1. Introduction

A recent report[1)] has given a detailed discussion of beam transport to the ISAC-II experimental area. This report is bulky (83 pages), somewhat convoluted, and, indeed, perhaps confusing. As such it makes difficult reading because it deals with several aspects of the beam-transport system. Consequently, it was felt that a more concise report should be issued that deals with only one mode of beam transport while still giving the essential details of the proposed beam-transport system.

This report is an attempt to produce such a document.

2. An overview of the proposed configuration

In this section an overview is presented of the entire system of beam transport. More detail will be given in subsequent sections.

Figure 1 shows the proposed configuration of beam transport to the ISAC-II experimental hall. The (quadrupole) elements shown in black are located in the accelerator vault. At the extreme left and labeled mβ exit is the exit of the medium-β accelerator. The locations labeled M1, M2, ... M5 are positions at which beam-diagnostic equipment will be placed. These locations correspond to the locations F1, F2, ... F5 that are shown on TRIUMF drawing ISK0116U. In the future the eight quadrupoles between the exit of the medium-β accelerator and the location M2 will be removed and the high-β accelerator will be installed in their place.

Although also located in the accelerator vault the two quadrupoles that are colored cyan immediately downstream of M5 are considered to be part of the beam-transport system to the experimental hall. The two vertical, cyan-colored lines downstream of these quadrupoles indicate the concrete wall that separates the accelerator vault from the experimental area. Elements of the beam-transport system are shown in more detail in figure 2.

From these figures it is seen that there are four target locations proposed. Initially only the beamlines leading to the the target positions labeled TGT1 and TGT4 will be installed. The `TIGRESS` experiment will be located at the TGT1 position and the `TUDA` experiment will be located at the TGT4 position. Later the beamline to the TGT5 and TGT6 locations are to be installed. Targets TGT1 and TGT5 are located such that the `TIGRESS` equipment can move in a straight line between them. When the beamline to TGT6 is installed it is anticipated that the `TUDA` experiment will move to that location.

Except as noted below, regardless of which accelerator is in operation or which target location is being used, the premise of this design is that the beam transport upstream of M5 is tuned such that the the beam spot required by an experiment is produced at the M5 location. The ten-quadrupole, two dipole system leading to the TGT1 location is designed such that the transfer matrix from M5 to TGT1 is $+\boldsymbol{I}$ in the horizontal plane and $-\boldsymbol{I}$ in the vertical plane. The transport system is also doubly achromatic; there is neither spatial nor angular dispersion at the TGT1 position. Thus the beam spot at M5 is reproduced at the TGT1 target. Transport between the M6 location and the TGT5 position has the same properties, except that in this case the beam spot required at TGT5 is produced at the M6 (rather than the M5) location.

For beam delivery to an experiment at the TGT4 position the six quadrupole between M5 and the TGT4 location are tuned symmetrically to reproduce the beam spot at M5 at the TGT4 location. An additional target location, labeled TGT4A in figures 1 and 2 is also shown. On this section of beamline a symmetric quadrupole triplet reproduces the TGT4 beam spot at the TGT4A location.

It is not possible to produce a $+\boldsymbol{I}$ in the horizontal plane and $-\boldsymbol{I}$ in the vertical plane *and* a doubly achromatic beam at the TGT6 location. Consequently, the beamline between the M6 and TGT6 locations is tuned to translate the beam spot at M5 to the TGT6 target position *and* also be doubly achromatic. This has some consequences that will be discussed later.

2.1 Emittances and their variation as a function of accelerated energy

R. Laxdal has provided the author with predictions of the beam parameters to be expected for beams accelerated by the medium-β and high-β accelerators [2)]. For beam from the medium-β accelerator he considered an ion with $A/q = 3$, $A = 30$, and $q = 10$ that was accelerated to an energy of $E = 7.162\,\mathrm{MeV/u}$; for beam from the high-β accelerator and ion with $A/q = 6$, $A = 30$, and $q = 5$ accelerated to an energy of $E = 7.88\,\mathrm{MeV/u}$ was considered. Because his results are based on calculations that use Twiss parameters α_x, β_x, α_y, and β_y, listed in tables 1(a) and 1(b) are the corresponding parameters that are used in calculations using the `TRANSPORT` program.

For completeness the relationships between the Twiss parameters and those required for the `TRANSPORT` program are given as follows. Defining

$$\gamma_x = \frac{1+\alpha_x^2}{\beta_x} \qquad \text{and} \qquad \gamma_y = \frac{1+\alpha_y^2}{\beta_y}\ ,$$

we have

$$x = \pm\sqrt{\beta_x\epsilon_x}, \quad \theta = \pm\sqrt{\gamma_x\epsilon_x}, \quad y = \pm\sqrt{\beta_y\epsilon_y}, \quad \text{and} \quad \phi = \pm\sqrt{\gamma_y\epsilon_y}\ .$$

Values listed in tables 1(a) and 1(b) have been used in the `TRANSPORT` calculations given in this report.

An estimate has been made of the variation of the emittance as a function of the accelerated energy of an ion over a range of energies from 0.5 MeV/u to 15 MeV/u. This is shown in figure 3 over a range of energies from 0.5 MeV/u to 7 MeV/u. The curves in cyan and marked $\epsilon_0 = 0.2\pi$ mm-mr correspond to the intrinsic emittances of the present ISAC-I ion sources. These may be taken as 2σ emittances for operation *without* the CSB [2)]. Those in magenta and marked $\epsilon_0 = 0.3\pi$ mm-mr are estimated to be the intrinsic emittances for operation *with* the CSB. For this case the emittances also may be considered as emittances at the 2σ level [2)].

The operative word in the above paragraph is *estimate*. Until there have been emittance measurements it is stressed that the values obtained from figure 3 should be considered only as a guide to what should be expected from the accelerators.

3. Beam transport within the accelerator vault

A stated in the introduction of this report only one tune for the beam transport in the accelerator vault will be considered in this report. This tune will be called the *unit section* tune. By this it is meant that the first quadruplet downstream of an accelerator is tuned to produce a beam of a given size and with specific characteristics at the end point of the quadruplet. All remaining quadruplets are tuned as $-\boldsymbol{I}$ sections, thus translating the beam size and characteristics from the end of the first quadruplet to the location labeled M5 which serves as the object point for beam transported to the target locations in the experimental hall. Should these characteristics not be those required by the experiment the quadruplet between locations M4 and M5 is retuned to produce the required beam parameters.

Most experiments have indicated that a beam spot 2 mm in diameter is suitable at their experimental targets. Only one, the `EMMA` experiment has requested a smaller beam spot—in this case, a beam spot 1 mm in diameter. Because the `EMMA` experimental apparatus will not be mounted for several years, it has been decided that the first quadruplet downstream of each accelerator should be tuned to produce a double waist 2 mm in diameter at its exit. Thus, regardless of which accelerator is in operation, only two tunes are required in the accelerator vault for those experiments that can be performed with a 2 mm beam spot at their targets—one tune for the matching section and another for the unit sections. (Strictly speaking this is not true because the each of the first three quadruplets has an overall length of 4.42 m and each of the remaining two has an overall length of 4.54 m. Further two different types of quadrupoles are used. Thus a total of four unit-section tunes is required. However, once established for a given momentum the tune for a given quadruplet and quadrupole type does not change.)

Clearly, the tune for the matching sections is emittance dependent. However, that for the unit sections is not; it depends only on the momentum of the accelerated beam. This then is the virtue of this unit-section mode of operation. On the other hand, the beam sizes in the unit sections are such that approximately 60% of the quadrupole apertures are occupied by the beam. It is pointed out if [1] that other tunes that occupy a smaller percentage of the quadrupole apertures are possible. Thus if beam size in the quadrupoles of the vault transport is of concern, alternate tunes are available.

3.1 Production of a 2 mm beam spot at M5

Table 2 gives a `TRANSPORT` listing for the production of a 2 mm beam spot at the M5 location for beam accelerated in the medium-β accelerator. Please note that in this listing (and others to follow) quadrupoles are listed with a bore radius of 100 cm. Their pole-tip fields are given in kilogauss. Consequently, for those operating with quadrupole gradients of Tesla/m the gradient of a quadrupole is simply the listed pole-tip field in kG divided by ten. Thus, for example, the first quadrupole of the first quadruplet is listed as

```
5.00    'VQ1 '      0.32500   -90.25147   100.00000;
```

and shows the `TRANSPORT` code for a quadrupole (5.00), its label (VQ1), its effective length in metres (0.32500), its pole-tip field in kG (-90.25147), and its half-aperture in cm (100.00000). Thus the gradient of this quadrupole is -90.25 kG/m or -9.025 T/m.

Table 3 gives the settings as a function of emittance of the four quadrupole in the first quadruplet to produce a 2 mm beam spot at the M1 location. All remaining quadrupoles are set as listed in table 2. Figure 4 shows the beam envelopes along this particular beamline.

Table 4 shows the `TRANSPORT` input for the production of a 2 mm beam spot at the M5 location for beam accelerated in the high-β accelerator. The listing is for a beam with an horizontal and vertical emittances of 3π mm-mr. In this case the quadruplet between M2 (which becomes the exit of the high-β accelerator) and M3 is adjusted to produce a 2 mm beam spot at M3. The two remaining quadruplets are tuned as unit sections. The settings required for quadrupoles VQ9/10/11/12 as a function of emittance are listed in table 5. Figure 5 shows the beam envelopes along this section of beamline.

3.2 Production of a 1 mm beam spot at M5

Note: This section applies for beam delivery to the TGT1 location *only*. If a beam spot 1 mm in diameter is requested at the TGT5 or TGT6 locations another method of its production is used. This is discussed in more detail in and following §4.3.

The `EMMA` experiment requires a beam spot no larger than 1 mm in diameter at its target. Were that experiment mounted at the TGT1 location or should another experiment located there request a 1 mm diameter beam spot, then the quadruplets upstream of the M4 location would be tuned as above for the production of a 2 mm diameter beam spot. The quadruplet between M4 and M5 then becomes a second matching section and is tuned to reduce the 2 mm diameter spot at M4 to one 1 mm in diameter at M5.

Table 6 lists the settings of quadrupoles VQ17/18/19/20 for the production of a 1 mm beam spot at M5 for beam extracted from the medium-β accelerator. All remaining quadrupole are powered according to the settings given in tables 2 and 3.

Table 7 lists the settings of quadrupoles VQ17/18/19/20 for the production of a 1 mm beam spot at M5 for beam extracted from the high-β accelerator. All other vault quadrupoles are powered according to the settings given in tables 4 and 5.

Beam profiles for this tune are shown in figures 6 and 7.

3.3 Discussion of the proposed vault transport configuration

Figures 4 and 5 show that it is possible to produce a beam spot that is 2 mm in diameter at the M5 location for all emittances less than or equal to 6π mm-mr. This is true regardless of which accelerator is in operation. Because the (clear) apertures of all of the quadrupoles in this transport line are 52 mm the beam occupies a maximum of approximately 64% of the apertures at the largest emittance, which corresponds to an accelerated energy of 0.5 MeV/u according to figure 3. For an emittance of 5π mm-mr this figure drops to 50% and it becomes smaller as the emittance of the beam decreases.

We again reiterate that the beamline tune presented here is not the only tune that could be used. Beam sizes in the quadruplets between M1 and M4 (for medium-β operation) and in the quadruplet between M4 and M5 (for high-β operation) can be reduced simply by tuning the first matching quadruplet to produce a larger beam size (and thus smaller divergence) at the M1 position. If this is done then the quadruplet between M4 and M5 becomes a second matching section that produces the desired beam size at the M5 location. As a result the beam sizes in this quadruplet will increase slightly from those shown in the figures 4 and 5.

Consequently, there should be no problem in producing a beam spot 2 mm in diameter at any target location *provided* of course that beam transport beyond the M5 location has been designed to produce such a beam size at a target from a beam with an emittance of 6π mm-mr.

However, the situation is not so straight forward if a beam spot 1 mm in diameter is required. Figures 6 and 7 clearly show that for such a tune the size of the beam in the final matching quadruplet becomes large, approaching ± 35 mm in the horizontal plane for the tune shown. This occurs regardless of the tune of the beamline upstream of the M4 location. The last two quadrupoles of this quadruplet must have larger apertures unless this tune is restricted to beams of emittance 4π mm-mr or less. On the assumption that such a restriction is untenable, a simple solution to this problem would be to replace these quadrupoles (VQ19 and VQ20) with TRIUMF standard 4Q14/8 quadrupoles that have a bore of 4 inches. This could be done at a later date when and if a small beam spot is required.

It is stressed again that this comment applies only to the production of a beam spot 1 mm in diameter at the TGT1 location. This problem will be addressed again in the discussion of beam delivery to the TGT5 and TGT6 target locations.

4. Beam delivery to the ISAC-II experimental area

In this section a more detailed description is presented of the beamlines that deliver beam to the various targets in the ISAC-II experimental hall. Because the present plans are initially to install beamlines to the TGT1 and TGT4 locations those beamlines are considered first. Beamlines to the TGT5 and TGT6 target positions are to be installed later; these will be dealt with following discussions of the TGT1 and TGT4 beam delivery systems.

A comment on notation should be made. In total there are a number of quadrupoles downstream of the M5 location that are involved in the beam transport to the various targets and, ultimately, each will be given its own name. To simplify notation for this report quadrupoles are numbered sequentially as they occur in the beamlines. With this notation the last two quadrupoles in the accelerator vault and the first quadrupole in the experimental area will *always* be numbered as Q1, Q2, and Q3 respectively because they are the first three quadrupoles of *any* beamline. Subsequent quadrupoles are then numbered Q4, Q5, to QN where N is the total number of quadrupoles (including Q1, Q2, and Q3) of the beamline under consideration.

4.1 Beam delivery to the TGT1 target position

As ref[1] was being written it was noted that the polarities of the two quadrupoles downstream of M5 in the accelerator vault and the quadrupole upstream of dipole B1 in the experimental hall (refer to figure 2) were of opposite polarity to that required for beam transport to the TGT5 and TGT6 locations. A consequence of this was that three reversing switches would be required. Because each switch was estimated to cost \$2K[3] for a total cost of \$6K, a second beamline configuration was devised that did not require reversing switches. The design requiring reversing switches is called Version 1; the second, later design not requiring reversing switches is termed Version 2. Each of these is considered below.

As was mentioned previously, the optics of either of these versions is such that the transfer matrix from M5 to the TGT1 location is $+\boldsymbol{I}$ in the horizontal plane and $-\boldsymbol{I}$ in the vertical plane. This is produced by a ten-quadrupole, two-dipole system that is symmetric about its midpoint. The beam transport is also doubly achromatic. However, there is dispersion between the entrance of the first dipole (B1) and the exit of the second dipole (B2). At the symmetry point there is spatial dispersion but no angular dispersion.

4.1.1 Beam delivery to the TGT1 target position—Version 1

In Version 1 of the beam transport to the TGT1 location the quadrupoles are tuned in an HVHHV–VHHVH configuration. `TRANSPORT` input for beams accelerated in the medium-β and high-β accelerators is listed in table 8 from immediately downstream of the M5 location to the TGT1 location for this version of the beam transport. Note that the field values for the high-β accelerator are listed in parentheses following those for the medium-β accelerator.

Note: If a complete beamline file is desired one would insert the data given in table 8 between the line that contains the label `'M5 '` and the next line that contains the word `SENTINEL` in the listings given in either of tables 2 and/or 4, whichever is appropriate.

This illustrates the usefulness of design of this system. Once the required beam size has been produced at the M5 location the optics of the beamline downstream ensure that the beam size is reproduced at the TGT1 target location regardless of the emittance of the transported beam. Settings of the transport elements change only when the momentum of the beam changes. Further, because there is a unit transformation (except for sign in the vertical plane) between M5 and the TGT1 target location beam profiles between these two points will be identical *for a given beam size* regardless of which accelerator has been used to accelerate the beam. This is illustrated in figures 8(a) and 8(b). Figure 8(a) shows the beam envelopes between M5 and TGT1 for a beam accelerated in the medium-β accelerator with the vault beamline tuned to produce a 2 mm beam spot at the M5 location. The beam envelopes shown in figure 8(b) are those for beam accelerated in the high-β accelerator and the vault beamline tuned to produce a 2 mm beam spot at the M5 location. These two figures are virtually identical (and could be the same figure reproduced twice—but they are independent calculations). Consequently, only the beam envelopes of beams accelerated by the medium-β accelerator will be shown for this beamline in this and subsequent sections.

4.1.2 Beam delivery to the TGT1 target position—Version 2

This version differs from Version 1 in that the quadrupoles are tuned in a VHVHV-VHVHV configuration. Settings for this tune are given in table 9, again with the settings for acceleration in the high-β accelerator given in parentheses.

This section of beamline between the M5 and TGT1 locations is also tuned to produce a transfer matrix of $+\boldsymbol{I}$ in the horizontal plane and one of $-\boldsymbol{I}$ in the vertical plane. This beamline is also doubly achromatic at the TGT1 location. Comments made regarding beam profiles in §4.1.1 apply equally to the beamline of

Version 2. It is best to consider these two versions of beam transport by means of comparison.

However, before that is done it should be pointed out that in order to retain the $+\boldsymbol{I}/-\boldsymbol{I}$ transformations in the horizontal/vertical planes a small change was necessary in the locations of the two doublets between dipoles B1 and B2. Each doublet was moved as a whole approximately 7 cm closer to midplane symmetry point. Because the center-to-center separation of the quadrupoles within a doublet was not changed a like distance was added to the drift distance upstream of the first doublet and downstream of the second doublet. Thus the overall optical and physical lengths of the transport line were not altered.

4.1.3 Comparison of Versions 1 and 2 for beam transport to the TGT1 target

The data given in tables 8 and 9 indicates that there are no gross differences required in the quadrupole settings of Version 1 and Version 2 of this beamline. Overall, however, those of Version 1 are slightly lower than those given for version 2. However, there is a significant difference between the beam envelopes of the two versions.

The beam envelopes of Version 1 between M5 and the TGT1 location when a 2 mm beam spot is produced at both M5 and TGT1 are shown in figure 9(a). Figure 9(b) is a similar plot for the tune of Version 2. Roughly speaking the x and y envelopes of Version 1 are interchanged in Version 2. One immediately notices that the beam is large in the doublet downstream of M5 and the doublet upstream of TGT1. That the beam is large in the vertical plane in the Version 1 tune and in the horizontal plane in the Version 2 tune results from the reversal of polarities of the first and last three quadrupoles between one tune and the other. This, of course is to be expected. However, because of beam size in the first and last doublets the use of TRIUMF standard 4Q14/8 quadrupoles has been specified for these four quadrupoles regardless of which version of the beamline is used.

There is, however, a notable difference between the two tunes elsewhere along the beamline. The horizontal beam size in dipoles B1 and B2 in the Version 1 tune is approximately two-thirds of that in the Version 2 tune. In the vertical plane the beam size of the Version 2 tune is roughly one-half of that of the tune of Version 2. Of these the vertical beam size is more critical because the clear vertical aperture of the dipole vacuum boxes is only 22 mm.

The horizontal beam size in the doublets between the dipoles is slightly larger in the Version 1 tune than in the Version 2 tune. However, in the vertical plane the beam size is considerably smaller in the Version 1 tune than it is in the tune of Version 2. The consequence of this is that the beam spot at the symmetry (MID) point of the system in Version 1 is approximately $(x, y) = (\pm 6\,\text{mm}, \pm 1.5\,\text{mm})$ while that in Version 2 is approximately $(x, y) = (\pm 10\,\text{mm}, \pm 10\,\text{mm})$ or 20 mm in diameter.

Recall that the Version 2 tune was developed in order to save the cost of reversing switches for the first three quadrupoles because the beam transport to the other three targets requires that the first three quadrupoles be powered in a VHV arrangement. The estimated cost of these switches was \$6K. However, depending on what instrumentation is being considered for installation at the symmetry point of the system, the considerable difference in beam size there might sway the balance from the installation of Version 2 to that of version 1 despite the additional cost that that involves.

The beam envelopes along this beamline for the production of a 1 mm beam spot at the M5 and TGT1 locations are shown in figure 10(a) for the tune of Version 1 and in figure 10(b) for that of Version 2. It is seen that the vertical beam size of Version 1 and the horizontal beam size of version 2 is very large and exceeds the bore diameter of the 4Q14/8 quadrupoles. This has been realized for some time but it has been tempered by the fact that only the `EMMA` experiment has specified a 1 mm beam size. Further, it has been assumed that this experiment would operate only at higher accelerated energies. Consequently, only beams of emittances at or below 4π mm-mr would be required. That being the case, an emittance of 4π mm-mr would fill 75% to 80% of the apertures of the first and last two quadrupoles. A more comfortable restriction to emittances less than or equal to 3.5π mm-mr would be seem more reasonable from that point of view.

Beam sizes in dipoles B1 and B2 again are smaller for the tune of Version 2 than that of Version 1. If it is assumed that only beams of emittance 4π mm-mr or less are transported in the 1 mm mode figure 10(a) indicates that the beam sizes in the doublets between the dipoles exceeds ± 20 mm, thus filling in excess of 80% of the aperures of the quadrupoles. If this version is chosen to be installed it is recommended that these four quadrupoles be type L5, which have a 70 mm aperture, rather than type L2, which have a 52 mm aperture, as specified in tables 8 and 9. On the other hand, with the Version 2 tune shown in figure 10(b) quadrupoles of the type L2 are satisfactory for this tune.

At the symmetry point the beam size of the tune of Version 1 is roughly one-half that of the tune of Version 2. This is true both in the horizontal plane and in the vertical plane. Again, the choice of which version to install may be dictated by what instrumentation is to be placed at the symmetry point.

4.1.4 Further discussion of beam transport to the TGT1 target

The above sections have shown that a beam spot 2 mm in diameter can be produced at the TGT1 target for all beams of emittance 6π mm-mr or less regardless of whether Version 1 or Version 2 of the transport system is installed. It has also been noted that the first two and last two quadrupoles of either version must have large apertures and quadrupoles of the TRIUMF standard type 4Q14/8 have been recommended. However, if Version 1 is installed it has also been recommended that the four quadrupoles between the two dipoles be type L5 rather than type L2 that are suitable for the Version 2 tune.

It has also been recommended that if a 1 mm beam spot is necessary at the TGT1 location, the emittance that can be transported through the beamline be restricted to at most 4π mm-mr and, preferably, 3.5π mm-mr. The reason for this restriction is because of the large beam size in the first and last two quadrupoles of the transport line. This is caused, of course, because the 1 mm beam size is produced at the M5 location and, with it, a corresponding doubling (relative to a 2 mm beam spot) of the horizontal and vertical angular divergences.

These divergences could be accepted by the beamline were the distance shortened between M5 and the first downstream quadrupole and between the TGT1 location and the quadrupole upstream. However, in consultation with the experimental groups it was agreed that the minimum distance from an upstream quadrupole to a target location would be 1.5 m. With that distance set the requirement of symmetry dictated that the distance from the object point (the M5 location) of the transport line to the nearest downstream quadrupole also be 1.5 m.

Perhaps a better way of stating this problem is as follows. What is important is that there be no scattering of beam from the beam pipe or the vacuum vessels of the dipoles. If a 1 mm beam spot is desired and the beam being transported has an emittance in excess of 4π mm-mr it is guaranteed that there will be scattering of the beam somewhere along the beamline.

It has been stated that there is both angular and spatial dispersion between dipoles B1 and B2. This is also illustrated in figures 9(a) and 9(b). The solid lines show the beam envelopes for beams that have a momentum spread of $\pm 1\%\ \delta p/p$, the maximum expected from the accelerators[4)]. The dotted curves show the beam envelopes for beams with a momentum spread of $\pm 0.1\%\ \delta p/p$. The effect of The momentum spread of the beam on beam sizes between the dipoles is evident.

For the tune of version 1 the beam envelope in the doublets between the dipoles is reduced for a beam of emittance 6π mm-mr to that of one with an emittance 5π mm-mr. At the symmetry point the beam size is reduced by a factor of three. For the tune of version 2 the beam envelope in the doublets between the dipoles of a 6π mm-mr emittance beam and a momentum spread of $\pm 0.1\%\ \delta p/p$ is smaller than that of a beam with an emittance of 3π mm-mr and a momentum spread of $\pm 1\%\ \delta p/p$. The beam size at the symmetry point is reduced roughly by a factor of two. Thus the smaller the momentum spread in the accelerated beam the less are dispersion effects on beam sizes between the two dipoles.

4.2 Beam delivery to the TGT4 and TGT4A locations

At the TGT4 and TGT4A locations *only* the production of a beam spot nominally 2 mm in diameter has been considered. It is not possible to produce a doubly achromatic beam spot with a single-dipole system (unless there is dispersion upstream of the dipole). However, with the beam-transport configuration shown in figure 2 it is possible to produce a double waist with a small ($\leq$0.02 cm/%δp/p) spatial dispersion and a somewhat larger ($\sim$4.2 mr/%δp/p) angular dispersion at the TGT4 target.

As shown in figure 2, the beam transport to the TGT4 location is symmetric about dipole B1 and corresponding quadrupoles are powered equally. Thus the first quadrupole downstream of M5 and the first quadrupole upstream of TGT4 are powered the same as are the center two and inner two quadrupoles of the system. Each set of two quadrupoles are powered at different excitations.

Also shown in figure 2 is an alternate target position designated TGT4A. As noted above, the distance between TGT4 and the quadrupole upstream of it is 1.5 m. If this distance is too short for an experiment to be mounted, the beam spot at TGT4 can be reproduced at the TGT4A location using a symmetric quadrupole triplet. As drawn in figure 2 the distance between the TGT4A position and the closest upstream quadrupole is 2.25 m.

Table 10 lists the `TRANSPORT` input for beams accelerated in the medium-β accelerator for an emittance of 3π mm-mr. Settings for those accelerated in the high-β are given in parentheses. Table 11(a) lists the quadrupole settings (in kG) for other emittances from the medium-β accelerator. Corresponding settings for acceleration in the high-β accelerator are given in table 11(b). Beam profiles along this beamline are shown in figure 11.

From figure 11 it is seen that a beam spot 2 mm in diameter can be produced at the TGT4 target for all emittances at and below 6π mm-mr. However, if the extension to the TGT4A location is installed it is recommended that the center quadrupole of the triplet between the TGT4 and TGT4A locations be one of the 4Q14/8 type rather than the type L2 given in the listings.

4.2.1 Discussion of the beamline to the TGT4 target

The solid curves in figure 11 are drawn for beams that have a momentum spread of $\pm 1\%\ \delta p/p$; the dotted curves are for beamswith momentum spreads of $\pm 0.1\%\ \delta p/p$. It is clear from the figure that the envelopes for beams of the lower momentum spread are more symmetric than those of beams with the larger momentum spread. Beam size downstream of the B1 dipole is affected by both the spatial and angular dispersions generated in the dipole. A low emittance beam is affected more than is one of high emittance. This is to be expected because for a given beam size low-emittance beams have a smaller divergence than do high-emittance beams. However, using the symmetric configuration shown—including installing two type 4Q14/8 quadrupoles upstream of the TGT4 target—the *spatial* dispersion at the target location is made small and a 2 mm beam spot is produced.

Although the spatial dispersion is, for practical purposes, zero there is angular dispersion at both the TGT4 and TGT4A locations. This causes the horizontal divergence at the targets to be momentum dependent with the result that the angular dispersion causes an effective increase in emittance. Consider, for example, the case of a beam with an emittance of 3π mm-mr. At the TGT4 target in the vertical plane—in which there is no dispersion—there is a waist of size $y = \pm 0.85$ mm. This implies a vertical divergence of $\phi = \pm 3\pi$ mm-mr$/0.85$ mm $= \pm 3.53$ mr. However, in the horizontal plane one also finds a waist of size $x = \pm 0.85$ mm but a horizontal divergence of $\theta = \pm 5.49$ mr. This corresponds to an *effective* emittance of

$\pi x\theta = \pi 0.85(5.49) = 4.67\pi$ mm-mr rather than the 3π mm-mr emittance of the initial beam. Thus the dispersion induced in the horizontal divergence of the beam has effectively *increased* the horizontal emittance by approximately 50%.

This effect becomes smaller as the emittance is increased. At an emittance of 6π mm-mr one finds that the effective horizontal emittance is $\pi x\theta = \pi 0.85(7.916) = 6.73\pi$ mm-mr rather than that in the vertical plane of $\pi y\phi = \pi 0.85(7.060) = 6.00\pi$ mm-mr. Thus the effective horizontal emittance is increased by approximately 12% at an initial emittance of 6π mm-mr.

The only way to reduce this effect is to increase the beam size at the target and/or decrease the momentum spread of the initial beam. The latter is of course a machine problem. The former can be dealt with to some extent in the beamline optics. If the beam size at the target is increased the corresponding geometrical divergence is decreased and the horizontal divergence then becomes dominated by the chromatic dispersion. Thus, for an emittance of 6π mm-mr, if the beam size at TGT4 is doubled to $x = y = \pm 1.7$ mm it is found that the horizontal divergence becomes $\theta = \pm 3.56$ mr and $\phi = 3.53$ mr, implying an effective increase of the horizontal emittance of approximately 1%.

This aspect of the proposed design is mentioned because the apparent increase of the horizontal emittance may need to be taken into consideration for some experiments.

4.3 Beam delivery to the TGT5 target – Version 1

As shown in figure 2 to produce beam at the TGT5 location an additional three quadrupoles are installed downstream of dipole B1, which is turned off. These, together with the three quadrupoles upstream of B1 are used for two purposes. First, these quadrupoles are tuned to produce a vertical waist in that dipole, thus reducing the vertical beam height in it. Second, they are used to produce at the M6 location an image the beam at the M5 position. The M6 location then becomes the object point for beam transport to the M5 and M6 targets.

Optics of the system between M6 and the TGT5 locations is identical to that for beam delivery to the TGT1 target. In the horizontal plane the transfer matrix between those two points is $+\boldsymbol{I}$ and in the vertical plane it is $-\boldsymbol{I}$. Beam transport is also doubly achromatic.

The TGT5 target has been located such that an experiment mounted there can move between the TGT5 and TGT1 locations. Because the beamlines between B2 and TGT1 and between B4 and TGT5 are parallel, the line along which the experimental apparatus moves is perpendicular to each of those two lines.

4.3.1 Production of a 2 mm diameter beam spot at the TGT5 target – Version 1

In this case the six-quadrupole array between M5 and M6 are tuned both to keep the beam height small in B1 and to produce a double waist that is 2—,mm in diameter at the M6 location. Table 12 lists `TRANSPORT` input from M5 to the TGT5 target for a beam of emittance 3π mm-mr that has been accelerated in the medium-β accelerator. The quadrupole fields in parentheses in table 12 are the settings for a beam of emittance 3π mm-mr that has been accelerated in the high-β accelerator.

The settings of the first six quadrupoles are a function of emittance. Table 13(a) lists those for beams extracted from the medium-β accelerator. Settings for beam accelerated in the high-β accelerator are given in table 13(b). Because beam transport between M5 and the TGT5 target operates as a unit section (aside from sign), quadrupoles in this section depend only on momentum and their settings remain as given in table 12.

4.3.2 Production of a 1 mm diameter beam spot at the TGT5 target – Version 1

Although a 1 mm beam spot has not been requested at the TGT5 target there is a possibility that the `EMMA` experiment could be mounted there[4)]. Consequently, the production of such a beam has been considered.

To produce a beam spot 1 mm in diameter at the TGT5 target the beamline in the vault is set to produce a 2 mm beam spot at M5 and the six quadrupoles between M5 and M6 are adjusted to produce a 1 mm beam spot at M6 and to maintain a small vertical height in dipole B1. Table 14(a) lists the settings of these six quadrupoles for beams accelerated in the medium-β accelerator. Corresponding settings for beams accelerated in the high-β accelerator are given in tables 14(b).

Again, because the M5–TGT5 section of beamline operates as a unit section (other than sign) the settings of quadrupoles between M5 and the TGT5 target remain the same as given in table 12. The triplet downstream of M6 and those upstream of the TGT5 and TGT6 targets are specified in table 12 to be of the type L5–4Q14/8–L5 and should be able to accept the large beam sizes in that region. Only for an emittance of 6π mm-mr might there be a problem.

4.3.3 Discussion of beam delivery to the TGT5 target – Version 1

Figure 12(a) shows the beam envelopes for delivery of a 2 mm diameter beam spot to the TGT5 target. Beam envelopes for the production of a 1 mm diameter beam spot at the target are shown in figure 12(b). In each of these figures the solid curves are drawn for beams with a momentum spread of $\pm 1\%\,\delta p/p$, the maximum expected from the accelerators [5)]. The effect of dispersion between dipoles B3 and B4 is shown by the dotted curves that are drawn for beams with a momentum spread of $\pm 0.1\%\,\delta p/p$.

Figure 12(a) shows that there should be no difficulty in producing a 2 mm beam spot at this location, although there are possible problems for beams of emittance larger than 4π mm-mr. Vertical beam size in the triplet between dipole B1 and the M6 position is seen to reach ± 19 mm. If type L5 quadrupoles are used then approximately 75% of the aperture of the center quadrupole would be occupied by a beam of emittance 6π mm-mr. Further, the beam in the vertical plane is diverging rapidly as it leaves dipole B3 and is converging rapidly as it enters dipole B4, reaching a height of ± 8 mm at those points. Given that the available gap of the (existing) dipoles is ± 11 mm, approximately 73% of the aperture would be filled with beam of that emittance.

With the beamline tuned to produce a 1 mm spot at the TGT5 target this problem becomes worse. Vertical beam height in the first two quadrupoles of the triplet between B1 and M6 is in excess of ± 30 mm and thus implies the use of type 4Q14/8 quadrupoles in those locations. Further, beam height in dipoles B3 and B4 exceeds the available gap (of existing dipoles) at emittances at and above 5π mm-mr and exceeds the available horizontal width of the vacuum vessel at an emittance of 6π mm-mr. In addition, beam sizes in the four quadrupoles between dipoles B3 and B4 is such that type L5 quadrupoles should be installed there rather than the type L2 quadrupoles that are specified in table 12.

The above are strong criticisms of the optical design of this beamline. Most of them arise from the need to produce a 1 mm beam spot at the TGT5 target. However, the problems are not insurmountable. The major problem is that existing with the vertical gaps of dipoles B3 and B4. It has been assumed that these would be the same as those of the (existing) dipoles B1 and B2. There are at least two choices, the first being to restrict the range of emittance for which this beamline can operate. This is believed probably untenable. Another choice would be to obtain dipoles with an air gap of, say, at least two inches. This option is more tenable because, as the dipoles will have to be manufactured when they are needed, there remains time to redesign them with the appropriate air gaps. In fact, at that time it would be best to replace dipoles B1 and B2 with dipoles of the new design. This latter option—redesign of the dipoles—is the recommended path to take.

Given that these dipoles are redesigned, the remaining problem lies in the apertures required in the quadrupoles. Recommendations have been made above as to which quadrupole types should be used in order to overcome this problem. Consequently, it is believed that with the proper choice of quadrupoles and a new dipole design, an operational beamline can be built.

4.3.4 Beam delivery to the TGT5 target – Version 2

Given the problems noted in the previous section it was thought best to offer an alternate tune for this beamline. In this tune the beamline is tuned solely to produce a doubly-achromatic double waist at the TGT5 location and the transfer matrix between M6 and the target is no longer required to be a unit section (except for sign) between M6 and the TGT5 target. The consequence of this is that quadrupoles Q7 through Q16 must be tuned as functions both of momentum and of emittance.

4.3.5 Production of a 2 mm beam spot at the TGT5 target – Version 2

To produce a 2 mm beam spot at the TGT5 target with this tune quadrupoles Q1 through Q6 are set as given in table 13(a) for beam accelerated in the medium-β accelerator and as in table 13(b) for beam accelerated in the high-β accelerator. The remaining quadrupoles Q7 through Q16 are set to the values listed in tables 15(a) and 15(b) for acceleration in the medium-β and high-β accelerators respectively.

4.3.6 Production of a 1 mm beam spot at the TGT5 target – Version 2

Quadrupoles Q1 through Q6 are set according to the values given in table 14(a) for acceleration in the medium-β accelerator and as in table and to the values given in table 14(b) for acceleration in the high-β accelerator. The remaining quadrupoles Q7 through Q16 are set to the values listed in tables 15(c) and 15(d) for acceleration in the medium-β and high-β accelerators respectively.

4.3.7 Discussion of beam delivery to the TGT5 target – Version 2

Figure 13(a) shows the beam profiles for the production of a 2 mm beam spot at the TGT5 location for beam accelerated in the medium-β accelerator. Again, the solid curves are for a beam with a momentum spread of $\pm 1\%\ \delta p/p$ and the dotted curves are for a beam with a momentum spread of $\pm 0.1\%\ \delta p/p$. The effect of momentum spread in the accelerated beam is seen to be much less than that that was seen in the tune of version 1.

This figure indicates that the tune of version 2 will accept beams of emittance 6π mm-mr and less. The maximum vertical beam size in dipoles B3 and B4 is ± 6.2 mm and the maximum horizontal size in the doublets between those dipoles is ± 17.2 mm. Thus the beam occupies a maximum of approximately 56% of the vertical aperture of the dipoles and 66% of the aperures of the quadrupoles between them.

A comparison of figures 12(a) and 13(a) shows that the most dramatic differences between the tunes of versions 1 and 3 are in the beam sizes at the midplane. For the tune of version 2 the maximum horizontal beam width there is ± 7.3 mm and the maximum vertical height there is ± 1.1 mm. For the tune of version 1 the maximum horizontal beam width there is ± 17.1 mm and the maximum vertical height there is ± 10 mm. The reason for this lies in the differences of the spatial dispersions of the two tunes at the midplane. In the version 1 tune the horizontal magnification is -0.67 cm/cm and the horizontal dispersion is -1.70 cm/%$\delta p/p$. Thus the horizontal beam size is dominated by the spatial dispersion. On the other hand the tune of version 2 has a horizontal magnification of 1.88 cm/cm and a dispersion of -0.31 cm/%$\delta p/p$ with the consequence that, roughly speaking, each term contributes equally to the horizontal beam size at the midplane.

Figure 13(b) shows the beam envelopes for the production of a 1 mm beam spot at the TGT5 location for beam, again for beam accelerated in the medium-β accelerator. Again, the effect of momentum spread in the accelerated beam is seen to be much less than that that was seen in the tune of version 1.

This figure indicates that the tune of version 2 will accept beams of emittance 5π mm-mr and less. At an emittance of 6π mm-mr the maximum vertical beam size in dipoles B3 and B4 is ± 11.4 mm, just exceeding that of the available aperture of the (existing) dipoles. The vertical beam height for an emittance of 5π mm-mr is 9.44 mm so that at this emittance approximately 86% of those apertures is being filled. This, is felt, is too large and it is again concluded that with the apertures of the existing dipole this beamline should be restricted to emittances of beams of emittances 4π mm-mr and less if a 1 mm beam spot is desired at the TGT5 location. Even at that emittance the vertical beam height is ± 7.44 mm, meaning that approximately 68% of the dipole apertures is filled with beam. The maximum horizontal width of the beam in the quadrupoles between the dipoles is ± 18.2 mm, implying that approximately 70% of the apertures of these quadrupoles would be filled with beam. Consequently, if the suggestion in §4.3.3 is followed, these quadrupoles would be of type L5 and would be satisfactory for this beamline.

Again the beam size at the midplane differs for the tunes of versions 1 and 2. Comments given above for the production of a 2 mm beam spot at the TGT5 target apply equally to the production of a 1 mm beam spot there.

It is reiterated that the major problems arise with the tune of version 1 and of version 2 because the apertures of dipoles B3 and B4 have been assumed to be those of the existing dipoles. Given that a new dipole design would have a larger gap, either version of the beamline can be successfully implemented. Overall, however, it is felt that of version 2 produces the smaller beam envelopes although one gives up the unit transformation property of the beamline.

4.4 Beam delivery to the TGT6 target

To deliver beam to the TGT6 target location the quadrupoles between the M5 and M6 locations are tuned as for delivery to the TGT5 target and dipole B4 is reversed in polarity.

The section of beamline between M6 and the TGT6 target cannot be operated as a unit section as is that between M6 and the TGT5 target. Instead, the beamline is tuned to produce a doubly-achromatic double waist at the TGT6 target. As a consequence the settings of the quadrupoles will change with the emittance of the transported beam.

4.4.1 Production of a 2 mm diameter beam spot at the TGT6 target

Table 16 gives the `TRANSPORT` input for the production of a 2 mm beam spot at the TGT6 target for a beam with an emittance of 3π mm-mr. These are listed for the elements between M6 and the TGT6 target; the settings for quadrupoles Q1 through Q6 are the same as in tables 13(a) and 13(b). Tables 17(a) and 17(b) give the quadrupole settings as a function of emittance for acceleration in the medium-β and high-β accelerators, respectively.

4.4.2 Production of a 1 mm diameter beam spot at the TGT6 target

Although not requested by the experimenters, it is possible to form a beam spot 1 mm in diameter at the TGT6 target. For this the six quadrupoles Q1 through Q6 are set according to the data given in tables 14(a) and 14(b). Settings of the quadrupoles for beam extracted from the medium-β accelerator are given in table 17(c) and those for extracted from the high-β accelerator are given in table 17(d).

4.4.3 Discussion of beam delivery to the TGT6 target

Figure 14(a) shows the beam envelopes between M6 and the TGT6 target when the beamline is tuned to produce a 2 mm diameter beam spot at that target after a beam has been accelerated in the medium-β accelerator. It is seen there should be no difficulty in providing such a beam spot for all emittances shown. The maximum beam height in the B3 and B4 dipoles is ± 4.3 mm, well within the apertures of the dipoles. The maximum horizontal beam width in the two doublets is ± 18.2 mm, suggesting that 70% of the quadrupole apertures are filled. However, if as suggested above, these quadrupoles are of type L5 only 50% of the apertures would be filled.

Figure 14(b) shows the beam envelopes between M6 and the TGT6 target when the beamline is tuned to produce a 1 mm diameter beam spot at that target. It is again seen that there is the problem of vertical beam height in the dipoles. At an emittance of 5π mm-mr and above the vertical beam height is larger than the gaps of the (existing) dipoles. At an emittance of 4π mm-mr the gaps are approximately 83% filled and at an emittance of 3π mm-mr they are approximately 63% filled. If one assumes that the (new) dipoles for this beamline each has an air gap of at (at least) two inches, this problem is resolved and the problem now becomes one of the apertures of the four quadrupoles between the dipoles, which can be alleviated by using type L5 quadrupoles.

5. General discussion

This report has presented details of the proposed beam delivery system to the ISAC-II experimental area. Throughout this report discussions of the various beamlines have been presented and recommendations have been made. These may be summarized as follows.

1. Generally speaking it is possible to produce a beam spot that is 2 mm in diameter at any target location with beam-transport elements as specified in the tables.

2. However, because it is possible to produce a beam spot that is 1 mm in diameter at the TGT1, TGT5, and TGT6 targets it has been recommended that the four quadrupoles between dipoles B1 and B2 on the line to the TGT1 target and those between B3 and B4 on the line to the TGT5 and TGT6 targets be replaced with type L5 quadrupoles rather than the specified type L2.

If it is assumed that the proposed configuration is accepted and that a 1 mm diameter beam spot is produced at the three targets, then some of these type L5 quadrupoles (or their equivalent) must be purchased. The proposed design for the beamline to the TGT5 and TGT6 targets requires six of the type L5 quadrupoles. The additional eight quadrupoles noted above bring the total to fourteen quadrupoles of this type. If it is assumed that the configuration of the triplet between the B1 and M6 locations is a L5-4Q14/8-L5 configuration the total number of type L5 quadrupoles required rises to sixteen. TRIUMF has on hand five quadrupoles of this type so an additional eleven type L5 quadrupoles would be required. Again, this number assumes that a 1 mm beam spot is required at each of the TGT1, TGT5, and TGT6 target locations.

Further, if a 1 mm beam spot will be required at the TGT1 target it would be best that the four quadrupoles between dipoles B1 and B2 could be installed when the beamline is initially implemented.

3. The major problems in the beam transport systems arise from the small vertical gap of the existing B1 and B2 dipoles. It is recommended that these $+30°/-30°$ dipoles be redesigned with an air gap of at least 2 inches and that these be installed when the beamline to the TGT5 and TGT6 targets is installed.

It is also recommended that a total of four dipoles of this new design be purchased and that the existing B1 and B2 dipoles be replace with ones of the new design.

4. It should be reiterated here that the production of a 1 mm beam spot at the TGT1 target restricts the emittance acceptance of the beamline to those of emittances 4π mm-mr and less. This is not only because of the small dipole apertures but also because of aperture limitations of the quadrupoles in the accelerator vault and upstream of the target. The use of larger-gap dipoles will not affect this restriction.

The difference between beam transport to this target and that to the TGT5 target is that in the beamline to TGT1 the triplet downstream of M5 is necessarily split because of the wall of the accelerator vault whereas that downstream of M6 in the line to TGT5 is close packed.

References

1. G. M. Stinson, *Present status of the beam transport to the* ISAC-II *experimental area*, TRIUMF report TRI-DNA-05-1, August, 2005.
2. R. E. Laxdal, *Private communication*, TRIUMF, December, 2004.
3. K. Reiniger, *Private communication*, TRIUMF, July, 2005.
4. P. Bricault, *Private communication*, TRIUMF, August, 2005.
5. R. E. Laxdal, *Private communication*, TRIUMF, January, 2005.

Note added in proof

In section §4.3 it was noted that if the unit-section nature of the beam transport to the TGT5 target was abandoned, better beam profiles along the beamline could be achieved. Because the beamline to the TGT1 target nominally operates in a unit-section mode, a similar technique could be employed on that beamline with the hope of a similar result. This is the subject of this added-in-proof note.

The unit-section requirement of the beamline to the TGT1 target is dropped and the requirement is relaxed to a doubly-achromatic double waist there. Symmetry of quadrupole powering is, however, maintained. In following with the text, this should be termed Version 3 of the M5 to TGT1 transport line.

As an example, the beam envelopes shown in figure 9(b) become those shown in figure N1 (next page) when the unit-section criterion is dropped from the Version 2, 2 mm beam-spot tune for the M5 to TGT1 section of beamline. These envelopes are for beam accelerated in the medium-β accelerator. It is clear that the vertical beam size at the symmetry plane is smaller in version 3 that in version 2.

Similarly, the envelopes shown in figure 10(b) become those shown in figure N2 when the unit-section criterion is dropped from the Version 2, 1 mm beam-spot tune of the beamline. In this case there is little difference between the tunes of versions 2 and 3.

Listed below are the quadrupole settings for these tunes. Because of midplane symmetry only the settings of the first five quadrupole are listed.

Table N1

Version 3 `TRANSPORT` input beam parameters for beam delivered from the medium-β accelerator
Production of a 2 mm beam spot at the TGT5 target as a function of emittance†

Element	$\epsilon = 3\pi$ mm-mr	$\epsilon = 4\pi$ mm-mr	$\epsilon = 5\pi$ mm-mr	$\epsilon = 6\pi$ mm-mr
Q7	−44.37465	−44.37465	−44.37465	−44.37465
Q8	37.92623	37.95062	37.97973	38.00607
Q9	−38.04459	−39.19013	−40.05520	−40.73706
Q10	47.99425	47.79308	47.61755	47.45188
Q11	−54.63972	−54.03250	−53.50746	−53.01594

† All other quadrupoles are set as in table 13(a).

Table N2

Version 3 `TRANSPORT` input beam parameters for beam delivered from the medium-β accelerator
Production of a 1 mm beam spot at the TGT6 target as a function of emittance†

Element	$\epsilon = 3\pi$ mm-mr	$\epsilon = 4\pi$ mm-mr	$\epsilon = 5\pi$ mm-mr	$\epsilon = 6\pi$ mm-mr
Q7	−44.86295	−44.34470	−44.10122	−43.94308
Q8	38.11208	38.13213	38.15968	38.19605
Q9	−41.31183	−43.76552	−45.37559	−46.87239
Q10	46.33768	46.02891	45.58101	45.24972
Q11	−49.80858	−48.94894	−47.72353	−46.83319

† All other quadrupoles are set as in table 13(b).

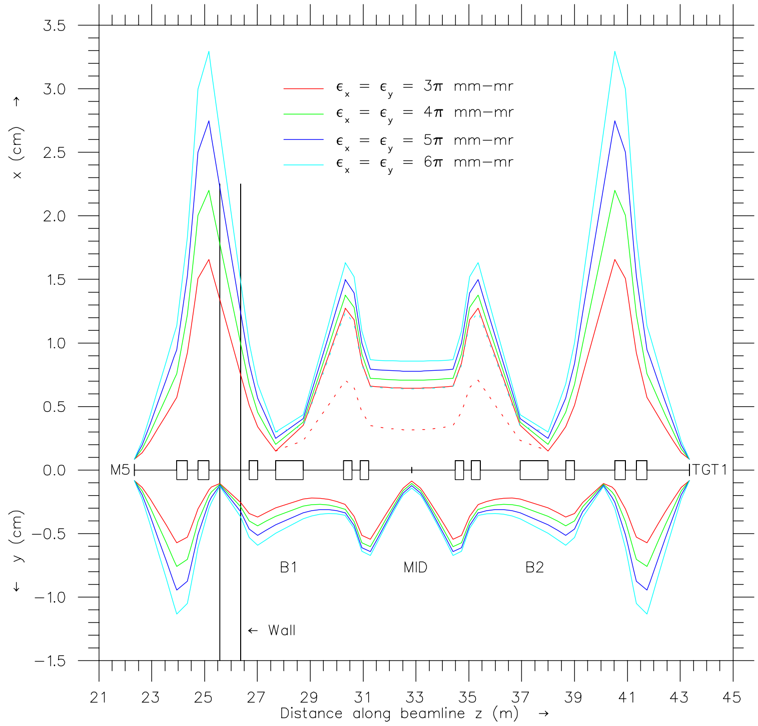

Fig. N1. Beam envelopes between M5 and TGT1 for beam accelerated in the medium-β accelerator with a 2 mm beam spot at the M5 and TGT1 locations—Version 3.

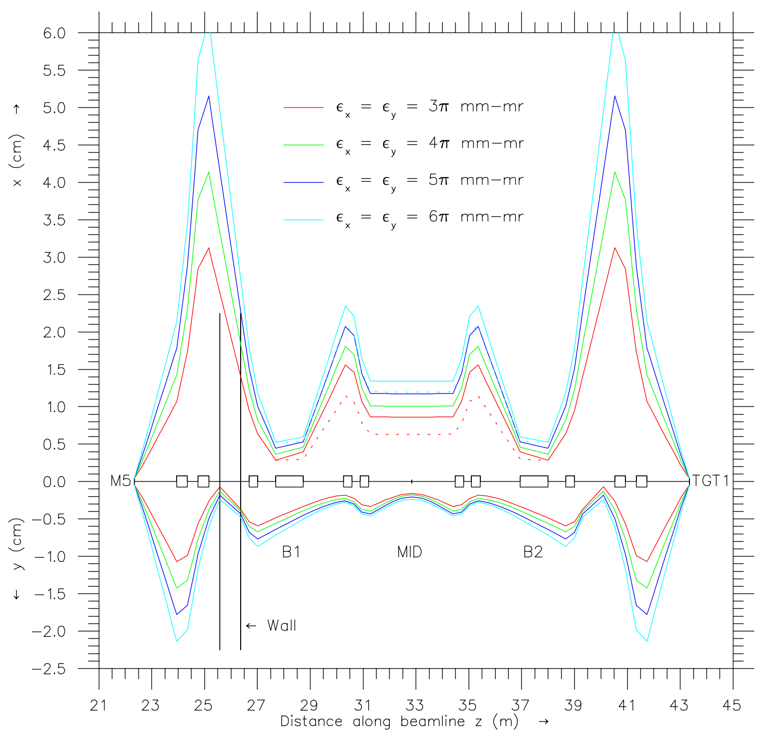

Fig. N2. Beam envelopes between M5 and TGT1 for beam accelerated in the medium-β accelerator with a 1 mm beam spot at the M5 and TGT1 locations—Version 3.

Table 1(a)

`TRANSPORT` input beam parameters for beam extracted from the medium-β accelerator
$A/q = 3$, $A = 30$, $q = 10$, $E = 7.162\,\mathrm{MeV}/\mu$, $\alpha_x = -0.107$, $\beta_x = 0.799\,\mathrm{mm/mr}$, $\alpha_y = 0.249$, and $\beta_y = 1.036\,\mathrm{mm/mr}$

Parameter	Emittance (mm-mr)			
	3π	4π	5π	6π
$\pm x\,(\mathrm{cm})$	0.1548	0.1788	0.1999	0.2190
$\pm\theta\,(\mathrm{mr})$	1.9488	2.2502	2.5158	2.7560
r_{21}	0.1064	0.1064	0.1064	0.1064
$\pm y\,(\mathrm{cm})$	0.1763	0.2036	0.2276	0.2493
$\pm\phi\,(\mathrm{mr})$	1.7537	2.0249	2.2640	2.4800
r_{43}	−0.2416	−0.2416	−0.2416	−0.2416

Table 1(b)

`TRANSPORT` input beam parameters for beam extracted from the high-β accelerator
$A/q = 6$, $A = 30$, $q = 5$, $E = 7.88\,\mathrm{MeV}/\mu$, $\alpha_x = 0.023$, $\beta_x = 0.938\,\mathrm{mm/mr}$, $\alpha_y = 0.0$, and $\beta_y = 1.969\,\mathrm{mm/mr}$

Element	Emittance (mm-mr)			
	3π	4π	5π	6π
$\pm x\,(\mathrm{cm})$	0.1678	0.1937	0.2166	0.2372
$\pm\theta\,(\mathrm{mr})$	1.7889	2.0656	2.3094	2.5298
r_{21}	−0.0230	−0.0230	−0.0230	−0.0230
$\pm y\,(\mathrm{cm})$	0.2430	0.2806	0.3138	0.3437
$\pm\phi\,(\mathrm{mr})$	1.2344	1.4253	1.5935	1.7456
r_{43}	0.0	0.0	0.0	0.0

Table 2

TRANSPORT input beam parameters for beam extracted from the medium-β accelerator
2 mm beam spot at M5
$A/q = 3$, $A = 30$, $q = 10$, $E = 7.162$ MeV/u, $\alpha_x = -0.107$, $\beta_x = 0.799$ mm/mr, $\alpha_y = 0.249$, $\beta_y = 1.036$ mm/mr, and $\epsilon_x = \epsilon_y = 3\pi$ mm-mr

```
'LINE TO M5 -- A=30,Q=10,E=7.162 MEV/U -- 3PI, 2MM, LB, UNITS  '
  0
13.             '    '    12.00000;
16.00           'G/2 '     5.00000     2.50000;
16.00           'K1  '     7.00000     0.45000;
16.00           'K2  '     8.00000     2.80000;
16.00           'X0  '    16.00000    19.00000;
16.00           'Z0  '    18.00000    26.10100;
 1.000000       'BEAM'     0.15480     1.94900     0.17630     1.75400
                           0.00000     1.00000     0.34720;
12.             '    '     0.10640     0.00000     0.00000     0.00000
                           0.00000    -0.24160     0.00000     0.00000
                           0.00000     0.00000     0.00000     0.00000
                           0.00000     0.00000     0.00000;
 3.0            'LBEX'     0.00001;
 3.0            '    '     0.64500;
 5.00           'VQ1 '     0.32500   -90.25147   100.00000;
 3.0            '    '     0.27000;
 5.00           'VQ2 '     0.32500    62.68981   100.00000;
 3.0            'MID1'     0.64500;
 3.0            '    '     0.64500;
 5.00           'VQ3 '     0.32500   -66.07297   100.00000;
 3.0            '    '     0.27000;
 5.00           'VQ4 '     0.32500    66.91876   100.00000;
 3.0            'M1  '     0.64500;
 3.0            '    '     0.71750;
 5.00           'VQ5 '     0.18000   100.01348   100.00000;
 3.0            '    '     0.41500;
 5.00           'VQ6 '     0.18000  -100.01348   100.00000;
 3.0            'MID2'     0.71750;
 3.0            '    '     0.71750;
 5.00           'VQ7 '     0.18000   100.01348   100.00000;
 3.0            '    '     0.41500;
 5.00           'VQ8 '     0.18000  -100.01348   100.00000;
 3.0            'M2  '     0.71750;
 3.0            '    '     0.64500;
 5.00           'VQ9 '     0.32500    59.39654   100.00000;
 3.0            '    '     0.27000;
 5.00           'VQ10'     0.32500   -59.39654   100.00000;
 3.0            'MID3'     0.64500;
 3.0            '    '     0.64500;
 5.00           'VQ11'     0.32500    59.39654   100.00000;
 3.0            '    '     0.27000;
 5.00           'VQ12'     0.32500   -59.39654   100.00000;
 3.0            'M3  '     0.64500;
```

Table 2 (Continued)

`TRANSPORT` input beam parameters for beam extracted from the medium-β accelerator
2 mm beam spot at M5

```
3.0           '    '        0.74750;
5.00          'VQ13'        0.18000      98.12886   100.00000;
3.0           '    '        0.41500;
5.00          'VQ14'        0.18000     -98.12886   100.00000;
3.0           'MID4'        0.74750;
3.0           '    '        0.74750;
5.00          'VQ15'        0.18000      98.12886   100.00000;
3.0           '    '        0.41500;
5.00          'VQ16'        0.18000     -98.12886   100.00000;
3.0           'M4  '        0.74750;
5.00          'VQ17'        0.32500      58.22753   100.00000;
3.0           '    '        0.27000;
5.00          'VQ18'        0.32500     -58.22753   100.00000;
3.0           'MID5'        0.67500;
3.0           '    '        0.67500;
5.00          'VQ19'        0.32500      58.22753   100.00000;
3.0           '    '        0.27000;
5.00          'VQ20'        0.32500     -58.22753   100.00000;
3.0           'M5  '        0.67500;
SENTINEL
SENTINEL
```

Table 3

Pole-tip fields (kG) of quadrupoles VQ1/2/3/4 for other emittances and 2 mm beam spot at M5
Beam is accelerated in the medium-β accelerator

Element	$\epsilon = 3\pi$ mm-mr	$\epsilon = 4\pi$ mm-mr	$\epsilon = 5\pi$ mm-mr	$\epsilon = 6\pi$ mm-mr
VQ1	−90.25147	−100.48595	−109.17272	−116.91201
VQ2	62.68981	63.81453	64.70484	65.46385
VQ3	−66.07297	−66.48635	−66.68892	−66.80241
VQ4	66.91876	68.53688	69.69308	70.54973

Table 4

TRANSPORT input beam parameters for beam extracted from the high-β accelerator
2 mm beam spot at M5
$A/q = 6$, $A = 30$, $q = 5$, $E = 7.88$ MeV/u, $\alpha_x = -0.107$, $\beta_x = 0.799$ mm/mr, $\alpha_y = 0.249$, $\beta_y = 1.036$ mm/mr, and $\epsilon_x = \epsilon_y = 3\pi$ mm-mr

```
'LINE TO M5 -- A=30,Q=5,E=7.88 MEV/U -- 3PI,2MM,HB,UNITS      '
   0
  13.              '    '     12.00000;
  16.00            'G/2 '      5.00000     2.50000;
  16.00            'K1  '      7.00000     0.45000;
  16.00            'K2  '      8.00000     2.80000;
  16.00            'X0  '     16.00000    19.00000;
  16.00            'Z0  '     18.00000    34.94100;
   1.000000        'BEAM'      0.16775     1.78885     0.24304     1.23435
                               0.00000     1.00000     0.75403;
  12.              '    '     -0.02300     0.00000     0.00000     0.00000
                               0.00000     0.00000     0.00000     0.00000
                               0.00000     0.00000     0.00000     0.00000
                               0.00000     0.00000     0.00000;
   3.0             'HBEX'      0.00001;
   3.0             '    '      0.64500;
   5.00            'VQ9 '      0.32500  -166.74751   100.00000;
   3.0             '    '      0.27000;
   5.00            'VQ10'      0.32500   129.95011   100.00000;
   3.0             'MID3'      0.64500;
   3.0             '    '      0.64500;
   5.00            'VQ11'      0.32500  -147.86404   100.00000;
   3.0             '    '      0.27000;
   5.00            'VQ12'      0.32500   158.52707   100.00000;
   3.0             'M3  '      0.64500;
   3.0             '    '      0.74750;
   5.00            'VQ13'      0.18000   213.11090   100.00000;
   3.0             '    '      0.41500;
   5.00            'VQ14'      0.18000  -213.11090   100.00000;
   3.0             'MID4'      0.74750;
   3.0             '    '      0.74750;
   5.00            'VQ15'      0.18000   213.11090   100.00000;
   3.0             '    '      0.41500;
   5.00            'VQ16'      0.18000  -213.11090   100.00000;
   3.0             'M4  '      0.74750;
   3.0             '    '      0.67500;
   5.00            'VQ17'      0.32500   126.45537   100.00000;
   3.0             '    '      0.27000;
   5.00            'VQ18'      0.32500  -126.45537   100.00000;
   3.0             'MID5'      0.67500;
   3.0             '    '      0.67500;
   5.00            'VQ19'      0.32500   126.45537   100.00000;
   3.0             '    '      0.27000;
   5.00            'VQ20'      0.32500  -126.45537   100.00000;
   3.0             'M5  '      0.67500;
SENTINEL
SENTINEL
```

Table 5

Pole-tip fields (kG) of quadrupoles VQ1/2/3/4 for other emittances and 2 mm beam spot at M5
Beam is accelerated in the high-β accelerator

Element	$\epsilon = 3\pi$ mm-mr	$\epsilon = 4\pi$ mm-mr	$\epsilon = 5\pi$ mm-mr	$\epsilon = 6\pi$ mm-mr
VQ9	−166.74751	−181.10686	−193.88266	−205.50401
VQ10	129.95011	130.88432	131.84708	132.78284
VQ11	−147.86404	−148.04641	−148.06915	−148.04163
VQ12	158.52707	161.00811	162.93581	164.45043

Table 6

Pole-tip fields (kG) of quadrupoles VQ17/18/19/20 for other emittances and 1 mm beam spot at M5
Beam is accelerated in the medium-β accelerator

Element	$\epsilon = 3\pi$ mm-mr	$\epsilon = 4\pi$ mm-mr	$\epsilon = 5\pi$ mm-mr	$\epsilon = 6\pi$ mm-mr
VQ17	13.88099	13.80771	13.77303	13.75415
VQ18	−41.80976	−41.70118	−41.65162	−41.62488
VQ19	62.92373	62.91983	62.91854	62.91791
VQ20	−78.65961	−78.50757	−78.43930	−78.40260

Table 7

Pole-tip fields (kG) of quadrupoles VQ17/18/19/20 for other emittances and 1 mm beam spot at M5
Beam is accelerated in the high-β accelerator

Element	$\epsilon = 3\pi$ mm-mr	$\epsilon = 4\pi$ mm-mr	$\epsilon = 5\pi$ mm-mr	$\epsilon = 6\pi$ mm-mr
VQ17	29.87107	29.87107	29.87107	29.87107
VQ18	−90.39872	−90.39872	−90.39872	−90.39872
VQ19	136.64159	136.64159	136.64159	136.64159
VQ20	−170.27028	−170.27028	−170.27028	−170.27028

Table 8

Version 1 `TRANSPORT` input beam parameters for beam delivered from the medium-β and high-β accelerators to produce a 2 mm beam spot at the TGT1 target[†]

```
 3.0     '    '    1.50000;
 3.0     '    '    0.10180;
 5.00    'Q1  '    0.40640   38.33557   (83.25510)   100.00000;
 3.0     '    '    0.10180;
 3.0     '    '    0.20000;
 3.0     '    '    0.10180;
 5.00    'Q2  '    0.40640  -36.47297  (-79.21001)   100.00000;
 3.0     '    '    0.10180;
 3.0     'WALI'    0.32000;
 3.0     'WALX'    0.78740;
 3.0     '    '    0.32000;
 5.00    'Q3  '    0.32500   48.14621  (104.56131)   100.00000;
 3.0     'B1IN'    0.67500;
20.0     '    '  180.00000;
 2.0     '    '    0.00000;
 4.000   'B1  '    1.04720    5.79059   (12.57569)     0.00000;
 2.0     '    '    0.00000;
20.0     '    ' -180.00000;
 3.0     'B1EX'    0.00001;
 3.0     '    '    1.52211;
 5.00    'Q4  '    0.32500   48.30157  (104.89871)   100.00000;
 3.0     '    '    0.30000;
 5.00    'Q5  '    0.32500  -53.79922 (-116.83821)   100.00000;
 3.0     'MID '    1.63400;
 3.0     '    '    1.63400;
 5.00    'Q6  '    0.32500  -53.79922 (-116.83821)   100.00000;
 3.0     '    '    0.30000;
 5.00    'Q7  '    0.32500   48.30157  (104.89871)   100.00000;
 3.0     'B2IN'    1.52211;
20.0     '    '  180.00000;
 2.0     '    '    0.00000;
 4.000   'B2  '    1.04720    5.79059   (12.57569)     0.00000;
 2.0     '    '    0.00000;
20.0     '    ' -180.00000;
 3.0     'B2EX'    0.00001;
 3.0     '    '    0.67500;
 5.00    'Q8  '    0.32500   48.14621  (104.56131)   100.00000;
 3.0     '    '    0.32000;
 3.0     '    '    0.78740;
 3.0     '    '    0.32000;
 3.0     '    '    0.10180;
 5.00    'Q9  '    0.40640  -36.47297  (-79.21001)   100.00000;
 3.0     '    '    0.10180;
 3.0     '    '    0.20000;
 3.0     '    '    0.10180;
 5.00    'Q10 '    0.40640   38.33557   (83.25510)   100.00000;
 3.0     '    '    0.10180;
 3.0     'TGT1'    1.50000;
```

[†] Field values for beam accelerated in the high-β accelerator are given in parentheses.

Table 9

Version 2 TRANSPORT input beam parameters for beam delivered from the medium-β and high-β accelerators to produce a 2 mm beam spot at the TGT1 target†

```
 3.0      '    '    1.50000;
 3.0      '    '    0.10180;
 5.00     'Q1  '    0.40640  -43.38161  (-94.21381)  100.00000;
 3.0      '    '    0.10180;
 3.0      '    '    0.20000;
 3.0      '    '    0.10180;
 5.00     'Q2  '    0.40640   38.32330   (83.22845)  100.00000;
 3.0      '    '    0.10180;
 3.0      'WALI'    0.32000;
 3.0      'WALX'    0.78740;
 3.0      '    '    0.32000;
 5.00     'Q3  '    0.32500  -52.54679 (-114.11825)  100.00000;
 3.0      'B1IN'    0.67500;
20.0      '    '  180.00000;
 2.0      '    '    0.00000;
 4.000    'B1  '    1.04720    5.79059   (12.57569)    0.00000;
 2.0      '    '    0.00000;
20.0      '    ' -180.00000;
 3.0      'B1EX'    0.00001;
 3.0      '    '    1.59479;
 5.00     'Q4  '    0.32500   37.36532   (81.14796)  100.00000;
 3.0      '    '    0.30000;
 5.00     'Q5  '    0.32500  -29.00584  (-62.99330)  100.00000;
 3.0      'MID '    1.56132;
 3.0      '    '    1.56132;
 5.00     'Q6  '    0.32500  -29.00584  (-62.99330)  100.00000;
 3.0      '    '    0.30000;
 5.00     'Q7  '    0.32500   37.36532   (81.14796)  100.00000;
 3.0      'B2IN'    1.59479;
20.0      '    '  180.00000;
 2.0      '    '    0.00000;
 4.000    'B2  '    1.04720    5.79059   (12.57569)    0.00000;
 2.0      '    '    0.00000;
20.0      '    ' -180.00000;
 3.0      'B2EX'    0.00001;
 3.0      '    '    0.67500;
 5.00     'Q8  '    0.32500  -52.54679 (-114.11825)  100.00000;
 3.0      '    '    0.32000;
 3.0      '    '    0.78740;
 3.0      '    '    0.32000;
 3.0      '    '    0.10180;
 5.00     'Q9  '    0.40640   38.32330   (83.22845)  100.00000;
 3.0      '    '    0.10180;
 3.0      '    '    0.20000;
 3.0      '    '    0.10180;
 5.00     'Q10 '    0.40640  -43.38161  (-94.21381)  100.00000;
 3.0      '    '    0.10180;
 3.0      'TGT1'    1.50000;
```

† Field values for beam accelerated in the high-β accelerator are given in parentheses.

Table 10

`TRANSPORT` input beam parameters for beam delivered from the medium-β accelerator
Production of a 2 mm beam spot at the TGT4 and TGT4A targets, $\epsilon_x = \epsilon_y = 3\pi$ mm-mr†

```
  3.0          '    '     1.50000;
  3.0          '    '     0.10180;
  5.00         'Q1  '     0.40640   -36.38109   (-79.02787)   100.00000;
  3.0          '    '     0.10180;
  3.0          '    '     0.20000;
  3.0          '    '     0.10180;
  5.00         'Q2  '     0.40640    33.74543   ( 73.29320)   100.00000;
  3.0          '    '     0.10180;
  3.0          '    '     0.32000;
  3.0          'WALL'     0.78740;
  3.0          '    '     0.32000;
  5.00         'Q3  '     0.32500    -7.44919   (-16.19569)   100.00000;
  3.0          '    '     0.30000;
  3.0          'B1IN'     0.37500;
-20.           '    '   180.00000;
  2.0          '    '     0.00000;
  4.000        'B1  '     1.04720     5.79059   ( 12.57569)     0.00000;
  2.0          '    '     0.00000;
-20.           '    '  -180.00000;
  3.0          'B1EX'     0.00001;
  3.0          '    '     0.37500;
  3.0          '    '     0.30000;
  5.00         'Q4  '     0.32500    -7.44919   (-16.19569)   100.00000;
  3.0          '    '     0.32000;
  3.0          '    '     0.78740;
  3.0          '    '     0.32000;
  3.0          '    '     0.10180;
  5.00         'Q5  '     0.40640    33.74543   ( 73.29320)   100.00000;
  3.0          '    '     0.10180;
  3.0          '    '     0.20000;
  3.0          '    '     0.10180;
  5.00         'Q6  '     0.40640   -36.38109   (-79.02787)   100.00000;
  3.0          '    '     0.10180;
  3.0          'TGT4'     0.30000;
  3.0          '    '     2.25000;
  5.00         'Q7  '     0.32500    38.13888   ( 83.00280)   100.00000;
  3.0          '    '     0.30000;
  5.00         'Q8  '     0.32500   -61.52783  (-133.74558)   100.00000;
  3.0          '    '     0.30000;
  5.00         'Q9  '     0.32500    38.13888   ( 83.00280)   100.00000;
  3.0          'TG4A'     2.25000;
```

† Field values for beam accelerated in the high-β accelerator are given in parentheses.

Table 11(a)

TRANSPORT input beam parameters for beam delivered from the medium-β accelerator
Production of a 2 mm beam spot at the TGT4 and TGT4A targets as a function of emittance

Element	$\epsilon = 3\pi$ mm-mr	$\epsilon = 4\pi$ mm-mr	$\epsilon = 5\pi$ mm-mr	$\epsilon = 6\pi$ mm-mr
Q1	−36.38109	−36.63409	−37.17740	−37.39523
Q2	33.74543	33.50199	33.33651	33.09433
Q3	−7.44919	-5.07664	−3.04018	−1.12042
Q4	−7.44919	-5.07664	−3.04018	−1.12042
Q5	33.74543	33.50199	33.33651	33.09433
Q6	−36.38109	−36.63409	−37.17740	−37.39523
Q7	38.13888	38.13888	38.13888	38.13888
Q8	−61.52783	−61.52783	−61.52783	−61.52783
Q9	38.13888	38.13888	38.13888	38.13888

Table 11(a)

TRANSPORT input beam parameters for beam delivered from the high-β accelerator
Production of a 2 mm beam spot at the TGT4 and TGT4A targets as a function of emittance

Element	$\epsilon = 3\pi$ mm-mr	$\epsilon = 4\pi$ mm-mr	$\epsilon = 5\pi$ mm-mr	$\epsilon = 6\pi$ mm-mr
Q1	−79.02787	−80.05103	−80.73863	−81.21241
Q2	73.29320	72.87625	72.39809	71.87516
Q3	−16.19569	−11.12862	−6.60133	−2.44108
Q4	−16.19569	−11.12862	−6.60133	−2.44108
Q5	73.29320	72.87625	72.39809	71.87516
Q6	−79.02787	−80.05103	−80.73863	−81.21241
Q7	83.00280	82.94004	82.90002	82.86988
Q8	−133.74558	−133.70137	−133.67331	−133.65066
Q9	83.00280	82.94004	82.90002	82.86988

Table 12

Version 1 **TRANSPORT** input beam parameters for beam delivered from the medium-β accelerator
Production of a 2 mm beam spot at the TGT5 target, $\epsilon_x = \epsilon_y = 3\pi$ mm-mr†

```
 3.0          '    '      1.50000;
 3.0          '    '      0.10180;
 5.00         'Q1  '      0.40640   -45.63856   (-98.04810)   100.00000;
 3.0          '    '      0.10180;
 3.0          '    '      0.20000;
 3.0          '    '      0.10180;
 5.00         'Q2  '      0.40640    37.88107    (82.08778)   100.00000;
 3.0          '    '      0.10180;
 3.0          '    '      0.32000;
 3.0          'WALL'      0.78740;
 3.0          '    '      0.32000;
 5.00         'Q3  '      0.32500   -52.02910  (-113.34649)   100.00000;
 3.0          'B1IN'      0.67500;
 3.0          'B1CL'      0.60000;
 3.0          'B1EX'      0.44720;
 3.0          '    '      1.43740;
 5.00         'Q4  '      0.32500    22.13777    (52.43290)   100.00000;
 3.0          '    '      0.30000;
 5.00         'Q5  '      0.32500   -67.29792  (-147.54756)   100.00000;
 3.0          '    '      0.30000;
 5.00         'Q6  '      0.32500    67.41001   (144.47950)   100.00000;
 3.0          'M6  '      0.90000;
 3.0          '    '      1.50000;
 5.00         'Q7  '      0.20000   -97.52968  (-211.80952)   100.00000;
 3.0          '    '      0.20000;
 3.0          '    '      0.10180;
 5.00         'Q8  '      0.40640    59.73781   (129.73529)   100.00000;
 3.0          '    '      0.10180;
 3.0          '    '      0.20000;
 5.00         'Q9  '      0.20000   -89.06864  (-193.43441)   100.00000;
 3.0          'B3IN'      0.67500;
20.0          '    '    180.00000;
 2.0          '    '      0.00000;
 4.000        'B3  '      1.04720     5.79059    (12.57569)     0.00000;
 2.0          '    '      0.00000;
20.0          '    '   -180.00000;
 3.0          'B3EX'      0.00001;
 3.0          '    '      0.90030;
 5.00         'Q10 '      0.32500   -40.13305   (-87.15878)   100.00000;
 3.0          '    '      0.30000;
 5.00         'Q11 '      0.32500    31.91417    (69.30946)   100.00000;
 3.0          'MID '      0.80620;
 3.0          '    '      0.80620;
 5.00         'Q12 '      0.32500    31.91417    (69.30946)   100.00000;
 3.0          '    '      0.30000;
 5.00         'Q13 '      0.32500   -40.13305   (-87.15878)   100.00000;
 3.0          'B4IN'      0.90030;
```

† Field values for beam accelerated in the high-β accelerator are given in parentheses.

Table 12 (Continued)

Version 1 TRANSPORT input beam parameters for beam delivered from the medium-β accelerator
Production of a 2 mm beam spot at the TGT5 target, $\epsilon_x = \epsilon_y = 3\pi$ mm-mr†

```
20.0       '    '   180.00000;
 2.0       '    '     0.00000;
 4.000     'B4  '     1.04720     5.79059    (12.57569)     0.00000;
 2.0       '    '     0.00000;
20.0       '    '  -180.00000;
 3.0       'B4EX'     0.00001;
 3.0       '    '     0.67500;
 5.00      'Q14 '     0.20000   -89.06864  (-193.43441)   100.00000;
 3.0       '    '     0.20000;
 3.0       '    '     0.10180;
 5.00      'Q15 '     0.40640    59.73781   (129.73529)   100.00000;
 3.0       '    '     0.10180;
 3.0       '    '     0.20000;
 5.00      'Q16 '     0.20000   -97.52963  (-211.80952)   100.00000;
 3.0       'TGT5'     1.50000;
```

† Field values for beam accelerated in the high-β accelerator are given in parentheses.

Table 13(a)

Version 1 TRANSPORT input beam parameters for beam delivered from the medium-β accelerator
Production of a 2 mm beam spot at the TGT5 target as a function of emittance†

Element	$\epsilon = 3\pi$ mm-mr	$\epsilon = 4\pi$ mm-mr	$\epsilon = 5\pi$ mm-mr	$\epsilon = 6\pi$ mm-mr
Q1	−45.63856	−46.72269	−46.80556	−46.87152
Q2	37.88107	38.08726	38.05793	38.05905
Q3	−52.02910	−52.34493	−52.80930	−53.05287
Q4	22.13777	12.80956	12.80956	12.80956
Q5	−67.29792	−63.01014	−62.71123	−62.62036
Q6	67.41001	68.28439	66.38768	65.74943

† All other quadrupoles are set as in table 12.

Table 13(b)

Version 1 TRANSPORT input beam parameters for beam delivered from the high-β accelerator
Production of a 2 mm beam spot at the TGT5 target as a function of emittance†

Element	$\epsilon = 3\pi$ mm-mr	$\epsilon = 4\pi$ mm-mr	$\epsilon = 5\pi$ mm-mr	$\epsilon = 6\pi$ mm-mr
Q1	−98.04810	−99.70389	−100.12450	−100.42523
Q2	82.08778	82.39954	82.44675	83.34626
Q3	−113.34649	−115.66655	−116.86062	−117.52860
Q4	52.43290	39.07934	37.10045	53.70668
Q5	−147.54756	−141.51674	−140.22343	−152.34566
Q6	144.47950	143.15097	140.63795	165.17382

† All other quadrupoles are set as parenthesized in table 12.

Table 14(a)

Version 1 `TRANSPORT` input beam parameters for beam delivered from the medium-β accelerator
Production of a 1 mm beam spot at the TGT5 target as a function of emittance†

Element	$\epsilon = 3\pi$ mm-mr	$\epsilon = 4\pi$ mm-mr	$\epsilon = 5\pi$ mm-mr	$\epsilon = 6\pi$ mm-mr
Q1	−51.13704	−51.43079	−51.56996	−51.64844
Q2	38.36413	38.38698	38.39985	38.40784
Q3	−48.67358	−48.77800	−48.82621	−48.85149
Q4	12.80956	12.80956	12.80956	12.79679
Q5	−63.04951	−62.98880	−62.96398	−62.94495
Q6	67.89495	67.50002	67.33561	67.25334

† All other quadrupoles are set as in table 12.

Table 14(b)

Version 1 `TRANSPORT` input beam parameters for beam delivered from the high-β accelerator
Production of a 1 mm beam spot at the TGT5 target as a function of emittance†

Element	$\epsilon = 3\pi$ mm-mr	$\epsilon = 4\pi$ mm-mr	$\epsilon = 5\pi$ mm-mr	$\epsilon = 6\pi$ mm-mr
Q1	−107.64271	−108.34729	−108.67872	−108.85928
Q2	82.38378	82.48642	82.53621	82.56367
Q3	−107.40980	−107.77177	−107.94039	−108.03212
Q4	51.23195	51.23195	51.23195	51.23195
Q5	−146.66567	−146.58953	−146.55706	−146.54013
Q6	138.90846	138.36405	138.12635	138.00094

† All other quadrupoles are set as parenthesized in table 12.

Table 15(a)

Version 2 TRANSPORT input beam parameters for beam delivered from the medium-β accelerator
Production of a 2 mm beam spot at the TGT5 target as a function of emittance†

Element	$\epsilon = 3\pi$ mm-mr	$\epsilon = 4\pi$ mm-mr	$\epsilon = 5\pi$ mm-mr	$\epsilon = 6\pi$ mm-mr
Q7	−88.95126	−88.88213	−88.81714	−88.76777
Q8	57.74779	57.71193	57.69145	57.67860
Q9	−50.18596	−50.18596	−50.18596	−50.18596
Q10	62.82720	62.98391	63.15701	63.34632
Q11	−79.33137	−79.99750	−80.74008	−81.56053
Q12	−82.29735	−79.99750	−80.74008	−81.56053
Q13	62.82720	62.98391	63.15701	63.34632
Q14	−50.18596	−50.18596	−50.18596	−76.32767
Q15	57.74779	57.71193	57.69145	57.67860
Q16	−88.95126	−88.88213	−88.81714	−88.76777

† All other quadrupoles are set as in table 13(a).

Table 15(b)

Version 2 TRANSPORT input beam parameters for beam delivered from the high-β accelerator
Production of a 2 mm beam spot at the TGT6 target as a function of emittance†

Element	$\epsilon = 3\pi$ mm-mr	$\epsilon = 4\pi$ mm-mr	$\epsilon = 5\pi$ mm-mr	$\epsilon = 6\pi$ mm-mr
Q7	−209.11456	−202.66466	−199.73206	−198.01706
Q8	126.89730	126.24060	125.91814	125.72235
Q9	−106.09961	−107.14150	−107.54135	−107.74401
Q10	136.81334	137.28876	137.71295	138.10991
Q11	−173.85532	−175.89891	−177.74360	−179.48843
Q12	−173.85532	−175.89891	−177.74360	−179.48843
Q13	136.81334	137.28876	137.71295	138.10991
Q14	−106.09961	−107.14150	−107.54135	−107.74401
Q15	126.89730	126.24060	125.91814	125.72235
Q16	−209.11456	−202.66466	−199.73206	−198.01706

† All other quadrupoles are set as in table 13(b).

Table 15(c)

Version 2 TRANSPORT input beam parameters for beam delivered from the medium-β accelerator
Production of a 1 mm beam spot at the TGT5 target as a function of emittance^{dagger}

Element	$\epsilon = 3\pi$ mm-mr	$\epsilon = 4\pi$ mm-mr	$\epsilon = 5\pi$ mm-mr	$\epsilon = 6\pi$ mm-mr
Q7	−88.49152	−88.34629	−88.11083	−87.99848
Q8	57.63405	57.61262	57.58082	57.56551
Q9	−50.18596	−50.18596	−50.18596	−50.18596
Q10	63.88650	64.36567	64.36567	64.36567
Q11	−83.95031	−86.13272	−86.13273	−86.13273
Q12	−83.95031	−86.13272	−86.13273	−86.13273
Q13	63.88650	64.36567	64.36567	64.36567
Q14	−50.18596	−50.18596	−50.18596	−50.18596
Q15	57.63405	57.61262	57.58082	57.56551
Q16	−88.49152	−88.34629	−88.11083	−87.99848

† All other quadrupoles are set as in table 13(a).

Table 15(d)

Version 2 TRANSPORT input beam parameters for beam delivered from the high-β accelerator
Production of a 1 mm beam spot at the TGT5 target as a function of emittance†

Element	$\epsilon = 3\pi$ mm-mr	$\epsilon = 4\pi$ mm-mr	$\epsilon = 5\pi$ mm-mr	$\epsilon = 6\pi$ mm-mr
Q7	−195.45986	−194.52771	−193.99224	−193.67258
Q8	125.31747	125.14646	125.02863	124.93829
Q9	−107.42106	−107.14692	−106.87303	−106.59258
Q10	139.73090	140.79855	141.75993	142.63120
Q11	−186.80485	−191.79855	−196.41977	−200.71363
Q12	−186.80485	−191.79855	−196.41977	−200.71363
Q13	139.73090	140.79855	141.75993	142.63120
Q14	−107.42106	−107.14692	−106.87303	−106.59258
Q15	125.31747	125.14646	125.02863	124.93829
Q16	−195.45986	−194.52771	−193.99224	−193.67258

† All other quadrupoles are set as in table 13(b).

Table 16

`TRANSPORT` input beam parameters for beam delivered from the medium-β accelerator
Production of a 2 mm beam spot at the TGT6 target, $\epsilon_x = \epsilon_y = 3\pi$ mm-mr[†]

3.0	' '	1.50000;			
5.00	'Q7 '	0.20000	-79.54631	(-180.33617)	100.00000;
3.0	' '	0.20000;			
3.0	' '	0.10180;			
5.00	'Q8 '	0.40640	58.07197	(127.66761)	100.00000;
3.0	' '	0.10180;			
3.0	' '	0.20000;			
5.00	'Q9 '	0.20000	-88.16709	(-194.64129)	100.00000;
3.0	'B3IN'	0.67500;			
20.0	' '	180.00000;			
2.0	' '	0.00000;			
4.000	'B3 '	1.04720	5.79059	(12.57569)	0.00000;
2.0	' '	0.00000;			
20.0	' '	-180.00000;			
3.0	'B3EX'	0.00001;			
3.0	' '	0.90030;			
5.00	'Q10 '	0.32500	-67.21605	(-141.70430)	100.00000;
3.0	' '	0.30000;			
5.00	'Q11 '	0.32500	81.96814	(177.06522)	100.00000;
3.0	'MID '	0.80620;			
3.0	' '	0.80620;			
5.00	'Q12 '	0.32500	81.96814	(177.06522)	100.00000;
3.0	' '	0.30000;			
5.00	'Q13 '	0.32500	-67.21605	(-141.70430)	100.00000;
3.0	'B4IN'	0.90030;			
-20.0	' '	180.00000;			
2.0	' '	0.00000;			
4.000	'B4 '	1.04720	5.79059	(12.57569)	0.00000;
2.0	' '	0.00000;			
-20.0	' '	-180.00000;			
3.0	'B4EX'	0.00001;			
3.0	' '	0.67500;			
5.00	'Q14 '	0.20000	-88.16709	(-194.64129)	100.00000;
3.0	' '	0.20000;			
3.0	' '	0.10180;			
5.00	'Q15 '	0.40640	58.07197	(127.66761)	100.00000;
3.0	' '	0.10180;			
3.0	' '	0.20000;			
5.00	'Q16 '	0.20000	-79.54626	(-180.33617)	100.00000;
3.0	'TGT5'	1.50000;			

[†] Field values for beam accelerated in the high-β accelerator are given in parentheses.

Table 17(a)

TRANSPORT input beam parameters for beam delivered from the medium-β accelerator
Production of a 2 mm beam spot at the TGT6 target as a function of emittance†

Element	$\epsilon = 3\pi$ mm-mr	$\epsilon = 4\pi$ mm-mr	$\epsilon = 5\pi$ mm-mr	$\epsilon = 6\pi$ mm-mr
Q7	−79.54631	−83.27743	−85.20141	−85.64988
Q8	58.07197	57.72824	57.28809	56.87301
Q9	−88.16709	−83.05281	−79.00623	−76.32767
Q10	−67.21605	−67.36822	−67.79258	−68.72914
Q11	81.96814	82.00151	82.09427	82.29735
Q12	81.96814	82.00151	82.09427	82.29735
Q13	−67.21605	−67.36822	−67.79258	−68.72914
Q14	−88.16709	−83.05281	−79.00623	−76.32767
Q15	58.07197	57.72824	57.28809	56.87301
Q16	−79.54626	−83.27743	−85.20141	−85.64988

† All other quadrupoles are set as in table 13(a).

Table 17(b)

TRANSPORT input beam parameters for beam delivered from the high-β accelerator
Production of a 2 mm beam spot at the TGT6 target as a function of emittance†

Element	$\epsilon = 3\pi$ mm-mr	$\epsilon = 4\pi$ mm-mr	$\epsilon = 5\pi$ mm-mr	$\epsilon = 6\pi$ mm-mr
Q7	−180.33617	−187.49093	−190.87288	−191.43414
Q8	127.66761	126.55504	125.31346	124.21781
Q9	−194.64129	−182.17611	−172.36621	−165.76427
Q10	−141.70430	−141.94188	−142.84362	−144.76151
Q11	177.06522	177.11857	177.32041	177.74664
Q12	177.06522	177.11857	177.32041	177.74664
Q13	−141.70430	−141.94188	−142.84362	−144.76151
Q14	−194.64129	−182.17611	−172.36621	−165.76427
Q15	127.66761	126.55504	125.31346	124.21781
Q16	−180.33617	−187.49093	−190.87288	−191.43414

† All other quadrupoles are set as in table 13(b).

Table 17(c)

TRANSPORT input beam parameters for beam delivered from the medium-β accelerator
Production of a 1 mm beam spot at the TGT6 target as a function of emittance^{dagger}

Element	$\epsilon = 3\pi$ mm-mr	$\epsilon = 4\pi$ mm-mr	$\epsilon = 5\pi$ mm-mr	$\epsilon = 6\pi$ mm-mr
Q7	−72.89856	−79.80663	−79.80529	−79.81518
Q8	55.39963	54.85535	54.85485	54.85607
Q9	−77.96699	−69.61589	−69.61554	−69.61554
Q10	−81.09617	−84.94441	−84.94444	−84.94444
Q11	84.78539	85.49306	85.49306	85.49307
Q12	84.78539	85.49306	85.49306	85.49307
Q13	−81.09617	−84.94441	−84.94444	−84.94444
Q14	−77.96699	−69.61589	−69.61554	−69.61554
Q15	55.39963	54.85535	54.85485	54.85607
Q16	−72.89856	−79.80663	−79.80529	−79.81518

† All other quadrupoles are set as in table 13(a).

Table 17(d)

TRANSPORT input beam parameters for beam delivered from the high-β accelerator
Production of a 1 mm beam spot at the TGT6 target as a function of emittance†

Element	$\epsilon = 3\pi$ mm-mr	$\epsilon = 4\pi$ mm-mr	$\epsilon = 5\pi$ mm-mr	$\epsilon = 6\pi$ mm-mr
Q7	−186.47632	−183.22396	−179.74331	−177.32941
Q8	121.15170	120.11190	119.48865	119.05467
Q9	−152.60464	−149.38354	−148.53493	−147.95324
Q10	−156.15501	−164.40939	−172.87133	−180.35654
Q11	180.18837	181.86798	183.51745	184.91920
Q12	180.18837	181.86798	183.51745	184.91920
Q13	−156.15501	−164.40939	−172.87133	−180.35654
Q14	−147.95324	−149.38354	−148.53493	−165.76427
Q15	121.15170	120.11190	119.48865	119.05467
Q16	−186.47632	−183.22396	−179.74331	−177.32941

† All other quadrupoles are set as in table 13(b).

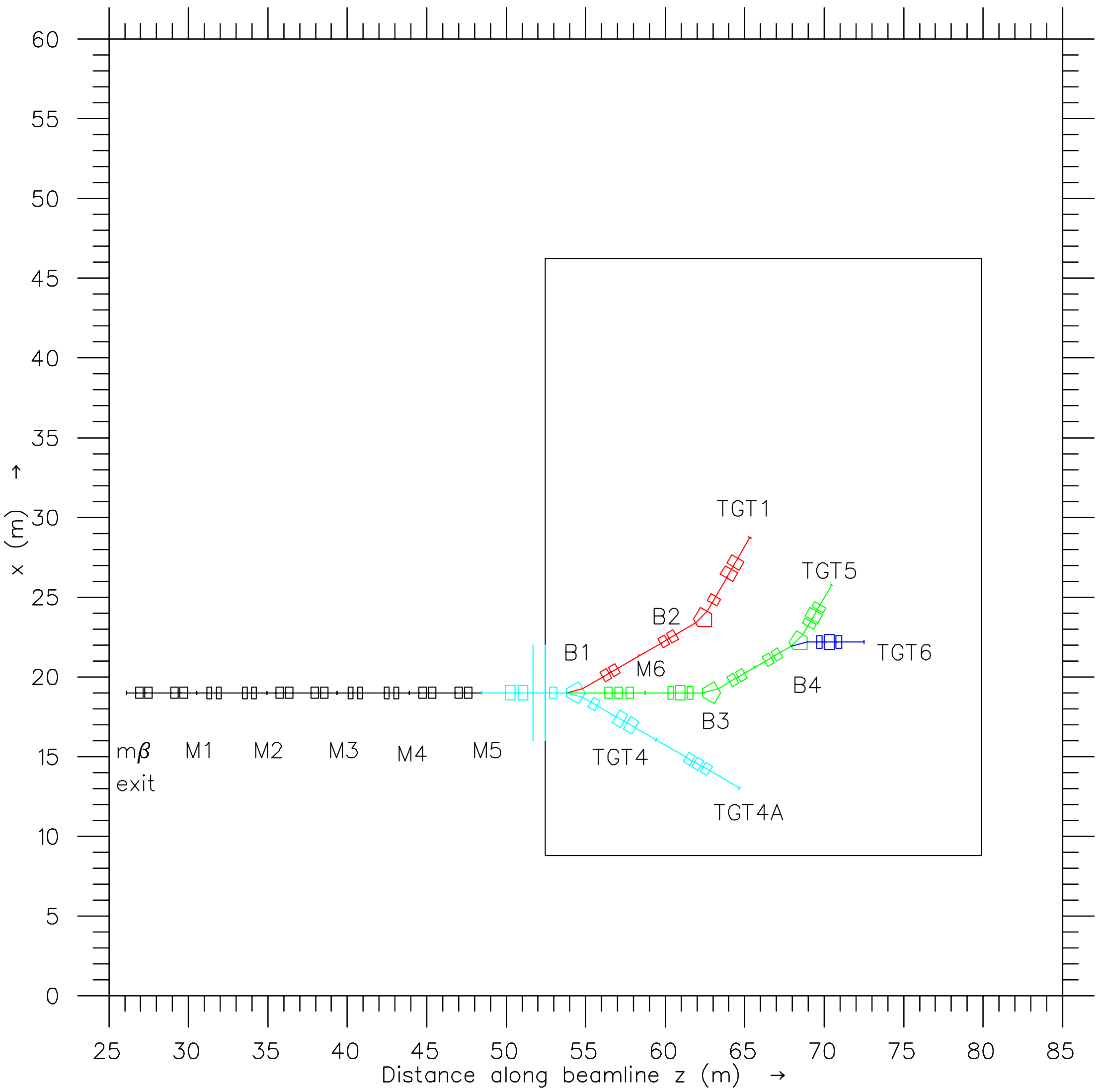

Fig. 1. Proposed final configuration of the ISAC-II beam transport to the experimental hall.

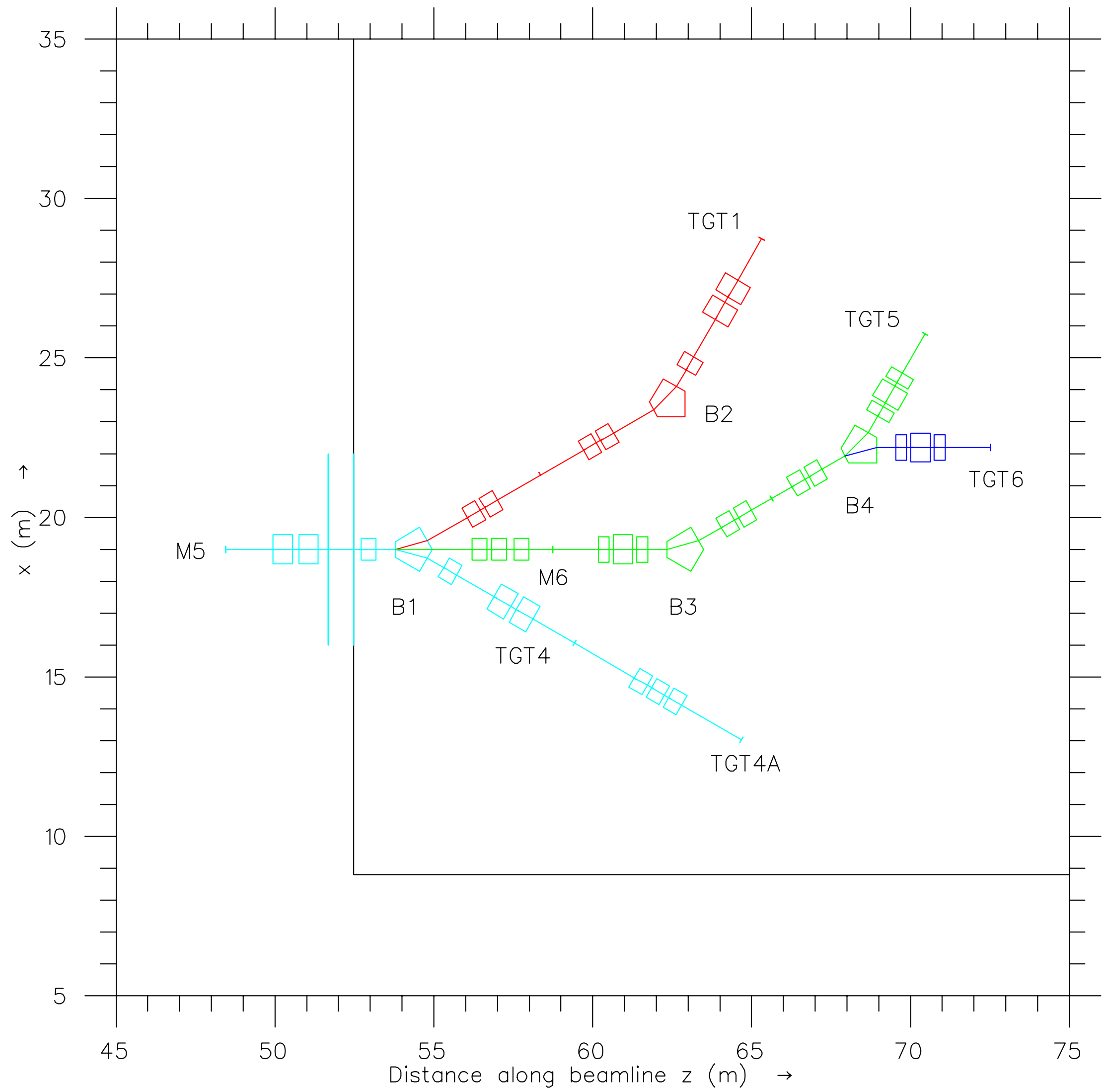

Fig. 2. Proposed final configuration of the ISAC-II beam transport to the experimental hall.

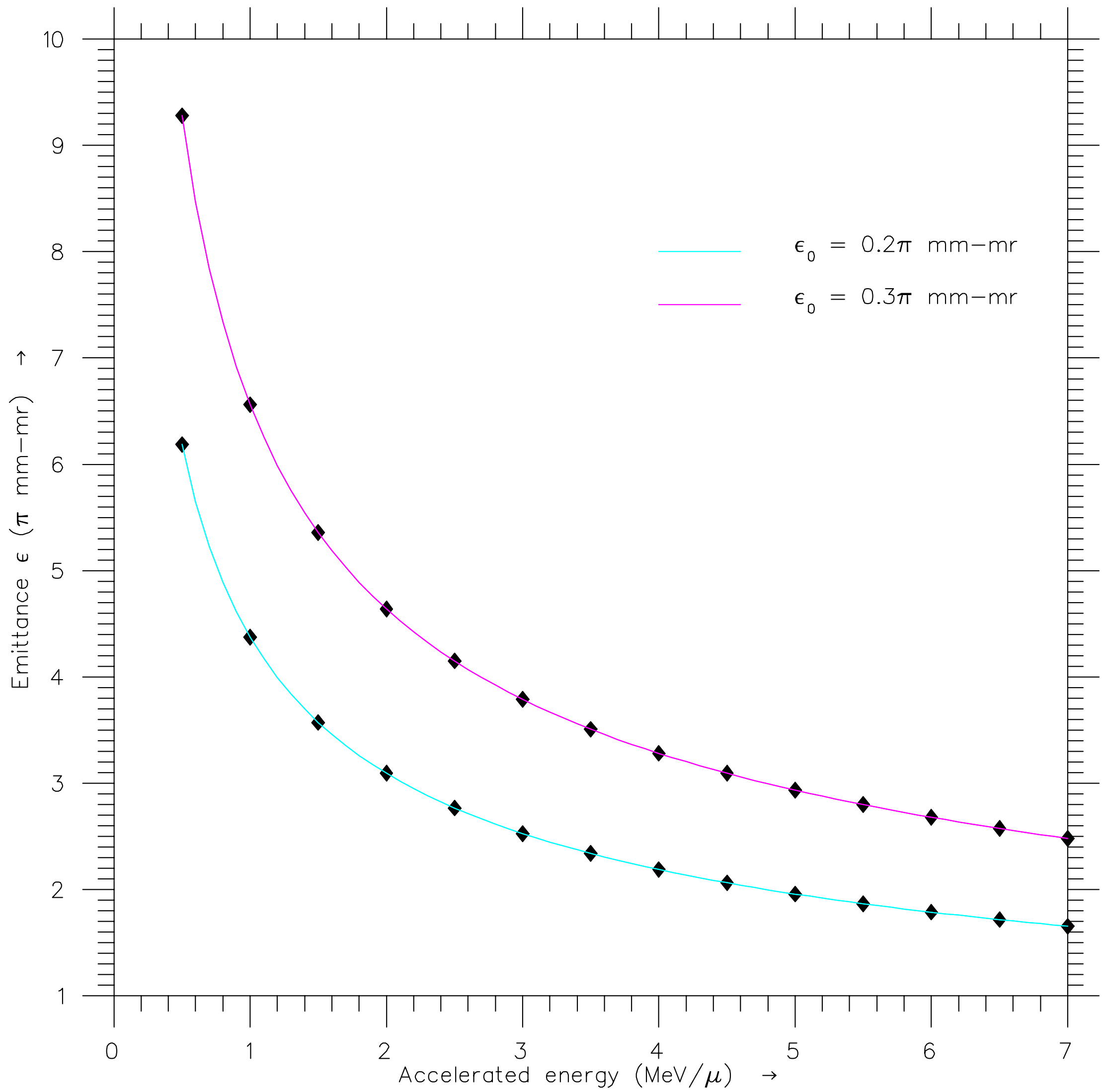

Fig. 3. Estimated emittance variation as a function of acceleration energy.

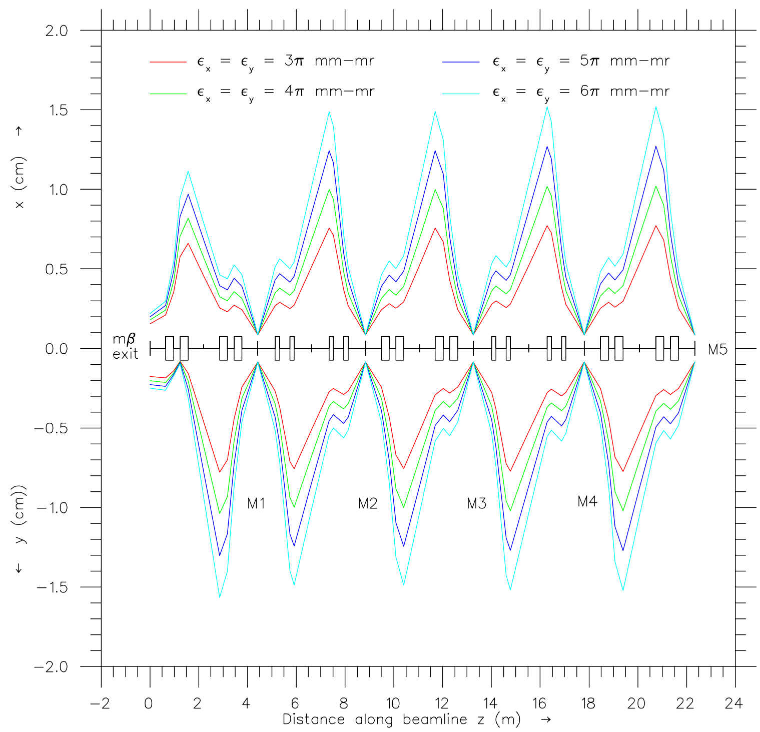

Fig. 4. Beam envelopes in the vault section for the production of a 2 mm beam spot at the M5 location with extraction from the medium-β accelerator.

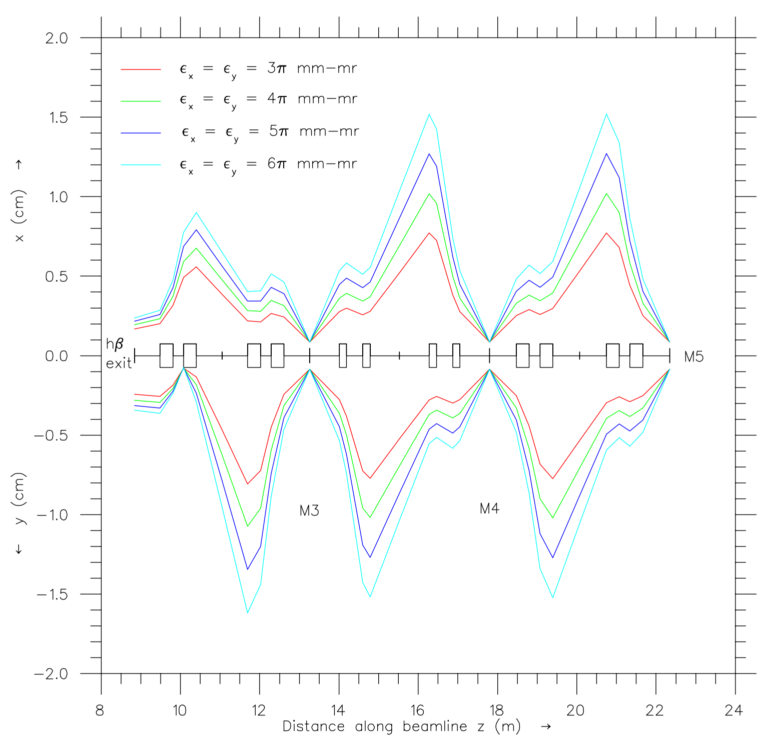

Fig. 5. Beam envelopes in the vault section for the production of a 2 mm beam spot at the M5 location with extraction from the high-β accelerator.

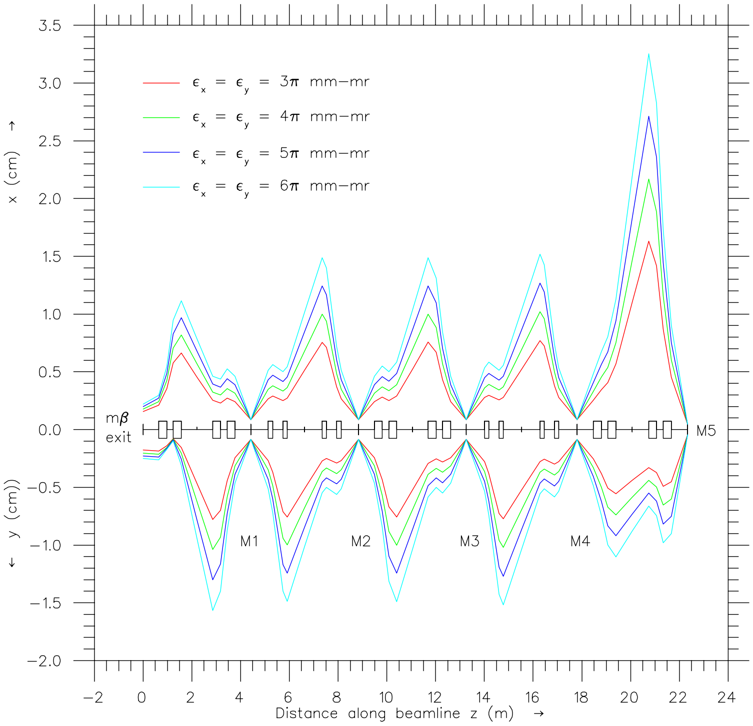

Fig. 6. Beam envelopes in the vault section for the production of a 1 mm beam spot at the M5 location with extraction from the medium-β accelerator.

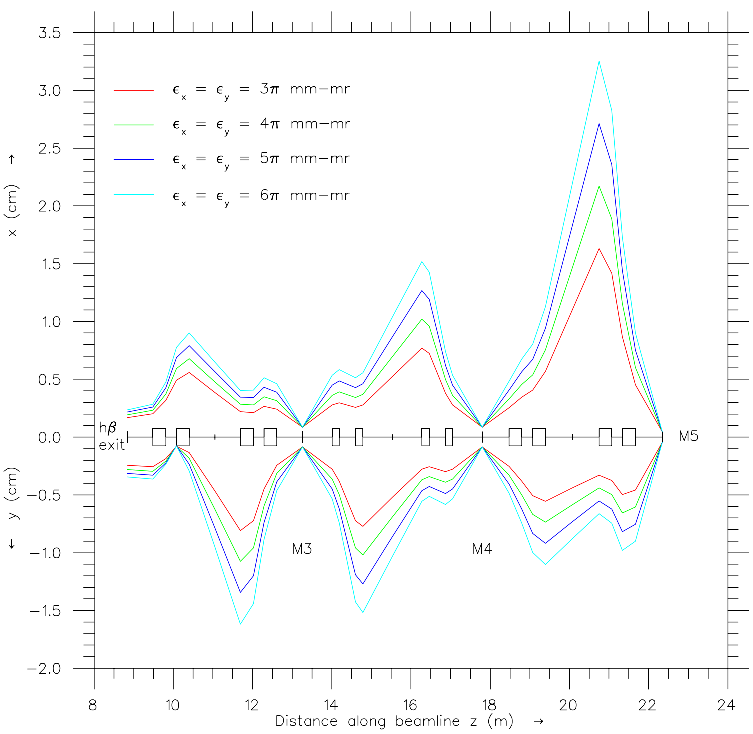

Fig. 7. Beam envelopes in the vault section for the production of a 1 mm beam spot at the M5 location with extraction from the high-β accelerator.

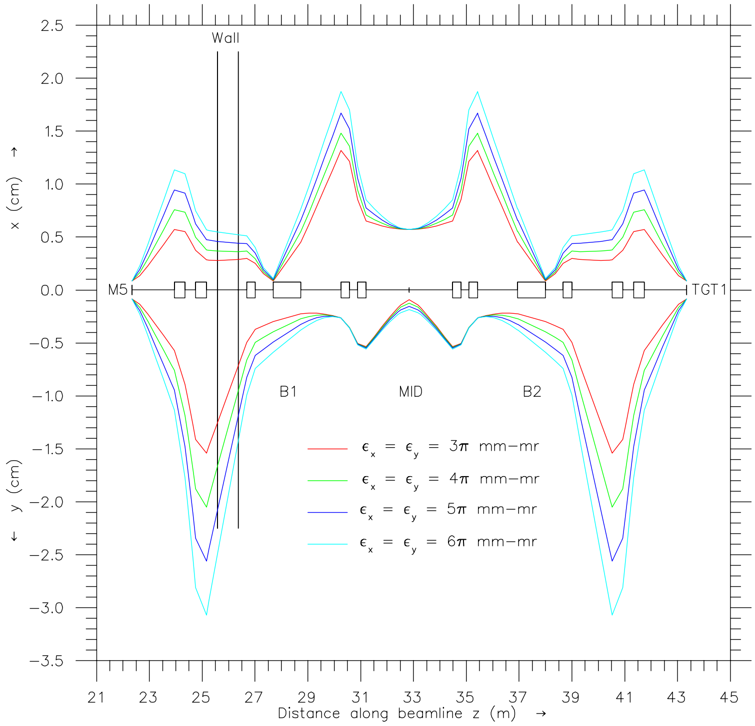

Fig. 8(a). Beam envelopes between M5 and TGT1 for beam accelerated in the medium-β accelerator and the vault section tuned to produce a 2 mm beam spot at the M5 location.

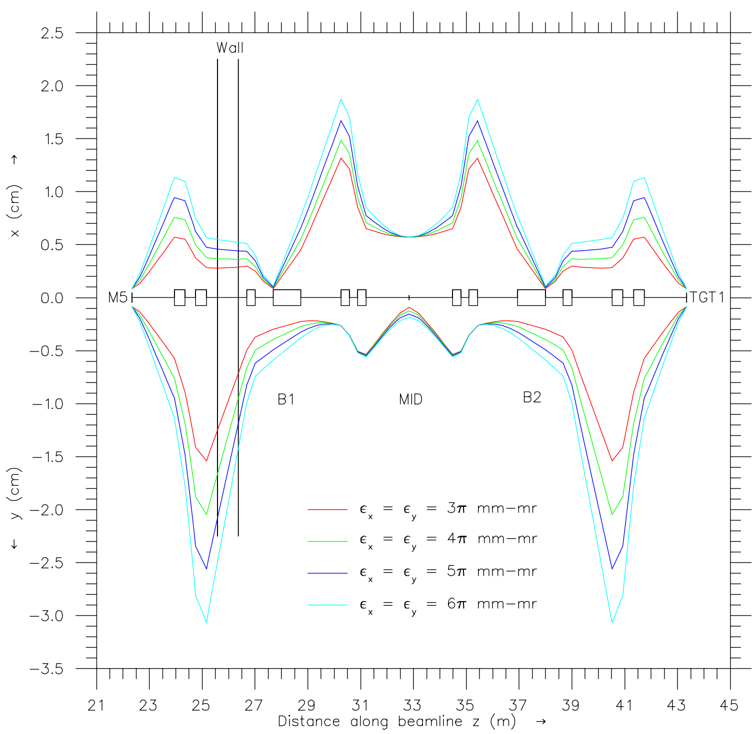

Fig. 8(b). Beam envelopes between M5 and TGT1 for beam accelerated in the high-β accelerator and the vault section tuned to produce a 2 mm beam spot at the M5 location.

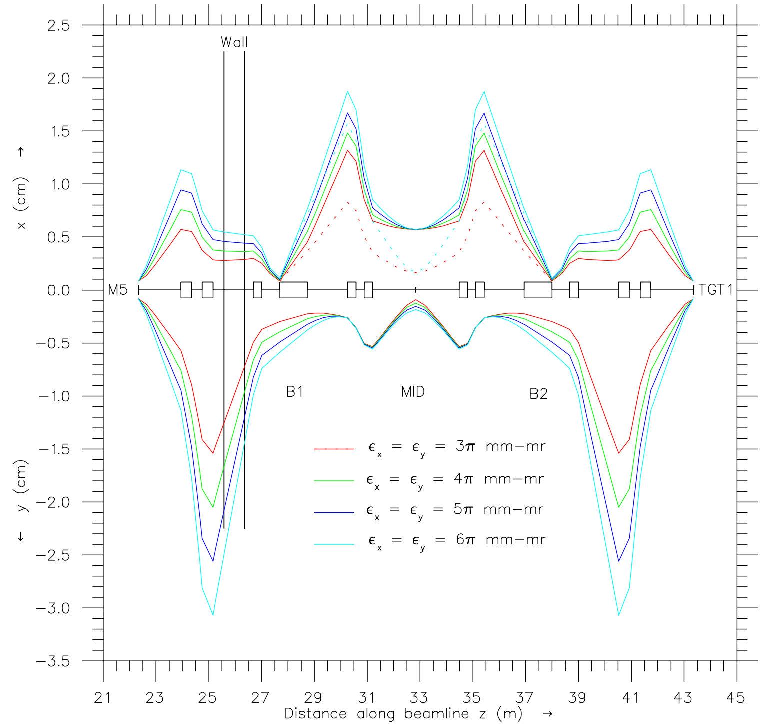

Fig. 9(a). Beam envelopes between M5 and TGT1 for beam accelerated in the medium-β accelerator with a 2 mm beam spot at the M5 and TGT1 locations—Version 1.

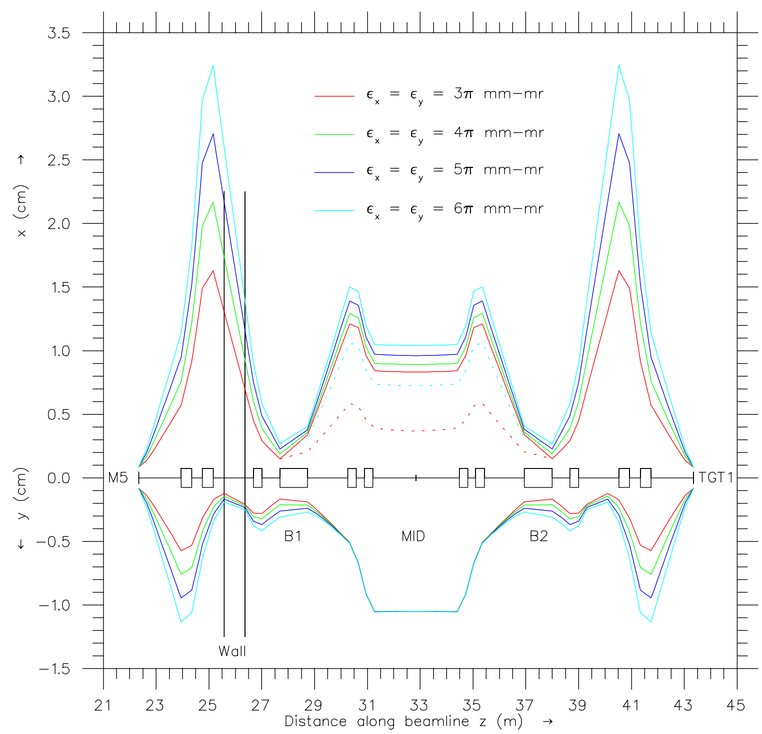

Fig. 9(b). Beam envelopes between M5 and TGT1 for beam accelerated in the medium-β accelerator with a 2 mm beam spot at the M5 and TGT1 locations—Version 2.

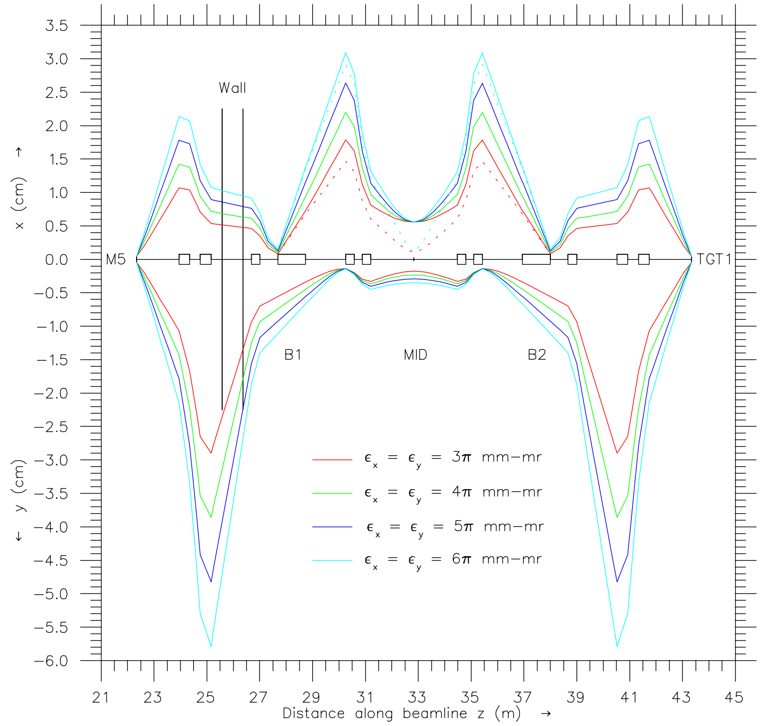

Fig. 10(a). Beam envelopes between M5 and TGT1 for beam accelerated in the medium-β accelerator with a 1 mm beam spot at the M5 and TGT1 locations—Version 1.

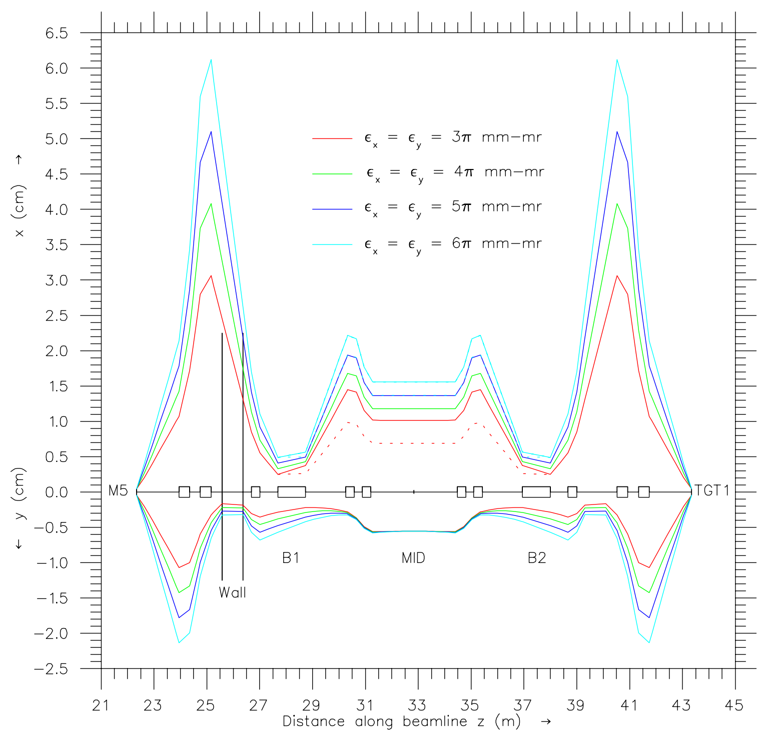

Fig. 10(b). Beam envelopes between M5 and TGT1 for beam accelerated in the medium-β accelerator with a 1 mm beam spot at the M5 and TGT1 locations—Version 2.

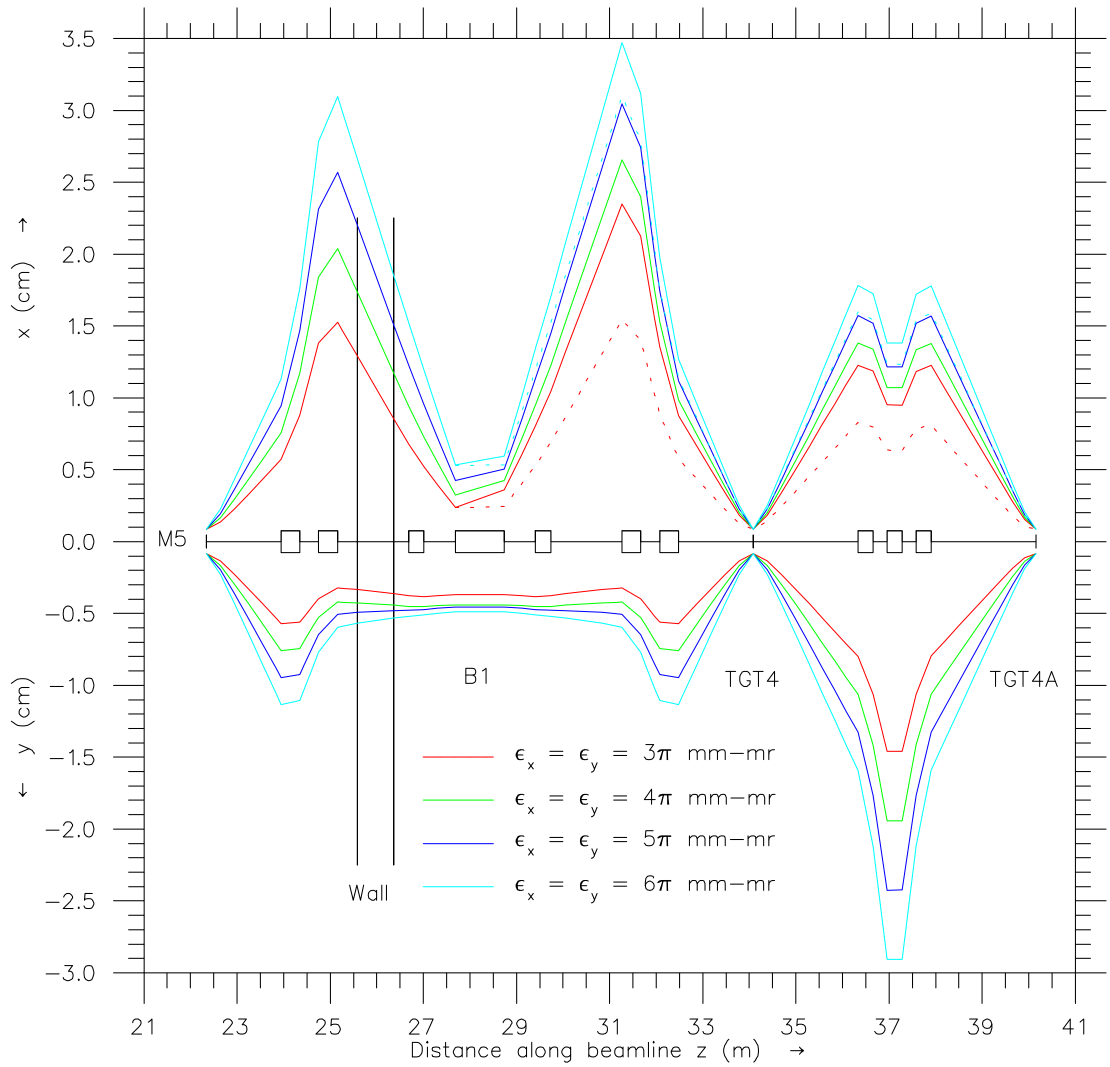

Fig. 11. Beam envelopes between M5 and targets TGT4 and TGT4A for beam accelerated in the medium-β accelerator with a 2 mm beam spot at the M5, TGT4, and TGT4A.

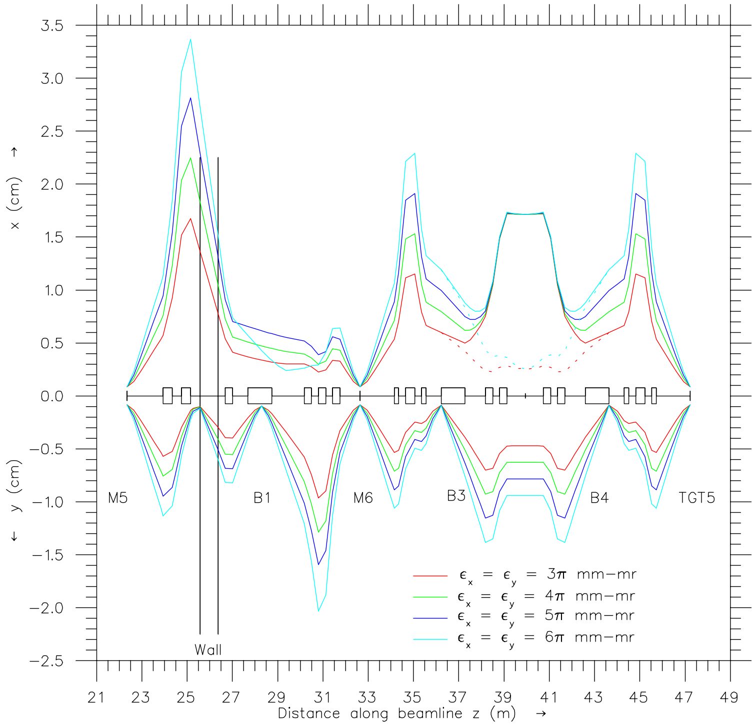

Fig. 12(a). Beam envelopes between M5 and TGT5 for beam accelerated in the medium-β accelerator with a 2 mm beam spot at the M5, M6, and TGT5 locations—version 1 of the beamline.

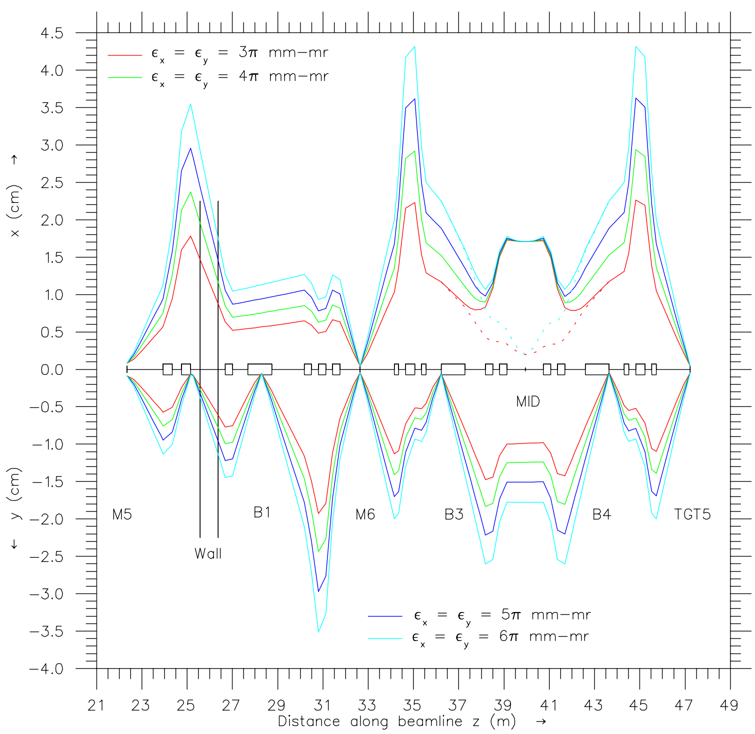

Fig. 12(b). Beam envelopes of version 1 between M5 and TGT5 for beam accelerated in the medium-β accelerator with a 2 mm beam spot at M5 and a 1 mm beam spot at the M6 and TGT5 locations.

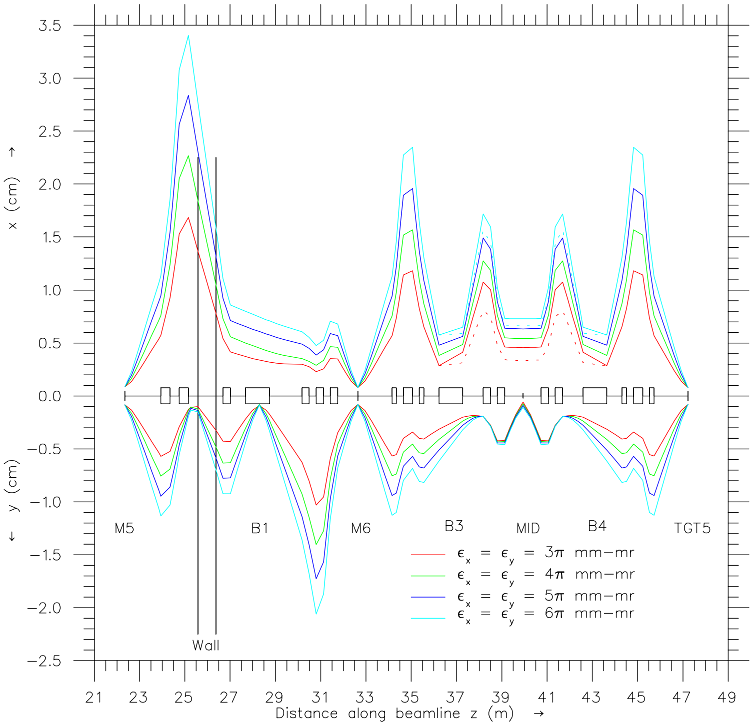

Fig. 13(a). Beam envelopes between M5 and TGT5 for beam accelerated in the medium-β accelerator with a 2 mm beam spot at the M5, M6, and TGT5 locations–version 2 of the beamline.

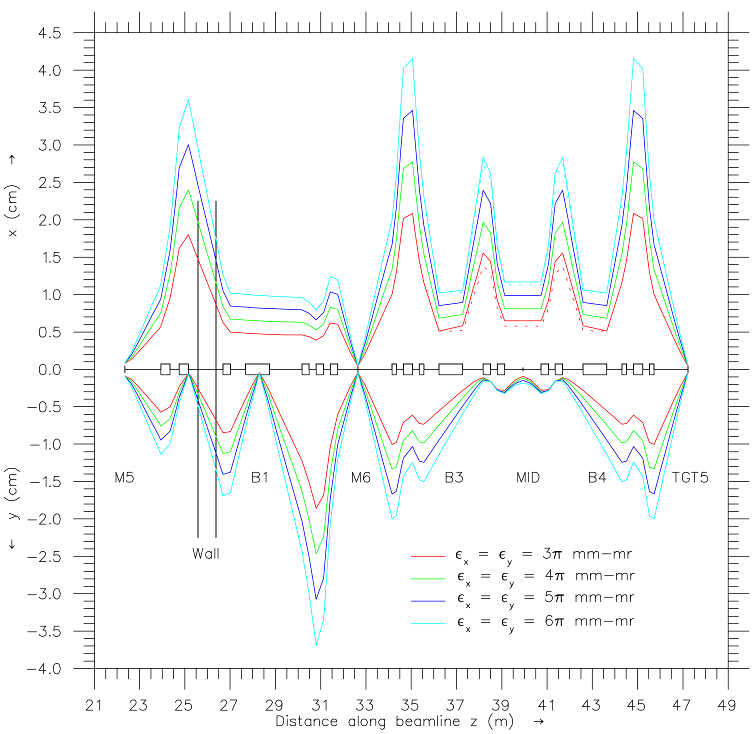

Fig. 13(b). Beam envelopes of version 2 between M5 and TGT5 for beam accelerated in the medium-β accelerator with a 2 mm beam spot at M5 and a 1 mm beam spot at the M6 and TGT5 locations.

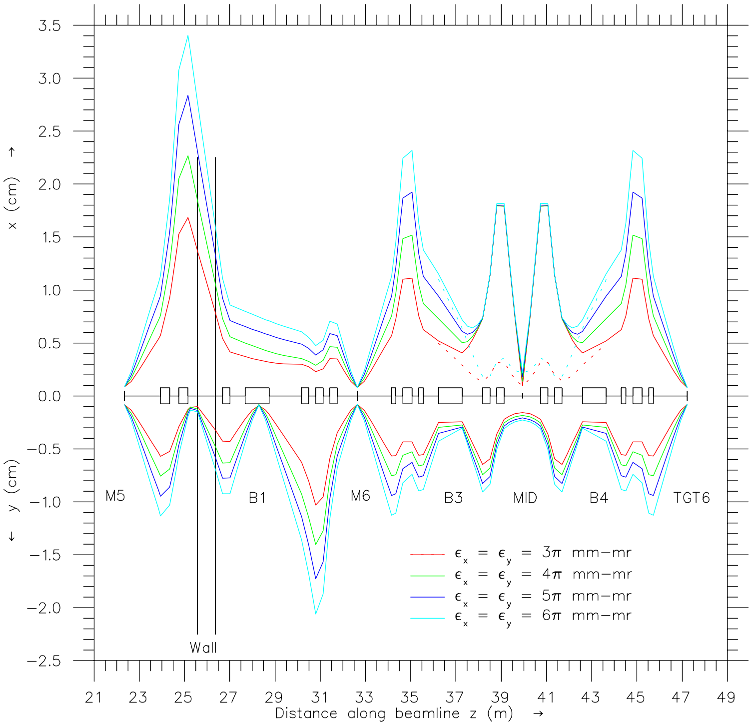

Fig. 14(a). Beam envelopes between M5 and TGT6 for beam accelerated in the medium-β accelerator with a 2 mm beam spot at the M5, M6, and TGT6 locations.

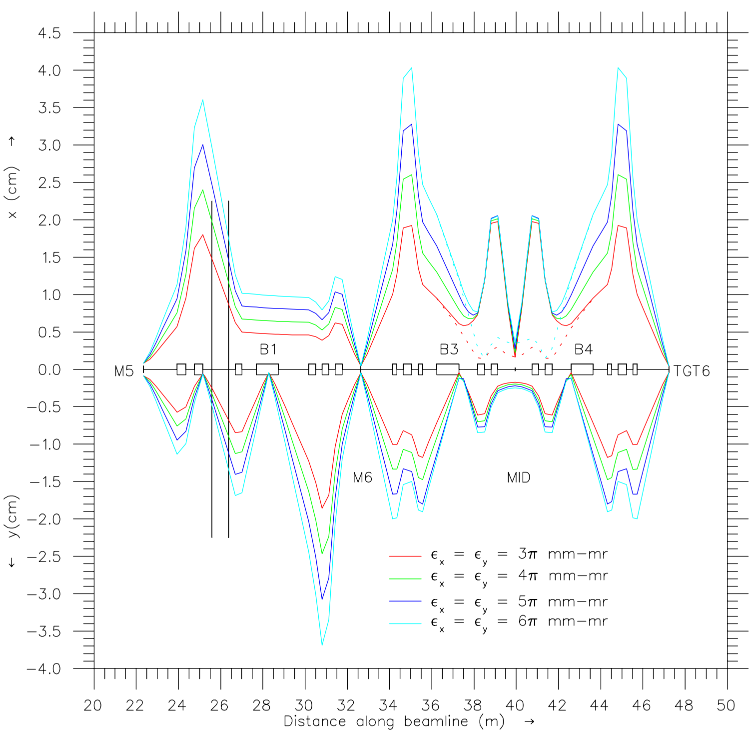

Fig. 14(b). Beam envelopes between M5 and TGT6 for beam accelerated in the medium-β accelerator with a 2 mm beam spot at M5 and a 1 mm beam spot at the M6 and TGT6 locations.