Effective Length of the Main Injector Dipole and its Effect on Main Injector

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Introduction

We present in this paper measurements of the effective length of the Main Injector Dipole Magnets and its effect on the accelerator. These measurements are used in the simulations of the Main Injector using a thin element tracking program *TEAPOT*[1]. The closed orbit errors and beta function deviations due to the change in the effective length are discussed.

Measurement of the MI Dipole Effective Length

The Main Injector (MI) will have two different size dipole magnets, their magnetic lengths are 6.096 and 4.064 meters at 120 GeV. At present two long MI dipole magnets have been built. Measurements of the magnetic length of these magnets were performed at the Magnet Test Facility of FNAL using Flatcoil and Rotating coil probes. Since the magnetic length variation is due to end effects and both length magnets will have identical end packs, we can use the measurements of the change in effective length of long magnets to estimate short magnet's magnetic length.

The effective length of the magnet is defined as

$$L_{eff} = \Big(\int_{Body+End} B.dl / < B >_{Body} \Big)$$

$$= \Big(\int_{Body+End} B.dl / \int_{Body} B.dl \Big) * \text{ Length of the Body Probe} \qquad (1)$$

At MTF we have used two Flat Coil probes one 24' long and other 16'4" long to measure body plus end and body $\int B.dl$. These two probes have two different coil thicknesses which introduces some error into the measurements. Effective length measured by this method averaged for both the magnets is shown in Figure 1. The measured effective length has been normalized at 120 GeV (7000 amps) to 6.096 meters. This normalization is discussed later. The ΔL of this dipole is shown in Figure 2. Using this value of ΔL for long magnet one can calculate the effective change in length of the short dipole magnet as shown in Figure 3.

The change in the length of the magnet will change the bending of the particle to the first order, which is mainly due to the dipole component of the field. The tracking calculations use all the measured multipoles, normal and skew of the body and two ends of the magnet. Section 2.2 of *MI66*[2] describes how the end and body multipoles are derived using the harmonic (rotating) coils measurements. The multipoles used in the tracking calculation were calculated using the measurements, where the 80" rotating coil was placed 50" inside the magnet rather than 30" as described in MI66. This change gives us more consistent results at all energies. These values are also in better agreement with the fit to the flat coil data between -1" to +1" in x. In these rotating coil measurements one directly measures the dipole component of the field. Using a set of rotating coil body and ends measurements one can calculate the $\int B_0.dl$ to replace $\int B.dl$ in equation 1. This gives the effective length of the magnet due to its dipole component only. The end dipole kick of the magnet is equal to zero at an energy where the magnetic length and the physical length are equal (chosen here to be 120 GeV). The effective length calculated by using only the dipole component of the field measured by rotating coil is 6.096 meters at 120 GeV. We have normalized the flat coil measurement to this value at 120 GeV giving $\Delta L = 0$ and hence zero dipole kick at 120 GeV. All the multipoles calculated by these measurements and calculations are consistent with each other. This length normalization should removes the measurement uncertainty due to flat coil probes.

We have also measured the change in the effective length by using an 80" Flatcoil probe. The Flat coil measures

$$J(z) = \int_{-\infty}^{z} Bdl$$

as a function of z. The data were measured at z = 0, 5", 10",.... up to 40". The effective length ,ΔL_{eff}, is calculated by fitting J(z) to a straight line $J(z) = (slope) * z + (intercept)$, and then calculating the change in effective length by

$$\Delta L_{eff} = Intercept/Slope$$

These results are shown in Figure 4 relative to L_{eff} at 120 GeV for one end. This result is very similar to the full length measurement.

We have studied the 80" Flat coil measurements to find the region in z which contributes to the change in effective length. We calculate $J(z0, z) = J(z) - J(z0)$ which gives us the integral measured between points z0 and z in the magnet. ΔL_{eff} is then calculated using procedure as before to give the dependence of ΔL_{eff} on the cutoff z0. For the z0 cutoff of $-\infty$ and 0 the ΔL_{eff} is similar to as show in figure 5. For z0 = 5" the ΔL_{eff} is very small as shown in figure 6. These results show that almost all of the current dependence of ΔL_{eff} is attributed to the region between $0 < z < 5"$. The contribution of the field external to the magnet contributes only slightly, and only at low current.

We are working to improve the Main Injector Magnet end pack design. Figure 5 shows the effective length measurement due to one of the new end pack design. The two different data points are to show the reproducibility of these measurements.

All tracking calculations were done using the ΔL from figure 2.

Closed Orbit Errors

The change in length of the magnet introduces a non zero dipole multipole at each end of the magnet and is represented in TEAPOT by a horizontal kick given by

$$H_{kick} = (\Delta L/2L_{ref}) * (2\pi/904/3) \qquad \text{radians}$$

This additional bending of the particle is corrected by adjusting the dipole strength calculated by eq-14 of MI-66. These two systematic changes introduce an error to the closed orbit of the particle.

The closed orbit error due to ΔL_{eff} at all energies is given in Table 1. The corrector strength required to correct the closed orbit error due to ΔL_{eff} is also listed in this table. The change in the effective length introduces a small closed orbit error in the horizontal direction. This error is small compared to the closed orbit error due to the dipole random and displacement errors[3]. The closed obrbit error due to change in the effective length for the MI at 8.9 GeV is shown in figure 7. This also has a very small effect on the beta function of the MI. The percentage change in the beta function due to ΔL at 8.9 GeV is shown in Figure 8.

References

1. L. Schachinger and R. Talman, Particle Accl. 22, 35(1987).

2. F. A. Harfoush and C. S. Mishra, MI notes 0066.

3. C. S. Mishra and F. A. Harfoush, MI notes 0070.

Table 1

Close Orbit Errors Due to ΔL at Different Energies

Energy GeV	Plane	RMS Deviation mm	Corr Strength μradian
8.9	H	1.05	6.
	V	0.0	
21.5	H	1.06	11.
	V	0.0	
120.	H	0.0	
	V	0.0	
150.	H	1.93	11.
	V	0.0	

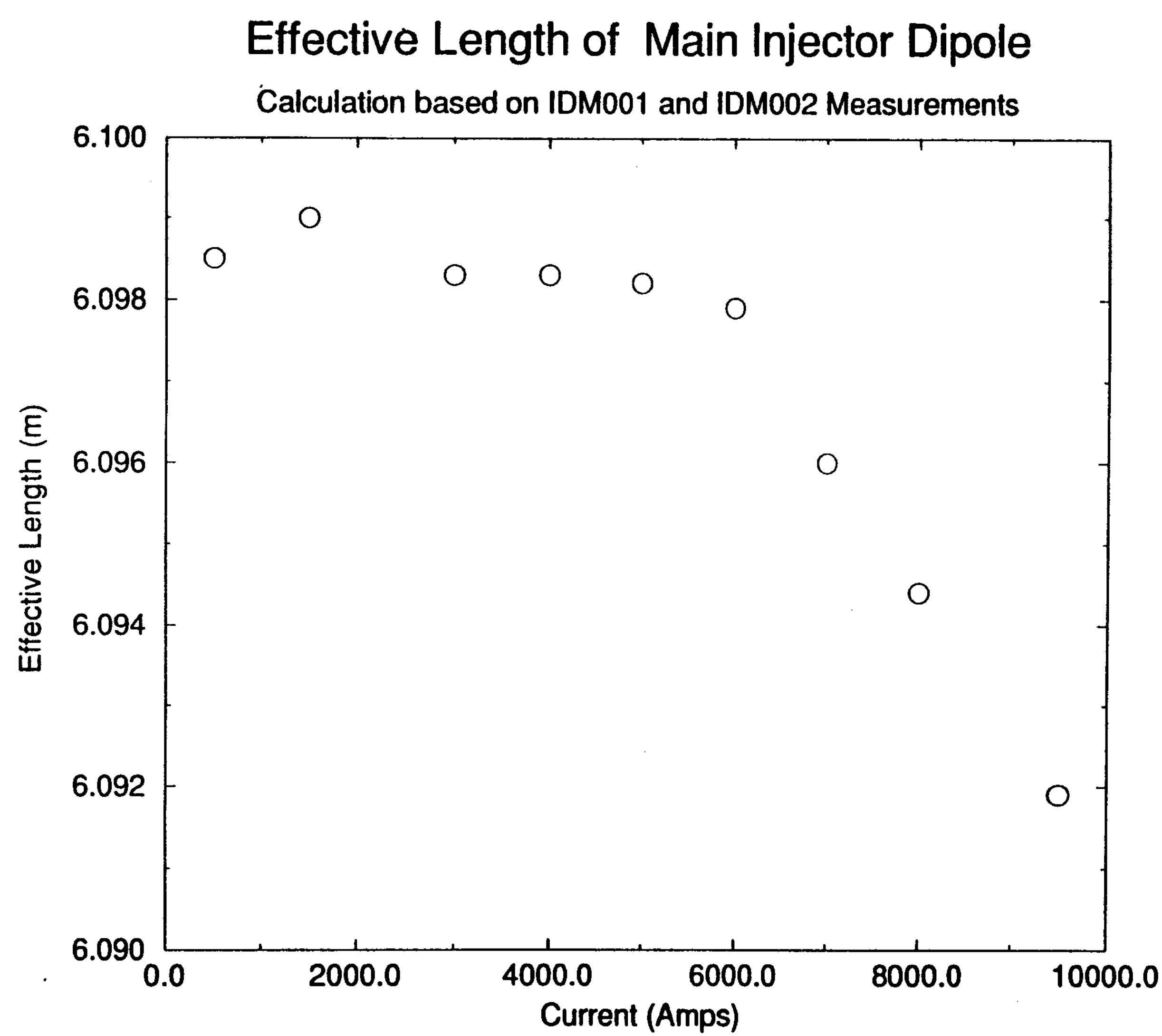

Fig. 1 Measured average effective length of Long Main Injector Dipole.

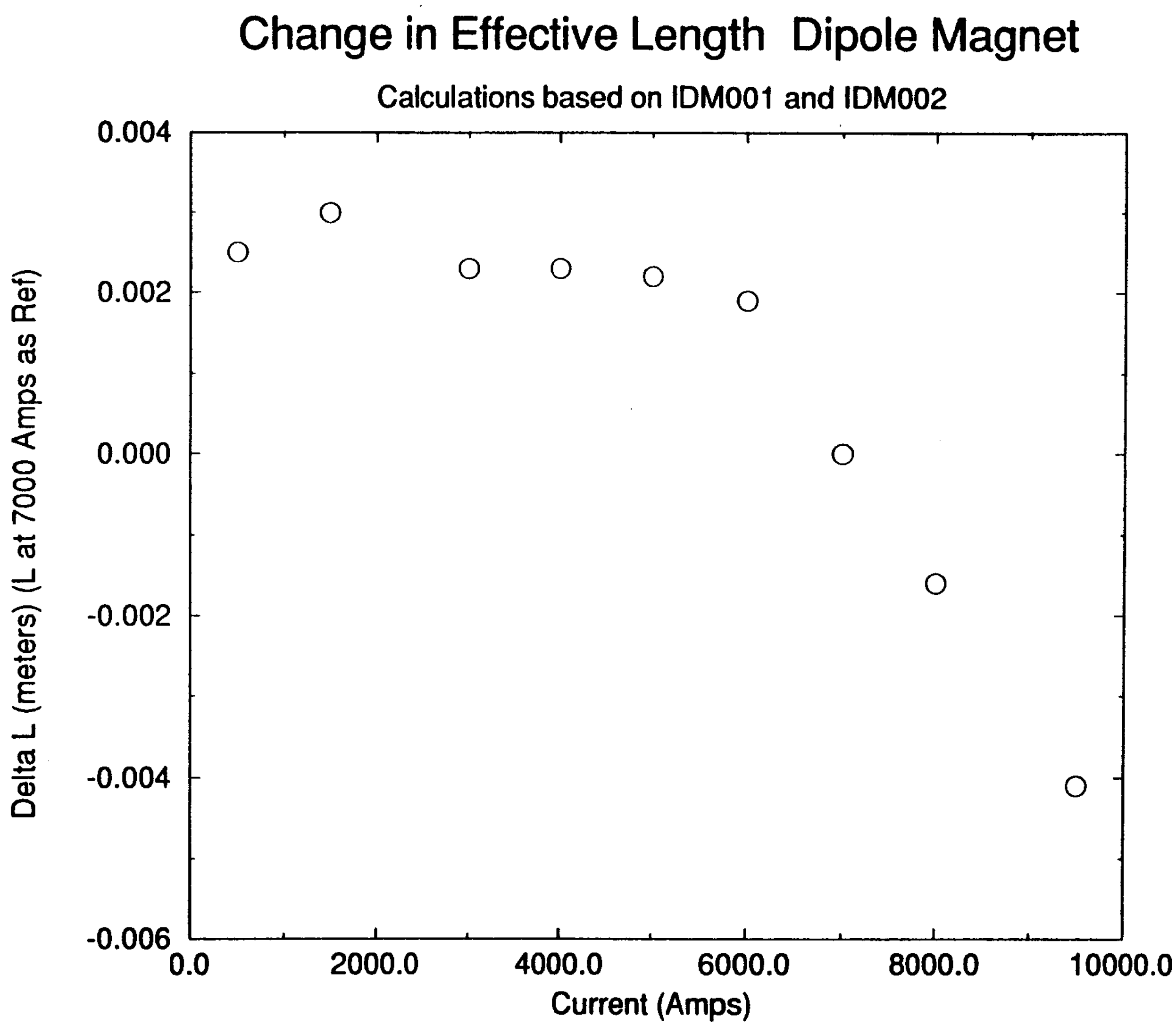

Fig. 2 ΔL of Main Injector Dipole.

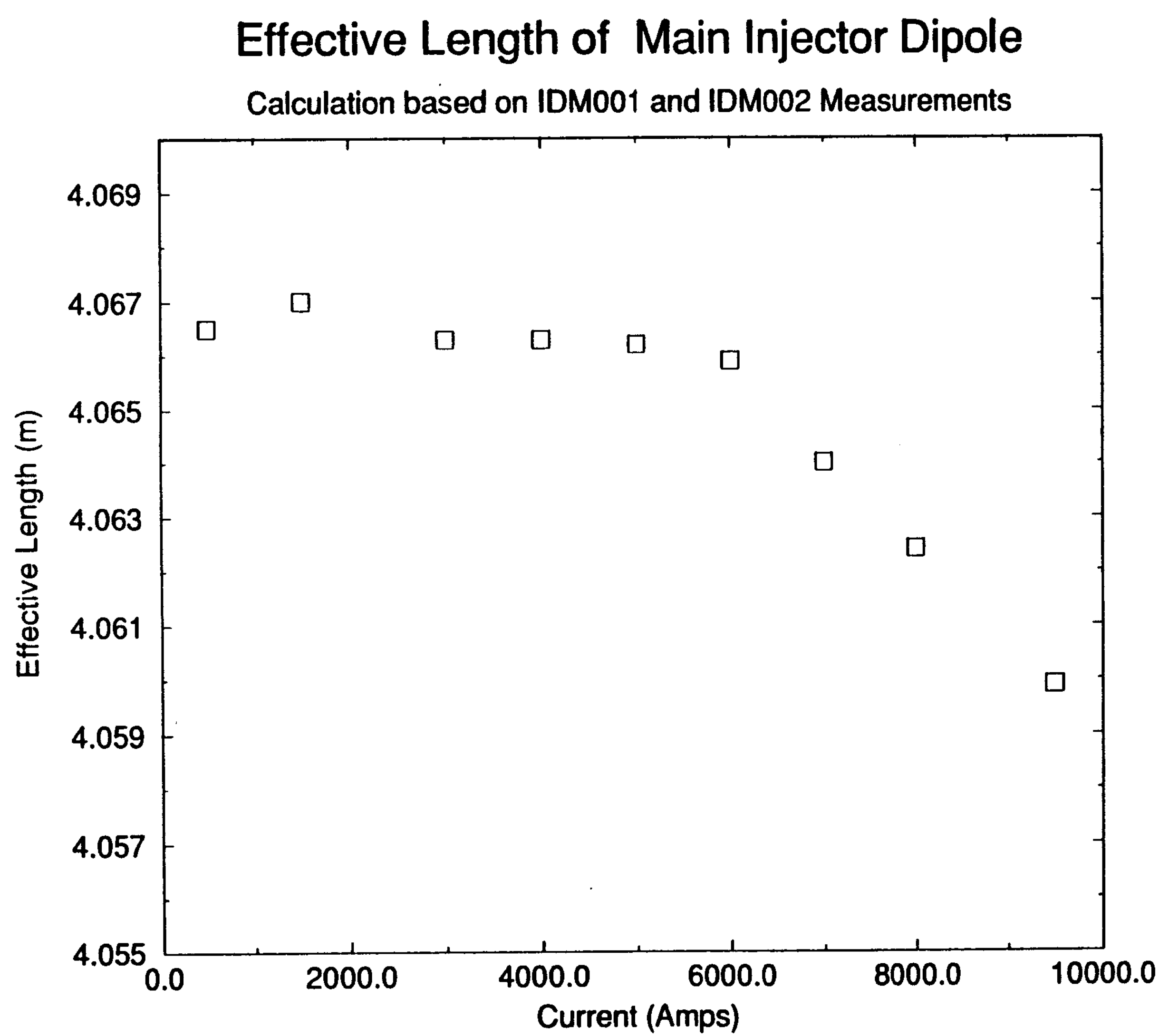

Fig. 3 Calculated effective length of short Main Injector Dipole.

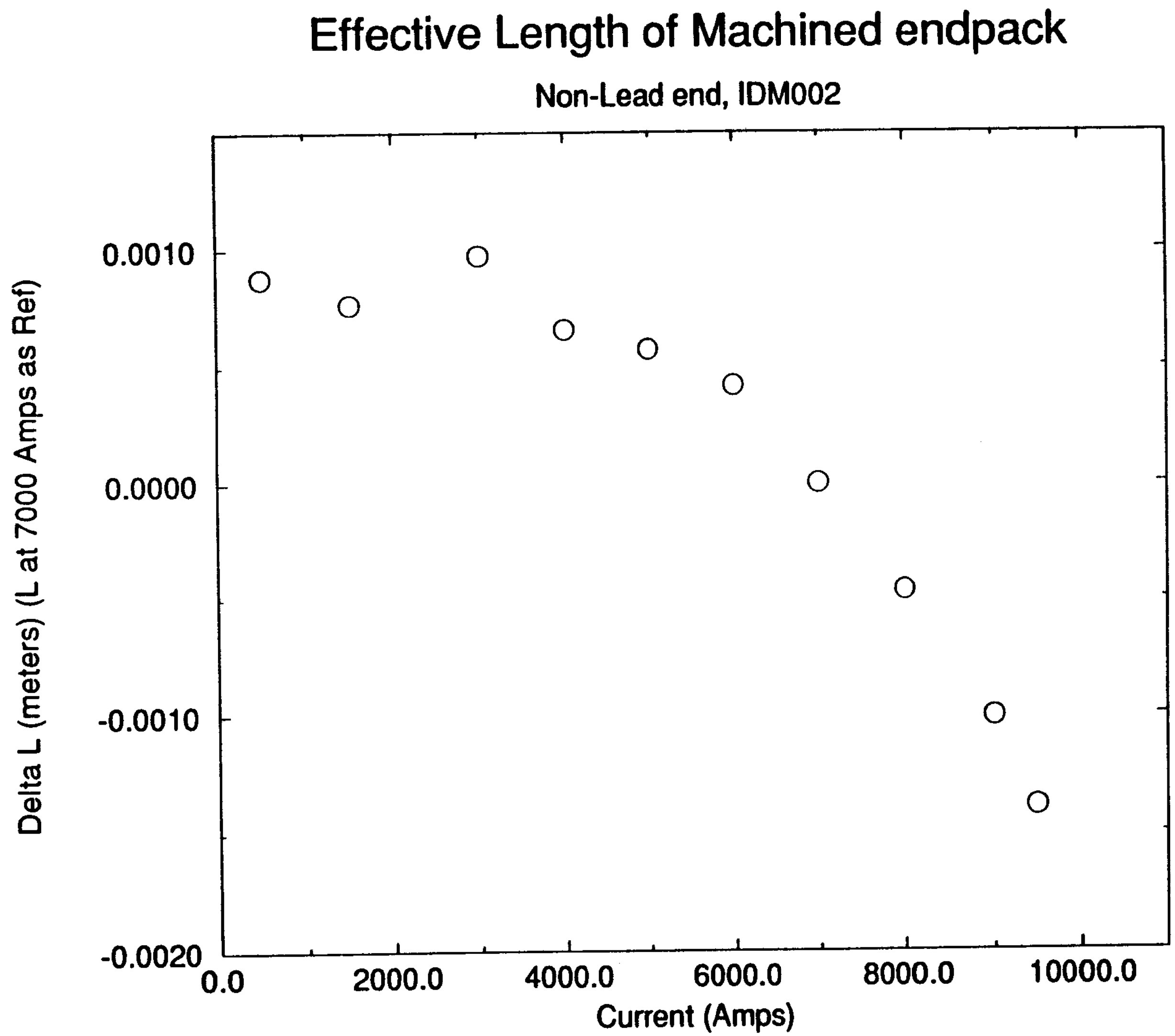

Fig. 4 Measured ΔL of the Main Injector Dipole end, Machined Endpack.

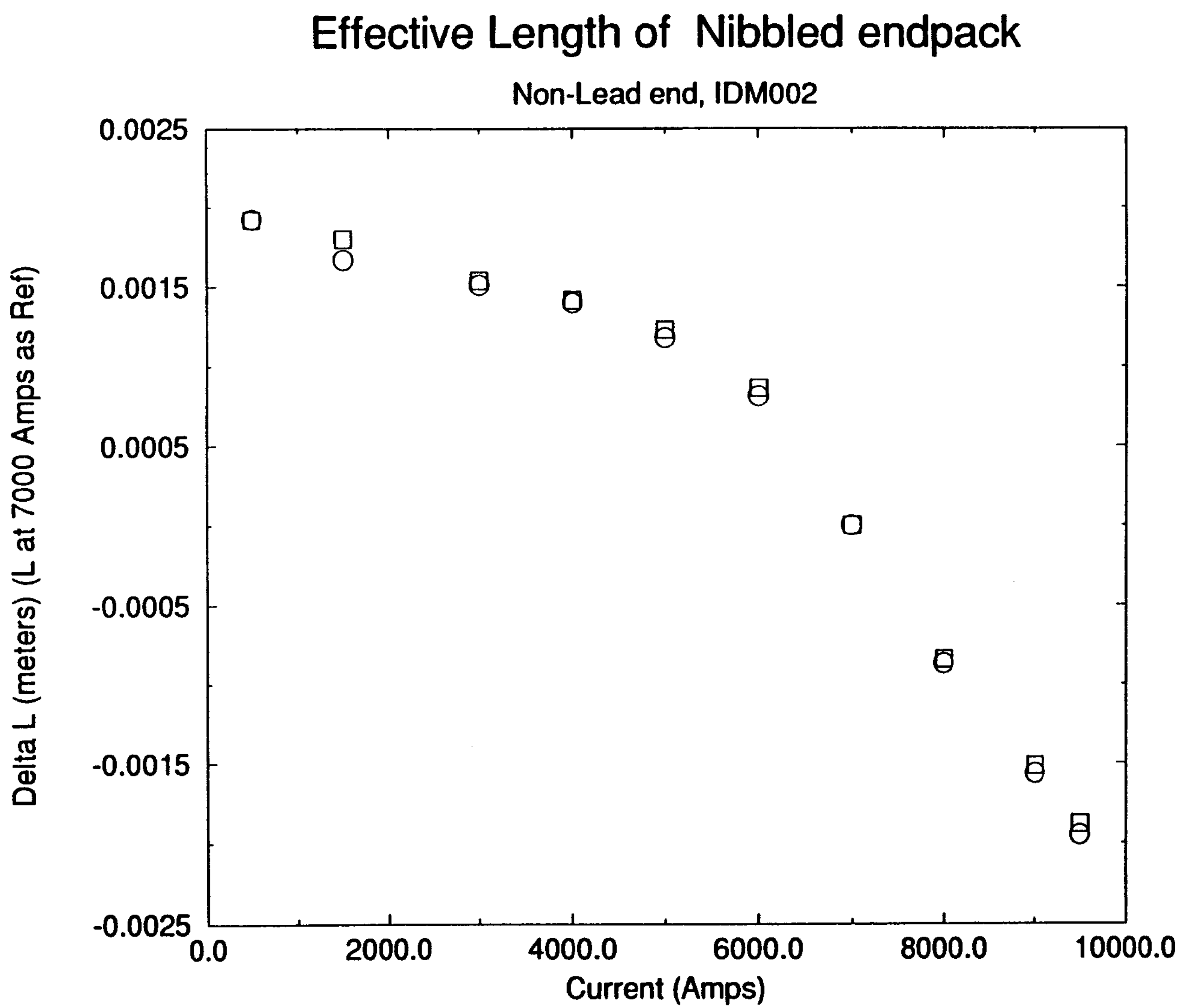

Fig. 5 Measured ΔL of the Main Injector Dipole end, Nibbled Endpack.

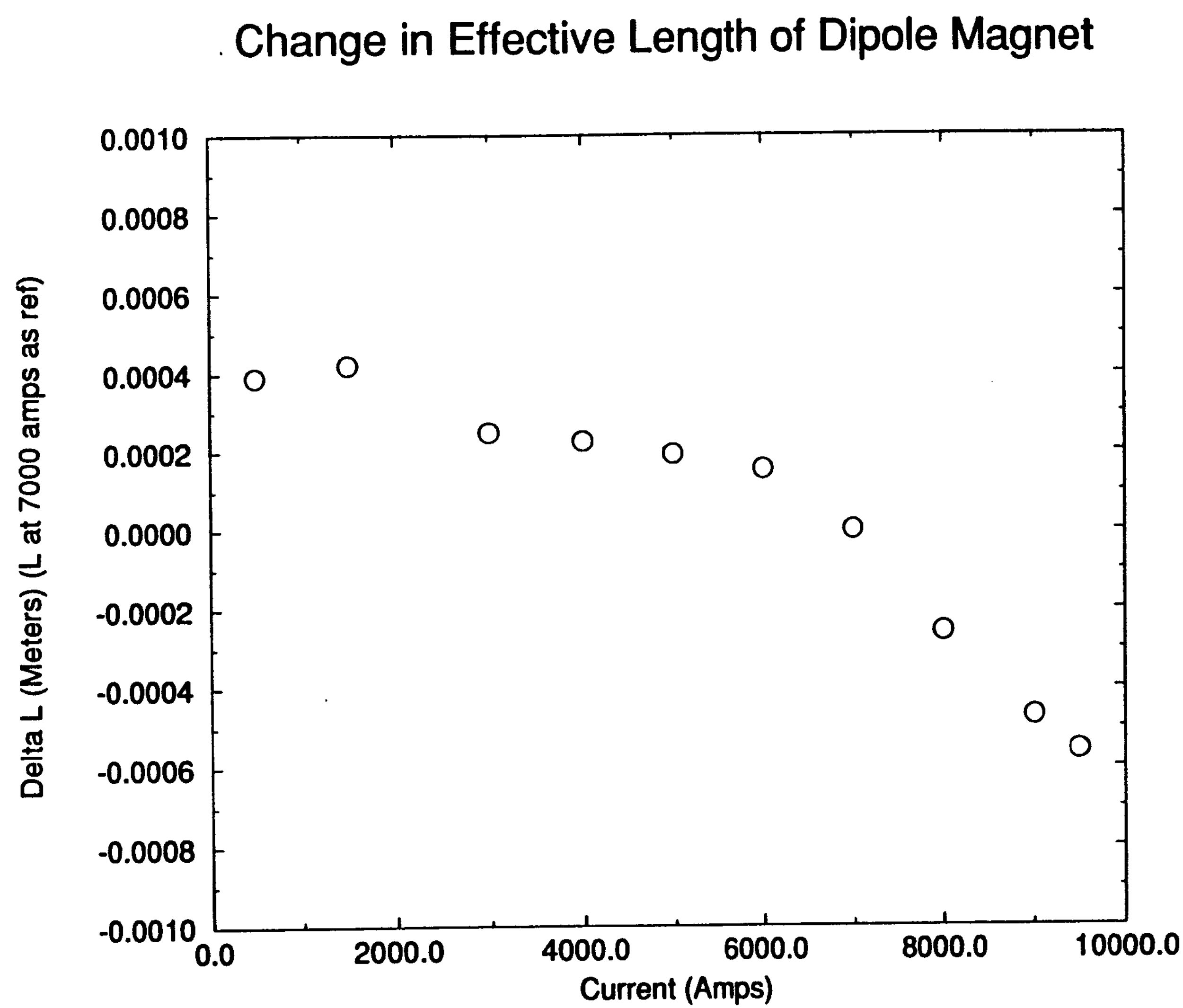

Fig. 6 Measured ΔL of the Main Injector Dipole end, for z > 5".

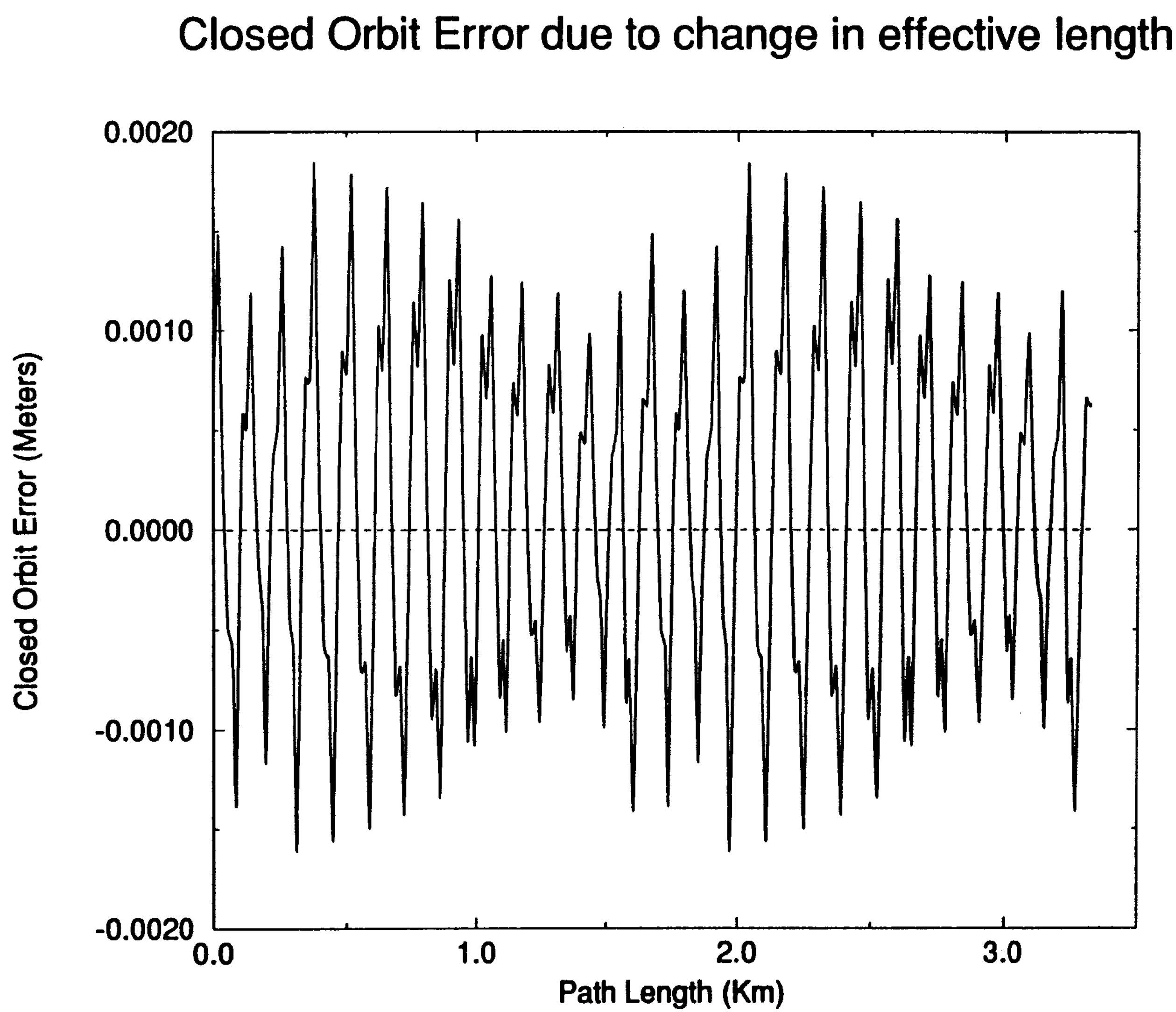

Fig. 7 Closed orbit error due to change in effective length.

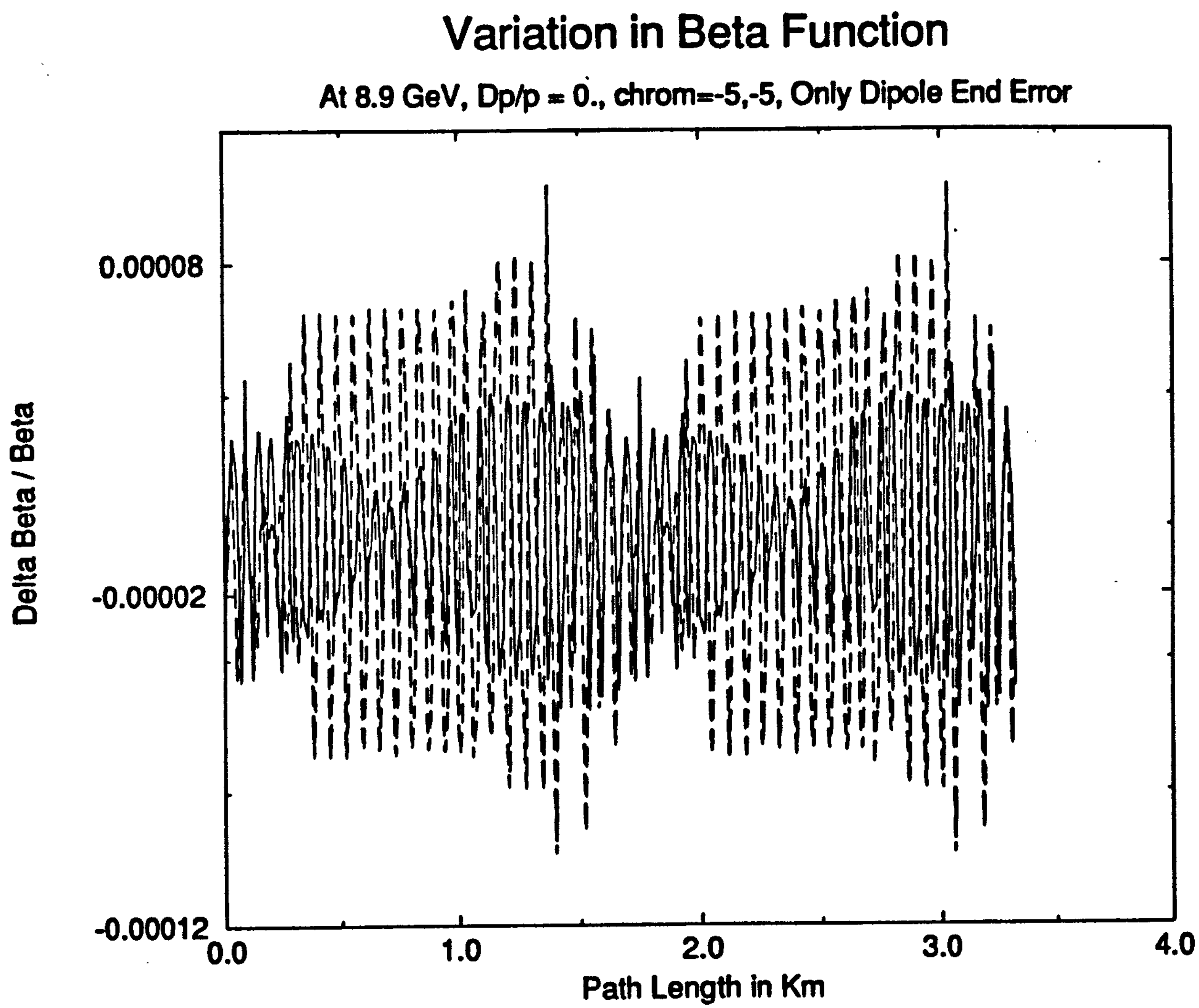

Fig. 8 Variation in Beta Function due to change in effective length errors .