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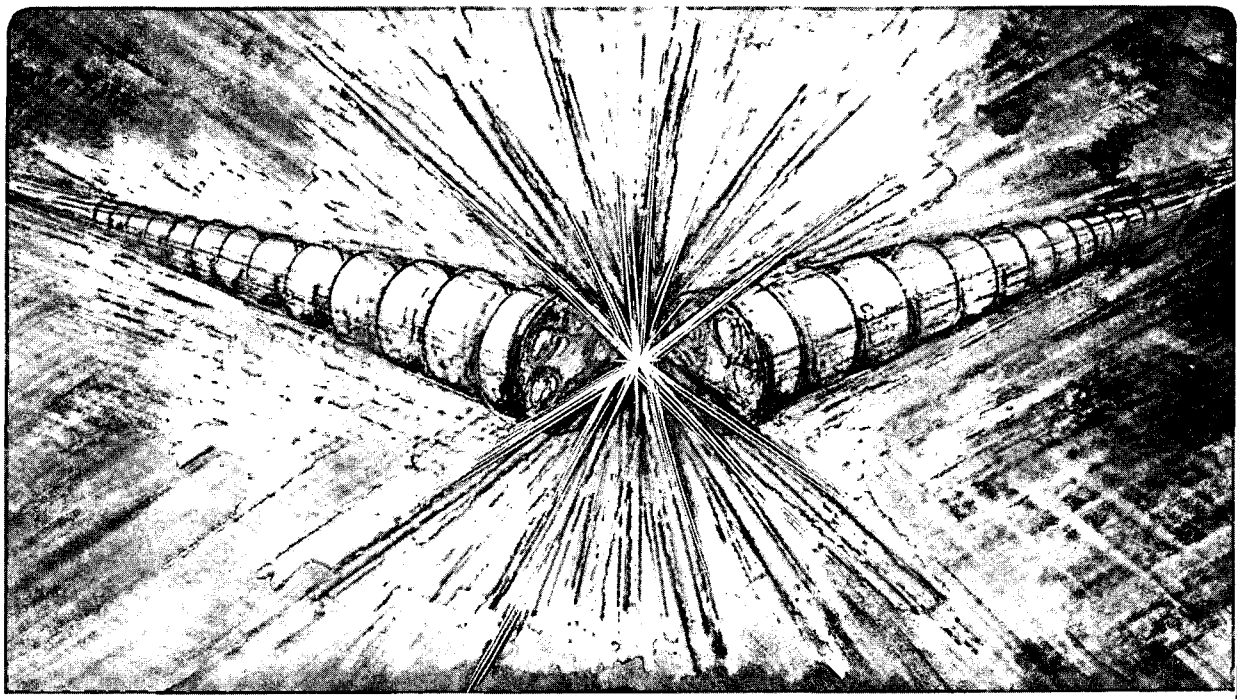

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TUNE-SPLIT EFFECTS AT THE ALS STORAGE RING*

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ABSTRACT

This paper is concerned with operational characteristics of the Advanced Light Source (ALS) storage ring [1], a synchrotron light source of the third generation that is capable of operating between 1.0 and 1.9 GeV beam energy. Even though the magnetic properties of its lattice magnets appeared to be very well understood [2] an anomaly was observed with the measured betatron tunes when the working point of any of the three quadrupole families or the bend magnets was switched from the upper to the lower hysteresis branch. In no case was it then possible to recover the standard horizontal and vertical tune values simultaneously at any given excitation current; either one was considerably off normal when the other one was set to the proper value. The nature of this so-called "tune-split effect" was investigated, and the solution to the problem is presented here, together with an outlook on consequences for operational scenarios resulting from this effect.

I. INTRODUCTION

The Advanced Light Source, ALS [1], is a third-generation synchrotron radiation facilitiy with an electron storage ring designed to operate between 1.0 and 1.9 GeV beam energy. The betatron tunes of the storage ring have to be reproduced from fill to fill, and kept constant during operation, within 5 kHz to keep the radiation source-points at their customary locations. This requirement implies that the fundamental integrated fields of the bend and quadrupole magnet families, see Fig. 1, have to be set to their absolute nominal values with a maximum deviation of about 0.03%; and in order to achieve this goal the magnets are subjected to a standardized conditioning procedure which guarantees the proper fields at nominal current set-points. In the case of ALS, a single conditioning loop from zero to maximum excitation current and then down to the nominal set point was used at first for all lattice-magnet families. This loop represents the fastest way to achieve well-defined working points after bringing the magnets as

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far into saturation as the power supplies would allow, and it establishes the working points on the upper hysteresis branches.

This simple conditioning procedure worked very well during the initial operation phase, but it soon became clear that it was not optimal in several regards. With the available 1.5-GeV synchrotron injector, the storage ring has to be ramped up to reach 1.9 GeV energy, and this process by definition shifts the magnet working points to the lower hysteresis branches. Furthermore, efforts to stabilize the magnet fields against power-supply output variations using a 'converging-loop conditioning' procedure [3], and also the requirement to retune at least some of the quadrupoles to compensate for tune changes when insertion-device gaps are being changed imply that the concept of well-defined working points on either one of the hysteresis branches might have to be given up entirely. Therefore a program was started at the ALS to examine the effects of applying various conditioning scenarios to the lattice magnets on betatron-tune and orbit stability.

II. HYSTERESIS EFFECTS AND CONDITIONING

Third-generation light sources such as the ALS impose very tight tolerances on the field quality of their lattice magnets with respect to 1), integrated fundamental strength of every magnet type as a function of transverse location; 2), magnet-to-magnet reproducibility within every magnet family; and 3), working-point reproducibility and stability during operation. The third of these requirements is instrumental to always maintaining the one beam orbit that provides the customary source points to the light-source users. Therefore the ALS magnets undergo a specific conditioning process that defines their history of excitation and ensures that their actual working points are well reproduced on the same branch of the hysteresis loop when setting the magnet currents to their nominal values.

The concept of hysteresis, in general, implies that for a given magnet there should be at least two working points where the integrated fundamental fields are exactly equal, one point on the lower branch of the hysteresis loop and one on the upper branch, at properly reduced excitation current, see Fig. 2.

A novel conditioning procedure, in this paper termed 'converging-loop conditioning,' had been described some time ago [3]. With this procedure a magnet working-point is approached by overshooting the final value several times in both directions, with decreasing intervals, until the procedure has converged. As illustrated in Fig. 3, it essentially generates a single, symmetric working line for a magnet near a given excitation point, with a slope that is significantly smaller than that of either hysteresis branch. This procedure promised to be very helpful for ALS, for long-term stability in the presence of power-supply ripple as well as with regard to the small tune corrections needed when insertion-device gaps are

being changed. After successful tests with a single dipole magnet in one of the ALS transfer lines by the author, however, it was very disappointing to experience that the procedure failed to provide sufficient reproducibility with the ALS bend magnets. A systematic study was started with bend and quadrupole magnets to understand the reason for the unexpected behavior.

Another reason to investigate hysteresis effects of the ALS lattice magnets was given by the necessity to change their working points from the upper hysteresis branches, where they had been during the early commissioning and operation phases of the storage ring, to the lower branches in order to allow ramping of the beam energy from 1.5 to 1.9 GeV. As mentioned earlier, ramping is needed because of the limitation in injection energy to 1.5 GeV, and increasing magnet currents automatically moves the working points to the lower hysteresis branches. For a variety of reasons such as power supply limitations, time consumption, and unnecessary increase of radiation losses at higher energies it is totally unfeasible to bring the magnets back to the upper hysteresis branches for a beam energy of 1.9 GeV.

With all the lattice magnets already installed in the ring and operating, only very rudimentary local Hall-probe measurements at poorly defined positions on the magnet pole faces could be made [4]. Therefore the horizontal and vertical betatron tune values of the machine were taken as indicators of global magnet-field reproducibility. The relative resolution of tune measurements amounts to 5kHz for both tunes or 0.003 fractional tune units. Such a tune change corresponds to approximately 3×10^{-4} relative change in the total focusing strength of one magnet family.

III. QUANTIFICATION OF TUNE-SPLIT EFFECTS

In principle, the change of a magnet working-point from the upper to the lower hysteresis branch should amount to a simple change of the necessary excitation current as illustrated in Fig. 2. With the ALS storage-ring quadrupoles and bend magnets, however, this change gave rise to an abnormal behavior of the ring, here termed 'tune-split effect:' with rising excitation of one of these families one betatron tune value could be set to its nominal value at a certain current, but the other one was still far off, and when the magnet current was raised more the second tune reached its nominal value, but now the first one was significantly off. Tune-split effects with all four families are demonstrated in Figs. 4 – 7.

To quantify the tune-split effects for the various lattice-magnet families, the difference in the excitation currents, where either the horizontal or the vertical

nominal tune is obtained, is taken and expressed as a percentage of the mean of both currents. Linear approximations to the measured data are used to identify these currents as accurately as possible. The results are given in Table 1.

Table 1. Tune-split effects with the ALS lattice-magnets.

Magnet Type	Rel. Tune Split [%]	Core Length [m]	Split / Length [% / m]
B	2.35	0.807	2.9
QFA	1.38	0.470	2.9
QF	0.60	0.318	1.9
QD	0.35	0.168	2.1

The data in Table 1 demonstrate that the tune-split effect varies monotonically, if not quite linearly, with the core length of the magnet type in question, even when including the bend magnets that in essence represent the inner halves of true quadrupole magnets. This trend points to a residual-field effect which would be more pronounced the more iron-dominated a magnet is.

IV. EXPLANATION OF TUNE-SPLIT EFFECTS

During the search for an explanation of the tune-split effect found with the ALS lattice magnets the dynamic behavior of the magnets was investigated first. Possible causes for the effect could have been fields induced by eddy-currents in the thick-walled aluminum vacuum-chamber or enhanced residual magnetization because of fast current reversal when switching between the hysteresis branches. Tune-split measurements performed at one tenth of the customary ramping speed, however, gave identical results, and the dynamics hypotheses had to be dropped. The pertinent clue was then obtained from local Hall-probe measurements on two of the four pole pieces of one QFA magnet [4] with high-resolution, differential readout. As mentioned earlier on, absolute field measurements would not have been very meaningful because the Hall probes could not be located on equivalent positions on both examined pole faces.

The two Hall probes were positioned close to the two inner pole pieces of the magnet, the ones near the return yoke, see Fig. 8, about 20 mm inside from the end chamfer, between the correction humps on the inner and outer side of each pole piece. The magnet was conditioned and left in its standard excitation state on the upper hysteresis branch at nominal current. After changing the current to zero and then back to nominal, a 15-G change in the difference value of the two

probe readings was recorded. This field difference can readily be explained by closer examining the remnant excitation of the magnet back leg [6]. Those of the flux lines that pass through the back leg have quite different total lengths inside the iron, depending on whether they connect the outer or the inner pole pair as illustrated in Fig. 8. Flux densities associated with these two kinds of flux lines are about inversely proportional to the line lengths, and therefore a net magnetization effect results which creates a dipole magnet field in the free space between the two upper and the two lower poles. When the magnet is brought from the upper to the lower hysteresis branch the back leg magnetization is subject to a hysteresis effect as well, amounting to the 15 G difference measured.

The dipole field resulting from the C-shape of the magnet yoke, superimposed on the main quadrupole field, is equivalent to a pure quadrupole field whose center of symmetry is shifted horizontally. This is a well-known feature of C-shaped magnets and had been quantified for each of the installed ALS quadrupoles during the original magnetic measurements [5], leading to individual positioning corrections for all these magnets. What had not been recognized at that time was that the magnitude of these shifts changes as the magnets are brought from one hysteresis branch to the other.

Once the idea of hysteresis-induced dipole fields is accepted, deriving a convincing explanation for the observed tune-split effects is straightforward. The dipole fields inside the quadrupole gaps give small kicks to the beam, and in consequence the beam is offset from its ideal path when it passes through the sextupoles in the ring, leading to a change in the total focusing strength. A tracking study was undertaken to investigate this effect for the case of the QFA quadrupole family [7]. In this study, 0.1-mrad kicks were added to the standard beam at all QFA locations, and as a result the betatron tunes changed by +0.057 and +0.042 in the horizontal and vertical directions, respectively. From Fig. 6 one can read that at 403.5 A excitation current, the tunes are shifted from their nominal values by +0.064 and + 0.048, respectively. A comparison of orbit distortions measured when the QFA family was brought to the lower hysteresis branch with simulated distortions from the same theoretical study likewise shows a remarkable agreement, see Fig. 9.

From linearly scaling the simulated tune shifts it would appear that applying 0.116-mrad instead of 0.1-mrad kicks in the simulation would have led to an even better match with the measured tune shifts and also brought the two orbit distortion curves in Fig. 9 closer together. In reality, the kick produced by a 15-G dipole field extended over the effective length of 0.485 m amounts to 0.15 mrad, but it was not determined which fraction of the 15-G field, measured orthogonally to the pole faces, actually contributes to the strength of the dipole field. A

dipole strength of about 10 G on the magnet axis appears to be a reasonable assumption, again leading to about 0.1-mrad kicks. All these numbers support the explanation postulated here that the C-shape of the quadrupole yokes is the cause for the tune split effect. However, the findings do not directly apply to the tune split caused by the bend magnets, even though, being gradient magnets, they could be thought of as half quadrupoles with very large horizontal axis offset relative to the electron beam.

In the case of the bend magnets, a similar reasoning as followed for the quadrupoles, again involving different lengths of the flux lines in the return yoke depending on where on the pole faces they start and end, leads to the conclusion that even parallel-faced C-shaped dipoles have a considerable quadrupole component [8]. This quadrupole component then must have a different hysteresis width than the main dipole component to explain the observed tune shifts upon switching between hysteresis branches.

V. OUTLOOK

After a satisfactory explanation for the observed tune-split effects was developed the first consequence for operating the ALS storage-ring was to painstakingly prescribe and follow conditioning procedures for all lattice magnets. Secondly, because energy ramping is one of the essential features offered to light-source users, the lattice-magnets are now all working on their lower hysteresis branches, and the closed-orbit deformations have been corrected accordingly for all standard modes of operation. And as a third consequence, even minute downward set-point corrections were prohibited in order to keep the beam orbit constant.

But one effect cannot be tackled in this way, and that is the change of vertical betatron tunes caused by variations of the insertion-device gap widths. Insertion devices (undulators and wigglers) are essentially periodic arrays of strong permanent magnets installed in some of the twelve straight sections of the storage ring and producing alternating dipole fields across the electron-beam path. As soon as the tune changes induced by their fields become too large a compensation scheme has to be applied, and because of the tune-split effects this compensation cannot consist of simple quadrupole-strength adjustments.

Three ways out of this problem come to mind. The first one would be administrative, permitting insertion-device gap-changes only in one direction such that quadrupole strengths will only have to be increased for compensation. This way is clearly impractical. On the other hand, one could try and compensate the

orbit changes with the existing steerer magnets which would involve either an orbit feedback system or a multidimensional feed-forward table, depending on the number of installed insertion devices. The big problem with this method is that the existing steerers are not located precisely where the perturbing fields are generated; therefore the corrections would be approximations at best. Lastly, the parasitic dipole components could be compensated for at their origins by installing back-leg windings that are excited by well-determined fractions of the main magnet currents. This method can easily be applied to all quadrupole magnets, and it is not even necessary to treat the bend magnets in this respect because they would not take part in a local tune-compensation scheme anyway.

VI. ACKNOWLEDGMENTS

Thanks are due to Alan Jackson and Klaus Halbach for many discussions that contributed to uncovering the roots of the tune-split effect. It is also a pleasure to express my gratitude towards the ALS operators for their help in carrying out the tune measurements and the Hall-probe investigations of the QFA magnet.

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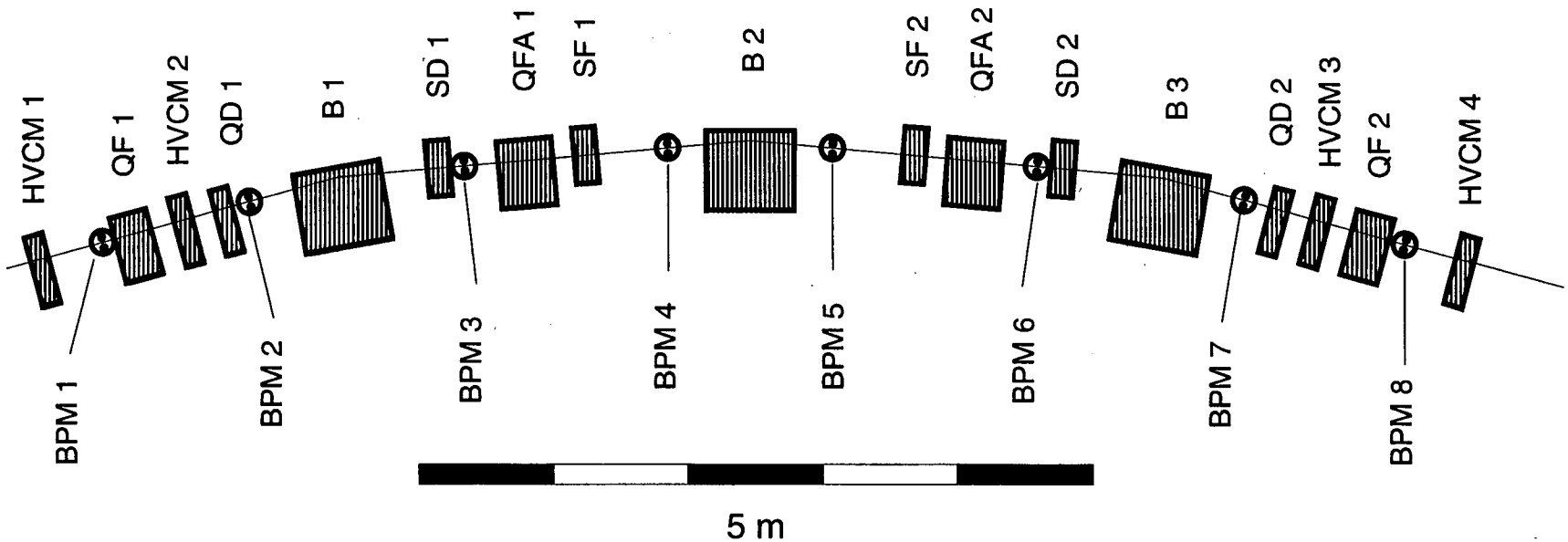

Figure 1. ALS storage-ring lattice showing one out of twelve curved sections. HVCM, horizontal and vertical corrector; QF, focusing quadrupole; QD, defocusing quadrupole; QFA, second focusing quadrupole determining the dispersion in the adjacent straight; B, bend magnet; SF, focusing sextupole; SD, defocusing sextupole. BPM, beam-position monitor. The bend magnets have gradients that generate a defocusing quadrupole component. All magnets are open towards the outside of the ring (C-type yokes) to avoid intercepting synchrotron radiation.

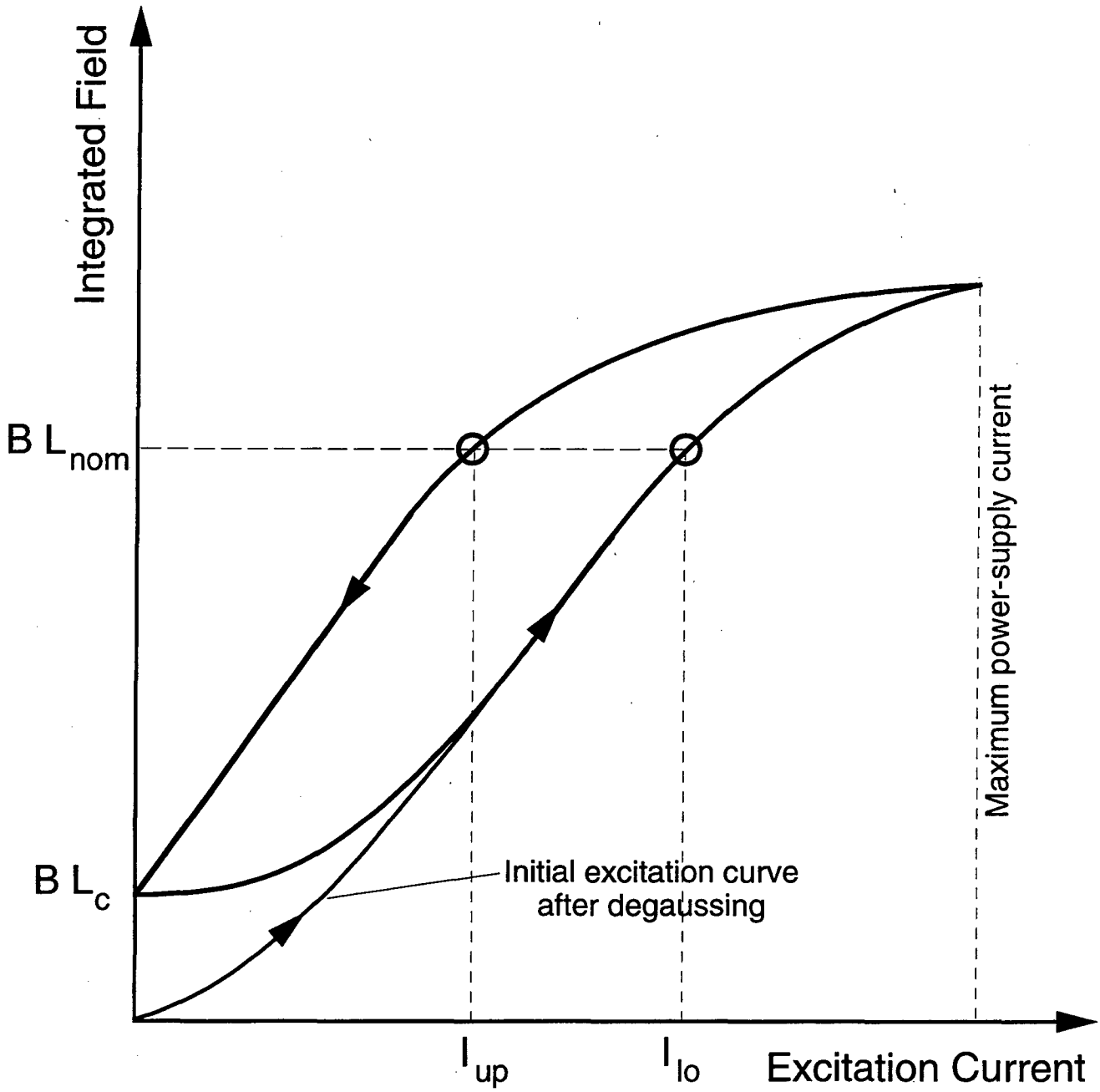

Figure 2. Schematic of the effective hysteresis loop described when using a unipolar power supply. Two excitation current values, I_{lo} and I_{up}, respectively, generate the same (nominal) integrated field value $B\,L_{nom}$ when operating the magnet on either the lower or the upper hysteresis branch. The magnitudes of hysteresis-loop width, saturation effects at higher current, and coercive field value, BL_c, are exaggerated in this schematic for illustration purposes.

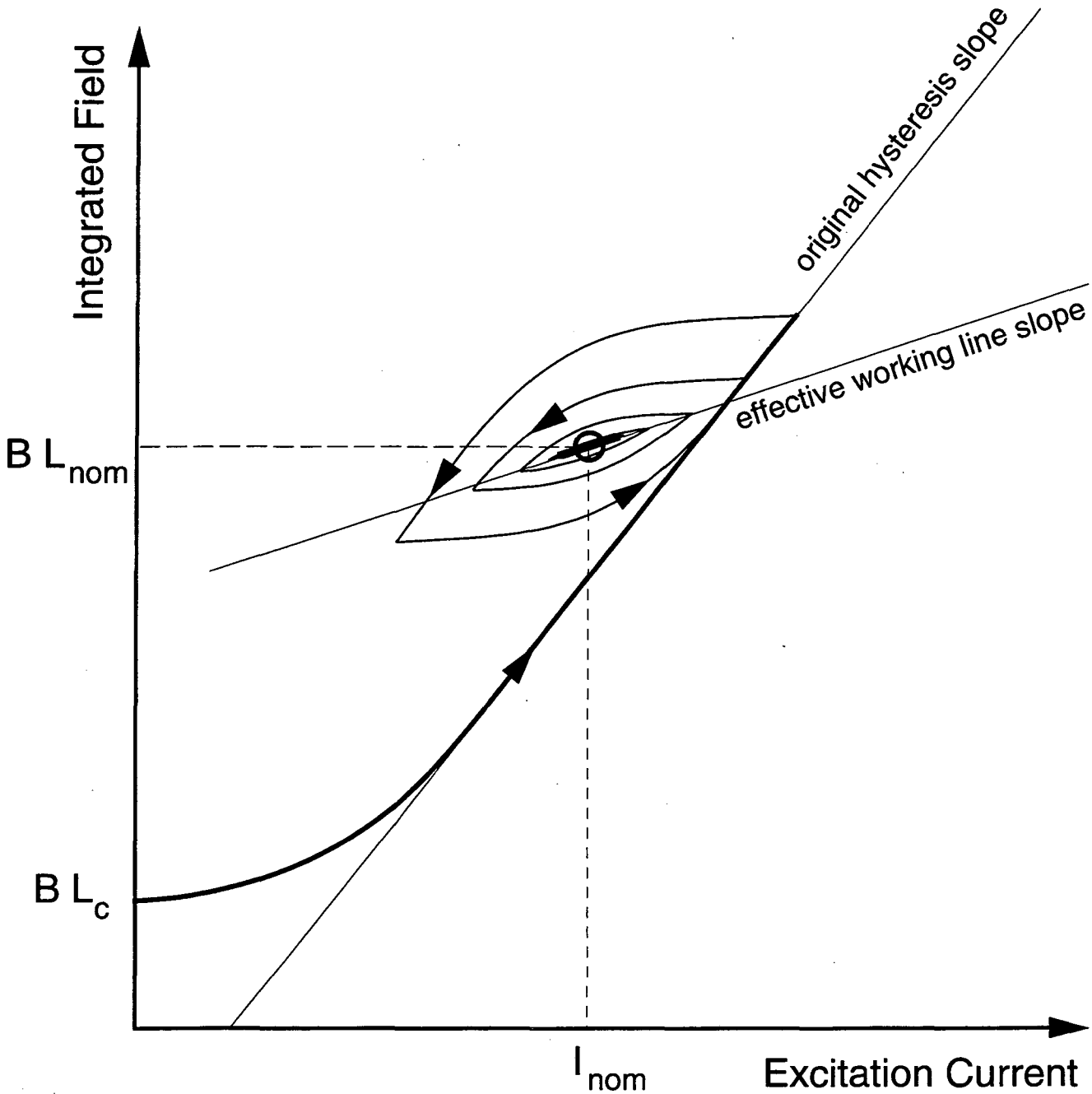

Figure 3. Schematic of the converging-loop conditioning procedure. The nominal working point (open circle) is approached overshooting it several times in both directions; this procedure leads to a significant reduction of the effective working-line slope. The effective working line (short bold line) is straight and symmetric with respect to the working point. The width of the original hysteresis loop is exaggerated.

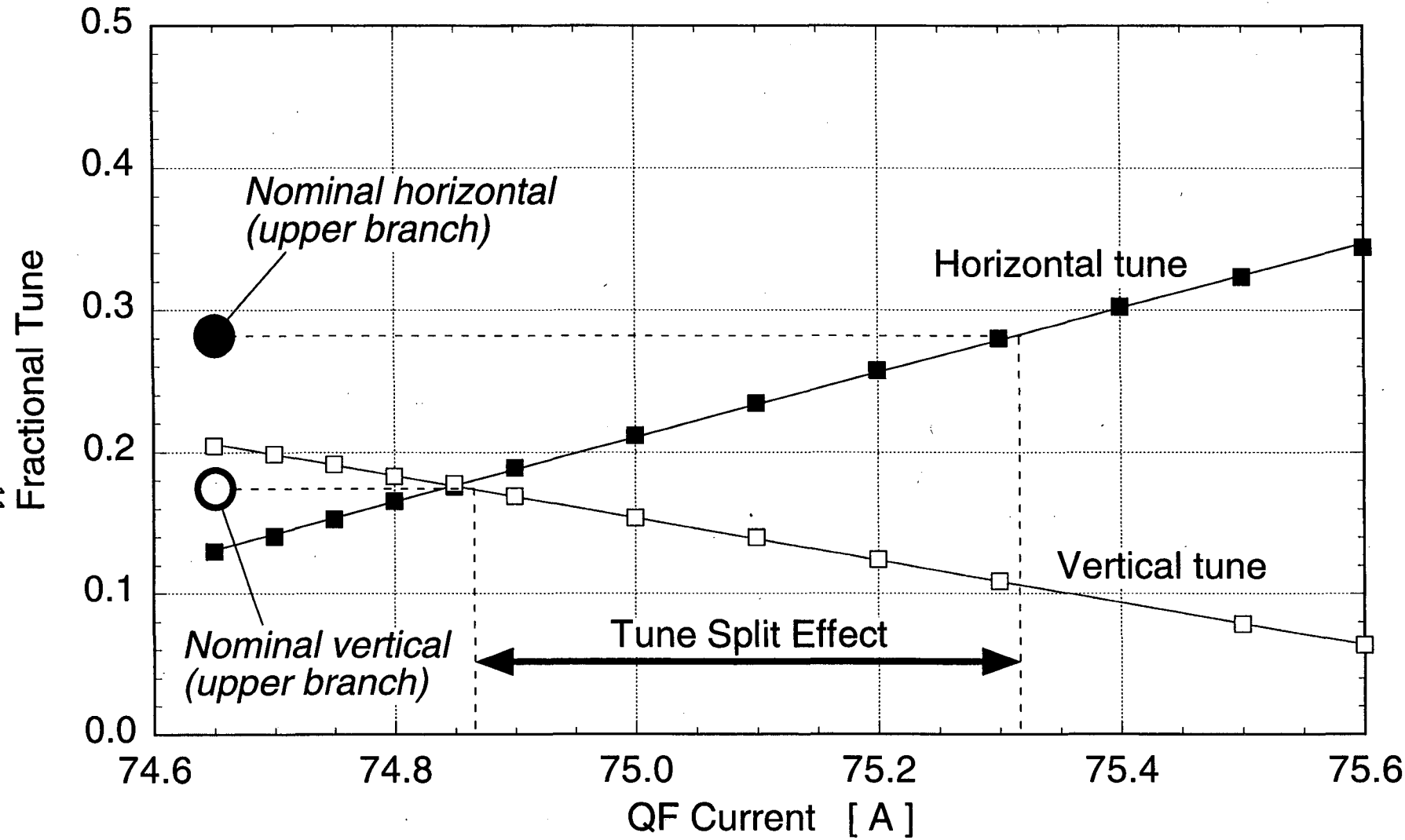

Figure 4. Tune variations with the QF family. The data points connected by straight lines show measured tunes with the magnets on the lower hysteresis branch, as the excitation current is being raised. These trends are normal for horizontally focusing quadrupoles. The nominal horizontal and vertical tune values as indicated by a closed and an open circle, however, are not recuperated at one common current value. This split in excitation current, indicated by the bold, double-headed arrow, quantifies the "tune-split effect."

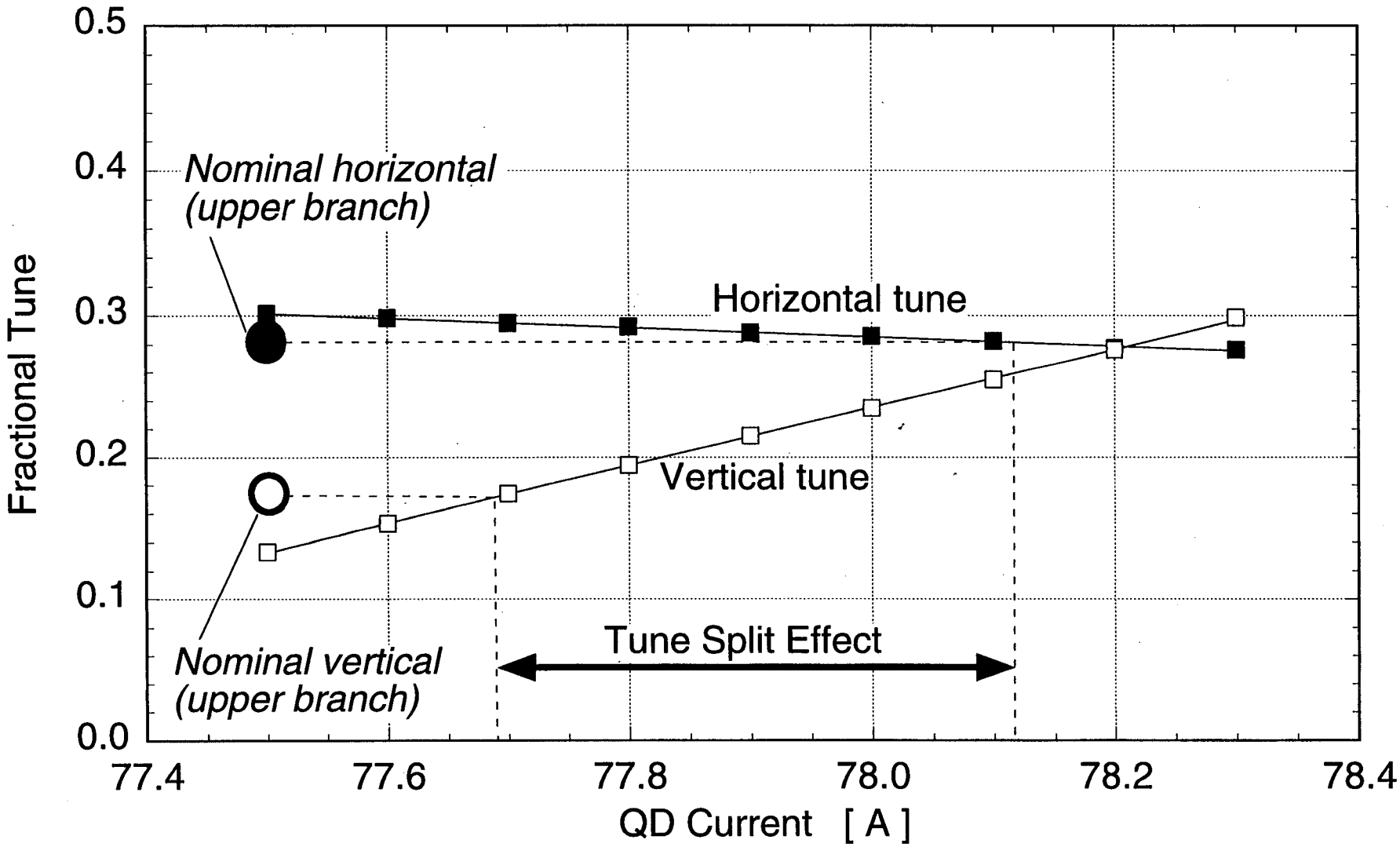

Figure 5. Tune variations with the QD family (horizontally defocusing). See Fig. 4 for other explanations.

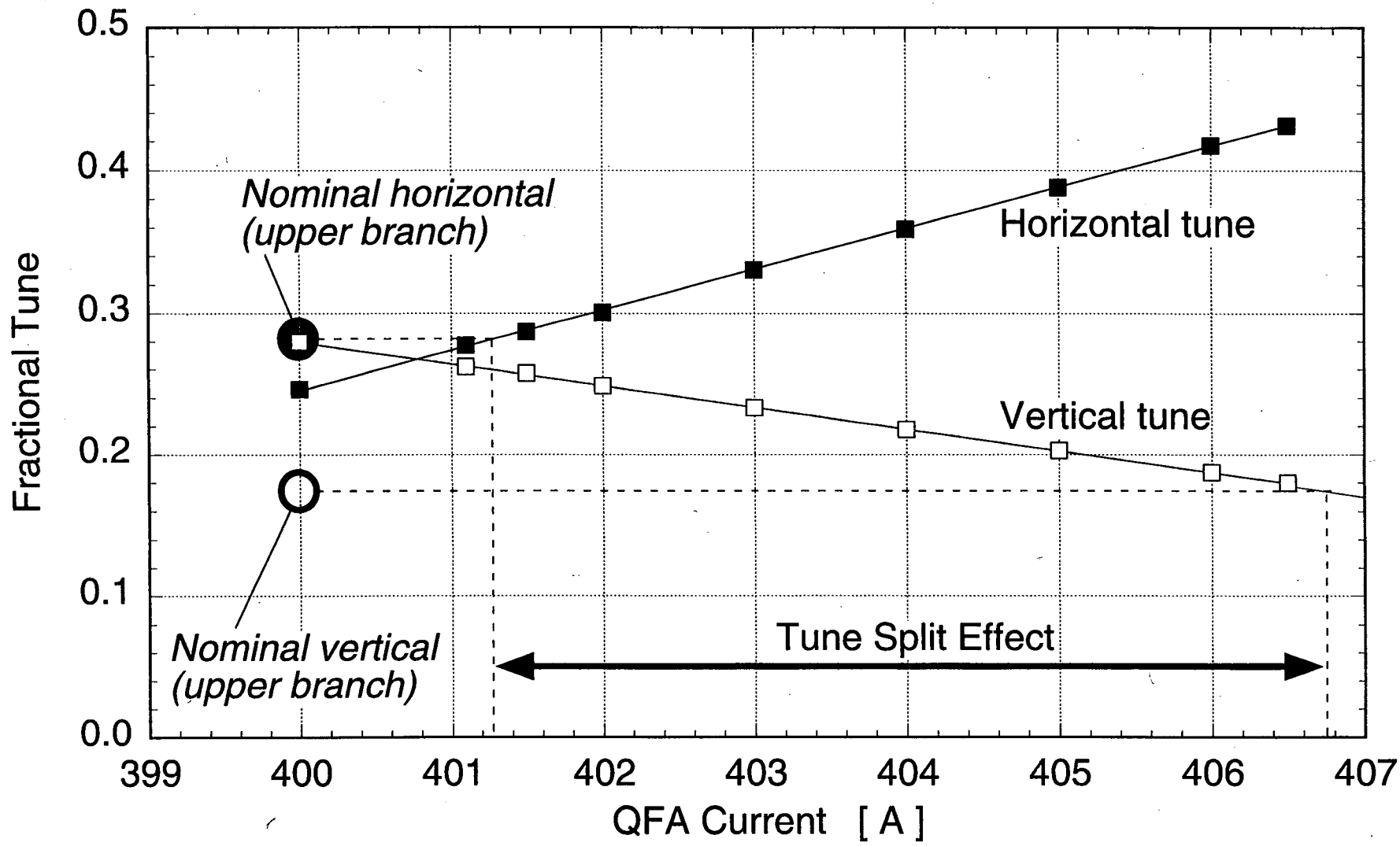

Figure 6. Tune variations with the QFA family (horizontally focusing). For other explanations see Fig. 4.

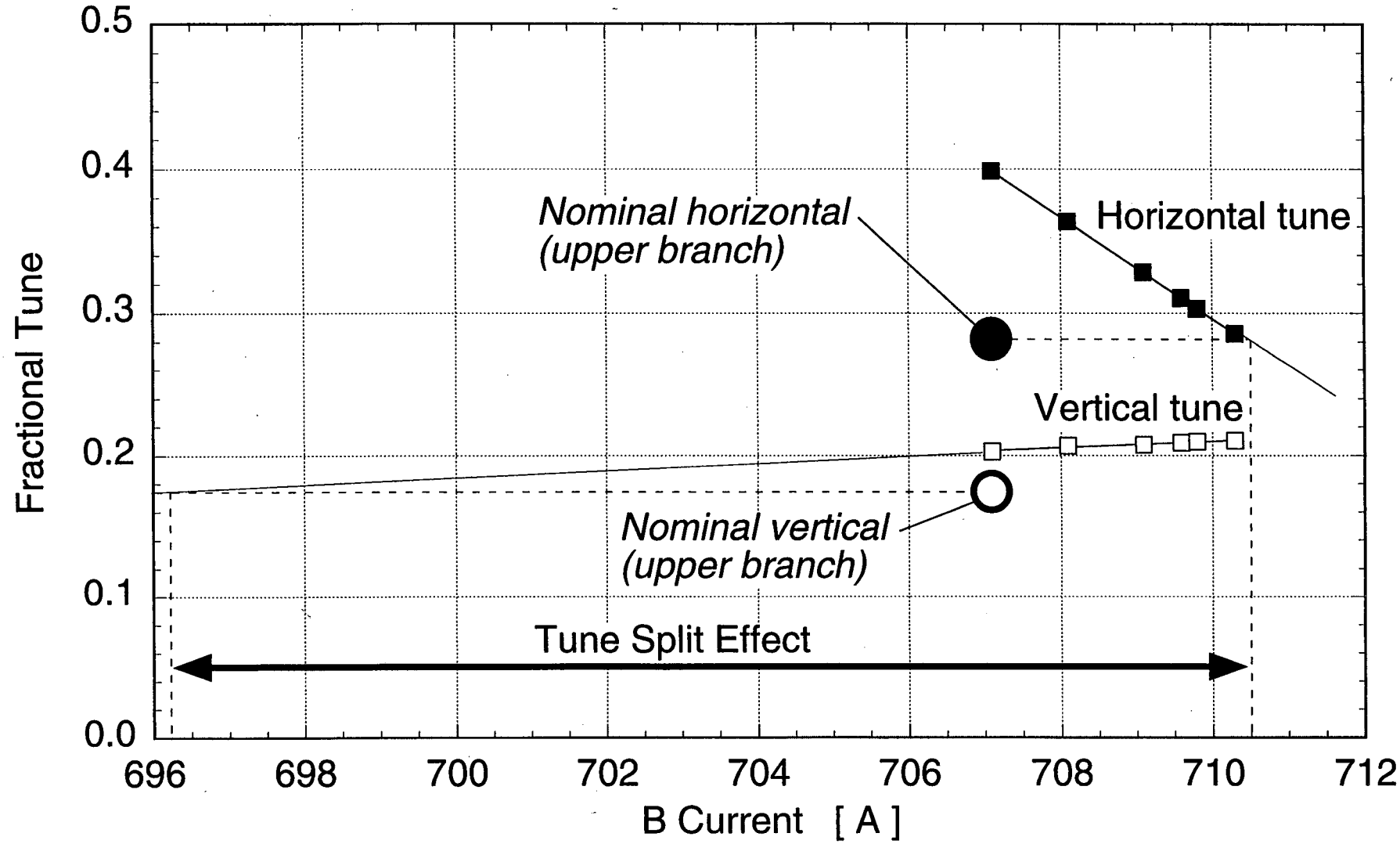

Figure 7. Tune variations with the bend magnets (horizontally defocusing). For other explanations see Fig. 4.

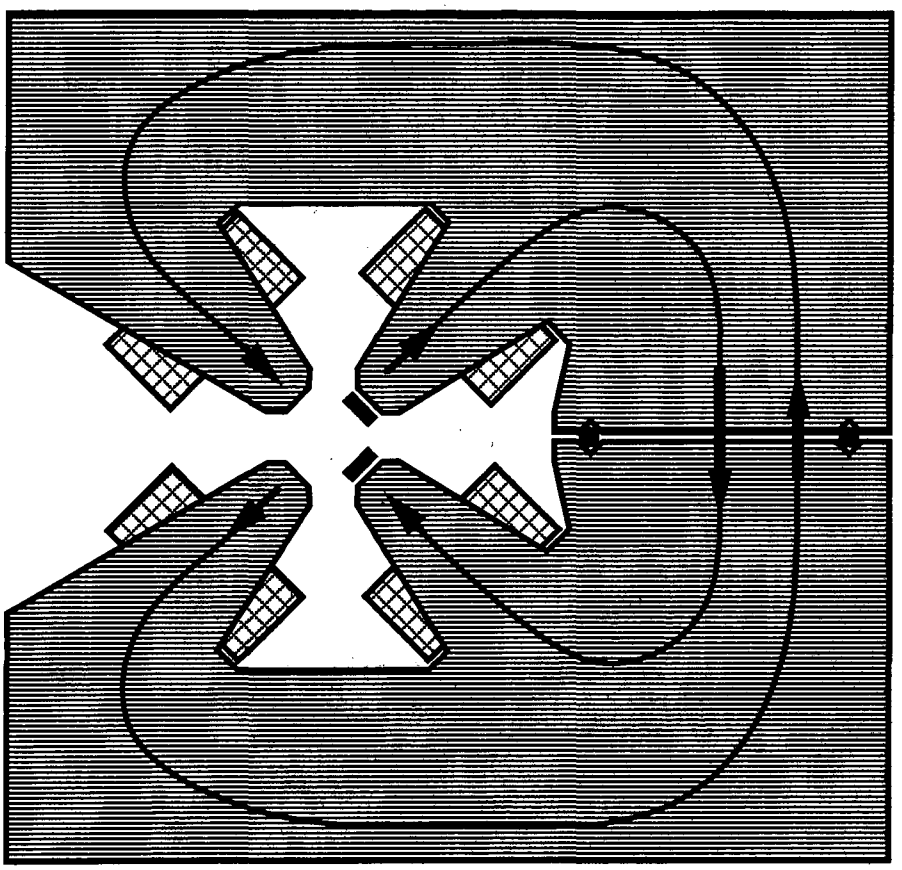

Figure 8. Magnetization of a C-shaped quadrupole; the illustration shows only those flux lines that pass through the back leg. The difference in flux density, caused by the path length difference within the iron and symbolized by the arrow lengths, results in a net magnetization of the back leg in downward direction, and this in turn creates a dipole field in the space between the poles, directed from the lower to the upper poles and superimposed on the much stronger quadrupole field. The approximate location of the Hall-probe tips is indicated by black rectangles.

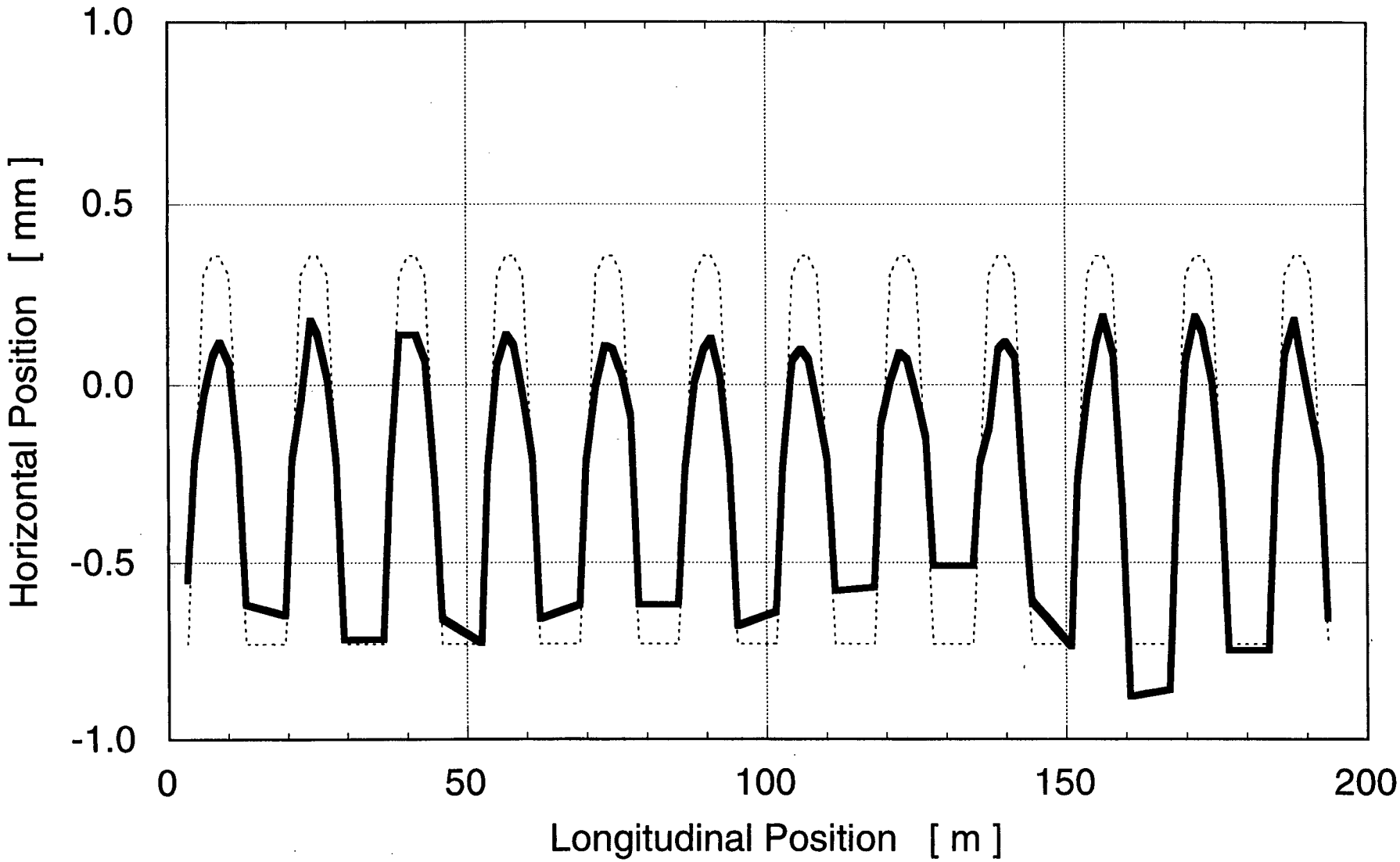

Figure 9. Orbit distortions measured after switching hysteresis branches with the QFA magnets (bold, solid line), compared to the results of the simulation [7] (broken line). The measured orbit also shows the effect of beta beat which is not related to the tune-split effect discussed in this paper.

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