

**SIMULATION OF MAGNETIC OPTICS IN THE FOCUSING
MAGNET OF A MEDICAL ACCELERATOR**

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Abstract: The computer programs MICKEY MOUSE† and its companion program MINNIE‡ have been developed to model a 270° bending magnet used in a medical linear accelerator. The magnet consists of a focusing gradient section surrounded by two constant field sections; it is a variable strength electromagnet which bends and focuses electrons within the range of 3-23 MeV. Using measured field data, MICKEY MOUSE parameterizes the magnetic fields with respect to the physical dimensions of the pole faces. Particular attention is paid to modeling the extended fringe field region. The reference trajectory is the integrated and the transfer matrix is computed. This matrix is used in MINNIE, which simulates electron transport based on the input energy spectrum and emittance of the accelerator provided beam. The programs are designed to be interactive, with menu-driven graphical displays, allowing for varied simulation with rapid feedback of results.

Introduction

The linear accelerators manufactured by Siemens Medical Laboratories for use in radiation therapy contain a 270 degree bending and focusing magnet system. It is a variable strength electromagnet for electrons in the range of 3 to 23 MeV. The optical requirements of the magnet are based on clinical applications which require a small focal spot size, a fixed position of the spot on the target, beam incidence perpendicular to the target, and minimal correlation between momentum and angular divergence of particles incident on the target. [1] The programs MICKEY MOUSE and MINNIE have been designed to simulate the optical properties of the Siemens magnet and provide a variety of graphic output for analysis. They use a ray tracing method based on measured field data which can be simply parameterized, and since it is a relatively simple system, the program runs on a PC with EGA graphics. Two of the most important features of the programs are the ability to interactively alter the geometry of the magnet pole faces and to specify distributions in phase space and momentum of the particles incident into the magnet which are used in the Monte Carlo portion of the program.

Description of the Magnet

The 270 degree bending magnet consists of two low carbon steel pole faces separated by 1.78 cm around which are fit two "D" shaped electromagnet coils (See Figure 1). Within the pole face gap fits the vacuum envelope, contiguous with the accelerating waveguide

† Making Interactive Calculations of Kinetic Electrons Yield Magnetic Optics Useful to Siemens Engineers.

‡ Modeling Interactively and Numerically Non-Interacting Electrons.

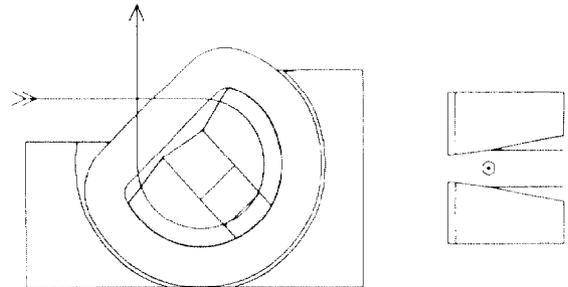


Figure 1. a) Plan view of magnet pole piece surrounded by electromagnet coils. b) View along midplane symmetry axis through the gradient section, where field strength is a function of the distance from the central trajectory.

vacuum, which is shaped to accommodate the 270 degree bend. In this configuration, the vacuum envelope acts as a rough energy filter which transmits a bandwidth of approximately +/- 7%. The pole faces can be divided into five regions: 1) the entrance pole face edge 2) constant field region 3) focusing gradient section 4) constant field region and 5) exit pole face edge. Both the entrance and exit edges have extended fringe fields which are important in beam focusing, and the angle at which the beam path intersects them becomes critical. The constant field regions are simple flat faces which do the beam bending. The gradient section does not have a radial symmetry, but is instead made up of two planes which intersect in a break line near the reference trajectory. This section provides the primary momentum focusing of the magnet.

Parameterization of Measured Fields

Each of the five magnetic regions can be parameterized independently, based on measured data. The magnetic fields were measured along the relevant coordinate used in the parameterization independently for each of the magnet's regions. Readings were taken for a variety of settings for the electromagnet coils, up to 50 Amperes, which cover the range of energies from 3 to 23 MeV. All parameterizations are based on I , the current through the electromagnet coils, which determines the field strength and thus the reference energy. Nonlinear effects over the range of currents made the parameterization more complicated, but also more accurate, so that it could reveal any achromatic effects when used for different electron beam energies.

The entrance and exit fringe fields can be parameterized by the perpendicular distance ξ from the pole face edge:

$$B = B_0 h(\xi) \quad (1)$$

where $h(\xi)$ has the Enge [2] inspired form

$$h(\xi) = \frac{1}{1 + e^{s(\xi)}} \quad (2)$$

with

$$S(\xi) = C_0 + C_1\xi + C_2\xi^2 + C_3\xi^3 \quad (3)$$

where the coefficients C_0, C_1, C_2, C_3 can be fit to linear functions of I .

The constant field sections are simply linear functions of I with some higher order terms to correct for the nonlinearity due to saturation effects:

$$B = 0.0118 + 0.290 I + 0.0022 I^2 - 5.45 \times 10^{-5} I^3 \quad (4)$$

The focusing gradient section can be parameterized by the distance from the break line, χ , as $B = A\chi + B$ where A and B have the following current dependence:

$$A = -0.291 + 0.134 I + 3.98 \times 10^{-4} I^2 - 2.62 \times 10^{-5} I^3 \quad (5)$$

$$B = -0.0041 + 0.306 I + 0.0013 I^2 - 4.65 \times 10^{-5} I^3 \quad (6)$$

MICKEY MOUSE Program Description

The first step is to specify the reference energy, thus determining I , and the magnet geometry. The critical parameters that can be altered are the angle of the entrance and exit pole faces, which determine the extent of the fringe field effects, and the width of the gradient section, which determines the degree of momentum focusing. In addition, various other reference points need to be entered in order to completely specify the magnet geometry. Following these parameters, the entire magnet can then be shifted in the x and y directions, as well as rotated about the central symmetry axis; these adjustments simulate the actual mechanical alignment of the bending magnet relative to the waveguide in the accelerator's overall structure.

The reference particle is then integrated in small steps through the magnet geometry. At each point, the field region the particle is currently in is determined (either fringe field, constant field, or gradient section) and then the reference coordinates are translated to the local parameterized coordinates from which the magnetic field is then calculated. The reference trajectory can then be displayed graphically, and additional ray traces performed where the electron may have initial deviations from the reference particle in position, phase, or momentum. (See Figure 2) For complete determination of the

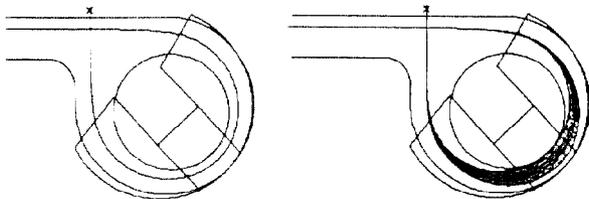


Figure 2. Graphic display of magnet pole face and contoured vacuum envelope. The X marks the location of the high-Z target upon which the beam is to be focused. a) The reference trajectory plotted on the magnet outline. b) The reference trajectory and ten rays with initial deviations in momentum ranging from +6% to -6%, but with no phase space deviation.

optical properties to first order the equations of motion are solved numerically by the Runge-Kuta method. With judicious selection of initial conditions the characteristic rays can be found which represent the linear solutions to the matrix equations:

$$\begin{pmatrix} x(s) \\ x'(s) \\ \delta \end{pmatrix} = \begin{pmatrix} c_x(s) & s_x(s) & d_x(s) \\ c'_x(s) & s'_x(s) & d'_x(s) \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x_0 \\ x'_0 \\ \delta \end{pmatrix} \quad (7)$$

$$\begin{pmatrix} y(s) \\ y'(s) \end{pmatrix} = \begin{pmatrix} c_y(s) & s_y(s) \\ c'_y(s) & s'_y(s) \end{pmatrix} \begin{pmatrix} y_0 \\ y'_0 \end{pmatrix}$$

These solutions can be displayed graphically as a function of s , the distance along the reference trajectory. (See Figure 3) Additional graphic

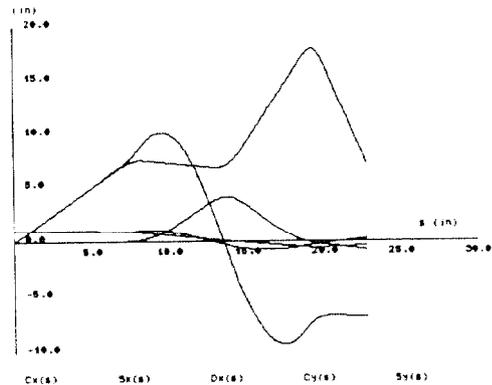


Figure 3. Plots of the solutions to the matrix equations (7) plotted as a function of distance along the reference trajectory. The focusing and defocusing effects on the beam as it passes through the different elements can be seen.

information is made available, including plots of the magnetic fields of the different regions as well as the field seen by the reference particle as a function of s . These help in analyzing the phase space and momentum focusing of the system.

Using these solutions, the paths of particles with given initial deviations in position, phase, and momentum can be described anywhere within the magnet as a function of distance along the reference trajectory.

MINNIE Program Description

The matrix solutions calculated by MICKEY MOUSE are then used as the primary input data for the Monte Carlo program MINNIE. Additional input data that are required consist of the spatial and angular distributions of the incident electron beam as well as its energy spectrum. The initial phase space distribution can be specified as Gaussian, uniform, or arbitrary file-specified, where an input file describing the distribution must be previously written. This is necessary as the spectra produced by linear accelerators are typically asymmetric about the peak intensity, with a shift towards the lower energies. The specified parameters consist of one-half the horizontal and vertical extents, one-half the horizontal and vertical angular divergences, the x and y correlation coefficients, and the electron beam energy spectrum.

A number of particles N is then specified and N random initial phase-space coordinates are chosen in accordance with the chosen distribution function. The particles are then tracked through the system by performing successive multiplication of the transfer matrices provided by MICKEY MOUSE.

Output can be provided at any point along the central reference trajectory and consists of scatter plots of the x and y distributions, x versus y , x versus x' and y versus y' , x versus δ and x' versus δ .

Phase space ellipses are plotted along with the appropriate scatter plot data, and the beam emittance is calculated as well. (See Figure 4)

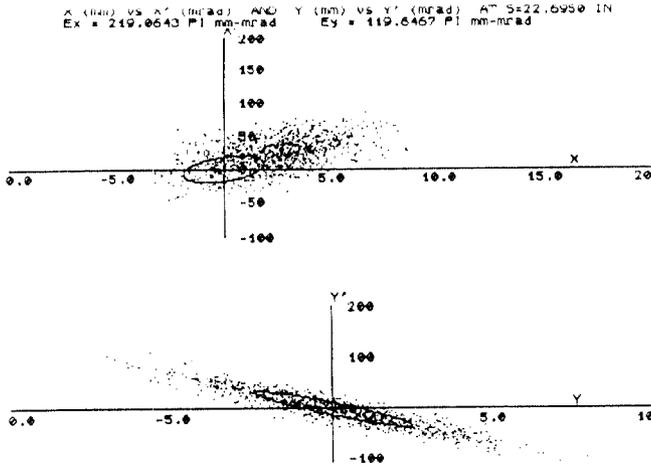


Figure 4. Scatter plots of the beam in phase space as it is incident on the high-Z target, showing the focusing and defocusing effects in the perpendicular planes.

Sample Runs of the Programs

Several examples are displayed in figures 5 through 8 to display the results obtained with the MICKEY MOUSE and MINNIE programs, and how they can be used to improve the optical system design to optimize the performance of the system.

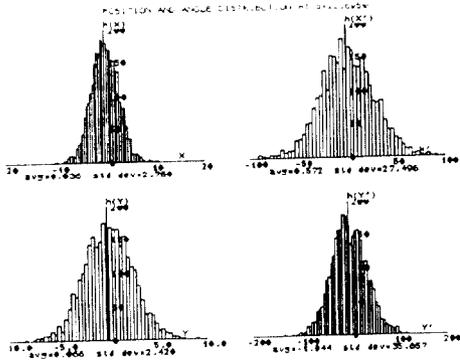


Figure 5. All Plots of the distributions in position and angle of a 6 MeV beam as it is incident on the high-Z target. The standard deviations in the x and y planes define the spot size on the target.

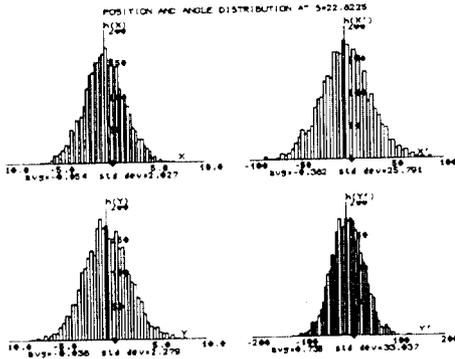


Figure 6. The same plots for a 20 MeV beam incident on the target. It should be noted that both Figures 5 and 6 were calculated using the same input distributions in order to reveal any achromaticity. In real situations, differences that exist between different energy beams may be due to differences in the input phase space and momentum distributions, which are different for the same accelerator operating at different energies.

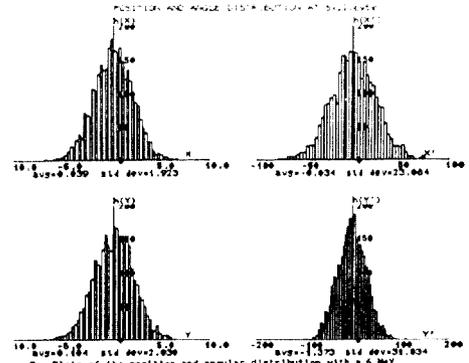


Figure 7. Plots of the position and angular distribution with a 6 MeV beam incident on the target for a magnet with a redesigned gradient section to improve momentum focusing. In order to achieve this simulation it is necessary to alter the code where the parameterization of the magnetic field is defined as a function of electromagnet coil current, as the slopes of the gradient were changed.

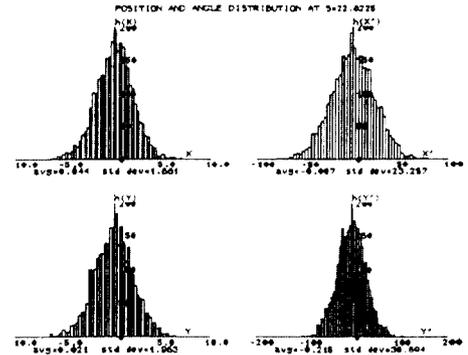


Figure 8. The same plots for the same gradient modified bending magnet for a 20 MeV beam. Again, similar input distributions were used in order to make a direct comparison. Better and more consistent momentum focusing is achieved, resulting in a smaller spot size on the target.

Conclusion

The relative simplicity of the 270° degree bending magnet system used by Siemens Medical Laboratories has enabled a series of ray tracing PC-based computer programs to be written which can integrate particles through a user-defined magnet geometry. Magnetic fields are parameterized to coordinates defined by the geometry, and the parameterizations are based on measured field data, where non-linear and/or achromatic effects are taken into account by based them on current through the electromagnet coils. Such a system works well for simulating different geometries so long as the basic concepts, such as extended fringe fields and focusing gradient section, are retained within the design. The codes can be used both for analysis of focusing, by investigating independently the momentum and phase-space effects, as well as for design, where new configurations may be simulated. In a broader context, the program can be used as the linking element between accelerator simulating codes such as PARMELA, which would provide the input data, and Monte Carlo codes such as EGS4, which can be used to simulate x-ray production from a high-Z target or electron scattering through collimators and other beam-defining components. Thus, a complete computer simulation of the medical accelerator as used for clinical radiotherapy can be constructed based on measured data for given configurations.

References

- [1] L. Sagalovsky, "Deflection Systems in Medical Linacs," presented at the European Particle Accelerator Conference, Rome, Italy, June 7-11, 1988.
- [2] H. A. Engle, in: Focusing of Charged Particles, Vol. 2, ed. A. Septier (Academic Press, New York, 1967)