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**BEAM-OPTICS STUDY OF THE GANTRY BEAM DELIVERY
SYSTEM FOR LIGHT-ION CANCER THERAPY**

M. PAVLOVIC

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BEAM-OPTICS STUDY OF THE GANTRY BEAM DELIVERY SYSTEM FOR LIGHT-ION CANCER THERAPY.

M. Pavlovic

*Department of Nuclear Physics and Technology
Faculty of Electrical Engineering and Information Technology
Slovak Technical University
Ilkovicova 3, 812 19 Bratislava, Slovak Republic
E-mail: marius@elf.stuba.sk*

Abstract:

Ion optics considerations on the gantry-like beam delivery system for light-ion cancer therapy are presented. A low-angle active beam scanning in two directions is included in the preliminary gantry design. The optical properties of several gantry modifications are discussed.

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1 INTRODUCTION

It is a well-known fact, that conventional radiotherapy uses radiation with bad physical selectivity. Sparing of healthy tissue around the tumour and conformal tumour irradiation are achieved by rotating the source of radiation around the patient (rotating gantries). It is also a well-known fact, that protons and light-ions exhibit superior physical selectivity (inverse dose profile with well-pronounced Bragg peak at the end of particles' tracks) which makes the 3D conformal tumour targeting easier even without using rotating gantries. And it is a well-known fact too, that because of high rigidity of ion therapy beams (up to 7 Tm), the rotating gantry is one of the most complicated and challenging parts of medical accelerators. So far, rotating gantries have been built only for protons (e.g. [1, 2]), while light-ion therapy beams have been applied using fixed (horizontal and/or vertical) beam lines (e.g. [3, 4, 5]). However, in order to exploit all potential advantages of light ions, the fixed beam lines must be replaced in the future by gantry-type beam delivery systems. It also should not be overlooked, that the final goal is to move light-ion therapy from large accelerator research centres into hospitals [6]. A great amount of experience accumulated during many years of using conventional radiotherapy could not be effectively passed on light-ion therapy, if the same or similar irradiation techniques which the physicians are familiar with could not be applied.

That was why, beam optics studies of the gantry started at GSI a few years ago [7, 8, 9, 10]. This paper describes the latest development of the gantry design activities at GSI.

1.2 Main gantry specifications

It is beyond the scope of this paper to discuss all details concerning performance specifications of the gantry for light-ion cancer therapy. Because the field is new, a generally accepted and unambiguous set of desirable gantry parameters does not exist anyway. However, when designing the ion optics for the gantry, it is necessary to set an aim the gantry should meet. The most important gantry characteristics are given below. In some cases, the parameters are specified rather accurately using recent experience from experimental tests of light-ion therapy beams, in other cases only vague 'boundaries' are given.

The main gantry specifications as used in our beam optics design:

- Achromatic beam optics;
- Adjustable beam size from 3 to 10 mm; 7 discrete steps maximum [11];
- Beam rigidity 7 Tm; this parameter is dictated by the range of particles in the body (ranges quoted in literature are usually between 23 and 30 cm);
- Overall gantry dimensions and weight as small as possible; this is important especially for gantries which are planned to be installed in hospitals;
- Scanning field as large as possible; the values quoted in literature are usually around $20 \times 20 \text{ cm}^2$, but this requirement can be satisfied also by combination of active beam sweeping and moving the patient table [1];
- Scanning speed consistent with the maximum tolerable treatment time; the treatment time is typically from 2 to 5 minutes. For fully active beam delivery system this translates to scanning speed of $\approx 2 \text{ cm/ms}$ [12];
- Parallel or low-angle beam scanning mode; this means, that the angle of incidence measured between the axis of incoming beam and the axis normal to the scanned surface must be less than 1° [13];
- Isocentric configuration;
- Beam-waists at the isocentre;
- Drift from the gantry exit to the isocenter 1.2 m; free space between the gantry exit and the patient is necessary for inserting a beam diagnostic equipment [14];

In addition to these requirements which reflect mostly the desirable beam parameters at the gantry exit, another set of 'internal limits' has been applied. These limits should guarantee the feasibility of all ion optics elements as well as reasonable conditions for their assembling. The maximum quadrupole excitation is set to 0.7 T at the pole tip and the minimum drift space between any neighbouring elements is 0.5 m. The typical effective length of quadrupole is 0.3 m and the maximum full-aperture is 6 cm. The aperture of bending magnets (except for the last dipole) is twice as large as the maximum beam size inside the magnet in order to keep the beam in a good-quality field region. In principle, two essentially different types of bending magnets can be considered: superconducting and conventional. Superconducting magnets are superior because of dramatic reduction of the gantry size, but their feasibility and operational reliability are still open questions. The conventional gantries are huge and heavy which makes their installation in hospitals also very difficult. The beam optics considerations presented in this paper can be equally applied to both possible gantry types. However, achieved results are demonstrated for superconducting case, as it was chosen as a more likely gantry candidate for hospital-based medical accelerators [10, 15]. Using of superconducting magnets imposes additional specific limits as far as ion optics is concerned. The 'edge focusing' effect (at iron magnets caused by a pole face rotation) cannot be used and sufficiently long drifts in front of and behind the magnet must be reserved for corresponding cryogenic equipment. In our design these drifts are 1 m or more.

The input beam parameters in all presented cases are: 5 mm x 0.5 mrad; waist; momentum spread 0.2%. The same input parameters are used in both bending and non-bending planes. Calculations were performed by TRANSPORT, SLAC VERSION 4.8, MARCH 22, 1974 [16].

In order to avoid any confusion concerning the terminology, the following explanation is given. The typical shape of a gantry is shown in Fig. 1a. The gantry can revolve around the axis which is identical with the original beam direction. When any explanations or descriptions are given, the gantry is assumed to be in its top position (see Fig. 1a). This is important especially for correct interpretation of the 'up' and 'down' symbols. The action of bending magnets and scanners can therefore be easily described as bending *up* or *down* keeping in mind the top position of the gantry. In accordance with the above definition, the gantry consists of bend-up shoulder, straight section and bend-down shoulder. We also prefer using '*bending*' and '*non-bending plane*' to distinguish between two planes which are different from the point of view of ion optics. However, in figure captions they are traditionally called '*horizontal*' and '*vertical*', where horizontal means bending and vertical non-bending plane. Other terminology is consistent with TRANSPORT [16].

2 THE LAST VERSION OF SUPERCONDUCTING GANTRY

The superconducting gantry designed by Janik et al. [9, 17] served as a starting point for further optimization. Figures 1a, 1b, and 1c show the most important gantry characteristics (overall dimensions, scanning mode and optical properties). The beam optics layout had been strictly derived from the guiding principle, that scanners must be placed into the focal points of the system in order to get parallel scanning mode at the gantry exit. That was why, additional quadrupoles had to be inserted inbetween the scanners and the bend-down shoulder in order to form point-to-parallel transformation. There are several disadvantages of this design:

- **The optics is not achromatic;** zero dispersion is achieved at the isocentre but zero derivative of the dispersion function is not (see Fig. 1c);
- **The gantry is not as small as it could be;** the minimum possible gantry radius is equal to the bending radius of the last bend-down dipole plus drift to the patient. Once any other beam optics components are introduced into the bend-down shoulder, the total gantry radius becomes larger. In this case, the bend-down dipole is split into two pieces and quadrupole is inserted inbetween them. That makes the resulting gantry radius 3.3 m instead of theoretical minimum 2.5 m;
- **The aperture of the elements which follow the scanners must be large;** in this case, the largest quadrupole has the full-aperture 24 cm, effective length 70 cm and excitation 1 T;
- Misalignment, mispowering or higher-order effects of the quadrupoles behind the scanners may lead to a **wrong position of the beam** at the gantry exit; if this problem is detected by the final beam-diagnostic equipment, it is not easy to find out what corrections should be done. Evaluation of some higher-order effects can be found in [17].

Figure 1a. The last version of superconducting gantry: schematic view and overall dimensions.

Figure 1b. The last version of superconducting gantry: beam envelopes for maximum excitation of scanners -parallel scanning mode.

Figure 1c. The last version of superconducting gantry: beam envelopes and dispersion function for zero excitation of scanners. Zero dispersion is achieved only in the isocentre.

3 A NEW ION OPTICS CONCEPT OF THE GANTRY

It is important to point out, that two essential changes were done concerning the set of requirements the gantry must meet. After consulting the experts and using the experience from raster-scanner tests [12, 13], the strict demand for parallel beam scanning mode was waived and replaced by the maximum tolerable angle of incidence to be less than 1° . On the other hand, achromatic beam optics was found to be an important feature which must be necessarily satisfied, otherwise particles with different momentum would be spatially distributed inside the beam. This might cause non-negligible differences in ranges between different parts of the beam.

There were several logical steps in the development of the new ion beam-optics concept of the gantry. They are going to be presented below.

3.1 A small superconducting gantry without scanning

As the first step, we removed the scanning option from the gantry and tried to make it as small as possible. The bend-down part, which determines the total gantry radius, consists now of the single 90° superconducting dipole ($B=5.56$ T, bending radius $\rho=1.25$ m) and drift to the patient only. The bend-up part consists of two 45° superconducting dipoles. Other elements are normalconducting. All parameters relevant to ion optics can be found in the TRANSPORT input file 'SMALL SUPERCONDUCTING GANTRY WITHOUT SCANNING' in the Appendix.

At the isocentre, 6 constraints must be fitted:

- **Achromatic beam optics** two constraints upon the overall transform matrix;
- **Adjustable beam size** one constraint upon the σ -matrix in the bending plane and one constraint upon the σ -matrix in the non-bending plane;
- **Beam waist** one constraint upon the σ -matrix in the bending plane and one constraint upon the σ -matrix in the non-bending plane.

A discussion may arise, whether it is really necessary to form waists at the isocentre. The waist has two favourable properties. The beam envelope changes very little in the vicinity of waist. In addition to this, the emittance diagram of the beam is an upright ellipse. That means, that the beam emittance at waist can be simply expressed as the product of the beam half-size and half-divergence [16]. The consequence is, that the beam having the same emittance and size in both bending and non-bending planes will have at waist also the same divergence in those two planes. In other words, applying the same size and waist constraints in both planes results in a symmetric beam, which makes treatment planning easier.

Theoretically, six constraints can be fitted by six variable parameters, in our case by six quadrupoles with variable excitation. The requirement for minimum gantry size stimulates looking for solutions with minimum number of quadrupoles. Although a solution with six quadrupoles was also found, beam optics became much more flexible when this number was increased to seven. There are also a few other reasons, why certain number of 'redundant' quadrupole is useful. It may happen for example, that final constraints are fitted, but the beam size exceeds the maximum tolerable value somewhere in the middle of the system. In order to avoid this problem, some additional 'invisible' constraints have been applied during the calculations mainly to keep the apertures of bending magnets small. The solution with seven quadrupoles was carefully examined. A conclusion was made that the optics was flexible enough and there was no need to add another quadrupole. Figures 2a - 2g illustrate the optical flexibility of the gantry. The optics is always achromatic and the beam has always waists at the isocentre. The beam diameter can be adjusted from 1.5 to 10 mm.

Figure 2a. Schematic view of the small superconducting gantry without scanning. Q=quadrupole, BM=bending magnet, dimensions in mm.

Figures 2b, 2c. Small superconducting gantry without scanning: beam diameters: 1.5mm, 3mm.

horiz. (upper) and vert. envelops; momentum disp.

horiz. (upper) and vert. envelops; momentum disp.

Figures 2d, 2e. Small superconducting gantry without scanning: beam diameters: 6mm, 10mm.

horiz. (upper) and vert. envelops; momentum disp.

horiz. (upper) and vert. envelops; momentum disp.

Figures 2f, 2g. Small superconducting gantry without scanning: different beam diameters in bending and non-bending planes: 1.5mm/10mm, 8mm/2mm.

Sensitivity of optics to quadrupole mispowering is an interesting question which has direct impact on gantry reliability. At this opportunity, another important feature of gantry-optics can be demonstrated. As it is seen from Figures 2a - 2g, those seven quadrupoles are distributed along the gantry by certain specific manner which is meaningful. Three of them are placed in front of the bend-up shoulder where the dispersion function is zero (they are assumed to be rotated together with the gantry). In this position, they can collaborate on the final beam size but cannot influence the dispersion function at all. The question arises, whether those quadrupoles can be effectively used for compensation of errors caused by mispowering of remaining four quadrupoles. To see the answer, the TRANSPORT was run under following circumstances:

1. The quadrupole excitations were calculated for the reference beam (3 mm, waists, achromatic).
2. All quadrupoles except for the first triplet were mispowered. The errors plus or minus 1% from the reference (calculated) value were applied.
3. Final constraints set has been modified; the constraints for achromatic beam optics and for beam waists have been removed; the 3mm beam diameter (i.e. original beam size) was required.
4. The TRANSPORT fitting routine was run allowing only first triplet to be varied. Dispersion at the isocentre and results of fitting (successful or failed) for three different beam-size tolerances (0.2 mm, 0.1mm, 0.02 mm) have been picked up.

Tables 1a and 1b show the results. Because of the above mentioned redundancy, many solutions exist for a given set of constraints at the gantry exit (those solutions which belong to Tables 1a and 1b are shown in Figures 3a and 3b, respectively). However, solutions which are equivalent as far as the final beam parameters are concerned may not be equivalent from the point of view of sensitivity to errors. Even more can be read out. In our example of the more sensitive solution (Table 1a), the fitting failed in those cases only, when the second quadrupole was mispowered by minus 1% error. This may indicate, which particular quadrupole is the critical one. Notice (compare the corresponding excitations), that the trend is to reduce the excitation of critical element in order to get better results.

Table 1a. Mispowering study of the small superconducting gantry without scanning. More sensitive solution; fitting failed when the second quadrupole was mispowered by -1% error. V-excitation of quadrupoles variable for fitting, R-reference excitation of mispowered quadrupoles, F-fitting failed, OK-fitting successful. Excitations are given in accordance with the TRANSPORT definition (magnetic field in kG at the pole tip) [16].

2.11431 (V) -4.56601 (V) 3.09964 (V) 2.49825 (R) -5.02122 (R) 4.40738 (R) -0.59749 (R)

Error combination	Tolerance of the beam diameter [mm]			Dispersion [mm/%]
	±0.2	±0.1	±0.02	
+ + + +	OK	OK	OK	0.2720
+ + + -	OK	OK	OK	0.2809
+ + - +	OK	OK	OK	-0.3223
+ + - -	OK	OK	OK	-0.3132
+ - + +	F	F	F	0.1049
+ - + -	F	F	F	0.1138
+ - - +	F	F	F	-0.4926
+ - - -	F	F	F	-0.4834
- + + +	OK	OK	OK	0.4770
- + + -	OK	OK	OK	0.4857
- + - +	OK	OK	OK	-0.1105
- + - -	OK	OK	OK	-0.1015
- - + +	F	F	F	0.3136
- - + -	F	F	F	0.3224
- - - +	F	F	F	-0.2770
- - - -	F	F	F	-0.2679

Figure 3a. Beam envelopes and dispersion function corresponding to Table 1a.

Table 1b. Mispowering study of the small superconducting gantry without scanning. Less sensitive solution; fitting always successful. V-excitation of quadrupoles variable for fitting, R-reference excitation of mispowered quadrupoles, F-fitting failed, OK-fitting successful. Excitations are given in accordance with the TRANSPORT definition (magnetic field in kG at the pole tip) [16].

1.81914 (V) -3.69273 (V) 2.43045 (V) 3.77164 (R) -4.52937 (R) 4.73653 (R) -2.24875 (R)

Error combination	Tolerance of the beam diameter [mm]			Dispersion [mm/%]
	± 0.2	± 0.1	± 0.02	
+ + + +	OK	OK	OK	0.3379
+ + + -	OK	OK	OK	0.3721
+ + - +	OK	OK	OK	-0.4018
+ + - -	OK	OK	OK	-0.3660
+ - + +	OK	OK	OK	0.1324
+ - + -	OK	OK	OK	0.1670
+ - - +	OK	OK	OK	-0.6116
+ - - -	OK	OK	OK	-0.5755
- + + +	OK	OK	OK	0.5672
- + + -	OK	OK	OK	0.6012
- + - +	OK	OK	OK	-0.1630
- + - -	OK	OK	OK	-0.1275
- - + +	OK	OK	OK	0.3660
- - + -	OK	OK	OK	0.4003
- - - +	OK	OK	OK	-0.3685
- - - -	OK	OK	OK	-0.3326

horiz. (upper) and vert. envelops; momentum disp.

Figure 3b. Beam envelopes and dispersion function corresponding to Table 1b.

3.2 Superconducting gantry with scanning

One of the main research and scientific goals of the GSI therapy project is development of a novel irradiation technique: raster-scanning with active energy variation from the accelerator [11, 18]. In contrast to all other techniques which have been used so far, no material is necessary to be inserted into the beam. This is an important advantage especially for light-ion beams, when the interaction with matter is very complicated and produces always 'dirty' radiation background. From the ion optics point of view, any amount of material traversed by a beam blows up the emittance and reduces the beam quality. It is therefore an essential thing, that the gantry must be constructed as a fully active beam delivery system.

In order to add a scanning option into the gantry, the previous design has been modified. Because the scanning magnets have only very little influence on the optical properties of the gantry (this assumption is justified by the facts, that bending angles of scanning magnets are very low, typically 10° , and parallel pole face orientation cancels the focusing effect in the bending plane), the drift between the last quadrupole and the bend-down shoulder was chosen as the best place for scanners. All optical properties as formed by a preceding optical system remain untouched, if the scanners are placed behind the optical system. Thus, the only necessary modification to the previous design was creating a sufficiently long drift space in front of the bend-down shoulder. The drift was prolonged from original 1m to final 4m. Beam optics has been carefully checked again and it has been concluded, that it fulfil all requirements: beam diameter can be adjusted from 2 to 10 mm, waists, achromatic. Figures 4a and 4b show two extreme cases: 2 mm and 10 mm beams. TRANSPORT input file for 3 mm reference beam is titled 'SUPERCONDUCTING GANTRY WITH SCANNING' and is given in the Appendix.

horiz. (upper) and vert. envelops, momentum disp.

horiz. (upper) and vert. envelops, momentum disp.

Figures 4a, 4b. Superconducting gantry with scanning; minimum (2mm) and maximum (10mm) beam size.

The mispowering study was done exactly by the same manner as in the previous case. Results are in Tables 2a and 2b. Similar behaviour has been observed. An improvement was achieved by reducing the excitation of the critical element.

Table 2a. Mispowering study of the superconducting gantry with scanning. More sensitive solution; fitting failed mostly when the second quadrupole was mispowered by -1% error. V-excitation of quadrupoles variable for fitting, R-reference excitation of mispowered quadrupoles, F-fitting failed, OK-fitting successful. Excitations are given in accordance with the TRANSPORT definition (magnetic field in kG at the pole tip) [16].

1.58219 (V) -0.03232 (V) -2.61294 (V) 5.36901 (R) -3.75174 (R) 5.41733 (R) -2.71230 (R)

Error combination	Tolerance of the beam diameter [mm]			Dispersion [mm/%]
	±0.2	±0.1	±0.02	
+ + + +	OK	OK	OK	4.0550
+ + + -	OK	OK	OK	2.8699
+ + - +	OK	OK	OK	-1.8386
+ + - -	OK	OK	OK	-3.0509
+ - + +	OK	OK	OK	3.1923
+ - + -	F	F	F	1.9954
+ - - +	F	F	F	-2.7432
+ - - -	F	F	F	-3.9675
- + + +	OK	OK	OK	3.8790
- + + -	OK	OK	OK	2.7053
- + - +	OK	OK	OK	-1.9487
- + - -	OK	OK	OK	-3.1494
- - + +	OK	OK	OK	3.0294
- - + -	F	F	F	1.8441
- - - +	F	F	F	-2.8396
- - - -	F	F	F	-4.0521

Table 2b. Mispowering study of the superconducting gantry with scanning. Less sensitive solution achieved by reducing the excitation of the second quadrupole. V-excitation of quadrupoles variable for fitting, R-reference excitation of mispowered quadrupoles, F-fitting failed, OK-fitting successful. Excitations are given in accordance with the TRANSPORT definition (magnetic field in kG at the pole tip) [16].

1.45404 (V) 0.44441 (V) -2.72070 (V) 6.52333 (R) -3.30000 (R) 5.56739 (R) -3.44415 (R)

Error combination	Tolerance of the beam diameter [mm]			Dispersion [mm/%]
	±0.2	±0.1	±0.02	
+ + + +	OK	OK	OK	4.7981
+ + + -	OK	OK	OK	3.2787
+ + - +	OK	OK	OK	-2.0688
+ + - -	OK	OK	OK	-3.6266
+ - + +	OK	OK	OK	3.8253
+ - + -	OK	OK	OK	2.2909
+ - - +	OK	OK	OK	-3.0880
+ - - -	F	F	F	-4.6610
- + + +	OK	OK	OK	4.5532
- + + -	OK	OK	OK	3.0487
- + - +	OK	OK	OK	-2.2346
- + - -	OK	OK	OK	-3.7770
- - + +	OK	OK	OK	3.5953
- - + -	OK	OK	OK	2.0760
- - - +	OK	OK	OK	-3.2382
- - - -	F	F	F	-4.7956

It has not been showed yet how that 4 m long drift space can be used for scanning. Situation is very simple in the non-bending plane. The bending magnet in the non-bending plane is like a drift; defocusing contribution of the fringing fields is weak and can be taken into account in calculations. In order to keep the angle of incidence as small as possible, the scanner-to-isocentre distance must be large. That is why, the scanner is favourably placed immediately after the last quadrupole. This alternative is shown in Figure 5. As an example, 0.6 m long scanning magnet is placed 0.5 m after the quadrupole. Scanner-to-isocentre distance is approximately 6.4 m (if measured from isocentre to the middle of the scanner). For this geometry, 5 cm beam displacement corresponds to the angle of incidence 0.45° , magnetic field of the scanner 0.09 T, and field ramp rate 37 T/s (last two quantities were calculated for 7 Tm beam rigidity and 2 cm/ms scanning speed). The angle of incidence stays below 1° until 11 cm beam displacement. Active beam scanning in one direction can be combined with the moving of the patient table in the other direction to cover a desirable scanning field.

Figure 5. Superconducting gantry with scanning in the non-bending plane only.

Although the previous solution represents a reasonable compromise between the gantry capabilities and technical difficulties (a similar system is used in PSI [1]), the medical community prefers active beam scanning in both directions without any movement of the patient table [19].

In the bending plane, the situation is a little bit more complicated because of focusing action of the bending magnet. When scanner is placed anywhere in the region which is reserved for scanners the bending magnet tries to focus the beam back. It can readily be shown, that conditions for nearly point-to-point imaging are satisfied (see Figure 6, scanner 2 m in front of the bending magnet). Two scanners for the bending plane must be used in order to overcome the problem. The first scanner deflects the beam away from the optical axis, the second one brings it back. If the focal point of the bending magnet is hit, even parallel scanning occurs. In order to exploit the space reserved for scanners effectively, the following configuration of scanning magnets has been proposed (see Figure 7).

Figure 6. Illustration of the problem with scanning in bending plane. One scanner placed 2m in front of the bend-down magnet. Conditions for nearly point-to-point imaging are satisfied.

Figure 7. Scheme of the two-direction scanning system for superconducting gantry. X1, X2 - scanners in bending plane, Y - scanner in non-bending plane. Dimensions in cm.

Figure 8 shows the beam envelopes calculated by TRANSPORT for reference 3 mm beam and maximum excitation of scanners. The required magnetic fields for full beam displacement (5cm) are 0.15T for non-bending plane scanner Y and 0.5T and 0.7T for bending plane scanners X1 and X2, respectively.

Figure 8. Two-direction scanning of the 3mm reference beam. Excitation of scanners: Y - 0.15T, X1 - 0.5T, X2 - 0.7T.

Calculations were also performed to prove, that the scanners have negligible influence on the optical properties of the gantry. Results are summarized in Table 3. A weak contribution from edge focusing is still visible in non-bending plane. Corresponding TRANSPORT input file called 'SUPERCONDUCTING GANTRY WITH SCANNING - TRUE DIPOLES' is given in the Appendix.

Table 3. Influence of the X-scanners on the output beam parameters and dispersion function for superconducting gantry. Excitation of scanners corresponds to the maximum beam displacement at the gantry exit (5cm).

Status	Dispersion [mm/%]	Beam radius (horizontal plane/vertical plane) [mm]
Both scanners switched off	-0.0174	1.00/1.01
First scanner active (up)	0.5188	1.00/1.01
Both scanners active (up-down)	0.4943	1.00/1.08
First scanner active (down)	-0.5094	1.00/1.01
Both scanners active (down-up)	-0.4718	1.00/1.08
Both scanners switched off	0.0125	5.00/5.00
First scanner active (up)	0.5488	4.99/4.93
Both scanners active (up-down)	0.5243	4.99/4.77
First scanner active (down)	-0.4795	4.99/4.93
Both scanners active (down-up)	-0.4419	4.99/4.77

3.3 Hybrid gantry with scanning

There are many mutations of the gantry configuration possible using the advantage, that the optical and scanning systems are independent. This section describes a so called 'hybrid gantry' which is derived from the previous superconducting gantry by replacing the superconducting magnets in the bend-up shoulder by conventional magnets. In order to keep the same gantry radius, two 30° normalconducting magnets are used instead of 45° superconducting ones. Also a quadrupole singlet is changed to doublet mainly to reduce the vertical gap of the magnets. Figures 10a - 10e show the scanned beam for different values of the beam size. The optics is always achromatic and the beam has always waists at the isocentre. The scanning system is identical with that one used in superconducting gantry. This set of figures clearly demonstrates, that the optical system is used exclusively for controlling the beam parameters and the scanning system provides desirable scanning without any 'help' from the optical system. This particular feature of the gantry optics is important for easy and reliable gantry operation. TRANSPORT input file is called 'HYBRID GANTRY' and is listed in the Appendix.

Figure 10a. Hybrid gantry: 2mm beam

Figures 10b, 10c. Hybrid gantry: 4mm and 6mm beams.

Figures 10d, 10e. Hybrid gantry: 8mm and 10mm beams.

Results of the mispowering study for 3mm reference beam are in Table 6.

Table 6. *Mispowering study of the hybrid gantry for 3mm reference beam. Fitting failed when the fourth quadrupole was mispowered by -1% error. F-fitting failed, OK-fitting successful.*

Error combination	Tolerance of the beam diameter [mm]			Dispersion [mm/%]
	± 0.2	± 0.1	± 0.02	
+ + + + +	OK	OK	OK	5.1569
+ + + + -	OK	OK	OK	3.4486
+ + + - +	F	F	F	-2.0604
+ + + - -	F	F	F	-3.8126
+ + - + +	OK	OK	OK	4.3854
+ + - + -	OK	OK	OK	2.6652
+ + - - +	F	F	F	-2.8647
+ + - - -	F	F	F	-4.6291
+ - + + +	OK	OK	OK	4.9479
+ - + + -	OK	OK	OK	3.2933
+ - + - +	F	F	F	-2.0200
+ - + - -	F	F	F	-3.7170
+ - - + +	OK	OK	OK	4.2075
+ - - + -	OK	OK	OK	2.5415
+ - - - +	F	F	F	-2.7919
+ - - - -	F	F	F	-4.5005
- + + + +	OK	OK	OK	5.0207
- + + + -	OK	OK	OK	3.3114
- + + - +	F	F	F	-2.1974
- + + - -	F	F	F	-3.9506
- + - + +	OK	OK	OK	4.2498
- + - + -	OK	OK	OK	2.5286
- + - - +	F	F	F	-3.0010
- + - - -	F	F	F	-4.7663
- - + + +	OK	OK	OK	4.8101
- - + + -	OK	OK	OK	3.1549
- - + - +	F	F	F	-2.1567
- - + - -	F	F	F	-3.8542
- - - + +	OK	OK	OK	4.0706
- - - + -	OK	OK	OK	2.4040
- - - - +	F	F	F	-2.9276
- - - - -	F	F	F	-4.6367

Because fitting failed in those cases only when **the fourth quadrupole** was mispowered by -1% error, a conclusion was made, that higher precision is required for powering of this quadrupole. Another set of calculations was done with exact (reference) excitation of the critical quadrupole. Results are summarized in Table 7 showing an expected improvement.

Table 7. Mispowering study of the hybrid gantry for 3mm reference beam and exact excitation of the critical quadrupole. F-fitting failed, OK-fitting successful, R-reference excitation.

Error combination	Tolerance of the beam diameter [mm]			Dispersion [mm/%]
	± 0.2	± 0.1	± 0.02	
+ + + R +	OK	OK	OK	1.5496
+ + + R -	OK	OK	OK	-0.1806
+ + - R +	OK	OK	OK	0.7617
+ + - R -	OK	OK	OK	-0.9805
+ - + R +	OK	OK	OK	1.4652
+ - + R -	OK	OK	OK	-0.2105
+ - - R +	OK	OK	OK	0.7092
+ - - R -	OK	OK	F	-0.9781
- + + R +	OK	OK	OK	1.4131
- + + R -	OK	OK	OK	-0.3182
- + - R +	OK	OK	OK	0.6258
- + - R -	OK	F	F	-1.1175
- - + R +	OK	OK	OK	1.3280
- - + R -	OK	OK	F	-0.3483
- - - R +	OK	OK	OK	0.5728
- - - R -	F	F	F	-1.1150

4 DISCUSSION

The principal advantage of the proposed ion-optics concept is **decoupling the optical system from scanning system**. The optical system is not involved in forming the point-to-parallel transformation and can be much more effectively used to control the beam parameters at the gantry exit. The optical and scanning systems can be designed and optimized nearly independently of each other, unless the scanning system is too large to fit the space reserved for it. That is why, large number of different mutations are possible and the gantry is still open to further optimization. Using two scanners in non-bending plane by the similar manner as they are used in bending plane would make the parallel scanning mode possible even in both planes.

The proper function of the gantry's subsystems can be checked and errors can be easily corrected. We recommend to insert beam diagnostic components not only at the gantry exit, but also in front of the scanning system. In this position, the beam parameters can be permanently monitored and the optical system can be checked independently from beam scanning.

It was also shown, that the first quadrupole triplet placed in the zero-dispersion region is predestinated to compensate beam size deviations caused by mispowering of other quadrupoles. In most cases (not in all of them), it is able to compensate mispowering errors as large as $\pm 1\%$. Some information can also be gained, which error-combinations cannot be compensated and which quadrupoles should be excited with considerably higher precision [20]. However, in this paper only few situations have been investigated and sensitivity of the system to all other possible errors needs further study.

5 CONCLUSION

Progress in the light-ion gantry design activities at GSI has been reported. A new ion-optics concept for the superconducting gantry with active beam scanning in two directions has been introduced and demonstrated. The optical system and scanning system have been decoupled, which offers higher degree of flexibility and reliability to both systems.

Acknowledgements

We would like to thank D. Böhne for supporting this work and B. Langenbeck, M. Müller, G. Kraft, Th. Haberer and G. Breitenberger for friendly atmosphere and many inspiring discussions. We are indebted to J. Janik for making his data available.

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APPENDIX - TRANSPORT INPUT FILES

The authentic input files are given as they were used in calculations.

Each version of the gantry is represented by one file which corresponds to the 3 mm reference beam.

```

' SMALL SUPERCONDUCTING GANTRY WITHOUT SCANNING '
0
(-----)
( This file describes the small superconducting gantry )
( Achromatic, Waists, No scanning; )
( The possible beam size from 1.5mm to 10mm )
( This is an example of the REFERENCE BEAM 3mm diameter )
( Last editing: 17.11.1995 by M. Pavlovic )
(-----)
13. 2.;
13. 12.;
1. 0.5 0.5 0.5 0.5 0. 0.2 2.08358;
16. 5. 2.; ( vertical half-aperture in CM )
16. 4. 2.; ( horizontal half-aperture in CM )
9. 5.;
3. 0.1 'dpm1';
9. 0.;
5.00 0.3 1.81914 2. 'QPM1';
9. 6.;
3. 0.1 'dpm1';
9. 0.;
5.00 0.3 -3.69273 2. 'QPM1';
9. 6.;
3. 0.1 'dpm2';
9. 0.;
5.00 0.3 2.43045 2. 'QPM2';
9. 10.;
3. 0.1 'dpm3';
9. 0.;
13. 1.;
2. 0.;
4. 0.218169 -55.6 0 'BM1';
4. 0.218169 -55.6 0 'BM1';
4. 0.218169 -55.6 0 'BM1';
4. 0.218169 -55.6 0 'BM1';
4. 0.1090845 -55.6 0 'BM1';
2. 0.;
9. 11.;
3. 0.1;
9. 0.;
5.00 .30 3.77164 2. 'QDt2';
9. 11.;
3. 0.1 'dzt1';
9. 0.;
16. 5. 3;
16. 4. 3;
2. 0.;
4. 0.218169 55.600 0. 'BM2';
4. 0.218169 55.600 0. 'BM2';
4. 0.218169 55.600 0. 'BM2';
4. 0.218169 55.600 0. 'BM2';
4. 0.1090845 55.600 0. 'BM2';
2. 0.;
10.2 3. 3. 1.49 .01; (beam size limit at the magnet aperture)
13. 1.;

```

```

9. 10.;
3. 0.1;
9. 0.;
5.00 0.30 -4.52937 3;
9. 10.;
3. 0.1;
9. 0.;
5.00 0.3 4.73653 2.;
9. 8.;
3. 0.1;
9. 0.;
5.00 0.3 -2.24875 1.;
9. 10.;
3. 0.1;
9. 0.;
16. 5. 2.;
16. 4. 2.;
2. 0.;
4.000 0.24544 55.600 0.00000 'BMA';
4.000 0.24544 55.600 0.00000 'BMA';
4.000 0.24544 55.600 0.00000 'BMA';
4.000 0.24544 55.600 0.00000 'BMA';
4.000 0.24544 55.600 0.00000 'BMB';
4.000 0.24544 55.600 0.00000 'BMB';
4.000 0.24544 55.600 0.00000 'BMB';
4.000 0.24544 55.600 0.00000 'BMB';
2. 0.;
9. 12.;
3. 0.1;
9. 0.;
10. 1. 1. 0.150 0.001;
10. 3. 3. 0.150 0.001;
10. -1. 6. 0.0 0.02;
10. -2. 6. 0.0 0.02;
10. 4. 3. 0.0 0.001;
10. 2. 1. 0.0 0.001;
13 4;
13 1;
(-----This is the END of DATA-----)
SENTINEL
SENTINEL

```

```

' SUPERCONDUCTING GANTRY WITH SCANNING '
0
(-----)
( This file describes the superconducting gantry )
( Achromatic, Waists, Scanning field 10cm x 10cm )
( Scanning angles 0.5/0.6 deg, 2.3/parallel respectively )
( This is an example of the REFERENCE 3mm diameter beam. )
( Last editing: 22.11.1995 by M. Pavlovic )
(-----)
13. 2.;
13. 12.;
1. 0.5 0.5 0.5 0.5 0. 0.2 2.08358;
-17.0;
16. 5. 2.; ( vertical half-aperture in CM )
16. 4. 2.; ( horizontal half-aperture in CM )
9. 5.;
3. 0.1 'dpm1';
9. 0.;
5.00 0.3 1.58219 2. 'QPM1';
9. 6.;
3. 0.1 'dpm1';
9. 0.;
5.00 0.3 -0.03232 2. 'QPM1';
9. 6.;
3. 0.1 'dpm2';
9. 0.;
5.00 0.3 -2.61294 2. 'QPM2';
9. 10.;
3. 0.1 'dpm3';
9. 0.;
13. 1.;
2. 0.;
4. 0.218169 -55.6 0 'BM1';
4. 0.218169 -55.6 0 'BM1';
4. 0.218169 -55.6 0 'BM1';
4. 0.218169 -55.6 0 'BM1';
4. 0.1090845 -55.6 0 'BM1';
2. 0.;
9. 10.;
3. 0.1;
9. 0.;
3. 0.075;
5.00 .35 5.36901 2. 'QDt2';
9. 10.;
3. 0.1 'dzt1';
9. 0.;
3. 0.075;
16. 5. 3;
16. 4. 3;
2. 0.;
4. 0.218169 55.600 0. 'BM2';
4. 0.218169 55.600 0. 'BM2';
4. 0.218169 55.600 0. 'BM2';
4. 0.218169 55.600 0. 'BM2';
4. 0.1090845 55.600 0. 'BM2';

```

```

2. 0.;
10.2 3. 3. 1.49 01; (beam size limit in the magnet)
13. 1.;
9. 15.;
3. 0.1;
9. 0.;
5.00 0.30 -3.75174 3;
9. 13.;
3. 0.1;
9. 0.;
10.2 1. 1. 2.15 .01; (beam size limit in QUAD)
5.00 0.3 5.41733 3;
9. 7.;
3. 0.1;
9. 0.;
5.00 0.3 -2.71230 3.;
9. 5.;
3. 0.1;
9. 0.;
3. 0.20;
-7. 0. 26.8 0. 0 0. 0. 'x1'; (B = 0.5 T)
3. 0.20;
9. 5.;
3. 0.1;
9. 0.;
3. 0.20;
-7. 0. 0. 0. -8.362 0. 0. 'y'; (B = 0.15 T)
3. 0.20;
9. 5.;
3. 0.1;
9. 0.;
3. 0.175;
-7. 0. -26.8 0. 0. 0. 0. 'x2';
3. 0.175;
3. 0.175; (B = 0.7 T)
-7. 0. -40.4 0. 0. 0. 0. 'x22';
3. 0.175;
9. 10.;
3. 0.1;
9. 0.;
16. 5. 5.5;
16. 4. 5.5;
2. 0.;
4.000 0.24544 55.600 0.00000 'BMA';
4.000 0.24544 55.600 0.00000 'BMA';
4.000 0.24544 55.600 0.00000 'BMA';
4.000 0.24544 55.600 0.00000 'BMA';
4.000 0.24544 55.600 0.00000 'BMB';
4.000 0.24544 55.600 0.00000 'BMB';
4.000 0.24544 55.600 0.00000 'BMB';
4.000 0.24544 55.600 0.00000 'BMB';
2. 0.;
9. 12.;
3. 0.1;
9. 0.;

```

```

10.    1.    1.    0.150  0.001;
10.    3.    3.    0.150  0.001;
10.   -1.    6.    0.0    0.02 ;
10.   -2.    6.    0.0    0.02 ;
10.    4.    3.    0.0    0.001;
10.    2.    1.    0.0    0.001;
13     4;
13     1;
(-----This is the END of DATA-----)
SENTINEL
SENTINEL

```

```

' SUPERCONDUCTING GANTRY WITH SCANNING - TRUE DIPOLES '
0
(-----)
( This file describes the superconducting gantry. )
( Achromatic, Waists, Scanning field 10cm x 10cm. )
( Scanning angles 0.5/0.6 deg, 2.3/parallel, respectively. )
( This is an example of the REFERENCE 3mm beam. )
( The X-scanners are simulated here as real dipole magnets )
( in order to investigate influence of the scanners on )
( final beam parametres and dispersion function. )
( Last editing: 20.11.1995 by M. Pavlovic )
(-----)
13. 2.;
13. 12.;
1. 0.5 0.5 0.5 0.3 0. 0.2 2.08358;
-17.0;
16. 5. 2.; ( vertical half-aperture in CM )
16. 4. 2.; ( horizontal half-aperture in CM )
9. 5.;
3. 0.1 'dpm1';
9. 0.;
5.00 0.3 1.58219 2. 'QPM1';
9. 6.;
3. 0.1 'dpm1';
9. 0.;
5.00 0.3 -0.03232 2. 'QPM1';
9. 6.;
3. 0.1 'dpm2';
9. 0.;
5.00 0.3 -2.61294 2. 'QPM2';
9. 10.;
3. 0.1 'dpm3';
9. 0.;
13. 1.;
2. 0.;
4. 0.218169 -55.6 0 'BM1';
4. 0.218169 -55.6 0 'BM1';
4. 0.218169 -55.6 0 'BM1';
4. 0.218169 -55.6 0 'BM1';
4. 0.1090845 -55.6 0 'BM1';
2. 0.;
9. 10.;
3. 0.1;
9. 0.;
3. 0.075;
5.00 .35 5.36901 2. 'QDt2';
9. 10.;
3. 0.1 'dzt1';
9. 0.;
3. 0.075;
16. 5. 3;
16. 4. 3;
2. 0.;
4. 0.218169 55.600 0. 'BM2';
4. 0.218169 55.600 0. 'BM2';

```

```

        4.    0.218169    55.600    0.    'BM2';
        4.    0.218169    55.600    0.    'BM2';
        4.    0.1090845    55.600    0.    'BM2';
        2.    0.;
10.2    3.    3.    1.49    .01;
13.    1.;
9.    15.;
3.    0.1;
9.    0.;
5.00 0.30    -3.75174    3.;
9.    13.;
3.    0.1;
9.    0.;
10.2    1.    1.    2.15    .01;
5.00 0.3    5.41733    3.;
9.    7.;
3.    0.1;
9.    0.;
5.00 0.3    -2.71230    3.;
9.    5.;
3.    0.1;
9.    0.;
16.    5.    3.;
16.    4.    3.;
-3.    0.4    ; (use this drift when scanner is switched off)
2.    0.;
4.    .40    -4.65656    0.; (simulation of the first X-scanner)
2.    -1.53553;
9.    5.;
3.    0.1;
9.    0.;
3. 0.20 ;
7.    0.    0.    0.    -8.362    0.    0.    'y'; (B = 0.15 T)
3. 0.20 ;
9.    5. ;
3. 0.1 ;
9.    0. ;
-3.    0.7; (use this drift when the scanner is switched off)
16.    5.    3.5;
16.    4.    6;
2.    1.53553;
4.    .70    6.67210    0. ; (second X-scanner)
2.    2.31475;
9. 10. ;
3. 0.1 ;
9.    0. ;
16.    5.    5.5;
16.    4.    5.5;
        2.    0. ;
        4.000 0.24544    55.600    0.00000 'BMA';
        4.000 0.24544    55.600    0.00000 'BMA';
        4.000 0.24544    55.600    0.00000 'BMA';
        4.000 0.24544    55.600    0.00000 'BMA';
        4.000 0.24544    55.600    0.00000 'BMB';
        4.000 0.24544    55.600    0.00000 'BMB';

```



```

4.000 0.24544    55.600  0.00000 'BMB';
4.000 0.24544    55.600  0.00000 'BMB';
2. 0. ;
9. 12.;
3. 0.1;
9. 0.;
3. 0.; ( matching drift, only positive, as small as possible)
10. 1. 1. 0.100 0.001;
10. 3. 3. 0.100 0.001;
10. -1. 6. 0.0 0.02 ;
10. -2. 6. 0.0 0.02 ;
10. 4. 3. 0.0 0.001;
10. 2. 1. 0.0 0.001;
13 4;
13 1;
(-----This is the END of DATA-----)
SENTINEL
SENTINEL

```

```

' HYBRID GANTRY '
0
(-----)
( This file describes the hybrid gantry )
( with conventional magnets in the first bend-up part. )
( This is an example of 3 mm REFERENCE beam. )
( Last editing: 14.11.1995 by M. Pavlovic )
(-----)
13. 2.;
13. 12.;
1. 0.5 0.5 0.5 0.5 0. 0.2 2.08358;
16. 5. 2.25; ( vertical half-aperture in CM )
16. 4. 2.25; ( horizontal half-aperture in CM )
9. 5.;
3. 0.1
9. 0.;
5.00 0.3 -0.25315 2.
9. 6.;
3. 0.1
9. 0.;
5.00 0.3 -3.00335 2.
9. 6.;
3. 0.1
9. 0.;
5.00 0.3 2.93189 2.
9. 6.;
3. 0.1
9. 0.;
13. 1.;
      2. 0.;
      4. 0.6739005 -18.0 0 'BM1';
      4. 0.6739005 -18.0 0 'BM1';
      4. 0.6739005 -18.0 0 'BM1';
      2. 0.;
10.2 3. 3. 1.09 .01;
9. 8.;
3. 0.1;
9. 0.;
5.00 .30 -3.80291 2;
9. 7.;
3. 0.1;
9. 0.;
5.00 .35 4.66353 2. 'QDt2';
9. 7.;
3. 0.1 'dzt1';
9. 0.;
16. 5. 2.25;
16. 4. 2.25;
      2.0 0.;
      4. 0.6739005 18.0 0. 'BM2';
      4. 0.6739005 18.0 0. 'BM2';
      4. 0.6739005 18.0 0. 'BM2';
      2.0 0.;
10.2 3. 3. 1.09 01;
13. 1.;

```

```

9. 14.;
3. 0.1;
9. 0.;
5.00 0.30      -1.96164 3.;
9. 13.;
3. 0.1;
9. 0.;
10.2 1. 1. 2.16 0.01;
5.00 0.3 5.45068 3.;
9. 7.;
3. 0.1;
9. 0.;
5.00 0.3 -3.86366 3.;
9. 5.;
3. 0.1;
9. 0.;
3. 0.20;
7. 0. 26.8 0. 0 0. 0. 'x1'; (B = 0.5 T)
3. 0.20;
9. 5.;
3. 0.1;
9. 0.;
3. 0.20 ;
7. 0. 0. 0. -8.362 0. 0. 'y'; (B = 0.15 T)
3. 0.20 ;
9. 5. ;
3. 0.1 ;
9. 0. ;
3. 0.175;
7. 0. -26.8 0. 0. 0. 0. 'x2';
3. 0.175;
3. 0.175; (B = 0.7 T)
7. 0. -40.4 0. 0. 0. 0. 'x22';
3. 0.175;
9. 10. ;
3. 0.1 ;
9. 0. ;
16. 5. 5.5;
16. 4. 5.5;
    2. 0. ;
    4.000 0.24544 55.600 0.00000 'BMA';
    4.000 0.24544 55.600 0.00000 'BMA';
    4.000 0.24544 55.600 0.00000 'BMA';
    4.000 0.24544 55.600 0.00000 'BMA';
    4.000 0.24544 55.600 0.00000 'BMB';
    4.000 0.24544 55.600 0.00000 'BMB';
    4.000 0.24544 55.600 0.00000 'BMB';
    4.000 0.24544 55.600 0.00000 'BMB';
    2. 0. ;
9. 12.;
3. 0.1;
9. 0.;
10. 1. 1. 0.150 0.001;
10. 3. 3. 0.150 0.001;
10. -1. 6. 0.0 0.02 ;

```

```
10.    -2.  6.   0.0   0.02 ;
10.     4.  3.   0.0   0.001;
10.     2.  1.   0.0   0.001;
13      4;
13      1;
(-----This is the END of DATA-----)
SENTINEL
SENTINEL
```