TRIUMF Beam Physics Note
TRI-BN-13-11
Dec., 2013

I1 Steering Correction

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Abstract: In I1, steering correction is affected by the Einzel lens, and conversely, Einzel tuning results in steering the beam at the Pulser dump aperture. There is currently insufficient steering to remotely correct the beam to centre on the Pulser dump aperture; currently it is achieved with a fixed permanent magnet scheme. The drawback is of course that one is not free to tune either the Einzel lens or the extraction optics. A steering scheme is proposed to alleviate this situation. Apertures are used to diagnose and select beam size, fixing the acceptance to be commensurate with the cyclotron acceptance. Thus, the aperture sizes must be carefully chosen. New sizes are suggested.

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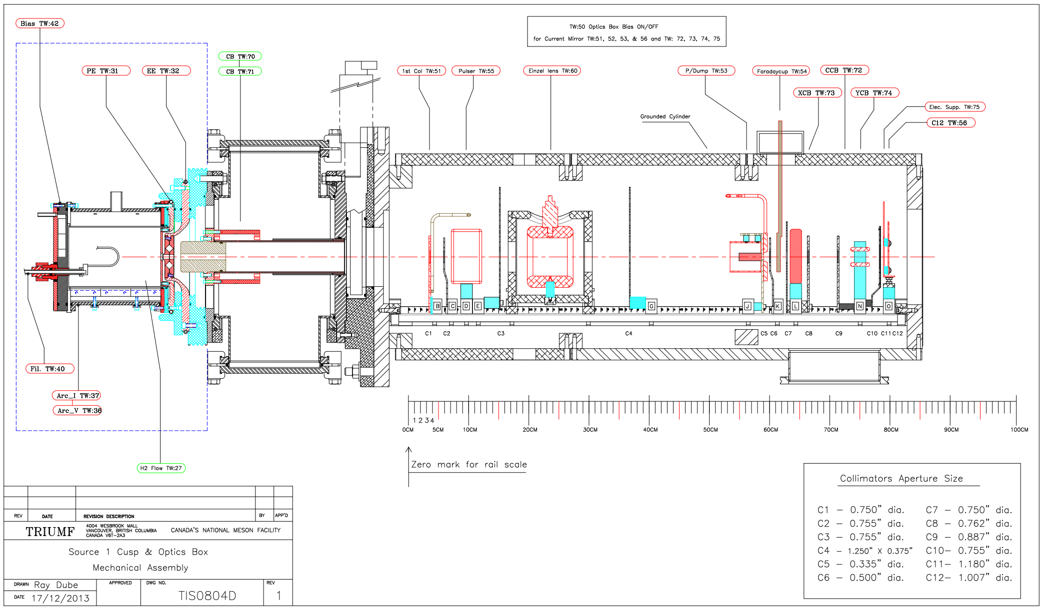

Figure 1: I1 source and optics layout

1 Introduction

The optics in the I1 region (Fig. 1) is significantly affected by a stray field from the cyclotron of about 12 Gauss. This results in the beam being continuously steered upwards with a radius of about 14 m, resulting in off-axis displacements of as much as a centimetre. Ideally, it would be best to shield this field and reduce it by about an order of magnitude. This is a complementary approach also being pursued, but is not the suject of this note.

There are two main apertures, both cooled, through which the beam must be centred: C1 centres beam at the start of the optics box, and C5 is the Pulser dump aperture. Centring on C5 is essential for proper performance of the Pulser, and yet there is no adjustable steerer for this task, only fixed steering from permanent magnet dipoles installed on top of the optics box. This fixed steering means that we are not free to tune the focus through C5 with the Einzel lens. We should overcome this with installation of a steerer near C1. A magnetic steerer would be ideal, but there is no space. An electrostatic steerer will disrupt the space charge neutralization for an additional length of the steerer length (somewhat less than 2 inches), but it is determined that this can be tolerated.

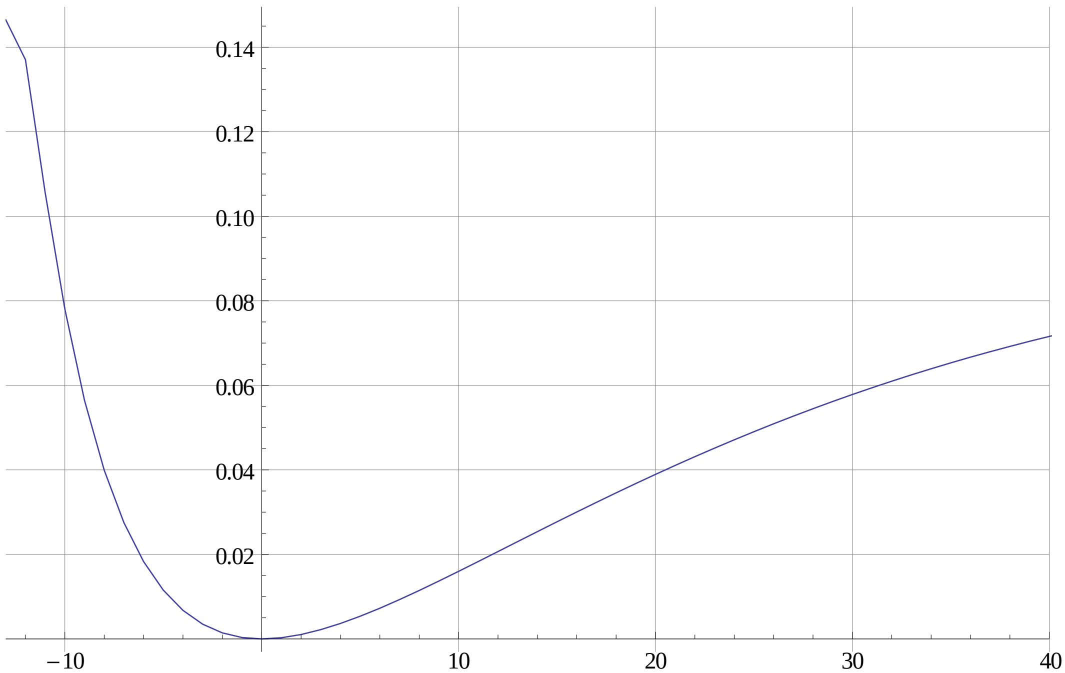

Figure 2: Use this plot to convert $1\,\mathrm{cm}/f$ (y-axis) to Einzel lens voltage (x-axis in kV).

2 Optics

The distances S_1 = source-to-lens, S_2 = lens-to-C5 are 64 cm and 35 cm resp., so we should have:

$$\frac{1}{f} = \frac{1}{S_1} + \frac{1}{S_2} = 0.044\,\mathrm{cm}^{-1} \tag{1}$$

and this would require an Einzel lens voltage of 22.5 kV. However, the space charge effect is to defocus the beam in regions where there are electric potentials larger than a few volts, and this must be counteracted. Both by `TRANSOPTR` calculation and from actual operating tunes, we find the necessary voltage is $26 \pm 1\,\mathrm{kV}$, $f = 20\,\mathrm{cm}$, or $1\,\mathrm{cm}/f = 0.05$.

This assumes that the region from the source to the C1 aperture is space charge neutralized and downstream of C1 is not at all neutralized. If C1 is moved upstream by 4.4 cm, this decreases the space charge neutralized region and the Einzel lens voltage must be about 0.5 kV higher.

At this setting, we can calculate the effect of the Pulser on beam position at the Pulser Dump C5. The R_{12} matrix element is 24 cm. Thus, a 300 volt plate potential difference moves the beam at the dump by 9.4 mm. This should be larger than the dump aperture or the pulsing will not be complete. It is only just barely larger, since the dump aperture is 8.5 mm.

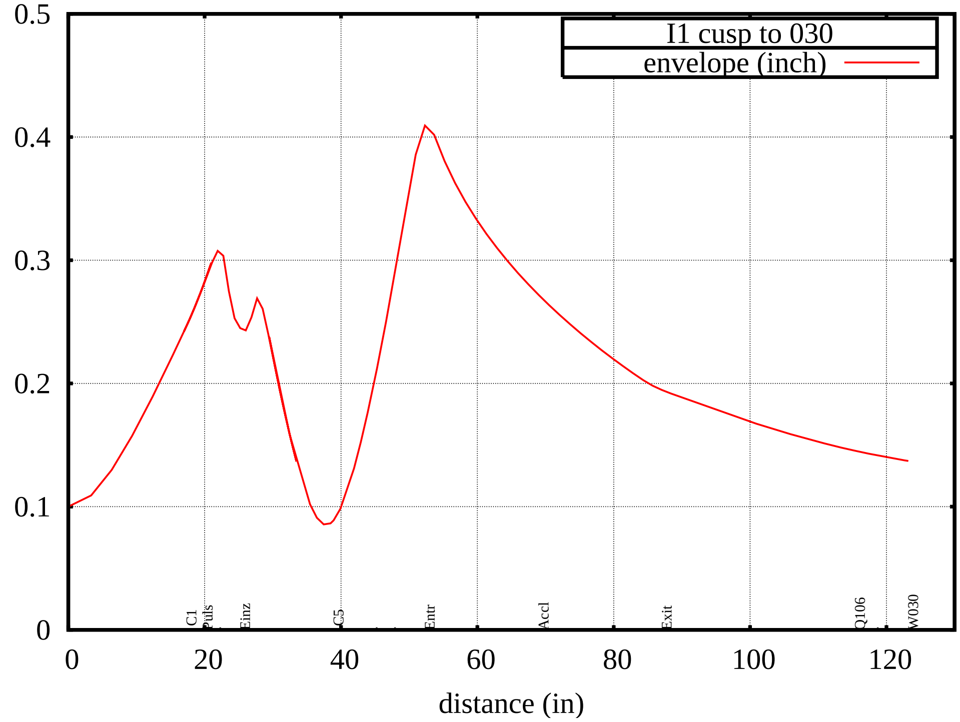

Figure 3: Envelopes (in inches, sorry) source to DBE030.

3 Emittance and Apertures

In experiments in 2012 with the emittance scanner, we measured 4 times rms emittance as 6.3 μm; 6.0 at 86% contour. The beam at 030 was about 53 μA at 10%; would be 530 μA at 100%. Under these conditions and using the periodic section quad voltage 3.05 kV, I find the matched 2 rms size of the beam is 0.114" at the locations of the slits in boxes 125 and 126.

Historically, we do not use slit sizes larger than 0.250"; this corresponds to a 100% emittance of 8 μm. Assume we might need a bit more for highest currents, we still in my estimation are not interested in any particles outside an amplitude of 10 μm. Translated to the I1 terminal, since the momentum ratio is 5, this largest amplitude is 50 μm.

The optics calculation using the envelope code `TRANSOPTR` can predict the correct Einzel voltage. Working backwards from measured profiles at 030 and using the measured emittance, we find that the waist at the source is 5 mm diameter and 13 mrad in half divergence. (Check: $2.5\text{mm} \times 13\text{mrad}/5 = 6.5\,\mu\text{m}$.)

The calculated envelope is meant to represent the 2rms. To find the 100% size, scale by the square root of emittances: $\sqrt{10/6.5} = 1.24$. We find for diameters:

Location	Max. Dia./mm	Current Aperture/mm
Source	6.2	8.0
C1	15.5	19.0
C5	5.1	8.5

These calculated beam sizes are all smaller than the existing apertures. Given that we will with new steerers be able to aim through the apertures, I propose reducing C1 and C5 to the calculated 100% sizes.

4 Ambient Magnetic Field

Proton energy is 13 keV, $B\rho = 165$ G-m. Ambient field is mostly horizontal 12 G (Thomas' measurement), so the radius of curvature is upward at $\rho = 14$ m. The distance from the collimator C1 to the pulser dump C5 is 55 cm and this would in a drift require an angle of $L/(2\rho) = 20$ mrad. However, there is an Einzel lens that will work against the steering. Since the beam must now be off-centre in the lens, it receives an additional steering kick towards the axis, causing it to overshoot the pulser dump. This requires the steering correction to double.

If this is not clear, think of the case where from the aperture to the dump aperture is a focus-to-focus condition. Then the amount of steering would approach infinity. The focal length for that condition is 12.7 cm, whereas in fact we have $f = 20$ cm, as stated above.

This is clarified in figure 4. The vertical line is the centre of the Einzel lens. Blue is the case of a 20 mrad initial kick followed by a $\rho = 14$ m arc. Red is two arcs of this radius with an additional focusing kick from the Einzel lens; this case requires a twice larger kick of 43 mrad at C1. All lengths in cm. Notice that to reach the pulser dump C5, the beam must be off-centre by 7 mm in the Einzel lens.

Interestingly, we could reduce overall effect of constant radius $\rho = 1400$ cm by misaligning C1 upward by about 4 mm (green in figure 4). This is further shown in figure 5. The case of beam at C1 4 mm above axis stays almost perfectly aligned in the Einzel lens. There is a singularity at lens strength of 47.5 kV (not attainable with our PS); at this strength there is focus-to-focus condition ($R_{12} = 0$) between C1 and C5. From this we can also see that when aligned at C1, and operational setting of Einzel, the beam is 7 mm below axis at Einzel centre.

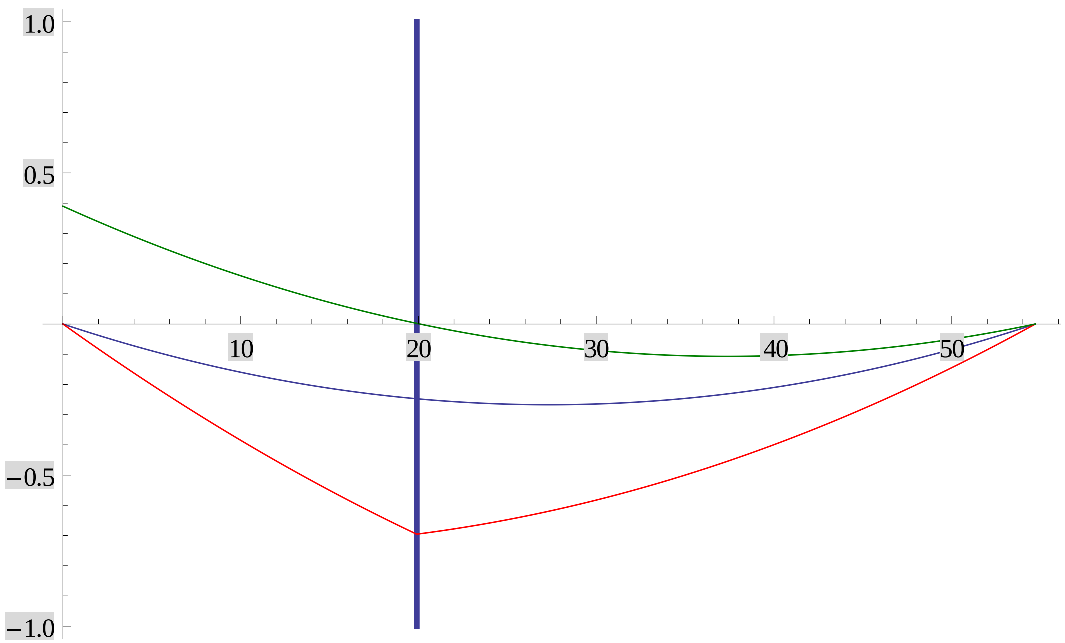

Figure 4: Orbits with $\rho = 1400\,\mathrm{cm}$ starting at C1 that are centred on target C5 at $s = 55\,\mathrm{cm}$. Lens is at $s = 20\,\mathrm{cm}$. Abscissa is s, ordinate is x transverse displacement from axis, both in cm. Blue: Starting centred and lens off. Red: Starting centred and lens at operational $1/f = 0.05\,\mathrm{cm}^{-1}$. Green: Starting off axis to pass through lens centre.

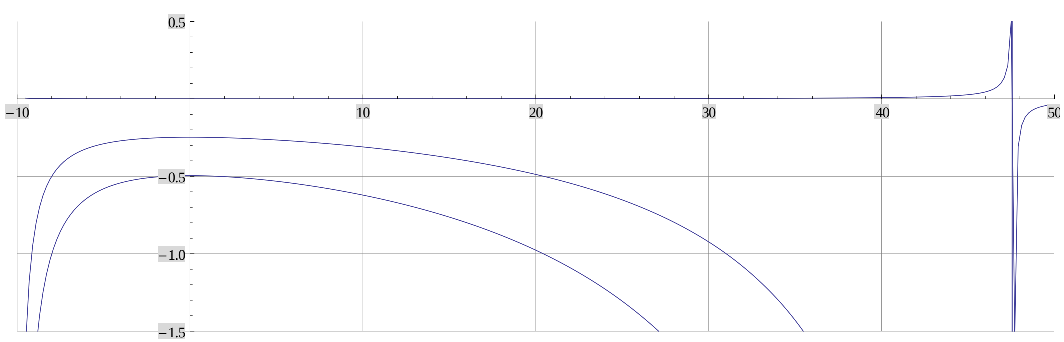

Figure 5: Misalignment of beam in the Einzel lens, as a function of Einzel lens voltage (kV). There are 3 curves; from the lowest to highest: beam at C1 4 mm below axis, beam at C1 on axis, beam at C1 4 mm above axis.

5 Steering Corrector Strength

At or near C1, a steerer corrector needs strength:

$$\Delta x' = -\frac{(S_E + S_2)^2 - S_E^2 S_2/f + 2x_1\rho(1 - S_2/f)}{2\rho S_E S_2(1/S_E + 1/S_2 - 1/f)} \tag{2}$$

The beam position at the steerer is x_1, assumed to be zero, $S_E = 19.9\,\text{cm}$ is C1-to-Einzel centre distance, $S_2 = 34.8\,\text{cm}$ is Einzel centre-to-C5 distance, $\rho = 1400\,\text{cm}$. The result is $\Delta x' = 0.043$.

Additionally, if the beam is to be centred at C1, the radius of 14 m means that it arrives there with a 12 mrad angle in the wrong direction. Thus the total kick needed at C1 is 55 mrad.

Steerer deflection follows from $F = ma$ or $qV/d = mv^2x'' = 2qV_Ex''$ where d is plate separation, V is voltage across plates, $V_E = 13\,\text{kV}$, the beam voltage, so

$$\Delta x' = \frac{VL}{2V_E d} \tag{3}$$

where L is effective length. The spare steerer has $d = 2.54\,\text{cm}$, $L \approx 3.5\,\text{cm}$. Equating the needed $\Delta x'$ to 55 mrad, we find finally:

$$V = 1.05\,\text{kV} \tag{4}$$

As the deflection is downward, it requires the lower plate to be positive this voltage with respect to the upper plate.

If the beam is allowed to be off-centre, say $x_1 = 4\,\text{mm}$ high at the steerer, this reduces only slightly to $V = 0.96\,\text{kV}$. Although this reduces the correction from equation 2, it increases the initial angle arriving at the steerer from 12 mrad to 24 mrad.

The Einzel lens is tunable up to 30 kV. If we wish to have the freedom to tune it that high, then for $x_1 = 0$ the voltage rises to $V = 1.25\,\text{kV}$.

All these values for V scale with the value of stray magnetic field.