Novel ion trap design concept as a LAr purity monitor

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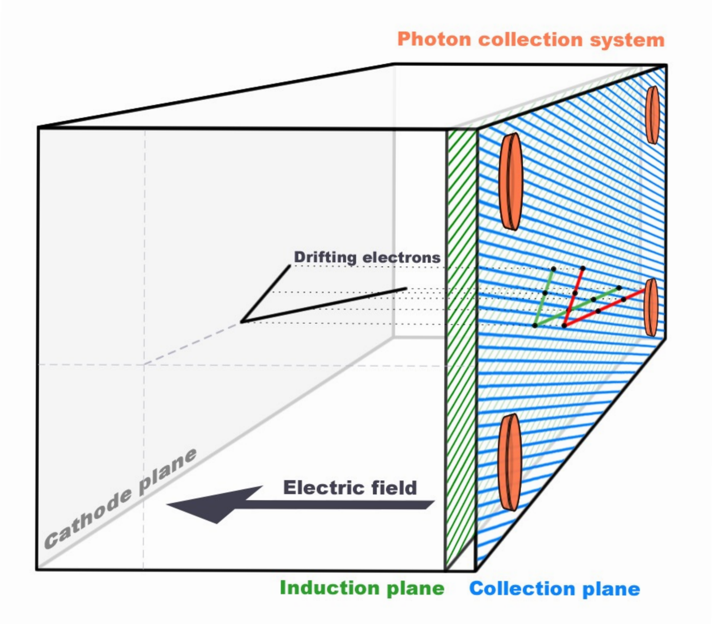
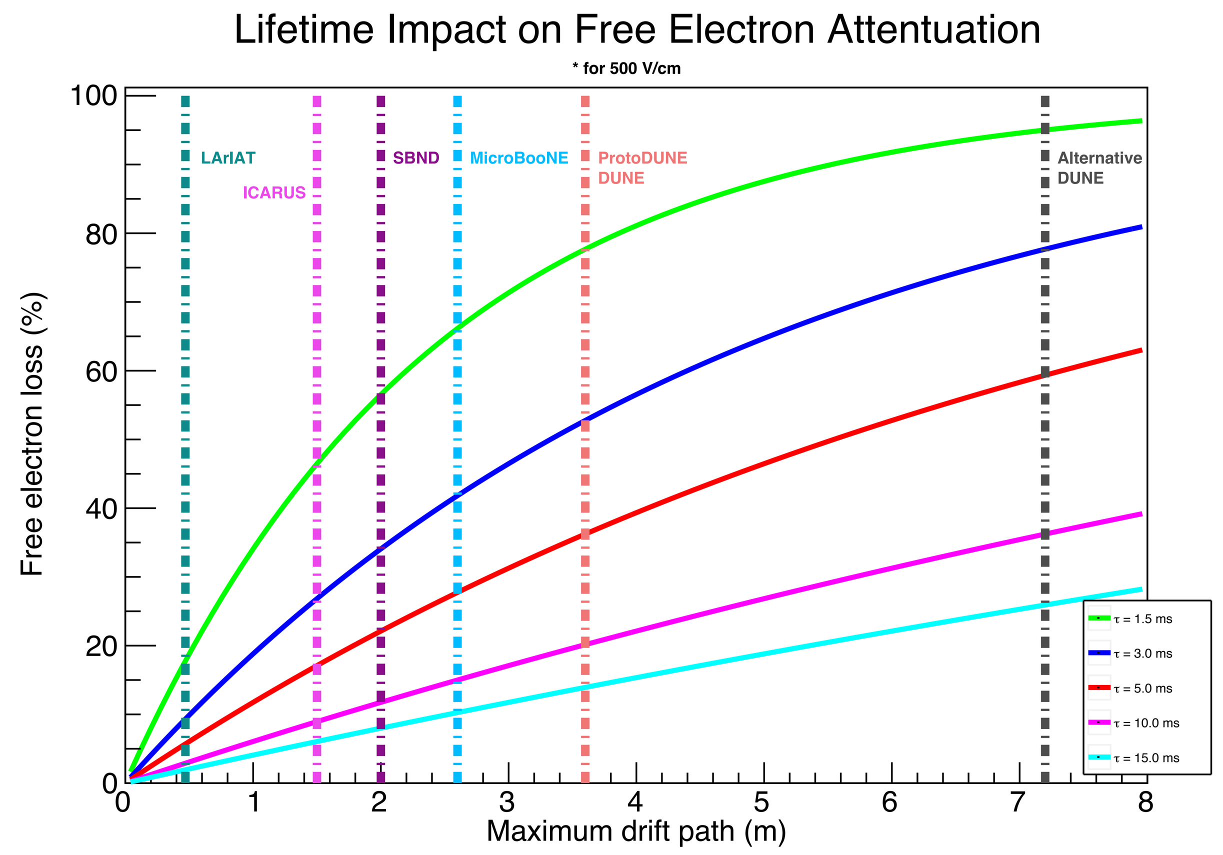
Introduction



- LArTPC reconstruction capability is based on the detection of ionization charge produced by particle interactions
- This capability is affected by detector size and amount of electronegative contaminants in LAr

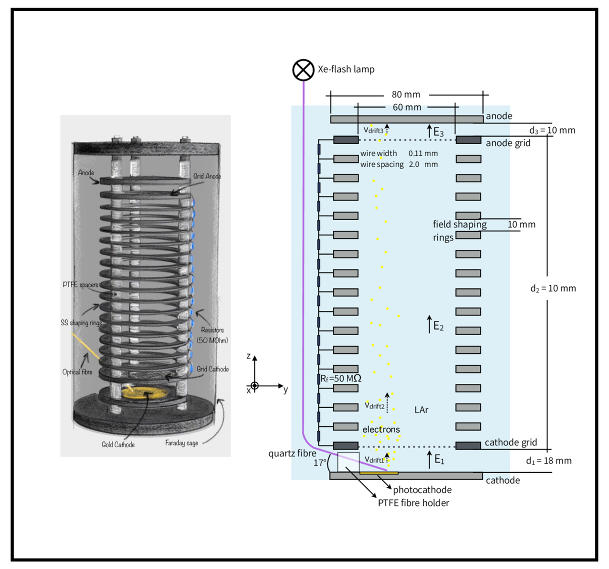


- LAr purity is therefore crucial, and is constantly monitored by measuring the electron lifetime in the medium. The electron attenuation is given by:

$$Q = Q_0 e^{\frac{-t}{\tau}}, \qquad t = \frac{x}{v}$$

Current LAr Purity Measurement Methods

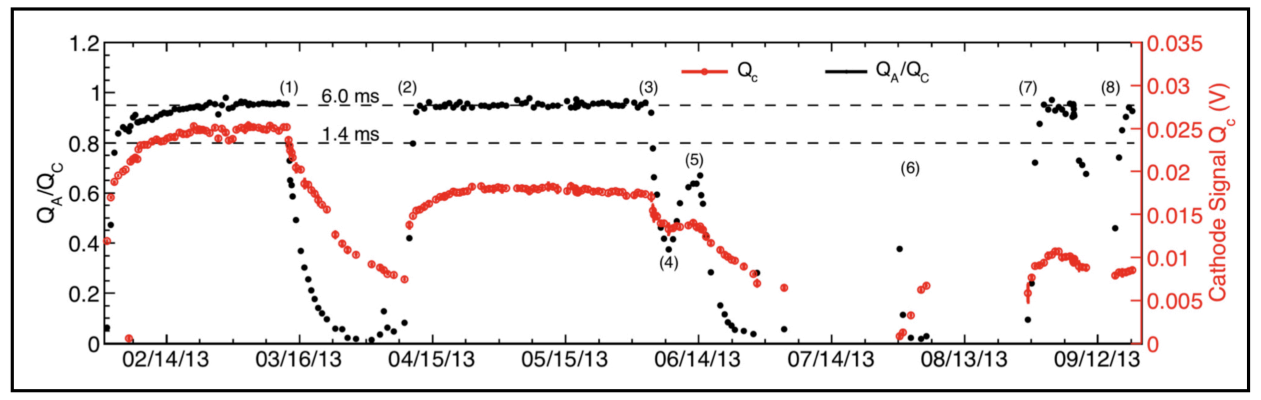
Purity Monitors



Xenon lamp connected to a photocathode via an optical fiber. The Xe lamp produces a charge that is drifted along the length of the purity monitor. The electron lifetime is inferred from the produced/measured charge ratio and the measured drift time. [1,2]

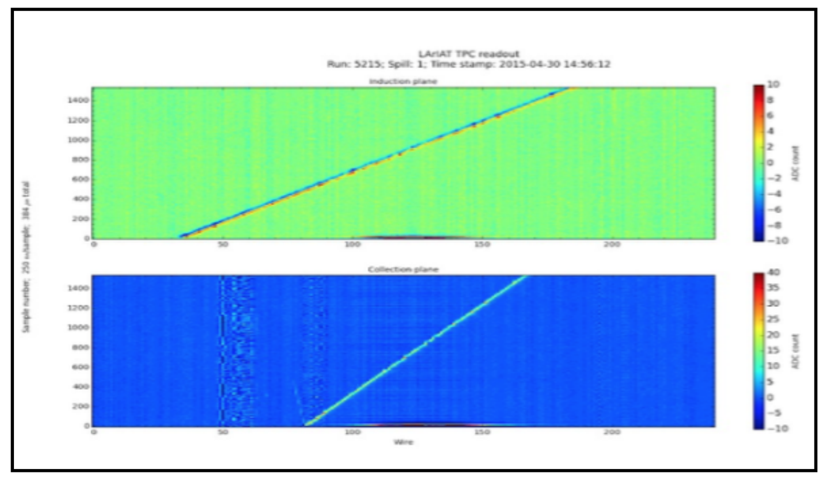
Pitfalls:

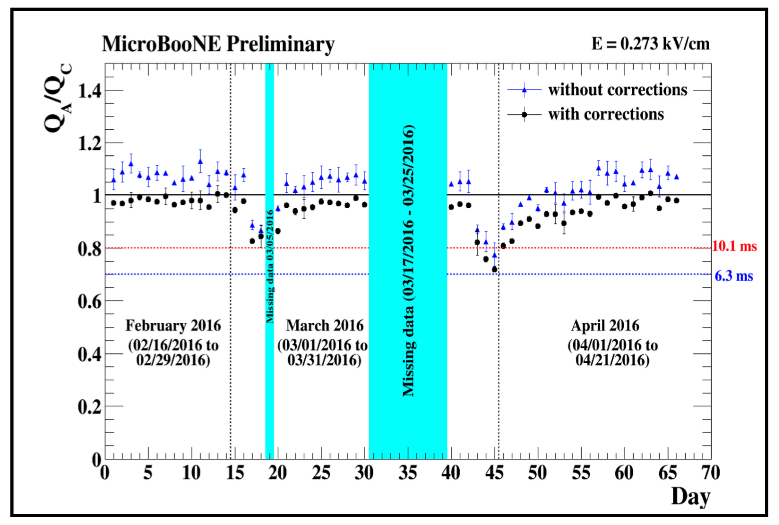
- Fiber and photocathode degrades within months
- Dynamic range of the purity monitor is limited by its length



Crossing Cosmic Muons

This method compares the measured ionization charge from minimum ionizing cosmic muons that cross the entire drift length of the LArTPC. [3, 4]

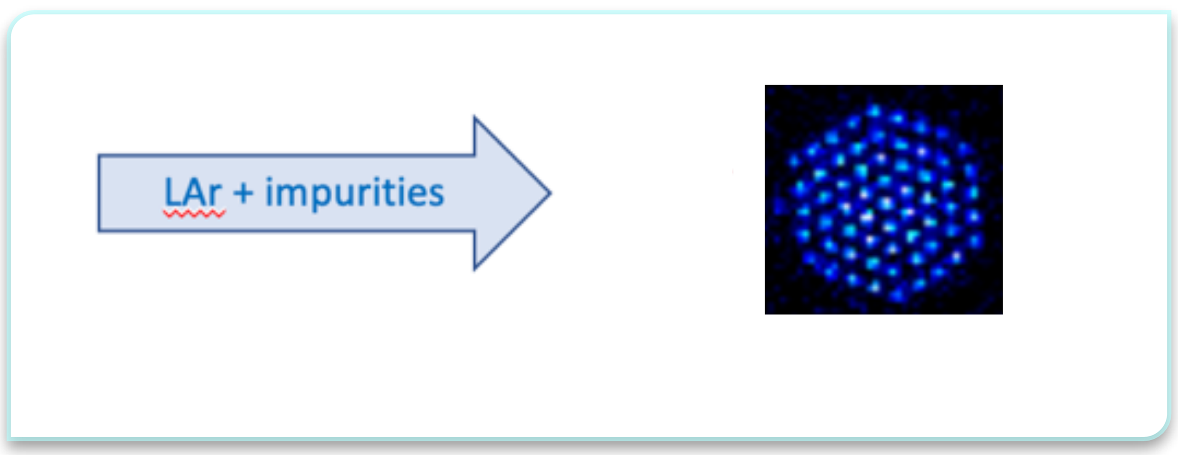




Pitfall:

- The method is most readily applicable to surface detectors
- Method is sensitive to space charge effect and reconstruction efficiency

Proposed New Method



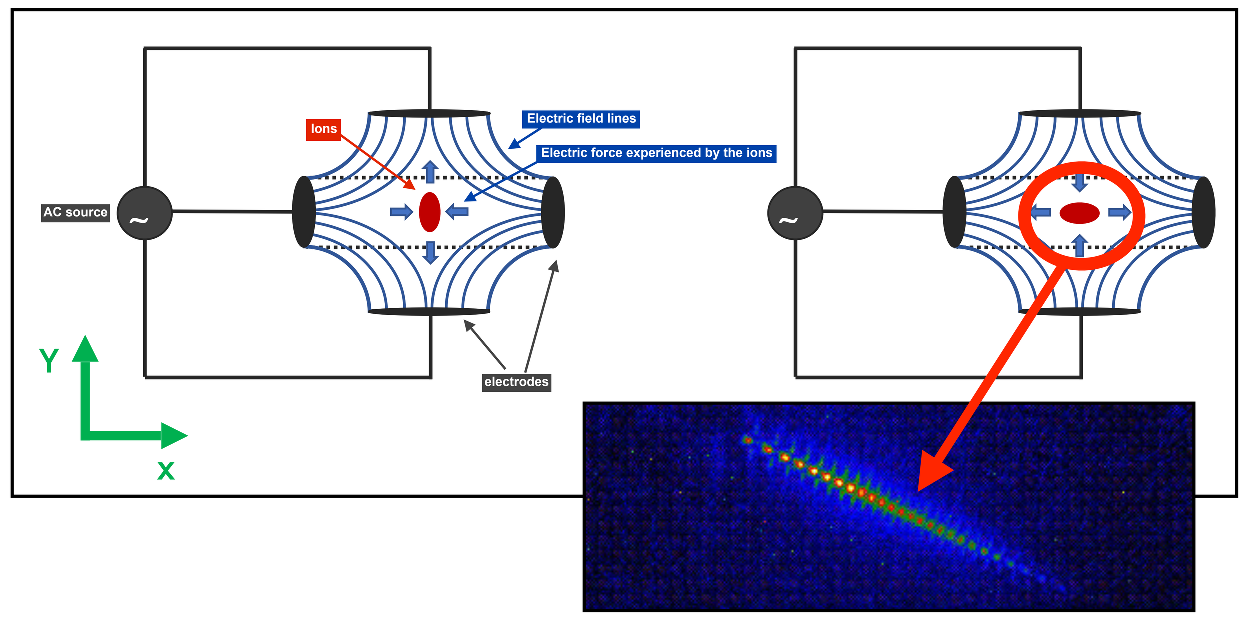
The proposed method consists of trapping a certain population of ions in a given region within the LAr and, considering a LAr flux crossing the trap, measuring the time it takes for it to be significantly decreased. The attachment rate between the ions and the impurities will be given by

$$R_{int} = \frac{\#imp}{\#LAr} \times \rho_{LAr} \times v_{ion,LAr} \times \#ion \times \sigma(ion - impurity)$$

Proposed New Method - cont.

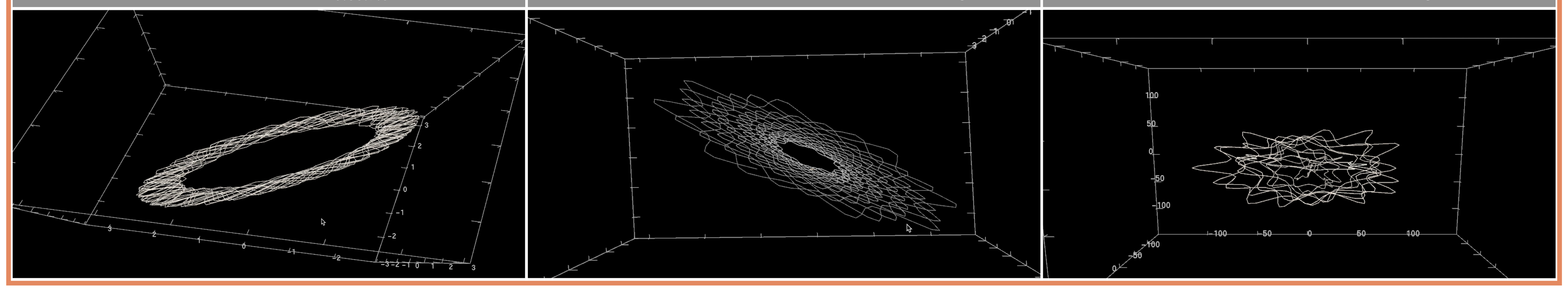
To contain the ion population, a RF Paul Trap will be used. In a RF trap in liquid medium, a particle experiences electric force, drag force, and Brownian motion [5], as indicated in the following:

$$m\frac{d\vec{r}^2}{d^2t} = -b\frac{d\vec{r}}{dt} - q(\nabla\phi) + \vec{N}(t)$$



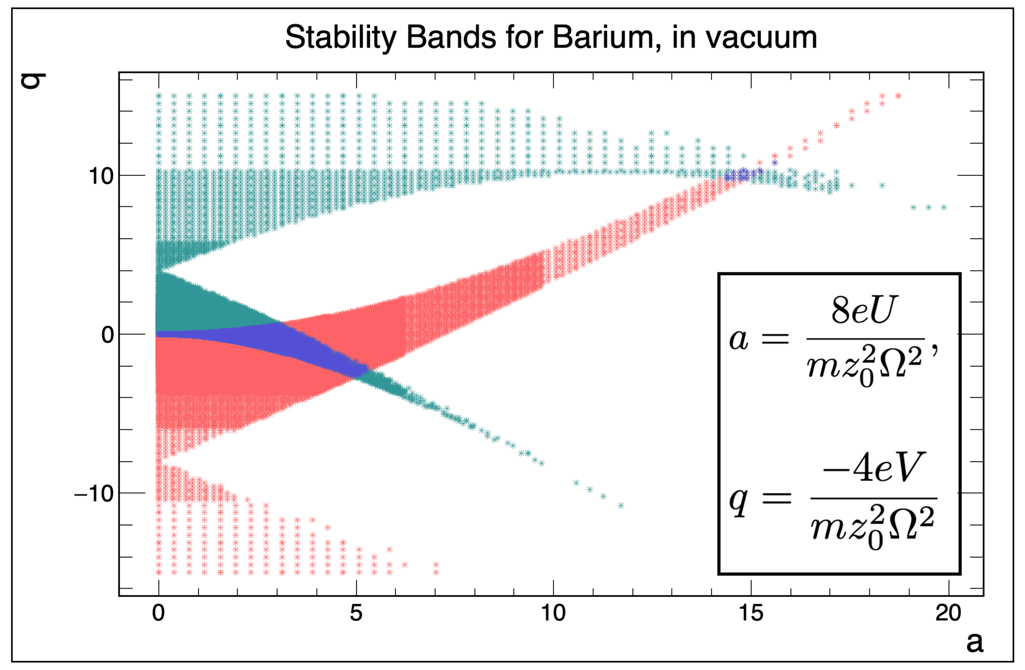
Validating Simulations Using Animations

Vacuum ($m\ddot{\vec{r}} = F_{electric}$)	Fluid at T= 0 K ($m\ddot{\vec{r}} = F_{electric} + F_{drag}$)	Fluid at T > 0 K ($m\ddot{\vec{r}} = F_{electric} + F_{drag} + F_{Brownian}$)



Assessing Ion Stability

In vacuum

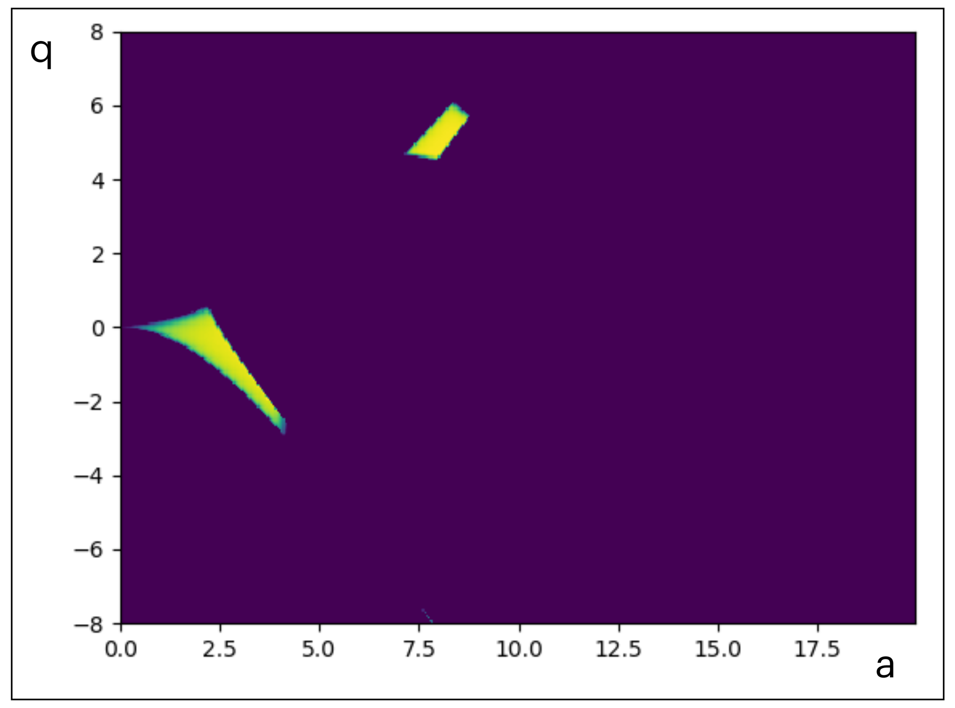


By looking at the following values for the DC field, AC field, and frequency:

$$0 < V < 500\ V,$$
$$-150 < U < 150\ V,$$
$$1 \times 10^5 < \Omega < 9 \times 10^6\ Hz$$

Regions of stably trapped phase space for Barium ions are depicted for z direction (green), r direction (pink), and both z and r (blue). This simulation result matches the known analytical solutions to ion motion in an RF quadrupole trap.

In a fluid at T= 0 K



In high viscosity regimes, any external force will push the ion to a terminal velocity, in which case it will escape the trap after a long time, given that:

$$\vec{r}_{term} = \frac{\vec{F}_{ext}}{\gamma}, \quad \lim_{t\to\infty} r(\vec{t}) = \frac{\vec{F}_{ext}}{\gamma}t$$

To evaluate the stability, we use the following criteria:

$$\frac{r}{\dot{r}_{term} * t} = \begin{cases} 0, & if\ trapped\ (yellow) \\ 1, & if\ not\ trapped\ (purple) \end{cases}$$

Next Steps

1. Assess stability a fluid at T > 0 K
2. Add attachment physics in the simulation -> Add the term of interaction between the ions and the impurities

References

1. https://twiki.cern.ch/twiki/bin/view/AIDA2020WP8/PurificationAndMonitoring
2. M. Adamowskia *et al.* "The Liquid Argon Purity Demonstrator". 2014.
3. M. Nunes. "Impact of Electron Lifetime on Electron-Photon Shower Separation". 2019.
4. The MicroBooNE Collaboration. "A Measurement of the Attenuation of Drifting Electrons in the MicroBooNE LArTPC". 2017.
5. Centre for Quantum Technologies. "Exacting measurements on atoms do better than theory". 2015.