LUX-ZEPLIN Sampling System

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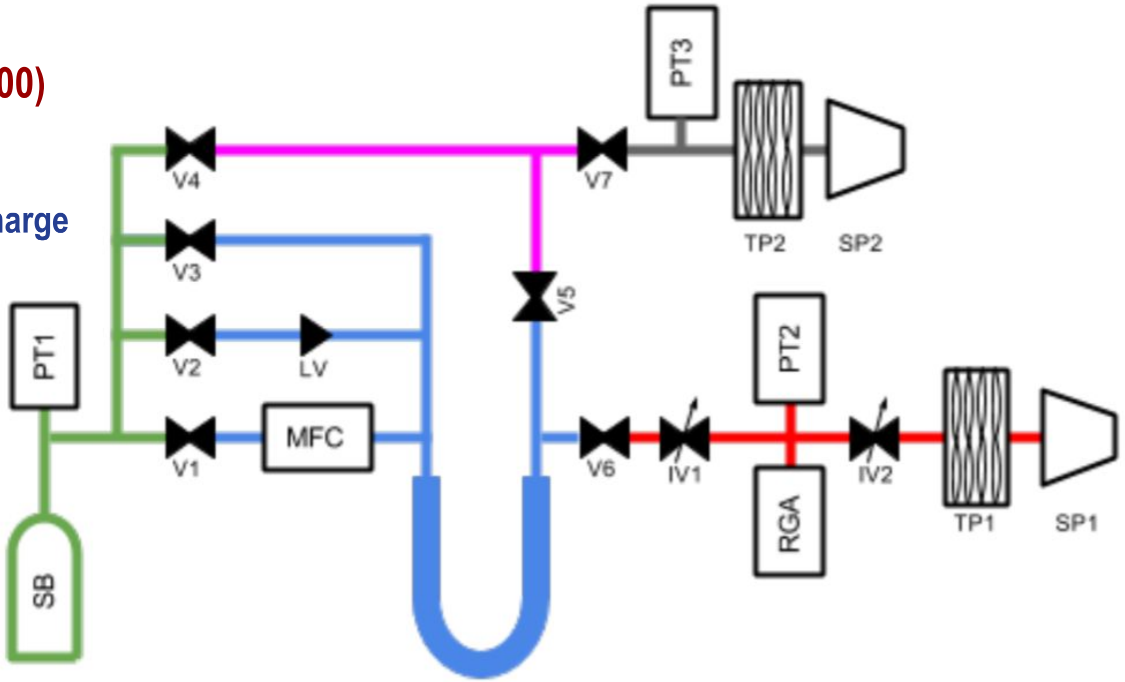
Demonstrating Parts per Quadrillion Sensitivity to Krypton in Xenon Gas.

Krypton Purity

- Krypton 85
  - Beta Decay
  - Half life of 10.8 years
  - Cannot be cleaned through chemical means
  - Can be cleaned through
    - Chromatography
    - Distillation
- Background Goal
  - 24 counts per 15 Tonne*year
  - Equivalent to 15 parts per quadrillion ^{Nat}Kr/Xe (gram/gram)
- Identifying Kr 85
  - Low statistics, could be weeks before noticed from detector data
  - In situ mass spectrometer to directly measure Krypton content

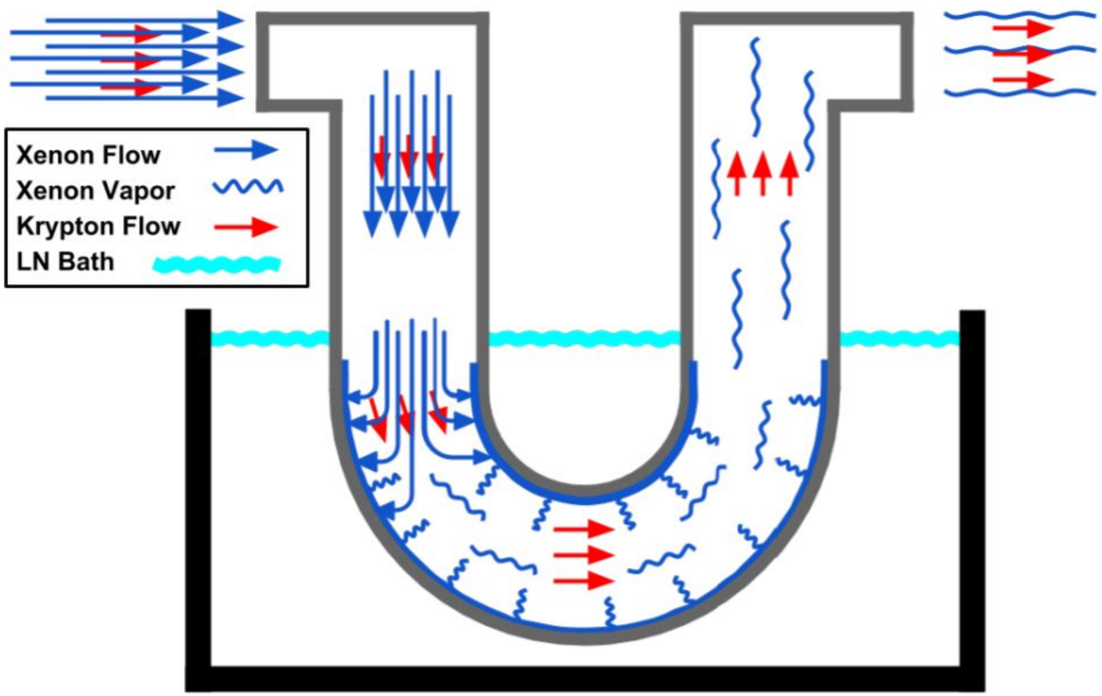
Sampling System: Overview

- **Main components**
  - Pressure Sensors
    - Monitor pressure at RGA with ion gauge
    - Monitor sample gas supplied to RGA
  - Mass Flow Controller (MFC)
    - Supplies gas to Cold Trap
  - Cold Trap (CT)
    - Freezes Xenon gas fed by MFC
  - Impedance valves
    - Tunes pressure seen by RGA
  - Mass Spectrometer (SRS RGA 200)
    - Filament ionizes gas
    - Quadrupole mass filter
    - Faraday cup/CDEM collects charge



Sampling System: Working Principle

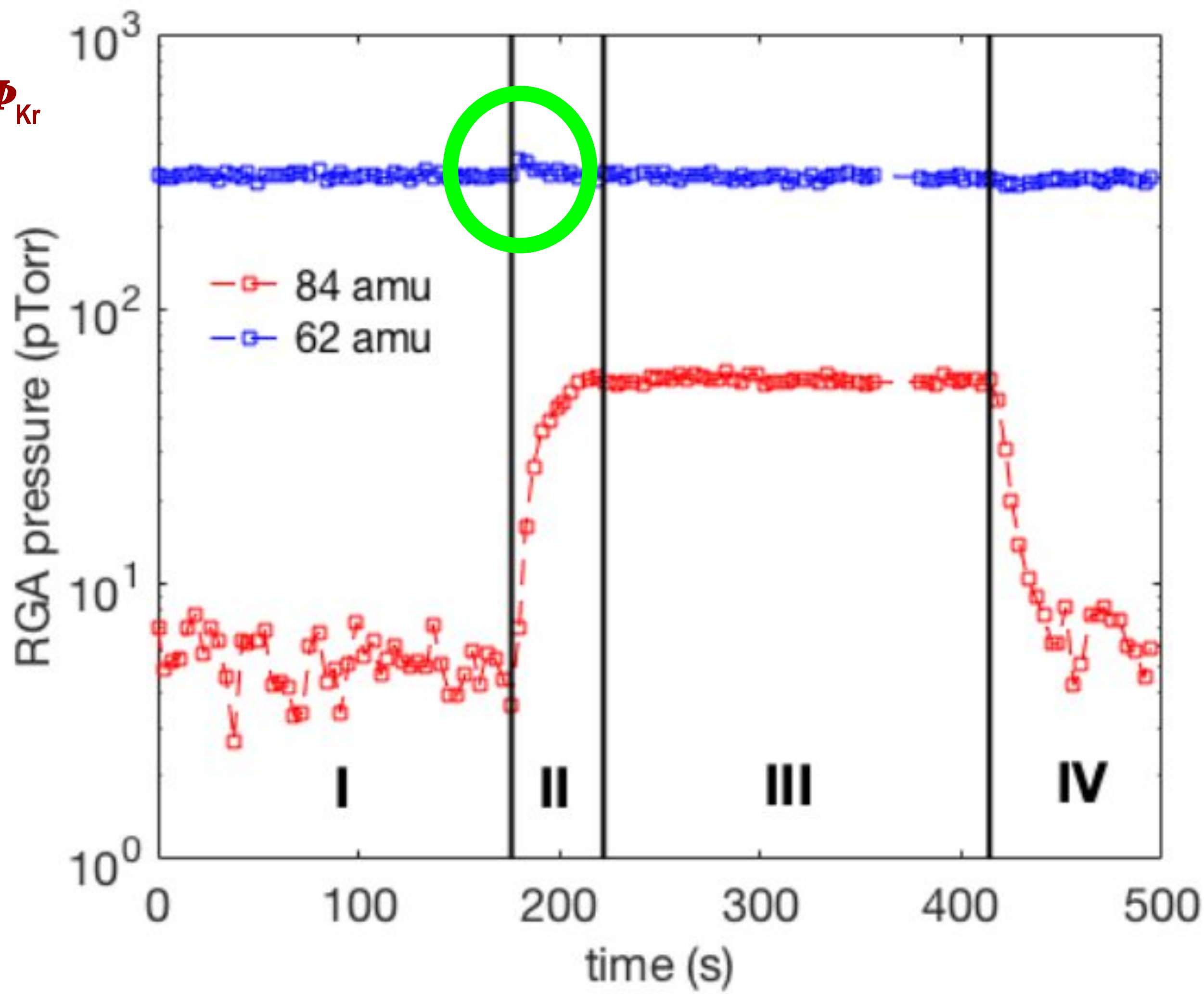
- **RGA limitations**
  - Sensitive to PPM (10^-6) of impurities in gas
  - Max operating pressure of 1e-5 torr (baseline behavior dominated by total gas pressure)
- **Cold Trap**
  - Xenon is frozen in cold trap
  - Constant pressure at RGA to ~1e-3 torr (ice vapor pressure at 77K)
  - Trace Kr passes through unaffected
  - Mixture at trap output is enriched up to a factor of 10^9 in Krypton



Sampling System: Working Principle

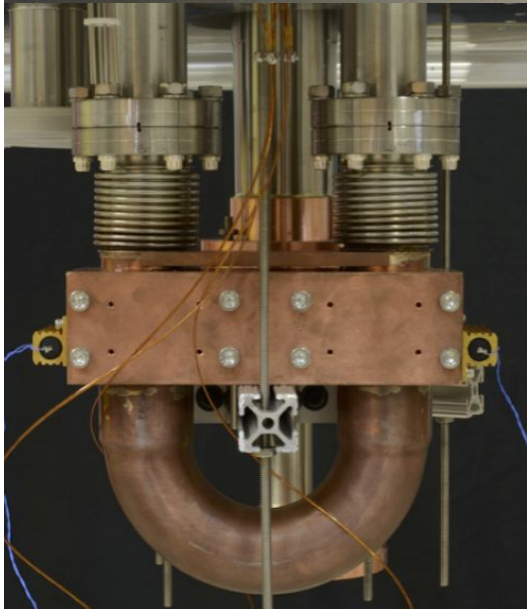
- **Using vacuum equations:**
  - Throughput parameter: α
  - Impedance: Z_1
  - Xenon flow: $Q_{XE,CT}$
  - Krypton concentration: Φ_{Kr}
- **Analysis**
  - Backgrounds (I)
  - Start flow (II)
  - Flow (III)
- **Punchthrough circled**
  - Xe pressure blip

$$PP_{Kr,eq} = \frac{\alpha}{180} Z_1 Q_{Xe,CT} \Phi_{Kr}$$



Sampling System: Upgrade

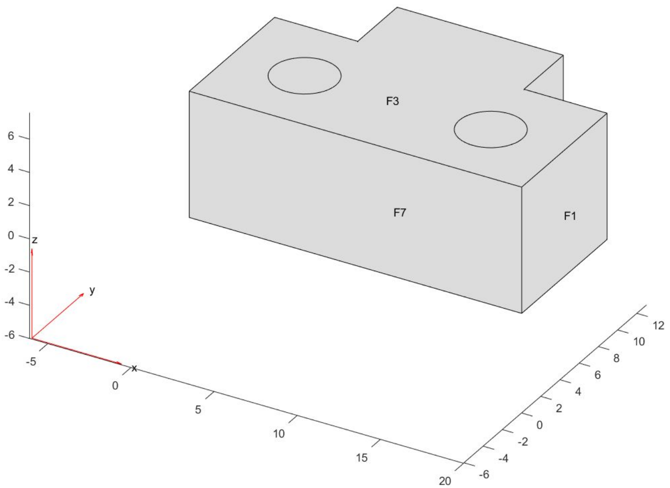
- Liquid Helium Pulse Tube Refrigerator
  - Automated cooldown, and warm up (Lakeshore)
  - Cooling power: 40 Watts @ 80K
    - Limited compared to LN
  - Variable temperature
    - Can move away from 77K
    - Xe vs Kr vapor pressure
    - Input and output temperature control
- Trap Material
  - Steel
    - Low thermal conductivity
    - Clean
    - Easy to manufacture
  - Copper
    - 10x greater thermal conductivity
    - Cleanliness depends on brazing, and copper quality
    - Very difficult to manufacture



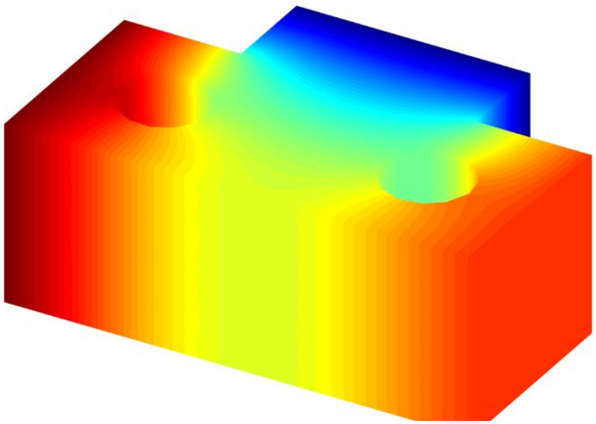
Sampling System: Thermal Simulations

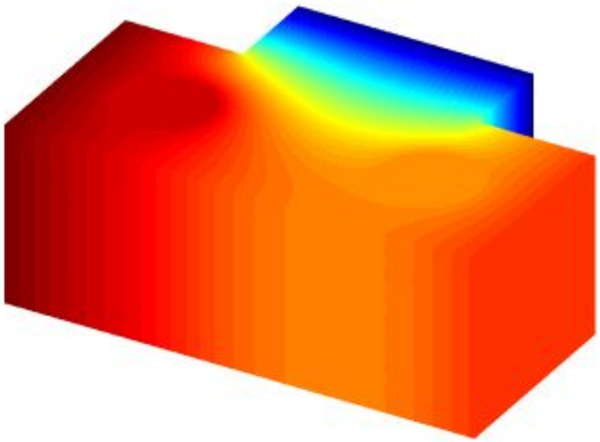
Temperature Gradients in the Copper Clamp

Copper clamp geometry



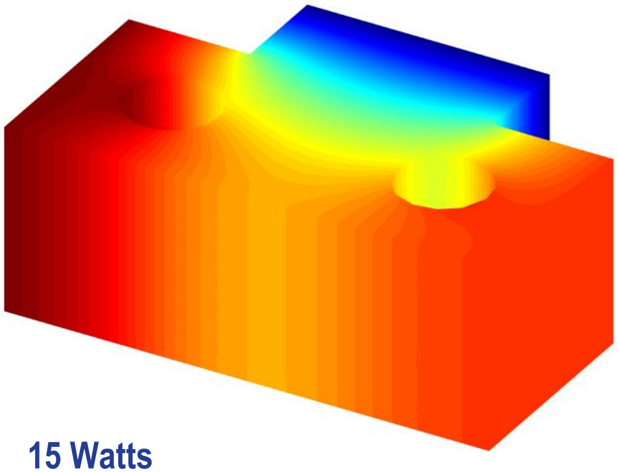
No flow





15 Watts of Xenon flow (1 SLPM)

No trap gradient

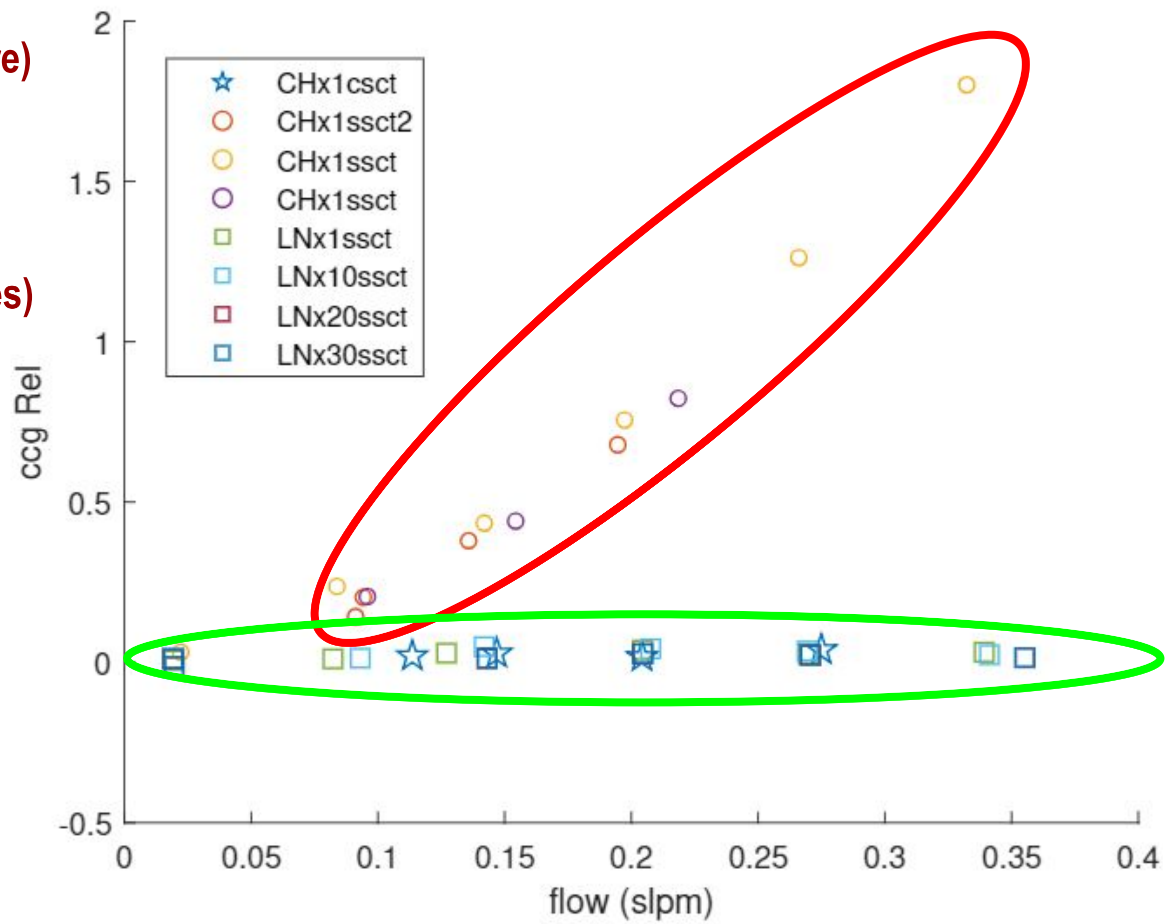


15 Watts

Trap has temperature gradient

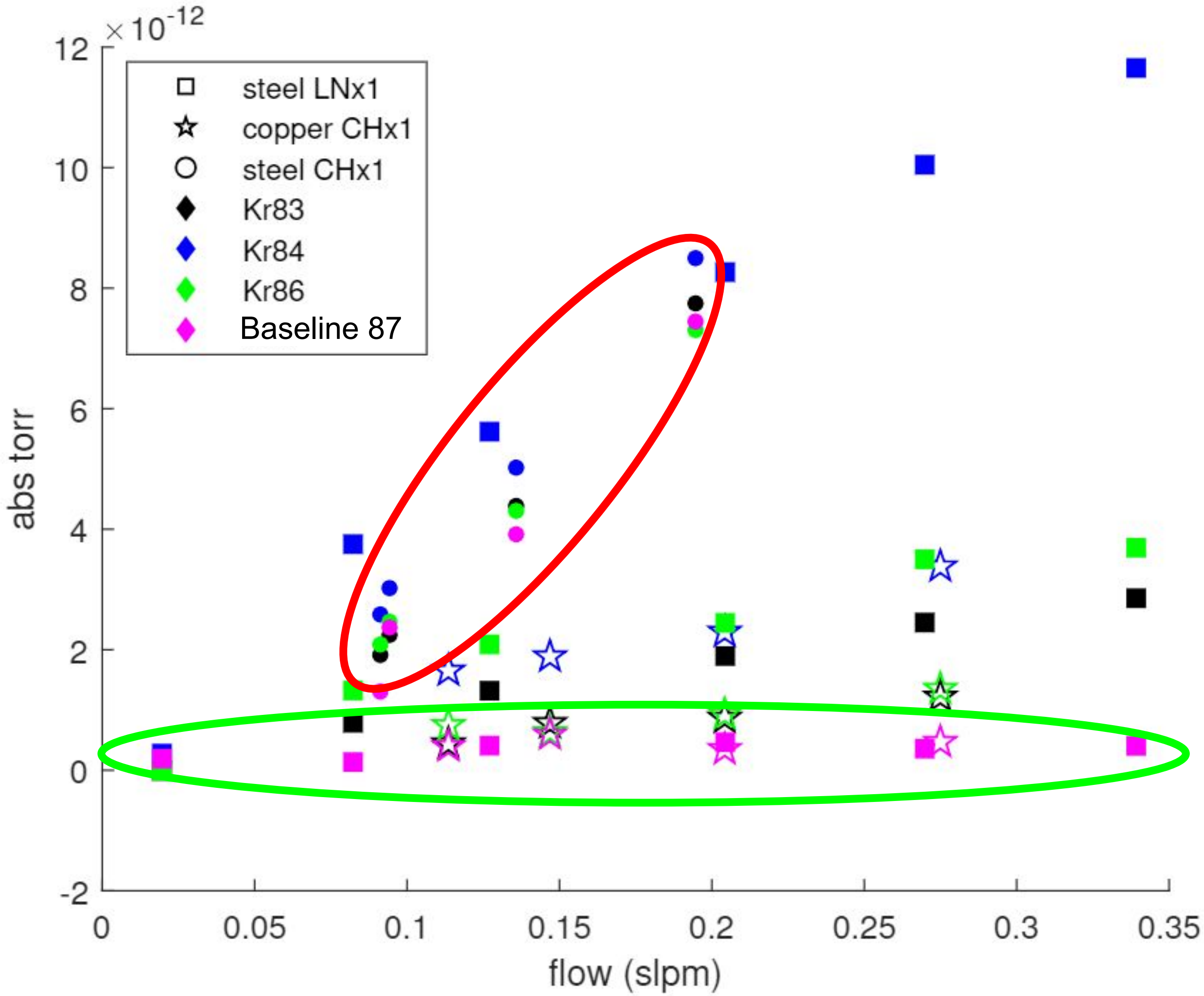
Sampling System: Xenon Punch Through

- Investigating SCT flow response
  - Stainless steel with LN (Square)
    - Ideal
  - Copper with CH (Stars)
    - Matches Squares
    - Pressure is steady
  - Stainless steel with CH (Circles)
    - Pressure rising with flow
    - Indicates Punch Through
- Punch Through
  - Pressure at RGA rising
    - Insufficient cooling



Sampling System: Stationary

- **Resulting Kr Signals**
  - Kr isotope abundance
    - Kr 84 @ 57%
    - Kr 86 @ 17.3%
    - Kr 83 @ 11.5%
  - RGA Baseline
    - 87 amu tracks RGA baseline
    - Should not change when flow starts
- **Red Circle**
  - Cold head, Stainless
    - Kr signals track 87
- **Green Circle**
  - Cold head, Copper
    - Stars well behaved
    - Baseline steady
    - Isotope separation
  - Liquid Nitrogen, Steel
    - Squares ideal
    - Baseline Steady
    - Isotope Separation

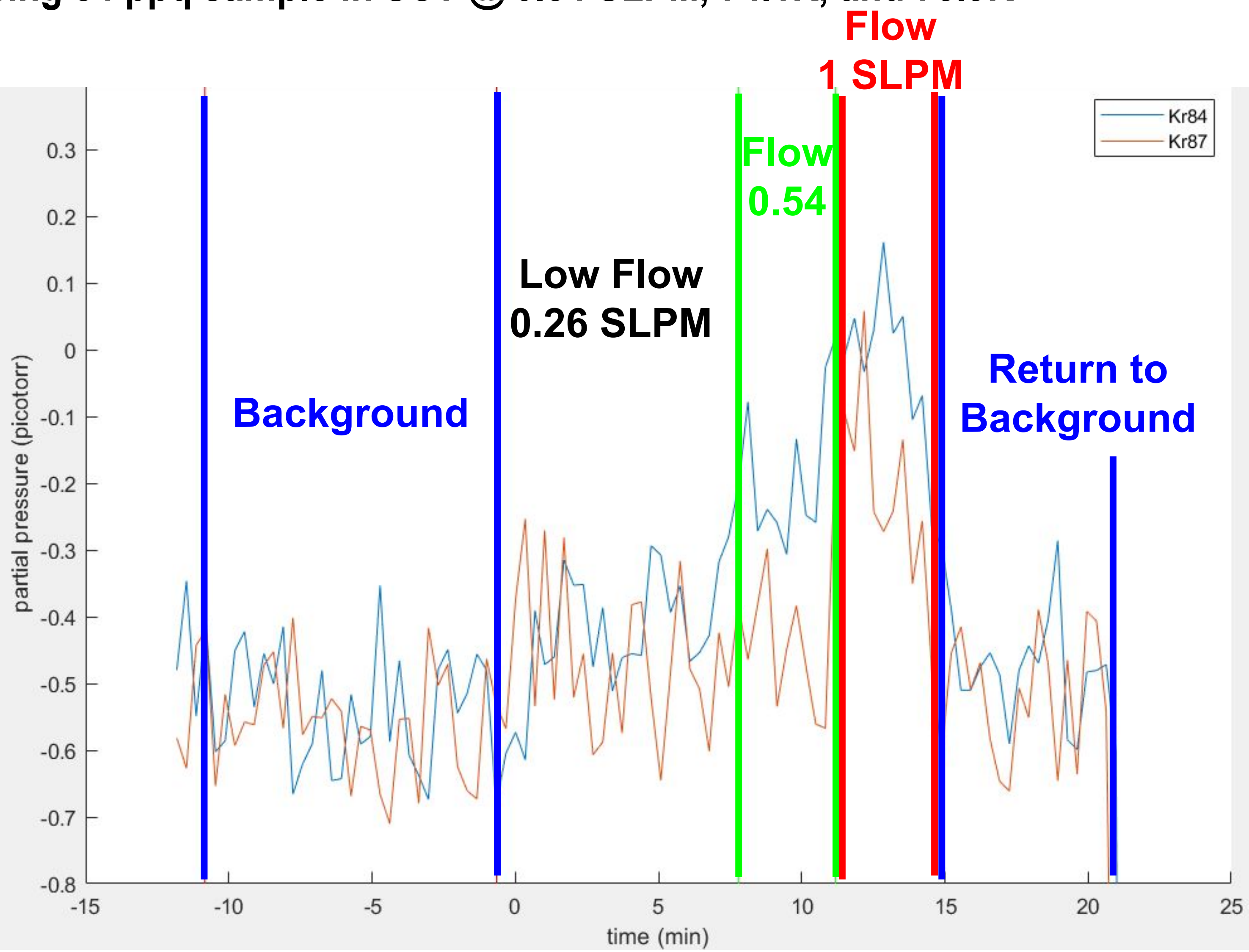


Sampling System: Stationary

Calibration Using 54 ppq sample in SCT @ 0.54 SLPM, 74.1K, and 73.9K

-Signal to noise ratio of 4

-13.5 PPQ limit of detection during green interval



Sampling System: Future

- Future and ongoing work
  - Ensure safe operation
    - Cryogens in fixed volumes
  - Map out temperature dependence
    - Around 77K (LN)
    - Around 116K (Kr ice temp)
    - Lower temps ~50-60K given enough cooling power
      - Xe has steeper vapor pressure fall off around 77K compared to Kr
  - Modify SCT
    - A bent (OFHC) copper trap
      - Brazed to for VCR interface
      - Electron Beam Welded for VCR interface
      - No bellows tubing
      - 1” OD, ⅛” thick
    - New (OFHC) copper bock
      - Decouple input and output
      - Increase actively cooled area
  - Construction of Final LZ system
    - Prepare at SLAC for Krypton removal
    - Move to final site at SURF
- Questions?

Sampling System: References

[1] Jon Balajthy, “Purity Monitoring Techniques and Electronic Energy Deposition Properties in Liquid Xenon Time Projection Chambers” 2018

Sampling System: Heater Response

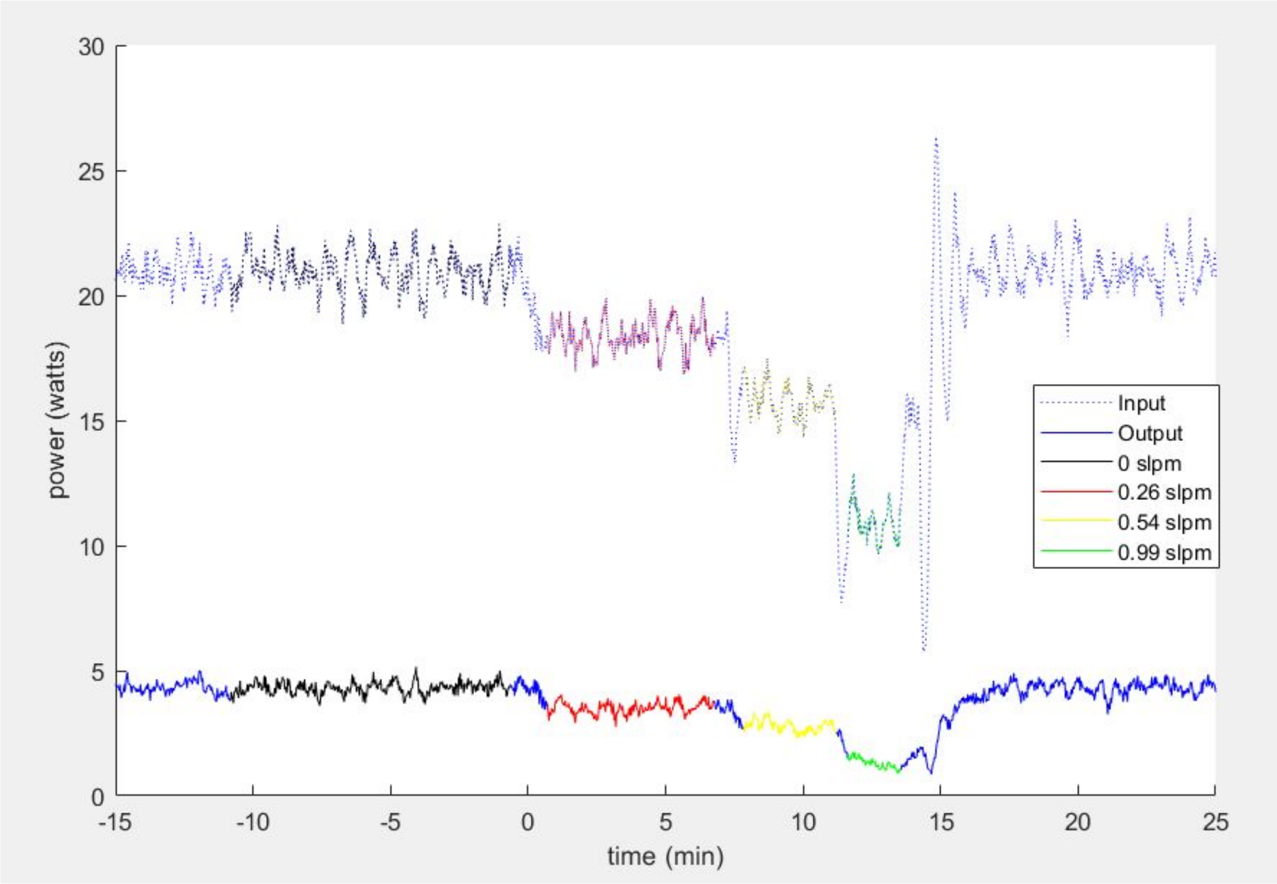
- **Temperature Response**
  - **Temperature chosen to mimic ^{62}Xe pressure seen when using stainless steel in LN (~2e-9 torr)**
  - **Flow limited by cooling power**
  - **Different temperatures chosen so input does bulk of freezing**
    - **Input @ 74.1K**
    - **Output @ 73.9K**

Xenon Power deposited:
FLOW: IN + OUT = TOTAL
Expected 15 watts/SLPM

0.26 SLPM: 2.6 + 0.8 = 3.4 Watts
Expected 3.9 Watts

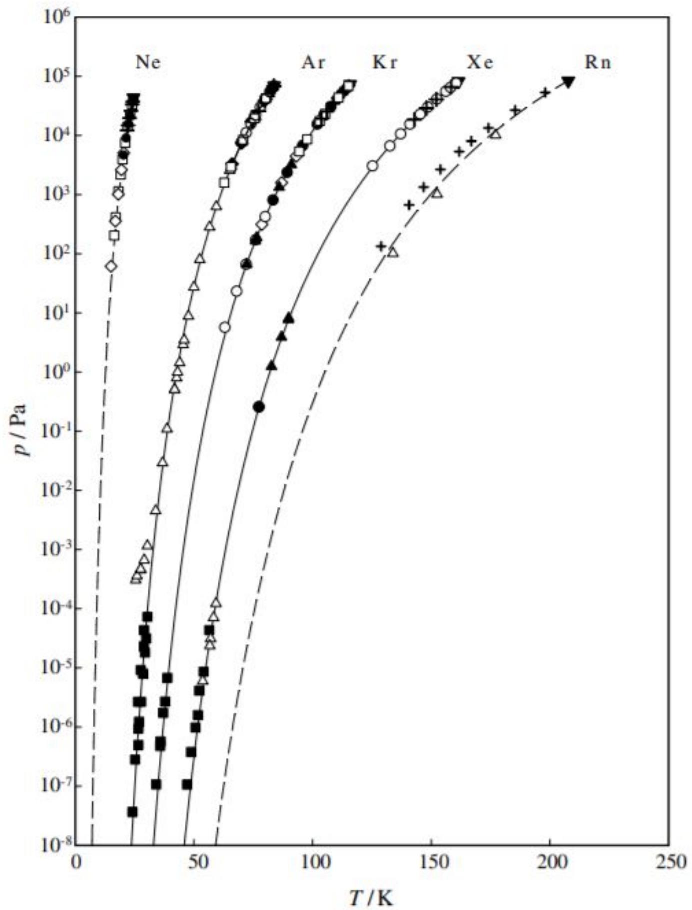
0.54 SLPM: 5.2 + 1.5 = 6.7 Watts
Expected 8.1 Watts

0.99 SLPM: 10 + 3 = 13 Watts
Expected 14.9 Watts



Sampling System: Vapor Pressure

- Cooling Power
  - Freezing 1SLPM of xenon at room temperature to 77K requires 15W of cooling power
  - Liquid nitrogen offers ~4W/mm of cooling in a 0.5” cold trap, and ~12W/mm for a 1.5” trap
  - The pulse tube refrigerator has fixed cooling power of ~40W total @77K



Flowing gas can change temperatures within the cold trap causing xenon vapor pressure to change.

This changes the RGA baseline behavior and can be viewed as a punch through effect (not all the xenon is not being cooled effectively).