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Abstract

The main obstacle to emittance preservation in the main linac of a linear collider is the alignment of the quadrupoles and accelerating cavities with respect to the beam. The misalignment tolerances in the case of the TESLA superconducting main linac are reviewed. Simulations of possible beam-based alignment algorithms to meet these tolerances are presented.

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BEAM-BASED ALIGNMENT OF THE TESLA MAIN LINAC

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Abstract

The main obstacle to emittance preservation in the main linac of a linear collider is the alignment of the quadrupoles and accelerating cavities with respect to the beam. The misalignment tolerances in the case of the TESLA superconducting main linac are reviewed. Simulations of possible beam-based alignment algorithms to meet these tolerances are presented.

1 INTRODUCTION

In order to achieve luminosity in excess of $10^{34}\mathrm{cm}^{-2}\mathrm{sec}^{-1}$, future linear colliders will need to generate beams with normalized vertical emittances of 20 nm or smaller, and effectively preserve the small vertical emittance through bunch compressor, linear accelerator, and beam delivery systems. In the main linac, the principal sources of emittance dilution are typically misalignment of components with respect to the beam: misaligned quadrupoles introduce unwanted dispersion, misaligned accelerating cavities produce deflections due to transverse wakefields, and cavities which are pitched relative to the accelerator survey line introduce time-varying transverse deflections.

We consider the case of the TESLA main linac, which uses superconducting accelerating cavities to achieve 500 GeV in the center of mass, and would deliver a luminosity in excess of $3 \times 10^{34}\mathrm{cm}^{-2}\mathrm{sec}^{-1}$.

2 TESLA MAIN LINAC

The TESLA main linac is 14.3 km in length, and contains 10,296 superconducting 9-cell cavities at 1.3 GHz frequency. The cavities are arranged in cryomodules, with 12 cavities per module. There are 355 superconducting quadrupoles in the linac: the quads are installed in special RF cryomodules, with 1 quad per 2 cryomodules for the first half of the linac and 1 quad per 3 cryomodules for the second half; this results in 65 m and 97 m cell lengths, respectively, in the two halves of the linac. The betatron phase advance per cell is 60° throughout the main linac. Each quadrupole is accompanied by a beam position monitor (BPM) and a vertical steering dipole; each horizontally-focusing quad also has a horizontal steering dipole.

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The TESLA configuration considered here introduces a correlated energy spread for BNS damping [1] by placing the beam 27 degrees behind the RF crest in the upstream portion of the linac; for the remainder, the beam is 5 degrees ahead of the crest. The initial, uncorrelated energy spread from the TESLA bunch compressor is 3%. With all cavities operating at their nominal gradient of 23.4 MeV/m, the main linac accelerates the nominal TESLA beam (charge of 2×10^{10}, RMS length of 0.3 mm) from 4.6 GeV to 251.3 GeV. Figure 1 shows the betatron function and RMS energy spread along the main linac.

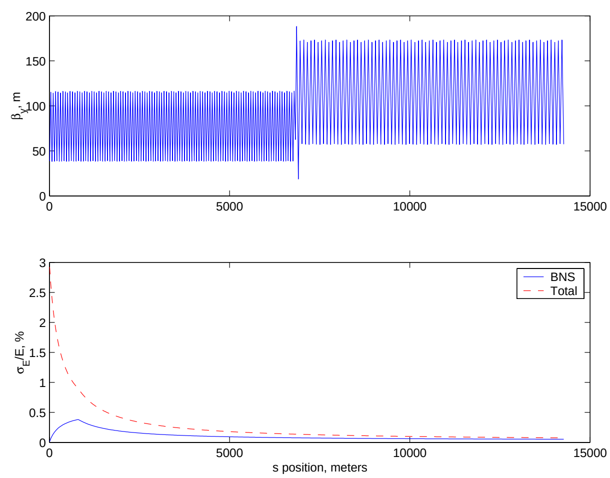

Figure 1: Vertical betatron function (top) and RMS energy spread (bottom) in the TESLA main linac; both the BNS energy spread (blue, solid) and the total energy spread (red, dashed) are shown.

3 MISALIGNMENT SENSITIVITIES

We considered the sensitivity of the TESLA main linac to three classes of misalignment: beam-to-quadrupole offsets, beam-to-cavity offsets, and cavity pitch angle with respect to the accelerator axis. For each class of misalignment, the LIAR (LInear Accelerator Research) program [2] was used to introduce the desired misalignments and estimate the emittance dilution.

It is important to note that the concept of "single-source sensitivity" is somewhat illusory, since misaligned elements introduce beam oscillations that, in turn, introduce emittance dilution from other sources than that intended.

For the purposes of this study, this effect was mitigated by instructing the simulation program to "move" elements to the beam axis; in this way, RF cavity offsets (for example) could be eliminated when studying beam-to-quad offsets. The results of the simulations of beam-to-quad offset, beam-to-structure offset, and structure pitch angle are shown in Figure 2. The TESLA tolerance for emittance growth from all sources between the damping ring and the IP is 50%, also shown.

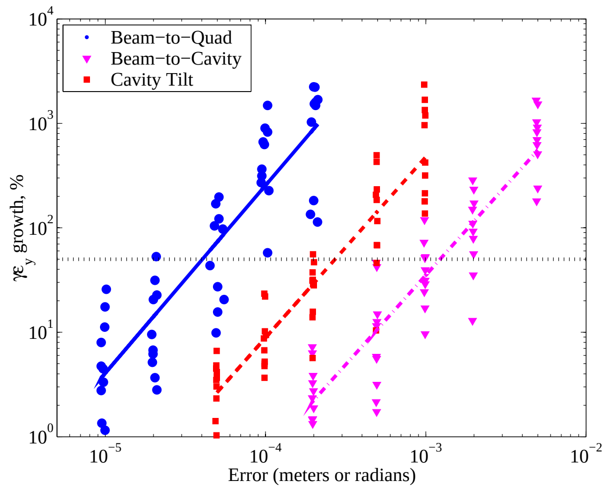

Figure 2: Sensitivity of TESLA main linac to beam-to-quad misalignments (blue circles), beam-to-cavity misalignments (pink triangles), cavity pitch angle (red squares). Lines show approximate fits to data. TESLA sitewide tolerance for emittance dilution also shown (black dotted line).

Figure 2 shows that the misalignment of the quadrupoles with respect to the beam has the most severe tolerance in the TESLA linac, with 50 micrometer RMS offsets resulting in 50% emittance growth. Beam-to-cavity misalignments, by contrast, are far less significant: 1 mm RMS beam-to-cavity offsets are required to achieve emittance dilution figures comparable to 50 micrometer beam-to-quad offsets. RF cavity pitch angles of 300 microradians will also result in comparable emittance dilutions. It is interesting to note that the source of emittance dilution in the latter case is not the "classical" source (time-varying transverse deflections); rather, it is the dispersion from the deflection acting on the energy spread in the beam.

Another factor which is important to the estimation of emittance dilutions is the correlation, if any, in cavity misalignments. For N consecutive cavities which have equal misalignment with respect to the beam, emittance dilution will grow with $N^{1/2}$, as long as the total length occupied by the N cavities is less than one-half the betatron wavelength; for longer regions of correlated misalignment the emittance growth is again reduced. For the first half of the TESLA main linac, the relevant distance is approximately 100 meters, or 72 cavities. This implies that, while 1 mm uncorrelated beam-to-cavity offsets result in 50% emittance dilution, for 100 m correlation length offsets of 85 micrometers will produce the same emittance dilution. In order to prevent such a situation, the TESLA tunnel alignment fiducials will be surveyed with 20 micrometer accuracy over 100 meters of tunnel length.

4 SIMULATIONS OF BEAM-BASED ALIGNMENT

In order to simulate the process of tuning the emittance in the TESLA main linac, uncorrelated *ab initio* misalignments are introduced, with RMS values shown in Table 1. In addition, a BPM resolution of 10 μm is assumed.

Table 1: RMS *ab initio* misalignment of components in TESLA main linac simulations. All values save cavity pitch are from the Technical Design Report (TDR) [3].

Element	With Respect To	RMS Misalignment
Quads	Cryomodules	0.3 mm
Cavities	Cryomodules	0.3 mm
BPMs	Cryomodules	0.2 mm
Cryomodules	Survey Line	0.2 mm
Cavities	Survey Line	0.2 mrad

The misalignments in Table 1 have been applied to the TESLA linac, and the vertical steering magnets were set to minimize the RMS BPM readings. Over 100 seeds, this resulted in an average emittance dilution of 1940%, with 90% of all seeds below 4390%.

Given that the principal sources of emittance dilution in the linac are dispersion (specifically, beam-to-quad offsets and cavity pitch angles), a sensible algorithm for emittance minimization is Dispersion-Free Steering (DFS) [4]. The DFS algorithm used here divides the linac into regions of 20 FODO cells, where each region overlaps each of the neighboring regions by 10 cells. Energy variation is achieved by switching off cavities upstream of the region until the energy at the start of the region is reduced by 20% or 18 GeV, whichever is less. A set of corrector settings is generated which simultaneously minimizes the on- to off-energy orbit change and the BPM readings for on-energy operation, with the former weighed approximately 20 times more important than the latter. Each region is steered twice before the next region is steered. It should be noted that this algorithm is unlike previous ones considered for TESLA in that only the energy gain upstream of the region to be steered is varied. Previous algorithms have varied the strength of the quadrupoles in the lattice [5] or a combination of the incoming beam energy and the energy gain throughout the accelerator [6]. The algorithm considered here is more conservative in that the elements in the region to be aligned are in their nominal condition.

The algorithm above does not permit alignment of the first few quadrupoles in the linac: there is insufficient energy gain upstream of these quads, and the incoming beam energy is difficult to change. It is therefore assumed that the first three quads are aligned by some other technique, or are engineered in some fashion to permit more accurate alignment to the beam than is possible for the rest of the quads.

Using the same 100 initial error distributions as for the simple steering, the TESLA main linac was first steered flat and then steered with the DFS algorithm described above. The average emittance dilution in this case was 142%, and 90% of all cases were below 315%. Both of these figures are improved by a factor of 14 compared to merely minimizing the BPM readings.

Experience on the Stanford Linear Collider (SLC) has shown that closed orbit bumps can be effectively used to reduce emittance growth in a linac [7]. After completing DFS, we scanned a total of 4 emittance bumps and found the settings of each bump which minimized the beam size on appropriate profile monitors at the end of the linac. Two bumps – one in each betatron phase – were introduced at the upstream end of the linac, and two at the downstream end. Due to an unforeseen error in the algorithm, two out of 100 cases experienced much larger emittance growth after application of bumps than before. Excluding these two cases, the mean emittance growth was 97%, and 90% of all cases experienced emittance growth below 233%. Figure 3 shows the distribution of results for all 3 steering models (BPM minimization, minimization + DFS, minimization + DFS + bumps).

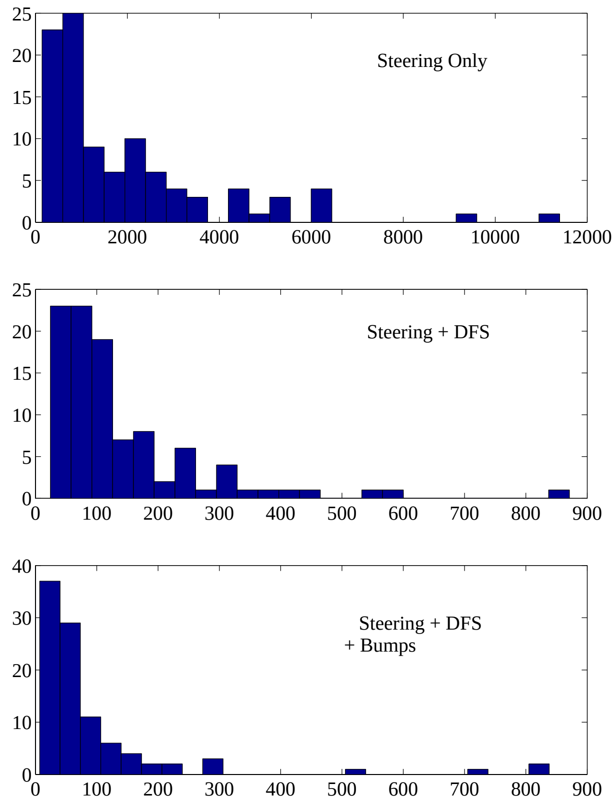

Figure 3: Resulting emittance dilution for 100 seeds of applying misalignments to the TESLA main linac and tuning via 3 algorithms described in the text.

5 CONCLUSIONS AND DISCUSSION

The importance of component alignment in the TESLA main linac has been studied. From the point of view of emittance preservation, the most crucial factor is the alignment of the quadrupoles to the beam axis, where 20 micrometer RMS offsets must be achieved. By contrast, the beam-to-cavity offsets are far less crucial, and 200 micrometer RMS offsets can be tolerated for this parameter. RF cavity pitch angles are moderately important: 100 microradian RMS angles are considered tolerable.

Since the quadrupole alignment tolerance certainly cannot be achieved through mechanical alignment alone, techniques for beam-based alignment of the TESLA main linac were studied. It was found that a combination of conventional steering, dispersion-free steering, and emittance bumps could limit typical emittance dilution to approximately 100%, or 20 nanometers. This is significantly larger emittance dilution than reported elsewhere [5, 6], where alternative DFS algorithms were used.

Although 20 nm emittance growth in a linac is already an impressive result, it is still several times the desired emittance growth for this beamline. There are several possible techniques which are likely to permit additional reduction in emittance growth. It is known, for example, that DFS is moderately sensitive to how the boundaries between regions are handled, and that the DFS technique can introduce dispersion-free oscillations which excite wakefield emittance growth [8]. Furthermore, the bumps used for emittance tuning were likely not optimal for this job, and better design of the bumps could yield substantial improvement. Finally, additional studies have shown that, in the case where the first 100 m of cavities have perfect alignment, the emittance dilution after DFS is only 1/3 as large as in the study discussed above; this indicates the disproportionate importance of the upstream end of the TESLA linac in emittance preservation.

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