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Abstract
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Accelerator & Fusion
Research Division

End Design of the SSC 58 mm High Gradient Quadrupole

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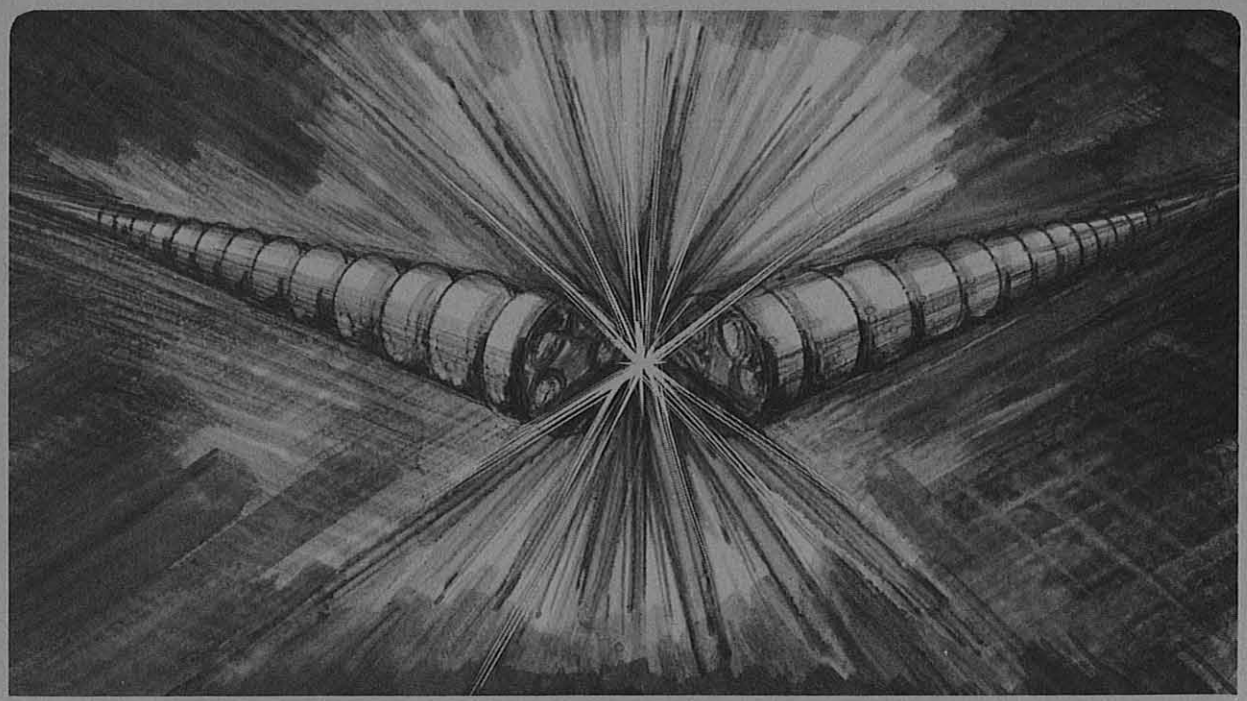
June 1992



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LBL — 32452a
SC-MAG-385

End Design Of The SSC 58 mm High Gradient Quadrupole.*

Shlomo Caspi

Lawrence Berkeley Laboratory

June 10, 1992

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End Geometry and Integrated Harmonics

The "end" design of the High Gradient Quad. was done with consideration to the integrated field harmonics, the iron contribution, and the maximum field at the conductor. Magnetic analysis was done on the ***return end*** only, however the physical dimension of the ***lead end*** were determined as well. Using the cross-section of the windings[1](Fig. 1) and Cook's program BEND, we generated the physical end windings around the return end. Placing a single wire at the center of each turn (Fig. 2,3) the integrated gradient was computed and iterating on the end block spacers the integrated harmonics minimized (Appendix A). The final geometry was then used for more extensive calculations, such as the field at the conductor and the 3D field harmonics[2]. For this detailed calculation we have placed a single line current at the center of each strand and included the iron contribution ($\mu = \infty$), see Appendix C.

With the termination of the iron serving as a reference, the maximum length of the inner and outer layers are 182 mm and 215 mm respectively (Fig. 4,5). The magnetic length of the end was computed from the gradient function A_2 (Appendix B) and was found to be 142 mm (Fig. 7,8). In reality we expect the physical length of the end to be somewhat larger, however this should have little or no effect on the magnetic length. The gradient in the straight section is 212.44 T/m at 7000 A and the integrated value of the gradient is —3.01665 E5 (G) in the end region marked by the magentic length of the end. The respective integrated harmonics for the end 12 pole and 20 pole are —10.6658 (G/cm^4) and 0.7279 (G/cm^8) corresponding to $b_6 = 0.351$, $b_{10} = -0.024$ units. The above was computed from the values of A_2, A_6, and A_{10} (Fig. 9–11).

Maximum Field

The maximum field at the conductor is located along the pole face of the inner layer. For each strand location on the pole face the field was calculated as a function of the cable length (Fig. 13,14). The field along each strand is plotted in Fig.15 as a function of strand number (strand #1 is the inner most strand and #18 the outer most). At 7000A and $\mu = \infty$ iron, the maximum field is 7.0987 tesla located on strand 14 in the straight section, and 5.9748 tesla for strand 11 located at tip end. Using POISSON to include saturation effects, the maximum field in the straight section at 7000A is 7.1 tesla.

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1 "A Proposed IR Quad For The SSC." Shlomo Caspi, Clyde Taylor, and Alan Wandesforde, SC-MAG-349 , LBL 32171a , 1992.

2 " 3D Field Harmonics" S.Caspi, M.Helm, and L.J.Laslett, SC-MAG-328 , LBL 30313, March 1991

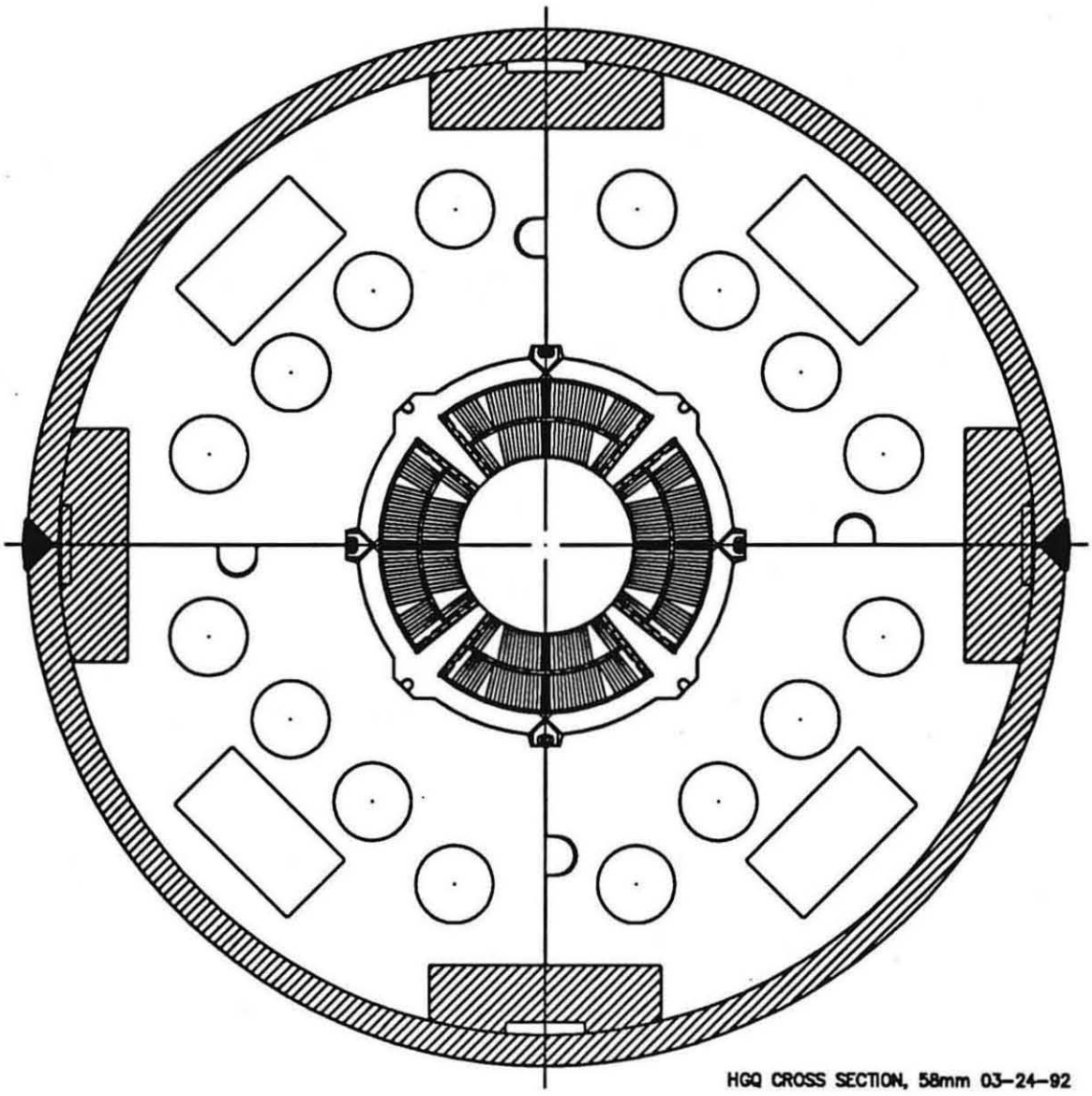

Figure 1 Quad cross-section.

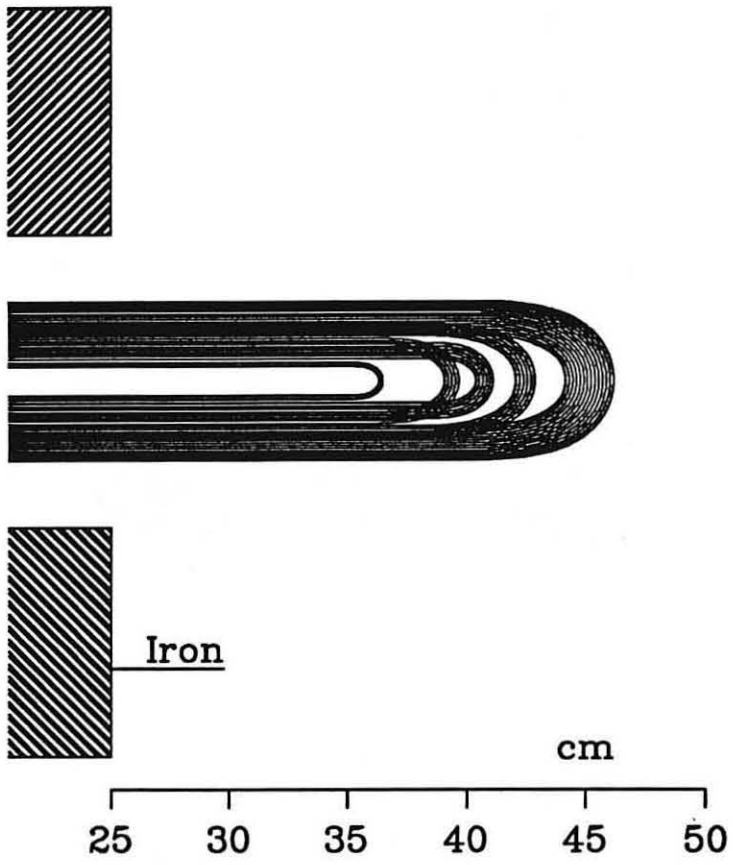

Figure 2 View of RETURN end (each turn represented by a single wire).

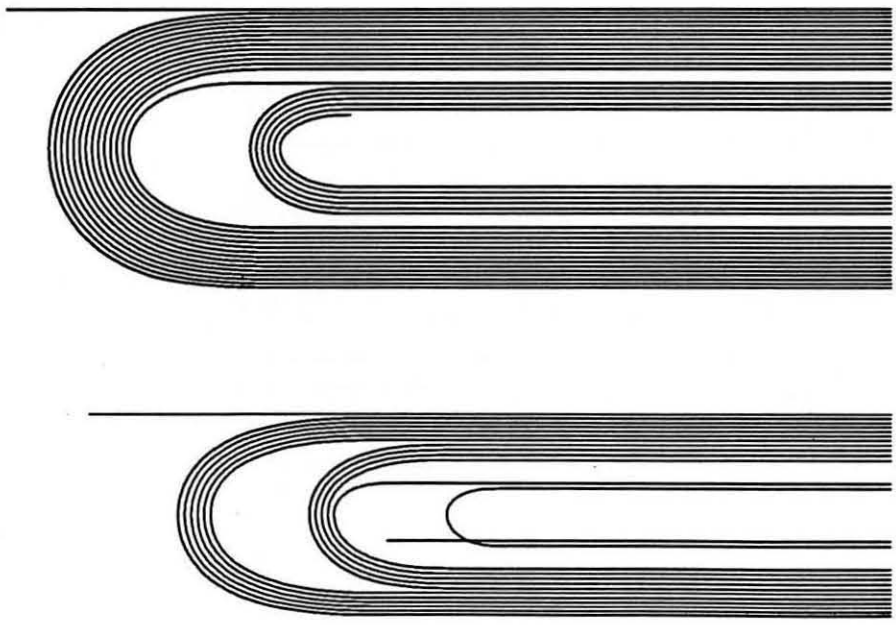

Figure 3 View of LEAD end (each turn represented by a single wire).

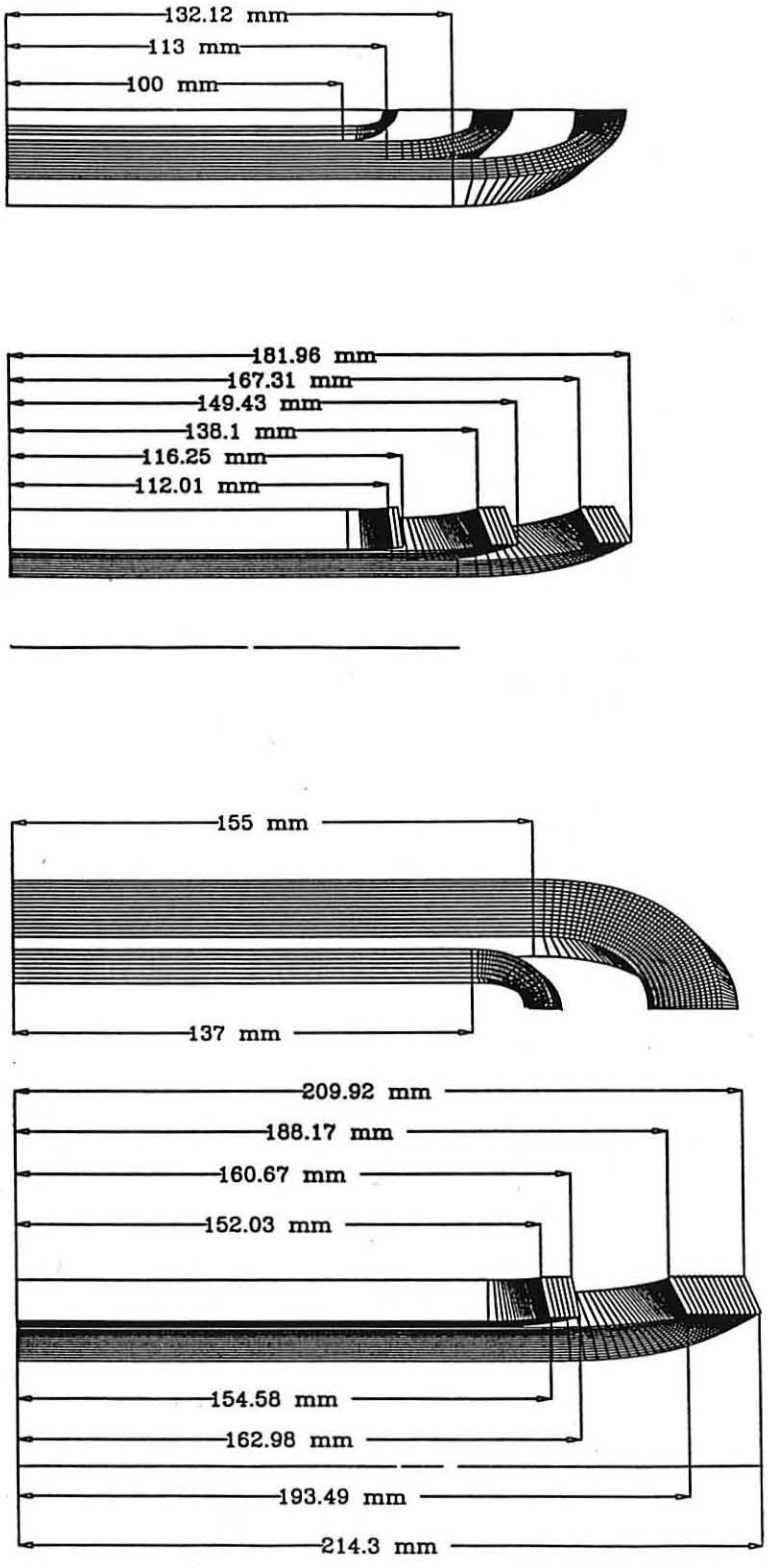

Figure 4 Top and side view of layer 1 (top), and view of layer 2 (bottom).

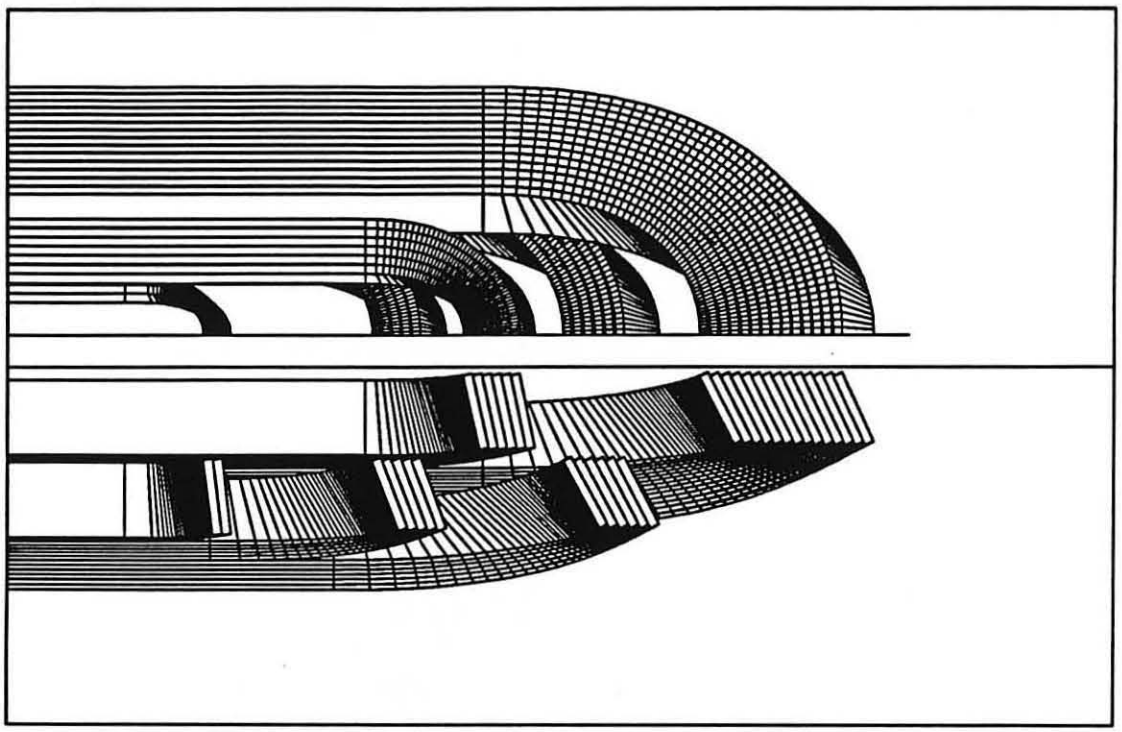

Figure 5 View of RETURN end.

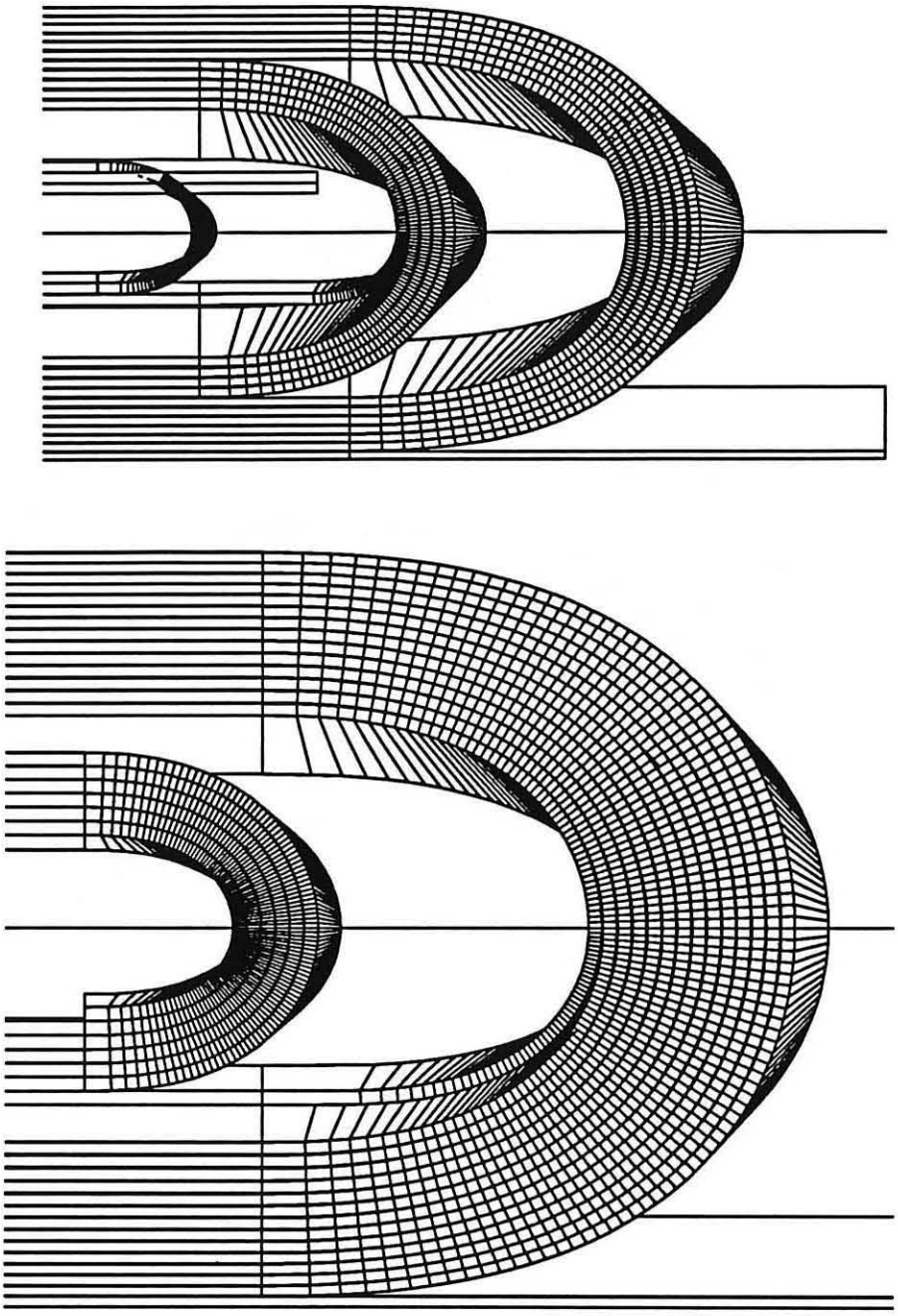

Figure 6 View of layers 1 and 2, LEAD end.

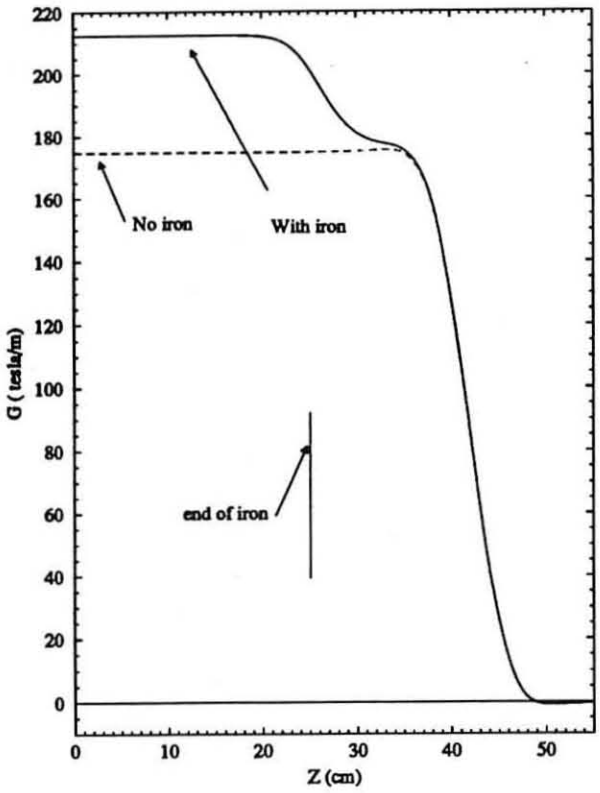

Figure 7 Gradient along RETURN "end" (7000 A, μ infinite iron).

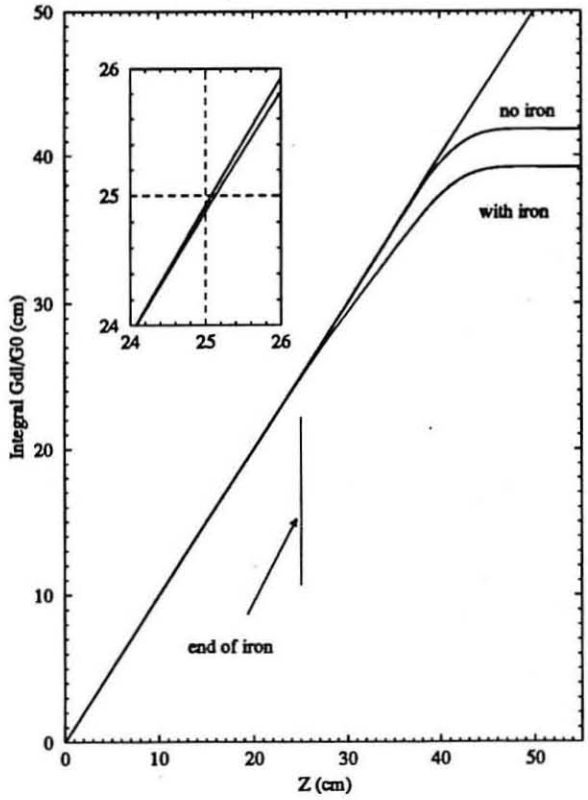

Figure 8 Integrated gradient along "end" (7000 A, μ infinite iron).

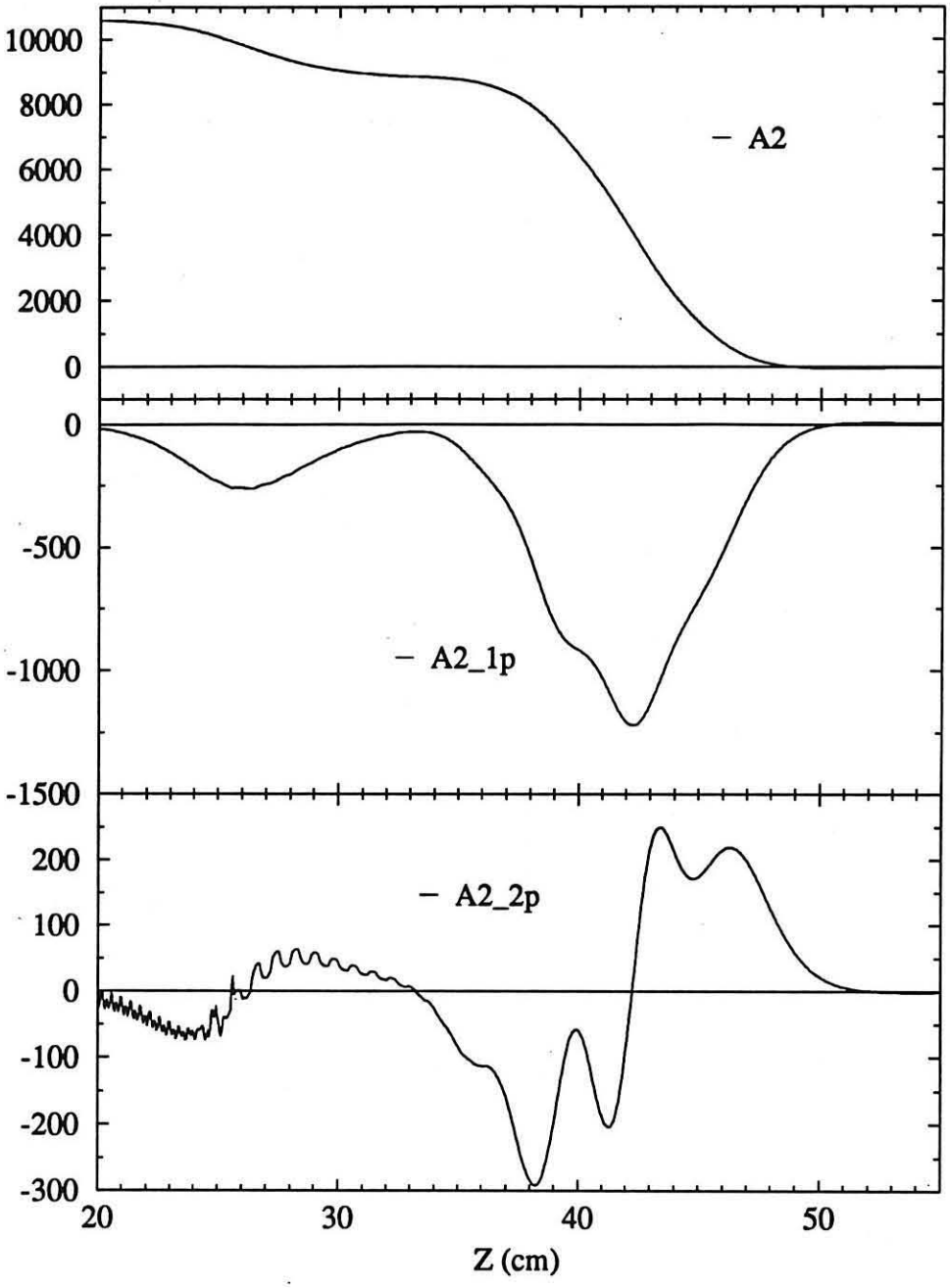

Figure 9 A2 and derivatives along the end, including contribution from both CONDUCTOR and IRON (I=7000 A).

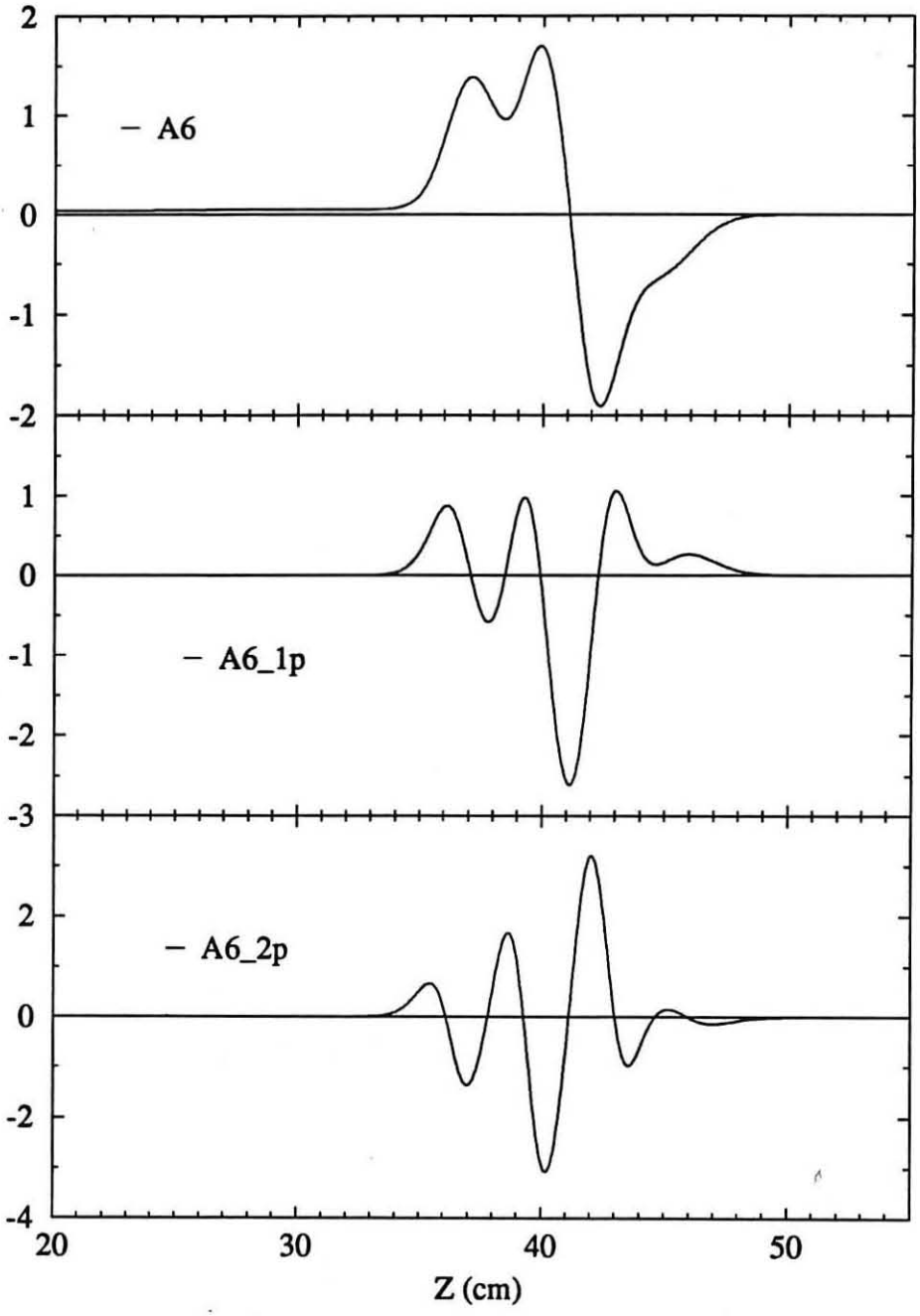

Figure 10 A6 and derivatives along the end, including contribution from both CONDUCTOR and IRON (I=7000 A).

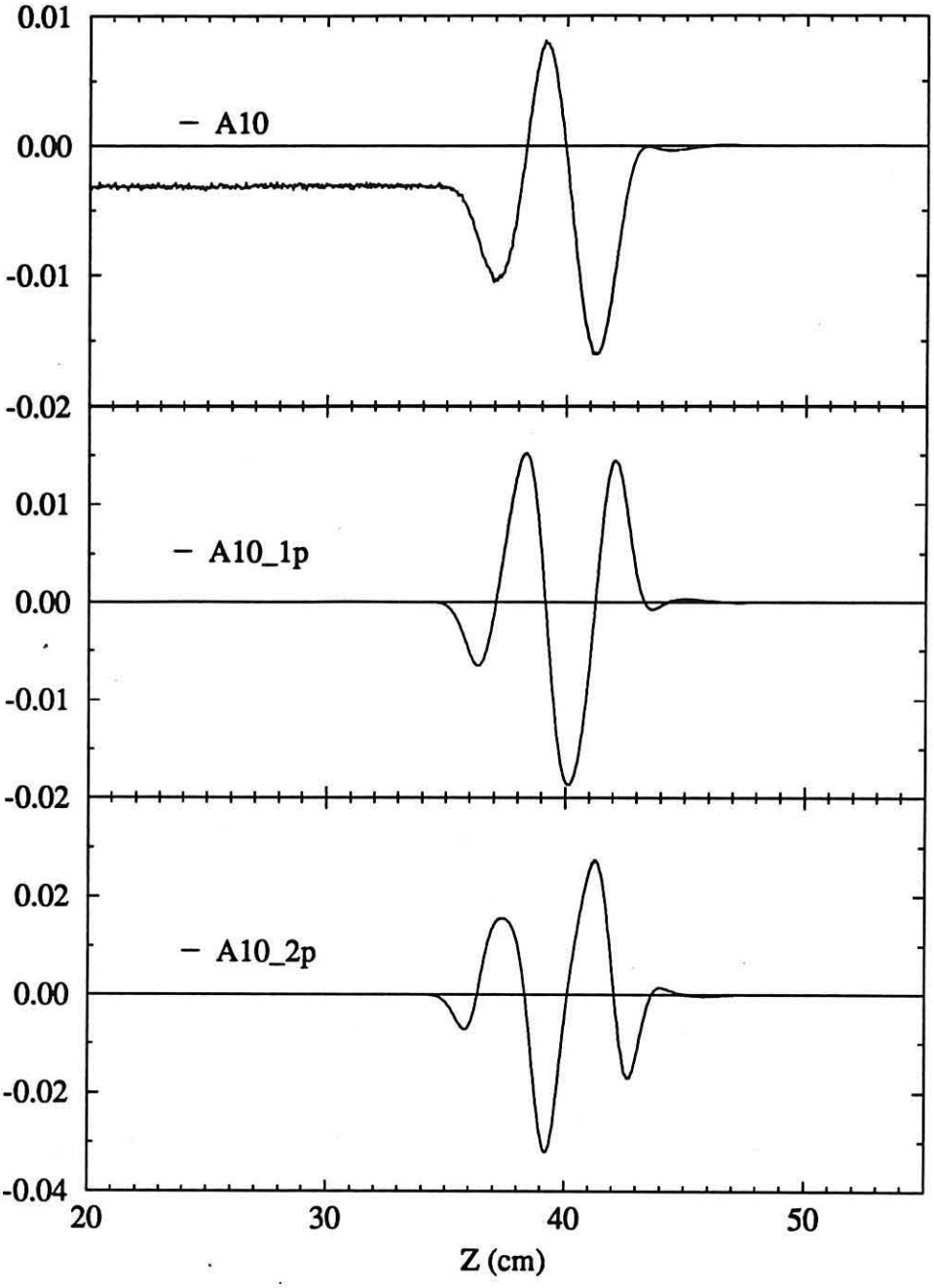

Figure 11 A10 and derivatives along the end, including contribution from both CONDUCTOR and IRON (I=7000 A).

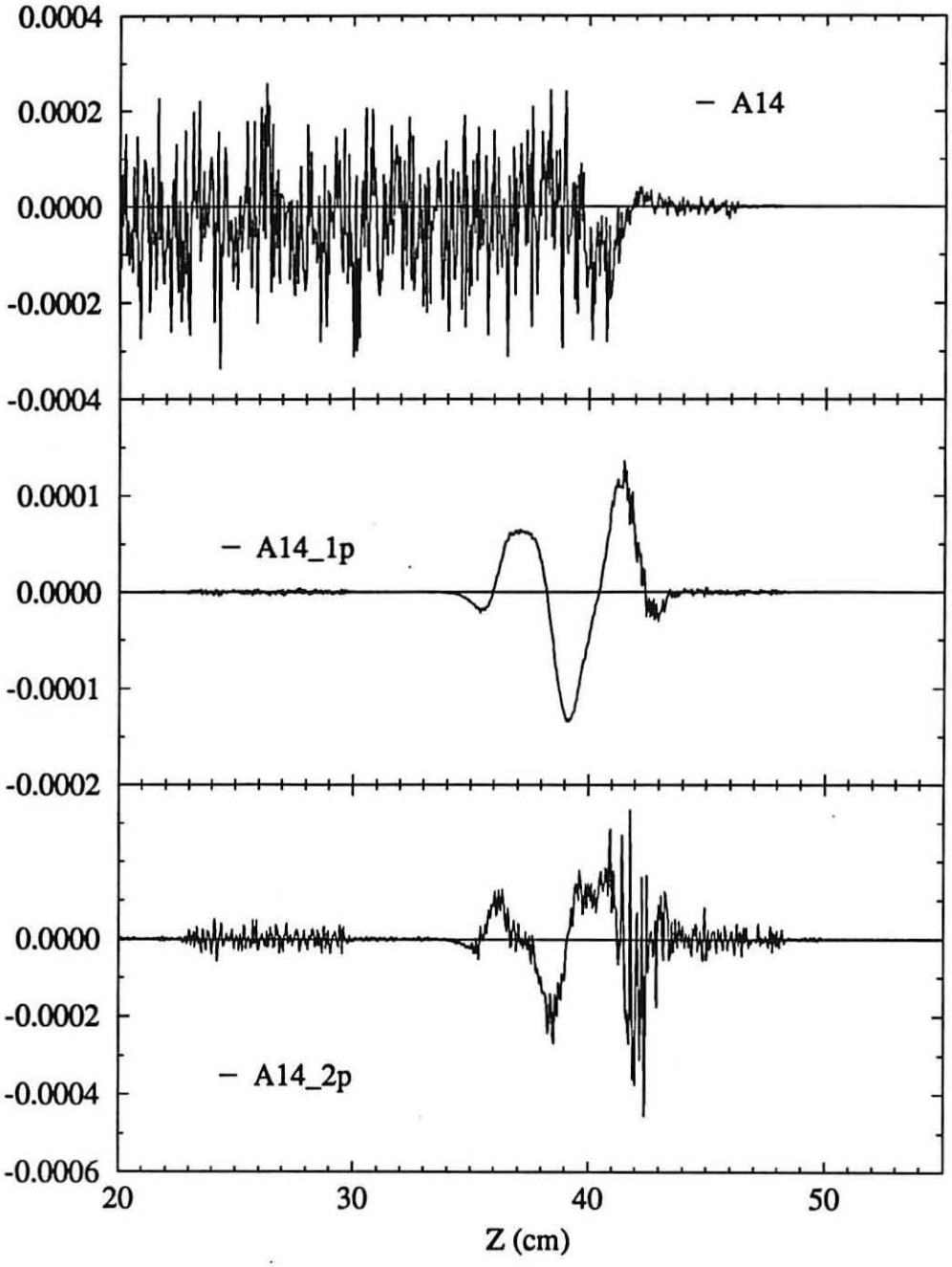

Figure 12 A14 and derivatives along the end, including contribution from both CONDUCTOR and IRON (I=7000 A).

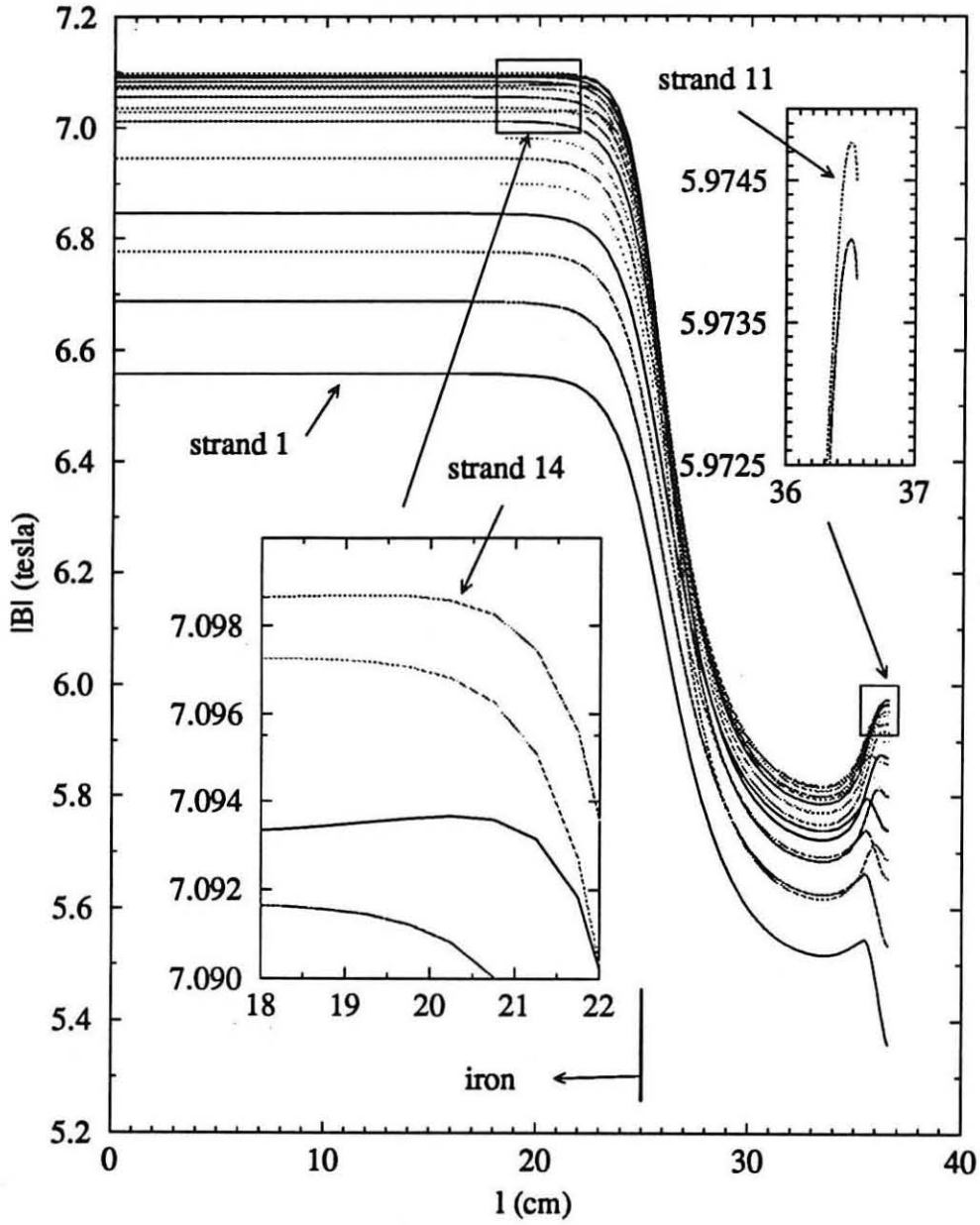

Figure 13 The field magnitude for each strand along the pole face of layer1 as a function of length along the cable — IRON INCLUDED .(I=7000 A).

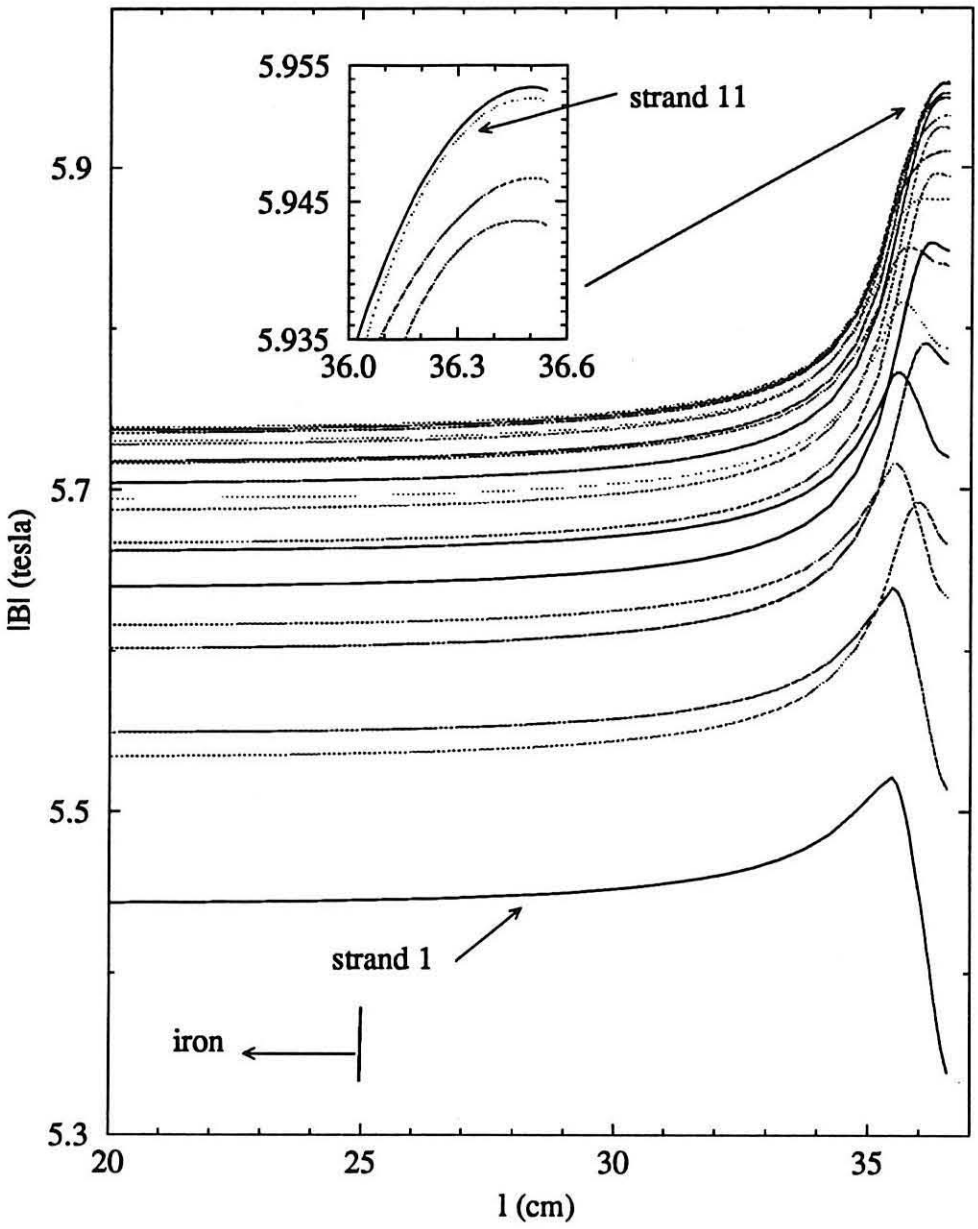

Figure 14 The field magnitude for each strand along the pole face of layer1 as a function of length along the cable — NO IRON (I=7000 A).

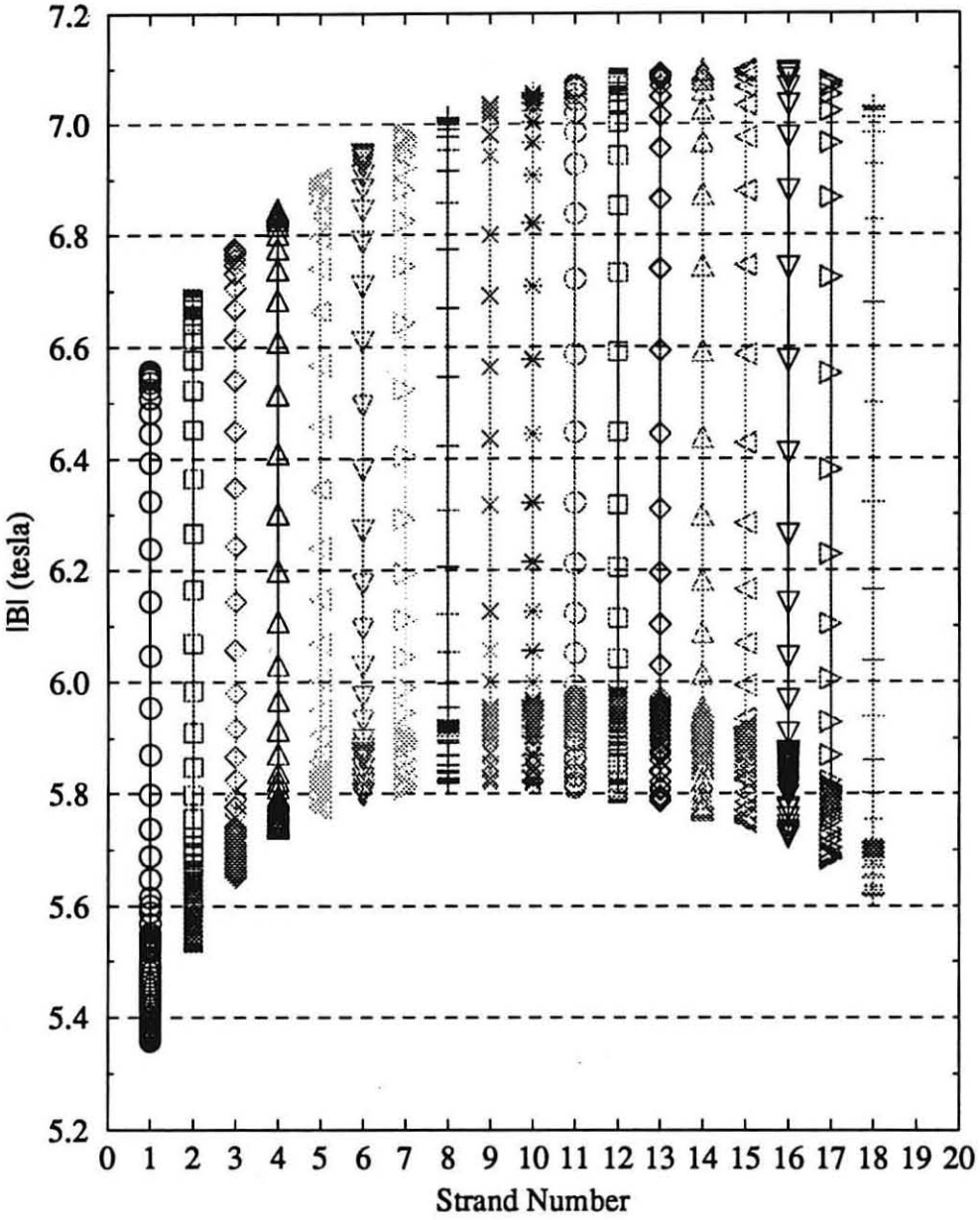

Figure 15 The field magnitude for each strand along the pole face of layer1 as a function of strand number (I=7000 A).

Appendix A integrated values — centroids

Inner layer

```
#  shemesh:/export/home/shemesh/u0/magi/caspi/
ssc_irquad/58mm/end/bend_stuff
 Fri Apr 17 15:33:55 PDT 1992
quadrupole
current  i  A
Ropt  1.0  cm
Rfe  0.0  cm
Input in mm, output in cm


 13 strands, 676 total segments


-----------

   n      bon for straight section
   2         1.36499966 G/(A*cm)
   6         4.01493500 (units)
  10        -0.01741317 (units)
  14        -0.00038058 (units)
  18         0.00000060 (units)
  22         0.00000002 (units)
  26        -0.00000000 (units)
  30         0.00000000 (units)
  34         0.00000000 (units)
  38        -0.00000000 (units)


-----------

   n      bo-oo from Cn (integral)
   2        89.26097382 G/(A*cm) * cm
   6         4.15454946 (units)
  10        -0.01962255 (units)
  14        -0.00037108 (units)
  18         0.00000052 (units)
  22         0.00000002 (units)
  26        -0.00000000 (units)
  30         0.00000000 (units)
  34         0.00000000 (units)
  38        -0.00000000 (units)



-----------
```

```
   n      bend  for ends
   2        1.36499966 G/(A*cm)
   6        4.60805901 (units)
  10       -0.02679929 (units)
  14       -0.00034023 (units)
  18        0.00000026 (units)
  22        0.00000001 (units)
  26       -0.00000000 (units)
  30        0.00000000 (units)
  34        0.00000000 (units)
  38       -0.00000000 (units)

Straight section  |  Integrated   |   End
Leff =  65.3927  Loo = 50  Le =  15.3927
```

Outer layer

```
#  shemesh:/export/home/shemesh/u0/magi/caspi/
ssc_irquad/58mm/end/bend_stuff
  Fri Apr 17 15:34:24 PDT 1992
quadrupole
current  i  A
Ropt  1.0  cm
Rfe  0.0  cm
Input in mm, output in cm


 20 strands, 1040 total segments


-----------

   n     bon for straight section
   2        1.08299529 G/(A*cm)
   6       -1.81629024 (units)
  10        0.00007931 (units)
  14        0.00000235 (units)
  18       -0.00000002 (units)
  22        0.00000000 (units)
  26        0.00000000 (units)
  30       -0.00000000 (units)
  34        0.00000000 (units)
  38        0.00000000 (units)


-----------

   n     bo-oo from Cn (integral)
   2       74.47428712 G/(A*cm) * cm
   6       -1.83736798 (units)
  10       -0.00030791 (units)
  14        0.00000167 (units)
```

```
 18       -0.00000002 (units)
 22        0.00000000 (units)
 26        0.00000000 (units)
 30       -0.00000000 (units)
 34        0.00000000 (units)
 38        0.00000000 (units)



-----------

   n      bend  for ends
   2        1.08299529 G/(A*cm)
   6       -1.89352453 (units)
  10       -0.00133956 (units)
  14       -0.00000014 (units)
  18       -0.00000002 (units)
  22        0.00000000 (units)
  26       -0.00000000 (units)
  30       -0.00000000 (units)
  34        0.00000000 (units)
  38        0.00000000 (units)

Straight section  |  Integrated   |   End
Leff =  68.767  Loo = 50  Le =  18.767
```

Both layers

```
#  shemesh:/export/home/shemesh/u0/magi/caspi/
ssc_irquad/58mm/end/bend_stuff
  Fri Apr 17 15:35:19 PDT 1992
quadrupole
current  i  A
Ropt  1.0  cm
Rfe  0.0  cm
Input in mm, output in cm


 33 strands, 1716 total segments


-----------

   n     bon for straight section
   2        2.44799496 G/(A*cm)
   6        1.43519542 (units)
  10       -0.00967448 (units)
  14       -0.00021118 (units)
  18        0.00000032 (units)
  22        0.00000001 (units)
  26       -0.00000000 (units)
```

```
 30        0.00000000 (units)
 34        0.00000000 (units)
 38       -0.00000000 (units)


-----------

   n     bo-oo from Cn (integral)
   2      163.73526094 G/(A*cm) * cm
   6        1.42915129 (units)
  10       -0.01083737 (units)
  14       -0.00020154 (units)
  18        0.00000027 (units)
  22        0.00000001 (units)
  26       -0.00000000 (units)
  30        0.00000000 (units)
  34        0.00000000 (units)
  38       -0.00000000 (units)



-----------

   n      bend  for ends
   2        2.44799496 G/(A*cm)
   6        1.41125387 (units)
  10       -0.01428083 (units)
  14       -0.00017301 (units)
  18        0.00000012 (units)
  22        0.00000001 (units)
  26       -0.00000000 (units)
  30        0.00000000 (units)
  34        0.00000000 (units)
  38       -0.00000000 (units)

Straight section  |  Integrated   |   End
Leff =  66.8855  Loo = 50  Le =  16.8855
```

Appendix B A's — conductor and iron

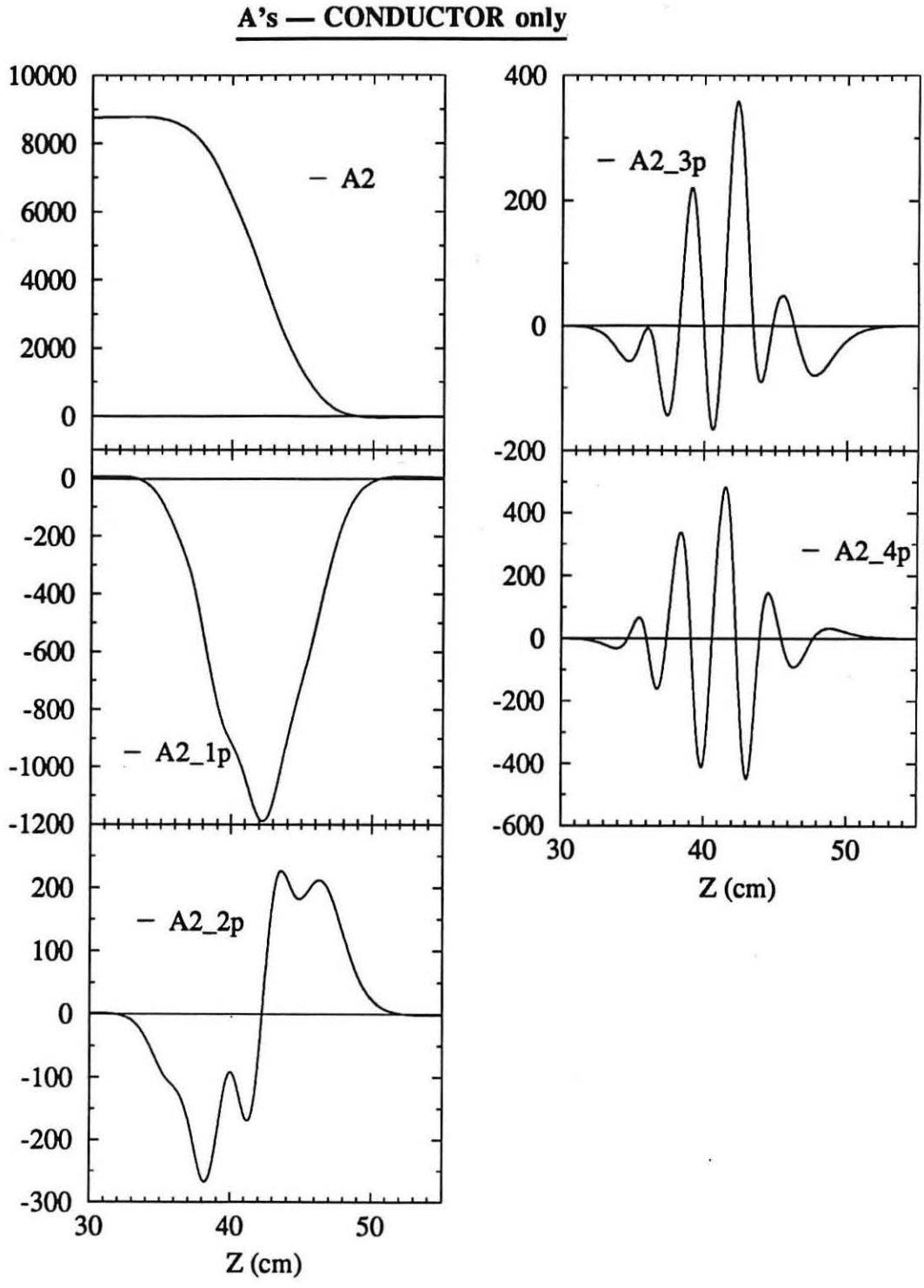

Figure 16 A2 and derivatives along the end, including contribution from CONDUCTOR only (I=7000 A).

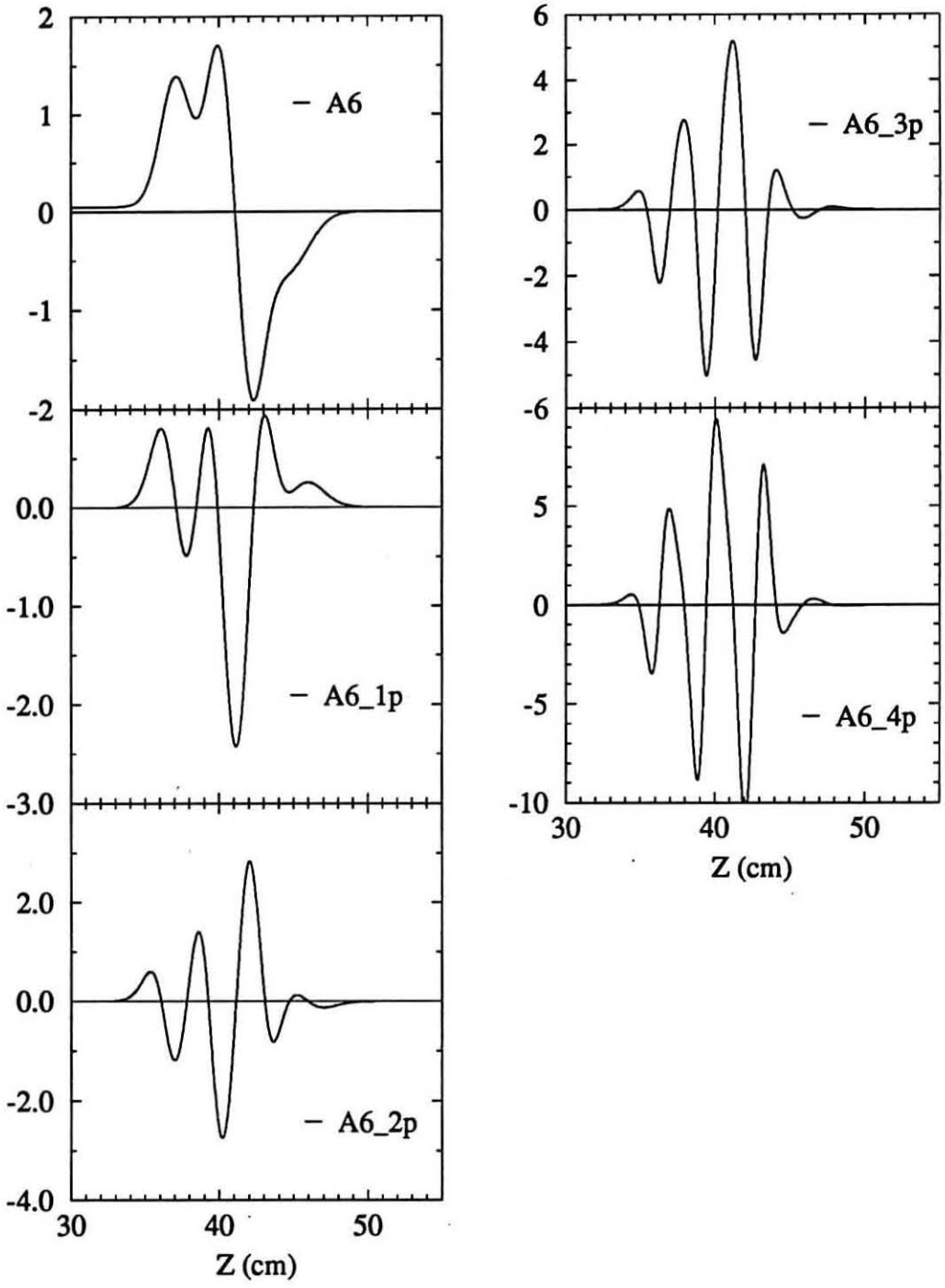

Figure 17 A6 and derivatives along the end, including contribution from CONDUCTOR only (I=7000 A).

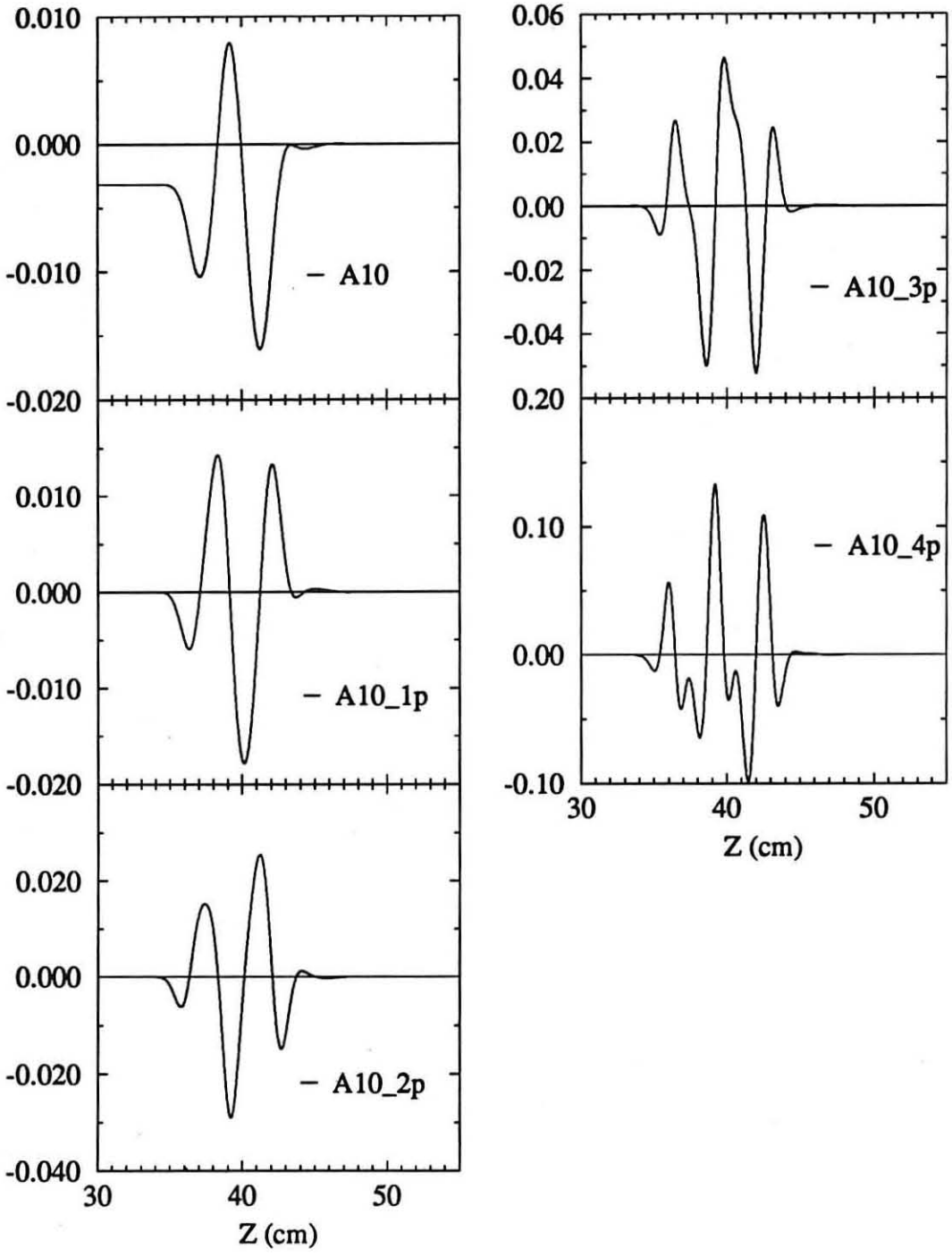

Figure 18 A10 and derivatives along the end, including contribution from CONDUCTOR only (I=7000 A).

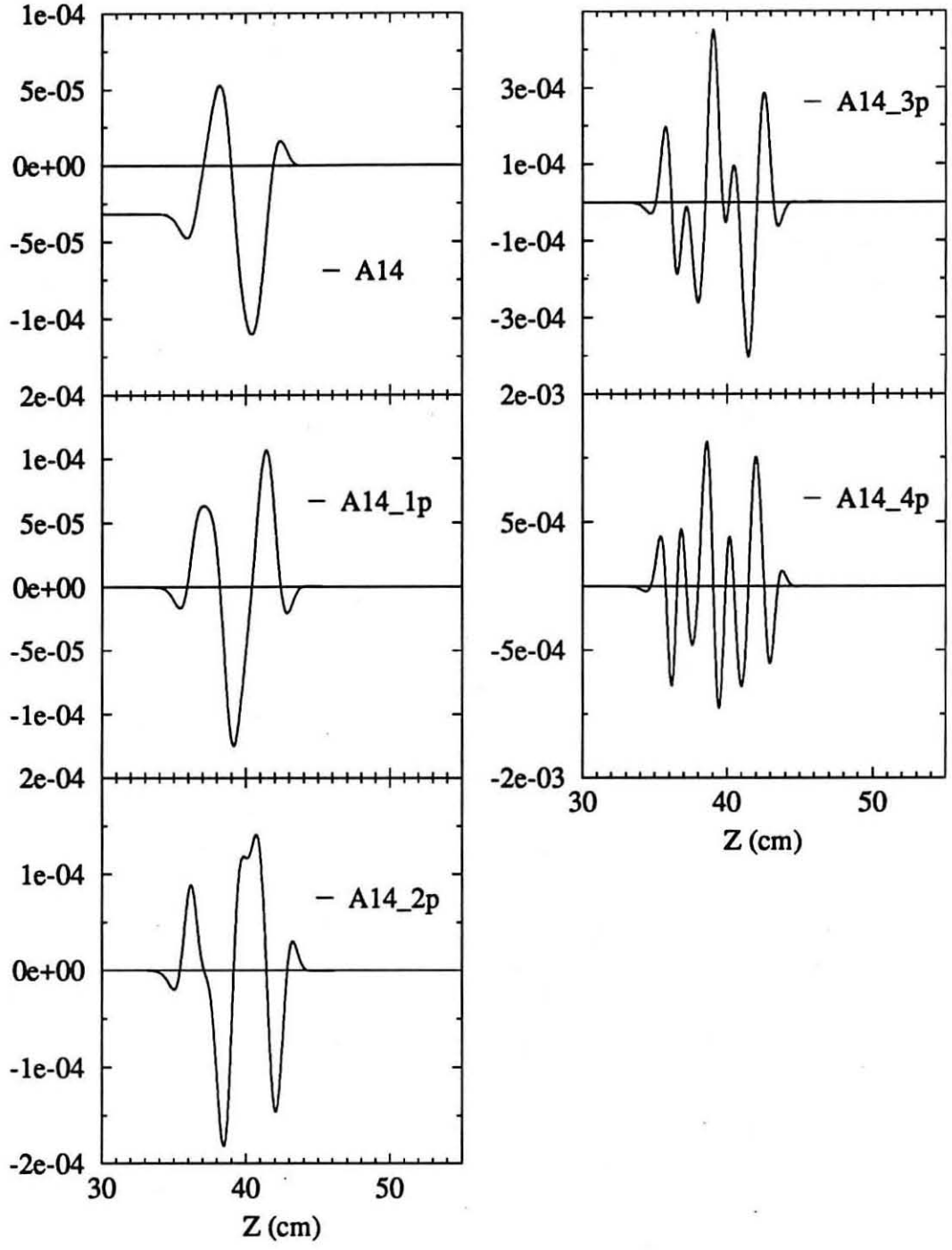

Figure 19 A14 and derivatives along the end, including contribution from CONDUCTOR only (I=7000 A).

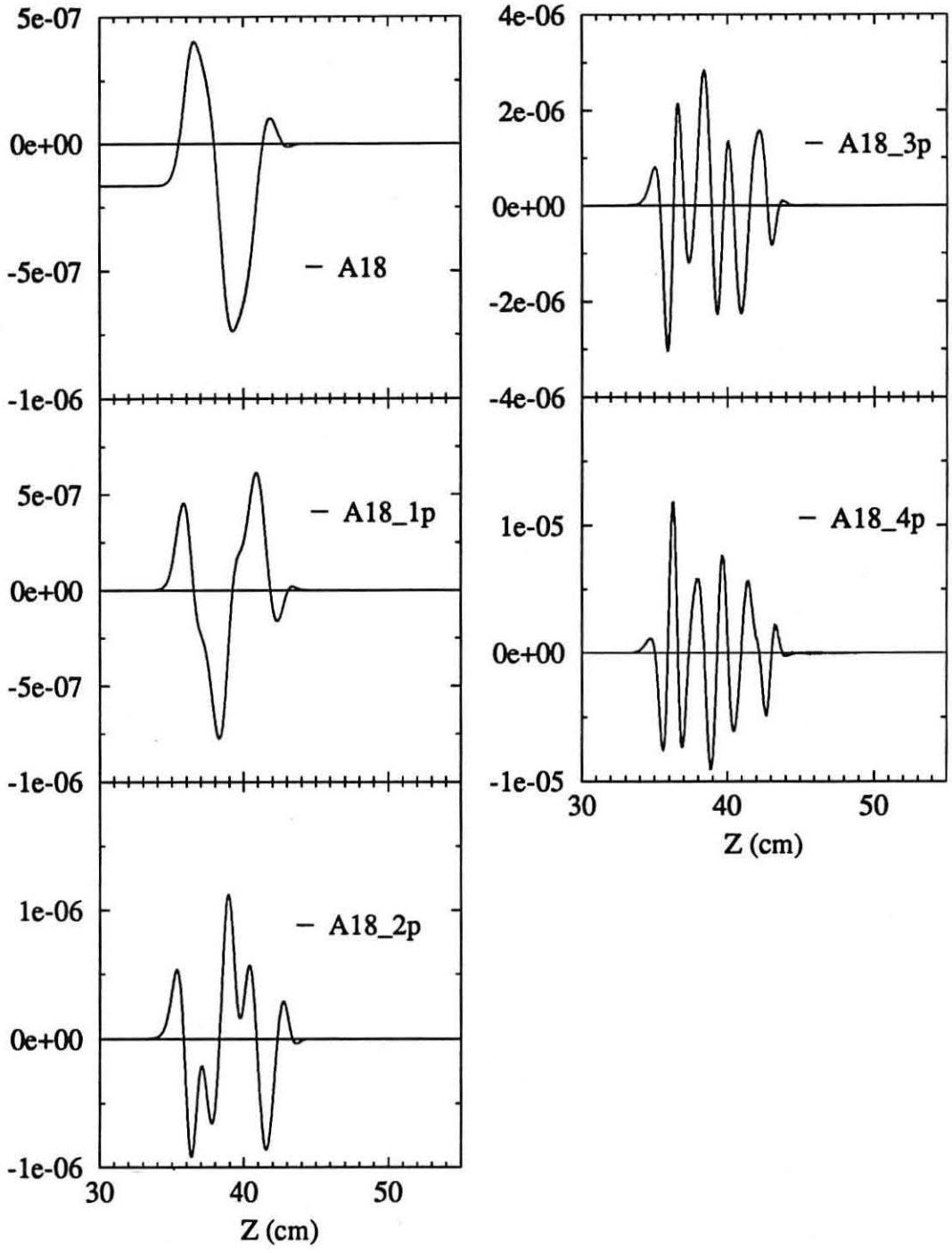

Figure 20 A18 and derivatives along the end, including contribution from CONDUCTOR only (I=7000 A).

A's — IRON only

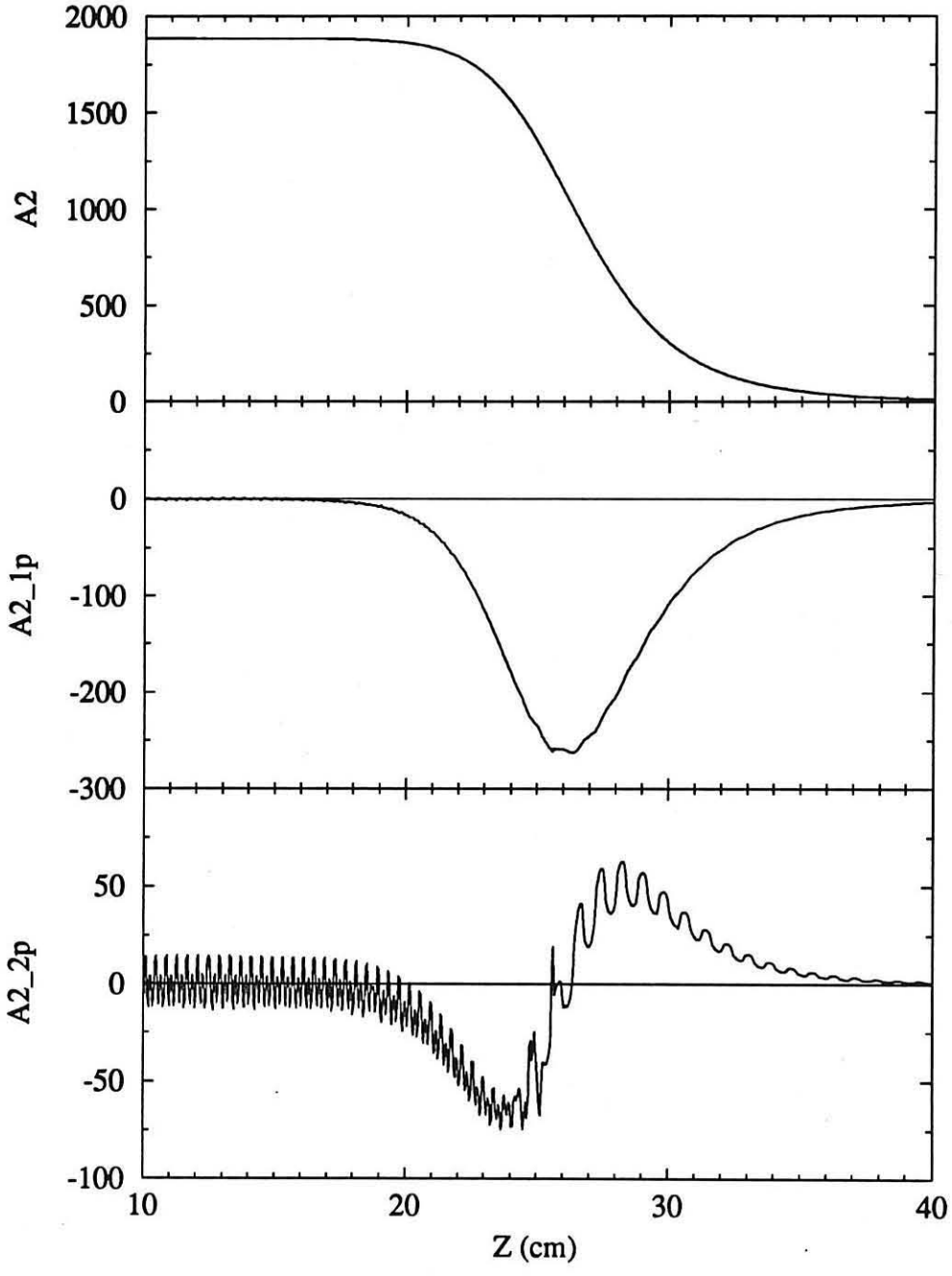

Figure 21 A2 and derivatives along the end, including contribution from IRON only (I=7000 A).

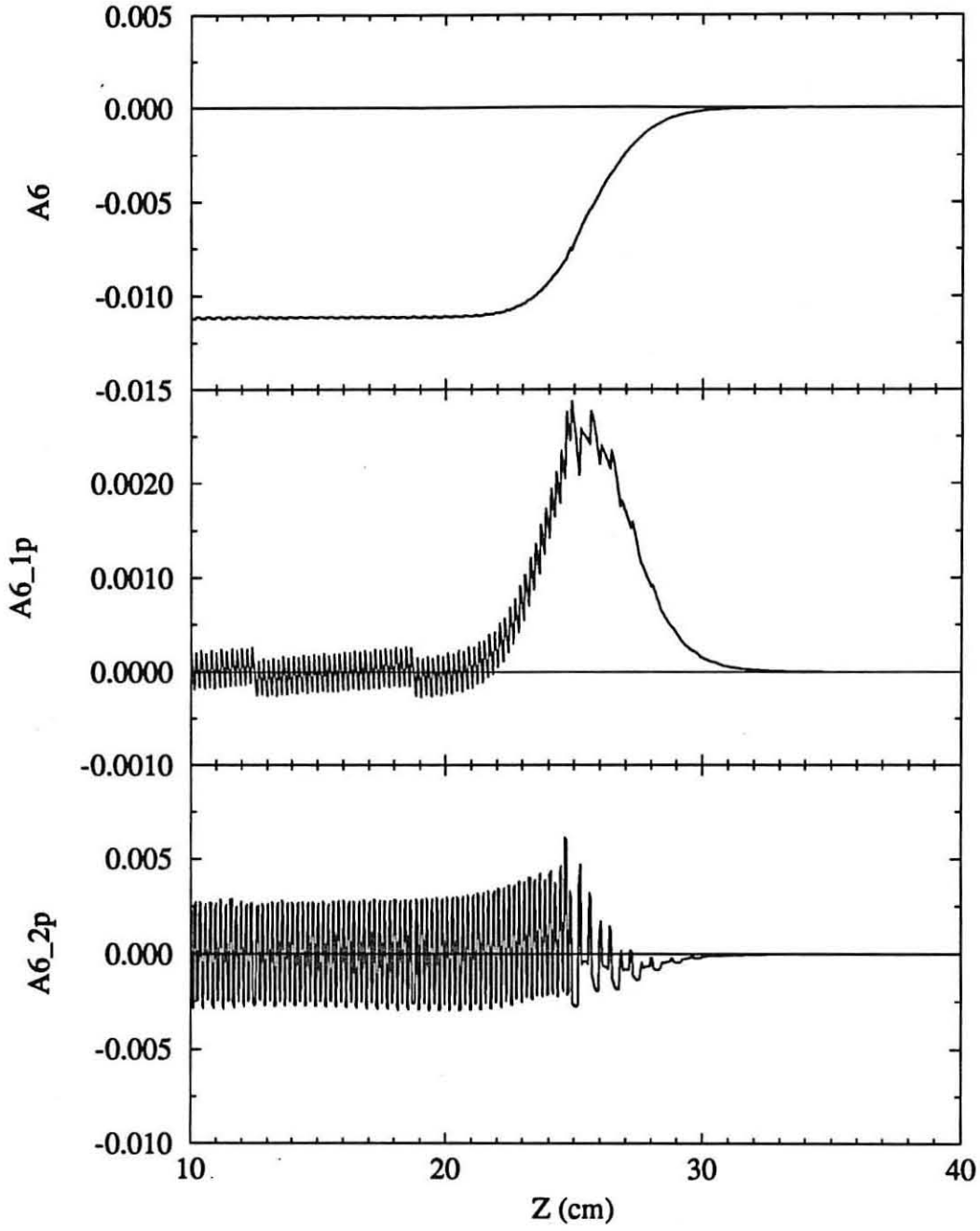

Figure 22 A6 and derivatives along the end, including contribution from IRON only (I=7000 A).

Appendix C Iron contribution

Flux plots

Using the method described in[3], we have computed the iron contribution in the end region.

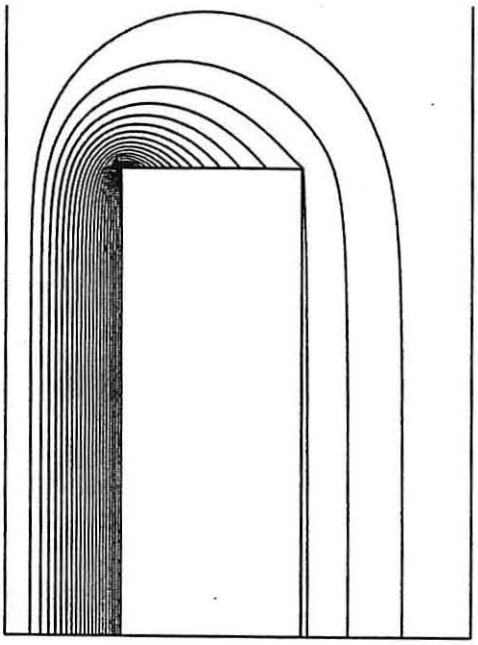

Figure 23 Solution of equal potential lines for the first harmonic, n=2

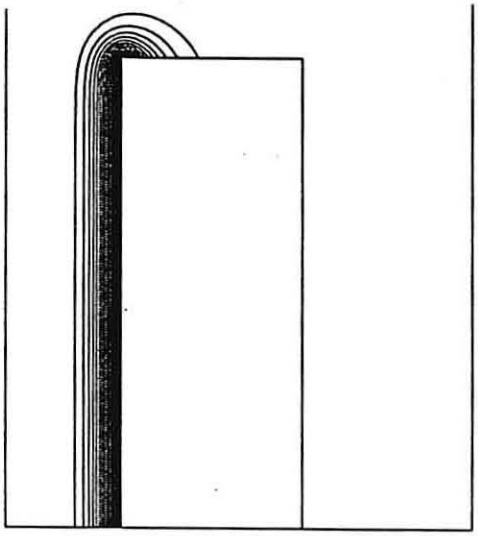

Figure 24 Solution of equal potential lines for the second harmonic, n=6

[3] "Three Dimensional Magnetic Field Produced by an Axisymmetric Iron Yoke." L.J.Laslett, S.Caspi, M.Helm, and V.Brady, SC-MAG-315 , LBL 29810, June 1991

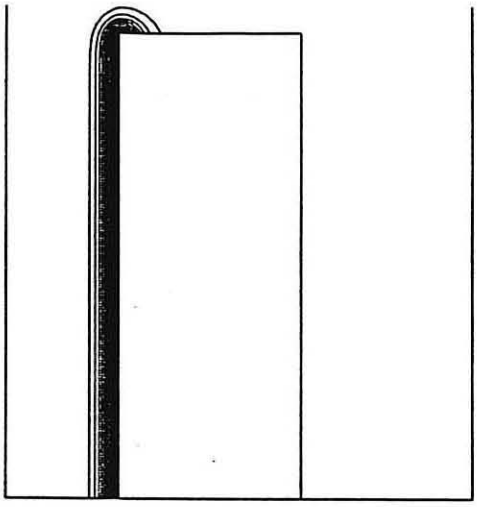

Figure 25 Solution of equal potential lines for the third harmonic, n=10