Capacitive Monitoring of Xenon Concentration in a Xenon-Doped Argon Detector

James Kingston (UC Davis, LLNL)

CPAD 2022

November 29th, 2022

LLNL-PRES-XXXXXX

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

Lawrence Livermore National Laboratory

Review of Xenon and Argon Time Projection Chambers (TPCs)

A noble element dual phase TPC contains a noble element in the liquid and gas phase. An electric field is established to drift electrons. Photosensors detect scintillation light.

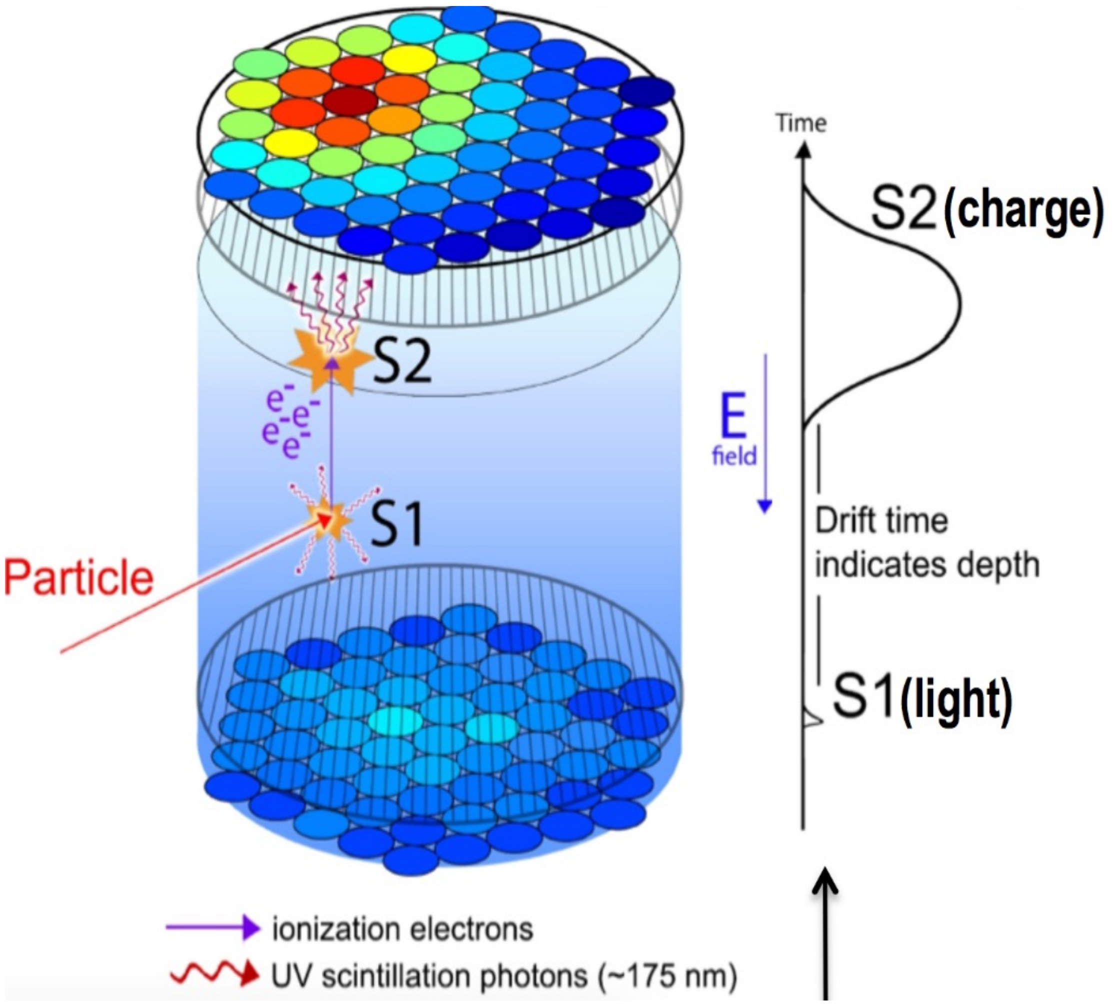
An energetic particle will generate:

- Scintillation light (S1)
- Ionization (S2)

The time between the S1 and S2 reveals the Z position of interaction

The S2 pulse hit pattern on array of top photosensors reveals (X,Y) position

S1/S2 ratio and pulse shape discrimination can be used for particle ID



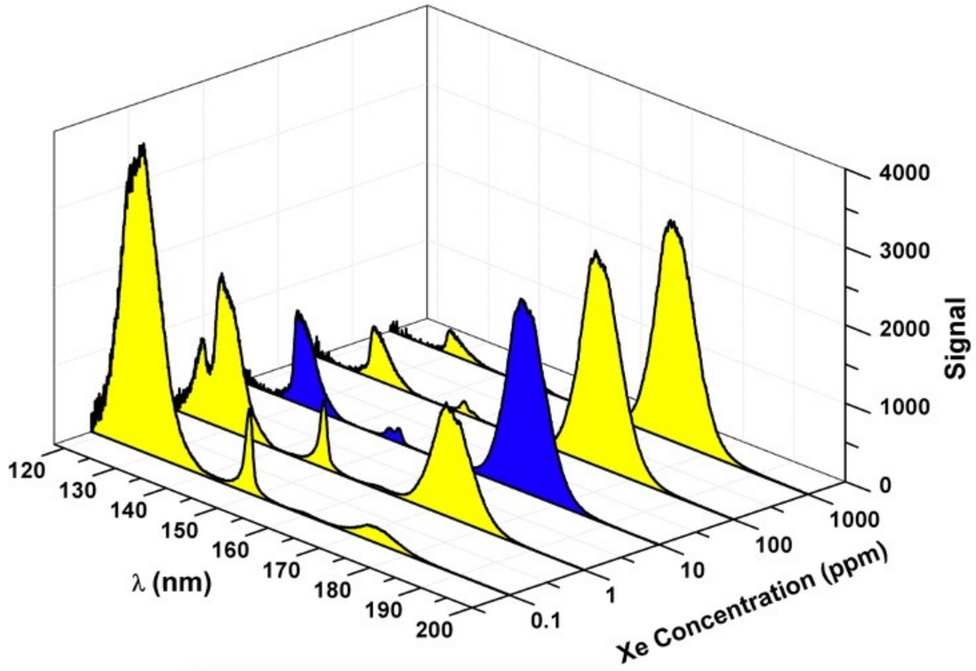
Comparison of Xenon and Argon for Detection Experiments

Argon and xenon are the two prominent noble element detection media

Both noble elements have their advantages and disadvantages, and have produced world-leading results in the field of dark matter and neutrino physics

Property	Argon	Xenon
Scintillation wavelength	128 nm	178 nm
Kinetic Match to Light Particles	A = 39.95	A = 131.29
Liquid phase ionization energy	14.3 eV	9.28 eV
Excitation Energy	11.8 eV	8.4 eV
Scintillation lifetime	1.5 us	22 ns
Price	Cheap	Expensive

Xenon-Doping of Liquid Argon



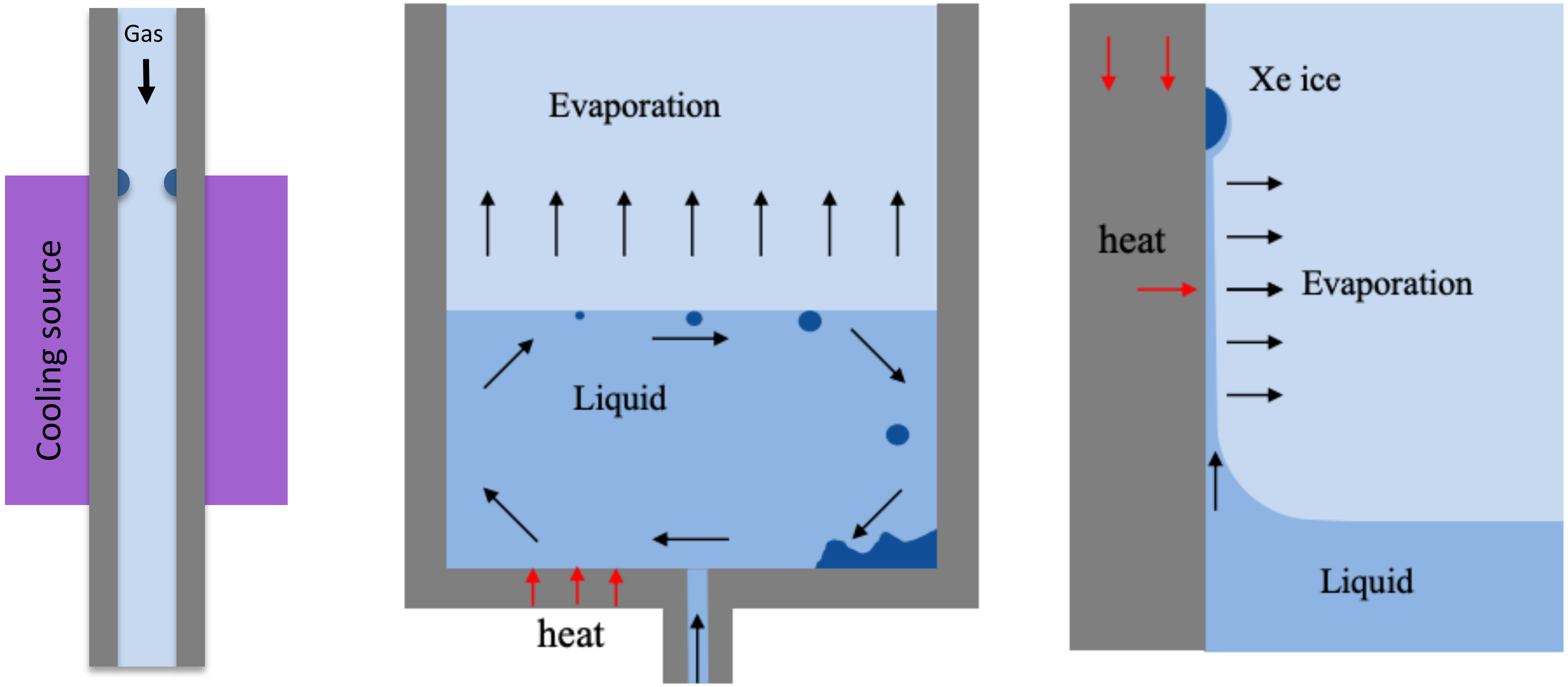
When liquid argon is doped with xenon at the O(ppm) level, the dominant excitation path transitions from Ar_2 dimers to Xe-containing excimers (ArXe and Xe_2)

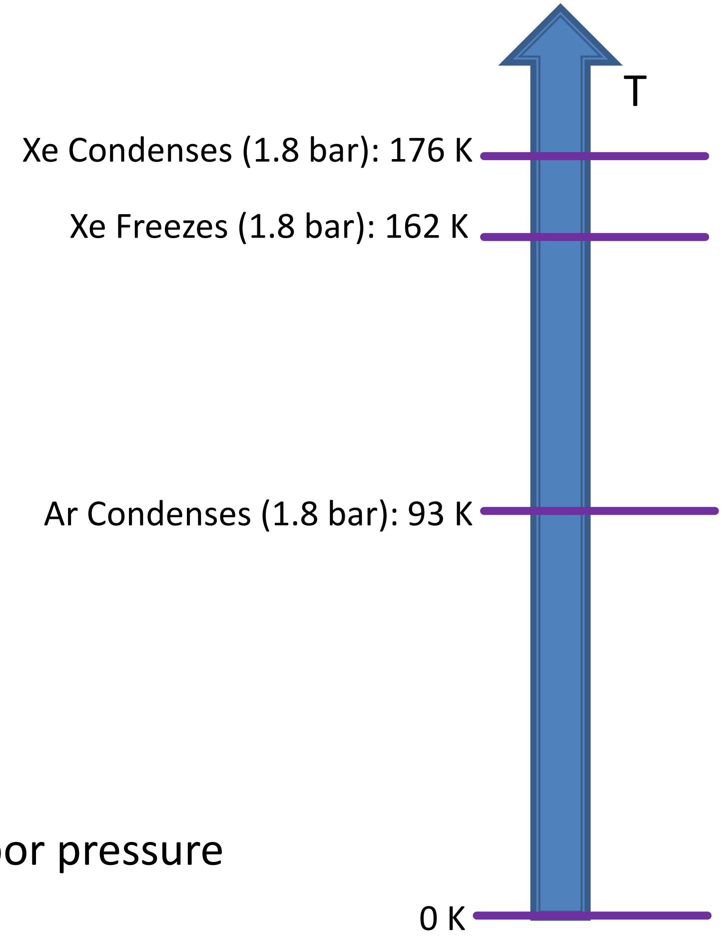
This implies numerous detection benefits:

- Wavelength shifting from 128 nm to 178 nm: better PDE!
- Sharper scintillation pulses: better timing on non-beam events and less pileup!
- Boost to ionization yield (due to lower ionization threshold of xenon): bigger signal!

Stability Challenges of Xenon Doping of Argon

The large temperature discrepancy between xenon and argon boiling points are a major source of system instability





Left: Condensation of Xe-rich Ar gas causes Xe to freeze if Xe pressure exceeds saturation vapor pressure
Middle: Evaporation of liquid mixture causes Xe concentration to increase in the liquid
Right: Unintended evaporation of liquid isolated by surface tension can cause Xe ice to form

Capacitive Technique to Measure Xenon Concentration in Argon

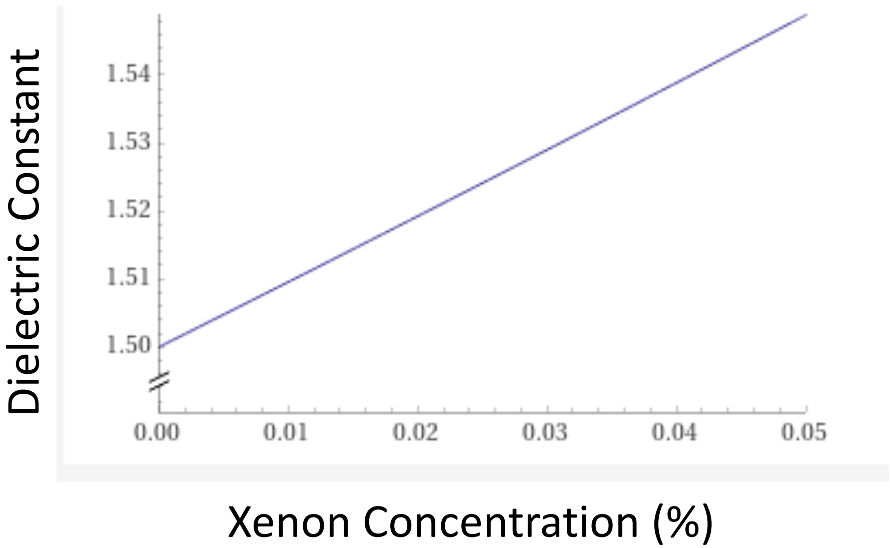
The dielectric constant of xenon-doped argon can be determined by the Clausius-Mossotti equation:

$$\frac{\varepsilon_r - 1}{\varepsilon_r + 2} = \sum_{i=1}^{2} \frac{n_i \alpha_i}{3\varepsilon_0}$$

n_i: number density of molecule (or atom) type i

α_i: atomic polarizability of molecule type i

One can derive a nearly linear dependence of ε_r on F_{Xe}:



Then the capacitance of a capacitor with a xenon-doped argon dielectric medium is linearly dependent on the xenon concentration

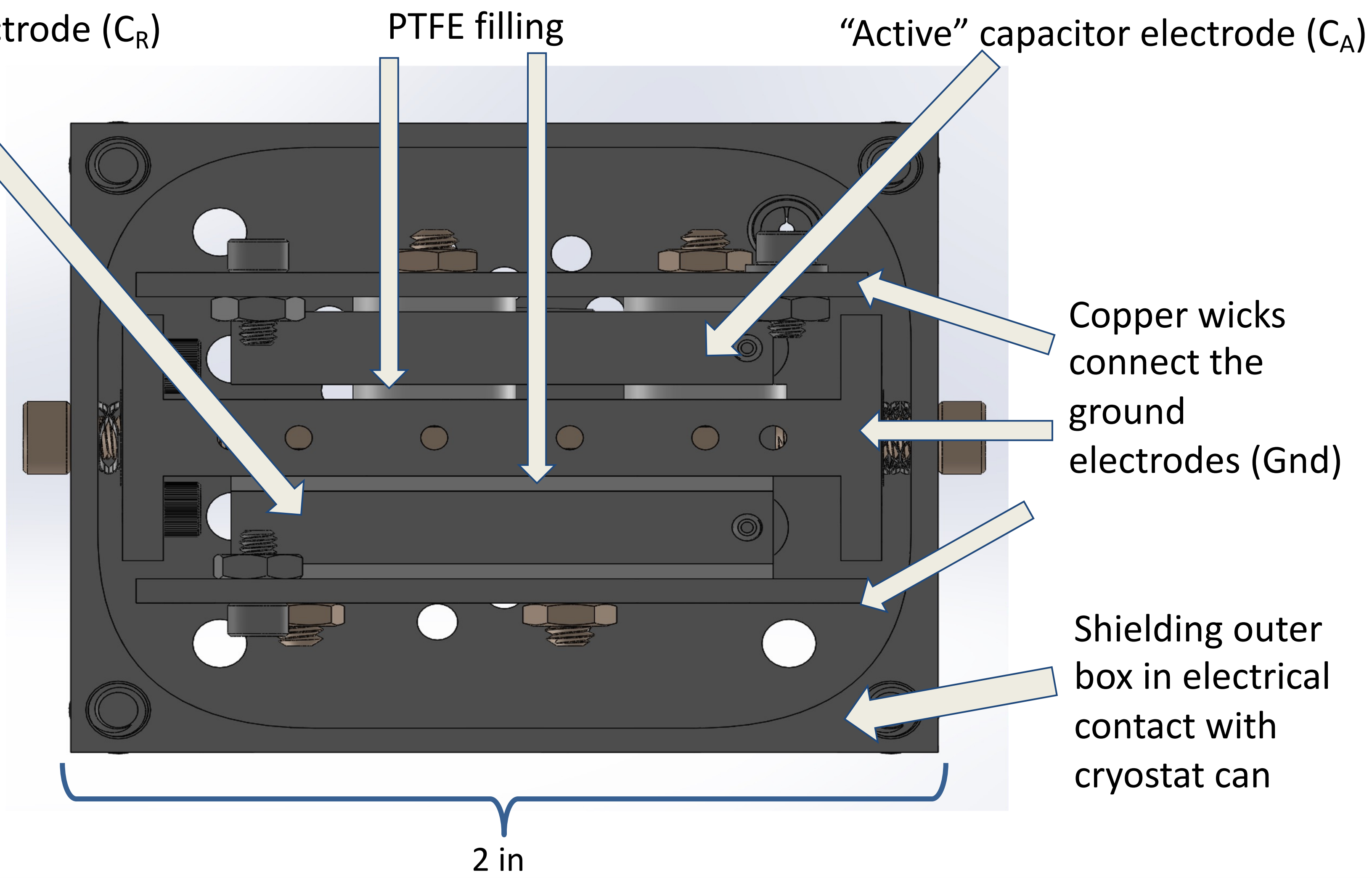
Capacitor Design and Concept

We designed a capacitor sensitive to changes in fluid dielectric constant

The capacitor is composed of two "mirror" capacitors:

C_A is designed to maximally increase in capacitance in response to doping

C_R is designed to minimally change in response to doping

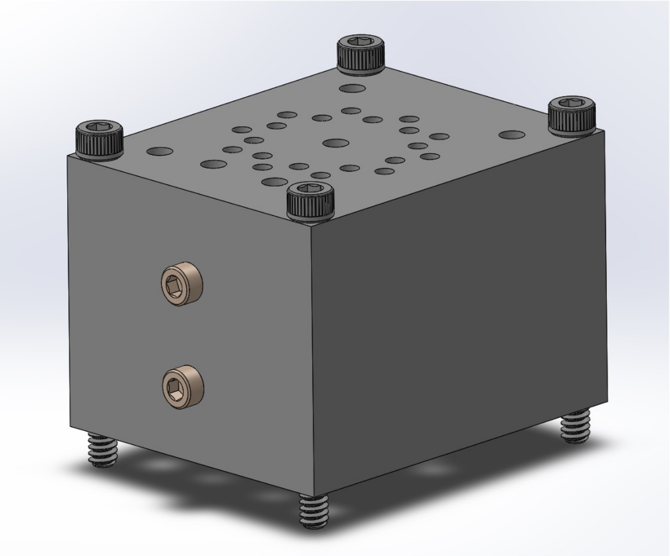


Capacitor Design and Expected Signal

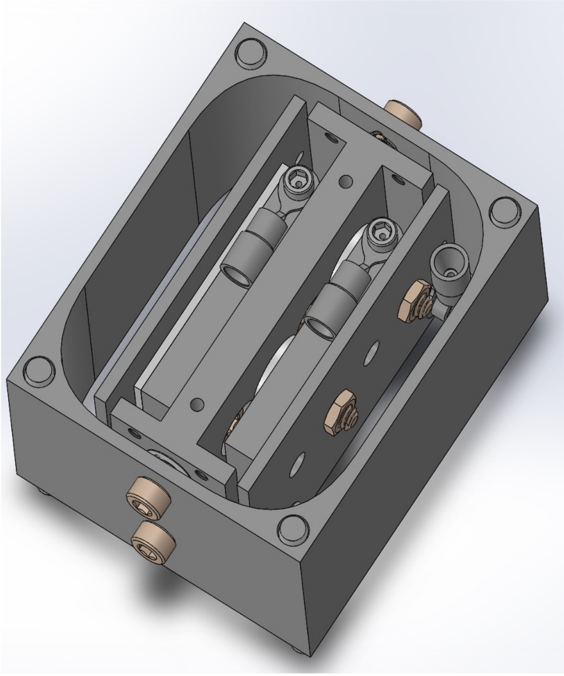
Dimensions: 1⅝”x2”x1.25”

Expected ΔC_R from 0.1% xenon doping: ~0.05 fF

Expected ΔC_A from 0.1% xenon doping: ~0.5 fF

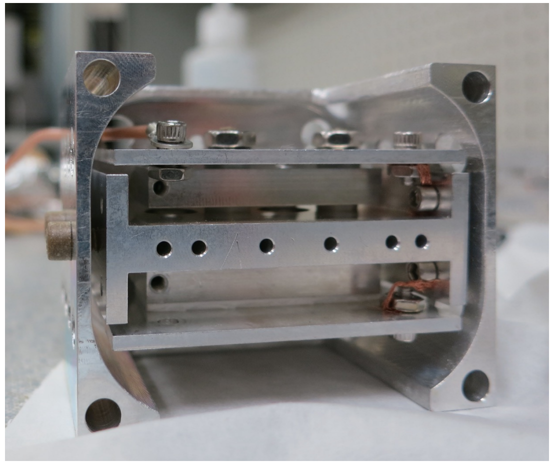


Capacitor is housed inside a box that can be secured in a liquid argon bath

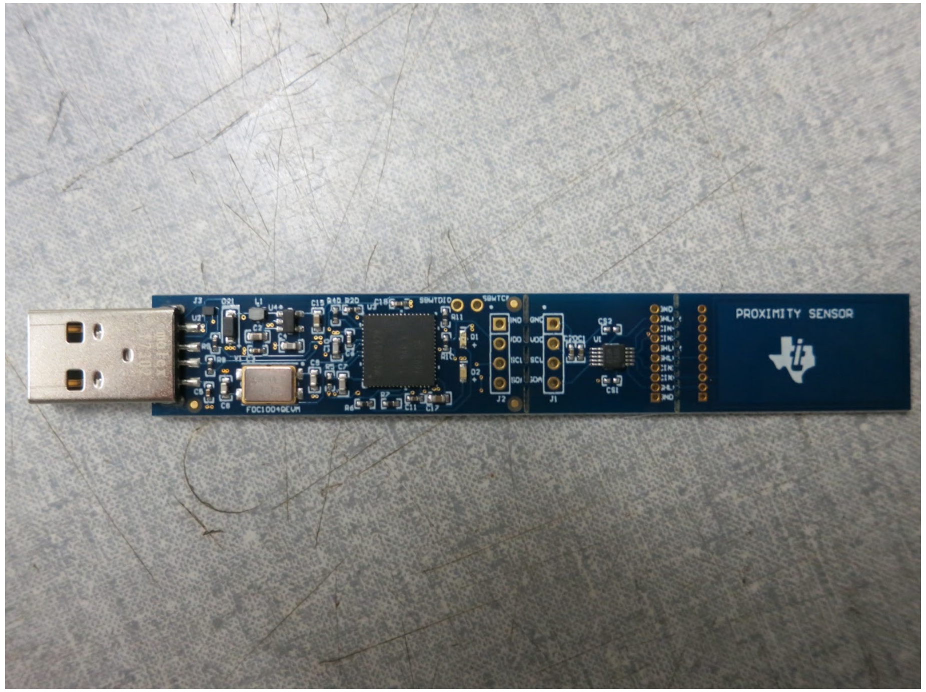


View of capacitor with top of outer box cut off. Cables for C_A, C_R, and Gnd exit holes at the top of the box

Capacitor with alternate outer box design



Measuring Capacitance with the FDC1004EVM



The FDC1004EVM has a proximity sensor for simple tests. The sensor can be removed.

The USB-powered FDC1004EVM contains the FDC1004Q capacitance-to-digital converter

Input Range: +/- 15 pF

Measurement Resolution: 0.5 fF

Number of Channels: 4

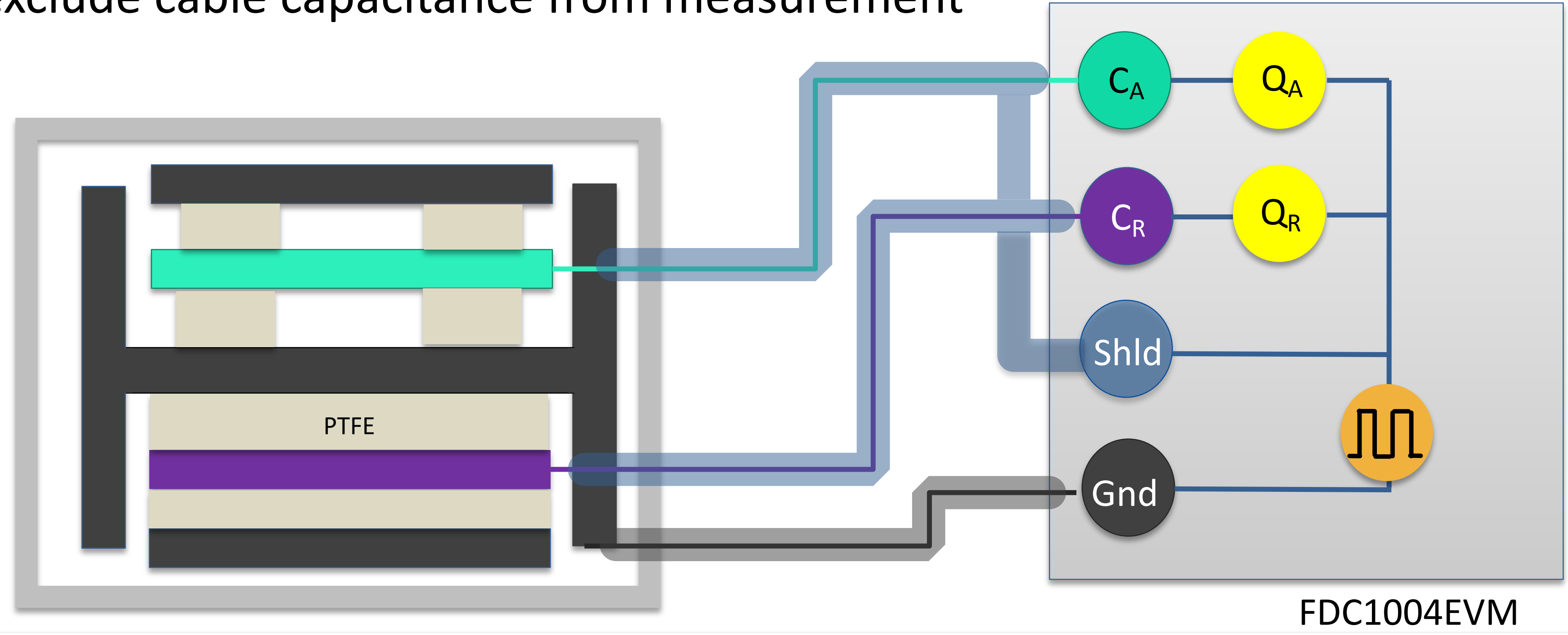
The resolution of the FDC1004EVM is compatible with our capacitor design goal of detecting xenon concentration changes below 0.1%

Wiring Schematic with the FDC1004EVM Shielding Technique

C_A and C_R coaxial cables have their own intrinsic capacitance

The FDC1004EVM supplies an active shield voltage to the C_A and C_R cables' outer conductors to exclude cable capacitance from measurement

With the shielding technique we achieve a capacitance sensitivity of <1 fF after averaging



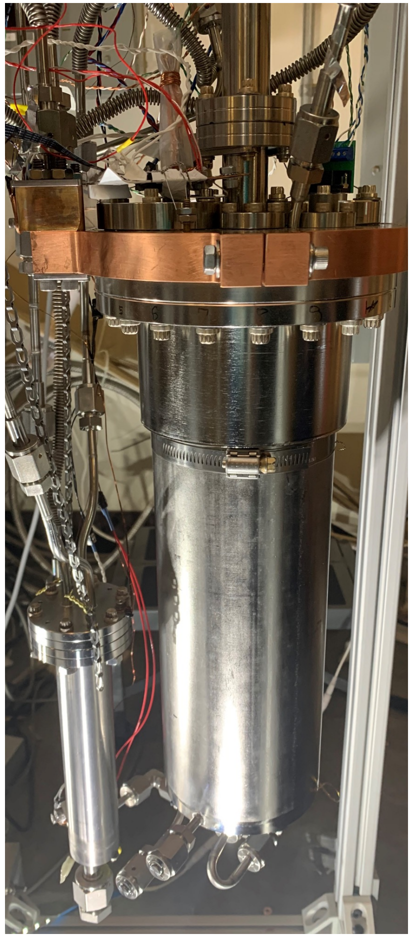
Deployment of Capacitor in CHILLAX (CoHerent Ionization Limit of Liquid Argon and Xenon)

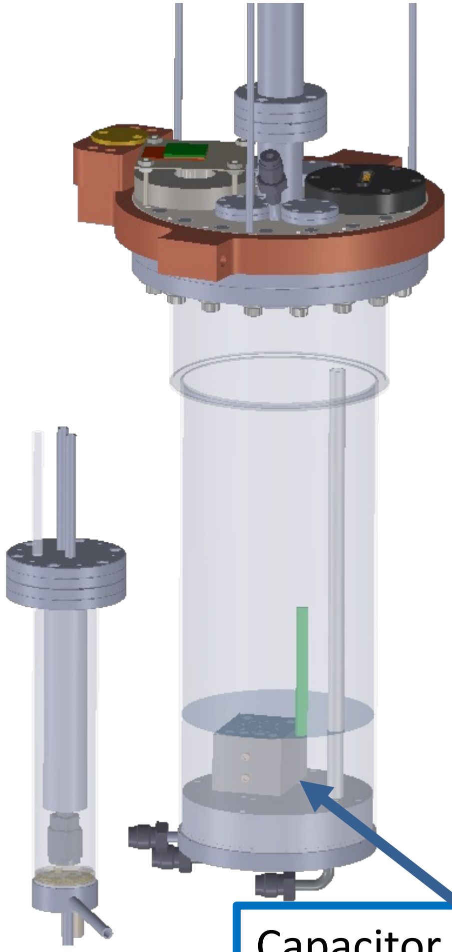
CHILLAX Concept: A liter-scale dual phase xenon-doped argon TPC

<u>Goals</u>

Investigate stability concerns from xenon-doped argon (see Ethan Bernard's talk) and benefits to an argon TPC's ionization signal from xenon doping

> We monitor xenon concentration in the liquid argon with a capacitive measurement





Capacitor deployed here

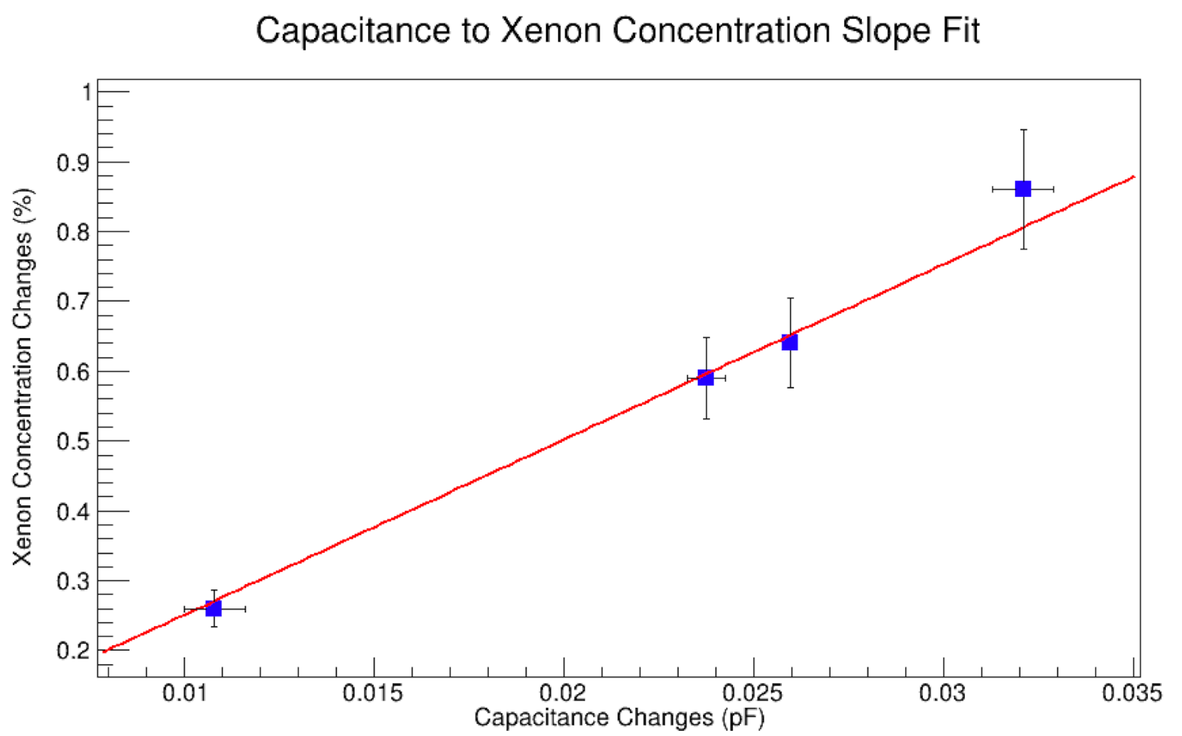
Calibrating the Capacitor

We to fit a calibration function of the form:

$$F_{xe}(C)=m*C+b$$

The slope of the calibration function is fit with data from the 4 doping stages:

Capacitance Increase (pF)	Xenon Concentration Increase (%)
0.0108 +/- 8e-4	0.26%
0.0321 +/- 8e-4	0.86%
0.02375 +/- 5e-4	0.59%
0.02597 +/- 4e-5	0.64%



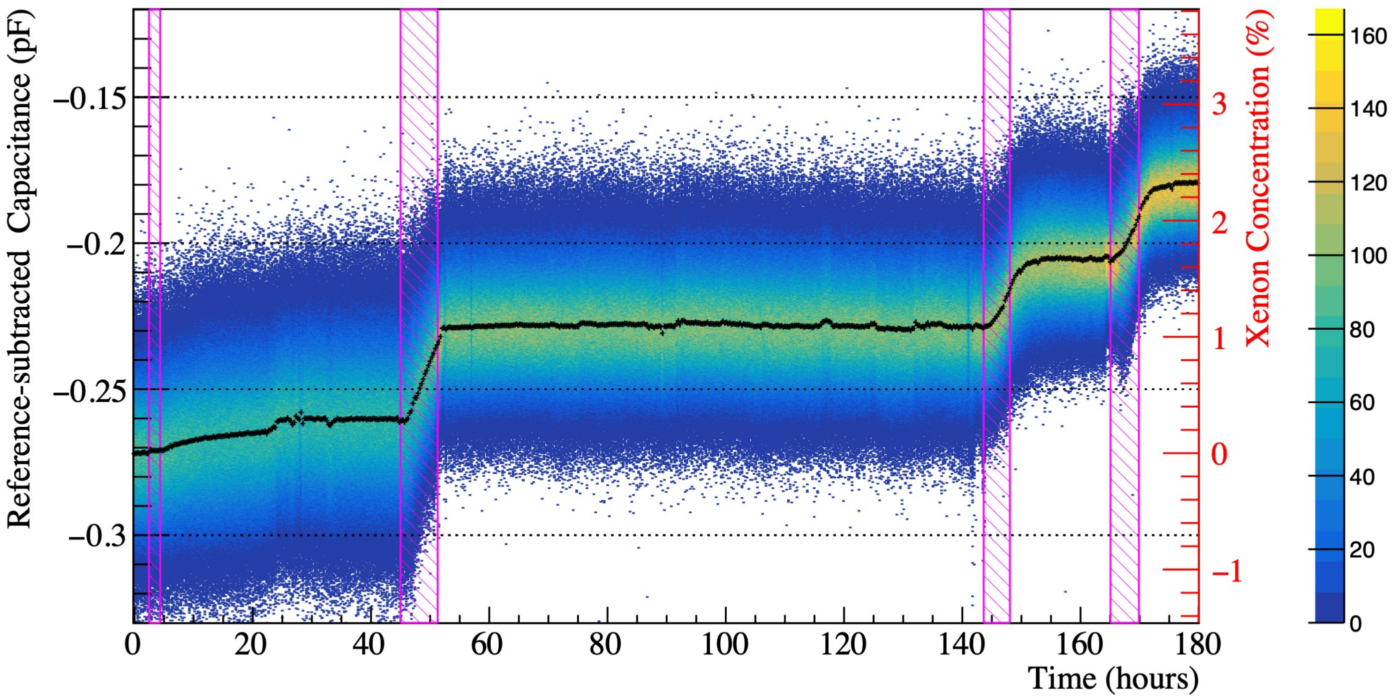
The y-intercept is found from the measuring the capacitance in pure liquid argon

Capacitance and Xenon Concentration in Response to Doping

The capacitor tracks xenon concentration throughout the doping process with 0.05% precision

The capacitor is sensitive to variations in doping conditions (fast vs slow introduction of xenon)

Drifts in capacitance should be attributed to changes in xenon concentration or temperature



Capacitance and xenon concentration in CHILLAX over time, with doping stages highlighted in pink

Capacitive Sensitivity to Temperature Fluctuations

Thermal changes in the measured capacitance have two sources:

$$C = \epsilon_r \cdot C_{\text{vac}}$$

$$\frac{dC}{dT} = \frac{d\epsilon_r}{dT} \cdot C_{\text{vac}} + \frac{dC_{\text{vac}}}{dT} \cdot \epsilon_r$$

From liquid density changes

From unwanted mechanical changes

Suppose no unwanted sources:

$$\frac{dC}{dT} = \frac{d\epsilon_r}{dT} \cdot C_{\text{vac}} + \cancel{\frac{dC_{\text{vac}}}{dT} \cdot \epsilon_r}$$

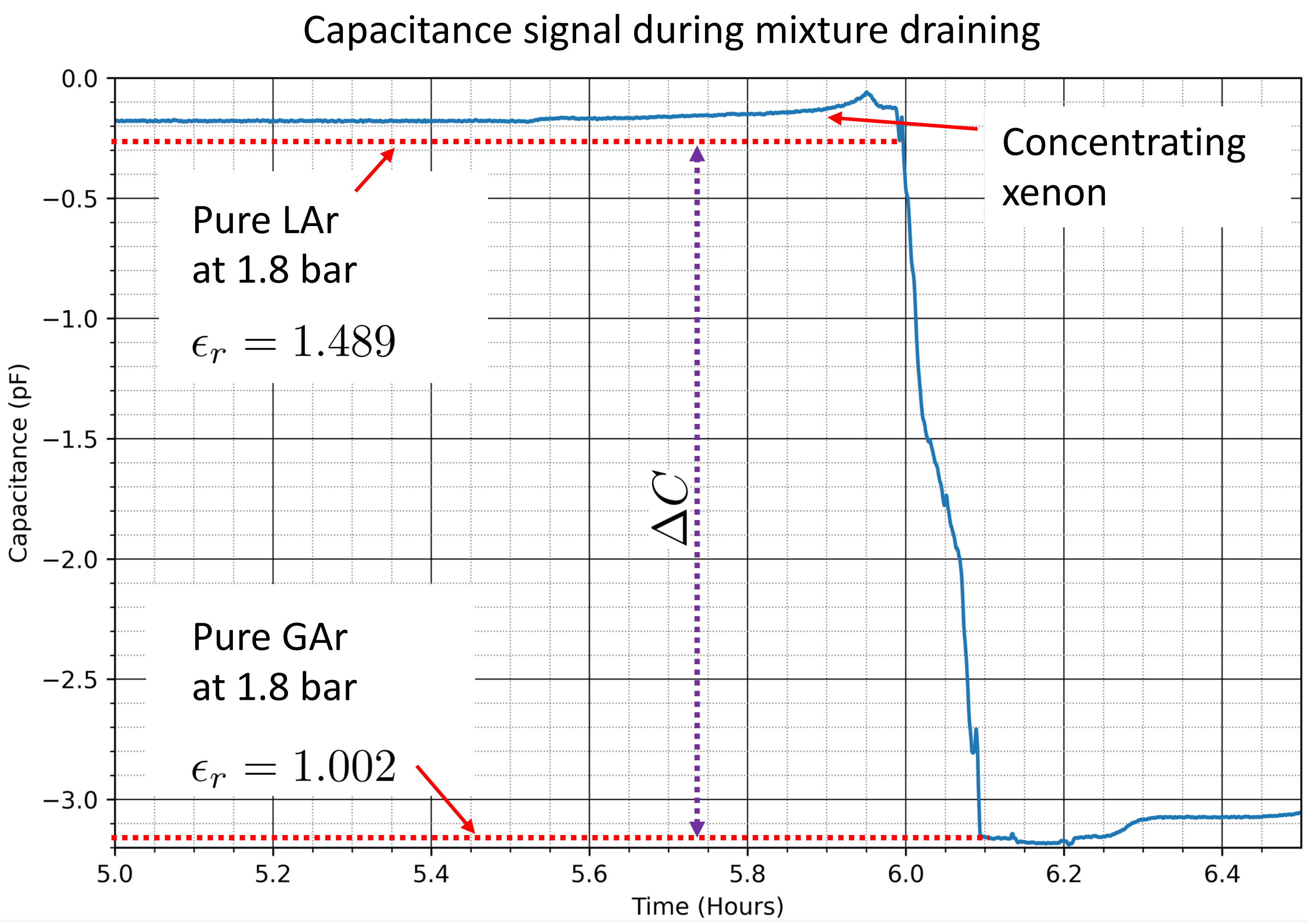
$$\frac{dC}{dT} = C_{\text{vac}} \cdot \underbrace{\frac{d\epsilon_r}{dn} \cdot n}_{\text{From C-M eq. at 1.8 bar LAr density}} \cdot \underbrace{n^{-1} \frac{dn}{dT}}_{\text{Fractional density change of LAr with temperature at 1.8 bar}}$$

Draining Measurement to Compute C_{vac}

Values of ϵ_r for non-standard densities can be produced by the C-M equation and the literature value of 1.505 for 1 bar on the vapor curve

$$C = \epsilon_r \cdot C_{\mathrm{vac}}$$

$$C_{\mathrm{vac}} = \Delta C / \Delta \epsilon_r = 5.926 \text{ pF}$$



Capacitive Sensitivity to Temperature Fluctuations

Thermal changes in the measured capacitance have two sources:

$$C = \epsilon_r \cdot C_{\text{vac}}$$

$$\frac{dC}{dT} = \frac{d\epsilon_r}{dT} \cdot C_{\text{vac}} + \frac{dC_{\text{vac}}}{dT} \cdot \epsilon_r$$

From liquid density changes

From unwanted mechanical changes

Suppose no unwanted sources:

$$\frac{dC}{dT} = \frac{d\epsilon_r}{dT} \cdot C_{\text{vac}} + \cancel{\frac{dC_{\text{vac}}}{dT}} \cdot \epsilon_r$$

$$\frac{dC}{dT} = \underline{C_{\text{vac}}} \cdot \underline{\frac{d\epsilon_r}{dn} \cdot n} \cdot \underline{n^{-1} \frac{dn}{dT}}$$

From draining measurement

From C-M eq. at 1.8 bar LAr density

Fractional density change of LAr with temperature at 1.8 bar

$$\frac{dC}{dT} = -16.13 \text{ fF/K}$$

Prediction

Capacitive Sensitivity to Temperature Fluctuations

Prediction from draining and density :

$$\frac{dC}{dT} = -16.13 \text{ fF/K}$$

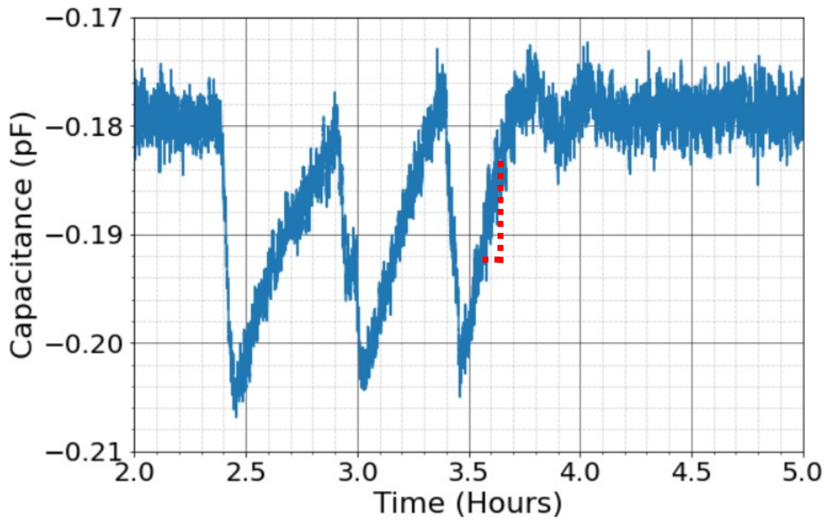
Measurement from recovery after last mixing heating:

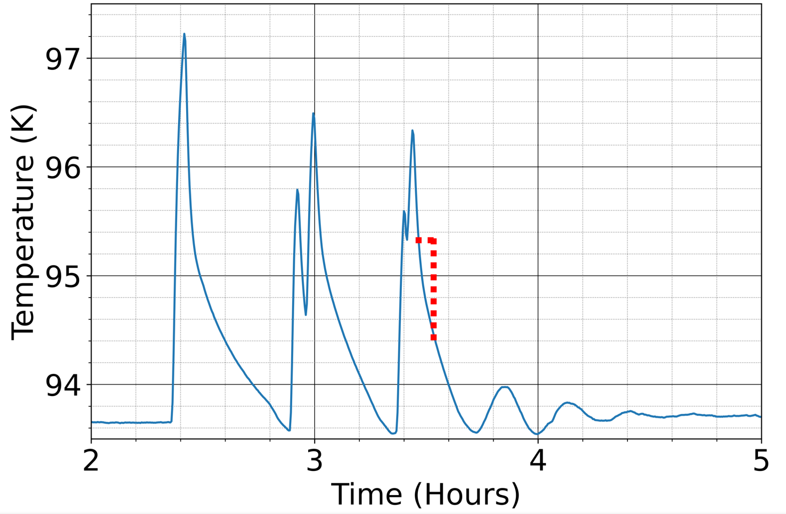
$$\frac{dC}{dT} = -15.46 \text{ fF/K}$$

Mismatch: 4.3 %

Conclusion:

Unwanted temperature sensitivity is strongly subdominant to signal from density changes



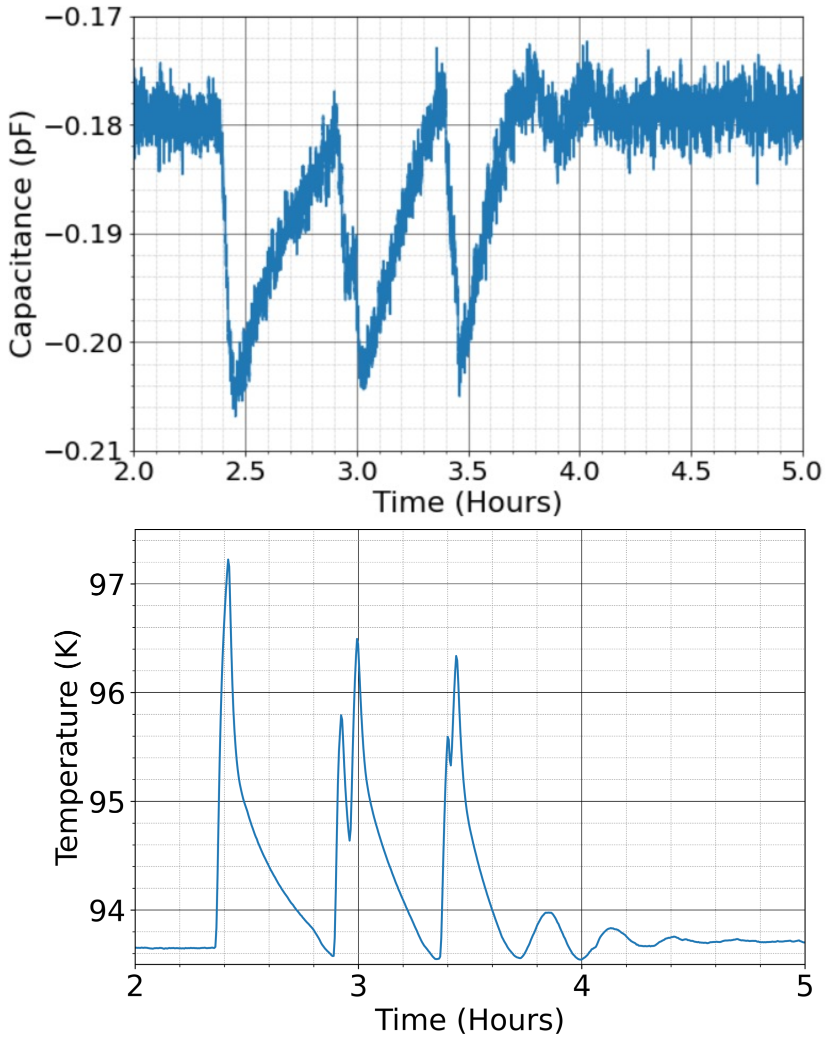


Application of Capacitor for Measuring Xenon Homogeniety

Even if xenon distillation is not occurring, it is possible that xenon is not uniformly distributed in the cryostat.

Test: Rapidly boil liquid to trigger aggressive mixing, then compare capacitance before and after

Conclusion: Capacitance returns to premixed state within uncertainty, indicating xenon was already well-mixed

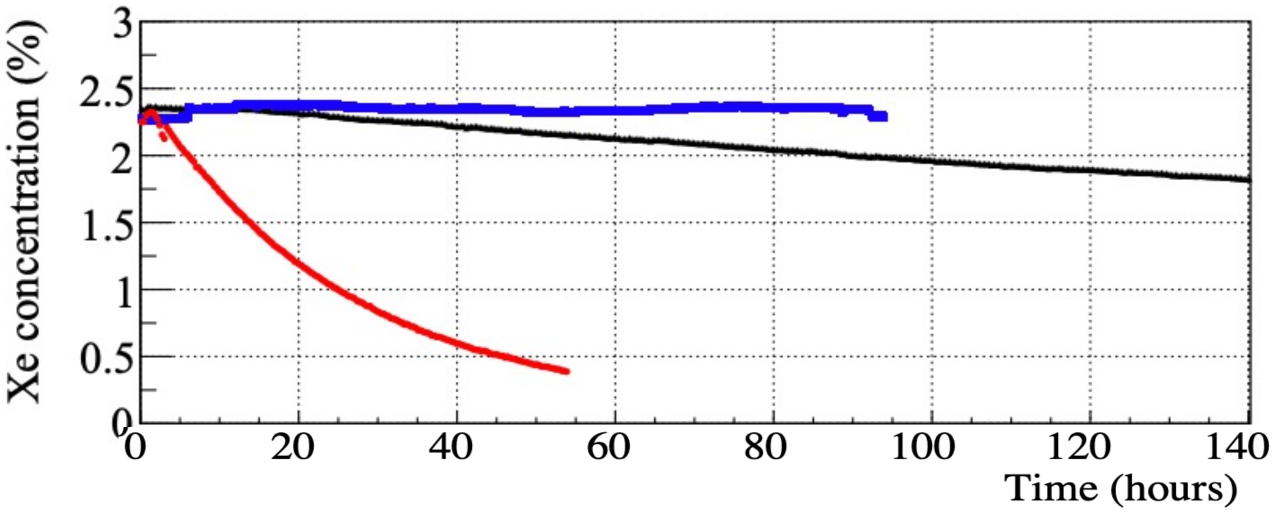


Implementation of Capacitor for Stability Studies in CHILLAX

Various thermal profiles were established in CHILLAX to observe rate of xenon distillation

The capacitance measurement provided a quantitative method to monitor changes in xenon concentration

The capacitor provided a handle for quantifying which thermodynamic settings were optimal for maintaining stability in xenon-doped argon (for more details see Ethan Bernard's talk)



Capacitive monitoring of xenon concentration in response to various stability tests in CHILLAX

Conclusion

Xenon-doping of argon has potential for achieving new sensitivities in noble element detectors, but maintaining stability is nontrivial

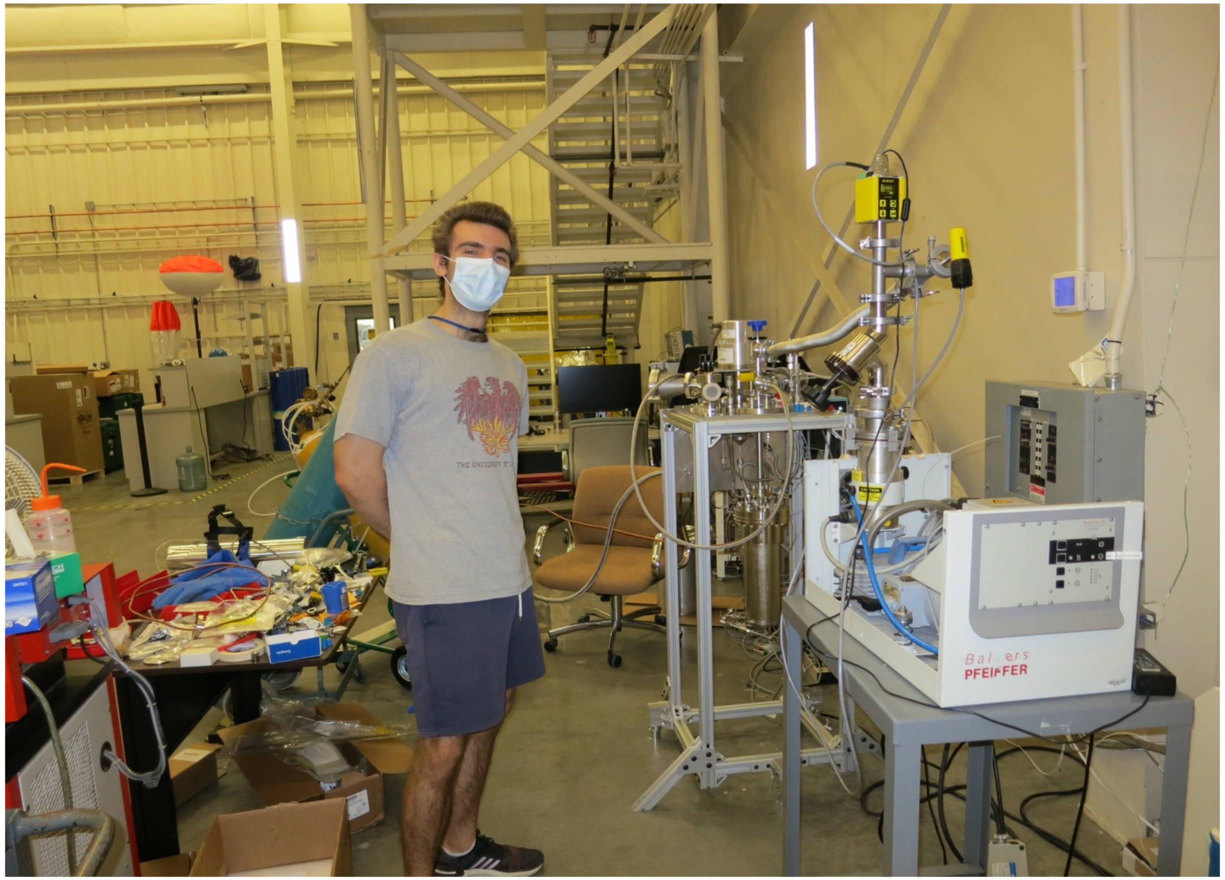
Capacitive measurements of xenon concentration in argon is one promising method of monitoring mixture stability

We have deployed a capacitor inside a xenon-doped argon detector that is sensitive to 0.05% shifts in xenon concentration

This capacitor successfully provided a handle to measure mixture homogeneity and stability over time

Similar technology could be implemented for future xenon-doped experiments

Thank you! Questions?



This material is based upon work supported by the Department of Energy National Nuclear Security Administration under Award Number DE-NA0000979 and DE-NA0003996.

Lawrence Livermore National Laboratory

Disclaimer

This document was prepared as an account of work sponsored by an agency of the United States government. Neither the United States government nor Lawrence Livermore National Security, LLC, nor any of their employees makes any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States government or Lawrence Livermore National Security, LLC. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States government or Lawrence Livermore National Security, LLC, and shall not be used for advertising or product endorsement purposes.