Design of a Multiple-Reflection Time-of-Flight Mass-Spectrometer for Barium-tagging with nEXO

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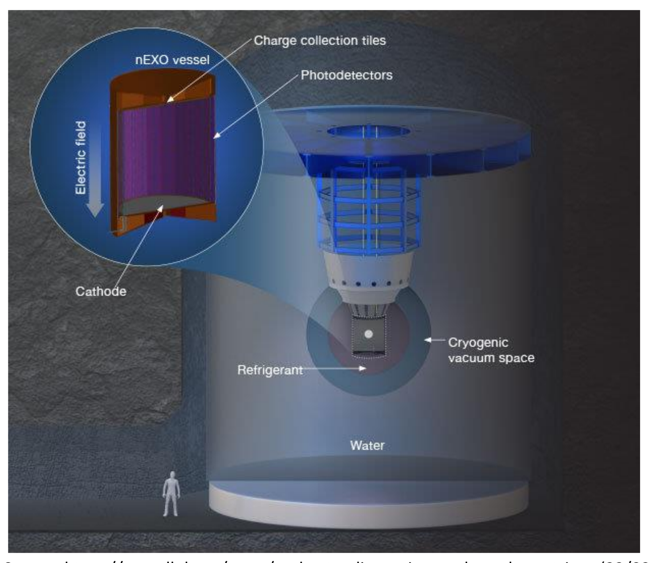
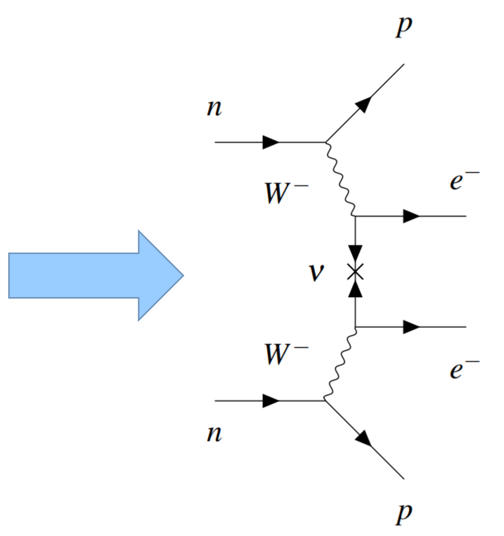
Searching for 0νββ

nEXO

- The nEXO collaboration is searching for neutrinoless double-beta (0νββ) decay in the isotope Xenon-136[1].
- 0νββ decay is only possible if the neutrino is a Majorana particle, i.e., the neutrino and antineutrino are the same particle.
- The nEXO experiment plans to deploy 5 tonnes of liquid Xenon in a Time Projection Chamber (TPC). The detector is anticipated to be located in the cryopit at SNOLAB[2].





Source: https://www.llnl.gov/news/understanding-universe-through-neutrinos (22/09/2018)

Barium-tagging

The process in which the daughter Barium-136 ion, produced by the double-beta decay of Xenon-136, is extracted from the TPC and identified.

$$^{136}\text{Xe} \rightarrow {}^{136}\text{Ba}^{++} + 2e^- + 0\nu$$

Extract and Identify

MR TOF Operation Mode

Requirements

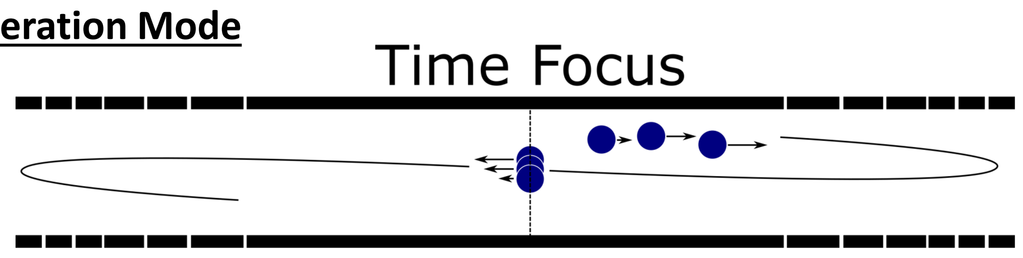
The MR TOF needs to function as a:

- **High-resolution mass-spectrometer**, capable of isobaric separation.
- **Broad-range mass-spectrometer**, for systematic studies of the Barium ion extraction technique.

To achieve this it must be able to:

- Correct for time-of-flight aberrations.
- Eject unwanted ions with precision using electrodes placed at a time focus
- Switch easily between the number of reflections.

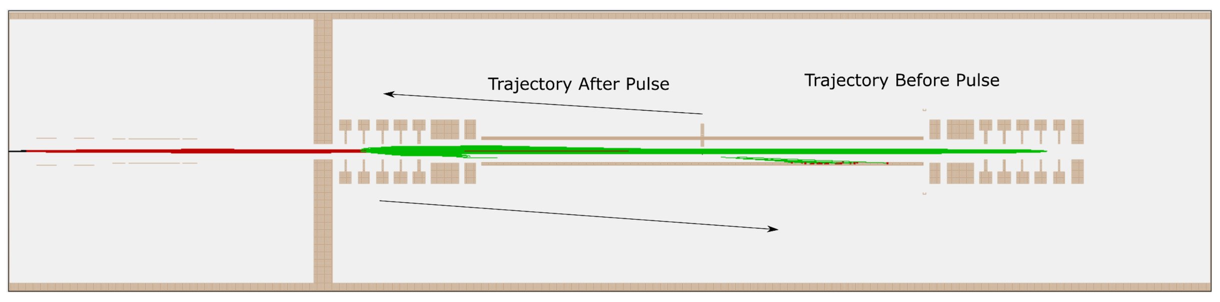
Operation Mode



- Increasing the number of turns increases the resolution but decreases the mass range.
- The number of reflections must be easy to adjust.
- A time focus is created in the center of the MR TOF with the first reflection.
- All intermediate reflections are isochronous.
- The time focus is shifted onto the detector with the last reflection[5].

Simulation and Optimization

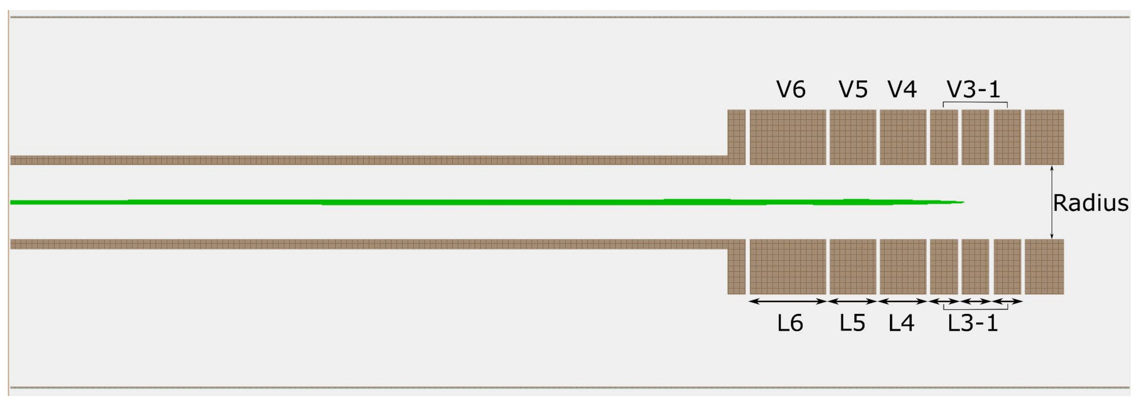
Mass Selector



The mass selector is pulsed in a 200 ns window when ions pass by, altering the ion's entrance angle into the mirror and destabilizing it.

Mirrors and Optics

- The einzel lens is optimized for multiple geometries, to increase point-to-parallel focusing ability, with the $(a|a)$ parameter.



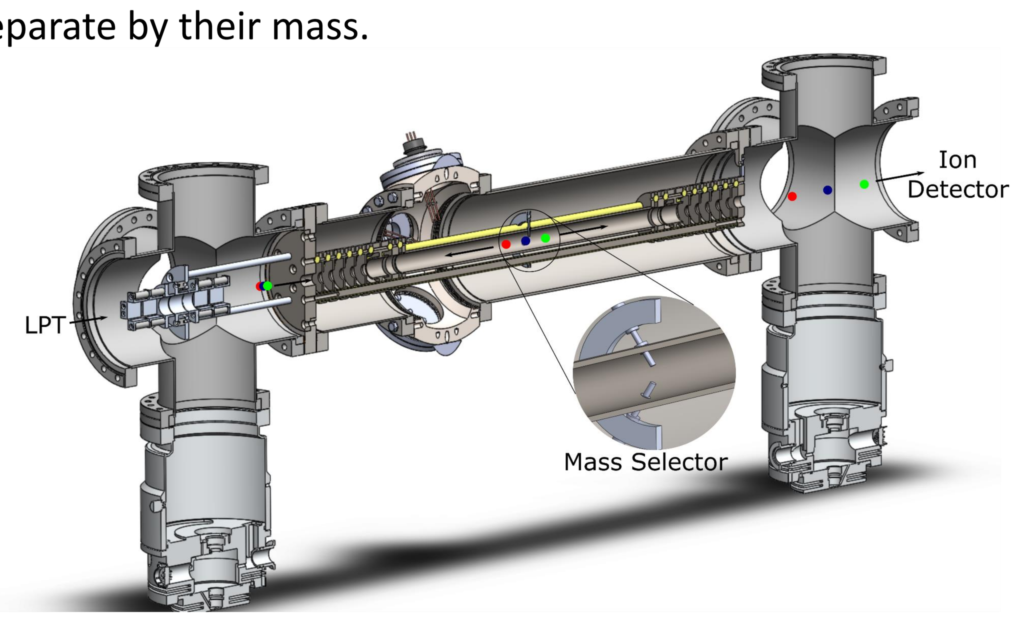
- The MR TOF has 6 potentials that must be tuned simultaneously.
- It also has physical parameters that may be altered, such as the electrode lengths, spacing and radius.
- To optimize the mirror potentials, they are first generated pseudo-randomly with a sobol-sequence[7].
- Ion-optical parameters are calculated using SIMION 8.1, for each set, with a single reflection.
- Each set is characterized with a weighted sum:

$$\chi = \omega_1 (x|x) + \omega_2 (t|\delta) + \omega_3 (t|\delta\delta) + \omega_4 (t|\delta\delta\delta) + \omega_5 (t|xx)$$

- The top 100 sets are further refined with a Nelder-Mead simplex optimizer, using the same sum.
- This procedure is performed for multiple mirror geometries.

Design of the MR TOF

- The Multiple-Reflection Time-of-Flight Mass-Spectrometer (MR TOF), reflects ion bunches between two electrostatic mirrors, with 6 electrodes in each, located on the ends of a drift-tube.
- All ions are given approximately the same kinetic energy and will separate by their mass.



The resolution can be calculated with[3]:

$$R = \frac{t}{2\Delta t} = \frac{t_0 + nT}{2\sqrt{(\Delta t)^2 + (n\Delta T)^2}}$$

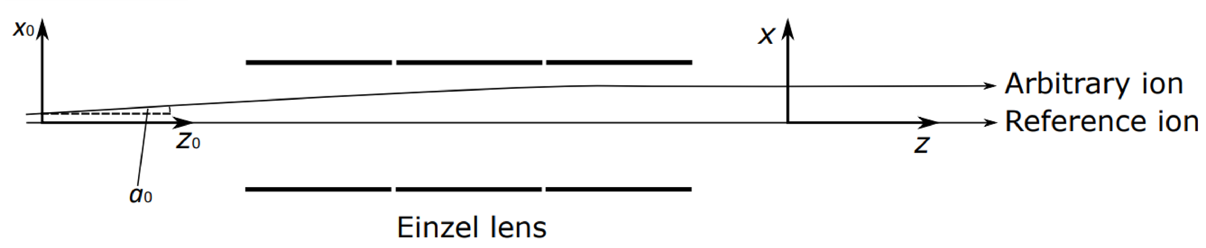
- t_0 – Time of flight from the LPT to the center of the MR TOF.
- n – Number of revolutions.
- T – Time of flight for a single revolution.
- Δt – Turnaround time for ions leaving the Linear Paul Trap (LPT).
- ΔT – Time of flight spread due to mirror aberrations.

Calculating Ion-Optical Aberrations

- To correct time-of-flight aberrations, the formalism of transfer matrices is used.
- The properties of an ion can be described at any point during its flight with the vector X.
- K_0 and t_0, are the kinetic energy and time of flight for the reference ion, respectively.

$$X = \begin{bmatrix} x \\ a \\ y \\ b \\ \delta \\ t' \end{bmatrix} \quad a = \frac{\partial x/\partial t}{\partial z/\partial t} \quad b = \frac{\partial y/\partial t}{\partial z/\partial t} \quad \delta = \frac{K - K_0}{K_0} \quad t' = t - t_0$$

Einzel lens



A simple 2D einzel lens may be described by the matrix equation:

$$\begin{bmatrix} x \\ a \end{bmatrix} = \begin{bmatrix} (x|x) & (x|a) \\ (a|x) & (a|a) \end{bmatrix} \begin{bmatrix} x_0 \\ a_0 \end{bmatrix}$$

MR TOF

For a reflection in the MR TOF, measuring from the mid-plane, ion parameters can be described in 2D with the equations[6]:

$$x = (x|x)x_0 + (x|a)a_0 + (x|x\delta)x_0\delta + (x|a\delta)a_0\delta + \ldots$$

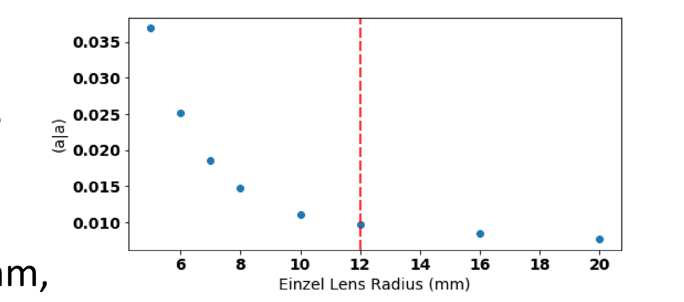
$$a = (a|x)x_0 + (a|a)a_0 + (a|x\delta)x_0\delta + (a|a\delta)a_0\delta + \ldots$$

$$\begin{aligned} t' = {} & (t|\delta)\delta + (t|xx)x_0^2 + (t|xa)x_0a_0 + (t|aa)a_0^2 + (t|yy)y_0^2 + (t|yb)y_0b_0 \\ & + (t|bb)b_0^2 + (t|\delta\delta)\delta^2 + (t|\delta\delta\delta)\delta^3 + (t|\delta\delta\delta\delta)\delta^4 + (t|xx\delta)x_0^2\delta \\ & + (t|xa\delta)x_0a_0\delta + (t|aa\delta)a_0^2\delta + (t|yy\delta)y_0^2\delta + (t|yb\delta)y_0b_0\delta + \\ & + (t|bb\delta)b_0^2\delta + \ldots \end{aligned}$$

Results and Conclusions

Einzel lens optimization

- The einzel lens' focusing ability is dominated by the lens radius.
- Focusing ability begins to plateau at a radius of 12 mm, which is currently the radius in use.

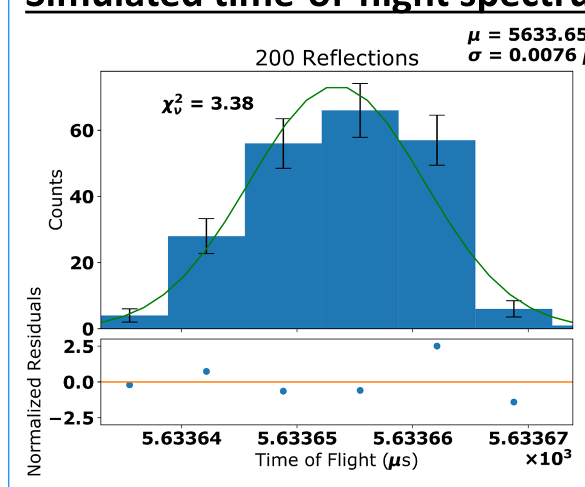


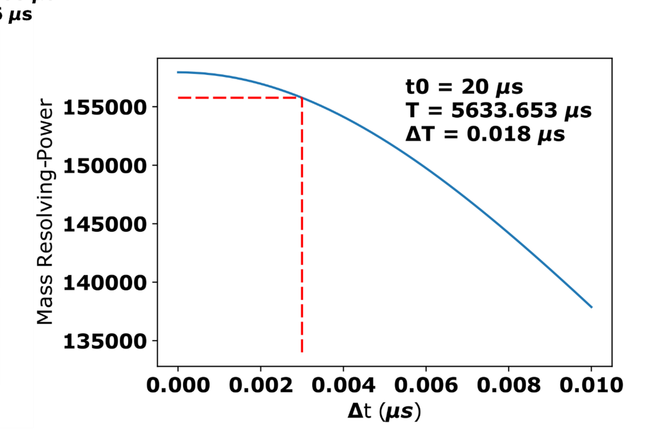
Current optimal parameters used for the MR TOF

Mirror Dimensions (mm)						
L1	L2	L3	L4	L5	L6	Radius
15	15	15	25	25	41	18

Electrode Potentials (V)					
V1	V2	V3	V4	V5	V6
1705	1206	1072	688	-479	-2018

Simulated time-of-flight spectrum and mass-resolving power

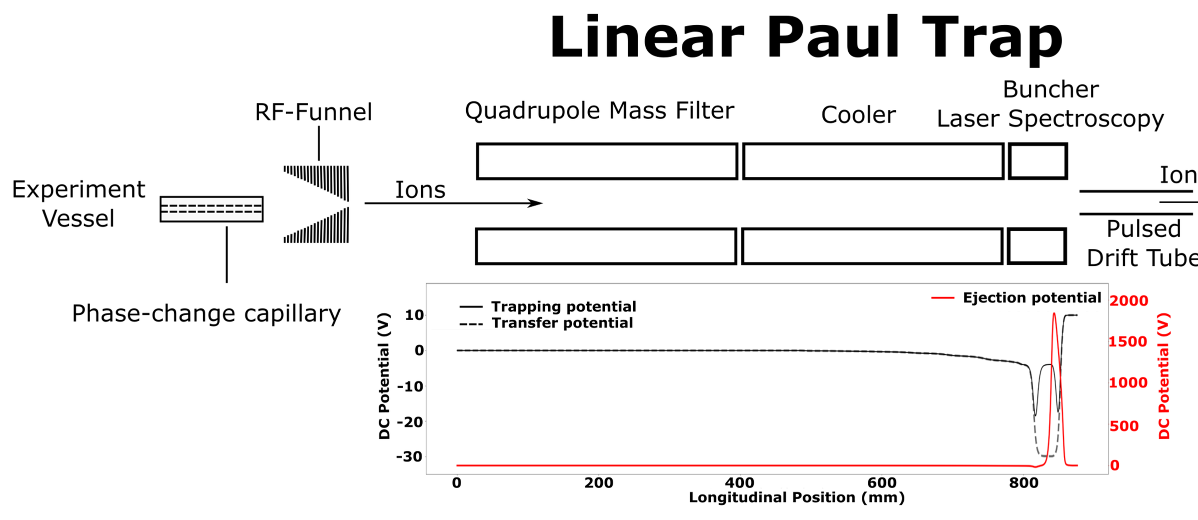


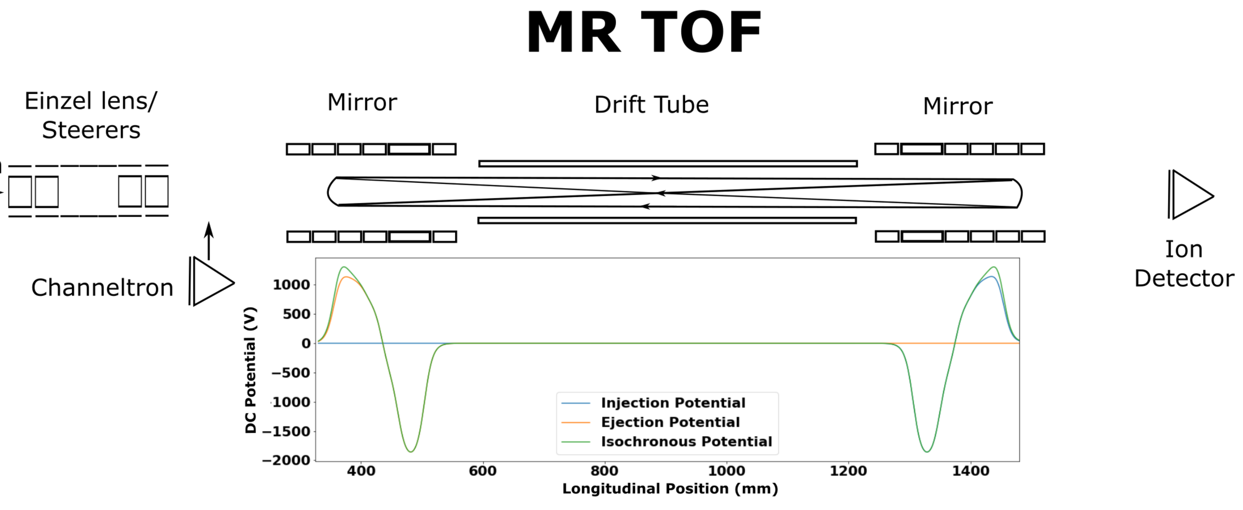


- The MR TOF reaches a resolution of approximately 155 000, for a turnaround time of 3 ns.
- The electrode potentials are independent of turn number.
- Pin electrodes, in the center of the MR TOF, can be pulsed to eject unwanted ions at the time focus.

The Ba-tagging System

After extraction from the TPC, ions are separated from the Xenon gas with the RF-Funnel[4]. The ions are then cooled and bunched with the LPT, here, the Barium ion can be identified with laser spectroscopy. Ion bunches are then injected into the MR TOF for further analysis.





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Acknowledgments

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