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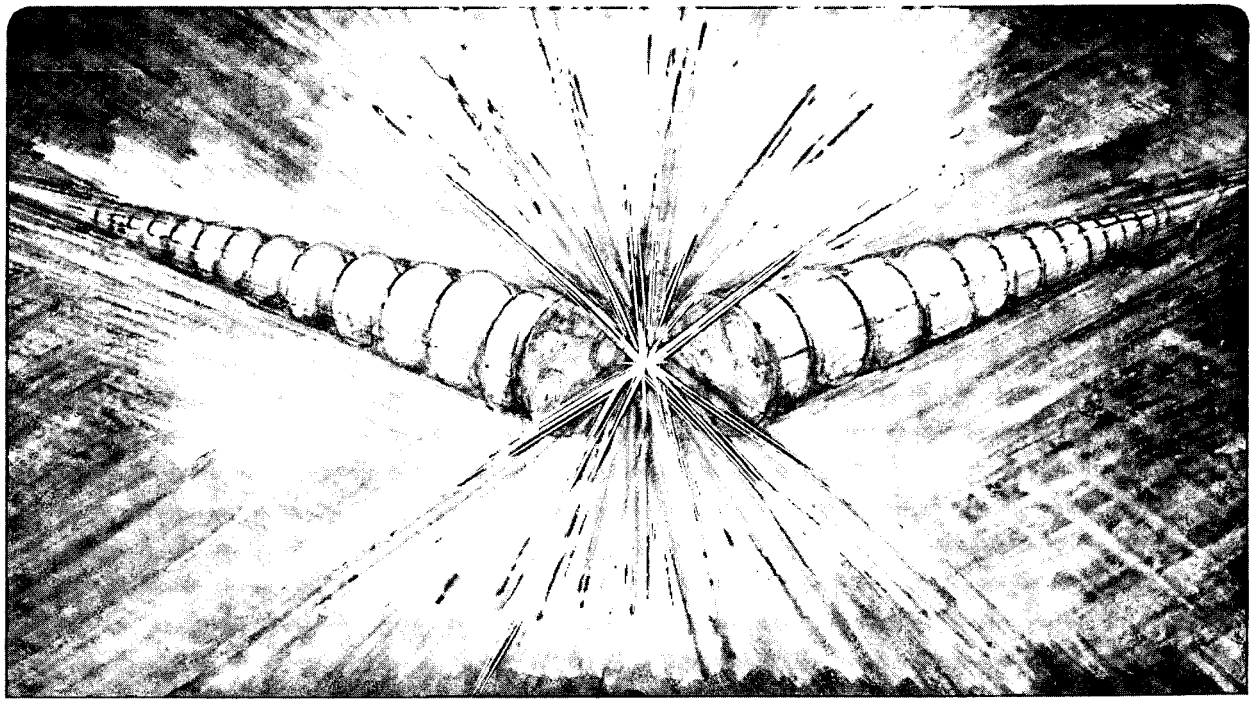

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HYSTERESIS AND SATURATION EFFECTS WITH THE ALS LATTICE MAGNETS*

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The primary purpose of the magnetic measurements performed on the ALS storage ring lattice magnets was to ascertain their compliance with the strict tolerances established for this third-generation synchrotron light source. In the course of the data evaluation, an approximation method has been developed that leads to four-parameter representations of all magnet transfer functions [1]. The expressions for the transfer functions were now used to change the standard working point of the ALS storage ring from the upper to the lower hysteresis branches of all lattice magnet families, and later to ramp the ring from the customary 1.5 GeV to the maximum design energy of 1.9 GeV in one uninterrupted process that did not require any intermediate tune correction. This achievement is all the more remarkable as no remnant fields had directly been measured with any of these magnets. A specific remnant field effect that led to anomalous machine behavior when trying to recuperate the betatron tunes on the lower hysteresis branch at standard energy could be ascribed to the C-shape of the quadrupole yokes.

I. INTRODUCTION

This paper is concerned with characterizing the integrated fundamental strengths of the ALS [2] lattice magnets, i.e. dipole, quadrupole, and sextupole strengths, in the form of analytical expressions. During the storage ring construction phase, the relative spread of fundamental strengths within each of the six magnet families was the parameter by which the placement of individual magnets along the ring was to be judged; conveniently the spreads for quadrupoles and bend magnets turned out low enough to allow arbitrary positioning, but the sextupoles required current shunts to narrow their spread [1].

To ascertain these fundamental strengths, and also to obtain reasonable interpolation values between the measured excitation points for energy ramping purposes, the original magnetic measurement data have to be smoothed, and analytical approximations are very convenient for this purpose. In addition, the ever present drive to push an accelerator's performance beyond the design limits had led to the question how the strengths of the lattice magnets would scale above the highest excitation conditions so far explored, representing an electron beam energy of 1.9 GeV.

Magnet strengths are commonly expressed by transfer functions,

$$F = T \times I \qquad (1)$$

where F is the integrated fundamental strength, $F = \int B_y \, dz$ for a dipole, $F = \int (B_r/r) \, dz$ for a quadrupole, etc.; T the (constant) transfer function value; and I the excitation current. This representation, however, is too simple to take into account residual field effects which are quite relevant for third-generation light sources with relative precision requirements of 10^{-3} and below. Other desired features of magnet transfer functions are that they be constant (for either hysteresis branch) at low excitation values, smooth over the entire range, include the measured saturation effects, and do not drop off too steeply beyond the highest measured excitation current value. Polynomial approximations do not generally fulfill most of these conditions, and therefore a new type of transfer function expressions has been introduced in the course of this work.

II. ELEMENTS OF TRANSFER FUNCTIONS

In deriving magnet transfer functions from measured data, one can distinguish three zones of the excitation curve, dependent on where 1), residual field effects are noticeable, 2), the excitation curve is linear, and 3), saturation effects show up, see Fig. 1.

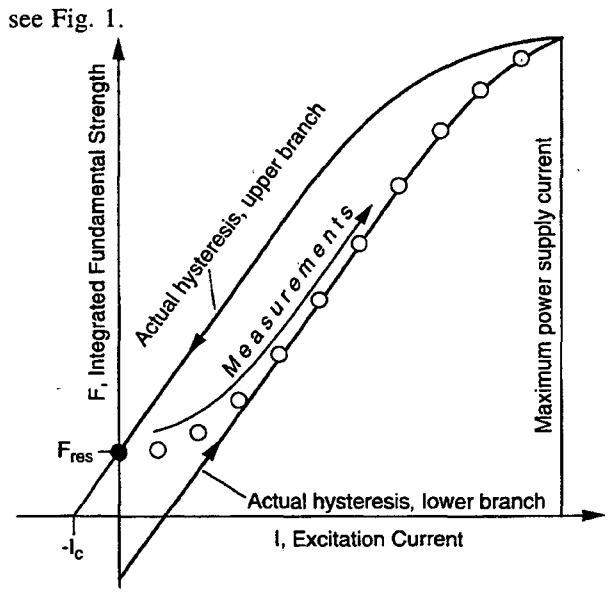

Figure 1: Schematic of a hysteresis loop with magnet measurement data, $F_{i,meas}$ (open circles). Residual field and saturation effects are exaggerated in this illustration.

In this paper the expression hysteresis is being used rather liberally because none of the magnets has ever been brought to full saturation. The maximum excitation currents applied during the magnet measurement activities, however, were nearly equal to the ones now applied in day-to-day conditioning. Therefore the measured excitation loops can be regarded as truly representative of the actual magnet operation conditions.

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The basic assumption about residual field effects made in this paper is that the two hysteresis branches of the excitation curve are parallel to each other at low currents. A look at the diagram, Fig. 1, suggests that one can substitute the actual excitation current I with an effective current $I_{eff} = I \pm I_c$ where I_c, the coercive current, is subtracted to represent the lower hysteresis branch and added for the upper branch. Then the hysteresis loop turns into one simple curve that starts at the origin and rises linearly until saturation begins to show, and the corresponding transfer function can be written as

$$F = T \times (I \pm I_c). \qquad (2)$$

In the case of the ALS the original ten excitation measurements had been taken with current settings rising from zero, see Fig. 1; and this fact makes it more complicated to derive a value for the coercive current without direct measurement, especially because not even the residual fundamental strength, F_{res}, was recorded. The solution offered here consists in extrapolating the linear part of the excitation curve back to zero strength, thereby determining I_c and F_{res}, and then shifting the first data points $F_{i,meas}$ into the lower hysteresis branch, with a damping term providing a smooth transition:

$$F_i = F_{i,meas} - 2\, F_{res} / \exp\{I_i / (C\, I_c)\} \quad [1 \le i \le 10] \qquad (3)$$

The constant C in the damping term has to be determined by empirical optimization, iterating the evaluations of I_c and F_{res}, to minimize the standard deviation for all available measurement points. The actual values for F_{res} and C are needed for the determination of the constant part of the transfer function; once this term is known I_c is the only parameter that accounts for residual field effects.

ALS lattice magnets typically show a few percent saturation at excitations corresponding to 1.9 GeV energy, and this drop is significant in view of the tolerance band of 10^{-3} relative strength. To represent saturation, Equ. (2) is modified:

$$F = \frac{T_{lin}(I \pm I_c)}{1 + \left(\frac{I \pm I_c}{I_s}\right)^A} \qquad (4)$$

and now contains four parameters in addition to the excitation current I as independent variable. The transfer function is now called T_{lin} to emphasize that it represents the linear part of the excitation function only. The action of the saturation term (denominator) in Equ. (4) is illustrated in Fig. 2.

The evaluation of all five transfer function parameters for every individual magnet is performed in iterations, separately optimizing residual field and saturation effects. After preliminary parameters for each member of one magnet family are established the exponent A and the damping parameter C are averaged for the entire family, and new iterations are performed for each magnet to find the definitive values of the other parameters.

III. APPLICATION OF TRANSFER FUNCTIONS

An example of a calculated transfer function is given in Fig. 3. A list of the averaged calculated transfer function parameters in terms of Equ. (4), as derived from the original measurements [3] for the ALS lattice magnets, is given in Table 1 below. This list was used to create a ramping table for the storage ring magnets, matching a raise of the electron beam energy from 1.5 to 1.9 GeV in 2-MeV steps, without applying any corrections during or after execution of the ramp. For every step Equ. (4) was solved with a "regula falsi" method to find the proper excitation-current set-values separately for each magnet family. Only very minimal differences in betatron tunes occurred during the ramp, see Fig. 4, corresponding to maximum transfer function errors of 8×10^{-4} and 7×10^{-4} for the QF and QD families, respectively, if the total error were ascribed to one of these families only. Similarly good results were achieved with an automatic energy ramping program [4] that solved Equ. (4) on-line using Newton's approximation.

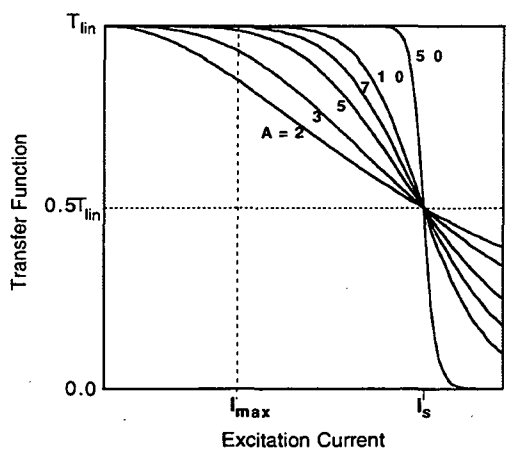

Figure 2: Effect of the saturation term in the denominator of Equ. (4). The exponent A determines the curvature of the transfer function, whereas the saturation current I_s scales the slope of the decay with respect to I_{max}, the maximum applied power supply current. Note that I_s is much larger than I_{max}.

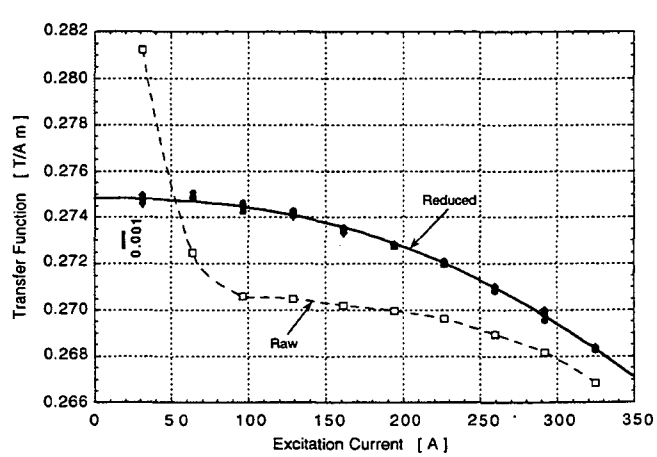

Figure 3: Transfer function for sextupole #10, bold line, evaluated in terms of Equ. (4); the full symbols represent five series of measurements after data reduction to account for residual field effects according to Equs. (2) and (3). The open symbols represent one of these series before reduction, after dividing the measured fundamental strengths by the corresponding excitation currents according to Equ. (1).

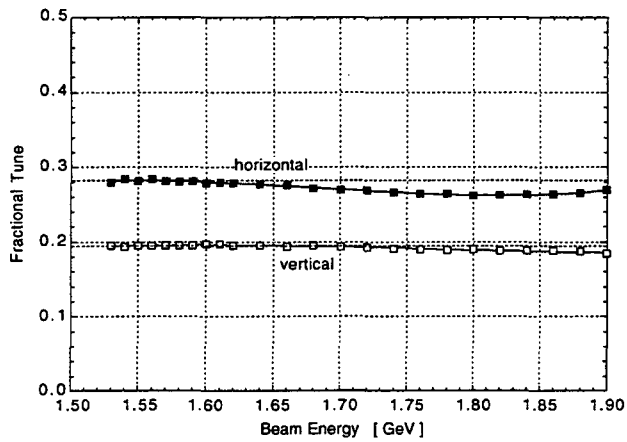

Figure 4: Fractional betatron tunes measured while ramping the storage ring energy with precalculated magnet set values. The full standard tune values at 1.5 GeV are 14.282 (horizontal) and 8.192 (vertical), as indicated by the broken lines.

IV. TUNE-SPLIT EFFECT

With the ALS storage ring lattice, magnet excitation values must be reproducible well within 10^{-3} to guarantee a consistent day-to-day beam position for photon users.

A novel magnet conditioning procedure, based on a converging-loop scheme, had earlier been suggested for SLC magnets [5], and first results with an ALS transfer-line dipole looked very promising. It was a major disappointment, however, finding out that with the ALS storage ring magnets the procedure failed to provide acceptable reproducibility. A closer investigation brought out a quite surprising fact: when the excitation of any one quadrupole family or the gradient magnets was moved from the upper to the lower hysteresis branch the two betatron tunes could not simultaneously be restored to their old values at any excitation current, see Fig. 5.

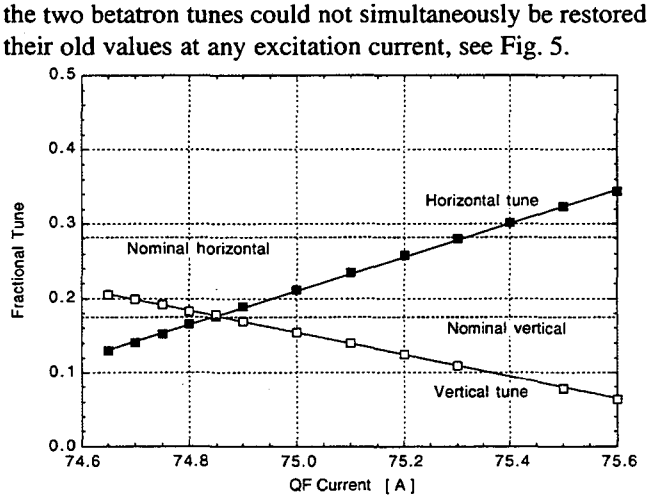

Figure 5: Tune-split effect. Measured fractional betatron tune values are shown as a function of the QF excitation current, after changing the working point from the upper to the lower hysteresis branch. The machine reaches the nominal horizontal tune at significantly higher excitation current than the nominal vertical tune.

After disproving that the effect could have been produced by eddy-currents, a Hall-probe measurement of relative field changes near the pole tips [6] indicated the real cause: remnant magnetization in the back leg of these C-shaped magnets produces a significant dipole field which distorts the electron beam orbit within the lattice sextupoles enough to create the observed tune split. Tracking studies with 0.1-mrad kicks applied to the electron beam at all homologous quadrupole locations confirm this hypothesis [7].

Excitation of dipole fields in C-shaped quadrupoles is a well known phenomenon that had been quantified by magnetic measurements and incorporated into the ALS quadrupole alignment tables as individual offsets between magnetic and mechanical axes. The tune-split effect is based on the fact that this residual dipole component varies upon transition between the two hysteresis branches and is undefined in between, depending on the actual excitation history.

The existence of the tune-split effect implies that the ALS storage ring has to be operated on the lower hysteresis branches of its lattice magnets, contrarily to the earlier practice, because the maximum energy of 1.9 GeV can only be reached by ramping the magnets up. Thus, the mechanical convenience of using C-shaped magnets is ultimately being paid for by operational constraints that might become even more complicated when undulator gap variations will require arbitrary local quadrupole adjustments.

Table 1.
Transfer Function Parameters for the ALS Lattice Magnets

Magnet Type	T_{lin}	I_c	A	I_s
B	0.001312	3	5.73	1739
QFA	0.01722	2.56	3.1	2250
QF	0.05292	0.661	2.8	604
QD	0.02875	0.711	4.3	353
SF	0.2742	2.767	2.4	1548
SD	0.2744	2.844	2.4	1542

V. ACKNOWLEDGMENTS

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