A Capillary Probe for Ion Extraction from Liquid Xenon

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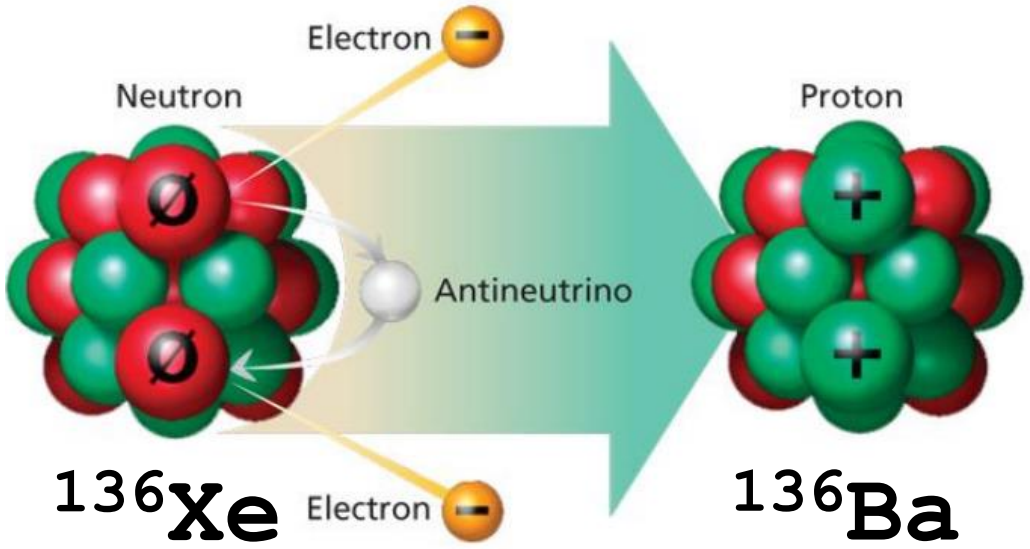
Outline

- 0νββ, nEXO, and barium tagging
- Capillary probe design
- Simulations
- Displacement frame

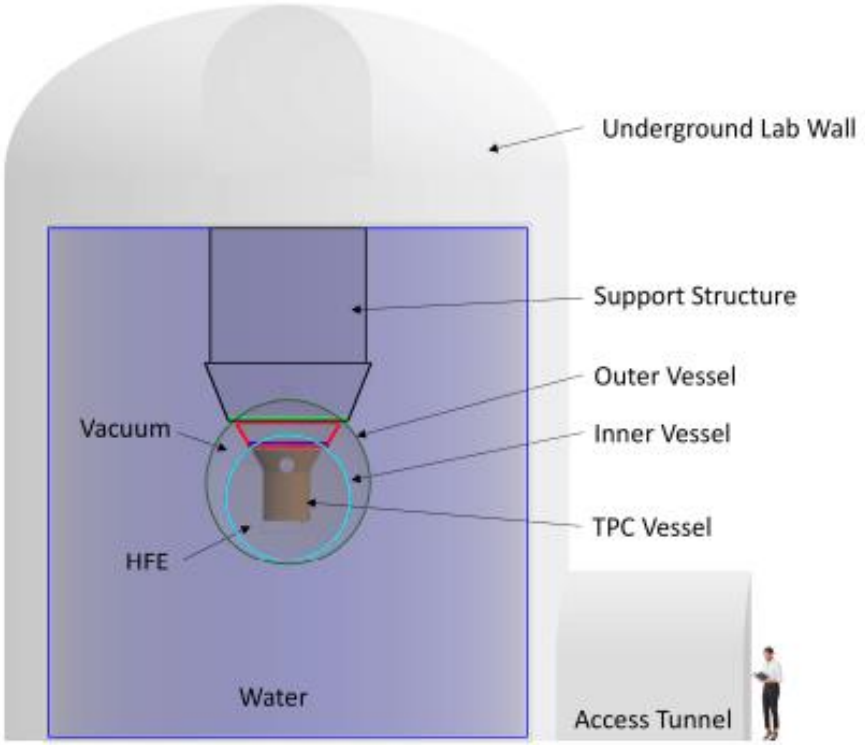
0νββ and ^{136}Xe

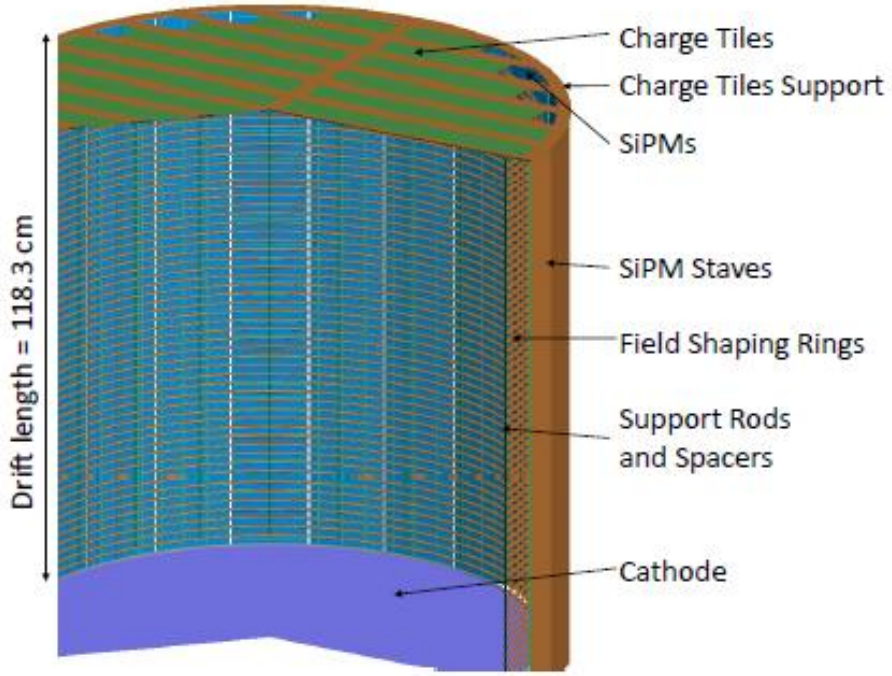
- 0νββ: 2n → 2p + 2e ($+0\bar{\nu}_e$)
- Violates lepton number conservation – new physics!
- Observation implies neutrinos are Majorana fermions
- Decay rate related to absolute mass scale of neutrinos – may solve hierarchy problem
- ^{136}Xe 0νββ half-life >2.3x10^{26} years[1]



[1]KamLAND-Zen 400+800 combined result
URL https://doi.org/10.48550/arXiv.2203.02139

nEXO and barium tagging





- multi-ton nEXO sensitive beyond 10^{28} years from e^- energy measurement
- Backgrounds would be greatly reduced by detecting the ^{136}Ba daughter ion, thereby excluding non-ββ events

Canadian Ba Extraction and Tagging Effort

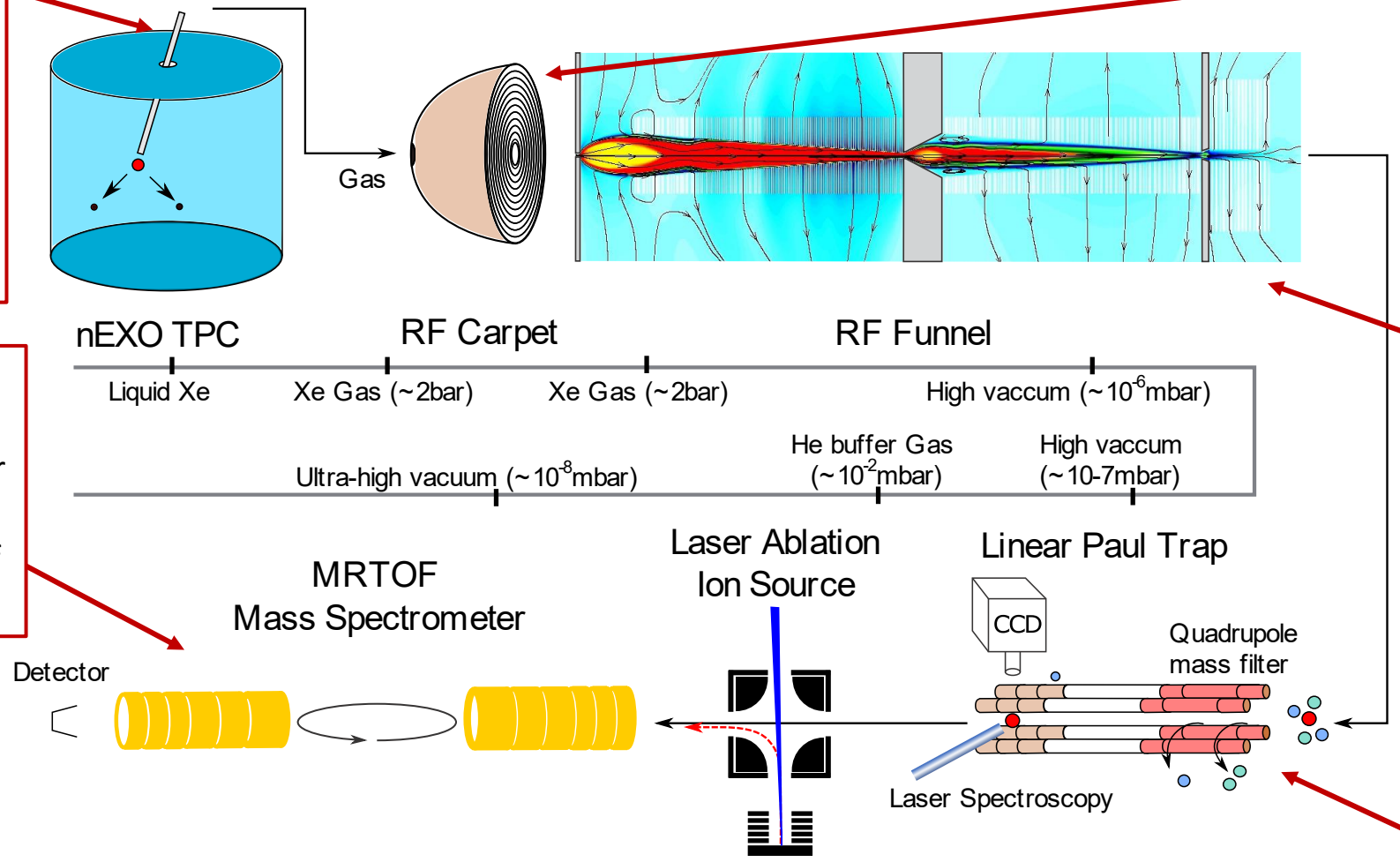
Stage1:
Extraction of detector volume around the location of the decay to gas phase using a capillary tube.

Stage2:
RF carpet for efficient transfer of ion from capillary to RF funnel

Stage3:
RF funnel facilitates separation of xenon accompanying the Barium ion.

Stage4:
The Linear Paul trap for detection of barium ion via laser fluorescence spectroscopy.

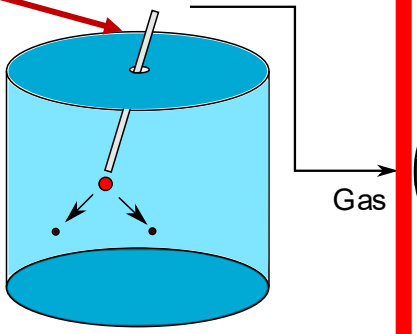
Stage5:
Multiple Reflection TOF Spectrometer for systematic studies and determination of ion mass.



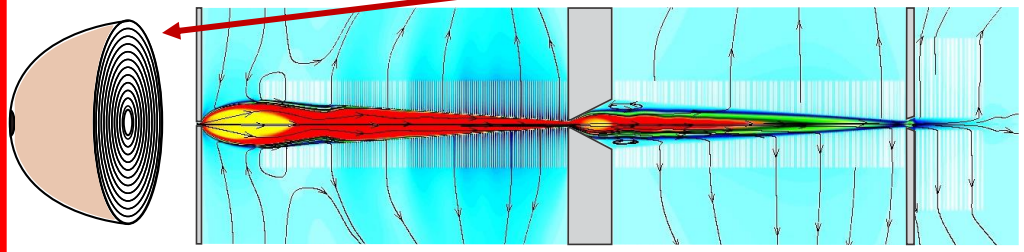
Canadian Ba Extraction and Tagging Effort

This project

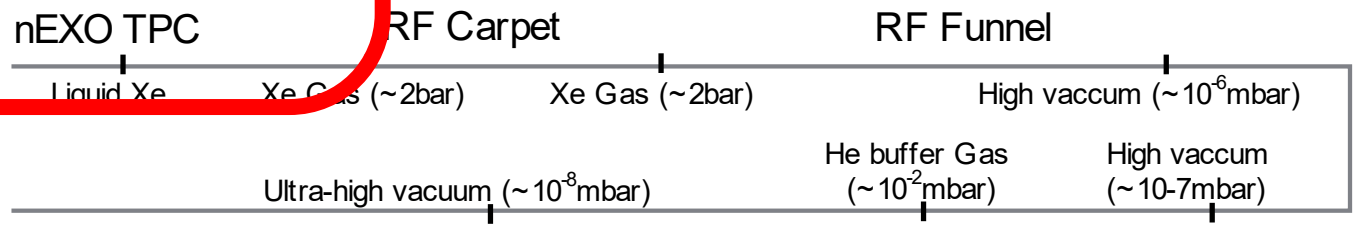
Stage1:
Extraction of detector volume around the location of the decay to gas phase using a capillary tube.



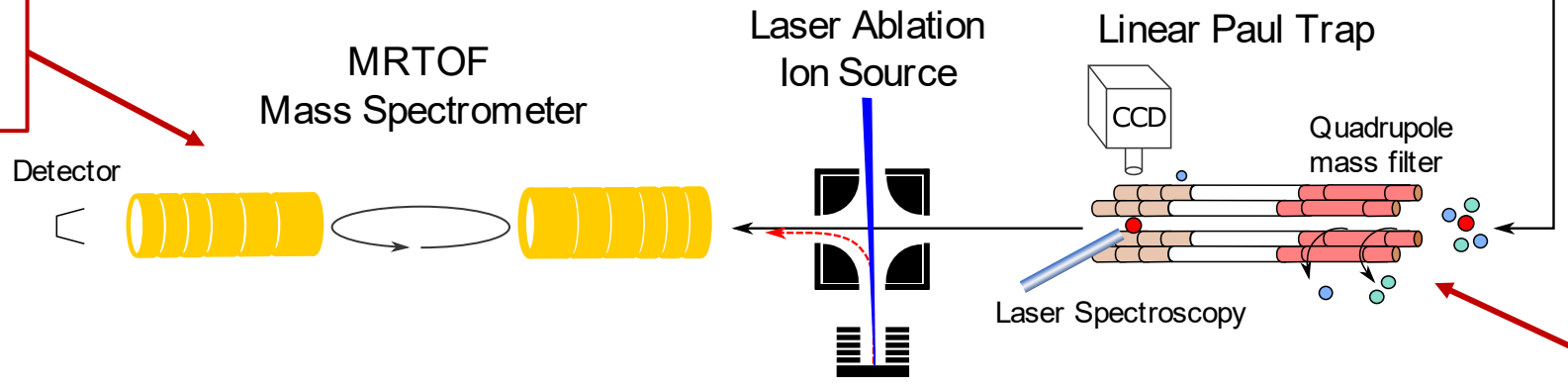
Stage2:
RF carpet for efficient transfer of ion from capillary to RF funnel



Stage3:
RF funnel facilitates separation of xenon accompanying the Barium ion.

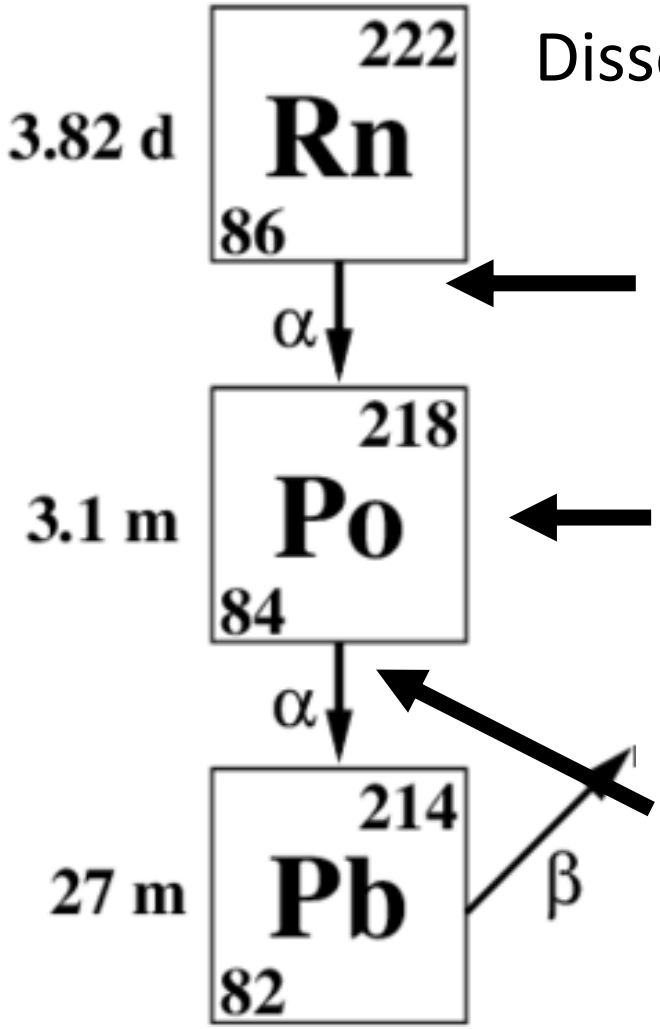


Stage5:
Multiple Reflection TOF Spectrometer for systematic studies and determination of ion mass.



Stage4:
The Linear Paul trap for detection of barium ion via laser fluorescence spectroscopy.

Ion extraction and transport from liquid xenon TPC

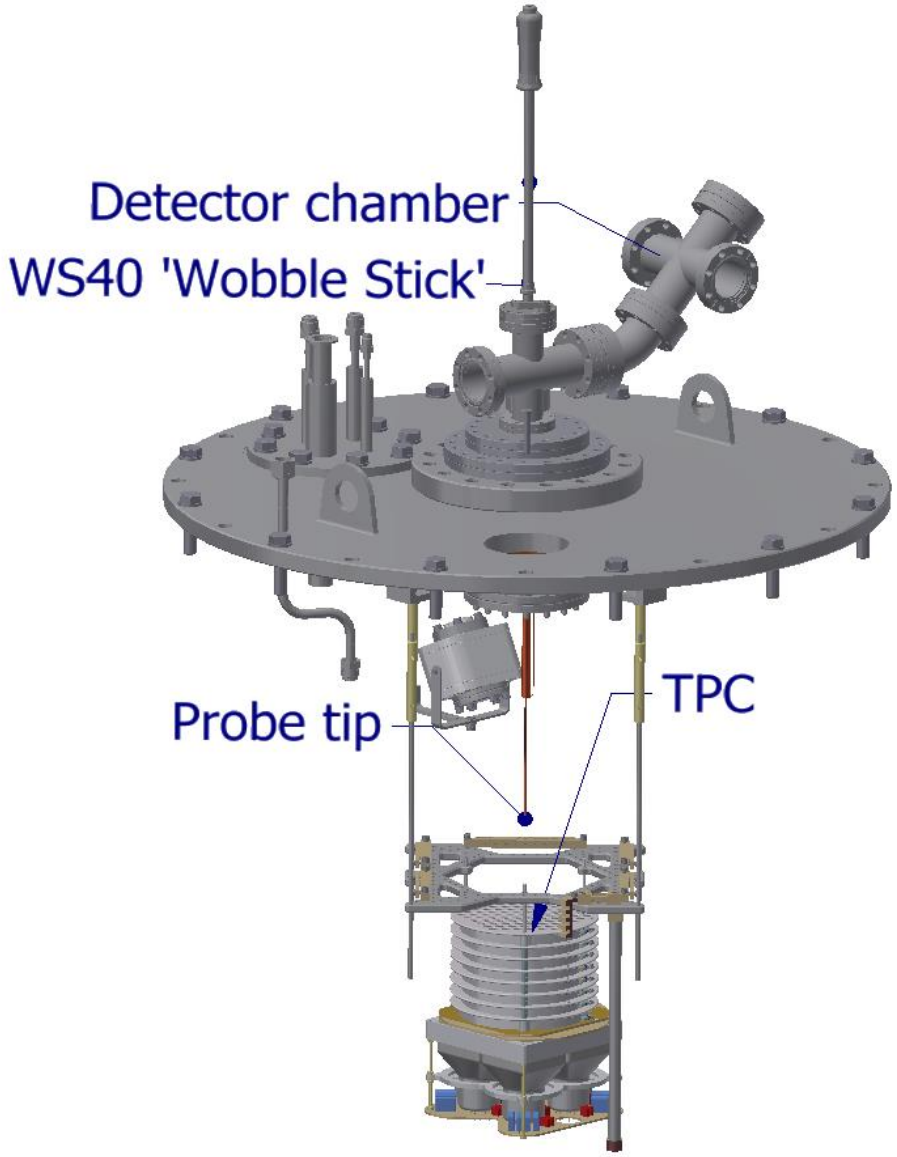


Dissolved in LXe

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

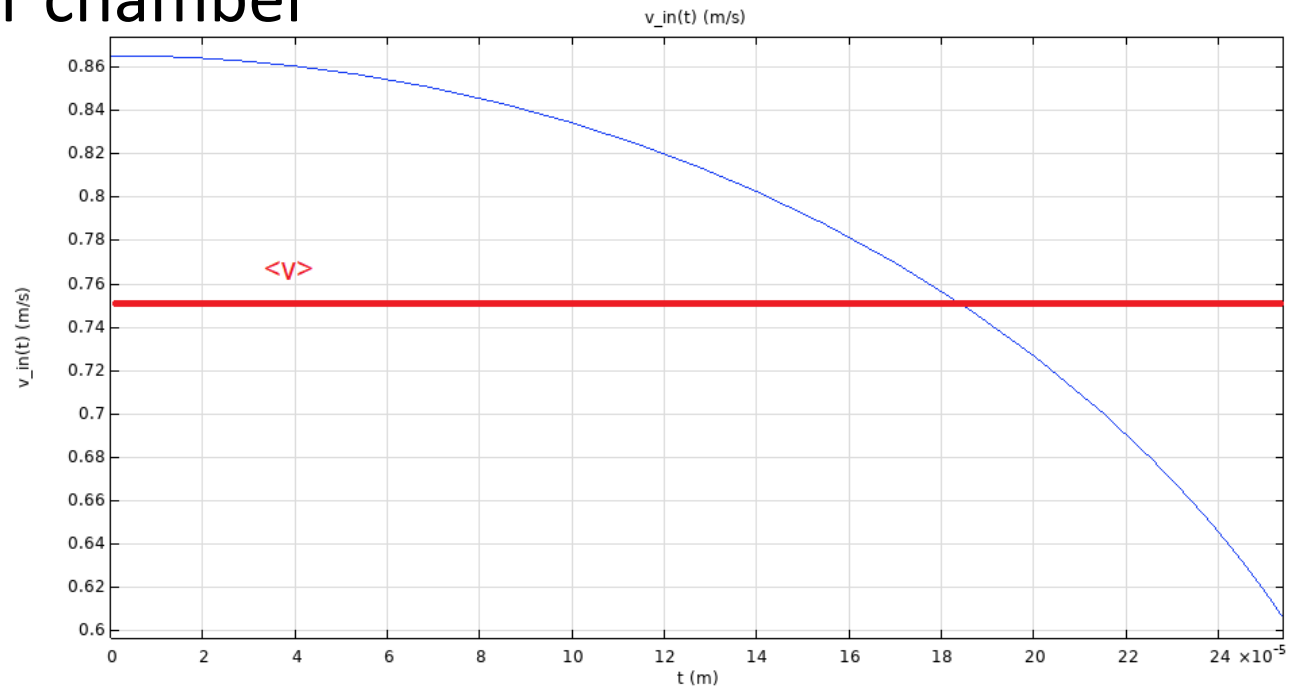


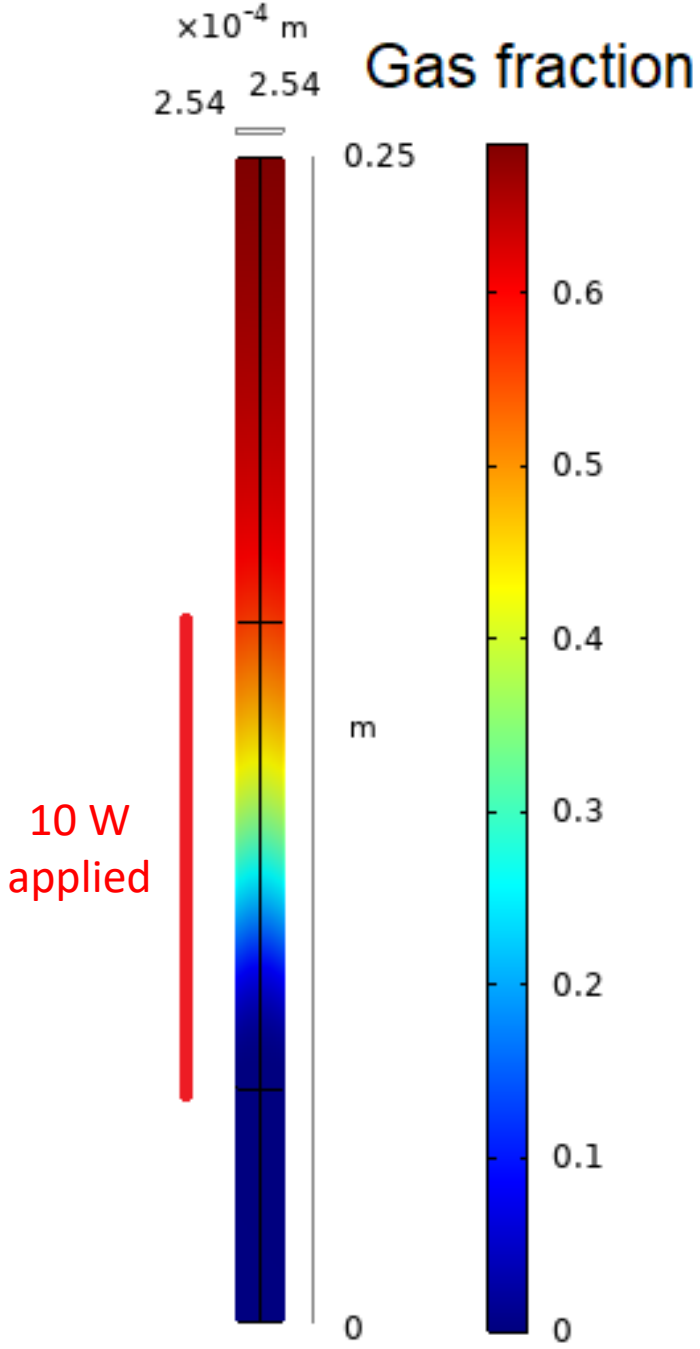
Transport through capillary

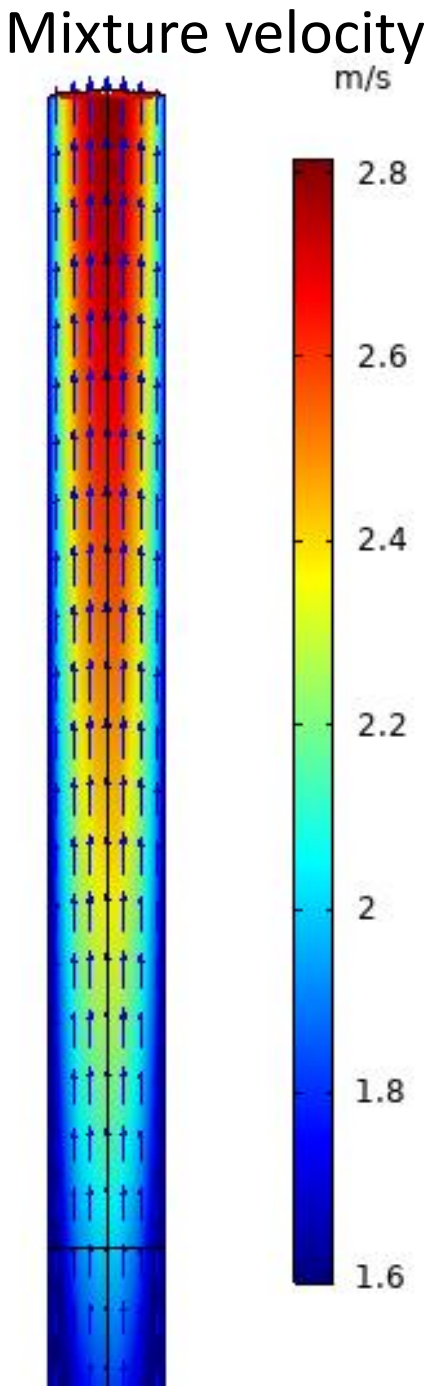
- Direct transfer to next stage of Ba-tagging
- Laminar flow prevents ion from hitting wall, neutralizing, and being lost
- Xenon flow carries ion to detector chamber
- Heat capillary near terminus
  - Phase change LXe → GXe
- Superheated liquid/gas mixture emerges into detector chamber

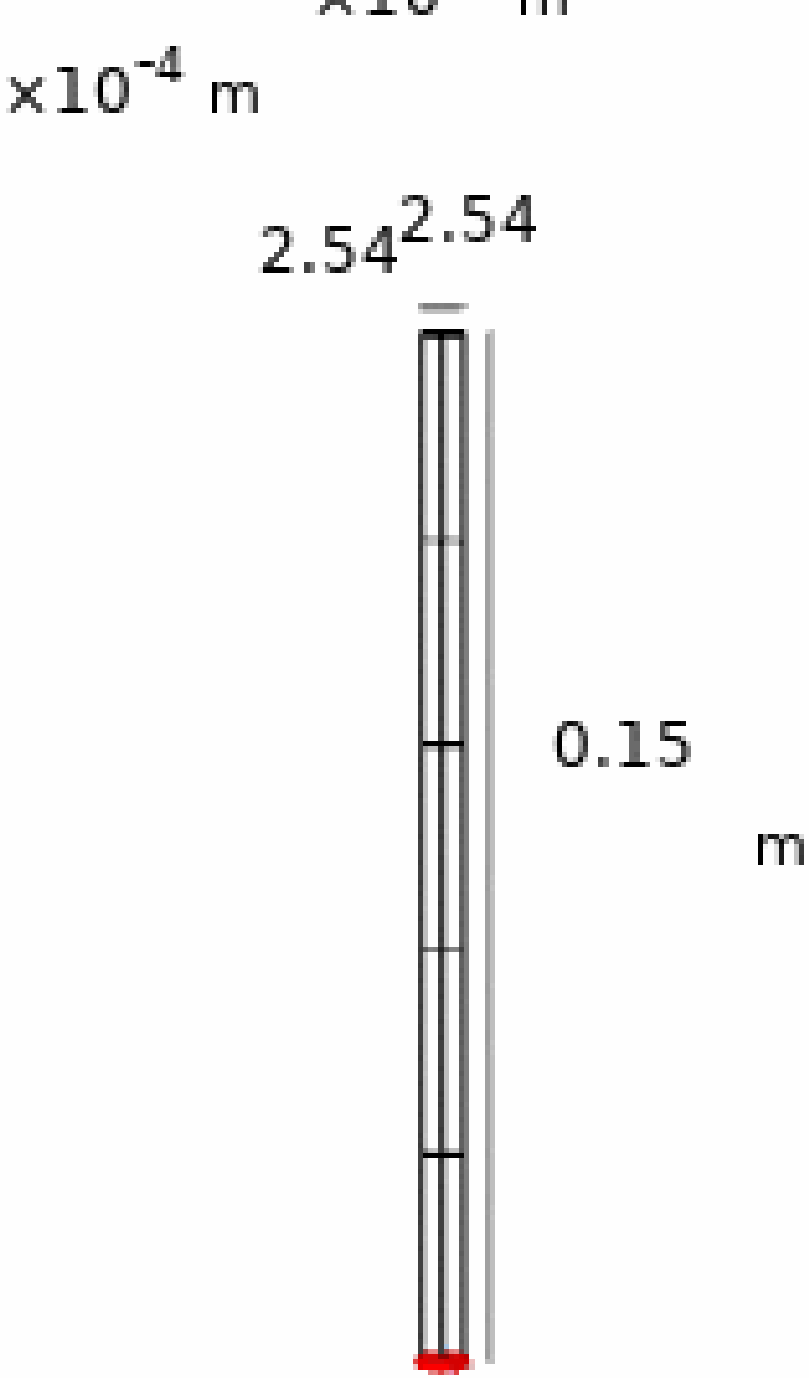
$$R_e = \frac{\rho D v}{\mu} < 2300$$

For D = 508 μm, v =75.7 cm/s




×10-4 m
2.54
2.54
Gas fraction
0.25
0.6
0.5
0.4
m
0.3
0.2
0.1
0
0
10 W
applied


Mixture velocity
m/s
2.8
2.6
2.4
2.2
2
1.8
1.6


×10-4 m
2.54
2.54
0.15
m

What we know of Po in LXe

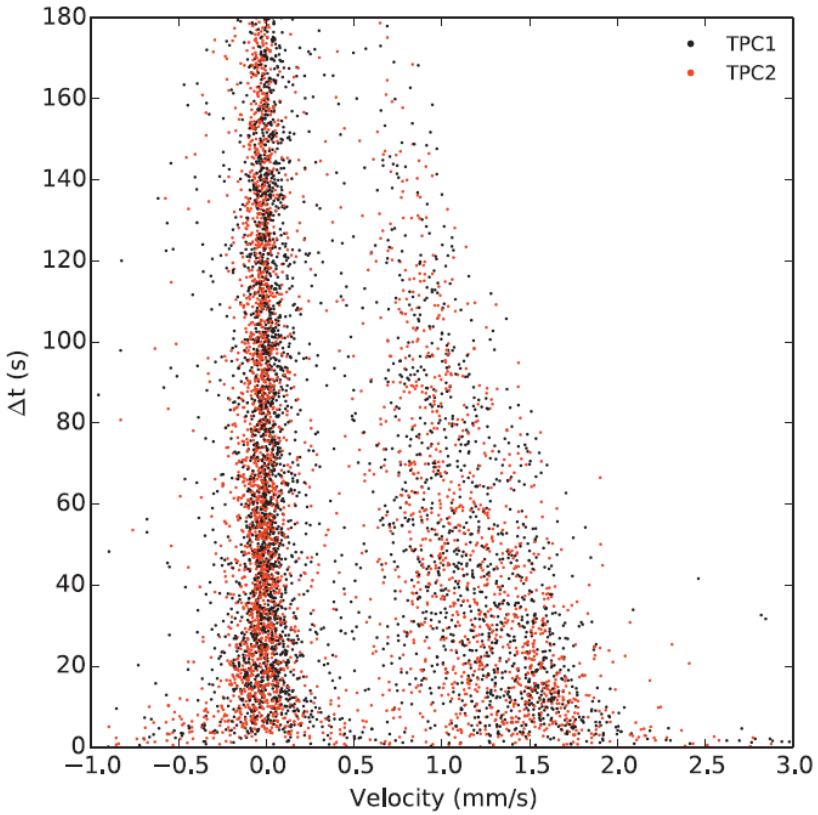


FIG. 11. (Color) The velocity versus time between Rn-Po coincident events (positive is towards the cathode). The TPC in which the events occur is indicated by the color of the points.

- Ion fraction ~50%
- Po+ ion randomly drifts <0.2 mm/s
- Po+ mobility 0.390(6) cm^2/kVs

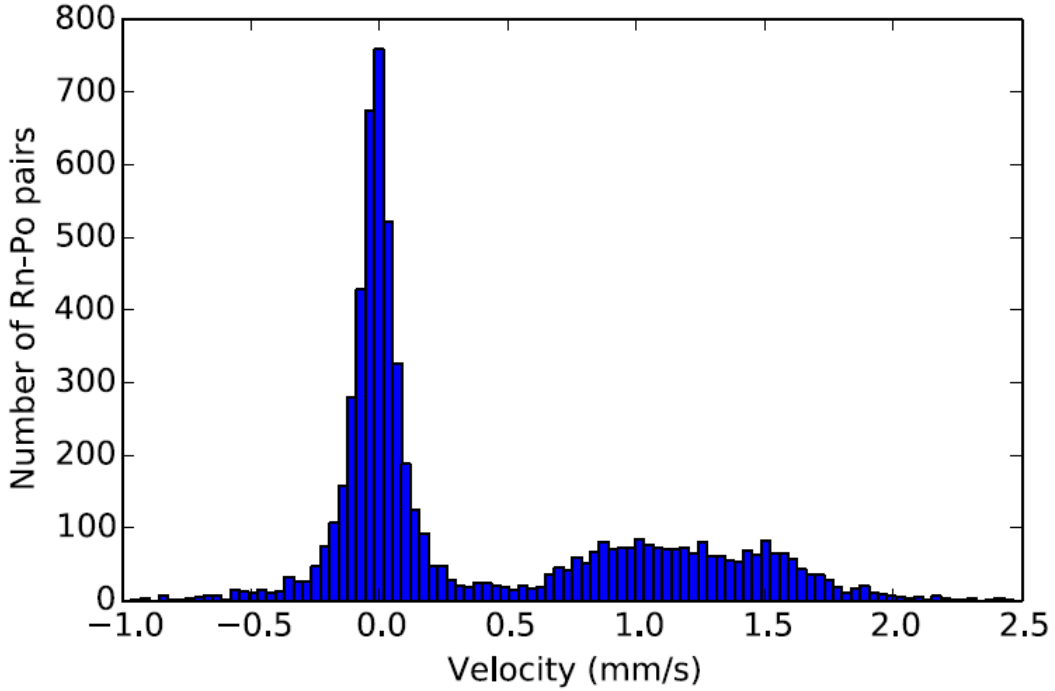
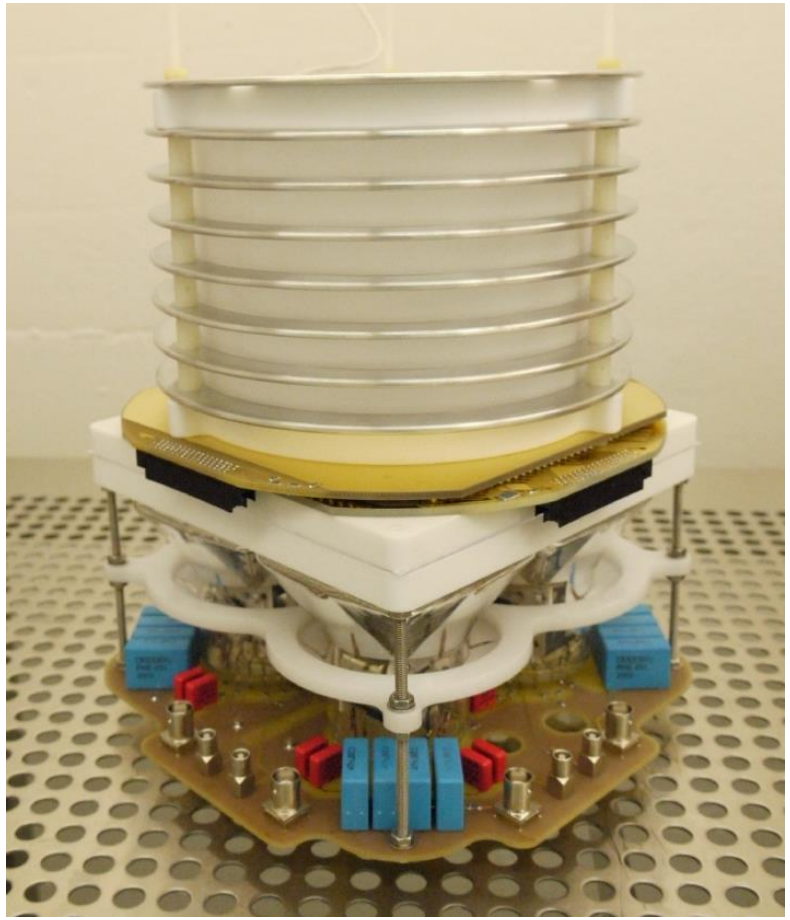


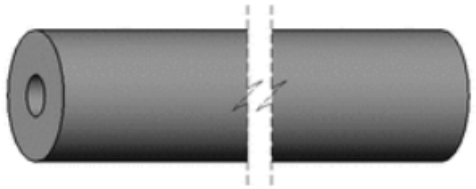
FIG. 9. (Color online) Histogram of the mean velocity of ^{218}Po ions and atoms extracted from ^{222}Rn - ^{218}Po coincidences.

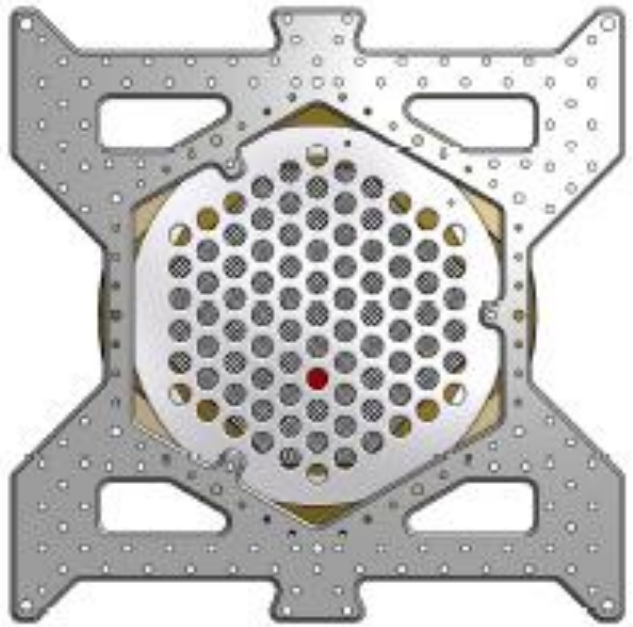
Albert JB et al. (EXO-200 Collaboration) 2015 Phys. Rev. C. **92** 045504
URL https://link.aps.org/doi/10.1103/PhysRevC.92.045504

EXO-100 TPC

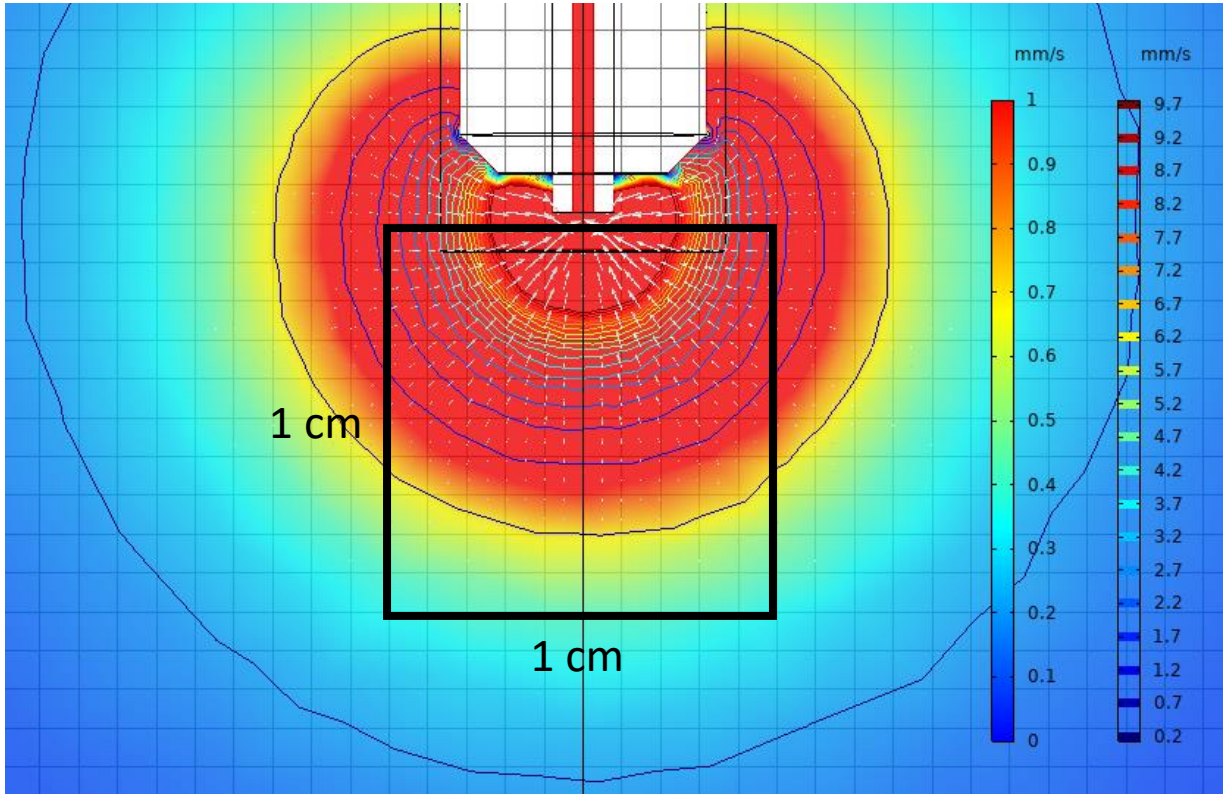


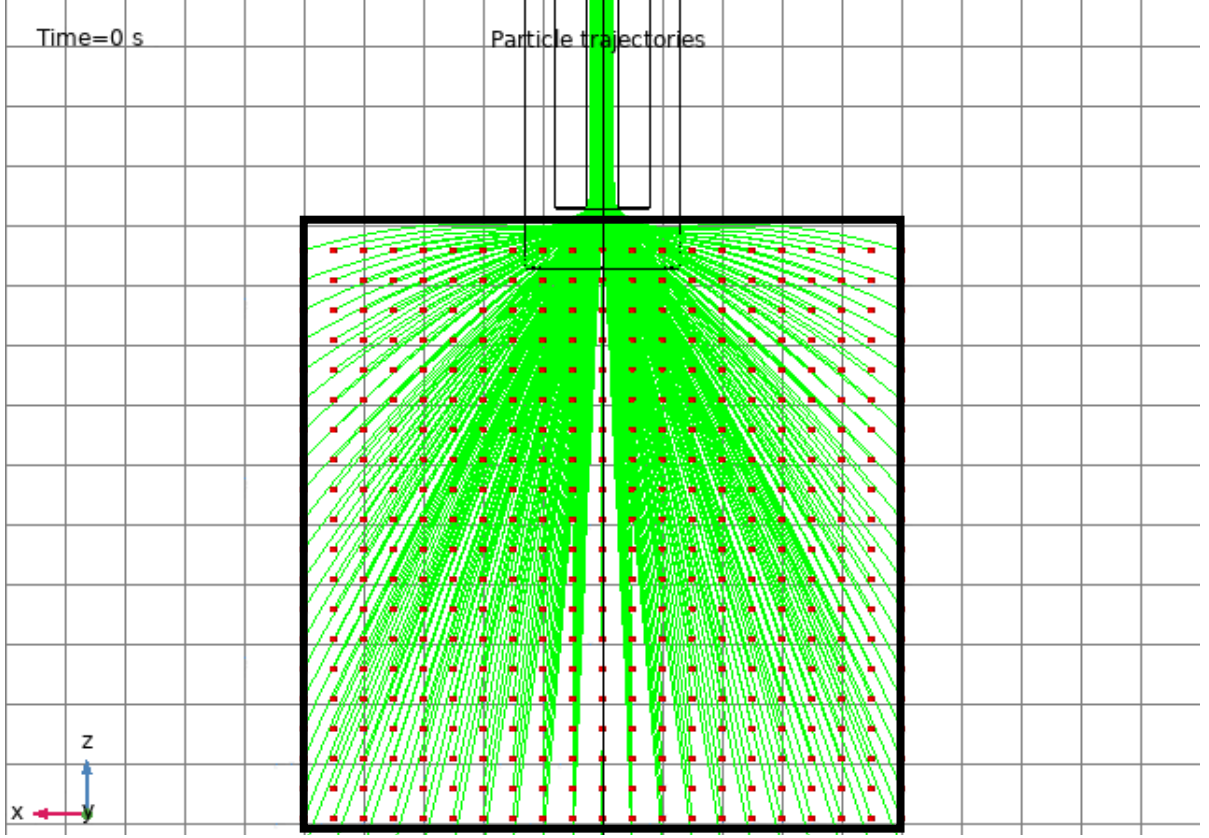
- 147 cm^2 area, 12.3 cm drift distance
- Holes in cathode for probe access
- Flow controlled by pressure difference between cryostat and detector chamber
- Capillary 508 μm ID, 1 m long

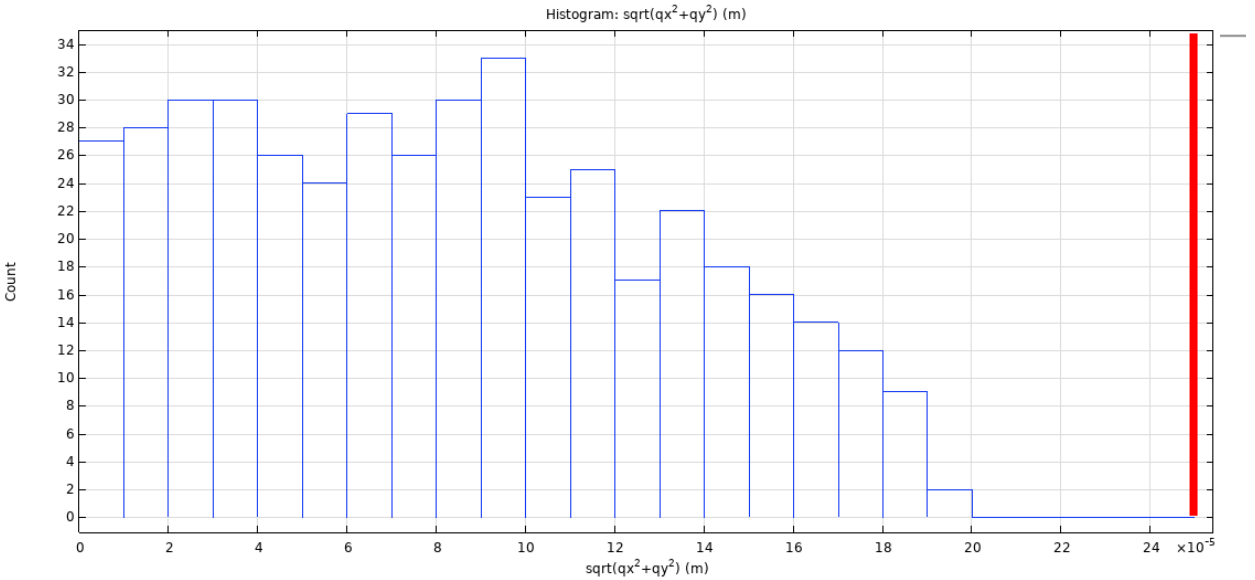




Extraction simulation





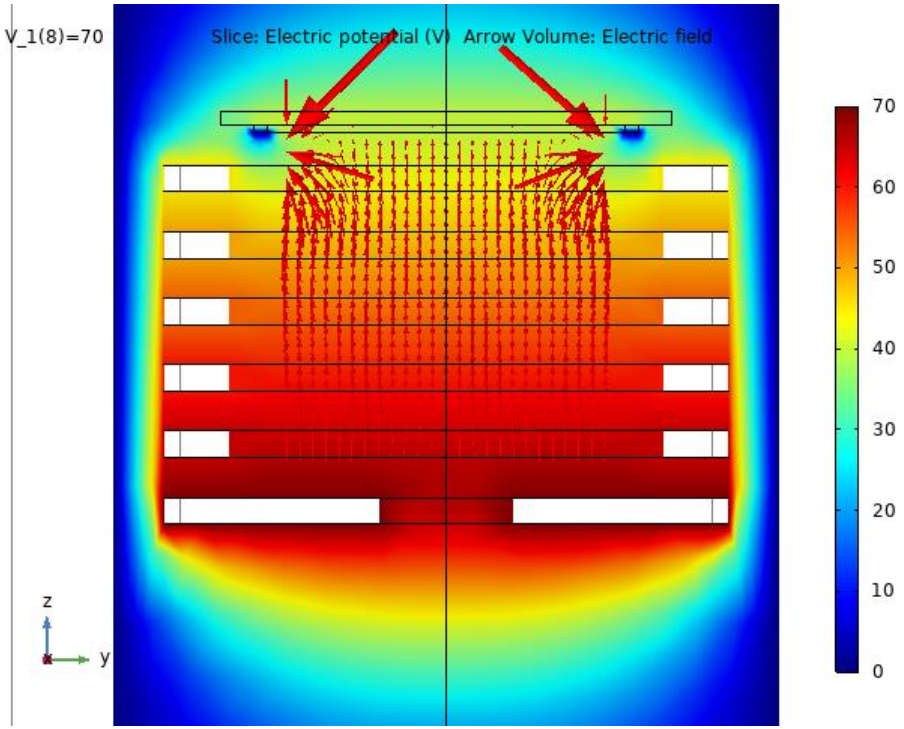


- Efficient extraction from volume below capillary tip

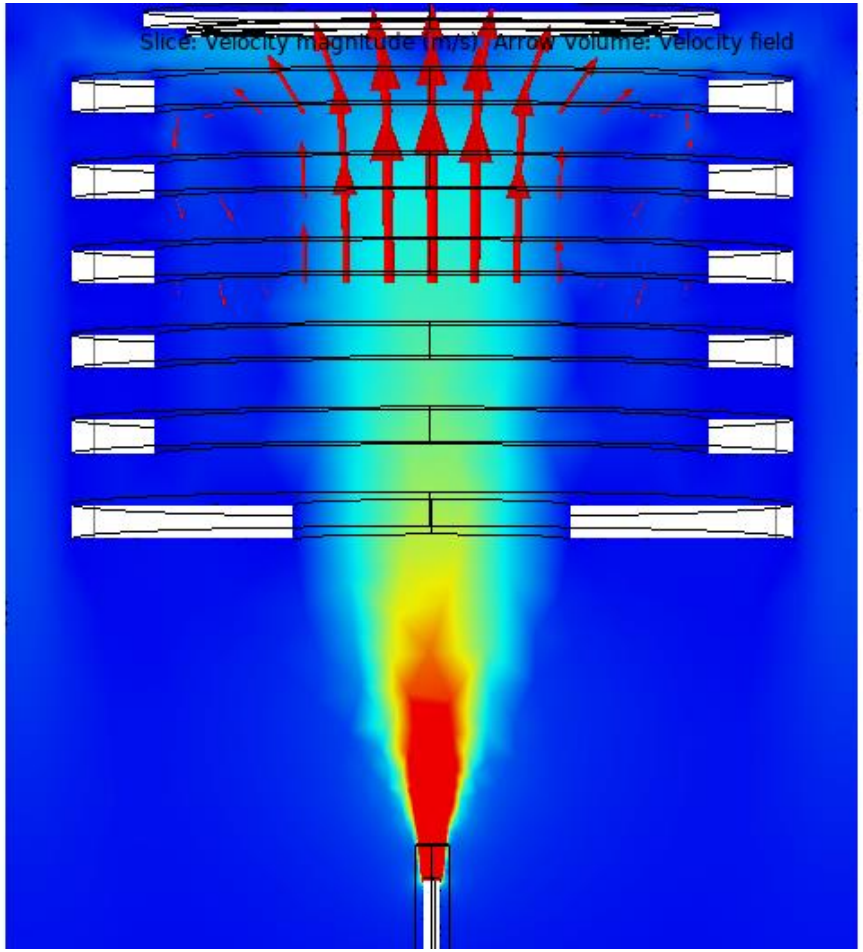
Deposition onto PIPS

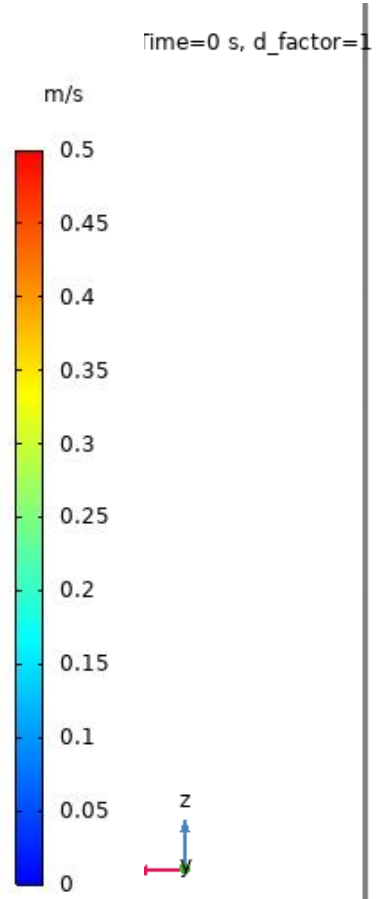
Canberra PD300-CB Custom 300mm^2 PIPS

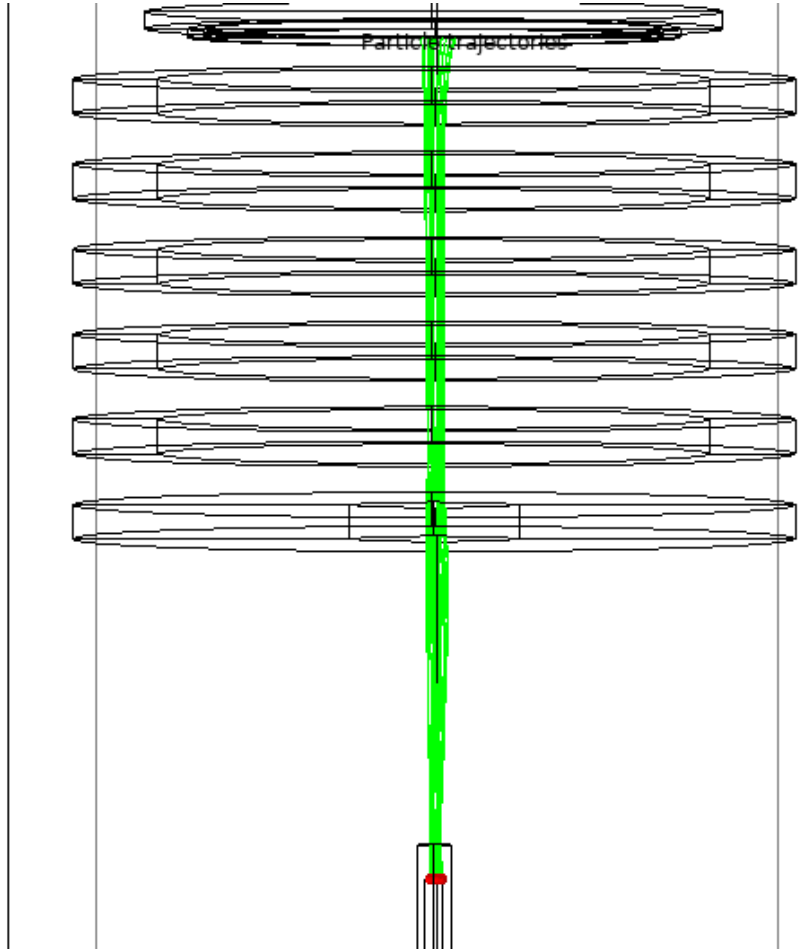
- PIPS back operates at +40 V
- Xenon gas carries ion towards PIPS, field rings give final push
- ~10 V/cm E-field



Deposition simulation



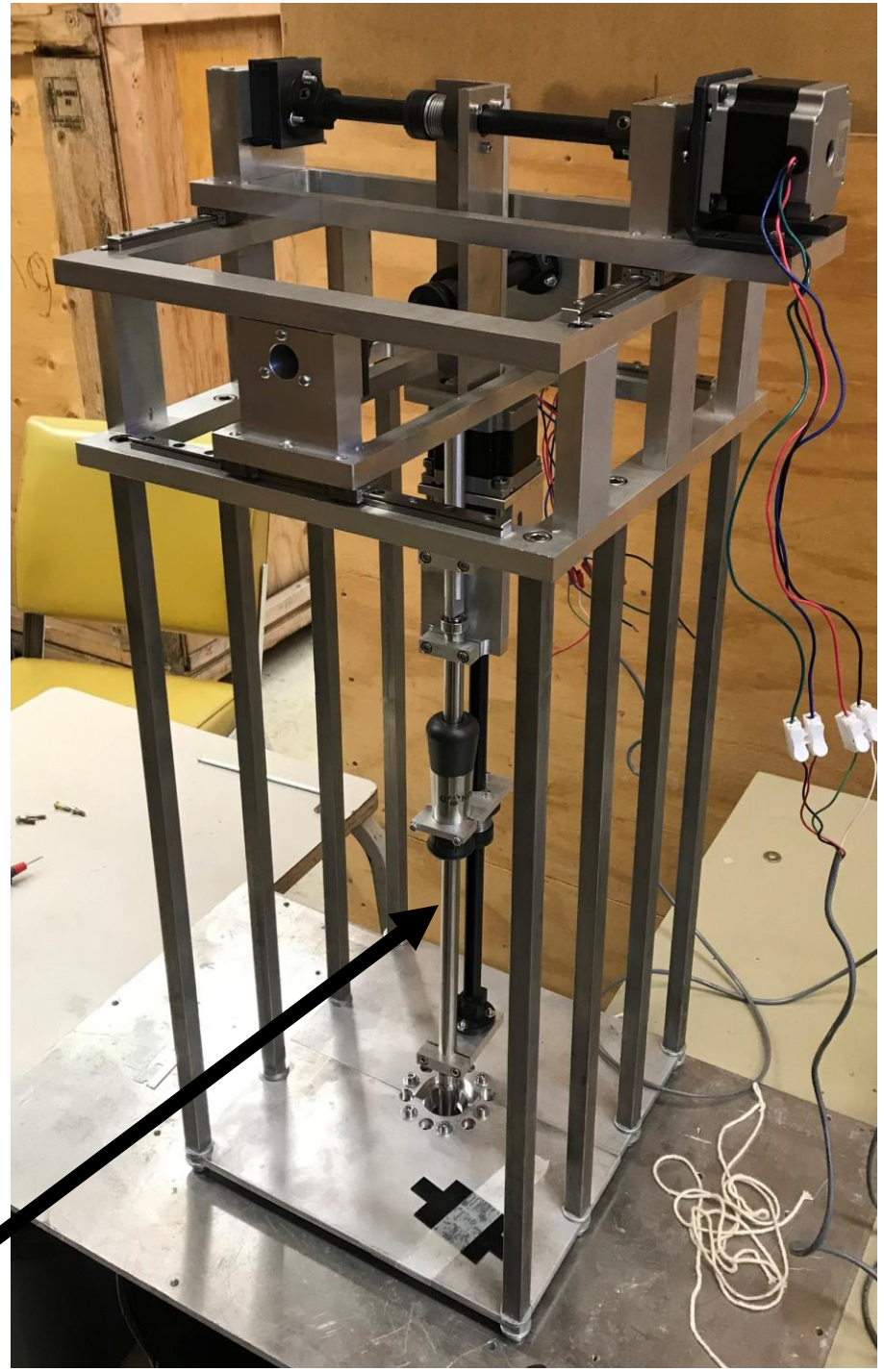




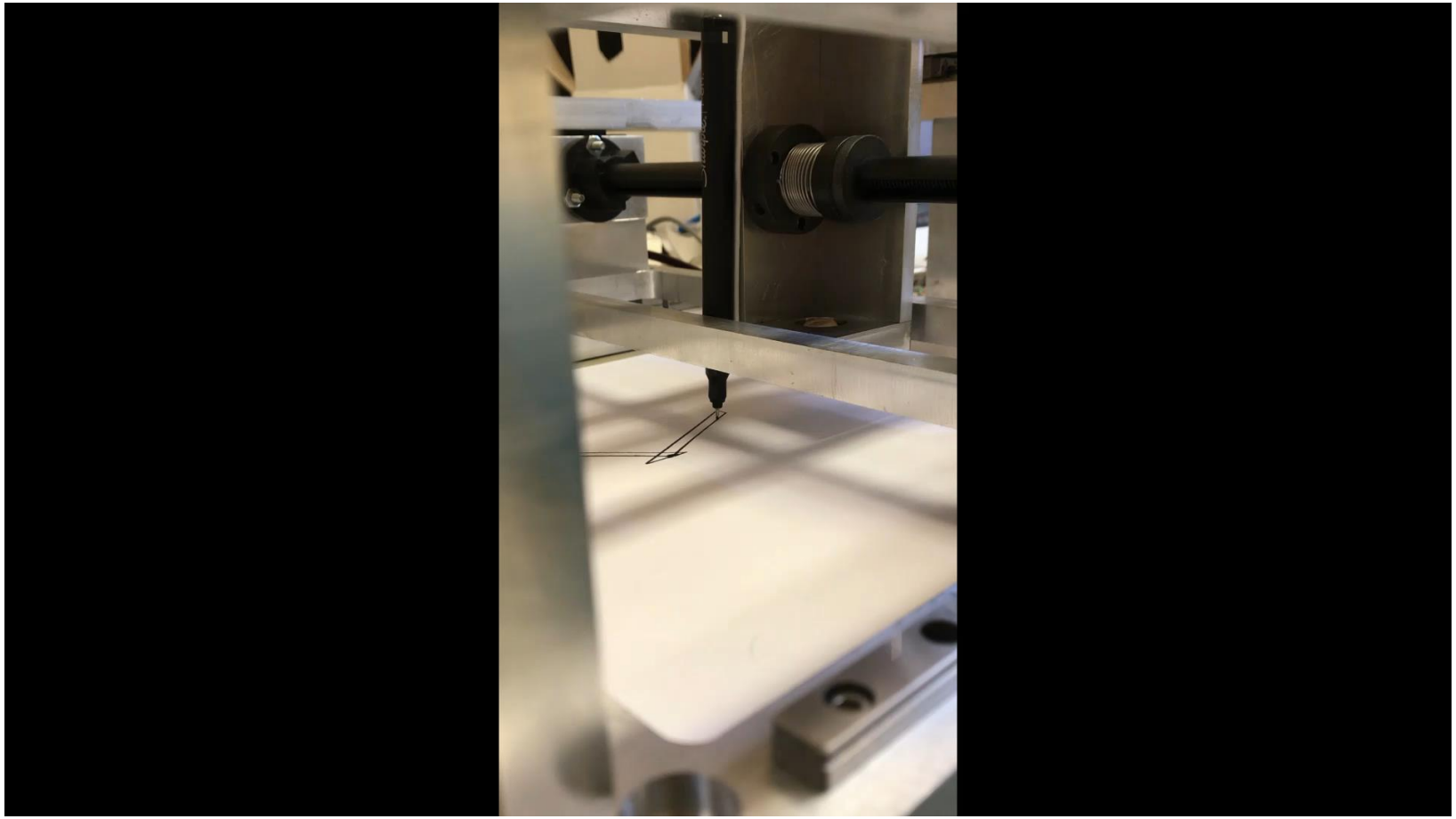
Displacement device

- Stepper motors move probe tip to location determined by TPC signals
- XY-stage sets angle around WS pivot
- R-motion controls insertion/retraction through openings in TPC cathode
- Precision machining, linear rails allow positioning to better than 1 mm^3
- Arbitrary velocity profile to minimize agitation of xenon

WS40 Wobble stick manipulation moves probe tip



Displacement frame XY motion



Ba-tagging group at Carleton

- Faculty

  Razvan Gornea, Thomas Koffas
- Postdoc

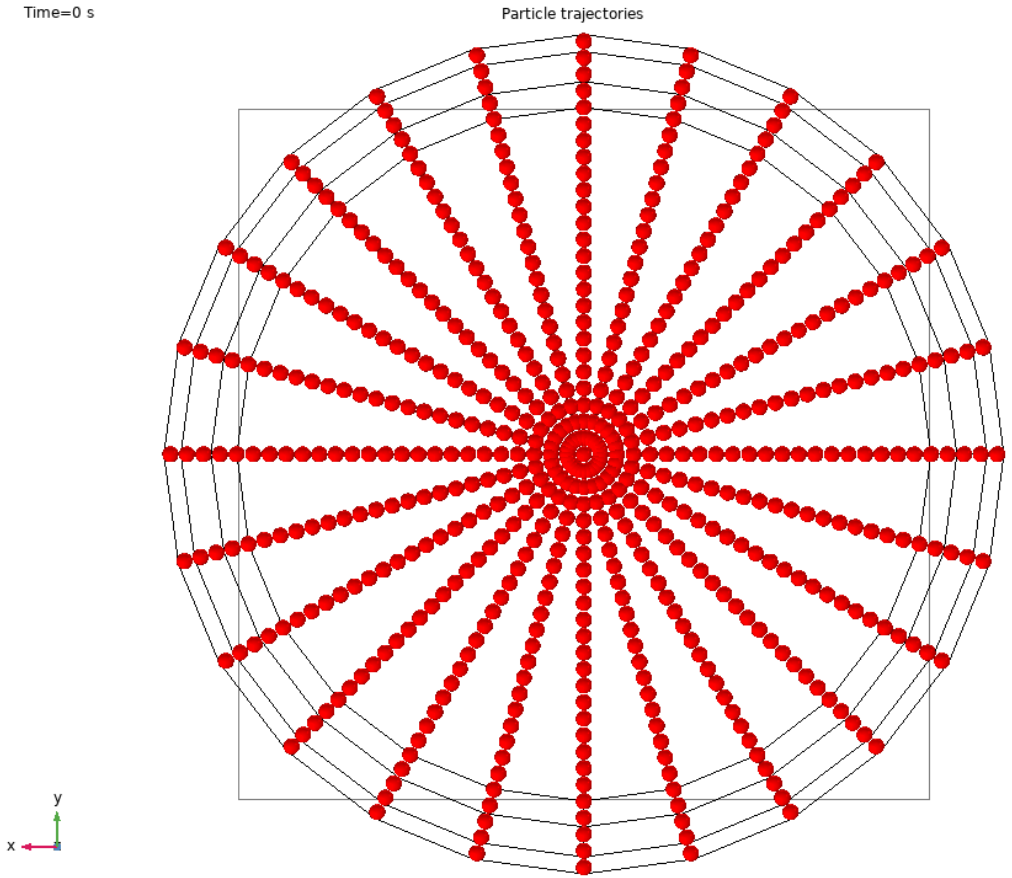
  Robert Collister
- M.Sc. Student

  Ryan Elmansali

Extras

Initial particle distribution

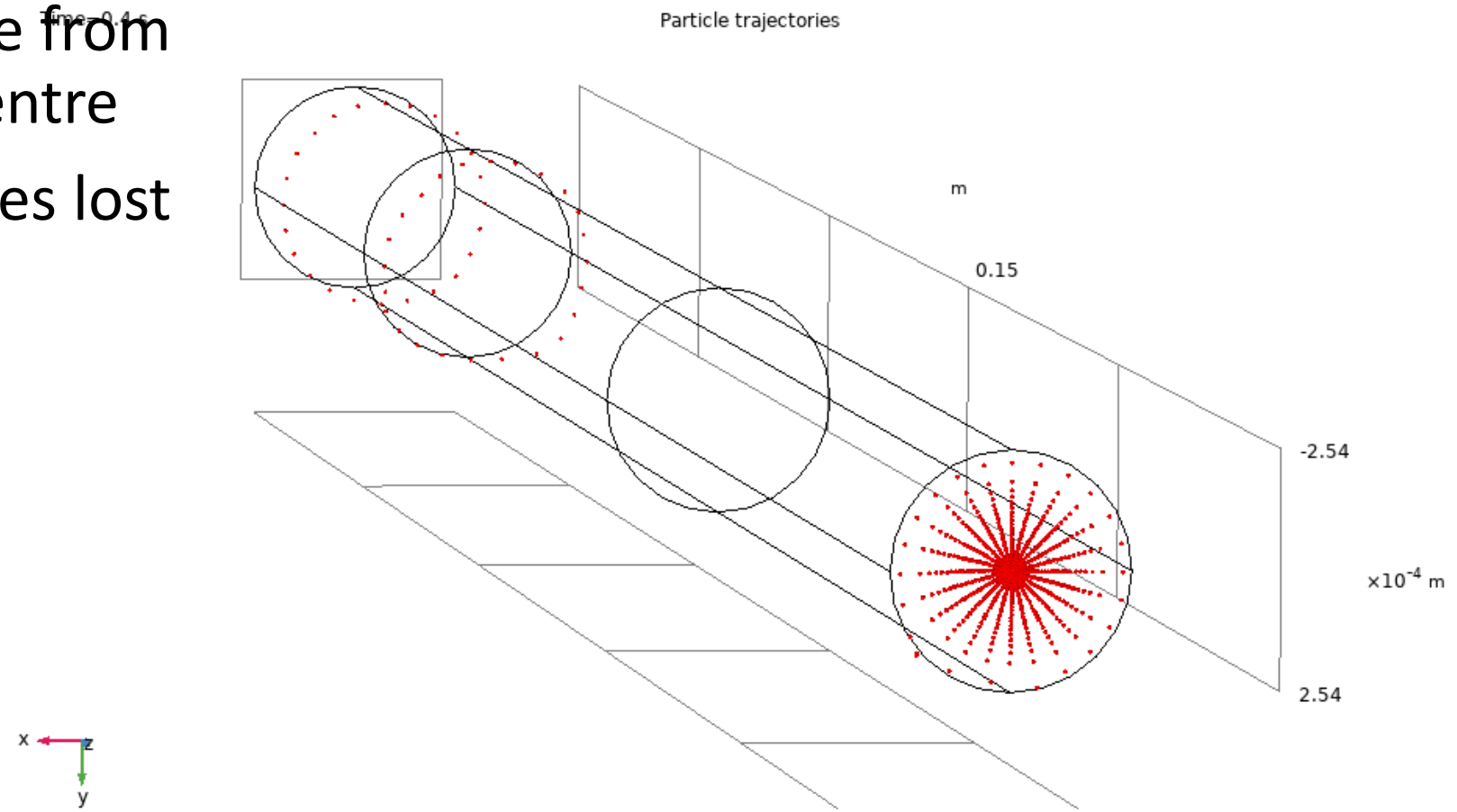
- 10 um spacing, 0-254 um
- 24 angles



Initial particle distribution

- Slight convergence from flow tending to centre
- Outermost particles lost

  <30 um



Po^+ behaviour

- Electron lifetime → xenon purity
- Ion fraction fairly constant with Xe purity

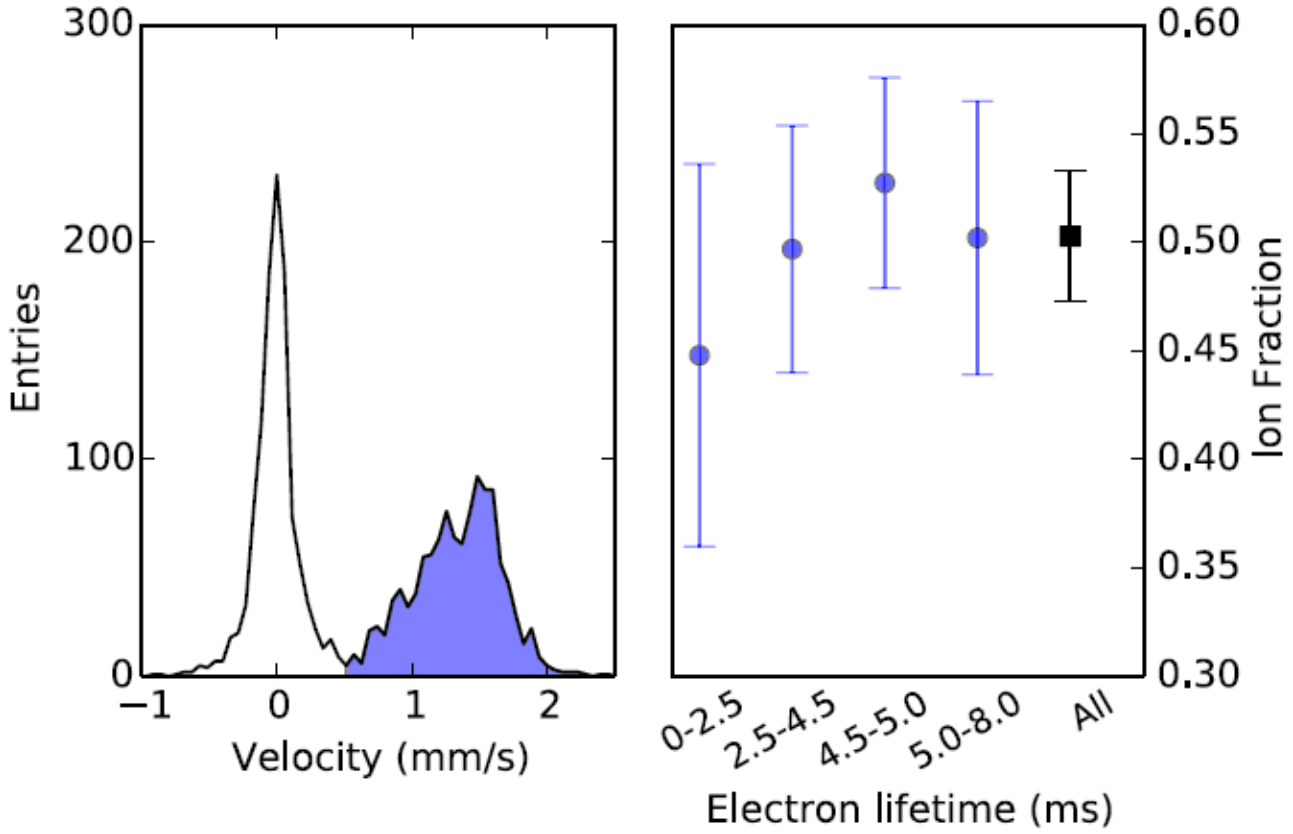


FIG. 13. (Color online) (Left) Velocity histogram after applying the Δt cut on all of the Rn-Po coincidences. The shaded region (velocity > 0.5 mm/s) is integrated to determine the number of ^{218}Po ions. (Right) The ion fraction found for different electron lifetime ranges.

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Po^+ behaviour

- Ion velocity increases with xenon purity
- Higher mobility, smaller ion cluster, less drag

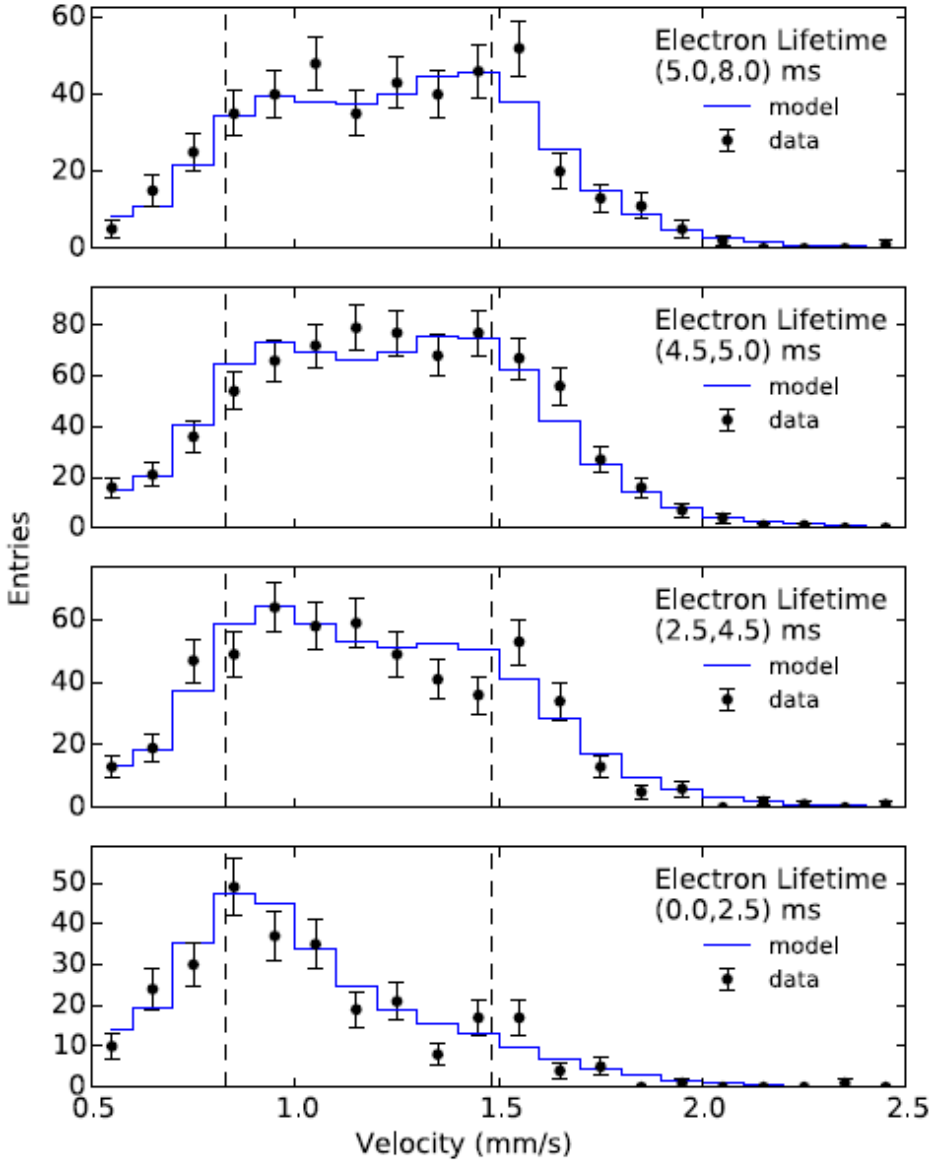

FIG. 12. (Color online) Histograms of the average velocity of positive ions separated into four ranges of electron lifetimes. A model (solid lines) is used to fit the data (points with error bars). The dashed lines indicate the velocities v_1 and v_2 of the fit.

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Ba+ in xenon gas

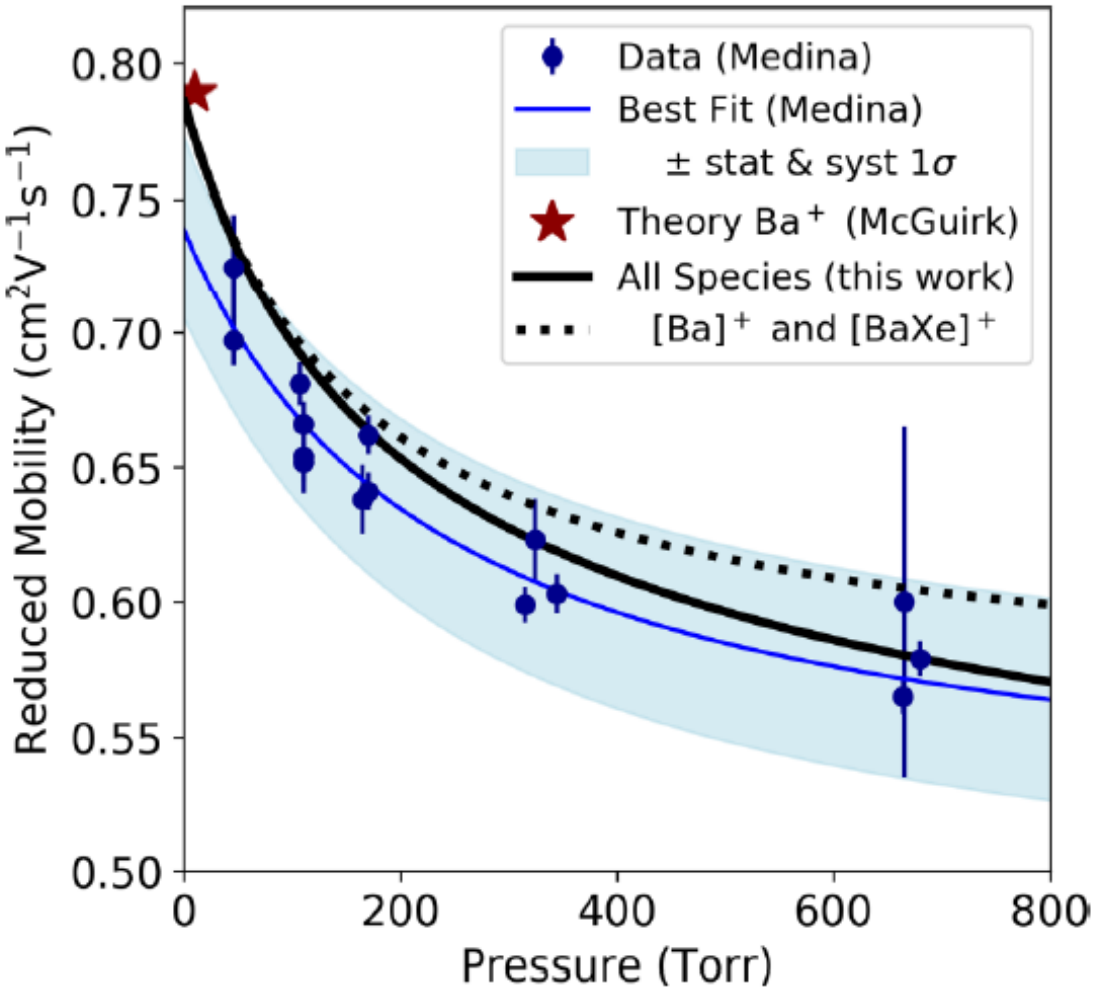

FIG. 4. Comparison of our predicted effective reduced mobility to experimental data from [9]. Equilibrium constants are evaluated at 296 K as specified in [9].

Capture simulation with TPC on

- 8 kV on cathode

  → 640 V/cm