Minimum spot size ISAC LEBT, applied to $\beta$-NMR

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Abstract: This addresses the question: How small can the beam spot be in ISAC LEBT?
1 Introduction

Let us assume an emittance of $12.5 \mu m$. This is typical for surface sources to contain > 90% of the beam. It’s not too wrong to simplify this into an idealized uniform distribution. This means that for example, if we select $6 \mu m$ emittance, the RIB rate would be reduced by a factor of 4; if $1 \mu m$, it’s reduced a factor of 150. This is because the emittance applies in both transverse planes so the intensity ratio is the square of the emittance ratio.

Typically, the beam energy is 30 keV. β-NMR ‘soft-lands’ their isotopes at energies down to about 100 eV. This changes the emittance by the square root of energy ratio:

$$\epsilon = 12.5 \mu m \sqrt{\frac{30 \text{ keV}}{E}}$$

Emittance is product of beam radius and radial divergence. Ultimately, the divergence must be $\ll 1$ or the optics aberrations are too severe, meaning you won’t get the spot you want. Optimistically, we assume here that the radial divergence does not exceed 0.5. This means extreme angles of $\pm 0.5$ radian.

Thus we can determine smallest possible spot diameter:

$$2a_{\text{min}} = 50 \mu m \sqrt{\frac{30 \text{ keV}}{E}}$$

For example, at 100 eV, $2a_{\text{min}} = 0.9 \text{ mm}$, at 1 keV, $2a_{\text{min}} = 0.3 \text{ mm}$.

2 Don’t get excited (Rob)!

There are only two ways to reach this minimum spot size limit.

1. The final focus is inside the final focusing element. This is of course the case of a solenoidal field and it turns out that the field must be at least $\sim 2$ Tesla. It is not possible for magnetic fields transverse to the sample.

2. The deceleration potential is linear right up to the sample. There is an electric field at the sample; it is normal to it. But: this can work down to zero solenoid field.
3 (1) Solenoid case

Some cases are shown below.

1 keV case:

These are implantations at 1000 eV, with solenoid fields $B = 2.4, 4.7, 8.0$ Tesla. The minima are indeed radius $a = 150 \mu m$. Because of the strong radial electric fields, the first minimum has to occur precisely at the point where the on-axis electric field derivative, in units of the beam energy, is a maximum. For high fields, this means there are many “bounces”; 7 in the case of 8 Tesla. Due to cubic aberration, it is unlikely that all particles stay in phase though. Moreover, large beam sizes in region where magnetic field derivative is high means spin aberration and polarization loss (see next section). Needs further investigation. It is not possible to do this if field is too small, $B < \sim 2$ Tesla: though the minimum beam size is not field-dependent, the beam size must modulate between large and small sizes and the max size increases to unworkable levels for magnetic field that is too small.

100 eV case:

At 100 eV it works better with lower solenoid fields reachable, but smallest beam is 3 times larger.

These are implantations at 100 eV, with solenoid fields $B = .84, 4.0, 7.3$ Tesla.

4 Solenoid Matched cases

More robust tunes are possible if we “match” to the solenoid optics, in which case the beam size is uniform, independent of energy, and given by

$$a = \sqrt{2} \rho e.$$
\( \rho \) is the ‘cyclotron’ radius of curvature \( \frac{p}{qB} \) \( (p = mv = \text{momentum}) \), and the emittance \( \epsilon \propto \frac{1}{\rho} \), so the momentum cancels. For our chosen emittance, this works out to diameter

\[
2a = \frac{2.6 \text{ mm}}{\sqrt{B/\text{Tesla}}}
\]

Cases are shown below.

1.0 keV:

The above 6 cases are for 1 keV implantation, matched optics, solenoid fields respectively: 0.8, 1.0, 1.3, 2.4, 4.7, 8.0 Tesla.

0.1 keV:

These 5 cases are for implantation at 100 eV. Matched optics, solenoid fields respectively: 3.0, 4.0, 7.3, 7.9, 8.8 Tesla. The final high field cases are seen to be no different from the “mismatched” cases. This is because they are at the 500 mrad divergence limit: diameter is 1 mm at this limit.
Two notes on the applicability of the above to the current $\beta$-NMR setup.

1. All of the above simulations use the einzel lens at 40 cm upstream of the final focus. It is doubtful that spots this small can be achieved without it. It was known from the start that this einzel could not be used with solenoid on. This issue was not mitigated.

2. To achieve smaller spots, a smaller emittance can be selected. This is the original purpose of the slits. But the installed slits are not up to the task. To achieve their original purpose, they should be irises, not V-shaped slits, and they should have motor drives that can be controlled remotely.

5 (2) Re-arrange the Deceleration

If there’s no solenoidal magnetic field, can we use existing $\beta$-NMR setup to focus on target? In general, no; see below where implantation energies are (left to right) 100 eV, 1 keV, 3 keV. The rightmost is the optimum; 1 mm dia. IOW, the minimum spot size can be achieved at only this one energy 3 keV. To go lower, the deceleration has to be brought closer to the sample.

In the current setup, the deceleration is set up to complete before the particles impinge on sample. The radial electric field at the downstream end near the target is too large. The focal strength is given by ratio of electric field $\mathcal{E}$ to energy:

$$\frac{1}{f} = \frac{q\Delta\mathcal{E}}{4E} = \left( \frac{30 \text{ keV}}{E} - 1 \right) \frac{0.08}{\text{cm}}$$

For the three cases above, focal lengths are $f = 0.4, 4, 14$ mm. At the preferred low energy deposition, the focusing is just too strong.

But this can be overcome. The idea is to design the sample holder as if it is an ion source. Just in reverse. In that case, there’s no strong radial force. TITAN has such a setup already both when injecting into and extracting from their RFQ cooler. It is shown below; einzel lens, decel field using a conical electrode (red).
The sample must sit at the vertex of the cone. This is capable of giving 1 mm dia. spots down to 100 eV implantation energy. I checked; below is a simple example with an einzel lens 7 cm upstream of the sample.

But this is not a simple solution. All of the metal boundary in red must be at the same temperature as the implantation target.

6 Depolarization

The solenoid field on axis is parallel to $^8\text{Li}$ spins, but there is radial field off axis. This field is

$$B_r = -\frac{r}{2}B'.$$

The $\gamma$ for $^8\text{Li}$ is 6.26 MHz/T. The off-axis spins precess by angle $\theta = 2\pi \int \gamma B_r dt$. All the radial field occurs where the beam is still at its original energy, so $dt = ds/v$ where $v = \sqrt{\frac{2 \times 0.030}{8 \times 931}} c = 0.85 \times 10^6$ m/s.

Roughly we assume $r$ is constant in this transition region, so we just get an integral of $B'$ and this gives dependence only on the final field $B$:

$$\theta = \frac{r}{43 \text{ mm}} \frac{B}{1 \text{ T}}.$$

The mismatched cases above at 1 keV implantation, which have the smallest spot sizes, all work out to about $\theta = 0.2 = 11^\circ$ (4 mm and 2.4 T, 2 mm and 4.7 T,...). Not good. The matched cases and the 100 eV cases are OK though.