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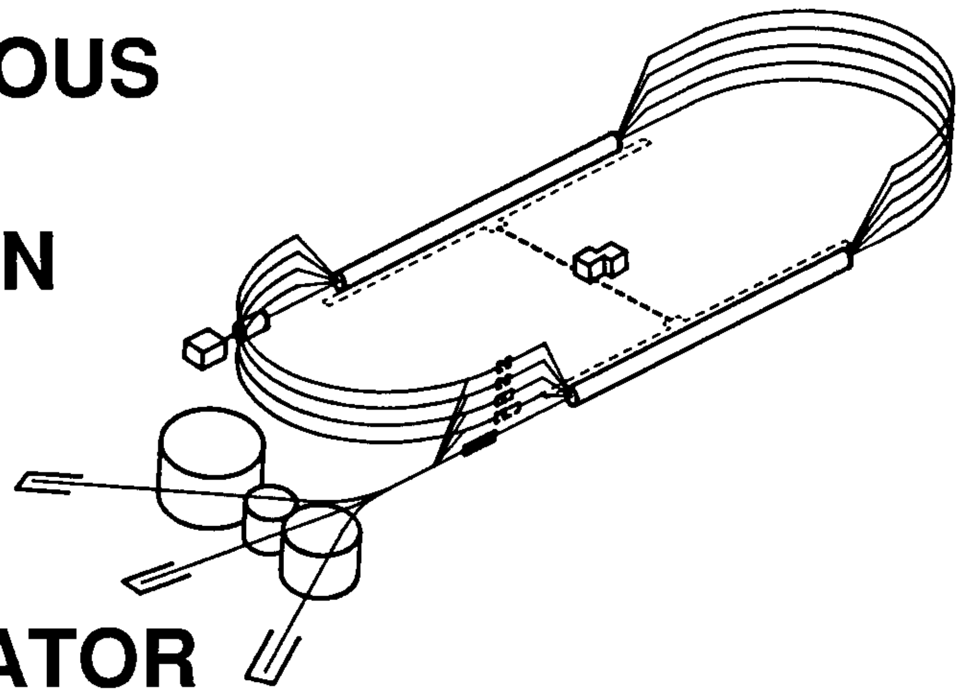

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ABSTRACT

The results of collective simulations of a typical TeV Energy Superconducting Linear Accelerator (TESLA) are reported. Because the accelerating gradient is low and the accelerator is long compared to other TeV colliders, betatron phase mixing must be suppressed along with the usual sources of emittance growth. Including single bunch effects, alignment tolerances consistent with reasonable emittance growth are given. When such tolerances are achieved, multibunch effects do not cause excessive effective emittance growth. In addition, longitudinal multibunch effects are discussed.

INTRODUCTION

A linear collider based on superconducting cavities has several advantages when compared to normal conducting proposals. For example RF peak power requirements are relaxed, high efficiency is possible, and because lower RF frequencies are possible, the influence of the transverse wake on the beam dynamics is significantly reduced. It is the purpose of this paper to determine misalignment tolerances consistent with the reduced transverse wakes of a TESLA machine and consistent with the final focussing system in a TESLA machine.

The parameters of the TESLA machine that was simulated are summarised in Table 1.[1] It would be the third upgrade in a series of machines that extends up to 1.5 TeV CM energy, and it should be compared with the SLAC's TLC proposal or KEK's JLC proposal.

Presently, the main challenge for TESLA designs is to reduce the cost of the superconducting linac, at least to a level competitive with other proposals. It seems necessary, that to be competitive, an accelerating gradient of 30 MV/m must be achieved. While such results are within the state of the art for single cell cavities, multi-cell cavities can perform at gradients of about 15 MV/m at present.[2]

CHROMATIC EFFECTS

The alignment of the quadrupoles is most constrained by chromatic effects in the TESLA linac, so the energy spread in the linac must be determined. The main source of energy spread is the longitudinal wake. The loss factor is given by[3]

$$k_{\|} = \frac{N_c Z_0 c}{2\pi^2 a}\sqrt{\frac{l}{\sigma}}\left(1+\frac{\sqrt{lN_c}}{2\sqrt{L}}\right)^{-1},$$

where Z_0 is 377 Ω, c is the velocity of light, a is the cavity aperture, $l = L = 10$ cm is the cell length for the superconducting cavity, N_c is the number of cells in the cavity, and σ is the *rms* bunch length. The nominal 1.5 GHz cavity geometry yields a numerical value of 12.1 V/pC at $\sigma = 0.25$ mm. When the energy spread is minimized by proper choice of linac phase,[4] the relative *rms* energy spread is 6.1×10^{-4}. Figure 1 presents an energy-time phase plot for the particles emerging from the TESLA linac computed by the simulation code. The bunch distribution was assumed parabolic. The linac phase is 13° off crest.

Table 1
TESLA Parameters for This Study

General	
Energy	2×0.5 TeV
Luminosity	7.41×10^{33} cm^{-2} sec^{-1}
Acceleration Length	16.67 km
Bunch Charge	9.6 nC $= 6 \times 10^{10} e^{\pm}$
Bunch Length	1.1 mm
Normalized x emittance	$1\pi \times 10^{-6}$ m rad
Normalized y emittance	$30\pi \times 10^{-6}$ m rad
β_x^*	2.4 mm
β_y^*	8.16 mm
σ_x	50 nm
σ_y	500 nm
D_V	13.87
H	1.83
Linac	
RF frequency	1500 MHz
Fundamental Mode r/Q	960 Ω/m
Q_0	8×10^9
Gradient	30 MV/m
Number of Cavities/Linac	16,670
RF Repetition Rate	9 Hz
Bunches per RF Pulse	400
Bunch Spacing	3 μsec
Duty Factor	1.08%
Peak Power/Length	100 kW/m
Total Peak Power/Linac	1550 MW
Beam Power/Linac	16.8 MW
Average Wall Power	200 MW

Given this estimate of the single bunch energy spread, it is possible to estimate the chromatic effects associated with various error sources. An example of effective emittance growth is seen in Figure (2), which shows the phase

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space coordinates of the electrons as they emerge from the linac when the injected beam is offset by 0.2 mm. In the run it was assumed that the cavities and focussing quadrupoles are perfectly aligned. The hole in phase space develops because the initial displacement is larger than the beam size. A factor of six emittance growth from the initial 1π mm mrad results. To suppress this growth requires the offset at injection to be less than 0.1 mm, *i.e.*, less than the beam size at the beginning of the linac.

Chromatic effects also limit the permissible quadrupole alignment error.[5] Because there are so many betatron oscillations over the length of the accelerator, betatron phase mixing may lead to significant emittance growth.

A simple model may be used to estimate this effect. The displacement at the end of a constant phase advance lattice due to quadrupole alignment errors, D_i is

$$x(\delta) = \sum_{i=1}^{N} \frac{D_i}{\psi} \frac{L}{f} \sin[\psi(N-i)(1-\delta)],$$

where N is the number of errors between correctors, δ is the energy offset, ψ is the phase advance per half cell, L is the length of a half cell, and f is the lens focal length. For a given set of D_i and if $|\psi N\delta| << 1$, performing the energy average gives

$$x^2_{rms} \sim N_{tot} D^2_{rms} \left(\frac{L}{f}\right)^2 \left(\frac{N}{2}\right)^2 \delta^2_{rms}, \qquad (1)$$

where N_{tot} is the total number of quadrupoles. On the other hand, if $|\psi N\delta| >> 1$,

$$x^2_{rms} \sim \frac{N_{tot} D^2_{rms} L^2}{2\psi^2 f^2},$$

Ruth's jitter result within a factor of order one. In his argument on orbit corrections, Ruth requires $N = 1$ in equation 1, *i.e.*, continuous correction of every error. If only occasional corrections are needed, equation 1 provides the suitable scaling rule. Notice that x_{rms} goes as $N^{3/2}$ for constant numbers of correctors.

For TESLA, the jitter tolerance is 0.04 μm. The quadrupole alignment tolerance is 160 μm if the beam is re-steered to the axis after each error or it is 16 μm if the beam is re-steered to the axis after each 10 errors. These tolerances may be relaxed through use of more complicated correction schemes.[6]

SINGLE BUNCH TRANSVERSE INSTABILITY

Due to the requirements placed on quadrupole alignment by chromatic effects and due to the fact that the transverse wake is reduced in the relatively large aperture superconducting cavities, the single bunch growth from injection errors and from instability generated by cavity misalignments is small. Several simulations were run using a transverse wake slope of 7.3 V/(pC cm^2), a value known from the CEBAF cavity. The increase in the emittance growth from adding the transverse wake was small.

MULTIBUNCH TRANSVERSE INSTABILITY

It has been shown previously that the cumulative BBU blow-up factor for a TESLA design limits the Qs for the cavity HOMs to about 10^6, given a manufacturing frequency spread in the cavity HOMs of 1 MHz.[7] Such an analysis does not place limits on cavity alignment; it demonstrates that Qs of order 10^6 for the HOMs are compatible with small effective emittance growth from cumulative BBU. Our simulation results, which calculate the multibunch instability generated by cavity misalignments, can be used to place tolerances on cavity alignment consistent with high-Q HOMs.

Figure 3 gives the transverse displacements of the 400 bunches emerging from one of the linacs. The simulation had four HOMs at each cavity location with HOM frequency spread of 1 MHz along the linac. The R/Qs of the HOMs were 41.4 Ω, 191 Ω, 79.3 Ω, and 43.2 Ω, for HOM frequencies 1948 MHz, 1961 MHz, 1969 MHz, and 2034 MHz, respectively. The Qs were 1.0×10^7. The 1961 MHz mode is the most serious HOM for the TESLA 10-cell cavity.

In the simulation, the cavities were assumed to have random offsets between ±1.0 mm. The position fluctuation in the result should be compared to the beam size at the end of the linac of $\sigma_x = 3$ μm. Several cavity misalignment seeds were simulated without substantial changes in the results. Because the fluctuation level is proportional to the misalignment in this parameter regime, it can be concluded that there is insignificant luminosity reduction as long as the cavities are aligned to an *rms* error of 0.3 mm ($\sigma_{bbu} < 2\sigma_x$). HOM Qs greater than 10^7 do not generate position displacements substantially greater than those at 10^7. If the quadrupoles jitter less than 0.001 cm, there is no further effective emittance increase in the cumulative BBU from the quad steering effect.

MULTIBUNCH LONGITUDINAL INSTABILITY

Finally, the longitudinal multibunch instability must not cause energy fluctuations exceeding the acceptance of the final focus system. Figure 4 gives the relative energy displacements of the 400 bunches emerging from one of the linacs calculated using the six largest longitudinal HOMs. The R/Qs of the HOMs were 7 Ω, 123 Ω, 3.5 Ω, 9 Ω, 8 Ω, and 11 Ω, for HOM frequencies 2851 MHz, 2907 MHz, 2947 MHz, 3002 MHz, 4413 MHz, and 4417 MHz, respectively. The Qs of all the modes are 10^7. As the acceptance of the final focus system is about $\Delta E/E = 10^{-3}$, longitudinal multibunch instability should not significantly reduce the luminosity.

CONCLUSIONS

The conclusions are summarized in Table 2. In Table 2, alignment tolerances are given that are consistent with preserving an *rms* normalized emittance of 1π mm mrad throughout the linac. Also given is the source of emittance growth most important in setting that tolerance.

The cavity alignment tolerance is set by multibunch beam breakup; other alignment tolerances are set by the need to suppress chromatic growth. Transverse single bunch effects do not add emittance growth beyond that generated by the chromatic effects. Self-consistent simulations (including all effects together) have been done both for single bunch effects and multibunch effects to verify these tolerances. Multibunch effects from high Q HOMs do not yield overly stringent cavity tolerances, supporting the possibility that HOMs in the TESLA cavities may remain undamped. The relaxed tolerances of TESLA designs compared to normal conducting designs may well be a main benefit of a superconducting linear collider.

Table 2
Tolerance List
Errors are *rms* values

Tolerance	Value	Source
Cavity Alignment	300 μm	multibunch BBU
Quadrupoles and BPMs		
Correction Frequency		
Every Error	160 μm	chromatics
Every 10 Errors	16 μm	chromatics
Injector	50 μm	chromatics
Jitter	0.04 μm	chromatics

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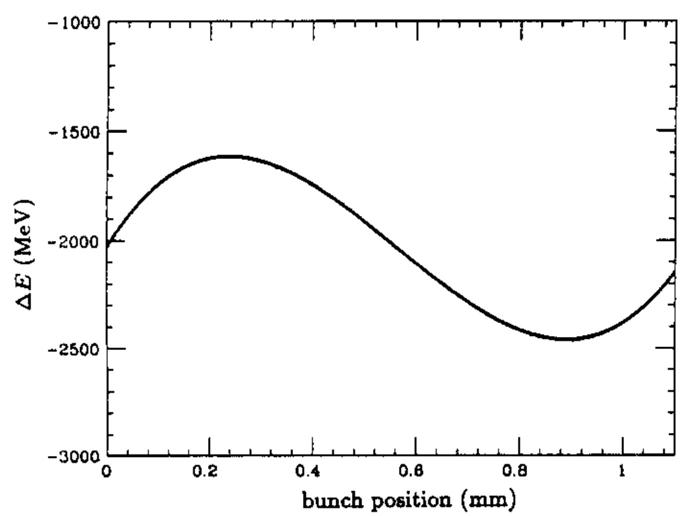

Figure 1 Energy-time phase plot of electrons emerging from the linac

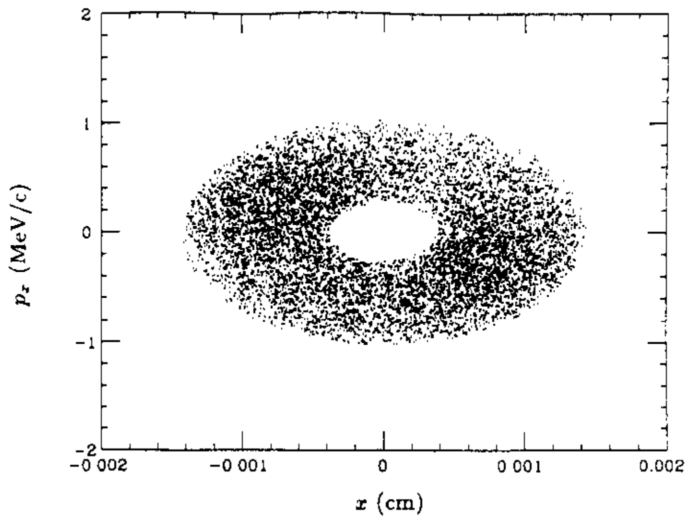

Figure 2 Transverse phase plot of electrons emerging from the linac when beam is injected off axis

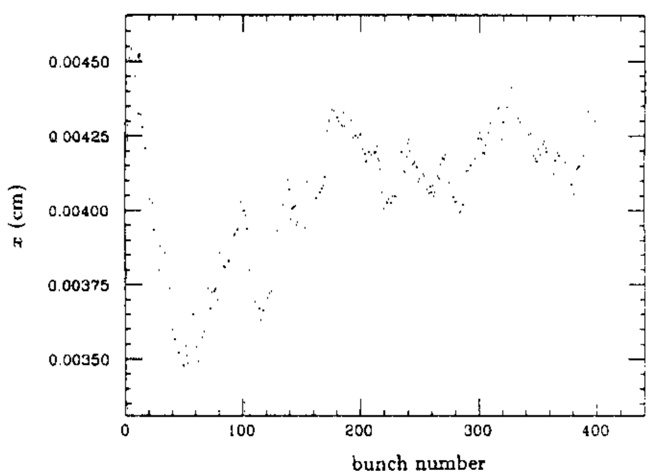

Figure 3 Multibunch BBU generated position displacements

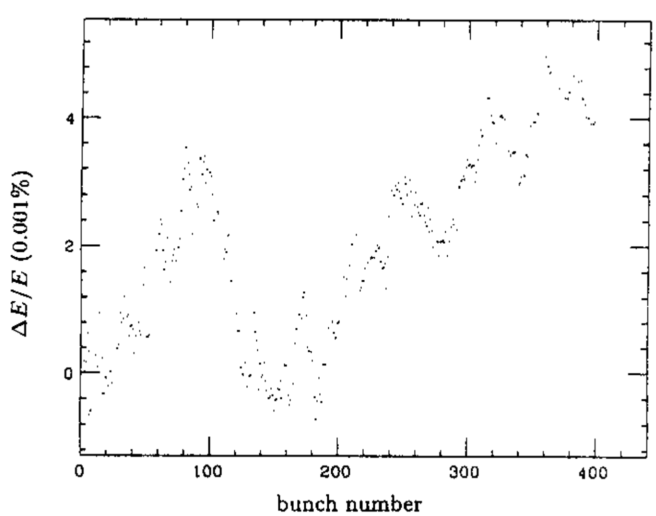

Figure 4 Multibunch BBU generated energy fluctuations