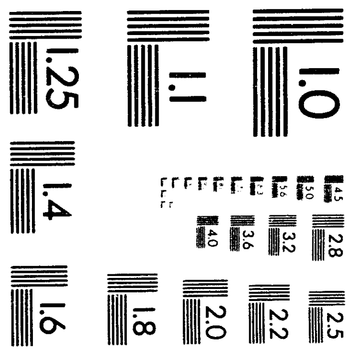

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Design consideration of relativistic klystron two-beam accelerator for suppression of beam-break-up*

H. Li, T. L. Houck[(a)], S. Yu and N. Goffeney
Lawrence Berkeley Laboratory
University of California, Berkeley, California 94720

ABSTRACT

It is demonstrated in this simulation study that by using the scheme of operating rf extraction structures on the betatron nodes of electron drive beam in conjunction with adequate de-Q-ing, appropriate choice of geometries for the rf structures (reducing transverse impedence) and/or staggered tuning we can suppress the overall growth of transverse instabilities to 4 e-folds in a relativistic klystron two-beam accelerator with 200 extraction cavities.

1. INTRODUCTION

A collaboration between the Lawrence Livermore National Laboratory (LLNL)'s Microwave Source Facility and the Lawrence Berkeley Laboratory's Collider Physics Group has been studying the feasibility of a relativistic klystron two-beam accelerator (RK-TBA) as a possible future linear collider.[1] In a RK-TBA, one beam line is a high-gradient rf linac which accelerates electrons or positrons to very high energies, ~TeV. The second beam line, the subject of this paper, is an induction linac which includes microwave generating structures located at regular intervals along the beam line. A schematic diagram of RK-TBA is given in Figure 1. These structures extract energy in the form of microwaves which are then

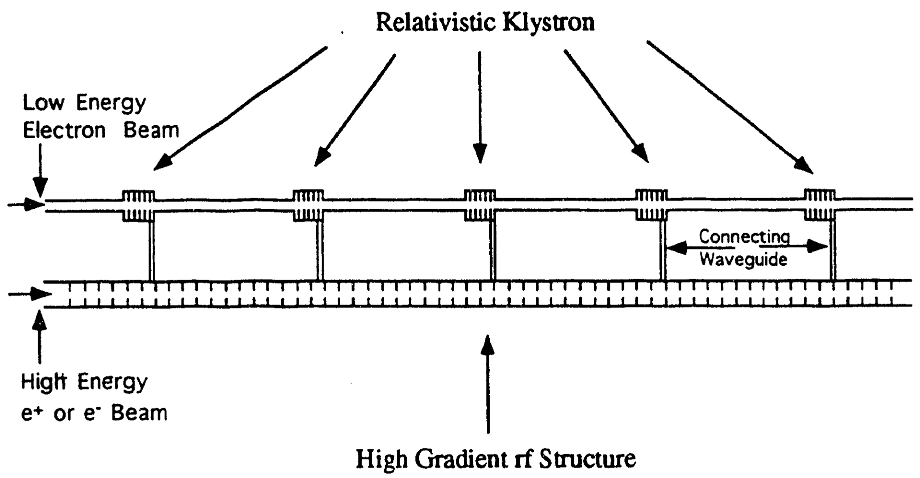

Fig. 1. Schematic diagram of RK-TBA

used to drive the rf linac. In a RK-TBA design, the microwave generating structures are rf structures, e.g. standing-wave cavities or traveling-wave structures (TWS). For the convenience of following discussion we use the latest parameters for Stanford Linear Accelerator (SLAC)'s concept of the next generation linear collider as a reference. The parameters are given in Table 1. According to Table 1 the required power is 350 MW per section. Since experiments at LLNL have demonstrated that traveling-wave structures are capable of producing the desired high-power microwave pulses, 200's MW per output,[2] so, we can put one RK structure every meter to match the power requirement. If we have a total of 200 such structures in one

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(a) Permanet address: Lawrence Livermore National Laboratory, Livermore, CA 94550 .

the BBU from happening even when the electron beam traverses a rather long distance (~100m). In section 5, we examine the effectiveness of cavity staggered tuning schemes in suppressing the BBU, and show that slight differences in the geometries of the cavities can break the conherency, and therefore the effectiveness, of the kicks of the wake fields to the beam and hence significantly reduce the BBU.

2. MODEL EQUATION AND PARAMETERS

2.1. Basic model and beam-break-up equation

In this study we adopt the model used in Reference 5 to describe the BBU related beam dynamics in a SWFEL/TBA. As illustrated in Figure 1 the SWFEL cavities are cyclinders in shape with the planar wiggler magnetic fields being placed in the y-z plane and the particles wiggling in the x-z plane. These wiggle oscillations excite the TE_{11p} FEL mode. A first order approximation separate the beam dynamics in the wiggle plane and that perpendicular to it and we study BBU in the y direction as that is the most severe case.

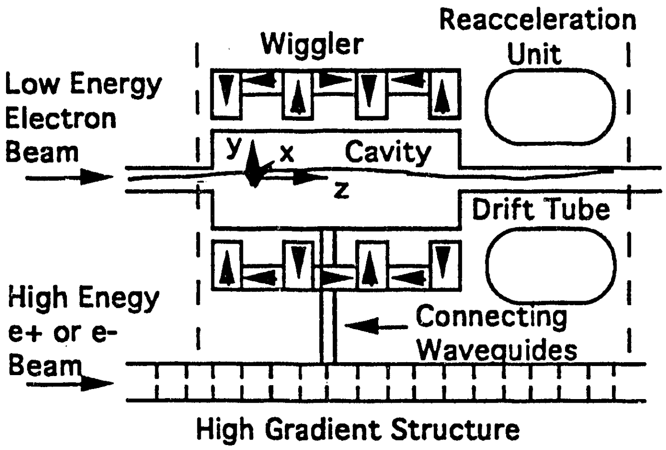


Fig. 1 Schematic diagram of SWFEL/TBA

In this model each bunch in the beam is treated as a macroparticle and they are eqaully spaced on the beam line. The transverse displacement, ξ_j, of the j-th with energy γ_j can be described by a standard BBU equation given bellow

$$\frac{\partial}{\partial z}[(\gamma_j(z)\frac{\partial}{\partial z}\xi_j] + \gamma_j(z)k_{\beta j}^2(z)\xi_j = \frac{Is_b}{I_0}\sum_{k=0}^{j} W((j-k))s_b)\xi_k , \qquad (1)$$

where z is the axial coordinate in *cm*, s_b is the distance between bunches in *cm*, W is the transverse wake function in cm^{-3}, I is the averaged current in *kA*, and $I_0 = mc^3/e = 17.05\ kA$ is the Alfven current.

Table 1. Base case parameters of a SWFEL for *17.1 GHz* with cylindrical cavities

cavity	dimension (radius x length) = 1.5 cm x 90 cm x 3 cm iris (radius x length) = 0.4 cm x 3cm junction = 2 cm length; cone ~ 30^o
beam	energy γ = 16 average current I = 1 kA pulse length = 100 ns interval between bunches = 1.74 cm
focussing	focussing length λ_β = 52 cm; (k_β = 0.12 cm^{-1})

2.2. Base case

To facilitate, in the later part of this study, the comparison of effectiveness of various schemes in suppressing the beam-break-up we use as our base case the same set of parameters as in Ref. 5, which is given in Table 1.

3. LANDAU DAMPING ALONG THE TUBES

The first scheme that is examined is related to Landau damping (or phase mixing) mechanism. We modify the Landau damping scheme in Reference 5 by allowing the electron beam to carry energy spread $\Delta\gamma$ (or equivalently, betatron frequency spread Δk_β) only when it is inside the tubes. This is a more reasonable model than the previous one in which the beam has energy spread all the way along the device. The rational that supports the new model is as follows: Since, as we know, finite energy spread in a FEL beam is likely to result in significant reduction in the efficiency of microwave generation of the device, so, it is prefered that electron beam is cold when it is inside FEL cavities. Thus, it can be conceived that the scenario in a real SWFEL/TBA operation is likely to be that when an initially cold electron comes out of the first SWFEL cavity it has certain energy spread due to its interaction with the operating mode inside the cavity. The beam then traverses inside a tube carrying this energy spread and just before it enters the next cavity it goes through a beam conditioner to get "cooled down" (in addition to be reaccelerated and get back its original average energy) so that the same high FEL efficiency can again be achieved in the second cavity. This process repeats itself throughout the whole SWFEL/TBA. Here we present the results of BBU in a typical case in which the the length of the cavity, $L_c=48\ cm$, and the length of the tube, $L_t=42\ cm$. Figures 2(a) and (b) are, respectively, $|\xi|_{max}$ v.s. z for $\Delta k_\beta/k_\beta = \Delta\gamma/\gamma = 0\%$ and 2%, and it is seen that at $z=100\ m$ $|\xi|_{max}$ for Fig. 2(b) has a factor of four reduction on BBU over the corresponding value in Fig. 2(a), i.e., the cold beam case. However, this number may have to be discounted since we probably need to increase the overall length of the device by a factor of $(L_c+L_t)/L_c$ (i.e, from *100 m* to *188 m*) to generate the same amount of power as that of the base case in which the lengths of the tubes are assumed to be negligibly short compared to that of the cavities. This will also result in larger, maybe considerably larger BBU at the end of the device. After taking these two factors into account it now looks like that this scheme is not very appealing. Therefore, we need to search for other alternatives.

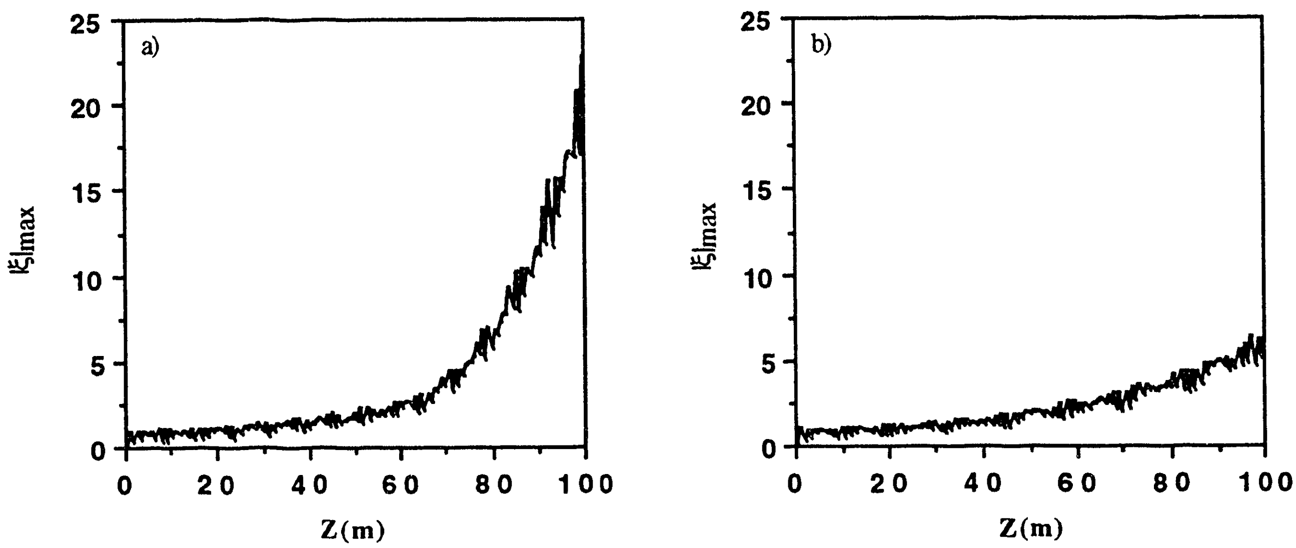


Fig. 2: Spatial evolution of BBU for (a) $\Delta\gamma/\gamma=0\%$; and (b) $\Delta\gamma/\gamma=2\%$.

4. CONE JUNCTION TAPERING

A different approach to suppress the BBU is to diminish the overall wake fields inside the cavities. As it has been pointed out (in Reference 5) these wake fields are generated due to the change in the transverse dimension from the cavities to the tubes. Therefore by smoothing this transition we can reduce the wake fields. This has been shown in the Ref. 5, in which a 30^{o} slope cone junction is used at each longitudinal side of a cavity and the dipole transverse wake fields are therefore substantially reduced from the one when the slope for cone junction is 90^{o} (i.e., square edges). To have a bigger reduction on the wake fields a simple idea is to carry this scheme a little bit further by using even more gradual cone junctions than the 30^{o}'s one, for example, 15^{o}'s which means just extending the longitudinal dimension of the cone junction from 2 cm to 4 cm while other parameters are the same as that of the base case. The corresponding transverse wake function for the dipole modes is obtained using ABCI[8] and is given in Figure 3(a). For the convenience of comparison, the range of the wake fields is also

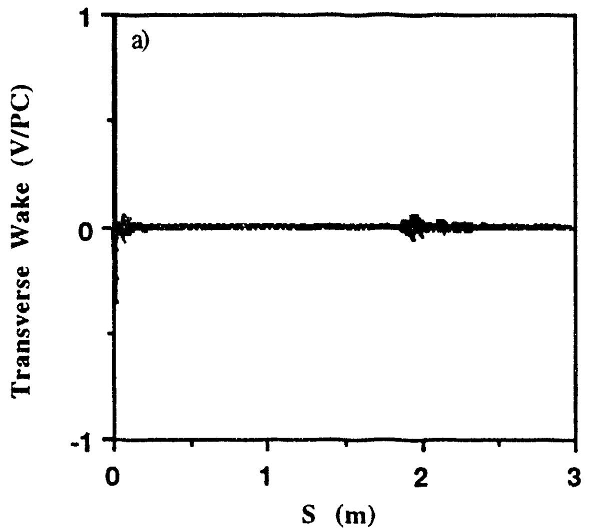


Fig. 3: Dipole transverse wake for a cylindrical cavity of 90cm long and 1.5cm in radius with a tube of 4mm radius on each side and a Gaussian bunch of σ=3 mm. The slope of the cavity-iris juction cone is (a) 15^{o}; (b) 30^{o}.

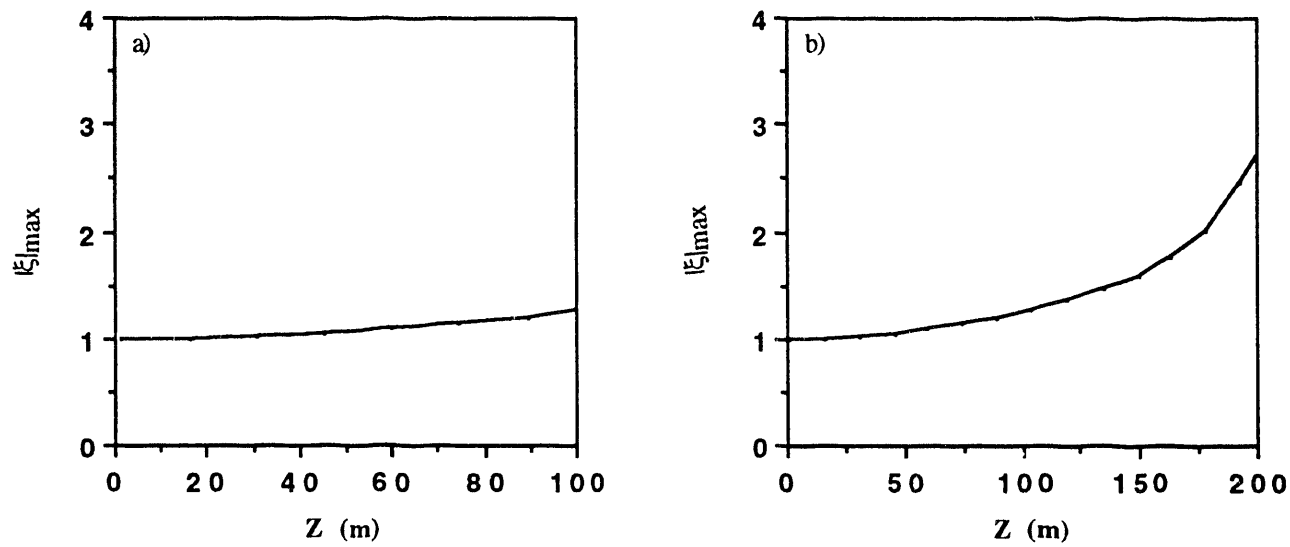


Fig. 4: Spatial evolution of BBU due to the wake fields given by Fig. 3(a) for a device of (a) 100 m long; (b) 200 m long.

kept to be 3 m long as the case in Ref. 5. and the wake fuction for the base case is reproduced and given in Figure 3(b). In both these two figures we can see that the wake field has a "hump" located at about twice the length of the cavity. This large amplitude wake oscillations which is likely the first wake generated by the signal charge reflected back to the entrance of the cavity[5] is the predominant contributor to the kicks the beam receives from the field. Compared with Fig. 3(b) it is seen that the "hump" in Fig. 3(a) shrinks by a facor of 2~3, which results in an even bigger reduction on the maximum transverse displacement ($|\xi|_{max}$) of the beam due to the wake field, a factor of 15~20 at z=100 m, as is shown in Figure 4(a). Since, general speaking, the more SWFEL cavities an electron beam drives the more efficient the rf source tends to be, therefore, we now calculate $|\xi|_{max}$ v.s. z for one section of SWFEL/TBA that has twice as many cavities as the previous one to see how the effect of the wake fields is for this longer device. The result is presented in Figure 4(b) It is found that at z=200 m $|\xi|_{max}$ is still a relative small number, ~2.5. Thus if a beam has an initial shift less than 1.6 mm its maximum displacement (at z=200 m) due to the wake fields should be less than 4 mm, i.e. the radius of the irises (also the tubes).

In the above calculations all the wake fields are assumed to have a range of 3 meters which normally can be achieved with certain amount of dampings on the cavities (i.e., reducing the Q factor). However, these dampings may potentially have undesirable effect(s) on the operating mode and there is also cost consideration, therefore, we want to minimize the use of them if possible. Since the scheme of the 15^o cone junction can reduce the wake field quite effectively so we can now "afford" to relax the damping on the wake fields somewhat and tolerate a longer range of wake fields. For example we extend the range of wake fields to 6 meters for the case of Fig. 3(a). The correponding wake function is given in Figure 5(a). It is noted in Fig. 5(a) that about twice the length of the cavity behind the first "hump" there exist a second one and about the same distance behind this second "hump" the head of a third "hump" starts to emerge (at the end of this 6 meters long wake field). The second and the third "hump" corresponds, respectively, the second and the third time the first wake generated by the signal charge reflected back to the entrance of the cavity. The additional large amplitude wake fields should increase the average amount of "kicks" a bunch in the beam receives, and therefore, result in larger transverse displacements of the beam. This is confirmed by the simulation result presented in Fig. 5(b). But still, the displacements are much smaller than the corresponding one's for the base case and at 100 m is well below the tolerable number 10.

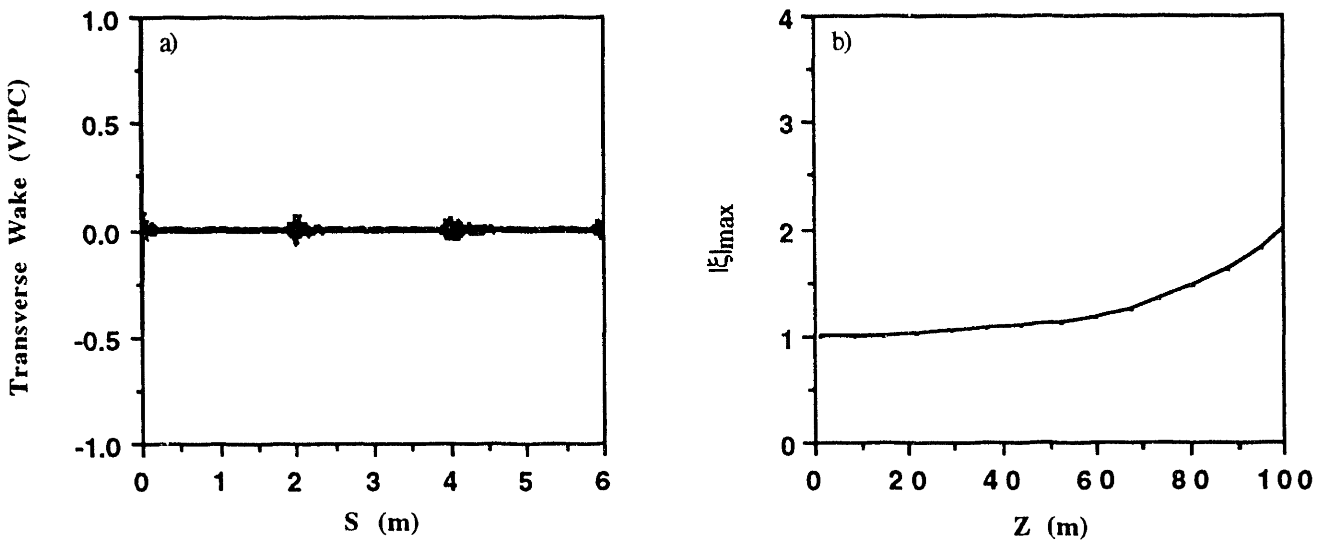


Fig. 5: (a) 6 m long transverse wake for the same cavity as the one for Fig. 3(a); (b):Spatial evolution of BBU due to the wake fields given by Fig. 5(a).

Another thing is that we have been using fairly long cavities, ~90 cm, to reduce the number of cavity-iris junctions which are responsible for the presence of the transverse wake fields. However, such a long cavity is normally more difficult to manufacture and more fragile than a shorter one. Hence, we cut the lengths of the previous cavities by half to 45 cm and calculate the BBU of the beam for the 15^o cone junctions case. The result is presented in Figure 6. It is seen that $|\xi|_{max}$ at 100 m is ~2.5 which is about the same as $|\xi|_{max}$ at 200 m for the 90 cm cavity case. Once again this number is considerably smaller than the one for the base case.

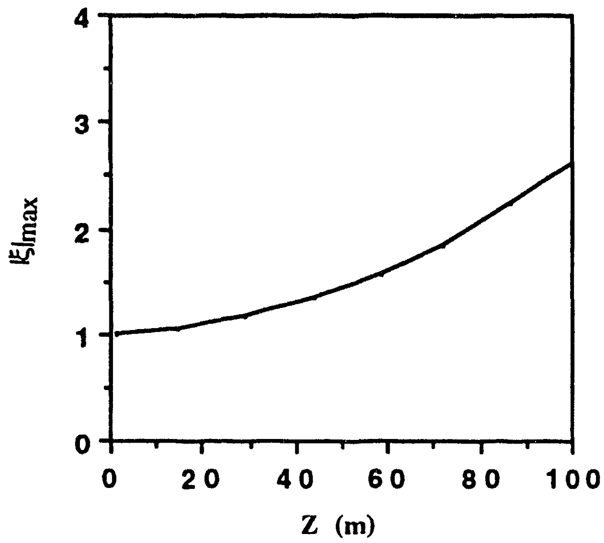


Fig. 6: Spatial evolution of BBU due to wake fields by cavities of the same type as the one for Figure 3(a) but of half longitudinal dimmension (45cm).

5. STAGGERED TUNING

Another scheme that can suppress the BBU effectively is cavity stagger-tuning[7]. In this scheme we can vary either (a) the slopes of the cone junctions; or (b) the longitudinal dimensions of the cavities.

(a) In the first case, the simplest situation, is that the cavities are grouped into two types which are the same except that the slopes of the cone junctions are slightly different from each other. Also the cavities are arranged in such a way that each cavity is followed by a cavity of the other type. To compare with the base case, the slopes of the cone junctions are chosen to be around 30^{o}, for examople, one is 27^{o} (denoted as type I) and the other one is 33^{o} (denoted as type II). The rest parameters are the same as that of the base case. The corresponding result for the effect of the transverse wake field on the beam is given in Figure 7(a) which shows that $|\xi|_{max}$ at z=100 m is brought down to 2.4 from 23 of the base case, i.e, a factor of 9

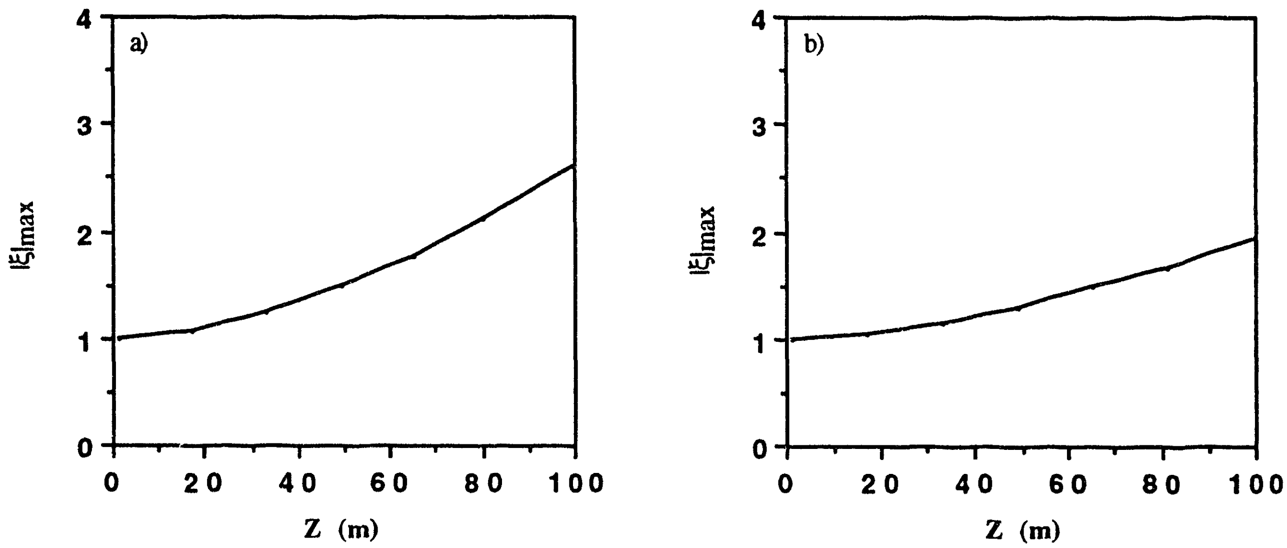


Fig. 7(a) and (b): Spatial evolution of BBU for the staggered tuning scheme that has two slightly different types of cavities with the cavity-iris junction cones being, respectively, (a) 27^{o} and 33^{o}; and (b) 24^{o} and 36^{o}.

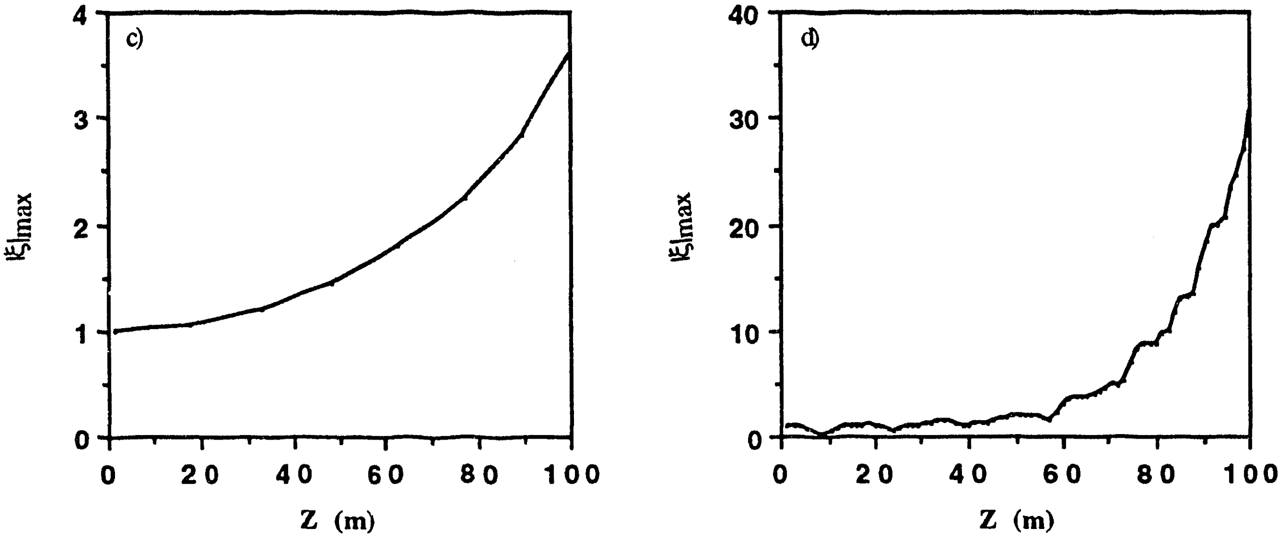
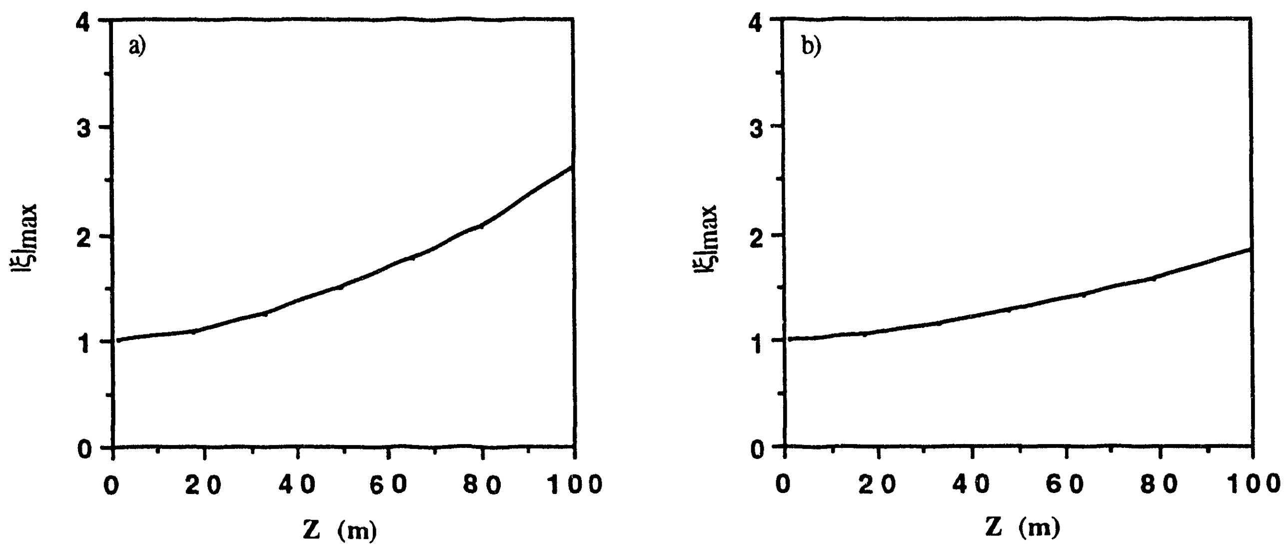


Fig. 7(c) and (d): Spatial evolution of BBU when all the cavities are of (c) type I (27^o); and (d) type II (33^o), respectively.

improvement. A slightly better result is obtained when the slopes of the cones are, respectively, 24^o and 36^o. It is presented in Figure 7(b). The result in Fig. 7(a) is better than that of the case when all the cavities are of type I, as seen in Figure 7(c), in which $|\xi|_{max}$ =3.6 at z=100 m,; while if all the cavities are type II a larger $|\xi|_{max}$ is found to be around 30 at z=100 m, as shown in Figure 7(d). Thus, it can be conceived that the staggered tuning breaks the coherency of the "kicks" from the wake fields generated by cavities of exactly the same configuration and, therefore, significantly reduces the effectiveness of those 'kicks'.

Doubling the number of the types of the cavities from 2 to 4 does not seem to make any significantly improvement on either case, as are shown in Figures 8(a) and (b). Since the staggered tuning scheme significantly reduce the growth rate of the transverse displacement of the electron beam due to the wake fields, the beam may now traverse more cavities without having BBU problem. For example as is shown in Figure 8(c) for the case of four different classes of cavities between 24^o and 36^o, $|\xi|_{max}$ at z=200 m is about 6. This is still an acceptable number since it is normally assumed that the initial offset of the beam due to various reasons is the order of 0.1 mm. Then it is easily calculated that at z=200 m, the maximum transverse shift of the beam is about 0.6 mm which is small compared to the radius of the tubes which is 4 mm.



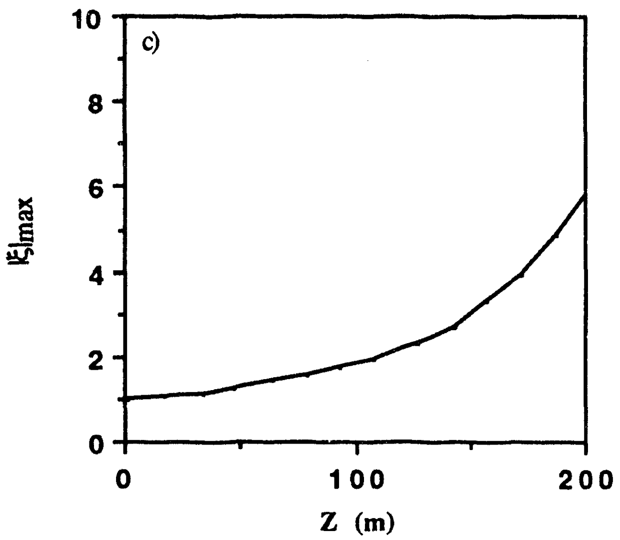


Fig. 8: Spatial evolution of BBU for the staggered tuning scheme that has four slightly different types of cavities with the cavity-iris junction cones being, respectively, (a) 27°, 29°, 31° and 33°; (b) 24°, 28°, 32° and 36°; and (c), which is case (b) but has twice as many cavities.

b) Another version of stagger tuning is that the cavities involved are almost the same except that some of their longitudinal dimensions may be slightly different from each other. The simplest case is that there are only two different types of such cavities and each cavity is followed by a cavity of the other type. For the convenience of comparison we set the longitudinal lengths of these two types of cavities as, respectively, 89 cm and 90.74 cm (one wavelength difference) and other parameters are the same as the base case. The corresponding effect of the wake field on the beam is evaluated and given in Figure 9. It is seen that at z=100 m, $|\xi|_{max}$ is only about 1.5 which is much smaller (a factor of 15) than that of the base case. Therefore, this is a quite effective scheme.

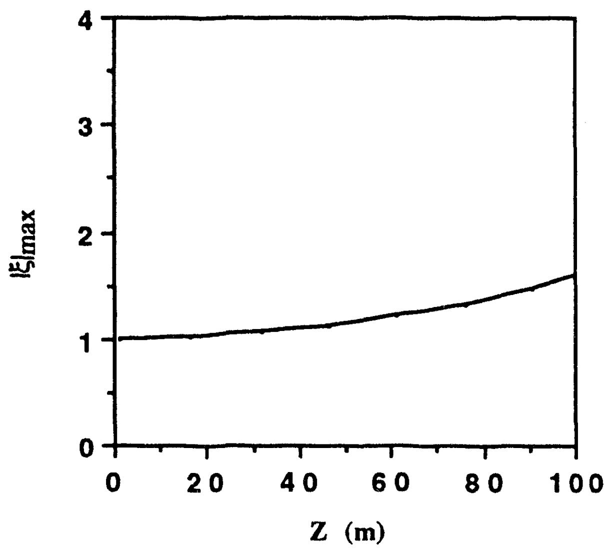


Fig. 9: Spatial evolution of BBU for the case of scheme that has two classes of cavities with slightly different longitudinal dimmensions.

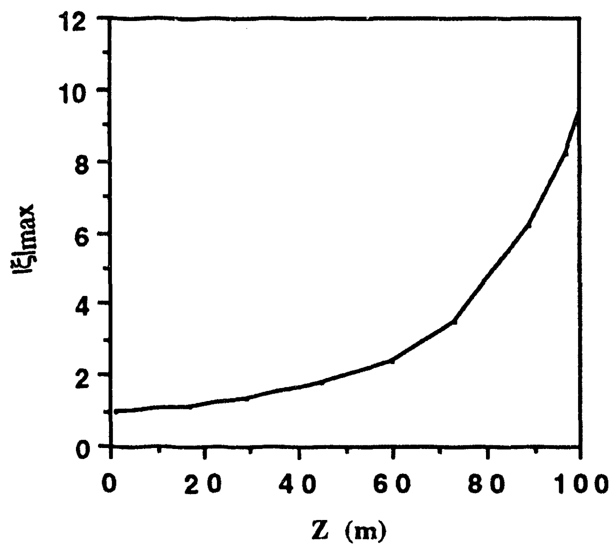


Fig. 10: Spatial evolution of BBU for the staggered tuning cavities with unsymmetric junction cones. In this case, one is 27° and the other one is 33°.

There are some other schemes that may also reduce the BBU. One of them is to use unsymmetric cones for the junctions on a cavity instead of symmetric ones. For example take one as 24^{o} and the other one as 33^{o}. The corresponding BBU result is given in Figure 10. It is seen that the reduction on BBU is only about a factor of two better than that of the base case, which indicates that the scheme is not so effective as staggered tuning.

6. SUMMARY

In this study, we explore and examine several schemes to search for those that can both effectively suppress the beam break-up and at the same time have minimum effect on the microwave generation processes inside the rf cavities for a SWFEL/TBA. The results show that using cavities with gradual slope cone junctions and cavity staggered tuning are the two most promising schemes and the best result may be obtained by combining these two schemes together. Although the numbers in the simulation results may vary when new factors are taken into account they do provide at least a qualitative measure of the effectiveness of the different schemes. In a future study, we will examine these schemes for a more realistic model by including the wiggler motions of the electrons. We are also going to examine BBU in rectangular cavities which seem to possess more merits than their cylindrical counterparts.

7. ACKNOWLEDGMENTS

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