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R. Keller
Accelerator and Fusion Research Division

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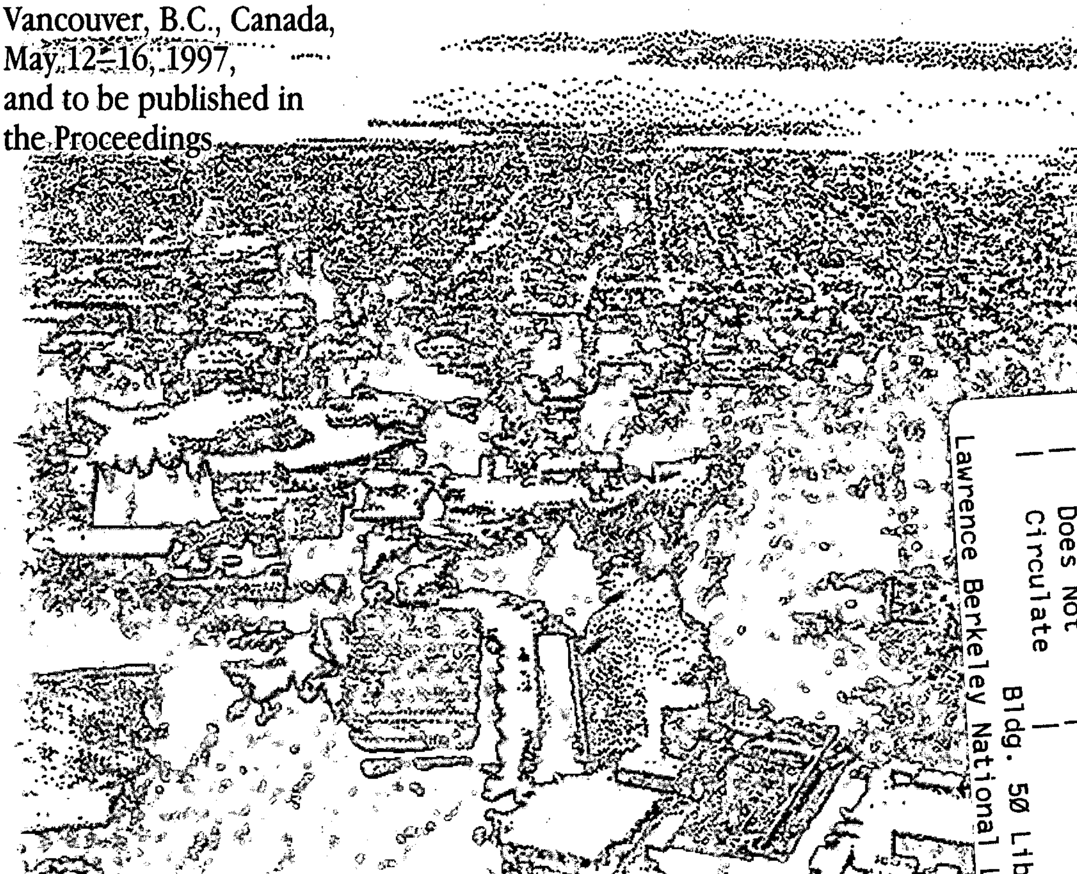

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R. Keller

Advanced Light Source
Accelerator and Fusion Research Division
Ernest Orlando Lawrence Berkeley National Laboratory
University of California
Berkeley, California 94720

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TUNE-SPLIT EFFECTS AT THE ALS STORAGE RING*

R. Keller, Advanced Light Source Center, E. O. Lawrence Berkeley National Laboratory
University of California, Berkeley, CA 94720 USA

This paper is concerned with operational characteristics of the Advanced Light Source (ALS) storage ring, 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 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.

1 INTRODUCTION

The ALS electron storage ring [1] is designed to operate between 1.0 and 1.9 GeV beam energy. Its betatron tunes have to be kept constant during operation within 5 kHz to maintain the radiation source-points in stable positions. This implies that the integrated fields of the bend and quadrupole magnet families, see Fig. 1, have to be held within about 0.03%; and therefore these 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 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, the requirement to retune at least some of the quadrupoles to compensate for tune changes when insertion-device gaps are being varied [2] imply that the concept of well-defined working points on either one of the hysteresis branches might have to be given up entirely.

2 CONDITIONING AND HYSTERESIS EFFECTS

Operation of the ALS storage ring requires very precise stability and working-point reproducibility for all lattice magnets to always maintain the one beam orbit that provides the customary source point locations to the light-source users. Therefore the ALS magnets undergo a specific conditioning process that defines their history of excitation and always leads to the same working points, on the same branch of the hysteresis loops when setting the magnet currents to nominal values. It is very impractical, however, to check the effectiveness of the conditioning routine with actual

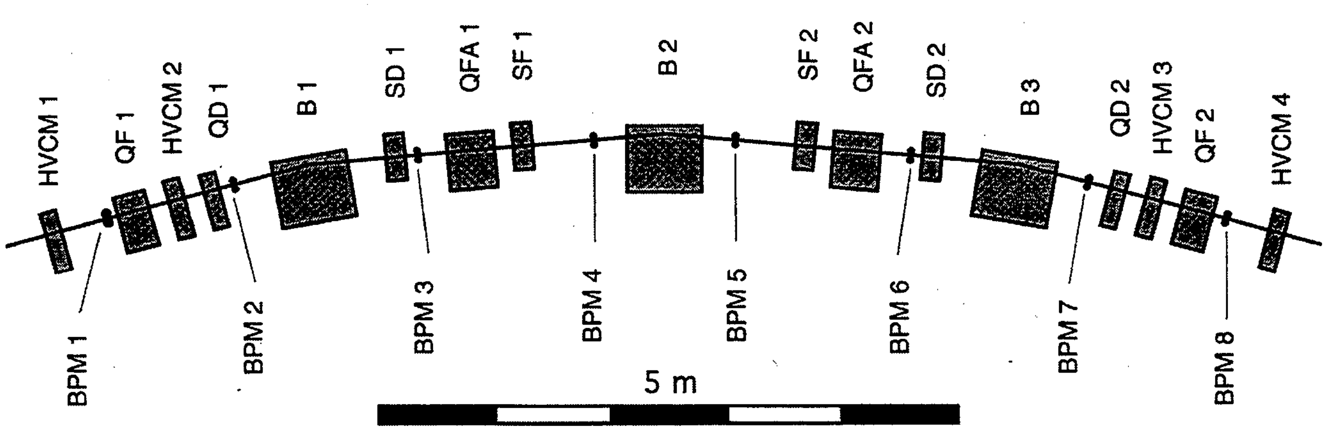

Figure 1. ALS storage-ring lattice showing one out of twelve arc sections. HVCM, horizontal and vertical corrector; QF, focusing quadrupole; QD, defocusing quadrupole; QFA, second focusing quadrupole; B, bend magnet; SF, focusing sextupole; SD, defocusing sextupole. BPM, beam-position monitor. The bend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

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field measurements. Instead, the horizontal and vertical betatron tune values of the machine are taken as indicators of global magnet-field reproducibility. The relative resolution of tune measurements amounts to 5 kHz or 0.003 tune units and corresponds to about 3×10^{-4} relative change in the total focusing strength of a quadrupole family.

The concept of hysteresis generally would imply that for a given magnet there should be 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. This assumption did not hold true, however, when the working points of the ALS lattice-magnets had to be moved from the upper hysteresis branches, where they had been during the commissioning and early 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. 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.

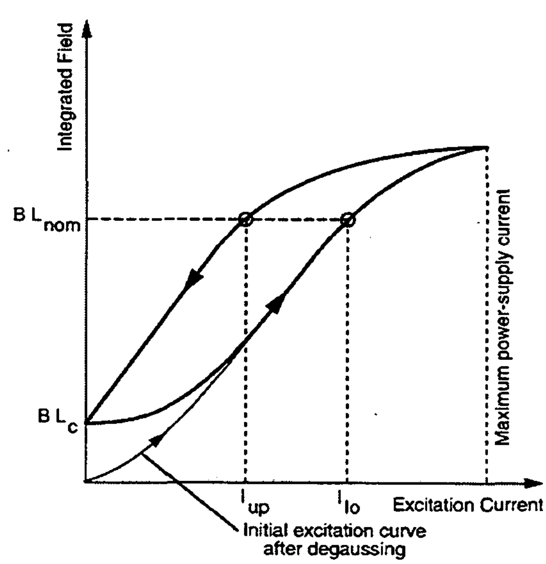

Figure 2. Schematic of the effective hysteresis loop described when using a unipolar power supply. Two excitation current values, I_{lo} and I_{up}, respectively, generate the same (nominal) integrated field value B L_{nom} when operating the magnet on either the lower or the upper hysteresis branch. 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.

With any of the quadrupole or gradient magnet families, the change between hysteresis branches 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 somewhat more the second tune reached its nominal value, but now the first one was significantly off. The tune-split effect as found with the QFA family is demonstrated in Fig. 3.

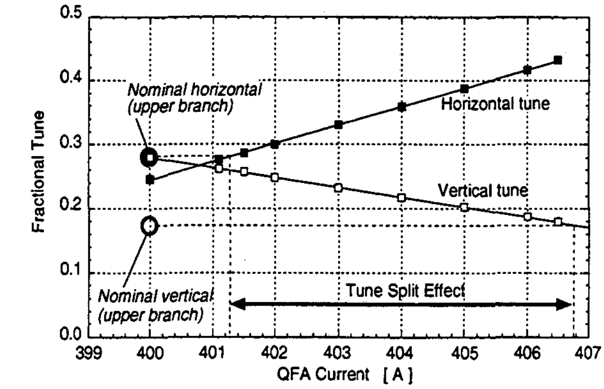

Figure 3. Tune-split effect. Measured fractional betatron tune values are shown as a function of the QFA excitation current, after changing the working point from the upper to the lower hysteresis branch. The machine reaches the nominal vertical tune at significantly higher excitation current than the nominal horizontal tune.

3 QUANTIFICATION OF TUNE-SPLIT EFFECTS

Tune split effects occurred with all three quadrupole families and with the gradient magnets; to a lesser degree even with the two sextupole families. To quantify these effects, 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. Results are given in Table 1.

Table 1. Tune-split effects found with 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 found with quadrupole-type magnets 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 stronger the more iron-dominated a magnet is.

4 EXPLANATION OF TUNE-SPLIT EFFECTS

Tune-split measurements performed at one tenth of the customary ramping speed gave identical results, leading to the exclusion of dynamics hypotheses such as eddy-current effects or enhanced residual magnetization because of fast current reversal. The pertinent clue was then obtained from local Hall-probe measurements on two of the four pole pieces of one QFA magnet with high-resolution, differential readout [3].

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 [4]. Those 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. 4. 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.

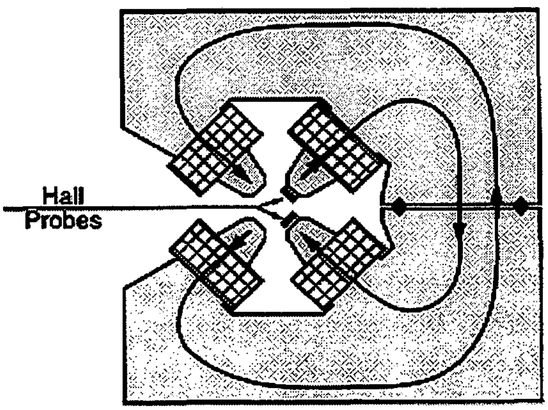

Figure 4. Cross section of an ALS quadrupole. Of the flux lines, only the ones passing through the back leg are drawn.

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 [6]. In this study, 0.1-mrad kicks were applied 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. 3 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.

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 [7]. If this quadrupole component then has a different hysteresis width than the main dipole component the observed tune shifts upon switching between hysteresis branches could be readily explained.

5 OUTLOOK

After deriving a convincing explanation for the observed tune-split effects the first consequence for operating the ALS storage-ring was to painstakingly follow established conditioning procedures for all lattice magnets. Secondly, because of the ramping option, the working points of all lattice-magnets were changed to the lower hysteresis branches. As a third consequence, even minute downward set-point corrections were prohibited.

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. Installation of back-leg windings on all quadrupole magnets would be the best solution to this problem. Luckily it is not necessary to compensate the bend magnets for tune-split effects because they would not take part in a local tune-compensation scheme anyway.

6 ACKNOWLEDGMENTS

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ERNEST ORLANDO LAWRENCE BERKELEY NATIONAL LABORATORY
ONE CYCLOTRON ROAD | BERKELEY, CALIFORNIA 94720

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