Emittance preservation in TESLA

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The main approaches to the emittance preservation in TeV Energy Superconducting Linear Accelerator (TESLA) are given. The study includes the beam emittance dilution in main linac caused by static misalignments of the machine components and uncontroled injection jitter. The corresponding correction procedure contsists of particle autophasing, non-dispersive beam bumps and beam based alignment technique to control the emittance dilution is presented.

1. Introduction

Emittance preservation in the main linac of a future linear collider is one of the basic problems to be solved to achieve design luminosity of the colliding beams. The emittance dilution can be uncorrelated with longitudinal position in the bunch due to initial uncorrelated energy spread, and correlated with longitudinal position in the bunch due to excited wakefields in accelerating structures.

An important feature of the 1.3 GHz TESLA linac [1] is that the wakefields excited in the cavities that scale with frequency like ω^2 for longitudinal and ω^3 for transverse wake functions and thus are very weak. This allows to avoid the resonant beam blow-up caused by transverse wakefields and keep the emittance dilution along the linac at the level of a few percent. In addition, the weak transverse wakefields allow to increase the number of accelerating sections per FODO cell and to reduce the phase advance per cell to 60 degree, thus decreasing the dispersive emittance dilution of the beam far below the beam filamentation. An important consequence of such a cell arrangement is that in TESLA the autophasing can be performed easily to reduce the emittance dilution caused by uncontroled injection jitter.

In this paper we give an overview of the emittance control procedure in TESLA main linac. The procedure includes the application of beam based trajectory correction[2] and the beam bump technique [3] to control emittance dilution caused by static misalignment of quadrupoles and accelerating sections. The autophasing solution is added to avoid the correlated emittance growth and reduction of the luminosity due to beam-beam effect[4]. The TESLA main linac is divided into two parts: from 5 to 125 GeV each FODO cell contains four accelerator modules with cell length of 65 m and from 125 to 500 GeV each FODO cell contains six accelerator modules with cell length of 96m. The nominal module consists of twelve 9-cell cavities. Two modules in FODO cell contain a quadrupole, steering coils and a BPM.

Table I TESLA tolerances

Uncorrelated energy spread σ_0	2.5%
Cavity misalignment y_c [mm]	0.3
Module misalignment y_m [mm]	0.2
Quadrupole misalignment y_q [mm]	0.3
BPM's misalignment y_b [mm]	0.2
BPM's resolution y_r [μ m]	10

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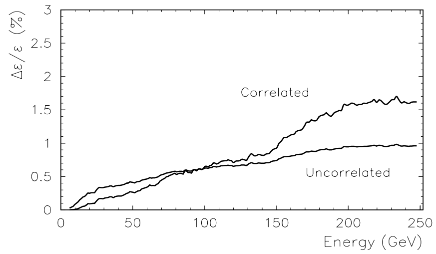

Figure 1: Correlated and uncorrelated emittance dilution along the linac after multi-stage DF correction.

2. Multi-layer beam based trajectory correction

The choice of the trajectory correction procedure for TESLA was based on the requirement that uncorrelated dispersive emittance dilution should be avoided and that the trajectory should be kept at the level of the BPM resolution. The technique that has been applied for this purpose was the dispersion free (DF) trajectory correction [2] performed by multi-stage steering algorithm along the entire linac to avoid the drift of the corrected orbit [5]. In DF correction technique the misalignments are deduced from BPM measurements with different beam trajectories. The two different trajectories in TESLA are produced by running the linac with 90 and nominal 60 degree of the phase advance per cell. The difference orbit is independent of the BPM misalignments and the amplitude of the difference orbit could be reduced at the level of the BPM precision errors. However, the errors add up and the real trajectory drifts along the linac. The minimization of the difference orbit in N independent stages along the linac reduces the trajectory drift by a factor of $N^{1/2}$ and the residual rms drift is given by

$$\sigma_t(n) \sim \left(1 - \frac{\mu_1}{\mu_2}\right)^{-1} \sigma_r k_1^2 D^2 \frac{n^{3/2}}{N^{1/2}}, \tag{1}$$

where μ_1, μ_2 are the phase advances per cell for the two runs, σ_r is the rms BPM resolution, k_1 is the nominal betatron wave number, D is the quadrupole spacing and n is the number of quadrupoles. The real trajectories still diverge from the linac centerline and the information about the absolute trajectory should be included while correcting the difference orbit. The two trajectory corrections algorithm for TESLA has been studied numerically using a multi-stage trajectory correction. A least square fit for the unknown dipole corrector strengths has been performed, using the original TESLA trajectory and the difference orbit weighted with the absolute accuracy with which these trajectories are known [2]. The trajectory correction has been applied by using an iterative procedure, in which the DF-algorithm is applied to sections of 20 FODO cell per step with overlaping of successive linac sections over 15 FODO cells. The total number of steps to correct the trajectory along the entire linac is 40. The resulting drift of the orbit at the end of the linac is at the level of 100 μm. The dispersive emittance growth obtained by averaging over 50 random sets of misalignment amounts to 1%. The residual orbit deviations after the DF-correction yield an additional emittance growth due to transverse wakefields of 2% (Fig.1).

3. Accelerator sections misalignment

A good analytical prediction of the emittance dilution in linac with misaligned accelerator sections and weak transverse wakefields can be obtained in two-particle model of the beam. For the constant beta lattice and taking into account the correlation between accelerator sections, the relative emittance growth is given by

$$\frac{\Delta\varepsilon(z)}{\varepsilon} = 2\frac{\sigma_c^2}{\varepsilon_0} C_w^2 \frac{\Delta\gamma}{\gamma_0} \frac{L_{cell}}{\mu \sin\mu} \frac{sin^2(\mu_c/2)}{\mu_c} \ln\frac{\gamma(z)}{\gamma_0} \tag{2}$$

where $C_w = QW_D/4G$, σ_c is the rms cavity misalignment, ε_0 is the initial absolute vertical emittance of the beam, Q is the bunch charge, W_D is the dipole wake potential at two sigma, G is the

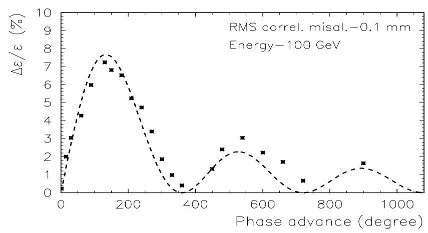

Figure 2: The simulation (star) and analytical prediction (solid line) of emittance growth from cavity misalignment correlation.

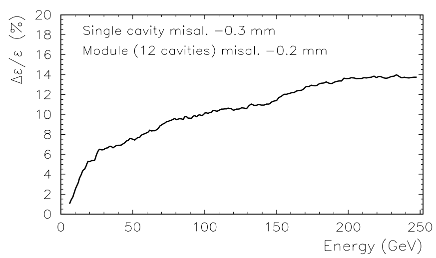

Figure 3: Emittance dilution due to TESLA cavities and modules misalignment averaged over 50 random sets.

acceleration gradient, γ_0, γ initial and actual particle Lorenz factor, L_{cell} is the FODO cell length, μ is the phase advance per cell and μ_c is the phase advance per cavities correlation length. Fig.2 shows the result of particle tracking simulations of emittance growth in TESLA main linac at 100 GeV for different correlation length (betatron phase advance) of misaligned cavities with rms offset 0.1mm. The analytical prediction (solid line) is in good agreement with tracking simulation. The maximum emittance growth is for the betatron phase advance per correlation length about 130 degree, which for TESLA case is about 104 cavities. The reference line in the TESLA tunnel will be kept at the level of $20\mu m$ vertical over a distance of more than half betatron wavelength, so the emittance growth will be below 0.3% over the entire linac. However the individual cavities in a module have random rms errors of 0.3 mm. Each group of 12 cavities in a module has a correlated rms alignment tolerance of 0.2 mm. The emittance growth over the entire linac with those realistic alignment errors of accelerator sections is shown in Fig3. The correction procedure to reduce the emittance enlargement due to the cavity misalignment is based on trajectory deflection by the non-dispersive (ND) bumps[3]. The emittance is measured at the end of the linac in the beam delivery system and the magnitude of the bumps adjusted until the emittance reaches a minimum. An individual ND bump extends over 5 quadrupole/dipole sets, starting at a focusing quadrupole. The simulation results for one selected set of misalignment show that optimal bumps for the emittance control are the single bumps with opposite polarities located at the positions with particle energy of 57 and 151 GeV. Fig.4 shows the reduction of the emittance enlargement with adjusted bumps for this particular bad random seed of cavity misalignment.

4. Free Coherent Oscillation

It is well known, that the particle autophasing regime can be provided if the focusing lattice is scaled along the linac via the betatron function or phase advance per cell with an additional requirement to actual correlated energy spread in the bunch. For the TESLA almost constant beta lattice, there is a simple solution for the autophasing condition with an initial correlated energy spread[6]. The initial correlated energy spread is induced at the beginning of the linac by acceleration of the bunch behind the crest of the radio-frequency wave. Fig. 5 (bottom, solid line) shows the vertical emittance enlargement along the main linac of TESLA due to short range wakefields, when the bunch performs coherent betatron oscillations with two sigma initial offset (jitter 30 μm). For TESLA the autophasing regime requires an initial rms correlated energy spread

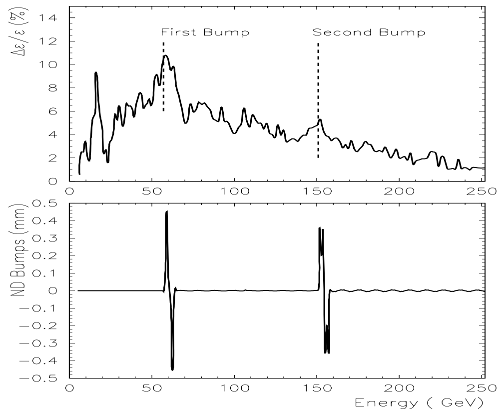

Figure 4: The ND Bumps and the reduction of the emittance dilution by cavity misalignment.

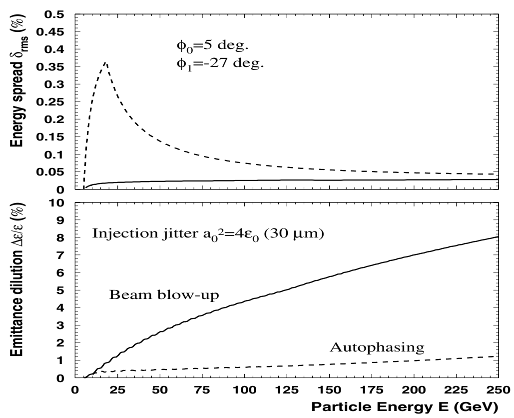

Figure 5: Particle transverse autophasing in TESLA.

of about 1.42%. If the autophasing regime is started at an energy $E \sim kE_0$, the required negative correlated energy spread is reduced by a factor of k and can be reached by acceleration of the bunch at a negative RF phase. For the TESLA design this is accomplished by accelerating the bunch in the first twelve FODO cells at the RF phase $\phi_1 = -27$ degree with an acceleration gradient $G = 19.6\ MV/m$. The final energy is reduced by 1.48 GeV, which is 0.6% for the 250 GeV beam energy. Starting from the 13'th FODO cell the RF phase is switched to $\phi_0 = 5$ degree that provides a small correlated energy spread (of the order of $\delta_{rms} = 3 \cdot 10^{-4}$) in the high energy part of the linac. The correlated energy variation along the linac is then as shown in Fig. 5 (top, dashed line). Starting from the energy $E = 17.2$ GeV, the condition for an exact autophasing regime is satisfied and hence a damping of the emittance enlargement is observed as clearly shown in Fig. 5 (bottom, dashed line). Since we expect the bunch orbit oscillation amplitudes due to injection errors, quadrupole vibrations and HOM to be in the range of 0.5-1 sigma, the single bunch correlated emittance growth from this source will be safety below 1%.

SUMMARY

The main aspects of the emittance degradation in the TESLA main linac, including the correction algorithm, have been studied. It has been shown, that an application of well established corrections techniques, like autophasing for coherent beam oscillations and non-dispersive bumps for cavity misalignment, reduces the emittance dilution of the beam caused by transverse wakefields to the level of 1-2 percent. A special study has been performed on the application of the dispersion free correction algorithm for the linac with misaligned quadrupoles. A multi-stage DF correction algorithm has been developed to minimize the deviation of the absolute beam trajectories from the linac centerline that results to emittance control also at the level of 1-2 percents.

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