Chapter 7

A NEW APPROACH TO TRANSFER LINE DESIGN

As was shown in the previous Chapter, the slowly extracted beam has a markedly different distribution in the two transverse phase spaces. In the vertical one, the beam looks “normal”, meaning that the phase-space distribution is approximately the same as in the synchrotron with the particles filling the self-ellipse. In the horizontal phase-space, the particles are distributed, for all practical purposes, in a long and thin rectangle, hereafter referred to as the “bar” of charge, which is the part of the extraction separatrix cut by the electrostatic septum. Such a strong asymmetry calls for a special design of the transfer lines to the treatment rooms.

The extraction lines have to be designed such that the beam size at the patient can be chosen in the range 4 to 10 mm at all the extraction energies and that the dispersion function at the end is null with its derivative. Since in a modern facility rotating gantries are to be foreseen the additional requirement of a rotational optics has to be considered.

7.1 The “unfilled” ellipse approach

In a transfer line the beta function is not uniquely determined by the periodicity as in a circular accelerator. Once the quadrupole gradients, edge angles, drift lengths etc. in a lattice have been defined, the transfer function is fixed. If a set of initial values for the Twiss parameters is chosen, the values along the line will adjust themselves in order to maintain the transfer function unchanged. Thus the trajectory of a particle is independent of whatever set of beta values is used. Since the initial values for the Twiss parameters are free, it is reasonable to choose them such that they give a useful description of the beam. Choosing the initial values for the vertical plane equal to those of the synchrotron, or even better matching them to the extracted beam ellipse, gives a good description of the beam in the transfer lines and thus matched values been chosen in this study. In a real facility, a measurement of the Twiss parameters would be, of course, the best beam description.

In the horizontal plane, the betatron function from the synchrotron does not represent the beam distribution and a direct fitting of an ellipse to the extracted beam would not be a good description for a series of reasons:

1) it would lead to very large $\beta_x$ values because the emittance is small while the beam size is large;
2) it would lead to strong chromatic effects because emittance and $\beta_x$ vary strongly within a small momentum deviation;
3) the thickness of the “bar” of charge, due to adiabatic damping in the vertical plane, depends on the extraction energy and a different $\beta_x$ value has to be foreseen for every extraction energy;
4) due to unavoidable variations in the closed orbit or other relevant parameters, the thickness of the “bar” of charge may change requiring a new matching of the lines;

briefly a direct matching of the “bar” of charge would be source of never-ending troubles.
The approach proposed in this thesis is that of using a “large” emittance and a “small” beta to describe an “unfilled” ellipse containing the beam, as shown in Figure 7.1.

![Figure 7.1](image-url)

Figure 7.1. An unfilled ellipse is used in the horizontal phase space (a), while a “normal” filled ellipse is used in the vertical plane (b).

The unfilled ellipse is chosen such that the “bar” of charge is a diameter of the ellipse itself. The use of a much larger ellipse solves all the problems listed above, because for off-momentum particles the ellipse is just less filled and because the same ellipse can be used to describe the beam also when the thickness varies. The price that is paid for such a great simplification is that the usual expression $\sqrt{E\beta}$ describing the beam size has now to be considered as an upper value for the beam dimensions, since the orientation of the “bar” of charge along the transfer line varies with the phase advance. The beam size corresponds to the projection of the beam distribution onto the $x$-axis and thus a variation of the orientation of the “bar” of charge corresponds to a variation of the beam size.

### 7.2 Horizontal beam size control

Despite requiring additional care, the proposed “unfilled ellipse” scheme offers an additional possibility for controlling the horizontal beam dimension. By a proper variation of the phase advance the “bar” of charge rotation can be used to set the beam size at the end of the line, as shown in Figure 7.2.

![Figure 7.2](image-url)

Figure 7.2. Rotating the “bar” of charge allows an independent horizontal beam size control.
For this method to work an insertion must be foreseen that is capable of varying the horizontal phase advance without changing the beta function at its exit. Such a device, hereafter called a “phase-shifter” will be described later in this Chapter.

The maximum required beam size at the patient determines the (minimum) product of the betatron amplitude function at the end of the line and the emittance of the unfilled ellipse. A criterion for deciding how much larger the unfilled ellipse should be than the “bar” of charge, arises naturally from the minimum beam size required at the patient. The width of the “bar” must be no bigger than this dimension when the “bar” is upright in the ellipse. This sets a minimum height for the ellipse, since the phase-space area of the “bar” is conserved through the line. As has been shown in the previous Chapter, the width of the separatrix can vary due to closed orbit distortions or because of other effects, thus it is preferable to choose a larger unfilled ellipse emittance than the minimum one to keep some safety margin.

Choosing to have $\alpha_x$ equal to zero and choosing that the required maximum beam size is obtained with an horizontal “bar” of charge fixes the betatron amplitude function at the end of the line. Similarly, choosing $\alpha_x$ equal to zero at the entrance to the line fixes the initial value of the betatron amplitude function.\footnote{The choice of $\alpha = 0$ is a natural one. At extraction, in PIMMS, the bar of charge is near horizontal and it is customary to choose $\alpha = 0$ at the patient. Moreover in the following Sections the matching condition between modules in the extraction lines will have $\alpha = 0.$}

### 7.3 Vertical beam size control

In the vertical plane, the phase-space ellipse of the beam is filled, the distribution is near-gaussian and a conventional Twiss description of the line is valid. Thus, the beam size can be controlled by adjusting the vertical betatron amplitude function at the patient.

In the present design, a module, called a “stepper” and described later in this Chapter, is introduced in the common section of the line. The stepper changes the vertical betatron amplitude function while leaving the horizontal betatron amplitude function and the horizontal phase advance unchanged. In order to transmit the action of the stepper to each of the treatment rooms, the downstream lines consist of modules with integer-$\pi$ phase advances and fixed magnification in the vertical plane (telescope modules, see later).

The stepping range depends on the specific design of the line (total magnification from the stepper to the end of the line) and on the vertical emittance which, since the extraction energy is not unique, has to consider the adiabatic damping as well. However the ratio $\beta_{\max}/\beta_{\min}$ is fixed and can be estimated by comparing the betatron amplitude necessary to have the maximum beam size with the minimum emittance (maximum extraction energy) to the betatron amplitude necessary to have the minimum beam size with the maximum emittance. Let $E_n$ be the normalised emittance, which does not change with the extraction energy, then

$$\beta_{\min} = \frac{R_{\min}^2 \gamma_{r,\min} \beta_{r,\min}}{E_n}; \quad \beta_{\max} = \frac{R_{\max}^2 \gamma_{r,\max} \beta_{r,\max}}{E_n}$$
whence, with the requirements $R_{\text{min}} = 2$ mm, $R_{\text{max}} = 5$ mm and considering the energy extraction range (60-250 MeV for protons and 120-400 MeV/u for carbon ions), it results

$$\frac{\beta_{\text{max}}}{\beta_{\text{min}}} = \frac{R_{\text{max}}^2 \gamma_{r,\text{max}} \beta_{r,\text{max}}}{R_{\text{min}}^2 \gamma_{r,\text{min}} \beta_{r,\text{min}}} = \left\{ \begin{array}{ll}
13.4 & \text{for protons} \\
12.2 & \text{for carbon}
\end{array} \right.$$  

The normalised emittances for protons and carbon ions in the synchrotron are better chosen such that the beta range for carbon ions falls inside the beta range for protons, to avoid a further enlargement of the total range. In PIMMS, the choice of having the same geometric emittance at the minimum extraction energy has been made.

### 7.4 Initial dispersion

As for the betatron amplitude function, the synchrotron values for $D_x$ and $D_x'$ are also not representative of dispersion for the extracted beam. Again, in principle, any value can be chosen as an initial value, but a useful one should be chosen. Since the dispersion function represents the displacement of the off-momentum particles, it is natural to choose as initial value the one which corresponds to the distance between the center of gravity of the on-momentum particles and the center of gravity of the off-momentum ones divided by the relative momentum difference, as shown in Figure 7.3.

![Figure 7.3. Definition of the initial value for $D$ and $D'$.](image)

Although to a close inspection neither is the spiral step exactly linear with the initial particle amplitude nor is the separatrix a straight line in the amplitude vs momentum Steinbach diagram is, such a definition is good for all practical purposes.

### 7.5 Basic design concepts

The principal steps in the design of the transfer lines can be summarised as:

- Exploiting the “bar” of charge to create an independent control of the beam size by rotating the “bar” in an unfilled phase-space ellipse using a “phase shifter” in the common part of the lines.
• Controlling the vertical beam size by a “stepper” that provides a variable magnification of the vertical betatron amplitude function while leaving the horizontal betatron amplitude function and the horizontal phase advance unchanged. The variable vertical beta function is ‘handed’ through telescope modules all the way to the different treatment rooms.
• Placing the phase shifter and the stepper in the common initial part of the line so that they can act for all treatment rooms in the complex.
• Using telescope modules (extension modules, switch modules and rotators) with integer-π phase advances in both planes that have one-to-one, one-to-minus one or fixed magnification properties.
• Matching the strongly asymmetric slowly extracted beam and non-zero dispersion functions to a rotating gantry by the use of a “rotator”.

The modular character of the extraction lines is illustrated schematically in Figure 7.4. The lay-out starts with a matching module that makes the liaison from the synchrotron to the main extraction line. This module, which must be custom designed for a specific centre, delivers zero dispersion and standard lattice functions to the modular line ($\beta_x = \beta_z = 3$ m and $\alpha_x = \alpha_z = 0$ for the present example). In the horizontal plane, the standard values are ‘handed’ from module to module throughout the line to the patient. In the vertical plane, the standard values are modified by the ‘stepper’ and then ‘handed’ through the modules to the patient. In this nomenclature, the planes between the modules are known as ‘hand-over’ planes.

This general strategy has been adapted to a specific example for PIMMS.

7.6 Telescopes

The basic matching scheme uses one-to-one and one-to-minus one modules with integer-π phase advances, but in certain cases there is a practical advantage in using the more general telescope module. Consider the transfer matrix,

$$
\begin{bmatrix}
C & S' \\
C' & S
\end{bmatrix} = \begin{pmatrix}
(b/\beta_0)^{1/2} (\cos \Delta \mu + \alpha \sin \Delta \mu) & (b\beta_0)^{1/2} \sin \Delta \mu \\
-(b\beta_0)^{1/2} (\alpha - \alpha \cos \Delta \mu + (1 + a\alpha) \sin \Delta \mu) & (b/\beta)^{1/2} (\cos \Delta \mu - \alpha \sin \Delta \mu)
\end{pmatrix}
$$

(7.1)
where \( C \) and \( S \) are known as the principal trajectories and the other symbols have their usual meanings. If \( \Delta \mu = n \pi \), then \( \sin(\Delta \mu) = 0 \) and \( S = 0 \). The transfer matrix is always independent of the choice of the initial Twiss parameters, therefore \( S \) must be zero for any initial \( \alpha_0 \) and \( \beta_0 \). This shows the first result:

*A lattice with integer-\( \pi \) phase advance in one plane, has the same phase advance for any incoming lattice functions in that plane.*

Now consider the transfer matrix for the Twiss parameters with \( S = 0 \):

\[
\begin{pmatrix}
\beta \\
\alpha \\
\gamma
\end{pmatrix} = \begin{pmatrix}
C^2 & -2CS & S^2 \\
CC' & CS' + SC' & -SS' \\
C'^2 & -2C'S' & S'^2
\end{pmatrix} \begin{pmatrix}
\beta_0 \\
\alpha_0 \\
\gamma_0
\end{pmatrix} = \begin{pmatrix}
C^2 & 0 & 0 \\
CC' & CS' & 0 \\
C'^2 & -2C'S' & S'^2
\end{pmatrix} \begin{pmatrix}
\beta_0 \\
\alpha_0 \\
\gamma_0
\end{pmatrix}
\]

(7.2)

If the lattice is matched for \( \alpha = \alpha_0 \) in (7.2), then \( C' = 0 \) must be true since \( CS' = 1 \), being the determinant of the transfer matrix (7.1). Thus it remains

\[
\begin{pmatrix}
\beta \\
\alpha \\
\gamma
\end{pmatrix} = \begin{pmatrix}
C^2 & 0 & 0 \\
0 & CS' = 1 & 0 \\
0 & 0 & S'^2
\end{pmatrix} \begin{pmatrix}
\beta_0 \\
\alpha_0 \\
\gamma_0
\end{pmatrix}
\]

(7.3)

and for any incoming set of lattice functions it follows that

\[
\frac{\beta}{\beta_0} = C^2; \quad \alpha = \alpha_0 \quad \text{(constant } \beta \text{ magnification)}
\]

Thus a telescope module provides a fixed magnification between the incoming and outgoing betatron amplitude functions while maintaining the alpha-functions equal. Normally, the extension and switching modules in Figure 4 would use \( C^2 = 1 \) and the action of the ‘stepper’ would be transmitted directly to the patient. For practical reasons, it may be necessary to reduce beam sizes in certain regions in which case a demagnification followed by a magnification could be used. An overall magnification can be used to move the range of the stepper.

### 7.7 Rotator

Another key module in the extraction line is the rotator that transcribes the normal modes and dispersion functions from the fixed line into those of the rotating gantry. The ability of this module to also map the dispersion function to the gantry system opens the possibility of closing the gantry’s dispersion bump in the fixed part of the line; a possibility that is not available for conventional gantries that use either the ‘symmetric’ or the ‘round’ beam method for matching [24]. The rotator is a quadrupole lattice with \( 2\pi \) and \( \pi \) phase advances in the two planes and unit magnification. The elements are mounted so that they can be rotated in proportion to the gantry angle. The rotator’s transfer matrix has the simple form,
If the rotator is rotated by half of the gantry angle \( \theta \), then it maps the incoming beam into the co-ordinates of the gantry as shown by the matrix multiplication

\[
\begin{pmatrix}
    x \\
x'
\end{pmatrix} =
\begin{pmatrix}
x_0 \\
0
\end{pmatrix}
\begin{pmatrix}
    1 & 0 & 0 & 0 \\
    0 & 1 & 0 & 0 \\
    0 & 0 & 0 & 1
\end{pmatrix}
\begin{pmatrix}
x_0 \\
0
\end{pmatrix}
\begin{pmatrix}
    \cos \theta & 0 & \sin \theta & 0 \\
    0 & \cos \theta & 0 & -\sin \theta \\
    0 & 0 & -1 & 0 \\
    0 & 0 & 0 & -1
\end{pmatrix}
\begin{pmatrix}
x' \\
x'_0 \\
z' \\
z'_0
\end{pmatrix}
\]

where on the left-hand side the three matrices represent (right to left) the rotation by an angle \( \theta \) before entering the rotator (to refer the beam to the proper axes of the rotator), the passage through the rotator and then a further rotation by \( \theta \) before entering the gantry (to refer the beam to the proper axes of the gantry). The right-hand side shows the result, that the beam is mapped one-to-one or one-to-minus one from the fixed line to the gantry, making the rotation completely transparent to the optics. Note that since the rotator is dipole free, any dispersion function entering the lattice behaves as a betatron oscillation. For this reason, the dispersion function is rotated in the same way and matched one-to-one from the fixed beam line to the rotating gantry.

### 7.8 Example modules

In the following sub-sections, design examples for the various modules are presented. As explained above, the slow-extracted beam is described with an unfilled phase-space ellipse in the horizontal plane. This makes it possible to use the standard Twiss-formalism but gives only an upper limit for the beam size. The effective beam size depends on the orientation of the “bar” inside the ellipse. In order to see the true excursions of the beam, for a given setting of the phase shifter, it is necessary to track the four ‘corners’ of the “bar” of charge. For designing the aperture, however, the unfilled ellipse is sufficient, since the beam will in principle move over the full ellipse area at different times, due to the action of the phase shifter (0 < \( \Delta \mu < \pi/2 \)).

#### 7.8.1 Matching section

The first part of the line is the matching section, whose task is to match the initial dispersion, as defined in Section 7.4, to zero. Moreover the matching section has to deliver at its end, the standard lattice functions \( \beta_x = \beta_z = 3 \) m and \( \alpha_x = \alpha_z = 0 \) to the modular line. The set of initial values chosen at the entry to the electrostatic septum is reported in Table 7.1 and the resulting ellipses together with the extracted beam distribution are shown in figure 7.5. The particle distribution is the same as in Figure 6.6, except for the coordinate translation to the extraction line reference system. On a “normal” scale it shows how thin the “bar” of charge is. The argument about not having to change the ellipse parameters when the thickness changes becomes evident.
Table 7.1 Initial set of Twiss parameters for the matching section.

<table>
<thead>
<tr>
<th>Twiss parameter</th>
<th>Chosen value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta_x$ [m]</td>
<td>5.000</td>
</tr>
<tr>
<td>$\alpha_x$</td>
<td>0.000</td>
</tr>
<tr>
<td>$\varepsilon_x$ [\pi mm mrad]</td>
<td>5.000</td>
</tr>
<tr>
<td>$\beta_z$ [m]</td>
<td>6.864</td>
</tr>
<tr>
<td>$\alpha_z$</td>
<td>0.087</td>
</tr>
<tr>
<td>$D$ [m]</td>
<td>1.942</td>
</tr>
<tr>
<td>$D'$</td>
<td>-0.026</td>
</tr>
</tbody>
</table>

Figure 7.5. Twiss ellipses and beam distribution at the entrance to the extraction line.

The initial part of the matching section is the part of the ring which is traversed by the beam before reaching the magnetic septa and being effectively extracted of the vacuum pipe of the synchrotron. Since the extracted beam is off axis, it crosses the quadrupoles
off-center and sees consequently a dipole component. This implies that the quadrupoles have to be considered as combined-function magnets. Moreover the orbit crosses the faces of the magnets at an angle, which means that the magnets have to be modelled with appropriate edge angle. The calculation of the distorted-orbit equivalent lattice can be done easily with a powerful calculation tool like WinAgile [25]. The geometry of the extraction line is illustrated in Figure 7.6 and the optical functions are shown in Figure 7.7.

Figure 7.6. Initial part of the extraction line (filled magnets) and synchrotron.

Figure 7.7. Optical functions in the matching section
7.8.2 Phase shifter
The horizontal beam size is controlled by varying the horizontal phase advance in the extraction line, so that the “bar” of charge rotates in the unfilled ellipse. Figure 7.8 shows a dedicated insertion that varies the horizontal phase advance while keeping the horizontal and vertical Twiss functions at the exit constant, as well as the vertical phase advance (although this is not strictly necessary).

![Betatron amplitude functions [m] versus distance [m]](image)

Figure 7.8. Optical functions in the phase shifter.
[Δμz = π/2 to π in steps of π/10, Δμz = 2.5 radian, βz = βx = 3 m and αz = αx = 0 at entry and exit.]

7.8.3 Stepper
For the control of the vertical beam size, a dedicated module, called the ‘stepper’, is used. In the design example shown in Figure 7.9, βz covers the range 2 to 27 m at the exit for an incoming value of 3 m with αx = 0 at entry and exit. In the horizontal plane, βx = 3 m at entry and exit, αx = 0 and Δμx = π/2. The horizontal phase advance has to be kept constant during the stepping in order not to vary the orientation of the “bar” of charge.

![Betatron amplitude functions [m] versus distance [m]](image)

Figure 7.9. Optical functions in the stepper.
[βx = 3 m at the entry and steps from 2, 3 to 27 m in steps of 6 m at the exit. Δμx = π/2, βx = 3 m and αx = αz = 0 at entry and exit.]

It should be recalled that the important feature is the ratio in βz provided by the stepper and not the absolute values. These can, according to the vertical emittance in a specific
machine design, be magnified in one of the downstream telescope modules to create whatever spot sizes are needed.

7.8.4 Phase shifter-stepper

The modules shown in Figures 7.8 and 7.9 are in fact identical and it is possible to combine their functions into a single unit. This is inconvenient inasmuch as a single module has to span over a two dimensional parameter space, which makes the operation more complicated and may reduce the global ranges, but it represents a considerable saving in space. Figure 7.10, shows the betatron amplitude functions in the combined phase shifter-stepper for four extreme cases in the parameter range.

![Betatron amplitude functions](image)

Figure 7.10. Extreme optical functions in the combined phase shifter-stepper.

7.8.5 Closed-dispersion switching module and extension section.

When designing a centre, it is necessary to have a number of utility modules as indicated in Figure 7.4, a switch with a closed dispersion bend and its corresponding extension section are needed for fixed beam lines and for closed dispersion gantries.

Figure 7.11 shows the optical functions for the extension module, Figure 7.12(a) shows the Twiss functions of a switching module with a closed dispersion bend and 7.12(b) shows the corresponding geometry. The lattice functions are shown with the range of 2 to 27 m in the vertical plane corresponding to the stepper in Figure 7.9.

![Betatron amplitude functions](image)

Figure 7.11. Optical functions for the extension module.
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7.8.6 Open dispersion switching module and extension section

The possibility introduced by a rotator to also map the dispersion function to the gantry system opens the possibility of closing the gantry’s dispersion bump in the fixed part of the line. In Subsection 7.8.8 a gantry of this type is described. The present module has to create a dispersion suitable for the following gantry. In a practical case, the open dispersion bend and the gantry must be designed as an integral unit.

As an example and as anticipated in Section 7.5, a magnification factor of 1/3 in the vertical plane has been chosen for the deflection module. Thus the module delivers a range of 0.67 to 9.0 m in vertical betatron amplitudes for the gantry. The reason for this choice is to limit the Twiss functions in the rotator. In the horizontal plane, the lattice is one-to-one for $\beta_x = 3 \, m \alpha_x = 0$ at entrance and exit. Figure 7.13 shows the optical functions for the extension module. Figure 7.14(a) shows the Twiss functions of the switching module and 7.14(b) shows the corresponding geometry.

Figure 7.12. Optical functions (a) and geometry (b) for the closed-dispersion switching module.

Figure 7.13. Optical functions for the extension module.
Betatron amplitude functions \([m]\) versus distance \([m]\)

Dispersion functions \([m]\) versus distance \([m]\)

0.000

0.000

20.576

20.576

45.000

6.500

-6.500

Horizontal

Vertical

Grid size 2.0000 [m]

Horizontal plan view [X-Y plane]

(b)

Figure 7.14. Optical functions (a) and geometry (b) for the closed-dispersion switching module.

7.8.7 Rotator

As explained in the general part, the rotator is a telescope with unit magnification and phase advances \(\pi\) and \(2\pi\). Its function is to rotate the beam by twice as much as the module rotation. Since the gantry which follows that insertion can be freely rotated by \(\pm180^\circ\), the rotator must be able to rotate by \(\pm90^\circ\) on its longitudinal axis. Since the beam is coupled inside the module, the beam sigma matrix description should be used rather than the Twiss-functions, however, at the exit, the distributions are uncoupled and the Twiss-formalism is again valid. In Figure 7.15 the Twiss functions are shown in the rotator, for a rotator at 0° and at 90°, where the \(x\) and \(z\) plane exchange their roles.

Figure 7.15. Twiss functions for a rotator at 0° and 90°.

Figure 7.16 shows an example of a rotator module, when rotating the beam by 90° (physical angles: gantry 90°, rotator 45°). Note that the range of incoming beam sizes is transferred to the orthogonal plane when going through the rotator. For illustration the incoming dispersion is non-zero (as would be the case for an open-dispersion module) and
also exchanges planes, like the beam sizes. Since the beam is coupled inside the module, the beam size is quoted rather than the Twiss-functions.

Figure 7.16. Beam sizes inside the rotator for beam rotation and gantry angle of 90°.

7.8.8 "Riesenrad" gantry

In conventional gantries, the beam is deflected away from the rotation axis and then is re-deflected towards the patient. This implies that the last bending magnet, which is a very big and heavy element, rotates on a mechanical structure at the maximum radius. Without a rotator there is, practically, no other solution since the dispersion at the entrance to the gantry must be zero and at least two magnets are then needed to have zero dispersion at the patient. The use of a rotator allows a, technically, more clever solution: a unique 90° dipole starting on the rotational axis together with a patient positioning system that positions the patient at the maximum radius. Such a device is referred to as "riesenrad" gantry. In this example, the initial dispersion created by the open dispersion switching module and mapped into the rotated gantry system by the rotator, closes inside the "riesenrad" gantry, as shown in Figure 7.17.

In the present set of modules, the deflection section is a telescope with magnification 1/3 in the vertical plane. Assuming that the $\beta_z$ range needed at the patient is the one spanned by the stepper, the gantry has to be a telescope with magnification 3.

In the horizontal plane a final beta value has to be chosen that satisfies the spot size requirements. The value $\beta_x = 7.2$ m has been chosen in this example that, recalling that the unfilled ellipse emittance is $5 \pi$ mm mrad, corresponds to a 6 mm beam half size. With this assumption the large spiral step particles are distributed in 12 mm and the short spiral step ones are distributed in 8 mm. The average, roughly assumed as FWHM, corresponds to the 10 mm required in the specifications.
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7.8.9 Resulting lines

A possible combination of the modules is shown in Figure 7.18. To demonstrate the behaviour of the beam along the line the initial distribution has been tracked for two different settings of the phase shifter ($\Delta \mu_x = \pi/2$ and $\pi$) and the phase space footprints at different locations along the line are shown in Figures 7.19 and 7.20. Finally the Twiss functions for the first gantry line are shown in Figure 7.21.

Figure 7.17. Optical functions in the “riesenrad” gantry.

Figure 7.18. Geometry of a possible set of lines
Figure 7.19. Beam distributions at entry to:
(a) line, (b) phase shifter, (c) switch module, (d) rotator, (e) patient.
Figure 7.20. Beam distributions at entry to:
(a) line, (b) phase shifter, (c) switch module, (d) rotator, (e) patient.
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7.9 Conclusions

The strong asymmetry in the distribution of the extracted beam creates a problem in the design of the transfer lines to the treatment rooms. A standard description of the beam by matching the optical functions to the beam is not suitable and would yield exotic and complicated lattices. A novel approach to the transfer line design has been proposed that solves those problems.

The proposed scheme is based on the use of an ‘unfilled’ ellipse and on a modular design that allows to extend the center by just joining the different modules according to the needs. The functionality of the scheme has been demonstrated by a series of example modules and by transporting the extracted beam through the resulting line.

![Graph of Betatron amplitude functions and Dispersion functions versus distance.](image)

Figure 7.21. Optical functions in the line to gantry 1.