

AN ALGORITHM TO DETERMINE THE COORDINATES OF A PROTON BEAM AT THE ENTRANCE TO THE LINAC-TO-BOOSTER TRANSFER LINE

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PROTON BEAM AT THE ENTRANCE TO THE
LINAC-TO-BOOSTER TRANSFER LINE**

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1. Introduction

In order to properly tune the proton transfer line from Linac to Booster, the position and angle of the proton beam at the entrance of the line should be known. The line contains several beam position monitors and beam profile monitors, but there is no monitor at its entrance. Thus, the entrance coordinates of the beam center should be indirectly measured. An algorithm is presented, based on the model MAD¹, that enables one to determine these coordinates with the use of position monitors and the steering properties of quadrupoles.

2. The Algorithm

Let us define the transverse coordinates, position and angle (x_0, x'_0) of the center of the beam at the entrance to the line, conventionally coincident with the location of the horizontal steering magnet K (Figure 1). At a quadrupole down the line the coordinates of the beam are given by (x_q, x'_q) . If the beam is not centered on the axis, the quadrupole steers the beam by an angle given by

$$\vartheta_q = \frac{\int B_q ds}{B\rho} \cong -K_1 L x_q \quad (1)$$

where K_1 is the quadrupole gradient

$$K_1 = \frac{1}{B\rho} \frac{dB_q}{dx} \quad (2)$$

¹ Iselin, F. Ch, and Niederer, J., "The MAD Program (Methodical Accelerator Design, Version 6, User's Reference Manual", Rept. CERN/LEP-TH/87-33, Geneva, April 1987

and L the length along the axis of the quadrupole.

At a monitor M located after the quadrupole Q , the coordinate of the beam is (x_m, x'_m) . At a monitor, we are only able to measure the position of the beam x_m , but not the angle x'_m .

The beam line, between K and M actually performs a coordinate transformation \mathfrak{R} , mapping (x_0, x'_0) to (x_m, x'_m)

$$\mathfrak{R} \begin{pmatrix} x_0 \\ x'_0 \end{pmatrix} = \begin{pmatrix} x_m \\ x'_m \end{pmatrix} \quad (3)$$

In principle, we would be able to determine both x_0 and x'_0 the entrance to the line if we measured x_m for two values of K_1 in the quadrupole, and inverted the transformation (3),

$$\left. \begin{aligned} \mathfrak{S}^{(1)} \begin{pmatrix} x_m^{(1)} \\ x'_m \end{pmatrix} &= \begin{pmatrix} x_0 \\ x'_0 \end{pmatrix} \\ \mathfrak{S}^{(2)} \begin{pmatrix} x_m^{(2)} \\ x'_m \end{pmatrix} &= \begin{pmatrix} x_0 \\ x'_0 \end{pmatrix} \end{aligned} \right\} \left(\mathfrak{S}^{(1)} \& \mathfrak{S}^{(2)} \right) \begin{pmatrix} x_m^{(1)} \\ x_m^{(2)} \end{pmatrix} = \begin{pmatrix} x_0 \\ x'_0 \end{pmatrix} \quad (4)$$

where \mathfrak{S} is the backward transformation ($= \mathfrak{R}^{-1}$) from M to K , the superscripts (1) and (2) mean "using the quadrupole with two different gradients" and "&" means "using the two transforms \mathfrak{S} ".

We first tried and write simple linear relations between (x_0, x'_0) and (x_m, x'_m) making use of the steering properties of a quadrupole expressed by Eq. (1). The results were not satisfactory because the quadrupoles are real "thick" and the distances between elements in the line are large compared to reasonable values of the lateral displacement of the beam, so the errors in evaluating the initial coordinate of the beam resulted too large. However, any optical transfer code provides us immediately with \mathfrak{S} . We used MAD. How, it is described in the next section.

3. Examples

Let us restrict ourselves to quadrupoles and monitors close to the entrance of the line. Refer again to Figure 1.

As a first example, we used the horizontal quadrupole Q1 and the first monitor, called PM019, located at $s = 6.127$ m downstream from K, shown with a vertical line in Figure 1. We considered 16 points in a (x_m, x'_m) diagram, as hypothetical beam centers, on the contour of an ellipse with semi-axes 20 mm and 4 mrad (Fig. 2). MAD, with the nominal value of the gradient $K_1 = 1.4$ in the quadrupole Q1 maps this ellipse into the skew ellipse "1" in (x_0, x'_0) , as shown in Figure 4: this mapping is $\mathfrak{S}^{(1)}$. Likewise, MAD with the quadrupole Q1 off, maps the ellipse into the ellipse "2" in (x_0, x'_0) : this is $\mathfrak{S}^{(2)}$.

Since we are able only to measure the beam position at M, the coordinates of a measured point may be located anywhere on the vertical line $x_m = \text{const}$ in Fig. 2. This line maps into two lines (straight because the transformation is linear) passing through the corresponding points on the ellipses "1" and "2" of Fig. 3, corresponding to the two values of K_1 . Also, a set of vertical lines on Fig. 2 maps into two sets of lines on Fig. 3. If now the measured position of the beam at the monitor for the two values of K_1 are $x_m^{(1)}$ and $x_m^{(2)}$, the intersection point of the two corresponding transformed lines in the space (x_0, x'_0) , gives us the coordinates of the center of the beam at the entrance of the transfer line.

As an example, assume that the reading was 10 mm with $K_1(Q1) = 0$ and 15 mm with $K_1(Q1) = 1.4$. Figure 4 shows that this was produced by a beam injected at -8 mm and -3.5 mrad.

The best sensitivity of the method is obtained when the two sets of lines intercept at a large angle, and a systematic search for this condition using different quadrupoles and different monitors is in order. There are many combinations, because for the method to work we are not bound to use a single monitor with a given quadrupole, and moreover, if this is the case, we can read two monitors with the same setting of all elements in the line, including quadrupoles, because also here the transform \mathfrak{S} provides different ellipses at (x_0, x'_0) from the same ellipse at (x_m, x'_m) .

This latter alternative is shown in Fig. 4. The sets of lines in this figure are obtained by transformation of the ellipse of Fig. 2 at the location of monitors PM019 and PM026 ($s = 8.384$

m) for the standard setting of all quadrupoles in the line. The angle of intersection of the lines in the two sets are clearly larger in this case, and the determination of the beam coordinate easier.

Assume that the reading was 10 mm at PM019 and -10 mm at PM026. Figure 4 shows that this was produced by a beam injected at 23 mm and 2 mrad.

4. Programming considerations

The procedure described above is in effect a model based algorithm. The model (MAD) is treated like a subroutine, invisible to the user. To make the whole process automatic, such that by entering the values of the readings at a given monitor(s) and the values of the quadrupole(s) setting, the result pops out, the Apollo Aegis script ENTRY shown in Fig.5 was written.

ENTRY asks for the monitor(s) and the quadrupole(s) names to be used, for the quadrupole(s) parameters and for the readings $x_m^{(1,2)}$, then builds up the input file to MAD (mad.in) and runs MAD 4 times, with the x_m data combined with two angles, typically $x'_m = \pm 3$ mrad. Another code module (entry_read) reads the line in the output of MAD (mad.out) that contains the 4 transformed points in the (x_0, x'_0) , then (entry_find) finds the intersection of the two lines connecting the proper point pairs. Maps are plotted (by cplot)². For the proton line, the entire procedure takes about 180 seconds.

At the present, the readings $x_m^{(1,2)}$ are simulated; during commissioning, real data from the monitors will be entered automatically, and line parameters will be read from the database. It is also conceivable that the code would only build once line patterns for some combinations of monitors and quadrupole settings to be stored permanently in the database. In this case, results will be immediately found by some interpolation process.

² A.Luccio, "CPLOT: An Apollo plotting program using Calcomp and GPR", AGS Booster Technical Note N0. 156, BNL January 9, 1990.

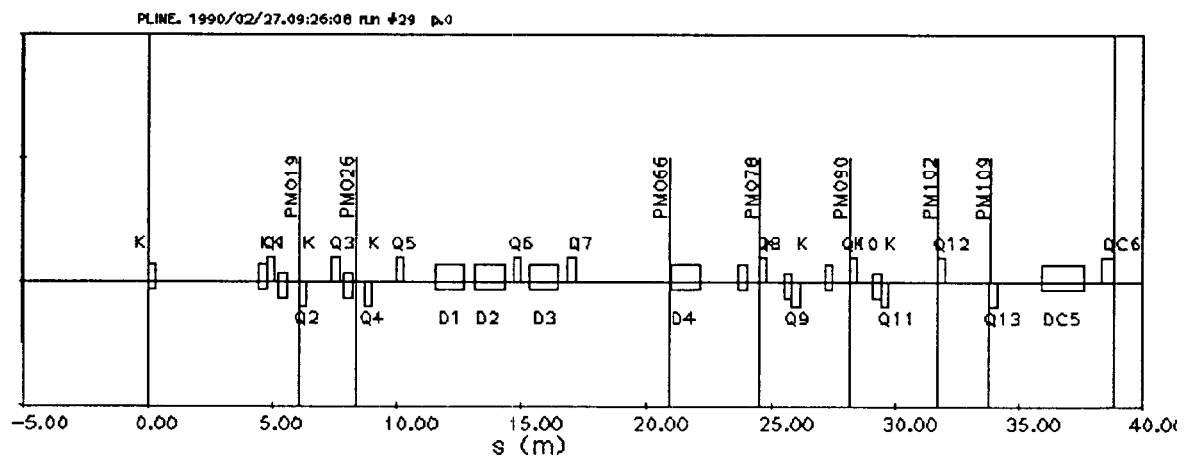


Fig.1. The proton line. The quadrupoles are shown labelled from Q1 to Q13. The beam position monitors are indicated by the vertical lines.

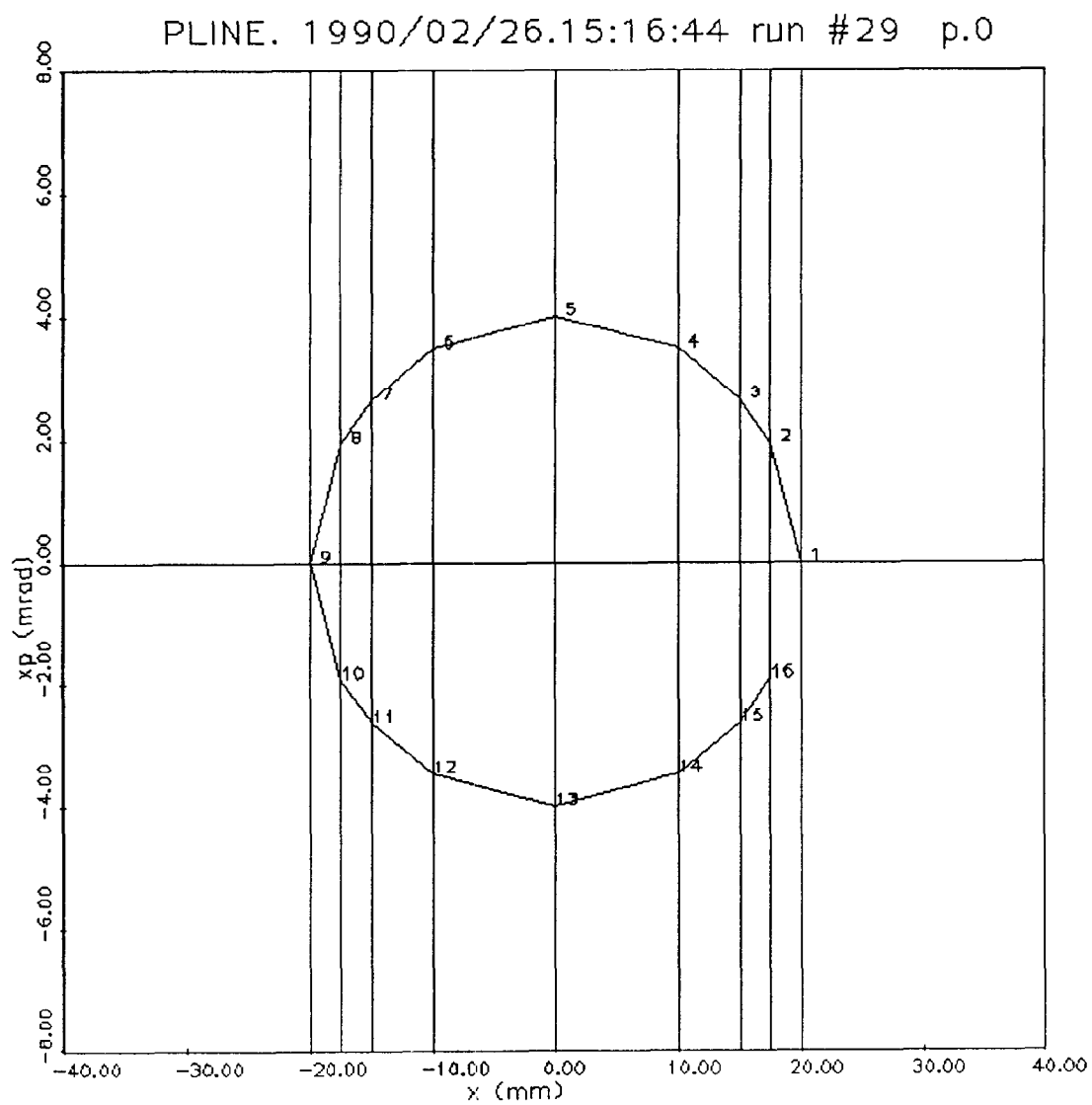


Fig.2. Representative points of beam position and angle at a monitor, taken on the contour of a 200 mm by 4 mrad ellipse.

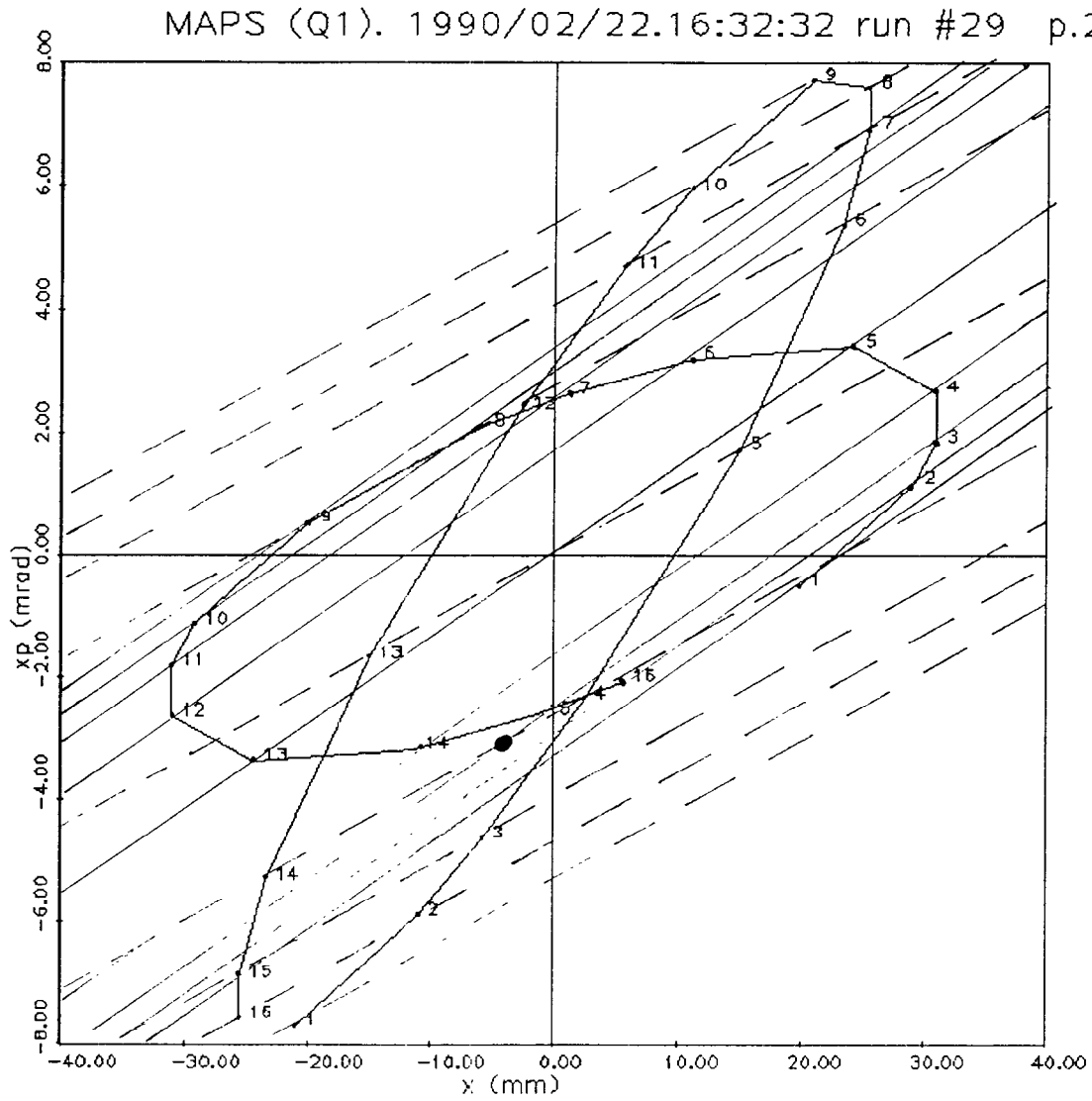


Fig.3. The ellipse of Fig. 2 taken at monitor PM019 is mapped at the location of the steering magnet K into two ellipses for two different values of the gradient in quadrupole QH1. Point pairs corresponding to the same location x_m at the monitor are joined by straight lines. Solid lines correspond to $K_1 = 1.4$ and dotted lines to $K_1 = 0$.

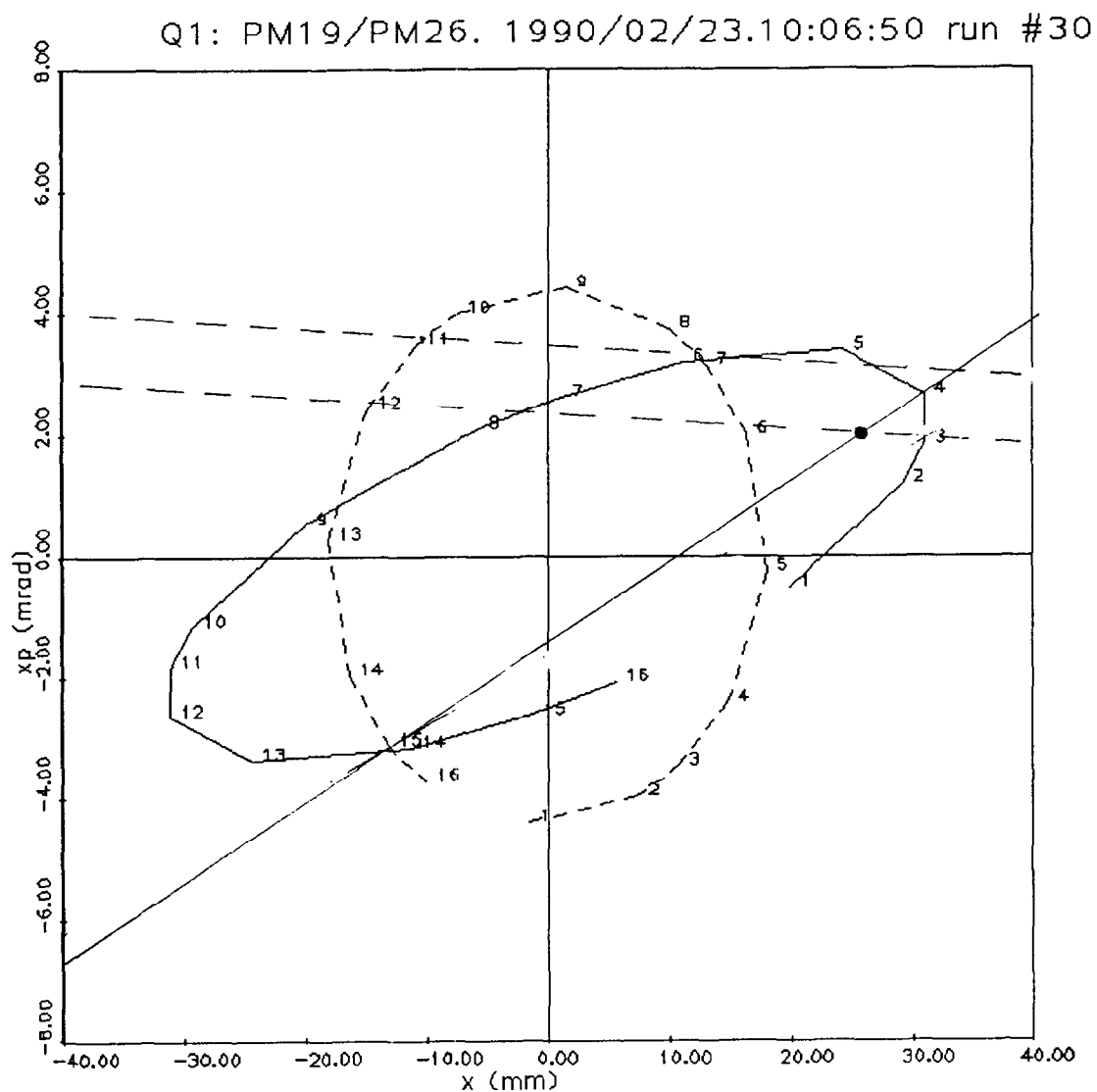


Fig.4. The ellipse of Fig. 2 taken at two different monitors is mapped at magnet K into two ellipses. Gradient of all quadrupoles are standard. Point pairs corresponding to the same location x_m at the monitors are joined by straight lines. Solid lines correspond to readings at monitor PM019 and dotted lines to readings at PM026.

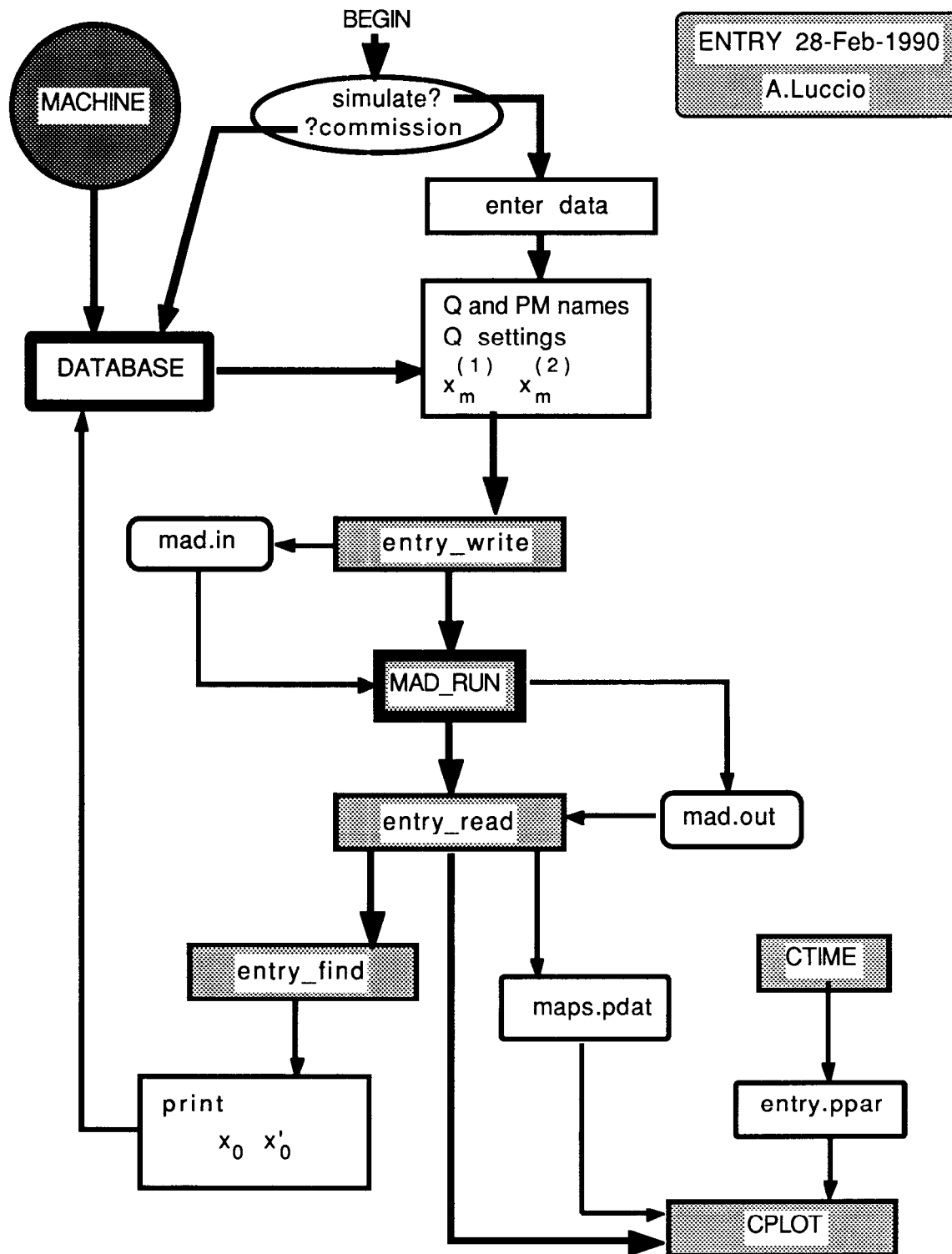


Fig.5. Flowchart of the Aegis script ENTRY to automatize the calculation of entry coordinates.