Study on the Gantry Beam Line for the Medical Synchrotron

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ABSTRACT

Presently the horizontal and vertical fixed beam lines are discussed for the clinical treatments with the medically dedicated proton synchrotron. Another method using the rotatable gantry beam line is being studied on the problems associate with the gantry optics.

INTRODUCTION

A gantry is invented to gain a flexible rotation to deliver the charged particles from any direction required for the clinical treatment. To obtain a directional flexibility of beam the beam delivery system must be rotated, so the space to install the system becomes inevitably large. It is the drawback of this device. However, the positioning of the patient can be eased by flexibility of the irradiation angle. The dose field formation by passive elements, such as collimator, bolus, scatterer and ridge filter, is widely adopted and the patient is under an uncomfortable condition during positioning and beam exposure. This situation will be alleviated by an introduction of the dynamic irradiation, 3D spot scanning, which is realized with an isocentric gantry, beam scanning by the magnetic field in the plane (2D) and depth control by beam energy.

To reduce the gantry room size the rotational radius should be smaller and/or the arm be arranged in one plane. The former is an idea by H.A. Enge and the latter by A.M. Koehler[1]. Drift space from the exit of the gantry to an isocenter, which is required to install the scanning magnets or beam scattering foils, range modulators, beam monitoring equipments, X-ray and laser positioning equipment and beam shaping device, has a length at least 4 m. Idea to reduce the radius in the former design will be attained by inserting the scatterer in the gantry arm but it results in the increased dimensions of gantry magnets by expanding beam aperture in both coordinates for the scattered particles. In this study two types are treated with no scatterer in the gantry.

GANTRY SYSTEM

The gantry system is summarized in three types according to the classification of Koehler, Classic, Enge and Corkscrew. They are compared in many aspects in the report of H. Blosser et al[2]. The IBA gantry[3] and the Novosibirsk gantry[4] are the developed forms of the Enge type. The former is designed to steer beam in 2D with a beam deflector placed upstream of last 90^o magnet and by the tilt of the last 90^o magnet. This idea allows the small sized gantry. The latter is very compact gantry designed to transmit proton beam with small transverse dimension and the gantry size is as small as to be installed in the normal room.

For the present purpose to guide the beam of fairly large size, the gantry naturally becomes big and requires large installation space as high as 13 m or more with the longitudinal depth of 5 m in the case of the corkscrew gantry.

The first consideration on the gantry system is to compare the room size required to both Koehler type (Corkscrew gantry) and Enge type. Assuming the same bending field (the same orbit radius) and the reasonable drift spaces for quadrupoles, the beam height (rotating radius) from the level of isocenter, H, and the longitudinal length, L, are expressed by

$$H = 2R_1(1 - \cos\alpha) + S_1\sin\alpha \tag{1}$$

$$L = 2R_1\sin\alpha + S_1\cos\alpha + S_2 + R_2 \tag{2}$$

for the Enge type (Fig.1) and

$$H = 2R_2 + S_3\sin45^o \tag{3}$$

$$L = R_1 + S_1\sin45^o \tag{4}$$

$$S_3\sin45^o = S_1\sin45^o + S_2 \tag{5}$$

for the Koehler type (Fig.2). Eq.(5) is to assure the isocentric condition.

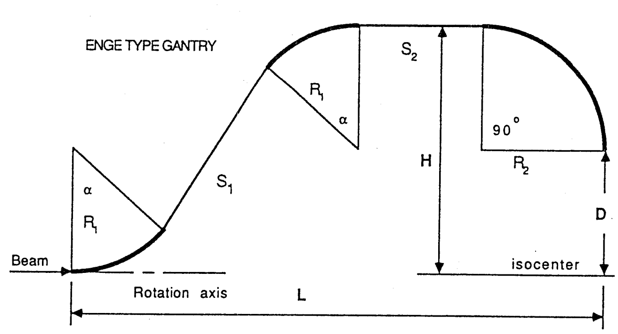

Fig.1 Enge gantry. Bending angle, α, is of bending magnets for translation. Rotation is given around the beam inlet axis by ±180 deg.

If $R_1 = R_2 = 1.5$ m (1.56 T for 230 MeV proton), $S_1 = 2$ m, $S_2 = 1$ m ($S_3 = 3.41$ m) and extra space is added by 1 m at outer sides of central beam lines, the required room volume is roughly obtained. Fig.3 is the space requirement of the Enge type gantry. In this case if the drift space (distance from the gantry exit to isocenter) of 4 m is required, the volume is as large as 1000 m^3. It is about 700 m^3 for the corkscrew type on the same assumption. As these estimation is based on the gross parameters, space saving will be done by the optimal design of beam optics. Length S_1 = 2 m is rather short for this type because the shortest distance to the beam line is only 1.15 m. To have enough space for the patient treatment, 3 ~ 4 m will be required.

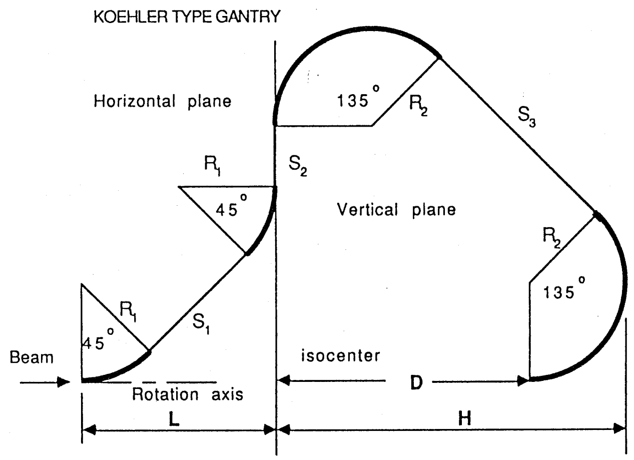

fig.2 Corkscrew gantry. Gantry arm of a vertical plane is in an upright position to the paper. It rotates around the beam inlet axis by ±180 deg.

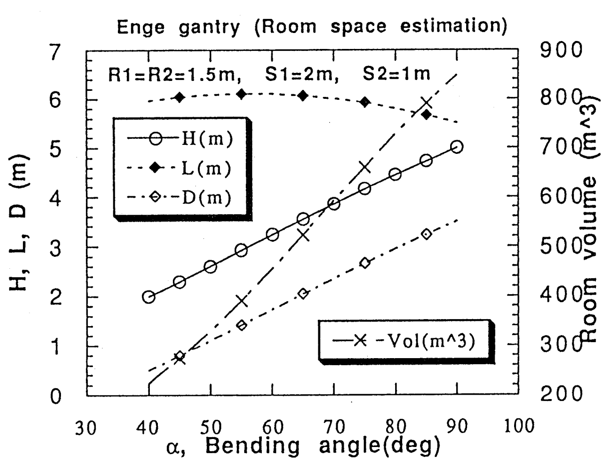

Fig.3 Estimation of the required space of Enge gantry for the case of S_1 = 2m, S_2 = 1m and $R_1 = R_2$ = 1.5m (see Fig.1).

GANTRY OPTICS

Beam transport lines to the treatment rooms are designed and given in the design report[5]. Accelerated beam is extracted in the beam channel by either slow or fast extraction[6] at 120, 180 and 230 MeV. In the horizontal plane both slow and fast extraction are planned. Whereas at Loma Linda only slow extraction in the vertical plane is adopted[7]. It is now under discussion which plane shall be used. Aside from the extraction method, the gantry optics can be treated separately.

There is a problem common to two gantries as regards beam optics. When the gantry arm is rotated, the beam line is rolled and the x and y symmetry is lost. The focusing magnets on the arm are also rotated and give rise to the skew quadrupole field which causes the cross-plane coupling. L.C. Teng invented new idea to uncouple the x and y motions by introducing the 6 quadrupole rotator in front of the gantry. Giving it the rotation by the angle determined from the gantry rotation, the gantry optics need not be altered.

If the quadrupole rotator is not used, distortions from the coupling result in the growth of emittances $\varepsilon_{x,y}$ in both planes[8]. The x and y emittance $\varepsilon_{x,y1}$ of the beam experienced the coupled motion is expressed as,

$$\varepsilon_{x1}^2 - \varepsilon_{y1}^2 = (\varepsilon_{x0}^2 - \varepsilon_{y0}^2)(1 - 2\det C) \quad (6)$$

$$\varepsilon_{x,y1} \geq \varepsilon_{x,y0} \mid 1 - \det C \mid + \varepsilon_{y,x0} \mid \det C \mid \quad (7)$$

where $\varepsilon_{x,y0}$ is the initial uncoupled x and y emittance, C is the off-diagonal 2x2 submatrix in the general 4x4 transfer matrix R between positions 0 and 1,

$$R = \begin{pmatrix} A & B \\ C & D \end{pmatrix}_{4x4} . \quad (8)$$

and detB = detC from the symplectic condition.

When $0 \leq \det C \leq 1$, the coupling is severe only for the very asymmetric emittances. The coupled emittances always are larger than the uncoupled ones[9]. From (6) and (7), if $\varepsilon_{x0} = \varepsilon_{y0}$, $\varepsilon_{x1} = \varepsilon_{y1} \geq \varepsilon_{x,y0}$ independent of the magnitude of coupling.

Assuming detC = 0.5, $\varepsilon_{x1} = \varepsilon_{y1} \geq 0.5(\varepsilon_{x0} + \varepsilon_{y0})$. If this condition is satisfied before entering the gantry, the equality of x and y emittances is maintained in the gantry and their growths will be inevitable. But they are minimized if the $0 \leq \det C \leq 1$ condition is found.

The above mentioned problem shall be reflected in the detailed design of the gantry. In the following the gantry beam optics is studied assuming the gantry arms at the horizontal or vertical position to treat by MAGIC code. The present beam beam line is designed to have the beam waist at 7 m downstream of the final septum magnet through double achromatic magnet system. Therefore the waist point is assumed as the starting point of the gantry beam channel and all bending magnets are assumed to have the edge focusing equivalent to half of the bending angle at both ends.

An example of the corkscrew gantry optics is given in Fig.4 (a) and (b). The first arm (a) to guide the beam to the second vertical arm (b) is designed to be double achromatic, because the optical plane differs in both arms. In the vertical arm, it is also double achromatic to give the sharp spot. Fig.5 also gives an example of the Enge gantry optics when the arm at the horizontal position.

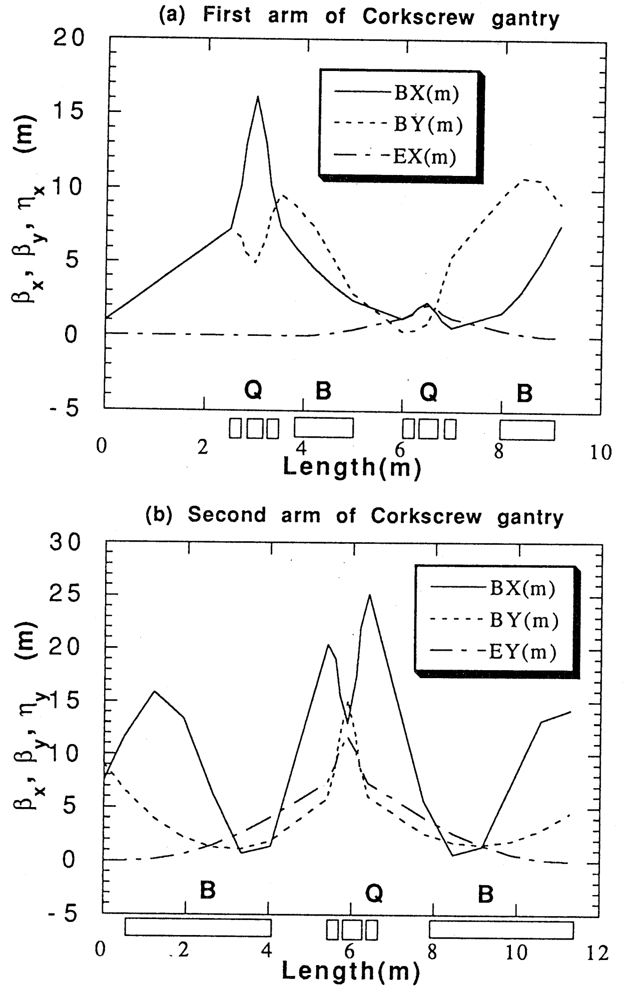

Fig.4 Corkscrew gantry optics in (a) the first arm and (b) second arm. $S_1 = 3$ m, $S_2 = 0.5$ m and $R_1 = R_2 = 1.5$ m are assumed.

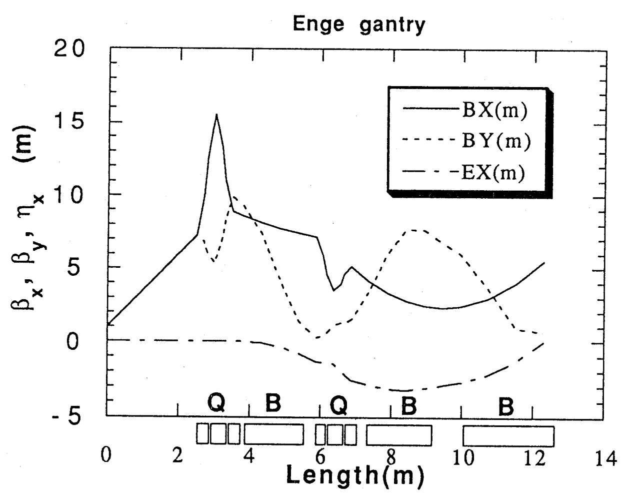

Fig.5 Enge gantry optics. $S_1 = 2$ m, $S_2 = 1$ m, $\alpha = 60^0$ and $R_1 = R_2 = 1.5$ m are assumed.

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