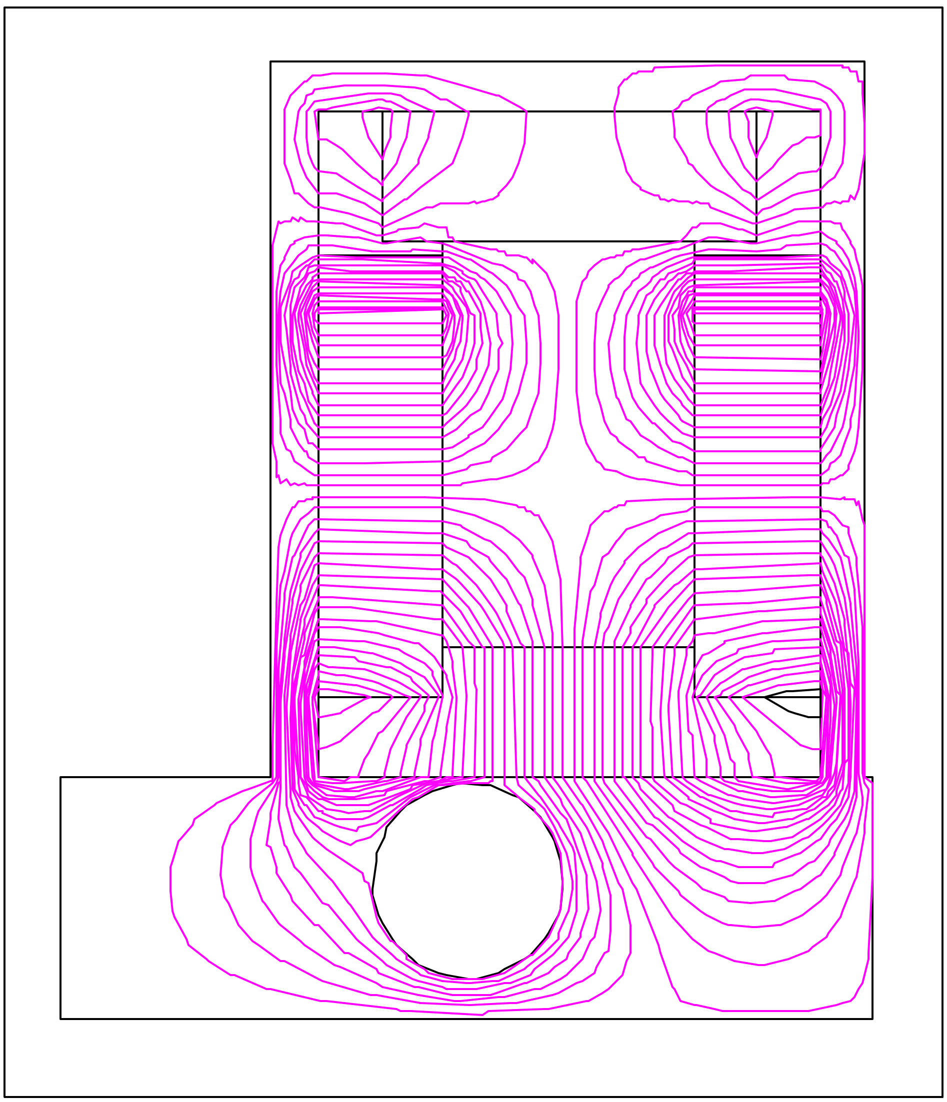
Recycler Lambertson Magnetic Design

G.W. Foster

March 24, 1999



RLA Permanent Magnet Lambertson

Introduction & Related Documents

This note describes the magnetic design of the Recycler Ring permanent magnet Lambertsons. The magnetic specifications are based on the Recycler transfer line designs described in MI-161. Five Lambertsons (RLA001-RLA005) were produced from four non-interchangeable designs that differ by brick polarization and assembly orientation as described in MI-0231. The production drawing for parts procurement was 8140-ME-341098 although this may have been transferred to the Technical Division archives under a possibly different designation. The magnetic measurements (multipole defects, etc.) are stored in the MTF database and hardcopies are included in the travelers.

<u>Table 1</u> – Summary of Recycler Lambertson Key Specifications

Bend Angle (8.9 GeV)	23 mr
Bend Field	0.1678 Tesla
Integrated Strength	0.6819 T-m
Magnetic (pole tip) Length	160" (4.064m)
Length (overall) at baseplate	168" (4.267m)
Bend Field Aperture (straight square tube)	1.9" x 1.9"
Field-Free Aperture	2.9" Diameter
Septum Width (nominal including beam pipes)	0.220"

Unique Features of the Recycler Lambertsons

- The use of permanent magnets avoids the need for power supplies and water connections. It also unfortunately precludes their use as "critical devices" in accelerator safety systems. Normally a line using permanent magnet Lambertsons will require one additional corrector for bend strength trim.
- The pole tip for the bend field is angled (by ½ the bend angle) and offset (by ½ the bend sagitta) with respect to the field-free cutout for the circulating beam. This maximizes bend field aperture for the injected/extracted beam. This allows the pole tip to be narrower, which uses less ferrite and yields a lighter and less expensive magnet. This is not normally done on electrically driven Lambertsons since the cost of additional gap width (as opposed to gap height) is small in copper/iron magnets.
- A solid steel baseplate with a gun-bored cutout for the field-free region was used. This was a partially successful attempt to deal with the vacuum and septum width problems often encountered in conventional (laminated baseplate) Lambertson designs. The discussion on baseplate fabrication below gives some suggestions on how the fabrication might be improved on subsequent designs.
- Side bricks which extended below the sides of the pole tips (see fig.1) were used to help shape the dipole bend field. This technique was also used in the "Double-Double Dipoles" of the 8 GeV Line and is found to be adequate for the ~0.2% field quality required of beam transfer line magnets. The main benefit is that one can use a less expensive flat steel pole tip. It also allows for factory trimming of the skew quadrupole, which is generally the largest field error in a mirror magnet design.

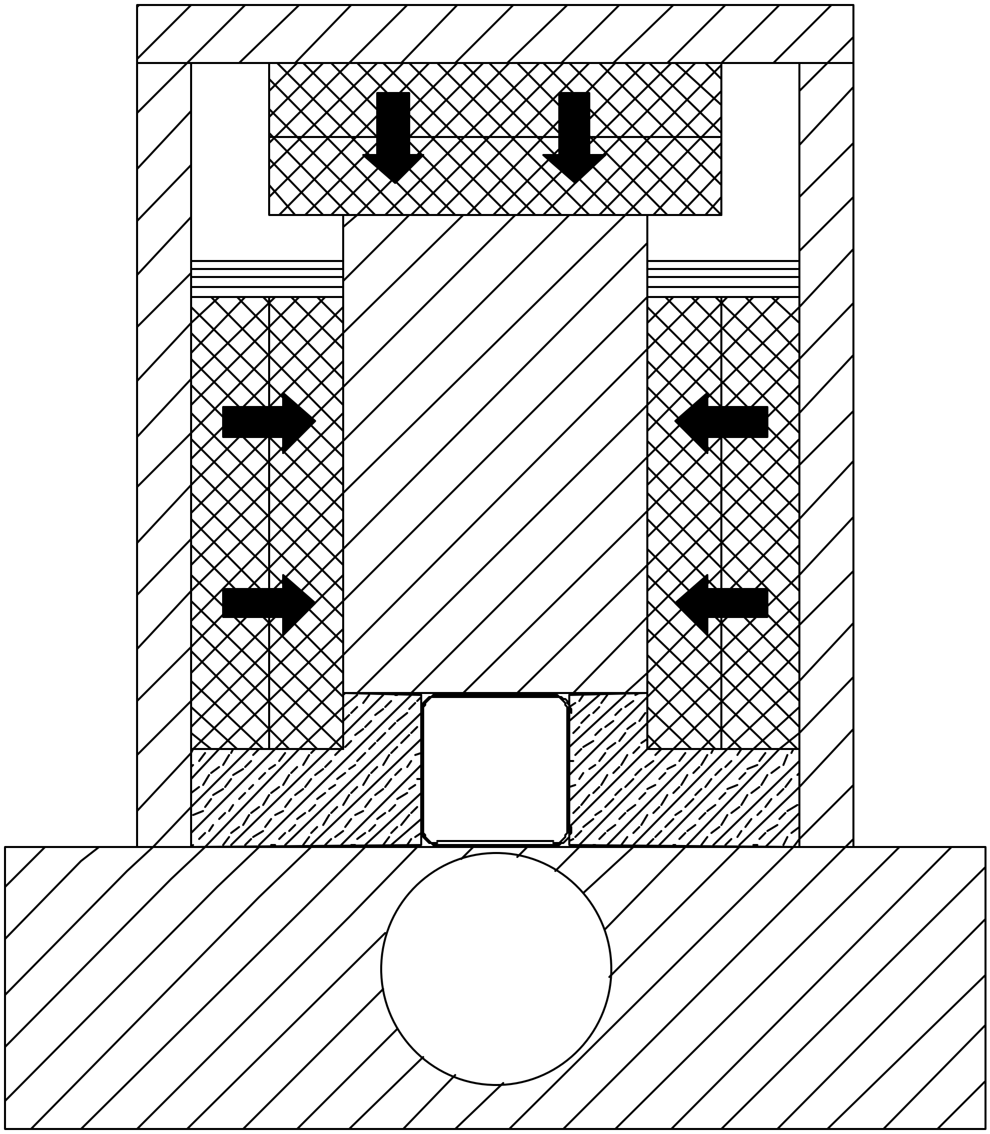


Fig. 1 - RLA Lambertson typical cross section. It is a mirror dipole which is energized by permanent magnets surrounding the pole tip. Arrows indicate polarization of permanent magnet bricks. A steel flux return box surrounds the magnet's pole tip. A circular cutout in the mirror base-plate allows the undeflected beam to circulate in a nearly field-free region. The bending field shape is determined mainly by the low-carbon steel pole tips and the solid steel base plate. Some additional field shaping is produced by the side bricks that protrude below the corners of the pole tips. Two layers of 1" thick bricks on top & sides of the pole tips are used in the RLA series. The sign of the brick polarities varies among the RLA magnets. Aluminum spacers on either side of the bend-field beam pipe control the positions of the bricks and support the pole tips. Strips of "compensator alloy" 2.0” wide x 0.050” thick run the full length of the pole tip above the side bricks. Additional 2”x6”x0.050” compensator strips (not shown) were interspersed transversely between the top ferrite bricks. The actual amounts of compensator and ferrite installed are in the magnet travelers.

Pole Tip Steel

The pole tip and baseplate of the Lambertson were built using low-carbon 1018 steel. It was not felt to be useful to go to lower carbon steels (eg 1008) since the bend field quality needed was that of a transfer line magnet. (In any case we have noticed no evidence that lower carbon steels result in better field quality in the hybrid permanent magnets.) The magnetic modeling used the B-H curves for the default 1010 steel provided with POISSON.

Flux Return Issues

The flux return boxes were built from common grades of low-carbon steel (1018 or A36). The thickness 3/4" which keeps the maximum flux density below ~0.8T in the flux return shells. A high flux density is introduced into the baseplate at the point of attachment (see fig.2). The design keeps the point of attachment well away from the septum of the field-free cutout which could not support this flux without saturation.

A related flux return issue is the need to provide an adequate transverse flux path *behind* the field-free region. When the pole tip is centered on the field-free cutout (fig 2a), little or no flux passes behind the cutout. However when the pole tip is placed off center (fig 2b), the flux does not enter the baseplate symmetrically and substantial flux must pass behind the cutout. If the cutout is too thin the flux tends to concentrate in the septum. A healthy thickness of steel is also desirable here for mechanical reasons.

Base Plate Fabrication and Septum Width

The RLA's features an adventurous design involving a 3.04" diameter gun boring through the full 168" length of the 3.75" thick solid steel baseplate. The original specification which was accepted by the vendor called for a maximum septum width in the iron of 0.060", plus an out-of flatness tolerance of ~0.010"(?). A 1m prototype piece was built without difficulty. However in attempting to bore the 168" long pieces, the vendor (Viking) was able to produce only five pieces (out of 10 attempts) which had an effective septum width of 0.090" or less. To meet this spec several pieces had to be finally straightened at another vendor (SVF). Some of these parts had spots on the septum as thin as 0.010". In fact, some of the "failed" pieces had the bore break through the surface. However these thin places did not seem to cause any anomalies in the field-free region of the assembled magnets. In retrospect most of the difficulties with the bore straightness could have been avoided if Fermilab had provided the vendor with FNAL's ultrasonic thickness gauge, since the vendor's difficulties arose not from steering the bore but from knowing where it was. The vendor's technique of boring the hole prior to a final machining pass on the top surface and straightening of the piece would also have benefited from the ultrasonic measurements. One advantage of the solid baseplate was that it maintained its straightness and effective septum width as the pole tip assembly was bolted on, as indicated by a final survey for the bore tube.

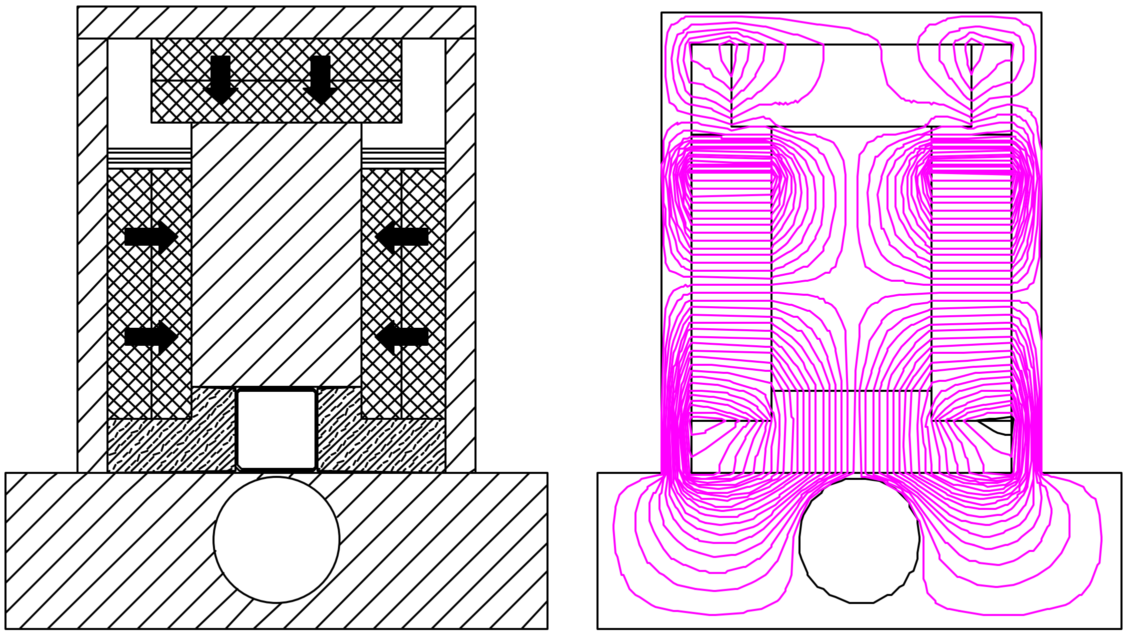


Fig. 2a - RLA cross section near end with beams merged

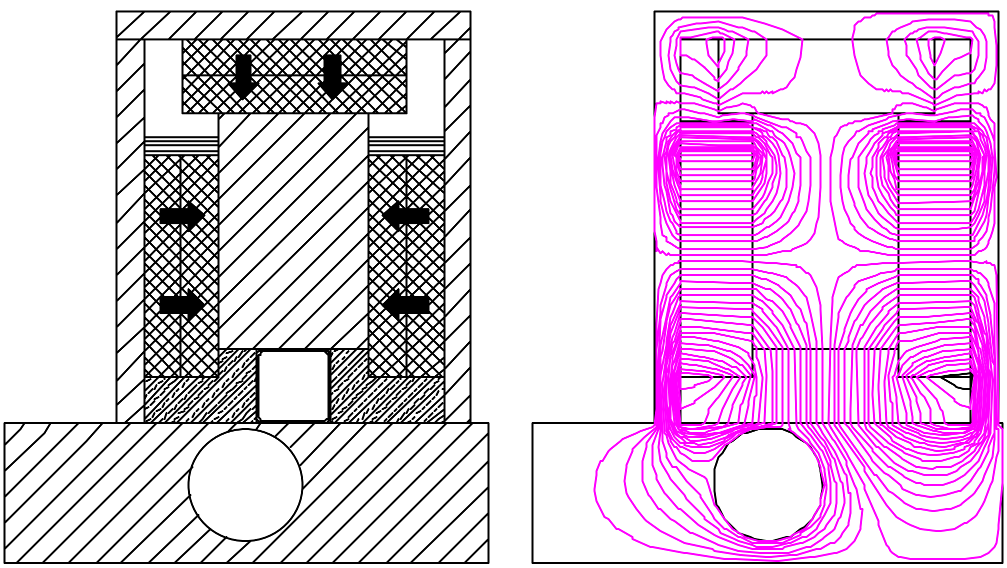


Fig. 2b - RLA cross section near end with beams separated

Vacuum system

The vacuum system as originally designed consisted of a 2"x2"x0.065" wall rectangular straight stainless tube in the bend region, a 3"OD x 0.050" wall low-carbon steel tube in the field-free region, and welded vacuum fixtures for merging and separation of the beam pipes outside the magnet.

The rectangular tube was necessary because of the sagitta in the extracted beam, which causes it to wander around inside the bend field beam pipe in the plane parallel to the baseplate. If a round pipe were used the effective septum width would be much larger. This approach seemed to work well and caused no difficulties.

The round low-carbon steel tube for the field-free region was originally chosen to help with the magnetic shielding. When the problems with the septum width on the baseplate surfaced, the performance of the field-free region *without* the iron tube was investigated and found to be adequate (a few Gauss-meters of field). A plan was developed to copper-plate the inside of the gun borings on the base plates, which would make the bore useable as high-vacuum beam pipe. This would reduce the effective septum width by the 0.050" wall thickness of the steel tube and more than recover the septum width lost from the gun boring tolerance. This plan was vetoed as too expensive ($2k for each of the 5 Lambertsons) by the Recycler project manager who felt that the bare (unplated) steel inside of the boring cold be made to work. After extensive polishing and cleaning this was proven not to be the case, and in frustration a normal .065" wall stainless tube was placed into the bore. Thus the effective final septum width turned out to be: 0.090"(baseplate)+0.065"(SS Bore tube)+0.065"(rectangular tube)=0.220" instead of the originally planned 0.060"+0.050"+0.065" = 0.175".

In summary, if we had to do the project again, I would recommend:

1) that the gun boring vendor be loaned an ultrasonic measuring device, under which circumstances he might be expected to hold a 0.040"+/-0.010" tolerance on the septum width,
2) The inside of the bored hole be copper plated to maintain high-vacuum compatibility, and
3) If further reductions in septum width are desirable, consideration should be given to copper plating and brazing an "arch" beam pipe for the bend region.
4) Consideration should also be given to having a separate steel "insert" for the septum which would fit into a machined trough in the baseplate.

Field Shape Optimization with Side Bricks

A feature of the side bricks that was mentioned in the introduction is that the field quality can be trimmed by adjusting the vertical positions of the side bricks. This was accomplished by inserting aluminum shims between the aluminum pole tip supports and the side bricks.

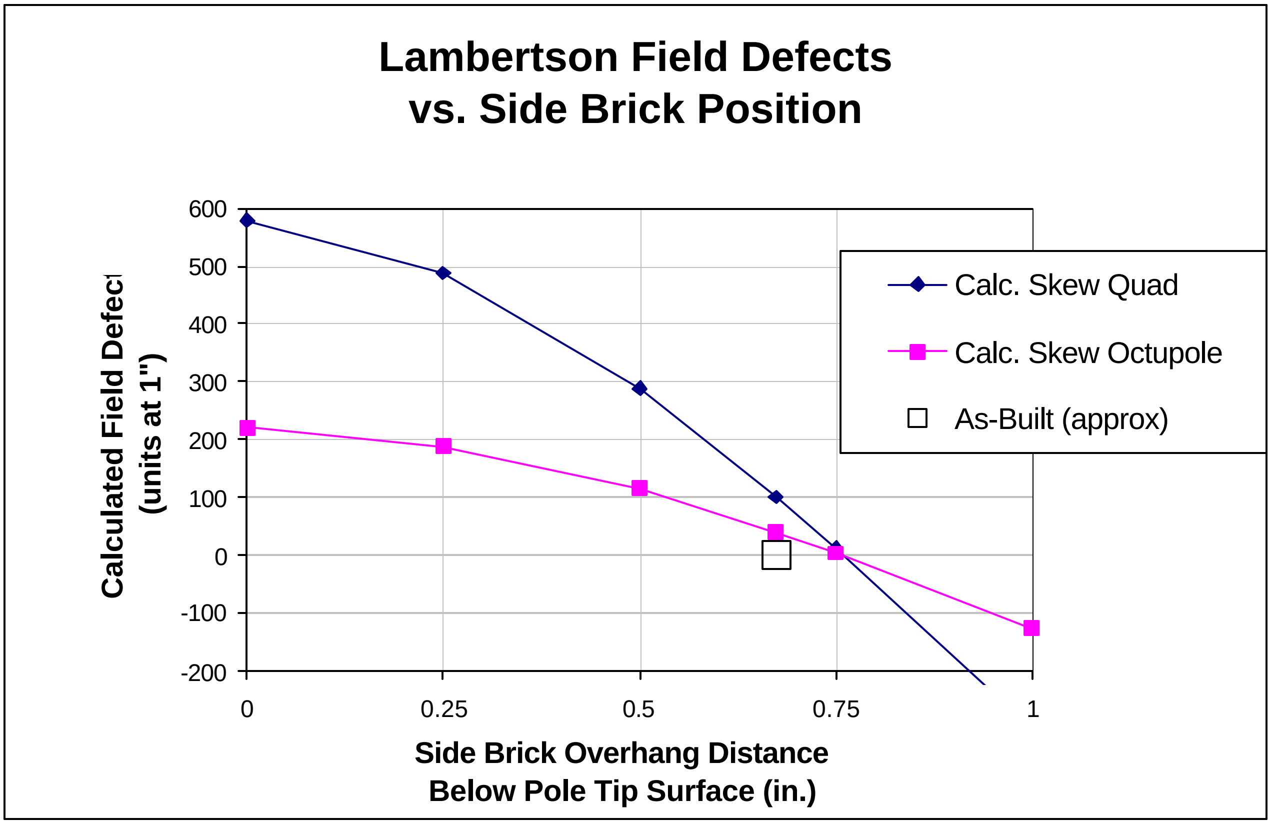


Fig. 3 – Dependence of the skew quad and skew octupole field defect on the positions of the side bricks, as calculated by POISSON and as found in reality.

In the POISSON design of the magnet it is found that the best position of the side bricks is to have them extend ~0.75" below the pole tips. See figure 3. Both the skew quad and skew octupole (the dominant field defects) are simultaneously (fortuitously?) minimized at this value. The mechanical design and the POISSON file included with this document are set up for this value. However for reasons not understood, better field quality could be achieved by shimming the bricks upward by 3/32" aluminum strips (J. Volk pvt. comm., also the info is on the travelers). This same behavior was observed in the double-double dipoles of the 8-GeV line, which also required side brick shims not predicted by POISSON. Possible reasons for this behavior include: end-field effects, 3-Dimensional effects from the gaps between bricks, and the fact that the optimum amount of side brick overhang depends on the ratio of strength between the uncompensated side bricks and the temperature compensated top bricks.

Magnetic Materials

Strontium Ferrite (Br~0.38T, Hc~0.35T) was used. The properties of this material are discussed in the 8 GeV line section of the Main Injector design report, the Recycler design report, and various MI notes. Interspersed in the ferrite were strips of Nickel-Steel "compensator alloy" in an approximately 1:5 ratio of compensator : ferrite. The compensator has a temperature dependence of magnetization which cancels that of the ferrite [Dallas PAC papers by Bertsche, Foster..]. The amount of Ferrite was adjusted to obtain the correct integrated strength for the bend field and the amount of compensator was adjusted to null out the temperature coefficient of the magnets. Final numbers for each magnet are in the travelers.

The POISSON ".CON" file specifying the magnetic properties is reproduced below There are three permanent magnetic materials corresponding to the three orientations of the magnetic material. The material (#6) for the top brick has been deliberately weakened (by reducing the stacking factor to 0.6) to approximately account for the flux lost due to the interspersed compensator material in the top brick. The compensator alloy data was obtained without warrantee from Bruce Brown. A reasonable alternative model for the compensator alloy at room temperature is iron with a density of ~0.2.

POISSON ".CON" FILE SPECIFYING MAGNETIC PROPERTIES
OF FERRITE AND COMPENSATOR ALLOY

```
            (see POISSON documentation for explanation)
0  (0=Dump # to be read in from lattice)
*18 4 *6 0  *42 1 41  1 1  *54 0.0 4.0 0.0 1.0 s
6     0.60000     -1   mat stack type  (top block, weakened to
                                         reflect compensator)
90.0 1.0 s
   -3500.00        3800.00        hcept bcept
7 1.0 -1   mat stack type   (right block,if used)
0.0 1.0 s
   -3500.00        3800.00        hcept bcept
8 1.0 -1   mat stack type   (Left block, if used)
180.0 1.0 s
   -3500.00        3800.00        hcept bcept
3 1.0 1   mat stack type  (Bruce Brown's data for compensator)
0    0.25
575  0.25
850  0.293103
1200 0.350877
1420 0.38587
2000 0.454545  count
end
```

Appendix - RLA Lambertson POISSON (PANDIRA) FILE

This file represents the case where the pole tip is centered over the baseplate and field-free region (similar to fig.1). To modify for off-center cases it is necessary to add an offset to all X coordinates in the two baseplate regions (#9 and #10), and possibly expand the boundary region (Xmin, Xmax, and the boundary limits on region #1).

```
Lambertson POISSON file, pole tip centered

 &reg nreg=          11, dx=   0.1250000  ,
  xmax=    7    ,ymax=   11    ,
  xmin=   -7    ,ymin=   -6    ,
  yreg1=2.0 , yreg2=3.0 ,
  Rint=0.85,RNorm=1.00,NTERM=11,
  ktype=1,Angle=360.,NPTC=       1440,
  npoint=5 &       Boundary region
 &po x=-7.000, y= -6.000 &
 &po x=-7.000, y= 11.000 &
 &po x= 7.000, y= 11.000 &
 &po x= 7.000, y= -6.000 &
 &po x=-7.000, y= -6.000 &

 &reg mat=2, npoint=       5 &   Pole Tip
 &po x=-2.0100000, y= 7.3550000 &
 &po x=-2.0100000, y= 1.01000000 &
 &po x= 2.0100000, y= 1.01000000 &
 &po x= 2.0100000, y= 7.3550000 &
 &po x=-2.0100000, y= 7.355000 &

 &reg mat=6, npoint=5 &          Top Brick
 &po x=-3.000000, y= 9.355000 &
 &po x=-3.000000, y= 7.35500 &
 &po x= 3.000000, y= 7.35500 &
 &po x= 3.000000, y= 9.355000 &
 &po x=-3.000000, y= 9.355000 &

 &reg mat=7, npoint=5 &    Right side brick
 &po x= 4.0200000, y= 0.25000 &
 &po x= 2.0100000, y= 0.25000 &
 &po x= 2.0100000, y= 6.250000 &
 &po x= 4.0200000, y= 6.250000 &
 &po x= 4.0200000, y= 0.25000 &

 &reg mat=3,npoint=5 & Right side
                       Compensator Strips
 &po x= 4.0200000, y= 7.15000 &
 &po x= 2.0100000, y= 7.15000 &
 &po x= 2.0100000, y= 6.250000 &
 &po x= 4.0200000, y= 6.250000 &
 &po x= 4.0200000, y= 7.15000 &

 &reg mat=   8, npoint=5 &     Left Brick
 &po x=-4.0200000, y= 0.25000 &
 &po x=-2.0100000, y= 0.25000 &
 &po x=-2.0100000, y= 6.25000000 &
 &po x=-4.0200000, y= 6.25000000 &
 &po x=-4.0200000, y= 0.25000 &

 &reg mat=3,npoint=5 &  Left side
                      Compensator
Strips
 &po x= -4.0200000, y= 7.15000 &
 &po x= -2.0100000, y= 7.15000 &
 &po x= -2.0100000, y= 6.250000 &
 &po x= -4.0200000, y= 6.250000 &
 &po x= -4.0200000, y= 7.15000 &

  &reg mat=2, npoint=9 &      Flux return
 &po x= 4.760000, y= 10.1250000 &
 &po x= 4.760000, y=-1.0100000 &
 &po x= 4.0200000, y=-1.0100000 &
 &po x= 4.0200000, y= 9.3550000 &
 &po x=-4.0200000, y= 9.3550000 &
 &po x=-4.0200000, y=-1.0100000 &
 &po x=-4.7600000, y=-1.0100000 &
 &po x=-4.760000, y= 10.1250000 &
 &po x= 4.760000, y= 10.125000 &

 &reg mat=2, npoint=8 &      Bottom Plate
                            Top Half
 &po x= -6.500000, y=-1.010000 &
 &po x=  6.500000, y=-1.010000 &
 &po x=  6.500000, y=-2.620000 &
 &po x=  1.520000, y=-2.620000 &
 &po nt=2,r=1.52,x0=0,y0=-2.62,theta=90. &
 &po nt=2,r=1.52,x0=0,y0=-2.62,theta=180. &
 &po x=  -6.50000, y=-2.620000 &
 &po x= -6.500000, y=-1.010000 &

 &reg mat=2, npoint=8 &      Bottom Plate
                            Bottom Half
 &po x= -6.500000, y=-4.760000 &
 &po x=  6.500000, y=-4.760000 &
 &po x=  6.500000, y=-2.620000 &
 &po x=  1.520000, y=-2.620000 &
 &po nt=2,r=1.52,x0=0,y0=-2.62,theta=270. &
 &po nt=2,r=1.52,x0=0,y0=-2.62,theta=180. &
 &po x=  -6.50000, y=-2.620000 &
 &po x= -6.500000, y=-4.760000 &

 &reg mat=1,cur=5.,npoint=2 & current line
                             for Pandira
 &po x= 3.000000, y= 7.35500 &
 &po x= 3.000000, y= 9.355000 &
```