Ba-ion extraction and identification for 0νββ searches in liquid xenon

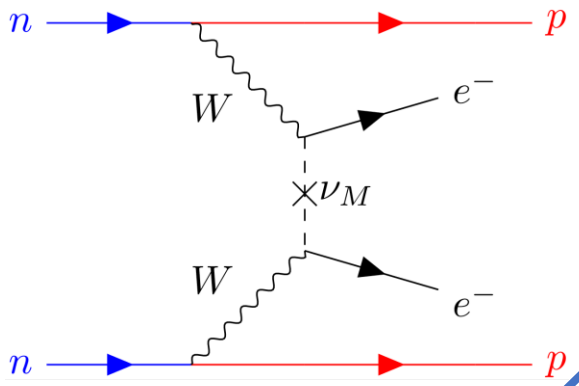
Thomas Brunner

McGill University

May 11, 2023

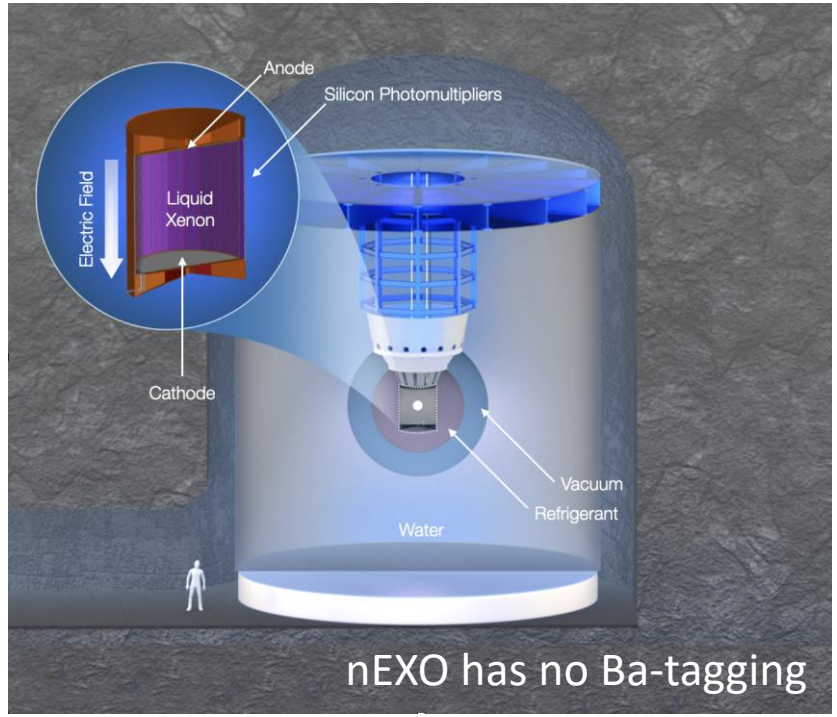
The nEXO Search for 0νββ

- An ultra-low background 0νββ search in ^{136}Xe.



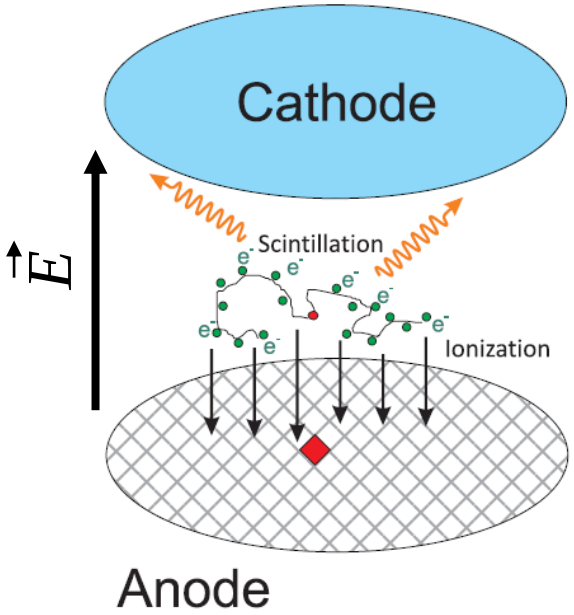
Can future 0νββ searches be improved by identifying, i.e., "tagging", the decay daughter?

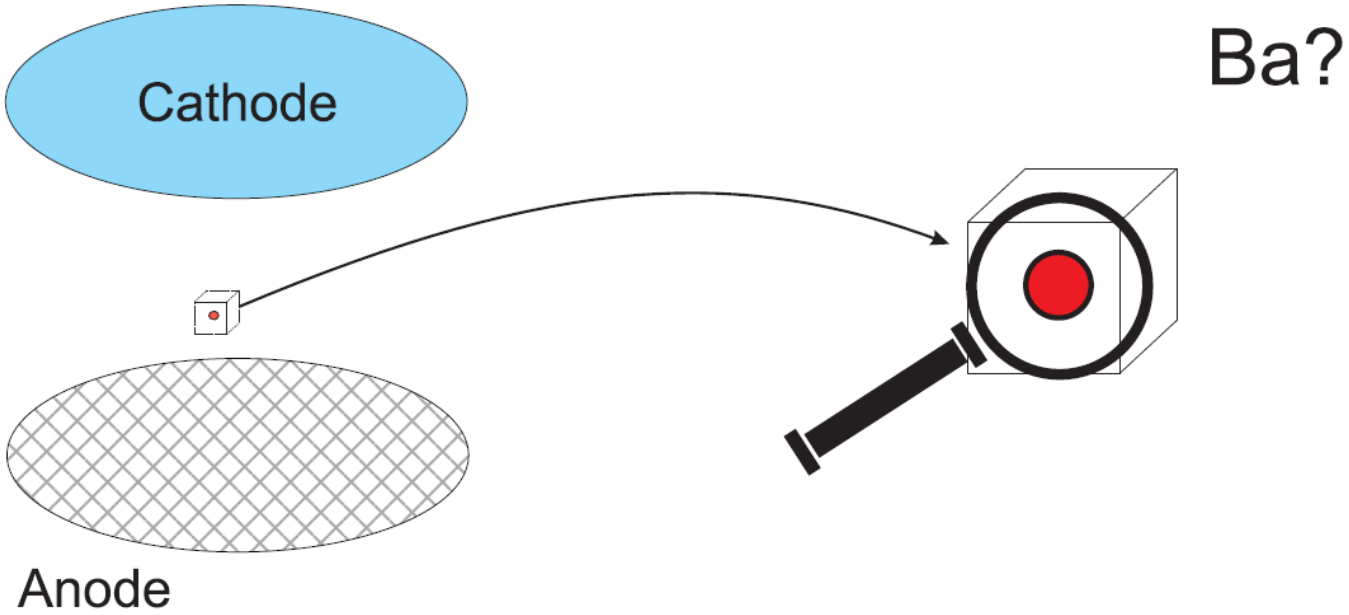
$$^{136}Xe \rightarrow {}^{136}Ba^{++} + 2e^{-}$$



- Proposed experiment, 5-tonne liquid Xe Time Projection Chamber (TPC), enriched to 90% in ^{136}Xe.
- Projected 90% C.L. sensitivity 1.35 x 10^{28} yrs after 10 years data taking (J.Phys.G 49 015104 (2022)).
- Observation of 0νββ would violate Lepton number in weak decays and demonstrate the Majorana nature of neutrinos.

What Is Barium Tagging?





Localization

- Reconstruct energy and position of each event in TPC.
- If ββ-like event in window around Q value: Classify event as 0νββ decay event candidate.

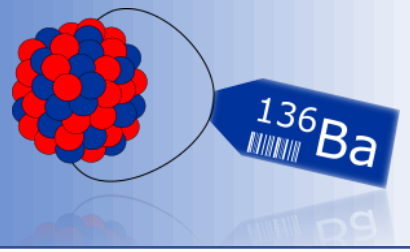
Extraction

- Extract volume surrounding the potential 0νββ-decay event from detector vessel.
- Extract potential ββ-decay daughter ^{136}Ba with this volume.

Identification

- Probe extracted volume for the presence of Ba(+).
- Positive ⇒ consider event for 0νββ search.
- Negative ⇒ classify event as background event.

Why Is Barium Tagging of Interest?



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

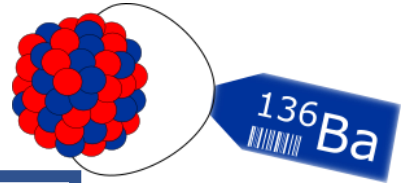
Barium Tagging

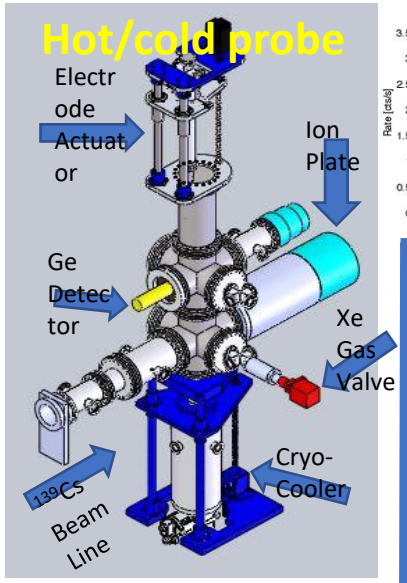
Advantages of Ba-Tagging:

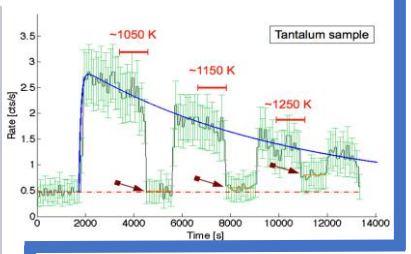
- Potential for **complete** background elimination, except from 2νββ decays
- For nEXO type detector, it could increase the sensitivity by factor of 2-3
- Provides **POSTITIVE** confirmation of ββ decay

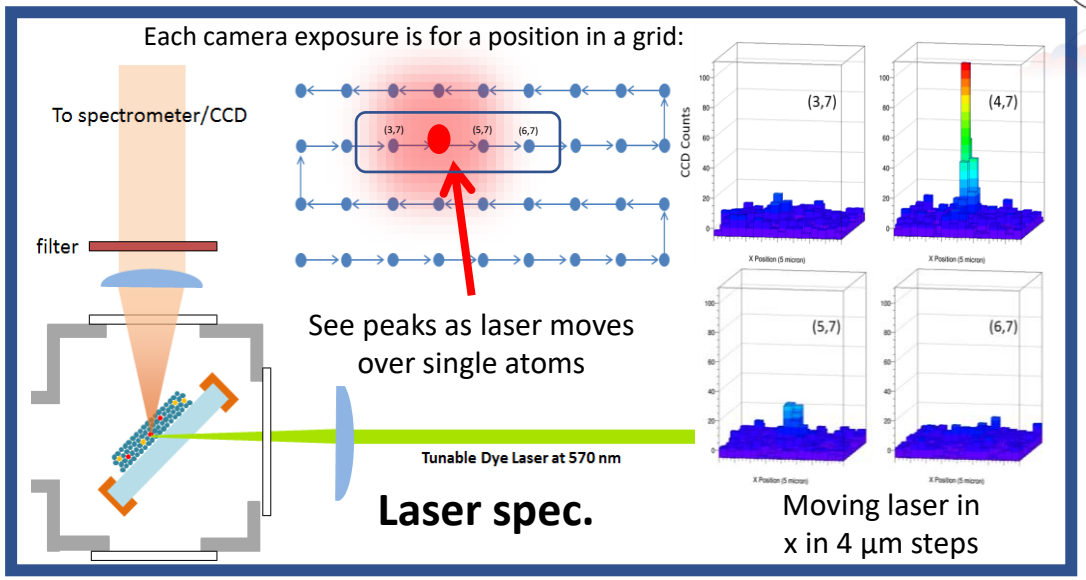
Requires counting of ***single*** Ba daughter in macroscopic amount of Xe

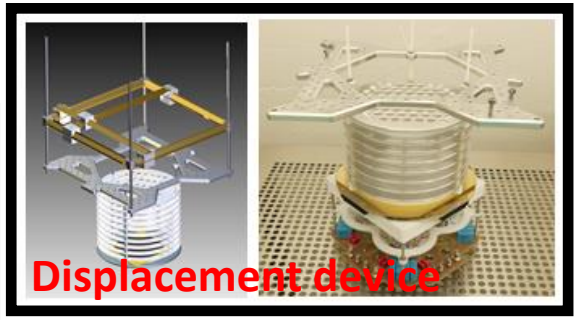
Ba tagging for nEXO – a multi-facetted approach

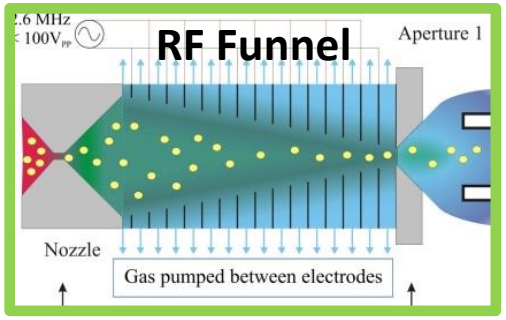


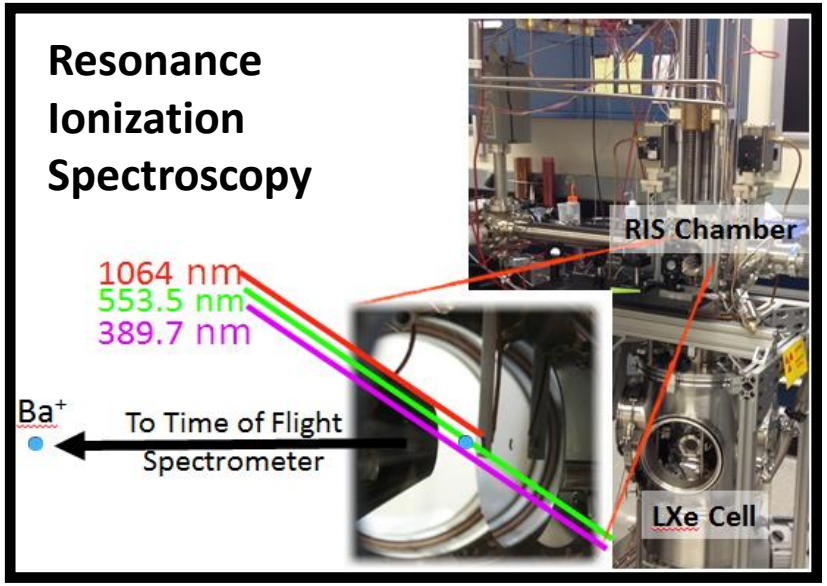












Recent nEXO Ba-tagging publications

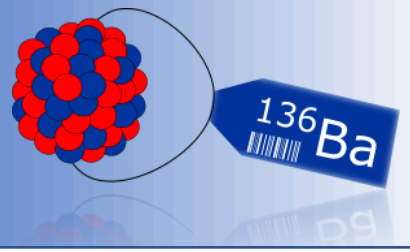
Imaging individual Ba atoms in solid xenon for barium tagging in nEXO
C. Chambers, et al., *arXiv:1806.10694, Nature 569, 203 (2019).*

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.*

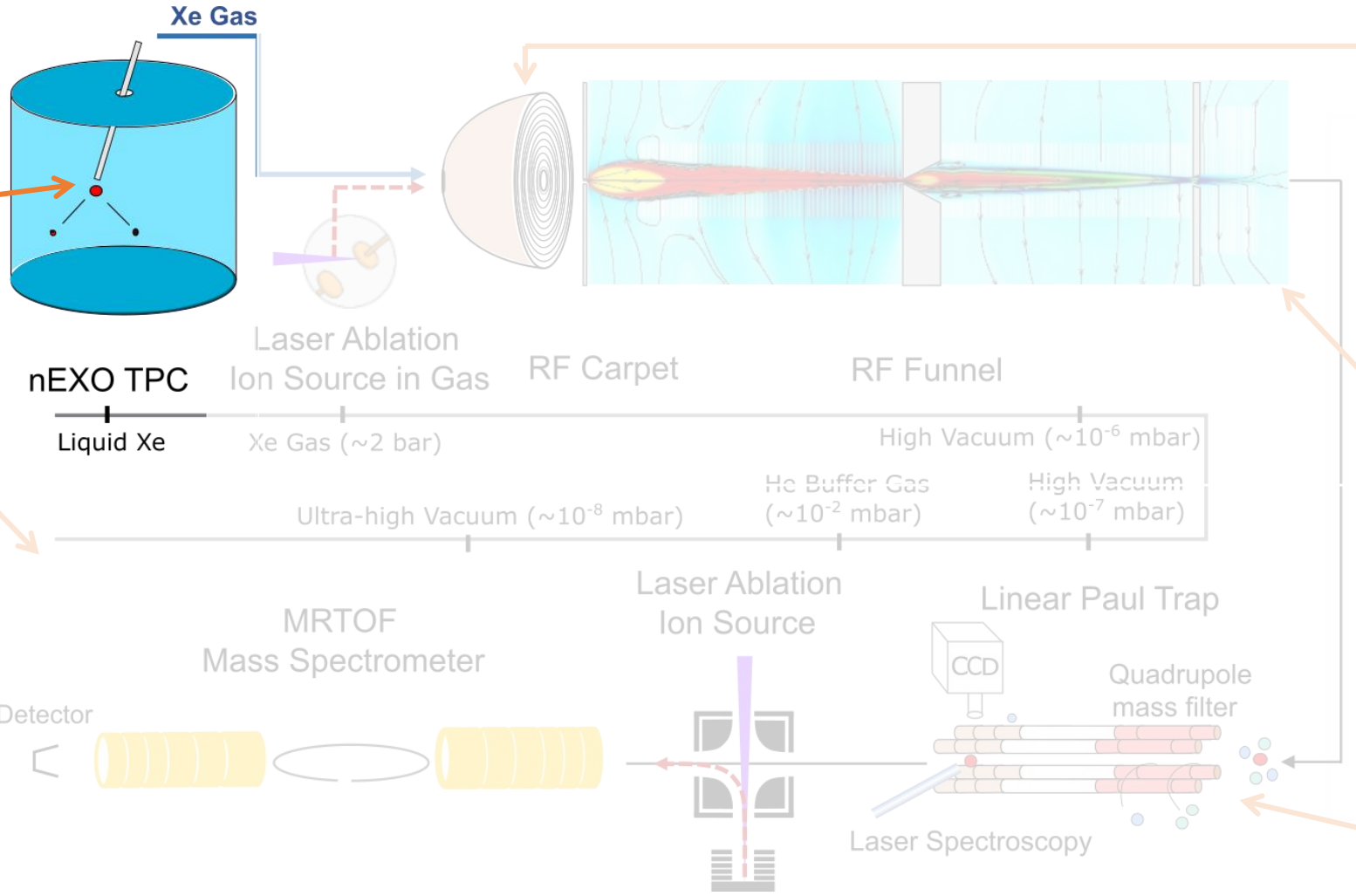
Spectroscopy of Ba and Ba$^+$ deposits in solid xenon for barium tagging in nEXO
B. Mong, et al., *Phys. Rev. A 91, 022505 (2015), arXiv:1410.2624.*

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.*

The Canadian Barium Tagging Concept



Stage 1:
A small volume of LXe is extracted around the decay location and changed to gas phase by a capillary.



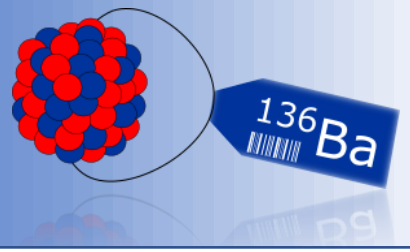
Stage 2:
The RF Carpet transports the ion from the capillary to the RF Funnel.

Stage 3:
The RF Funnel separates ions from neutral particles and transports them to the Linear Paul Trap (LPT) .

Stage 4:
The LPT detects the Ba ion with laser fluorescence spectroscopy, then cools and bunches ions for ejection to the MRTOF.

Stage 5:
The Multiple reflection time-of-flight (MRTOF) mass spectrometer is used for systematic studies of the extraction technique and mass determination of the Ba ion. Mass-resolving Power (MRP) of 50000 need to separate ^{136}Ba from ^{136}Xe.

The Canadian Barium Tagging Concept



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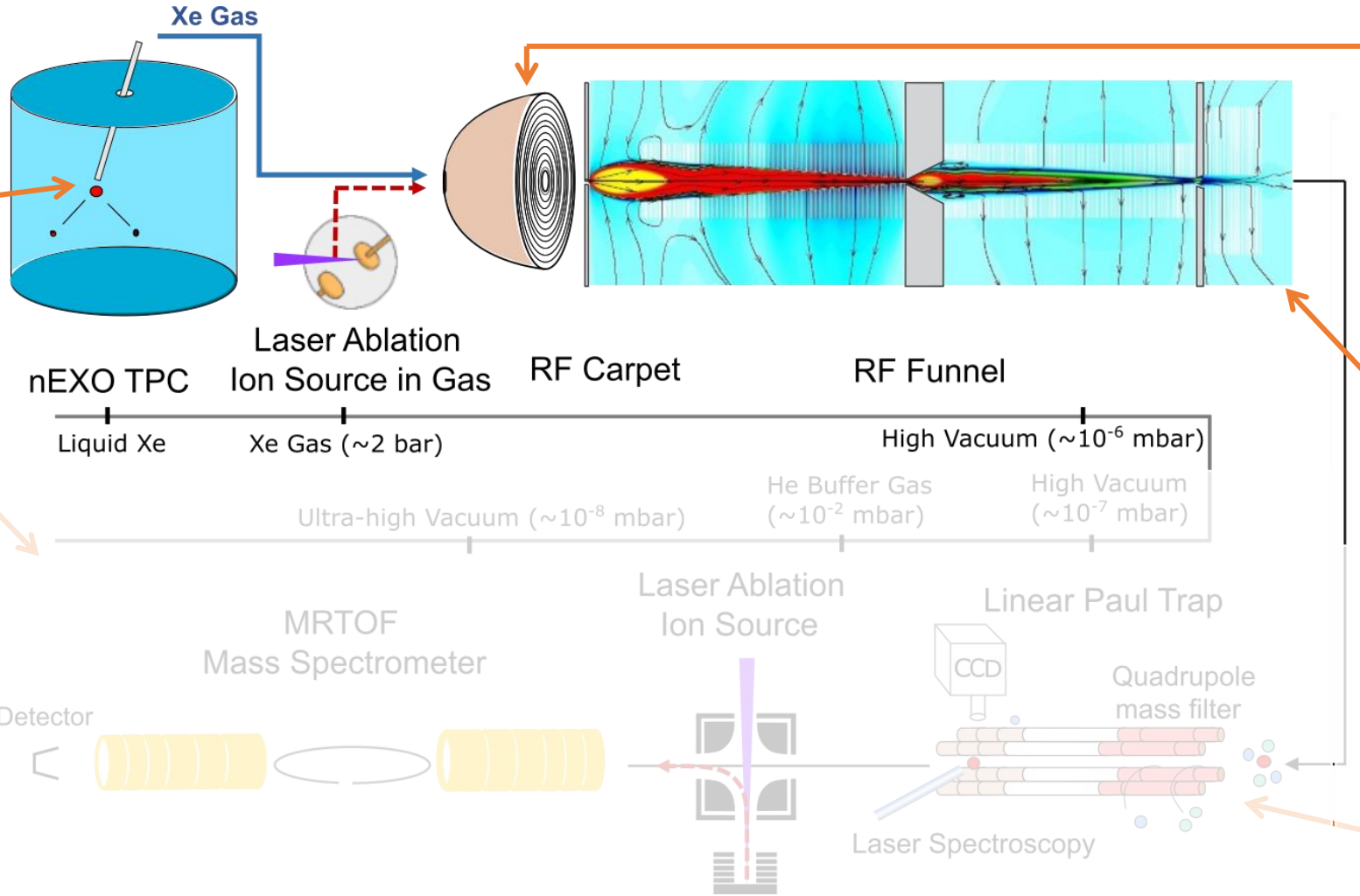

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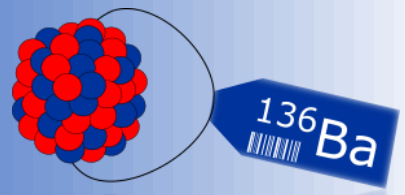

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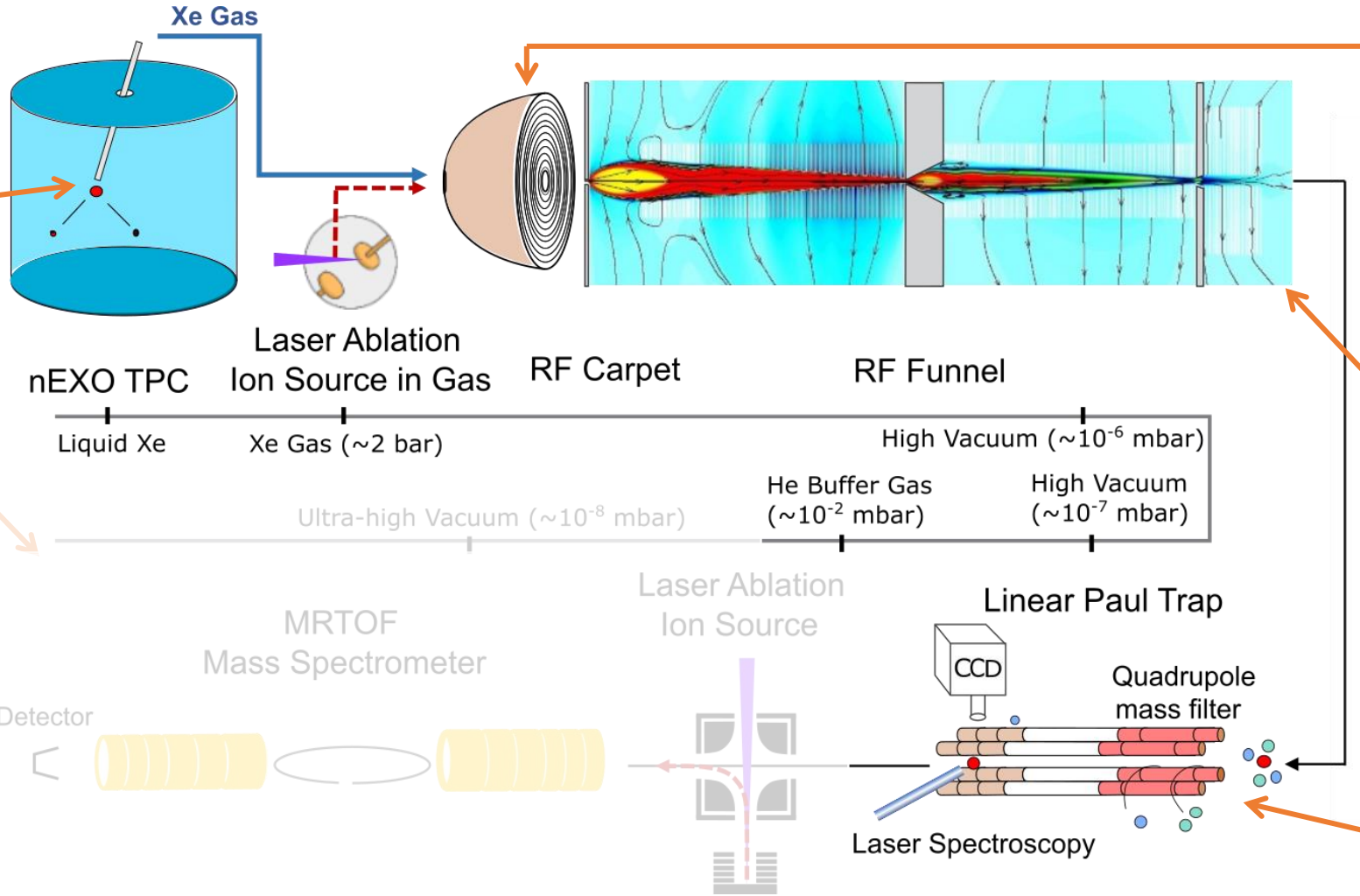

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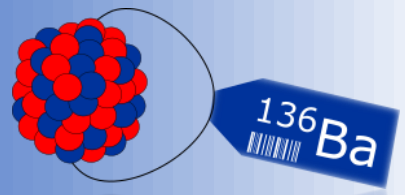

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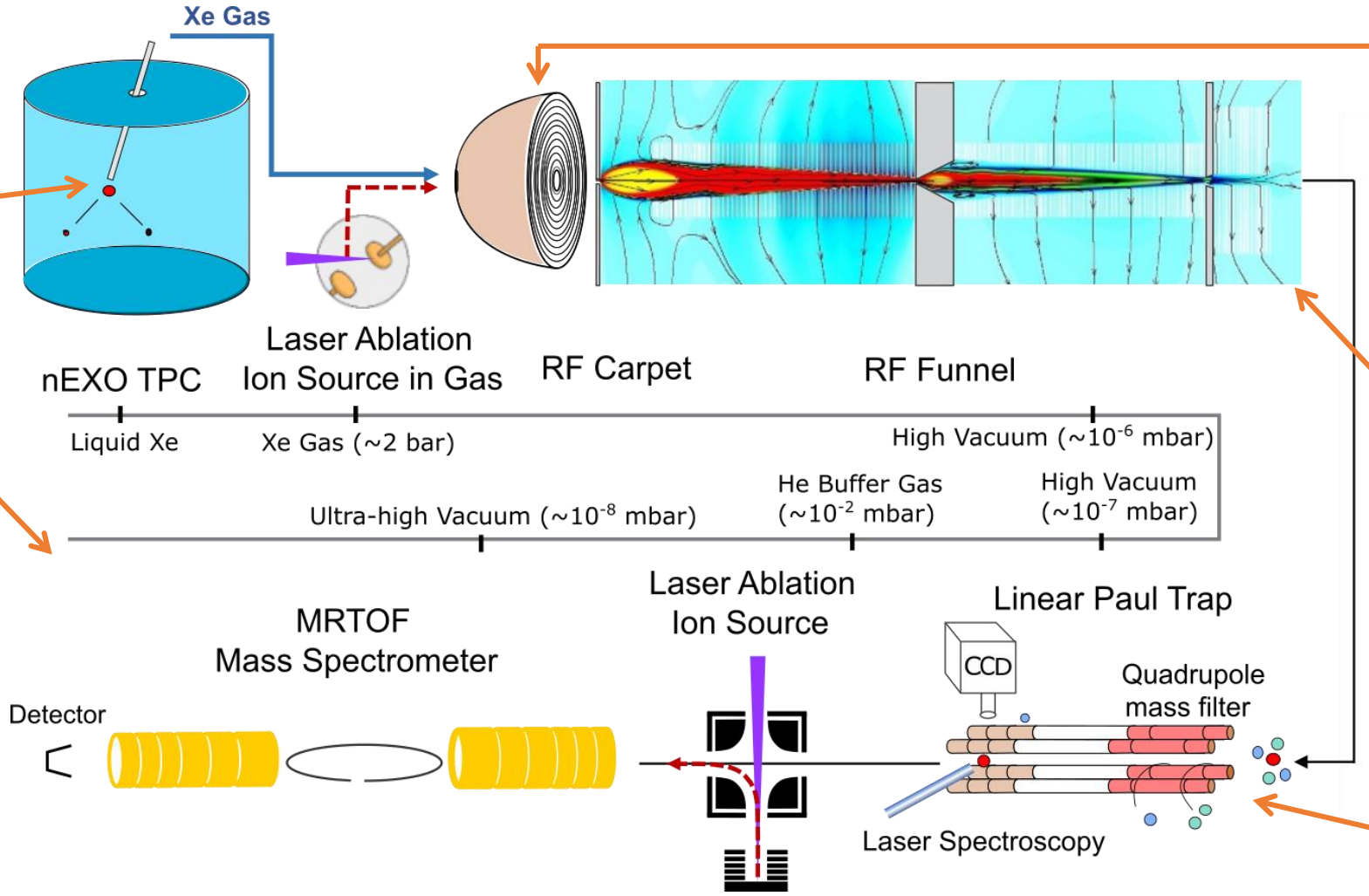

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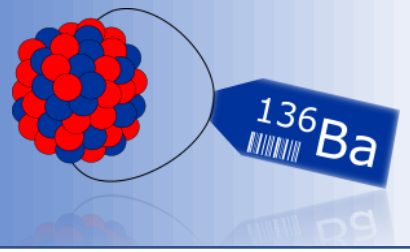
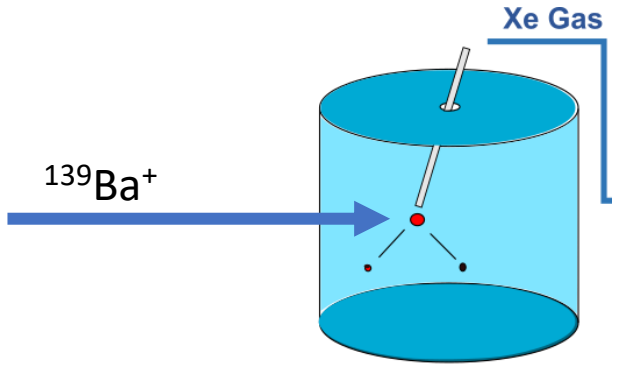
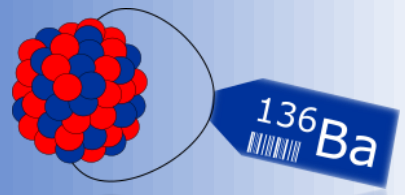


In liquid Xe (LXe) Ba-ion source development

TRIUMF
Megan Cvitan, Ania Kwiatkowski, Annika Lennarz, Dwaipayan Ray, and undergraduate students
McGill University
Thomas Brunner



Accelerator driven Ba-ion source R&D

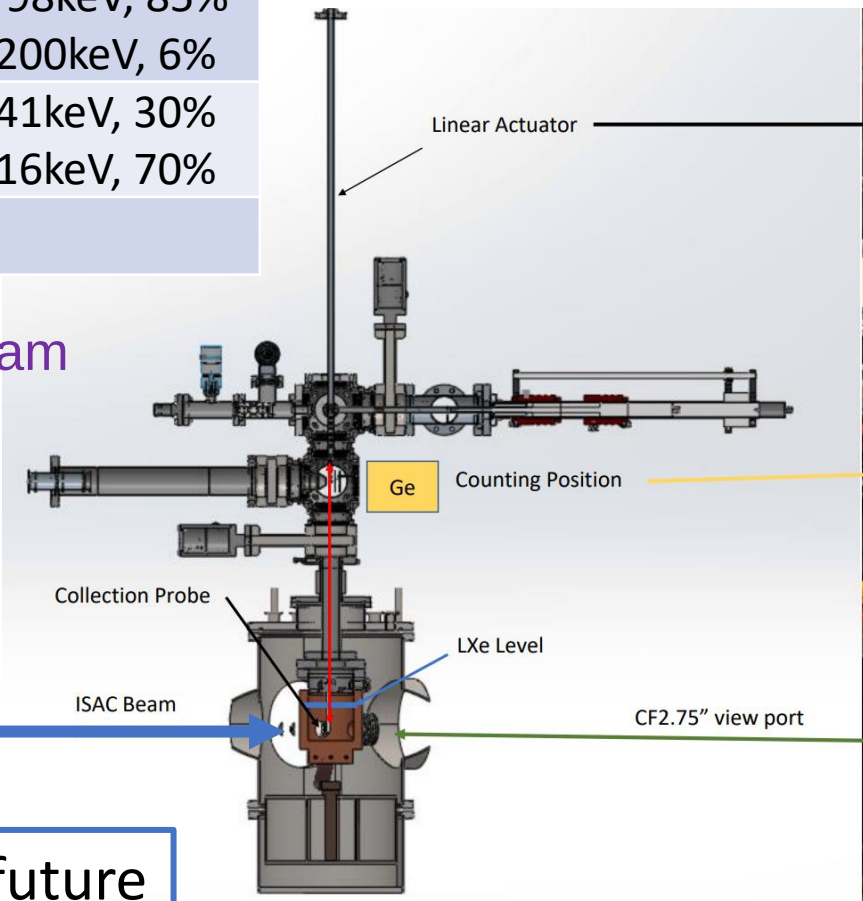


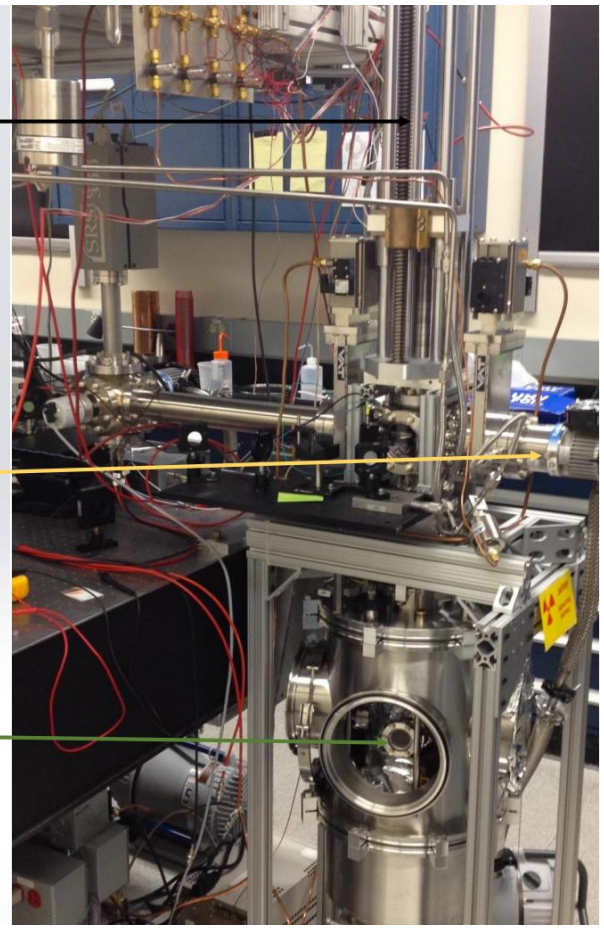
Isotope	$T_{1/2}$	Yield [pps]	#shifts (8hrs)	γ lines
^{139}Cs	9.27 min	~1-2x10^{8}	3	1798keV, 85% 1200keV, 6%
^{139}Ba	1.38 hr	~5x10^{7}	3	841keV, 30% 916keV, 70%
^{138}La	stable			

- 2 - 10 MeV/u beam energy
- Commissioning planned for fall 2023 (S2131LOI)

- Inject radioactive ^{139}Cs (and/or ^{139}Ba) beam into LXe using TRIUMF's ISAC II beam.
- Collect radioactive ions on electrostatic probe, remove them from LXe.
- Ge counter for identification.

Coupled to TRIUMF
ISAC II beam

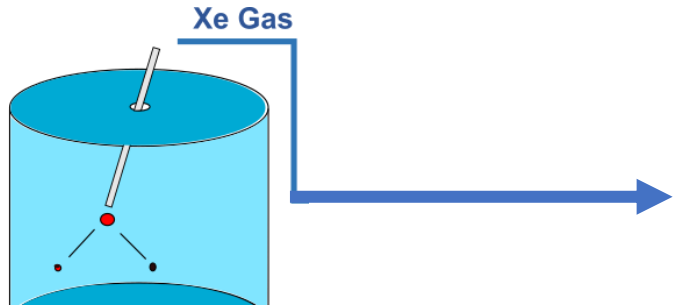




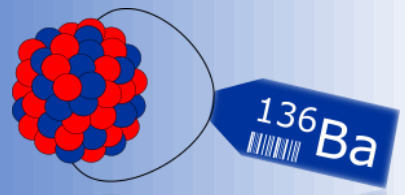
Goal: develop in-LXe Ba-ion source for future demonstration of extraction efficiency.

Displacement device and capillary R&D

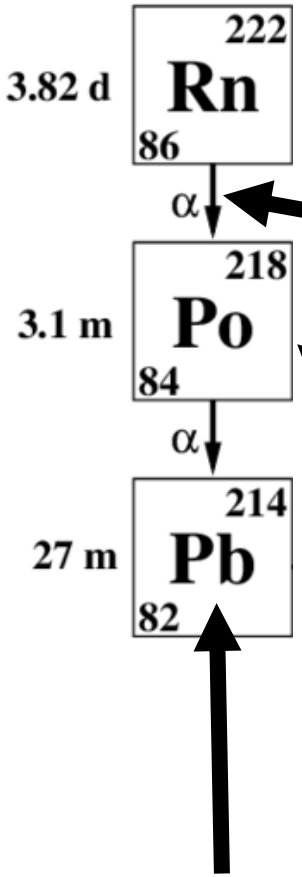
Carleton University
Rob Collister, R. Elmansali, Razvan Gornea, Thomas Koffas, R. Shaikh
and undergraduate students



Ion extraction and transport from liquid xenon TPC



Dissolved in LXe in EXO-100



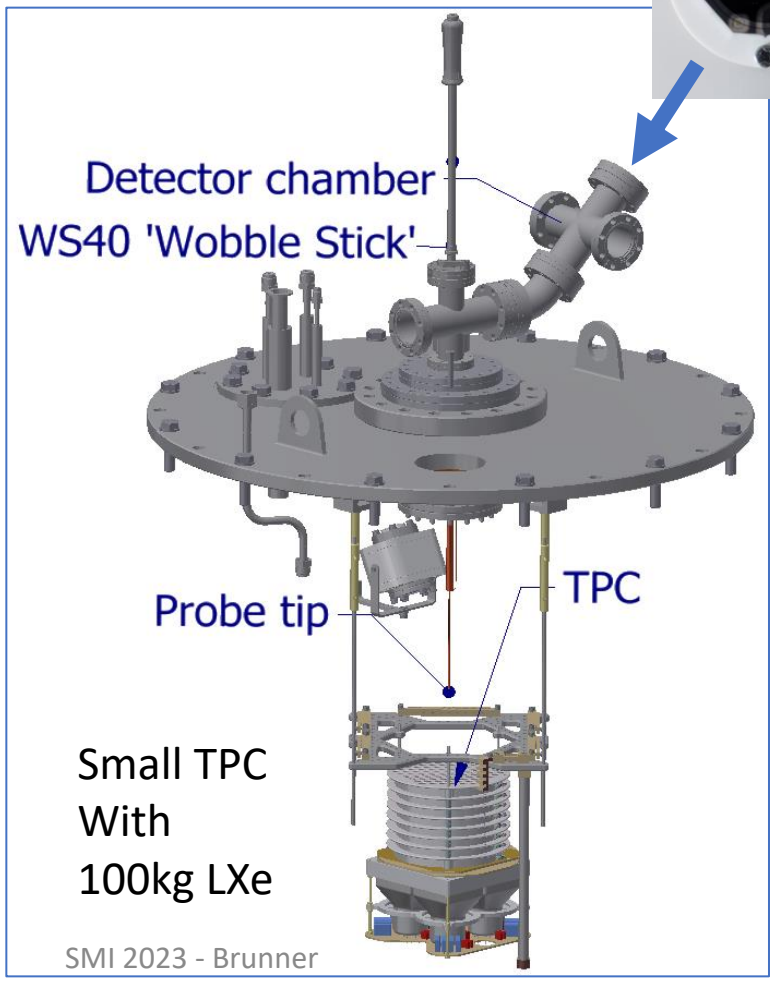
Distinctive signature detected by TPC; location determined for extraction

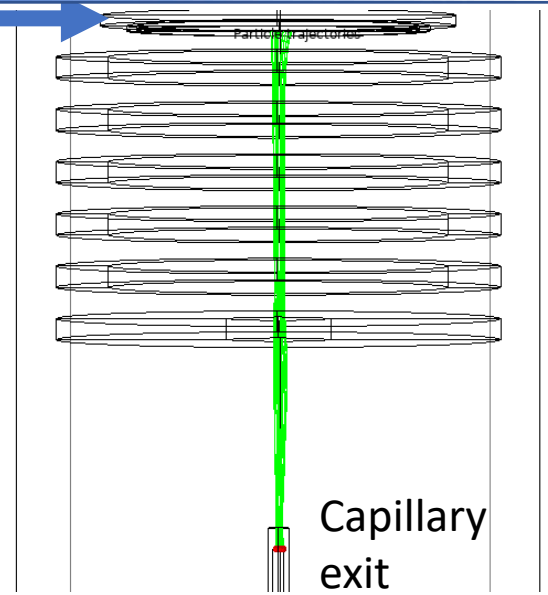
Ion extracted by capillary, transported to PIPS detector with high efficiency

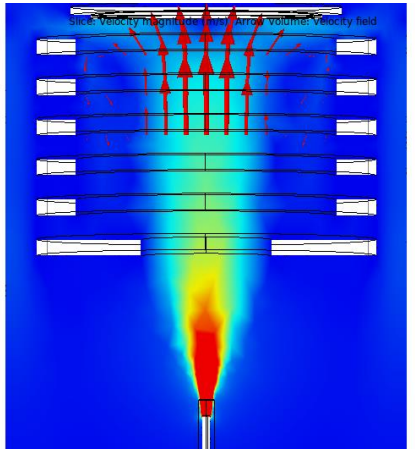
Decay identified by energy deposited in PIPS

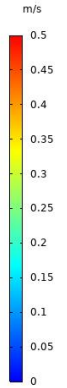
Setup under construction. Commissioning in summer 2023.

PIPS detector



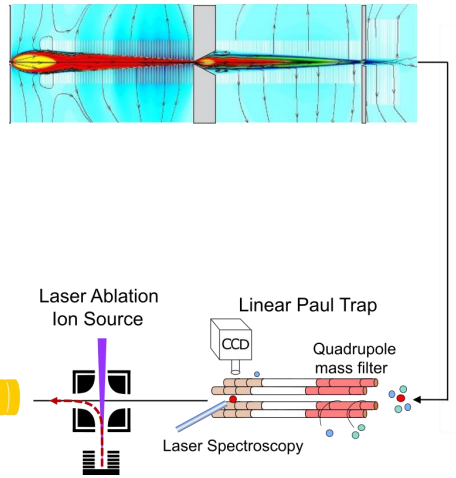




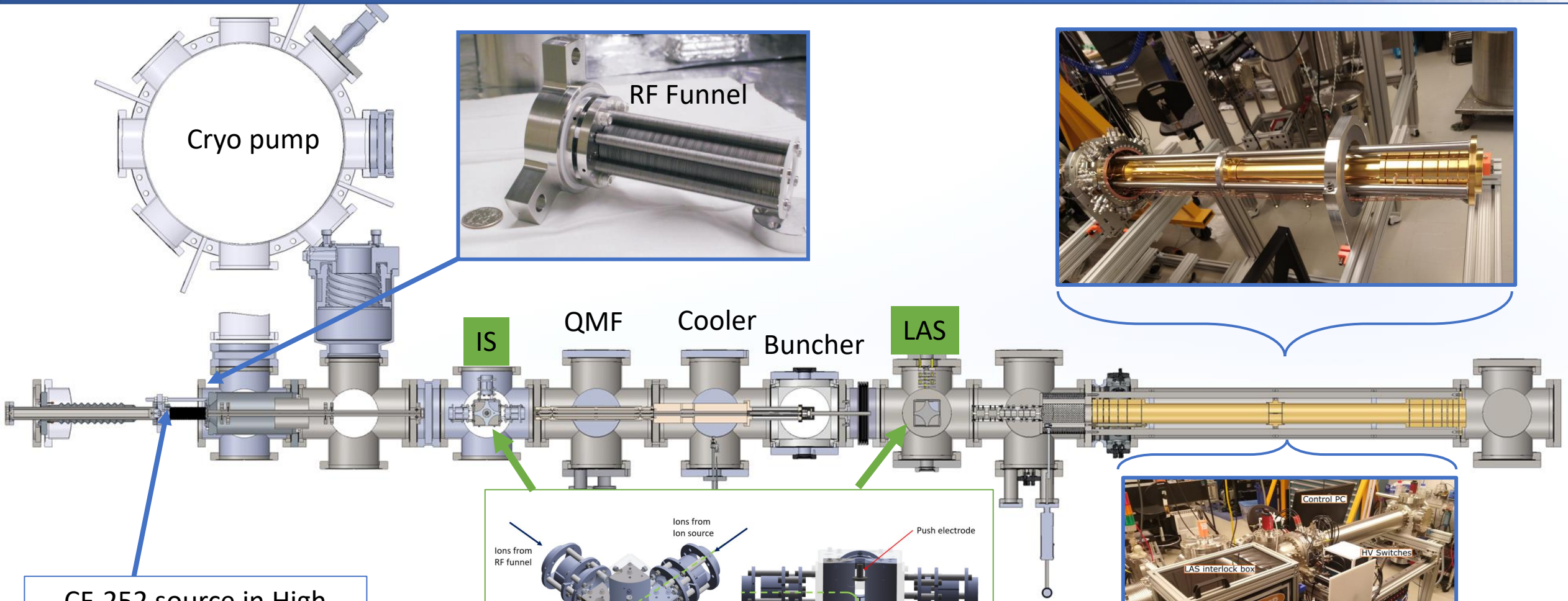


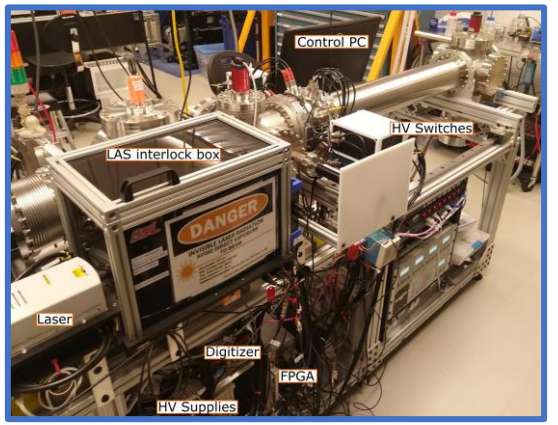
RF-Funnel Ion Extraction and Identification

TRIUMF
Ania Kwiatkowski, Yang Lan, Jens Dilling
McGill University
Thomas Brunner, Chris Chambers, Yuta Ito, Kevin Murray, Hussain Rasiwala, and undergraduate students
ITEP
Victor Varentsov



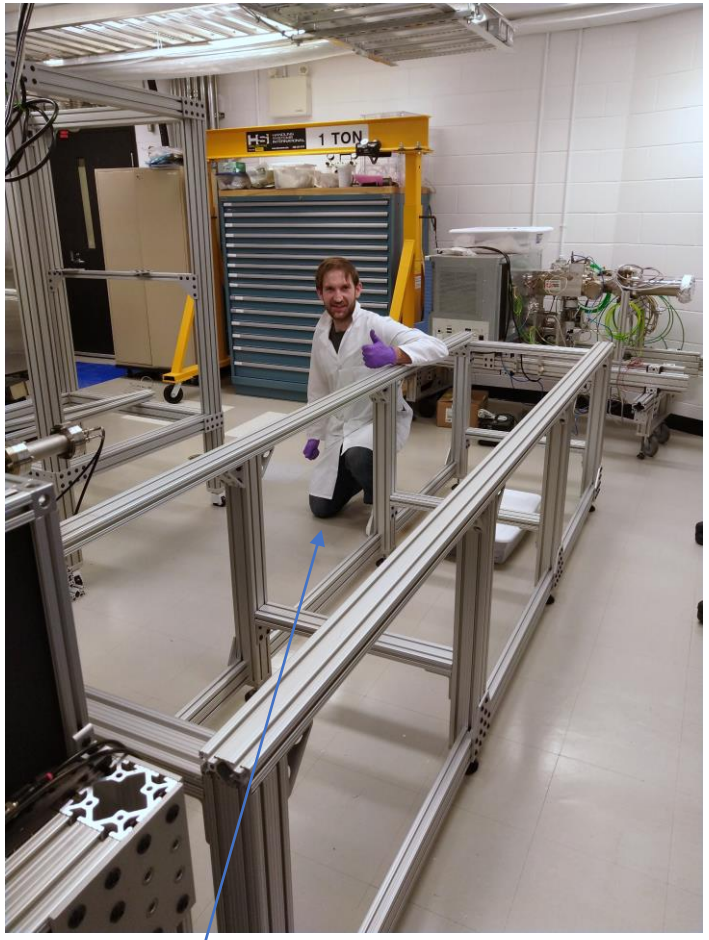
The RF Funnel Ba Tagging System



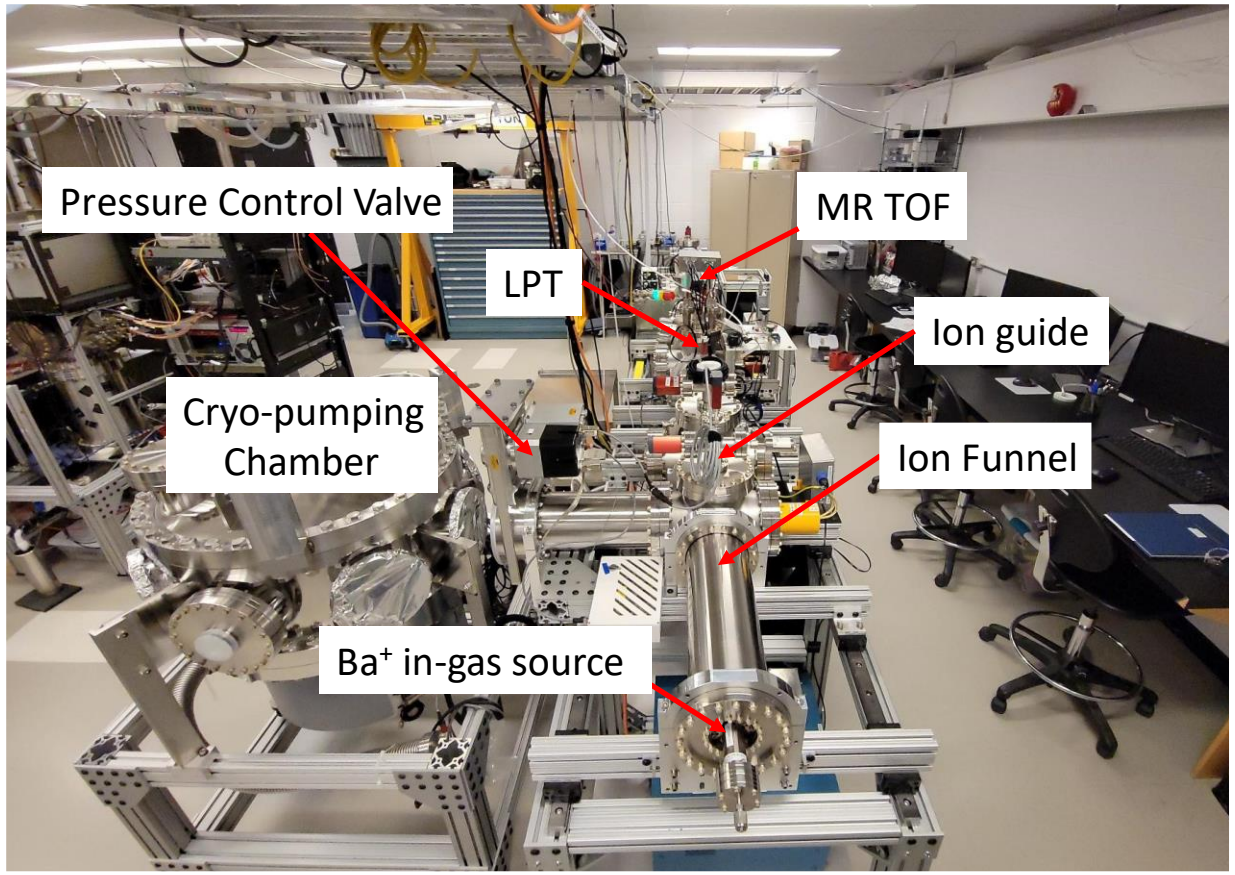


The RF Funnel Ba Tagging System

(circa 2019)

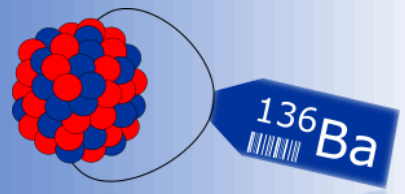


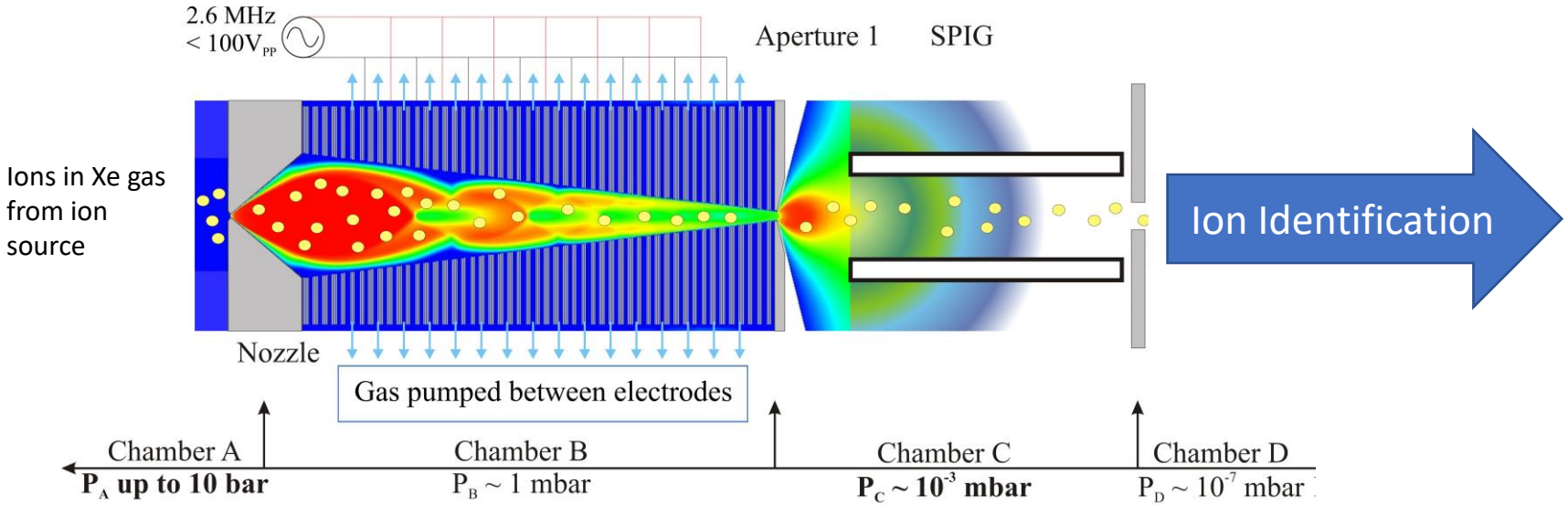
(present)



Christopher Chambers, for scale.

RF-Funnel Ion Extraction Prototype





Ion Identification

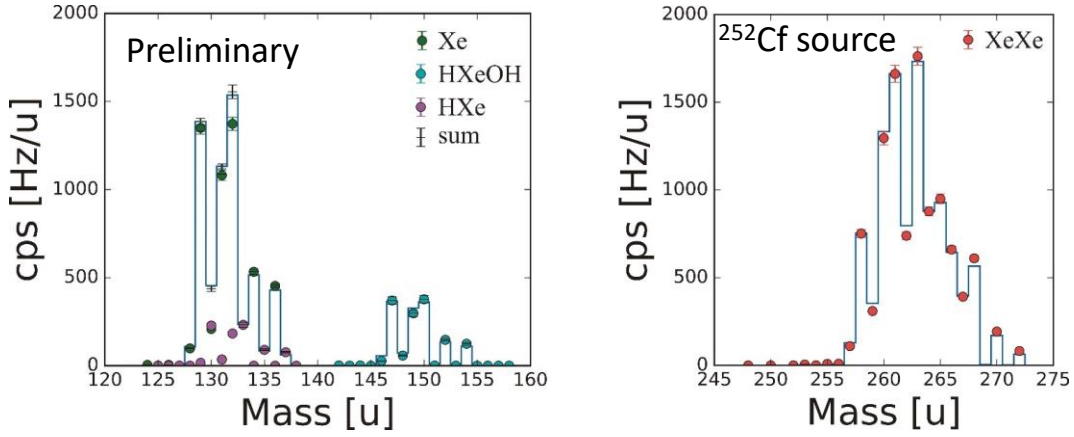
V_{RF} = 120 V, f = 10 MHz
Simulated funnel Ba^+ transmission ~95%

V_{RF} = 25V, f = 2.6 MHz
Simulated funnel Ba^+ transmission ~72%

RF-funnel concept by V. Varentsov:

- Converging-diverging nozzle
- 2 Stacks total 301 electrodes (0.1 mm thick)
- **0.25 mm electrode spacing**
- RF-field applied to electrodes
- **P_0 = 10 bar!** to 1 mbar in only one stage
- Xe gas is recaptured by a cryo pump

Previously: Commercial Mass Spectrometer

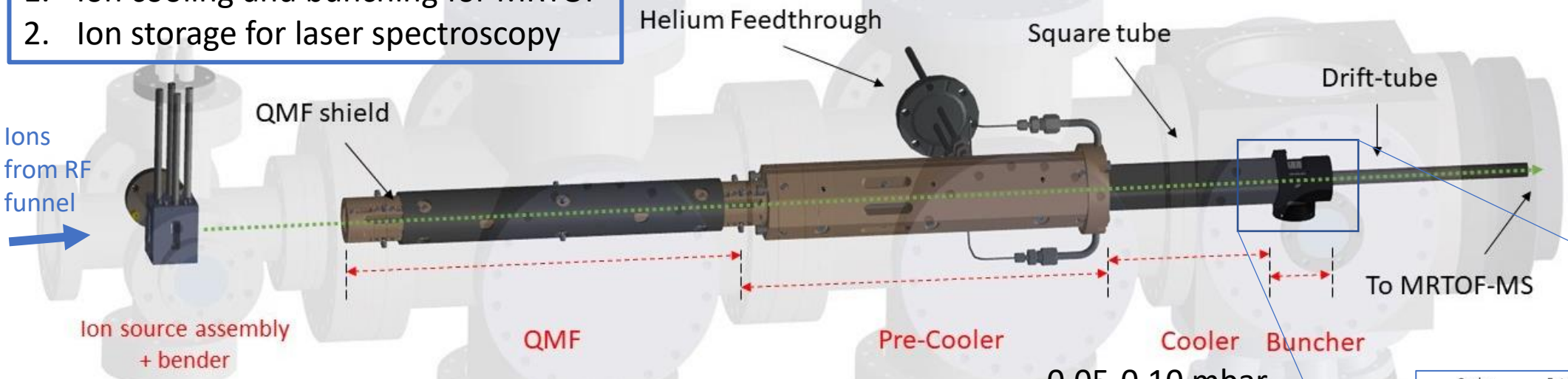


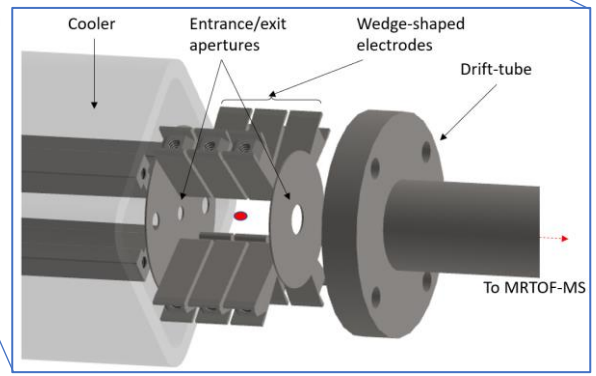
Int. J. Mass. Spectrom. (2015) doi:10.1016/j.ijms.2015.01.003

Linear Paul Trap Setup

Designed for dual purpose:
1. Ion cooling and bunching for MRTOF
2. Ion storage for laser spectroscopy

0.75MHz for QMF and 0.85MHz for LPT





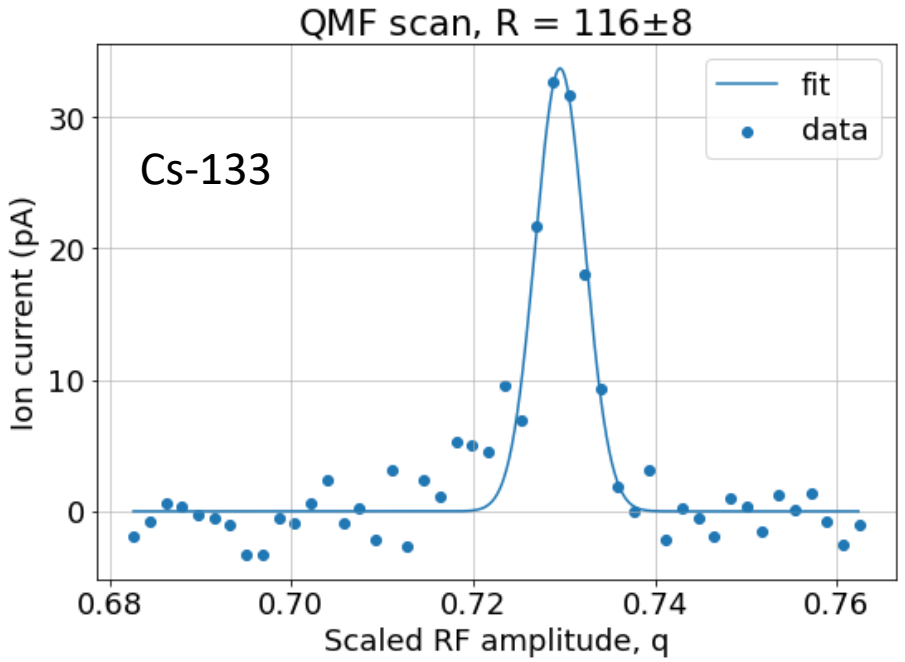
PhD thesis Y. Lan
MSc thesis H. Rasiwala

- Quadrupole mass filter (QMF) → commissioned
- Ion cooler and buncher (ICB) → commissioning of cooling and bunching is ongoing

Initial Tests with the QMF

QMF resolving power, R:

$$R = \frac{m}{\Delta m} = \frac{q}{\Delta q}$$

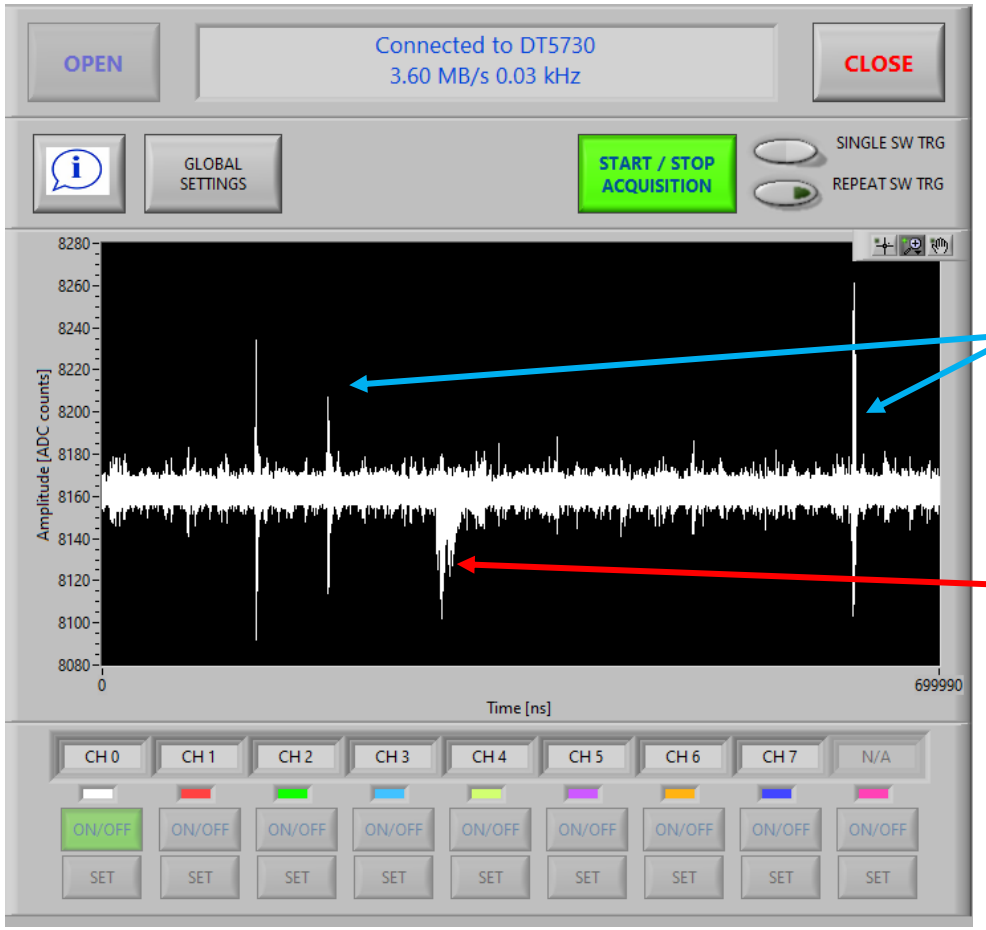


- DC - RF potentials are varied with constant DC/RF ratio.
- **Target mass resolving power of R ~ 80** was achieved in the test runs along specific scan lines.

Ion bunching with LPT

Ion bunching is currently being tested and optimized to achieve low ToF spread ~O(1 ns).

- Image on the right shows waveform of signal from the CEM upstream of the MRTOF.
- Work is underway to set up analysis to take data of ion bunching as well as to minimize noise in the signal.



Cs-133 thermal ion source

Pickup from buncher electrodes.

Ion signal

The MRTOF

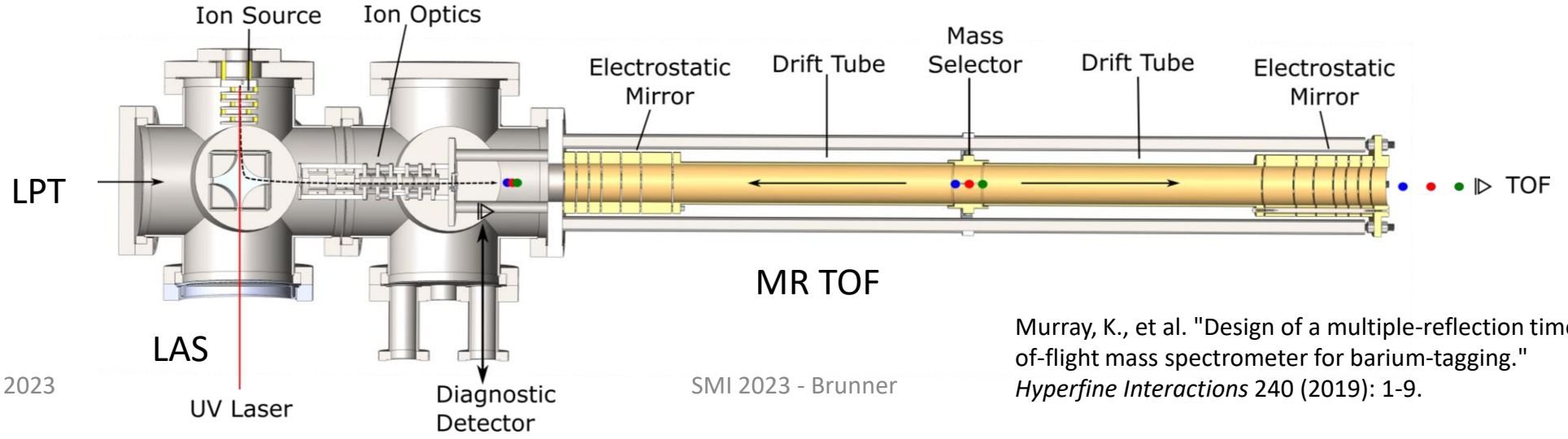
Operating Principle

- Ions accelerated by potential U gain kinetic energy $E_{kin} = z_i eU = \frac{m_i v_i^2}{2} \rightarrow t \propto \sqrt{m/q}$
- Ions with different mass-to-charge separate in time, and can be resolved if $\Delta t_{ij} > \Delta t_i, \Delta t_j$
- Calculated with mass-resolving power (MRP), $R = m/\Delta m = t/(2\,\Delta t)$

^{136}Xe mass = 135.907219(8) u, ^{136}Ba mass = 135.9045759(4) u , $\therefore \Delta m$ =0.0026 and $R = m/\Delta m \approx$ 52000

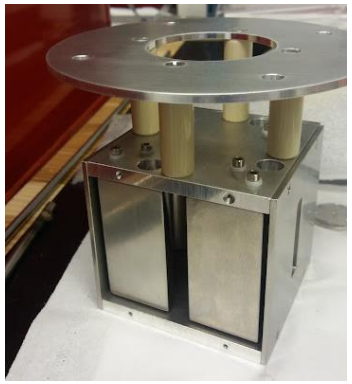
Design

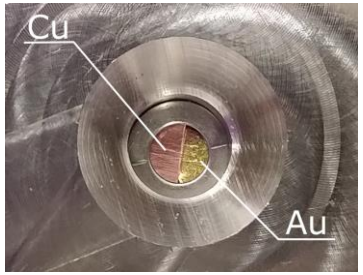
- Consists of central drift-tube and 2 electrostatic mirrors formed by 6 cylindrical electrodes.
- Ions are reflected between the mirrors to dramatically increase the MRP.



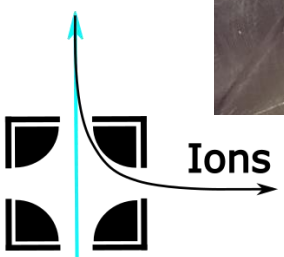
Murray, K., et al. "Design of a multiple-reflection time-of-flight mass spectrometer for barium-tagging." *Hyperfine Interactions* 240 (2019): 1-9.

The MRTOF

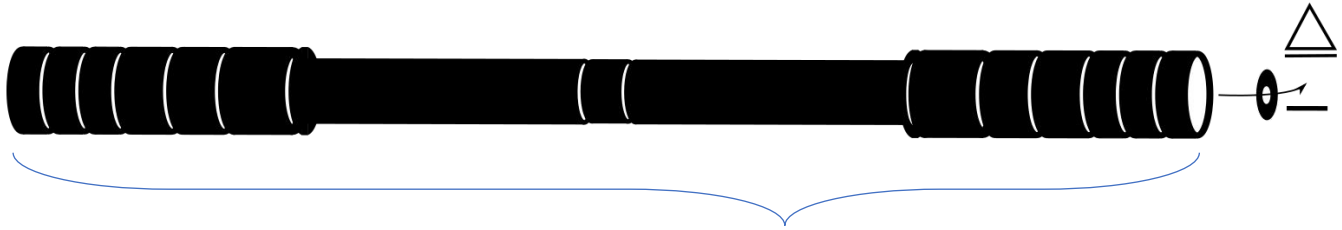


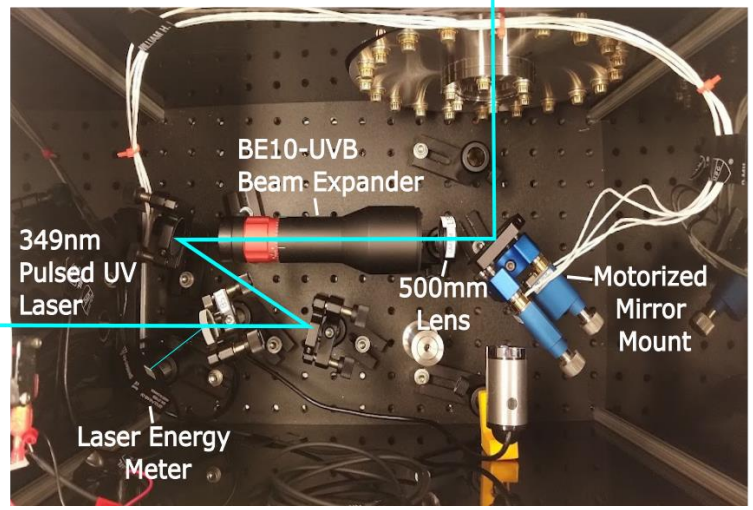


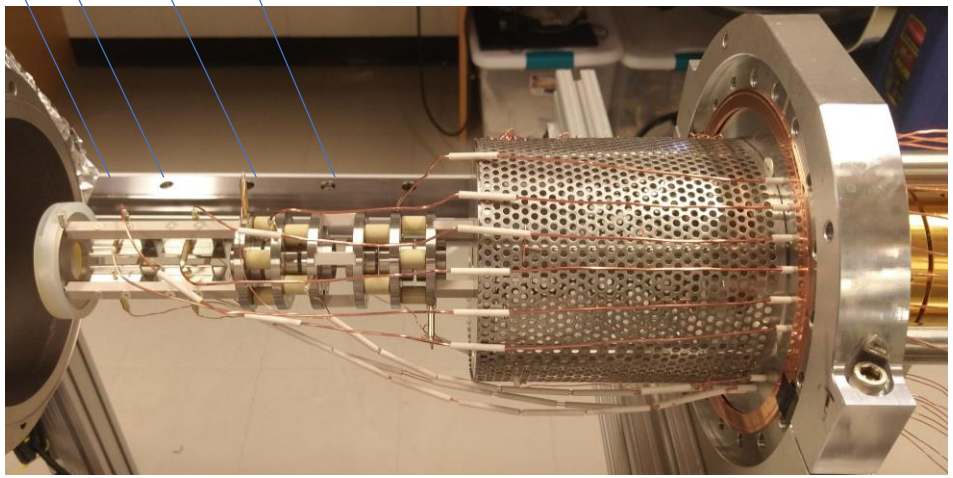
Ion source produces 1keV ion bunches, with relatively large emittance compared to cooled ions from the LPT, but useful for testing!

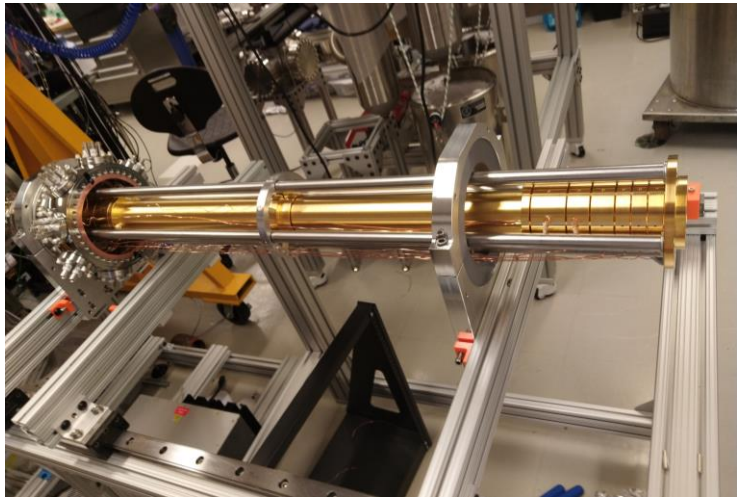


Quad Bender



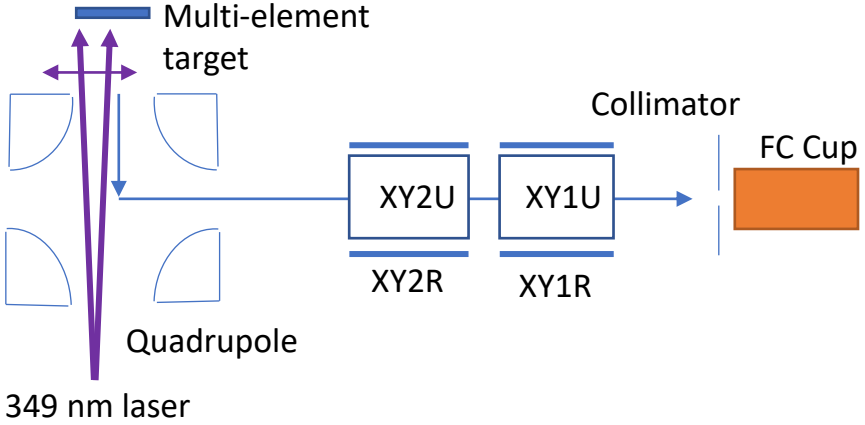






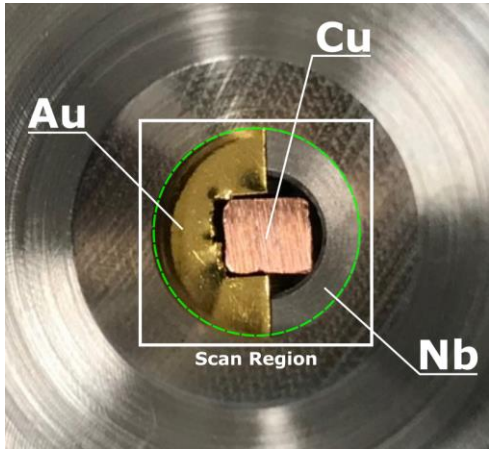
Steerers and lenses align and focus the beam.

Ion Current Measurements

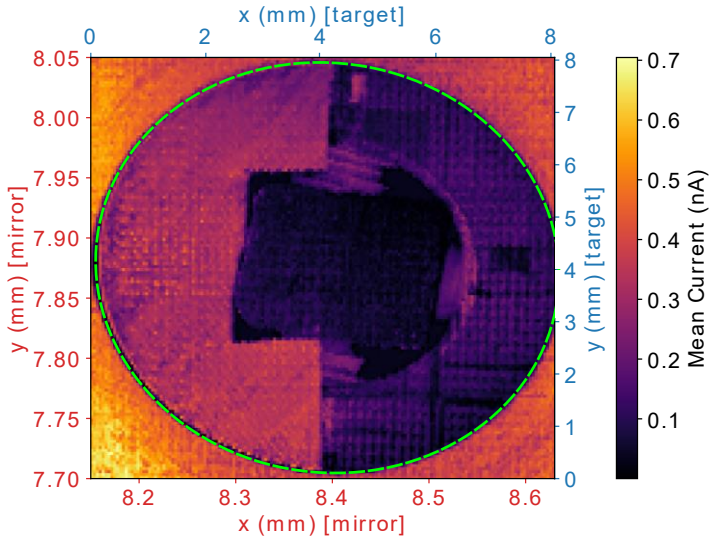


Murray, K., et al. Characterization of a Spatially resolved multi-element laser ablation ion source. *International Journal of Mass Spectrometry* 472 (2022): 116763.

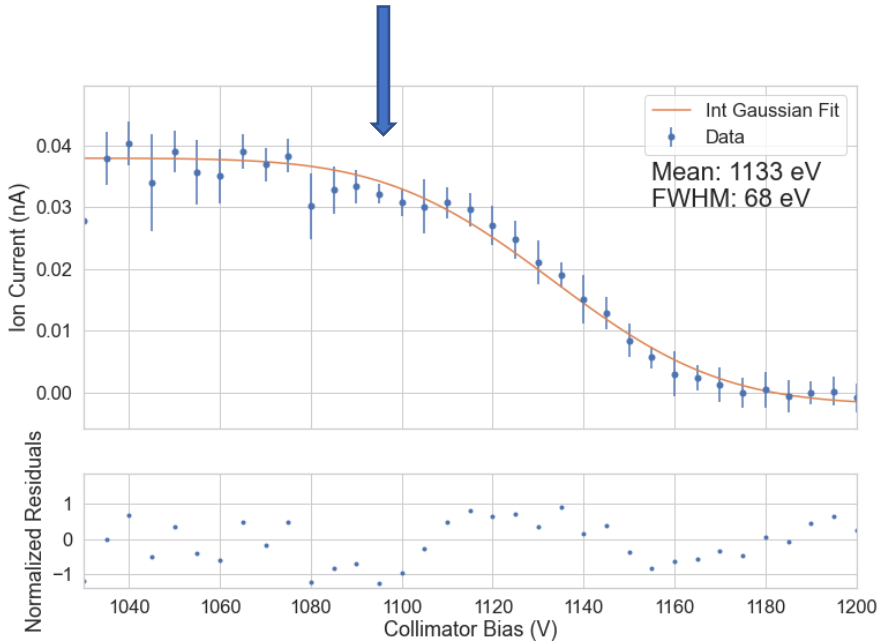
- Collimator aperture used as a retarding field analyzer.
- **Kinetic energy spread of LAS ions much larger than from LPT.**



Multi-element target.
Laser raster across surface.
$1/e^2$ diameter: 50(3) µm

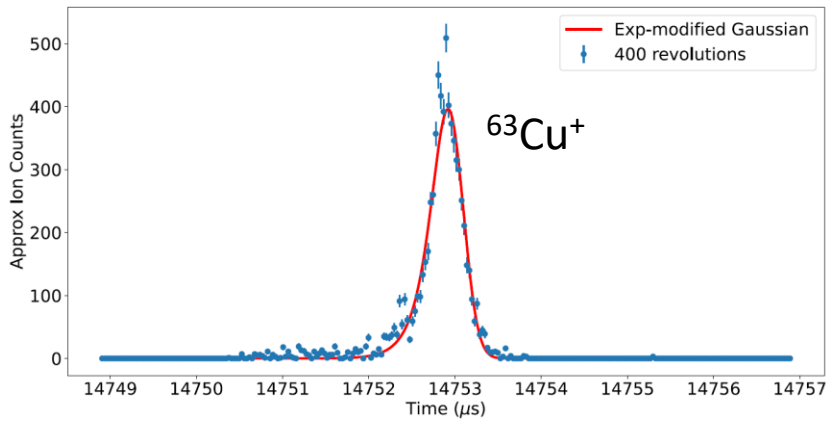


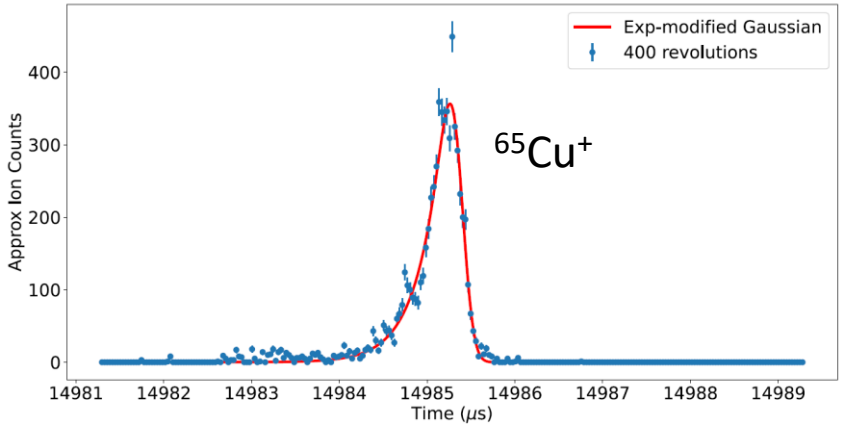
Reconstructed ion-current image from target scan.



Cu^+ Mass Peaks

Two visible ToF peaks are produced from the Cu region of the target, if the lighter peak is assumed to be ^{63}Cu, does the second peak measure correctly as ^{65}Cu?





ToF extended to 15ms, for 400 revolutions.

20k MRP, despite large kinetic energy spread of ions from the LAS.

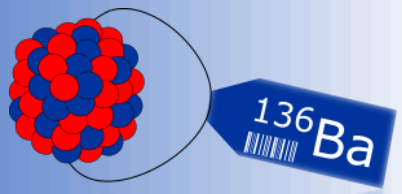
Table 7.2 TOF meausurements for Cu isotopes at 400 revolutions, atomic mass and relative abundance figures are taken from ref [134].

Isotope	Center (μs)	FWHM (μs)	t_{rev} (μs)	Atomic Mass	Abundance (%)
$^{63}Cu^+$	14753.442	0.331	36.793	62.92959772(56)	69.15(15)
$^{65}Cu^+$	14985.467	0.290	37.373	64.92778970(71)	30.85(15)

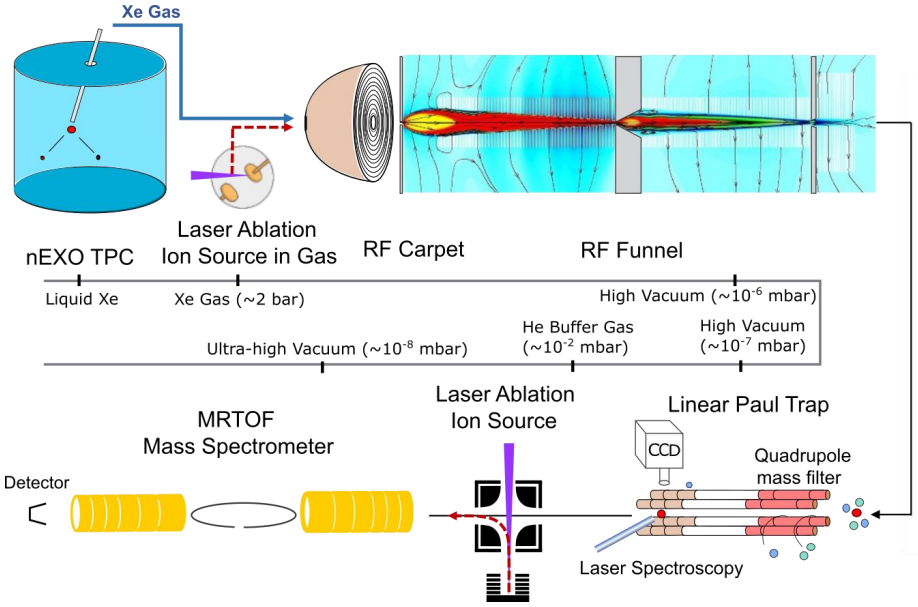
Commissioning is ongoing!

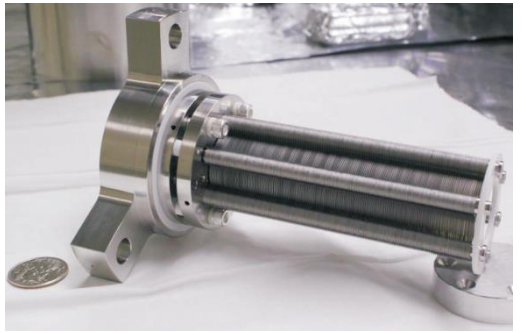
Mass of ^{65}Cu measured as **64.9245(39) amu**, agreeing with 64.9278 amu.

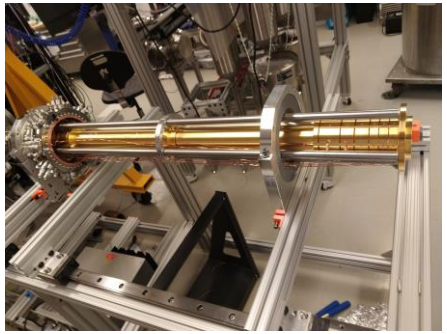
Summary



- Ba-tagging is a unique technique to unambiguously identify 0νββ decay products in a liquid Xe TPC.
- The extraction of individual ions from macroscopic amounts of Xe is challenging.
- We are pursuing a trans Canadian approach to Ba-tagging.
- We are close to demonstrating ion extraction from a Cf-252 fission source in Xe gas and subsequent ion identification.







Thank you for your attention!

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Stanford University, Stanford, CA, USA - G. Gratta

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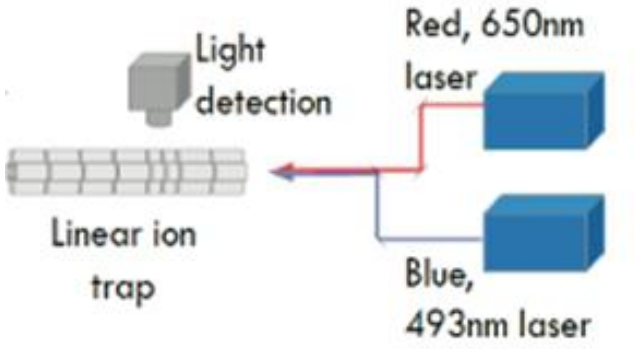
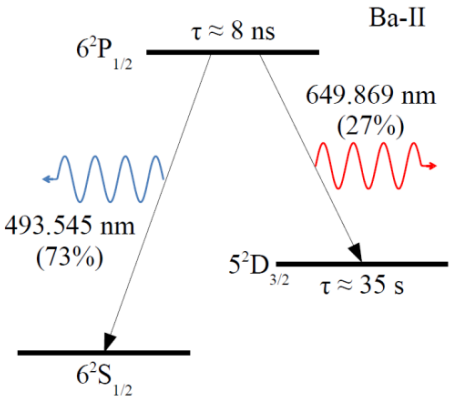
University of California San Diego, La Jolla, CA, USA - L. Yang

Ba ion detection & identification

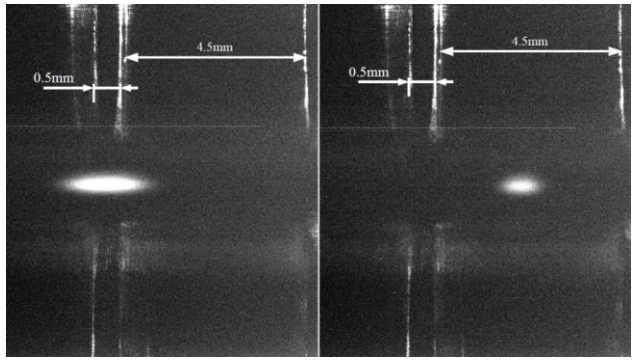
Existing laser fluorescence spectroscopy to be implemented in future with developed linear Paul trap



Using a relatively simple and well understood fluorescing system

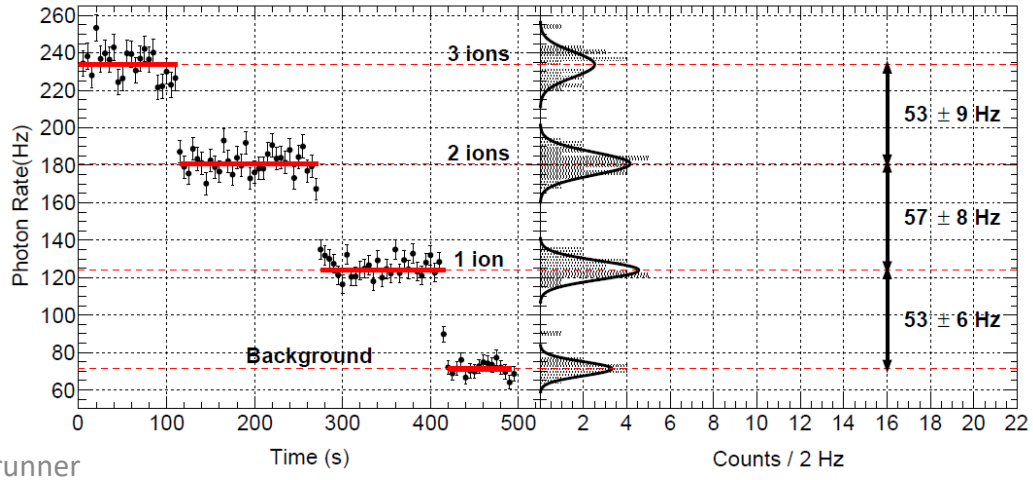


Demonstrated ion cloud imaging and accurate position control

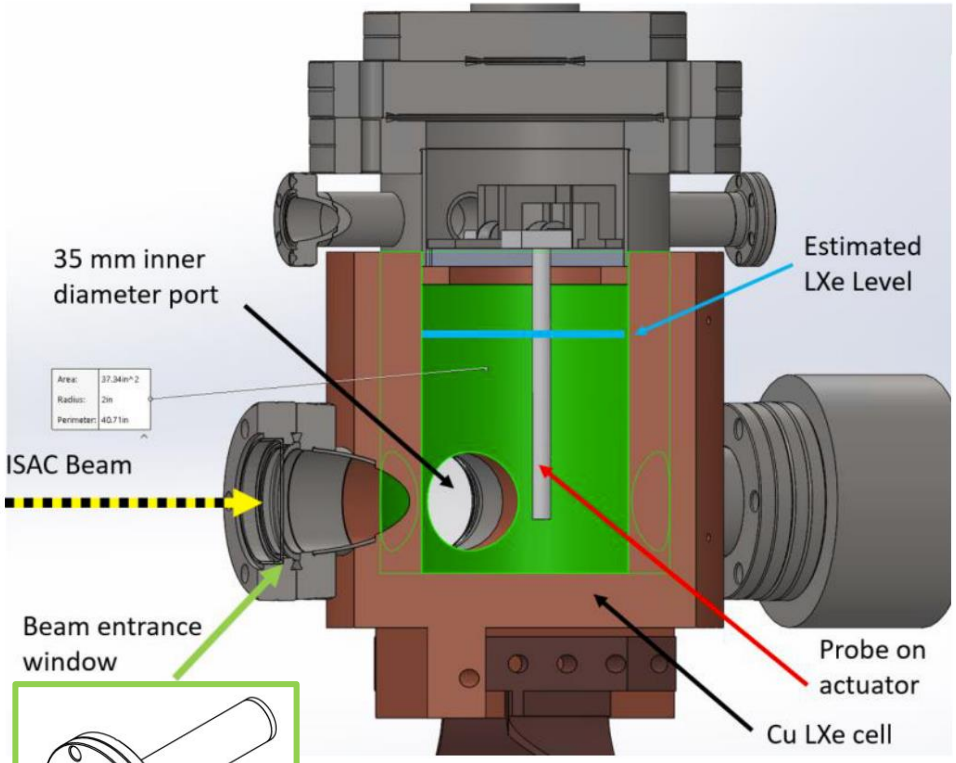


Demonstrated by M. Green et al., Phys. Rev. A **76** 023404 (2007)

Demonstrated single ion sensitivity using intermodulation technique (background control)

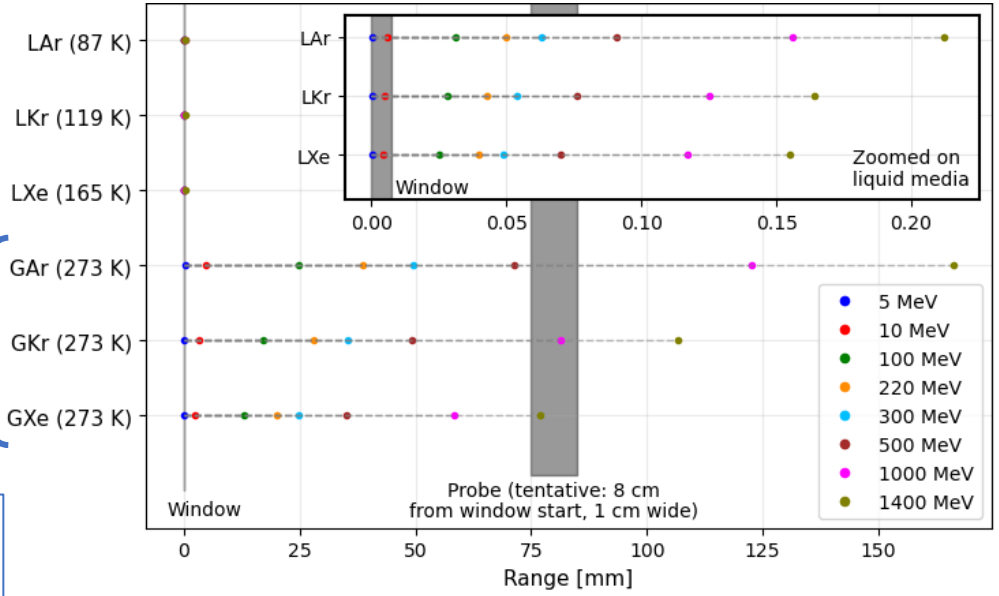


Accelerator driven Ba-ion source R&D



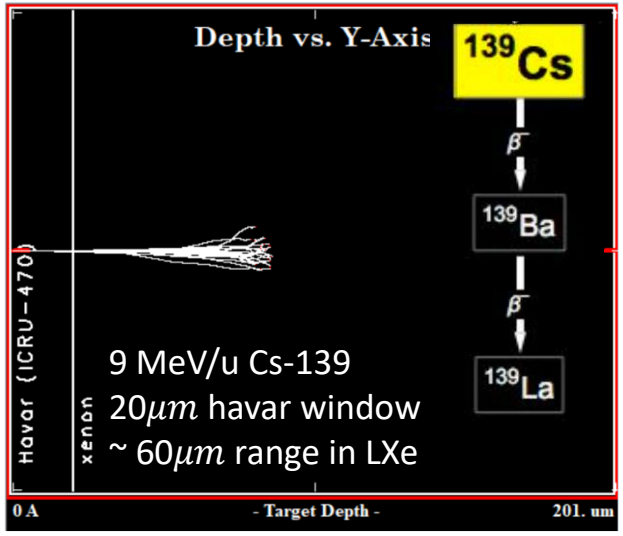
^{139}Cs range in different media after passing through a 0.3 mil Be window
(1 atm medium pressure)

Commissioning planned with noble gasses

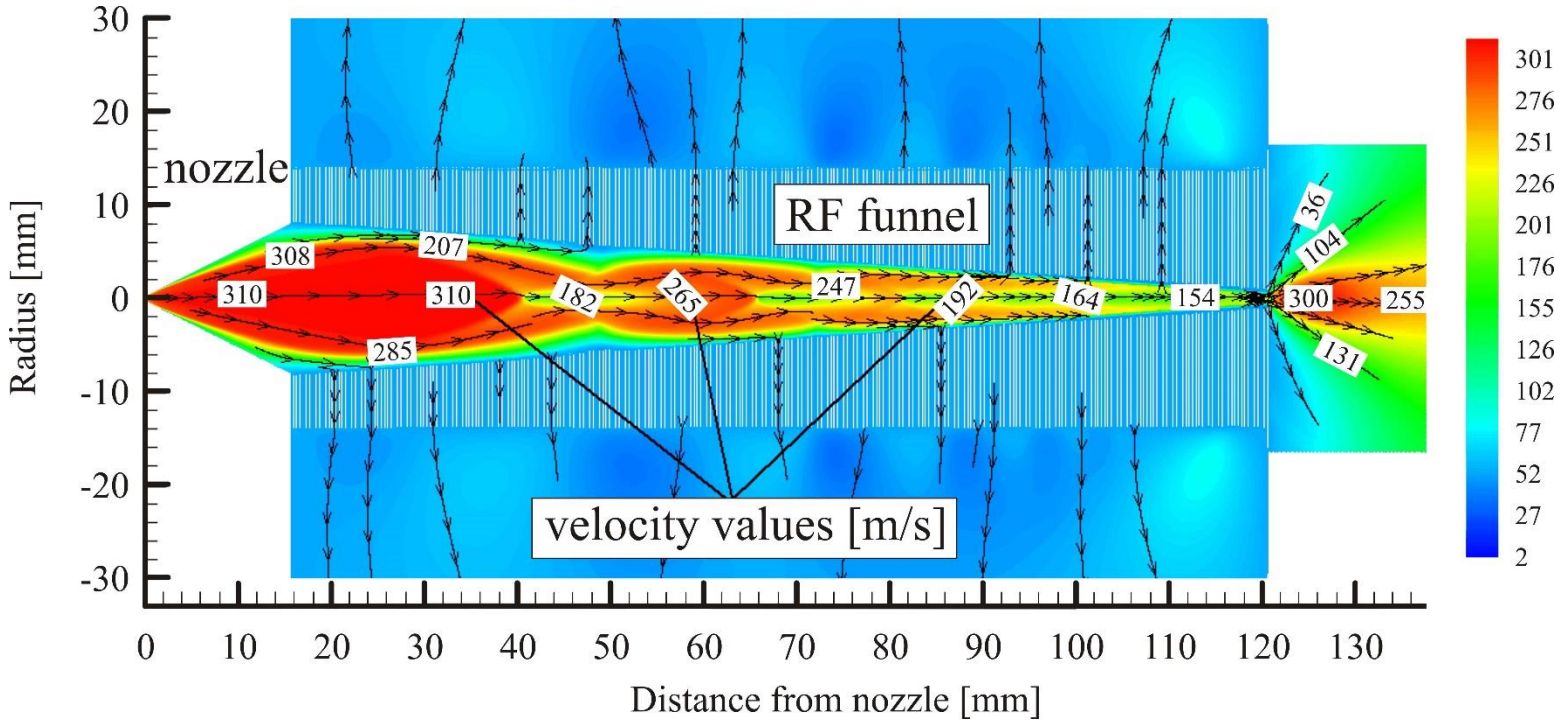


First ion-injection planned for fall 2023

- 2 - 10 MeV/u beam energy
- Beam intensity ~10^5 pps
- Be window
- Ions will not travel far
- ~10x10x10 cm^3 LXe volume
- LXe at ~1000 Torr, 165 K



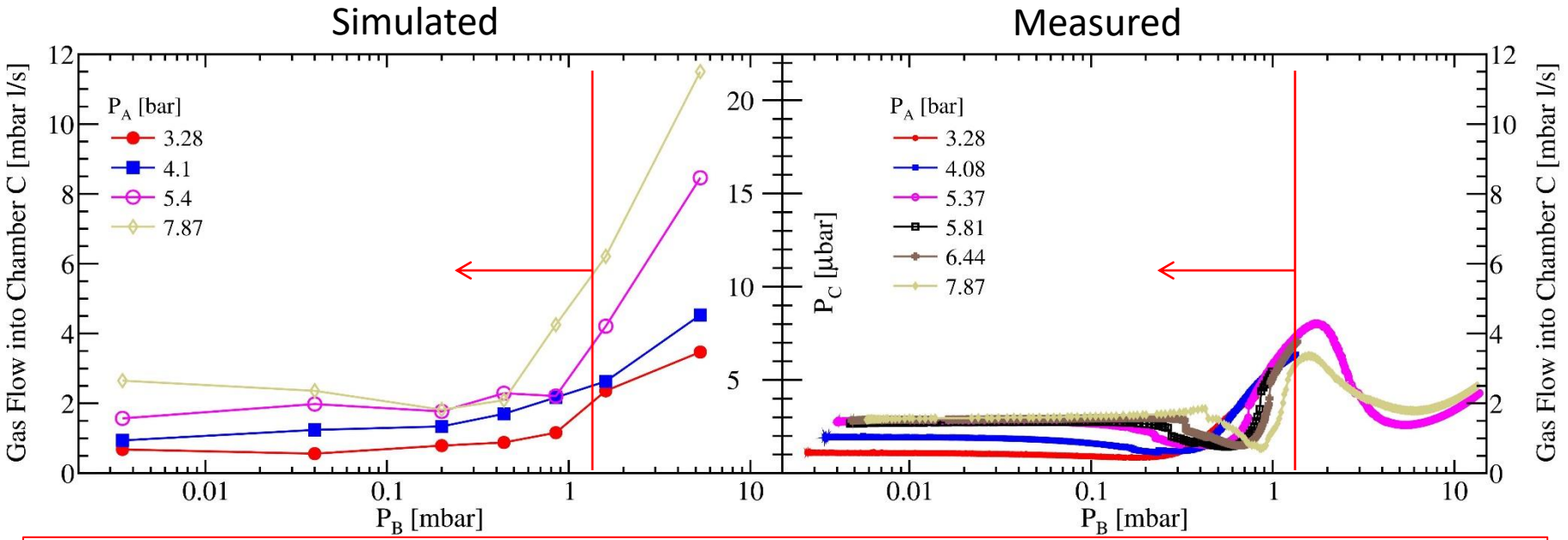
Gas dynamic calculations



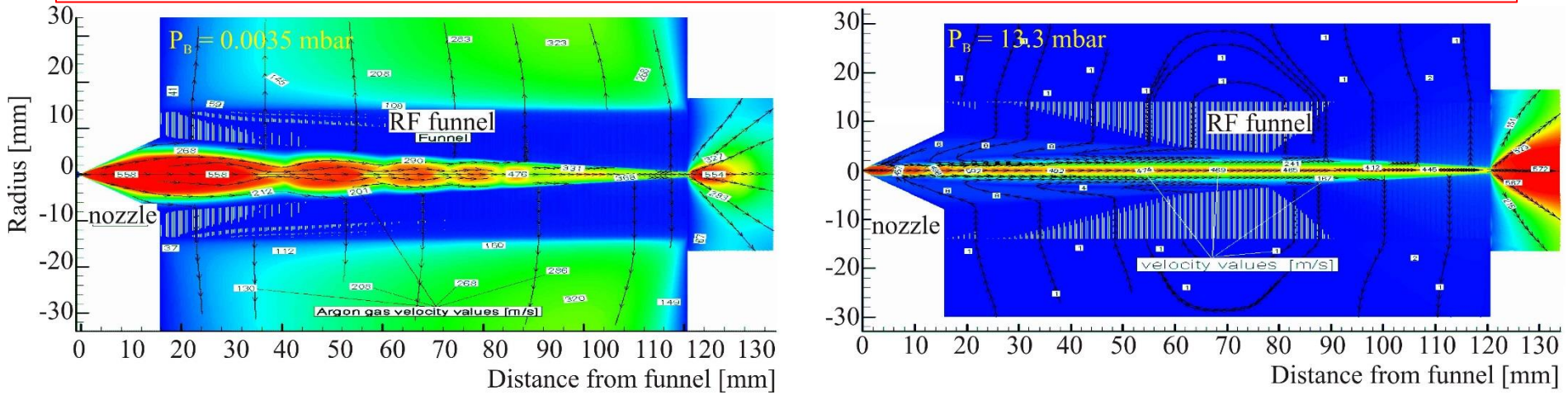
Converging-diverging nozzle	
Half-angle of subsonic cone	45°
Half-angle of supersonic cone	26.6°
Throat diameter	0.28 mm
	0.33 g/s
Exit diameter	16.0 mm
Subsonic part length	0.5 mm
Supersonic part length	15.5 mm

RF-funnel electrodes	
Entrance aperture diameter	16.0 mm
Exit aperture diameter	1.0 mm
Ring electrode diameter	28 mm
Change in aperture diam./el.	0.05mm
Ring electrode thickness	0.1 mm
(design tolerance)	+/- 2.54 μm
Gap between electrodes	0.25 mm
Total number of electrodes	301

Pressure measurements in argon



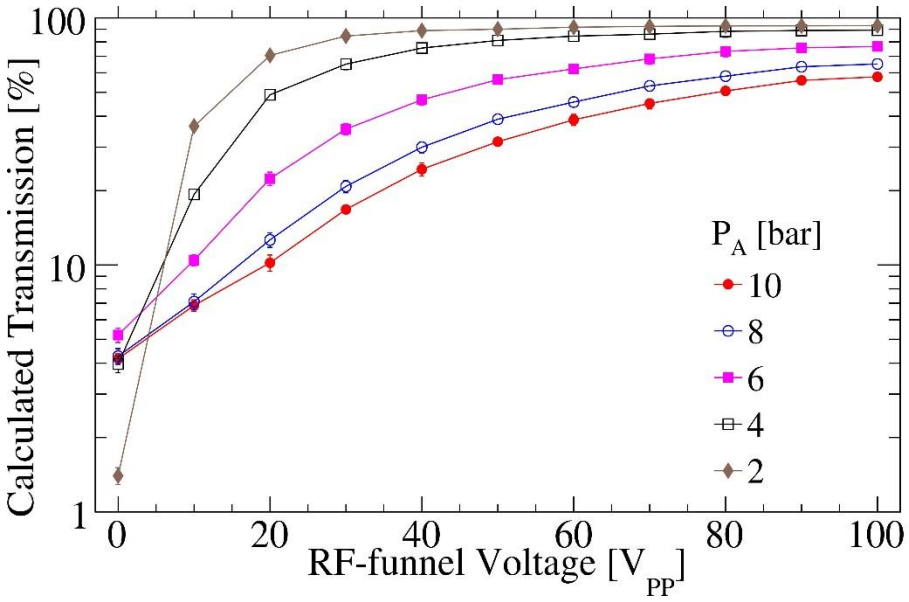
Agreement between calculated and measured pressures in chamber C (P_C) for P_B<1mbar



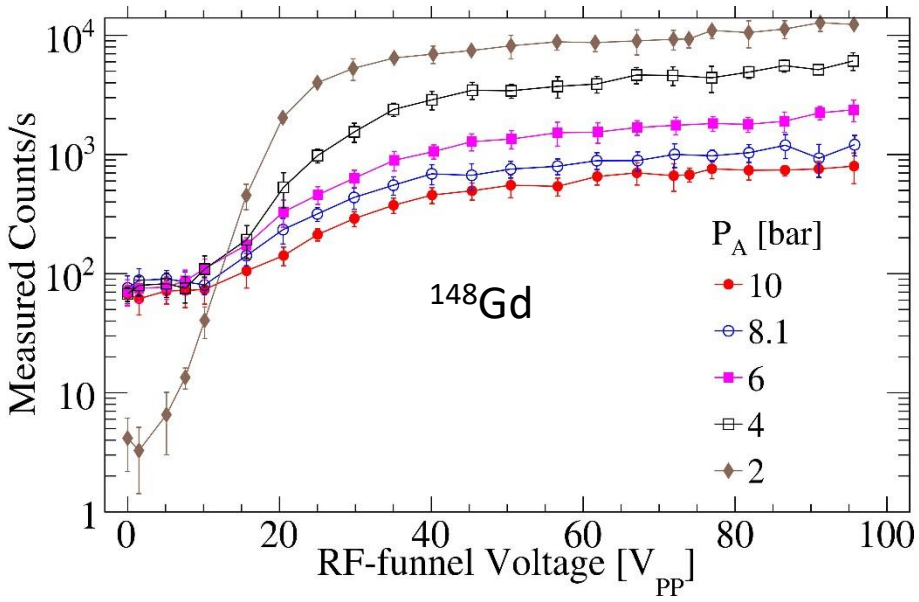
Int. J. Mass. Spectrom. (2015) doi:10.1016/j.ijms.2015.01.003

Ion extraction rate in xenon gas

Calculation



Measurement



- General shape well reproduced
- Ion extraction up to 10 bar!

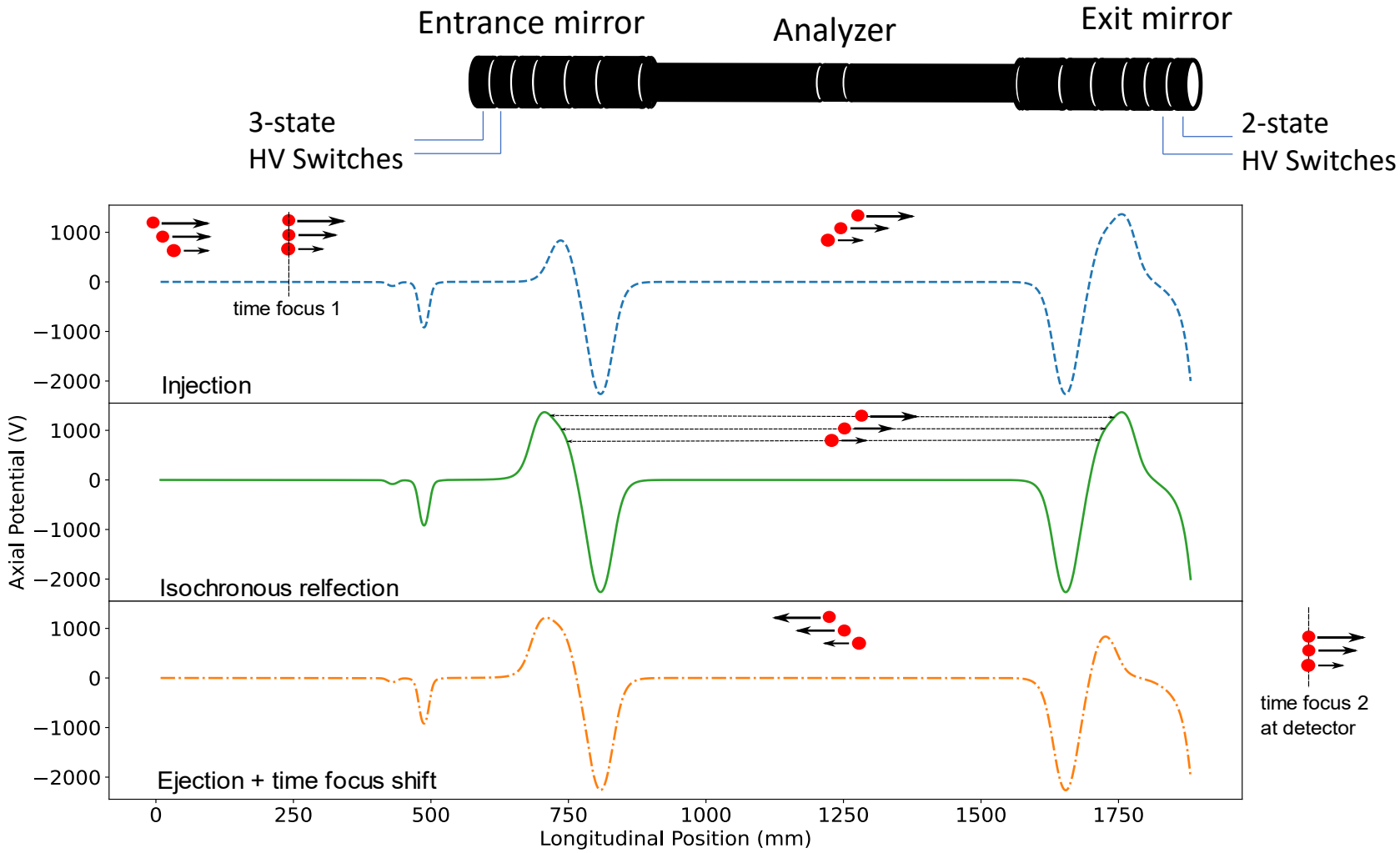
- Ions not identified!
- Ion extraction efficiency unknown!

Int. J. Mass. Spectrom. (2015) doi:10.1016/j.ijms.2015.01.003

Operation mode of the MRTOF

Time Focus:
Point in space at which ions with same m/q but slightly different KE arrive at the same time.

- HV switches let ions into and out of the analyzer.
- Mirrors of the MRTOF can be tuned to adjust the path lengths of ions with different KE.
- Time focus is shifted from the initial position to the detector with final reflection.



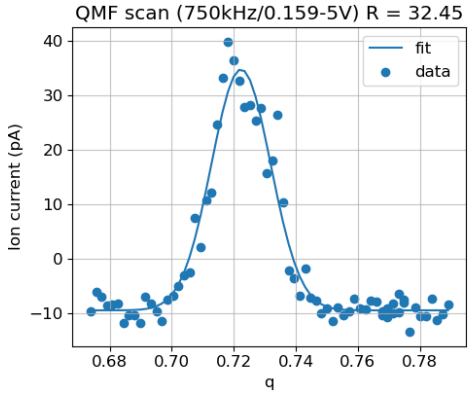
Rosenbusch, M., et al. "Delayed bunching for multi-reflection time-of-flight mass separation." *AIP Conference Proceedings*. Vol. 1668. No. 1. AIP Publishing LLC, 2015.

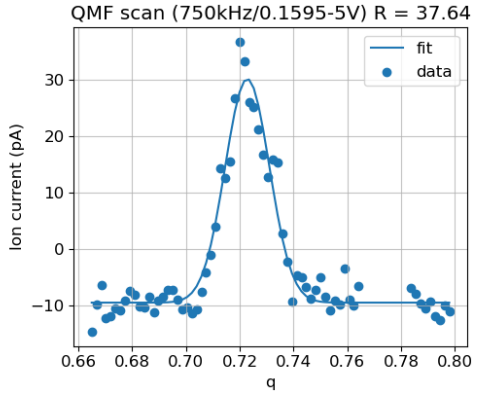
Initial Tests with the QMF

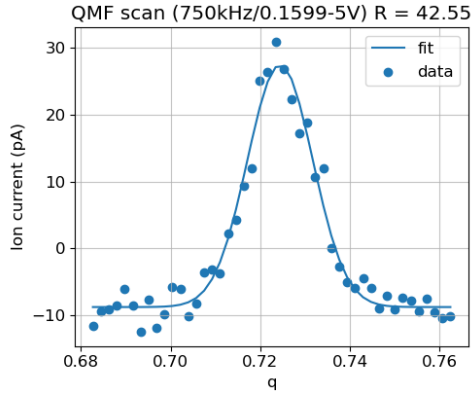
Scanning tip region for measuring QMF resolving power, R:

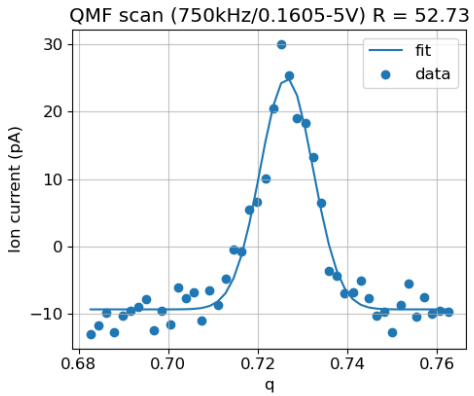
$$R = \frac{m}{\Delta m} = \frac{q}{\Delta q}$$

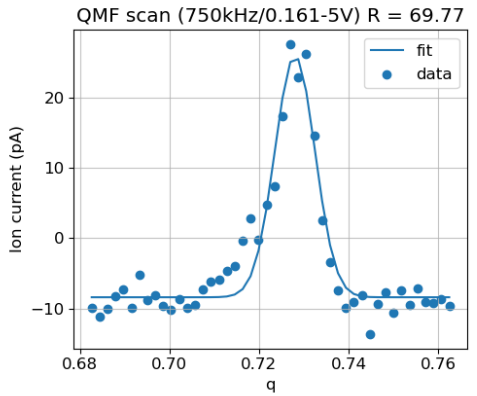
- DC - RF potentials are varied with constant DC/RF ratio.
- Target mass resolving power of R ~ 80 was achieved in the test runs so specific scan lines.
- Ions from Cs-133 thermal ion source

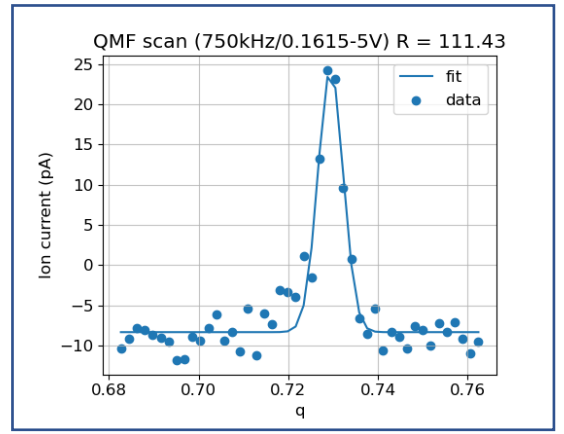




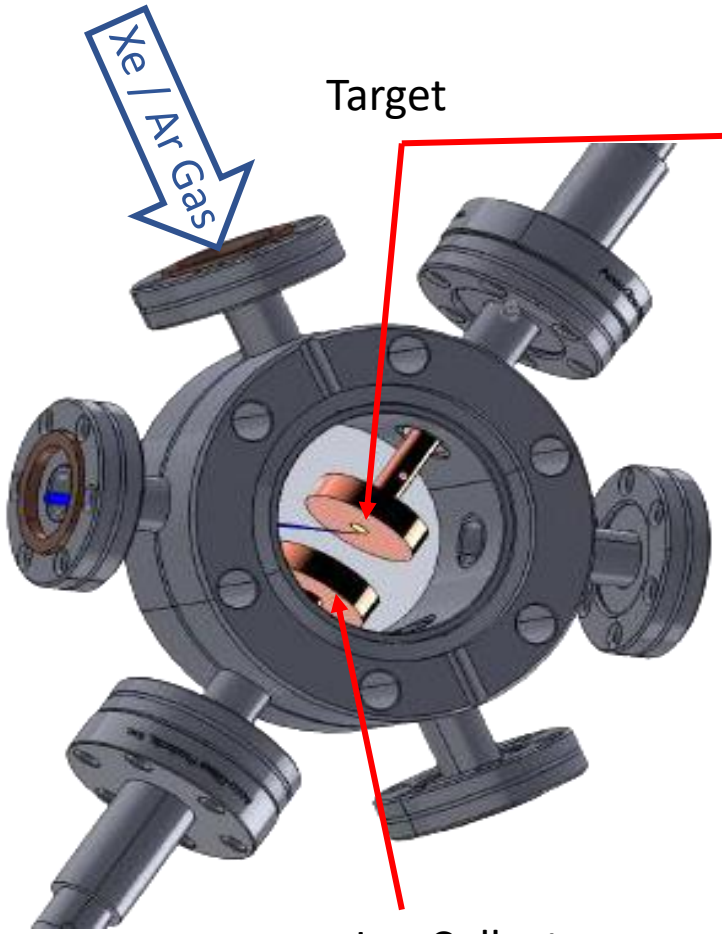


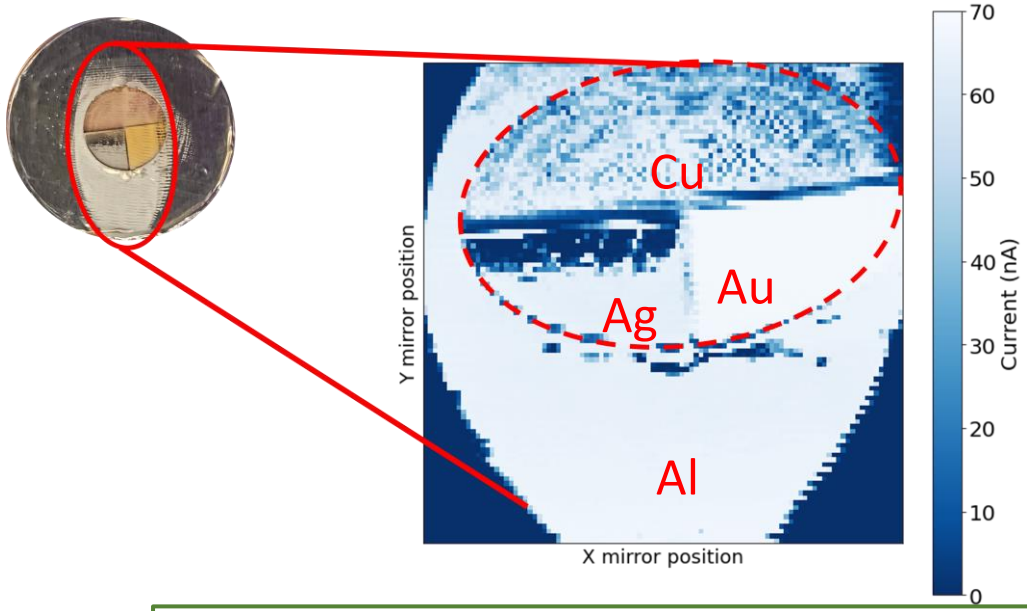






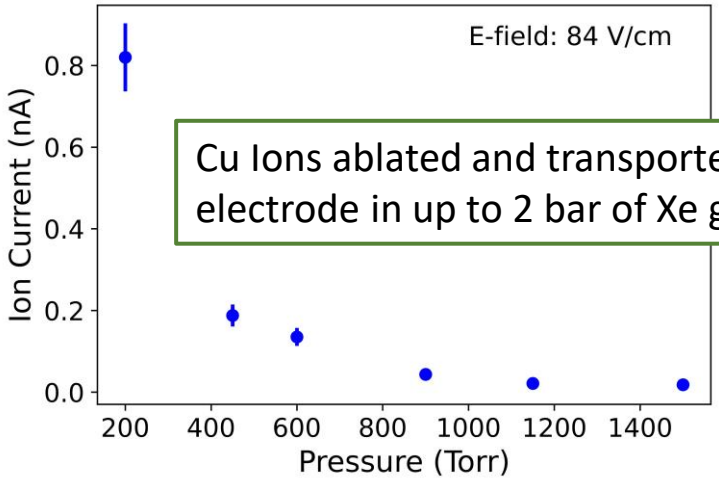
In-Gas Laser Ablation Source





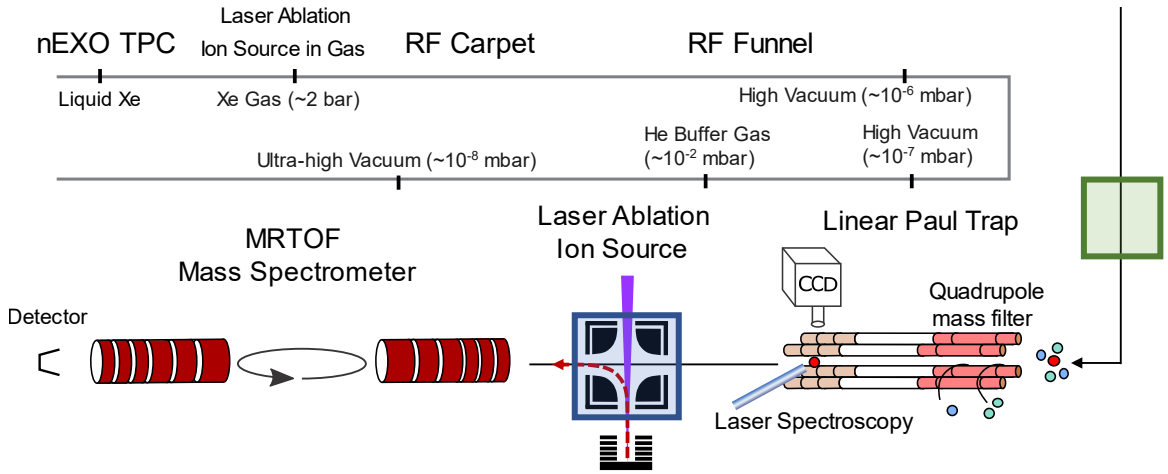
- Small positive pressure chamber
- Parallel plate target and ion collector geometry
- Can use Xe or Ar gas

- Cu, Au, Ag and Al ions ablated and transported to ion collector
- Can identify ion species by ion current at given laser fluence

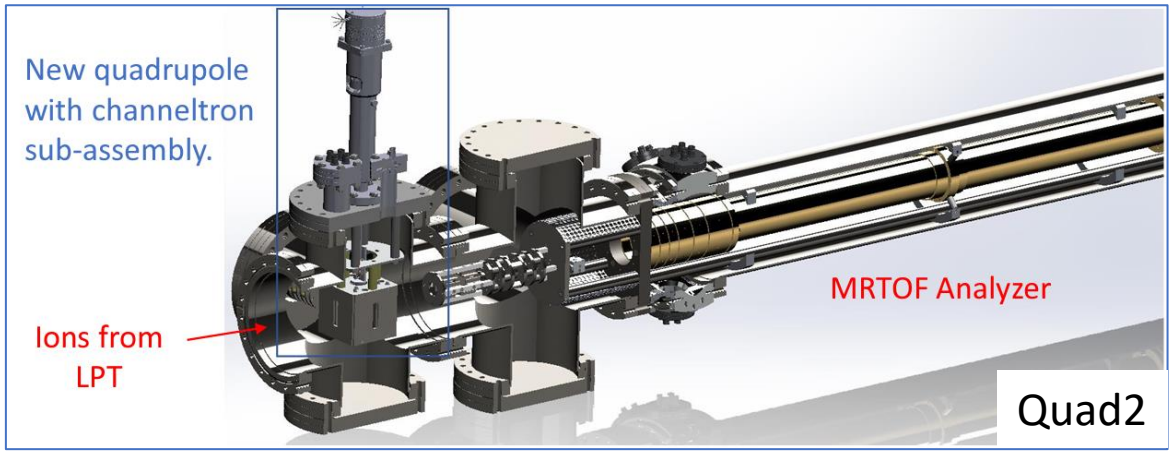


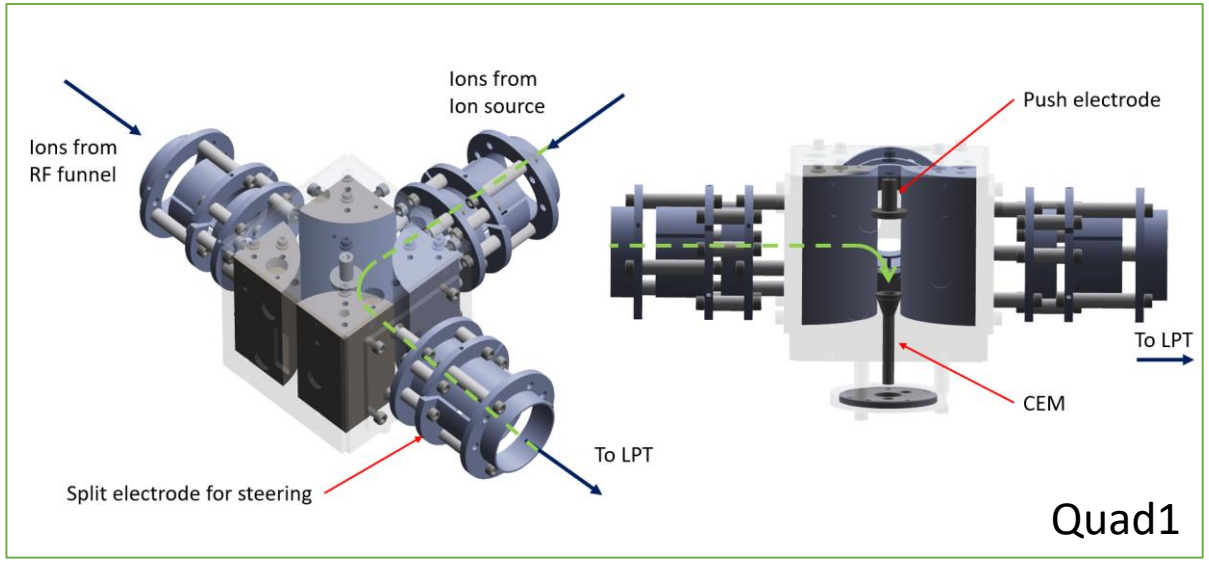
Cu Ions ablated and transported to collection electrode in up to 2 bar of Xe gas

Ion sources upgrades

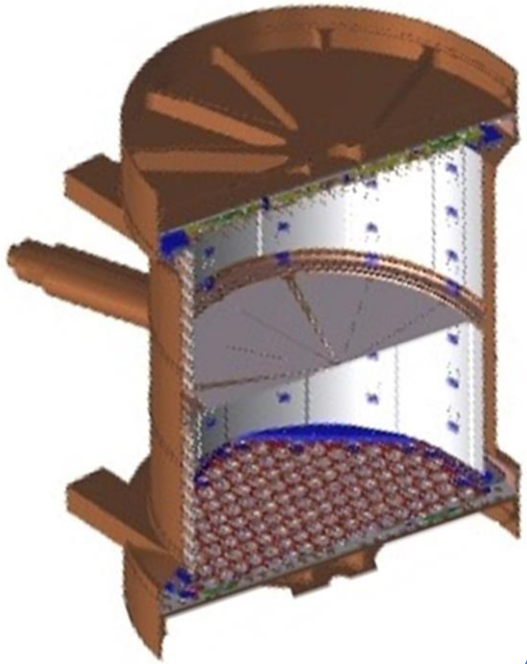


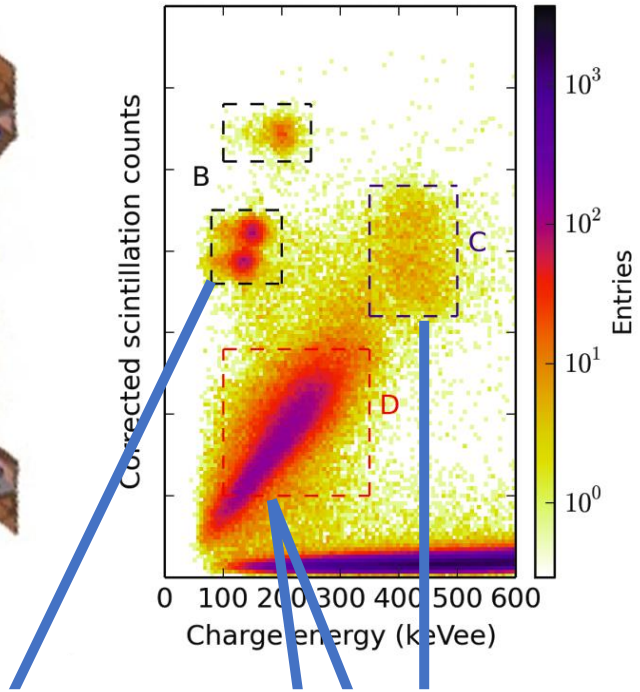
Ion sources providing ions for the commissioning of LPT and MRTOF have been upgrades to provide means to study ions from the RF Funnel and ejected ion bunch from LPT.

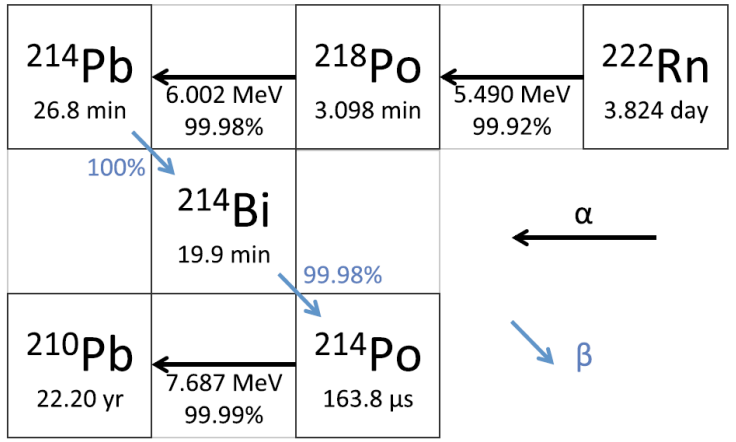




Ion Fraction in LXe after α and β Decay







EXO-200 with drift field 380 ± 5 V/cm

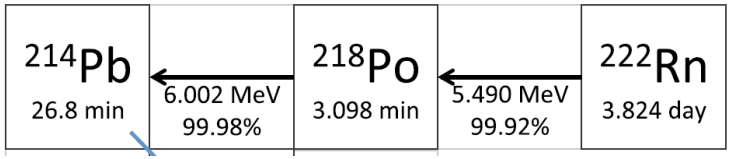
Ion Fraction

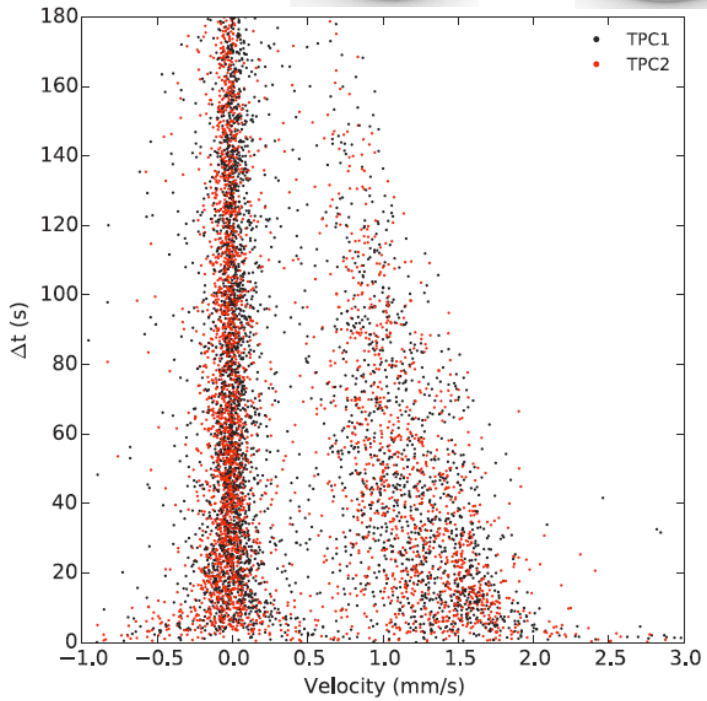
$^{214}Bi^{+}$ from ^{214}Pb β decay: 76.4 ± 5.7%

$^{218}Po^{+}$ from ^{222}Rn α decay: 50.3 ± 3.0%

Phys. Rev. C 92(2015)045504

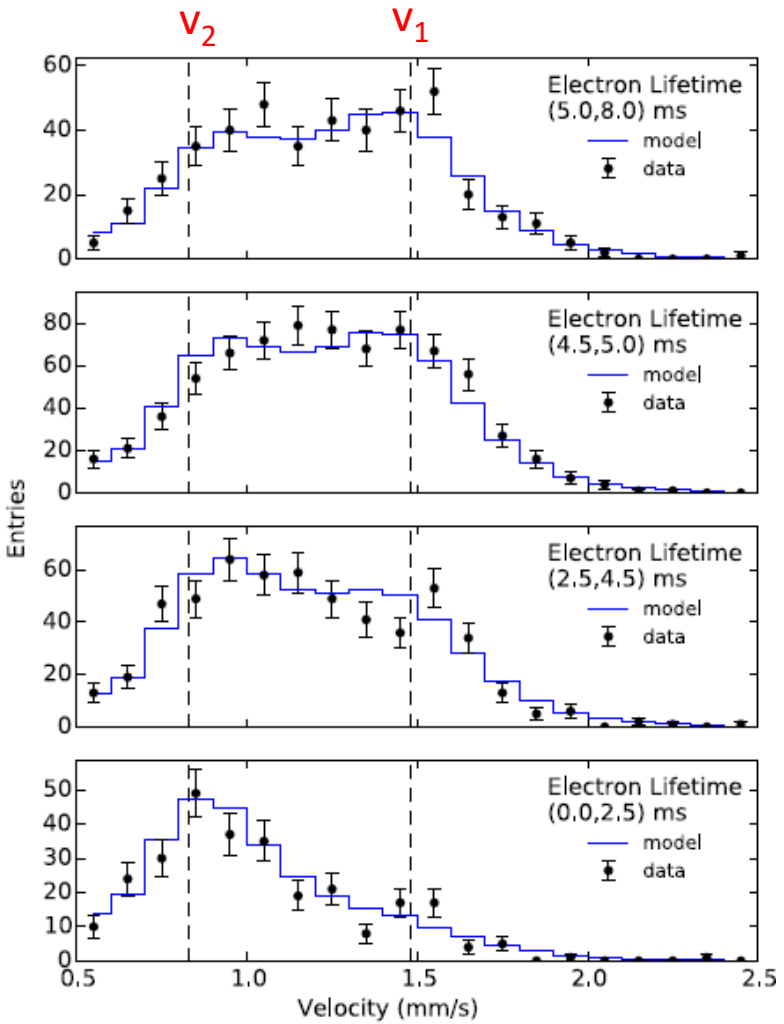
Ion Mobility in LXe





^{218}Po Drift Velocity

- Initial velocity v_1
- Reaction or charge transfer occur
- Reduced velocity v_2



Increasing e⁻ lifetime

Two Drift Velocities

v_1=1.48 ± 0.01 mm/s

v_2=0.83 ± 0.01 mm/s

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