## TRIUMF 300 keV Vertical Injection Line



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## As built (1974~2011)



- HV1: up to $1 \mathrm{~mA} \mathrm{H}^{-}$.
- HV2 and HV3 decommissioned,
- Chopper not useful at $>10 \mu \mathrm{~A}$.
- 13 m vertical section needs replacing.


## Some Particulars

1. All electrostatic; 100s of delicate, uncooled electrodes.
2. Typically, $300-400 \mu \mathrm{~A}$, or $\sim 100$ Watts of beam; can easily melt a quadrupole (which, after all, is just 4 small pieces of aluminum extrusion).
3. $\mathrm{H}^{-}$, so vacuum must be better than $10^{-7}\left(f_{\text {lost }}=P /\left(2 \times 10^{-5}\right.\right.$ Torr $\left.)\right)$. Even so, it easily sheds electrons and these are electrically indistinguishable from beam particles, confusing the diagnostics.
4. Large energy spread from bunchers, so beamline must be achromatic. (DC beam is bunched to a peak of $\sim 5 \mathrm{~mA}$.)
5. Space charge dominated at typical high intensity operation: 5 mA peak means space charge forces are larger than average quadrupole focusing force.
6. But the space charge force is intrisically nonlinear, generating beam "halo".
7. Centre of cyclotron field is 3 kG : almost the whole vertical line can be thought of as in the fringing field of a (poorly designed) solenoid: strong coupling between transverse planes.
8. Beam is injected into the spiral inflector: possibly the most optically complicated element ever devised. (Also insulated, uncooled, can melt.)
9. Must (try to) match to the first turn of the cyclotron where essentially all vertical focusing comes from RF: tail of the bunch is much more strongly focused than the head. Space charge defocusing causes progressive loss of the head.
10. Old line took $\sim 5$ years before $100 \mu \mathrm{~A}$ cyclotron running was routine.

## Why a New Vertical Section?

- Insulators dirty, shorting. Had to ground some electrodes.
- Vacuum bad, somewhat leaky (o-rings). $>1 \%$ loss but prefer $\sim 0.1 \%$.
- Very poor alignment making quads very difficult to tune.
- Insufficient diagnostics (no BPMs).
- In spite of much effort, optics never understood, polarities doubtful.

So in 2011 replaced the whole 13 metre section. Complete re-design of optics. (But how?)

## Beam Dynamics Complexity

1. Intense 3D space charge (up to 5 mA peak at 300 keV )
2. Bunching into a $36^{\circ}$ phase acceptance (roughly 30 mm long bunch)
3. Strong $x-y$ coupling due to cyclotron's axial field
4. Strong and complicated $x-y-z$ coupling in the inflector.
5. Vertical acceptance depends upon particle's phase because all focusing comes from RF on first few turns.
6. Cannot match, even in principle, so what now? How to optimize?.

In spite of this, we successfully designed, built, commissioned a totally new section without using multi-particle simulations. Used only the statistical approach sometimes called "envelope equation".

## Review of Statistical Approach

If there is a distribution of particles, one would like to calculate the final distribution from the initial. The behaviour of the beam centroid

$$
\begin{equation*}
\langle\mathbf{X}\rangle=\sum_{i=1}^{N} \mathbf{X} / N \tag{1}
\end{equation*}
$$

(where $N$ is the number of particles, and $\mathbf{X}$ is the column vector $\left(x, P_{x}, y, P_{y}, z, P_{z}\right)^{T}$ as in eqn. 11) is determined by the same transfer matrix M as for an individual particle. This is the equation of 'first moments'. At the next level, one would like to calculate the evolution of the beam widths, or, 'second moments' given by

$$
\begin{equation*}
\boldsymbol{\sigma} \equiv \frac{1}{N} \sum_{i=1}^{N} \mathbf{X X}^{T} \tag{2}
\end{equation*}
$$

For example, $\sigma_{11}=\left\langle x^{2}\right\rangle, \sigma_{12}=\left\langle x P_{x}\right\rangle, \sigma_{13}=\langle x y\rangle, \ldots$. For a distribution of particles so dense that we do not see graininess on any scale of our diagnostics, the sums go over into
integrals. For example,

$$
\sigma_{12}=\iiint \iiint x P_{x} f\left(x, P_{x}, y, P_{y}, z, P_{z}\right) d x d P_{x} d y d P_{y} d z d P_{z}
$$

where $f$ is the distribution in phase space, normalized so that its integral over all 6 phase space dimensions is 1 .

By direct substitution into the definition of $\sigma$, we find

$$
\begin{equation*}
\boldsymbol{\sigma}_{\mathrm{f}}=\mathbf{M} \boldsymbol{\sigma}_{\mathrm{i}} \mathbf{M}^{T} \tag{3}
\end{equation*}
$$

As well, recalling the infinitesimal transfer matrix $\mathbf{F}$ where $\mathbf{X}^{\prime}=\mathbf{F X}$ and the transfer matrix of an infinitesimal length $d s$ is $\mathbf{M}=\mathbf{I}+\mathbf{F} d s$, we find directly

$$
\begin{equation*}
\boldsymbol{\sigma}^{\prime}=\mathbf{F} \boldsymbol{\sigma}+\boldsymbol{\sigma} \mathbf{F}^{T} \tag{4}
\end{equation*}
$$

This is the envelope equation. Elaborated for the case with space charge, DC, uncoupled, it becomes the Kapchinsky-Vladimirsky eqns.

## Digression: Envelope equation

A particular case is where the beamline consists only of elements that keep all 3 degrees of freedom independent of each other, and there is only a focusing force $K(s)$ that varies with $s$. In other words, the Hamiltonian is $P^{2} / 2+K(s) x^{2} / 2$, so

$$
\mathbf{F}=\left(\begin{array}{cc}
0 & 1  \tag{5}\\
-K & 0
\end{array}\right)
$$

Plugging into 4, we have

$$
\left(\begin{array}{ll}
\sigma_{11}^{\prime} & \sigma_{12}^{\prime}  \tag{6}\\
\sigma_{12}^{\prime} & \sigma_{22}^{\prime}
\end{array}\right)=\left(\begin{array}{cc}
2 \sigma_{12} & \sigma_{22}-K \sigma_{11} \\
\sigma_{22}-K \sigma_{11} & -2 K \sigma_{12}
\end{array}\right)
$$

or, combining some,

$$
\begin{equation*}
\sigma_{11}^{\prime \prime}=2 \sigma_{12}^{\prime}=2 \sigma_{22}-2 K \sigma_{11} \tag{7}
\end{equation*}
$$

Knowing that the emittance $\epsilon$ is constant, and is given by the determinant

$$
\begin{equation*}
\epsilon^{2}=\sigma_{11} \sigma_{22}-\sigma_{12}^{2} \tag{8}
\end{equation*}
$$

we can eliminate $\sigma_{22}$ :

$$
\begin{equation*}
\sigma_{11}^{\prime \prime}=2\left(\epsilon^{2}+\sigma_{12}^{2}\right) / \sigma_{11}-2 K \sigma_{11} \tag{9}
\end{equation*}
$$

Now introduce the RMS size as $\tilde{x}=\sqrt{\sigma_{11}}$. Then $\sigma_{11}^{\prime}=2 \tilde{x} \tilde{x}^{\prime}$ so $\sigma_{12}=\tilde{x} \tilde{x}^{\prime}$ and $\sigma_{11}^{\prime \prime}=2 \tilde{x} \tilde{x}^{\prime \prime}+2 \tilde{x}^{\prime 2}$. Putting this all together, we get

$$
\begin{equation*}
\tilde{x}^{\prime \prime}+K \tilde{x}-\frac{\epsilon^{2}}{\tilde{x}^{3}}=0 \tag{10}
\end{equation*}
$$

This is the envelope eqn; looks like the single particle equation except for the emittance term. (Remember: $\tilde{x}$ is the beam size, not the particle coordinate.)

## TRANSPORT $\rightarrow$ TRANSOPTR

If all elements are integrable then the transfer matrices M are known, and they are simply multiplied together to find the matrix of the whole beamline or synchrotron, and the final beam is found from the initial as in 3 . This is the traditional approach, e.g. TRANSPORT.

If not, as in the case of space charge, 4 is solved with a Runge Kutta integrator. This is what is done in TRANSOPTR. This allows calculation in the general case, e.g. varying axial fields, linacs, 3D space charge...

## Infinitesimal Transfer Matrix

The general Hamiltonian can be Taylor-expanded by orders in the 6 dependent variables ${ }^{1}$,

$$
H\left(x_{1}, x_{2}, x_{3}, x_{4}, x_{5}, x_{6} ; s\right)=\left.\sum_{i} \frac{\partial H}{\partial x_{i}}\right|_{0} x_{i}+\left.\frac{1}{2} \sum_{i, j} \frac{\partial^{2} H}{\partial x_{i} \partial x_{j}}\right|_{0} x_{i} x_{j}+\ldots
$$

The subscript 0 means that the derivatives are evaluated on the reference trajectory $\forall i, x_{i}=0$. (Keep in mind though that these partial derivatives in general are functions of the independent variable $t$ or $s$.)

Terms of first order are eliminated by transforming to a coordinate system measured with respect to the reference trajectory. The remaining terms are second order and higher, and for linear motion, we simply truncate at the second order.

[^0]Then the Hamiltonian looks like $H=A x^{2}+B x P_{x}+C x y+\ldots+U P_{z}^{2}$ : there are 21 independent terms. $A=\frac{1}{2} \frac{\partial^{2} H}{\partial x^{2}}$, and so on; all derivatives are evaluated on the reference trajectory, and may be a function of the independent variable. We know the equations of motion from the Hamiltonian to be: $x^{\prime}=\partial H / \partial P_{x}, P_{x}^{\prime}=-\partial H / \partial x$, etc., where primes denote derivatives w.r.t. the independent variable. Therefore the equations of motion can be summarized by

$$
\left(\begin{array}{c}
x^{\prime}  \tag{11}\\
P_{x}^{\prime} \\
y^{\prime} \\
P_{y}^{\prime} \\
z^{\prime} \\
P_{z}^{\prime}
\end{array}\right)=\left(\begin{array}{cccccc}
\frac{\partial^{2} H}{\partial P_{x} \partial x} & \frac{\partial^{2} H}{\partial P_{x}^{2}} & \frac{\partial^{2} H}{\partial P_{x} \partial y} & \frac{\partial^{2} H}{\partial P_{x} \partial P_{y}} & \frac{\partial^{2} H}{\partial P_{x} \partial z} & \frac{\partial^{2} H}{\partial P_{x} \partial P_{z}} \\
-\frac{\partial^{2} H}{\partial x^{2}} & -\frac{\partial^{2} H}{\partial x \partial P_{x}} & -\frac{\partial^{2} H}{\partial x \partial y} & -\frac{\partial^{2} H}{\partial x \partial P_{y}} & -\frac{\partial^{2} H}{\partial x \partial z} & -\frac{\partial^{2} H}{\partial x \partial P_{z}} \\
\frac{\partial^{2} H}{\partial P_{y} \partial x} & \frac{\partial^{2} H}{\partial P_{y} \partial P_{x}} & \frac{\partial^{2} H}{\partial P_{y} \partial y} & \frac{\partial^{2} H}{\partial P_{y}^{2}} & \frac{\partial^{2} H}{\partial P_{y} \partial z} & \frac{\partial^{2} H}{\partial P_{y} \partial P_{z}} \\
-\frac{\partial^{2} H}{\partial y \partial x} & -\frac{\partial^{2} H}{\partial y \partial P_{x}} & -\frac{\partial^{2} H}{\partial y^{2}} & -\frac{\partial^{2} H}{\partial y \partial P_{y}} & -\frac{\partial^{2} H}{\partial y \partial z} & -\frac{\partial^{2} H}{\partial y \partial P_{z}} \\
\frac{\partial^{2} H}{\partial P_{z} \partial x} & \frac{\partial^{2} H}{\partial P_{z} \partial P_{x}} & \frac{\partial^{2} H}{\partial P_{z} \partial y} & \frac{\partial^{2} H}{\partial P_{z} \partial P_{y}} & \frac{\partial^{2} H}{\partial P_{z} \partial z} & \frac{\partial^{2} H}{\partial P_{z}^{2}} \\
-\frac{\partial^{2} H}{\partial z \partial x} & -\frac{\partial^{2} H}{\partial z \partial P_{x}} & -\frac{\partial^{2} H}{\partial z \partial y} & -\frac{\partial^{2} H}{\partial z \partial P_{y}} & -\frac{\partial^{2} H}{\partial z^{2}} & -\frac{\partial^{2} H}{\partial z \partial P_{z}}
\end{array}\right)\left(\begin{array}{c}
x \\
P_{x} \\
y \\
P_{y} \\
z \\
P_{z}
\end{array}\right)
$$

or, more compactly, $\mathbf{X}^{\prime}=\mathbf{F X}$, where $\mathbf{F}$ is called the 'infinitesimal transfer matrix'. We note that of the 36 elements of $\mathbf{F}$ there are only 21 independent ones.

## 1. Intense 3D Space Charge

The beam is in bunches rather than continuous, so we need the electric field of an ellipsoidal distribution of charge. For this case as well, it turns out, surprisingly (Sacherer, 1971), that the RMS linear part of the space charge self-field depends mainly on the RMS size of the distribution and only very weakly on its exact form. To within a few percent, the RMS linear part of space charge is the same as that for a uniformly populated ellipsoid. The space charge infinitesimal transfer matrix is now

$$
\mathbf{F}_{\mathrm{sc}}=\left(\begin{array}{cccccc}
0 & 0 & 0 & 0 & 0 & 0  \tag{12}\\
K_{x \mathrm{sc}} & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & K_{y \mathrm{sc}} & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & K_{z \mathrm{sc}} & 0
\end{array}\right)
$$

where

$$
\begin{align*}
K_{x \mathrm{sc}} & =\frac{3 Q}{8 \pi \epsilon_{0}\left(m c^{2} / e\right) \beta^{2} \gamma^{3}} \frac{1}{a^{3}} g\left(\frac{b^{2}}{a^{2}}, \frac{c^{2}}{a^{2}}\right)  \tag{13}\\
K_{y \mathrm{sc}} & =\frac{3 Q}{8 \pi \epsilon_{0}\left(m c^{2} / e\right) \beta^{2} \gamma^{3}} \frac{1}{b^{3}} g\left(\frac{c^{2}}{b^{2}}, \frac{a^{2}}{b^{2}}\right)  \tag{14}\\
K_{z \mathrm{sc}} & =\frac{3 Q}{8 \pi \epsilon_{0}\left(m c^{2} / e\right) \beta^{2} \gamma^{3}} \frac{1}{c^{3}} g\left(\frac{a^{2}}{c^{2}}, \frac{b^{2}}{c^{2}}\right) \tag{15}
\end{align*}
$$

where $Q$ is the bunch charge, the ellipsoid semi-axes in the $x, y, z$ directions are $a, b, c$, and the function $g$ is

$$
\begin{equation*}
g(u, v)=\int_{0}^{\infty}(1+s)^{-3 / 2}(u+s)^{-1 / 2}(v+s)^{-1 / 2} d s \tag{16}
\end{equation*}
$$

This is from the family of Carlson elliptic integrals.

## arbitrary bunch shapes

For arbitrary distributions of the type $f(x, y, z)=f\left(\frac{x^{2}}{a^{2}}+\frac{y^{2}}{b^{2}}+\frac{z^{2}}{c^{2}}\right)$, replace $a, b, c$ with the RMS values according to the values they have for the uniform case, namely, $\sqrt{5} \tilde{x}, \sqrt{5} \tilde{y}, \sqrt{5} \tilde{z}$.

For arbitrary orientations, have to apply a rotation matrix to $F$, thus making also $F_{23}, F_{25}, F_{41}, F_{45}, F_{61}, F_{63}$ also non-zero.

For further reading, again refer to Sacherer (1971), but also de Jong (1983).
The above applies in the case of non-relativistic beams, or equivalently, to the reference frame of the bunch. For the case of relativistic bunches, see Baartman (2011).

## 2. Bunching into a $36^{\circ}$ phase acceptance

Ignore the details of 2-harmonic bunching, take only the linear part. I.e. launch the beam at buncher with a negative correlation between phase and energy. $r_{56}=-1, \sqrt{5 \sigma_{55}}=\beta \lambda / 2$, and $\sqrt{5 \sigma_{66}} \propto V_{\text {buncher }}$ optimized to give minimum bunch length at injection gap.


Test calculation of bunching beam in a periodic section. Final bunch is 12 mm dia. by 34 mm long. ( $\beta \lambda=329 \mathrm{~mm}$ at 23 MHz , so this is roughly the $36^{\circ}$ desired.)

## 3. Strong $x-y$ coupling due to axial field



$$
F_{\text {axial } B}=\left(\begin{array}{cccccc}
0 & 1 & \frac{-1}{2 \rho} & 0 & 0 & 0  \tag{17}\\
\frac{-1}{4 \rho^{2}} & 0 & 0 & \frac{-1}{2 \rho} & 0 & 0 \\
\frac{1}{2 \rho} & 0 & 0 & 1 & 0 & 0 \\
0 & \frac{1}{2 \rho} & \frac{-1}{4 \rho^{2}} & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 \\
0 & 0 & 0 & 0 & 0 & 0
\end{array}\right)
$$

which arises from the solenoid Hamiltonian

$$
\begin{equation*}
H_{\mathrm{axial} B}=\frac{1}{2}\left(P_{x}-\frac{y}{2 \rho}\right)^{2}+\frac{1}{2}\left(P_{y}+\frac{x}{2 \rho}\right)^{2}+\frac{1}{2} P_{s}^{2}, \tag{18}
\end{equation*}
$$

where $1 / \rho=B(s) /(B \rho)$, is a function of the independent variable $s$. Interpolate it using cubic spline.

## 4. Strong $x-y-z$ coupling in the inflector

(See A Canonical Treatment of the Spiral Inflector for Cyclotrons Baartman and Kleeven, Part. Acc. 41 (1993).)

$$
\begin{aligned}
& H\left(x, y, z, P_{x}, P_{y}, P_{z} ; s\right)= \\
& \frac{1}{2}\left[\left(P_{x}+\frac{T C}{A} y\right)^{2}+\left(P_{y}-\frac{T C}{A} x\right)^{2}+\left(P_{z}+\frac{2 T S}{A} y+\frac{2}{A} x\right)^{2}\right] \\
& -\frac{1}{2 A^{2}}\left[\xi\left(x+k^{\prime} S y\right)^{2}+x^{2}+k k^{\prime}\left(C^{2} x^{2}+y^{2}\right)+2 T S x y\right]
\end{aligned}
$$

where

$$
\xi=\frac{1+k k^{\prime} S^{2}}{1+k^{\prime 2} S^{2}}, S=\sin (s / A), C=\cos (s / A), T=\frac{k+k^{\prime}}{2}, k=\frac{A}{\rho}+k^{\prime},
$$

$A$ is electric radius, $\rho=\rho(s)$ is magnetic radius, $k^{\prime}$ is tilt parameter.

## inflector matrix

$$
F_{\text {inflector }}=\left(\begin{array}{cccccc}
0 & 1 & \frac{T C}{A} & 0 & 0 & 0  \tag{20}\\
\frac{3-\xi+\left(T^{2}-k k^{\prime}\right) C^{2}}{-A^{2}} & 0 & \frac{3 T S-k^{\prime} \xi S}{-A^{2}} & \frac{T C}{A} & 0 & \frac{-2}{A} \\
\frac{-T C}{A} & 0 & 0 & 1 & 0 & 0 \\
\frac{3 T S-k^{\prime} \xi S}{-A^{2}} & \frac{-T C}{A} & \frac{\left(1+3 S^{2}\right) T^{2}-k k^{\prime}-k^{\prime 2} \xi S^{2}}{-A^{2}} & 0 & 0 & \frac{-2 T S}{A} \\
\frac{2}{A} & 0 & \frac{2 T S}{A} & 0 & 0 & 1 \\
0 & 0 & 0 & 0 & 0 & 0
\end{array}\right) .
$$

BTW, if integrated with no space charge, this gives matrix that agrees with other codes (CASINO, AXORB).

The inflector is followed by a deflector: crossed $E$ and $B$ fields so looks like a Wien filter.

## 5. Vertical acceptance depends upon particle's phase

A simple cyclotron model is a flat field with thin lenses at the dee gaps. The focal length depends upon rf phase (i.e. it is an inherently nonlinear coupling), so one must choose an appropriate central phase. As the bunch charge is raised, the weakest-focused phases (leading the crest and near crest) are lost first. This requires some fiddling: place bunch phase too late and at will not gain sufficient energy.

Below: Blue is bunch length, red is radial, black is radial with dispersion removed, green is vertical.

## some results vs. phase






## tRANSOPTR Calculation of Injection into TRIUMF Cyclotron and First Turns



Beam envelopes through the injection line and into the cyclotron versus distance in metres. Charge per bunch is $22 p \mathrm{C}$ for a time average current 0.50 mA . This is for bunch injection phase $28^{\circ}$.

## Injection Matching Detail



New line in detail is very different from the old.
Notice the strong vertical mismatch. Causes factor $\sim 5$ increase in emittance.

## 6. How to optimize?

Three additional constraints:

- Keep the maximum quadrupole voltage below 5 kV .
- Accommodate anywhere from 0 to $500 \mu \mathrm{~A}$ ( 5 mA peak) with little change to quad settings.
- Minimize number of matching quad knobs.

The calculation was run with a simulated annealing optimizer that varied the placement, strength and orientation of the final matching quadrupoles.

The minimization penalty parameter was the vertical and horizontal beam sizes weighted by their tunes. Sizes are calculated every half turn. Importantly, the radial size used is not the apparent size, but the size with dispersion removed, which is considerably smaller. The reason for this is we do not care about radial turn width as long as turn width and energy width are correlated, because we do not need separate turns.

## New (left) vs. Old (right)



## Detail: New (left) vs. Old (right)




## Results

Selected e-log entries...

| 2011-04-14 14:00:00 | Injecting, seeing a few nA on Q2 VF. | - Bob Scheepmaker |
| :--- | :--- | ---: |
| 2011-04-15 08:18:32 | Roman has been tuning the cyclotron. <br> Transmission is 12\%. 73nA to HE3. | - Angela Hoiem |
| [intervening time] | [Bunchers inoperative; attempts to fix.] |  |
| 2011-04-16 15:00:57 | With louri's help, we have found the other end <br> of the cable from the RF and connected it up. <br> We now have bunching. | - Jaswinder Uppal |
| 2011-04-16 15:04:55 | We now have ISIS Bunchers working. We <br> have 24\% tx after about 5 minutes of tuning. | - Jaswinder Uppal |
| 2011-04-16 15:20:00 | Roman is here tuning ISIS. | - David Prevost |
| 2011-04-16 15:45:00 | Cyc at 62\% transmission. | - David Prevost |

IOW, theoretical tune worked right out of the box.
N.B. 12\% unbunched is about as good as we ever get at 90 kV rf dee voltage. Somewhat later, we achieved $70 \%$ transmission bunched, which is about as good as we ever get.

## Periodic Section: Before re-matching



## Periodic Section: After re-matching



## Skimmers and Collimators

We use collimators to trim the halo.
Skimmers are uncooled and are used to protect uncooled electrodes; all quads but most importantly also the inflector.

Sizing collimators is a tough call: too large and there will be spill on uncooled elements, too small and it'll be a bottleneck; there won't be enough transmitted to reach desired intensity.

Ideally, would like variable slits, but because of the high magnetic fields and confined space near the inflector, this was out of the question.

A fallback used in the design is to design collimators slightly large, and if needed to defocus the halo onto the collimator, re-focus into the inflector.


## Typical running today



## Typical Injection Line Losses

| O- 5L on ccscs2 v2.3-started on Sep 12015 at 12:07:46 by BAARTMAN XTPAGE BAARTM1 <@CCSCS2> |  |  |  |  |  |  |  |  | $\underset{\text { Help }}{\theta \in \bullet \Delta x}$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| File Vieu Comands Grtions | Print |  |  |  |  |  |  |  |  |
| ISIS BEAM LOSSES |  |  |  |  |  |  |  | Page 5L |  |
| Collimators | TW\# | Readings |  | Skimmers | TW\# |  |  |  |  |  |
| 030 | 511 | 2.3 | $\mathrm{u}_{\text {A }}$ | 1 | 570 | $\begin{gathered} \text { Readings } \\ 0.00 \end{gathered}$ | uA |  |  |  |
| 061 | 512 | 32.3 | $\mathrm{u}_{\text {A }}$ | 2 | 571 | -0.10 | uA |  |  |  |
| 063 | 542 | -0.4 | $\mathrm{u}_{\text {A }}$ | 3 | 572 | -0.06 | uA |  |  |  |
| 127 | 543 | 0.4 | $\mathrm{u}_{\text {A }}$ | 4 | 573 | -0.60 UA |  |  |  |  |
| 144 | 544 | 0.1 | $\mathrm{u}_{\text {A }}$ | 5 | 574 | -0.11 UA |  |  |  |  |
| 145 | 545 | 0.2 | $\mathrm{u}_{\text {A }}$ | VIB-6 | 575 | 0.01 UA |  |  |  |  |
| 155 | 546 | -0.1 | $\mathrm{u}_{\text {A }}$ | VIB-7 | 576 | -0.03 UA |  |  |  |  |
| 165 | 547 | -0.2 | $\mathrm{u}_{\text {A }}$ | VIB-8 | 577 | 0.06 UA |  |  |  |  |
| 166 | 550 | 0.3 | $\mathrm{u}_{\text {A }}$ | Sum | 578 | -0.89 | uA |  |  |  |
| VIB-003 | 551 | -0.2 | $\mathrm{u}_{\text {A }}$ |  |  |  |  |  |  |  |
| VIB-007 | 552 | -0.4 | $\mathrm{u}_{\text {A }}$ | TNIMs | TW\# | Readings |  |  |  |  |
| VIB-013 | 553 | 0.3 | $\mathrm{u}_{\text {A }}$ | 030 | 440 | $495 \text { uA }$ |  |  |  |  |
| VIB-017 | 554 | 0.8 | $\mathrm{u}_{\text {A }}$ | 063 | 451 | 456 UA |  |  |  |  |
| VIB-021 | 555 | 0.2 | $\mathrm{u}_{\text {A }}$ | 145 | 452 | 287 UA |  |  |  |  |
| VIB-023 | 556 | 0.7 | $\mathrm{u}_{\text {A }}$ | 165 | 453 | 286 UA |  |  |  |  |
|  |  |  |  | VIB-004 | 454 | 291 UA |  |  |  |  |
| Pulser (I1) | 55 | 90.3 | \% | VIB-012 | 455 | 291 UA |  |  |  |  |
| Beamstop 030 | 411 | -1 | $\mathrm{u}_{\text {A }}$ |  | 457 | 294 UA |  |  |  |  |
| Beamstop IB Coll \& BST Sum* aartman, TRIUMF 2015 | 406 | -1 -1 | UAUA | VIB-022 VIB-023 | 458 | 288 | uA |  |  |  |
|  | 502 | 29 |  | $\begin{aligned} & \text { ISIS Tx } \\ & \text { Adj. ISIS TX } \end{aligned}$ |  |  |  |  |  |  |
| ISIS Slits Sum | 517 | 176 | uA |  | 460 | $\begin{aligned} & 58.0 \\ & 90.1 \end{aligned}$ | \% |  |  |  |

## Conclusions

- Envelope Technique: Compared with multiparticle simulation, envelope code is fast and efficient, unambiguous.
- Did it work? Yes. Theoretical tune worked great; 4 years later it still works.
- Other TRIUMF-ISIS improvements: Better steering, alignment, diagnostics; reduced 9 matching quads to 5 . Finetuning is simple.

Download link:
http://lin12.triumf.ca/text/Talks/2015ECPM/ISIS.pdf


## Stop Motion Video


[^0]:    ${ }^{1}$ In this shorthand, $x_{1}=x, x_{2}=P_{x}, x_{3}=y, \ldots$

