE BEAM BREAKUP INSTABILITY IN A W-BAND CORRUGATED STRUCTURE

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Abstract

The corrugated wakefield structure has wide application in electron beam energy manipulation and high frequency RF radiation generation. The transverse wakefield which cause beam breakup (BBU) instability is excited when the drive beam is not perfectly centered through the structure. Here we report on the numerical and experimental investigation of the BBU effect in a W-band corrugated structure, for both cases of short range wakefield and long range wakefield. In the numerical part we develop a point to point (P2P) code that allows rapid and efficiency simulations of the beam dynamics effect by wakefield. The P2P code is based on the the particle-wake function coupled dynamics equation of motion. And the experimental observations of the BBU effects are in good agreement with the simulations.

INTRODUCTION

The corrugated wakefield structure becomes one of the research hotspots for its considerable cost and the wide applications [1]. It can work as a dechirper to control the electron beam energy phase space precisely. And it is also attractive as high power RF radiation source of high frequency towards Terahertz. Recently the application of the corrugated structure has been forward to diagnose the longitudinal profile of the electron beam based on the transverse wakefield inside [2].

The interaction of intense drive beam with the wakefield in corrugated structure is an important issue [3]. The transverse wakefields are excited when the electron beam is not perfectly centered through the structure, which causes the beam breakup (BBU) instability and thus provide a potentially serious limitation to the performance of the wakefield structure [4]. Take an example of the high impedance W-band (91 GHz) wakefield structure, here we report on the detailed numerical and experimental study on the interaction of beam with the main dipole modes transverse wakefield in the corrugated structure.

NUMERICAL STUDY WITH A P2P CODE

Features of the W-band Corrugated Structure

Two identical copper plates with periodic grooves make up the W-band wakefield structure as shown in Fig. 1. It is a traveling wave structure which is similar to the SLAC mm-wave structures in Ref. [5]. The dimensions of the grooves are all about 1 mm. There are 110 regular cells in total, and the periodic length of the regular cell is $z_p = 1.1$ mm, the half width of the regular cell $x_{max} = 1.25$ mm and the depth of the regular cell $y_{max} = 0.9$ mm. The total length of the grooved structure is $L_s = 123\,mm$. When set the gap $2a = 0.94$ mm, the fundamental mode is $f_{TM01} = 91$ GHz.

In our previous work [6], we had demonstrated that the longitudinal wakefield (TM01 mode) can be used for the high power RF generation and high gradient acceleration. Here the main dipole modes of the W-band structure are concerned in this paper in order to further control the beam breakup (BBU) instability caused by the transverse wakefield.

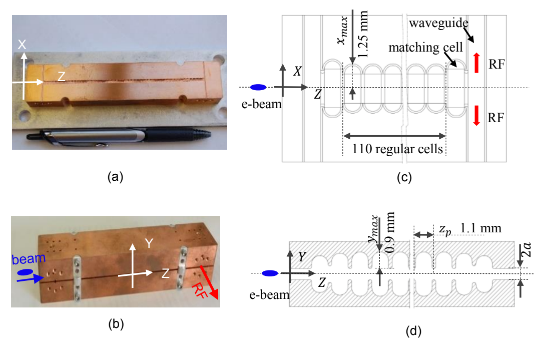

Figure 1: ketch of the W-band corrugated structure.

Wake Function of the Main Dipole Modes

The transverse kick can be decomposed into X-dipole mode and Y-dipole mode because the structure is axially nonsymmetric. As shown in Fig. 2, we assume that the electron beam is off center in one direction when entering the structure, then the corresponding dipole modes is excited.

The wake function is used to describe the integrated effect from the wakefield excited by a drive particle on the witness particle along the whole structure. For each single transverse wakefield mode with frequency $\omega = 2\pi f$, the analysis expression of the wake function in the traveling wave structure with consideration of the structure attenuation is:

$$w_{\perp}(s) = -w_0 e^{-\frac{\alpha s}{l_w/L_s}}(1 - s/l_w)\mathrm{U}(L_w - s)\cdot\sin(ks) \quad (1)$$

with

$$l_w = c\cdot(L_s/v_g - L_s/c) = L_s(1/\beta_g - 1) \quad (2)$$

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Where w_0 = is amplitude of the wakefield in the unit of [V/nC/mm], $\alpha = \omega/2Qv_g$ is the structure attenuation, with Q is the quality factor and v_g is the group velocity. s is the wakefield coordinate, $s > 0$ means behind the particle, l_w is the space duration of the wakefield mode, expression $\mathrm{U}(L_w - s)$ return 1 when $s \leq l_w$ and returns 0 otherwise.

We can apply the CST particle studio's wakefield solver to get the wake functions of the dipole modes. Figure 2 shows the comparisons between the CST simulations with the analysis by Eq. 1, which get good agreement with each other.

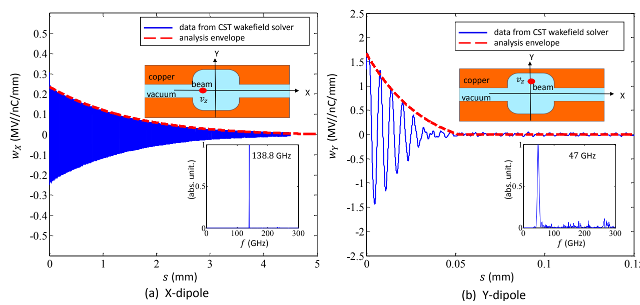

Figure 2: wake function of X-dipole and Y-dipole mode

Dynamic Equations of Motion

For a finite beam distribution (including the bunch train distribution) with total number of particles N, the i^{th} particle at position s_i (longitudinal) and x_i (horizontal) in the beam experiences both the longitudinal and transverse wakefield generated by all the particles ahead of it. Dynamics equations of motion at each small step ΔL go as [4]:

$$F_z = q_i \sum_{m=0}^{1} \sum_{n=1} \sum_{j=1}^{i-1} (x_i x_j)^m q_j A_{mn}(s_j - s_i) \times \cos(k_{mn}(s_j - s_i))\Delta L \tag{3a}$$

$$F_x = q_i \sum_{m=0}^{1} \sum_{n=1} \sum_{j=1}^{i-1} x_j q_j B_{mn}(s_j - s_i) \sin(k_{mn}(s_j - s_i))\Delta L \tag{3b}$$

$$dP_{z,i}/dt = F_z \tag{3c}$$

$$dP_{x,i}/dt = F_x \tag{3d}$$

Here F_z and F_x are the longitudinal and transverse wake forces, $P_x = m\gamma x'$ and $P_z = m\gamma c$ are the momentum respectively. m and n are the azimuthal and radial mode numbers. We just concern the first radial mode ($n = 1$) the dipole mode ($m = 1$), i.e., the 138.8 GHz X-dipole mode and the 47 GHz Y-dipole mode as shown in Fig. 2. q_j is the charge of particle j. $A_{mn}(s_j - s_i)$ and $B_{mn}(s_j - s_i)$ are the amplitudes of longitudinal component and transverse component of the wakefield strength respectively, which could achieved with the wake function envelop divided by the structure length L_s, and the unit of $A_{mn}(s_j - s_i)$ and $B_{mn}(s_j - s_i)$ is MV/m/nC and MV/m/nC/mm respectively.

The dynamics equations of motion shows that the wakefield forces strength is decided by the distribution of electron beam, while the wakefield will effect the distribution in turn. A point to point (P2P) code is developed with the MATLAB program to deal with this iteration progress step by step. Each point in the P2P code represented as a microparticle of certain charge, and all the information (including the position and momentum in both longitudinal and transverse space) of each particle at each step is recorded. The P2P code is more suitable compared to the existing codes to simulate the beam dynamics effected by the long range wakefield in bunch train case, especially for the bunch train with relatively large bunch intervals, say, with the single bunch length of a few ps and the bunch interval in the scale of ns. It leads to a complicated mesh problem for codes that deal with wakefield in the way of convolutions [7], the empty space (ns scale) between the sub bunches also make numerous meshes, which is quit time consuming for the simulation. However, it's not a problem for the P2P code which just record the particles informations no matter what the detail distributions are.

MEASUREMENT OF THE BBU

The layout of the experiment at the AWA facility is shown in Fig. 3. The upgraded AWA drive beam line consists of a 1.3 GHz RF photocathode gun and 6 RF linac tanks, which has the capability to generate intense charged electron beam of 65 MeV, with picosecond rms bunch length and initial bunch interval z_0 = 23.6 cm (1.3 GHz).

Electron bunches will then be focused with triplet into the wakefield structure. trims magnets are used to adjust the trajectory of the electron beam. The TM01 mode RF radiation was measured with a calibrated power meter. We captured the images of the transverse distribution of the electron beam (X-Y distribution) at the downstream YAG luminescent screen, which is 2.0 m away from the exit of the W-band structure. The 2 nC Gaussian bunches with rms bunch length 0.5 mm are used in our experiment.

Single Bunch BBU

In the experiment, when electron beam is centered through the structure, the wakefield radiation (signal of the power meter) is maximum because beam-TM01 mode coupling is strongest. And also the transverse beam image on the YAG screen is gaussian distribution in both X and Y direction, we set the trim strength as the baseline. Then we finely adjust the strength of trim magnets to change the initial off-axis (displacements) of the beam in both X and Y directions, the images captured at the YAG screen compared with the simulations are shown in Fig. 4. In the P2P simulations, the transverse wakefield effects on the beam from both X-dipole mode and Y-dipole mode are combined. Figure 4 (a) corresponding to the simulation results of the drive beam with initial 0.5 mm displacement in X direction and 0.3 mm displacement in Y direction. Figure 4 (b) is the case of initial 1.0 mm displacement in X direction and 0.2 mm displace-

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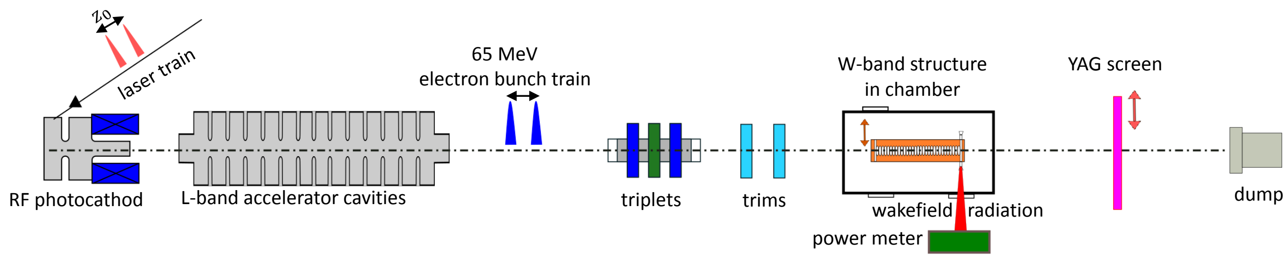

Figure 3: Experimental set up at the AWA facility

ment in Y direction. Figure (c) and (d) are the experimental observations which agree well with the Fig.(a) and (b) respectively. The beam distribution is more "C" type like when the beam has more displacement in X direction, and the tail of the beam is longer when the beam is has more displacement in Y direction.

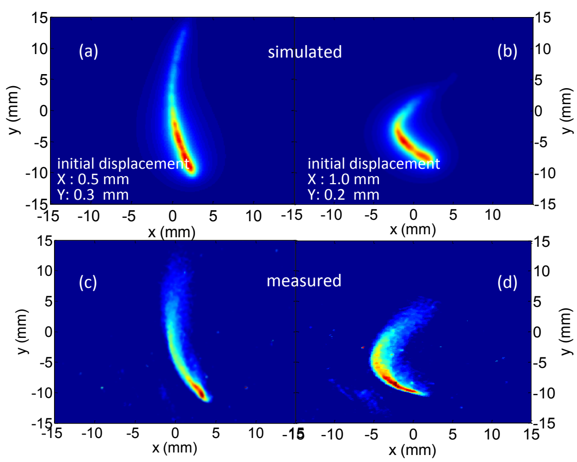

Figure 4: comparison between the simulations with the experimental observations, different initial displacement in front of the W-band structure leads to different beam transverse image (X-Y distribution) on the YAG screen due to the difference strength of the dipole modes

Two Bunch BBU

The electron bunch train of two sub-bunches with adjustable separation are generated with the UV laser train. The leading bunch and the tailing bunch in front of the W-band structure are the same, thus the self-wakefield (short range wakefield) of the two bunch is the same. We are able to scan the separation between the two bunches, i.e., the phase of the the X-dipole mode (wavelength $\lambda_{139\,\mathrm{GHz}} = 2.16$ mm) long range wakefield from the leading bunch that tailing bunch experienced is changed, which leads to the different images of two separated sub-bunches. When the separation between the leading and tailing bunch is $z_0 + 1.1$ mm and $z_0 + 1.8$ mm, the corresponding images are shown in Fig. 5(c)~(d). which agree with the simulations in Fig 5(a)~(b), the initial displacement is 0.4 mm in X direction and 0.2 mm in Y direction.

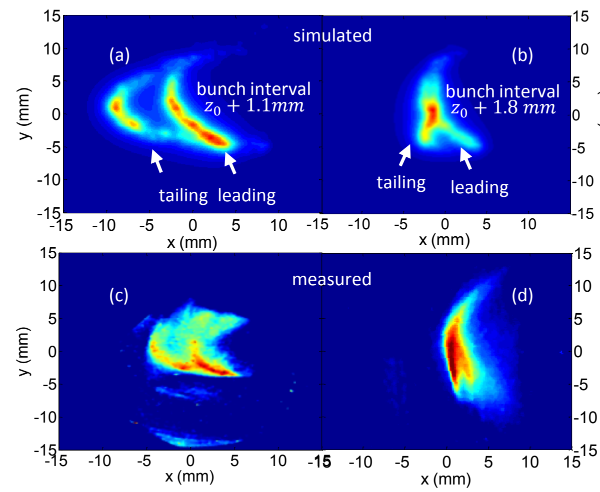

Figure 5: comparison between the simulations with the experimental observations, different bunch separation leads to different beam transverse image (X-Y distribution) on the YAG screen due to the difference phase and strength that tailing bunch experiences from the dipole modes of the leading bunch

SUMMARY

In summary, we performed a systemic study on the interaction of the electron beam with the transverse W-band wakefield in a corrugated structure, which including the numerical and experimental investigation of the BBU effect for both cases of short range wakefield effect and long range wakefield effect. The numerical part is based on a point to point (P2P) code which allows rapid and efficiency simulations of beam dynamics effects by wakefield, and the experimental measurements of BBU are found to be in good agreement with simulations. Our work should forward the further control of the BBU effect and forward the applications of the corrugated structures.

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