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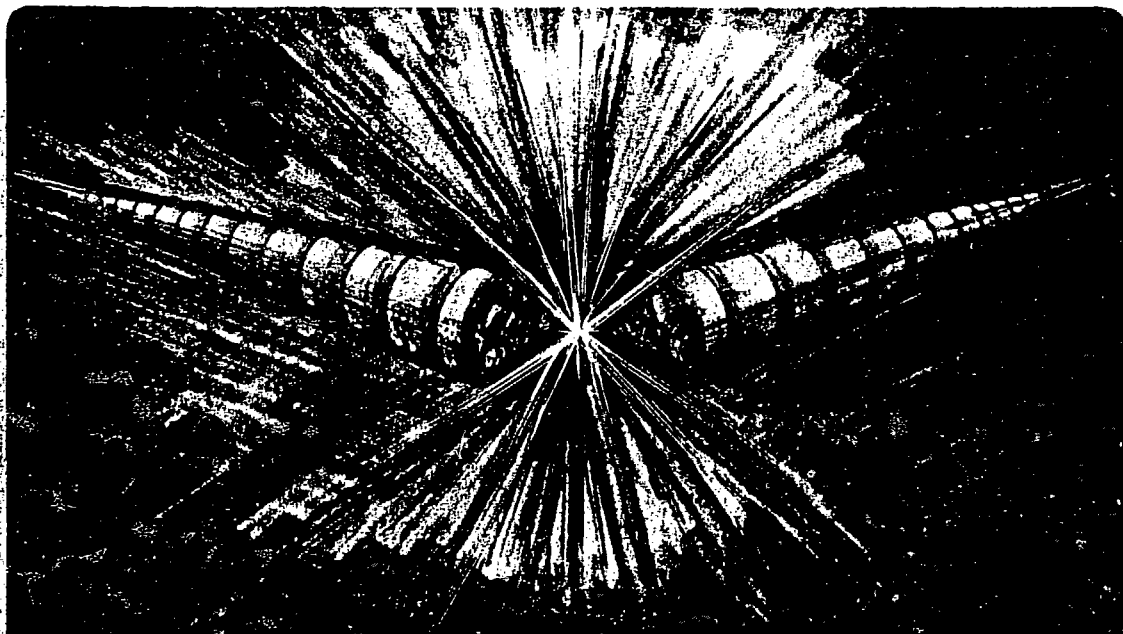## UNIVERSITY OF CALIFORNIA

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HIGH ENERGY BEAM TRANSPORT SYSTEM FOR
A HEAVY ION MEDICAL ACCELERATOR

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Abstract

A beam transport system for a Heavy Ion Medical Accelerator is presented. The design allows for ease of tuning, similarity of tuning between different beam lines, and future expansion of the number of beamlines. An option for generating secondary beams with acceptable transmission losses to all treatment areas is also included in the design, as is a vertical beamline option for use with patients in a horizontal position.

Introduction

A transport system has been designed for transporting heavy ion beams extracted from a synchrotron accelerator with magnetic rigidities as high as 9.7 T-m to various experimental areas for use in radiotherapy and biomedical research programs.[1,2] The design of the transport system is in three parts: 1) transport from the accelerator to an area where the beam is used via a 90° bend section, 2) transport along a straight section that parallels the beam use areas and 3) the switching of the beam from this straight section into a particular beam use area. See Figure 1. The advantage of dividing the system in this way is that a minimum of retuning is required to switch from one beam use area to another. Starting from general assumptions of the beam characteristics after extraction from the synchrotron, the properties of the transport system are discussed in the framework of the needs of radiotherapy and biomedical users. Further consideration is given to the production and transport of secondary beams of radioactive nuclei to beam use areas for research purposes. A vertical beamline in one beam use area is also discussed.
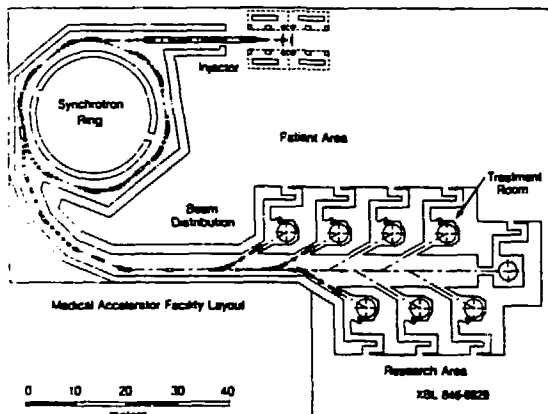

Fig. 1 Medical Accelerator Layout

A general design goal was to make expansion of the system as easy as possible. Utilization of magnets designed for the accelerator was adopted whenever possible to minimize the number of magnet designs, fabrication fixtures and need for spares. Finally as fully an achromatic transport system as possible was attempted.

Transport System Requirements

The main requirements placed on the beam transport system come from: 1) the radiotherapy program, 2) the biology program, and 3) the secondary beam research. Additional constraints are imposed on the design by the accelerator, the physical site, and the cost.

In general the radiotherapy program needs high reproducibility and reliability for a short operation time. The biology program on the other hand requires higher beam intensities for high dose rates, longer operating times, and a number of beam species. The secondary beam requirements are generally even more stringent and not always achievable. Not all requirements placed on the beam transport system were compatible so optimization of the various constraints was attempted in the design.

The basic requirements placed on the transport system by the radiotherapy program are beam size, beam intensity, beam stability, and momentum spread. Beam sizes as small as 1 cm at intensities of 2×10^9 particles/sec with less than 0.1% momentum spread are currently used at the LBL Bevatron and are a minimum requirement. In addition positional stability currently achieved and required is on the order of one millimeter. The use of advanced beam delivery systems may add additional constraints in the future.

Unlike primary beams where the extracted beam emittance is reasonable and a transport system of 100% transmission is easily obtainable, the secondary beams have emittances an order of magnitude larger making complete transmission harder. A lower limit of 2×10^7 particles/sec for secondary beam intensities requires high production efficiency and efficient beam transport. In addition spot sizes as small as a few millimeters in diameter are requested without loss of intensity due to collimation.

The physical size of the site also places constraints on the system. The rectangular shape of the envisioned site for the accelerator complex requires a 90° bend in the transport system as well as adjustment of its length to fit within the given boundaries. Use of elements already designed for the synchrotron ring is desirable to reduce design and construction costs.

To minimize turn around time between patient treatments in different treatment areas, the optics for each area is made as similar as possible. Switching time from one area to another is thus minimized, costs are reduced by the modular design of the system, and time is saved in tuning each area since beamline tunes are similar.

Implementation

A starting set of betatron parameters was assumed See Table 1. The extraction of the beam in the accel-

erator considered contains two magnetic septa. The optics calculations include these two elements. After the initial extraction, a set of triplet quadrupoles is used to focus the beam. For secondary beam production a target is placed after these quadrupoles. A beam dump is located in line with the quadrupole triplet. See Figure 2.

Table 1 Initial Parameters

$\epsilon_x = \epsilon_y = 1.0$ cm mrad

$\beta_x = \beta_y = 7.0$ meters

$\dfrac{dp}{p} \leq = 0.5\%$

A pair of 22.5° bending magnets with a quadrupole triplet in between constitutes the basic elements of a bend section. Two such groups of magnets and quadrupoles form the 90° bend section with another triplet quadrupole set in between for matching purposes. The magnets are of the same design as the accelerator magnets only shorter, while the quadrupoles are of identical design to the accelerator quadrupoles. For beams with dp/p≤0.5% the system is fully achromatic if the dispersive effects of the extraction system are ignored. With the effect of the extraction system taken into account the derivative of the dispersion function is small.
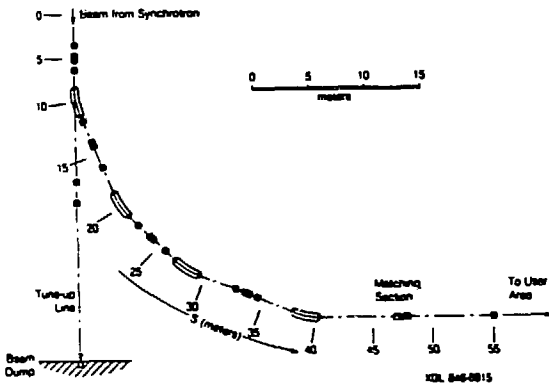
Fig. 2   90° Bend Section Layout

Following the 90° bend section is a straight section parallel to the beam use areas. The beam is transported through this area in a periodic fashion with a series of alternatingly focusing and defocusing quadrupoles spaced 5.2 m apart. The envelope of the beam through this section is essentially flat with a small oscillation in the planes perpendicular to the transport direction. See Figure 3.

The presence of momentum spread in the beam causes a certain amount of 'throbbing' of the beam but it is of an acceptable level. As a result small differences in tuning between beam use areas will exist. See Figure 3. The major advantage of such a design is its periodicity which allows similar beamline tunes for areas on one side or the other of the straight section. Addition of beam use areas can be done in a modular fashion.

The 90° bend section and the straight section are then matched to each other by a pair of quadrupoles 0.6 m in length. The total length of the system was fit to a particular site by adjusting this matching section. Also from this matching section the beam is bent vertically for a vertical beamline.
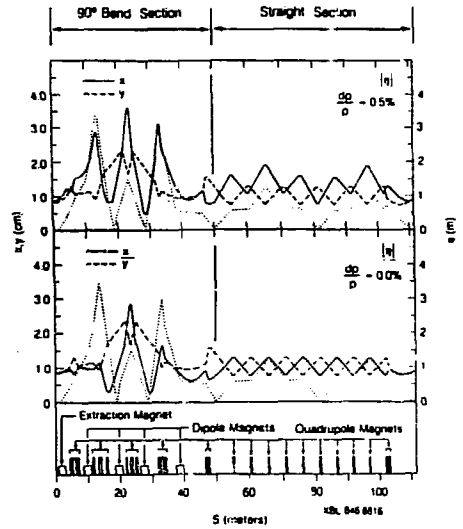
Fig. 3   Beamline Optics

From the straight section of the beamline a 30° bend magnet identical in design to ones used in the accelerator is used to bend the beam into a beam use area. See Figure 4. Again a quadrupole triplet is used to focus the beam to a 1 cm spot at a point 7.7 m downstream from the last quadrupole. This part of the transport system is identical for each beam use area with the exception of the one at the end of the straight section which uses only two quadrupoles to focus the beam. The beam characteristics at the 'isocenter' of a typical beam use area is given in Table II.

Table II Final Parameters

β_x=10.0 meters η_x=0.0 meters

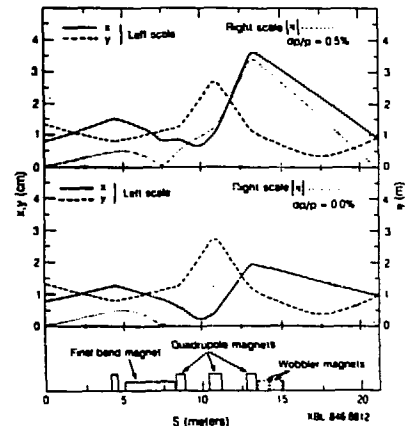β_y= 9.9 meters η_y=0.0 meters

Fig. 4   Beam User Area Optics and Layout

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One more important requirement for the system is that the beam be held to a constant position within about 1 mm at the isocenter. To achieve such accuracy the 30° bend magnets must be regulated to better than 1 part in 10^4. Current technology using dynamic feedback from a Hall probe measuring the magnetic field can achieve this. Transmission through the entire beamline is shown in the Polygon plots of Figure 5. For beams of reasonable momentum spread (dp/p < 0.5%) the transmission is 100%.

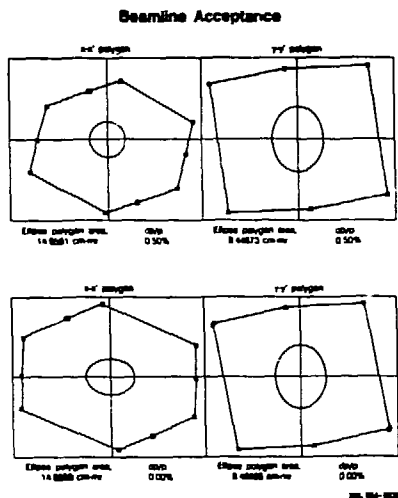**Beamline Acceptance**

Fig. 5 Beamline Acceptance

A list of the elements used in the transport system is given in Table III.

Table III

Elements in the High Energy Beam Transport System for an Eight-Room Facility

	Element	Quantity	Length (m)	Field (T)	Gradient (T/m)	Aperture (mm)
90° Bend Section	Quads	8	0.4		7	50
		2	0.6		12	50
		4	0.8		7	50
	Dipoles	4	2.4	1.6		40×40
Straight Section	Quads	10	0.4		7	50
		2	0.4		12	50
Beam Room Section	Quads per room	2	0.6		8	50
		1	0.8		8	50
	Dipoles per room	1	3.2	1.6		40×40

Secondary Beams

The production of secondary (radioactive) beams begins after the first quadrupole triplet where a target is placed. The primary beam is focused on the target where nuclear interactions then produce a variety of radioactive and non-radioactive nuclei which can be magnetically separated from the primary beam and one another. The radioactive isotope ^{19}Ne at an energy of 670 MeV per nucleon was chosen for study because of the experience with it at the Bevatron [3]. The results should be applicable to other types of beams. The general feature of such interactions which bear on beam transport is the momentum spread of the secondary beam. A dp/p ~ 1% is common. This translates into an angular spread of about 10 milliradians for the highest energy beams, which along with multiple scattering produces a net angular spread of about 12 milliradians. The emittance of the secondary beam is then estimated to be about an order of magnitude larger than that of the primary beam. The momentum spread of the beam also grows. The transmission was estimated and found to be about 70% for transporting a secondary beam to the first beam use area. Angular and momentum distributions were assumed to be Gaussian in shape. Beams of lower rigidity with larger emittances will have poorer transmissions. The actual beam intensity also depends on the intensity of the primary beam and the secondary beam production efficiency. The latter is of course a function of target thickness and reaction cross section. Collimation after the analyzing magnet will help to reduce primary beam contamination of the secondary beam. The analysis of the secondary beams for a certain charge to mass ratio can be done by the first dipole magnet where, for a 5% difference in beam rigidity, the separation will be about 5 cm. Beam spot sizes are about one centimeter. The resolving power of the first bending magnet is about 1/200.

Vertical Beamline

A strong clinical need for a vertical beamline arises from the fact that many patients are not ambulatory or are more easily treated lying down. To satisfy this need a vertical beam has been designed for the last treatment area. The beamline consists of two vertical bends of ±30° which raise the beamline to a height of fifteen meters. A long straight section transports the beam to a 90° bend section with a bend radius of about 6 meters. The beam is bent vertically downward into the treatment room and focused at isocenter. A further refinement which might result in a more economical use of space would be to use superconducting magnets of higher field and shorter radius of curvature. The vertical height requirement for such a beamline would then be smaller. This option is currently being studied.

Conclusion

The transport system design as a whole is quite successful, achieving complete transmission for primary beams and acceptable transmission of secondary beams. The system is modular in design and allows for future expansion. Almost all beamline components are identical or similar to those found in the accelerator.

References

[1] R. A. Gough, E. L. Alpen, The Heavy Ion Medical Accelerator/Final Design Summary, PUB-5122, 1984

[2] R. A. Gough, Medical Heavy Ion Accelerator Proposals, elsewhere in these proceedings

[3] J. Alonso, A. Chatterjee, C. A. Tobias, LBL Report, 8951

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