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Title: A MCNP6 model of the Mottershead times 3 magnifier (U)

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XCP-7 Transport Applications

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SUBJECT: A MCNP6 model for the Mottershead times 3 magnifier (U)

Abstract

In order to improve the position resolution of the Line C proton radiography system a permanent magnet (PM) magnifier was constructed and has been used in several experiments. In this note a model of this magnifier for MCNP6 is developed. However, before the PM magnifier is discussed, we will discuss a bit of the history of Line C magnifiers.

I. Introduction

Early in the development of proton radiography with a magnetic lens it was realized that **if** the resolution of the overall system was defined by the radiation (proton) – to – light converter and subsequent light-to-pixel part of the system, **then** the resolution could be improved if the image in the proton beam was magnified. The original proton radiography magnetic-lens developed circa 1996 was as minus-identity lens (-I) [1]. To lowest order the transport matrix from the object to image plane for this –I lens looks like:

$$\begin{bmatrix} X_{\text{image}} \\ X'_{\text{image}} \\ Y_{\text{image}} \\ Y'_{\text{image}} \end{bmatrix} = \begin{bmatrix} -1 & 0 & 0 & 0 \\ a & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & b & -1 \end{bmatrix} \begin{bmatrix} X_{\text{object}} \\ X'_{\text{object}} \\ Y_{\text{object}} \\ Y'_{\text{object}} \end{bmatrix} \qquad \text{Eq. 1}$$

with **a** = **b** = **0** in the 4-by-4 matrix of Eq. 1. It should be noted that with these values, in addition to focusing positions, angles are also focused. Prior to finding this solution (which C. L. Morris calls the Zumbro identity lens), a magnetic lens with **a** and **b** non-zero, called the Russian quadruplet (a quadrupole doublet inside a quadrupole doublet), was being proposed by C. T. Mottershead for proton radiography.

In Equation 1 the un-primed variables are the transverse positions and the image plane or object plane (note the beam is propagating in the Z direction). The primed quantities X′ and Y′ are, respectively, dX/dZ and dY/dZ. Later we will used A and B for the terms dX/dZ and dY/dZ, respectively; these are the variables used in the beam optics code COSY Infinity[2].

If the image cast by the protons due to the magnetic lens onto the detector was magnified, i.e. the -1's in positions (1,1) and (3,3) of the 4-by-4 matrix of Eq.1 increase to, say, -3.1 (note that the terms a and b are now non-zero), then the resolution of the system would be improved if this were the only change to the system. This case is illustrated conceptually in the Figure 1.

[1] "Magnetic Optics for Proton Radiography", C. Thomas Mottershead and John D. Zumbro, in the Proceedings of the 1997 Particle Accelerator Conference, Vancouver, B.C., Canada, 12-16 May 1997, p.1397-1399; also LA-UR-97-1699.
[2] http://bt.pa.msu.edu/index_cosy.htm

The initial attempt at magnification used the existing magnets[3] in the LANSCE Line C proton radiography beamline and re-wired the magnets so that they could be energized in a different configuration. The re-wiring scheme is shown in Figure 2. Each of the –I imaging lenses in Line C is 938.8-cm from object plane to image plane, so this magnifier system has a length of 1877.6-cm for the object-to-image plane distance.

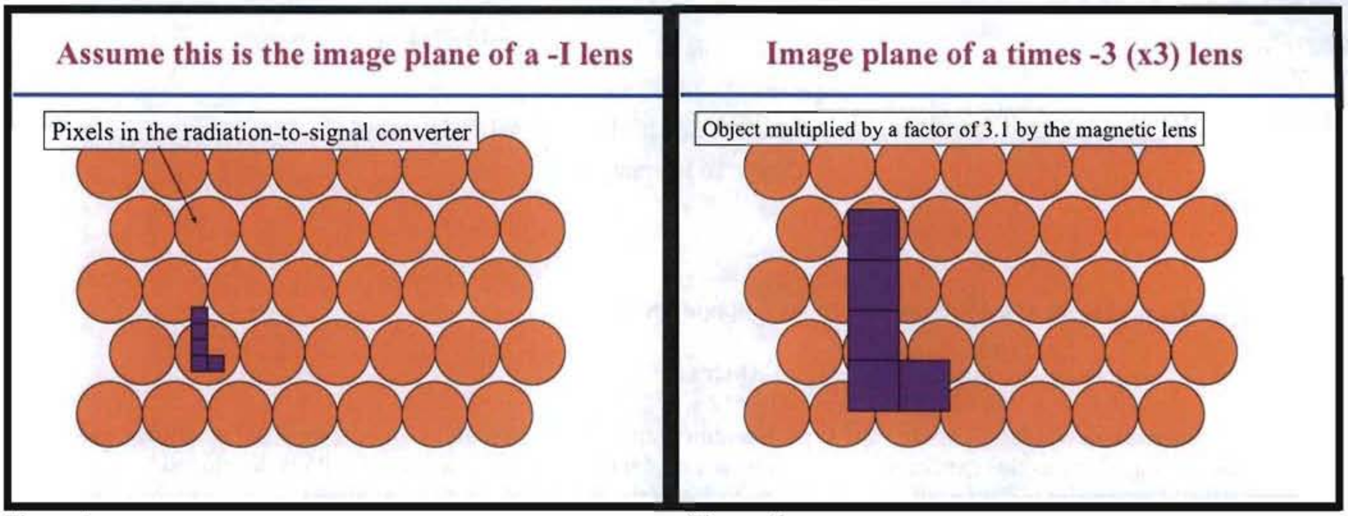

Figure 1a Figure 1b

Figure 1 – These figures compare a feature imaged on a set of pixels (orange, filled circles) with a magnetic lens with magnification 1.0 (1a) [the –I lens] and with magnification 3.1 (1b). One sees that the feature, not resolved in (1a) would be resolved if it were magnified (1b).

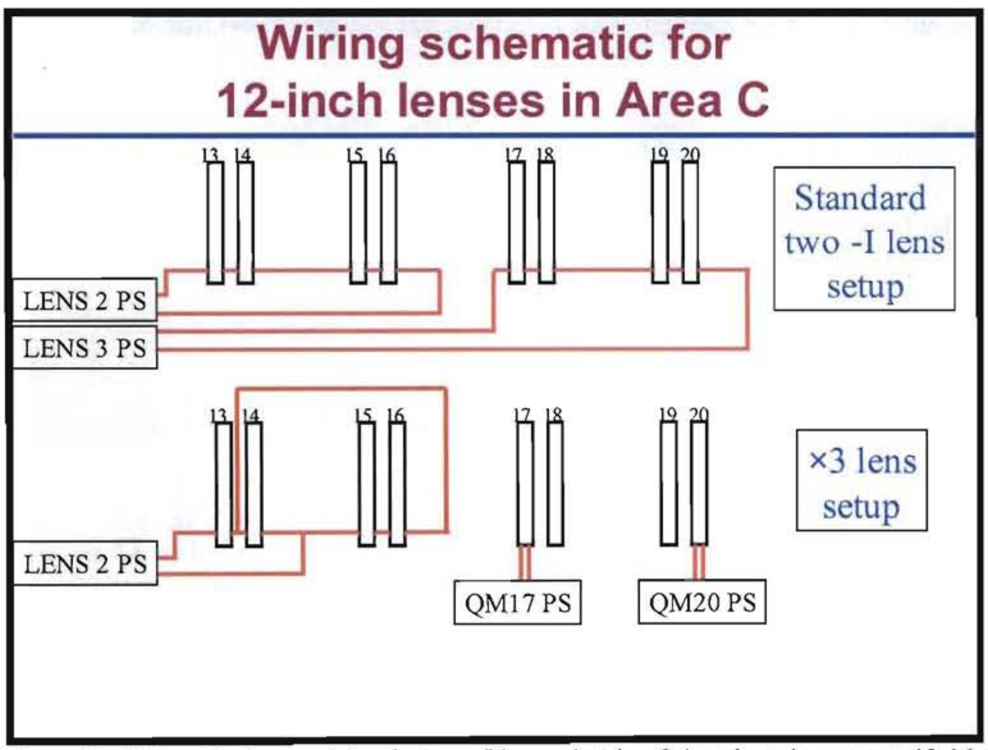

Figure 2 – Schematic for re-wiring the two –I lenses in Line C (quadrupole magnets 13-16 and 17-20 indicated by the rectangles above are energized in series by two power supplies (PS), respectively, in the upper portion of the figure. The lower portion of the

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[3] Proposed by J. D. Zumbro and implemented circa the end of 1999.

figure shows how these magnets were re-wired to make a ×3 magnifier (note that quadrupole magnets 18 and 19 are not energized in this system).

The nominal trajectories through the Line C –I system and the ×3 magnifier are shown in Figure 3 and 4, respectively. Note that the angles at image plane are smaller in the case of the magnifier (due to conservation of phase space) compared to the angle for the –I system. Figure 5 shows one of the first images of a resolution pattern obtained with the ×3 magnifier.

The improvement in the resolution is clearly seen in Figure 5, but it should be noted that subsequent improvements were made to the overall system for the –I lens. The resolution is this early experiment was seen to improve by a factor of about 5 as opposed to the expected improvement of 3.1. Subsequent study indicated that the large angles in the –I system at the 2-cm thick radiation-to-light converter compared to the smaller angles with the ×3 proton imager lead to a degradation in the –I system, hence rather then the expected factor of 3.1 improvement, the factor of 5 improvement was observed.

This observation was a contributing reason in eventually going from a 20-mm thick radiation-to-light-converter to a ~2-mm thick converter (which is currently used).

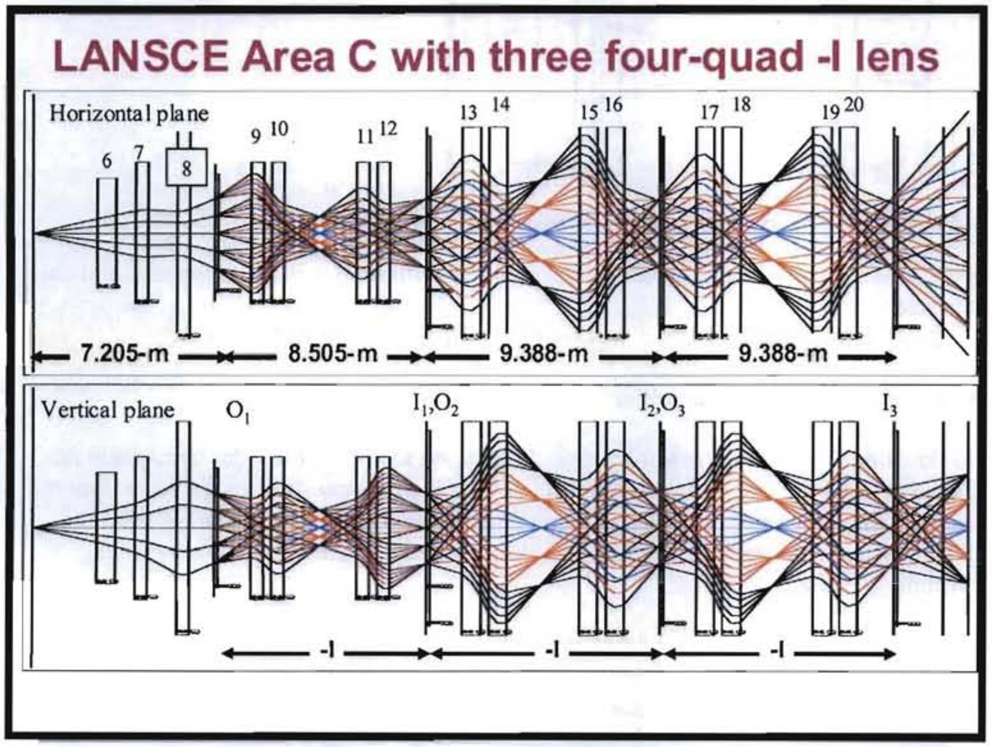

Figure 3 – Nominal trajectories through the Line C –I system for the horizontal plane (top) and vertical plane (bottom). The particles travel from left to right starting at the diffuser location of the left and proceeding past the last image location I_3. The numbers above the rectangular boxes (quadrupoles with the length and aperture size represented by the box) in the horizontal plane plot are the numbers of the quadrupole in the beamline.

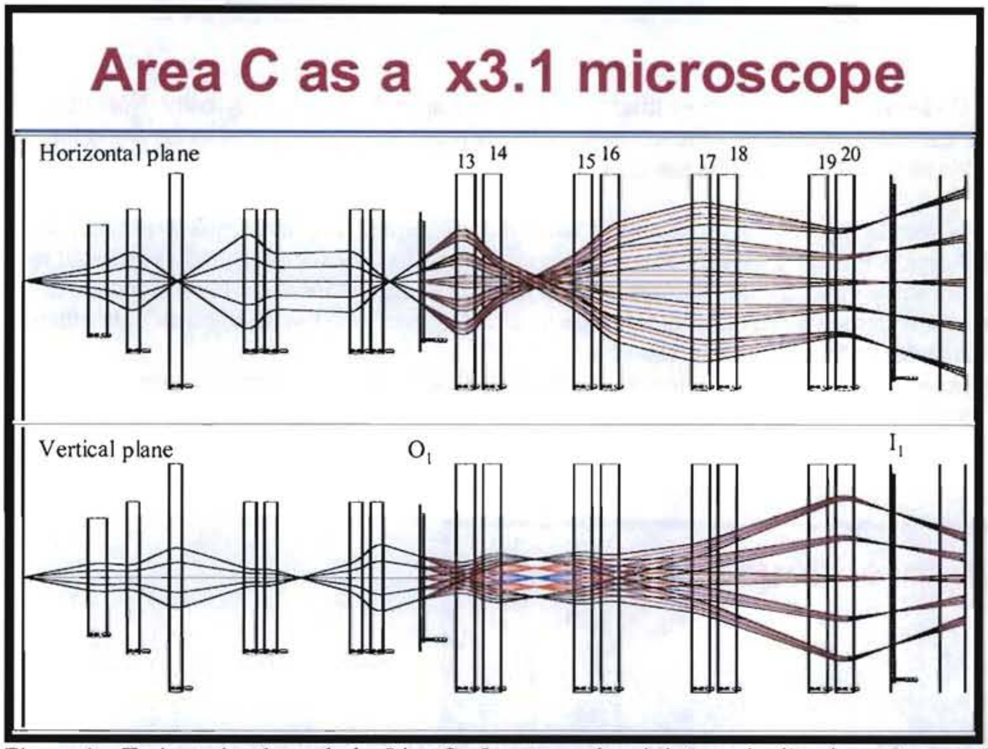

Figure 4 – Trajectories through the Line C -I system when it is 're-wired' to be a -3x magnifier.
Note that this magnifier lens is twice as long as a –I imaging lens in Figure 3. The numbers indicate the magnet numbers, and only the magnets in the magnifier section are numbered.

II. Lens with the Line C magnets and the Permanent Magnet magnifier

In the world of magnetic optics the terms in Equation 1 are **NOT** the whole story. In addition to the lowest order terms there are terms to the next order, and the next, and the next, and et cetera. Below we present examples of the coefficients for the transport equations for the lowest two orders (1[st] order in position or angle, and then position or angle multiplied by the term ($\Delta T/T_o$) for various Line C lens systems starting with the –I system (for protons near 800-MeV kinetic energy). These coefficients were calculated using the transport code COSY Infinity (version 7).

For the –I system (see Figure 3) from O_2 to I_2 (total length of the lens is 9.388 meters):

$X_{image} = -1.000\ X_{object} + 0.638E\text{-}08\ A_{object} + [-2.429\ X_{object} + 7.901\ A_{object}]\ (\Delta T/T_o)$ + higher order

$A_{image} = -0.129E\text{-}08\ X_{object} + -1.000\ A_{object} + [-1.597\ X_{object} + 2.429\ A_{object}]\ (\Delta T/T_o)$ + higher order

$Y_{image} = -1.000\ Y_{object} + 0.583E\text{-}08\ B_{object} + [+2.429\ Y_{object} + 7.901\ B_{object}]\ (\Delta T/T_o)$ + higher order

$B_{image} = 0.118E\text{-}08\ Y_{object} + -1.000\ B_{object} + [-1.596\ Y_{object} + -2.429\ B_{object}]\ (\Delta T/T_o)$ + higher order

For the original ×3 magnifier (see Figure 4) form O_1 to I_1 (total length of the lens is 18.776 meters):

$X_{image} = -3.090\ X_{object} + 0.193E\text{-}13\ A_{object} + [-7.966\ X_{object} + 8.602\ A_{object}]\ (\Delta T/T_o)$ + higher order

$A_{image} = -0.191\ X_{object} + -0.324\ A_{object} + [-2.705\ X_{object} + 1.366\ A_{object}]\ (\Delta T/T_o)$ + higher order

$Y_{image} = -3.090\ Y_{object} + 0.949E\text{-}14\ B_{object} + [+8.782\ Y_{object} + 23.675\ B_{object}]\ (\Delta T/T_o)$ + higher order

$B_{image} = 0.913\ Y_{object} + -0.324\ B_{object} + [-3.830\ Y_{object} + -7.913\ B_{object}]\ (\Delta T/T_o)$ + higher order

For the Mottershead PM magnifier[4] (see example of trajectories in Figure 7) for 750-MeV protons from O_1 to I_1: (total length of the lens is 9.388 meters):

$X_{image} = -2.726\ X_{object} + 0.222E\text{-}14\ A_{object} + [3.721\ X_{object} + 12.214\ A_{object}]\ (\Delta T/T_o)$ + higher order

$A_{image} = -0.524\ X_{object} + -0.367\ A_{object} + [0.200\ X_{object} + 1.846\ A_{object}]\ (\Delta T/T_o)$ + higher order

$Y_{image} = -2.726\ Y_{object} + 0.143E\text{-}10\ B_{object} + [3.896\ Y_{object} + 9.143\ B_{object}]\ (\Delta T/T_o)$ + higher order

$B_{image} = 0.515\ Y_{object} + -0.367\ B_{object} + [0.138\ Y_{object} + 1.202\ B_{object}]\ (\Delta T/T_o)$ + higher order

In the above equations $\Delta T = (T-T_o)$ where T_o is the proton energy that the lens is tuned for, and T is the value of the energy for the proton being transported. The units in the above equations are meters (or millimeters) for X and Y, and radians (or milliradians) for the angle terms A and B, respectively.

In each of these systems the beam incident on the object is prepared or 'matched' so that there is a specific position – angle correlation at the object. This matching is such that the contribution to the position resolution due to the second order terms in the lens is minimized. For the –I lens this means that the terms

$$-2.429\ X_{object} + 7.901\ A_{object} = 0 \quad \text{and}$$
$$+2.429\ Y_{object} + 7.901\ B_{object} = 0$$

so that the position – angle correlation for the horizontal and vertical planes are, respectively:

$$A_{object} = (+2.429\ /\ 7.901)\ X_{object} = (+0.307 \text{ milliradians per mm})\ X_{object} \quad \text{and}$$
$$B_{object} = (-2.429\ /\ 7.901)\ Y_{object} = (-0.307 \text{ milliradians per mm})\ Y_{object}$$

Here the sign in front of the 0.307 indicates whether the beam trajectories are converging or diverging.

III. The MCNP model of the Permanent Magnet (PM) magnifier

The MCNP6 model of a system with electro-magnets at fixed positions is relatively straight forward to setup. One simply allows for regions where a magnetic field card is defined. The value of the quadrupole field is subsequently varied to 'tune' or adjust the focus of the magnetic lens. However for the permanent magnet system the values for the quadrupole fields are fixed and the positions of the quadrupoles are changed in order to adjust the focus. Figure 8 shows the extremes of the PM quadrupole positions in the magnifier.

Note that permanent magnet quadrupoles were purchased in six, nominally identical segments. For the central two magnets two-segments are stacked together and therefore the dip in the gradient in the center of these two magnets in Figure 8.

The MCNP6 (note that MCNP6 is a version of MCNP above and beyond the current release of MCNP) allows the transport of protons in magnetic fields via COSY transfer maps from one location to another; or transport via numerical integrations of kicks due to a magnetic field. MCNP6 currently has three types of fields: dipole, quadrupole, or quadrupole with fringe field kick that can be applied to a cell. The latter approach (numerical integration) allows a magnetic field to be applied in a region where there is material, the COSY map approach requires the region (cell) where the map is applied by free of material. A description of the MCNP6 magnetic field card is found in Appendix I.

For the PM system the actual field gradient data was used to generate the values for each segment. If a region of field from one magnet overlapped the field from another magnet the gradients for the overlap regions are added. If the collimator happens to be inside of a magnet the collimator material was assumed to have a field in it. To accomplish tuning the MCNP6 input was broken up into several parts with four of the parts remaining the same and the other three parts changed as the positions of the PM quadrupoles changed for a calculation – these three sections that changed were the cells, the surfaces, and the field values for the individual cells. These three sections were generated for each setting of magnet positions by FORTRAN code, and then these sections were appended with the other four sections to make the MCNP6 input and then MCNP6 was run.

[4] "Design and Operation of a Proton Microscope for Radiography at 800 MeV", T. Mottershead, D. Barlow, B. Blind, G. Hogan, A. Jason, F. Merrill, K. Morley, C. Morris, A. Saunders, R. Valdiviez, in the Proceeding of the 2003 Particle Accelerator Conference, Portland, Oregon, 12-16 May 2003, p. 702-704; also LA-UR-03-3082.

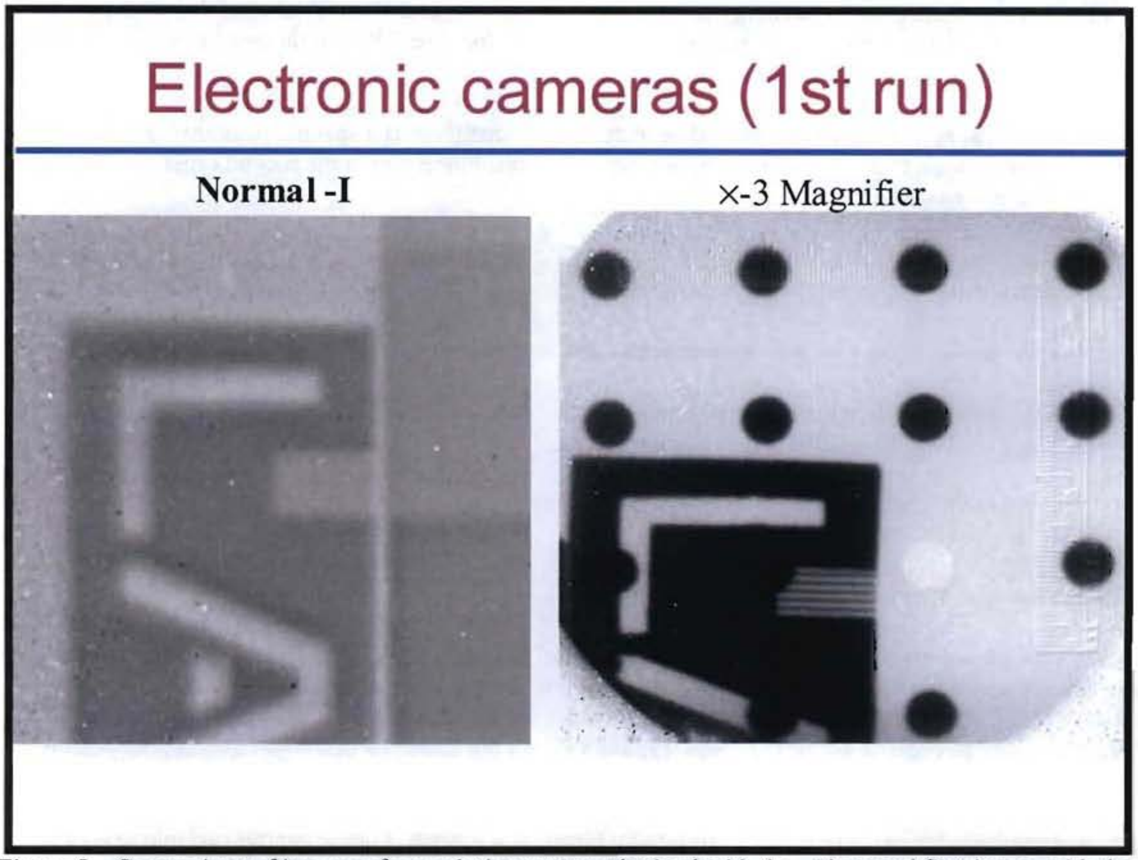

Figure 5 – Comparison of images of a resolution pattern obtained with the –I lens and first image with the first Line C magnifier. The feature above the L is 2-lp/mm. The radiation-to-light converter for these images was a 2-cm thick bundle of plastic scintillating fibers. Note that only a portion of the –I image is shown.

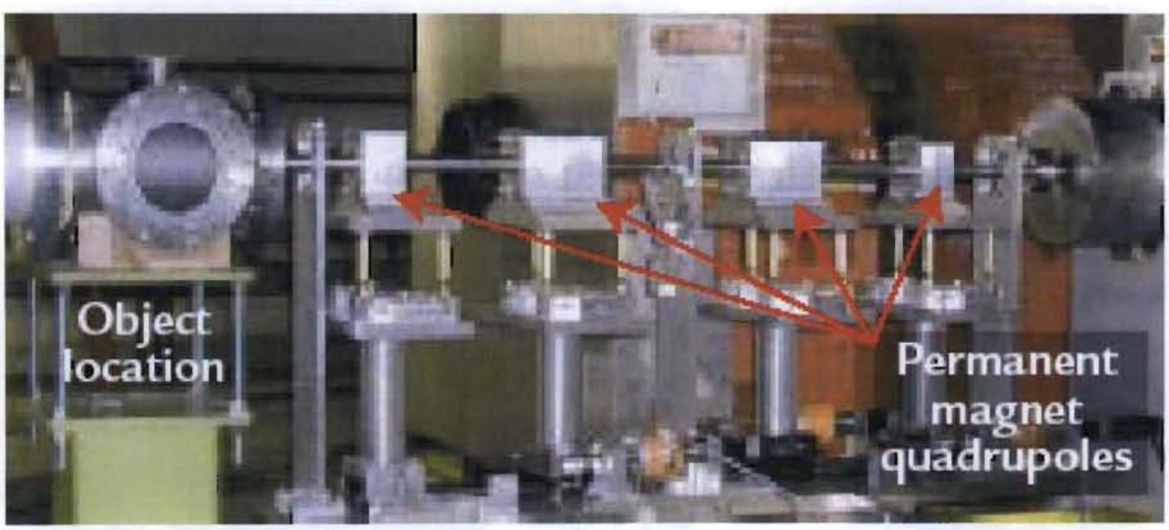

Figure 6 – A photograph of the PM (Motterhead's) magnifier system in place (Figure 5 from Ref. 4). Note the first two magnets (orange) of the –I system that are plus out of the way on precision rollers can be seen in the background.

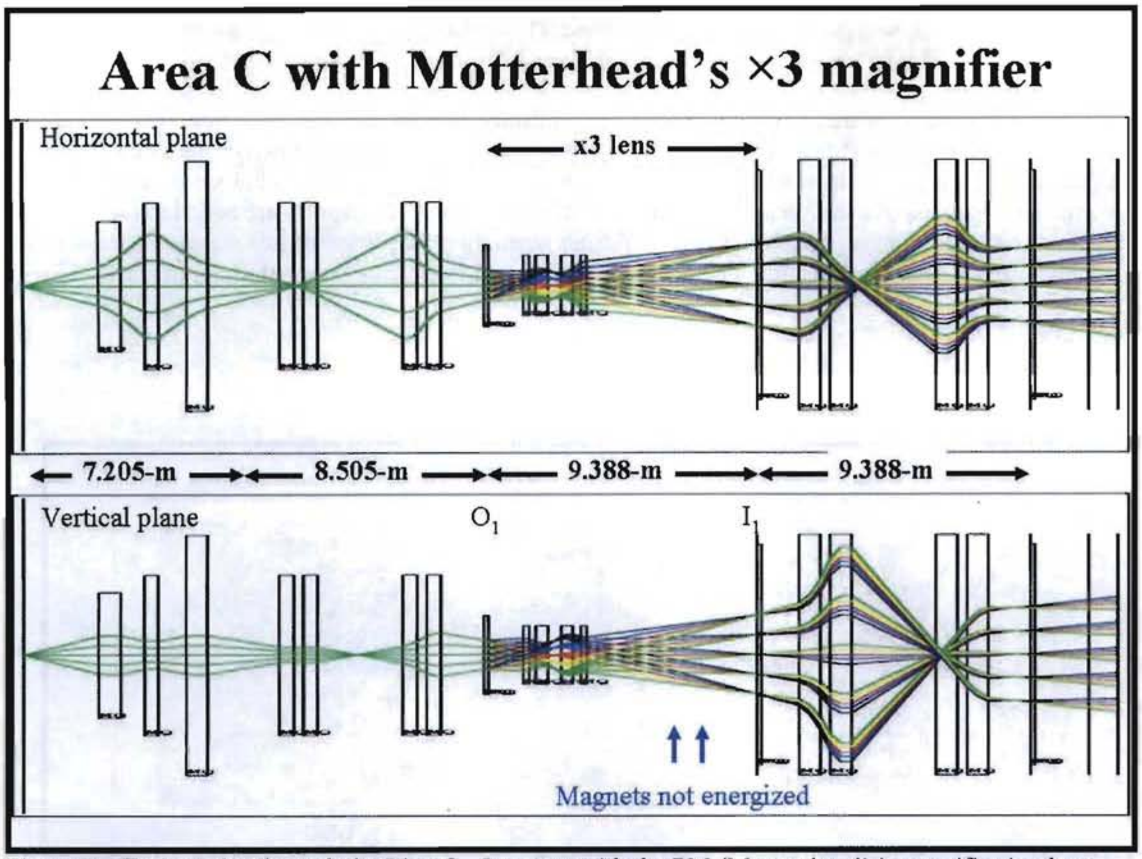

Figure 7 – Trajectories through the Line C -I system with the PM (Mottershead's) magnifier in place.
Note that since the magnets are PM quadrupoles, and therefore have constant quadrupole fields, the system is tuned by adjusting the longitudinal positions of the permanent magnets.

The basic flow of a fitting run was:

- as a function of the PM positions [D12, D13, and D14 (positions of magnets with respect to the position of the fixed first magnet)], generate surface values, to make a list of surfaces (planes along the beam direction):
  - one surface for each magnetic field cell start/stop
  - each magnet material start / stop
  - collimator start / stop
- sort these surfaces from low z-value to high z-value (here the z-coordinate is the longitudinal position)
- determine field gradient in each segment from each of the four PM quadrupoles, then the sum the four gradients to get the gradient for that segment
- generate cell and field cards for each segment
  - vacuum regions, may or may not have a gradient
  - a beam pipe section, may and may not have a gradient
  - outside of the beam pipe, assumed to have no field
  - collimator material, may and may not have gradient
  - in the PM quad material and outside of the PM material, no field
- put the three sets of cards together into a MCNP6 input (the subroutine to generate these cards is given in Appendix II
- run MCNP6 generating a PTRAC output consisting of positions and angles at object location and image location
- analyze MCNP6 PTRAC output to determine weight function (χ^2) involving magnification and resolution
- pass the χ^2 results to fitter to determine whether resolution and magnification are converged, if not determine new values for D12, D13, and D14, and do it again.

Figure 9 and figure 10 show the results for an ensemble of protons transported through the lens in the horizontal and vertical planes, these plots were generated using a mesh tally. The MCNP6 input used to generate these plots used results from a fitting run [with specific D12, D13, and D14 values]. In these figures (9 and 10) the individual segments for the magnets are show/not shown, respectively.

In Table 1 the results for the MCNP6 fitter are compared to a fitter using COSY Infinity. In both case the same field map data for the permanent magnet quadrupoles was used. While the two methods do not give exactly the same results two of the three distances agree within the MCNP6 error. Part of the difference (this has not been investigated) might the technique for treating the overlap of the field from the permanent magnets. As stated earlier the fields from each of the four magnets are added in each MCNP6 segment (only two are non-zero in a given segment). In the COSY fitter when there is overlap of two magnets a trajectory continues through the first magnetic, back steps to the position where the 2nd magnet starts, and then steps through the next magnet.

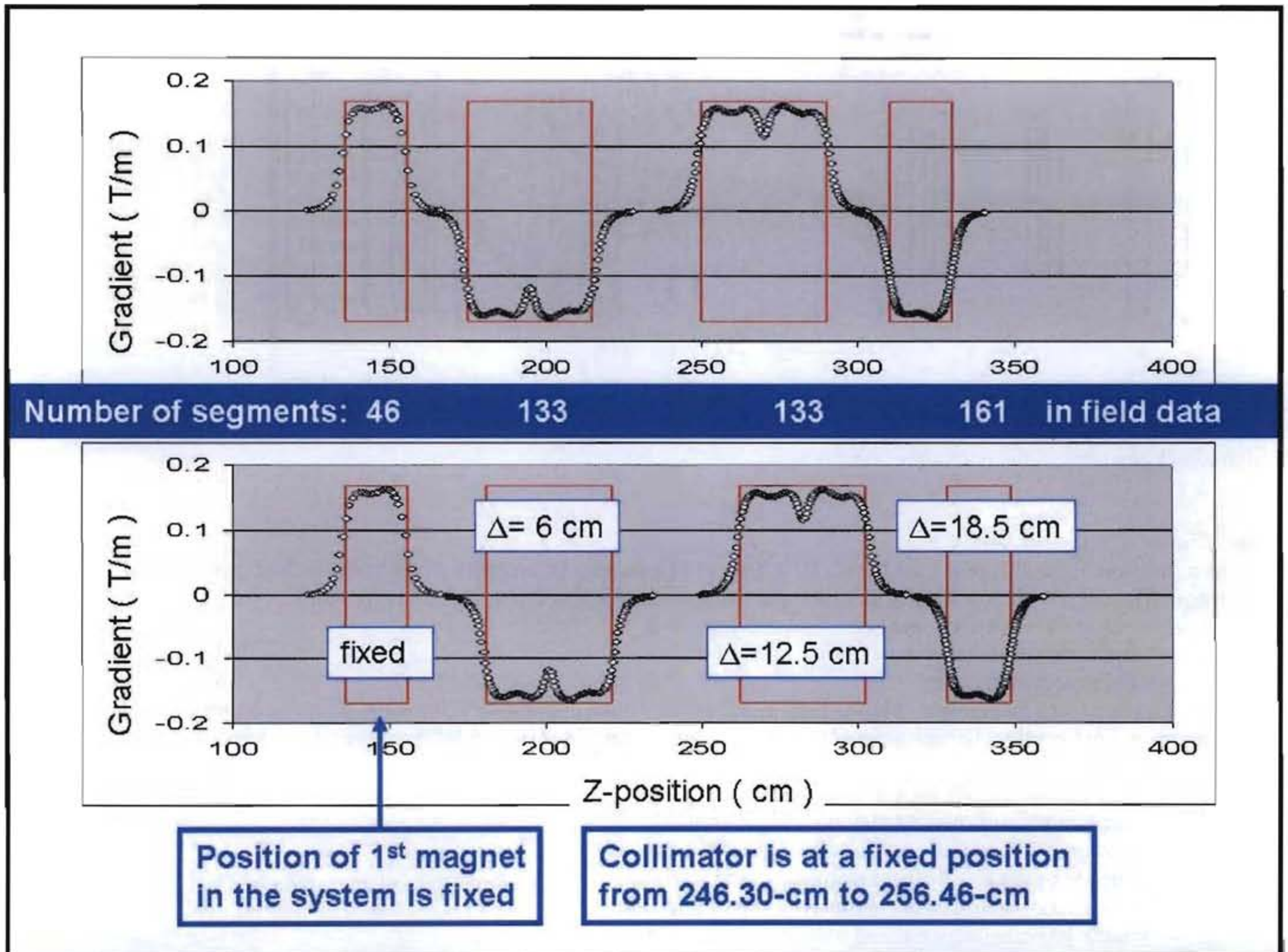

Figure 8 – The extreme longitudinal positions of the PM quadrupoles in the Motterhead's magnifier system and the measured value of each magnets gradient. The top sketch indicates the PM position in locations [red rectangles] closest to the object center (Z-position equal to 0-cm); and the bottom sketch shows the magnets positions at their maximum distance from the object. As indicated the position of the first magnet is fixed and the collimator position is fixed. The Δ's on the location part of the figure indicate the range of motion, minimum longitudinal position to maximum, for each magnet. The number of magnet segments in the field maps for each magnet is also indicated.

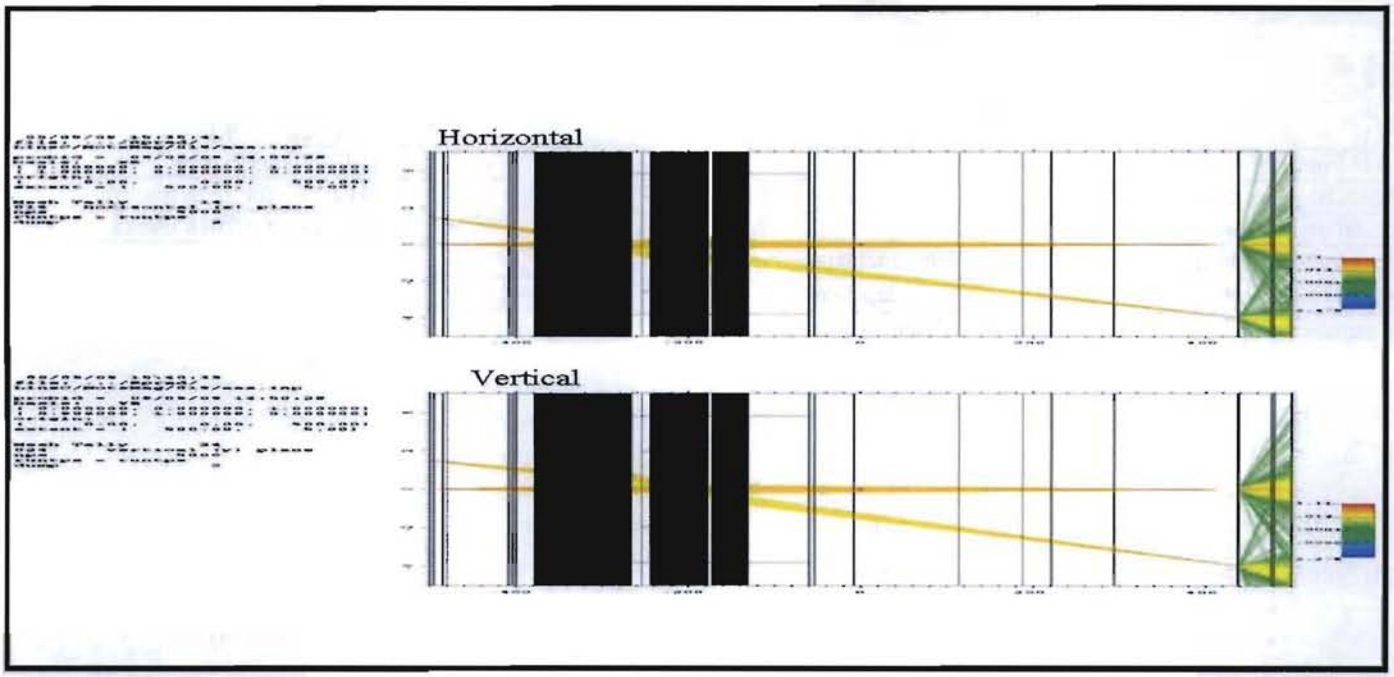

Figure 9 – Results after a fitting run were the magnet segments are drawn. The angles from the object are ±1 milliradians about the central trajectory. The scatter on the right side of the figure is due to a window in the problem.

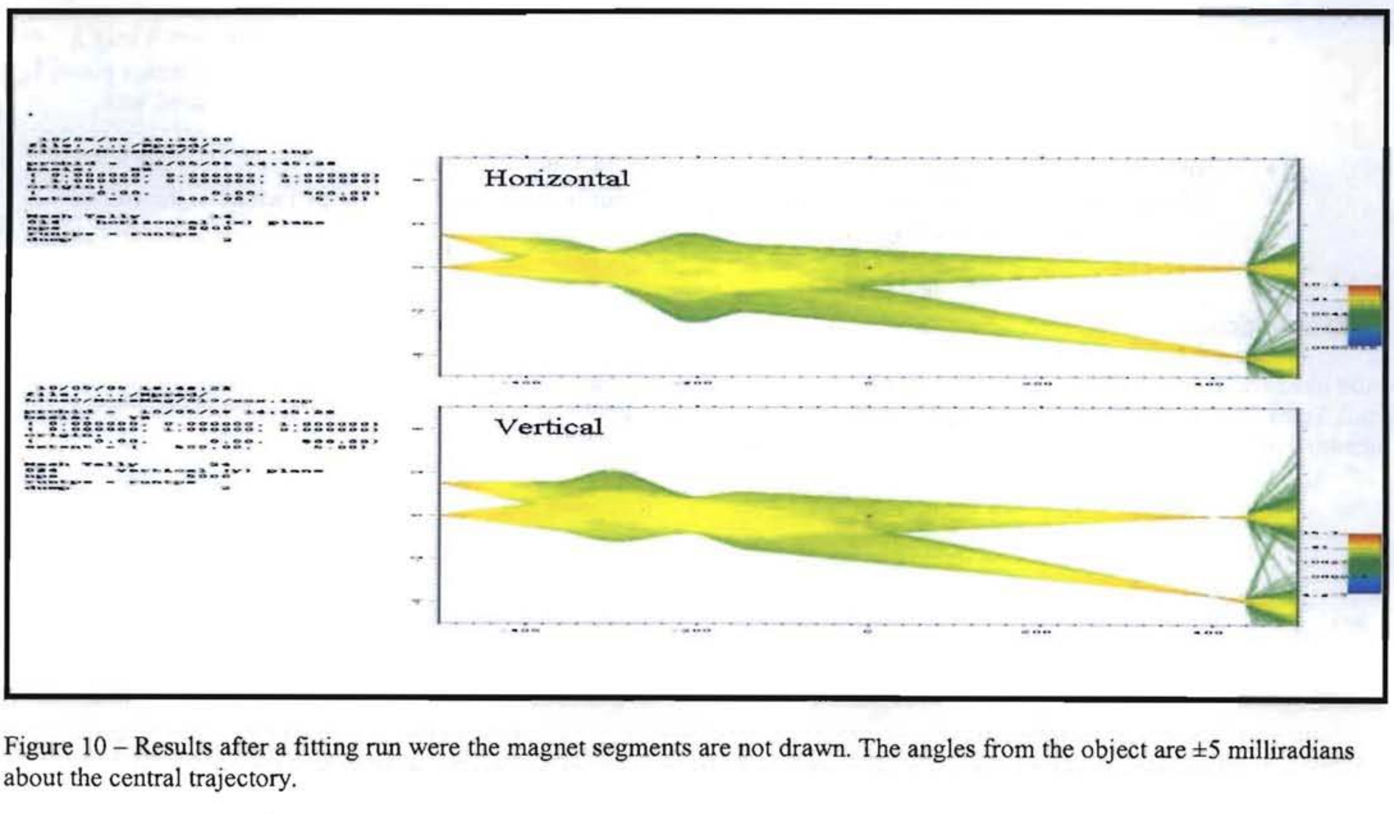

Figure 10 – Results after a fitting run were the magnet segments are not drawn. The angles from the object are ±5 milliradians about the central trajectory.

Table 1 -- Comparison of the COSY and MCNP6 fitters for Motterhead's PM magnifier		
Parameter	**COSY fitter**	**MCNP6 fitter**
D01 (object to 1st magnet)	Fixed	fixed
D12 (1st magnet to 2nd magnet distance)	55.770 cm	55.481 (226) cm
D13 (1st magnet to 3rd magnet distance)	144.136 cm	144.020 (279) cm
D14 (1st magnet to 4th magnet distance)	204.078 cm	203.780 (315) cm
Horizontal magnification	-2.6469	-2.6591 (21) for 1628 tracks
Vertical magnification	-2.6469	-2.6527 (18) for 1618 tracks
Horizontal resolution	Not calculated	20.51 μM
Vertical resolution	Not calculated	19.36 μM

The numbers in parenthesis in the "MCNP6 fitter" column are the errors in the last digits of the value.

IV. Conclusions

A MCNP6 model of the Mottershead permanent magnet magnifier has been built. The model assumes:

- that the permanent magnet fields are additive,
- higher order terms in the magnets are neglected (i.e. PM's are assumed to be pure quadrupoles)
- a COSY model of the system generates nearly identical values for distances D12, D13 and D14 that are used to generate the MCNP6 input describing the system.

This model has yet to be used to image an object but if should be straight forward to do this.

Concerns:

- the collimator, while made of a machine-able tungsten alloy and high density, is short (only 4-inches long),
- and there is not much in the way of magnetic field after the collimator before the long drift to the image plane, I would speculate that it would be a good source of potential background. This could easily be studied with MCNP6 and I intend to do so at some point.
- I have yet to see any step wedge data that was taken with this magnifier system.
- while the field map data was used for the magnets, I am not sure that the data are implemented in the correct order, i.e. as they occur in the system in Line C.

V. Acknowledgements

I would like to take Debbie Clark (P-25) for supplying several drawing for the system and answering questions. I would also like to thank Frank Merrill (P-25) for supplying the permanent magnet quadrupole gradient versus position data for the four magnets as measured by Dave Barlow (AOT-RFE).

JDZ:jdz

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XCP-7 File

Appendix I — Description of the MCNP6 Magnetic Field cards [due to J.S. Bull (XCP-3)]

BFLCL Magnetic Field Cell Card.

Assigns the magnetic field to the cells

Form: BFLCL m_1 m_2 m_3 … m_n
where m_n corresponds to a magnetic field defined by a BFLD card.

Magnetic Field Description Card

Form: BFLD*n* type keyword = value
n: magnetic field number

Type: CONST (dipole field)
QUAD (hard edge quadrupole field)
QUADFF (hard edge quadrupole field with fringe field edge kicks)

Keywords:

FIELD:	magnetic field strength (Tesla) (for CONST field) or magnetic field gradient (in Tesla/cm) for QUAD and QUADFF fields
MXDEFLC:	Maximum deflection angle per step size (mrad)
MAXSTEP:	Maximum step size (cm)
AXS:	the direction cosines of the quadrupole beam axis (does not need to be normalized)
VEC:	direction of magnetic field (CONST) or; the plane that corresponds to the x axis of a focusing quadrupole
REFPNT:	a point anywhere on the quadrupole beam axis (ie, it does not need to be in the quadrupole field cell)
FFEDGES:	list of surfaces to which fringe field edge kicks are to be applied. (QUADFF only)

Appendix II — Fortran subroutine to generate the portion of the MCNP input for PM magnifier
(Note that this subroutine DOES NOT generate the whole MCNP6 input)

```
      subroutine permanent_magnet_numbers( d12, d13, d14 )
c
c purpose: generates surfaces, cells, and magnet field cards for LineC permanent magnet x3 magnifier
c created / started: 2009-07-20 by JDZ
c
c compile as (on xcompute2):   f77 -e -o permanent_magnet_numbers permanent_magnet_numbers.f
c
c compile as (on YellowRail) after doing:
c ( f77 )    module load  intel-f/10.0.023
c ( f77 )    ifort -extend_source -o permanent_magnet_numbers permanent_magnet_numbers.f
c
c  modifications:
c   2009-08-24 JDZ  since we have overlaps in the fields (depending on the quad spacings,
c                   system is tuned by changing the spacings) and other material (PM and collimator)
c                   in the system, we first make a list of the start (or stop) on z of all of the segments.
c                   Then we will write the mcnp cards.
c input:
c    d12   is the center-to-center distance from magnet 1 to magnet 2
c    d13   is the center-to-center distance from magnet 1 to magnet 3
c    d14   is the center-to-center distance from magnet 1 to magnet 4
c output:
c    fort.41  the mcnp cell cards
c    fort.42  the mcnp surface cards
c    fort.43  the mcnp field cards

      implicit none

      real*8      d12, d13, d14

      integer*4  i,ii,  j,jj,   k,kk,   l,ll,   m,mm,   n,nn      ! counters
      integer*4  lll                                              ! gradient inside this surface
      integer*4  surf_1st, surf_last                              ! first and last surfaces of magnet
      integer*4  nseg
      integer*4  nsurf, ncell, nfield
      integer*4  nsurf0, nsurf_last

      integer*2  nmag(4)
      real*8     temp
      real*8     zz, zz1, zz2
      real*8     zstart(4), zlast(4)          ! first and last z-values of field for a given magnet
      real*8     zpos(4,180),  grad(4,180), len(4,180)
      real*8     llen, llen_min, llen_max
      integer*2          lmin,    lmax
      real*8           gmin,    gmax               ! min and max gradients
      integer*2          ming,    maxg             ! point with min and max gradients
      real*8     zzoff, zoff(4)
      real*8     zcentroid(4)                      ! centroid of the field
      real*8     lmag(4)                           ! 1/2 of magnet material length (not the same as field length)
      real*8     zmat_in(4), zmat_out(4)           ! z-values where the magnets material starts and ends
      integer*4  izmat_in(4),izmat_out(4)          ! surface numbers where the magnets material starts and ends
c
c    collimator from (251.38-2*2.54)-cm to (251.38+2*2.54)-cm
```

```
c              246.30          to 256.46
      real*8    zcol_in,   zcol_out              ! z-values where the collimator starts and ends
      integer*4  izcol_in,  izcol_out            ! surface number where the collimator starts and ends

      real*8    zlist(1001), qlist(1001)         ! z-value and gradient (filled initially)
      real*8    z1(1001),  z2(1001)              ! first and last z-values of a cell (to be filled later)
      integer*2  magmat(1001),magno(1001)        ! whether there was material and magnet number
      integer*2  mcoll(1001)                     ! whether there was collimator material
      integer*4  list                            ! initial counter value and counter as the above are being accumulated
      real*8    agrad(4,1001)
      real*8    tgrad(1001)
c
      data lll  /590 /                           ! inside surface of beam pipe
c
c      data nmag/ 4,  4,  4,  4 /  ! number of segments per magnet
      data nmag/ 46, 133, 133, 161 /  ! number of segments per magnet
c
c      data zoff(1)/145.080d0/         ! this is the object to Mag1 CL and is fixed
c -----------------------------------------------------------------------------------------------------------------
c      data zoff(2)/ 56.000d0/         ! one CL to two   CL is  50.0   to  56.0           ! 008
c      data zoff(3)/124.800d0/         ! one CL to three CL is 124.8   to 137.3
c      data zoff(4)/174.835d0/         ! one CL to four  CL is 174.835 to 193.335
c
c      data zoff(2)/ 56.000d0/         ! one CL to two   CL is  50.0   to  56.0           ! 007
c      data zoff(3)/124.800d0/         ! one CL to three CL is 124.8   to 137.3
c      data zoff(4)/180.000d0/         ! one CL to four  CL is 174.835 to 193.335
c
c      data zoff(2)/ 50.000d0/         ! one CL to two   CL is  50.0   to  56.0           ! 006
c      data zoff(3)/124.800d0/         ! one CL to three CL is 124.8   to 137.3
c      data zoff(4)/174.835d0/         ! one CL to four  CL is 174.835 to 193.335
c -----------------------------------------------------------------------------------------------------------------
      data zcol_in /246.300d0/         ! input (upstream) end of the collimator
      data zcol_out/256.460d0/         ! exit (downstream) end of the collimator

      data lmag(1)/ 10.0d0/            ! 1/2 the physical length of the magnet - use to define surfaces for PM material
      data lmag(2)/ 20.0d0/            ! 1/2 the physical length of the magnet - use to define surfaces for PM material
      data lmag(3)/ 20.0d0/            ! 1/2 the physical length of the magnet - use to define surfaces for PM material
      data lmag(4)/ 10.0d0/            ! 1/2 the physical length of the magnet - use to define surfaces for PM material


      data zpos( 1, 1)/ -21.10994d0/,  grad( 1, 1)/0.001314169/,  len( 1, 1)/ 1.016d0/
      data zpos( 1, 2)/ -20.09394d0/,  grad( 1, 2)/0.001825886/,  len( 1, 2)/ 1.016d0/
      data zpos( 1, 3)/ -19.07794d0/,  grad( 1, 3)/0.002562943/,  len( 1, 3)/ 1.016d0/
      data zpos( 1, 4)/ -18.06194d0/,  grad( 1, 4)/0.003651226/,  len( 1, 4)/ 1.016d0/
      data zpos( 1, 5)/ -17.04594d0/,  grad( 1, 5)/0.005249046/,  len( 1, 5)/ 1.016d0/
      data zpos( 1, 6)/ -16.02994d0/,  grad( 1, 6)/0.007655313/,  len( 1, 6)/ 1.016d0/
      data zpos( 1, 7)/ -15.01394d0/,  grad( 1, 7)/0.011307084/,  len( 1, 7)/ 1.016d0/
      data zpos( 1, 8)/ -13.99794d0/,  grad( 1, 8)/0.016989373/,  len( 1, 8)/ 1.016d0/
      data zpos( 1, 9)/ -12.98194d0/,  grad( 1, 9)/0.025945232/,  len( 1, 9)/ 1.016d0/
      data zpos( 1,10)/ -11.96594d0/,  grad( 1,10)/0.040320436/,  len( 1,10)/ 1.016d0/
      data zpos( 1,11)/ -10.94994d0/,  grad( 1,11)/0.061816076/,  len( 1,11)/ 1.016d0/
      data zpos( 1,12)/  -9.93394d0/,  grad( 1,12)/0.089910354/,  len( 1,12)/ 1.016d0/
      data zpos( 1,13)/  -8.91794d0/,  grad( 1,13)/0.118528610/,  len( 1,13)/ 1.016d0/
      data zpos( 1,14)/  -7.90194d0/,  grad( 1,14)/0.138754496/,  len( 1,14)/ 1.016d0/
      data zpos( 1,15)/  -6.88594d0/,  grad( 1,15)/0.150286921/,  len( 1,15)/ 1.016d0/
      data zpos( 1,16)/  -5.86994d0/,  grad( 1,16)/0.156213896/,  len( 1,16)/ 1.016d0/
      data zpos( 1,17)/  -4.85394d0/,  grad( 1,17)/0.158487738/,  len( 1,17)/ 1.016d0/
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data zpos( 4,45)/ -9.144d0/,  grad( 4,45)/-0.115667575/,  len( 4,45)/ 0.254d0/
data zpos( 4,46)/ -8.890d0/,  grad( 4,46)/-0.121880109/,  len( 4,46)/ 0.254d0/
data zpos( 4,47)/ -8.636d0/,  grad( 4,47)/-0.127574932/,  len( 4,47)/ 0.254d0/
data zpos( 4,48)/ -8.382d0/,  grad( 4,48)/-0.132574932/,  len( 4,48)/ 0.254d0/
data zpos( 4,49)/ -8.128d0/,  grad( 4,49)/-0.137043597/,  len( 4,49)/ 0.254d0/
data zpos( 4,50)/ -7.874d0/,  grad( 4,50)/-0.140831063/,  len( 4,50)/ 0.254d0/
data zpos( 4,51)/ -7.620d0/,  grad( 4,51)/-0.144373297/,  len( 4,51)/ 0.254d0/
data zpos( 4,52)/ -7.366d0/,  grad( 4,52)/-0.147288828/,  len( 4,52)/ 0.254d0/
data zpos( 4,53)/ -7.112d0/,  grad( 4,53)/-0.149741144/,  len( 4,53)/ 0.254d0/
data zpos( 4,54)/ -6.858d0/,  grad( 4,54)/-0.151852861/,  len( 4,54)/ 0.254d0/
data zpos( 4,55)/ -6.604d0/,  grad( 4,55)/-0.153596730/,  len( 4,55)/ 0.254d0/
data zpos( 4,56)/ -6.350d0/,  grad( 4,56)/-0.155040872/,  len( 4,56)/ 0.254d0/
data zpos( 4,57)/ -6.096d0/,  grad( 4,57)/-0.156185286/,  len( 4,57)/ 0.254d0/
data zpos( 4,58)/ -5.842d0/,  grad( 4,58)/-0.157084469/,  len( 4,58)/ 0.254d0/
data zpos( 4,59)/ -5.588d0/,  grad( 4,59)/-0.157752044/,  len( 4,59)/ 0.254d0/
data zpos( 4,60)/ -5.334d0/,  grad( 4,60)/-0.158242507/,  len( 4,60)/ 0.254d0/
data zpos( 4,61)/ -5.080d0/,  grad( 4,61)/-0.158801090/,  len( 4,61)/ 0.254d0/
data zpos( 4,62)/ -4.826d0/,  grad( 4,62)/-0.158937330/,  len( 4,62)/ 0.254d0/
data zpos( 4,63)/ -4.572d0/,  grad( 4,63)/-0.158964578/,  len( 4,63)/ 0.254d0/
data zpos( 4,64)/ -4.318d0/,  grad( 4,64)/-0.158910082/,  len( 4,64)/ 0.254d0/
data zpos( 4,65)/ -4.064d0/,  grad( 4,65)/-0.158787466/,  len( 4,65)/ 0.254d0/
data zpos( 4,66)/ -3.810d0/,  grad( 4,66)/-0.158596730/,  len( 4,66)/ 0.254d0/
data zpos( 4,67)/ -3.556d0/,  grad( 4,67)/-0.158378747/,  len( 4,67)/ 0.254d0/
data zpos( 4,68)/ -3.302d0/,  grad( 4,68)/-0.158106267/,  len( 4,68)/ 0.254d0/
data zpos( 4,69)/ -3.048d0/,  grad( 4,69)/-0.157833787/,  len( 4,69)/ 0.254d0/
data zpos( 4,70)/ -2.794d0/,  grad( 4,70)/-0.157574932/,  len( 4,70)/ 0.254d0/
data zpos( 4,71)/ -2.540d0/,  grad( 4,71)/-0.157465940/,  len( 4,71)/ 0.254d0/
data zpos( 4,72)/ -2.286d0/,  grad( 4,72)/-0.157179837/,  len( 4,72)/ 0.254d0/
data zpos( 4,73)/ -2.032d0/,  grad( 4,73)/-0.156907357/,  len( 4,73)/ 0.254d0/
data zpos( 4,74)/ -1.778d0/,  grad( 4,74)/-0.156675749/,  len( 4,74)/ 0.254d0/
data zpos( 4,75)/ -1.524d0/,  grad( 4,75)/-0.156471390/,  len( 4,75)/ 0.254d0/
data zpos( 4,76)/ -1.270d0/,  grad( 4,76)/-0.156335150/,  len( 4,76)/ 0.254d0/
data zpos( 4,77)/ -1.016d0/,  grad( 4,77)/-0.156253406/,  len( 4,77)/ 0.254d0/
data zpos( 4,78)/ -0.762d0/,  grad( 4,78)/-0.156212534/,  len( 4,78)/ 0.254d0/
data zpos( 4,79)/ -0.508d0/,  grad( 4,79)/-0.156253406/,  len( 4,79)/ 0.254d0/
data zpos( 4,80)/ -0.254d0/,  grad( 4,80)/-0.156362398/,  len( 4,80)/ 0.254d0/
data zpos( 4,81)/  0.000d0/,  grad( 4,81)/-0.156553134/,  len( 4,81)/ 0.254d0/
data zpos( 4,82)/  0.254d0/,  grad( 4,82)/-0.156757493/,  len( 4,82)/ 0.254d0/
data zpos( 4,83)/  0.508d0/,  grad( 4,83)/-0.157084469/,  len( 4,83)/ 0.254d0/
data zpos( 4,84)/  0.762d0/,  grad( 4,84)/-0.157493188/,  len( 4,84)/ 0.254d0/
data zpos( 4,85)/  1.016d0/,  grad( 4,85)/-0.157942779/,  len( 4,85)/ 0.254d0/
data zpos( 4,86)/  1.270d0/,  grad( 4,86)/-0.158460490/,  len( 4,86)/ 0.254d0/
data zpos( 4,87)/  1.524d0/,  grad( 4,87)/-0.159019074/,  len( 4,87)/ 0.254d0/
data zpos( 4,88)/  1.778d0/,  grad( 4,88)/-0.159632153/,  len( 4,88)/ 0.254d0/
data zpos( 4,89)/  2.032d0/,  grad( 4,89)/-0.160245232/,  len( 4,89)/ 0.254d0/
data zpos( 4,90)/  2.286d0/,  grad( 4,90)/-0.161144414/,  len( 4,90)/ 0.254d0/
data zpos( 4,91)/  2.540d0/,  grad( 4,91)/-0.161743869/,  len( 4,91)/ 0.254d0/
data zpos( 4,92)/  2.794d0/,  grad( 4,92)/-0.162302452/,  len( 4,92)/ 0.254d0/
data zpos( 4,93)/  3.048d0/,  grad( 4,93)/-0.162752044/,  len( 4,93)/ 0.254d0/
data zpos( 4,94)/  3.302d0/,  grad( 4,94)/-0.163092643/,  len( 4,94)/ 0.254d0/
data zpos( 4,95)/  3.556d0/,  grad( 4,95)/-0.163378747/,  len( 4,95)/ 0.254d0/
data zpos( 4,96)/  3.810d0/,  grad( 4,96)/-0.163542234/,  len( 4,96)/ 0.254d0/
data zpos( 4,97)/  4.064d0/,  grad( 4,97)/-0.163555858/,  len( 4,97)/ 0.254d0/
data zpos( 4,98)/  4.318d0/,  grad( 4,98)/-0.163487738/,  len( 4,98)/ 0.254d0/
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data zpos( 4,99)/  4.572d0/,  grad( 4,99)/-0.163256131/, len( 4,99)/ 0.254d0/
data zpos( 4,100)/  4.826d0/,  grad( 4,100)/-0.162861035/, len( 4,100)/ 0.254d0/
data zpos( 4,101)/  5.080d0/,  grad( 4,101)/-0.162534060/, len( 4,101)/ 0.254d0/
data zpos( 4,102)/  5.334d0/,  grad( 4,102)/-0.161784741/, len( 4,102)/ 0.254d0/
data zpos( 4,103)/  5.588d0/,  grad( 4,103)/-0.160912807/, len( 4,103)/ 0.254d0/
data zpos( 4,104)/  5.842d0/,  grad( 4,104)/-0.159863760/, len( 4,104)/ 0.254d0/
data zpos( 4,105)/  6.096d0/,  grad( 4,105)/-0.158501362/, len( 4,105)/ 0.254d0/
data zpos( 4,106)/  6.350d0/,  grad( 4,106)/-0.156948229/, len( 4,106)/ 0.254d0/
data zpos( 4,107)/  6.604d0/,  grad( 4,107)/-0.155149864/, len( 4,107)/ 0.254d0/
data zpos( 4,108)/  6.858d0/,  grad( 4,108)/-0.153092643/, len( 4,108)/ 0.254d0/
data zpos( 4,109)/  7.112d0/,  grad( 4,109)/-0.150708447/, len( 4,109)/ 0.254d0/
data zpos( 4,110)/  7.366d0/,  grad( 4,110)/-0.147997275/, len( 4,110)/ 0.254d0/
data zpos( 4,111)/  7.620d0/,  grad( 4,111)/-0.144877384/, len( 4,111)/ 0.254d0/
data zpos( 4,112)/  7.874d0/,  grad( 4,112)/-0.141553134/, len( 4,112)/ 0.254d0/
data zpos( 4,113)/  8.128d0/,  grad( 4,113)/-0.137574932/, len( 4,113)/ 0.254d0/
data zpos( 4,114)/  8.382d0/,  grad( 4,114)/-0.132970027/, len( 4,114)/ 0.254d0/
data zpos( 4,115)/  8.636d0/,  grad( 4,115)/-0.127779292/, len( 4,115)/ 0.254d0/
data zpos( 4,116)/  8.890d0/,  grad( 4,116)/-0.122043597/, len( 4,116)/ 0.254d0/
data zpos( 4,117)/  9.144d0/,  grad( 4,117)/-0.115640327/, len( 4,117)/ 0.254d0/
data zpos( 4,118)/  9.398d0/,  grad( 4,118)/-0.108746594/, len( 4,118)/ 0.254d0/
data zpos( 4,119)/  9.652d0/,  grad( 4,119)/-0.101185286/, len( 4,119)/ 0.254d0/
data zpos( 4,120)/  9.906d0/,  grad( 4,120)/-0.093705722/, len( 4,120)/ 0.254d0/
data zpos( 4,121)/ 10.160d0/,  grad( 4,121)/-0.085940054/, len( 4,121)/ 0.254d0/
data zpos( 4,122)/ 10.414d0/,  grad( 4,122)/-0.078256131/, len( 4,122)/ 0.254d0/
data zpos( 4,123)/ 10.668d0/,  grad( 4,123)/-0.070899183/, len( 4,123)/ 0.254d0/
data zpos( 4,124)/ 10.922d0/,  grad( 4,124)/-0.063828338/, len( 4,124)/ 0.254d0/
data zpos( 4,125)/ 11.176d0/,  grad( 4,125)/-0.057329700/, len( 4,125)/ 0.254d0/
data zpos( 4,126)/ 11.430d0/,  grad( 4,126)/-0.051321526/, len( 4,126)/ 0.254d0/
data zpos( 4,127)/ 11.684d0/,  grad( 4,127)/-0.045953678/, len( 4,127)/ 0.254d0/
data zpos( 4,128)/ 11.938d0/,  grad( 4,128)/-0.041117166/, len( 4,128)/ 0.254d0/
data zpos( 4,129)/ 12.192d0/,  grad( 4,129)/-0.036811989/, len( 4,129)/ 0.254d0/
data zpos( 4,130)/ 12.446d0/,  grad( 4,130)/-0.032956403/, len( 4,130)/ 0.254d0/
data zpos( 4,131)/ 12.700d0/,  grad( 4,131)/-0.029604905/, len( 4,131)/ 0.254d0/
data zpos( 4,132)/ 12.954d0/,  grad( 4,132)/-0.026539510/, len( 4,132)/ 0.254d0/
data zpos( 4,133)/ 13.208d0/,  grad( 4,133)/-0.023801090/, len( 4,133)/ 0.254d0/
data zpos( 4,134)/ 13.462d0/,  grad( 4,134)/-0.021430518/, len( 4,134)/ 0.254d0/
data zpos( 4,135)/ 13.716d0/,  grad( 4,135)/-0.019264305/, len( 4,135)/ 0.254d0/
data zpos( 4,136)/ 13.970d0/,  grad( 4,136)/-0.017356948/, len( 4,136)/ 0.254d0/
data zpos( 4,137)/ 14.224d0/,  grad( 4,137)/-0.015640327/, len( 4,137)/ 0.254d0/
data zpos( 4,138)/ 14.478d0/,  grad( 4,138)/-0.014141689/, len( 4,138)/ 0.254d0/
data zpos( 4,139)/ 14.732d0/,  grad( 4,139)/-0.012765668/, len( 4,139)/ 0.254d0/
data zpos( 4,140)/ 14.986d0/,  grad( 4,140)/-0.011566757/, len( 4,140)/ 0.254d0/
data zpos( 4,141)/ 15.240d0/,  grad( 4,141)/-0.010463215/, len( 4,141)/ 0.254d0/
data zpos( 4,142)/ 15.494d0/,  grad( 4,142)/-0.009468665/, len( 4,142)/ 0.254d0/
data zpos( 4,143)/ 15.748d0/,  grad( 4,143)/-0.008610354/, len( 4,143)/ 0.254d0/
data zpos( 4,144)/ 16.002d0/,  grad( 4,144)/-0.007806540/, len( 4,144)/ 0.254d0/
data zpos( 4,145)/ 16.256d0/,  grad( 4,145)/-0.007098093/, len( 4,145)/ 0.254d0/
data zpos( 4,146)/ 16.510d0/,  grad( 4,146)/-0.006485014/, len( 4,146)/ 0.254d0/
data zpos( 4,147)/ 16.764d0/,  grad( 4,147)/-0.005885559/, len( 4,147)/ 0.254d0/
data zpos( 4,148)/ 17.018d0/,  grad( 4,148)/-0.005354223/, len( 4,148)/ 0.254d0/
data zpos( 4,149)/ 17.272d0/,  grad( 4,149)/-0.004891008/, len( 4,149)/ 0.254d0/
data zpos( 4,150)/ 17.526d0/,  grad( 4,150)/-0.004468665/, len( 4,150)/ 0.254d0/
data zpos( 4,151)/ 17.780d0/,  grad( 4,151)/-0.004087193/, len( 4,151)/ 0.254d0/
data zpos( 4,152)/ 18.034d0/,  grad( 4,152)/-0.003760218/, len( 4,152)/ 0.254d0/
data zpos( 4,153)/ 18.288d0/,  grad( 4,153)/-0.003433243/, len( 4,153)/ 0.254d0/
data zpos( 4,154)/ 18.542d0/,  grad( 4,154)/-0.003133515/, len( 4,154)/ 0.254d0/
data zpos( 4,155)/ 18.796d0/,  grad( 4,155)/-0.002888283/, len( 4,155)/ 0.254d0/
```

```
      data zpos( 4,156)/  19.050d0/,  grad( 4,156)/-0.002670300/, len( 4,156)/  0.254d0/
      data zpos( 4,157)/  19.304d0/,  grad( 4,157)/-0.002425068/, len( 4,157)/  0.254d0/
      data zpos( 4,158)/  19.558d0/,  grad( 4,158)/-0.002220708/, len( 4,158)/  0.254d0/
      data zpos( 4,159)/  19.812d0/,  grad( 4,159)/-0.002043597/, len( 4,159)/  0.254d0/
      data zpos( 4,160)/  20.066d0/,  grad( 4,160)/-0.001880109/, len( 4,160)/  0.254d0/
      data zpos( 4,161)/  20.320d0/,  grad( 4,161)/-0.001730245/, len( 4,161)/  0.254d0/

c     data nsurf0/15000/, ncell/15000/, nfield/10/

      do ii=1,1001
       mcoll(ii)=0
       magmat(ii)=0
       magno(ii)=0
       zlist(ii)=0.0d0
       qlist(ii)=0.0d0             ! z-value and gradient (filled initially)
       z1(ii)=0.0d0
       z2(ii)=0.0d0                ! first and last z-values of a cell (to be filled later)
      enddo

      nsurf0=15000
      ncell =15000
      nfield=10

      zoff(1) = 145.080d0        ! this is the object to Mag1 CL and is fixed
      zoff(2) = d12
      zoff(3) = d13
      zoff(4) = d14

      write(6,'(a,4(2x,f10.4))') ' calculating PM magnifier with offsets: ', (zoff(ii),ii=1,4)
cc
cc calculate the centroid positions of the magnetic field
      do ii= 1, 4
       zcentroid(ii)=0.0d0               ! zero before calculating zentroid position of field
       do jj=nmag(ii)+1, 180             ! make sure the other stuff is zero
        zpos(ii,jj)=0.0d0
        grad(ii,jj)=0.0d0
        len(ii,jj) =0.0d0
       enddo
       do jj=1,nmag(ii)
        zcentroid(ii)=zcentroid(ii)+grad(ii,jj)*zpos(ii,jj)
        llen=llen+grad(ii,jj)
       enddo
       zcentroid(ii)=zcentroid(ii)/llen
       write( 6,'(a,i2,a,f10.5,a)') ' the centroid of magnet ',ii,' is at ',zcentroid(ii),'-cm'
       write(44,'(a,i2,a,f10.5,a)') ' the centroid of magnet ',ii,' is at ',zcentroid(ii),'-cm'
      enddo
      write( 6,'(a)') ' '
      write(44,'(a)') ' '

cc
cc initialize the following variables before we start the loop on magnets
      list=1
      izcol_in=0                  ! this will be the surface where the collimator material starts
      izcol_out=0                 ! this will be the surface where the collimator material ends

cc
cc  start loop over the four (4) permanent magnet quadrupoles
```

```
  do ii= 1, 4                    ! loop over the number of magnets
   if( ii .eq. 1 ) then
    zzoff=zoff(ii)               ! absolute (from object) offset for 1
    zmat_in(ii) =zzoff-lmag(ii)
    zmat_out(ii)=zzoff+lmag(ii)
   else
    zzoff=zoff(1)+zoff(ii)           ! CL is relative to magnet 1 CL
    zmat_in(ii) =zzoff-lmag(ii)
    zmat_out(ii)=zzoff+lmag(ii)
   endif
   write( 6,'(/,a,i2,a,f10.5,a,f10.5,a)') ' mag ',ii,' - Material goes from ',zmat_in(ii),' to ', zmat_out(ii),'-cm'
   write(44,'(/,a,i2,a,f10.5,a,f10.5,a)') ' mag ',ii,' - Material goes from ',zmat_in(ii),' to ', zmat_out(ii),'-cm'
   llen=0.0d0                    ! this with be the length of the magnet at the end of loop
   nseg=0                        ! segment number of the magnet being worked on, reset to 0 at start

   llen_min=+1.0d9
   llen_max=-1.0d9
   gmin=+1.0d9
   gmax=-1.0d9
   izmat_in(ii)=0                  ! this will be the surface of this magnet where permanent magnet material starts
   izmat_out(ii)=0                 ! this will be the surface of this magnet where permanent magnet material ends

   write( 6,'(a)') ' making list of the z-values of various segments'
   write(44,'(a)') ' making list of the z-values of various segments'
   write( 6,'(a,i4,a,i4,a)') ' start loop on magnet ', ii,' which has ',nmag(ii),' segments'
   write(44,'(a,i4,a,i4,a)') ' start loop on magnet ', ii,' which has ',nmag(ii),' segments'
   do jj= 1, nmag(ii)
    nseg=nseg+1
    if( jj .eq. 1 ) then
      llen=llen+len(ii,jj)          ! this is the integral of the magnet length
      zz=zpos(ii,jj)+ zzoff -len(ii,jj)/2.d0
      zlist(list)=zz
      list=list+1
      zstart(ii)=zz                 ! z-position where the magnetic field starts

      zz=zpos(ii,jj)+ zzoff +len(ii,jj)/2.d0
      zlist(list)=zz
      list=list+1

    else
      llen=llen+len(ii,jj)
      zz=zpos(ii,jj)+ zzoff +len(ii,jj)/2.d0

cc  zz will be the next point in the list unless we find that should come before it
cc  note that we sort them later, but we look for another point first so that the material
cc  indexing (PM material or collimator) is similar to the gradient indexing

      if( zz .gt. zcol_in    .and. izcol_in    .eq. 0 ) then
       zlist(list)=zcol_in
       izcol_in=list           ! will probalby change this later but need value here to mark that it has been done
   write( 6,'(a,f10.6,a,i4,a,f10.6)') ' zz is ', zz,' --- marking the start of collimator with list=', list,' at z= ', zcol_in
  write(44,'(a,f10.6,a,i4,a,f10.6)') ' zz is ', zz,' --- marking the start of collimator with list=', list,' at z= ', zcol_in
       list=list+1
      endif
      if( zz .gt. zcol_out   .and. izcol_out   .eq. 0 ) then
       zlist(list)=zcol_out
       izcol_out=list
```

```
          list=list+1
         endif
         if( zz .gt. zmat_in(ii) .and. izmat_in(ii) .eq. 0 ) then
          zlist(list)=zmat_in(ii)
          izmat_in(ii)=list
          list=list+1
         endif
         if( zz .gt. zmat_out(ii) .and. izmat_out(ii) .eq. 0 ) then
          zlist(list)=zmat_out(ii)
          izmat_out(ii)=list
          list=list+1
         endif
         zlist(list)=zz
         list=list+1
         zlast(ii)=zz

       endif
      enddo                    ! end loop on segments for this magnet
      write( 6,'(7x,a,f10.5,a,f10.5,a)') ' -    field goes from ',zstart(ii),' to ', zlast(ii),'-cm'
      write(44,'(7x,a,f10.5,a,f10.5,a)') ' -    field goes from ',zstart(ii),' to ', zlast(ii),'-cm'
      write( 6,'(a,i4,a, i4)') ' end loop on magnet ', ii,' -- list =',list
      write(44,'(a,i4,a, i4)') ' end loop on magnet ', ii,' -- list =',list
     enddo                     ! end loop on the magnets
cSub   write(6,'(//,a,i4,a, i4)') ' we now have a list of all the z-values through the system where there is field'
cSub   write(6,'(a,i4,a, i4)') ' we will use this in the case of overlaping fields to get the field in the overlap region'
cc
cc sort zlist from minimun to maximum
     do kk=1,list-1
      do jj=kk,list-1
       if( zlist(jj) .lt. zlist(kk) ) then
        temp=zlist(kk)
        zlist(kk)=zlist(jj)
        zlist(jj)=temp
       endif
      enddo
     enddo
cc
cc mark the various z-values
     do kk=1,list-1
      zz=zlist(kk)
      if( zz .eq. zcol_in ) mcoll(kk)=1
      if( zz .gt. zcol_in ) mcoll(kk)=mcoll(kk-1)
      if( zz .eq. zcol_out) mcoll(kk)=0
      do ii=1,4
       if( zstart(ii) .le. zz  .and.  zz .lt. zlast(ii)   ) magno(kk)=ii
       if( zmat_in(ii).le. zz  .and.  zz .lt. zmat_out(ii)) magmat(kk)=ii
      enddo
     enddo
cc get the gradient of each magnet at each zlist point
     do ii=1,4
      if( ii .eq. 1 ) then
       zzoff=zoff(ii)                     ! absolute (from object) offset for 1
      else
       zzoff=zoff(1)+zoff(ii)               ! CL is relative to magnet 1 CL
      endif
      do jj=1,nmag(ii)
       zz1=zpos(ii,jj)+ zzoff -len(ii,jj)/2.d0
```

```
        zz2=zpos(ii,jj)+ zzoff +len(ii,jj)/2.d0
        do kk=1,list-2
         temp=(zlist(kk)+zlist(kk+1))/2.0d0          ! center of the segment
         if( zz1 .le. temp .and. temp .le. zz2 ) then
          agrad(ii,kk)=grad(ii,jj)
         endif
        enddo
       enddo
      enddo
cc compute the total gradient in each segment
      write(44,'(a)') ''
      write(44,'(a)') ''
      do kk=1,list-1
       tgrad(kk)=0.0d0
       do ii=1,4
        tgrad(kk)=tgrad(kk)+agrad(ii,kk)
       enddo
      enddo

cc
cc we now have a list of the segment z-values:          [zlist(i) and zlist(i+1)],
cc         gradient in the segment:              [tgrad(i)],
cc              magnet number:                 [magno(i)],
cc  whether there is PM material in the segment:          [magmat(i)], and
cc  whether there is collimator material in the segment:    [mcoll(i)].
cc
cc  and this has been written to fort.44

c  ================================================
      write(41,'(a)') 'c start of info for permanent magnet x3 magnifier'
      write(41,'(a,3(f12.8,a))') ' c info generated for d12=',d12,'-cm  d13=',d13,'-cm  d14=',d14,'-cm '
      write(42,'(a)') 'c start of info for permanent magnet x3 magnifier'
      write(43,'(a)') 'c start of field info for permanent  x3 magnifier'

      mm=magno(1)
      write(41,'(a,/,a,i2)') 'c ','c start of info for permanent magnet ',mm
      write(42,'(a,/,a,i2)') 'c ','c start of info for permanent magnet ',mm
      write(43,'(a,/,a,i2)') 'c ','c start of info for permanent magnet ',mm
c
      write(44,'(a)')' list   z-value    magno     mcoll  Tgrad  grad1   grad2   grad3   grad4    surface '
      write(44,'(a)')'  #      ( cm )        magmat      -------------- ( T / cm ) -------------------    #  '
c -----------------------------------------------------------------------------------------------------------

      do ii=1,list-1
       nsurf=nsurf0+ii
       write(44,'(i5,4x,f11.6,4x,3i6,3x,5f10.6,i10)')
     1      ii,zlist(ii),magno(ii),magmat(ii),mcoll(ii), tgrad(ii),(agrad(jj,ii),jj=1,4),nsurf
       write(41,'(i8,1x,a,1x,f10.6)')  nsurf, ' PZ ', zlist(ii)
       l =nsurf
       ll=nsurf+1                          ! ending surface number for segment (1st segment)
       if( ii .eq. list-1 ) then
        ll=15800
        nsurf_last=ll                      ! this should be defined in the rest of the mcnp input
       endif

       if( mm .ne. magno(ii)  .and. magno(ii) .gt. 0) then
        mm=magno(ii)
```

```
  write(41,'(a,/,a,i2)') 'c ','c start of info for permanent magnet ',mm
  write(42,'(a,/,a,i2)') 'c ','c start of info for permanent magnet ',mm
  write(43,'(a,/,a,i2)') 'c ','c start of info for permanent magnet ',mm
  ncell=ncell+5
 endif

 if( abs(tgrad(ii)) .gt. 0.0d0 ) then                ! check for non-zero gradient in the cell
  if( ii .eq. 1 ) then
   nfield=nfield+1
   call write_bfld( nfield, tgrad(ii) )
  else
   if( tgrad(ii) .ne. tgrad(ii-1) ) then
    nfield=nfield+1
    call write_bfld( nfield, tgrad(ii) )
   endif
  endif

  if( mcoll(ii) .eq. 1 ) then
     k = 589                          ! collimator aperture
     kk= 590                          ! inside radius of beam tubing
     write(42,'(i8,1x,a,6x,1x,i6,1x,i6,1x,i6,a,i3)') ncell, ' 0        ',    -k, l, -ll,' imp:h=1   bflcl ',nfield      ! vacuum inside
     ncell=ncell+1
     write(42,'(i8,1x,a,i6,1x,i6,1x,i6,1x,i6,a,i3)') ncell, ' 107 -17.00  ', k, -kk, l, -ll,' imp:h=1   bflcl ',nfield    ! collimator l
     ncell=ncell+1
     k=kk
     kk= 591                          ! outside radius of beam tubing
     write(42,'(i8,1x,a,i6,1x,i6,1x,i6,1x,i6,a,i3)') ncell, '  26  -7.87  ', k, -kk, l, -ll,' imp:h=1   bflcl ',nfield     ! tubing material
     ncell=ncell+1
  else
     k = 590
     write(42,'(i8,1x,a,6x,1x,i6,1x,i6,1x,i6,a,i3)') ncell, ' 0        ',    -k, l, -ll,' imp:h=1   bflcl ',nfield      ! vacuum inside
     ncell=ncell+1
     kk= 591                          ! outside radius of beam tubing
     write(42,'(i8,1x,a,i6,1x,i6,1x,i6,1x,i6,a,i3)') ncell, '  26  -7.87  ', k, -kk, l, -ll,' imp:h=1   bflcl ',nfield   ! tubing material
     ncell=ncell+1
  endif
 else                    ! tgrad(ii)=0, i.e. no field in the cell          NO FIELD IN SEGMENT CASE
  if( mcoll(ii) .eq. 1 ) then
     k = 589                          ! collimator aperture
     kk= 590                          ! inside radius of beam tubing
     write(42,'(i8,1x,a,6x,1x,i6,1x,i6,1x,i6,a  )') ncell, ' 0        ',    -k, l, -ll,' imp:h=1'                  ! vacuum inside
     ncell=ncell+1
     write(42,'(i8,1x,a,i6,1x,i6,1x,i6,1x,i6,a  )') ncell, ' 107 -17.00  ', k, -kk, l, -ll,' imp:h=1'               ! collimator l
     ncell=ncell+1
     k=kk
     kk= 591                          ! outside radius of beam tubing
     write(42,'(i8,1x,a,i6,1x,i6,1x,i6,1x,i6,a  )') ncell, '  26  -7.87  ', k, -kk, l, -ll,' imp:h=1'               ! tubing material
     ncell=ncell+1
  else
     k = 590
     write(42,'(i8,1x,a,6x,1x,i6,1x,i6,1x,i6,a  )') ncell, ' 0        ',    -k, l, -ll,' imp:h=1'                  ! vacuum inside
     ncell=ncell+1
     kk= 591                          ! outside radius of beam tubing
     write(42,'(i8,1x,a,i6,1x,i6,1x,i6,1x,i6,a  )') ncell, '  26  -7.87  ', k, -kk, l, -ll,' imp:h=1'               ! tubing
     ncell=ncell+1
  endif
 endif
```

```
      enddo

      write(42,'(a,/,a,i2)') 'c ','c start of info for permanent magnet x3 magnifier outside of beam tubing'
      mm=magmat(1)
      do ii=1,list-1
       nsurf=nsurf0+ii
       if( ii .eq. 1 ) l = nsurf
       if( (mm-magmat(ii)) .ne. 0 ) then
        ll=nsurf
        if( mm .ne. 0 ) then
         k = 591                              ! outside radius of beam tubing
         kk= 592                              ! outside radius of PM material
         write(42,'(i8,1x,a,i6,1x,i6,1x,i6,1x,i6,a  )') ncell, ' 108  -8.300 ', k, -kk, l, -ll,' imp:h=1'     ! PM material
         ncell=ncell+1
         k = 592                                                            ! outside radl
         kk= 593                                                            ! outside radm
         write(42,'(i8,1x,a,i6,1x,i6,1x,i6,1x,i6,a  )') ncell, '  7  -0.001 ', k, -kk, l, -ll,' imp:h=1'     ! outside of l
         ncell=ncell+1
         write(42,'(a)') 'c '
        else
         k = 591                                                            ! outside radg
         kk= 593                                                            ! outside radm
         write(42,'(i8,1x,a,i6,1x,i6,1x,i6,1x,i6,a  )') ncell, '  7  -0.001 ', k, -kk, l, -ll,' imp:h=1'     ! outside of g
         ncell=ncell+1
         write(42,'(a)') 'c '
        endif
        mm=magmat(ii)
        l = ll
       endif
      enddo
c
c write cell to the end of the system
      ll=nsurf_last
      k = 591
      kk= 593
      write(42,'(i8,1x,a,i6,1x,i6,1x,i6,1x,i6,a  )') ncell, '  7  -0.001 ', k, -kk, l, -ll,' imp:h=1'
      ncell=ncell+1
c
c write the last surface again with a fixed number that will always be the same in the rest of the mcnp input file
c     nsurf=15800
c     write(41,'(i8,1x,a,1x,f10.6,a)') nsurf,' PZ ',zlist(list-1),'  $ fixed surface number in the rest of the mcnp input'

cSub  write(6,'(a)') ' '
cSub  write(6,'(a)') ' mcnp surface cards have been written to fort.41 '
cSub  write(6,'(a)') ' mcnp cell    cards have been written to fort.42 '
cSub  write(6,'(a)') ' mcnp field   cards have been written to fort.43 '
cSub  write(6,'(a)') ' surface segment info and gradients been written to fort.44 -- this is not mcnp input '

      close(unit=41)
      close(unit=42)
      close(unit=43)
      close(unit=44)

      return
      end
c ------------------------------------------------------------------------------------------------------------------------
      subroutine write_bfld( iii, ttt )
```

```
      implicit none

      integer*4 iii              ! nfield
      real*8 ttt                 ! gradient value

      if( iii .lt. 100 ) then
       write(43,'(a,i2,a,f10.7)')' bfld0',iii,' quad  axs 0 0 1  vec 1 0 0  mxdeflc 0.1 maxstep .1  field ', ttt
      else
       write(43,'(a,i3,a,f10.7)') ' bfld',iii,' quad  axs 0 0 1  vec 1 0 0  mxdeflc 0.1 maxstep .1  field ', ttt
      endif

      return
      end
c ------------------------------------------------------------------------------------------------------------------
```