

Impurity Propagation of O₂ in a Dual-Phase Xenon System

VASSAR



COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

Author: Benjamin Almquist

Advisors: Prof. Elena Aprile, Dr. Guillaume Plante, Dr. Michael Murra

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Dark Matter & Direct Detection Methods

XENON Project & Dual-Phase TPC

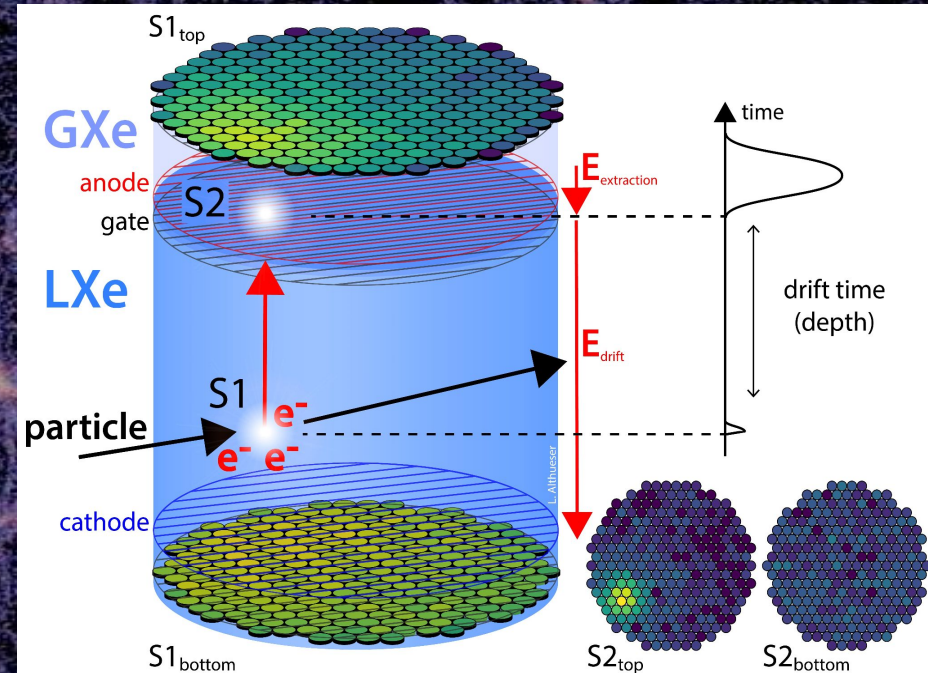
- ❖ Searching for theorized DM particle: Weakly Interacting Massive Particle (WIMPs)
- ❖ XENONnT is a Dual-Phase Xenon TPC
 - Liquid & Gas Xenon Phases

Detection Process:

- ❖ Particle interactions create two signals:
 - Light (Photons) & Charge (Electrons)
- ❖ Signals are recorded as scintillation flashes

Important Features of XENONnT

- ❖ Array of PMTs provides a 3D reconstruction of events
 - Time difference provides Z axis and PMTs provide X and Y directions
- ❖ Particle identification
 - Ratio of light to charge defines interaction as Electron or Nuclear Recoil



XENONnT Dual-Phase TPC Diagram

Credit: L.Altheuser for the XENON collaboration

Intrinsic Contaminants/Impurities

Signal Distortion in XENONnT

- ❖ When a particle deposits energy into XENONnT, signals can be distorted
 - Photons & electrons can be absorbed by elements in xenon mixture

Impurity Types:

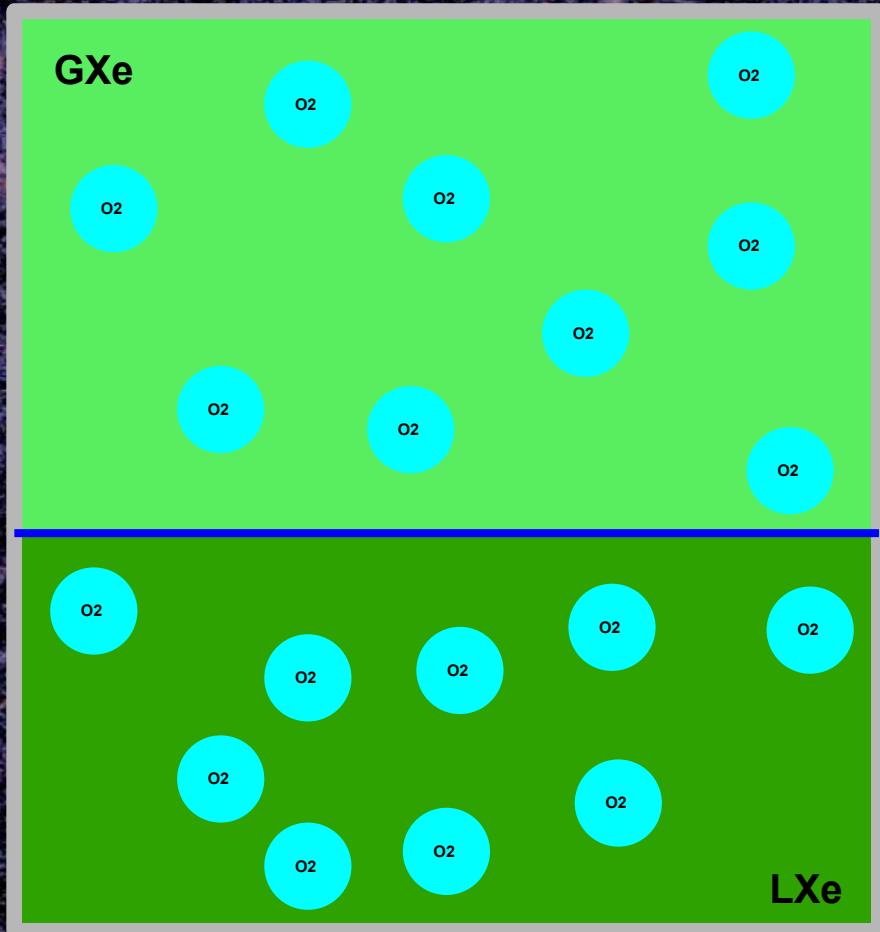
- ❖ 2 Types: Non-Radioactive & Radioactive
 - Some impurities are non-radioactive & diminish the signal
 - Some impurities are radioactive and induce a background signal
 - Electron Recoil through β -decay
- ❖ Examples: O_2^+ , N_2^+ , Ar^+ , Kr^+

Xenon Production & Impurity Removal

- ❖ Contaminants enter xenon medium during its extraction from air
- ❖ Because these distort DM interactions, they must be removed



Impurity Propagation Analysis Motivation



$$\mathcal{P}_{pressure} = \frac{I_i - I_{bcg}}{G_{rel} \cdot K_{RGA} \cdot N_{abund}}$$

$$\chi_{O2/phase} = \frac{\mathcal{P}_{O2}}{\mathcal{P}_{phase}}$$

$$\mathcal{K}_{O_2} = \frac{\chi_{O2/(O2+GXe)}}{\chi_{O2/(O2+LXe)}}$$

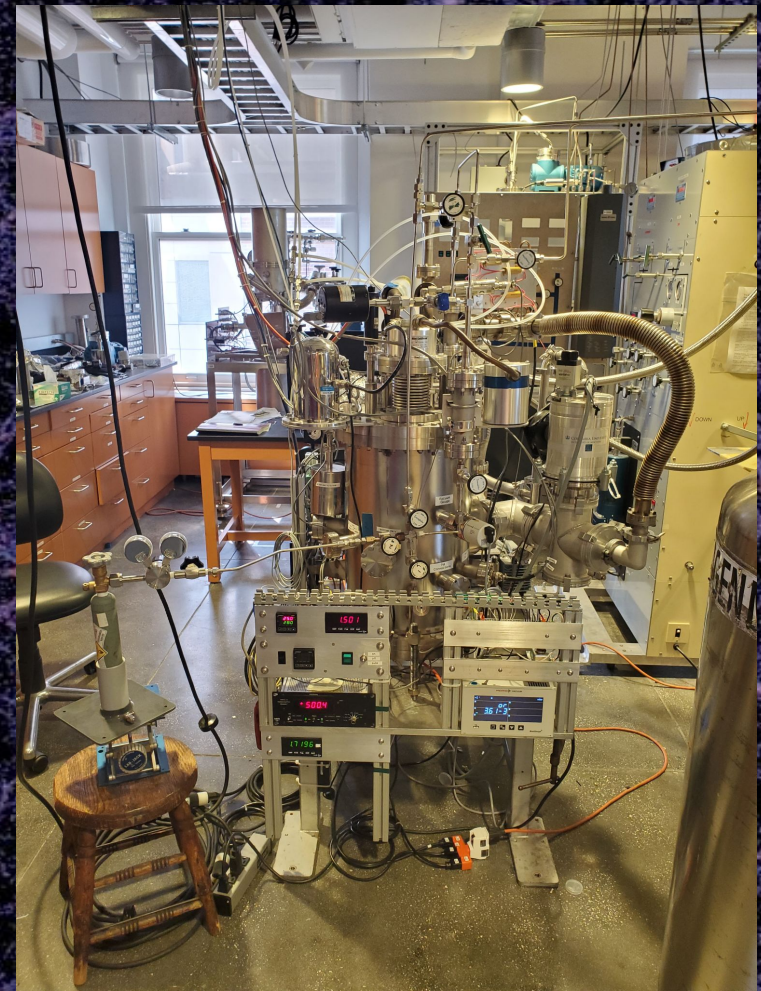
IMiX Overview & Goals

What is IMiX?

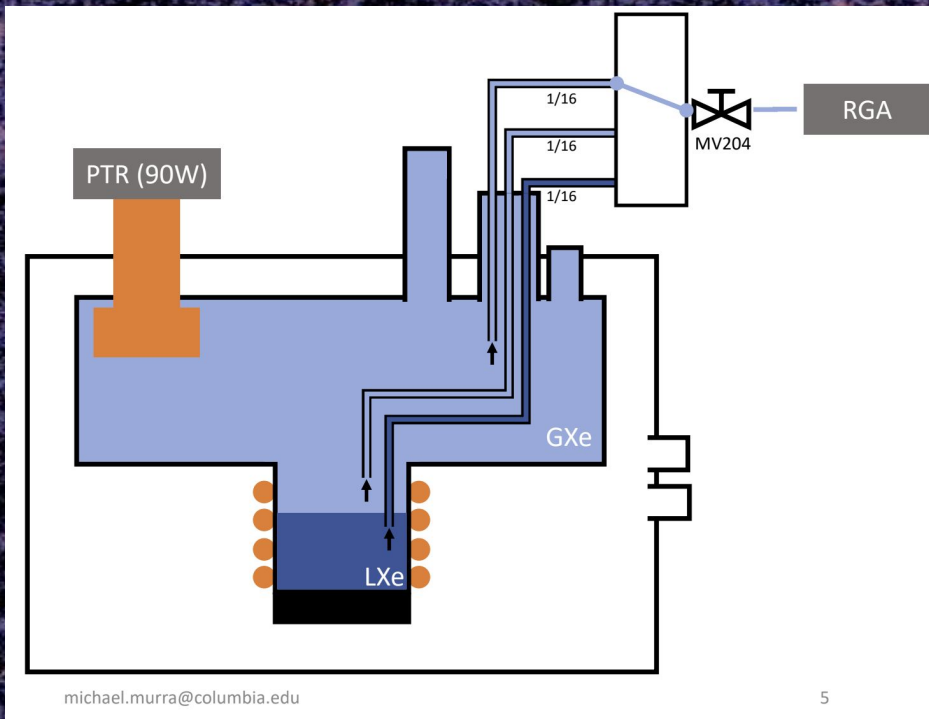
- ❖ Impurity Measurements in Xenon (IMiX) is a system used to analyze impurity propagation
- ❖ Contains both a liquid and gas phase, making impurity analysis scalable to XENONnT

Long-term goals for IMiX:

- ❖ Impurity propagation analysis aids in XENONnT purification system improvements
- ❖ Studies can help improve system calibration for XENONnT
 - Includes determining best calibration mixture of short-lived isotopes



IMiX Goals for REU Summer 2023



IMiX Simplified Schematic

Credit: Michael Murra

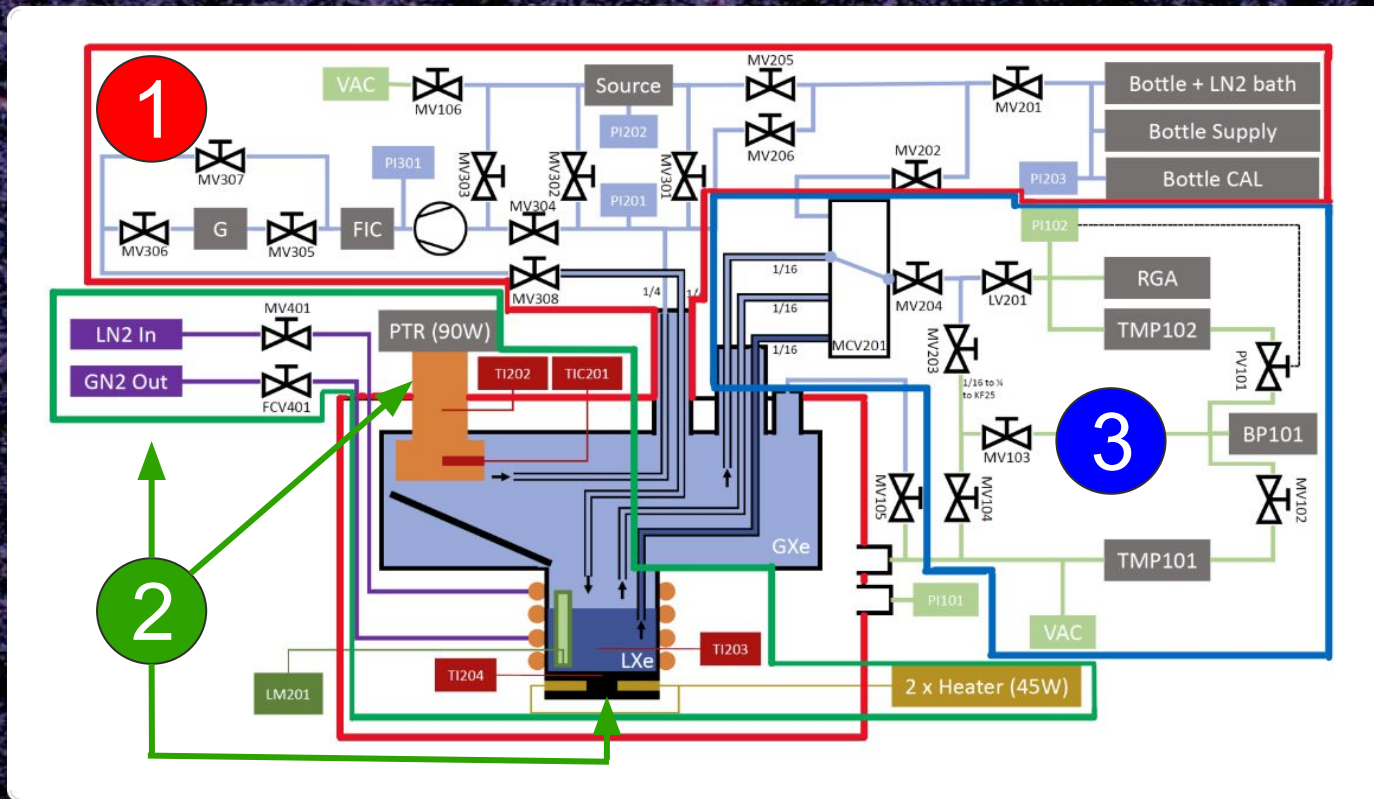
Current IMiX Goals:

- ❖ Complete a first Run of IMiX
 - Ensure all individual mechanisms work: Heaters, Refrigerator, etc.
 - Calibrate RGA with calibration gas
 - Inject an impurity and complete full propagation analysis

Impurity Choice for first run?

- ❖ O₂ is the first impurity choice
 - Main impurity in XENON1T & XENONnT which diminishes signal by absorbing electrons
- ❖ In XENONnT, typical concentrations of O₂ are below 0.1 ppb
- ❖ In IMiX, our concentration is 5 orders of magnitude higher
 - 1.82 bar Xe
 - From 100 ppm to 0.1%

IMiX System and General Sections

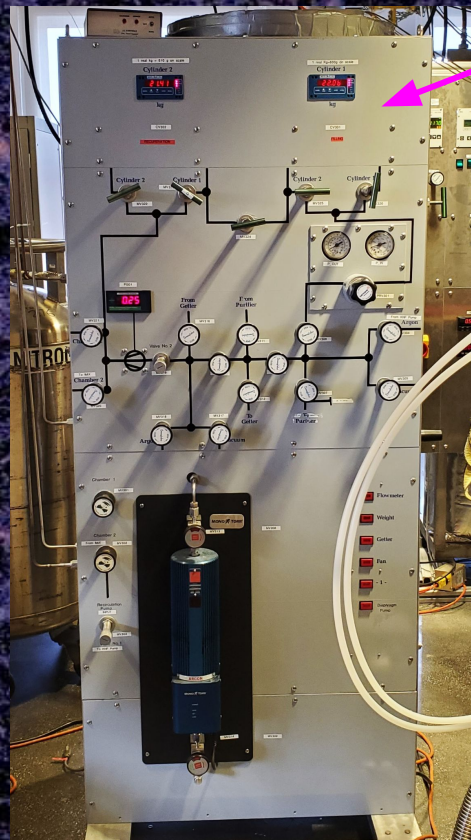


1) Filling System, Mixing Volume, Internal Chamber

2) PTR, Heating Systems, Liquid Nitrogen Cooling (LN2)

3) Residual Gas Analyzer (RGA), and Chamber

IMiX Filling System and Mixing Volume

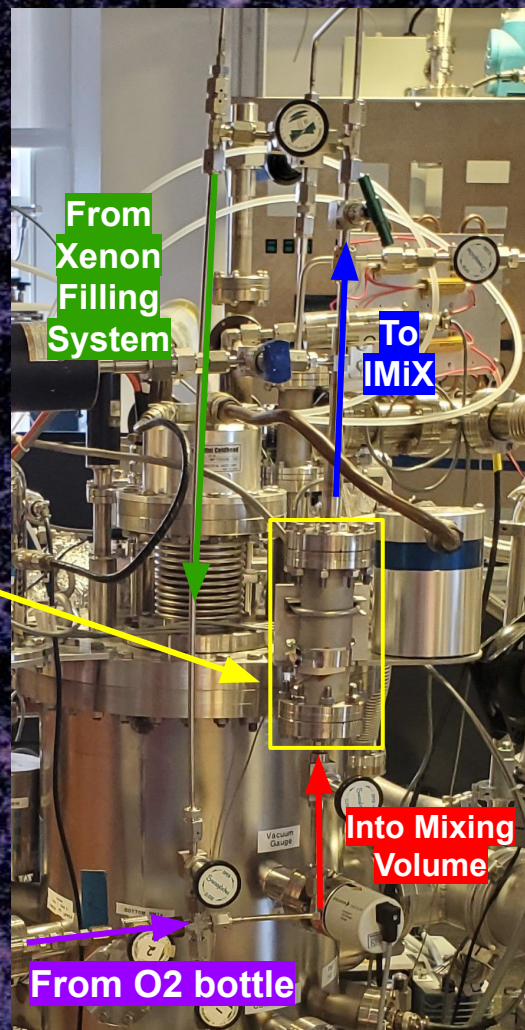


Xenon Filling & Purification System

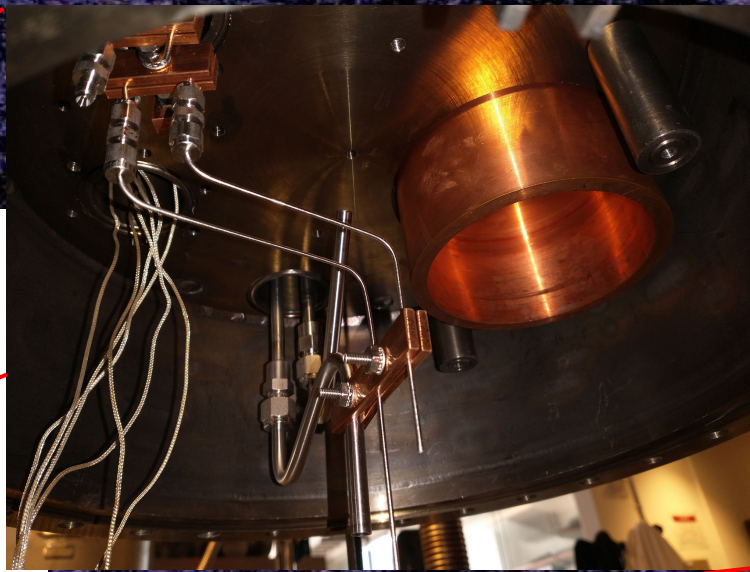
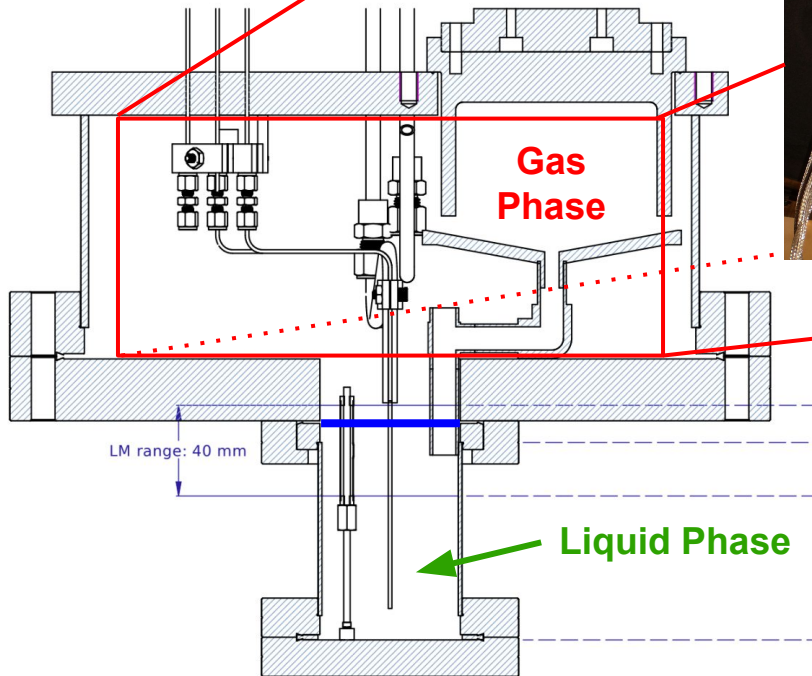
- ❖ Input source and recuperation location for xenon in IMiX
- ❖ Measures flow and pressure entering IMiX to maintain equilibrium

Mixing Volume

- ❖ Allows for controlled injection of an impurity into IMiX
- ❖ Every controlled injection, whether only xenon or as a mixture, entrance tubes to IMiX must be evacuated to ensure no additional contamination



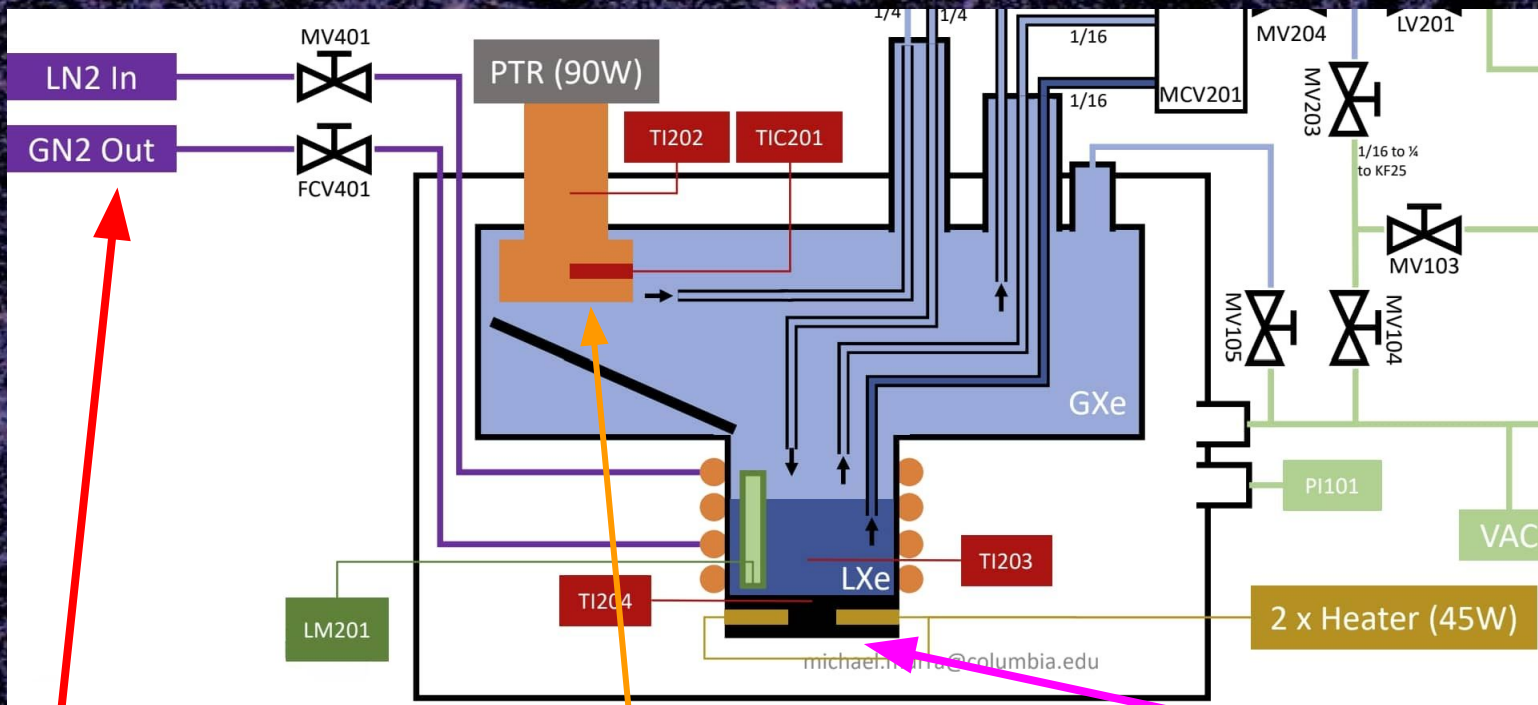
IMiX Internal Chamber



Internal Chamber:

- ❖ Two phases: Gas and Liquid Xenon
- ❖ Liquid phase is set at -96.5°C
 - Corresponds to Xenon Vapor pressure of ~ 1.882 bar

IMiX PTR, Heaters & LN2 Cooling



Liquid Nitrogen Cooling

Coil surrounding liquid phase chamber to prevent “over-boiling”

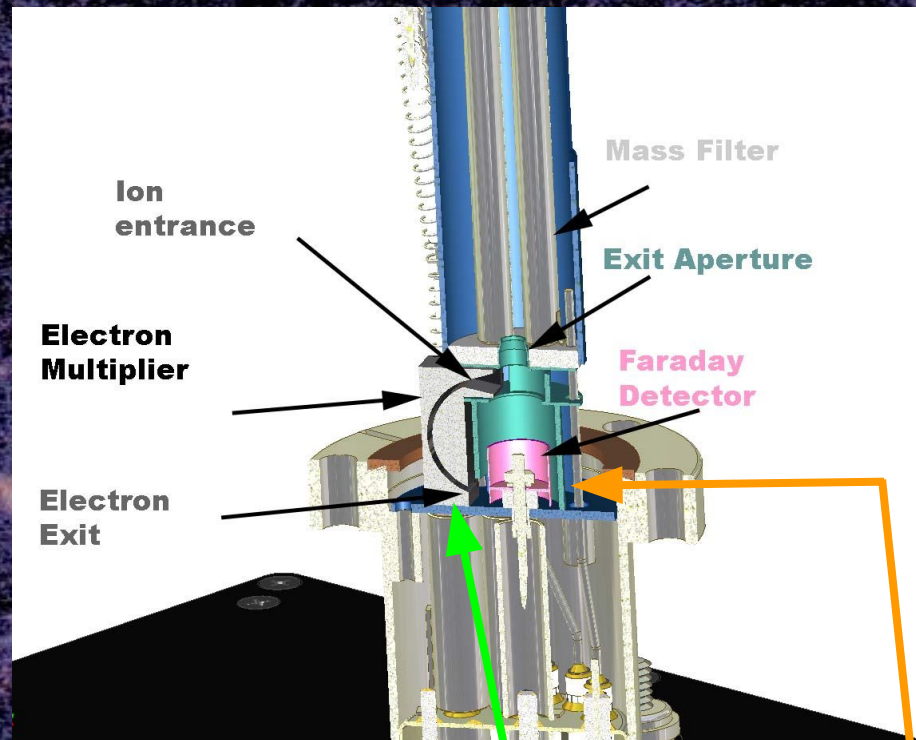
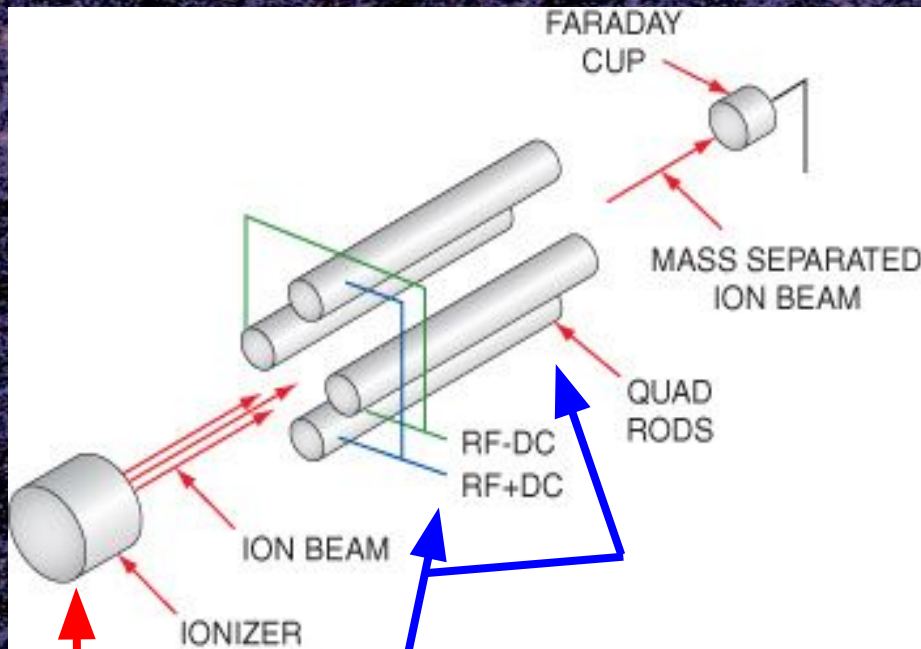
Pulse Tube Refrigerator & Cold-Finger

Combo condenses GXe to LXe and keeps system at a fixed temperature

Bottom Flange Heaters

Cause direct phase changes by boiling liquid phase

IMiX RGA



Residual Gas Analyzer (RGA) Components:

Open Ion Source (Thoria-coated Iridium)

Quadrupole Mass Analyzer

Electron Multiplier (EM)

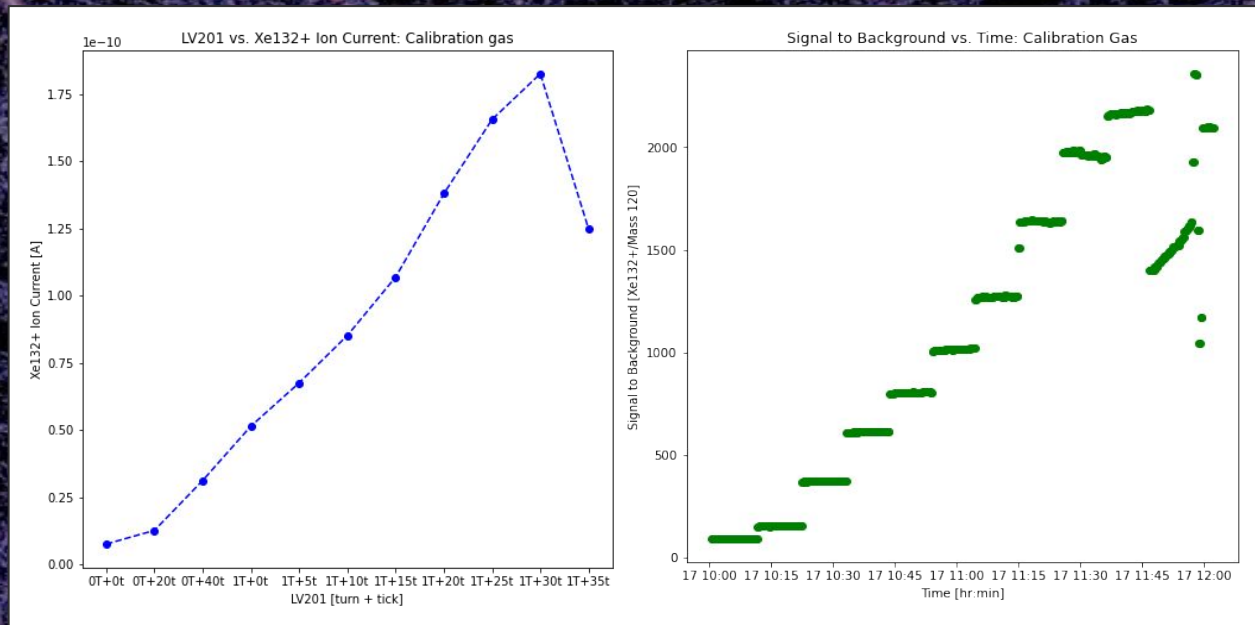
Faraday Cup

IMiX Run: Setup and Preparation



System Prep Steps:

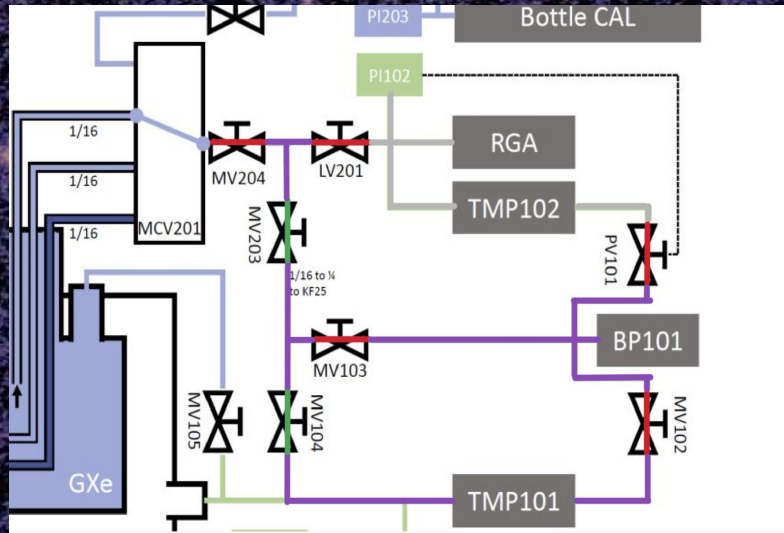
- ❖ Xenon cooled to -96.5°C
- ❖ All heating and cooling mechanisms are in operation
- ❖ Calibrate the RGA



RGA Calibration / Signal to Background Ratio:

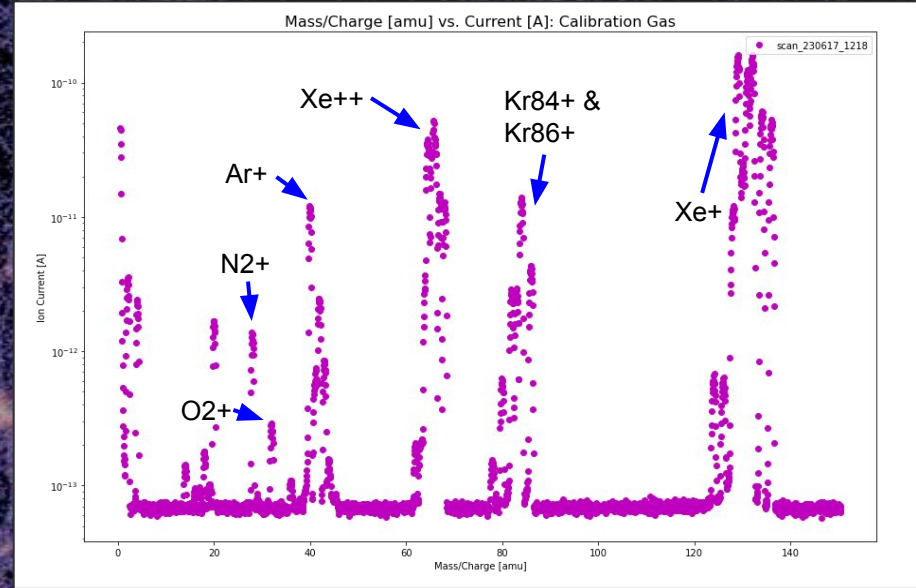
- ❖ Calibration gas is essential to confirm RGA is reading current
- ❖ Find the best Signal to Background ratio by determining how much gas mixture is let into RGA chamber
- ❖ Best ratio $\rightarrow \sim 2000$ for 1 turn + 25 ticks

IMiX Run: Run Procedure and Completion



Gas Evacuation & Injection Process:

- ❖ “Flushing” process must be completed prior to any RGA scan
- ❖ Ensures no two samples are mixed during the RGA scan



RGA Scans:

- ❖ 2 RGA scan modes: Sweep and Trend
- ❖ Sweep Mode: One scan of all masses for one time stamp
- ❖ Trend Mode: Selected masses for a time period
- ❖ 3 days of runs: 6/17, 6/19, 6/20
 - Sampled GXe and LXe each day

IMiX Data Analysis Overview

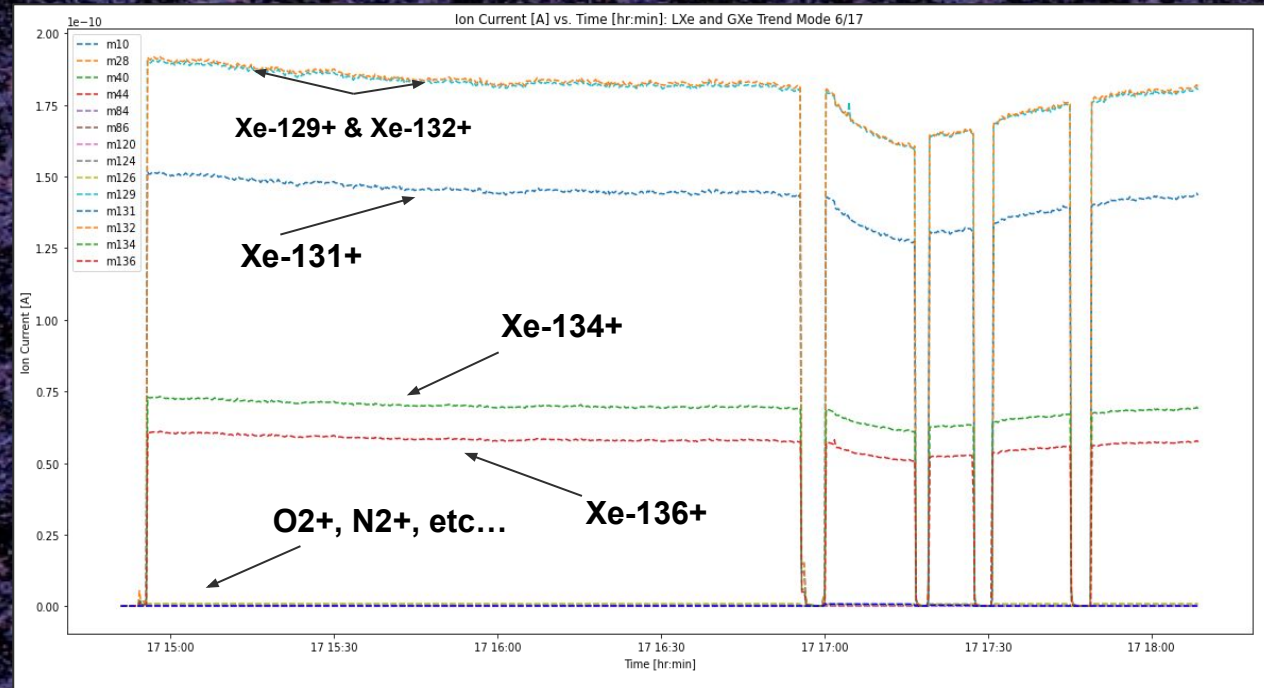
Data available to Analyze:

- ❖ 3 days of runs: 6/17, 6/19, 6/20
- ❖ Calibration Tests and Actual Data for Gas and Liquid Xenon phases
- ❖ Data for 15 different masses, including 2 background masses

Data Analysis Calculations:

- ❖ For the first run of IMiX, we assessed its efficiency and functionality in several formats:
 - Ion Current vs. Mass/Charge (Sweep Mode)
 - Ion Current vs. Time (Trend Mode)
 - Ion Current → Partial Pressure Calculations
 - Molar Fraction Calculations for days 6/17, 6/19, 6/20
 - Average Mole Fraction Calculations
 - Confirmation of O₂ above background in the Liquid Xenon phase

IMiX First Analysis of O2



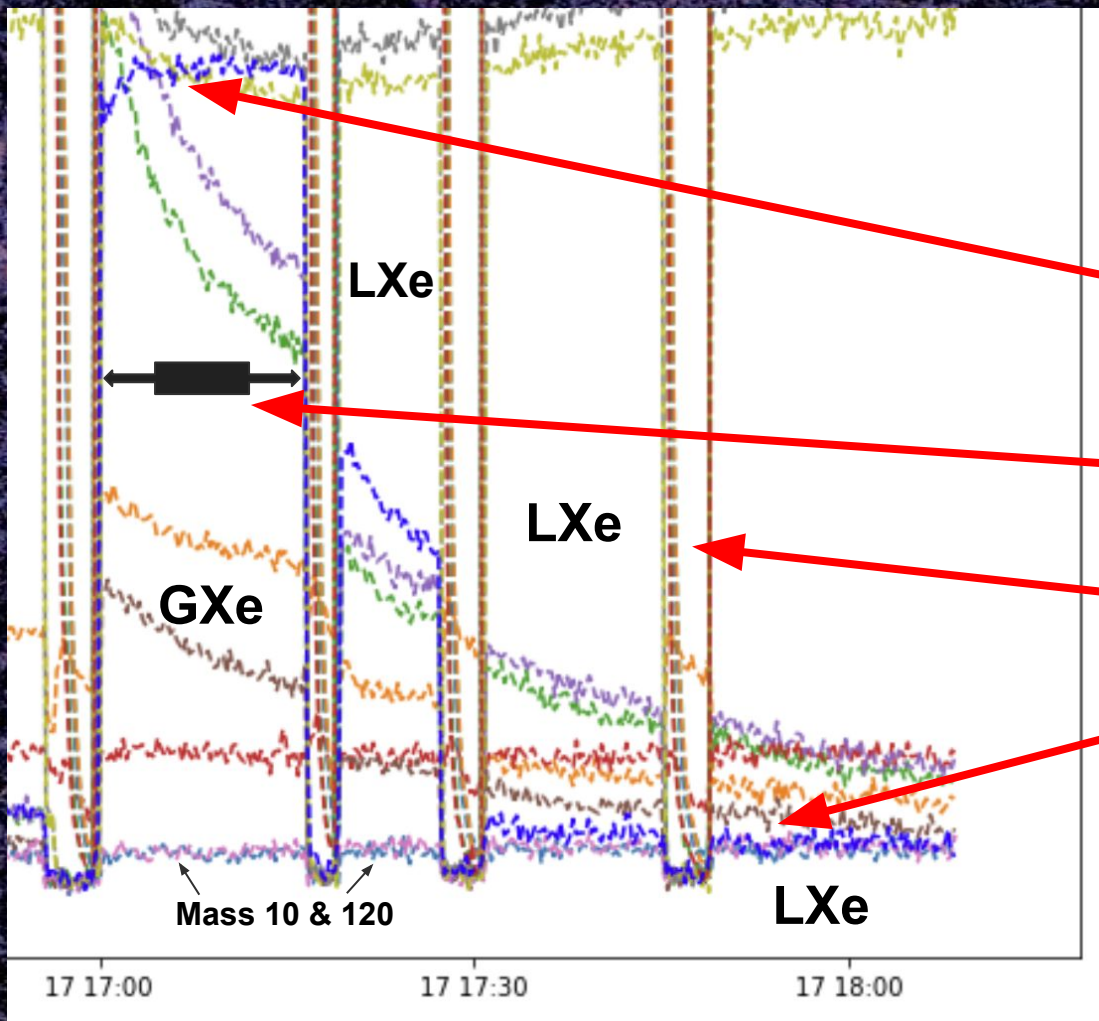
RGA Actual Data Results:

- ❖ Three sets of trend mode, Ion Current vs. Time graphs for 6/17, 6/19, and 6/20
- ❖ Stable lines are sampling periods, dipping curves/valleys are “flushing” periods
- ❖ Xenon isotopes are orders of magnitude higher than impurities in the xenon gas

$$P_{pressure} = \frac{I_i - I_{bcg}}{G_{rel} \cdot K_{RGA} \cdot N_{abund}}$$

<- Partial Pressure Conversion Formula

Ion Current Graphs Classification



O2 Xenon Mixture Gas
Phase Testing

Sampling Period

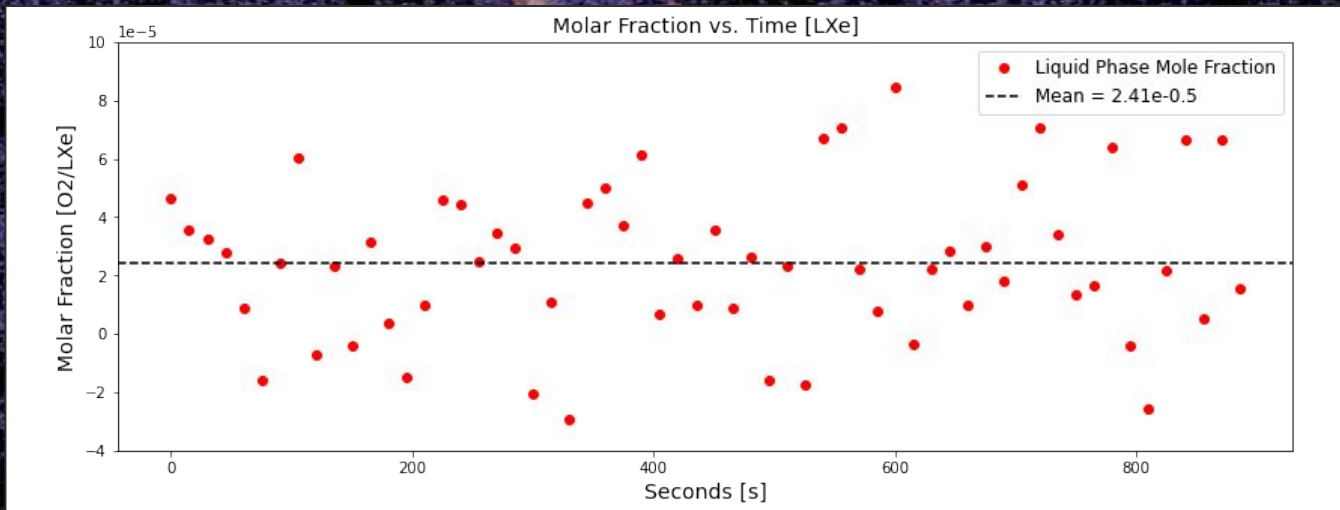
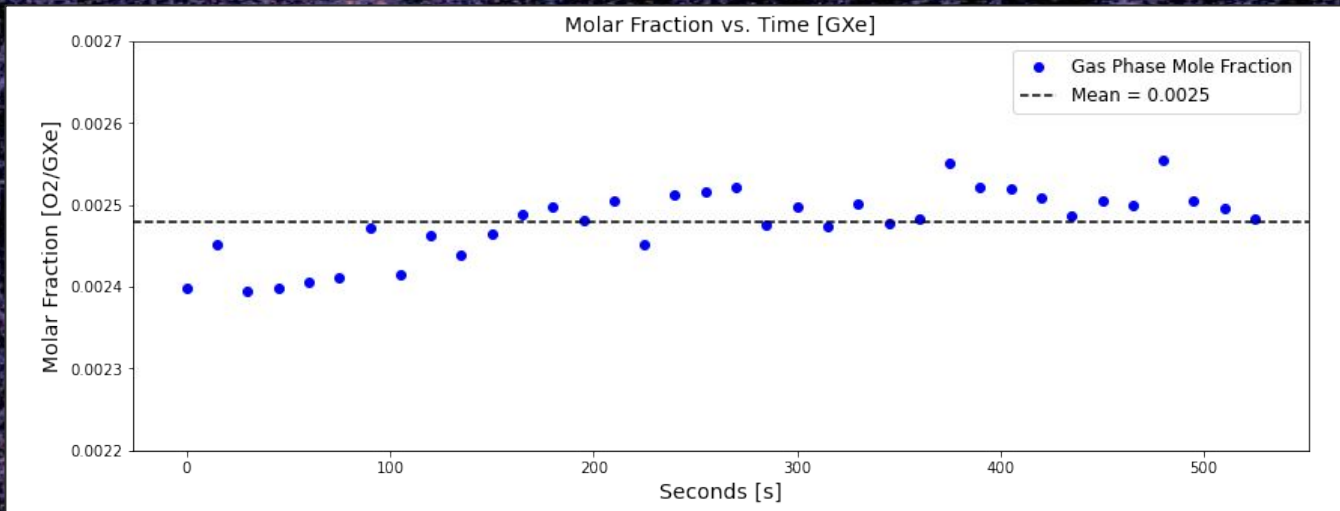
"Flushing" Period

O2 Xenon Mixture Liquid
Phase Testing

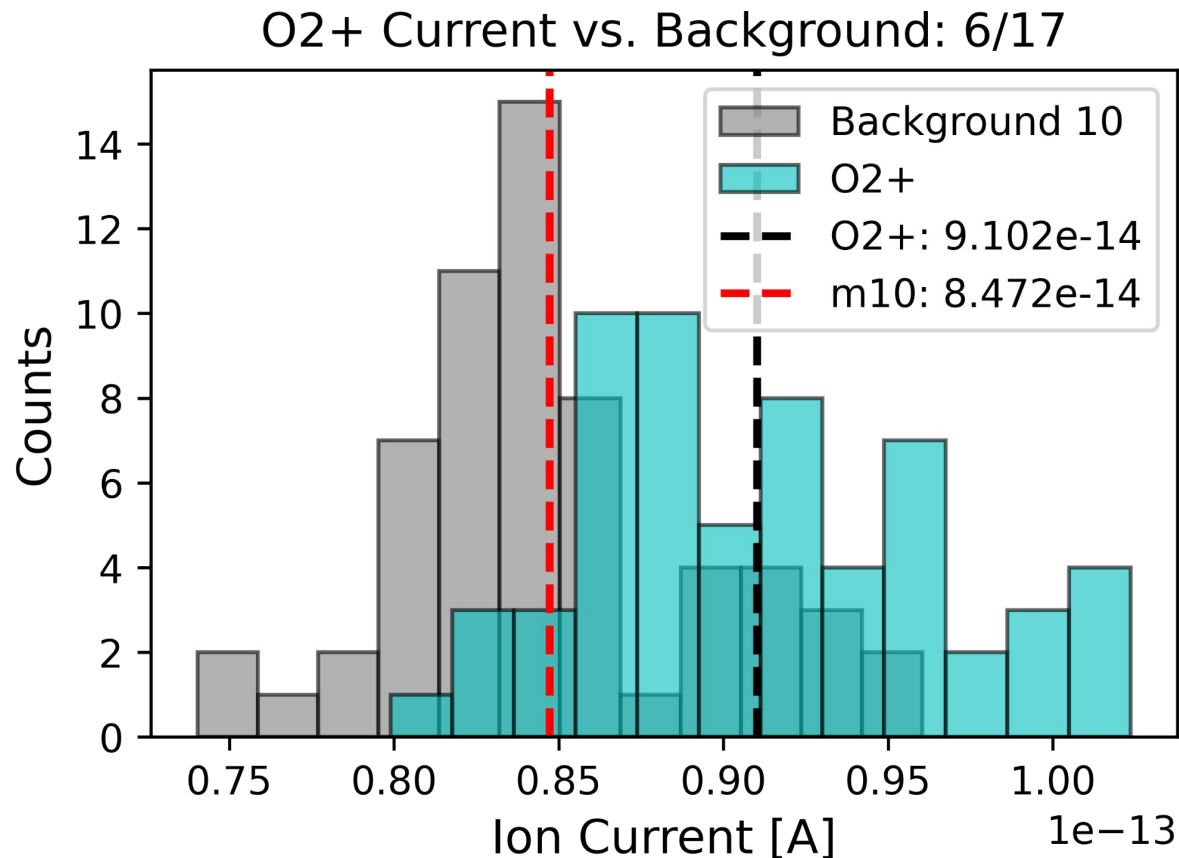
Important Notes:

- ❖ Dark Blue = Oxygen
- ❖ Pink & Light Blue at the bottom are Mass 10 & 120 background

IMiX Molar Fraction Calculations: June 17th Run



Does O2 exist above the background for the LXe phase?



$$\mathcal{T}_{\text{t-test}} = \frac{\mu_i - \mu_{\text{bcg}}}{\sqrt{\frac{\sigma_1^2}{N_1} + \frac{\sigma_2^2}{N_2}}}$$

Welch T-Test Formula

Analysis Conclusions & Next Steps

Henry Coefficient Results:

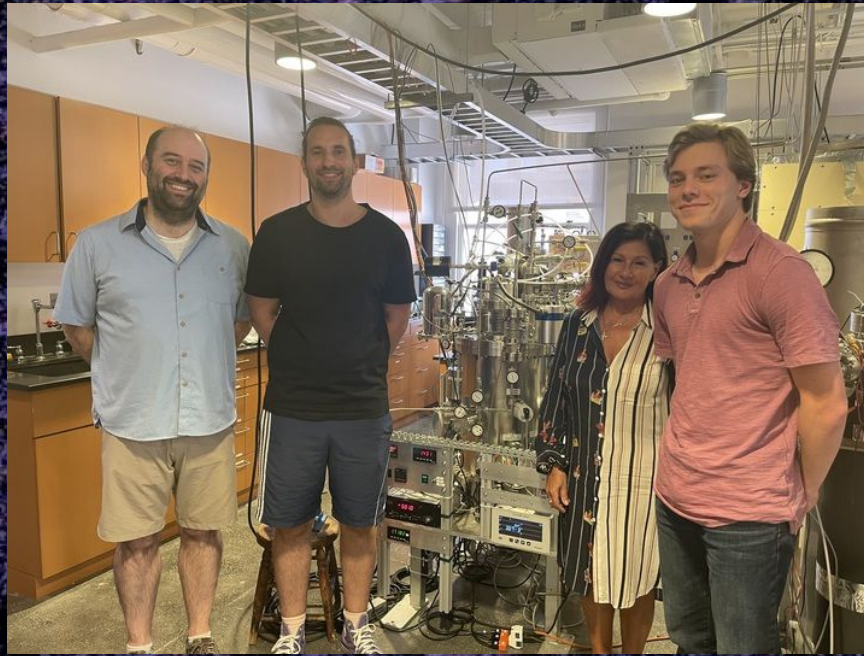
- ❖ Henry Coefficient Calculations
 - 6/17/2023: 102 ± 14
 - 6/19/2023: 187 ± 39
 - 6/20/2023: 110 ± 16

Conclusions:

- ❖ We have solid results for a first run of IMiX
 - In order to calculate more instructive Henry Coefficients, need more O₂ input
- ❖ IMiX as a system ran, impressive for construction being recently completed!

Future IMiX Runs:

- ❖ Need to attempt adjusting the GXe and LXe phases directly and indirectly
 - Use LN₂ for diffusion and Bottom Flange Heaters for boiling
- ❖ Test new impurities!
 - N₂⁺, Ar⁺, Kr⁺, CO₂⁺, H₂O⁺, etc.



Acknowledgements

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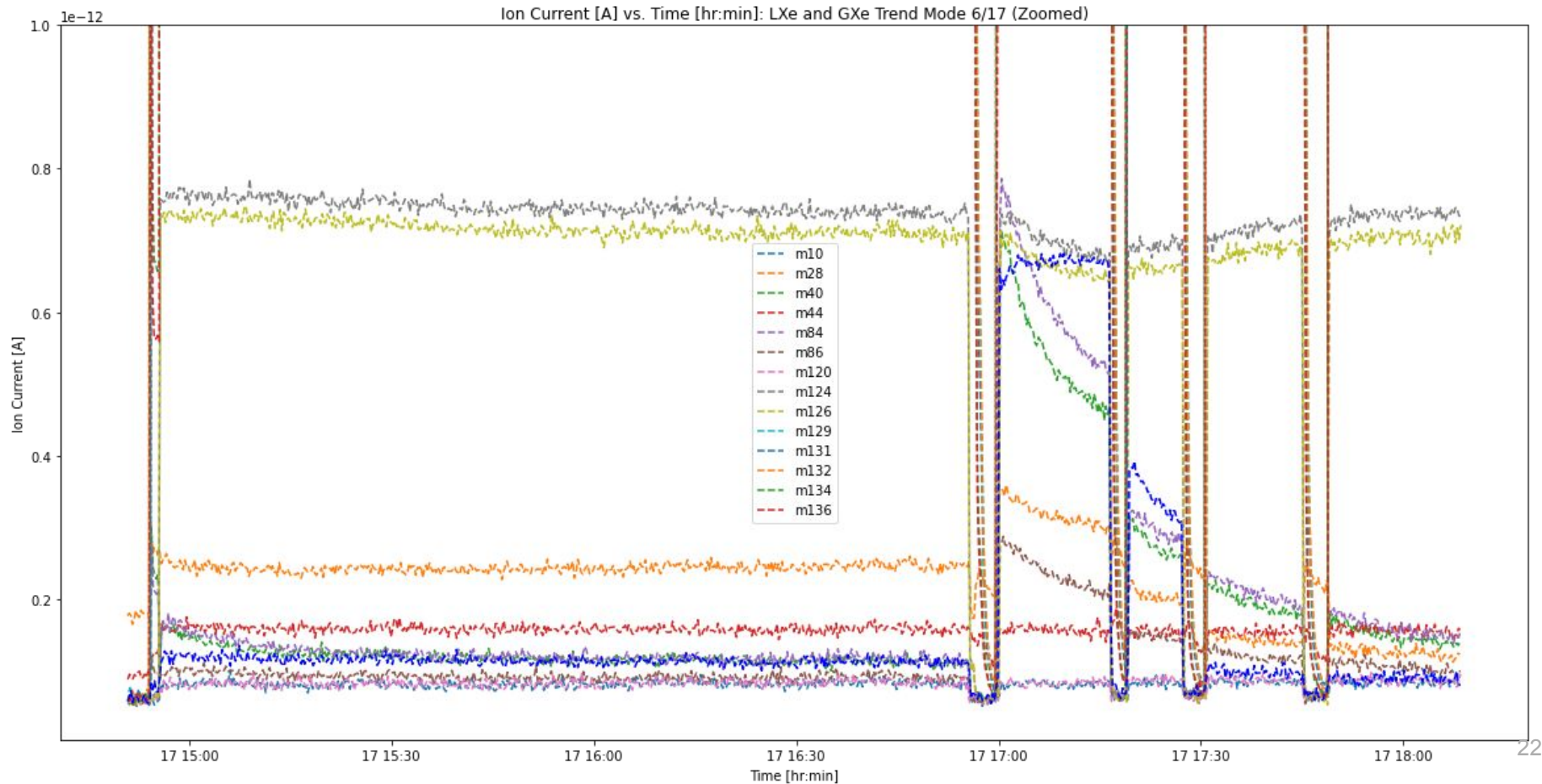
Thank you to Prof. Georgia Karagiorgi & Prof. John Parsons for the chance to participate in the Nevis Labs REU!

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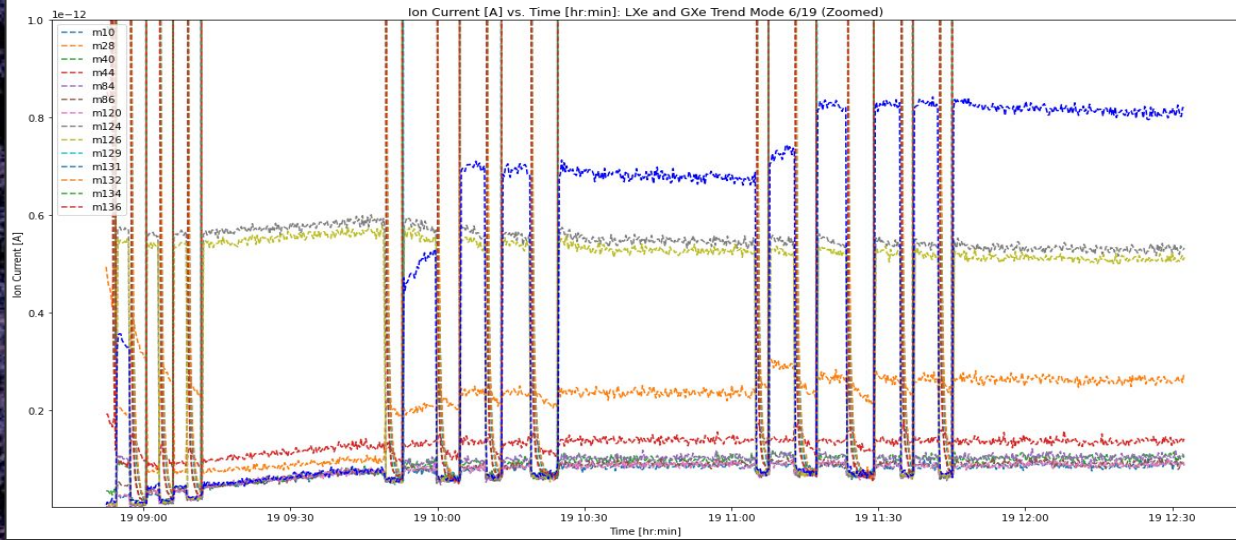
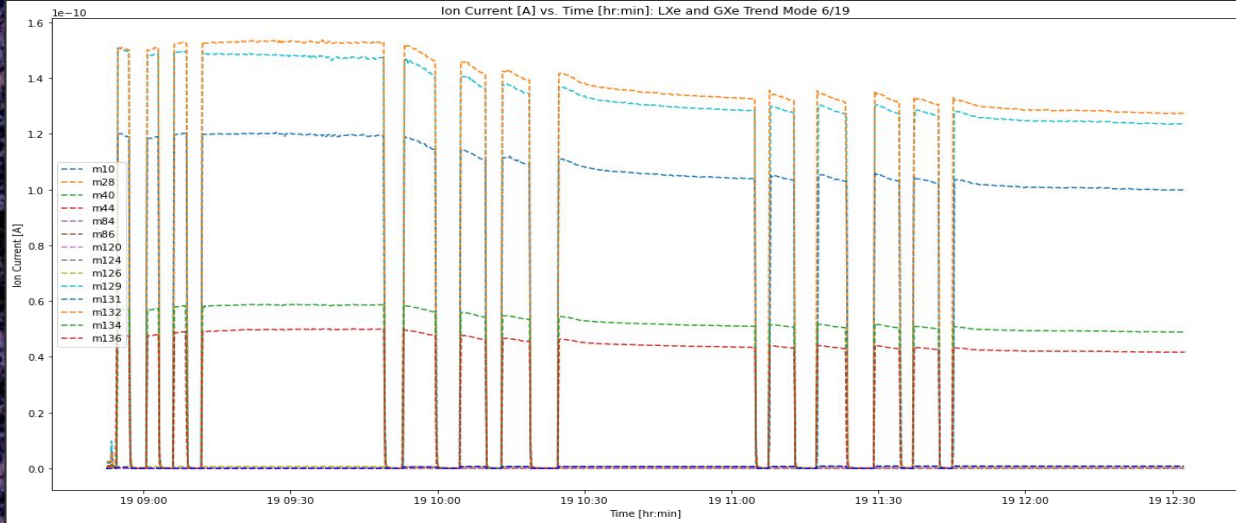
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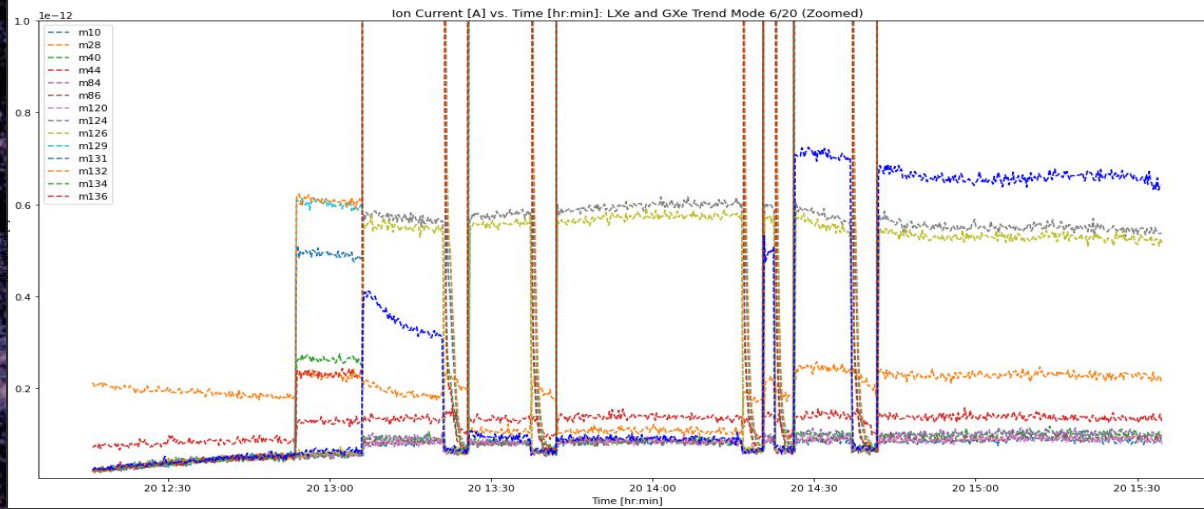
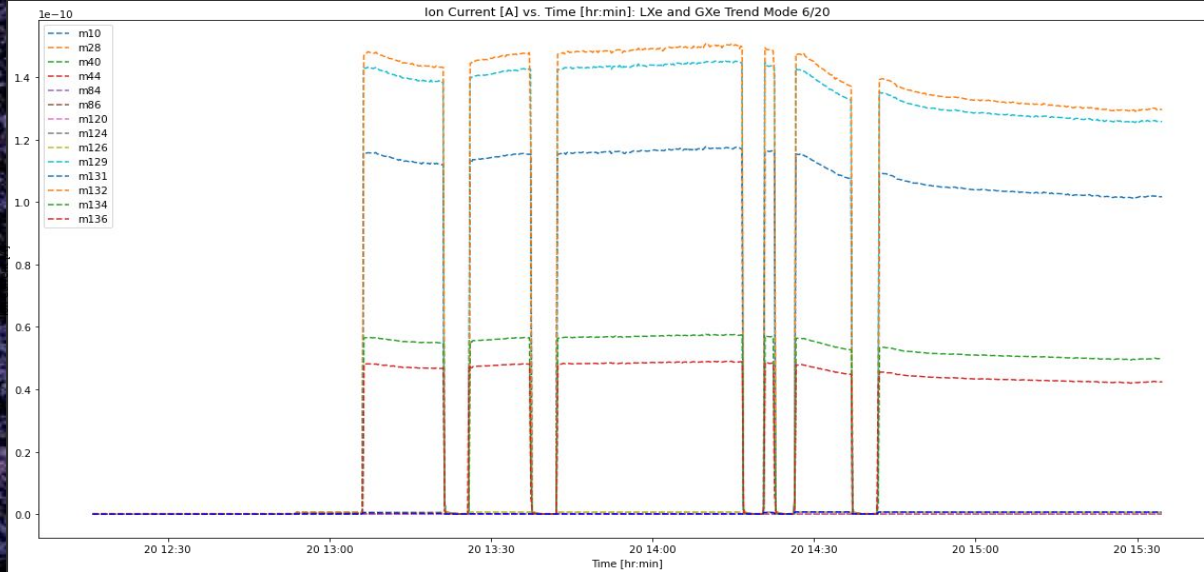
Appendix A: Ion Current Graph 6/17 (Zoomed)



Appendix B: Ion Current Graphs 6/19

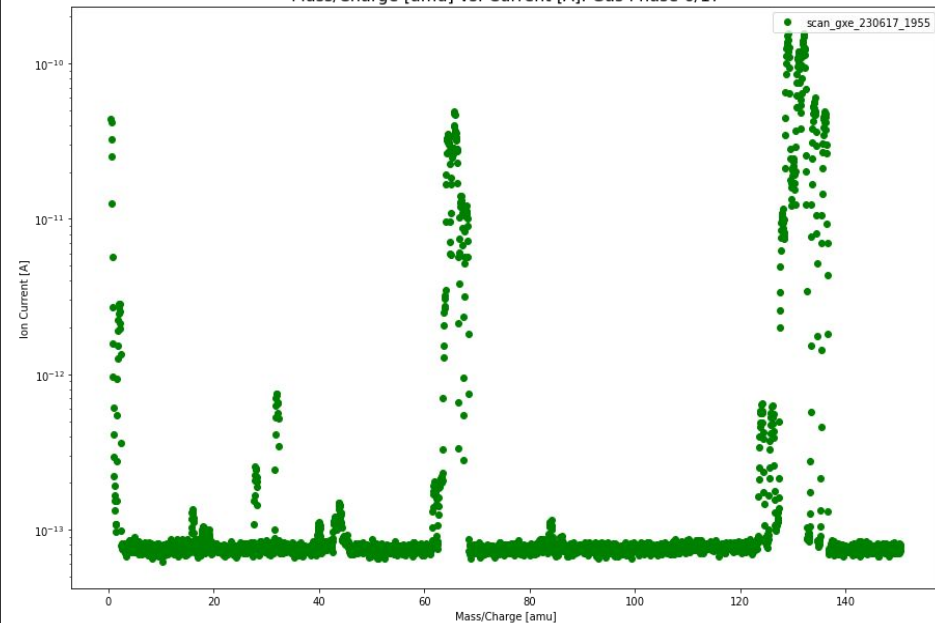


Appendix C: Ion Current Graphs 6/20

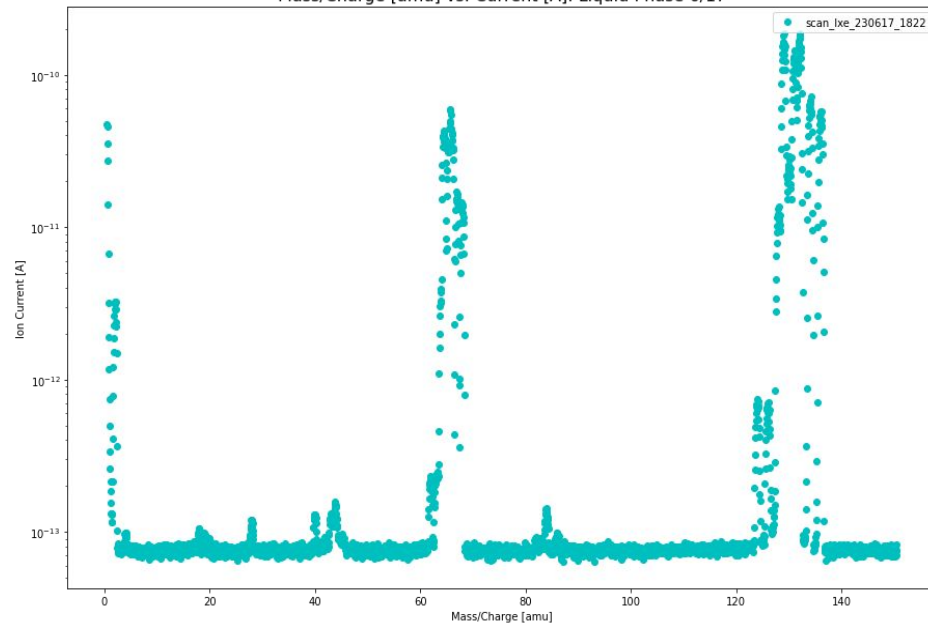


Appendix D: Mass/Charge Sweep Scans from 6/17

Mass/Charge [amu] vs. Current [A]: Gas Phase 6/17

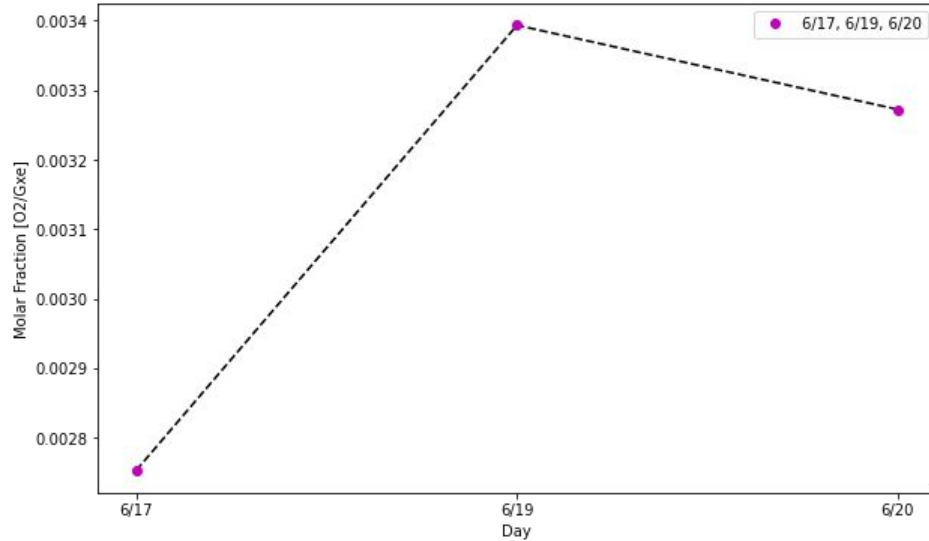


Mass/Charge [amu] vs. Current [A]: Liquid Phase 6/17

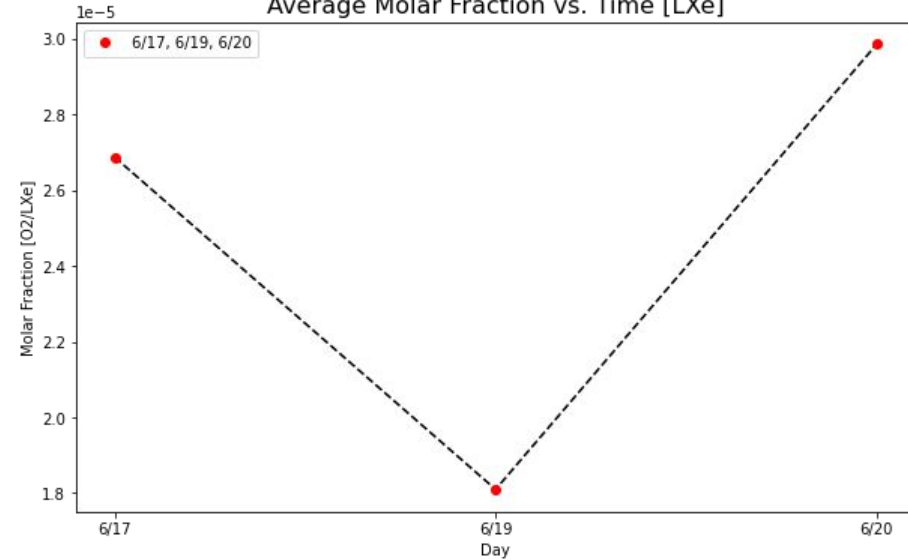


Appendix E: Average Mole Fraction Calculations

Average Molar Fraction vs. Time [GXe]



Average Molar Fraction vs. Time [LXe]



Appendix F: Formulas & Equations

$$\mathcal{P}_{pressure} = \frac{I_i - I_{bcg}}{G_{rel} \cdot K_{RGA} \cdot N_{abund}}$$

$$\chi_{O_2/phase} = \frac{\mathcal{P}_{O_2}}{\mathcal{P}_{phase}}$$

$$\mathcal{T}_{t-test} = \frac{\mu_i - \mu_{bcg}}{\sqrt{\frac{\sigma_1^2}{N_1} + \frac{\sigma_2^2}{N_2}}}$$

$$\mathcal{K}_{O_2} = \frac{\chi_{O_2/(O_2+GXe)}}{\chi_{O_2/(O_2+LXe)}}$$