LBL-35323
UC-414

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

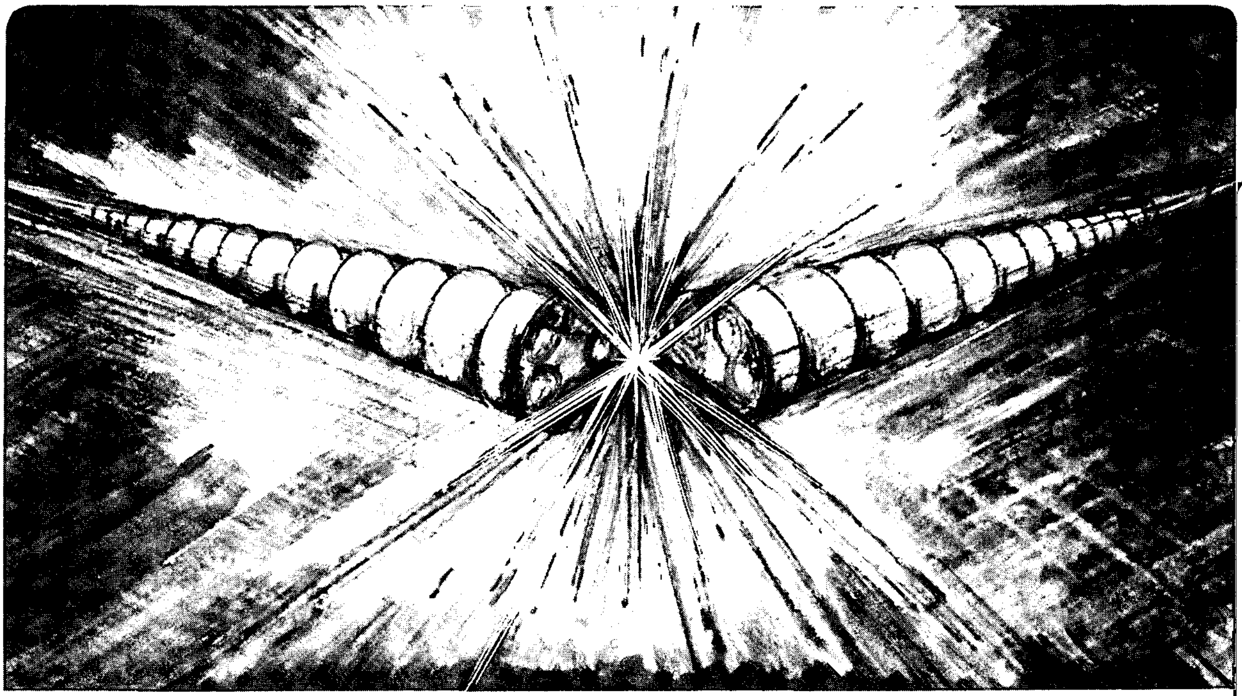
Accelerator & Fusion Research Division

Presented at the SPIE International Symposium on Laser Engineering,
Los Angeles, CA, January 22–29, 1994, and to be published
in the Proceedings

Design Consideration of Relativistic Klystron Two-Beam Accelerator for Suppression of Beam-Break-Up

H. Li, T.L. Houck S. Yu, and N. Goofeney

March 1994



Prepared for the U.S. Department of Energy under Contract Number DE-AC03-76SF00098

Design Consideration of Relativistic Klystron Two-Beam Accelerator for Suppression of Beam-Break-Up*

H. Li, S. Yu and N. Goffeney

Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720

T. L. Houck

Lawrence Livermore National Laboratory, University of California,
Livermore, CA 94550

January 1994

* Work supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, Division of High Energy Physics, of the U.S. Department of Energy, under Contract No. DE-AC03-SF-00098 at Lawrence Berkeley Laboratory and under Contract No. W-7405-ENG-48 at Lawrence Livermore National Laboratory.

LBL # 35323
UC 414
CBP 71

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 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

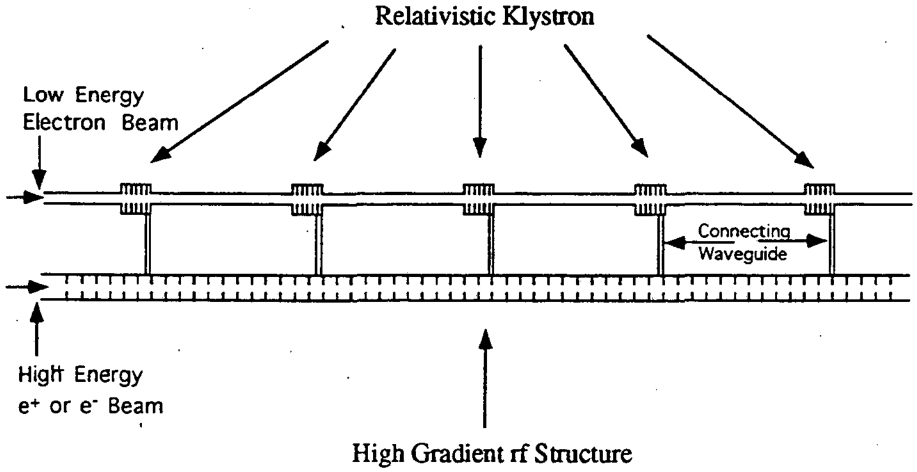


Fig. 1. Schematic diagram of RK-TBA

---

* The work was performed under the auspices of the U.S. Department of Energy, Division of Nuclear and High Energy Physics, under contract No. W-7405-ENG-48 at Lawrence Livermore National Laboratory and under contract No. DE-AC03-SF-00098 at Lawrence Berkeley Laboratory.

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

Table 1 Some latest parameters for SLAC's concept of 1 TeV linear collider

RF frequency of main linac (GHz)	11.4
Accelerating gradient (MV/m)	100
Pulse length (ns)	250
Section length L (m)	1.8
RF power per section (MW)	350

section of RK-TWS and we use 10 MeV, 600 A drive beam (300 ns pulse length planned) the efficiency of such a system (beam to rf) should be around 85%. The challenge in designing such a system is to suppress the transverse instabilities resulting from the propagation of the above high current, low energy beam through the narrow apertures of x-band microwave structures[3], especially for a long distance, 200 meters in this case. The instabilities are due to excited transverse wake fields of dipole and/or higher order modes. In the RK-TBA drive beam, we encounter both the regenerative as well as the cumulative beam breakup instabilities. The first one is due to coupling between cells within individual traveling-wave structures. This one is more dangerous, but with sufficient damping its threshold current can be raised above that of the drive beam.[3] The second one is due to cumulative growth of beam displacement from wake fields over a sequence of RK structures. Although it is less threatening within short distance, if unsuppressed, it can grow to an untolerable level for a long device (such as RK-TBA), pushing the beam to iris walls, and resulting in loss of beam.

The issue of transverse instabilities in a RK-TBA has been addressed and studied in a recent paper by Houck[4]. It was shown that with sufficient damping, e.g., the de-Q-ing technique used at LLNL[5], the onset of violent regenerative BBU can be prevented. It was also found that for the set of parameters of the TWS that are currently being tested at LLNL with the use of modest de-Q-ing in conjunction with staggered tuning or inclusion of effect of phase mixing damping under a fairly strong magnetic focusing field ($B_z=8\ KG$) the number of TWS that the electron beam can traverse before scraping the irises is less than 25 which is far from enough for an efficient RK-TBA. Using stronger de-Q-ing and/or stronger staggered tuning may further increase the practical number of rf structures in a RK-TBA, but both of them have limitations. Therefore, it is necessary to find additional scheme(s) that can also suppress the BBU so that when all the above schemes combined together they can keep BBU in a RK-TBA to a controlable level.

In this study we carry out numerical simulation examining a particular scheme that potentially can reduce significantly the growth of transverse instabilities on the electron beam in a RK-TBA. In this scheme each RK structure, TWS for this study, is placed on a betatron node where the beam crosses the axis, therefore, the kicks the beam receives from the transverse wake fields of the TWS's are the minimum when compared to other locations for the TWS's. For the convenience of latter discussion we call this scheme the "betatron node scheme". It is shown in the simulation that in conjunction with adquate de-Q-ing, appropriate choice of geometries for the RK structures (reducing transverse impedence) and/or staggered tuning the "betatron node scheme" is able to suppress the overall growth of the BBU to around 4 e-fold for the latest proposed RK-TBA with 200 rf extraction cavities. Within the context of the "betatron node scheme" we have examined the effect of varying transverse impedence of TWS, Q-factor of individual cells, as well as detuning. These studies will form the basis for further cost optimizations of RK-TBA schemes.

2. NUMERICAL MODELING AND BETATRON NODE SCHEME

2.1 Numerical modeling

The numerical modeling in this study is basically adopted from Reference 4. In the following we give a brief description on the modeling for the convenience of later discussion. For further detailed explanation on the modeling please refer Ref. 4.

In this study we use the Beam Breakup (BBU) Code[6] developed at LLNL to numerically explore schemes that can suppress the transverse instability in a microwave generator comprised of many equally spaced traveling-wave structures (TWS). The BBU Code assumes that a single dipole cavity mode is dominant and the x-polarization of the electric field in the n^{th} cavity can be expressed as

$$\vec{E}_n(\vec{r},t) = f_n(t)\,\vec{\xi}_n(\vec{r})\,e^{i\omega t}, \tag{1}$$

where $\vec{\xi}_n$ denotes an eigenmode with eigenfrequency ω_n, ω denotes a characteristic frequency of the generator assumed near the transverse instability resonance. It is possible to show that the excitation amplitudes f_n are governed by the following circuit equations:

$$\begin{aligned} &\frac{\partial^2 f_n}{\partial t^2} + \left(\frac{\omega_n}{Q_n} - 2i\omega\right)\frac{\partial f_n}{\partial t} + \left(\omega_n^2 - \omega^2 - \frac{i\omega\omega_n}{Q_n}\right) f_n = \\ &K_n^{n-1} f_{n-1} + K_n^{n+1} f_{n+1} + \frac{\omega_n^3}{\varepsilon c^2}\left(\frac{Z_\perp}{Q}\right)_n \frac{\partial Ix}{\partial t}\, e^{-i(\omega t + \phi_n)}, \end{aligned} \tag{2}$$

where Q_n is the quality factor of the n^{th} cavity, $K_n^{n\pm1}$ denotes the coupling of the n and n±1 cavities, I is the current, x is the transverse displacement of the beam centroid in the x direction from the center line, ϕ is a phase advance, and $Z_\perp$ is the transverse impedance. A second equation is used for the y-polarization as well as single particle equations of motion in the x and y directions. There are several features in the BBU Code necessary for modeling a realistic structure:

a. RF structures are treated as separate entities with specific rf properties, and they have a finite longitudinal length;
b. Electromagnetic coupling can exist between adjacent rf cavities to allow the effect of regenerative BBU to be modeled.

2.2 Betatron node scheme

In a RK-TBA the electron beam that drives the RK traveling wave structures (TWS) performs betatron oscillation along the axis of the structures due to the magnetic focusing field. The beam experiences transverse kicks from wake fields only when it is inside the TWS. The further the centroid of the beam is away from the axis when it is inside the TWS the harder the kicks are, and therefore the larger the transverse beam displacement is resulted. In this study we designe a scheme to avoid the above situation and minimize the effect of the wake fields on the beam. The scheme is illustrated in Figure 2. The basic idea is to place each TWS on a betatron node where the beam crosses the axis and therefore, ideally should receive almost no kicks from the transverse wake fields (not entirely zero since a TWS has finite dimension), which would significantly reduce the BBU growth. We call this scheme the "betatron node scheme" for the convience of latter discussion. The numerical results presented in section 4 are obtained within the context of the "betatron node scheme".

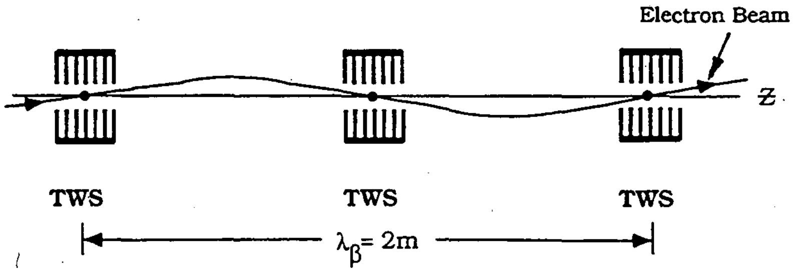


Fig. 2 Schematic diagram of "betatron node scheme"

3. NUMERICAL RESULTS

We now examine the BBU for the new design parameters of RK-TBA under the "betatron node scheme". Our objective is to find out if in conjunction with adquate damping (de-Q-ing) as well as reasonable small transverse impedence for the cells (Zp/Q) the "betatron noe scheme" is able to keep the BBU to a tolerable level for an electron beam traversing 200 TWS's, one section of RK-TBA. The main parameters that are used in our numerical simulation are given in Table 2. TWS's are spaced by 1 meter

TABLE 2.
TWS Modeling Parameters in Simulations

dipole mode	lower "HEM_{11} branch"
frequency (GHz)	13.6
# cells per TWS	6
TWS electrical length	5.2626 cm
cell aperture (mm)	14 ,
group velocity	0.14c,
Q_{wall} (cells)	3000 (2), 7000 (4)
Q_{ext} (damped cells)	10
$Z_{\perp}/Q_{wall}$	5 Ω/cell
TWS spacing	100 cm (center to center)
dc currents	600 amps
pulse length	100 ns
beam energy	10 MeV
initial offset	10^{-7} (normalized)
solenoidal field (B_z)	2.2029 KG

and magnetic field $B_z \approx 2.2$KG. All six cells within each of TWS are de-Q-ed (Q=10) and Zp/Q per cell is 5 (experiments at LLNL have indicated that Zp/Q < 10 per cell is possible). The simulation result is presented in Figure 3. It shows that the growth of BBU is fairly slow and at the end of 200 structures the overall growth is only around 4 e-fold, which is an acceptable number.

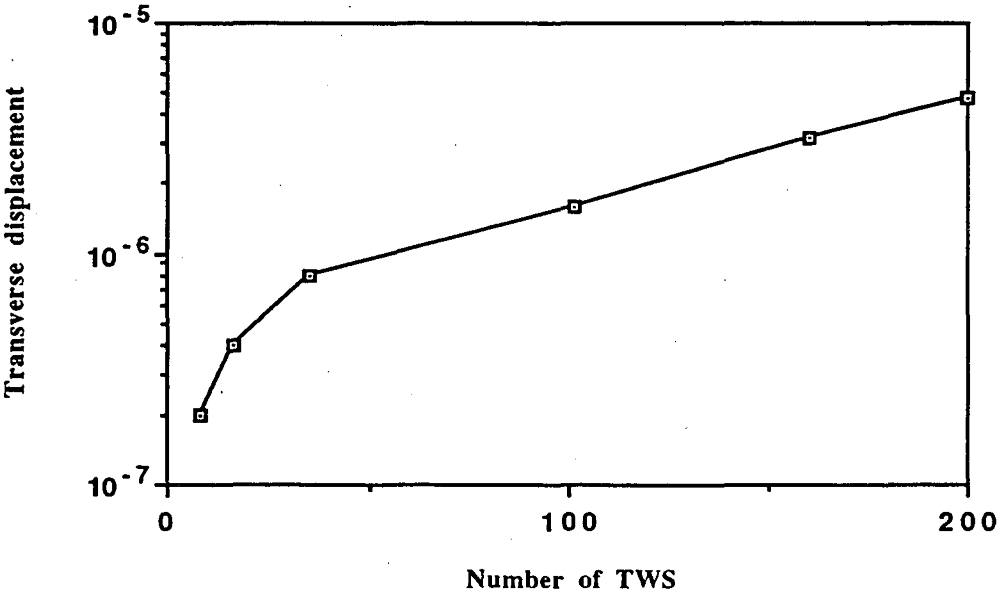


Fig. 3 BBU growth versus number of TWS under "betatron node scheme" for a RK-TBA with 10 MeV, 600 A drive beam with $Z_p/Q=5$ and Q=10 for each of six cells of a TWS.

Figure 4 show evolution of the transverse displacements of the beam centroid at two TWS's. It is seen that the growth of the centroid features convective instability. Also the portion of the envelope that is diplaced from the axis mainly concentrates within a narrow region and is also fairly close to the front of the pulse. Even at the 200th TWS, the maximum displacement of the envelope is still within 50 ns. Thus, our simulation results for the 100 ns pulse can also be applied to the corresponding cases of a 300 ns pulse, i. e., the pulse length proposed for the latest RK-TBA.

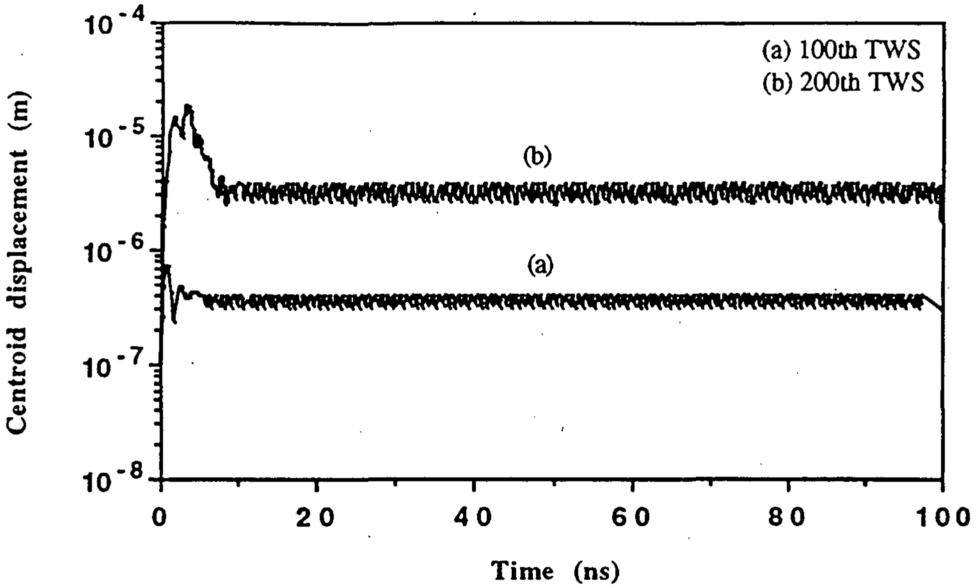


Fig. 4 Centroid displacement of the beam for Fig. 3 at (a) 100th TWS, and (b) 200th TWS

3.2 Various parameter studies

In the following, we examine the effects of varying magnetic field, staggered tuning and Q-factor of individual cells. These studies serve to have better understanding on the scheme and form the basis for further cost optimizations of RK-TBA schemes.

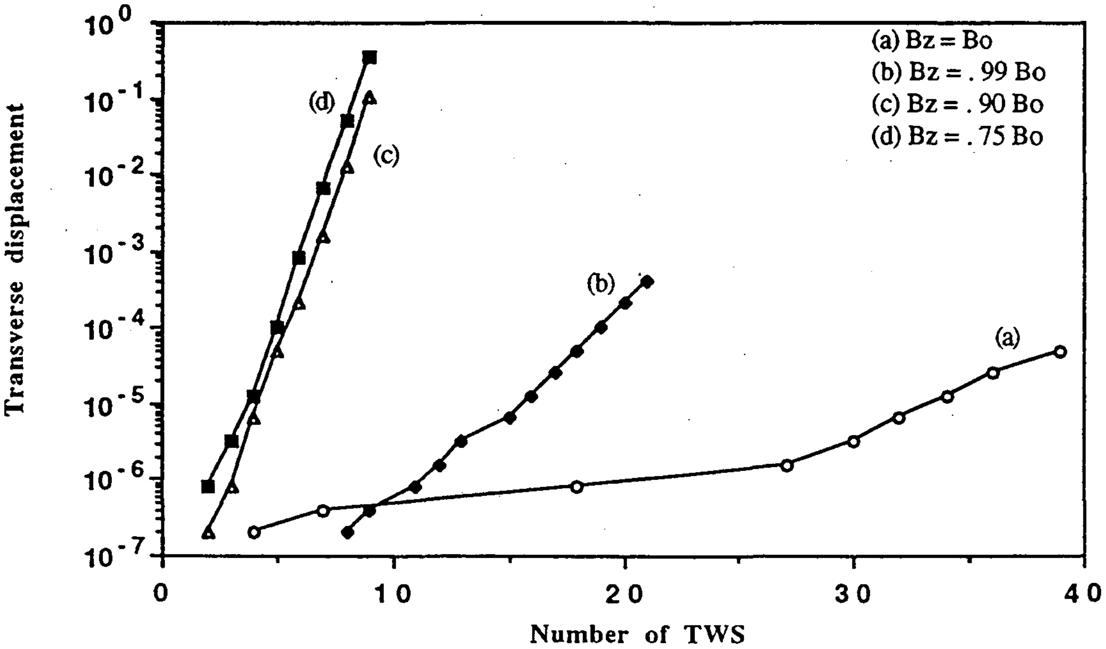


Fig. 5 BBU growth versus number of TWS for different magnetic field values (20MeV, 1.2kA beam with Z_p/Q=10 per cell and Q_i (i=1-6) the base case)

3.2.1 Sensitivity to magnetic field:

Figure 5 gives a comparison of BBU growths for four cases which corresponds to locating TWS's at four different places with respect to the betatron nodes. It is seen that when all the TWS's are located on the nodes (a) the growth is significantly slower than the other three cases when TWS's are off the nodes by (b) $\lambda_\beta/100$, (c) $\lambda_\beta/10$ and (d) $\lambda_\beta/4$. Case (d) corresponds to the worst case when the structures are located on the anti-nodes where the beam reaches the peaks of its betatron oscillation. All the measurements are taken at the TWS's where the restriction on the transverse dimmension of the beam is the most severe. Looking at curve (a) in Figure 5, we may find that the BBU growth has two regimes, the first one features a slow and relatively flat growth (call it "plateau") and the second one shows a faster, exponential growth. The slow growth feature is unique for the "betatron node scheme" while the exponential growth one shared by all four cases. It is believed that the "take off" of the fast growth for the case of the "betatron node scheme" is due to phase slippages of the nodes of the beam with respect to the TWS's. This phase slippages are likely caused by the perturbations of the wake fields on the beam. It is seen that for one case, case (b), when B_z is just *1%* less than the exact (B_0) value after 8 structures's cumulation of phase slippage the exponential growth takes off. Of course this is somewhat differnt from the case when B_z is at the exact value. The situation there is little bit more complicated and the exponential growth is also slower than that of not on-node cases. Fig. 5 shows that the "betatron node scheme" is very sensitive to the phases of the nodes (with respect to the center of the structures). To make it work on a real device we can use feedback technique to correct the phase slippage so that the growth of the BBU effect can be kept on the "plateau" regime for more TWS's.

3.2.2 Staggered tuning:

varying the structures along the beam line we can shift the frequency of the dipole mode and decoherence the kicks from the wake fields to the beam, which reduces the BBU. This is the so called staggered tuning technique. General speaking, staggered tuning costs less than de-Q-ing, therefore, from the economical point of view we want to apply this technique and relax the number of cells that needs to be de-Q-ed. To illustrate the effect of the staggered tuning on the BBU we present in Figure 6 a comparison between a case with staggered tuning and the correponding one without. For the first case 5 different configurations of TWS's are used (frequencies (GHz): 13.75, 13.675, 13.6, 13.525; cell apertures (mm): 13.45;13, 13.5, 14, 15, 16; group velocities: 0.12 c, 0.13c, 0.14c, 0.15c, 0.16c), the spread on the dipole frequency is about 2.%.

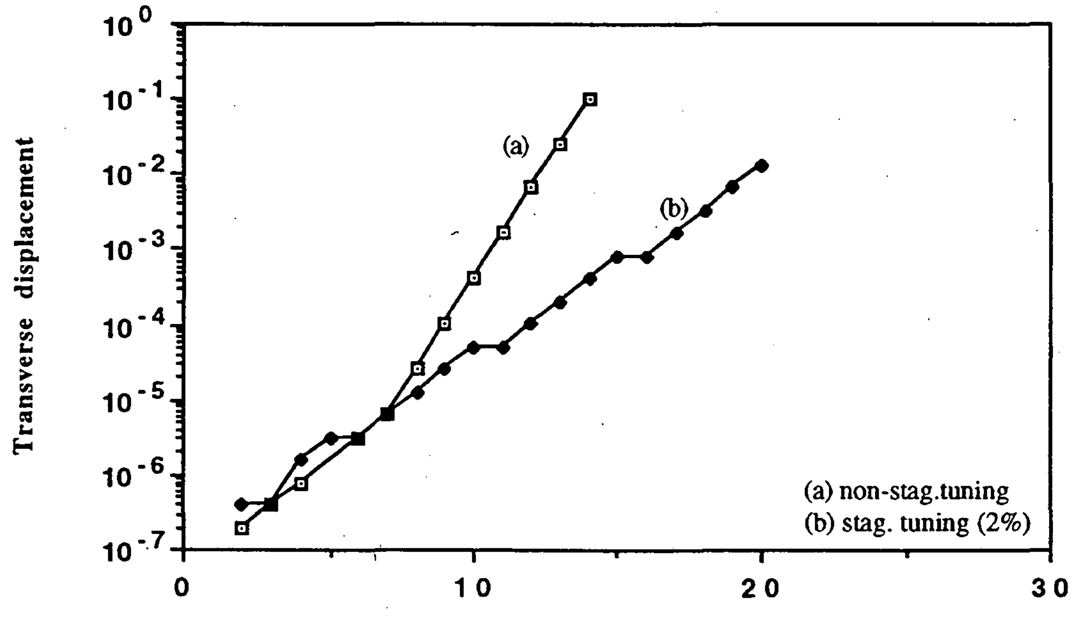


Fig. 6 BBU growth versus number of TWS for both with and without staggered tuning cases (20MeV, 1.2kA beam with Z_p/Q=40 per cell and Q_i (i=1-6) the base case).

3.2.3 Location of unde-Q-ed cell(s):

If not all the cells are de-Q-ed the location(s) of unde-Q-ed cell(s) can also make a lot of difference on the growth of BBU. Take as an example one case in which five out of six cells of each TWS are de-Q-ed ($Q=10$) and one is not ($Q=10^9$). It is found that when the unde-Q-ed cell is located at the middle of the structure the BBU growth stays in the slow growth regime (so called "plateau") about three times as long as that of the case when it is located close to the end of the structure, as is shown in Figure 7. Therefore, it is possible that by choosing the locations of unde-Q-ed cell(§) wisely we may be able to reduce the number of cells that needs to be de-Q-ed.

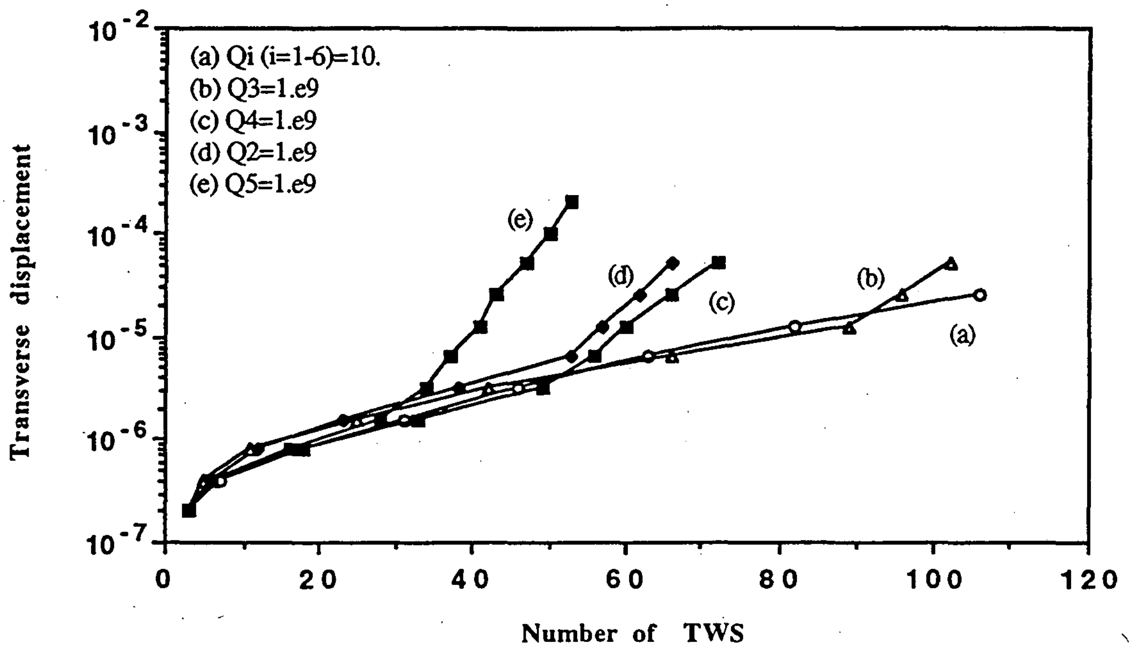


Fig. 7 BBU growth versus number of TWS for different locations of the unde-Q-ed cell. (20MeV, 1.2kA beam with $Z_p/Q=20$ per cell).

4. SUMMARY

It is found in the this simulation study that by placing the relativistic klystron traveling wave structures on the betatron nodes, in conjunction with adquate 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-fold for the new design of RK-TBA.

5. ACKNOWLEDGMENT

The authors would like to thank A. Sessler and G. Westenskow for many helpful discussions and thank S. Vanecek for preparing some of the figures.

6. REFERENCE

1. G. M. Fiorentini, C. Wang, and T. L. Houck, "Design of a Reacceleration Experiment Using the Choppertron", Presented at the *SPIE'.s International Symposia on Laser Engineering, Los Angeles, CA, January 16-23, 1993,* to be published in the Proceedings.

2. T.L. Houck and G.A. Westenskow, "Status of theChoppertron Experiments," *Proc. 16th Int'l LINAC Conf.*, Aug , 1992, pp. 498-500.

3. G.A. Westenskow, et. al., "Transverse Instabilities in a Relativistic Klystron Two-Beam Accelerator," *Proc. 16th Int'l LINAC Conf.*, Aug, 1992, pp.263-267.

4. T. H. Houck, "Design Study of a Microwave Driver for a Relativistic Klystron Two-Beam Accelerator", *1993 Particle Accelerator Conference*, Washington D. C., May 17-20, 1993, to be published in the Proceedings.

5. Haimson and B. Mecklenburg, "Suppression of beam induced pulse shortening ...," *SPIE Vol. 1629 Intense Microwave and Part. Beams III* (1992), pp. 209-219.

6. T.L. Houck, et. al., "BBU Code Development for High-Power Microwave Generators," *Proc. 16th Int'l LINAC Conference,* Aug, 1992, pp. 495-497.