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IRON YOKE EDDY CURRENT INDUCED LOSSES WITH APPLICATION TO THE ALS SEPTUM MAGNETS*

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August 16, 1991

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Iron Yoke Eddy Current Induced Losses with Application to the ALS Septum Magnets

Ross D. Schlueter

August 16, 1991

Abstract

The theoretical development of relations governing the eddy current induced losses in iron electromagnet yokes is reviewed. A baseline laminated electromagnet design is analyzed and a parametric study illustrates the sensitivity of core losses to perturbations of various geometrical, material, and excitation parameters. Core losses and field gradients for the ALS septum magnets are calculated. Design modifications capable of eliminating transverse and longitudinal field gradients are discussed.

1 Summary

For large enough $\tau \omega$, where $\tau \equiv \sigma \mu_0 \mu_r d^2, \omega \equiv 2\pi f$, and $f$ = excitation frequency, the B-field just inside the face of the iron yoke (or lamination) can be several times the value of that for an identical magnet having a DC excitation of equivalent magnitude. For a real material with nonlinear B-H the ratio of $H$ just inside the iron face where $x = d$ to $H$ of the DC case, $H(B_{\text{iron}}(d))/H(B_{\text{ironDC}})$ is several times the ratio of the corresponding $B_{\text{iron}}(d)/B_{\text{ironDC}}$, and thus losses in the iron can be huge. A subtle damping/wave propagation/saturation effect diminishes these losses somewhat in such a nonlinear material by limiting the maximum attained value of $B_{\text{iron}}(d)$.

For the ALS septum magnet iron losses are expected to be $\sim 1.40\%$ and $\sim 1.05\%$, at the entrance and exit, respectively. (A 1% loss corresponds to a 100 G reduction of $B_{\text{gap}}$ for the 10 kG excitation). The longitudinal field drop is thus expected to be $\sim 35$ G (0.35%). If desired, this gradient could be eliminated by tapering the gap $\sim +0.35\%$ ($\sim +0.002$ inches) from entrance to exit.

The transverse field drop is expected to be $\sim 20$ G (0.20%). If desired, this gradient could be eliminated by slotting the laminations at the location of the coil/gap junction.

2 Theoretical Groundwork

Here we investigate the eddy-current induced losses in a solid core or laminated electromagnet, following the theoretical development by Halbach$^{[1,2]}$. 
Figure 1. Generic upper-half electromagnet cross section

Assume that to first order in the region of interest in Figure 1 the variables are invariant with \( y \) and \( z \), \( B = B_y(x), H = H_y(x), E = E_z(x), A = A_z(x), \) \( t \equiv \frac{\partial}{\partial x} \) and that \( \cdot \equiv \frac{\partial}{\partial t} \). Ampere's Law for the circuit across the gap and just inside the iron face (or any path just inside the face of a lamination) is

\[
\mu_0 I = \mu_0 \int H \cdot ds = g B_{\text{gap}} \left( 1 + \frac{L}{g} \frac{H_{\text{iron}}(d)}{H_{\text{gap}}} \right) = g B_{\text{gap}} \left( 1 + \frac{L B_{\text{iron}}(d)}{g B_{\text{gap}}} \frac{1}{\mu_r} \right) \tag{1}
\]

where \( L \) is the effective path length in the iron and \( \mu_r = \mu_r(B_{\text{iron}}(d)) \). Assuming losses in the linearly behaved iron are small, a coil excitation \( I(t) \) gives rise to a field in the gap \( B_{\text{gap}}(t) \propto I(t) \) and

\[
B_{\text{iron}}(t) = B_{\text{gap}}(t) \frac{w_{\text{gap}}}{w_{\text{iron}}}
\]

where the '-' denotes the \( x \)-direction spatial average over \( 0 - d \), with \( d \) being the yoke width (or, for a laminated magnet, the lamination half-thickness, in which case we switch the coordinate axes \( x \rightarrow -z, z \rightarrow x \)).

From field equations \( B = \nabla \times A \), and \( \nabla \times E = -\dot{B}, \Rightarrow E = -\dot{A} \). This result, combined with \( \nabla \times H = J = \sigma E, \Rightarrow H' = \sigma \dot{A} \). The vector potential is thus given by

\[
\frac{\partial A}{\partial t} = \frac{1}{\sigma} \frac{\partial}{\partial x} \left( \frac{\partial A}{\partial x} \right) \tag{3}
\]

subject to \( A(x,0) = \text{given}, A(0,t) = 0 \), and \( A(d,t) = -B_{\text{iron}}(t)d \). Numerically, the following algorithm is convenient:

\[
A(x,t) \Rightarrow B(x,t) \Rightarrow H(x,t) \Rightarrow \dot{A}(x,t) \Rightarrow A(x,t + \delta t) \tag{4}
\]

Program \texttt{septum.rk4} in Appendix A uses a fourth order Runge Kutta algorithm to solve for the 1-D eddy current induced spatial field distribution in a yoke (or lamination) at chosen time intervals. Program \texttt{sep_edge.rk4} similarly solves for the temporal behavior of various parameters of interest including \( B_{\text{iron}}(d,t), H(B_{\text{iron}}(d,t)), \dot{B}_{\text{iron}}(t), \text{and } H(\dot{B}_{\text{iron}}(t)) \).
$B_{iron}(t) = -\frac{A(d)}{d} = B_0 \sin \omega t$, $0 \leq t < \pi / \omega$, $B_0 = 12$ kG,
$= 0$, $\pi / \omega \leq t$

$1/\sigma = 50\mu \Omega \cdot \text{cm}$, $f = \omega / 2\pi = 5$ kHz, $d = 0.007$ inch, $\mu$ for M-19 transformer steel

Figure 2a,b,c,d. B and H distributions and temporal history for baseline eddy current induced losses in a laminated magnet.
3 Baseline: An Eddy Current Induced Loss Calculation in a Laminated Magnet

Assuming a gap excitation \( B_{gap}(t) = B_{gap} \sin \omega t, \) \( 0 \leq t < \pi/\omega, \) then \( \bar{B}_{iron}(t) = B_0 \sin \omega t \) and from Eqn. (2), \( B_0 = B_{gap} \omega \mu_{iron} \). Figure 2a shows the field distribution across a lamination half-thickness (0 - 0.007 inches) at time intervals of \( 1/12 \) of 100 \( \mu \)sec for the baseline parameters given. Also shown on the right in the Figure are \( B_{iron} \) values corresponding to the field distribution at these time intervals. Figures 2b and 2c show the temporal B and H history, respectively, at the lamination face \((x = d)\) along with the average (excitation) values. The \( H(B_{iron}(d,t)) \) and \( H(B_{iron}(t)) \) in Figure 2d are proportional to, respectively, the eddy current induced losses and those of a DC excitation of the same magnitude. The B-H curve for M-19 transformer steel used is given in Figure 2e and is listed in the programs in Appendix A.

From Eqn. (1), assuming \( \frac{L}{g} \approx 10 \) and \( \frac{\omega_{gap}}{\omega_{iron}} \approx 1 \), eddy current induced losses in the iron for this baseline case are 1.03%. This is over five times the loss level of a DC excitation of the same magnitude.

4 Parametric Study: Eddy Current Induced Losses in Laminated M-19 Transformer Steel and in Steel with \( \mu_r = 1000 \)

Figure 3a lists data of a parametric study for perturbations about the baseline. The left third of the figure lists the varied parameters, the middle third lists maximum B and H in the iron along with losses in the M-19 transformer steel, and the right third lists data for the same parameters but for a fictitious constant permeability steel with \( \mu_r = 1000 \). Also included in the right third are numerical data for a continuous sinusoidal excitation; these
results agree with the closed form solution shown in Figure 3c. Here \( B_{\text{iron}}(d)|_{\text{max}}/B_0 = \alpha/\tanh \alpha \), where \( \alpha \equiv \sqrt{\pi \omega} \). In Figure 3b are plotted the excitation \( H(B_{\text{iron}}(t)) \) and the response \( H(B(d,t)) \) histories to a half-sine wave excitation in M-19 transformer steel for the parameters listed in Figure 3a.

Effect of \( \mu_r \). Application of the relation given in Figure 3c shows that for large enough \( \tau \omega \), \( B_{\text{iron}}(d)|_{\text{max}} \) can be several times \( B_0 \); for a real material with nonlinear B-H the corresponding \( H(B_{\text{iron}}(d)|_{\text{max}})/H(B_0) \) is several times the \( B_{\text{iron}}(d)|_{\text{max}}/B_0 \) ratio, and thus losses in the iron can be huge. A subtle damping/wave propagation/saturation effect diminishes these losses somewhat in such a nonlinear material by limiting the maximum attained value of \( B_{\text{iron}}(d)|_{\text{max}} \).

<table>
<thead>
<tr>
<th>#</th>
<th>parameters</th>
<th>M-19 transformer steel</th>
<th>( \mu_r = 1000 )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( B_0 )</td>
<td>1/( \sigma )</td>
<td>( f )</td>
</tr>
<tr>
<td></td>
<td>kG</td>
<td>( \mu \Omega \cdot \text{cm} )</td>
<td>kHz</td>
</tr>
<tr>
<td>0</td>
<td>12</td>
<td>50.0</td>
<td>DC</td>
</tr>
<tr>
<td>a</td>
<td>12</td>
<td>50.0</td>
<td>5</td>
</tr>
<tr>
<td>b</td>
<td>14</td>
<td>50.0</td>
<td>5</td>
</tr>
<tr>
<td>c</td>
<td>12</td>
<td>12.5</td>
<td>5</td>
</tr>
<tr>
<td>d</td>
<td>12</td>
<td>50.0</td>
<td>20</td>
</tr>
<tr>
<td>e</td>
<td>12</td>
<td>50.0</td>
<td>20</td>
</tr>
</tbody>
</table>

\[ \alpha \equiv \sqrt{\pi \omega}, \tau \equiv \sigma \mu_0 \mu_r d^2, \omega \equiv 2\pi f, B_{\text{iron}}(t) = -A(d)/d = B_0 \sin \omega t, \quad 0 < t < \pi/\omega, \quad \tau/\omega \leq t \]

Figure 3a,b,c. Parametric study data of eddy current induced losses in a laminated magnet.
\[ B_{\text{iron}}(t) = -A(d)/d = B_0 \sin \omega t, \quad 0 \leq t < \pi/\omega, \quad B_0 = 12 \text{ kG}, \]
\[ \frac{1}{\sigma} = 50 \mu\Omega\text{-cm}, \quad f = \omega/2\pi = 5 \text{ kHz}, \quad d = 0.007 \text{ inch} \]

Figure 4a,b,c,d. Effect of iron permeability on eddy current induced losses in a laminated magnet.
For the baseline parameters of Figure 2, Figures 4a,b,c show the B-field wave propagation in the half-lamination for (1) soft iron (Poisson default Material #2) steel, (2) $\mu_r = 1000$, and (3) $\mu_r = 4000$, respectively. Figure 4d shows temporal history of $B_{\text{iron}}(d,t)$ for the various cases in Figures 4a,b,c. Notice that for the nonlinear iron case the permeability ranges $1250 < \mu_r \leq 4000$ everywhere and for all times, yet because of the damping/wave propagation/saturation interplay mentioned above, $B_{\text{iron}}(d)_{\text{max}}$ never reaches the level of even that of the case with constant $\mu_r = 1000$.

5 Iron Losses in the ALS Septum Magnet

5.1 Iron Losses at the Entrance and Exit; Gap B-field Longitudinal Gradient

Figures 5a,b show cross sections of the ALS septum magnet entrance and exit where the gap width is $\sim 86\%$ and $\sim 68\%$ of the yoke width, respectively. Current strawman parameters for this magnet are: $B_{\text{gapmax}} = 10 \text{ kG}$, $1/\sigma = 50\mu\Omega \text{-cm}$, $f = 5 \text{ kHz}$, and M-19 transformer steel lamination half thickness $d = 0.007 \text{ inches}$.

Figure 6a,b show eddy current induced loss tabulations from $\text{sep\_edge\_rk4}$ for three $\frac{\nu_{\text{sep}}}{\nu_{\text{iron}}}$ ratios. For this magnet the estimated $L_g = 20$. Thus, a first approximation to the entrance and exit losses are $1.34\%$ and $0.89\%$, respectively. (A 1% loss corresponds to a 100 G reduction in $B_{\text{gapmax}}$). A [n improved?] calculation could account for an initial $\frac{\nu_{\text{sep}}}{\nu_{\text{iron}}}$ ratio of $\sim 1$ near the gap/steel interface. Then $\int H \cdot ds_{\text{iron}} \approx \Sigma_{i=1}^2 H_i ds_i$. For the entrance $H_1 = 7 \text{ A/cm}$, $ds_1 = 6g \text{ cm}$, $H_2 = 5.32$, $ds_2 = 14g$, and losses come to $175 \text{ A}$ ($1.45\%$). For the exit $H_1 = 7$, $ds_1 = 5g$, $H_2 = 3.51$, $ds_2 = 17g$, and losses come to $140 \text{ A}$ ($1.19\%$).

If desired, this gradient could be eliminated by tapering the gap $\sim +0.35\%$ ($\sim +0.002$ inches) from entrance to exit to compensate for the decreasing losses in the iron as one travels from the magnet entrance to exit.

5.2 Gap B-Field Transverse Gradient

For $B_{\text{gapmax}} = 10 \text{ kG}$, the field on the face of a lamination near the gap/iron interface can reach $\sim 14.2 \text{ kG}$ (see Figure 6a).

Poisson runs for the ALS septum magnet entrance and exit cross section geometries with the static $B_{\text{gap}}$ set to $14.2 \text{ kG}$ (so as to simulate the gap/iron eddy current interface condition for a $5 \text{ kHz}$ half sine wave excitation of magnitude $10 \text{ kG}$) result in a transverse field gradients of $\sim 20 \text{ G}$ ($\sim 0.20\%$ of the $10 \text{ kG}$, $5 \text{ kHz}$ field in the gap).

The gradient arises because, although at all locations and times $\mu_r \gg 1$, it is not infinite. This gives rise to a nonzero $H_{//}$ along the gap/iron interface in the transverse direction. Forcing $H$ to be perpendicular to this interface, for example by slotting the laminations in the axial direction at the location of the coil/gap junction would largely eliminate the transverse field gradient.[3]
Figure 5. Cross sections of the ALS septum magnet entrance and exit

<table>
<thead>
<tr>
<th>parameters</th>
<th>M-19 transformer steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_{\text{gap max}}$</td>
<td>$\frac{w_{\text{gap}}}{w_{\text{iron}}}$</td>
</tr>
<tr>
<td>kG</td>
<td>kG</td>
</tr>
<tr>
<td>entr.</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>10</td>
</tr>
<tr>
<td>exit</td>
<td>10</td>
</tr>
</tbody>
</table>

$B_{\text{iron}}(t) = -A(d)/d = B_0 \sin \omega t, \quad 0 \leq t < \pi/\omega$

$= 0, \quad \pi/\omega \leq t$

$1/\sigma = 50\mu\Omega\cdot\text{cm}, \quad f = \omega/2\pi = 5 \text{ kHz}, \quad d = 0.007 \text{ inch}, \quad \mu$ for M-19 transformer steel

Figure 6a, b. Eddy current induced losses in ALS septum magnet
6 Acknowledgements

I am happy to acknowledge Klaus Halbach's guidance in the theoretical aspects of the work presented herein.

7 Literature Cited


Appendix A: Codes \textit{Septum\_rk4} and \textit{sep\_edge\_rk4}
Program septum_rk4: For analysis of fields in iron due to eddy currents.

(this version uses 4th order Runge-Kutta)

(refer to K.H. Mag. Tech. #1, pgs. 1.7-1.10)

created: 7/91 Ross Schlueter

DECLARATIONS

character ddevice*3
character*60,string

common/xylim/xmin,xmax,ymin,ymax !for use w/ pcont
common/device/ddevice
common/fun/ pi, Hz, B_0, d , mur
common/sub/ sigma, mu_0, dx, time
real k1(101), k2(101), k3(101), k4(101)
real mu_0, mur, mur_min
dimension x(101), xshift(101), A(101), Bip(101), Hip(101),
& dHdx(101)

ddevice='qms'

ccc open (unit=1, file='oldfilenarname.dat', status='old')

INITIALIZATIONS

pi = 4.*atan(1.)
mu_0 = .4*pi ! G-cm/A
mur varies and ! is unitless
B_0 = 12000. ! G
Hz = 5000. ! cycles/s
sigma = 1./(50.e-6) ! 1/Ohm-cm stainless steel (LEB vac. ch.)
sigma = 1./(12.5e-6) ! 1/Ohm-cm 1010 steel
sigma = sigma*1.e-8 ! A-s/G-cm^3
sigma_mu_0 = sigma*mu_0 ! s/cm^2
d=.014*2.54/2. ! (cm) septum half-thickness, = 14/2 mils

dt = 0.5*sigma_mu_0*mu_0*(dx**2)/2. ! (sec), dt < sigma*mu_0*mu*dx^2/2

tau- = sigma_mu_0*mu*dx^2/2. ! (sec)
tprint_init = sigma*mu_0*1000.*((dx**2)/10). ! (sec) printout interval
tprint_init = pi/(Hz**2*pi)/12. ! (sec) printout interval
time_max = 2.*sigma*mu_0*1000.*(dx**2) ! (sec)
if(11. .lt. 2) then
  B_0 = 20000. ! alt
d = 100. ! alt
tau = 60. ! sec
  tprint_init = tau/12. ! alt
  time_max = 5.*tau ! alt
end if

tprint = tprint_init

N = 21 ! number of spatial intervals
dx = d/float(N-1) ! cm
do 10 i=1,N+1 ! one extra array space for storing B_avg in B(N+1)
x(i) = dx*dfloat(i-1) ! cm
xshift(i)=(x(i)+dx/2.)/.00254 ! mils
10 continue

xshift(N) = x(N)/.00254 ! redefine xshift(N) to be at interface (not shifted)
c initially...
do 20 i=1,N
   A(i) = 0.
20  continue
time = 0.
c**********************************************************************2
c BEGIN GRAPHING
c call plstart('mac')
c call plstart('QMS')
iquad=0
xmax = float(ifix((d/.00254)+.01)) +.6
ymin = -25000.
ymax = 25000.
call pscale('linlin',xmin,xmax,ymin,ymax,IQUAD)
c call pfont('ROMAN')
call pgrid('on','on')
call ptitle('B(x,t) in septum magnet',
 & ' distance from center of lamination (mils) $ ',
 & ' B (Gauss)$', '$')
c**********************************************************************2
cLOOP as time marches forward
c do 99, it = 1,100000
c for next time step... this is 4th order Runge-Kutta
c call deriv(A,k1,dt,N, 1)
do 31 i=2,N-1
   A(i) = A(i) + k1(i)
31  continue
time = time + dt/2.
   A(N) = A_N(time)
c call deriv(A,k2,dt,N, 2)
do 32 i=2,N-1
   A(i) = A(i) + k2(i) - k1(i)
32  continue
time doesn't change
   A(N) doesn't change
c call deriv(A,k3,dt,N, 3)
do 33 i=2,N-1
   A(i) = A(i) + 2.*k3(i) - k2(i)
33  continue
time = time + dt/2.
   A(N) = A_N(time)
c call deriv(A,k4,dt,N, 4)
do 34 i=2,N-1
   A(i)=A(i)+k1(i)+k4(i) +2.*k3(i) -4.*k2(i)
34  continue
time doesn't change
   A(N) doesn't change
c end Runge Kutta...
c if(time .gt. time_max) then
go to 999
else if(time .gt. tprint) then
do 36 i=1,N-1
   Bip(i) = (A(i)-A(i+1))/dx
   Hip(i) = H(Bip(i))
12
Bip(N) = Bip(N-1) + .5*(Bip(N-1)-Bip(N-2))! linear extrapol. to edge  
Bip(N+1) = - A(N)/d  
Hip(N) = H(Bip(N))

print *, time, dt, A(N), Bip(N-1), Bip(N), Hip(N)
PLOT B(x,t)  
call pstyle('solid')  
call pcur(xshift, Bip, N+1)
call pcur(x, A, N)
tprint= tprint+tprint_init
end if

continue
99 continue
999 call pclose
type *, it
close (unit=l, status='keep')
end

c**********************************************************************2
function A N(t)
common/fun/ pi, Hz, B_0, d , mur  
real mur  
w = 2.*pi*Hz  
if (t .le. 1./(2.*Hz)) then  
A_N = - d*B_0*sin(w*t)  
else  
A_N = 0.  
end if  

tau = 60. ! seconds  
if(l. gt. 2.) A_N = - d*B_0*(1.-exp(-t/tau)) ! alternate excitation function
return
end

c**********************************************************************2
function H(B)
common/fun/ pi, Hz, B_0, d , mur  
real mur  
dimension Btable(37), Htable(37), qBtable(37), qHtable(37)
dimension break(37), cscoef(4,37)

c this is POISSON's default B-H curve (Gauss-Oersted)
data Btable/0.,
8944.27, 12000., 14000., 15000., 15500., 16000.,  
16500., 17000., 17500., 18000., 18500., 19000.,  
19500., 20000., 20500., 21000., 2149., 21500.,  
21750., 22000., 22500., 22796.6, 23068.6, 23443.,  
23995.6, 24905., 25627.2, 26706., 28498.1, 32073.7,  
35644.1, 42782.4, 48134.2, 57051.7, 64185.7, 74887.2/
data Htable/ 0.,
2.24, 3.70, 6.30, 10.01, 14.49, 22.56,  
35.97, 55.08, 75.95, 102.06, 133.01, 171.00,  
216.45, 266.00, 336.20, 424.20, 480.25, 550.40,  
659.03, 829.40, 1249.99, 1519.78, 1774.51, 2131.18,  
2666.18, 3557.85, 4271.21, 5341.20, 7124.52, 10691.13,  
14257.64, 21391.20, 26740.95, 35657.31, 42790.49, 53490.81/
c**********************************************************************2

c this is M-19 transformer steel B-H curve (Gauss-Oersted) !accurate up to 20kG
data qBtable/0.,
11000., 12000., 14000., 15000., 15500., 16000.,  
16500., 17000., 17500., 18000., 18500., 19000.,  
19500., 20000., 20500., 21000., 21249., 21500.,  
21750., 22000., 22500., 23000., 23500., 24000.,
& 74000., 74001., 74002., 74003., 74004., 74005.,
& 74006., 74007., 74008./
data qHtable/0., .73, 1.09, 1.32,
& 1.65, 2.20, 7.60, 22.00, 33.00, 48.00,
& 67.00, 92.00, 120.00, 158.00, 205.00, 257.00,
& 315.00, 385.00, 585.00, 985.00, 1210.00, 1450.00,
& 1695.00, 1942.00, 2438.00, 2936.00, 3435.00, 3935.00,
& 53935.00, 53936., 53937., 53938., 53939., 53940.,
& 53941., 53942., 53943./
c**********************************************************************2
iBHdim=37
nintv = iBHdim-1
c csdec (ndata,xdata,fdata,ileft, dleft, iright, dright, break, cscoef)
if(ido .lt. 100) then !do it just once (ido = 0 (undefined) initially)
c call csdec(iBHdim,Btable,Htable,2, 0.,break,cscoef)
c call cscon(iBHdim,Btable,Htable,break,cscoef)!minimize wiggles
call csakm(iBHdim,Btable,Htable,break,cscoef) !maintain convexity
ido = 101
end if
if(Abs(B) .lt. Btable(1))then
   H = Htable(1)*B/Btable(1)
else if(Abs(B) .ge. Btable(iBHdim))then
   write (5,100) B
   100 format(‘B = ’, f7.0, ’ is out of B-H table range’)
else
   BA = Abs(B)
do 1, i= 2,iBHdim
      if(Abs(B) .ge. Btable(i-1) .and. Abs(B) .lt. Btable(i))then
         H = (Htable(i-1)*Btable(i)-BA)+Htable(i)*(BA-Btable(i-1)) /
         (Btable(i)-Btable(i-1))
c23456789012345678901234567890123456789012345678901234567890123456789012
         H = csval(BA, nintv, break, cscoef)
      if(B .lt. 0.) H=-H
      end if
1 continue
end if
mur = Btable(2)/Htable(2)
if(Abs(H) .gt. 0.01) mur=B/H !unitless (relative)
c if(ll. lt. 2.)then ! alternative B vs. H relation... fixed mu
   mur=1000.
   H = B/mur
end if
c H = H/(.4*pi) ! H in A/cm
return
end

c**********************************************************************2
subroutine deriv(A,k,dt,N, nK)
common/fun/ pi, Hz, B0, d, mur
common/sub/ sigma, mu_0, dx, time
dimension A(101), Hip(101), dHdx(101)
real mur, mur_min, mu_0, k(101)
c mur_min=100000. ! arbitrary high enough number
do 40 i=1,N-1
   B = (A(i)-A(i+1))/dx ! G
   Hip(i) = H(B) ! A/cm
   if(i .ne. 1) then
      dHdx(i)=(Hip(i)-Hip(i-1))/dx ! A/cm^2
   end if
40 continue
ccc if(mur .lt. mur_min) mur_min = mur
40 continue

14
mur = mur_min  ! (sec), dt < sigma*mu_0*mur*dx^2/2
if(nK .eq. 1) dt = .05*sigma*mu_0*mur*(dx**2)/2.
ccc    if(nK .eq. 1) type *, dt, time, A(N), B, Hip(N-1), nK
    do 41 i=1,N-1
        k(i) = -dHdx(i)*dt/(sigma*2.)
    41 continue
return
end

C
C*************************************************************************
C
Program sep_edge_rk4:  For analysis of fields in iron due to eddy currents.
   (this version uses 4th order Runge-Kutta)
   (refer to K.H. 'Mag. Tech. #1, pgs. 1.7-1.10)
   created: 7/91 Ross Schlueter

DECLARATIONS

character ddevice*3
character*60,string
common/xylim/xmin,xmax,ymin,ymax        !for use w/ pcont
common/device/ddevice
common/fun/ muri, imu, pi, Hz, B_0, d, mur, dA_N
common/sub/ sigma, mu_0, dx, time
real  k1(101), k2(101), k3(101), k4(101)
real mu_0, mur, muri, mur_min

dimension x(101), xshift(101), A(101), Bip(101), Hip(101),
         dHdx(101), ti(199),
         Bedge(199), Hedge(199), Bavg(199), BNml(199), Bint(199),
         H_Bavg(199), H_BNm1(199)

ddevice='qms'

ccc open (unit-1, file='oldfilename.dat', status='old')

INITIALIZATIONS

pi = 4.*atan(1.)        ! G-cm/A
mu_0 = .4*pi

mur varies and        ! is unitless
B_0 = 12000.        ! G
Hz = 5000.        ! cycles/s
sigma = 1./(50.e-6)        ! 1/Ohm-cm stainless steel (LEB vac. ch.)
            also M-19 ???
sigma = 1./(12.5e-6)        ! 1/Ohm-cm 1010 steel
sigma = sigma*1.e-8
sigma_mu_0 = sigma*mu_0

      d=.014*2.54/2.        ! (cm) septum half-thickness, = 14/2 mils

dt =  0.5*sigma*mu_0*mur*(dx**2)/2.        ! (sec), dt < sigma*mu_0*mur*dx^2/2

tau = sigma*mu_0*mur*d^2

tprint_init = sigma*mu_0*1000.*(d**2)/10.        ! (sec) printout interval

tprint_init = pi/(Hz*2*pi)/96.        ! (sec) printout interval
time_max = 2.*sigma*mu_0*1000.*(d**2)

if(1. .gt. 2) then
   B_0 = 15000.
   d = 100./2.
   tau = 60. !sec
   tprint_init = tau/4.        ! (sec) printout interval
   time_max = 4.*tau
end if

N = 21        ! number of spatial intervals
dx = d/float(N-1)
do 10 i=1,N+1  ! one extra array space for storing B_avg in B(N+1)
x(i) = dx*dfloat(i-1)
xshift(i)=(x(i)+dx/2.)/.00254 ! mils
10 continue

xshift(N) = x(N)/.00254 ! redefine xshift(N) to be at interface (not shifted)
BEGIN GRAPHING

**BEGIN GRAPHING**

call plstart('mac')
call plstart('QMS')
iquad = 0
xmin = 0.
xmax = time_max !2.
ymin = -50. !-10. ! 0. ! -35000. ! -50. !-35000.
call pscale('linlin',xmin,xmax,ymin,ymax,iquad)
call pfont('ROMAN')
call pgrid('on','on')
call ptitle('B_e_d_g_e(t), B_a_v_g(t) in septum magnet',
& 'time (seconds)$', '$
& 'B (Gauss)$', '$
call ptitle('H(B_e_d_g_e(t)), H(B_a_v_g(t)) in septum magnet',
& 'time (seconds)-$ 1 ,-
& 'H (Amp/em)$', '$
call ptitle('H(B_e_d_g_e(t)) vs. H(B_a_v_g(t)) in septum magnet',
& 'H(Bavg) (Aiiip/cm)$', ---
& 'H (B
dge) (Amp/em) $' , ' $')

**BEGIN GRAPHING**

do 900
irnu ~ 1, 5
B_0 = 12000. ! G Hz- 5000. cycles/s
sigma - 1.e-8/(50.e-6) ! 1/Ohm-cm stainless steel (LEB vac. ch.)
muri(1) = varies
if (irnu .eq. 2) B_0 = 14000. ! muri = 400
if (irnu .eq. 3) sigma = 1.e-8/(12.5e-6) ! muri = 400
if (irnu .eq. 4) Hz = 20000. ! muri = 2000
if (irnu .eq. 5) then
d = 2.*d ! muri=4000
dx = d/float(N-1) ! cm
do 510 i=1,N+1 ! one extra array space for storing B_avg in B(N+1)
   x(i) = dx*dfloat(i-1) ! cm
   xshift(i) = x(i)+dx/2./.00254 ! mils
continue
xshift(N) = x(N)/.00254 ! redefine xshift(N) to be at interface (not shift,
end if

**BEGIN GRAPHING**

Initially...
iprint = 0
time = 0.
div = 10.
tprint = tprint_init/div
do 20 i=1,N
   A(i) = 0.
20 continue

**BEGIN GRAPHING**

LOOP as time marches forward

do 99, it = 1,200000
for next time step... this is 4th order Runge-Kutta

call deriv(A,k1,dt,N, 1)
do 31 i=2,N-1
   A(i) = A(i) + k1(i)
   time = time + dt/2.
   A(N) = A_N(time)
31 continue

**BEGIN GRAPHING**

G-cm = (A/cm^2) (s)(G-cm^3/A-s)

G-cm
call deriv(A,k2,dt,N, 2)
do 32 i=2,N-1
A(i) = A(i) + k2(i) - k1(i) ! G-cm = (A/cm^2)(s)(G-cm^3/A-s)
continue
c time doesn’t change
A(N) doesn’t change

c call deriv(A,k3,dt,N, 3)
do 33 i=2,N-1
A(i) = A(i) + 2.*k3(i) - k2(i) ! G-cm = (A/cm^2)(s)(G-cm^3/A-s)
continue
time = time + dt/2.
A(N) = A_N(time)

c call deriv(A,k4,dt,N, 4)
do 34 i=2,N-1
A(i) = A(i) + k1(i) + k4(i) + 2.*k3(i) - 4.*k2(i) ! G-cm = (A/cm^2)(s)(G-cm^3/A-s)
continue
c time doesn’t change
A(N) doesn’t change

c end Runge Kutta...

if(time .gt. time_max) then
go to 999
else if (time .gt. tprint) then
do 36 i=1,N-1
Bip(i) = (A(i)-A(i+1))/dx ! G
Hip(i) = H(Bip(i)) ! A/cm
continue
Bip(N) = Bip(N-1) + .5*(Bip(N-1)-Bip(N-2)) ! linear extrap. of B
! (equiv. to constant curvature of A to edge)
Bip(N+1) = - A(N)/d ! B_avg stored here
Hip(N) = H(Bip(N))

iprint = iprint + 1
ti(iprint) = time
Bedge(iprint) = Bip(N)
Hedge(iprint) = Hip(N)
Bavg(iprint) = Bip(N+1)
H_Bavg(iprint) = H(Bip(N+1))
BNml(iprint) = Bip(N-1)
H_BNml(iprint) = H(Bip(N-1))

dB = 10.
Bint(iprint) = -dB
sAADot = A_N(time)*dA_N*sigma
do 154 ij= 1,50000
Bint(iprint) = Bint(iprint) + dB
continue

if(Bint(iprint)*H(Bint(iprint)) .gt. sAADot) go to 155
continue

if(time .lt. tprint_init) then
tprint= tprint+tprint_init/div
else
tprint= tprint+tprint_init
end if

end if
c continuenc
999 continue
!PLOT B(x,t)
call pstyle('solid')
call pcur(ti, Bedge, iprint)
call pcur(ti, BNm1, iprint)
call pcur(ti, Bint, iprint)
call pcur(ti, Hedge, iprint)
call pcur(ti, H_BN, iprint)
c if(iimu .eq. 1) call pcur(ti, Bavg, iprint)
c if(iimu .eq. 1) call pcur(ti, H_Bavg, iprint)
c call pcur(ti, Bavg, iprint)
900 continue
c call pclose
type *, it
close (unit=1, status='keep')
end

function A_N(t)
common/fun/ muri, imu, pi, Hz, B_0, d, mur, dA_N
!pi, Hz, d, B_0 needed he:
real mur, muri
w = 2.*pi*Hz
if (t .le. 1./(2.*Hz)) then
A_N = - d*B_0*sin(w*t)
else
A_N = 0.
end if
tau = 60. ! seconds
if(1. .gt. 2.) then
A_N = - d*B_0*(1.-exp(-t/tau)) ! alternate excitation function
dA_N = -d*B_0*(1./tau)*exp(-t/tau)
end if
return
end

function H(B)
common/fun/ muri, imu, pi, Hz, B_0, d, mur, dA_N
!pi, Hz, d, B_0 needed he:
real mur, muri
dimension Btable(37), Htable(37), qBtable(37), qHtable(37)
dimension break(37), cscoef(4,37)
c this is POISSON's default B-H curve (Gauss-Oersted)
data qBtable/ 0.,
8944.27, 12000., 14000., 15000., 16000.,
16500., 17000., 17500., 18000., 18500., 19000.,
19500., 20000., 20500., 21000., 21249., 21500.,
21750., 22000., 22500., 22796.6, 23068.6, 23443.6,
23995.6, 24905., 25627.2, 26706., 28498.1, 32073.7,
35644.1, 42782.4, 48134.2, 57051.7, 64185.7, 74887.2/
data qHtable/ 0.,
2.24, 3.70, 6.30, 10.01, 14.49, 22.56,
35.97, 55.08, 75.95, 102.06, 133.01, 171.00,
216.45, 266.00, 336.20, 424.20, 480.25, 550.40,
659.03, 829.40, 1249.99, 1519.78, 1774.51, 2131.18,
2666.18, 3557.85, 4271.21, 5341.20, 7124.52, 10691.13,
14257.64, 21391.20, 26740.95, 35657.31, 42790.49, 53490.81/
c this is M-19 transformer steel B-H curve (Gauss-Oersted) !accurate up to 20kG
data Btable/0.,
11000., 12000., 14000., 15000., 15500., 16000.,
16500., 17000., 17500., 18000., 18500., 19000.,
19500., 20000., 20500., 21000., 21249., 21500.,
& 21750., 22000., 22500., 23000., 23500., 24000.,
& 74000., 74001., 74002., 74003., 74004., 74005.,
& 74006., 74007., 74008./
data Htable/0., .73, 1.09, 1.32,
& .73, 1.09, 1.32,
& 1.65, 2.20, 7.60, 22.00, 67.00, 92.00, 120.00, 158.00,
& 315.00, 385.00, 585.00, 985.00, 315.00, 385.00, 585.00, 985.00,
& 1695.00, 1942.00, 2438.00, 2936.00, 315.00, 385.00, 585.00, 985.00,
& 53935.00, 53936., 53937., 53938., 53939., 53940.,
& 53941., 53942., 53943./

100 iBHdim=37
nintv = iBHdim-1
c ccsdec (ndata,xdata,fdata,ileft,dleft,iright,dright,break,cscoef)
if(ido .lt. 100) then !do it just once (ido = 0 (undefined) initially)
c call ccsdec(iBHdim,Btable,Htable,2, 0., break,cscoef)
c ccall cscon(iBHdim,Btable,Htable,break,cscoef)!minimize wiggles
ccall csakm(iBHdim,Btable,Htable,break,cscoef)!maintain convexity
type *, ibhdim,ibhdim,ibhdim,ibhdim,ibhdim,ibhdim,ibhdim,ibhdim
ido = 101
end if
if(Abs(B) lt. Btable(1))then
H = Htable(1)*B/Btable(1)
else if(Abs(B) ge. Btable(iBHdim))then
write (5,100)B
format('B = ', f7.0,' is out of B-H table range')
else
BA = Abs(B)
do 1, i= 2,iBHdim
if(Abs(B) ge. Btable(i-1) .and. Abs(B) lt. Btable(i))then
clin H=(Htable(i-1)*(Btable(i)-BA)+Htable(i)*(BA-Btable(i-1)))/
clin (Btable(i)-Btable(i-1))
c2345678901234567890123456789012345678901234567890123456789012
H = csval(BA, nintv, break, cscoef)
if(B .lt. 0.) H = -H
end if
1 continue
end if
mur = Btable(2)/Htable(2)
if(Abs(H) .gt..001) mur=B/H !unitless (relative)
c if(imu .gt. 5)then ! alternative B vs. H relation... fixed mu
mur=muri
H = B/mur
end if
c H = H/(.4*pi) ! H in A/cm
return
end
c******************************************************************************2
subroutine deriv(A,k,dt,N, nK)
common/fun/ muri, imu, pi, Hz, B_0, d , mur, dA_N
common/sub/ sigma, mu_0, dx, time
dimension A(101), Hip(101), dHdx(101)
real mur, muri, mur_min, mu_0, k(101)
c mur_min=200000. ! arbitrary high enough number
do 40 i=1,N-1
B = (A(i)-A(i+1))/dx ! G
Hip(i) = H(B) ! A/cm
if(i .ne. 1) then
   dHdx(i)=(Hip(i)-Hip(i-1))/dx ! A/cm^2
end if
if(mur .lt. mur_min) mur_min = mur
ccc if(mur .lt. 1000. .or. mur .gt. 4001.) type *, mur, mur, mur
continue

mu_rmur_min ! (sec), dt < sigma*mu_0*mu_rmur*dx^2/2

if(nK .eq. 1) dt = .05*sigma*mu_0*mu_r*(dx**2)/2.

if(nK .eq. 1) type *, dt, time, A(N), E, Hip(N-1), nK
  do 41 i=1,N-1
    k(i) = -dHdx(i)*dt/(sigma*2.)
  continue
  return
end

end

**********************************************************************2