Conceptual and Ion–Optical Designs of an Isocentric Gantry for Light–Ion Cancer Therapy

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Abstract

Conceptual and ion-optical designs of an isocentric gantry are presented. The gantry is designed for light-ion therapy using a 6 Tm carbon beam. Its main characteristics are: 5 m overall radius, 1.4 m drift to the patient, 20 x 10 cm^2 treatment field, and two-direction active parallel scanning of a fine focused pencil beam. To achieve these features, the beam scanners are optimally positioned upstream the last 90° bending section consisting of two 45° sector magnets with 4 oblique field boundaries and different apertures. The gantry concept is a compromise between 'barrel' and 'conical' gantry shapes and is likely the most space-saving configuration of single-plane isocentric gantries. This new so-called 'short barrel' configuration features also small aperture quadrupole lenses, low intermediate dispersion and a fully achromatic beam transport system. Its overall dimensions stay close to the size of the existing proton gantries.

Keywords: Beam-delivery, Beam-transport, Gantry, Ion-optics, Light-ion therapy

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1 INTRODUCTION

Beams of light ions (Z=1 - 6) have favourable properties for their use in radiotherapy. Their advantages can be fully exploited if the dose is delivered in a tumour-shape conformed way. This can be best achieved by a rotating gantry. Recent development of proton therapy facilities indicates indeed that rotating gantries become inevitable components of medical accelerator complexes. Loma Linda University Medical Centre operates three cork-screw gantries [1, 2, 3] and a compact eccentric gantry was commissioned in Paul Scherrer Institute Villigen in 1996 [4]. Four large-throw gantries are being installed in U.S.A. and Japan: two in Northeast Proton Therapy Centre at Massachusetts General Hospital Boston [5] and two in National Cancer Centre Hospital East Kashiwa [6]. Other proton gantries are proposed for Hyogo Ion Beam Medical Centre [7] and proton therapy facilities in Tsukuba and Sizouka in Japan [8]. Typically, proton gantries transport the beams with the maximum magnetic rigidity of about 2.2 Tm and have a weight of $\approx$110 tons. Except for the PSI gantry, all existing gantries are isocentric with a beam delivery system located downstream the last gantry magnet. In this so–called 'large-throw' configuration the radius of a proton gantry is close to $\approx$5 m. Compactness of the PSI gantry (4 m diameter) is achieved by mounting the patient table off-axis (eccentric gantry) and by placing the sweeper magnet upstream the last dipole [9]. A detailed parameter list of existing proton gantries has been published in refs. [10 - 12].

Carbon ions have physical properties similar to protons, but they are biologically more effective, which is an important advantage for treatment of radioresistant tumours. On the other hand, the desirable penetration range requires carbon beams with magnetic rigidity of $\approx$6 Tm, which makes the construction of a rotating gantry more difficult. That is why, no rotating gantry for carbon beam has been built so far and only few design studies exist. In 1992, four gantry modifications were designed for the EULIMA Project [13] and beam-optics studies of the gantry were commenced at GSI Darmstadt [14 - 17] and continued in collaboration with University of Giessen [18]. EULIMA gantries had only one-direction scanning option while GSI designs include two-direction raster scanning system [19]. In most of the previous designs, the authors tried to reduce the gantry size either by assuming superconducting magnets in the gantry [16, 17] or by applying eccentric position of the patient table in the normalconducting gantry versions [14]. Some authors prefer a set of fixed beam lines instead of a rotating structure [20, 21].

We propose to build an isocentric rotating gantry by using exclusively steel-dominated magnets whose coils can be normal- or superconducting. There are big advantages for such systems because of their well-established technology and absence of long-distance stray fields. In the case of normalconducting coils, there is no danger of quenching. Very important is also that the pole-face rotation providing the edge-focusing effect can easily be implemented, which is advantageous for the ion-optical design since it allows also focusing in the non-bending plane of the dipoles. A disadvantage of such systems is that the magnetic flux density is limited to values about 2T, which corresponds to radii of curvature of sector fields of more than 3 m and leads to relatively large overall gantry dimensions. Our design, however, stays within the size of the existing large-throw proton gantries.

2 CONCEPTUAL DESIGN OF THE GANTRY

It is beyond the scope of this paper to discuss all possible gantry concepts. Because the field is new, no particular gantry concept is generally preferred and accepted. That is why we had studied many gantry alternatives [12, 16 - 18] and applied some filtering later on. The filtering was based on numerous discussions with radiation oncologists and other gantry designers [22], existing experience from proton therapy facilities as well as on our own experience. Without reporting details of the filtering process, the resulting gantry configuration is described in this paragraph.

Radiation oncologists prefer isocentric systems to eccentric ones, which is also reflected in the existing proton gantries. There are 7 isocentric proton gantries world-wide in operation or under construction, but only one eccentric proton gantry. That is why we propose to construct the gantry as an isocentric system. On the other hand, the downstream location of the beam delivery system which dominates the proton gantries would for carbon beam lead to a gantry radius as large as 7 m, which makes an upstream location of the beam delivery equipment mandatory. We also assume that light-ion therapy beams should be delivered by an active scanning technique. The beam delivery equipment then consists of a scanning system which is located upstream the last gantry magnet, and a beam-monitoring system which must be located downstream the magnet in order to monitor the authentic beam really getting to the patient. In addition to this, the beam should preferrably be scanned over an irradiation field actively in both cartesian directions in such a way, that it stays always perpendicular to the scanned surface (so–called 'parallel scanning'). This feature has been studied theoretically in refs. [14, 15] but no detailed gantry design has followed yet these studies. The 'cork-screw' geometry was excluded as it requires a large amount of total bend (90° in one plane and 270° in the other plane). The resulting gantry configuration is a single-plane isocentric gantry with upstream location of a two-direction scanning system.

Such a gantry can be basically considered in two versions [13], barrel (cylindrical) or conical, which are defined in Fig. 1. The advantage of the barrel gantry (Fig. 1a) is that a large aperture is required only for the last 90° dipole. A disadvantage is that the length of the gantry is relatively large due to the contribution of a long upper straight section. The conical version (Fig. 1b) enables to reduce the gantry length but the scanning system is followed by a large-aperture dipole with bending angle more than 90°. That is why these gantries are usually proposed with the bend-down dipole split into several magnets with different apertures starting from the smallest aperture on the side of the scanning system and reaching the largest aperture at the exit of the gantry [18]. This, however, increases the gantry radius due to the additional contributions of gaps inbetween the magnets.

The advantages of barrel and conical designs can be combined as it is done in the proposed 'short-barrel' version. In this case, the last dipole is split in a special way which is illustrated in Fig. 2. The first bending angle is identical with the bend-up angle but has opposite orientation. The following part of the beam line is therefore horizontal and does not contribute to the gantry radius. The scanning system has been moved behind the dipole magnet, which enabled to minimise its aperture. Thus, the resulting arrangement reminds the barrel concept with a very short upper straight section which contains only the scanning system but does not contain any quadrupole lenses. The overall gantry length is close to the conical situation, but the last dipole which requires a large aperture allowing for beam scanning is identical with the dipole of a barrel gantry. The Short-barrel gantry has been found as a compromise between barrel and conical gantry shapes combining advantages of both. It is likely the most space-saving concept for isocentric single-plane gantries. The beam transport system has been designed for the gantry in a tailored way preserving the short-barrel concept as an input specification for the ion-optical design.

3 ION-OPTICAL DESIGN OF THE GANTRY

The carbon beam with maximum magnetic rigidity of 6 Tm is expected to be extracted from a heavy ion synchrotron that allows an active energy variation and produces a beam of $\pm 0.2\%$ energy spread. As far as the ion-optical properties of the gantry are concerned we have postulated similar specifications as in ref [18]:

1. A pencil beam with diameter less than 3 mm must be formed at the isocenter. The contribution from multiple scattering is not included in this beam size specification.

2. The beam transport must be fully achromatic.

3. In order to ensure a homogeneous irradiation of the scanned area it is also necessary to guarantee an approximately constant image magnification over the whole treatment field.

4. The beam is going to be scanned over the 20 x 10 cm^2 treatment field in a parallel scanning mode, i.e. it always stays perpendicular to the scanned surface.

5. A depth scanning should be achieved by the active energy variation from the accelerator which must be followed by corresponding changes of excitation of all beam transport elements [23, 24].

These constraints are partially contradictory and put rigid limitations on the ion optical design of the gantry. This is especially true for the last bend which must accept a wide sweep of the ion beam, which requires a very good field homogeneity within the sector magnets. Satisfactory beam focusing is also not easy to achieve due to the relatively long quadrupole-free beam path from the last quadrupole lens in the bend-up shoulder to the isocenter. It was found in our previous gantry designs [18] that it is a good solution to divide the last dipole of the gantry into smaller parts so that the vertical focusing is more evenly distributed over the length of the ion-optical system. There are also more free parameters (pole face rotation) available to achieve focusing and parallel scanning over the whole treatment field. To allow for a wide scanning area rather large magnet air gaps are required. We relaxed this requirement by varying the magnet air gaps G_o for the different sector magnets. Additionally we varied the flux densities B_0 from one sector magnet to the next one and consequently the radii of curvature ρ_0 of the central trajectory. The reason for this measure is that good field homogeneity is expected to be more easily achieved using narrow air gap magnets. In detail we chose the radii of curvature $\rho_0, \rho_1, \rho_2, \rho_3$, flux densities $B_{00}, B_{01}, B_{02}, B_{03}$, magnet air gaps $G_{00}, G_{01}, G_{02}, G_{03}$, and angles of deflection $\Phi_0, \Phi_1, \Phi_2, \Phi_3$ as well as the entrance pole face rotation angles $\epsilon_{01}, \epsilon_{11}, \epsilon_{21}, \epsilon_{31}$ and exit pole face rotation angles $\epsilon_{02}, \epsilon_{12}, \epsilon_{22}, \epsilon_{32}$ of the gantry sector magnets. They are listed in table I.

Table I

magnet BM0	$\rho_1 = 3.2m$ $\Phi_1 = 39°$	$B_{00} = 1.87T$ $G_{00} = \pm 25mm$	$\epsilon_{01} = 0°$ $\epsilon_{02} = 0°$
magnet BM1	$\rho_1 = 2.8m$ $\Phi_1 = 39°$	$B_{01} = 2.1T$ $G_{01} = \pm 25mm$	$\epsilon_{11} = 0°$ $\epsilon_{12} = 0°$
magnet BM2	$\rho_2 = 3.0m$ $\Phi_1 = 45°$	$B_{02} = 2.0T$ $G_{02} = \pm 40mm$	$\epsilon_{21} = 10°$ $\epsilon_{22} = 10°$
magnet BM3	$\rho_3 = 3.2m$ $\Phi_1 = 45°$	$B_{01} = 1.87T$ $G_{03} = \pm 50mm$	$\epsilon_{31} = 10°$ $\epsilon_{32} = 10°$

In table II the overall parameters of the "short-barrel gantry" are given. The emittances of the 6 Tm carbon beam are $\epsilon_x = \epsilon_y = 2.0\pi$ mm mrad. The beam diameter at the isocenter is less than three milimeters in both the horizontal and vertical plane.

Table II

Element	Length [m]	Pole-tip flux density [T]	Half gap (dipoles) Half aperture (quads) [m]
Drift	2.8		
Quadrupole	0.3	-0.5437	0.03
Drift	0.4		
Quadrupole	0.3	0.59251	0.03
Drift	0.4		
Quadrupole	0.3	0.55241	0.03
Drift	0.4		
Magnet BM0	2.178	1.8762	0.025
Drift	1.0		
Quadrupole	0.3	-0.3729	0.025
Drift	1.05		
Quadrupole	0.3	0.803	0.025
Drift	1.05		
Quadrupole	0.3	-0.47897	0.03
Drift	1.05		
Quadrupole	0.3	0.37461	0.03
Drift	0.5		
Magnet BM1	1.9059	2.14	0.025
Drift	2.8		
Magnet BM2	2.3562	2	0.04
Drift	0.65		
Magnet BM3	2.513	1.876	0.05
Drift	1.4		

Figures 3-7 illustrate the gantry concept and the ion optical and beam scanning properties of the beam transport system.

Higher-order calculations

Third order calculations have been performed to proof that the aberrations have neglegible influence on the performance of the gantry. As can be seen from Fig. 8 there is no noticeable difference between the beam intensity as determined from the first –and from the third– order calculations.

4 DISCUSSION AND CONCLUSION

The gantry design presented in this paper has been mainly focused on finding the most appropriate concept for a light-ion gantry containing a two-direction raster scanning system. After evaluation of many possible gantry alternatives (from technical as well as medical points of view), the isocentric single-plane gantry with the upstream position of the scanning system has been selected. For this gantry, the new **short barrel concept** has been introduced as the most space- and weight saving configuration. The feasibility of the achromatic beam transport system with parallel scanning mode has been demonstrated, but the beam transport system is still open to further optimisation. In the next step, the work will proceed with magnet-design studies [25].

ACKNOWLEDGEMENTS

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5 References

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[Fig.1] shows the general layout of the “short barrel” gantry and the found main specifications are the following: R=5 m, rotatable part has a length of 14.5m. Shown is also an ion beam with xa- and yb-phase space areas of both ±2mm mrad and energy spreads of ±0.2%.

[Fig.2] shows the scanning properties of the gantry of Fig.1. for an ion beam of x- and y-phase space areas of ± ?? mm mrad and energy spreads of ±0.2%. In Fig.2a this ion beam is shown in the projection on the plane of deflection of the gantry in its middle position as in Fig.1 as well as in its two most extreme x-positions ±100mm. In Fig.2b the same ion beam is shown again. This time, however, the three beams are shown in a ''straight plot'' in which all curvatures of the beam axis are left off. Additionally also the beam projections on a perpendicular surface are shown. Also here the ion beam is indicated in its middle position as well as in its two most extreme y-positions ±50mm.

[Fig.3] Plot of the field strengths on the pole faces along the beam axis. Note that the last magnets have different apertures and magnetic flux densities. When the beam sizes are small, the magnet air gaps are narrower and higher fields strengths are available. Whenever the swept beam requires wider magnet air gaps, lower fields are used.

[Fig.4] The intensity distribution in a fine focused ion beam that is to be scanned across the target area. In Fig. 4a this intensity distribution has been calculated to first order. In Fig.4b this intensity distribution has been calculated to third order. As one can see from a comparison of these two distributions, the influence of the image aberrations is not very large. In the x-direction some unsymmetry is visible which is due to some second aberration. However, the influence on the intensity distribution of the scanned beam seems to be extremely small.

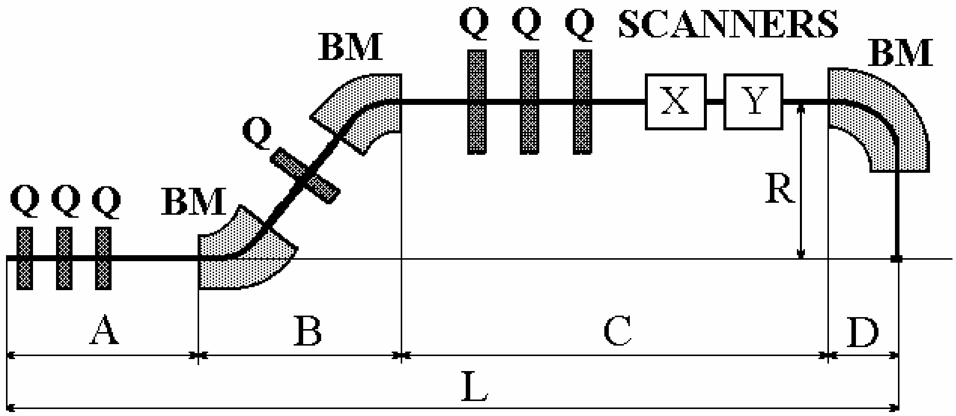


Fig. 1a

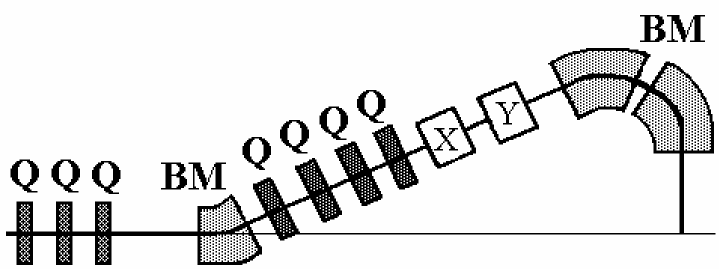


Fig. 1b

Fig. 1. Principal scheme of a barrel (1a) and conical (1b) gantries.

Q - quadrupoles, BM - bending magnets, X,Y - horizontal and vertical scanners. For convenient description of different gantry shapes, the following gantry parts can be defined: A - input straight section, B - bend-up shoulder, C - upper straight section, D - bend-down shoulder, L - gantry length, R - gantry radius. Typical feature of the conical gantry is that the bend-up shoulder is followed immediately by the bend-down shoulder with no upper straight section in-between.

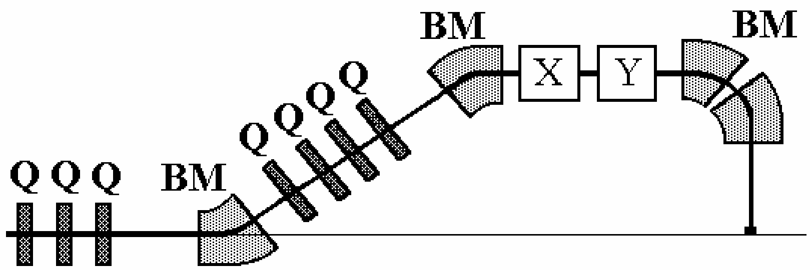
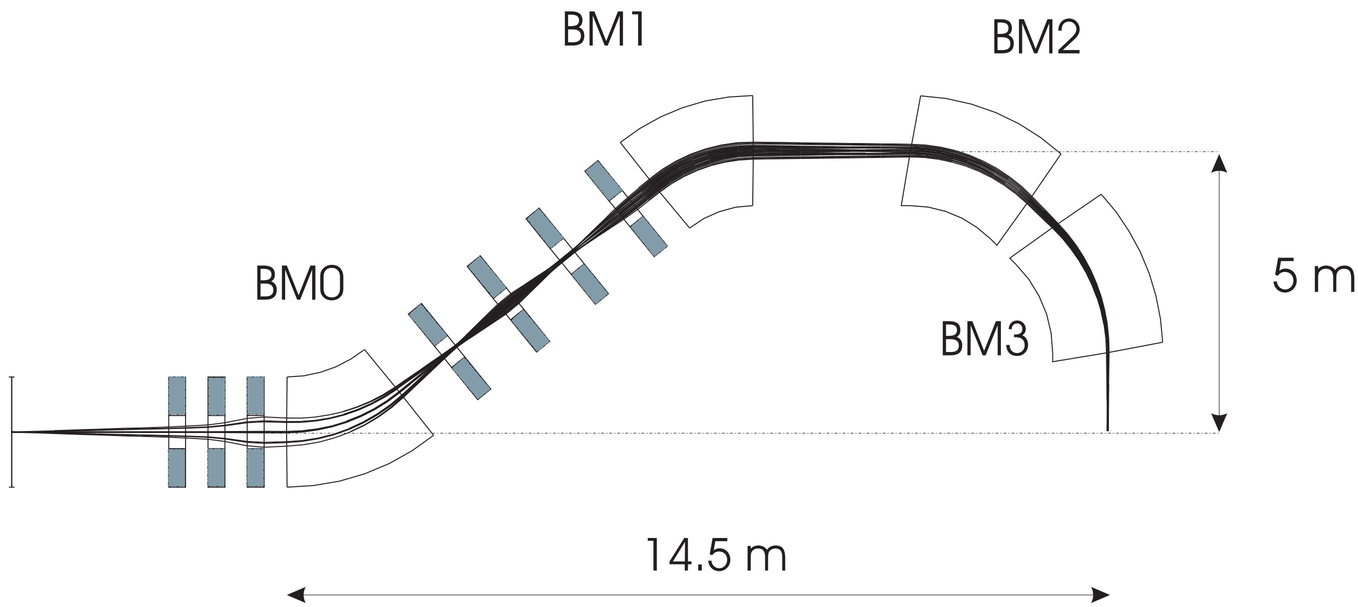
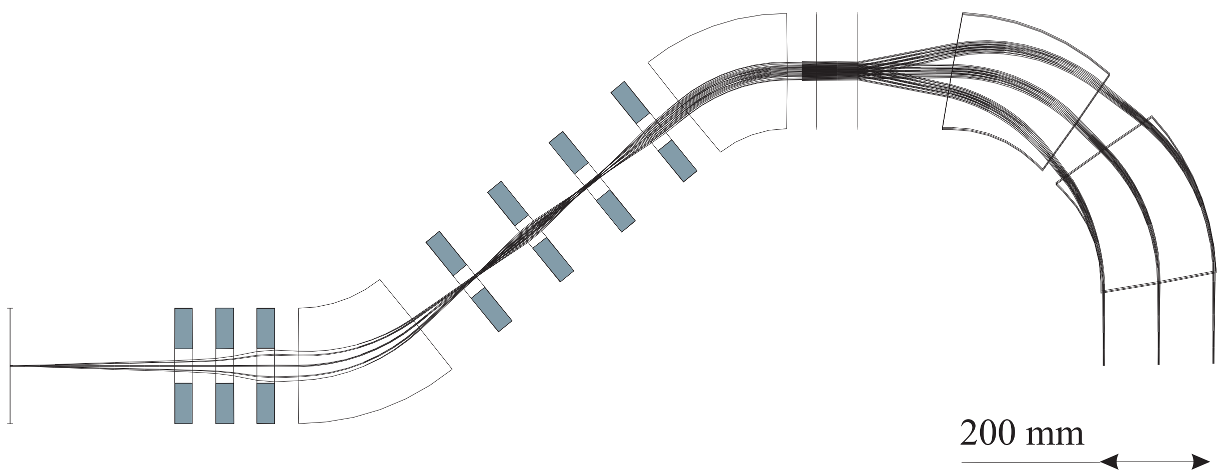
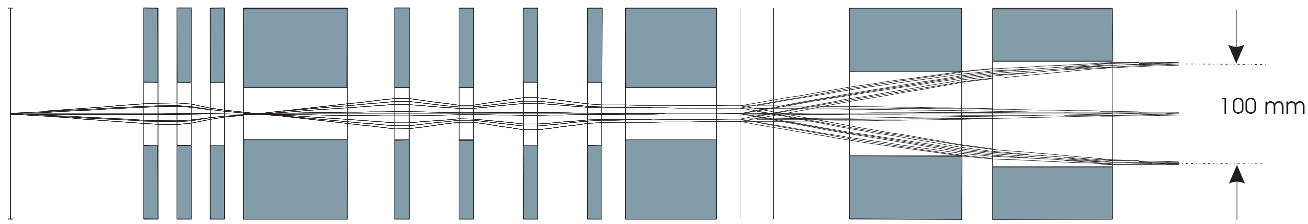


Fig. 2. Layout of the short-barrel gantry.

Short-barrel arrangement is a compromise between barrel and conical gantry shapes. Its upper straight section contains only the scanner magnets but does not contain any quadrupole lenses. That is why the gantry length is close to the conical gantry, but the amount of large-aperture bending magnets is the same as in the barrel gantry. Meaning of symbols is identical with Fig. 1.


BM1
BM2
BM0
5 m
BM3
14.5 m


200 mm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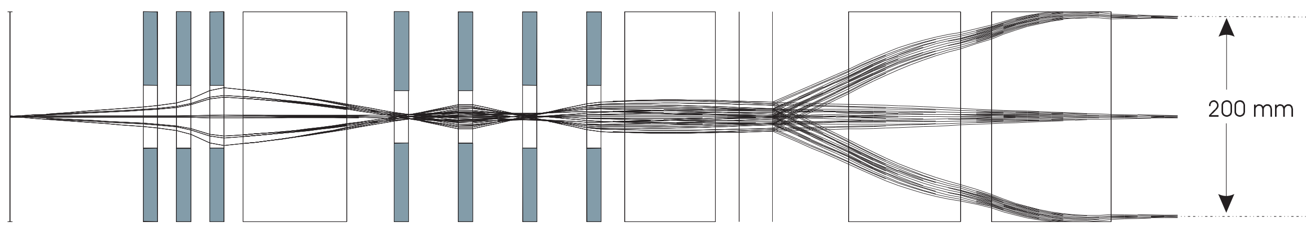
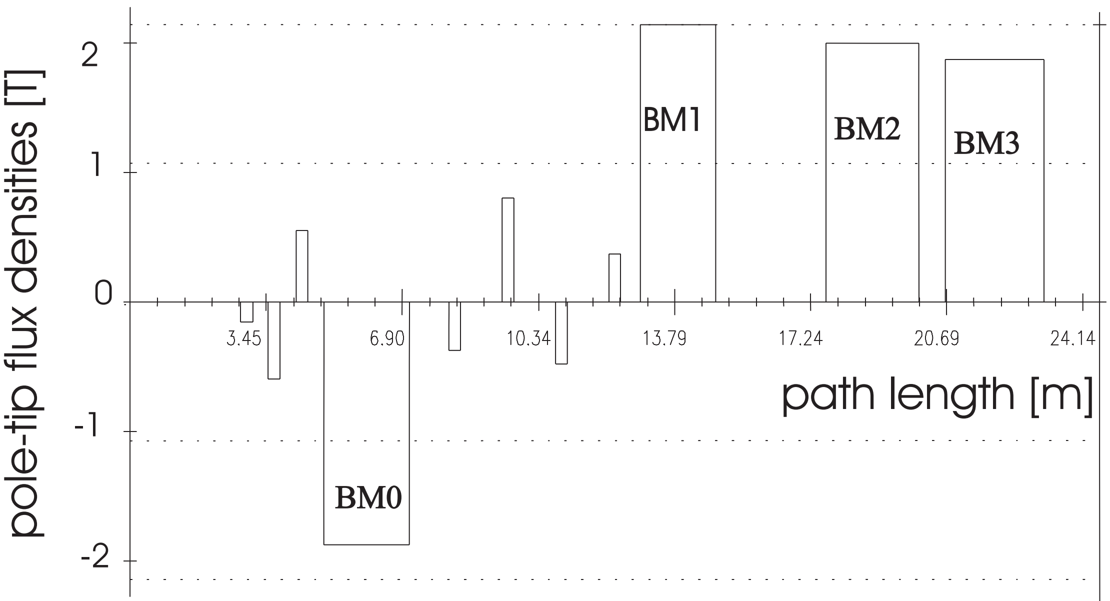
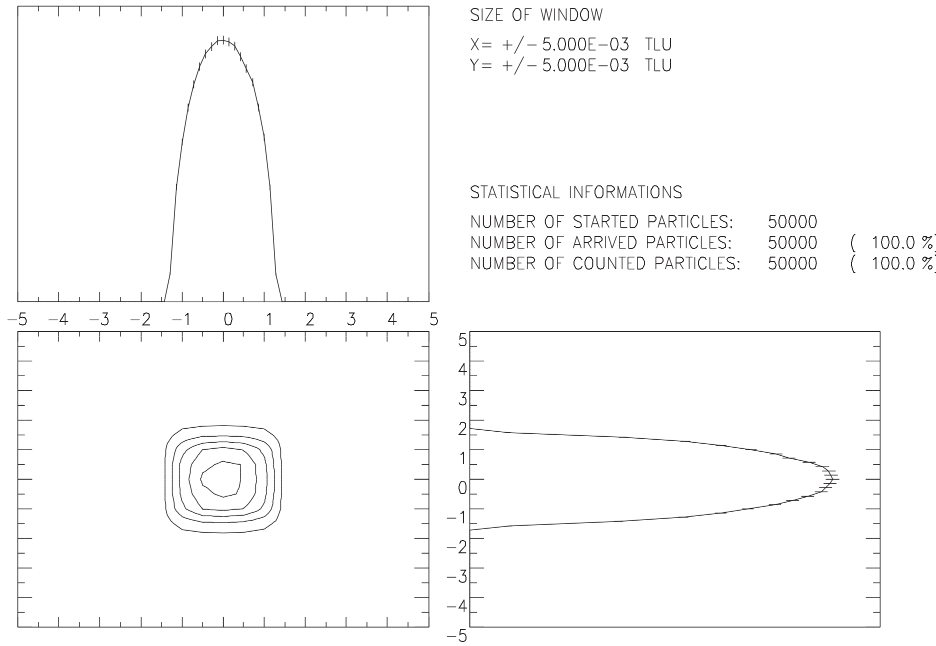

200 mm



pole-tip flux densities [T]
2
1
0
-1
-2
3.45
6.90
10.34
13.79
17.24
20.69
24.14
path length [m]
BM0
BM1
BM2
BM3

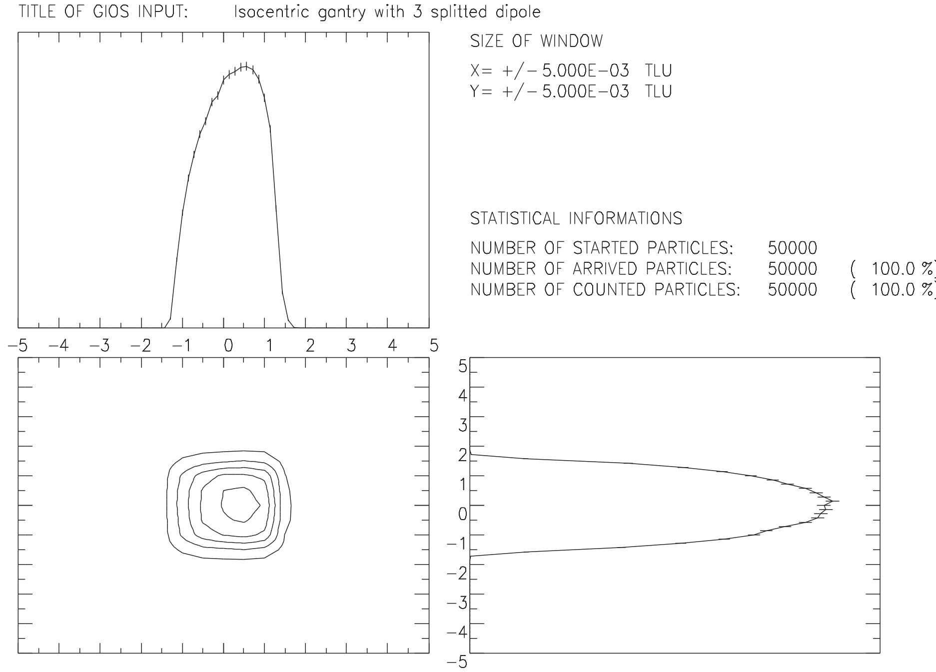
PLOT OF (Xversa Y) AT Z = 2.455E+01 LLU

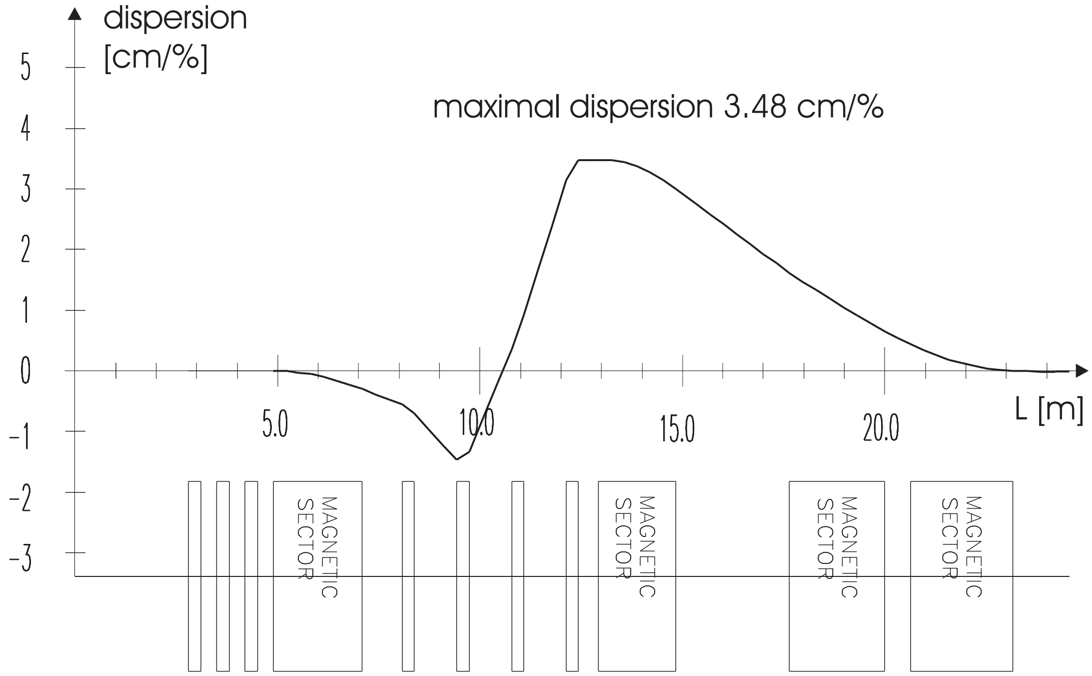
TITLE OF GIOS INPUT: Isocentric gantry with 3 splitted dipole



PLOT OF (Xversa Y) AT Z = 2.455E+01 LLU

TITLE OF GIOS INPUT: Isocentric gantry with 3 splitted dipole




dispersion
[cm/%]
maximal dispersion 3.48 cm/%
5
4
3
2
1
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-1
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MAGNETIC SECTOR
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