A feasibility study for manufacturing of the wake-compensated detuned accelerator tube with the brazing and dimpling method

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Abstract

Global linear collider, GLC project[1] have to be an epoch to open the new horizon of the particle physics. To obtain a large luminosity in GLC, the low emittance beam is one of the most important feature. In this article, we discuss the detuned method on the S-band acceleration tube for GLC pre-linac to preserve the beam emittance. The manufacturing of the tube with the standard dimpling method is also considered.

INTRODUCTION

In the high-energy physics, the collider based on a storage ring has been a most powerful tool. It is considered, however, that LEP at CERN would be the last ring based collider because of the synchrotron radiation loss that diverges as forth-order of the beam energy. GLC can break the energy limit of the ring collider because of no synchrotron radiation. On the other hand, GLC may have a difficulty on the luminosity, since the beam pass the interaction region only once.

Large luminosity on LC can be taken with extremely low emittance beam. Since there is no convergence effect on the emittance in the linac, it is important to preserve it during the acceleration. The main phenomena to spoil the beam emittance is transverse kick by the beam induced dipole mode in the accelerator tube, wake field.

Let us assume the leading particle with charge q travels in a cylindrically symmetrical structure with a displacement from the center axis, a_0. The field observed by a witness particle delayed with time t from the leading particle, $F(t)$ is expressed as $qa_0W(t)$, where $W(t)$ is the wake field. The wake field in a accelerating tube is expressed as the sum of the each cell's contributions as;

$$W(t) = \sum_{i=1}^{N} 2\left(\frac{k_i c}{\omega_i a_i^2}\right) \sin\omega_i t, \qquad (1)$$

where N is the number of cells in a tube, k_i is loss parameter given by,

$$k_i = \left(\frac{R_i}{Q_i}\right)\frac{\omega_i}{4}, \qquad (2)$$

R_i and Q_i are the shunt impedance and the quality factor for the dipole modes, c is speed of light, ω_i is frequency of the dipole mode, and a is iris radius of the cell. The shunt impedance is defined along an axis parallel to the center axis, at the iris edge.

There are three methods to compensate the wake field, damping, detune, and the hybrid. Here we employ the detuned method because the dimpling frequency tuning, that is a popular way to manufacture the tube, can not be used with the damping method.

In the detuned method, the cell geometry is varied so that the accelerating modes are kept and the dipole modes are spread widely. If the infinite number of dipole modes are distributed as a Gaussian shape, the sum of them becomes

$$W(t) = \left(\frac{\bar{k}c}{\bar{\omega}\bar{a}^2}\right)\sin(\bar{\omega}t)\exp\left(-\bar{\omega}\sigma_{sf}t\right), \qquad (3)$$

where the variables with bars mean its average over the tube, σ_{sf} is the sigma of the Gaussian distribution. This equation means the wake is “damped” quickly by the exponential term. This effect can be explained as the cancellation among the dipole modes, so that the sum of the wake looks small, but it is not damped at all.

In a reality, the number of modes is finite, so that the cancellation is not perfect. After some period, the detuned modes are re-synchronized and the amplitude of the sum grows up again like FM wave.

If the modes are distributed linearly, the damping speed is much slower than that with Gaussian, but the re-synchronization is slow too. The wake function is

$$W(t) = \left(\frac{\bar{k}c}{\bar{\omega}\bar{a}^2}\right)\sin(\bar{\omega}t)\frac{\sin(\bar{\omega}t\sigma_{sf}/2)}{\sin(\bar{\omega}t\sigma_{sf}/2N)}, \qquad (4)$$

the last term shows the slow damping.

In GLC, the beam is accelerated in 195 bunches in a train with 1.4 or 2.8 ns spacing. If the sinusoidal oscillation term of the wake field synchronizes with the bunch spacing, the wake felt by the beam could be much lower than its envelope. This Bunch spacing Harmonized Detuned Structure, BHDS originally proposed by Bane[2].

DESIGN

Cell geometry was determined by MAFIA 2.5 dimension eigen mode solver. Because the solution depends on the mesh size in MAFIA calculation, the final value was obtained with the extrapolation toward the zero mesh size.

The phase advance per cell on the acceleration mode was set to $3/4\pi$ to decrease the group velocity. The cell radius, b was determined giving 2856 MHz resonant frequency at $3/4\pi$ phase advance for the various $iris$ radius, a as shown in Figure 1.

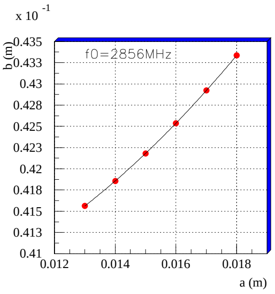

Figure 1: Cell radius b as function of iris radius a for 2856MHz $3/4\pi$ mode cells.

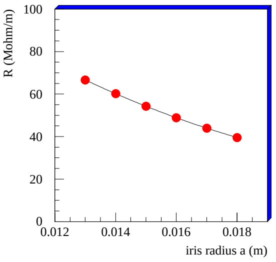

Figure 2: Shunt impedance per unit as function of iris radius a for 2856MHz $3/4\pi$ mode cells.

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33. There are still an ambiguity to determine the tube design; which a should be used. In the conventional design of accelerator tubes, there are two styles to determine the series; constant impedance, CI and constant gradient, CG. On the detuned tube, as are distributed so that the wake field is compensated. The design procedure of the detuned tube is similar to CG, but the purpose is different.

The dipole mode driven by the beam is a synchronous mode to the light. To obtain this synchronous frequency, we have to model the dispersion curve of the dipole mode. Since the lowest dipole mode is strongly coupled to the second dipole mode[3], the actual mode is a mixed state of the two modes. It can be modeled by the equivalent circuit as fllows;

$$\left(\frac{1+\eta\cos\phi}{f_0^2}-\frac{1}{f^2}\right)\left(\frac{1-\hat{\eta}\cos\phi}{\hat{f_0}^2}-\frac{1}{f^2}\right)-\frac{\eta\hat{\eta}}{f_0^2\hat{f_0}^2}\sin^2\phi=0, \quad (5)$$

where η and $\hat{\eta}$ are the band width for TE and TM modes, f_0 and $\hat{f_0}$ are the fundamental mode frequencies for TE and TM modes, ψ and f are the phase advance per cell and the frequency of the oscillating mode respectively. The cross term can be vanished with $\psi = 0$ or π. In that case, the modes are isolated and the formulas becomes independent. η, $\hat{\eta}$,f_0, and $\hat{f_0}$ are then determined from the mode frequencies at $\psi = 0$ and π respectively. Once the parameters are determined, the dispersion curve is drawn by Eq. 5. The cross point of the curve and the light line corresponds to the synchronous mode.

The wake for a whole tube are obtained by Eq. 1. The synchronous dipole mode frequency is evaluated assuming an infinite series of the identical cells. Eq. 1 means that the dipole mode behavior in an actual tube is same as this ideal case. In a real tube, the next cell's geometry is slightly different. This calculation ignores this small difference. Even the difference is small, the impact to the final result could be large. This is one of the next issues.

From the wake function, the beam averaged wake S_{Nb} for a beam train is calculated as follows;

$$S_{Nb}=\sum_{i=1}^{N_b}\frac{W(\Delta t(i+1))}{N_b}, \quad (6)$$

where N_b is number of bunches in a train, Δt is the bunch spacing in time. If the oscillation period of the wake function $W(t)$ is harmonized with the bunch spacing, the averaged wake S_{Nb} is minimized. Other words, the tube geometry is optimized to minimize the averaged wake.

As mentioned, we employ the linear detuning. The linear detuning is parameterized the initial point a_1, the end point a_2, and the tilt parameter, α. The tilt parameter α is defined as $(n_1 - n_2)/(n_1 + n_2)$ where n_1 and n_2 are the mode densities at a_1 and a_2 respectively. n_1 and n_2 can be expressed as $n_1 = \frac{1+\alpha}{a_2-a_1}$ and $n_2 = \frac{1-\alpha}{a_2-a_1}$, so the mode distribution is determined identically with the three parameters.

If some a_1 is taken, a_2 is naturally determined giving the mean dipole frequency harmonized with the bunch spacing. The purpose of α is the compensation of the a dependence of the loss parameter. There is some optimum value of α for given a_1 and a_2 pair. The initial choice on a_1 fixes the size of the detuning. The size of the detuning determined the damping speed on the wake, but the speed is not critical for this harmonized detuning. Therefore, there is some ambiguity on the a_1 selection. This time, a_1 is set to make the tube semi-CG behavior, i.e. the field gradient along the tube becomes constant.

Table 1: Specifications of the designed tube. The acceleration is estimated without beam-loading.

item	value
Number of cells	76
Total length	3m
Phase advance	$3/4\pi$
First iris radius	0.017044 m
v_g	0.044 c
Last iris radius	0.015850 m
v_g	0.035 c
Tilt parameter α	0.035
Total acceleration	60.25 MV @ 100MW input
Highest field	20.38 MV/m
Lowest field	19.89 MV/m

According to these procedures, a S-band tube is designed. The total length is set to 3m that is limited by size of the brazing oven. The phase advance per cell was set to $3/4\pi$ to decrease the group velocity of the accelerating mode because the tube optimized for the lowest wake function was organized with larger as giving higher group velocity. The number of cells in a tube was 76. The specifications were summarized in Table 1. The acceleration is estimated without beam-loading. The field uniformity is nearly 1%. The shunt impedance is $44 - 50M\Omega/m$, but the group velocity is still high due to the large iris radius, $0.035 - 0.044c$ resulting this low acceleration efficiency.

The wake function is calculated according to Eq. 1 for the designed tube. The result is shown in Fig. 3. The horizontal and vertical axes are time in ns and the wake in MV/m^2nC. The wake function is plotted as a curve, but it looks like a shaded area due to its high density. The wake at the beam position (every 1.4ns) is marked as the closed circles. The tolerance on the transverse wake is estimated less than $0.035MV/m^2nC$. All of the points are below the threshold.

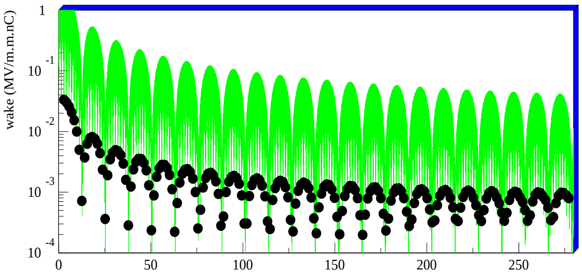

Figure 3: The wake function $W(t)$ for the designed tube as funtion of time t is plotted. The closed circles show the wake where the beam is placed with 1.4 ns spacing. All circles are positioned below the threshold, $0.035MV/m^2nC$

MANUFACTURING

In the previous section, it is demonstrated that the designed tube fits to the GLC requirement. It is a human nature that a question arises; is it difficult to manufacture it?

The tolerance on the averaged wake against errors were examined. The random error corresponds to the machining error and the systematic error corresponds to some scale error on the dipole mode frequency like temperature shift, systematic error on the EM simulation were assumed.

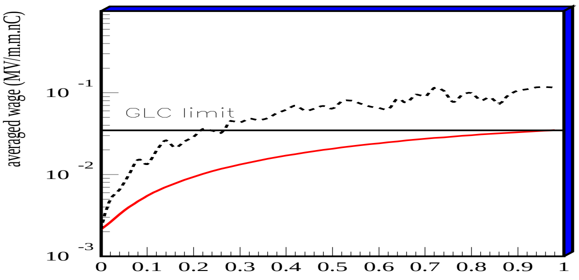

Figure 4: The averaged wake felt by the bunched beam as function of the size of errors on the dipole frequency. The solid and dashed line show those by the systematic error and the random error. The random error more than 0.2 MHz makes it above the threshold, $0.035 MV/m^2nC$, but the averaged wake is kept less than the threshold even with 1 MHz systematic error.

Fig. 4 shows the averaged wake as function of the size of errors. The solid and dashed lines are those with the systematic and random errors respectively. For the systematic error, the dipole frequencies for all cells is shifted toward a same direction with a same size. On the other hand, for the random error, the size and direction of the frequency shift is determined randomly for each cell according to a Gaussian distribution. The size of error means sigma of the Gaussian distribution. One datum was obtained as mean of 100 trials.

From the simulations, the wake does not exceed the tolerance even with the 1MHz systematic shift. On the other hand, more than 0.2 MHz random shift destroys the wake compensation. As the summary, the systematic and random frequency errors on the dipole mode have to be less than 1MHz and 0.2 MHz to keep the detuning respectively.

A conventional method for the accelerating tube manufacturing is the brazing and dimpling. The copper cells are unified by brazing that moves the acceleration mode. The reason is not understood well, but the amount of the drift is about 0.3 MHz. To absorp this drift, the cell is designed slightly lower than the target frequency and adjusted by the dimpling that is a deformation of the cavity wall by an external force.

To examine the feasibility of the brazing method for the detuned tube, we simulated the dimpling with 3D MAFIA eigen mode solver. The absolute frequency resolution is very limited in this 3D code, but only the frequency shift is matter for this study. Using the calculated EM fields of the acceleration and dipole modes, the frequency shift by the dimpling was estimated with the field perturbation method[4]. Fig. 5 and 6 show the frequency shifts(%) of the acceleration and dipole modes as function of the dimpling size respectively. From these plots, the frequency shift on the dipole is roughly 80% of that on the acceleration.

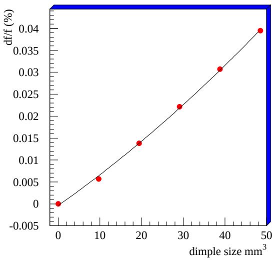

Figure 5: Relative furequency shift of the acceleating mode in % as function of the dimpling size in mm^3. The curve is drawn for $a = 0.016$.

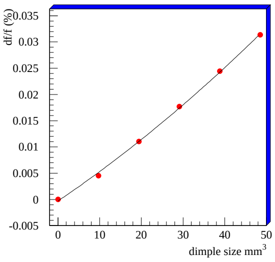

Figure 6: Relative furequency shift of the first dipole π mode in % as function of the dimpling size in mm^3. The curve is drawn for $a = 0.016$.

Including the dimpling effect, the tube is designed once with 2855 MHz acceleration mode frequency. The dipole frequency is also evaluted with this geometry. The dimpling effects for various iris size are parameterized with quadratic curves each for the accelerating mode, first and second dipole modes at $\psi = 0$ and $\psi = \pi$ respectively. The amount of the dimpling is determined for each cell giving +1MHz frequency shift on the accelerating mode. The dipole modes are also shifted for each cell with this dimpling amount according to the dimpling cureves. Using the dispersion curves defined by these dipole modes frequencies, the synchronous frequency for each cell is obtained. The wake is then estimated.

As mentioned already, the frequency shift by the brazing process is about 0.3 MHz. If this shift is made by some deformation on the cavity wall that is equivalent to the dimpling deformation, the dipole mode frequency after the dimpling adjustment is exactly same as expected.

Even this shift is made by some other reason, the random error caused by the brazing process is $0.8\sigma fb$, where σ_{fb} is sigma of distribution of the frequency shift for all cells. The frequency shift by the brazing is distributed around 0.2- 0.3 MHz empiricaly, so the sigma should be much smaller than 0.2 Mhz. By this fact, the detuned tube can be manufactured by the brazing and dimpling method.

SUMMARY

For GLC pre-linac, a wake-compensated S-band acceleration tube with the detuning technique is considered. We designed a tube with $3/4\pi$ phase advance with the detuning wake compensation mechanism. The wake compensation was enough for GLC requrement. The acceleration efficiency is slightly lower, but it can be recovered by the slower v_g cell, e.g. $7/8\pi$. Assuming the estimated tolerances against the random and systematic errors on the dipole frequency, the conventional method, brazing and dimpling, can be applied to manufacture the detuned tube.

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