Deflection Systems in Medical Linacs

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Abstract

Different requirements and systems for radiation machines are discussed. Bending magnet used in Siemens units is described to illustrate methods of computer design.

1 Introduction

Deflection magnet is one of the most critical elements encountered by the beam in a medical linear accelerator. It is common practice in radiation treatment systems to have the accelerating waveguide extending in a horizontal direction and then to bend the emergent electron beam magnetically into a vertical plane. In the X-ray mode the beam then strikes a target and generates an X-ray beam; alternatively, the electron beam itself may be used for treatment.

In addition to bending, a successful deflection system must also provide *stigmatic* and *achromatic* focusing as well as satisfy spatial constraints of the treatment head assembly. In order to vary the angle at which the beam is incident on a patient, the head assembly must be able to rotate about the horizontal axis and to pass underneath the patient. Therefore, the radial extent of the deflection system with respect to the axis of rotation must be minimized. Finally, a practical magnet must be simple, easy to manufacture and use readily available materials and fabrication techniques.

This paper describes the deflection systems used in modern radiation therapy machines that satisfy all of the above criteria.

2 Optics Requirements

In most applications of X-ray therapy one requires high uniformity in the radiation field, which is determined by the optical properties of the beam at the bremsstrahlung target. Three conditions must be satisfied to insure symmetry and flatness of the resultant dose distribution:

- Small size of the spot.
- Fixed position of the spot on the target.
- Incidence normal to the target.

The latter two points are illustrated in Fig. 1.

The electron accelerator beam is typically characterized by small diameter ($\leq$ 6 mm), very small divergence angle ($\leq \pm 3$ mrad) and up to 20% energy spread [7]. The deflection system is required to transport this to a beam of $\leq$ 3 mm diameter and $\leq \pm 7$ mrad divergence at the target over a wide range of electron energies, typically from 5 to 25 MeV. The beam optical constraints can be summarized as follows:

1. The system must be *achromatic*, i. e. it must bring originally paraxial particles of different energies to the same focus. Moreover, particles must not diverge but remain parallel after reaching the focal point; otherwise, a change in the beam mean energy will result in a change in mean angle of the beam at the target and hence in the x-ray field asymmetry.
2. Originally divergent particles eminating from the same point must be focused to the same point also.

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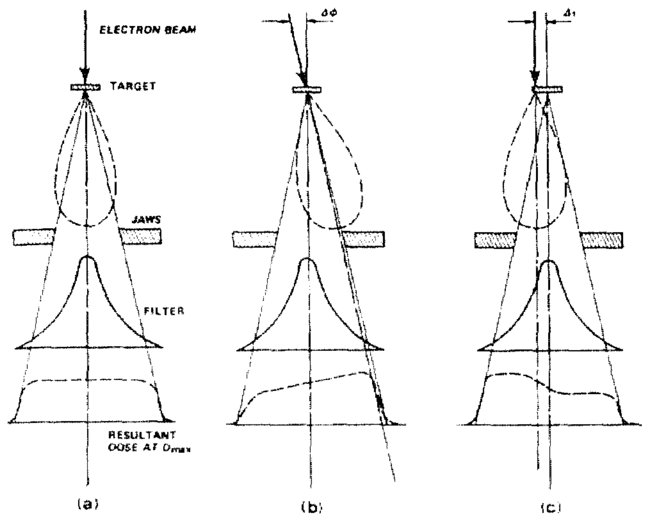

Figure 1: Resultant X-ray dose distribution for: (a) properly aligned beam, (b) beam with an angular divergence $\Delta\phi$, (c) beam with a radial displacement Δr. From [1].

3. Particles starting out parallel must remain so at the end of the system.
4. Spatial focus for both the radial and transverse direction must occur at the same point along the central trajectory. In this case the system is said to be *stigmatic*.

3 Typical 270° Systems

3.1 Mathematical Formulation

Mathematical design of a deflection system begins with laying out the *central orbit reference trajectory* along which particles of design momentum p_0 travel in the median (symmetry) plane. The task is then to configure the magnetic field so that the phase-space deviations from this design trajectory satisfy the requirements outlined in Section 2.

Let us designate s as a distance along the central orbit and define x, y to be the lateral displacements from the central orbit in the horizontal and vertical plane respectively, $x' = dx/ds$, $y' = dx/ds$ to be the angular divergences, and $\delta = (p - p_0)/p_0$ to be the momentum deviation. A general solution $x(s)$, $y(s)$ to the electron transport problem involves a second-order differential equation. Since the variables are "small" we can express the solution as a Taylor series in the initial conditions. In linear approximation each magnetic element can then be represented by a *transport matrix* relating the final to the initial coordinates. The matrix approach is used for the preliminary design of the system; the transport matrix for the entire system is given by the product of matrices for individual magnetic elements. Analytic expressions for matrix elements of common accelerator components have been worked out in the literature [2,4,9,10] and are used in design computer programs such as TRANSPORT [3]. The general linear solution can be written as follows:

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

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

Designing a system with $d_x = d'_x = 0$ at the target location would correspond to satisfying the first constraint of Section 2. Similarly, requiring $s_x = s_y = 0$ and $c'_x = c'_y = 0$ at the same point would take care of the second and the third (as well as the forth) constraint respectively. Then, c_x, c_y would determine the size of the spatial focus and s'_x, s'_y — the divergence angle. In total, we have 10 parameters characterizing the optics; our deflection system must provide at least as many to work with.

3.2 Common Optical Schemes

A three-sector 270° double achromat system due to Brown [5] is shown in Fig. 2. It consists of three uniform field magnets, each providing a 90° deflection, and short connecting drift tubes. Two energy selection slits placed at 135° to the entering central trajectory intercept all particles outside ±3% momentum range. Entering lateral displacements

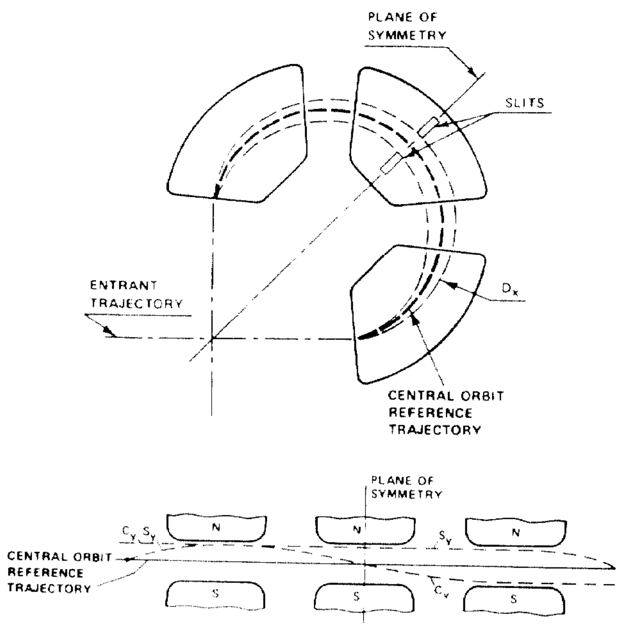

Figure 2: Three-sector achromat: cross-section view in the bend and the cross plane. From [1].

c_x, c_y and angular divergences s_x, s_y are reproduced at the target plane with no significant increase in magnitude. The design parameters varied to satisfy the optical constraints are: the pole face rotation angles with respect to the design trajectory, the lengths of the drifts, and the lengths of the sectors. This system is employed in the Varian Clinac 18 treatment unit which operates over the 6 – 18 MeV energy range.

A slightly different three-magnet system [6] is shown in Fig. 3. Here, the dipole magnets deflect the beam alternately in opposite directions, the first and second by angles of less than 50° and the third by an angle of at least 90°. Such a design, with the optical properties being the same as those of the previous system, is more compact in the direction in which the beam exits; the height of the head assembly is thus reduced. Philips uses this system for its SL 25 linac.

Schematic diagram of the two-dipole, doubly achromatic 270° system [7] is shown in Fig. 4. The first bend is 180° or more, the second 90° or less. The dipoles are preceded by an antisymmetric quadrupole doublet

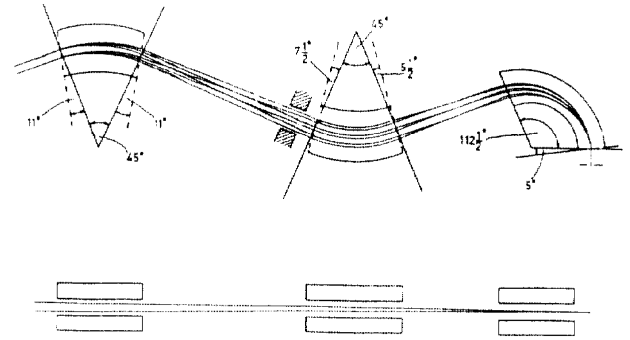

Figure 3: Three-magnet alternate achromat: median plane lay-out From [6].

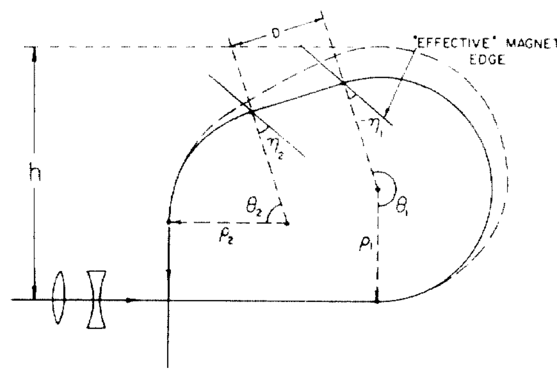

Figure 4: Two-dipole achromat with input quadrupoles. This design minimizes distance h. From [7].

to match the input beam spatial characteristics to the magnet focusing properties. The net effect is to reduce the height by approximately one bending radius over the design in Fig. 1. Quadrupoles' focusing gradients, lengths of drifts, pole face rotation angles, and one of the bend angles are the free parameters in this design employed by the AECL Therac 25 and suitable for 5 – 25 MeV.

A single-magnet system due to Enge [8] is shown in Fig. 5. It combines two uniform regions with the nonuniform gradient section inbetween. Its pole face angles can be adjusted by a pair of moveable shim pieces for optimal spatial focusing. Another pair of shims adjusts the angle which determines the radial field gradient. Free design parameters are pole face rotation angles, middle section's gradient and field strength, as well as lengths of the drifts and bend angles in the uniform sections. The Siemens Mevatron treatment unit employs the

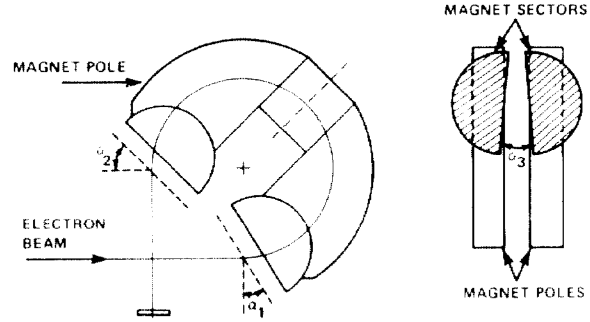

Figure 5: Enge single-magnet achromat: angles α_1, α_2, and α_3 can be adjusted by moveable shims to satisfy optical constraints. From [8].

bending magnet based on Enge's design; a more detailed description is given in Section 4.

3.3 Fringe Fields and Fine-Tuning

Magnet edges contribute important focusing properties [1]. In initial design one assumes that the vertical field begins and ends abruptly near the entrance and the exit of the magnet. In this approximation, a pole face tilt with respect to the design trajectory produces equal but opposite focusing action in the two planes. In practice, fringe fields can be extended over appreciable distances changing the optics prescribed by the design (one effect is reduced focusing in one of the planes, another is that the particle of nominal momentum p_0 starting out on the central orbit no longer continues to stay on it). The second and higher order aberrations also contribute to disrupt the linear design performance [2].

One can try to cure these problems by fine-tuning the beam, e. g. by winding a small trim coil about a pole to steer the particles. The next section addresses the "fine-tuning" of the design itself.

4 Siemens Deflection System

Bending magnet used in the machines produced by Siemens Medical Laboratories, Inc. is based on the design in Fig. 5. The crucial difference is the absence of moveable shims and the shape of the gradient section. The lay-out of the magnet and one of the gradient pole pieces are shown in Fig. 6. Two important factors contribute to make the optical properties of the magnet differ from those of the linear design:

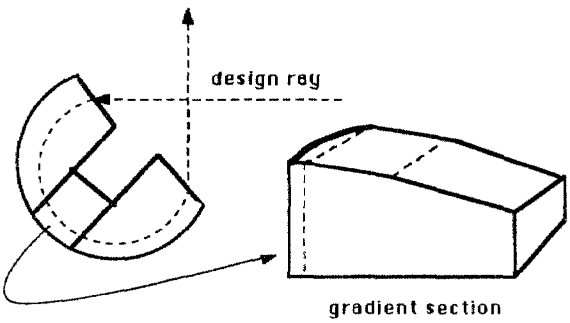

Figure 6: Schematic view of the Siemens magnet. Non-uniform field in the middle section is produced by two poles shaped as shown.

- Edge effects. Long extended fringe fields introduce astigmatism [2,9] and chromatic aberrations [11].
- Gradient section geometry. The pole pieces do not possess rotational symmetry making the curves of constant magnetic field to be straight lines rather than circles as assumed by the linear design; the effect is that the particle following the design trajectory gets "shifted" in the non-uniform region.

One can try to recalculate the transport matrices taking the above points into account. However, analytic expressions are not readily available and a useful parametrization of the fringe field is not obvious. A more practical approach — after all, we are dealing with a very simple system — involves ray tracing.

It has been shown [4] that the optics of a system is fully determined (to any order) by specifying five representative trajectories; they are the linear solutions $c_x(s)$, $s_x(s)$, $d_x(s)$, $c_y(s)$, and $s_y(s)$ mentioned in Section 3. We can obtain them numerically from the equations of motion by making some judicious choices in initial conditions. For example, suppose we want to know c_x at some point s_1 in the system. We would solve the differential equation for $x(s_1)$ with all initial coordinates except x_0 equal to zero. Then, we get (see **3.1**):

$$c_x(s_1) = \frac{x(s_1)}{x_0}$$

We pick several x_0's and average (the deviation from the average tests the non-linearity of the system). Fig. 7 illustrates this procedure for the gradient section. Other four characteristic rays can be obtained in the similar manner [12]. Of course, one needs the magnetic fields in different regions to input into the differential equation. These have to be measured; however, one does not need the complete three-dimensional mapping: for example, in the fringe region it suffices to measure the field along the line perpendicular to the pole face [9,11].

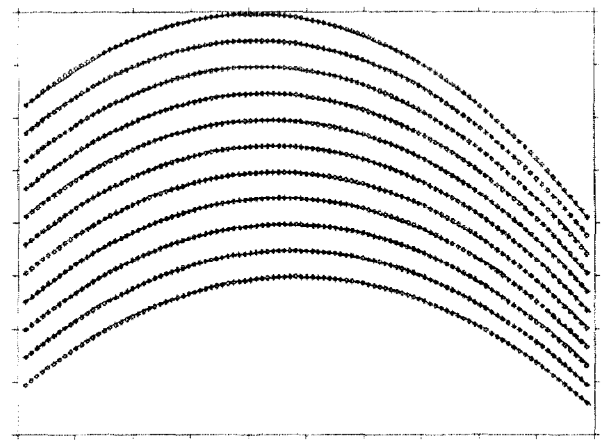

Figure 7: Rays for the determination of c_x and c'_x. Here $-5mm \leq x_0 \leq 5mm$ and $x'_0 = y_0 = y'_0 = \delta = 0$, i. e. the rays start out in the median plane parallel to the central ray. The focusing effect is quite noticeable at the end of the system.

Given the initial design of the system, one can do "fine-tunining" on a computer: by computing the change in characteristic rays due to slight adjustments and using them as an input for a graphics program, one obtains an intractive way to alter the design and observe the resulting optical changes.

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