Working Group Summary
Group Three: Accelerator Physics*

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ABSTRACT

This paper summarizes the progress in the accelerator physics of the TESLA machine achieved since the last conference. Progress has been made in understanding both the single bunch phenomena and the multibunch phenomena, and the tolerances they place on machine alignment. The main single bunch phenomenon that must be suppressed is betatron phase mixing, which provides the main limitation on quadrupole alignment and injection error. It also seems clearer that single bunch transverse instability should not be a large problem. The limitations placed on the High Order Mode (HOM) Qs from multibunch effects are discussed for both transverse and longitudinal modes. Finally, the main open issues for future study are summarized.

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.

In this summary, the effects of the short term wake are discussed first. The most important effect of the short term longitudinal wake is to set the energy spread within a bunch. The short term transverse wake is much less in superconducting cavities compared to normal conducting cavities, and it does not produce substantial emittance growth in TESLA. Given the energy spread within the bunch, it is possible to determine the quadrupole alignment tolerances from estimating chromatic effects within the focussing lattice of the collider. Finally, multibunch effects are considered with the view of showing that longitudinal HOM Qs of 10^7 are permitted consistent with the final focus constraint, and that transverse HOM Qs of 10^7 would produce acceptable cavity alignment tolerances if the focusing lattice is strong.

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CHROMATIC EFFECTS[1]

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[2]

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

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,[3] 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 a simulation code. The bunch distribution was assumed parabolic. The linac phase is 13° off crest.

Given this estimate of the single bunch energy spread, it is possible to estimate the chromatic effects associated with various error sources. If the relative energy spread multiplied by the number of betatron oscillations exceeds unity, then an initial injection error fully spreads in phase space at the end of the linac. To suppress this source of emittance growth requires the offset at injection to be less than 50 μm in position, *i.e.*, less than the beam size at the beginning of the linac, and less than 4 μrad in angle.

Chromatic effects also limit the permissible quadrupole alignment error.[4] 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 quadrupole focal length. For a given set of D_i and if $|\psi N \delta| << 1$, performing the energy average gives

$$x_{rms}^2 \sim N_{tot} D_{rms}^2 \left(\frac{L}{f}\right)^2 \left(\frac{N}{2}\right)^2 \delta_{rms}^2, \tag{1}$$

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

$$x_{rms}^2 \sim \frac{N_{tot} D_{rms}^2 L^2}{2\psi^2 f^2},$$

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 the TESLA design considered in Ref. 1, 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.[5,6]

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 $\mathrm{V/(pC\,cm^2)}$, a value known from the CEBAF cavity. The increase in the emittance growth from adding the transverse wake was small.

MULTIBUNCH TRANSVERSE INSTABILITY

At the previous conference, it was shown 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 did not place limits on cavity alignment; it demonstrated that Qs of order 10^6 for the HOMs are compatible with small effective emittance growth from cumulative BBU. The displacements to excite the instability might arise from injection error, cavity misalignments, or quadrupole misalignments. Given that the injection error is smaller than 50 μm to suppress chromatic effects, no substantial emittance growth is added by this source of multibunch transverse instability. Since the last conference, two calculations have been done to directly address the following question: How much cavity misalignment and quadrupole misalignment are consistent with low emittance growth generated by multibunch instabilities?

From the first set of calculations,[1] which model the multibunch instability generated by cavity misalignments and quadrupole misalignments together, tolerances can be placed on cavity alignment consistent with high-Q HOMs.

Figure 2 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 10 μm, there is no further effective emittance increase in the cumulative BBU from the quad steering effect.

The second set of calculations, by R. Wanzenberg, at lower HOM Q values of 10^6, treated the quadrupole and cavity misalignments separately, for a less strongly focusing lattice than above. He found a cavity alignment tolerance of 100 μm and a quadrupole alignment tolerance, without correctors, of 10 μm also. The results of both calculations are summarized in Tables 1 and 2. The main differences are that the stronger focusing lattice from the first calculation gives a more relaxed alignment tolerance and a stiffer jitter tolerance than in the relatively weak focussing lattice of the second calculation. There has been no attempt to optimize the focusing lattice in either of these calculations. Perhaps it is useful to try to find more optimal focusing lattices.

A suggestion for relaxing the alignment tolerances was resurrected, particularly in the talk by Weiland on the normal conducting collider proposal. In this proposal the multibunch beam breakup problem is more severe, mainly because the cavity impedance is so much greater. Stagger tuning of the worst HOM is used to reduce the effects of multibunch beam breakup. In discussions with the cavity group, it was felt that stagger tuning the 1961 mode by $\pm$10 MHz, i. e., having three groups of slightly different cavities with HOM frequencies 1951 MHz, 1961 MHz, and 1971 MHz, would not substantially increase the cavity production costs. It is interesting to know how much the alignment tolerance would be relaxed for a TESLA so constructed.

MULTIBUNCH LONGITUDINAL EFFECTS

During the last conference, it was felt that the energy spread in the beam generated by multibunch effects was at the 10^{-3} level and that the acceptance of the final focus was also at the 10^{-3} level. The question arose whether a final focus constraint limits the Q values of the longitudinal HOMs. Since then, a more complete calculation addressing this issue was reported in Ref. 1.

The energy fluctuations generated by the longitudinal multibunch effect were calculated in a model that retains the effects of 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 were 10^7. Figure 3 gives the calculated relative energy displacements of the 400 bunches emerging from one of the linacs. The relative energy fluctuation is at the 10^{-4} level.

At the conference, Thomas Weiland reported that their normal conducting proposal required an energy acceptance of about 1%, and presented a beam optics solution to this problem. It is possible to use this, or a similar, design for the TESLA final focus. Therefore, longitudinal multibunch effects should not significantly reduce the luminosity, even at HOM Qs of 10^7. To summarize, there is no final focus constraint on the Qs of the longitudinal HOMs.

Table 1
Tolerance List Calculated by Krafft, Fripp, and Bisognano
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

Table 2
Tolerance List Calculated by Wanzenberg

Tolerance	Value	Source
Cavity Alignment	100 μm	multibunch BBU
Quadrupoles	10 μm	multibunch BBU
Injector	50 μm	chromatics
Jitter	0.8 μm	chromatics

CONCLUSIONS

Through the work of Weiland's group on final focus design, and through better computations of multibunch longitudinal effects, it seems clear that longitudinal multibunch instability will not reduce the luminosity of the TESLA collider, even if the longitudinal modes remain undamped. Likewise, theoretical calculations of the short-term wake have been improving. This has allowed fairly confident prediction that transverse single bunch instability should not be a problem for TESLA, if some care is taken to insure that the beamline remains smooth. There have been some initial efforts at calculating alignment tolerances for TESLA. Most of the difficulties arise from chromatic effects generated by the fact that the corrected energy spread is finite and from the fact that a large number of betatron oscillations must be present in traversing the entire machine. In addition to the requirements placed on quadrupole alignment by chromatic effects, the cavity transverse alignment tolerance is produced by transverse multibunch effects. Even if the HOM Qs are of order 10^7, tolerances of order 300 μm are possible if one relies on a strong focusing lattice to control the beam. In a more standard scheme, these same Qs would produce emittance growth if the cavities are misaligned at the 100 μm level, indicating that de-Qing to 10^6 is needed. In either case, it should be investigated whether stagger tuning provides as large an advantage in TESLA as it has in the normal conducting proposal. If so, cavity alignment will probably not be a problem even at large Qs.

Little progress has been made on the following issues. There is no optimized damping ring design. The beam-beam problem in the collision has not been investigated in detail. The linac focussing lattice should be optimized, given some estimate of the jitter expectations. And finally, the positron production problem has not been addressed in depth. It would be interesting to have some experimental data on the short term wake, confirming or denying the theoretical predictions. One problem that might be solved by the next conference is whether the electrons can be produced directly with an RF photocathode gun, without damping rings.

The best estimates on tolerances are summarized in Tables 1 and 2. In the tables, 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 relaxed tolerances of TESLA designs compared to normal conducting designs may well be a main benefit of a superconducting linear collider.

ACKNOWLEDGEMENTS

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REFERENCES

[1] Much of the material in the summary is taken from the paper "Emittance Growth in TESLA", by G. A. Krafft, M. Fripp, and J. J. Bisognano, to be published in the *Proc. 1991 Particle Accel. Conf.*
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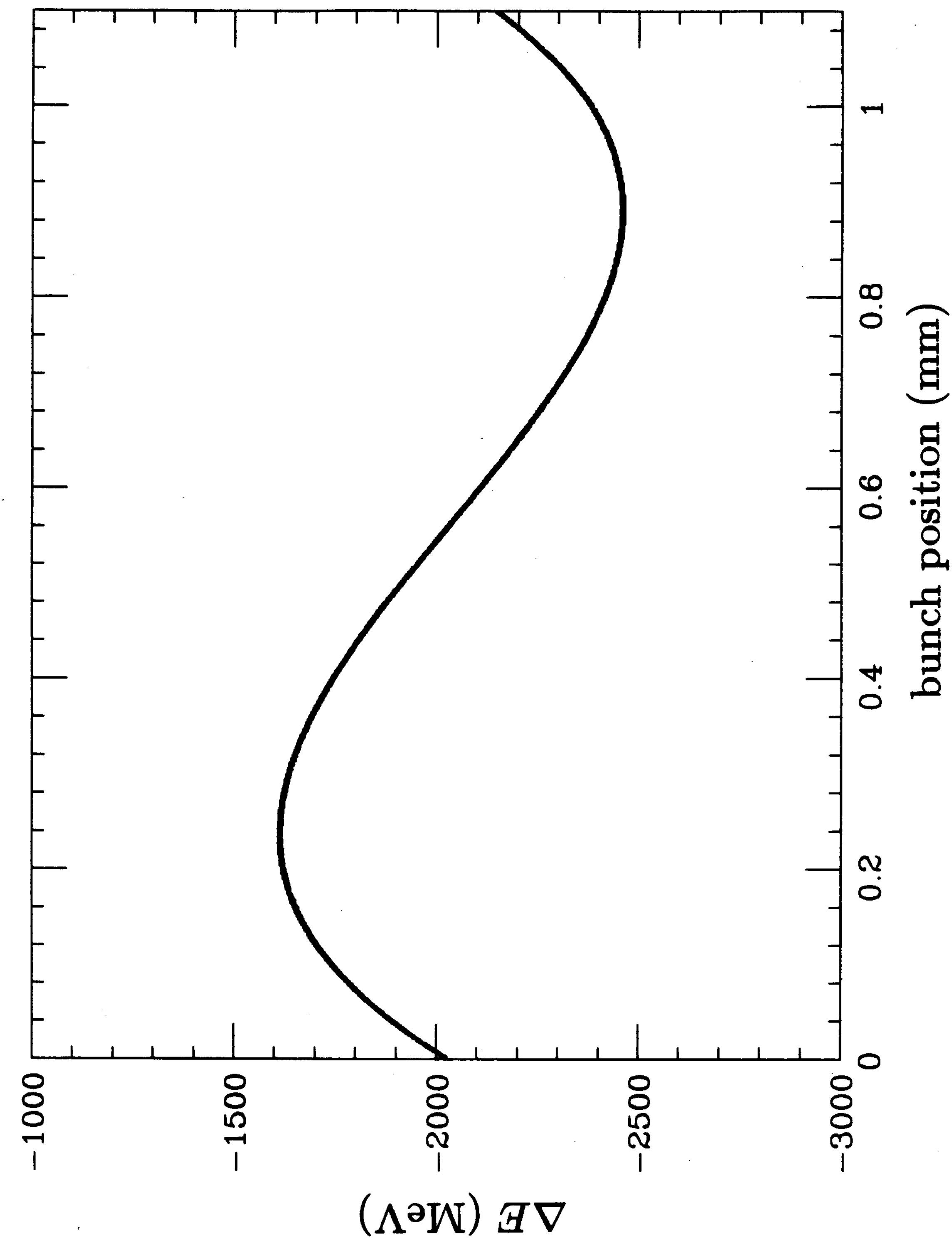
FIGURE CAPTIONS

Figure 1. Energy-time phase plot of electrons emerging from the linac
Figure 2. Position displacements generated by transverse multibunch effects
Figure 3. Energy fluctuations generated by longitudinal multibunch effects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−1500
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−2500
−3000
ΔE (MeV)
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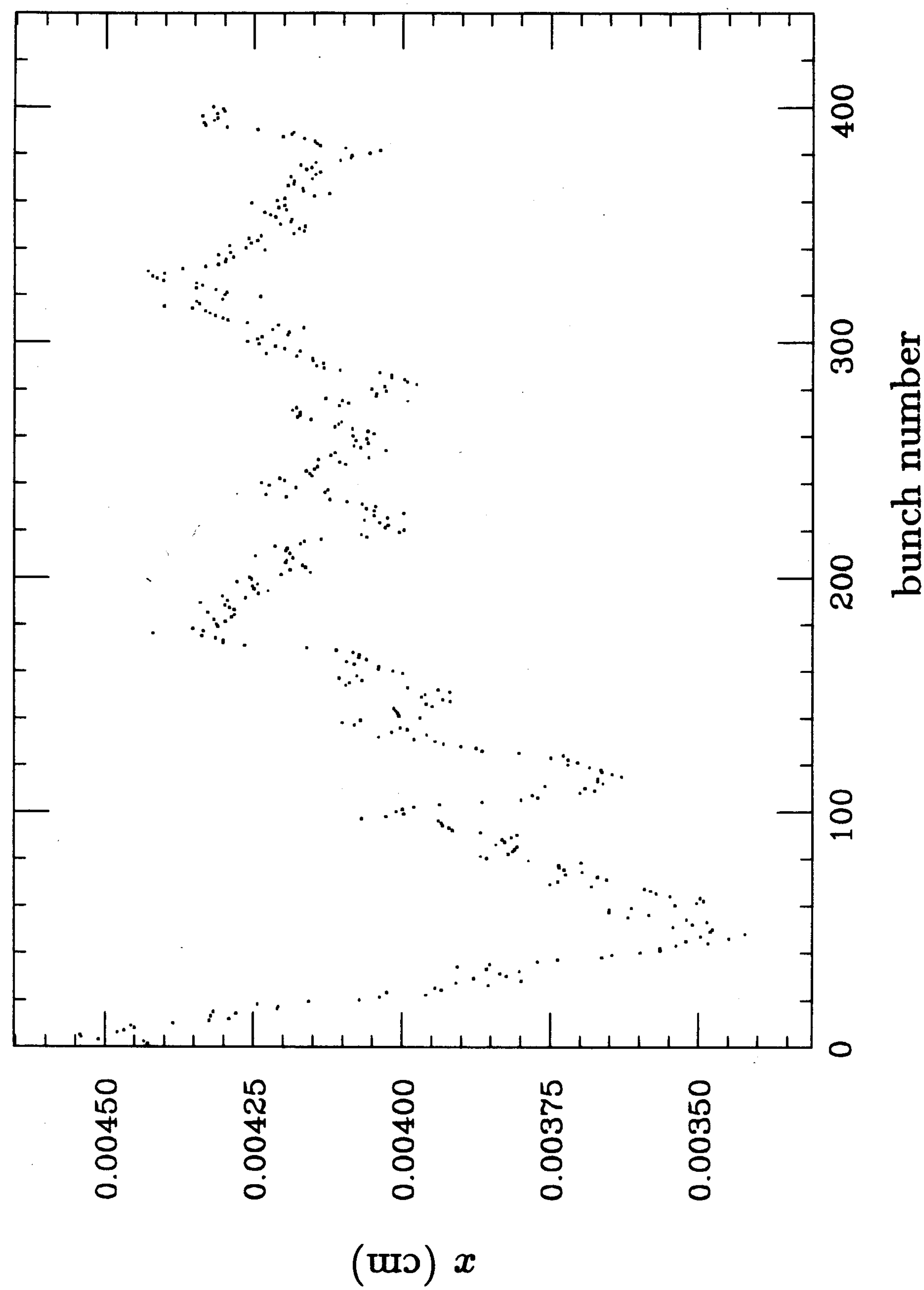
0.4
0.6
0.8
1
bunch position (mm)



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0.00350
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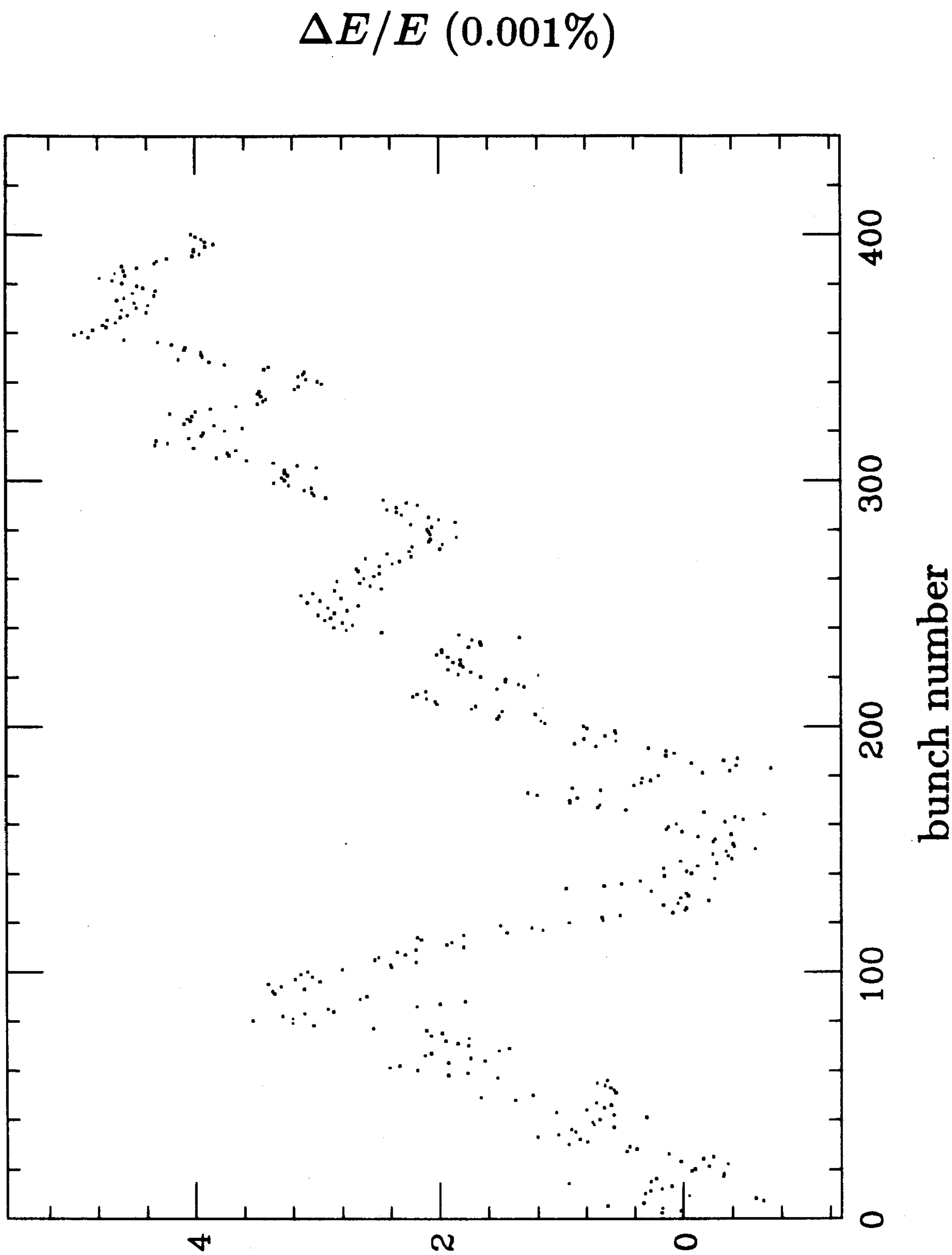
200
300
400
bunch number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bunch number
0
100
200
300
400
4
2
0