1. Introduction

Beam line 2A delivers a 500 MeV proton beam to the targets of the ISAC facility of TRIUMF. That beam line is designed such that beam may be delivered to either of two targets that are located symmetrically about the incident proton beam. At present one, the west target, is operational; the second, the east target, is under construction. When that is completed, each target could have its own ion source and/or its own target material. In this manner, should one target develop a problem, beam could be redirected to the other target while repairs were being made to the faulty target. However, were problems to develop in either beam line 2A and/or the cyclotron, until problems associated with those components were addressed no radioactive beam would be available to experimenters.

It has been suggested that in planning for the future, consideration of the provision for an alternate beam delivery system to ISAC should be made. This report presents a study of such an alternative.

2. An overview of this report

The schemes reported here involve the use of extraction port 4. As such, this would allow beam delivery to two independent ISAC targets and, consequently, to two different experiments at ISAC. Also, were beam line 2A have problems, beam to ISAC could still be delivered to one target. However, it does not alleviate the unavailability of beam should the cyclotron itself develop a problem.

In what is presented here, an attempt to use as many existing beam-transport elements as possible. Thus one or more of the following have been assumed in this study.

1. Beam line 4B is decommissioned.

   This frees one 35° dipole (currently designated 4AB2) and seven standard 4Q14/8 quadrupoles for use in any designs. One additional quadrupole of this type becomes available if its (leaking) coils are replaced.

2. Beam line 4A2 is decommissioned—that is, the Parity experiment will be finished within the next few years.

   This frees one 12° dipole and three more 4Q14/8 quadrupoles.

3. Beam line 4A may or may not be decommissioned—that is, the existing TISOL facility may or may not be required in the future.

   If the TISOL facility will be required in the future, beam line 4A could be maintained as it exists. Alternately, the beam line could be reconfigured to run parallel to the east-west wall of the proton area. This would allow the existing beam dump to be used but would require that TISOL be moved to a new location *and* additional optics added at its top end.

   If the TISOL facility will *not* be required in the future, an additional 35° dipole and are seven 4Q14/8 quadrupoles become available.

4. The existing stores building will be relocated.

   Servicing requirements of the cyclotron require that the foundation of the remote-handling building be at the same level as that of the cyclotron building. Consequently, it is not possible to tunnel under the remote-handling complex. For one, and possibly both, of the designs presented here, relocation of the existing stores building will be required.

Thus a minimum of one 35° dipole, one 12° dipole, and ten 4Q14/8 quadrupoles are expected to become available for reuse because of the decommissioning of beam lines 4B and 4A2. This rises to a total of two 35° dipoles, one 12° dipole, and seventeen 4Q14/8 quadrupoles if beam line 4A is also decommissioned.

Figure 1 shows beam line 2A (the existing beam line that feeds experiments at ISAC), beam line 4A (the existing beam line that feeds experiments at TISOL), and the two new extraction lines that are considered in this report. Each of the latter two will be discussed in more detail in what follows. Here we give a synopsis their designs only.

One possible extraction line, labelled beam line 4R (for beam line 4, Reverse bend) in figure 1, is similar to beam line 2A in that there is a long drift length through the berm. Beam is then directed north to a target assembly similar to that that exists on beam line 2A. After extraction, radioactive beam would pass through a mass separator (not shown) and continue east, eventually being brought to grade level as in the existing ISAC facility. Beam is then transported to the crossover of the first dipole of the OLIS (On Line Ion Source) from which it could be delivered to either the low energy areas or to the accelerator complex.

Alternatively, radioactive beam could be analyzed and passed on to a small accelerator where it could be accelerated and sent directly to an experimental setup.

The other line, labelled beam line 4PR, is directed into the proton hall Parallel to its east-west wall and then directed north in a Reverse direction. Alternately, beam could continue parallel to the wall of the proton hall to a relocated TISOL assembly. The present TISOL location is indicated in figure 1 by the (more-or-less) reverse L-shaped line near the end of beam line 4A. Its new location on beam line 4PR is indicated in a similar manner.

We now proceed to a more detailed discussion of these beam lines. It is stressed at the outset that the configurations given in the following sections are by no means unique; let it be recognized that other arrangements of beam-transport components are equally viable and possible.

3. Beam line 4R

Figure 2 shows this beam line on a larger scale. This configuration begins with the existing configuration of the vault components of the existing beam line 4. To these a quadrupole doublet is added to complete the vault section of the beam line. These elements have been adjusted to produce a dispersed double-waist at the point labelled $W1$ at the midpoint of a 16 m drift below the berm that exists at grade level around the cyclotron vault. Beam size at this waist is nominally $(x, y) = (\pm 0.59$ cm, ± 0.49 cm$)$. In conjunction, the quadrupole doublet upstream of dipole $4AB2$ and another downstream of it are adjusted to produce a doubly-achromatic double waist at the point $W2$ where the nominal beam size is $(x, y) = (\pm 0.49$ cm, ± 0.27 cm$)$.

There follow two quadrupole doublets that act as a matching section to produce another double waist at the point $W3$ with a beam size of $(x, y) = (\pm 0.20$ cm, ± 0.20 cm$)$. Another pair of doublets operate as a unit section to produce the same beam size at the target location $W4$. All quadrupoles are of the standard 4Q14/8 variety. Horizontal and vertical beam envelopes along the line are shown in figure 3.

As drawn, it has been assumed that all of the existing proton-hall beam lines have been decommissioned. As such the vault dipole 4VB1 has been rotated from its present orientation and deflects the beam through an angle of 32.59°. Dipole 4AB2 also deflects the beam through an angle of 32.59°. Thus the existing 4VB1 and 4AB2 dipoles are used in this particular beam transport configuration.

Table 1 lists the TRANSPORT input for this beam line. Beam properties and overall transfer-matrix elements are listed in table 2 at the waist locations.

Figure 4 shows a possible variation of the above design. As in the design of figure 1, the five vault quadrupoles and the two doublets either side of dipole 4AB2 are adjusted to produce a dispersed double waist at the midpoint of the long drift through the vault berm, $W1$, and a doubly-achromatic double waist at the $W2$ location. At $W1$ the beam dimensions are nominally $(x, y) = (\pm 0.58$ cm, ± 0.48 cm$)$. However, at the $W2$ location a beam size of $(x, y) = (\pm 0.20$ cm, ± 0.20 cm$)$ is produced. Downstream of $W2$ a six-quadrupole unit section translates the beam spot found at $W2$ to the target location $W3$. All quadrupoles of the six-quadrupole section are powered equally and, in principle, could be operated from one single power supply.

Beam envelopes along this configuration are shown in figure 5.

Table 3 lists the TRANSPORT input for this beam line. Beam properties and overall transfer-matrix elements at the waist locations are listed in columns 2, 3, and 4 of table 4.

Were a beam line with a smaller quadrupole count desired, the six-quadrupole unit section described above could be replaced with a four-quadrupole one. TRANSPORT input for such a section is given in table 5; all transport parameters up to and including the location designated $W2$ are identical to those given in table 3. The beam-line configuration is identical to that shown in figure 4 except that the six-quadrupole arrangement between points $W2$ and $W3$ is replaced with a ℓ-QQ-2ℓ-QQ-ℓ array with $\ell = 3.83976$ m.

Beam properties and overall transfer-matrix elements at the $W3$ location are listed in column 5 of table 4. Figure 6 shows the beam envelopes for this four-quadrupole, unit section scheme.

4. Beam line 4PR

An option that does not involve tunneling under the vault berm is beam-line 4PR. This line leaves the cyclotron vault Parallel to the east-west vault wall, enters the proton area, and is then deflected north in a Reverse direction by two 45° dipoles. This line is shown in more detail in figure 7.

In this configuration the 4VB1 vault dipole bends the extracted beam through 24.81°. Another quadrupole, 4VQ4, is added between the exit of the dipole and the vault wall. Existing quadrupoles 4AQ4 and 4AQ5 are relabelled 4AQ5 and 4AQ6 respectively and, in conjunction with the four vault quadrupoles, are operated to produce an achromatic double-waist at the location labelled $W1$. There the nominal beam size is $(x, y) = (\pm 0.94$ cm, ± 1.46 cm$)$.

Beam is deflected north through the wall of the proton hall by two 45° dipoles. For the configuration shown, these dipoles are new—that is, it is felt that the existing dipoles of beam line 4 cannot produce the required field for the required deflection. Between these two dipoles are two quadrupole doublets, separated by 4.40 m, that are adjusted to produce doubly-achromatic, double waists at the location $W2$. Here the nominal beam size is $(x, y) = (\pm 0.04$ cm, ± 0.23 cm$)$. A following quadrupole doublet produces another double waist at the location $W3$ where the beam size is predicted to be $(x, y) = (\pm 0.93$ cm, ± 0.56 cm$)$.

Between locations $W3$ and $W4$ lies a four-quadrupole matching section that produces a nominal beam size of $(x, y) = (\pm 0.25$ cm, ± 0.25 cm$)$ at the $W4$ point. A subsequent four-quadrupole unit section reproduces the beam characteristics of $W4$ at the target location $W5$.

A TRANSPORT listing for this configuration is given in table 6. Beam characteristics and overall transfer matrices at the waist positions are given in table 7. Horizontal and vertical envelopes along this beam line are shown in figure 8.

As noted in §2, this beamline could deliver beam to a relocated TISOL facility by turning off dipole 4AB2. and continuing to transport beam parallel to the east-west wall of the Proton Experimental Hall. This configuration is shown in more detail in figure 9. Beam profiles in this instance are shown in figure 10. A TRANSPORT input listing is given in table 8 and beam parameters at various points along the line are listed in table 9.

For this mode of operation vault quadrupoles 4VQ1/2/3 are tuned for 'normal' operation of beamline 4PR. Quadrupoles 4VQ4 and 4AQ5/6 are slightly detuned from that normal operation so as to provide an achromatic double waist at the location labelled $WST1$ 3.288 m downstream of quadrupole 4AQ6 and somewhat upstream of dipole 4AB2. At this point the nominal beam sizes are $(x, y) = (\pm 0.925$ cm, ± 1.46 cm). Dipole 4AB2 is turned off and the beam drifts some 6 m further to a four-quadrupole array that produces a nominal beam size of $(x, y) = (\pm 0.25$ cm, ± 0.25 cm) at the center of the TISOL target. A quadrupole doublet and a 19.8° dipole are used to direct beam to the (existing) beamline 4A beam dump.

5. Discussion

Admittedly, this study is speculative. Its intent has been to indicate that it is indeed possible to provide an additional beamline to the ISAC facility. It will also be noted that an extracted energy of 460 MeV has been used. This was chosen somewhat arbitrarily to be well below any energy that might be extracted into beamline 2A, thus allowing simultaneous extraction into that beamline and into beamline 4A.

Finally, we present in figure 11 a completely speculative schematic diagram that shows a production target—similar to that of beamline 2A—located in the Proton Hall. The dashed lines are meant to indicate extraction from the that target and injection into a small cyclotron located in the hall. Accelerated beam from that cyclotron could the be directed into either of beamlines 4P or 4PR and transported to the ISAC facility. In the event that the main cyclotron were not operational, the small cyclotron with its own ion source could provide accelerated beam for experimental use in the main ISAC complex.

Table 1

Listing of TRANSPORT for beam line 4R

```
'01/02/21 - 460MEV - BL4 REVERSE 33 DEG BEND - ACHROMATIC '
 0
13.      ' '     12.00000;
16.00    'X0 '   16.00000    9.82964;
16.00    'Z0 '   18.00000   -5.31156;
16.00    'T0 '   19.00000  155.18701;
 1.00    'BEAM'   0.12700    1.60400   0.56100   0.57500   0.0    0.10000   1.03673;
12.      ' '      0.0        0.0       0.0       0.0       0.0   -0.94900   0.0       0.0
                  0.0        0.0       0.0       0.0       0.0    0.0       0.0;
 1.00    'FOIL'   0.0        0.27300   0.0       0.27300   0.0    0.0       0.0       0.0;
14.      'ROW1'  -0.04140    0.32970   0.0       0.0       0.0    1.46880   1.00000;
14.      'ROW2'  -3.11000    0.11160   0.0       0.0       0.0    1.97800   2.00000;
14.      'ROW3'   0.0        0.0       1.14100   0.65040   0.0    0.0       3.00000;
14.      'ROW4'   0.0        0.0       0.51000   1.16500   0.0    0.0       4.00000;
 3.0     '4VM1'   0.31440;
 3.0     'Q1IN'   0.16825;
 5.00    '4VQ1'   0.41110    1.65930   5.08000;
 3.0     'Q2IN'   0.62755;
 5.00    '4VQ2'   0.40700   -1.49164   5.08000;
 3.0     ' '      0.49970;
 3.0     'Q3IN'   0.50460;
 5.00    '4VQ3'   0.39720    1.22467   5.08000;
 3.0     ' '      0.95496;
19.00    'SOL1'   0.59055    0.00001;
 3.0     ' '      0.95037;
 3.0     'B1IN'  -0.04528;
 2.0     ' '     16.29675;
 4.000   '4VB1'   1.56290   12.58686   0.00000;
 2.0     ' '     16.29675;
 3.0     'B1EX'   0.00001;
 3.0     ' '      0.65000;
 5.00    '4AQ4'   0.40640   -1.38044   5.08000;
 3.0     'Q4EX'   0.00001;
 3.0     'Q5IN'   0.30480;
 5.00    '4AQ5'   0.40640    2.02138   5.08000;
 3.0     'Q5EX'   0.00001;
 3.0     'D1 '    1.00000;
 3.0     'D2 '    1.00000;
 3.0     'D3 '    1.00000;
 3.0     'D4 '    1.00000;
 3.0     'D5 '    1.00000;
 3.0     'D6 '    1.00000;
 3.0     'D7 '    1.00000;
 3.0     'W1 '    1.00000;
 3.0     'D9 '    1.00000;
 3.0     'D10 '   1.00000;
 3.0     'D11 '   1.00000;
 3.0     'D12 '   1.00000;
 3.0     'D13 '   1.00000;
 3.0     'D14 '   1.00000;
```

Table 1 (Continued)

3.0	'D15 '	1.00000;		
3.0	'D16 '	1.00000;		
5.00	'4AQ6'	0.40640	3.16063	5.08000;
3.0	' '	0.30480;		
5.00	'4AQ7'	0.40640	−2.62615	5.08000;
3.0	' '	0.65000;		
2.0	' '	16.29675;		
4.000	'4AB2'	1.56290	12.58686	0.00000;
2.0	' '	16.29675;		
3.0	' '	1.00000;		
5.00	'4AQ8'	0.40640	1.77314	5.08000;
3.0	' '	0.30480;		
5.00	'4AQ9'	0.40640	0.34895	5.08000;
3.0	'W2 '	2.00000;		
3.0	' '	0.18728;		
3.0	' '	0.50000;		
3.0	' '	0.50000;		
5.00	'4Q10'	0.40640	2.31451	5.08000;
3.0	' '	0.30480;		
5.00	'4Q11'	0.40640	−3.50555	5.08000;
3.0	' '	0.50000;		
3.0	' '	0.30480;		
3.0	' '	0.50000;		
5.00	'4Q12'	0.40640	2.83247	5.08000;
3.0	' '	0.30480;		
5.00	'4Q13'	0.40640	−2.01143	5.08000;
3.0	' '	0.50000;		
3.0	' '	0.50000;		
3.0	'W3 '	0.18728;		
3.0	' '	1.00000;		
3.0	' '	0.36109;		
3.0	' '	1.00000;		
5.00	'4Q14'	0.40640	−3.61888	5.08000;
3.0	' '	0.30480;		
5.00	'4Q15'	0.40640	3.61888	5.08000;
3.0	' '	1.00000;		
3.0	' '	0.36109;		
3.0	' '	1.00000;		
3.0	'MID '	0.00001;		
3.0	' '	0.00001;		
3.0	' '	1.00000;		
3.0	' '	0.36109;		
3.0	' '	1.00000;		
5.00	'4Q16'	0.40640	−3.61888	5.08000;
3.0	' '	0.30480;		
5.00	'4Q17'	0.40640	3.61888	5.08000;
3.0	' '	1.00000;		
3.0	' '	0.36109;		
3.0	'W4 '	1.00000;		
SENTINEL;				
SENTINEL;				

Table 2

Beam sizes an overall transfer-matrix elements at the waists of beam line 4R

Parameter	W1	W2	W3	W4
x (cm)	0.590	0.487	0.200	0.200
θ (mr)	0.371	0.433	1.055	1.055
y (cm)	0.487	0.266	0.200	0.200
ϕ (mr)	0.377	0.690	0.917	0.917
R_{11} (cm/cm)	0.3697	−1.5334	−1.5554	1.5554
R_{12} (cm/mr)	−0.3523	0.2743	−0.0191	0.0191
R_{16} (mr/%)	1.3173	0.0000	0.0000	0.0000
R_{21} (mr/cm)	2.8698	−3.1257	1.2833	−1.2839
R_{21} (mr/mr)	0.0260	−0.1064	−0.6405	0.6405
R_{26} (mr/%)	0.5448	0.0000	0.0000	0.0000
R_{33} (cm/cm)	1.2670	−0.4883	−0.5427	0.5426
R_{34} (cm/mr)	1.4624	−0.0153	−0.6052	0.6051
R_{43} (mr/cm)	−0.8603	−2.0257	1.9716	−1.9720
R_{44} (mr/mr)	−0.2056	−2.1066	0.3604	−0.3607

Table 3

Listing of TRANSPORT for beam line 4R with a 6-quadrupole unit section

```
'01/02/21 - 460MEV - BL4 REVERSE 33 DEG BEND - ACHROMATIC + 6Q UNIT SECTION'
 0
13.      ' '     12.00000;
16.00   'X0 '    16.00000    9.82964;
16.00   'Z0 '    18.00000   -5.31156;
16.00   'T0 '    19.00000  155.18701;
 1.00   'BEAM'    0.12700    1.60400   0.56100   0.57500   0.0    0.10000   1.03673;
12.      ' '      0.0        0.0       0.0       0.0       0.0   -0.94900   0.0       0.0
                  0.0        0.0       0.0       0.0       0.0    0.0       0.0;
 1.00   'FOIL'    0.0        0.27300   0.0       0.27300   0.0    0.0       0.0       0.0;
14.     'ROW1'   -0.04140    0.32970   0.0       0.0       0.0    1.46880   1.00000;
14.     'ROW2'   -3.11000    0.11160   0.0       0.0       0.0    1.97800   2.00000;
14.     'ROW3'    0.0        0.0       1.14100   0.65040   0.0    0.0       3.00000;
14.     'ROW4'    0.0        0.0       0.51000   1.16500   0.0    0.0       4.00000;
 3.0    '4VM1'    0.31440;
 3.0    'Q1IN'    0.16825;
 5.00   '4VQ1'    0.41110    1.65818   5.08000;
 3.0    'Q2IN'    0.62755;
 5.00   '4VQ2'    0.40700   -1.45369   5.08000;
 3.0     ' '      0.49970;
 3.0    'Q3IN'    0.50460;
 5.00   '4VQ3'    0.39720    1.15685   5.08000;
 3.0     ' '      0.95496;
19.00   'SOL1'    0.59055    0.00001;
 3.0     ' '      0.95037;
 3.0    'B1IN'   -0.04528;
 2.0     ' '     16.29675;
 4.000  '4VB1'    1.56290   12.58686   0.00000;
 2.0     ' '     16.29675;
 3.0    'B1EX'    0.00001;
 3.0     ' '      0.65000;
 5.00   '4AQ4'    0.40640   -1.36565   5.08000;
 3.0    'Q4EX'    0.00001;
 3.0    'Q5IN'    0.30480;
 5.00   '4AQ5'    0.40640    2.01145   5.08000;
 3.0    'Q5EX'    0.00001;
 3.0    'D1 '     1.00000;
 3.0    'D2 '     1.00000;
 3.0    'D3 '     1.00000;
 3.0    'D4 '     1.00000;
 3.0    'D5 '     1.00000;
 3.0    'D6 '     1.00000;
 3.0    'D7 '     1.00000;
 3.0    'W1 '     1.00000;
 3.0    'D9 '     1.00000;
 3.0    'D10 '    1.00000;
 3.0    'D11 '    1.00000;
 3.0    'D12 '    1.00000;
 3.0    'D13 '    1.00000;
 3.0    'D14 '    1.00000;
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Table 3 (Continued)

3.0	'D15 '	1.00000;		
3.0	'D16 '	1.00000;		
5.00	'4AQ6'	0.40640	3.22112	5.08000;
3.0	' '	0.30480;		
5.00	'4AQ7'	0.40640	−2.82851	5.08000;
3.0	' '	0.65000;		
2.0	' '	16.29675;		
4.000	'4AB2'	1.56290	12.58686	0.00000;
2.0	' '	16.29675;		
3.0	' '	1.00000;		
5.00	'4AQ8'	0.40640	4.30532	5.08000;
3.0	' '	0.30480;		
5.00	'4AQ9'	0.40640	−1.80486	5.08000;
3.0	'W2 '	2.00000;		
3.0	' '	0.37353;		
3.0	' '	1.00000;		
3.0	' '	1.00000;		
5.00	'4Q10'	0.40640	2.55186	5.08000;
3.0	' '	0.30480;		
5.00	'4Q11'	0.40640	−2.55186	5.08000;
3.0	' '	0.37353;		
3.0	' '	1.00000;		
3.0	' '	1.00000;		
3.0	' '	1.00000;		
3.0	' '	1.00000;		
3.0	' '	0.37353;		
5.00	'4Q12'	0.40640	2.55186	5.08000;
3.0	' '	0.30480;		
5.00	'4Q13'	0.40640	−2.55186	5.08000;
3.0	' '	0.37353;		
3.0	' '	1.00000;		
3.0	' '	1.00000;		
3.0	' '	1.00000;		
3.0	' '	1.00000;		
3.0	' '	0.37353;		
5.00	'4Q14'	0.40640	2.55186	5.08000;
3.0	' '	0.30480;		
5.00	'4Q15'	0.40640	−2.55186	5.08000;
3.0	' '	1.00000;		
3.0	' '	1.00000;		
3.0	' '	0.37353;		
3.0	'W4 '	1.00000;		
SENTINEL;				
SENTINEL;				

Table 4

Beam sizes an overall transfer-matrix elements at the waists of beam line 4R with 4- and 6-quadrupole unit sections

Parameter	W1	W2	W3 (6Q)	W3 (4Q)
x (cm)	0.584	0.200	0.200	0.200
θ (mr)	0.375	1.055	1.055	1.055
y (cm)	0.482	0.200	0.200	0.200
ϕ (mr)	0.381	0.917	0.917	0.917
R_{11} (cm/cm)	0.3293	−1.4001	1.4001	1.4006
R_{12} (cm/mr)	−0.3481	0.0563	−0.0563	−0.0562
R_{16} (mr/%)	1.3620	0.0000	0.0000	0.0000
R_{21} (mr/cm)	2.9090	−3.8007	3.8008	3.7996
R_{21} (mr/mr)	0.0246	−0.5763	0.5763	0.5763
R_{26} (mr/%)	0.5308	0.0003	−0.0003	−0.0003
R_{33} (cm/cm)	1.2449	−0.5741	0.5741	0.5743
R_{34} (cm/mr)	1.4444	−0.2581	0.2581	0.2585
R_{43} (mr/cm)	−0.8772	−1.7753	1.7753	1.7751
R_{44} (mr/mr)	−0.2165	−2.5358	2.5358	2.5359

Table 5

Listing of TRANSPORT for beam line 4R with a 4-quadrupole unit section

```
'01/02/21 – 460MEV – BL4 REVERSE 33 DEG BEND – ACHROMATIC + 4Q UNIT SECTION'
  0
13.       ' '     12.00000;
16.00    'X0 '    16.00000      9.82964;
16.00    'Z0 '    18.00000     −5.31156;
16.00    'T0 '    19.00000    155.18701;
 1.00   'BEAM'     0.12700      1.60400   0.56100   0.57500   0.0   0.10000   1.03673;
                   ⋮
                   ⋮

            Identical to table 3

                   ⋮
                   ⋮
 5.00   '4AQ9'     0.40640     −1.80486   5.08000;
 3.0     'W2 '     2.00000;
 3.0      ' '      0.95994;
 3.0      ' '      0.95994;
 3.0      ' '      0.95994;
 3.0      ' '      0.95994;
 5.00   '4Q10'     0.40640     −2.86412   5.08000;
 3.0      ' '      0.30480;
 5.00   '4Q11'     0.40640      2.86410   5.08000;
 3.0      ' '      0.95994;
 3.0      ' '      0.95994;
 3.0      ' '      0.95994;
 3.0      ' '      0.95994;
 3.0    'MID '     0.00001;
 3.0      ' '      0.95994;
 3.0      ' '      0.95994;
 3.0      ' '      0.95994;
 3.0      ' '      0.95994;
 5.00   '4Q12'     0.40640     −2.86412   5.08000;
 3.0      ' '      0.30480;
 5.00   '4Q13'     0.40640      2.86410   5.08000;
 3.0      ' '      0.95994;
 3.0      ' '      0.95994;
 3.0      ' '      0.95994;
 3.0      ' '      0.95994;
 3.0     'W3 '     1.00000;
SENTINEL;
SENTINEL;
```

Table 6

Listing of TRANSPORT input for beam line 4PR

```
'01/02/21 – 460MEV – BL4 PERP 25 + 2x45 DEG BENDS – ACHROMATIC'
 0
13.       ' '     12.00000;
16.00     'X0 '   16.00000     9.82964;
16.00     'Z0 '   18.00000    −5.31156;
16.00     'T0 '   19.00000   155.18701;
 1.00     'BEAM'   0.12700     1.60400   0.56100   0.57500   0.0    0.10000   1.03673;
12.       ' '      0.0         0.0       0.0       0.0       0.0   −0.94900   0.0       0.0
                   0.0         0.0       0.0       0.0       0.0    0.0       0.0;
 1.00     'FOIL'   0.0         0.27300   0.0       0.27300   0.0    0.0       0.0       0.0;
14.       'ROW1'  −0.04140     0.32970   0.0       0.0       0.0    1.46880   1.00000;
14.       'ROW2'  −3.11000     0.11160   0.0       0.0       0.0    1.97800   2.00000;
14.       'ROW3'   0.0         0.0       1.14100   0.65040   0.0    0.0       3.00000;
14.       'ROW4'   0.0         0.0       0.51000   1.16500   0.0    0.0       4.00000;
 3.0      '4VM1'   0.31440;
 3.0      'Q1IN'   0.16825;
 5.00     '4VQ1'   0.41110     4.55095   5.08000;
 3.0      'Q2IN'   0.62755;
 5.00     '4VQ2'   0.40700    −4.49870   5.08000;
 3.0      ' '      0.49970;
 3.0      'Q3IN'   0.50460;
 5.00     '4VQ3'   0.39720     5.17075   5.08000;
 3.0      ' '      0.95496;
19.00     'SOL1'   0.59055     0.00001;
 3.0      ' '      0.95037;
 3.0      'B1IN'  −0.04528;
 2.0      ' '     20.00000;
 4.000    '4VB1'   1.56290     9.58221   0.00000;
 2.0      ' '      4.81300;
 3.0      'B1EX'   0.00001;
 3.0      ' '      2.19360;
 5.00     '4VQ4'   0.40640     0.99394   5.08000;
 3.0      'VWL1'   0.50000;
 3.0      'VWL2'   0.90000;
 3.0      'Q5IN'   3.30000;
 5.00     '4AQ5'   0.40640     1.31171   5.08000;
 3.0      'Q5EX'   0.00001;
 3.0      'Q6IN'   0.30480;
 5.00     '4AQ6'   0.40640    −1.44748   5.08000;
 3.0      'Q6EX'   0.00001;
 3.0      'W1 '    1.00000;
 3.0      'D2 '    1.00000;
 3.0      'D3 '    0.71120;
 3.0      'D3 '    0.71120;
 3.0      'D7 '    0.65000;
 2.0      ' '     22.50000;
 4.000    '4RB1'   1.81067    15.00000   0.00000;
 2.0      ' '     22.50000;
 3.0      ' '      0.65000;
 5.00     '4AQ7'   0.40640     3.44276   5.08000;
```

Table 6 (Continued)

3.0	' '	0.30480;		
5.00	'4AQ8'	0.40640	−1.73280	5.08000;
3.0	'D9 '	1.00000;		
3.0	'D10 '	1.00000;		
3.0	'MID '	0.10000;		
3.0	' '	0.10000;		
3.0	'D12 '	1.00000;		
3.0	'D13 '	1.00000;		
5.00	'4AQ9'	0.40640	3.48116	5.08000;
3.0	' '	0.30480;		
5.00	'4Q10'	0.40640	−2.52674	5.08000;
3.0	'D14 '	0.65000;		
2.0	' '	22.50000;		
4.000	'4RB2'	1.81067	15.00000	0.00000;
2.0	' '	22.50000;		
3.0	'D15 '	0.65000;		
5.00	'4Q11'	0.40640	−2.07304	5.08000;
3.0	' '	0.30480;		
5.00	'4Q12'	0.40640	4.40737	5.08000;
3.0	'W2 '	1.00000;		
3.0	'D16 '	0.42669;		
3.0	'D16 '	1.00000;		
3.0	'D16 '	1.00000;		
5.00	'4Q13'	0.40640	3.90306	5.08000;
3.0	' '	0.30480;		
5.00	'4Q14'	0.40640	−2.91054	5.08000;
3.0	'D16 '	1.00000;		
3.0	'D16 '	1.00000;		
3.0	'W3 '	0.42669;		
3.0	' '	2.57191;		
5.00	'4Q15'	0.40640	−2.00625	5.08000;
3.0	' '	0.30480;		
5.00	'4Q16'	0.40640	2.11211	5.08000;
3.0	' '	2.57191;		
3.0	' '	2.57191;		
5.00	'4Q17'	0.40640	0.37847	5.08000;
3.0	' '	0.30480;		
5.00	'4Q18'	0.40640	−1.42526	5.08000;
3.0	'W4 '	2.57191;		
3.0	' '	2.26309;		
5.00	'4Q19'	0.40640	−3.67945	5.08000;
3.0	' '	0.30480;		
5.00	'4Q20'	0.40640	3.68502	5.08000;
3.0	' '	2.57191;		
3.0	' '	2.57191;		
5.00	'4Q21'	0.40640	−3.67945	5.08000;
3.0	' '	0.30480;		
5.00	'4Q22'	0.40640	3.68502	5.08000;
3.0	'W5 '	2.57191;		
SENTINEL;				
SENTINEL;				

Table 7

Beam sizes an overall transfer-matrix elements at the waists of beam line 4PR

Parameter	W1	W2	W3	W4	W5
x (cm)	0.935	0.040	0.932	0.251	0.250
θ (mr)	0.226	5.323	0.226	0.842	0.842
y (cm)	1.459	0.226	0.556	0.250	0.252
ϕ (mr)	0.126	0.812	0.330	0.733	0.727
R_{11} (cm/cm)	1.4991	0.3111	0.2180	−1.7554	1.7510
R_{12} (cm/mr)	0.5624	−0.0019	0.5724	0.0703	−0.0708
R_{16} (mr/%)	0.0000	0.0000	0.0000	0.0000	0.0000
R_{21} (mr/cm)	−1.7392	3.2097	−1.7816	−3.0371	3.0472
R_{22} (mr/mr)	0.0284	3.2619	0.0041	−0.4598	0.4598
R_{26} (mr/%)	0.0000	0.0000	0.0000	−0.0001	0.0001
R_{33} (cm/cm)	3.1101	−0.2321	1.2179	0.2064	−0.2224
R_{34} (cm/mr)	4.1552	−0.5141	0.2431	0.5375	−0.5515
R_{43} (mr/cm)	−0.3428	2.6855	0.8842	−2.4682	2.4318
R_{44} (mr/mr)	−0.1372	1.6500	0.9955	−1.5942	1.5449

Table 8

Listing of TRANSPORT input for beam line 4PR for beam delivery to TISOL

```
'01/02/21 – 460MEV – BL4 PERP 25 DEG BEND – ACHRO – LONG – TO TISOL'
 0
13.       ' '      12.00000;
16.00     'X0 '    16.00000     9.82964;
16.00     'Z0 '    18.00000    -5.31156;
16.00     'T0 '    19.00000   155.18701;
 1.00     'BEAM'    0.12700     1.60400    0.56100    0.57500    0.0    0.10000    1.03673;
                    ⋮

           Identical to table 6

                    ⋮
 5.00     '4VQ4'    0.40640     1.00023    5.08000;
 3.0      'VWL1'    0.50000;
 3.0      'VWL2'    0.90000;
 3.0      'Q5IN'    3.30000;
 5.00     '4AQ5'    0.40640     1.31171    5.08000;
 3.0      'Q6IN'    0.30480;
 5.00     '4AQ6'    0.40640    -1.44882    5.08000;
 3.0      'WST1'    3.28807;
 3.0      'D2A '    0.35000;
 3.0      'D3A '    5.71149;
 3.0      'Q7IN'    3.30000;
 5.00     '4AQ7'    0.40640    -2.77518    5.08000;
 3.0      'Q8IN'    0.30480;
 5.00     '4AQ8'    0.40640     2.93645    5.08000;
 3.0      'D4A '   -1.00143;
 3.0      'D5A '    3.35990;
 5.00     '4AQ9'    0.40640     1.58952    5.08000;
 3.0      'Q10I'    0.30480;
 5.00     '4Q10'    0.40640    -5.95239    5.08000;
 3.0      'TIN '    1.35016;
 3.0      'TCL '    0.35000;
 3.0      'TEX '    1.35016;
 3.0      'Q12I'    1.00000;
 5.00     '4Q12'    0.40640    -1.59953    5.08000;
 3.0      'Q13I'    0.30480;
 5.00     '4Q13'    0.40640     1.65113    5.08000;
 2.0      ' '       9.89950;
 4.000    '4RB1'    1.56290     7.64591    0.00000;
 2.0      ' '       9.89950;
 3.0      ' '       1.00000;
 3.0      ' '       0.40640;
 3.0      ' '       0.30480;
 3.0      ' '       0.40640;
 3.0      'PWAL'    0.71649;
 3.0      ' '       1.00000;
 3.0      ' '       1.00000;
 3.0      'DUMP'    1.00000;
```

Table 9

Beam sizes an overall transfer-matrix elements at the waists for beam delivery to TISOL on line 4PR

Parameter	WST1	TCL*	PWAL	DUMP
x (cm)	0.925	0.249	0.582	0.717
θ (mr)	0.228	0.846	0.611	0.611
y (cm)	1.463	0.250	0.529	0.704
ϕ (mr)	0.125	0.733	0.657	0.657
R_{11} (cm/cm)	1.0702	−1.3114	−4.1551	−4.5694
R_{12} (cm/mr)	0.5622	0.1140	−0.1300	−0.2167
R_{16} (mr/%)	0.0000	0.0000	1.2566	2.3037
R_{21} (mr/cm)	−1.7760	−4.9550	−1.3811	−1.3811
R_{22} (mr/mr)	0.0208	−0.3475	−0.2889	−0.2889
R_{26} (mr/%)	0.0000	0.0000	3.4903	3.4903
R_{33} (cm/cm)	3.0430	−0.3389	1.6055	2.2872
R_{34} (cm/mr)	4.1361	−0.6176	0.8144	1.3466
R_{43} (mr/cm)	−0.3465	2.3346	2.2722	2.2722
R_{44} (mr/mr)	−0.1431	1.3112	1.7739	1.7739

* TCL = TISOL centerline; PWAL = west wall of Proton Hall; DUMP = beamline 4A beam dump.

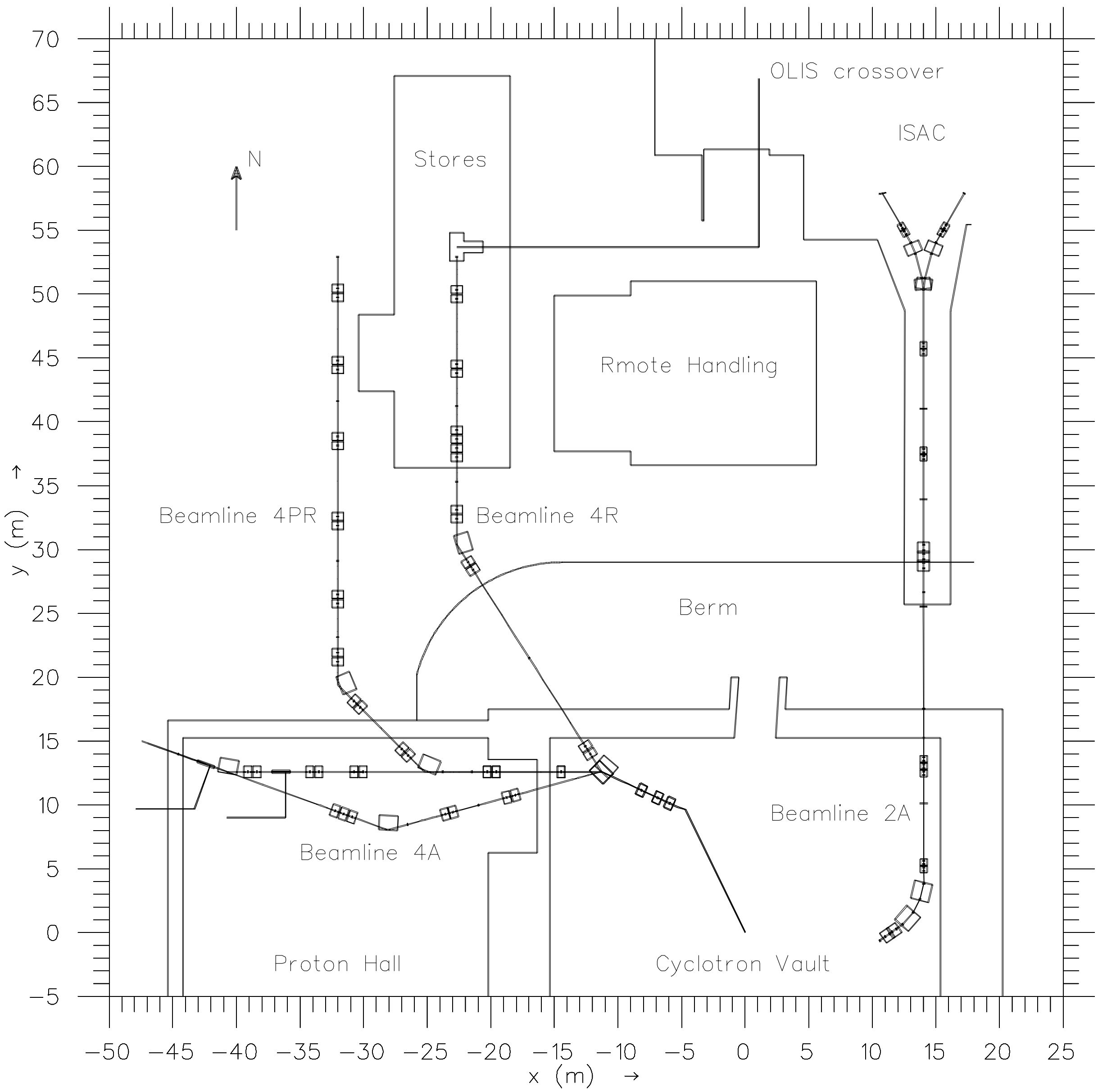

Fig. 1. An overview of the beamlines discussed in this report.

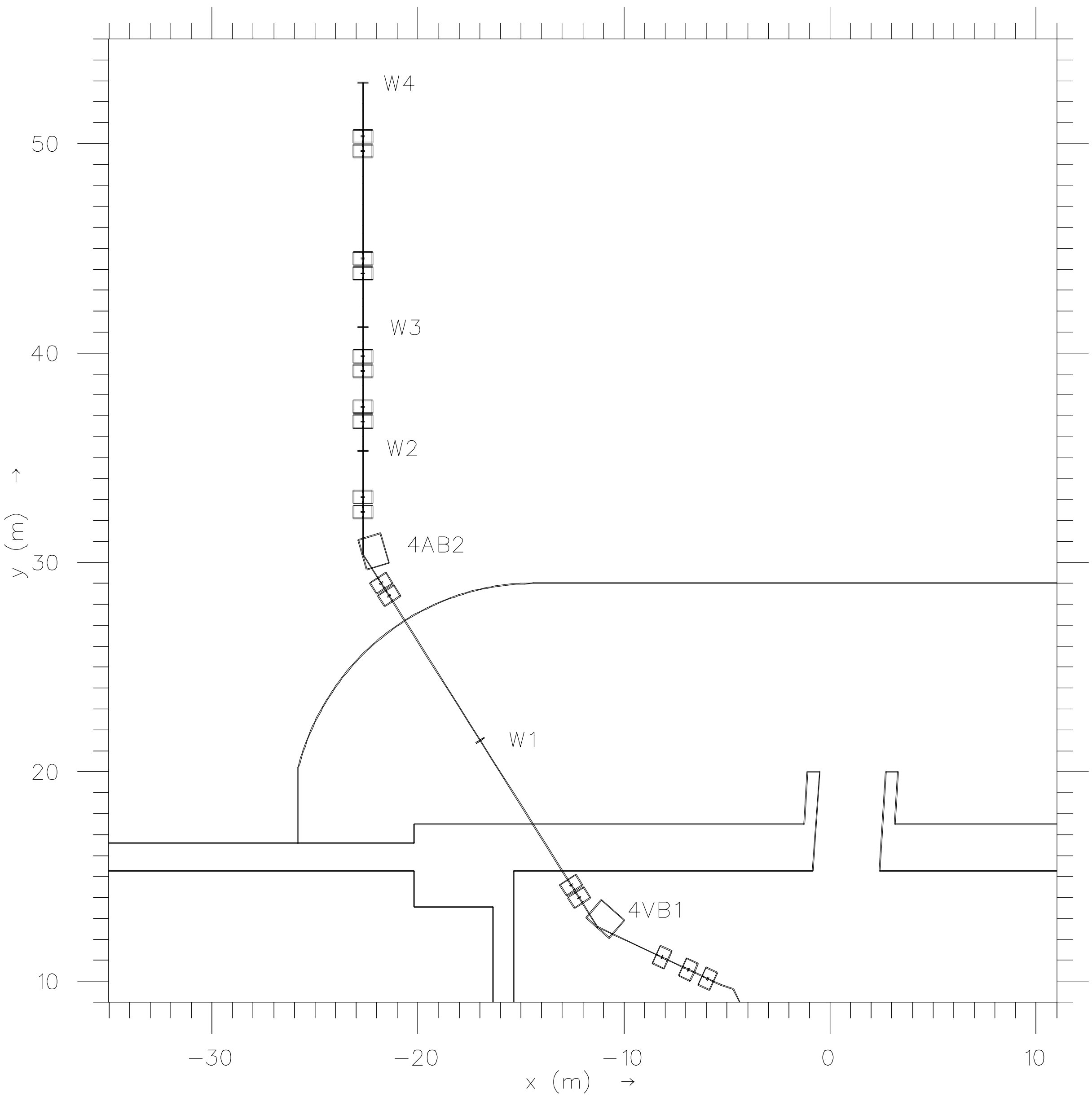

Fig. 2. Detail of the beamline 4R.

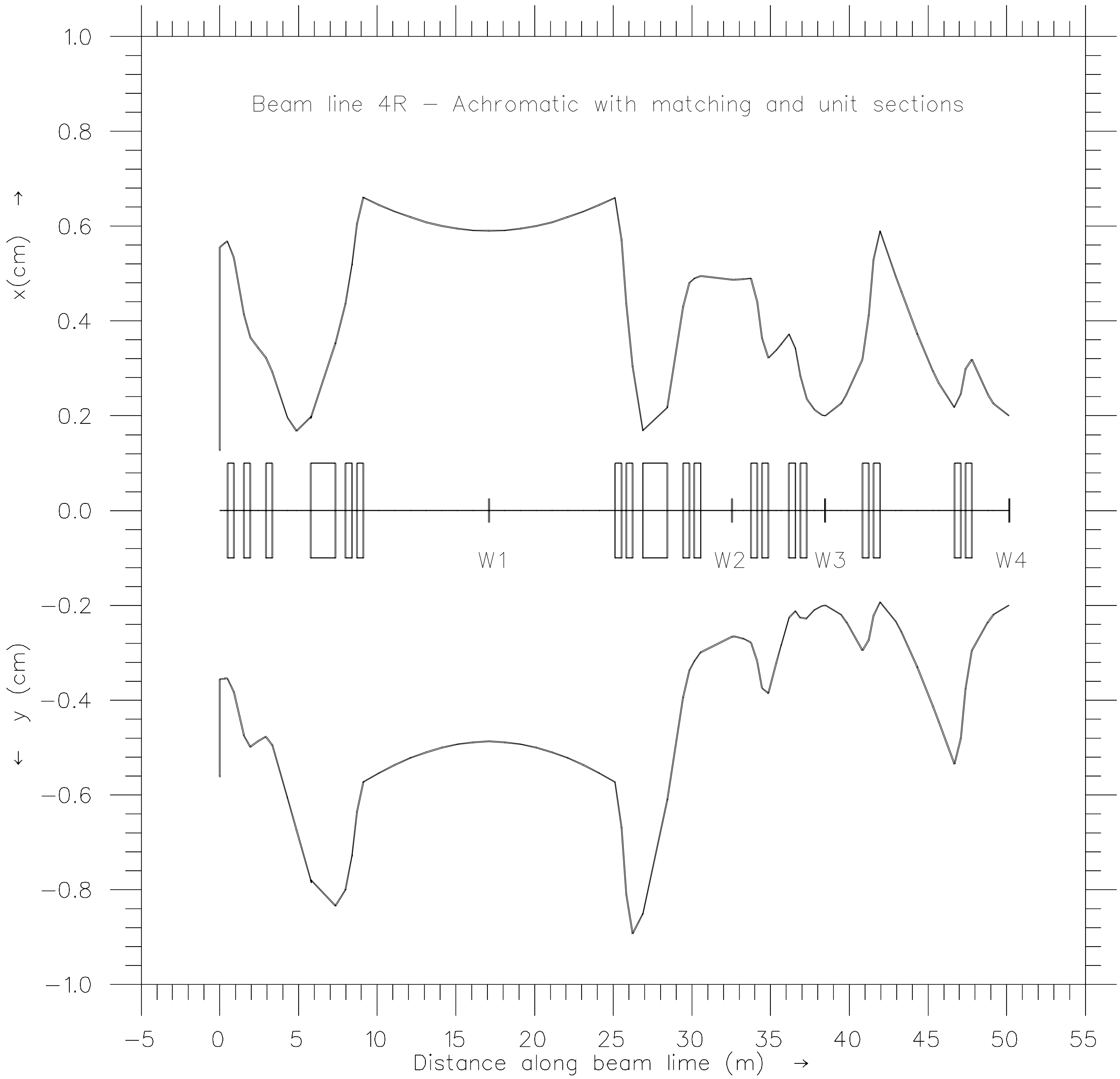

Fig. 3. Beam profiles along beamline 4P.

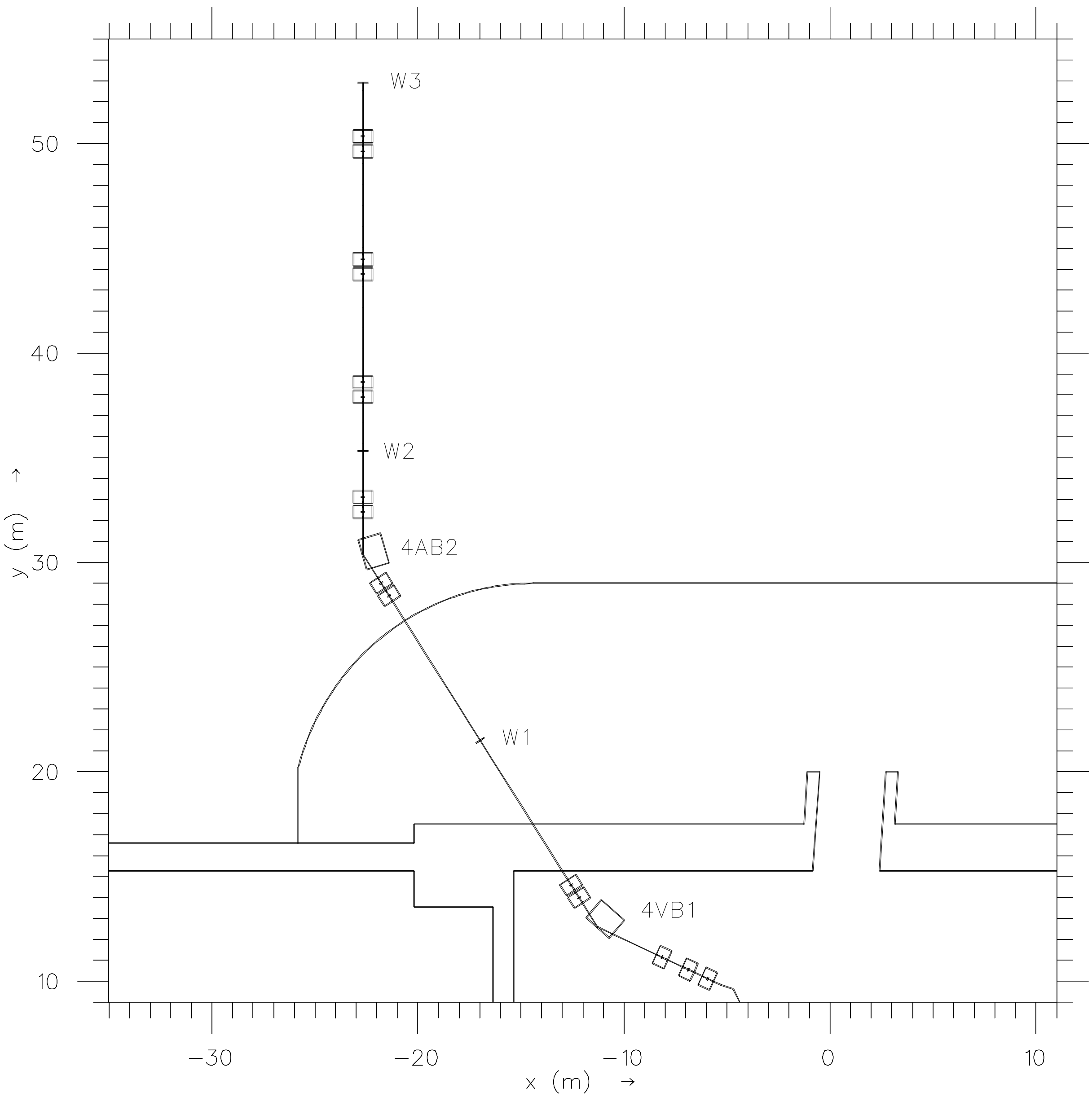

Fig. 4. A variation of beamline 4P that uses a six-quadrupole unit section.

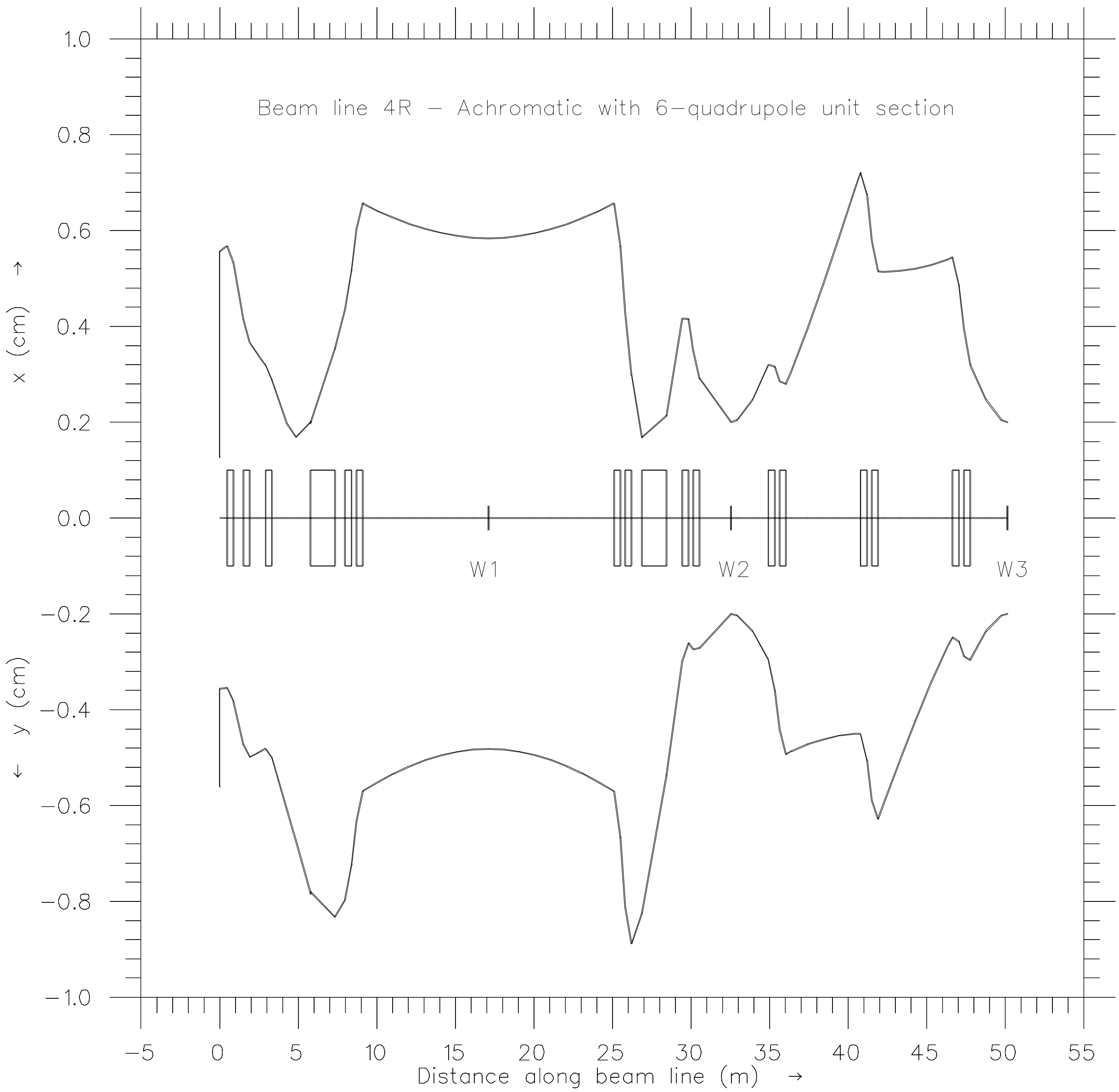

Fig. 5. Beam profiles along the line 4P that uses a six-quadrupole unit section.

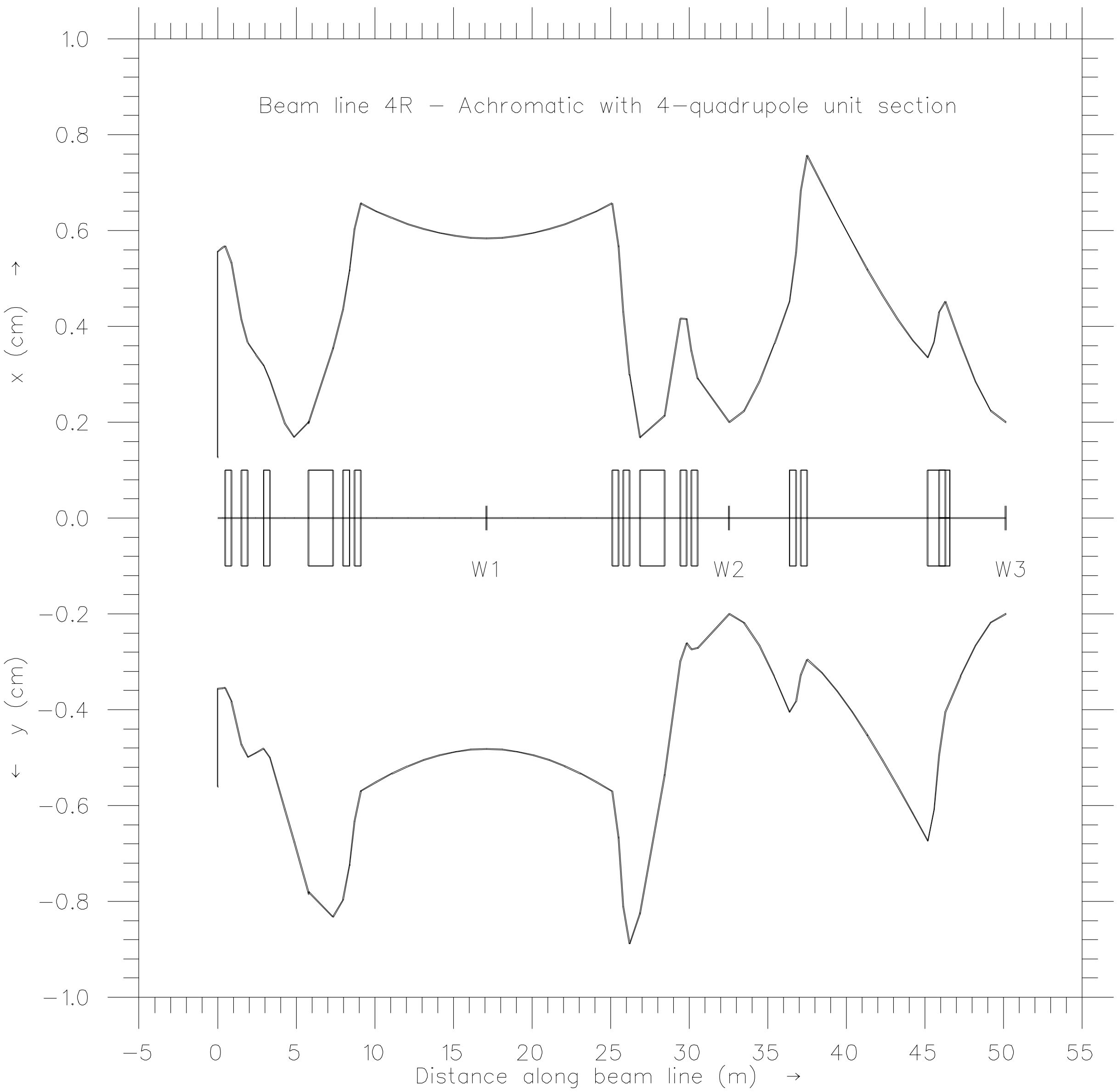

Fig. 6. Beam profiles along the line 4P that uses a four-quadrupole unit section.

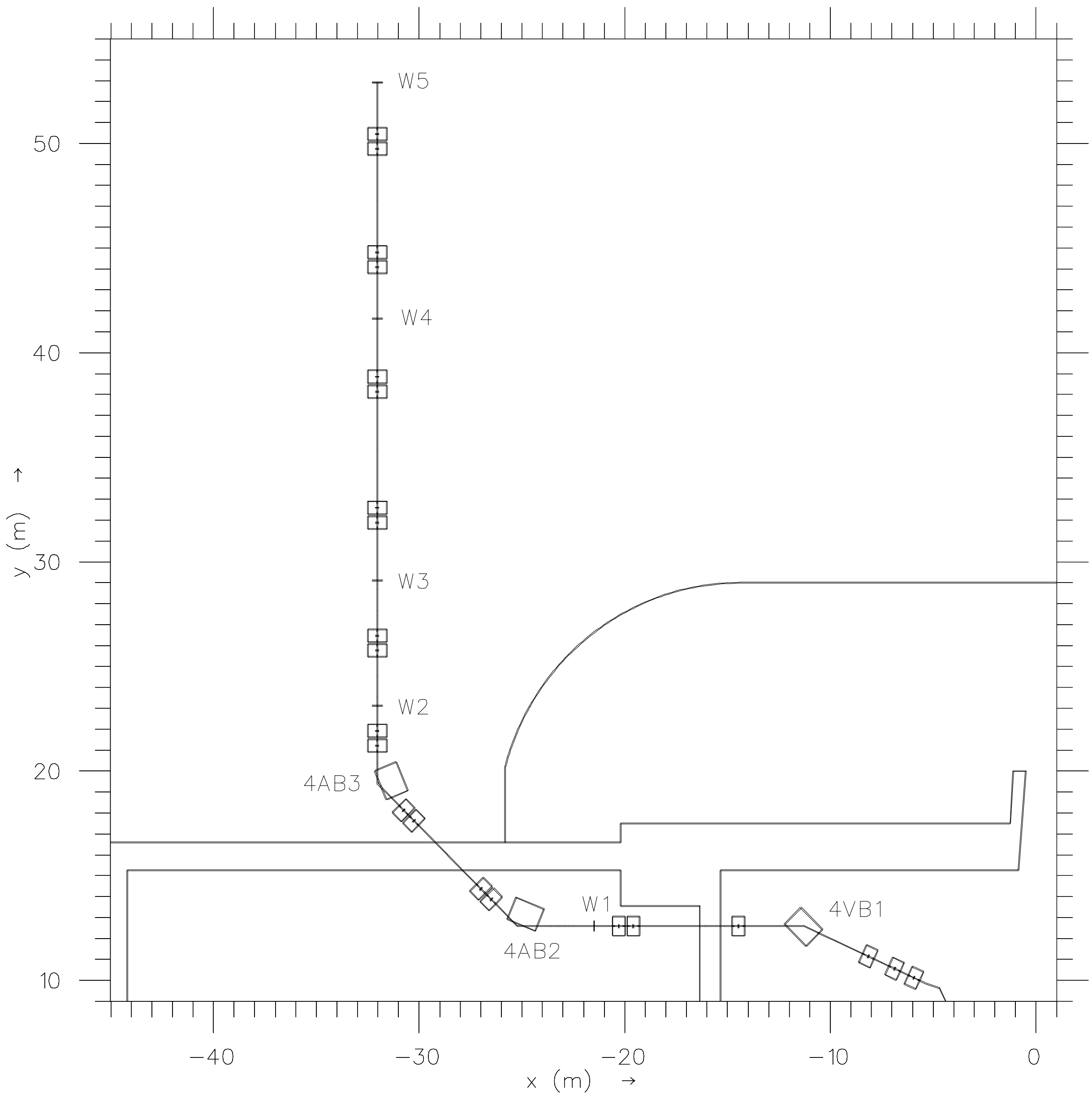

Fig. 7. Details of beamline 4PR.

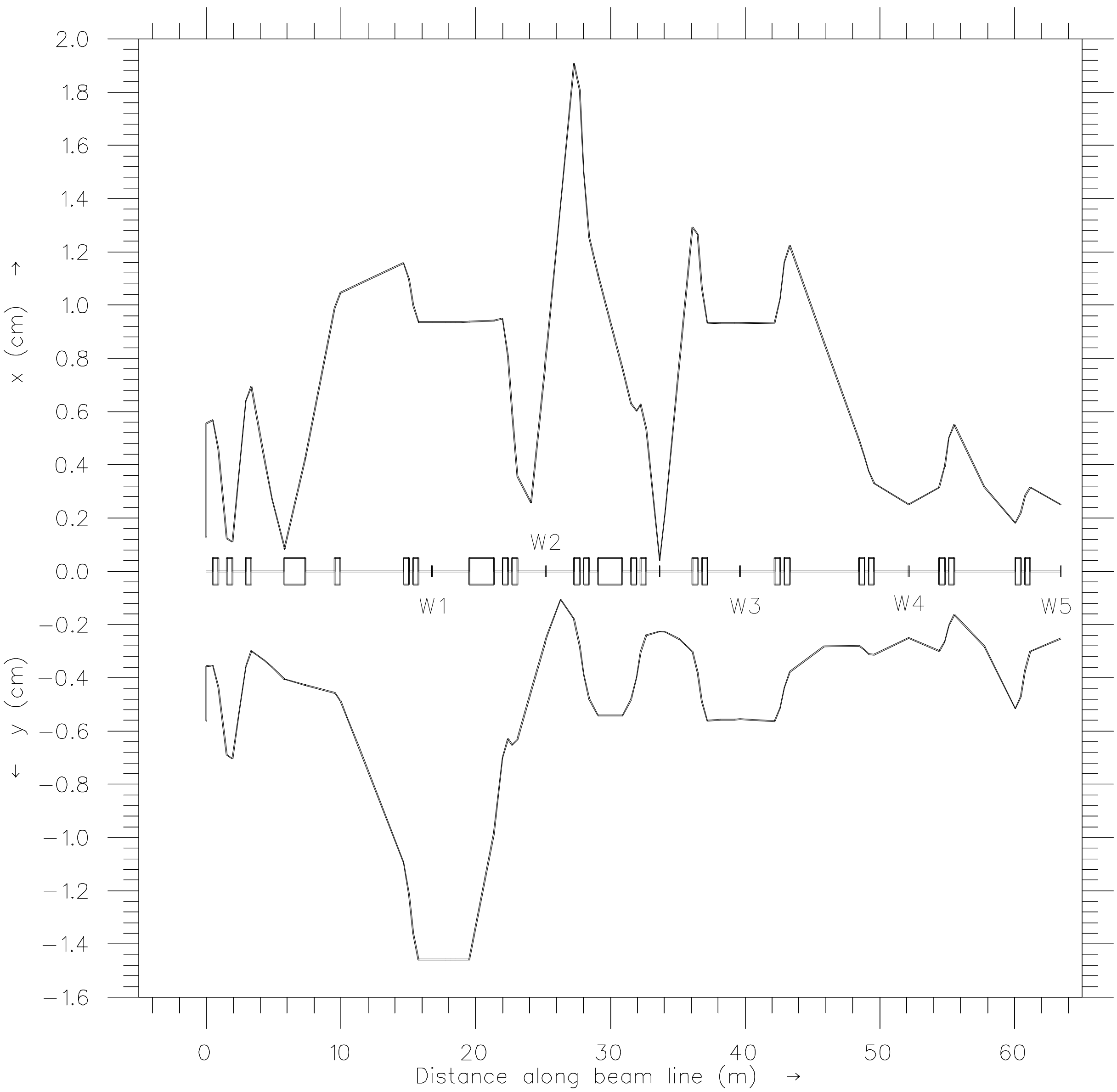

Fig. 8. Beam profiles along beamline 4PR.

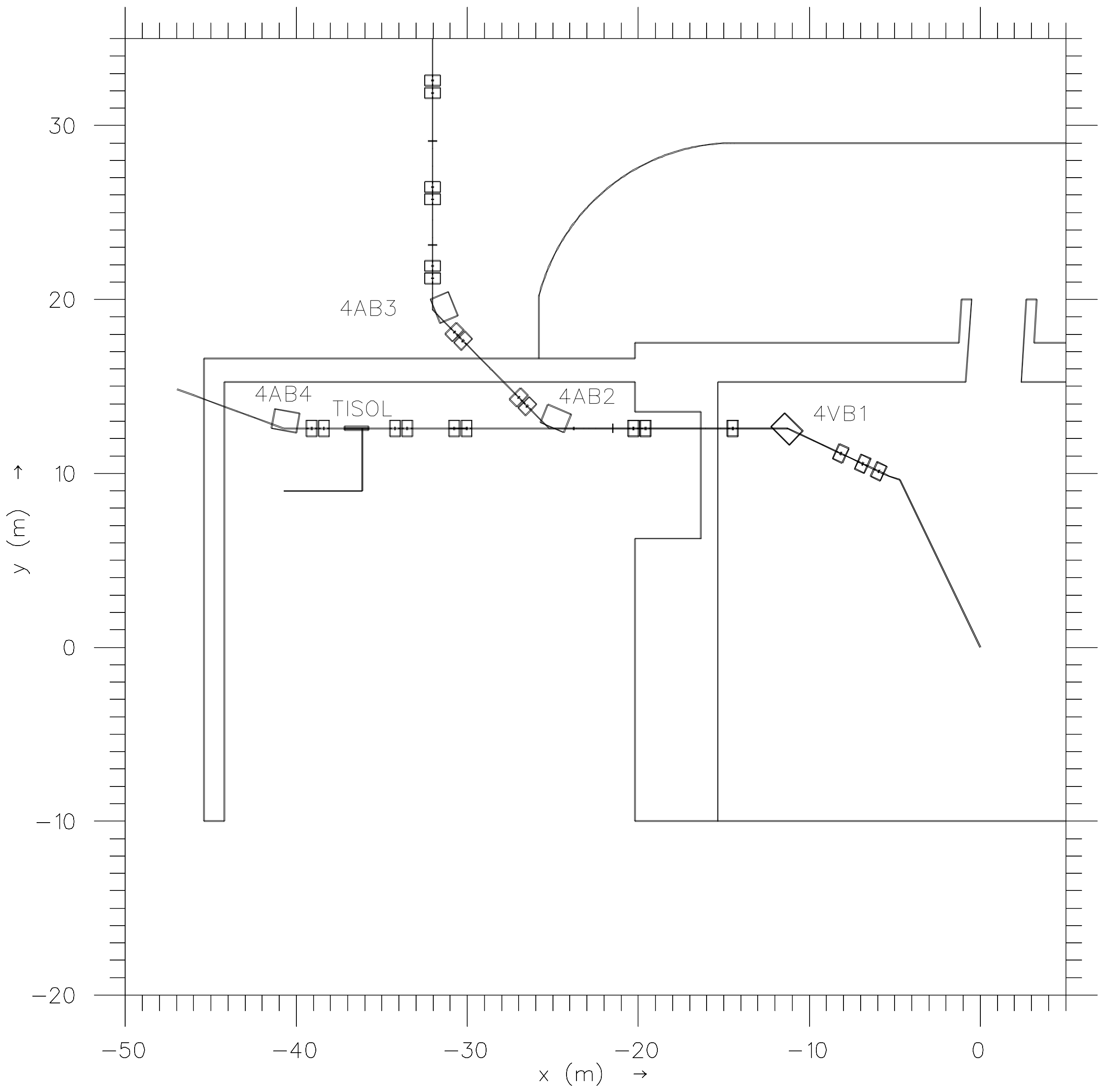

Fig. 9. Details of beam delivery to TISOL with beamline 4PR.

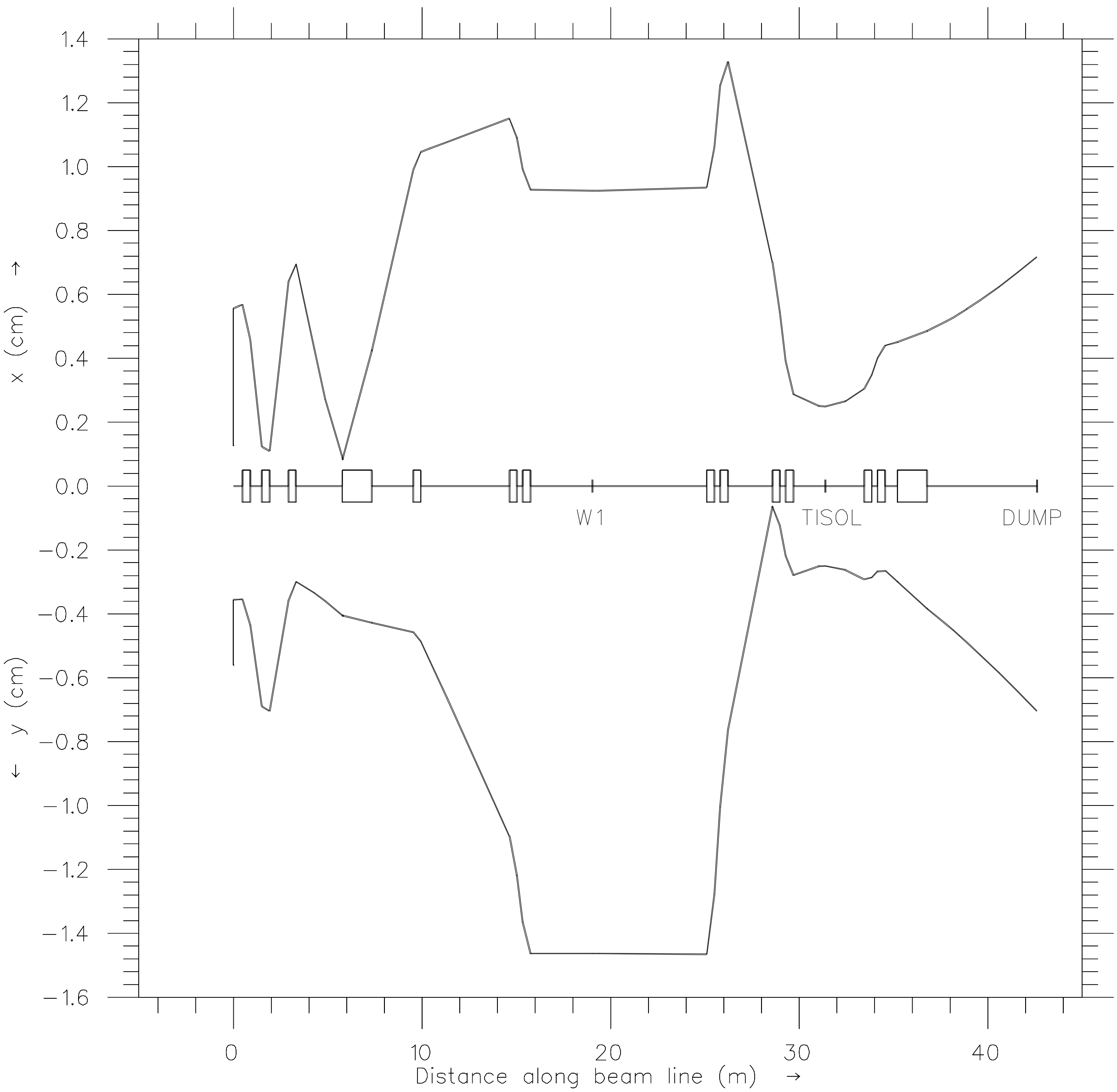

Fig. 10. Beam profiles for beam delivery to TISOL with beamline 4PR.

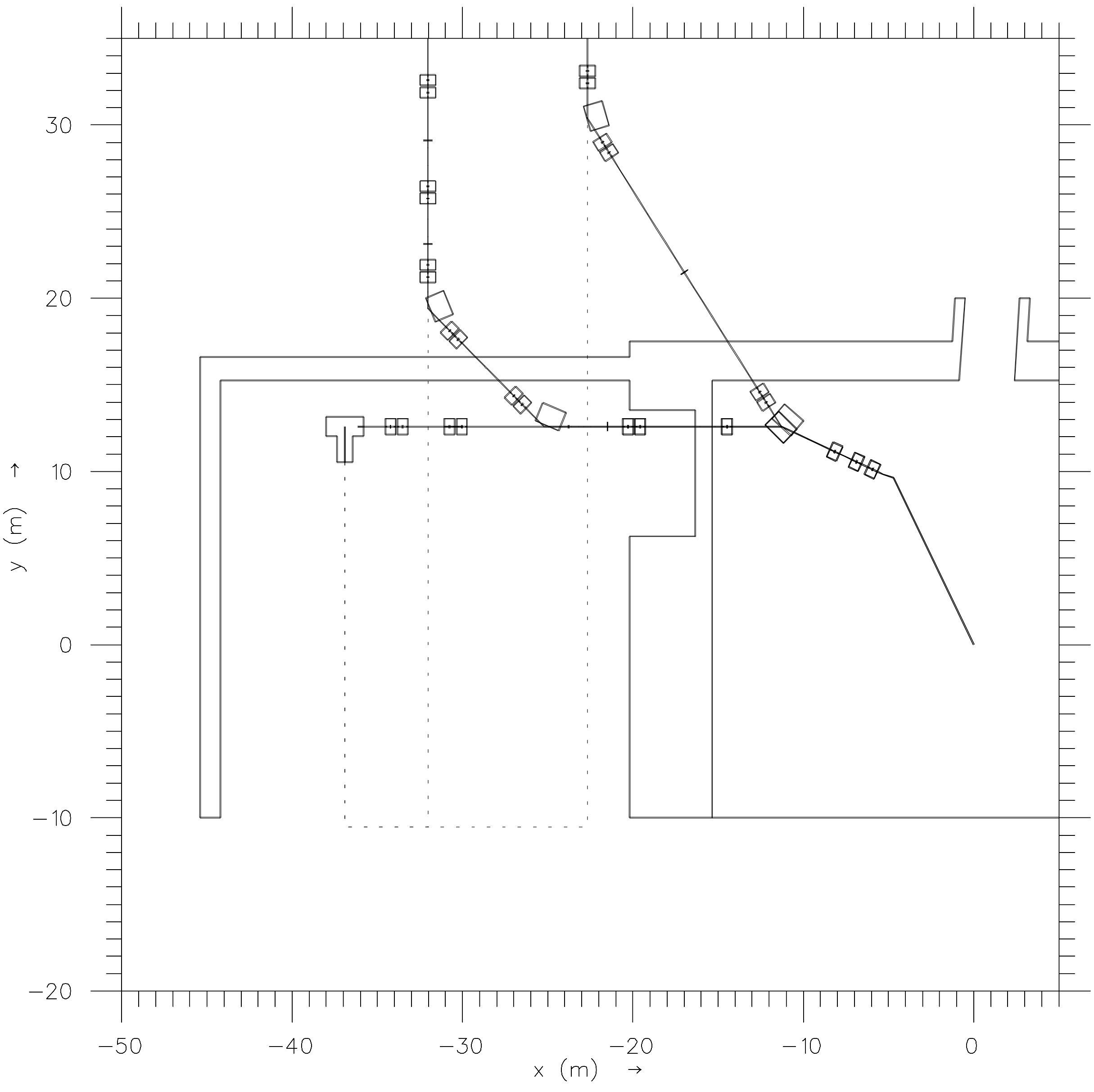

Fig. 11. Speculation of beam delivery to a small cyclotron located in the Proton Hall.