BEHAVIOUR OF NON-LAMINATED CORE ARMCO-IRON MAGNETS AT LOW INDUCTION.

In the Storage Ring Model for electrons having a kinetic energy on the central orbit of 1.879 MeV 12 solid core iron magnets are used to give the necessary bending. A thirteenth magnet is included in the servo-circuit that is to assure an energy stabilisation of the beam coming from the Van de Graaff generator.

The machine having the shape of a 12 corner polygon the bending angle is 30° and the bending radius has been specified for electrons on the central orbit to be $\varrho = 60$ cm.

Assuming the so-called hard edged distribution of the induction as a function of azimuth (fig. 1) we can define the $\int B d\ell$ that will give the right deflection.

We can write $\int_{-\frac{\varrho}{2}}^{+\frac{\varrho}{2}} B d\ell = \int_{-\varphi}^{+\varphi} Br d\varphi$ when we have the distribution of induction as shown in fig. 1.
In this way $\int B d\ell = 1.1295 \, \text{G cm}$ for electrons having a kinetic energy of 1.879 MeV and $B_o$ becomes 129.5 G. We shall conserve $\int B d\ell = 1.1295 \, \text{G cm}$ as the value that we shall have to measure in a real magnet. Then the situation will change slightly because of the fringing field existing at the edges of the magnet. The induction $B$ plotted as a function of azimuth is shown in fig. 2.

![Graph showing B as a function of azimuth]

$B = \text{const.}$

This represents an admissible approximation to measure $\int B d\ell$ in reality.

Having set the current and thereby $B$ such as to obtain $\int B d\ell$ of fig. 2 equal to $\int B d\ell$ of fig. 1 the bending action of the magnet configurations is equivalent and we find the induction $B_o$ in the soft edged magnet to be smaller than $B_o$ in the hard edged approximation.

Actually we measure $B_o$ to be 121.2 G for a typical magnet giving a bending radius of the electron trajectory of $r = 60$ cm. Small variations in this value occur due to coil dimensions and positioning accuracy of the coils. The current, however, which is needed to energize the magnets at this induction level varies between the 5 magnets measured so far by 2.5 o/o. This variation in current is mainly due to variations in $\mu$ of the iron of the magnets.

Careful measurements of the $\int B d\ell$ as a function of current have revealed a strong dependency on the magnetic treatment which the magnet had undergone before making the measurement.

K. Johnsen\(^1\) has outlined the severe tolerances that have to be imposed on the uniformity of the induction $B$. Errors in $B$ of $\frac{\Delta B}{B_{\text{nominal}}} = 1 \, \text{o/o}$

\(^1\) K. Johnsen
between the 12 magnets bring already about a closed orbit deviation of 1 mm.

This leads us to explore in some more detail where the variations of \( \int Bdl \) in one and the same magnet could come from after having gone through several complete demagnetizing and magnetizing cycles.

It also is of great importance to assure that once all the magnets are aligned on the ring the magnetic field can be cut off and turned on again without disturbing their uniformity.

Two effects were found to explain the variations of \( \int Bdl \) in one magnet and between several of them.

1) Original Remanence

By original remanence we understand the state in which the magnets were delivered from the factory. Typical values for the remanence in several magnets are between -150 to +500 mG giving a total \( \Delta B \) of 650 mG. With respect to \( B_0 = 121.2 \) G this means an error \( \frac{\Delta B}{B} = 5.5 \) o/oo which is reflected by the measurement of \( \int Bdl \). The best possibility to remove this remanence consists in applying a proper demagnetizing cycle. By proper we understand a cycle that is sufficiently slow to allow the field to penetrate into the solid structure of the magnet. It will be interesting to find the penetration depth of the field due to eddy currents assuming \( H \) varying sinusoidally with time. The theory of eddy currents has been described extensively elsewhere (2, 3) also with special application to accelerator magnets.

We confine ourselves to give the formulae for the behaviour of electric and magnetic field strengths as functions of time \( t \) and distance \( y \) from the surface of the magnetically conducting material.
In xy plane: \[ a \frac{dH}{dy} - (|H| + \frac{\partial|H|}{\partial y} \, dy) \, a = G \, a \, dy \]
\[ = KE \, a \, dy \]
\[ \frac{dH}{dy} = KE \tag{1} \]

In zy plane: \[ -|E| \cdot b + (|E| + \frac{\partial|E|}{\partial y} \cdot dy) \cdot b = -\mu_b \frac{\partial|E|}{\partial t} \cdot dy \]
\[ \frac{dE}{dy} = -j\omega\mu H \tag{2} \]

With (1) and (2) we find
\[ \frac{d^2E}{dy^2} = j\omega\mu KE \tag{3} \]

And a possible solution for \( \vec{E} \) is:
\[ \vec{E} = c_1 e^{-y/\delta} - j(y/\delta - \omega t) \tag{4} \]

under the assumption that \( \vec{H} \) varies sinusoidally in time.
δ is defined by

\[ \delta = \frac{1}{\sqrt{\pi f \mu K}} \]  

\( f \) = frequency
\( \mu = \mu_0 \mu_r \) = permeability
\( K = \frac{1}{\rho} \) = conductance
\( C_1 \) = arbitrary constant that depends on boundary conditions for E.

δ is also called penetration depth and as defined by equation (4) the field has dropped to \( \frac{1}{e} \) for \( y = \delta \). We can conclude then that the field is contained in about a layer \( 4 + 8 \delta \) thick.

As an illustrating example it is of interest to calculate δ for a 50 Hz excitation of \( \overrightarrow{H} \).

In iron

\[ \mu = \mu_0 \cdot \mu_r \]

\[ \mu_r \approx 560 \text{ at } B \approx 300 \text{ G.} \]

\[ \frac{1}{\rho} = K = 10^5 \text{ (}\Omega \text{ cm})^{-1} \]

\[ \delta_{50 \text{ Hz}} \approx 1 \text{ mm.} \]

In other words the layer affected by \( \overrightarrow{H} \) is about 4 to 8 mm thick.

In the bending magnets the greatest distance from the surface is about 10 cm and it is important to know what time variation in H is permissible to have B penetrate throughout the iron. Therefore we assume \( \delta = 5 \text{ cm} \) and then \( f \) becomes

\[ f = \frac{1}{56} \cdot 1/3 \]

This implies that within a period of \( \frac{1}{f} = 56 \text{ s} \) we can change the polarity of \( \overrightarrow{H} \) twice and still affect the core of the magnet throughout its thickness.
In other words a rise time of \( T = \frac{1}{4f} = 14 \text{ S} \) is the minimum desirable time if the core is to be magnetized nearly uniformly over its total cross section.

2). The influence of eddy currents which are set up by the switch-on and off of the magnets.

As it is explained above changes in the magnetic field that occur at periods shorter than 14 S do not affect the core of the magnet. On the contrary we impress especially after switch off a field distribution of \( \vec{B} \) which is governed mainly by the distribution of eddy currents. That is why we must carefully control the switch-on and off procedure when we want to remain within the time range that can be considered as slow \((T \geq 14 \text{ S})\).

If we do not respect the slow rise nor decay of the induction \( B \) we find for example after turn on a slow rise of the field of about 3 o/oo over a time of about 3 + 4 minutes. We can explain this effect by the concentration of \( B \) in a layer at the surface the thickness of which is determined by the speed \((in \text{ other words } f)\) of the turn-on. This layer slowly extends with the time constant \( T \) into the core once \( H \) has attained its nominal value and \( B \) spreads uniformly over the cross-section. The distribution of the remanent field seems also to be governed by the eddy currents that are produced once \( H \) is switched off. Therefore we also have to be very careful to change \( H \) always sufficiently slowly \((T \geq 14 \text{ S})\).

3). Reproducibility of \( B \) between several magnetizations.

This problem is extremely important once the magnets are in place and the vacuum chamber installed. There is no place to include monitoring devices for the induction \( B \) and we have to rely upon the reproducibility of the magnetic induction once it has been measured. A demagnetizing cycle can not be envisaged since all magnets need slight adjustments in their
cycle in order to give good demagnetization. We found the best method to consist in switching $H$ on and off about 10 times (always respecting $T \geq 14 \text{ S}$) thereby establishing a remanence around a saturation value that is characteristic for each magnet (see Table 1). We then had an induction $B$ at nominal value that was reproducible to better than 1 o/oo. We therefore recommend careful turn-on and turn-off cycles for the current respecting the condition that all changes should occur more slowly than $T = 14 \text{ S}$.

Besides this we shall have to find a protection against failures of the mains because this will mean an abrupt cut of $H$. We must have at least an indication that $H$ has been turned off especially during standby periods of the machine.

**Conclusion:**

The non laminated iron core of the bending magnets needs careful and slow cycling of the magnets if they are to be used at very low fields as this is the case in the Storage Ring Model. The cycling time depends on the actual dimensions of the iron core and can be determined with formula (5). Thereby it is possible to reduce the influence of eddy currents to below the required tolerances of 1 o/oo in $B$. The demagnetising cycle must follow the same routine as outlined above when it is to affect the total iron cross-section.

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PD

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References

1) K. Johnsen, PS Int/AR 60-30
   Some Magnet Parameters and Tolerances for the Electron Storage.

   Eddy Current Phenomena in the Cosmotron.

**TABLE 1**

A typical example for the saturation effect of the remanent field, starting at a remanence of 60 mG.

<table>
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