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Effect of Persistent Currents in SSC Dipole Magnets on Chromatic Behavior and Dynamic Aperture

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INTRODUCTION

The importance of the systematic sextupole component driven by the persistent currents in SSC dipole magnets for the chromatic properties of the machine was recognized very early on by Cornacchia[1]. He concludes that from the accelerator physics point of view the preferred correction scheme is a local sextupole scheme. The presently available SSC-magnet data[2] show however that the persistent current not only produce a large sextupole component but also a substantial 10-pole and a noticeable 14-pole contribution. In the present study we investigate the effect of the systematic sextupole, decapole and 14-pole moments due to persistent currents on the chromatic behavior and the dynamic aperture of a test lattice with clustered IR's using the code "RACETRACK"[3].

Lattice

The lattice used for this study is of the type $(2,4)_b$ according to the adopted nomenclature.[4] It's circumference is 103,200 m and the insertions are grouped in two clusters on opposite sides of the ring: One containing four IR's, the other two IR's and two utility insertions. All insertions have a length of 3800 m, and a phase advance of 0.25, and are equipped with a pair of phase trombones and dispersion suppressors. The IR's have a $\beta^* = 1$ m (no beam crossing, however), while the utility insertions are made up of regular cells (plus trombones and dispersion suppressors). A lattice schematic is

Fig. 1. Magnetic imperfections are included only for the arc cell dipole magnets. The values for the multipole moments used are those given in ref. 2 for magnet design "D" (4 cm coil diameter) and a 9μ filament. They are listed in Tables 1 and 2.

Correction Schemes

Two correction schemes have been considered as possible solutions to the persistent current problem: local and lumped correction. The local correction scheme includes extra windings on dipole magnets to compensate locally for the multipole moments due to persistent currents in that magnet. Not only from an accelerator physics point of view but also for practical considerations is the local scheme much preferred: The integrated strengths of the chromaticity sextupoles for the bare lattice with 0 chromaticity are

$$SF^{\circ} = -0.0047 \quad m^{-2}$$

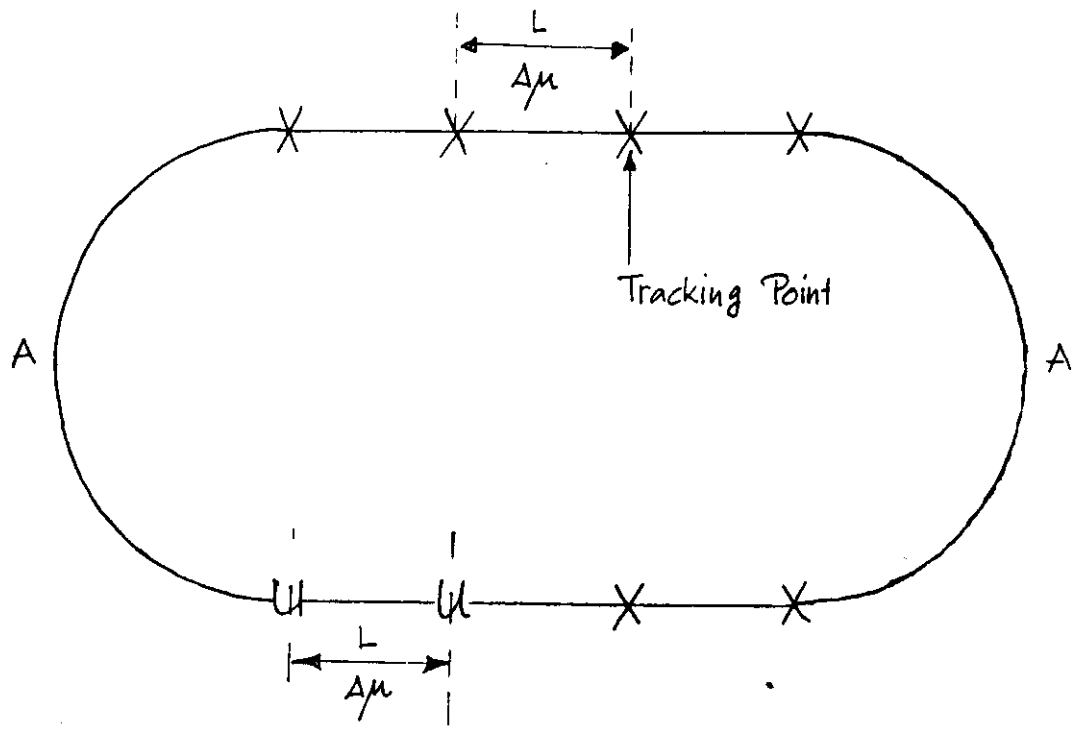
$$SD^{\circ} = +0.0075 \quad m^{-2} \; .$$

When the b_2-term due to persistent currents is included in the arc dipole magnets the chromaticity sextupole strengths required to bring the chromaticity back to zero are increased by a factor of 10

$$SF(b_2) = +0.0470 \quad m^{-2}$$

$$SD(b_2) = +0.0788 \quad m^{-2} \; .$$

The very strong sextupole values required, make the lumped corrector scheme rather unattractive. A further complication comes from the fact that for the decapole correction there is no global lattice parameter (corresponding to the chromaticity for the b_2-correction) that can be calculated easily to determine the decapole corrector strength. As a consequence we have investigated systematically the local correction scheme only.



$\Delta\mu$	=	0.25
L	=	3800 m
A	=	40200 m
X		IR $\beta^* = 1$ m
U		"Utility Insertion" (regular cells with phase trombones and dispersion suppressors)

Figure 1. Schematic of test lattice $(2, 4)_b$.

Table 1.

Systematic errors due to persistent currents.

b_n = normal coefficient of 2(n+1) pole

Magnet Design "D" (4 cm), 9μ filament.[2] Units: 10^{-4} at 1 cm

b_2	b_4	b_6
-7.5	+0.67	+0.13

Table 2.

RMS Multiple Variations σ_{Tot}

a_n, b_n = skew, normal coefficient of 2(n+1)-pole.

Magnet Design "D" (4 cm), 9μ filament.[2] Units: 10^{-4} at 1 cm

n	=	2	3	4	5	6
$\sigma_{a,n}$	=	0.63	0.69	0.14	0.16	0.034
$\sigma_{b,n}$	=	2.15	0.35	0.59	0.059	0.076

Chromatic Behavior

Three different correction schemes have been investigated. They differ in the number of multipole moments that are being corrected. For this part of the study systematic errors have been included only, and the variations of tune ΔQ and betatron function β^* at the IP have been determined as a function of momentum for various configurations of systematic errors b_2, b_4, and b_6. Without rigorously adopting the "ground rules" established for the clustered IR lattice study[4)], we might use some of them as guide lines. In particular we assume that in the momentum range

$$-10^{-3} \leq \delta \leq 10^{-3}$$

the magnitude of the tune shift shall not exceed 0.005, and the variation of β^* shall not exceed $\pm$ 0.1. All the calculations and the tracking have been done for lattices with zero chromaticity, by first adjusting the strength of two family sextupole scheme. The systematic error values used for $b_{2n}(n = 1, 2, 3)$ are

$$b_{2n}^{eff} = f_{2n} \cdot b_{2n}$$

where b_{2n} are the nominal values listed in Table 1, and the values used for f_{2n} ran through the series

$$f_{2n} = 0,\ 0.01,\ 0.03,\ 0.1,\ 0.3,\ 1 \quad .$$

These factors reflect not only the effectiveness of a correction scheme but also the filament size used in the conductor of the magnets.

1) "Complete" Correction Scheme

In this scheme there are correction windings assumed for all multipole moments originating from persistent currents. The values for the multipole moments b_{2n}^{eff} used in the calculations are a common fraction of the corresponding tabulated values b_{2n}(Table 1):

$$b_{2n}^{eff} = f \cdot b_{2n} \qquad n = 1, 2, 3$$

Figure 2 and 3 show the data, ΔQ and β^*, as a function of $\delta = \Delta p/p$, for two cases: The solid lines represent the uncorrected lattice, i.e. f = 1, which is clearly not acceptable by any standards, particularly with the unphysically strong lumped sextupoles required to correct the chromaticity. As the fraction f is reduced the behavior of β^* and ΔQ improve gradually and become acceptable for f = 0.03. This case is indicated by the dashed lines in Figs. 2 and 3.

2) "Sextupole" Correction Scheme

In this scheme the values for b_4^{eff} and b_6^{eff} are kept constant as the nominal value given in Table 1, only b_2^{eff} is varied:

$$b_2^{eff} = f \cdot b_2$$

$$b_6^{eff} = b_4$$

$$b_6^{eff} = b_6$$

The results are shown in Figs. 4 and 5. Again the solid lines represent the uncorrected case f = 1, while the dashed line shows the case where b_2 is

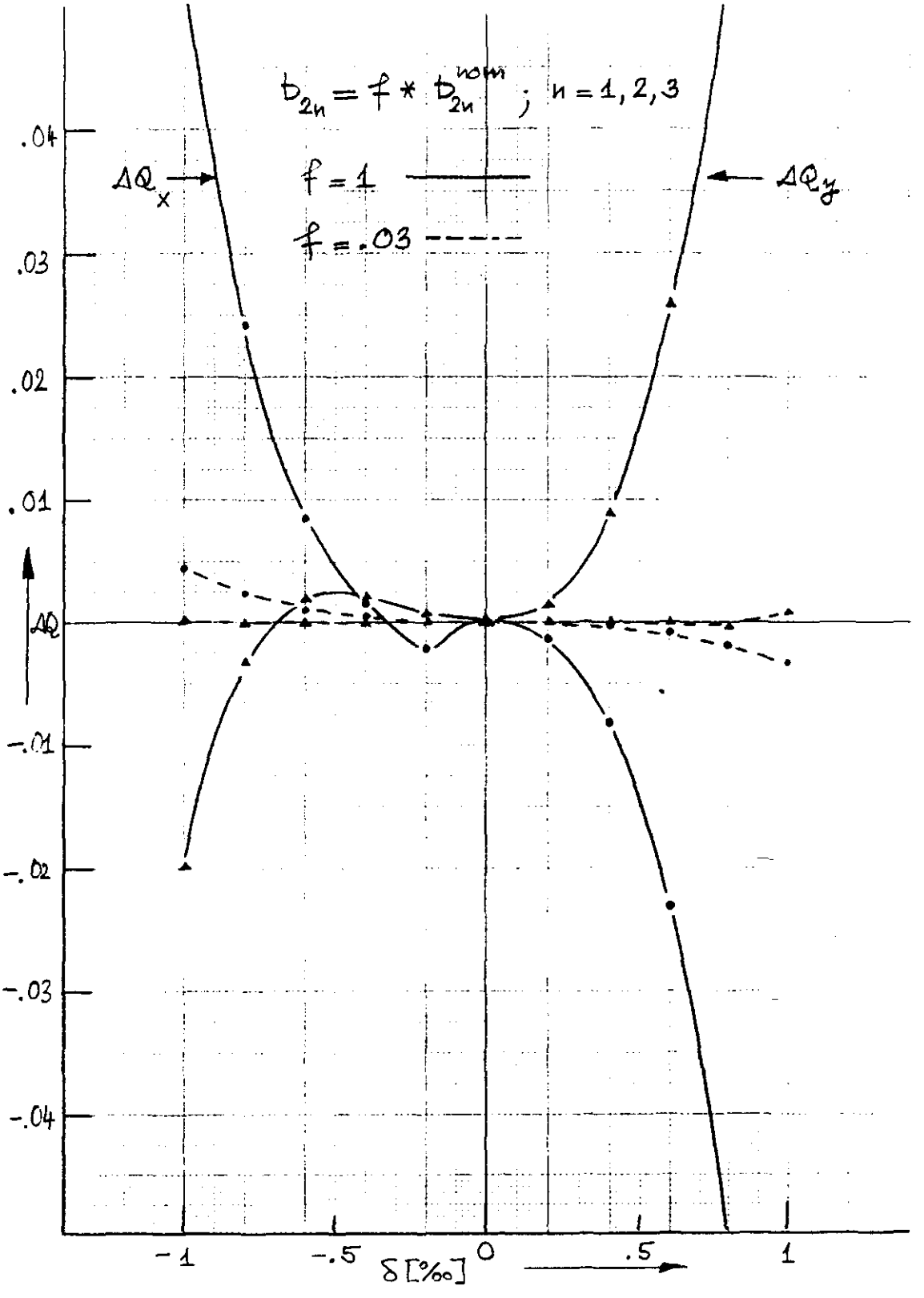


Figure 2. "Complete" correction scheme, chromatic behaviour of ΔQ.

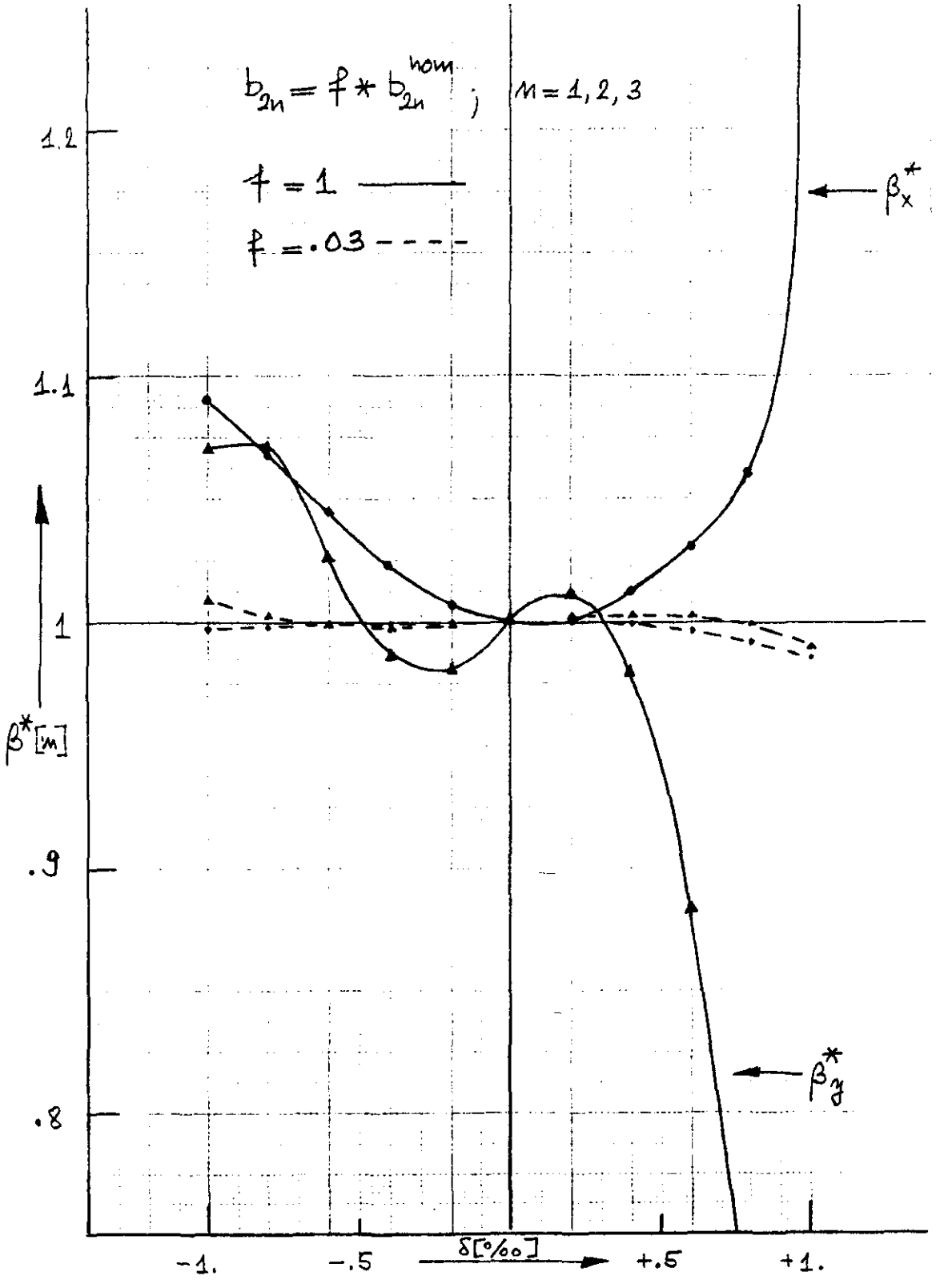


Figure 3. "Complete" correction scheme, chromatic behavior of β*.

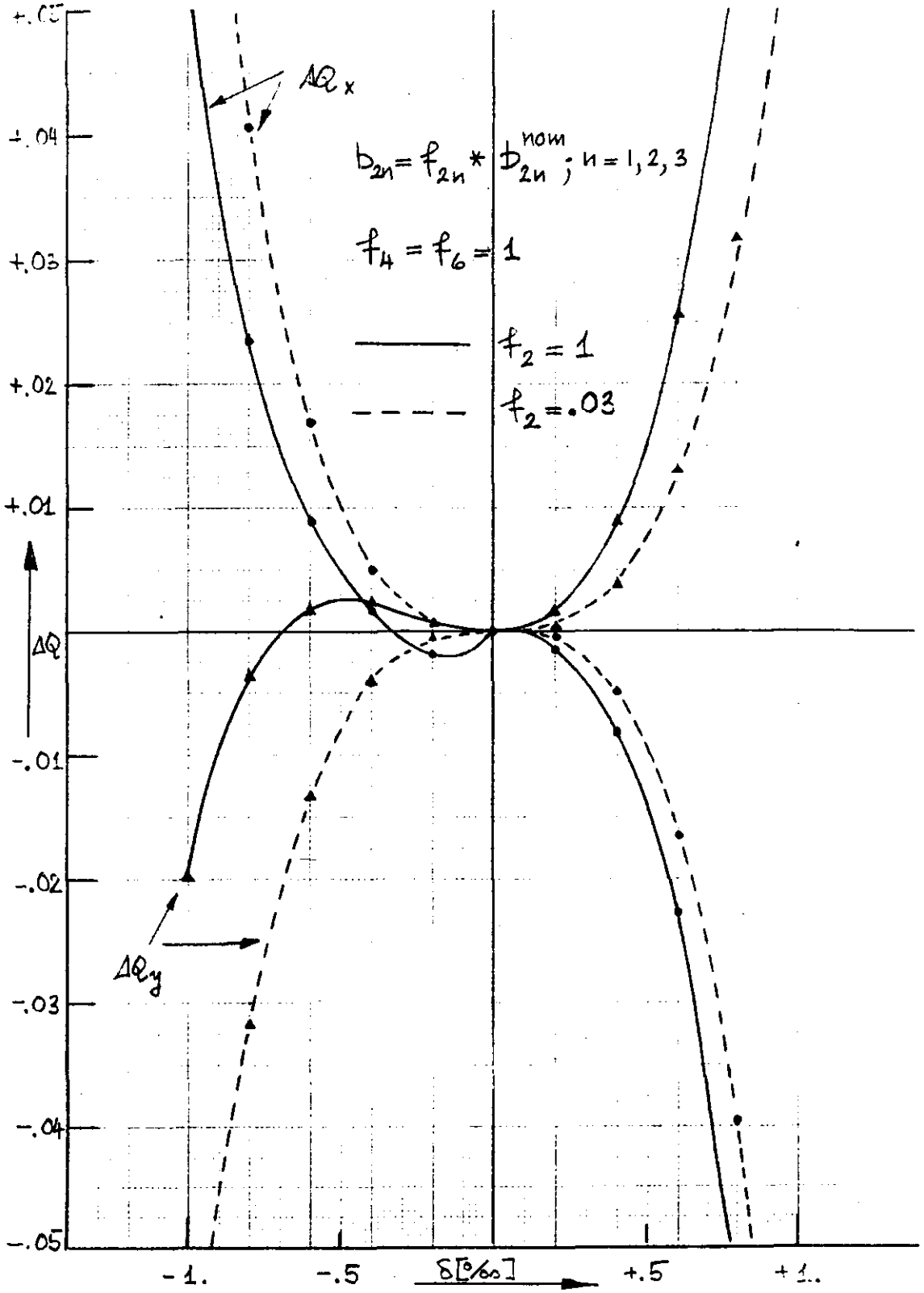


Figure 4. "Sextupole" correction scheme, chromatic behavior of ΔQ.

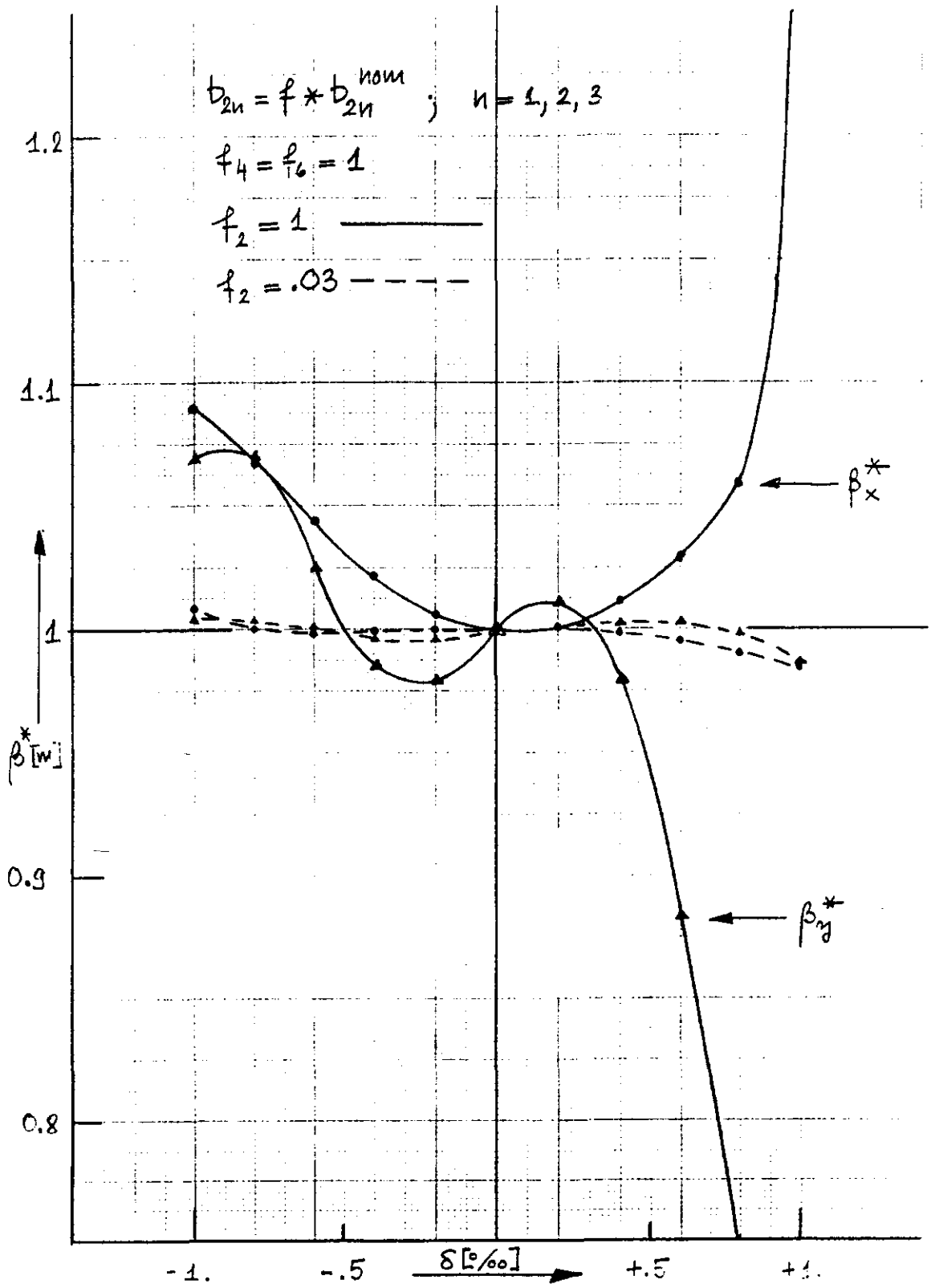


Figure 5. "Sextupole" correction scheme, chromatic behavior of β*.

corrected to 97% ($f = 0.03$). The variation of β^* shows a significant improvement over this range, however this is not so for the tune shift ΔQ. Going from $f = 1$ to $f = 0.03$ hardly changes the tune shift variation. This does not imply that the b_2 term is unimportant, but rather that the locally uncorrected part b_2^{eff} is well corrected by the lumped sextupole. The culprit, however, is the sextupole feed down from the decapole.

3) "Sextupole - Decapole" Correction Scheme.

In this scheme the value for b_6^{eff} is kept constant at the nominal value given in Table 1, but b_2^{eff} and b_4^{eff} are varied by a common factor:

$$b_2^{eff} = f \cdot b_2$$

$$b_4^{eff} = f \cdot b_4$$

$$b_6^{eff} = b_6$$

The results for this correction scheme are shown in Figs. 6 and 7, the solid lines representing the uncorrected case, the dashed lines the case of 97% correction for b_2 and b_4 ($f = 0.03$). These results must be compared to those for the "complete" correction scheme (Fig. 2 and 3). The only difference between the 2 cases is the correction of b_6. The lack of correction of that term is quite evident more so for the variation of β^* than for ΔQ. This scheme, strictly speaking, violates the "ground rules" [ΔQ (- 0.001) > 0.005], however this is not serious, because the 14-pole term can be taken care of by lumped b_6 correctors.

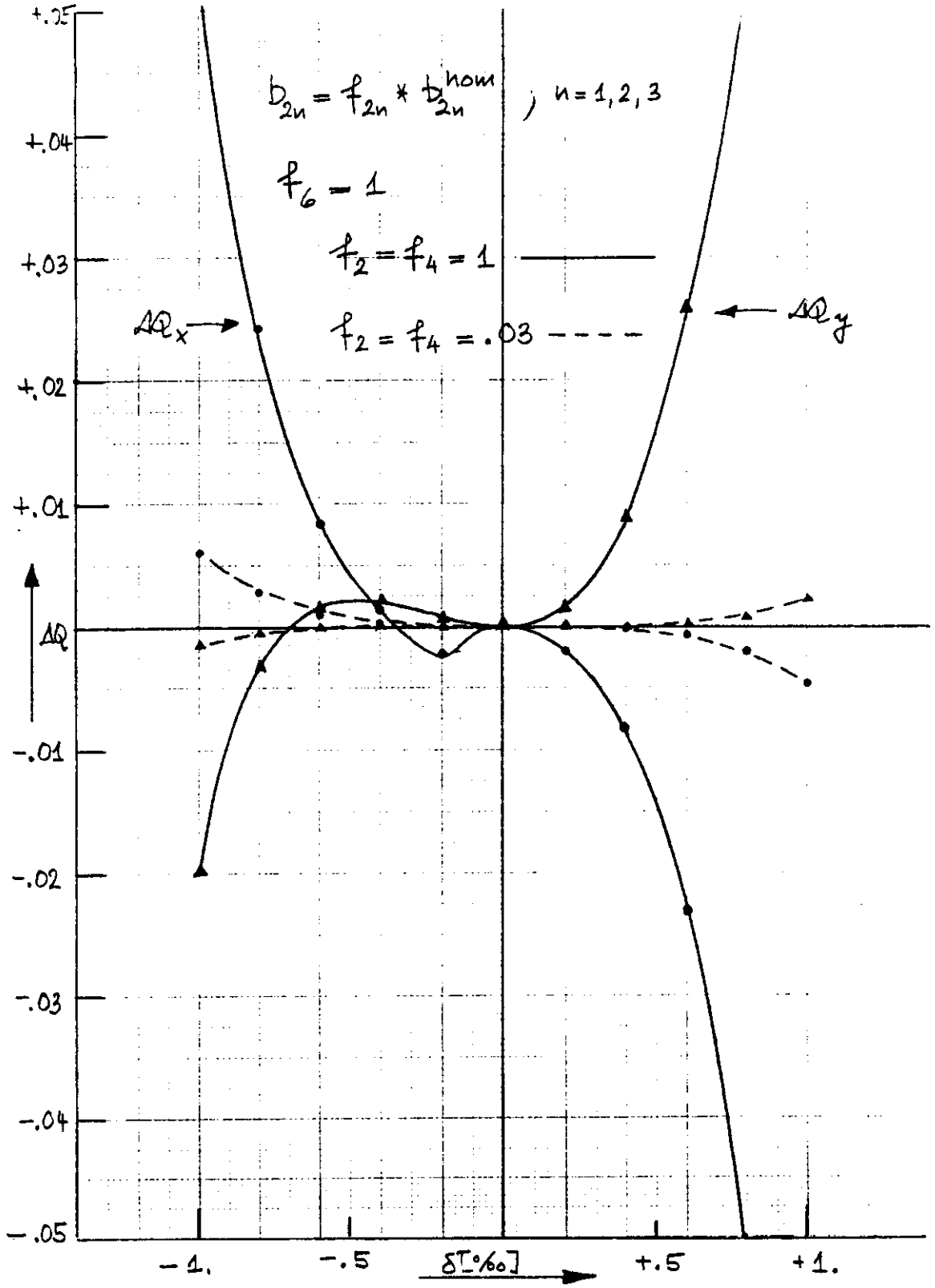


Figure 6. "Sextupole - Decapole" correction scheme, chromatic behavior of ΔQ.

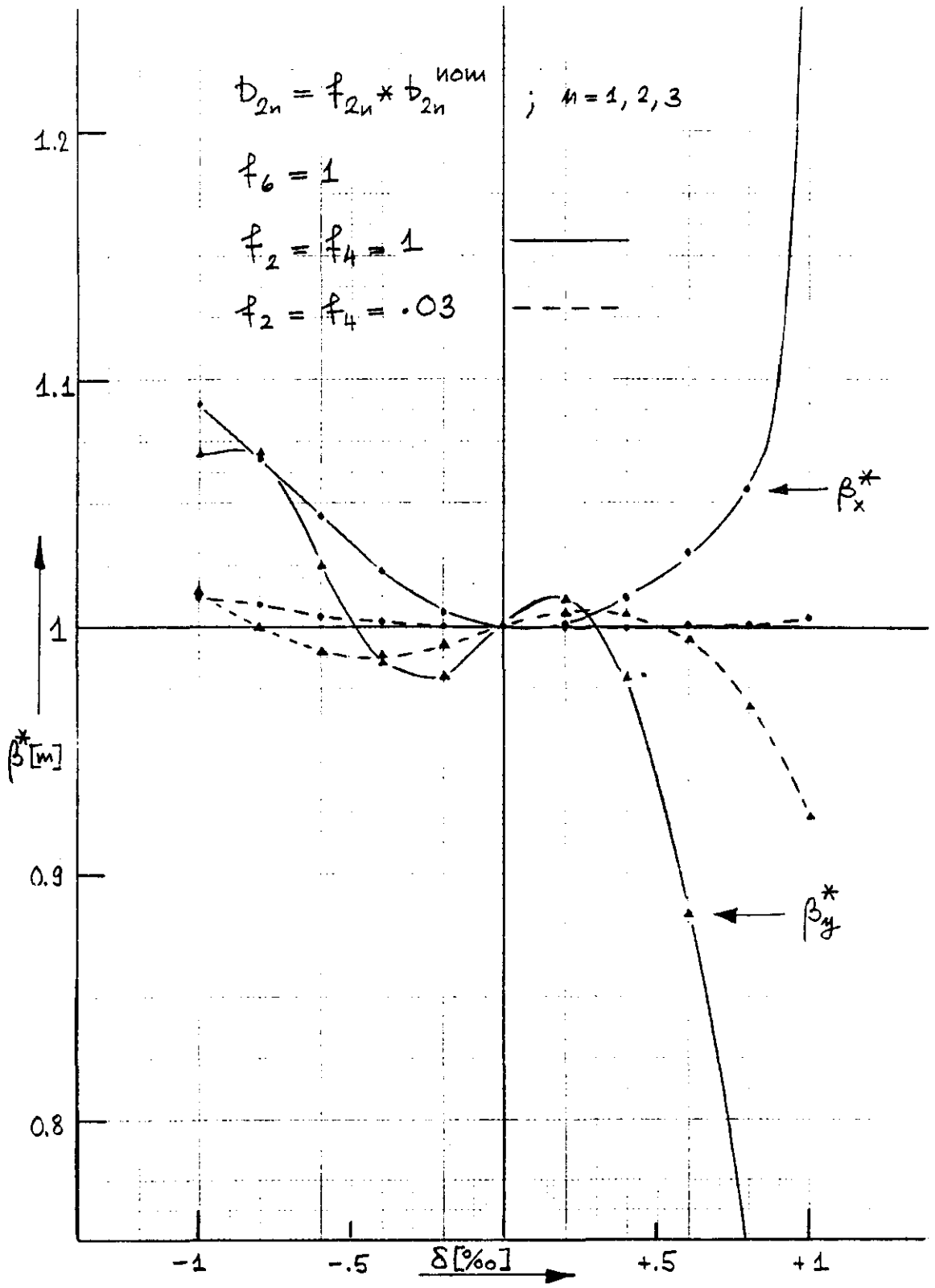


Figure 7. "Sextupole - Decapole" correction scheme, chromatic behavior of β*.

Dynamic Aperture

The dynamic aperture is determined by tracking 4 particles distributed on a normalized hypersphere in 4 dimensional phase space (x, x', y, y') for 400 turns and finding the maximum radius of that hypersphere for which all 4 particles survive. If the corresponding initial amplitudes are x and y then the dynamic aperture is given by

$$a = \sqrt{x^2 + y^2}.$$

Since the tracking is done at the interaction point (Fig. 1.)

$$a^* = \sqrt{x^{*2} + y^{*2}}.$$

In a first step the dynamic aperture was determined for the "complete" correction scheme mentioned above, i.e., the dynamic aperture as a function of the correction fraction f defined by

$$b_{2n}^{eff} = f \cdot b_{2n}, \; n = 1, 2, 3$$

without any random errors included and for $\Delta p/p = 0$.

For f values between 0.1 and 1 the aperture is very flat, but increases by over a factor of 4 when going from f = 0.1 to f = 0, as can be seen in Fig. 8, where these data points are represented by solid circles. This behavior follows essentially what has been observed for the chromatic properties. However, when random multipole errors are included this behavior changes completely as the two datapoints marked by squares in Fig. 8 demonstrate. These points represent the average based on 5 different random seeds for f = 0 and f = 0.1, respectively. The size of the square corresponds to $\pm \sigma$ for these 5 samples. In Fig. 9 the chromatic aperture for the case f = 0 is shown

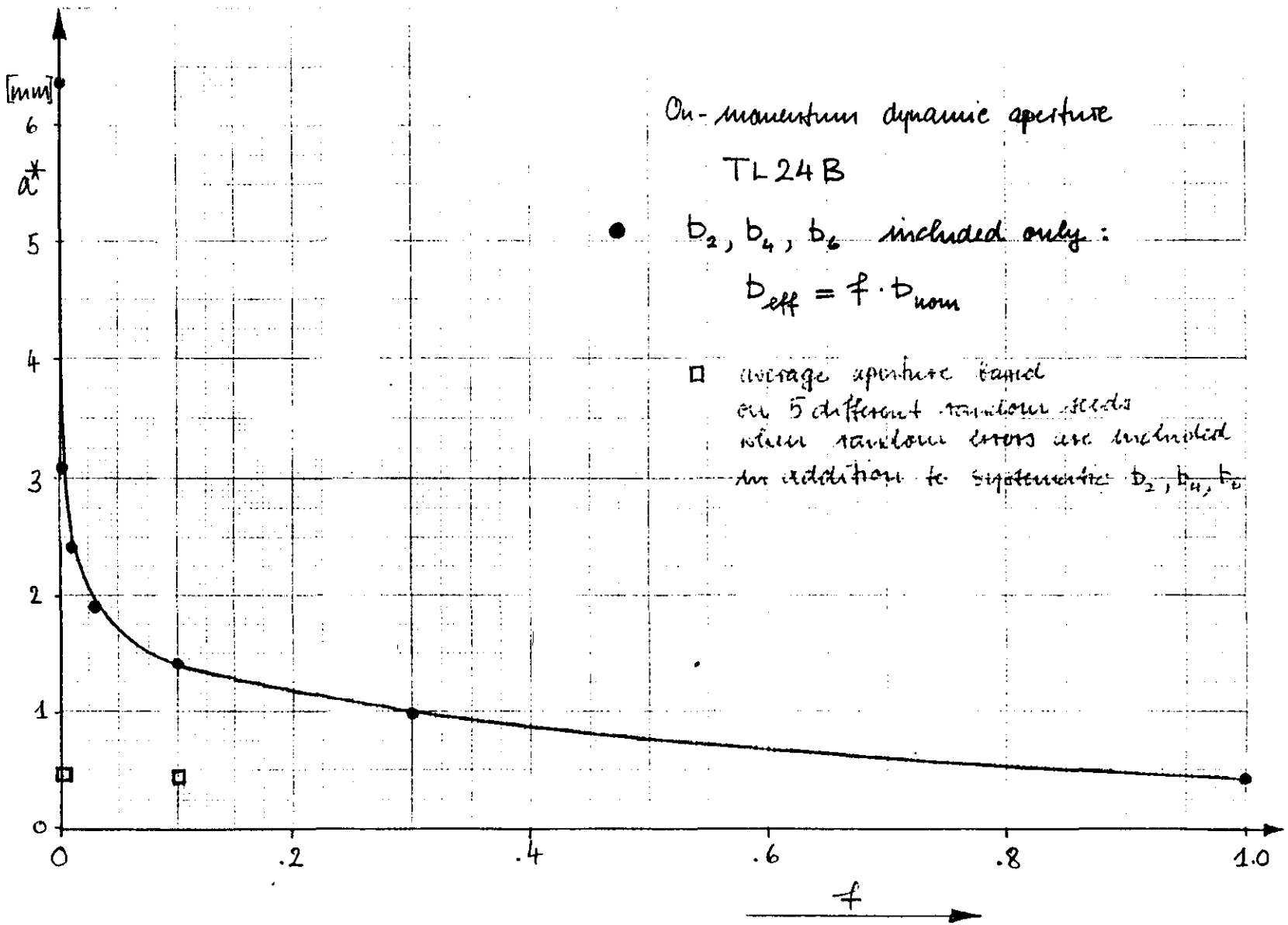


Figure 8. On-momentum dynamic aperture "complete" correction scheme.

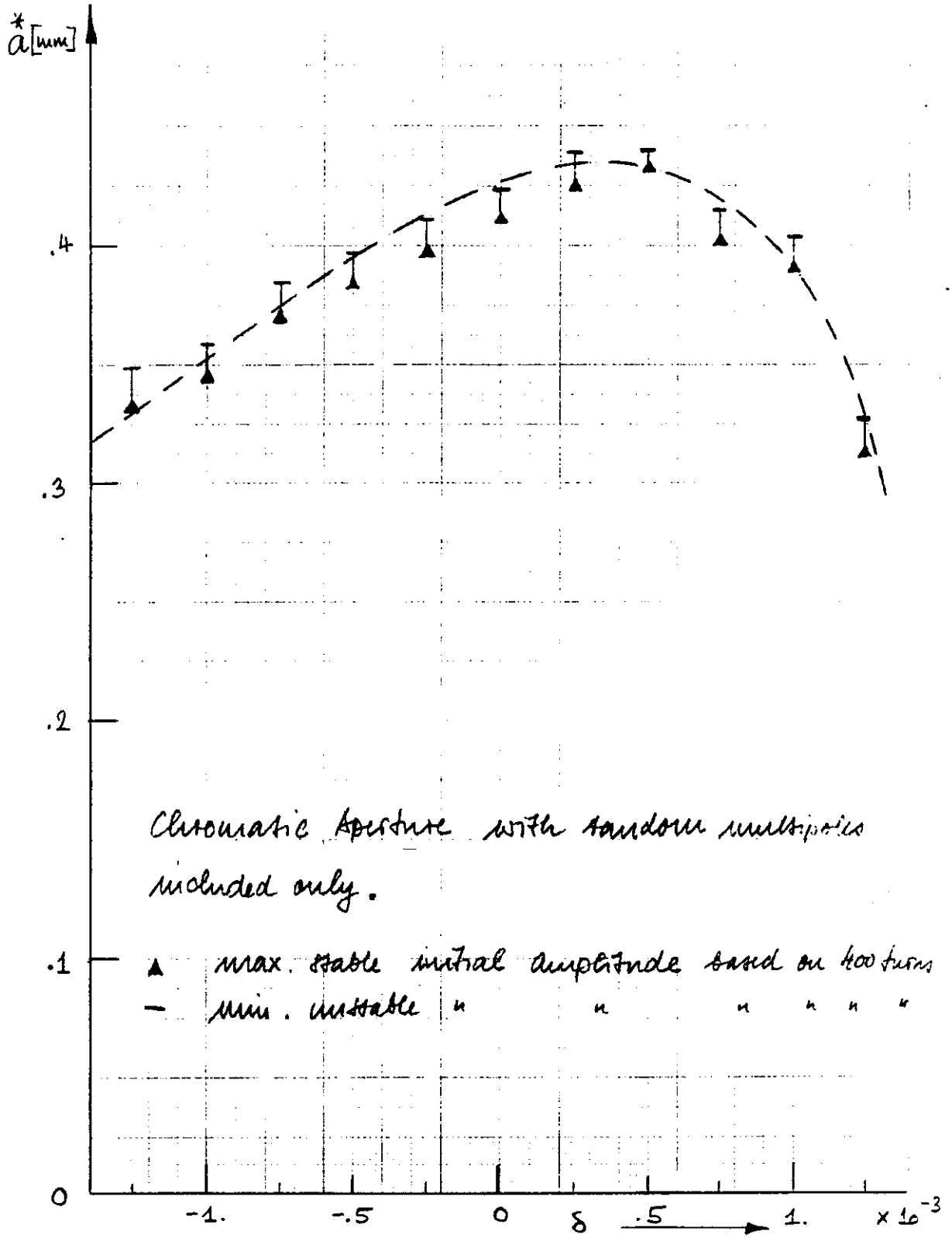


Figure 9. Chromatic aperture of "complete" correction scheme, with f = 0 random errors included.

for the random number seed producing an aperture value closest to the average. It is obviously skewed and the maximum is shifted to an off-momentum value for δ. The phenomenon has been observed frequently in the past and it should be noted that the σ determined from samples which show this shift of the centroid is likely to be an overestimate.

A final aperture test was done for the "sextupole-decapole" correction scheme with $f_2 = f_4 = 0.03$, $f_6 = 1$ which produced an acceptable chromatic behavior. For tracking the random errors have been included using the same random number seed as in the above case with complete correction. The result is shown in Fig 10. The maximum aperture again occurs for $\delta = +0.035\%$ and having the same value as in the completely corrected case. The main difference is the narrower distribution caused by a faster drop-off with increasing off-momentum values of δ. Compared to the fully corrected case the aperture at $\pm$ 0.01% is about 25% smaller, but overall still perfectly acceptable.

CONCLUSION

On the basis of the chromatic properties $\Delta Q(\delta)$ and $\beta^*(\delta)$ a local correction scheme for b_2 and b_4 due to persistent currents is needed with a correction of 0.97 or better. While the dynamic aperture for this scheme, which leaves the b_6 uncorrected, is narrower than for the fully correct scheme, it is still perfectly acceptable.

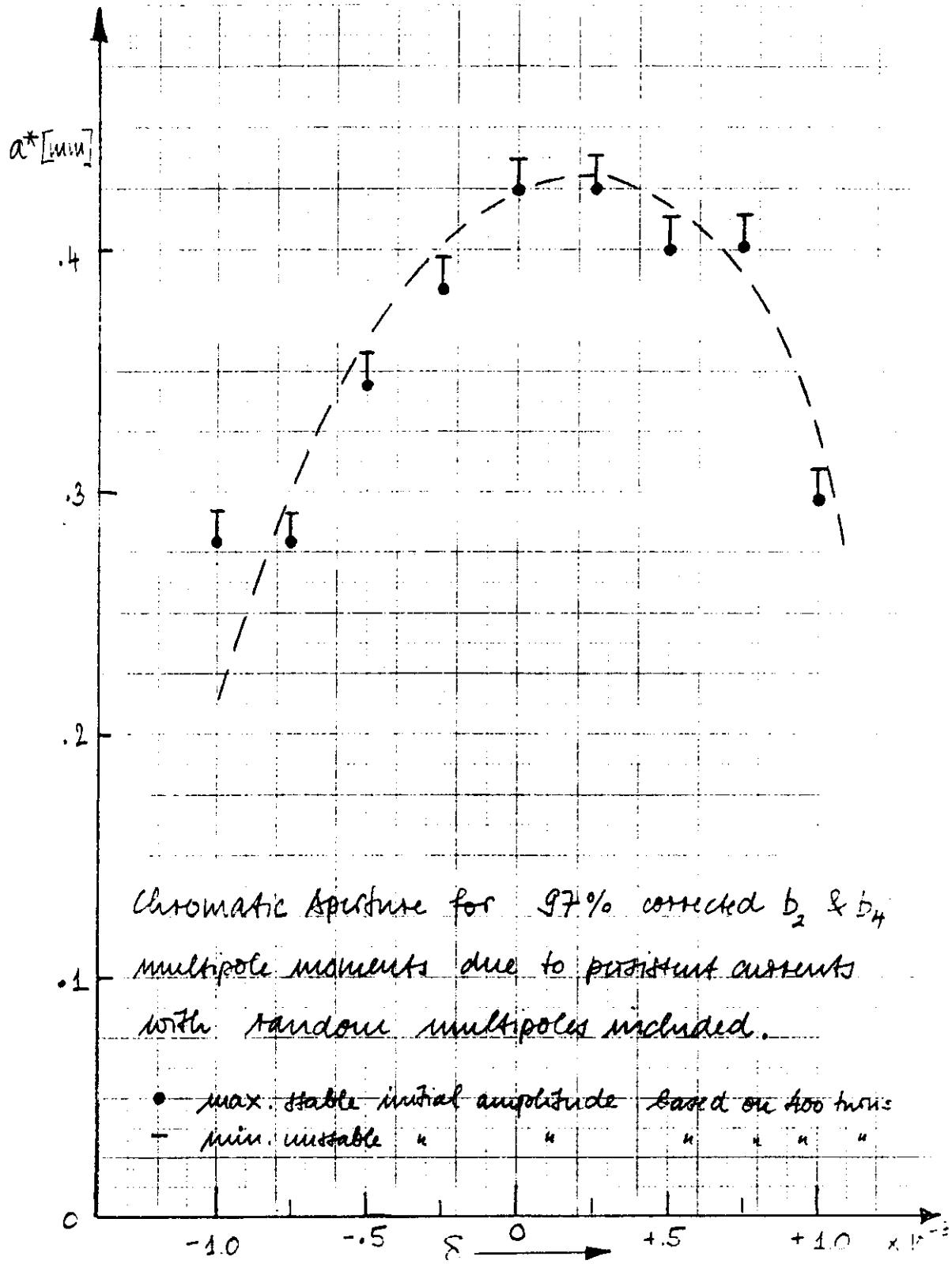


Figure 10. Chromatic aperture of "Sextupole - Decapole" correction scheme. b_2 and b_4 97% corrected with random multipoles included.

REFERENCES

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