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The Physical Way of Standardizing Magnets

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Abstract

Most accelerator magnets contain iron or other ferromagnetic materials to increase the magnetic field of a coil. Unfortunately these materials have a strong dependence on their history (hysteresis). To obtain a desired magnetic field, a particular current must be supplied with respect to that history. Usually a history map is chosen in such a way that one of the main branches, up or down, of the hysteresis curve is selected. The choices are arbitrary and not natural. The disadvantages of these schemes are, for instance, long standardizing times going up and down the hysteresis, different slopes for increasing or decreasing the field and unstable, but quite reproducible values along the hysteresis loop.

These problems can be overcome by choosing the curve showing the physical dependence of a magnet upon the current. This curve, in the middle of the hysteresis, shows the following advantages: reproducibility by cycling (up and down, going closer) to a certain current; stability to shock, small current changes, heat, even a temperature rise over the Curie temperature and back is possible; the same behavior (slope) going up or down in current for a small range of adjustments, therefore easier to correct by hand or computer (feedback); faster to adjust, especially for small changes. Different theoretical ideas are discussed and some experimental tests are described.

1 Introduction

In particle accelerators, magnets with ferromagnetic yokes are used to guide (bend) and shape (focusing) a beam. The ferromagnetic material increases the magnetic B–field, but it has the disadvantage that the field depends on the earlier excitation, called hysteresis. A typical 1 % difference in the field going up or down the hysteresis loop is in many cases intolerably high. For instance, a 0.5 % change in a quadrupole in the RTL (Ring-To-Linac) section of the SLC (Stanford Linear Collider) would cause a betatron mismatch and therefore an emittance growth by about a factor of two. This is normally avoided by standardizing the SLC magnets, e.g. the magnet current is slowly increased and decreased a few times with a pause at the top and bottom and then trimmed from one side to the desired value [1]. Whether the trimming is done by going up or down on the hysteresis loop, is more or less a human choice and has, in principle, no physically determined reason. A physical way of standardizing magnets would also get rid of the history of this human choice. It can be achieved in a way similar to "degaussing" a magnet. The magnet current I is cycled around I_*, e.g. by:

$$I(t) = I_* + \Delta I e^{-t/\tau} \cdot \sin \omega t, \qquad (1)$$

till at the end ($t \to \infty$) a central, history–free, magnetic field B_* is achieved (see Fig. 1).

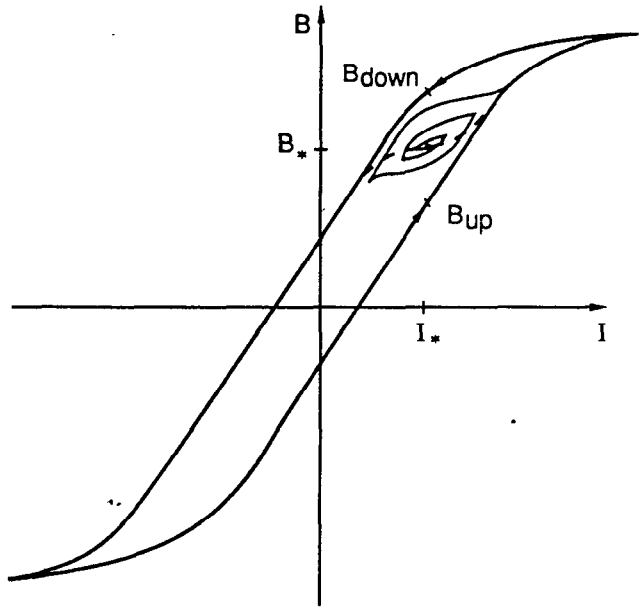

Figure 1: Principle of Physical Standardization.

At a certain current I_* there should be only one value B_* for the magnetic field and not two, one for going up and one down the hysteresis loop. B_* can be achieved by cycling the current around I_*.

The advantages and disadvantages of the two procedures are compared, regarding different topics such as reproducibility, field changes, stability, cycle times, field errors, etc.

2 Reproducibility

It is desired that the measured magnetic fields are reproducible after the magnet is in the beam line. Also, optimal settings for the beam, achieved by field changes, should be able to be found again.

2.1 Global Dependence

The main reason for standardizing is to make the magnetic field dependence on the current through the coils reproducible. Thus the necessary field can be achieved. A new

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strategy would generate only one curve, B_* versus I_*, and not one for up and one for down. If the B_{up} and B_{down} dependence on I is known, B_* can be approximated by $B_* = (B_{up} + B_{down})/2$.

2.2 Local Dependence

Often the magnetic field is changed by a small amount to adjust the steering or focusing of the beam. These small changes of the order of the hysteresis width are especially difficult to reproduce. For instance, if the magnet has been normally standardized by going up, only a further increase of the field would be reproducible. A decrease will cause a loss of standardization, which means that an optimal adjustment cannot be reproduced, e.g. if the magnet has been turned off. This can be partly prevented by always going down and reaching this optimal point from below. Some every day problems are mentioned here:

1. People normally don't tweak adjusting knobs from only one side, or they may proceed with a "going-up" convention, so magnets which were standardized "going down" will suffer.

2. Multiknobs: Several magnets (e.g. four) can be combined by software with different coefficients and signs for variation and controlled by one knob, called a multiknob. (Sometimes, even worse, they are combined by hardware and controlled by one trim power supply in opposite directions.) With such a combination only one parameter of the magnet lattice (e.g. the betatron function in x: β_x) should vary, while a mathematical cancellation is desired for the orthogonal parameters (e.g. $\alpha_x, \beta_y, \alpha_y$). In practice the gap of the hysteresis loop makes a cancellation not only imperfect, but the effect on the orthogonal parameters (which should be zero) is of the same order as the change on the desired parameter (discussed in [2]).

On the other hand a tweaking around an optimal setting automatically generates a cycling around this value, which approximates the final cycles of the new standardization method to B_* (compare eq. 1). Besides the local reproducibility there are more advantages of the new scheme.

3 Stability

An accurately reproduced magnetic field should be kept stable. Small disturbances will cause a loss of the normal standardization, while B_* is the most stable point between B_{up} and B_{down}, if different disturbing mechanisms, like electrical, mechanical and temperature effects are present. With the new standardization very small changes around I_* will have a weaker B vs. I dependence and the values will lie on a kind of "new-curve" (see dashed line in Fig. 1). It is quite symmetric and has a certain quasi-reproducible range, because the boundaries of the magnetic domains are reversibly displaced, which can be described similarly to the Rayleigh relation [3] by

$$\mu_n = \mu_i + \nu \Delta H, \qquad (2)$$

where μ_n is the permeability of the new-curve, μ_i is the initial permeability, which is about 1/10 of μ_r the normal relative permeability at higher fields, ν is a constant and ΔH is the small change in the H field.

3.1 Electrical Stability

A current-regulated power supply may have jitters, power dips or spikes. In most cases, if I_* is reached again, a nonreversible point on the outer hysteresis loop will have moved from B_{up} up (or from B_{down} down) towards B_*. Dips are less disturbing than spikes at B_{up} (and vice versa at B_{down}). A standardization by cycling around B_* has the following advantages. Within the reversible region the magnetic field B_* will be achieved again and a jittering is like the final cycles around B_*. It doesn't move the magnetic field away from this value. The B vs. I slope is smaller around B_* ($\mu_n \approx \mu_i \approx 1/10 \cdot \mu_r$, compare equation 2), so a higher power supply jitter is tolerable.

3.2 Mechanical Effects

An unmagnetized nail or screw driver will be magnetized by hammering (or just lying around) as it sits in the north-south direction, due to the earth's magnetic field. The effect is a movement from an unstable point near B_{up} towards B_*. Although an operating magnet will hopefully not be treated with a hammer, it has to stand different mechanical influences. The vibration level of the cooling water might be small, but it excites all the time. Beam losses, besides a temperature rise (see below), might have an effect similar to a hammer. The resultant gradual drift away from B_{up} (say) is probably one of the main reasons that huge accelerator systems need a long "switching-on" period, lots of adjusting tweaks, and they don't recover properly after a failure.

3.3 Temperature Effects

Besides creating variations in magnet gap size and length [4], temperatures and gradient changes may cause stresses in the material, which may shift ferromagnetic domains to a more stable configuration. Although an enormous temperature rise above the Curie-temperature is quite hypothetical and might only happen locally due to a concentrated beam loss, the field would come back to the stable point B_* (I_* is on!), if the ferromagnetic material was not especially treated while cooling down.

4 Other Reasons

Additional other reasons may influence the choice of a standardization method. The time for a standardization, higher order field components and the available software can be a reason.

4.1 Time for Standardization

When a lack of activity is recognizable in the control room, it is often a time for standardizing one or more magnets. Times of the order of 15 minutes lead to situations where unwanted running conditions, like an uncoupled damping ring or a mismatch in betatron functions, have to be accepted, in order to proceed with the scheduled program. One reason for this long time is that all the magnetic domains have to be driven to the boundary of the hysteresis

curve. A cycling around B_* would occur in a smaller region of about $\pm 10\,\%$ of the whole range of the hysteresis loop. Therefore it would be faster even though more smaller cycles may be necessary.

4.2 Field Errors

The main field errors of a magnet are generated at its ends. Assuming a long magnet or a very careful design of the ends, the desired symmetric n-pole will have only contributions of a 3n-pole and higher. A dipole will have a sextupole and a quadrupole will have a dodecapole component.

A careful design can minimize this, if the nonlinear behavior of the material is taken into account. At different places on the hysteresis curve (up or down) these higher order components might have different signs, but no change around (B_*, I_*) is expected. By choosing one special branch of the hysteresis loop, one might be able to compensate some remaining end effects.

5 Experimental Results

An SLC vertical bend magnet has been set up and tested. At the investigation current $I = 300\,\mathrm{A}$ the gap magnetic field is about $B = 0.62\,\mathrm{T}$ or $\int B\,dl = 0.193\,\mathrm{Tm}$. First a normal standardization with five cycles going up and down between 10 A and 400 A, with a 30 s pause at the top and bottom, was applied. The difference in $B_{up} = 0.61744\,\mathrm{T}$ and $B_{down} = 0.61972\,\mathrm{T}$ is about $(0.37 \pm 0.01)\,\%$. The measurement error is around $\pm 1 \cdot 10^{-4}$.

The new standardization method, approximated with (400, 225, 350), 275, 312, 294, 303, 298.5, 300.75, 300 A, has less effective steps (the first three are on the outer hysteresis loop). It achieved a reproducible ($< \pm 0.4 \cdot 10^{-4}$) magnetic field and was about $1.4 \cdot 10^{-4}$ below the average of B_{up} and B_{down}.

The stability has been checked by changing the current from I to $I + \Delta I$ and back to I, $I + 2\Delta I$, I, . . . up to 10 % maximum current change, see Fig. 2. For the big changes of 10 % the center point B_* is about twice as stable as starting at B_{up}. B_{down} seems more stable, but is similar to B_{up} for a decreasing current. The new standardization method is about 4 times more stable than the usual method for 1 % changes in current. Since the change in B_{up} going up and back is bigger than going down and back, B_{up} will drift towards B_*, while B_* would stay constant.

Some of the measurement points in Fig. 2 are a little outside the area of the standard hysteresis loop. The explanation seems not to lay in the experimental procedures, such as too short pauses or different rates in current rise (Eddy currents) [5]. This might be explained by a stabilization of the magnetic domains with time leading to a weaker B vs. I dependence such as around B_*.

6 Conclusion

A new standardization method, using decreasing current cycles around the desired magnetic field B_*, seems to have many advantages over the old scheme using one of the outer branches of the hysteresis loop. Some experimental measurements have demonstrated the quick and good reproducibility and enhanced stability of the new method. The next step would be to apply some of the these advantages to critical SLC, or other accelerator, magnets.

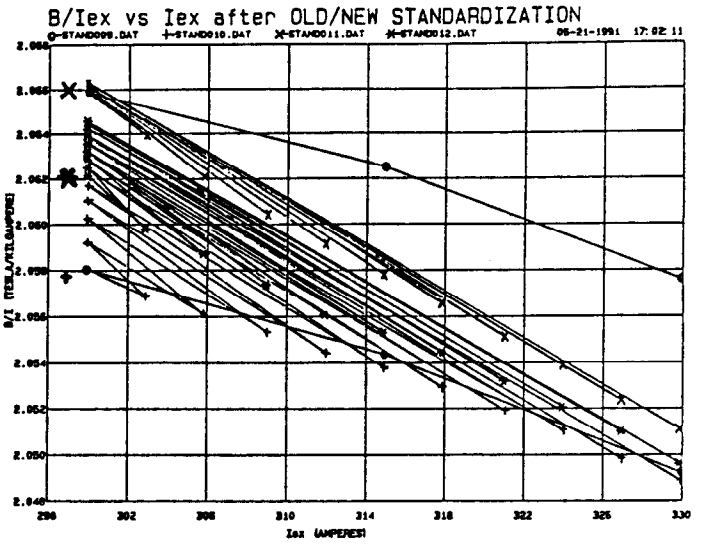

Figure 2: Stability Check.

A part of the hysteresis curve is shown. The magnetic field B is divided by the exciting current I to increase the visibility of the 0.4 % wide hysteresis loop indicated by the symbol (0). Three other curves starting at 2.058, 2.062 and below 2.066 in B/I represent the stability of going up and back in current, with different step sizes, for B_{up} (+), B_* (*) and B_{down} (X).

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