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SSCL-N-826
2/24/93

Effects of the GEM solenoidal magnetic field on SSC beam dynamics

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We study the effect of the GEM solenoidal magnetic field on the SSC beam dynamics. The principal effect is induced xy betatron coupling, and this is within the correction range of the skew quadrupole correctors. To reduce this coupling during normal operation, we recommend that the solenoidal fields of GEM and SDC be antiparallel.

* Operated by the Universities Research Association, Inc., for the U. S. Department of Energy under contract DE-AC35-89ER40486.

INTRODUCTION

The GEM solenoid produces an unshielded field [1]. The longitudinal field B_z rotates the beam through an angle

$$\theta = \frac{\int B_z dl}{B_0 \rho}, \tag{1}$$

where dl is a differential length along the solenoidal axis. The effective bending field B_0 of bending radius ρ is related to the beam momentum p through

$$eB_0\rho = p, \tag{2}$$

where e is the electric charge. At collision this rotation for a GEM field strength of 1.0 Tesla is $\theta_c \sim 600$ μrad, and at injection it is ten times this value. This can produce xy coupling of the transverse betatron motions of the beam. We define the effective coupling constant as the coefficient of the term driving the difference resonance in the equations of motion. If β_x, β_y are the beta functions at the location of the solenoid, then this effective coupling constant due to the solenoid(measured in radians) is

$$C = \frac{\theta}{2}[\sqrt{\frac{\beta_x}{\beta_y}} + \sqrt{\frac{\beta_y}{\beta_x}}]. \tag{3}$$

With equal beta functions at the interaction point(IP), the coupling coefficient is equal to the rotation angle. The effect of this coupling on the beam can be determined using the beam simulation code TEAPOT [2]. Additional effects on the beam could appear if the detector solenoidal field has multipole moments. These could result from the gravitational distortion of the magnetic field from its circular axial symmetry. This turns out not to be significant because the magnet is stressed into a circular shape when the magnet is powered. The solenoidal detector SDC [3] produces similar effects. In the simulation, the coupling effects are investigated when both detectors are present.

Numerical values for the longitudinal component B_z for the GEM solenoid are shown in Figure 1a through 1c. This field extends well outside the end of the detector, and it has a value of approximately .05 Tesla at the location of the final focusing quadrupoles. In the present design of the Interaction Regions, the final focusing quadrupole magnets start at 20.5 m from the IP for SDC while for GEM this distance is 35 m. The radial

component B_r of the solenoidal field, resulting from a 1 cm transverse offset of the solenoid, is shown in Figure 2a through Figure 2c for z values from 0 to 35 m. These field values are in general small, approaching zero beyond 30 m, and the largest value is at the location of the forward field shaper. There are components in opposite directions which give opposite contributions to $\int B_r dl$, and the larger contributions tend to act over short distances along the solenoidal axis. The presence of the radial component can contribute to the distortion of the closed orbit. If the axis of the solenoid is misaligned in the transverse direction by approximately 1 cm, then these radial components result in a small bending angle of the beam, which can be easily corrected. The amount of bending produced by a radial component is given by

$$\theta_r = \frac{\int B_r dl}{B_0 \rho}. \tag{4}$$

For an estimated uniform value of $B_r = .004$ Tesla, the angular deflection at collision is approximately

$$\theta_r = l[\mathrm{m}] \times (6 \times 10^{-8} \text{ rad/m}).$$

For $l \sim 2$ m, the deflection angle is ~ 0.012 μrad. At injection the deflection is ten times this value, and this is well within correction range of the steering correctors.

The dipole, quadrupole, and sextupole magnets in the Collider lattice contribute to the induced skew quadrupole error. This effect is represented in terms of the coupling coefficient per cell. Measured in radians, this is given by [4]

$$C_{cell} = (\sqrt{\beta_x \beta_y})_{ave} \sigma_{sq}, \tag{5}$$

where

$$\sigma_{sq} = [\sigma_{sq}(D) + \sigma_{sq}(Q) + \sigma_{sq}(S)]^{1/2}.$$

The error contributions per cell from the dipoles, quadrupoles and sextupoles are respectively $\sigma_{sq}(D)$, $\sigma_{sq}(Q)$, and $\sigma_{sq}(S)$. They are determined by various errors as follows

$$\sigma_{sq}(D) = \frac{a_1 \theta_{cell}}{\sqrt{n}} = \frac{[1.25\text{x}10^{-2} \text{ m}^{-1}][1.51939\text{x}10^{-2} \text{ rad}]}{\sqrt{10}}$$

$$\sigma_{sq}(Q) = \frac{2\sqrt{2}\sigma_{\Delta\phi}}{f} = \frac{[2\sqrt{2}][0.5\text{x}10^{-3}\text{ rad}]}{62.405\text{ m}}$$

$$\sigma_{sq}(S) = \frac{\sqrt{2}\sigma_{\Delta y} r}{f\eta_{ave}} = \frac{[\sqrt{2}][10^{-3}\text{ m}][2]}{[62.405\text{ m}][1.314\text{m}]},$$

where a_1 is the skew quadrupole field error in each dipole, θ_{cell} is the bending angle per cell, n is the number of dipoles per cell, $\sigma_{\Delta\phi}$ is the rms roll-angle alignment error per quadrupole, f is the focal length of a quadrupole in each cell, $\sigma_{\Delta y}$ is the rms vertical orbit deviation, r is the ratio of the total chromaticity to the natural chromaticity due to the quadrupoles, and η_{ave} is the average dispersion in each cell.

With $(\sqrt{\beta_x\beta_y})_{ave} = 131.8\,\text{m}$, one finds

$$C_{cell} = 0.0096 \text{ rad.} \tag{6}$$

The corresponding numbers contributed by each solenoid are,

$$\begin{aligned} C_{Injection} &\sim 0.006 \text{ rad} \\ C_{Collision} &\sim 0.0006 \text{ rad.} \end{aligned} \tag{7}$$

At present it is envisaged [5] that a total of 32 skew quadrupoles will correct for the coupling due to all the cells and special quadrupoles in the Collider. Even when both solenoids are powered with parallel B_z fields, the extra coupling is small enough that no additional correctors are required to remove the effects due to the solenoids. The Collider can be decoupled by using the above mentioned set of 32 skew quadrupoles and without any significant increase in the strengths of these correctors.

SIMULATION

The effect of the solenoidal field on the properties of the beam can be estimated using the simulation program TEAPOT. This simulation takes account of the rotational effect of the axial field and transverse kick effect of the fringe field. The presence of a solenoid induces xy coupling. This effect is parameterized by the eigenplane angle, the angle by which the beam ellipse rotates in the transverse $x - y$ plane. In the simulation,

two solenoids with an uniform axial field of 1 Tesla and an integrated field of 41 Tesla-m each are present. This is greater than the actual values for the detector solenoids, which are approximately 18 Tesla-m for SDC and 26 Tesla-m for GEM. The larger value used in the simulation ensures that the suggested compensation scheme discussed below remains valid even if the integrated fields of the detectors were to increase. Without the solenoids, coupling is induced as a result of the skew quadrupole contributions from the dipoles, quadrupoles and sextupoles in the lattice. The coupling is determined by the set of systematic and random errors in the lattice. The specifications for these errors are listed in the Collider 3B document [6], and for our simulations we studied one lattice with a particular set of random errors. For this lattice the eigenangle is within ± 0.05 radians at injection, after correction by the 32 skew quadrupoles. The resulting eigenangle distribution throughout the lattice at injection is shown in Figure 3a. When both solenoids are turned on with parallel fields and no correction is done for their effects, the eigenangles increase to a maxima of approximately ± 0.09 radians. The maxima occurr near the IPs. The eigenangle distribution for this case is shown in Figure 3b.

The observed coupling can be reduced in one of two ways. The simplest is to cancel the coupling due to one solenoid by the other. If the currents in the two detector solenoids flow in opposite directions, the direction of rotation of the beams in these solenoids is also opposite and the beams remain nearly decoupled. The closer the betatron phase advances between the solenoids in the two planes are to each other, the more complete is the cancellation. Figure 3c shows that the eigenangle distribution in this case is very nearly the same as in the case without solenoids. If the axial magnetic fields in the solenoids are in the same direction, their effects can still be removed by increasing the strengths of the 32 skew quadrupole correctors. The required strengths of these quadrupoles are shown in Table I. The largest change occurs for one of the weakest quadrupoles whose gradient increases from 0.107 T/m to 0.289 T/m. For all quadrupoles, the strengths required to correct for the solenoids are well within the specifications. The limits are 123 T/m for the 'csq' skew quads and 75 T/m for the others. The eigenangle variation with path length is shown in Figure 3d.

Name	Gradient without Solenoids (T/m)	Gradient with Solenoids at Injection (T/m)	% Change
csq	−0.170	−0.171	0.784
csq	−0.284	−0.264	−7.059
csq	−2.008	−1.975	−1.661
csq	0.361	0.377	4.436
csq	−2.962	−2.909	−1.802
csq	−2.675	−2.628	−1.746
csq	1.321	1.388	5.051
csq	−1.581	−1.568	−0.844
csq	1.334	1.194	−10.500
csq	−2.588	−2.435	−5.928
csqe1	−3.462	−3.482	0.578
csqe3	1.935	1.788	−7.586
csqe5	−4.296	−4.216	−1.863
csqe7	0.502	0.287	−42.895
csque1	−1.041	−0.961	−7.692
csque3	−0.107	−0.289	170.625
csq	−0.416	−0.552	32.745
csq	−0.102	−0.084	−17.647
csq	−0.310	−0.303	−2.366
csq	−1.054	−1.107	5.063
csq	−1.087	−1.094	0.613
csq	−1.341	−1.414	5.473
csq	−1.995	−1.975	−1.003
csq	−1.321	−1.334	1.010
csq	−0.629	−0.625	−0.636
csq	0.095	0.093	−1.408
csqw1	−2.422	−2.422	0.000
csqw3	1.715	1.715	0.000
csqw5	0.887	0.887	0.000
csqw7	−1.815	−1.808	−0.368
csquw1	1.154	1.161	0.578
csquw3	1.434	1.434	0.000

Table I. Injection lattice: Corrector skew quadrupole strengths.

At collision, the maximum eigenangle without solenoids lies within ± 0.07 radians. The rotation angles due to the solenoids are ten times smaller than at injection and the effects of the solenoids are negligible. Figure 4a shows the eigenangles at collision without the solenoids, and Figure 4b shows the eigenangles when the currents in both solenoids are in the same direction. The two distributions are nearly identical. Consequently no decoupling is required for the solenoids at collision.

In addition to the xy coupling induced by the solenoidal fields there is also an induced tune shift. The tune shifts associated with parallel solenoidal fields are shown in Table II. When decoupling is done at injection in either of the two ways mentioned above, the tune shift falls below 1.0×10^{-5}.

Case	ν_x	ν_y
Collision	$< 1.0 \times 10^{-5}$	-1.0×10^{-5}
Injection	8.0×10^{-5}	-8.0×10^{-5}

Table II. Tune shifts for the cases when both detectors are active with their magnetic fields parallel.

CONCLUSIONS

The simulation results show that the coupling induced by both solenoidal detectors can be easily corrected at injection while no special correction is necessary in the collision mode. Since both detectors are likely to be powered at the same time, it would be best to have the axial fields in opposite directions. This reduces the coupling and tune shifts resulting from the detectors at all times. Furthermore, if one of the solenoids is not powered, then less correction is required to remove the coupling induced by a single solenoid. Even when both detectors are operating with the longitudinal fields in the same direction, these effects can be corrected with the existing skew quadrupole correctors.

The authors wish to thank N. Martovetsky for providing plots of the longitudinal and radial components of the GEM magnetic field and R. Talman for additional insight and guiding us through the intricacies of TEAPOT. Also we are grateful to Y. Cai, F. Pilat and M. Syphers for helpful discussions.

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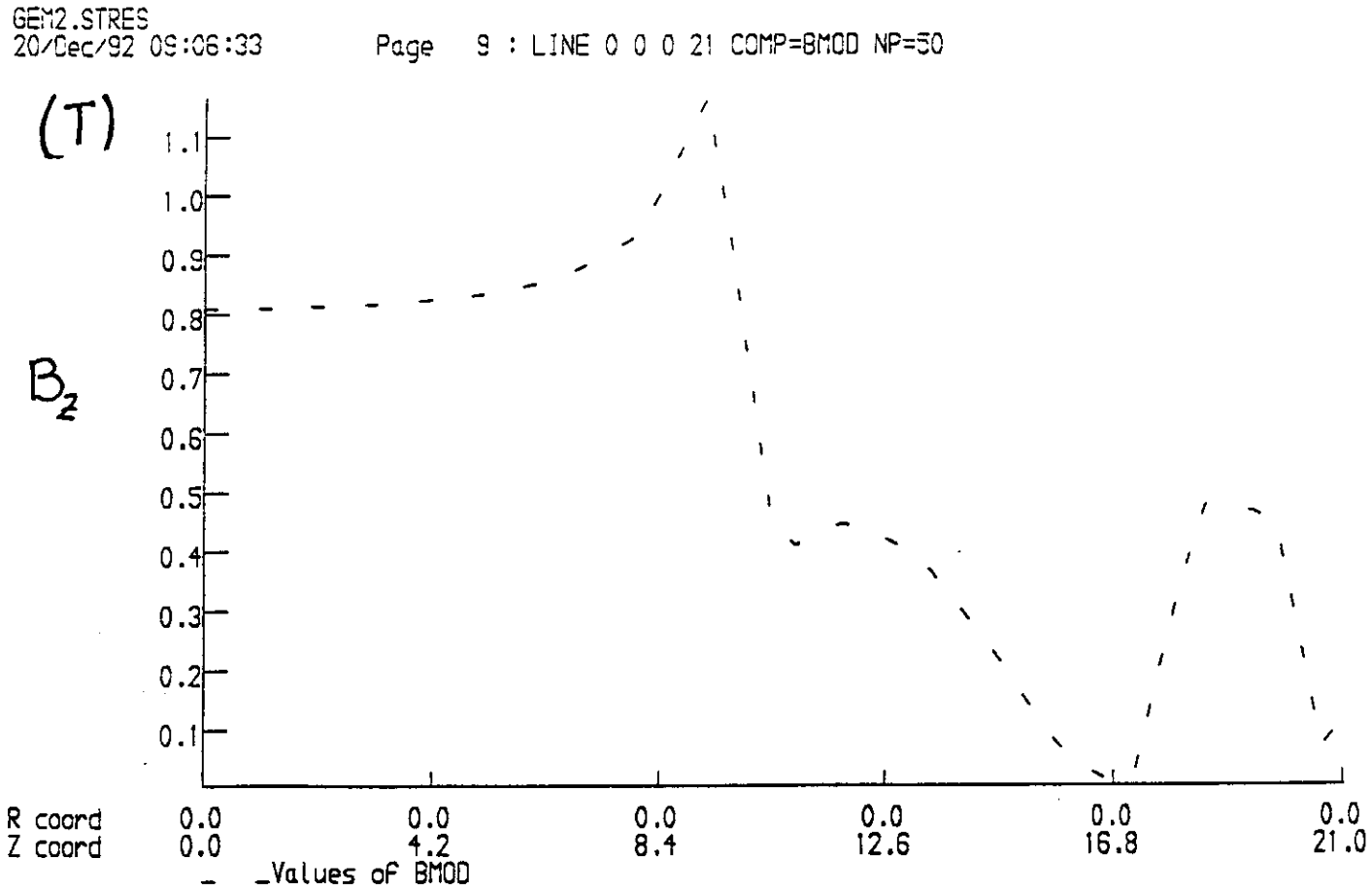

Fig. 1a The GEM longitudinal magnetic field B_z (Tesla) vs Z=0-21 m.

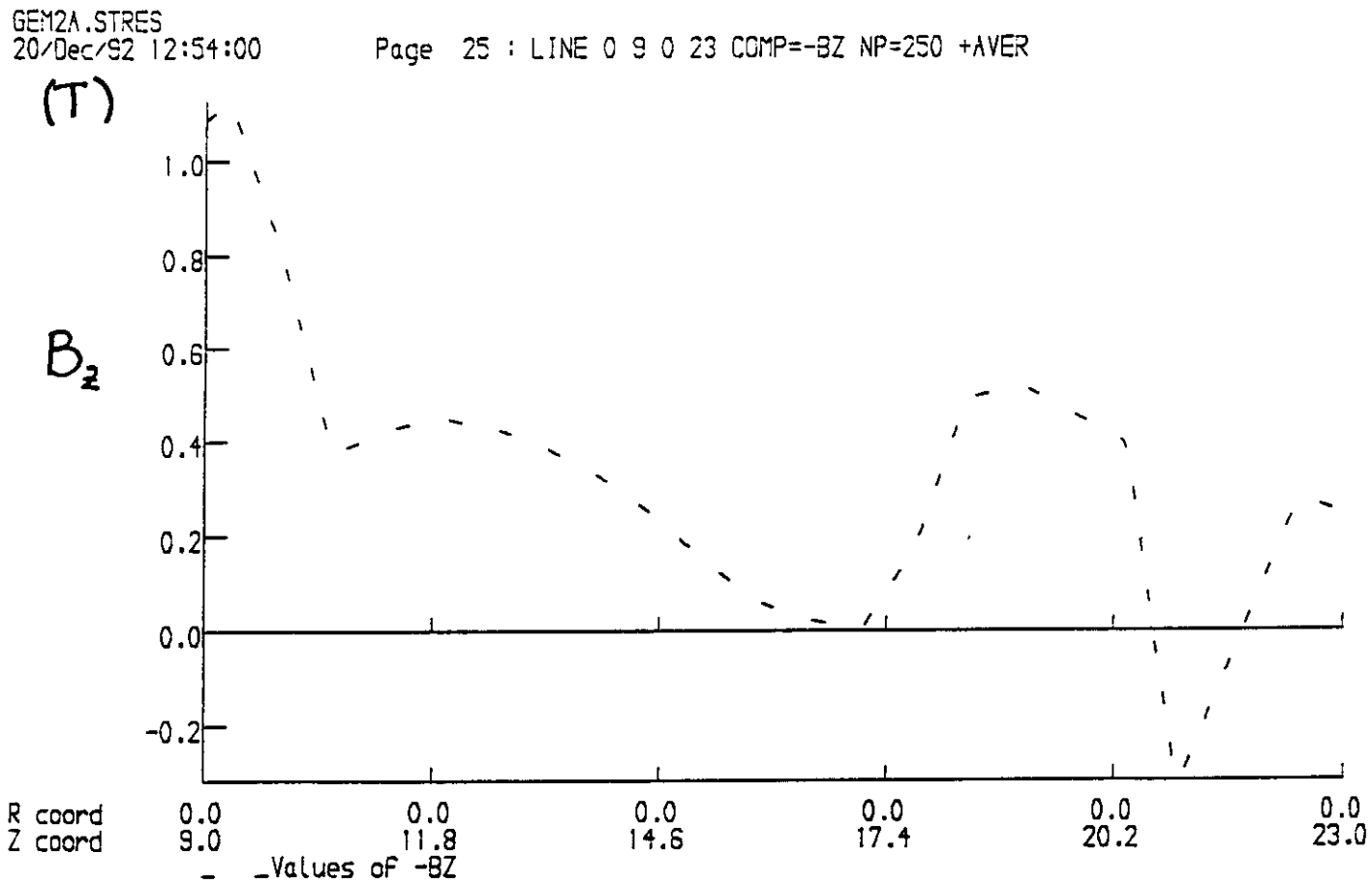

Fig. 1b The GEM longitudinal magnetic field B_z (Tesla) vs Z=9-23 m.

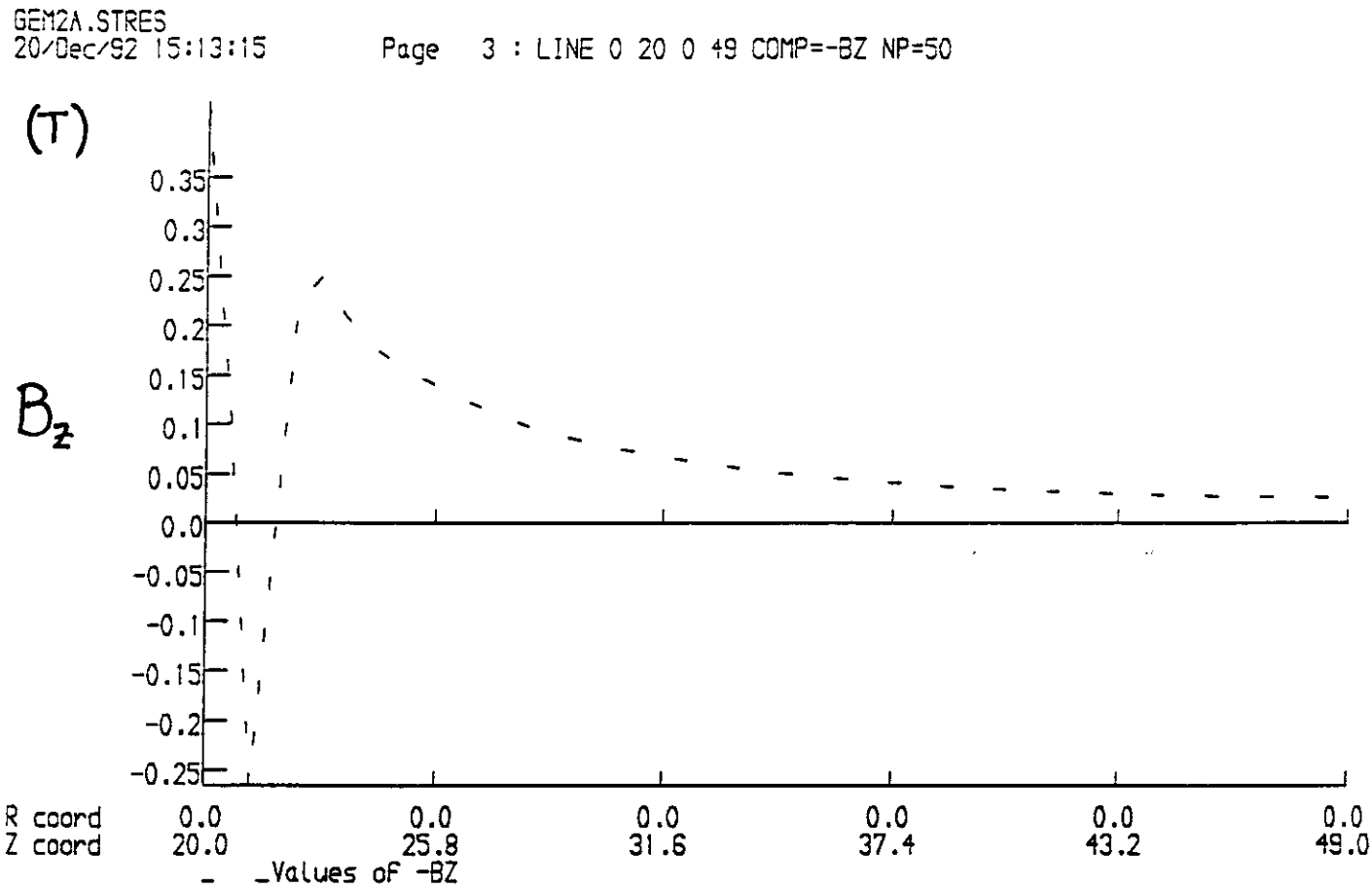

Fig. 1c The GEM longitudinal magnetic field B_z (Tesla) vs Z=20-49 m.

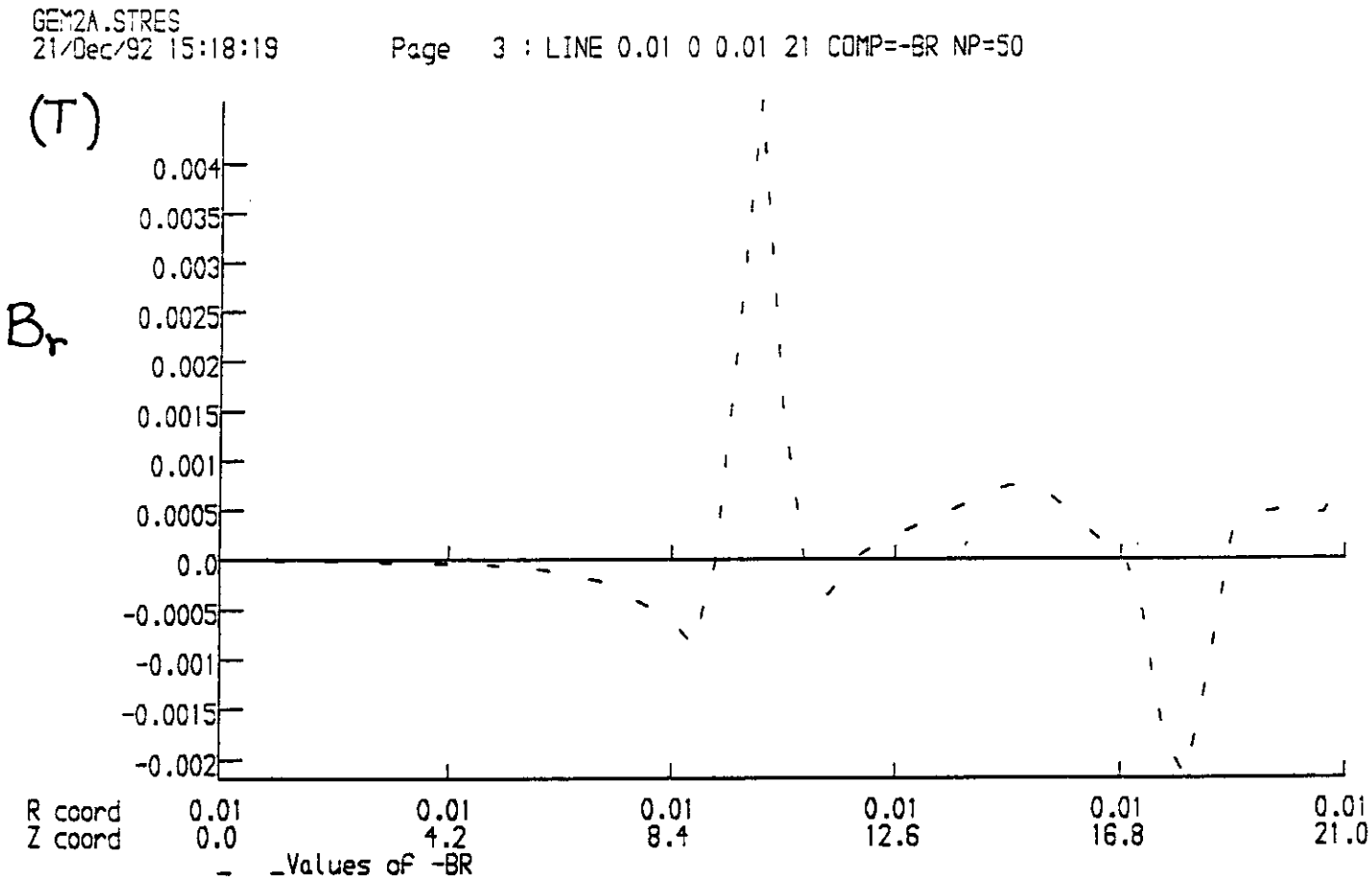

Fig. 2a The GEM radial magnetic field (1 cm axial offset) B_r (Tesla) vs Z=0-21 m.

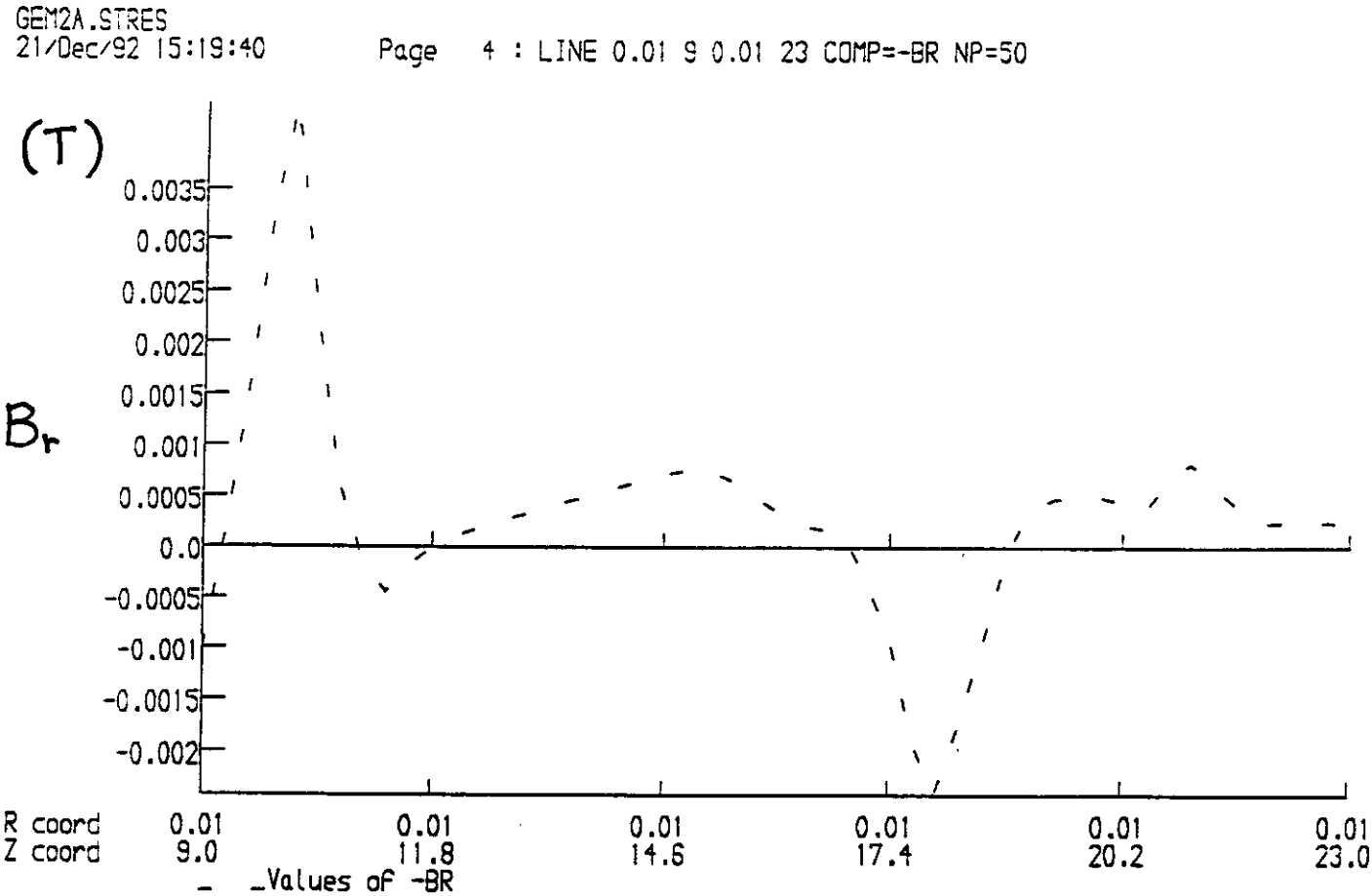

Fig. 2b The GEM radial magnetic field (1 cm axial offset) B_r (Tesla) vs Z=9-23 m.

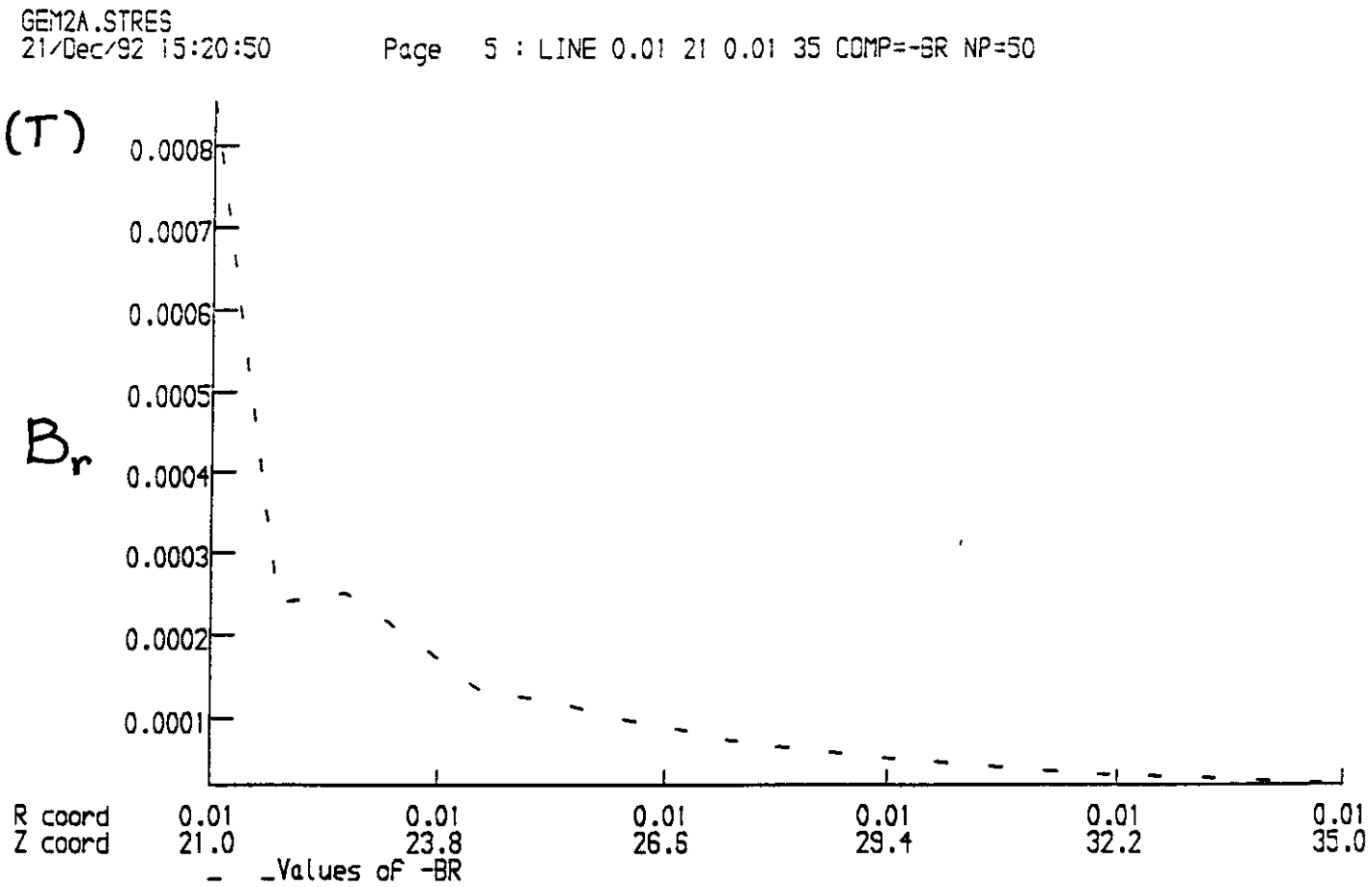

Fig. 2c The GEM radial magnetic field (1 cm axial offset) B_r (Tesla) vs Z=20-35 m.

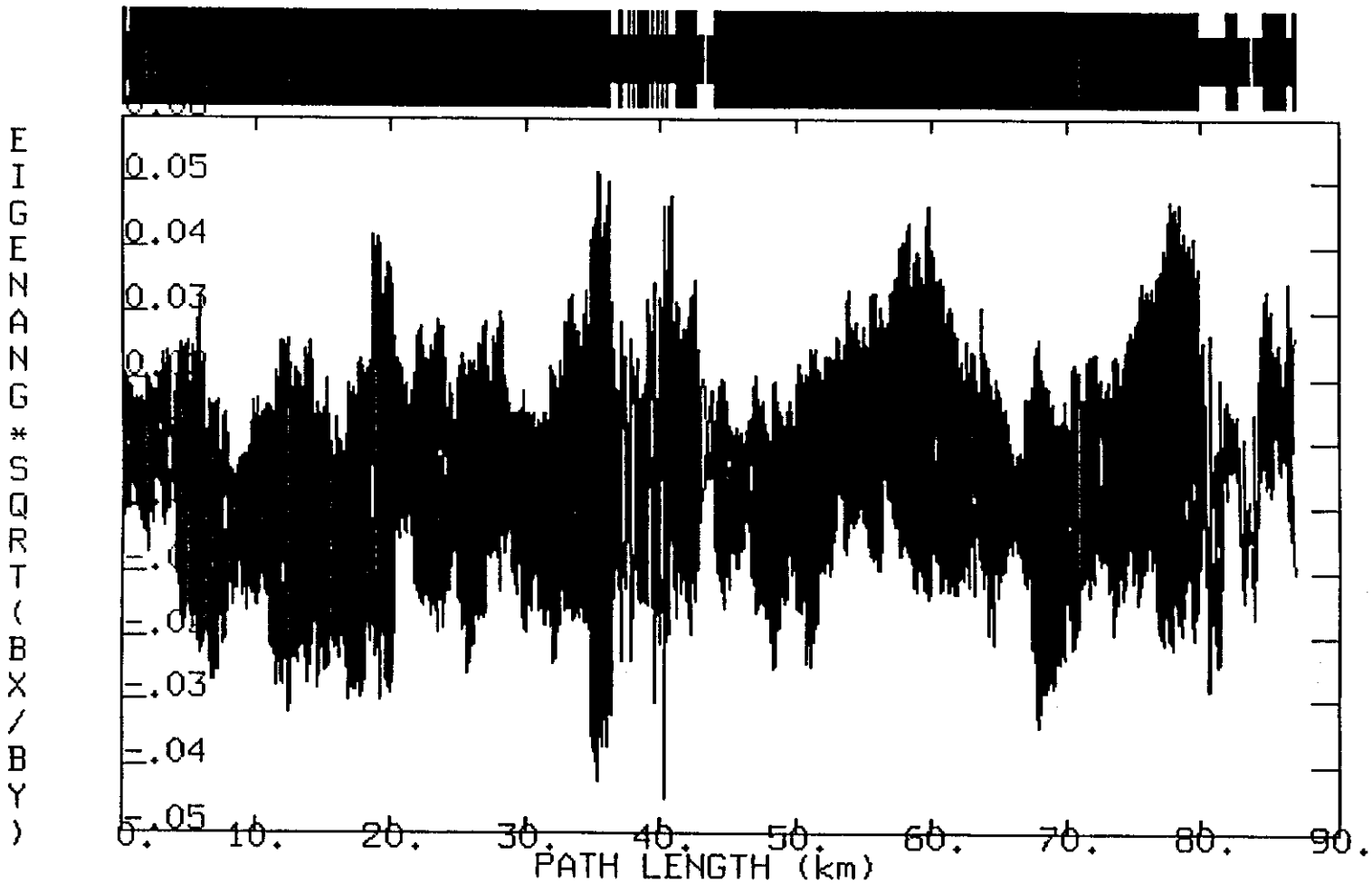

Fig. 3a The eigenangle vs path length without solenoidal fields at injection.

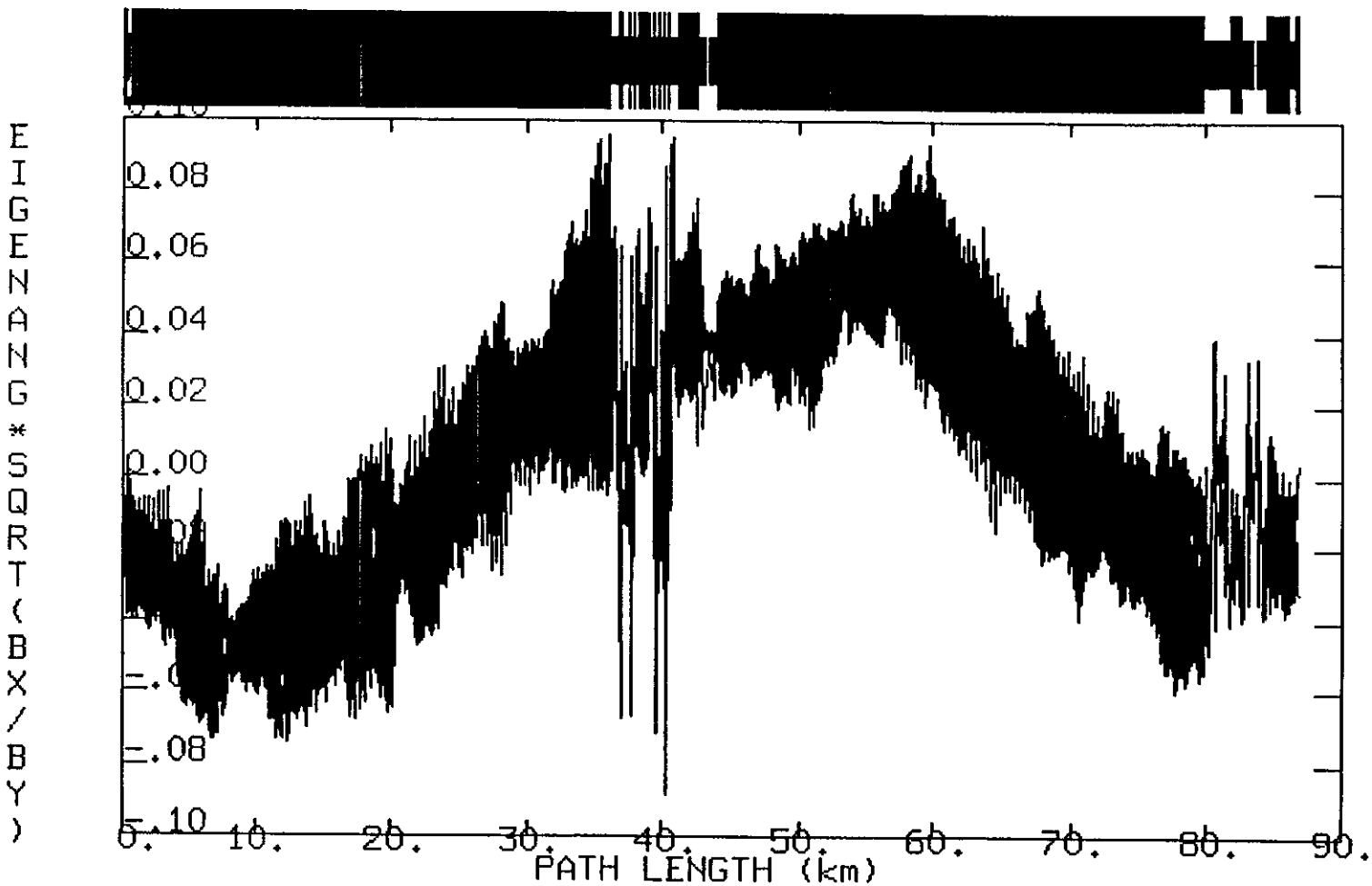

Fig. 3b The eigenangle vs path length with parallel solenoidal fields at injection.

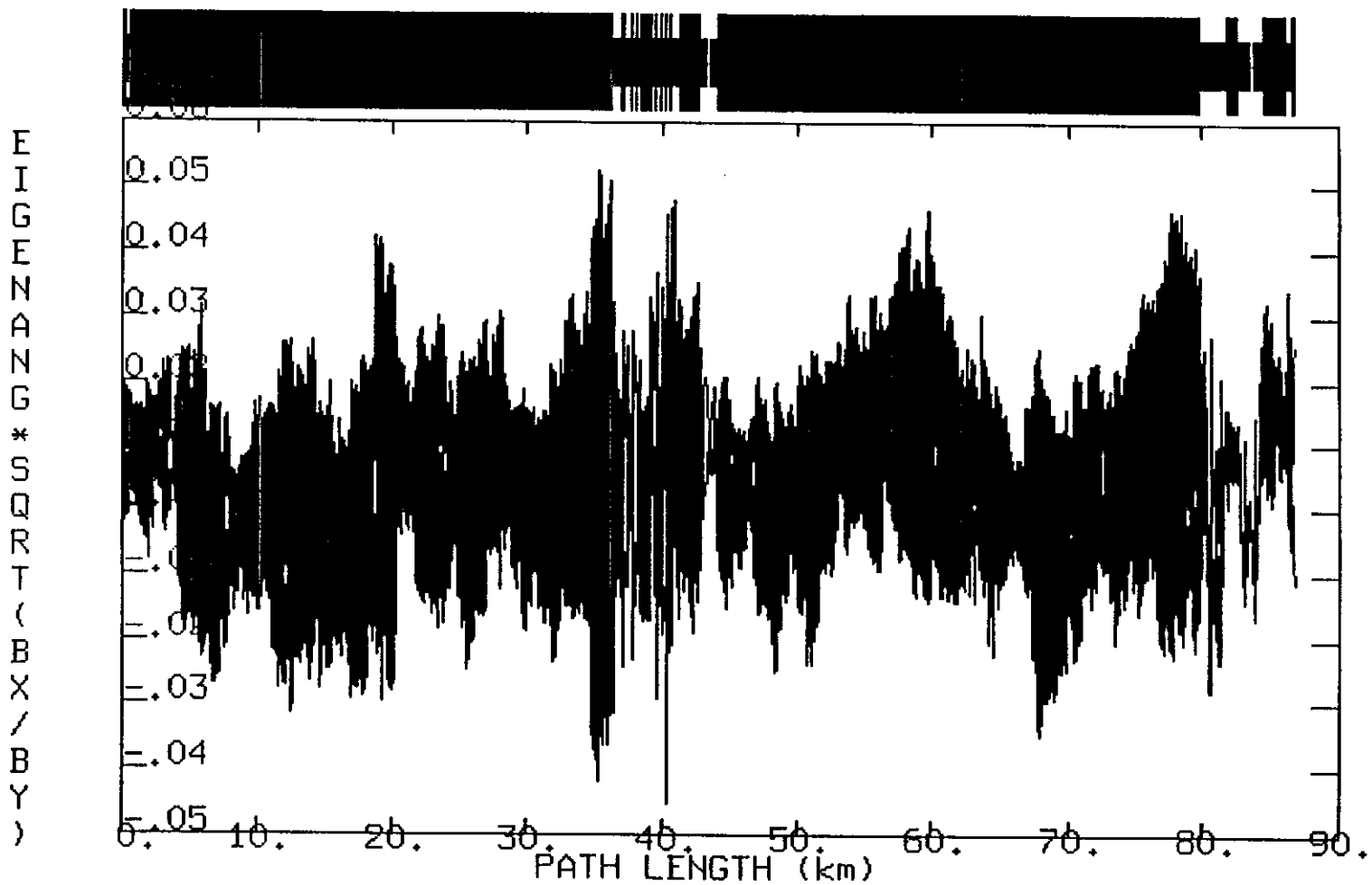

Fig. 3c The eigenangle vs path length with antiparallel solenoidal fields at injection

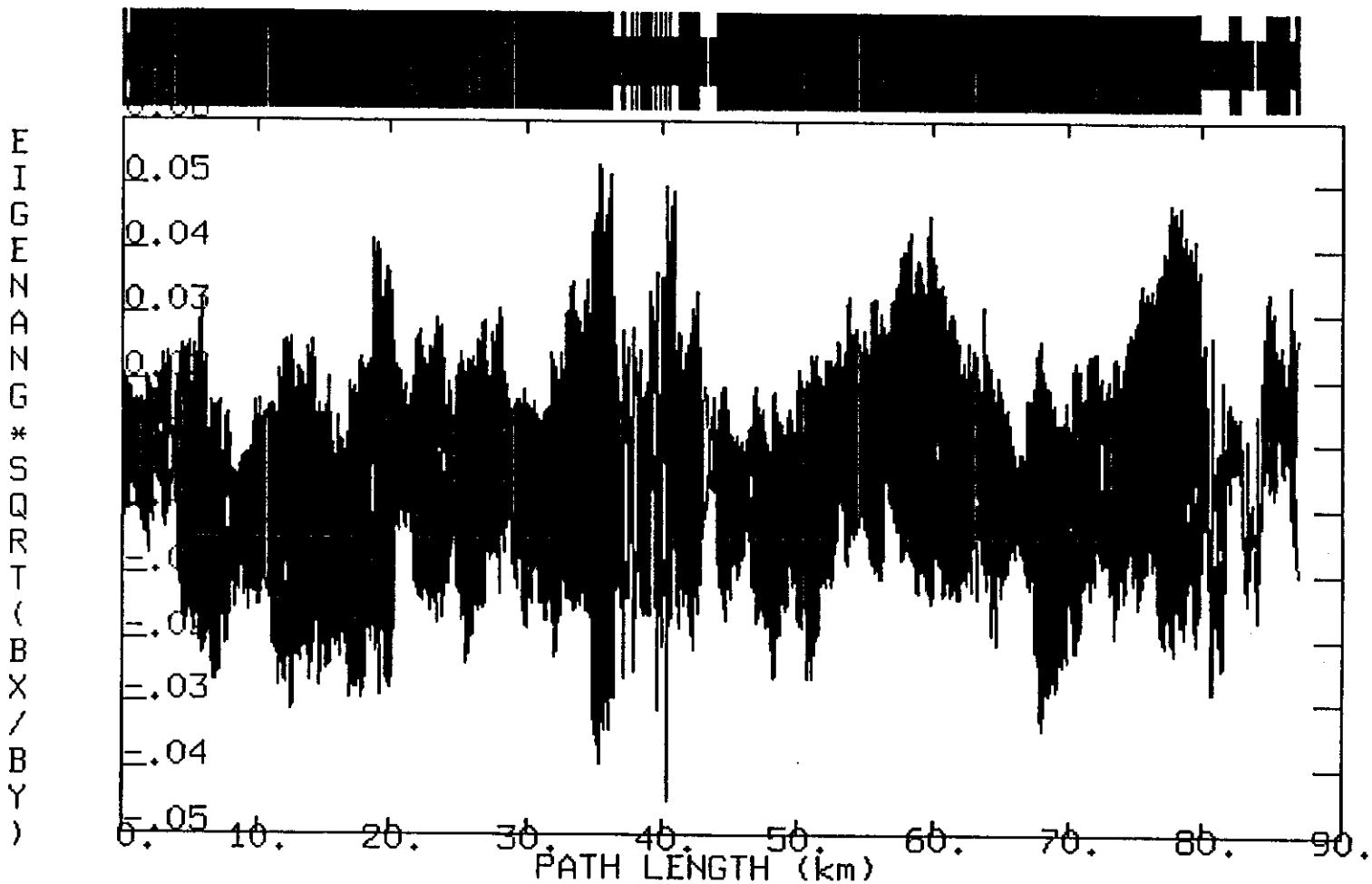

Fig. 3d The eigenangle vs path length with parallel solenoidal fields after skew quadrupole correction at injection.

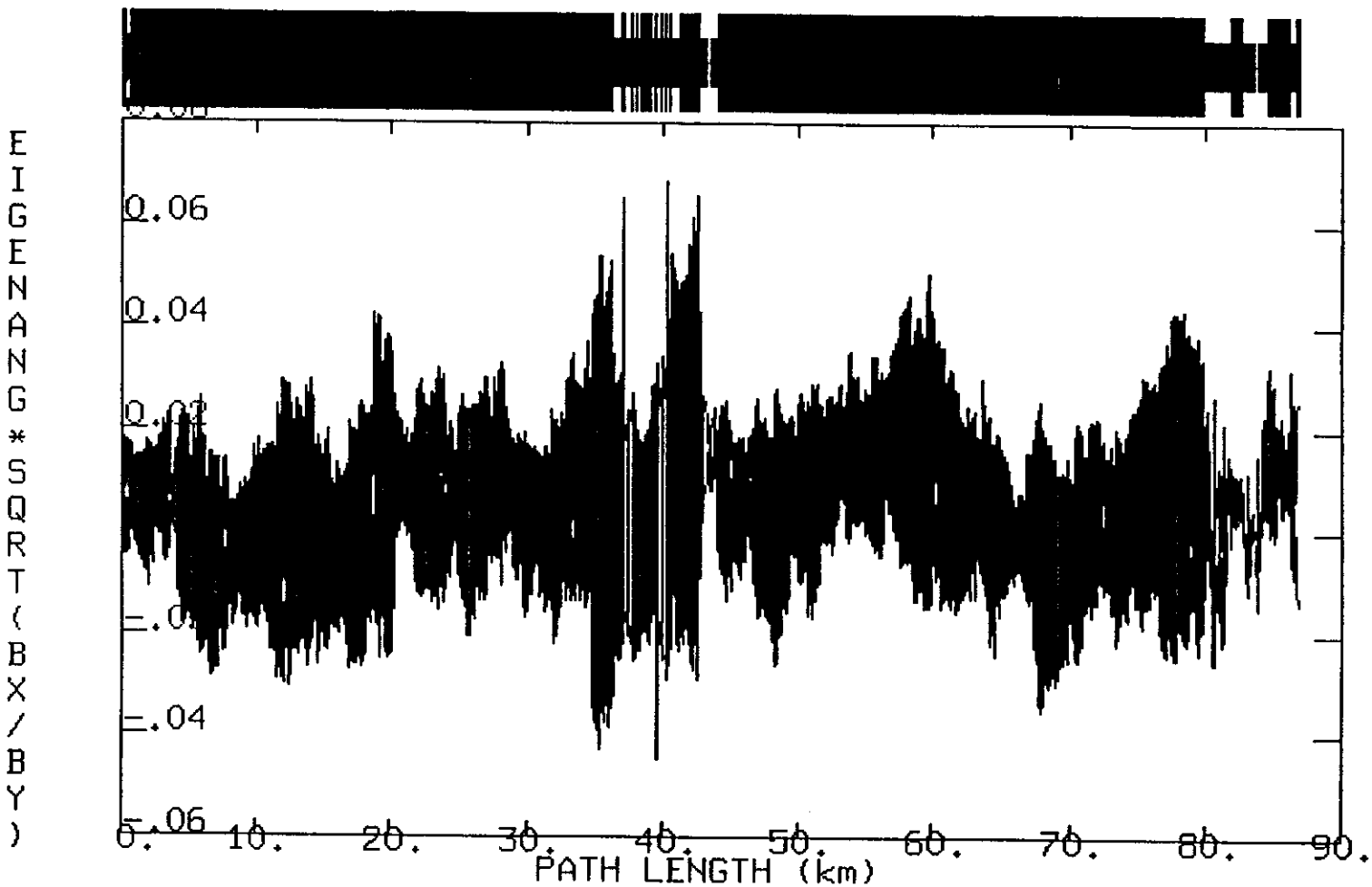

Fig. 4a The eigenangle vs path length without solenoidal fields at collision

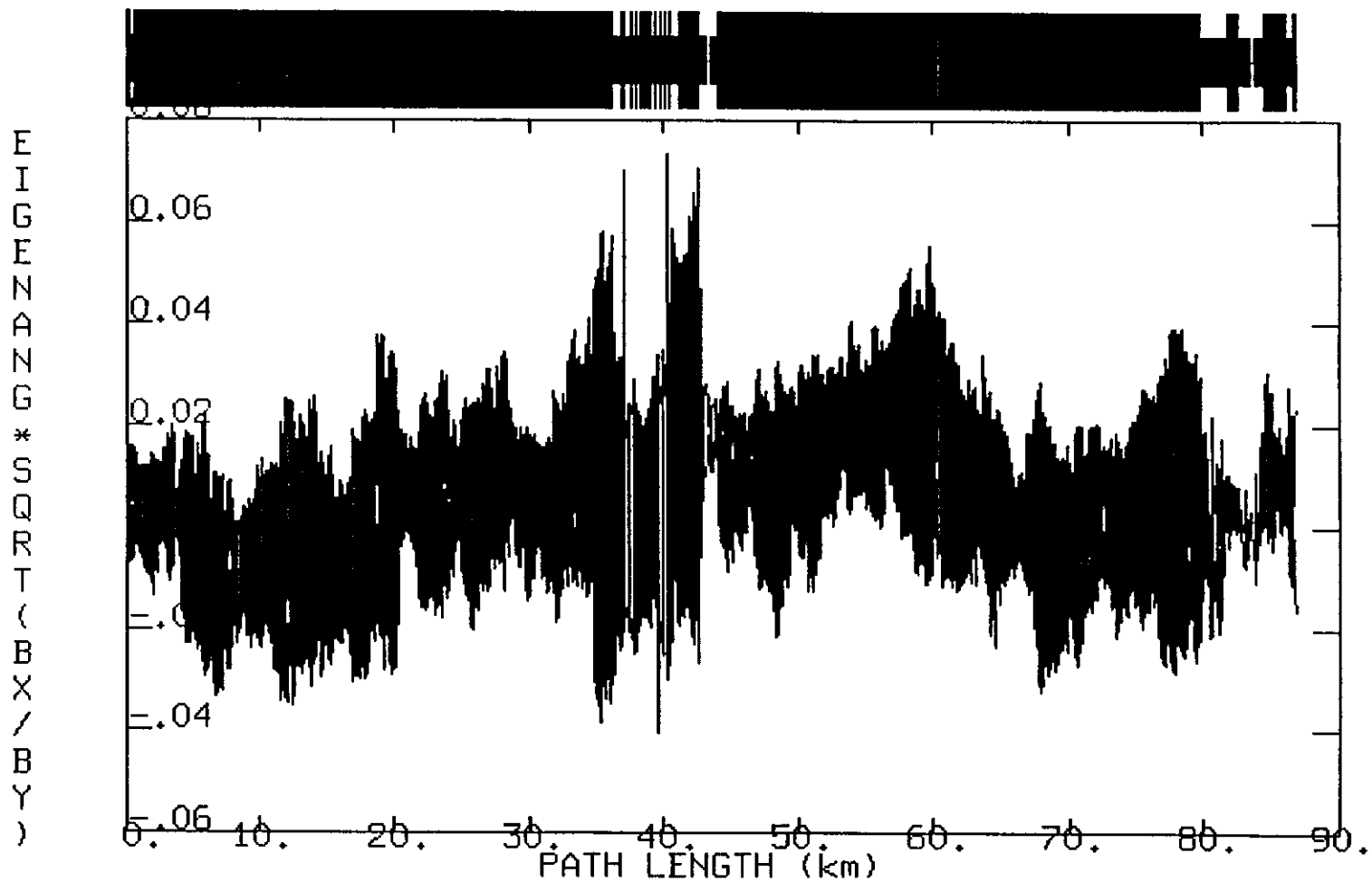

Fig. 4b The eigenangle vs path length with parallel solenoidal fields at collision.