Linear Paul Trap for Ba-tagging

Hussain Rasiwala, for the nEXO collaboration
McGill University

CAP Virtual Congress 2020, June 8-12

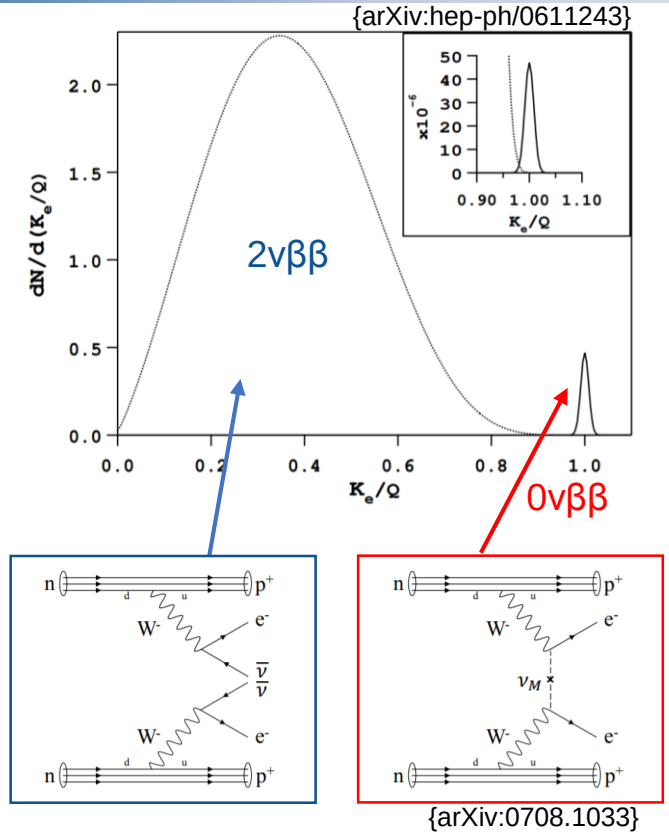
Motivation for 0νββ searches

- Double beta decay are rare nuclear decay observed only in about 12 nuclei.
- Involves 2 simultaneous decay beta decays.

$$^{A}X_{z} \rightarrow {}^{A}Y_{z+2} + 2e^{-} + 2\bar{\nu}_{e}$$

Neutrinoless double beta decay is special case of double beta decay.

$$^{A}X_{z} \rightarrow {}^{A}Y_{z+2} + 2e^{-} + 0\bar{\nu}_{e}$$



http://pdg.lbl.gov/2018/listings/rpp2018-list-double-beta-decay.pdf

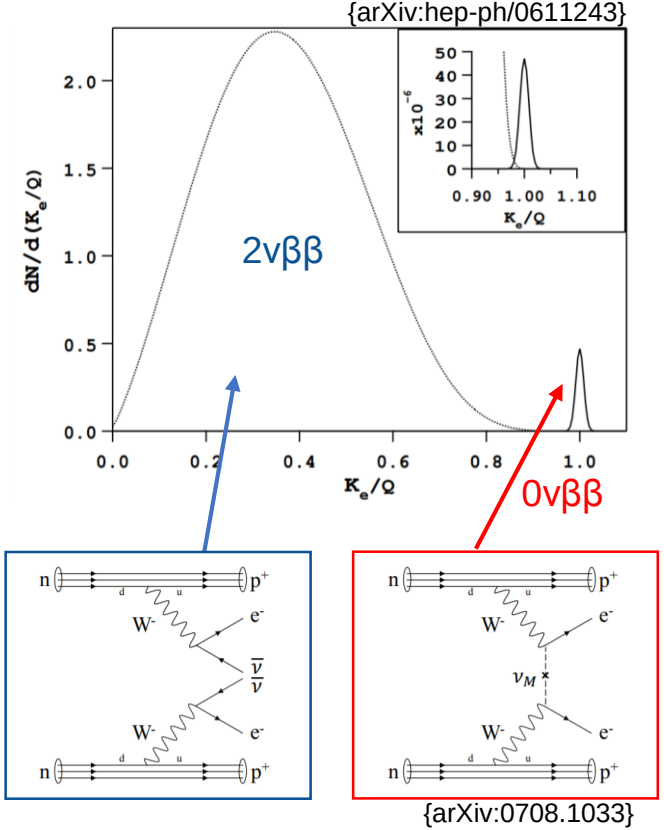
Motivation for 0νββ searches

$$^{A}X_{z} \rightarrow {}^{A}Y_{z+2} + 2e^{-} + 0\bar{\nu}_{e}$$

Consequences of 0νββ observation:

- Neutrino is its own antiparticle
- Lepton number violation
- Absolute neutrino mass scale
- Matter-Antimatter asymmetry

{arXiv:hep-ph/0611243}



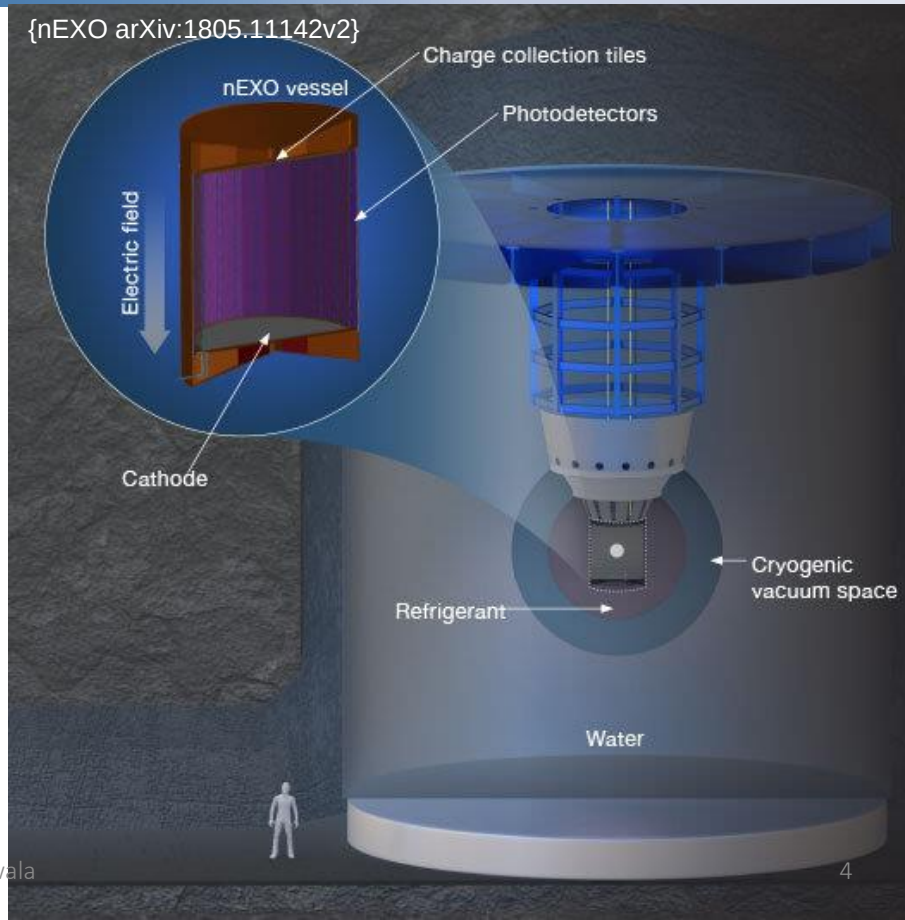
{arXiv:0708.1033}

nEXO Experiment

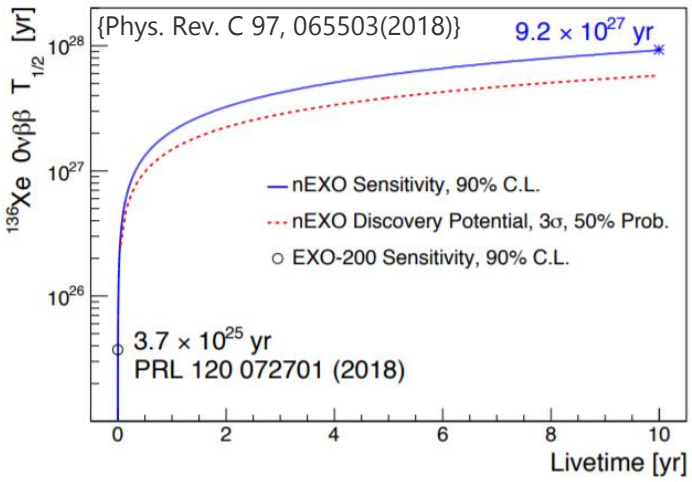
- Searches for 0νββ events in liquid xenon (LXe) enriched in Xe-136 isotope (90%).

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

- Uses large time projection chamber (TPC), holding 5000kg of LXe.
- Charge collection pads used at the anode.
- VUV-SiPM line the curved face of TPC.
- Refrigerant (maintain xenon as liquid)
- Water tank for shielding.
- nEXO is anticipated to be located at SNOLAB.



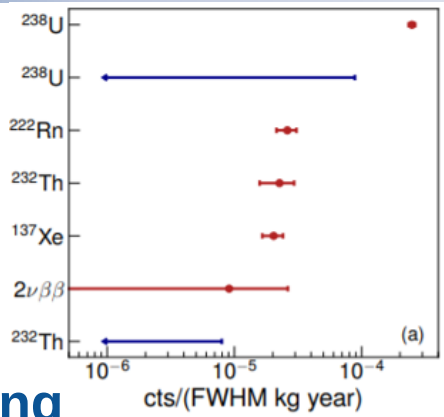
Experimental background



Projected sensitivity of reaching 9.2×10^{27} yr through a 10 yr run.

{J. B. Albert *et al.* (nEXO Collaboration) Phys. Rev. C **97**, 065503}

Backgrounds limit the projected sensitivity of the experiment.



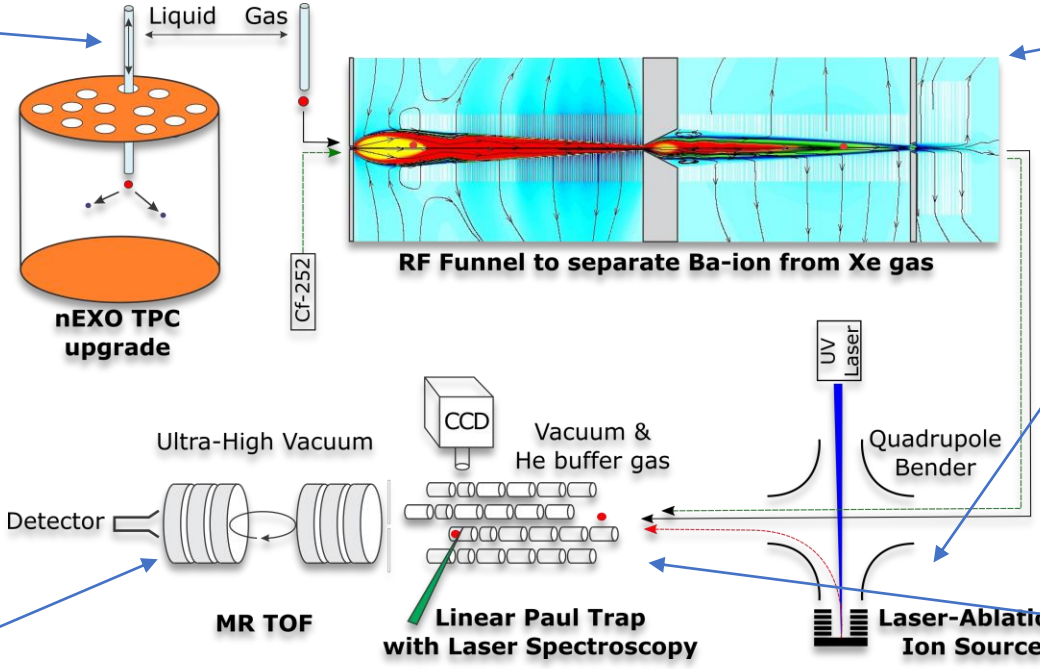
Solution: **Barium tagging**

- Required for the unambiguous detection.
- Detect Ba-136 ion at the position of 0νββ decay.

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

Ba-tagging technique (Canadian approach)

Stage1:
Extraction of detector volume around the location of the decay to gas phase.



Stage2:
RF funnel facilitates separation of xenon accompanying the Barium ion.

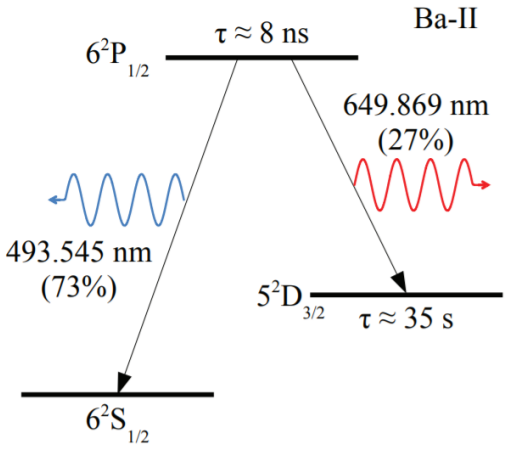
Stage2*:
Serves as source of Barium ion for testing assembly.

Stage3:
The Linear Paul trap for detection of barium ion via laser fluorescence spectroscopy.

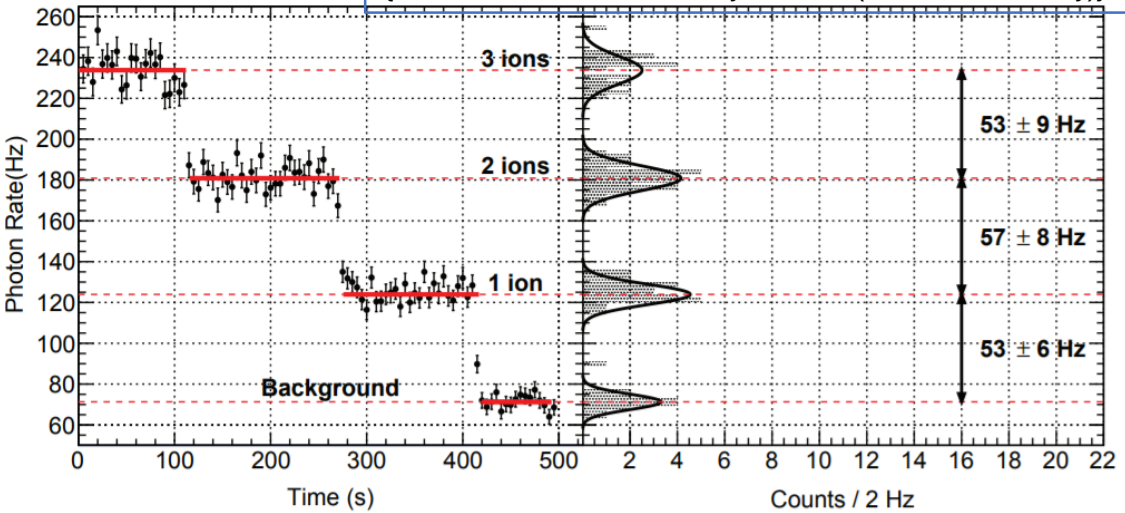
Stage4:
Multiple Reflection TOF Spectrometer for systematic studies and determination of ion mass.

{K. Murray, et al., Hyperfine Interact. 240 (2019) 1, 97}

Single Barium ion detection



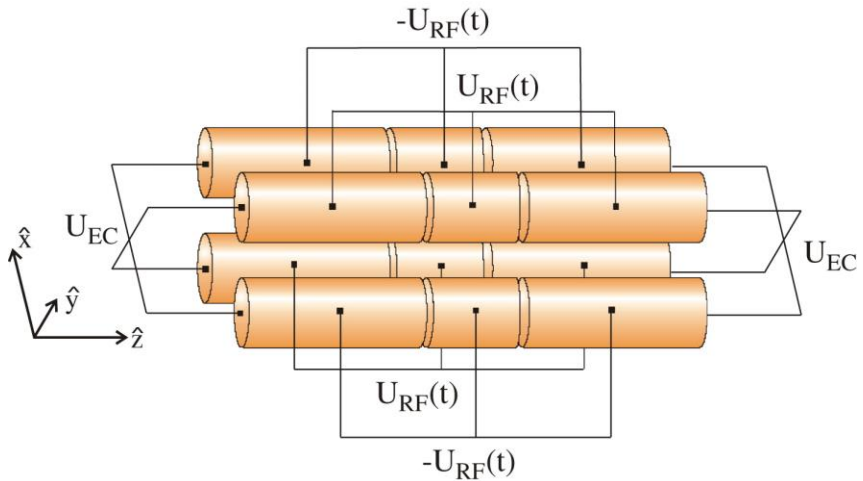
{Retrived from: PhD thesis, Ryan Killick (Carleton University)}



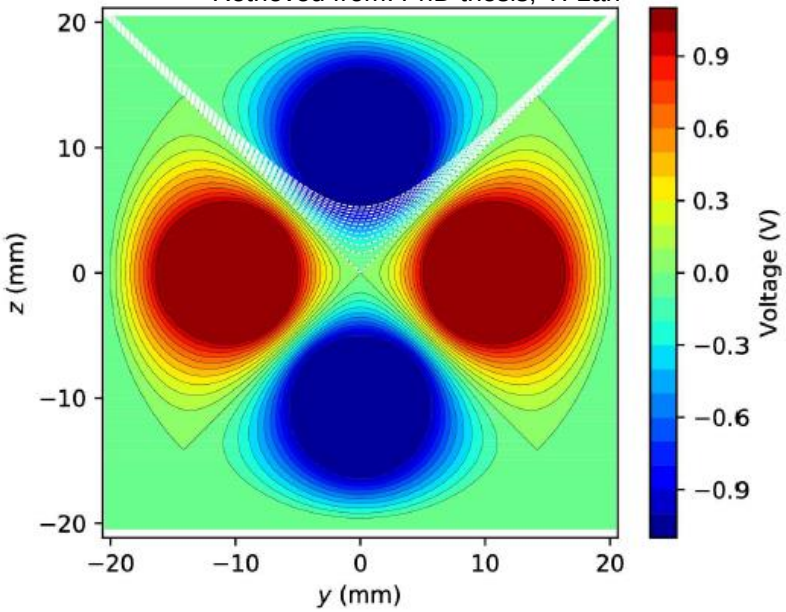
- Uses ion trap for confining ions and laser induced fluorescence for barium ion detection.
- Single ion detection has been demonstrated by collaborators at Carleton University.
- Demonstrated first by M. Green et. al by studying 493nm florescence intensity from single barium ion.

{M.Green, et al., Phys.Rev.A 76 (2007) 023404}

Linear Paul Trap



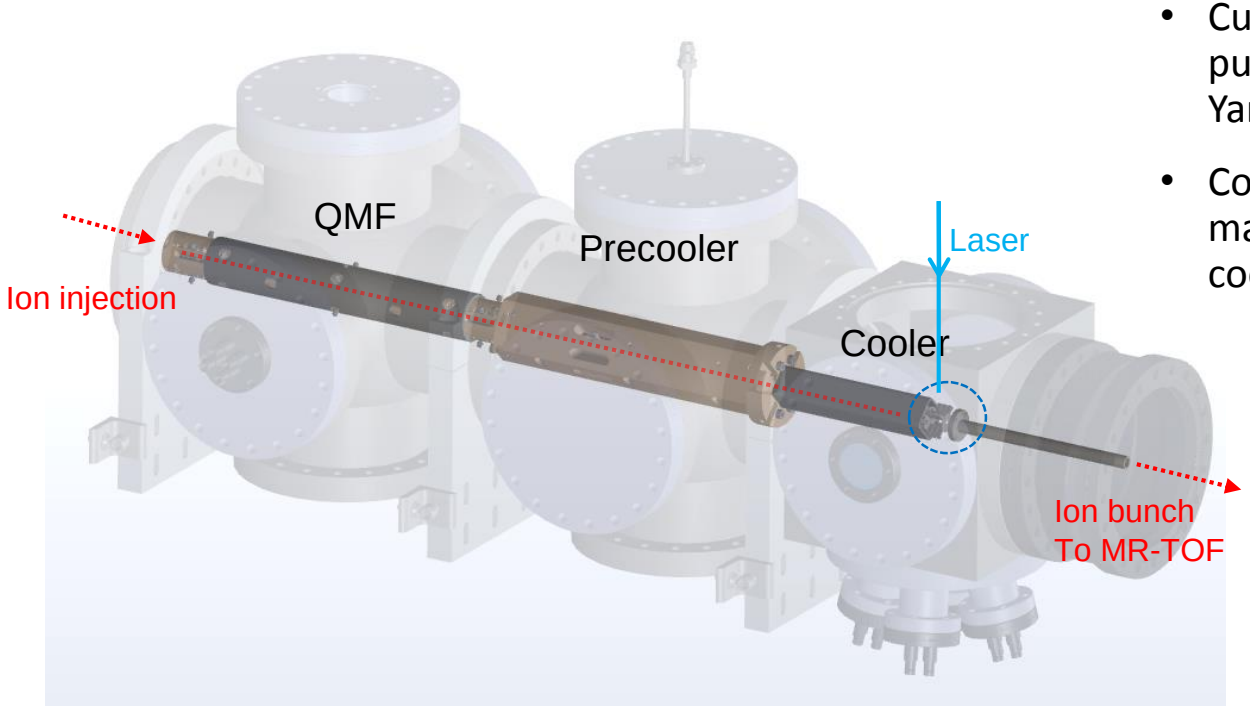
Retrieved from: PhD thesis, Y. Lan



Quadrupolar potential

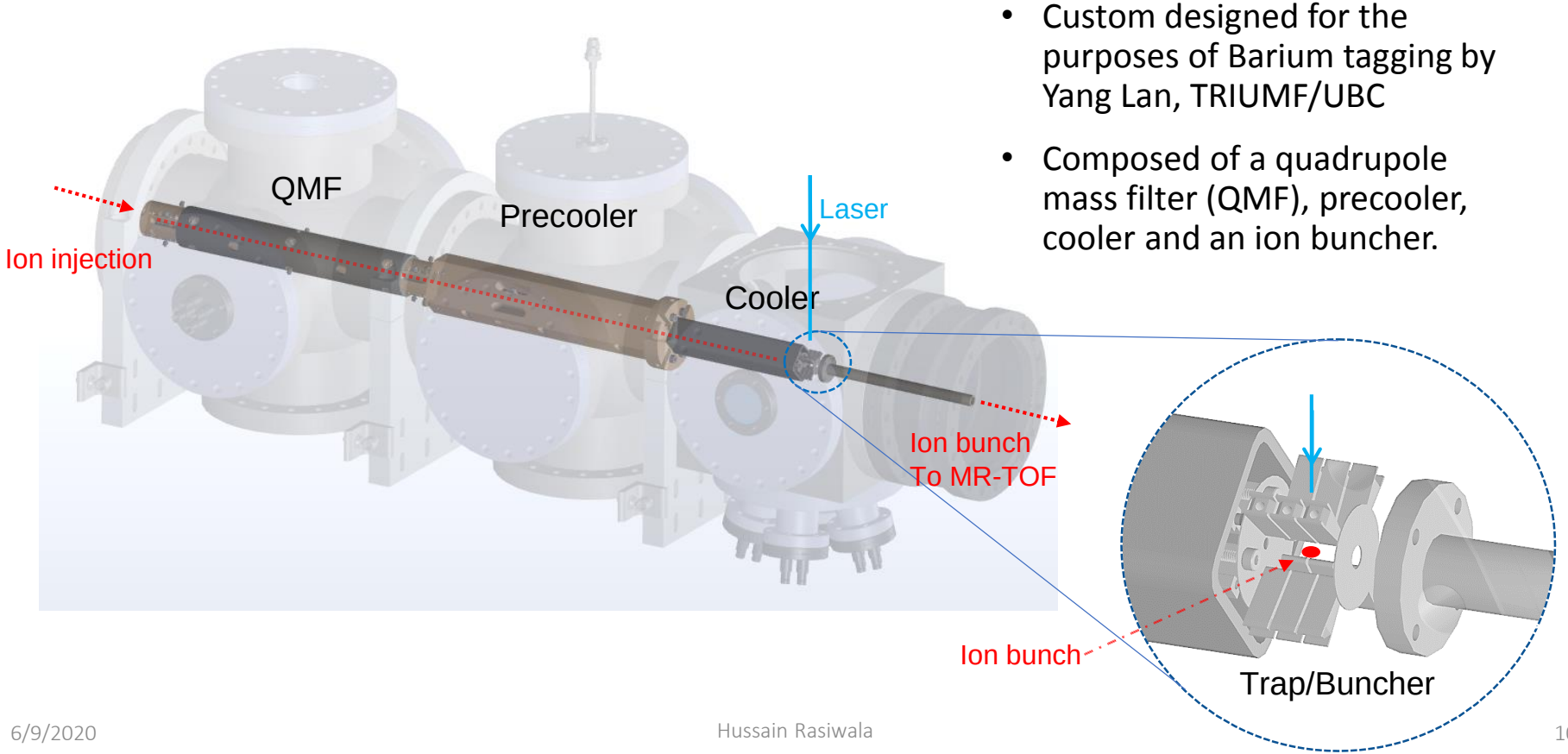
- Manipulation of ions using electric fields.
- Radial confinement using radio-frequency (RF) potentials.
- DC field for directing and confining axial motion.

Linear Paul trap for Ba-tagging



- Custom designed for the purposes of Barium tagging by Yang Lan, TRIUMF/UBC.
- Composed of a quadrupole mass filter (QMF), precooler, cooler and an ion buncher.

Linear Paul trap for Ba-tagging

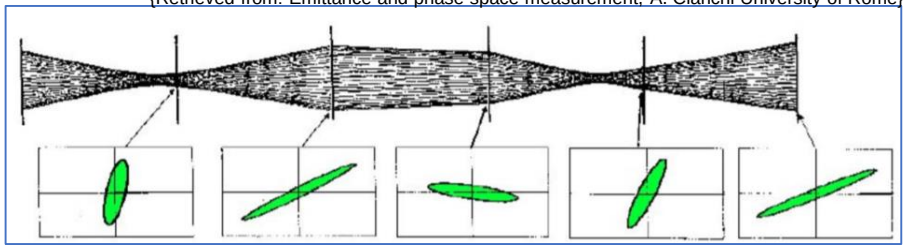


- Custom designed for the purposes of Barium tagging by Yang Lan, TRIUMF/UBC
- Composed of a quadrupole mass filter (QMF), precooler, cooler and an ion buncher.

Ion cooling

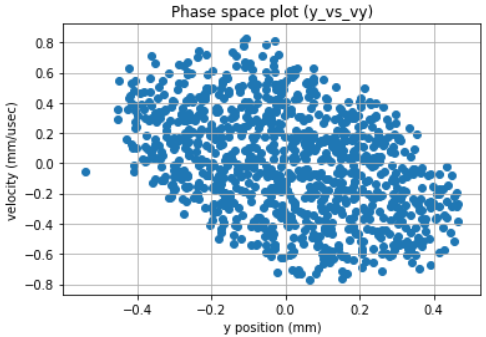
- RF potential confines ion radially.
- Buffer gas cools the ions, ions get thermalized by the time they reach towards the end.

{Retrieved from: Emittance and phase space measurement, A. Cianchi University of Rome}

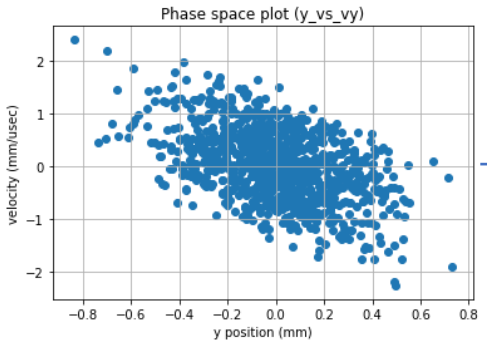


Schematic showing evolution in phase space.
(Liouville theorem), the phase space density doesn't change under the action of conservative forces.

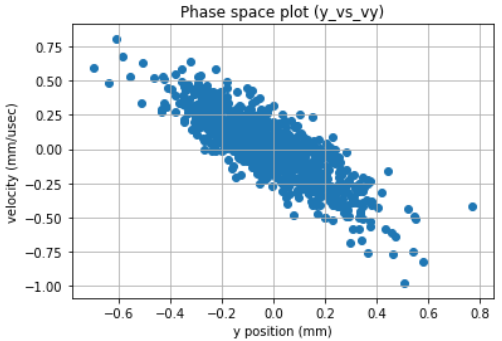
→ Injected ions



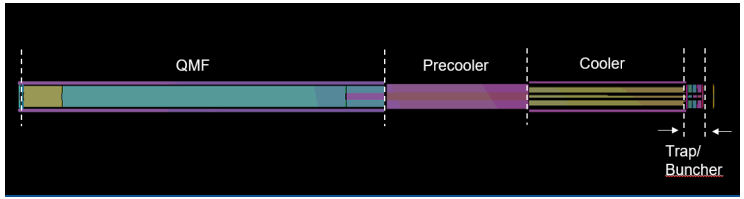
To Precooler

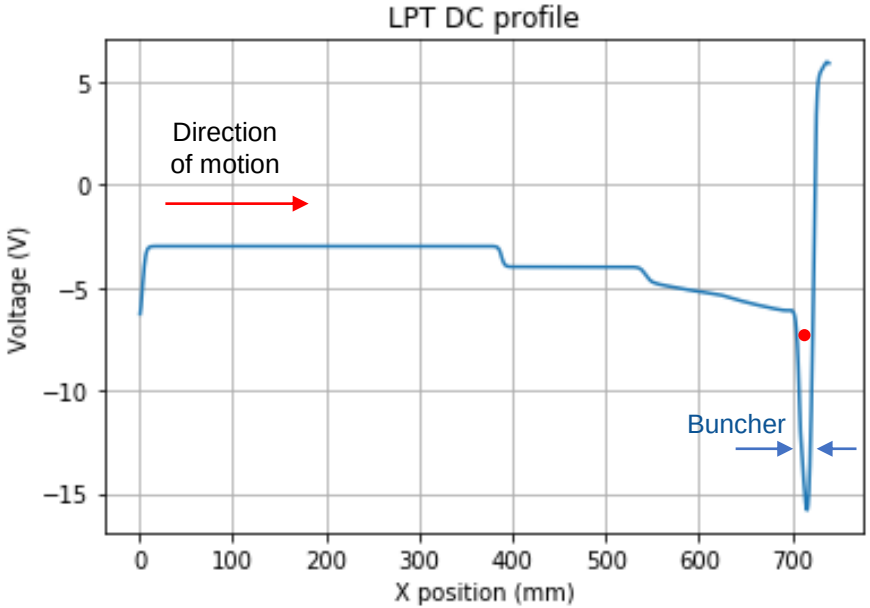


To Cooler

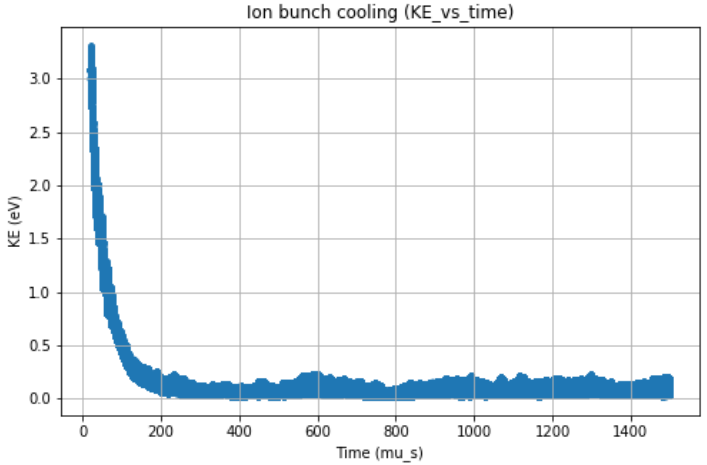


Axial drift and trapping

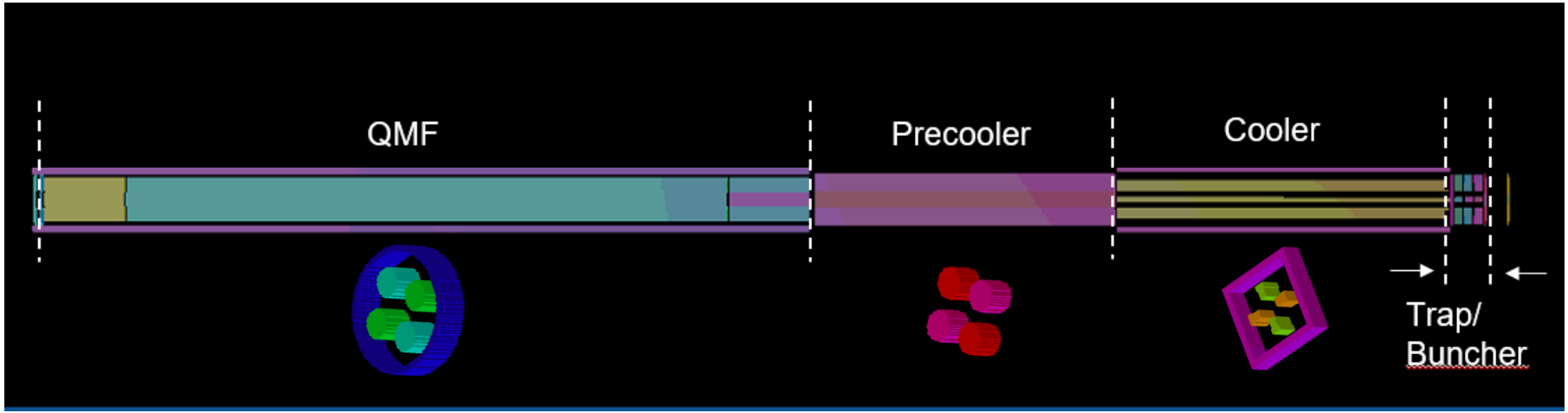




- Injected ions entering from x = 0mm travel down the potential towards the buncher.
- Trapped ions are then cooled collisional with helium gas.
- Equilibrium is established between buffer gas cooling and RF heating.



Components in the LPT



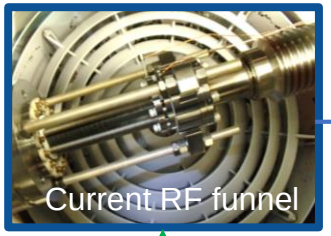
QMF:
Perform filtering of incoming ions based on their mass-charge ratio.

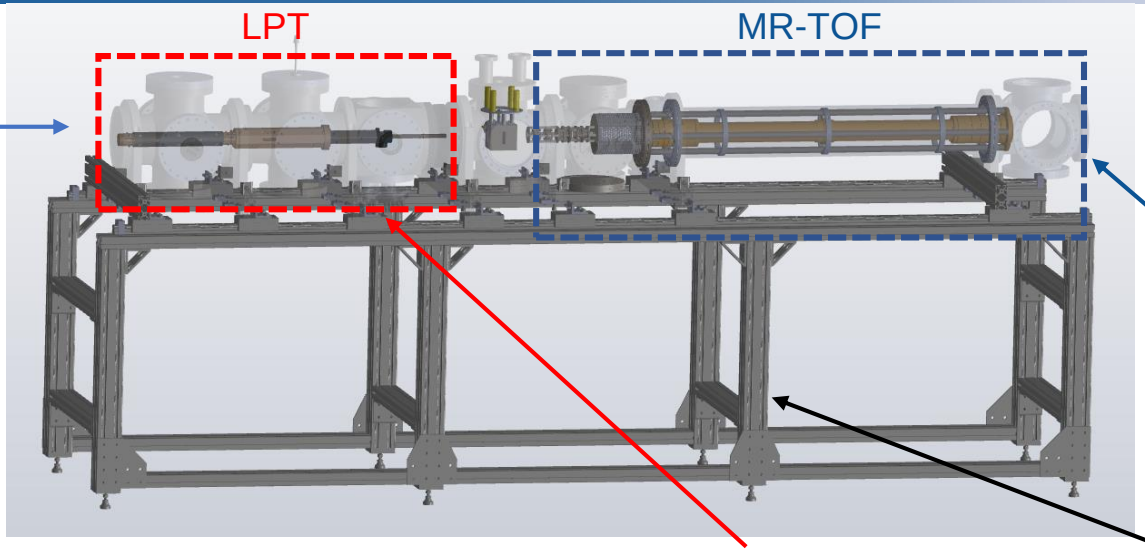
Precooler:
- Required for differential pumping.
- Acts as ion guide for filtered ions.

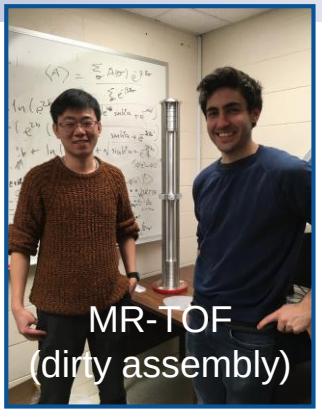
Cooler:
- Helium buffer axially cools incoming ions.
- Tapering electrode provide axial drift field.

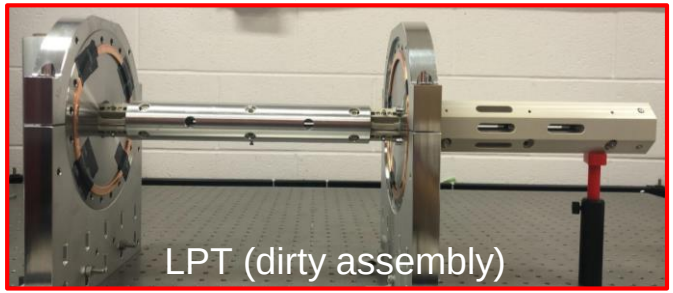
Buncher:
- Trapped ions are further cooled down and bunched.
- Perform laser spectroscopy on stored ions.

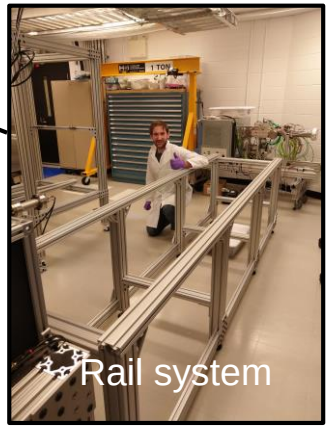
Ba-tagging status at McGill











- In-gas Ion source: M. Medina Peregrina
- Linear Paul trap: Y. Lan, H. Rasiwala, X. Shang
- MR-TOF: K. Murray
- Rail system: C. Chamber

Summary and future outlook

- nEXO is a next generation 0νββ detector with a projected sensitivity for Xe-136 half-life of close to 10^{28} yr.
- Ba-tagging as an upgrade to nEXO for explicit detection of barium ion.
- Upgrade activities and goals following restart of research at McGill:
  - Upgrade current RF funnel to a 3-stage RF funnel
  - Begin commissioning of the LPT and MR-TOF
- Next year, we will be able to show results once assembling is done.

nEXO Collaboration, June 2019

nEXO

TRIUMF · THE UNIVERSITY OF BRITISH COLUMBIA · Laurentian University / Université Laurentienne · Carleton University · McGill · Université de Sherbrooke

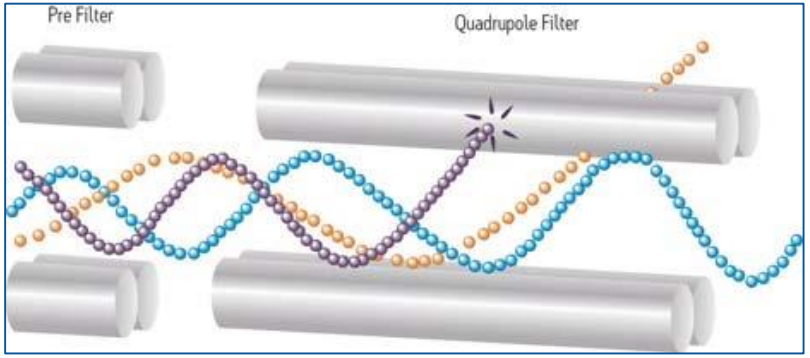
Extra slides

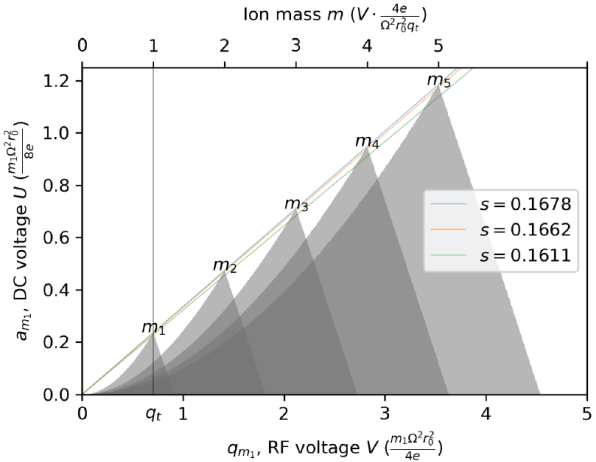
Quadrupole mass filter

DC coupled RF frequency voltages filter ions based on (m/q) ratio.

$$q = q_y = -q_z = \frac{4eV}{m\Omega^2 r_0^2} \qquad a = a_y = -a_z = \frac{8eU}{m\Omega^2 r_0^2}$$

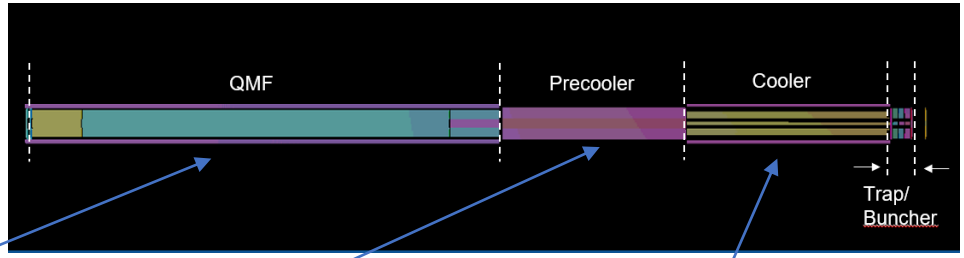
- Based on selection of trajectory parameters (a,q), DC and RF amplitudes are scaled for selective passage on specific ions.
- Pre filter facilitates ramping of RF field to avoid track instabilities due to fringing fields.



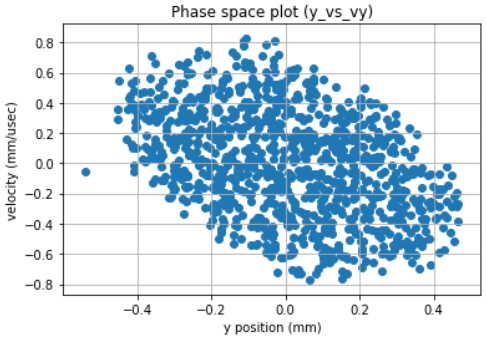


Ion cooling

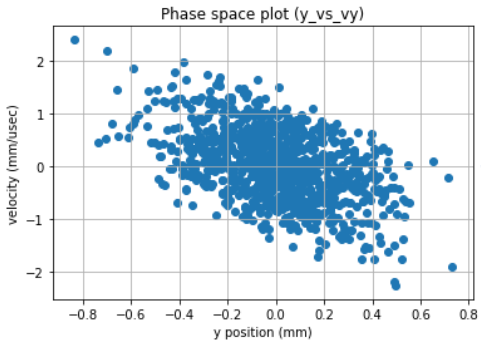
- RF potential confines ion radially
- Buffer gas cools the ions, ions get thermalized by the time they reach towards the end.



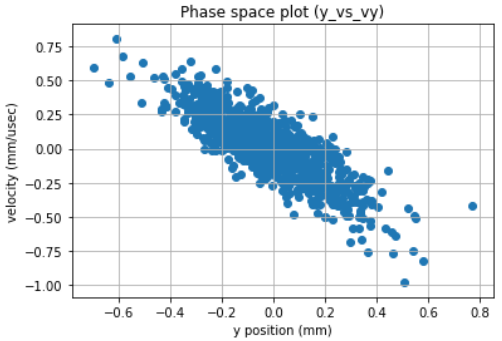
→ Injected ions



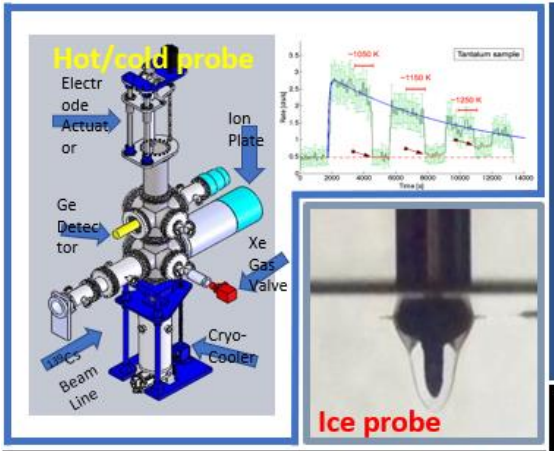
To Precooler

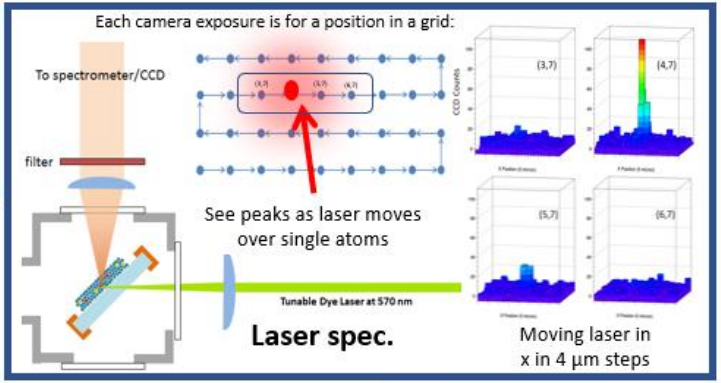


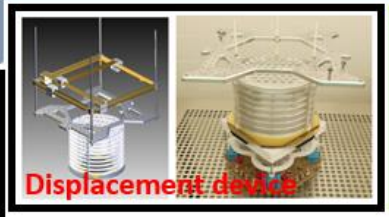
To Cooler

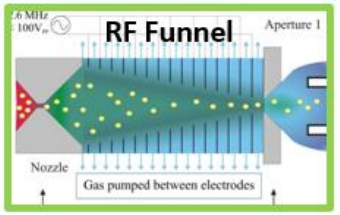


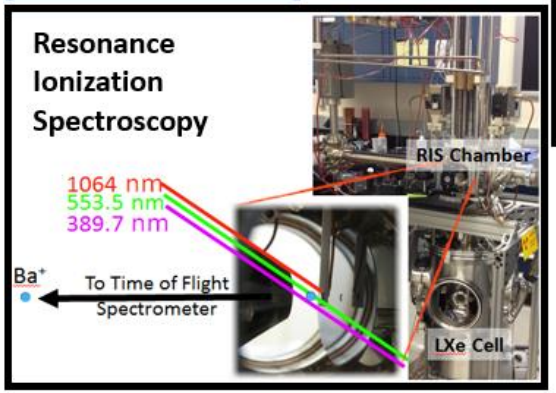
Ba-tagging technique











Recent nEXO Ba-tagging publications

Imaging individual Ba atoms in solid xenon for barium tagging in nEXO
C. Chambers, et al., *arXiv:1806.10694*, *Nature 569, 203 (2019)*.

An RF-only ion-funnel for extraction from high-pressure gases
T. Brunner, et al., *Int. J. Mass Spec. 379, 110 (2015)*, *arXiv:1412.1144*.

Spectroscopy of Ba and Ba+ deposits in solid xenon for barium tagging in nEXO
B. Mong, et al., *Phys. Rev. A 91, 022505 (2015)*, *arXiv:1410.2624*.

An apparatus to manipulate and identify individual Ba ions from bulk liquid Xe
K. Twelker et al., *Rev. Sci. Instrum. 85, 095114 (2014)*, *arXiv:1407.0618*.

Slide credits:
Thomas Brunner, SLAC
FPD Experimental seminar, Mar 3 2020

Image of trapped barium ion