EMITTANCE-IMPOSED ALIGNMENT AND FREQUENCY TOLERANCES FOR THE TESLA LINEAR COLLIDER

N. Baboi, DESY, Hamburg, Germany and R.M. Jones†, SLAC, Stanford, CA 94309, USA

Abstract

One option in building a future 500 GeV c.m. linear collider is to use superconducting 1.3 GHz 9-cell cavities. However, wakefields excited by the bunch train in the TESLA (TeV-Energy Super Conducting Linear Accelerator) collider can resonantly drive the beam into unstable operation such that a BBU (Beam Break Up) mode results or at the very least significant emittance dilution occurs. The largest kick factors (proportional to the transverse fields which kick the beam off axis) are found in the first three dipole bands and hence multi-bunch emittance growth is mainly determined from these bands. These higher order dipole modes are damped by carefully orientating special couplers placed at both ends of the cavities. We investigate the dilution in the emittance of a beam with a random misalignment of cavities down the complete main linac. The beneficial effects of frequency errors on ameliorating the beam dilution are discussed.

INTRODUCTION

The fundamental consideration in a linear collider is the luminosity of the colliding beams at the interaction point. The luminosity of flat beams is proportional to $L \propto P_b / \sqrt{\varepsilon_{y,n}}$, where $P_b \propto f_{rep} n_b q$ is the beam power and $\varepsilon_{y,n}$ the normalized vertical emittance at the interaction point. For TESLA a high P_b is achieved by compensating the low pulse repetition frequency, f_{rep}, with a high bunch charge q, and a large number of bunches n_b. In order to maximize the luminosity it is however also important to minimize the vertical emittance.

As the highly charged bunches traverse the linac any misalignment in the structure, focusing magnets, or initial offset in the leading bunch, gives rise to wakes [1] which dilute the emittance and the beam may break up down the linac. This BBU [2] can result from short range wakes over the bunch itself, in which the head drives the tail, or from a long range wake, in which trailing bunches are driven by leading ones and BBU occurs due to the coupled motion of the bunches.

Table 1: Fundamental L-band TESLA RF parameters

Quantity	Symbol	L
Accelerating freq. (GHz.)	f_{acc}	1.300
Loaded gradient (MV/m)	G_{acc}	23.4
Bunch train length (T_{fill})	T_b	2.3
Bunch spacing (T_{RF})	T_{bb}	438
Charge per bunch (10^{10})	N_e	2
Structure Iris radius (λ_{RF})	A	0.15
Bunch length (μm)	σ_z	300
Pulse rate	f_{rep}	5

We investigate the emittance dilution due to the long-range wakefield left behind accelerated bunches in the main linacs of the TESLA collider [3,4]. RF parameters for the linacs of this L-band collider are given in Table 1. For the TESLA design, as the cavities are superconducting, the losses are minimal and the fill time and the length of the train of particle bunches can be very long. For this reason 2820 bunches are in the charged particle train, which is 950 μs long. Each cavity consists of 9 cells, operating in the standing wave mode and with a π phase advance per cell. A typical 9-cell cavity structure is illustrated in Fig. 1. There will be close to 21,000 of these cavities in the collider.

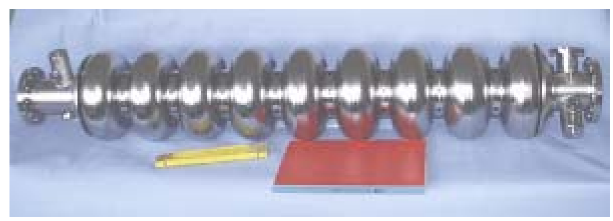

Figure 1: Fabricated nine-cell niobium TESLA cavity.

In this paper, due to space considerations, we concern ourselves entirely with how the emittance of the beam is diluted due to misaligned accelerator cavities. However, we refer the interested reader to [5] for an analysis of the impact on emittance dilution of a beam injected offset from the axis of the accelerator.

This paper is organized in two main sections. The following section describes the transverse wakefields calculated from numerically evaluated kick factors, and measured Qs and synchronous frequencies. The second section investigates the alignment tolerances that are allowable for a specified emittance dilution.

TRANSVERSE WAKEFIELDS

For the TESLA cavities, there are no more than a few modes that interact strongly with the beam in the first three pass-bands. Using HOM couplers attached to the beam pipe at either side of each cavity, the Q of these modes is reduced from the order of 10^9 to below 10^5. Measurements made in the majority of cavities built to date indicate this damping level is achieved. Fig. 2 shows the Qs and kick factors [6] of the dipole modes. It is clear that only a few modes have appreciable kick factors. The frequencies and quality factors given here are results from

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measurements of 36 cavities made in the single-cavity test setup [7].

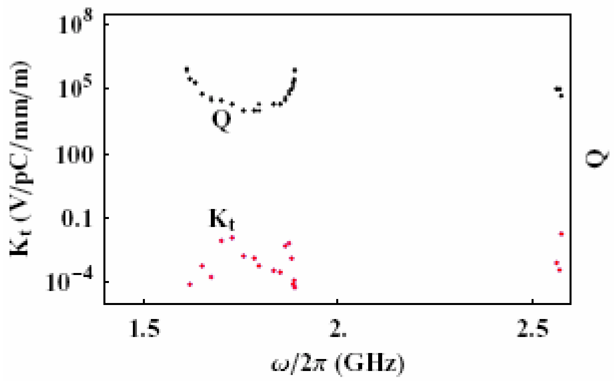

Figure 2: Calculated transverse kick factors and measured Q values for TESLA accelerating cavities.

The envelope of the long-range transverse wakefield, a distance s behind the first bunch, is calculated from the absolute value of the modal sum:

$$\hat{W}(s) = 2\left|\sum_{n=1}^{N} K_n e^{i\omega_n s/c} e^{-\omega_n s/2Q_n c}\right|, \quad (1)$$

where N is the number of modes, the n^{th} mode has a quality factor of Q_n, a kick factor K_n and a synchronous frequency $\omega_n/2\pi$. The envelope of the wakefield obtained from applying Eq. (1) is illustrated in Fig. 3. The characteristic 'e-folding' length ($=2cQ_n/\omega_n$) for a mode with Q ~ 10^5 is ~ 6.4 km and at this distance

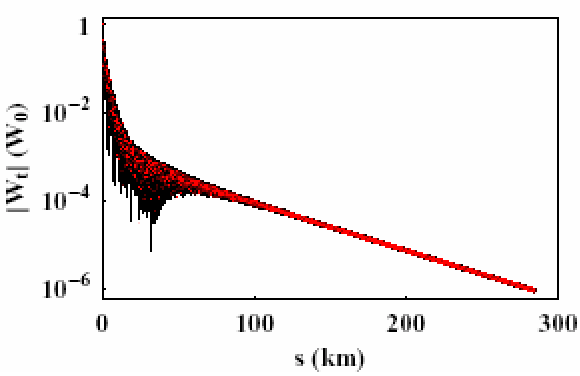

Figure 3: Envelope of the TESLA transverse wakefield. The abscissa runs over the distance of the complete bunch train. The ordinate has been normalized with respect to W_0, (0.11V/pC/mm/m). The red dots indicate the location of the individual bunches.

the mode has decayed by 63 %. However, up until 6.4 km there are ~ 65 bunches and thus we would expect significant emittance dilution to occur if no action is taken to prevent the resonant build-up of the wake.

We investigate the impact of this wakefield on the emittance dilution of a beam traversing a linac composed of randomly misaligned accelerator structures in the next section.

MISALIGNMENT TOLERANCES

Introduction

In the process of fabricating the collider, accelerating cavities of length approximately 1 meter must be aligned with respect to each other in order to prevent significant emittance dilution occurring over the 14 km of the entire L-band linac. In order to assess the impact of the long-range transverse wakefield on the emittance of the beam we track the progress of the beam down the linac using MAFIA-L [8] allowing random transverse cavity misalignments with an RMS value of 500 µm.

The results of such a tracking simulation with no frequency errors included in the simulation are illustrated in Fig 4. The abscissa used in Fig. 4 is the percentage change in the bunch spacing and this corresponds to a systematic error in the frequencies of all accelerating cavities. At the nominal bunch spacing of 337 ns ($\Delta s_b/s_b = 0$) the emittance dilution is appreciable as it is of the order of 10^3 %. There is a peak value of $9.7\cdot10^5$ % in

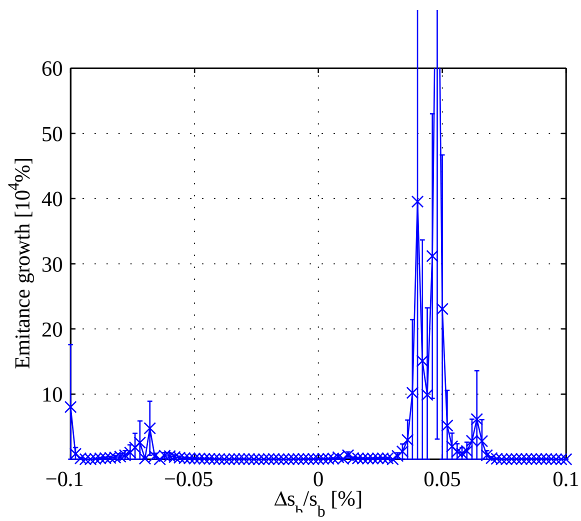

Figure 4: Percentage emittance dilution down the linac for randomly misaligned cavities with an RMS value of 500 µm. versus $\Delta s_b/s_b$, the percentage change in the bunch spacing.

the emittance dilution at $\Delta s_b/s_b \approx 0.05$ % (corresponding to a systematic shift in the frequencies of all cavities of the order of 800 kHz).

Clearly these emittance dilutions are disturbingly large. However, in the fabrication of the collider small errors in the dimensions of the cavities lead to small errors in the dipole frequencies of the cavities. These frequency errors will be randomly distributed throughout the entire linac and they will randomize the overall kick that the beam receives. It is anticipated that these errors will reduce the emittance dilution significantly.

The effectiveness of such frequency errors in reducing the emittance dilution to acceptable values is investigated in the following section.

Fabrication Errors

In the process of fabricating several thousand accelerating cavities, frequency errors will be an unavoidable part of the manufacturing process. The effect of these errors on the emittance growth for misalignments of 100 μm, 500 μm and 1 mm is illustrated in Fig. 5. For

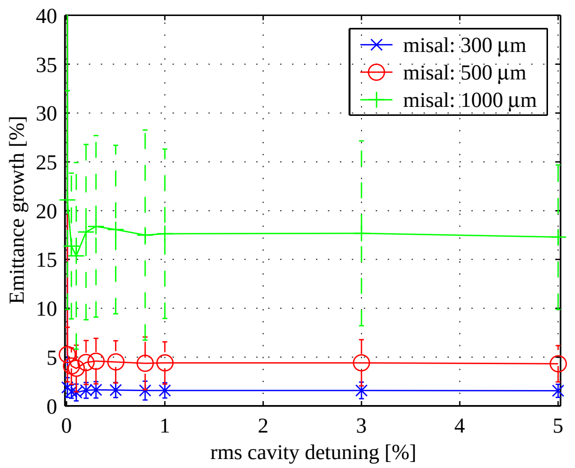

Figure 5: Percentage emittance growth versus the RMS value of the random frequency detuning (expressed as a percentage of the unperturbed dipole frequencies). Three random misalignment cases are illustrated.

the design specification of 500 μm RMS misalignment one sees that even a small frequency error of 0.01% (~200 kHz) has a remarkably beneficial effect, reducing the beam emittance from 10^3 % to about 5 %, and the high peak in Fig. 4 ($\Delta s_b/s_b \approx 0.05$ %) to about 12 % (not shown in Fig. 5).

It is also important to point out that the emittance dilution is rather independent of the degree of random

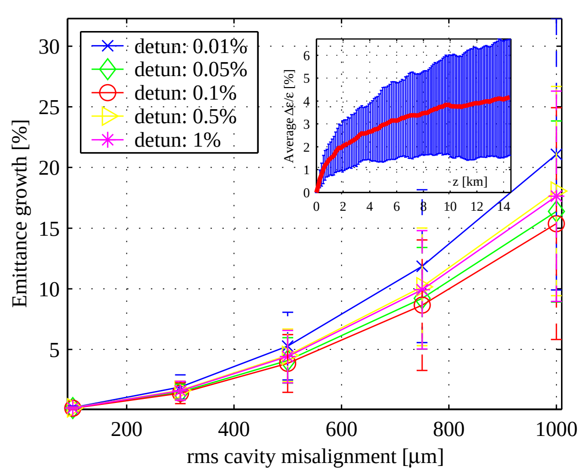

Figure 6: Percentage emittance growth versus the RMS value of the random cavity misalignment for a wide range of frequency detuning errors. Shown inset is the percentage emittance dilution down the linac for RMS random misalignment tolerance of 500 μm and a 1 % frequency detuning error. The red curve in the inset represents the mean emittance dilution along the main linac taken over 80 samples.

detuning of the HOM frequencies. Indeed, for the middle curve in Fig. 5 the dilution stays between 4.2 % and 5.1 % for detuning between 0.01 % and 5 %. This shows that the RMS values of the frequency spread measured in TTF cavities, between 0.05% and 0.45%, depending on the mode, will reduce the emittance dilution markedly.

Thus, only a small frequency detuning error is required to make a dramatic improvement in the emittance dilution. This is further testified to in Fig. 6, where the emittance dilution is illustrated versus the RMS value of the random cavity misalignment. For the example given, a RMS random offset of 700 μm the dilution in the emittance of the beam is kept below 10 % for an RMS frequency detuning error as small as 0.01 % (~ 200 kHz). The inset to Fig. 6 shows the emittance dilution down the linac for the TESLA baseline design case in which the cavities are allowed an RMS misalignment offset of 500 μm and an RMS frequency detuning error of 0.1 %. The mean emittance dilution taken over 80 machines reaches a maximum of 4 % at the end of the linac.

In conclusion, a large dilution in the emittance of the beam in the TESLA linac will occur for cavities constructed with no random frequency errors. However, in reality random frequency errors will occur as a natural consequence of the fabrication process and thus rather loose transverse misalignment tolerance are allowable. In particular, a misalignment tolerance of 0.5 mm with a 0.1 % RMS detuning of cavity frequencies restricts the emittance dilution to less than 6 %. For convenience the crucial alignment tolerances are collected in Table 2.

Table 2: Percentage emittance dilution for various misalignment tolerances. The standard error of the sampled mean is also given.

RMS Frequency Detuning (%)	RMS Misalignment (μm)		
	100	500	1000
0	47.2±53.6	1180±1339	4721±5357
0.01	0.20±0.11	5.12±2.77	20.47±11.08
0.05	0.17±0.08	4.20±2.07	16.80±8.29
0.1	0.17±0.10	4.18±2.53	16.71±10.12
0.2	0.18±0.08	4.38±2.02	17.51±8.08
0.3	0.18±0.09	4.55±2.30	18.19±9.21
0.5	0.19±0.10	4.68±2.44	18.71±9.74
0.8	0.18±0.10	4.58±2.41	18.31±9.66
1.0	0.17±0.08	4.20±2.00	16.79±8.01
3.0	0.18±0.09	4.42±2.32	17.66±9.29
5.0	0.19±0.08	4.67±2.11	18.66±8.44

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