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A STUDY OF DISPERSION EFFECTS IN TRANSPORT OF ION–THERAPY BEAMS

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Ion beams are an ideal type of radiation for the treatment of well-localized deep-seated tumours. Modern pencil-beam scanning irradiation techniques require precise beam transport including a proper control of the dispersion function of the beam-transport line. Quantitative assessment of dispersion effects in the transport and application of ion-therapy beams at the treatment point is presented in the paper. General specifications for the dispersion function are derived analytically and checked by computer simulations. The results are particularly relevant for the design of rotating ion gantries that have to satisfy a demanding set of ion-optical constraints including the dispersion-control.

K e y w o r d s: beam transport, dispersion, ion therapy, medical accelerators, rotating gantry

1 INTRODUCTION

Ion beams are an ideal type of radiation for the treatment of well-localized deep-seated tumours [1, 2]. Modern pencil-beam scanning irradiation techniques require precise beam transport including a proper control of the dispersion function of the beam-transport line. The problem is particularly relevant for rotating ion gantries that have to satisfy a demanding set of ion-optical constraints especially if non-symmetric beams are delivered by an accelerator [3–5]. Double-achromatic beam transport is usually included in the set of ion-optical constraints [6-10]. This approach is justified if the gantry is designed in a universal way, *ie* without knowledge of the momentum spread of the incoming beam, because double-achromatic beam transport makes some beam properties fully independent of the momentum spread of the beam. However, modern ion-therapy accelerator complexes have ambition to be installed in hospitals, which requires an extremely compact design. This can be achieved — among other measures — by relaxing the requirements on the perfect double-achromatic beam transport, which may simplify the gantry design. Quantitative assessment of dispersion effects in the transport of ion-therapy beams is presented in the paper in order to derive the tolerances for the dispersion function at the treatment point as a function of the momentum spread of the incoming beam. This approach is new compared to the common strategy of setting the dispersion function and its derivatives identically to zero, which has been traditionally applied so far.

2 THEORETICAL BACKGROUND

The particle trajectory in a planar beam transport system is described by the set of differential equations [11]:

$$\frac{\mathrm{d}^2 x(s)}{\mathrm{d}s^2} + \Big(\frac{1}{\rho^2} - k\Big) x(s) = \frac{1}{\rho}\frac{\Delta p}{p_0}\,, \qquad (1)$$

$$\frac{\mathrm{d}^2 z(s)}{\mathrm{d}s^2} + k z(s) = 0 \qquad (2)$$

where x is the transverse particle co-ordinate with respect to the reference trajectory in the plane of bending (*horizontal plane*), z is the transverse particle co-ordinate with respect to the reference trajectory in the plane perpendicular to the plane of bending (*vertical plane*), s is the longitudinal particle co-ordinate along the reference trajectory, ρ is the local radius of curvature of the reference trajectory, $k = -\frac{g}{B\rho}$ is the normalized gradient of the magnetic field, $B\rho$ is the magnetic rigidity of the reference particle, g is the gradient of the magnetic field, p_0 is the reference momentum and $\frac{\Delta p}{p_0}$ is the relative momentum deviation of the particle with respect to the reference momentum.

The planar beam transport system stands for a system that bends the reference trajectory exclusively in one plane. Conventionally, the co-ordinate system is chosen in such a way that the plane of bending is set to be the horizontal plane. Furthermore, equations (1) and (2) are valid for uncoupled beam-lines in a region of a constant gradient of the magnetic field without acceleration. The guiding external magnetic field is typically designed in

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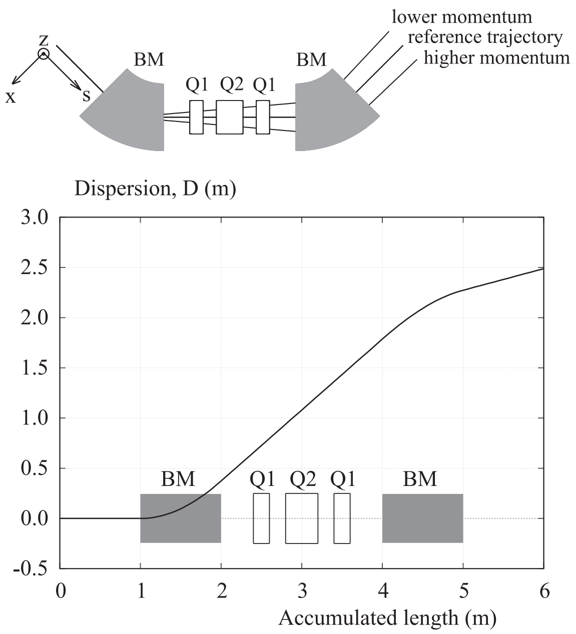

Fig. 1. Layout and dispersion function of a chromatic 90° bending section. BM — bending magnet, Q1, Q2 — quadrupole magnets. Upper: configuration of the bending section with the reference and off-momentum trajectories, quadrupole magnets are not powered. Lower: dispersion function of the bending section.

such a way that particles make oscillations around the reference trajectory. In an uncoupled beam-line, there is no coupling between the oscillations in the horizontal and vertical planes.

Equation of particle trajectory in the horizontal plane (1) is inhomogeneous. This means that the solution $x(s)$ consists of two components: harmonic oscillation $x_\beta(s)$ that is a solution of the homogeneous equation plus a particular solution of the inhomogeneous equation, $x_D(s)$:

$$x(s) = x_\beta(s) + x_D(s) \tag{3}$$

where $x_\beta(s)$ and $x_D(s)$ satisfy the differential equations:

$$\frac{\mathrm{d}^2 x_\beta(s)}{\mathrm{d}s^2} + \Big(\frac{1}{\rho^2} - k\Big) x_\beta(s) = 0\,, \tag{4}$$

$$\frac{\mathrm{d}^2 x_D(s)}{\mathrm{d}s^2} + \Big(\frac{1}{\rho^2} - k\Big) x_D(s) = \frac{1}{\rho}\frac{\Delta p}{p_0}\,. \tag{5}$$

The $x_\beta(s)$-solution is called *betatron oscillations*. The inhomogeneous component, $x_D(s)$ is usually expressed with the aid of another function that is called *dispersion function*, $D(s)$:

$$x_D(s) = D(s)\frac{\Delta p}{P_0}\,. \tag{6}$$

The dispersion function satisfies the equation:

$$\frac{\mathrm{d}^2 D(s)}{\mathrm{d}s^2} + \Big(\frac{1}{\rho^2} - k\Big) D(s) = \frac{1}{\rho} \tag{7}$$

and can be calculated from the cosine-like and sine-like principal trajectories [12]. After having introduced the dispersion function, the particle trajectory will be given as:

$$x(s) = x_\beta(s) + D(s)\frac{\Delta p}{p_0}\,. \tag{8}$$

2.1 Physical meaning of the dispersion function

There are two important aspects concerning the physical meaning of the dispersion function. The first, the dispersion function is a special trajectory corresponding to the particle with no betatron oscillations, but with relative momentum deviation $\frac{\Delta p}{p_0} = 1 = 100\,\%$. *Dispersion function is a characteristic property of the beam-transport system* and is followed by a particle entering 'perfectly' the beam-transport system ('perfectly' means with initial co-ordinates $x(s)\big|_{s=0} = x_0 = 0$), but with relative momentum deviation $\frac{\Delta p}{p_0} = 1$. Such a particle makes no betatron oscillations and follows the dispersion trajectory. This interpretation is strictly true only for beam-transport systems with zero initial dispersion function, *ie* $D(s)\big|_{s=0} = D_0 = 0$ and $\frac{\mathrm{d}D(s)}{\mathrm{d}s}\Big|_{s=0} = D_0' = 0$. The second meaning is evident from Equation (8). The actual particle co-ordinate in a given position along the beam-transport system, s_1, is given by the superposition of the actual betatron oscillation, $x_\beta(s_1)$, plus an additional contribution $D(s_1)\frac{\Delta p}{p_0}$. This means that *the dispersion introduces a correlation between the particle position and its relative momentum deviation*. When assuming a beam as an ensemble of many particles with different momenta (inside a certain interval that is called *a momentum spread of the beam*), the particles with higher momenta will be shifted in the horizontal plane to one side of the beam whereas the particles with lower momenta will be shifted to the opposite side of the beam. It should be noted that dispersion function can be both positive and negative. The same is true for particle angles with respect to the reference trajectory. The angles will be shifted according to the $D' = \frac{\mathrm{d}D(s)}{\mathrm{d}s}$ function. In the horizontal phase-space $[x, x']$, the actual particle position at s_1 is given as:

$$\Big[x_\beta(s_1) + D(s_1)\frac{\Delta p}{p_0}, x_\beta'(s_1) + D'(s_1)\frac{\Delta p}{p_0}\Big]. \tag{9}$$

2.2 Chromatic and achromatic beam-transport systems

Dispersion in the beam-line is created by beam-transport elements that bend the reference trajectory, *ie* with final radius of curvature, ρ. Magnetic elements without bending do not create dispersion, because $1/\rho \to 0$ and the term $\frac{1}{\rho}\frac{\Delta p}{p_0}$ in Equation (1) vanishes. A typical dispersive element is a bending magnet. Because of its dispersive properties, it can be used as a mass-separator or

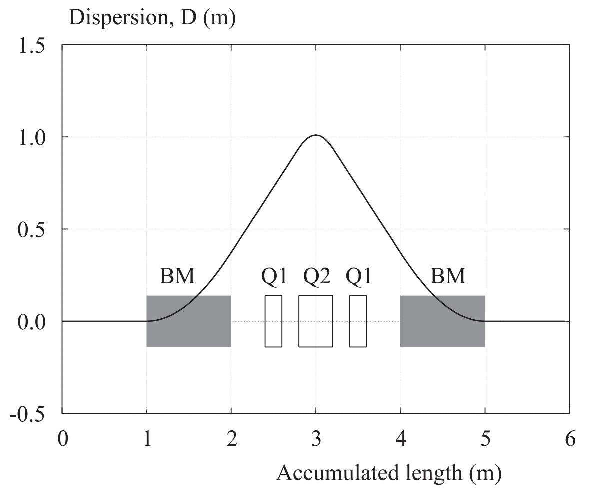

Fig. 2. Dispersion function of a double-achromatic bending section, quadrupole Q2 focuses horizontally, quadrupoles Q1 are not powered.

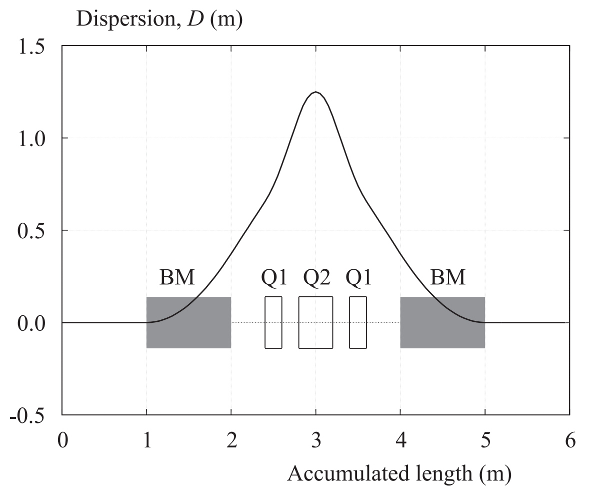

Fig. 3. Dispersion function of a double-achromatic bending section with a symmetrical quadrupole triplet. Quadrupoles Q1 focus vertically, quadrupole Q2 focuses horizontally.

an analyzing magnet in the beam-line. Typical dispersion-free elements are drift space and quadrupole magnet. Without special precautions, a beam-transport system containing bending elements is, in general, chromatic. However, a so called double-achromatic beam transport is required in many practical cases in order to get the smallest possible beam-spot on the target (without contribution from the dispersion). The double-achromatic beam-transport means that the dispersion function satisfies at a given position s_1 along the beam-line (typically at the beam-line exit) the constraints:

$$D(s_1) = 0\,, \tag{10}$$

$$\frac{\mathrm{d}D(s)}{\mathrm{d}s}\Big|_{s=s_1} = D'(s_1) = 0\,. \tag{11}$$

These constraints can be satisfied by a special configuration of at least two bending magnets and at least one quadrupole magnet.

2.3 Example of an achromatic beam-transport system

Let us assume a simple 90° bend made of two identical 45° bending magnets (BM) separated by a drift space with a quadrupole triplet (Q1+Q2+Q1) located symmetrically in-between the bending magnets. Let the initial dispersion function and its first derivative be zero at the entrance to the beam-line. Without powering the quadrupoles, the beam-line is chromatic because particles with higher momenta are bent less and particles with lower momenta are bent more in the bending magnets compared to the reference trajectory that is followed by particles with the reference momentum, p_0. Trajectories of off-momentum particles and the corresponding dispersion function are shown in Fig. 1. The upper part shows schematically an arrangement of the beam line with above mentioned trajectories. The lower part displays the dispersion function that represents excursion of the off-momentum trajectory for $\frac{\Delta p}{p_0} = 1$ with respect to the reference trajectory.

In order to achieve the double-achromatic beam transport, the central quadrupole Q2 must be properly powered 'to focus' the dispersion trajectory into the second bending magnet. The dispersion function is illustrated in Fig. 2, quadrupole Q2 focuses horizontally.

One quadrupole focusing horizontally may cause intolerable defocusing in the vertical plane. That is why an improved configuration of an achromatic bend is made with a symmetric quadrupole triplet instead of a singlet. The achromatic bend with triplet enables to keep the beam-size in the vertical plane inside the reasonable aperture. Quadrupoles Q1 focus vertically, quadrupole Q2 focuses horizontally. The dispersion function is shown in Fig. 3.

3 EVALUATION OF THE DISPERSION EFFECTS AT THE GANTRY EXIT

Traditionally, double-achromatic beam transport from the gantry entrance to the treatment point at the gantry exit is quoted in the gantry designs published so far [3–10, 13, 14]. The double-achromatic beam transport can only be achieved by additional quadrupoles [4] or by using a special matching section called rotator [5]. This approach is justified in the situation, when the gantry is designed as a stand-alone unit without knowledge about the momentum spread of the incoming beam. Such a gantry can be theoretically connected to any accelerator supposing that the aperture corresponds to the beam-emittance. The emittance, however, always depends on the accelerator design, thus the gantry can never be really designed without knowledge about the parameters of the incoming beam.

Our approach differs from the conventional one in the sense that the constraints on the dispersion function at

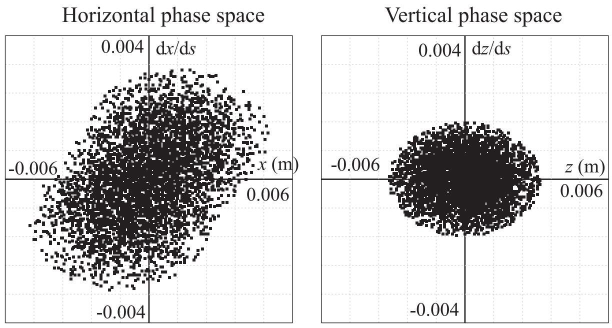

Fig. 4. Emittance diagrams of a beam in the horizontal (left) and vertical (right) plane. The horizontal plane is chromatic, example is given for $D = 1$ and $D' = 1$. The vertical plane is achromatic. The relative momentum spread of the beam is 1.2%%. The RMS normalized beam emittance in both planes is $0.52\,\pi$ mm.mrad [16].

the gantry exit are relaxed in order to simplify the ion-optical system or even to reduce the number of gantry quadrupoles. Non-zero dispersion at the treatment point causes a correlation between the particle position/angle and its momentum. In such a case, different parts of the beam can have different ranges in the patient body and the treatment voxel could be irradiated irregularly. The extreme precision — a main advantage of charged particle beams — could be lost. On the other hand, the position-to-momentum and angle-to-momentum correlations can be compensated by multiple Coulomb scattering in the patient body that alters both the particles' positions as well as their angles. It is investigated quantitatively in this paper, what dispersion function can be tolerated at the treatment point. The specification is derived by comparing the multiple Coulomb scattering effect to the particle distribution under the presence of chromatic effects. The study is done for proton and carbon ions representing the low-LET and high-LET treatment modality, respectively.

3.1 Simulation of dispersion effects

Let us assume a simplified representation of the beam in the phase-space. The beam consists of three groups of particles: (a) particles with reference momentum, $p = p_0$, (b) particles with maximum momentum, $p_{\max} = p_0 + \Delta p$, (c) particles with minimum momentum, $p_{\min} = p_0 - \Delta p$. In reality, there will be some distribution of particle momenta in-between $p_{\min}$ and $p_{\max}$. The beam is characterized by its relative momentum spread $\frac{\Delta p}{p_0}$. Momenta of all particles in the beam are between $p_0 \pm \Delta p$. In our study, the relative momentum spread of the incoming beam is assumed to be 1.2%% [15]. In the phase-space (see Fig. 4), the emittance diagrams in the horizontal plane containing off-momentum particles are shifted with respect to the emittance diagram containing particles with reference momentum by:

$$\Delta x = D\frac{\Delta p}{p_0} \text{ and } \Delta x' = D'\frac{\Delta p}{p_0} \tag{12}$$

where D and D' are the dispersion function and its first derivative at the gantry exit. In the vertical, dispersion-free plane, emittance diagrams of reference particles and off-momentum particles overlap perfectly. It can also be seen in Fig. 4 that the dispersion contribution blows-up the beam-spot in the horizontal plane.

Penetration of ion beam in the patient body has been studied by means of the WinAGILE code [17]. The body has been cut into 1 mm drift spaces filled-in with water. Relevant beam parameters were calculated at the significant points, namely at 30 mm and 275 mm penetration depths.

3.2 Derivative of the dispersion function

If derivative of the dispersion function at the gantry exit is not zero ($D' \neq 0$), the particle angles will be distributed according to Equation (9). However, the particles suffer many small angular kicks due to the multiple Coulomb scattering that has stochastic character and can compensate the dispersive angle-to-momentum correlation. As a matter of choice, a criterion has been formulated: the value of D' that causes angular distribution smaller than mixing effect due to the multiple scattering can be tolerated. In order to be on the safe-side of the assessment, an ideal point-beam with zero emittance has been assumed. It means, the natural angular spread of the beam has been neglected and merely the multiple Coulomb scattering has been taken into account. An RMS (1σ) value defined as $\sqrt{\langle x'x'\rangle}$ has served as a measure of the particle angular distribution due to the multiple Coulomb scattering after passing the whole beam-range in the patient body. The WinAGILE "Tracking distributions" routine was used to calculate the $\sqrt{\langle x'x'\rangle}$-term. 10^5 particles have been tracked in 20 bunches each containing 5,000 particles. The resulting $\sqrt{\langle x'x'\rangle}$-values are the following:

- 60 MeV protons: 54.27 mrad ±0.9 %
- 210 MeV protons: 60.18 mrad ±0.9 %
- 120 MeV/A carbon ions: 14.42 mrad ±0.8 %
- 400 MeV/A carbon ions: 16.22 mrad ±0.7 %

These results demonstrate also clearly one of the main physical advantages of carbon ions compared to protons: smaller multiple scattering, *ie* better preservation of the original beam quality. Taking the lowest value of 14.42 mrad as a criterion, a constraint can be set:

$$\Delta x' = D'\frac{\Delta p}{p_0} \ll 14.42\,\text{mrad}, \tag{13}$$

$$\frac{\mathrm{d}D(s)}{\mathrm{d}s} = D' \ll \frac{14.42 \times 10^{-3}}{\frac{\Delta p}{p_0}} = \frac{14.42 \times 10^{-3}}{1.2 \times 10^{-3}} \approx 12\,. \tag{14}$$

Taking the 10 % level of the boundary value as a choice satisfying relation (14), the resulting specification is $D' \leq 1.2$. Under these circumstances, the particles with angles

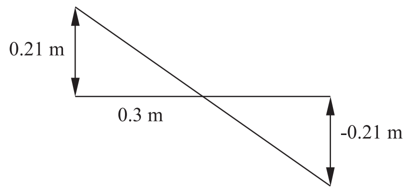

Fig. 5. Dispersion function inside the treatment volume: limiting case.

originally separated in the phase-space are safely mixed-up by multiple scattering in the patient body. The verifying simulations have been done for 120 MeV/A carbon-ion beam (point, zero-emittance) entering the patient body at $D' = 1.2$ in the horizontal plane. The difference in the final beam-divergence between the horizontal (dispersive) and vertical (non-dispersive) plane was about 0.6 %, which is below one standard deviation. This means that the original angular distribution caused by the $D' \neq 0$ is no longer preserved and horizontal plane becomes equivalent to the vertical non-dispersive plane.

3.3 Dispersion function

Using the same strategy and taking into account exclusively the multiple scattering effect would lead to a specification for the dispersion function of $D \leq 0.01$ m. However, its interpretation becomes complicated for active pencil-beam scanning [18]. In this case, the beam position is changed by the scanning system and particle distributions within the irradiation-voxel overlap each other during the scanning. Therefore, it makes no sense to compare the static particle distribution with the multiple scattering effect because the original particle distribution is not preserved due to the scanning. In this situation, the accuracy of the beam spot-size has been taken as an underlying criterion. According to the practical experience, the beam spot-size accuracy must be better than ± 12.5 %. The off-momentum particles are shifted with respect to the reference momentum particles by $\Delta x = D\frac{\Delta p}{p_0}$ giving the overall contribution to the beam spot-size $2D\frac{\Delta p}{p_0}$. This contribution must be smaller than 12.5 % of the beam spot-size. The most critical spot-size is 4 mm (FWHM).

$$2D\frac{\Delta p}{p_0} \leq 0.125 \cdot 0.004\,\mathrm{m}, \tag{15}$$

$$D \leq \frac{0.125 \cdot 0.004}{2\frac{\Delta p}{p_0}} \approx 0.21\,\mathrm{m}. \tag{16}$$

Let us assume that this criterion must be satisfied along the whole penetration range, which limits also the derivative of the dispersion function (see Fig. 5). The maximum allowable slope of the dispersion function is $D' = \frac{0.42}{0.3} = 1.4$. This is in principle consistent with the specification obtained by simulation of multiple Coulomb scattering of particles in the patient body.

4 DISCUSSION AND CONCLUSIONS

If the dispersion function is limited to ± 0.21 m, the position-to-momentum correlation can still be preserved, especially for short penetration ranges with little multiple scattering. This means, that there may be some distribution of particle ranges across the irradiated voxel. It should be checked, how significant this effect can be. Ranges were calculated by SRIM [19] for the worst case, 120 MeV/A carbon ions and 12 %% relative momentum spread of the beam. The difference between penetration ranges was 0.29 mm, while the natural range-straggling is about 1.4 mm. Such a difference is below the natural range straggling and can be tolerated. In reality, it will be further compensated by other effects like scattering in the vacuum window, beam-monitoring devices, mini-ridge filter, *etc.* As a final conclusion, the specification for the dispersion function of $|D| \leq 0.2$ m and $|D'| \leq 1.2$ can be quoted. Some tutorial introduction to achromatic beam-transport systems has also been presented.

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