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

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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, $H(B_{iron}(d))/H(B_{iron_{DC}})$ is several times the ratio of the corresponding $B_{iron}(d)/B_{iron_{DC}}$, 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 $B_{iron}(d)$.

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_{gap} for the 10 kG excitation). The longitudinal field drop is thus expected to be ~ 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 ~ 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 , $B = B_y(x)$, $H = H_y(x)$, $E = E_z(x)$, $A = A_z(x)$, $' \equiv \frac{\partial}{\partial x}$ and that $\dot{} \equiv \frac{\partial}{\partial t}$. 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

$$\mu_0 I = \mu_0 \oint H \cdot ds = g B_{gap} \left(1 + \frac{L}{g} \frac{H_{iron}(d)}{H_{gap}} \right) = g B_{gap} \left(1 + \frac{L}{g} \frac{B_{iron}(d)}{B_{gap}} \frac{1}{\mu_r} \right) \quad (1)$$

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

$$\bar{B}_{iron}(t) = B_{gap}(t) \frac{w_{gap}}{w_{iron}} \quad (2)$$

where the $\bar{}$ 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

$$\frac{\partial A}{\partial t} = \frac{1}{\sigma} \frac{\partial}{\partial x} \left(\frac{1}{\mu} \frac{\partial A}{\partial x} \right) \quad (3)$$

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

$$A(x, t) \Rightarrow B(x, t) \Rightarrow H(x, t) \Rightarrow \dot{A}(x, t) \Rightarrow A(x, t + \delta t) \quad (4)$$

Program *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 *sep_edge_rk4* in Appendix A similarly solves for the temporal behavior of various parameters of interest including $B_{iron}(d, t)$, $H(B_{iron}(d, t))$, $\bar{B}_{iron}(t)$, and $H(\bar{B}_{iron}(t))$.

$$\begin{aligned} \bar{B}_{iron}(t) &= -A(d)/d = B_0 \sin \omega t, & 0 \leq t < \pi/\omega, & & B_0 = 12 \text{ kG}, \\ &= 0, & \pi/\omega \leq t & & \\ 1/\sigma &= 50 \mu\Omega\text{-cm}, & f = \omega/2\pi = 5 \text{ kHz}, & & d = 0.007 \text{ inch}, & \mu \text{ for M-19 transformer steel} \end{aligned}$$

Figure 2a,b,c,d. B and H distributions and temporal history for baseline eddy current induced losses in a laminated magnet.

Figure 2e. B-H curve for M-19 transformer steel

3 Baseline: An Eddy Current Induced Loss Calculation in a Laminated Magnet

Assuming a gap excitation $B_{gap}(t) = B_{gapmax} \sin \omega t$, $0 \leq t < \pi/\omega$, then $\bar{B}_{iron}(t) = B_0 \sin \omega t$ and from Eqn. (2), $B_0 = B_{gapmax} \frac{w_{gap}}{w_{iron}}$. Figure 2a shows the field distribution across a lamination half-thickness (0 - 0.007 inches) at time intervals of $\frac{1}{12}$ of 100 μsec for the baseline parameters given. Also shown on the right in the Figure are $\bar{B}_{iron}$ 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 $H(\bar{B}_{iron}(t))$ 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 $\frac{L}{g} \simeq 10$ and $\frac{w_{gap}}{w_{iron}} \simeq 1$, 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^[2] shown in Figure 3c. Here $B_{iron}(d)|_{max}/B_0 = \alpha / \tanh \alpha$, where $\alpha \equiv \sqrt{i\tau\omega}$. In Figure 3b are plotted the excitation $H(\bar{B}_{iron}(t))$ 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 μ_r . Application of the relation given in Figure 3c shows that for large enough $\tau\omega$, $B_{iron}(d)|_{max}$ can be several times B_0 ; for a real material with nonlinear B-H the corresponding $H(B_{iron}(d)|_{max})/H(B_0)$ is several times the $B_{iron}(d)|_{max}/B_0$ 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 $B_{iron}(d)|_{max}$.

#	parameters				M-19 transformer steel			$\mu_r = 1000$		
	B_0 kG	$1/\sigma$ $\mu\Omega\text{-cm}$	f kHz	d mils	$B_{iron}(d)$ max. kG	$H(d)$ max. A/cm	max loss in iron $\frac{L}{g} = 10, \frac{w_{gap}}{w_{iron}} = 1$ % of excitation	$\tau\omega$	$B_{iron}(d) _{max}$ half-sine wave	continuous excitation
0	12	50.0	DC	7	12.00	1.75	.183	0	1.00	1.00
a	12	50.0	5	7	14.49	9.87	1.03	2.5	16.47	16.62
b	14	50.0	5	7	14.71	13.2	1.18	2.5	19.21	19.40
c	12	12.5	5	7	15.90	35.5	3.73	10.	31.87	37.70
d	12	50.0	20	7	15.90	35.5	3.73	10.	31.87	37.70
e	12	50.0	20	14	15.90	35.5	3.73	10.	31.87	37.70

$$\alpha \equiv \sqrt{i\tau\omega}, \quad \tau \equiv \sigma\mu_0\mu_r d^2, \quad \omega \equiv 2\pi f, \quad \bar{B}_{iron}(t) = -A(d)/d = B_0 \sin \omega t, \quad 0 < t < \pi/\omega, \\ = 0, \quad \pi/\omega \leq t$$

Figure 3a,b,c. Parametric study data of eddy current induced losses in a laminated magnet.

$$\begin{aligned} \bar{B}_{iron}(t) &= -A(d)/d = B_0 \sin \omega t, & 0 \leq t < \pi/\omega, & & B_0 = 12 \text{ kG}, \\ &= 0, & \pi/\omega \leq t & & \\ 1/\sigma &= 50 \mu\Omega\text{-cm}, & f = \omega/2\pi = 5 \text{ kHz}, & & d = 0.007 \text{ inch} \end{aligned}$$

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 $B_{iron}(d, t)$ 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, $B_{iron}(d)|_{max}$ 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: $B_{gap_{max}} = 10$ kG, $1/\sigma = 50\mu\Omega\text{-cm}$, $f = 5$ kHz, and M-19 transformer steel lamination half thickness $d = 0.007$ inches.

Figure 6a,b show eddy current induced loss tabulations from *sep_edge_rk4* for three $\frac{w_{gap}}{w_{iron}}$ ratios. For this magnet the estimated $\frac{L}{g} = 20$. 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 $B_{gap_{max}}$). A [n improved?] calculation could account for an initial $\frac{w_{gap}}{w_{iron}}$ ratio of ~ 1 near the gap/steel interface. Then $\int H \cdot ds_{iron} \simeq \sum_{i=1}^2 H_i ds_i$. For the entrance $H_1 = 7$ A/cm, $ds_1 = 6g$ cm, $H_2 = 5.32$, $ds_2 = 14g$, and losses come to 175 A (1.45%). For the exit $H_1 = 7$, $ds_1 = 5g$, $H_2 = 3.51$, $ds_2 = 17g$, and losses come to 140 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 $B_{gap_{max}} = 10$ kG, the field on the face of a lamination near the gap/iron interface can reach ~ 14.2 kG (see Figure 6a).

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

	parameters		M-19 transformer steel						
	B_{gapmax}	$\frac{w_{gap}}{w_{iron}}$	B_0	$H(B_0)$	$B_{iron}(d)$ max.	$H(B_{iron}(d))$ max.	loss at $\frac{L}{g} = 20$		
	kG		kG	A/cm	kG	A/cm	$\hat{A}$	% of DC loss	% of excitation
entr.	10	1.00	10.0	1.05	14.20	7.00	210	670	1.76
	10	0.86	8.6	0.83	13.90	5.32	160	640	1.34
exit	10	0.68	6.8	0.66	13.24	3.51	106	530	0.89

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

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

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

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

1. Halbach, K., *Some Eddy Current Effects in Solid Core Magnets*, NIM 107, 529-549, 1973.
2. Halbach, K., *1990 Magnet Technology Lectures at LBL*, LBL Report V-902-2.1-6, pp. 1.4 - 1.11, April 1990.
3. Halbach, K., *Jülich Magnet Lecture Series*, pp 2.3 - 2.5, Jülich, Germany, 1985.

Appendix A: Codes *Septum_rk4* and *sep_edge_rk4*

```

C*****
C
C Program septum_rk4:      For analysis of fields in iron due to eddy currents.
C                          (this version uses 4th order Runge-Kutta)
C                          (refer to K.H. Mag. Tech. #1, pgs. 1.7-1.10)
C
C      created:    7/91      Ross Schlueter
C
C*****
C  DECLARATIONS
C
C
C      character ddevice*3
C      character*60,string
C
C      common/xylim/xmin,xmax,ymin,ymax      !for use w/ pcont
C      common/device/ddevice
C      common/fun/ pi, Hz, B_0, d , mur
C      common/sub/ sigma, mu_0, dx, time
C      real k1(101), k2(101), k3(101), k4(101)
C      real mu_0, mur, mur_min
C      dimension x(101), xshift(101), A(101), Bip(101), Hip(101),
C      &          dHdx(101)
C
C      ddevice='qms'
C
C      open (unit=1, file='oldfilename.dat', status='old')
C
C*****
C  INITIALIZATIONS
C
C      pi = 4.*atan(1.)
C      mu_0 = .4*pi      ! G-cm/A
C      mur varies and    ! is unitless
C
C      B_0 = 12000.      ! G
C      Hz = 5000.        ! cycles/s
C      sigma = 1./(50.e-6) ! 1/Ohm-cm stainless steel (LEB vac. ch.)
C                          also M-19 ???
C      sigma = 1./(12.5e-6) ! 1/Ohm-cm 1010 steel
C      sigma = sigma*1.e-8 ! A-s/G-cm^3
C      sigma_mu_0 = sigma*mu_0 ! s/cm^2
C      d=.014*2.54/2.      ! (cm) septum half-thickness, = 14/2 mils
C
C      dt = 0.5*sigma*mu_0*mur*(dx**2)/2. ! (sec), dt < sigma*mu_0*mur*dx^2/2
C      tau= sigma*mu_0*mur*d^2             ! (sec)
C      tprint_init = sigma*mu_0*1000.*(d**2)/10. ! (sec) printout interval
C      tprint_init = pi/(Hz*2*pi)/12.         ! (sec) printout interval
C      time_max = 2.*sigma*mu_0*1000.*(d**2)   ! (sec)
C      if(11. .lt. 2) then
C          B_0 = 20000.      ! alt
C          d = 100.          ! alt
C          tau = 60. !sec    ! alt
C          tprint_init = tau/12. ! alt
C          time_max = 5.*tau ! alt
C      end if
C      tprint = tprint_init
C
C      N = 21      ! number of spatial intervals
C      dx = d/float(N-1) ! cm
C      do 10 i=1,N+1 ! one extra array space for storing B_avg in B(N+1)
C          x(i) = dx*dfloat(i-1) ! cm
C          xshift(i)=(x(i)+dx/2.)/.00254 ! mils
C      10 continue
C      xshift(N) = x(N)/.00254 ! redefine xshift(N) to be at interface (not shifted)
C

```

```

c initially...
  do 20 i=1,N
    A(i) = 0.
20  continue
    time = 0.
c
c*****2
c  BEGIN GRAPHING
c
c  call plstart('mac')
c  call plstart('QMS')
    iquad=0
    xmin = 0.
    xmax = float(ifix((d/.00254)+.01)) +.6
    ymin = -25000.
    ymax = 25000.
    call pscal('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
c*****2
c  LOOP as time marches forward
c
c  do 99, it = 1,100000
c
c  for next time step... this is 4th order Runge-Kutta
c
c  call deriv(A,k1,dt,N, 1)
c  do 31 i=2,N-1
c    A(i) = A(i) + k1(i) ! G-cm = (A/cm^2) (s) (G-cm^3/A-s)
31  continue
c  time = time + dt/2.
c  A(N) = A_N(time) ! G-cm
c
c  call deriv(A,k2,dt,N, 2)
c  do 32 i=2,N-1
c    A(i) = A(i) + k2(i) - k1(i) ! G-cm = (A/cm^2) (s) (G-cm^3/A-s)
32  continue
c  time doesn't change ! G-cm
c  A(N) doesn't change ! G-cm
c
c  call deriv(A,k3,dt,N, 3)
c  do 33 i=2,N-1
c    A(i) = A(i) + 2.*k3(i) - k2(i) ! G-cm = (A/cm^2) (s) (G-cm^3/A-s)
33  continue
c  time = time + dt/2.
c  A(N) = A_N(time) ! G-cm
c
c  call deriv(A,k4,dt,N, 4)
c  do 34 i=2,N-1
c    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)
34  continue
c  time doesn't change ! G-cm
c  A(N) doesn't change ! G-cm
c
c  end Runge Kutta...
c
c  if(time .gt. time_max) then
c    go to 999
c  else if(time .gt. tprint) then
c    do 36 i=1,N-1
c      Bip(i) = (A(i)-A(i+1))/dx ! G
c      Hip(i) = H(Bip(i)) ! A/cm

```

```

36      continue
      Bip(N) = Bip(N-1) + .5*(Bip(N-1)-Bip(N-2)) ! linear extrap. to edge
      Bip(N+1) = - A(N)/d ! B_avg stored here
      Hip(N) = H(Bip(N))

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

c
99      continue
999     call pclose
      type *, it
      close (unit=1, status='keep')
      end

c
c*****2
      function A_N(t)
      common/fun/ pi, Hz, B_0, d , mur !pi, Hz, d, B_0 needed here
      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

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

c
      return
      end

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

c
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., 21249., 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., 6000., 8944.27, 10000.,
&          11000., 12000., 14000., 15000., 15500., 16000.,
&          16500., 17000., 17500., 18000., 18500., 19000.,
&          19500., 20000., 20500., 21000., 21249., 21500.,
&          21750., 22000., 22500., 23000., 23500., 24000.,

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&          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., 539343./
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., 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..001) mur=B/H !unitless (relative)
c
    if(11. 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
c*****2
  subroutine deriv(A,k,dt,N, nK)
  common/fun/ pi, Hz, B_0, 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
    if(mur .lt. mur_min) mur_min = mur
ccc  if(mur .lt. 1000. .or. mur .gt. 4001.) type *, mur, mur, mur
40  continue
c

```

```

        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*****2

```



```

C*****
C
C Program sep_edge_rk4:   For analysis of fields in iron due to eddy currents.
C                        (this version uses 4th order Runge-Kutta)
C                        (refer to K.H.'Mag. Tech. #1, pgs. 1.7-1.10)
C
C      created:   7/91      Ross Schlueter
C
C*****
C  DECLARATIONS
C
C
C      character ddevice*3
C      character*60,string
C
C      common/xylim/xmin,xmax,ymin,ymax      !for use w/ pcont
C      common/device/ddevice
C      common/fun/ muri, imu, pi, Hz, B_0, d , mur, dA_N
C      common/sub/ sigma, mu_0, dx, time
C      real kl(101), k2(101), k3(101), k4(101)
C      real mu_0, mur, muri, mur_min
C      dimension x(101), xshift(101), A(101), Bip(101), Hip(101),
C      &          dHdx(101), ti(199),
C      &          Bedge(199), Hedge(199), Bavg(199), BNml(199), Bint(199),
C      &          H_Bavg(199), H_BNml(199)
C
C      ddevice='qms'
C
C      open (unit=1, file='oldfilename.dat', status='old')
C
C*****
C  INITIALIZATIONS
C
C      pi = 4.*atan(1.)
C      mu_0 = .4*pi      ! G-cm/A
C      mur varies and    ! is unitless
C
C      B_0 = 12000.      ! G
C      Hz = 5000.        ! cycles/s
C      sigma = 1./(50.e-6) ! 1/Ohm-cm stainless steel (LEB vac. ch.)
C                        also M-19 ???
C      sigma = 1./(12.5e-6) ! 1/Ohm-cm 1010 steel
C      sigma = sigma*1.e-8  ! A-s/G-cm^3
C      sigma_mu_0 = sigma*mu_0 ! s/cm^2
C      d=.014*2.54/2.      ! (cm) septum half-thickness, = 14/2 mils
C
C      dt =      0.5*sigma*mu_0*mur*(dx**2)/2. ! (sec), dt < sigma*mu_0*mur*dx^2/2
C      tau=      sigma*mu_0*mur*d^2            ! (sec)
C      tprint_init = sigma*mu_0*1000.*(d**2)/10. ! (sec) printout interval
C      tprint_init = pi/(Hz*2*pi)/96.          ! (sec) printout interval
C      time_max = 2.*sigma*mu_0*1000.*(d**2)    ! (sec)
C      if(1. .gt. 2) then
C          B_0 = 15000.      ! alt
C          d = 100./2.      ! alt
C          tau = 60. !sec    ! alt
C          tprint_init = tau/4. ! alt
C          time_max = 4.*tau ! alt
C          ! (sec) printout interval
C      end if
C
C      N = 21      ! number of spatial intervals
C      dx = d/float(N-1) ! cm
C      do 10 i=1,N+1 ! one extra array space for storing B_avg in B(N+1)
C          x(i) = dx*dfloat(i-1) ! cm
C          xshift(i)=(x(i)+dx/2.)/.00254 ! mils
C      10 continue
C      xshift(N) = x(N)/.00254 ! redefine xshift(N) to be at interface (not shifted)

```

```

C
C*****2
C      BEGIN GRAPHING
C
C      call plstart('mac')
C      call plstart('QMS')
C      iquad=0
C      xmin = 0.
C      xmax = time_max !2. !
C      ymin = -50. !-10. ! 0. ! -35000. ! -50. !-35000.
C      ymax = 50. ! 10. ! 10. ! 35000. ! 50. ! 35000.
C      call pscale('linlin', xmin, xmax, ymin, ymax, IQUAD)
C      call pfont('ROMAN')
C      call pgrid('on', 'on')
C      call pttitle('B_e_d_g_e(t), B_a_v_g(t) in septum magnet',
C      & ' time (seconds) $', '$')
C      & 'B (Gauss) $', '$')
C      call pttitle('H(B_e_d_g_e(t)), H(B_a_v_g(t)) in septum magnet',
C      & ' time (seconds) $', '$')
C      & 'H (Amp/cm) $', '$')
C      call pttitle('H(B_e_d_g_e(t)) vs. H(B_a_v_g(t)) in septum magnet',
C      & ' H(B_a_v_g) (Amp/cm) $', '$')
C      & 'H(B_e_d_g_e) (Amp/cm) $', '$')
C*****2
C
C      do 900 imu = 1,5
C      B_0 = 12000. ! G
C      Hz = 5000. ! cycles/s
C      sigma = 1.e-8/(50.e-6) ! 1/Ohm-cm stainless steel (LEB vac. ch.)
C      muri(1) = varies
C      if(imu .eq. 2) B_0 = 14000. ! muri = 400
C      if(imu .eq. 3) sigma = 1.e-8/(12.5e-6) ! muri = 400
C      if(imu .eq. 4) Hz = 20000. ! muri = 2000
C      if(imu .eq. 5) then
C          d = 2.*d ! muri=4000
C          dx = d/float(N-1) ! cm
C          do 510 i=1,N+1 ! one extra array space for storing B_avg in B(N+1)
C              x(i) = dx*dfloat(i-1) ! cm
C              xshift(i)=(x(i)+dx/2.)/.00254 ! mils
510      continue
C          xshift(N) = x(N)/.00254 ! redefine xshift(N) to be at interface (not shift)
C          end if
C
C      c initially...
C      iprint = 0
C      time = 0.
C      div = 10.
C      tprint = tprint_init/div
C      do 20 i=1,N
C          A(i) = 0.
20      continue
C
C*****2
C      LOOP as time marches forward
C
C      do 99, it = 1,200000
C
C      c for next time step... this is 4th order Runge-Kutta
C
C      call deriv(A,k1,dt,N, 1)
C      do 31 i=2,N-1
C          A(i) = A(i) + k1(i) ! G-cm = (A/cm^2) (s) (G-cm^3/A-s)
31      continue
C      time = time + dt/2.
C      A(N) = A_N(time) ! G-cm
C

```

```

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)
32 continue
c time doesn't change ! G-cm
c A(N) doesn't change ! G-cm
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)
33 continue
time = time + dt/2.
A(N) = A_N(time) ! G-cm
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)
34 continue
c time doesn't change ! G-cm
c A(N) doesn't change ! G-cm
c
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 ! G
        Hip(i) = H(Bip(i)) ! A/cm
36 continue
Bip(N) = Bip(N-1) + .5*(Bip(N-1)-Bip(N-2)) ! linear extrap. of B
c ! (equiv. to constant curvature of A to edge)
Bip(N+1) = - A(N)/d ! B_avg stored here
Hip(N) = H(Bip(N))
c
    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))
c
    dB = 10.
    Bint(iprint) = -dB
    sAAdot = A_N(time)*dA_N*sigma
    do 154 ij=1,50000
        Bint(iprint)=Bint(iprint)+dB
c        type *, ij, Bint(iprint)*H(Bint(iprint)), sAAdot
        if(Bint(iprint)*H(Bint(iprint)) .gt. sAAdot)go to 155
154 continue
155 continue
type 117, time, dt,A(N), Bip(N-2),Bip(N-1), Bip(N),
& Bip(N+1), Hip(N-1), Hip(N), H(Bip(N+1))
117 format(3(e9.3,x),4(f7.0,x),f7.2,x,f7.2,x,f7.2,x)
c
    if(time .lt. tprint_init)then
        tprint= tprint+tprint_init/div
    else
        tprint= tprint+tprint_init
    end if
end if
c
99 continue
999 continue

```

```

c      !PLOT B(x,t)
c      call pstyle('solid')
c      call pcur(ti, Bedge, iprint)
c      call pcur(ti, BNml, iprint)
c      call pcur(ti, Bint, iprint)
c      call pcur(ti, Hedge, iprint)
c      call pcur(ti, H_BNml, iprint)
c      call pcur(H_Bavg, H_BNml, iprint)
c      if(imu .eq. 1) call pcur(ti, Bavg, iprint)
c      if(imu .eq. 1) call pcur(ti, H_Bavg, iprint)
c      call pcur(ti, Bavg, iprint)
900  continue
c
c      call pclose
c      type *, it
c      close (unit=1, status='keep')
c      end
c
c*****2
c      function A_N(t)
c      common/fun/ muri, imu, pi, Hz, B_0, d , mur, dA_N !pi, Hz, d, B_0 needed he:
c      real mur, muri
c      w = 2.*pi*Hz
c      if (t .le. 1./(2.*Hz)) then
c          A_N = - d*B_0*sin(w*t)
c      else
c          A_N = 0.
c      end if
c
c      tau = 60. ! seconds
c      if(1. .gt. 2.) then
c          A_N = - d*B_0*(1.-exp(-t/tau)) ! alternate excitation function
c          dA_N = -d*B_0*(1./tau)*exp(-t/tau)
c      end if
c
c      return
c      end
c
c*****2
c      function H(B)
c      common/fun/ muri, imu, pi, Hz, B_0, d , mur, dA_N !pi, Hz, d, B_0 needed he:
c      real mur, muri
c      dimension Btable(37), Htable(37), qBtable(37), qHtable(37)
c      dimension break(37), cscoef(4,37)
c
c      this is POISSON's default B-H curve (Gauss-Oersted)
c      data qBtable/0.,
c      &          8944.27, 12000., 14000., 15000., 15500., 16000.,
c      &          16500., 17000., 17500., 18000., 18500., 19000.,
c      &          19500., 20000., 20500., 21000., 21249., 21500.,
c      &          21750., 22000., 22500., 22796.6, 23068.6, 23443.,
c      &          23995.6, 24905., 25627.2, 26706., 28498.1, 32073.7,
c      &          35644.1, 42782.4, 48134.2, 57051.7, 64185.7, 74887.2/
c      data qHtable/ 0.,
c      &          2.24, 3.70, 6.30, 10.01, 14.49, 22.56,
c      &          35.97, 55.08, 75.95, 102.06, 133.01, 171.00,
c      &          216.45, 266.00, 336.20, 424.20, 480.25, 550.40,
c      &          659.03, 829.40, 1249.99, 1519.78, 1774.51, 2131.18,
c      &          2666.18, 3557.85, 4271.21, 5341.20, 7124.52, 10691.13,
c      &          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
c      data Btable/0., 6000., 8944.27, 10000.,
c      &          11000., 12000., 14000., 15000., 15500., 16000.,
c      &          16500., 17000., 17500., 18000., 18500., 19000.,
c      &          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,
&          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., 539343./
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., 2, 0.,break,cscoef)
c    call cscon(iBHdim,Btable,Htable,break,cscoef)!minimize wiggles
  call csakm(iBHdim,Btable,Htable,break,cscoef) !maintain convexity
  type *, 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
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
clin      H=(Htable(i-1)*(Btable(i)-BA)+Htable(i)*(BA-Btable(i-1)))/
clin      & (Btable(i)-Btable(i-1))
c234567890123456789012345678901234567890123456789012345678901234567890123456789012
      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
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

```

```

40    continue
c
    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*****2

```

END

**DATE
FILMED**

11 / 6 / 92