# APPLICATIONS OF BEAM-LINE SIMULATORS

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**Abstract**
At TRIUMF's smaller cyclotrons, help was needed with tuning, training and solving beam-line problems. The use of a beam-line simulator program was investigated at this facility that has a high demand on isotope production. Could it help with operator training? Could it be used to solve problems with beam line tuning and/or beam-line optics? Some of these challenging problems will be discussed and it will be shown how one beam-line was modified using the analysis of such programs.

## 1.      INTRODUCTION

This paper discusses how a user-friendly beam-line simulator program was used at TRIUMF to assist with the operation of an isotope-production cyclotron. Such a program has been used not only as an aid in routine beam-line tuning but in the solution of beam transport difficulties as well. It has also proven to be an excellent teaching aid for new operators.

About 11 years ago when the TR30 cyclotron was commissioned, it was capable of extracting about 700 μA of protons split between two beam lines of which about 500 μA was transmitted to two targets. Five years or so later the machine received an upgrade which enabled it to extract about 1 mA of protons. On a good day it could be pushed as high as 1.2 mA. The beam transport system was well designed for the 350 μA beams, but the increased capability pushed it to its limits. A beam-line simulator program [1] was used to help with finding beam tunes at these higher currents while keeping beam spills to a minimum.

## 2.      STUDY OF A BEAM LINE OF A SMALL CYCLOTRON

### 2.1    Definition of a real-life problem

The TR30 is a 30 MeV H- cyclotron used for the commercial production of isotopes. It is capable of producing a 1 mA proton beam that is divided between 2 beam lines. Prior to February 1999, a 450 μA beam was routinely extracted into each beam line, of which 350 μA reached each target. Thus about 100 μA was being spilled on each beam line. Further, to increase isotope production, it was desired to double the current to a target half the size of the existing one. Given that 100 μA of beam were lost now, the challenge was to find how the current to a smaller target could be doubled and the beam spill reduced simultaneously.

For about two weeks, various operators tried to tune the beam manually but given the limited diagnostics and other limitations of the system it was found that it could not be done easily. Eventually, a beam tune was found but the beam spills were high and they worsened quickly as the extraction foil started to wear.

A computer in the control room had an easy to use graphical program [1] that was already set up for the beam line in question. That is to say, the extraction parameters and relevant beam-transport element data had already been entered. It was decided to put the beam-line tuning parameters into it, in an attempt to understand what was happening and possibly, to find a way of reducing the beam spills in the beam line.

The configuration of the beam line is shown schematically in Fig. 1.
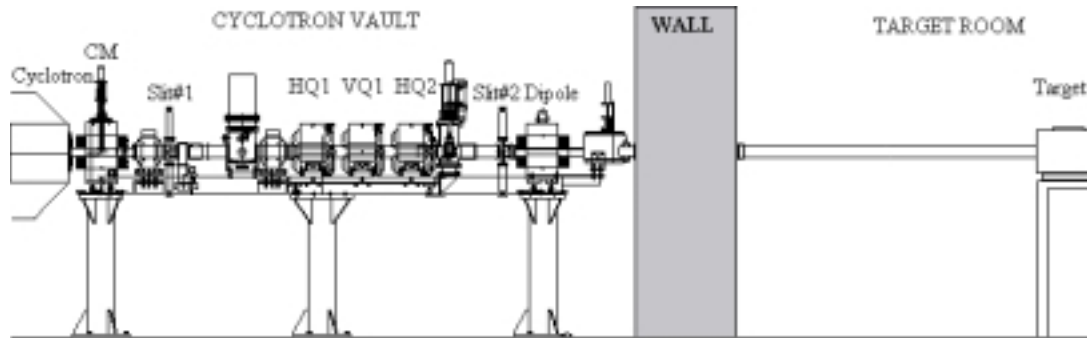


**Fig. 1:** A schematic of the existing beam line

In this beam line, the quadrupoles are equally spaced and are arranged in a horizontal-vertical-horizontal (HVH) configuration. Horizontal and vertical slits (Slit #2) are located at the exit of the quadrupole triplet. When the simulator program was run with the appropriate data of this beam line, it immediately became apparent that the horizontal beam envelope was too large at the location of these slits. This is shown in Fig. 2A, a plot generated by the program of the beam envelope in the horizontal plane. The vertical plane is shown in Fig. 2B from which it is clear that there is no vertical problem. For completeness, Fig. 2C shows the size of the beam spot predicted relative to the target (represented by the rectangle) in the existing configuration. The target shown is one-half the size of the original target. The remaining figures are discussed later.

On the existing beam line this resulted in large spills (10 to 20 μA) at the slits. In fact, the beam line was noticeably more radioactive there and frequent O-ring failures occurred because of radiation damage.

Using the simulator, the beam envelope was narrowed at the slits by increasing the field of the first quadrupole. However, although the beam envelope down stream of the triplet was narrowed, the horizontal beam width at the target was increased. This was confirmed when the tuning parameters were changed the same way on the real beam line.
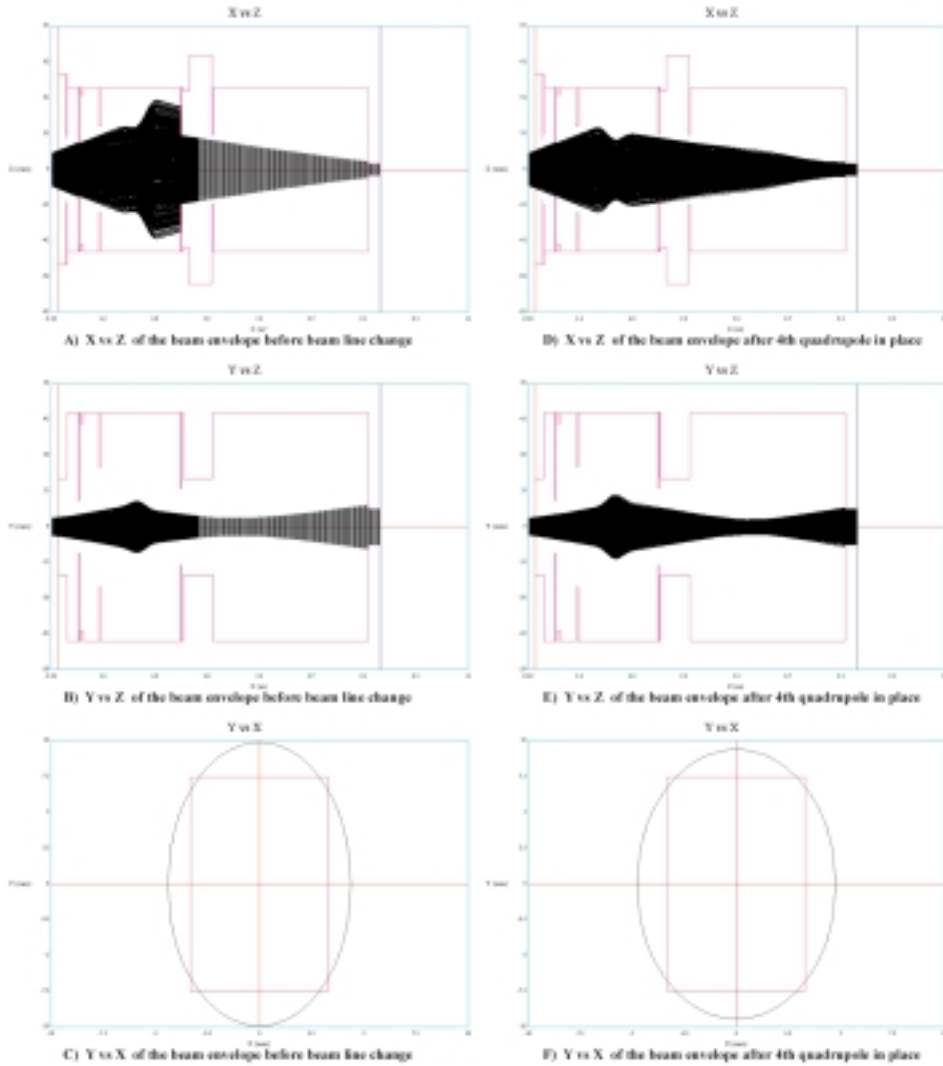
**Fig. 2:** Calculated beam envelopes. A) Shows the beam being collimated horizontally within the beam line with a high level of spills on the slits. D) Represents the changes after the beam line was modified by adding the fourth quadrupole. Relative to A, the spills are reduced to a negligible levels. B, C, E and F show that overall the beam shape was maintained at the target.

## 2.2    Solution of the problem

Confidence in the program increased as it was confirmed, by using the program, that a problem existed and that the beam envelope behaved as predicted. It was decided to vary several parameters with the program that would not be so easy to change in practice. For example, different positions of the quadrupoles and different polarities could be tested in the simulator.

As noted above, the three quadrupoles operate in an HVH configuration. Using the program, the polarities were changed from HVH to VHV and it was quickly found that that would not help. Then the distance between the second quadrupole and the last was increased and again, it was found not to help.

Finally, an extra quadrupole was added. This had been discussed a few years ago as a possible beam-line optimization but was not needed then because the extracted current was lower and the target was larger. After many variations of the positions and polarities of the quadrupoles, the most effective model was found. It was to leave the first three quadrupoles in their initial locations and to add a fourth

in the target room as shown in Fig. 3. It was now possible to make the beam profile smaller than the target aperture. This was good because it allowed an operating margin when the extraction foil starts to deteriorate. In Fig. 2 the beam is tuned to create the same spread at the target, while reducing spills upstream. Figure 2D indicates smaller beam horizontally, 2E shows there was no change in the vertical beam profile and 2F shows the beam shape on target was maintained.

For completeness, Table 1 shows (some of) the various beam-line configurations modeled with the program. It shows the sequence of quadrupoles, i.e. HVH space H, and the distances to various beam-line magnets. The highlighted row yielded the best solution and required minimal change to the existing beam line.

**Table 1:** TR30 Beam line structure analysis

| Beam line Configuration | Combination Magnet | Drift Length | Quadrupole | Drift Length | Quadrupole | Drift Length | Quadrupole | Drift Length | Quadrupole or Dipole | Drift Length | Quadrupole or Dipole | Drift Length |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| HVH-H | CM | 1119 | Horizontal | 139.8 | Vertical | 139.8 | Horizontal | 706.5 | Vertical | 118 | Dipole | 4796.8 |
| HVHH | CM | 1119 | Horizontal | 139.8 | Vertical | 139.8 | Horizontal | 139.8 | Vertical | 684.7 | Dipole | 4796.8 |
| HVHV | CM | 1119 | Horizontal | 139.8 | Vertical | 139.8 | Horizontal | 139.8 | Vertical | 684.7 | Dipole | 4796.8 |
| VHVH | CM | 1119 | Vertical | 139.8 | Horizontal | 139.8 | Vertical | 139.8 | Horizontal | 684.7 | Dipole | 4796.8 |
| -VHVH | CM | 1427 | Vertical | 139.8 | Horizontal | 139.8 | Vertical | 139.8 | Horizontal | 379.7 | Dipole | 4796.8 |
| -HVHV | CM | 1427 | Horizontal | 139.8 | Vertical | 139.8 | Horizontal | 139.8 | Vertical | 379.7 | Dipole | 4796.8 |
| HVH-l-H | CM | 1427 | Horizontal | 139.8 | Vertical | 139.8 | Horizontal | 776.7 | Dipole | 2500 | Horizontal | 2036.8 |
| **HVH-l-H** | **CM** | **1427** | **Horizontal** | **139.8** | **Vertical** | **139.8** | **Horizontal** | **776.7** | **Dipole** | **2268.4** | **Horizontal** | **2268.4** |
| HVH-l-H | CM | 1427 | Horizontal | 139.8 | Vertical | 139.8 | Horizontal | 776.7 | Dipole | 900 | Horizontal | 3636.8 |
| HV-HV | CM | 1119 | Horizontal | 139.8 | Vertical | 305 | Horizontal | 139.8 | Vertical | 379.7 | Dipole | 4796.8 |
| VH-VH | CM | 1119 | Vertical | 139.8 | Horizontal | 305 | Vertical | 139.8 | Horizontal | 379.7 | Dipole | 4796.8 |

Fortunately, a quadrupole with the correct effective length and bore diameter was available at TRIUMF. The solution was also tested on a different simulator program [2] and similar results were obtained.

This solution, the addition of another quadrupole downstream of the existing dipole, was presented to the administration who decided to adopt it.
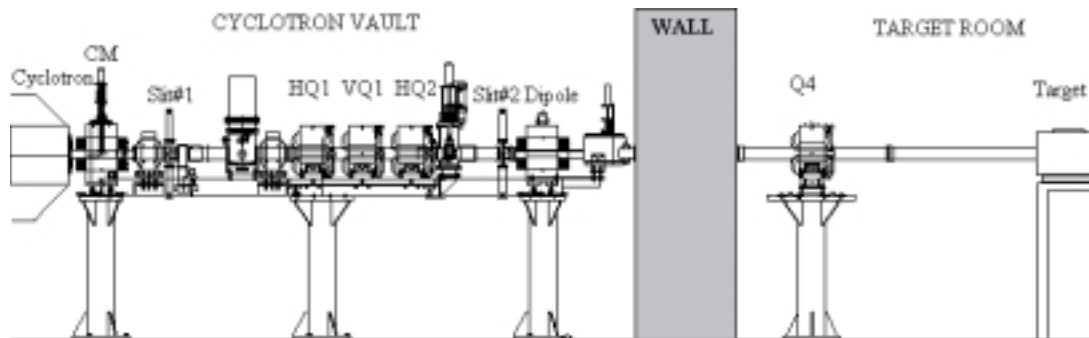


**Fig. 3:** A schematic of the existing beam line

## 2.3 Final results with the above solution

After the fourth quadrupole was installed, tests were run with the beam on target to commission the new beam-line configuration.

Table 2 shows one example of several tests, which demonstrated good agreement of the predicted beam shape with what was attained. The total beam extracted for this test was 266.5 µA

**Table 1:** Predicted result versus actual

| Total System Loss: | Predicted | Actual |
|---|---|---|
| | 32.60% | 28.70% |
| **Combination Baffle** | | |
| Left Collimator: | 0.00 µA | 0.15 µA |
| Right Collimator: | 0.00 µA | 2.47 µA |
| **Protection Slit #1** | | |
| Top Collimator: | 0.00 µA | 0.07 µA |
| Bottom Collimator: | 0.00 µA | 0.46 µA |
| Left Collimator: | 0.53 µA | 2.90 µA |
| Right Collimator: | 0.79 µA | 2.73 µA |
| **Protection Slit #2** | | |
| Top Collimator: | 0.00 µA | 0.15 µA |
| Bottom Collimator: | 0.00 µA | 2.37 µA |
| Left Collimator: | 0.00 µA | 0.00 µA |
| Right Collimator: | 0.00 µA | 0.10 µA |
| **Bender Baffle** | | |
| Collimator: | 0.00 µA | 0.10 µA |
| **Target Collimators** | | |
| Top Collimator: | 21.59 µA | 14.0 µA |
| Bottom Collimator: | 23.18 µA | 13.0 µA |
| Left Collimator: | 19.72 µA | 19.0 µA |
| Right Collimator: | 21.05 µA | 19.0 µA |
| **Total Beam Loss** | 86.88 µA | 76.5 µA |
| **Beam Hitting Target** | 179.62 µA | 190 µA |
| **Total Beam Extracted** | 266.5 µA | 266.5 µA |

## 3. USEFULNESS OF BEAM-LINE SIMULATOR AS A TUNING AID

### 3.1 To refine and improve a beam-line tune

Suppose it is desired to increase the target current on one of the beam lines. Without a simulator one would start by entering the parameters for a standard tune. Based on their experience and knowledge, the operators would then try to adjust the field strengths of the quadrupoles. In practice it was found that the results varied considerably depending on the skills of the operators.

Using a beam-line simulator program an operator can see immediately the effect of various quadrupoles settings. This would help them to know which way to vary the parameters.

Consider for example, the situation shown in Fig. 4. Figure 4A shows the beam profile in the horizontal plane of an existing beam line. Clearly, there is beam spill on some slits. The beam profile in the vertical plane, shown in Fig. 4B, shows no such spill. With the use of a beam-simulator program, an operator has obtained the horizontal and vertical beam profiles shown in Figs. 4C and 4D. It is apparent that the beam spill in the horizontal plane has been reduced without causing spill in the vertical plane.

Thus, with the use of a simulator program, an operator has achieved a solution to a beam-spill problem without doing any 'knobbing around' on a real machine. It immediately becomes apparent to the operator what is really happening when settings are changed on the beam line. This is a safer, as well as a faster, way of finding a means to an end.
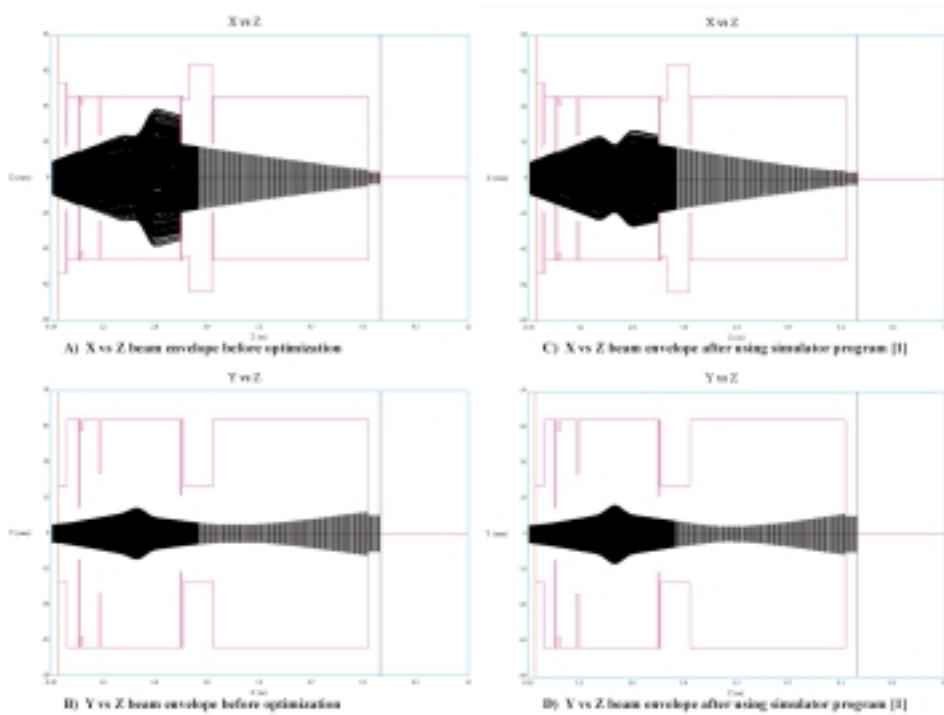
**Fig. 4:** The beam envelopes before and after 'tuning' with the simulator program. A) Shows the beam being collimated horizontally within the beam line with a high level of spills on the collimators. C) Represents the changes in the beam envelope after changing the parameters in the beam-line simulator program. B) and D) show that the beam shape was maintained for the target in vertical plane.

In this example, a relatively simple beam line with only three quadrupoles was discussed. Imagine the complexities that would arise in a beam line that has many quadrupoles, or many types of targets, or if tuning for different energies was required. In each case, the parameters could be tried on a beam-line simulator.

## 3.2    To obtain a new tune

A new tune can be found with much less frustration. Once an optimum tune is found on the simulator, it should be producible on the real machine. The simulator would no longer be needed after a working tune has been established, but it could still be used as a teaching tool.

## 3.3    As a teaching aid

All that has been discussed above can equally well be used to teach new operators the basic concepts of beam dynamics. For example, they could be instructed in:

- beam envelope or multi-particles diagrams.
- collimation.
- quadrupole tuning and how it affects the beam envelope.
- effects of different energies.
- how positioning of elements affects beam size and loss.

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### 3.4 As an aid in visualizing beam shape

Before we had the beam-line simulator program, we tried to explain how to focus the beam with a quadrupole. We told the operator to imagine that the beam was like a balloon, and the quadrupole was squeezing it in only one direction at a time. For example, when the balloon was squeezed horizontally it would blow up vertically and vice versa. This can be easily demonstrated with the beam-line simulator. As each quadrupole is adjusted the operator can see the effect on the beam envelope.

## 4.   CONCLUSION

The usefulness of a beam-line simulator has been demonstrated in one operating group at TRIUMF. Of course, the simulation is only as good as the model being used. That is, the properties of the extracted beam and all of the beam-line elements must be well known. It is necessary to know accurately:

- the parameters of the extracted beam (emittance, horizontal and vertical sizes and divergences, and momentum spread).
- the effective lengths of all elements.
- the relative positions of the elements.

It is the author's opinion that a user-friendly, graphical program of this kind is not only useful but is essential for any accelerator control room.

## 5.   ACKNOWLEDGEMENTS

### References

[1]    Beamline Simulator version 1.3c. Dehnel Consulting Ltd. WWW.DEHNEL.COM.

[2]    INTRAN, TRIUMF report TRI-CD-96-xx TRIUMF 1996. Publication is available at WWW.TRIUMF.CA/INTRAN/INTRAN.PS.