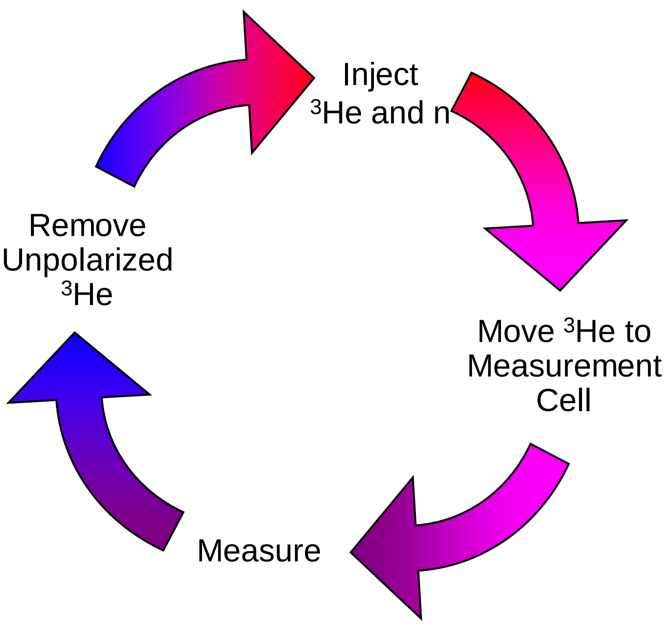
^{3}He Polarization & Transport

Steven Williamson

- Overview of the ^{3}He Services for nEDM@SNS
- Challenges for ^{3}He Services
- R&D Example: Superfluid helium film control

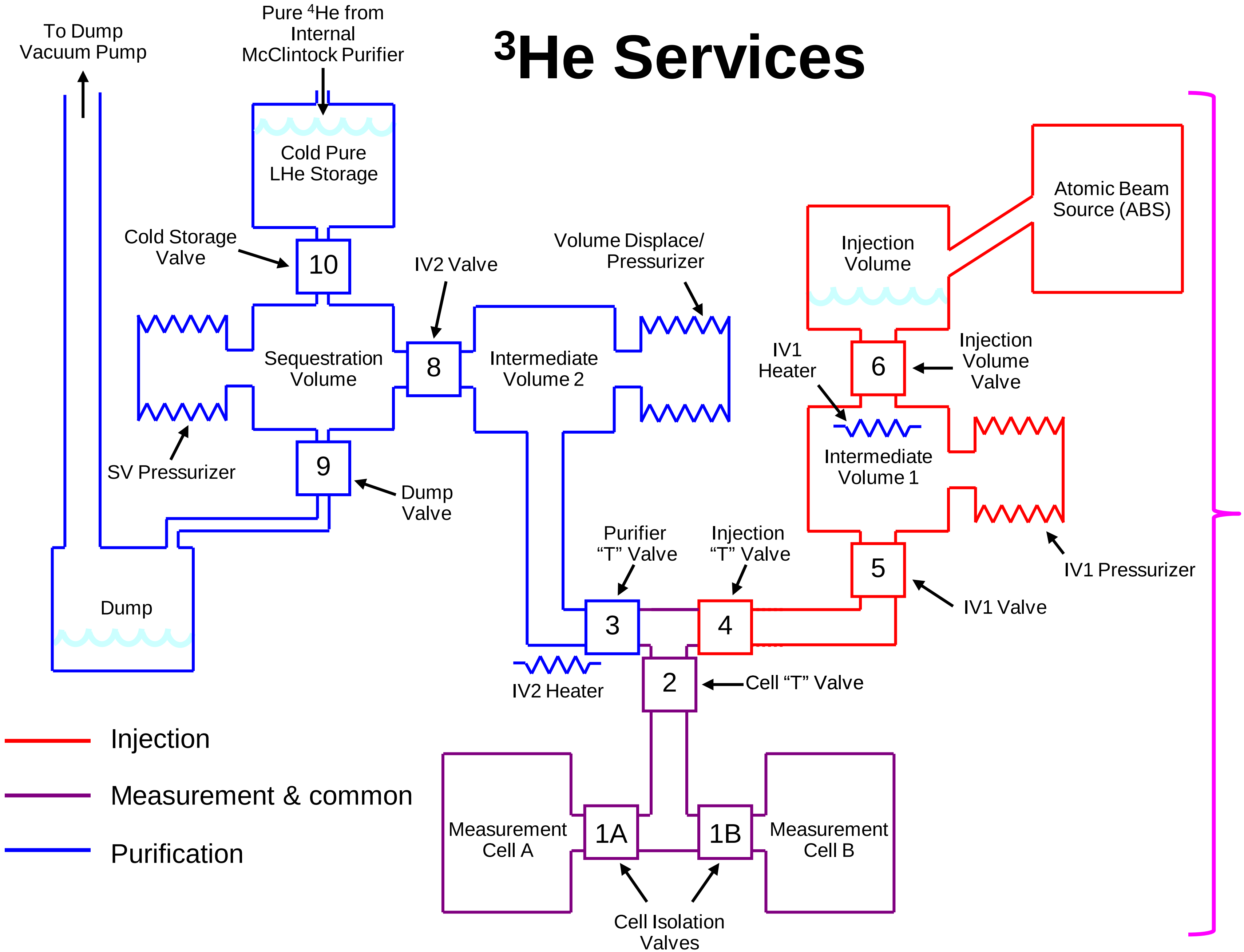
Polarized ^{3}He in nEDM@SNS

- Polarized ^{3}He provides:
  - Comagnetometer measure of B field seen by neutrons
  - Mechanism for detecting neutron spin precession
- The experiment relies on efficient…
  - **injection** of polarized ^{3}He into isotopically purified ^{4}He
  - **transport** of the polarized ^{3}He to the measurement volumes
  - **maintenance** of polarization during the measurement
  - **removal** of unpolarized ^{3}He when a precession measurement is complete.



Time	Neutrons	^{3}He
Measurement complete		
200 s		Remove from cell to holding volume 2
100 s		Move to cell
700 s	Accumulate in cell	Move to dump
700 s	Measure	Inject ^{3}He into He II
		Move to holding volume 1

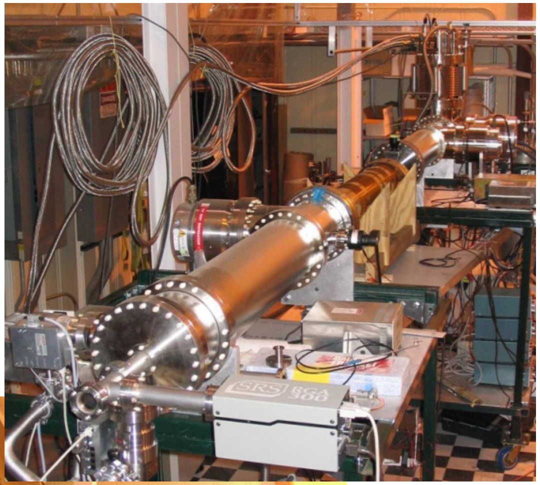
^{3}He Services

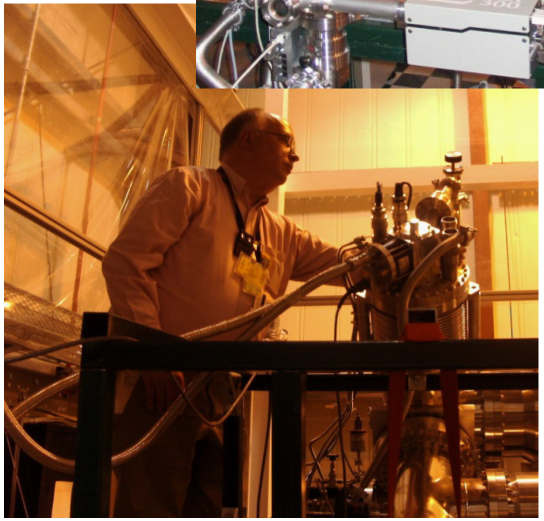


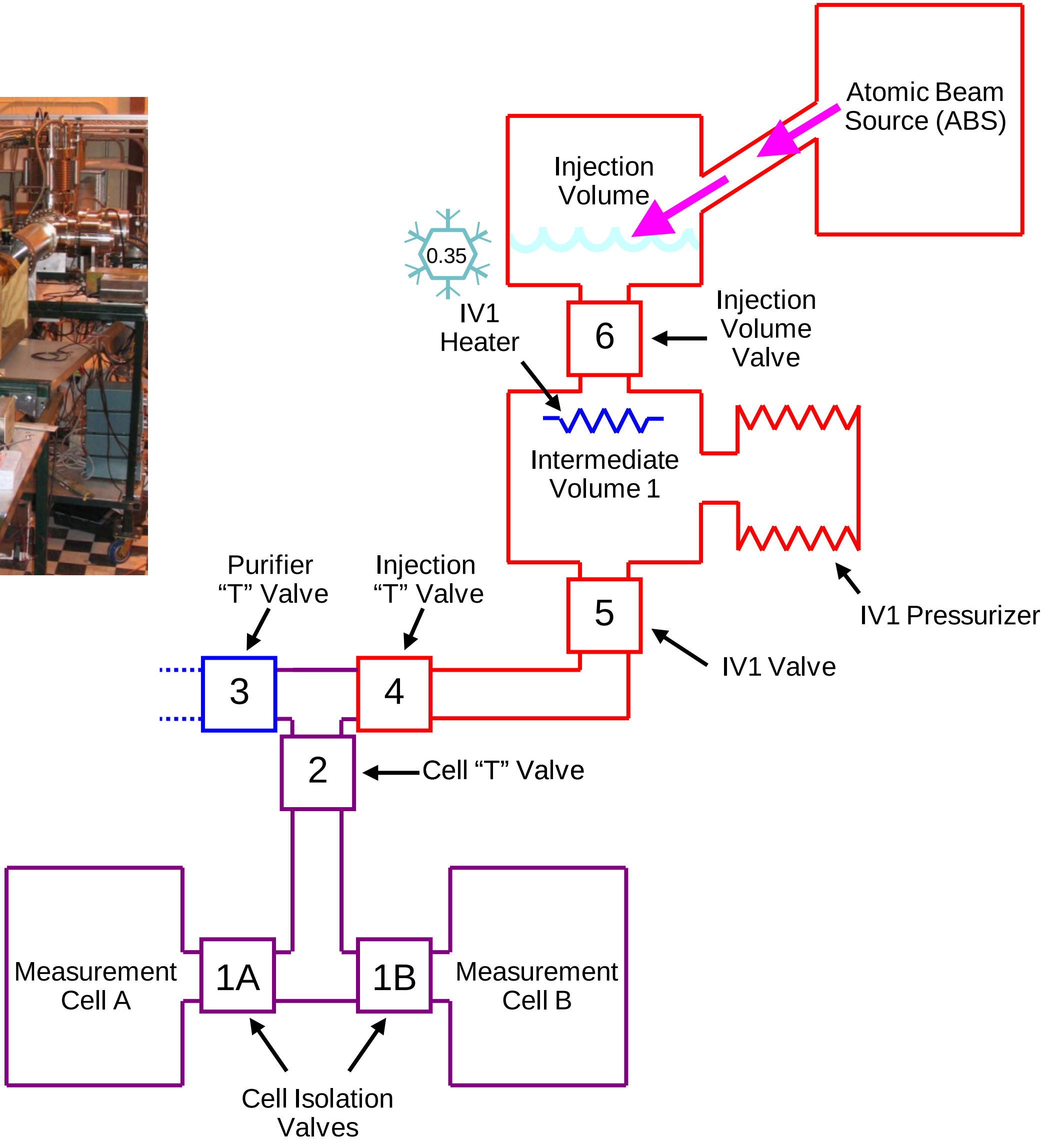
Injection and Measurement components contains polarized ^{3}He Must be "^{3}He Friendly"

Injection

- Step 1: Inject Polarized ^{3}He from ABS
  - Existing Equipment
  - 2×10^{14} atoms per sec
  - 99.6% Polarization
  - 30 s

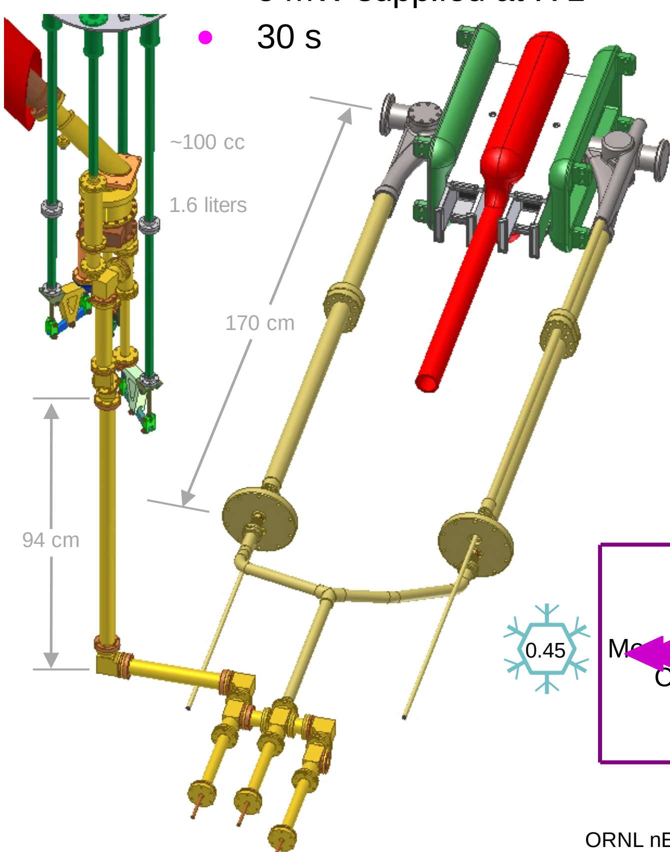


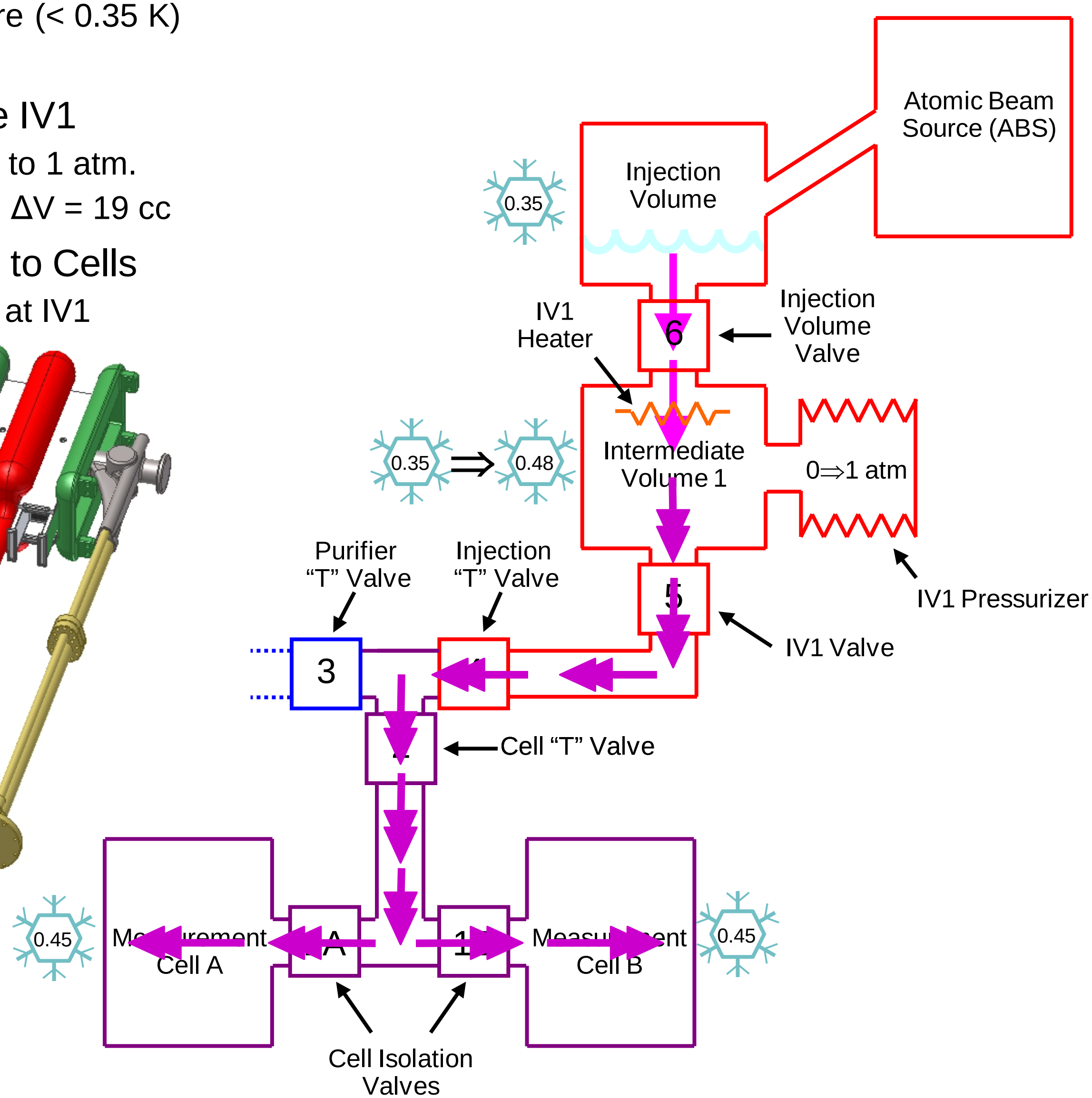




Injection

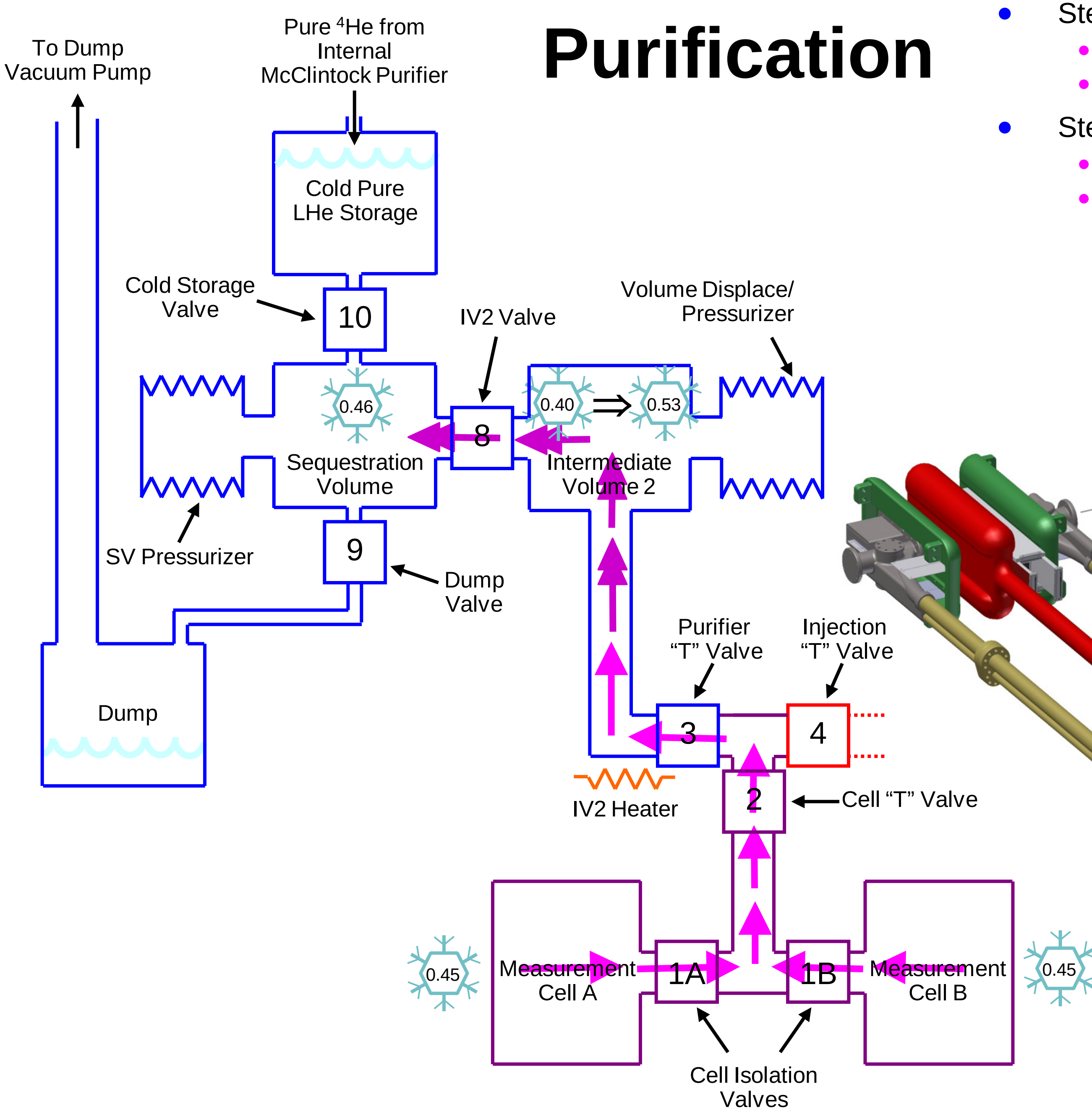
- Step 1: Inject Polarized ^{3}He from ABS
- Step 2: ^{3}He Diffuses to IV1
  - Low (~zero) pressure
  - Low temperature (< 0.35 K)
  - 2 sec
- Step 3: Pressurize IV1
  - Raise pressure to 1 atm.
  - $\Delta V / V = 1.19\%$, $\Delta V = 19$ cc
- Step 4: Heat flush to Cells
  - 5 mW supplied at IV1
  - 30 s

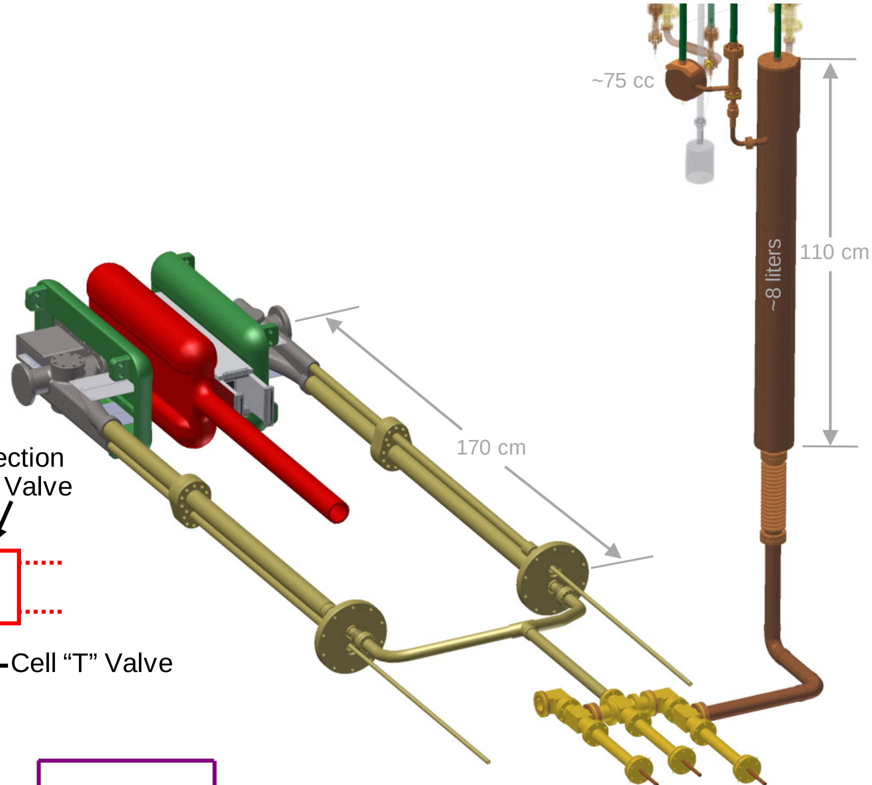




Purification

- Step 1: Flush from cells to IV2
  - 5 mW extracted at IV2
  - 350 s
- Step 2: Heat flush from IV2 to SV
  - 8 mW extracted at SV
  - 150 s





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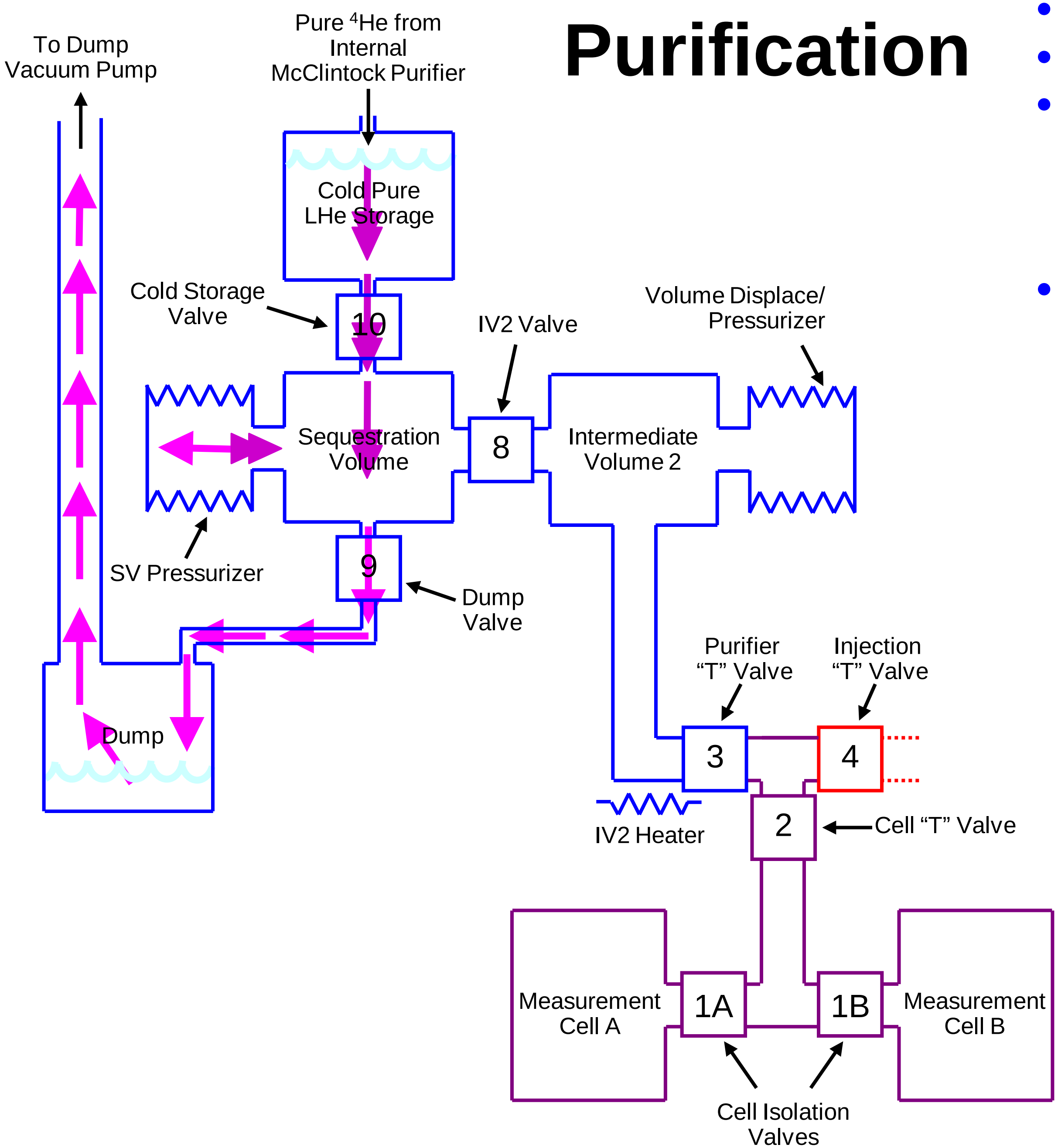
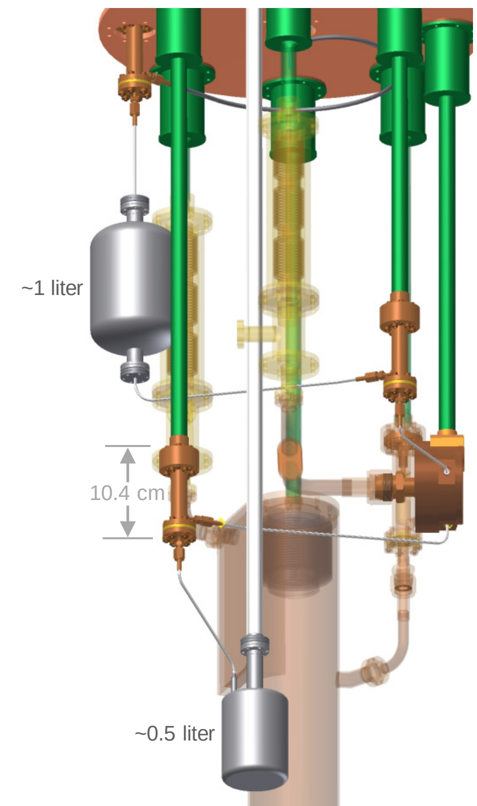


- Step 1: Flush from cells to IV2
- Step 2: Heat flush from IV2 to SV
- Step 3: Dump the SV
  - Depressurize the SV first
  - Evaporate and pump away depolarized ^{3}He
  - 85 s
- Step 4: Replace ^{4}He
  - Pure ^{4}He from internal McClintock Purifier
  - Pure storage provides reservoir
  - Re-pressurize SV after filling
  - 60 s



Challenges for ^{3}He Services

- Heat Budget
  - Thermal isolation (e.g. of valves)
  - Adjustable thermal links
- Valves
  - Superfluid tight
  - Large diameter
  - ^{3}He friendly
  - etc.
- Depolarization
  - Wall depolarization
  - Gradient Depolarization
- ^{3}He Transport
  - Diffusion at $T \leq 300$ mK
  - Heat flush for $T \geq 400$ mK
- Thermal contraction of long plumbing runs
- Many joints and flange-seals
- Film control in the injection beam line

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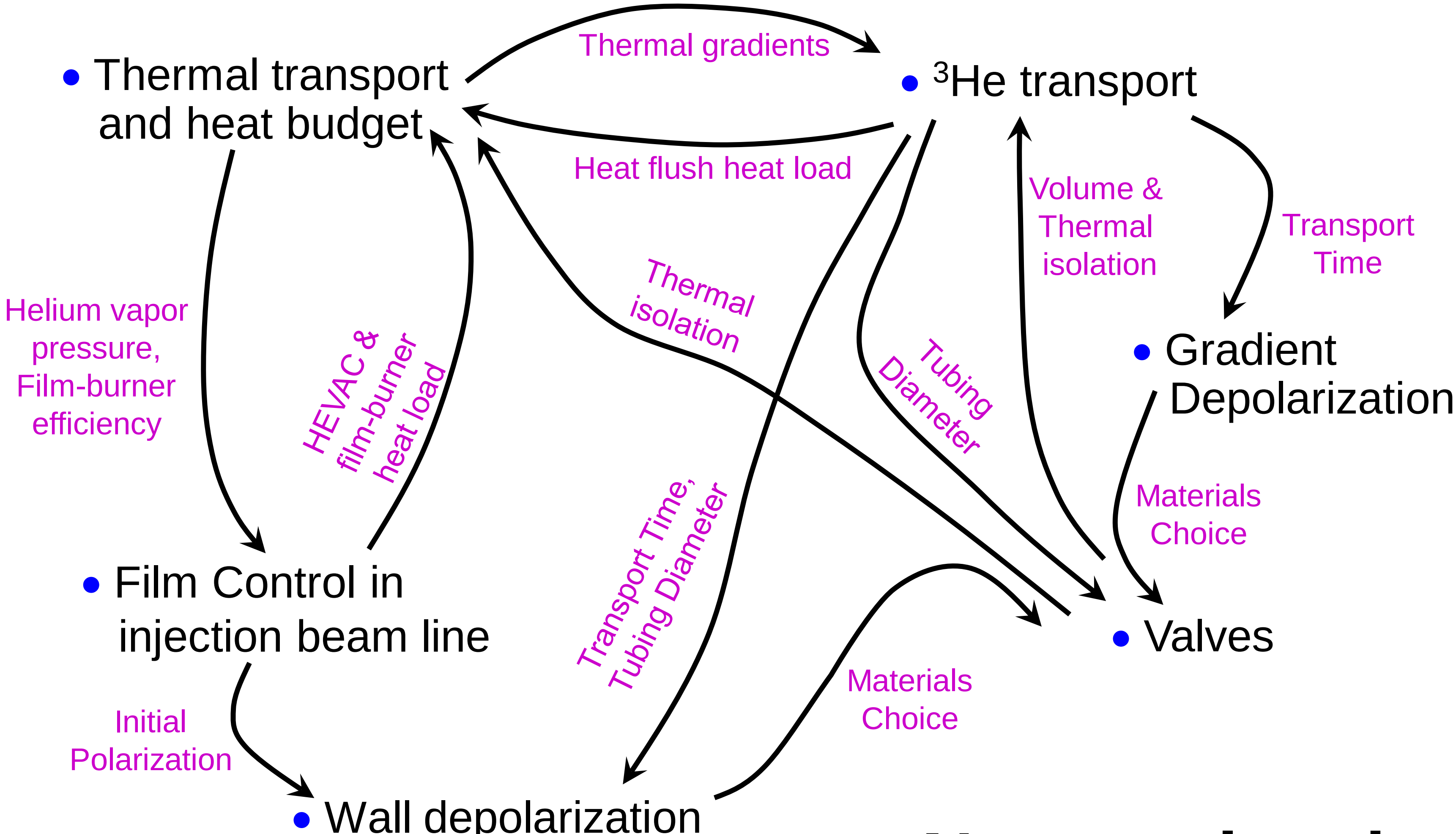

… Not unrelated

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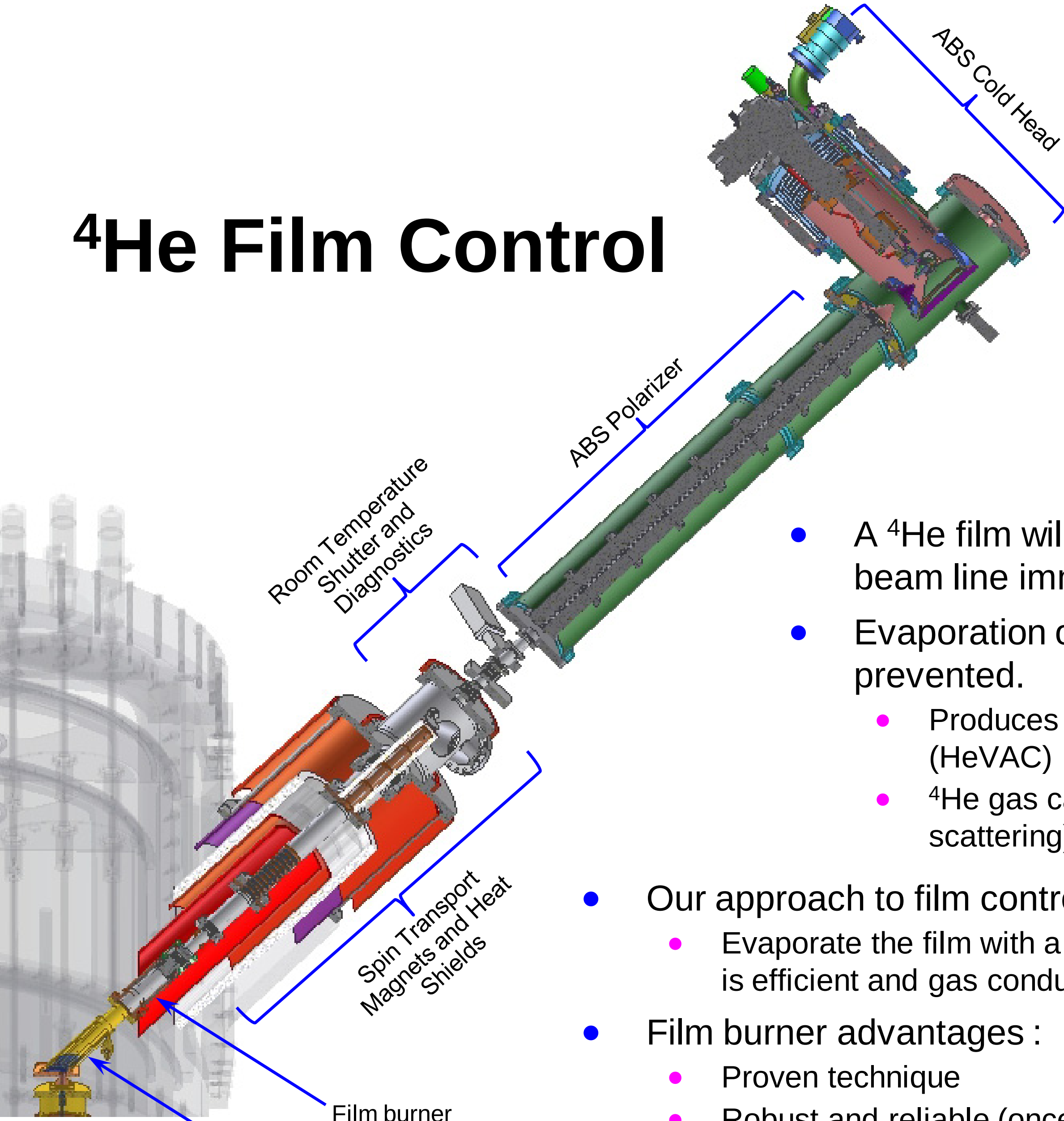
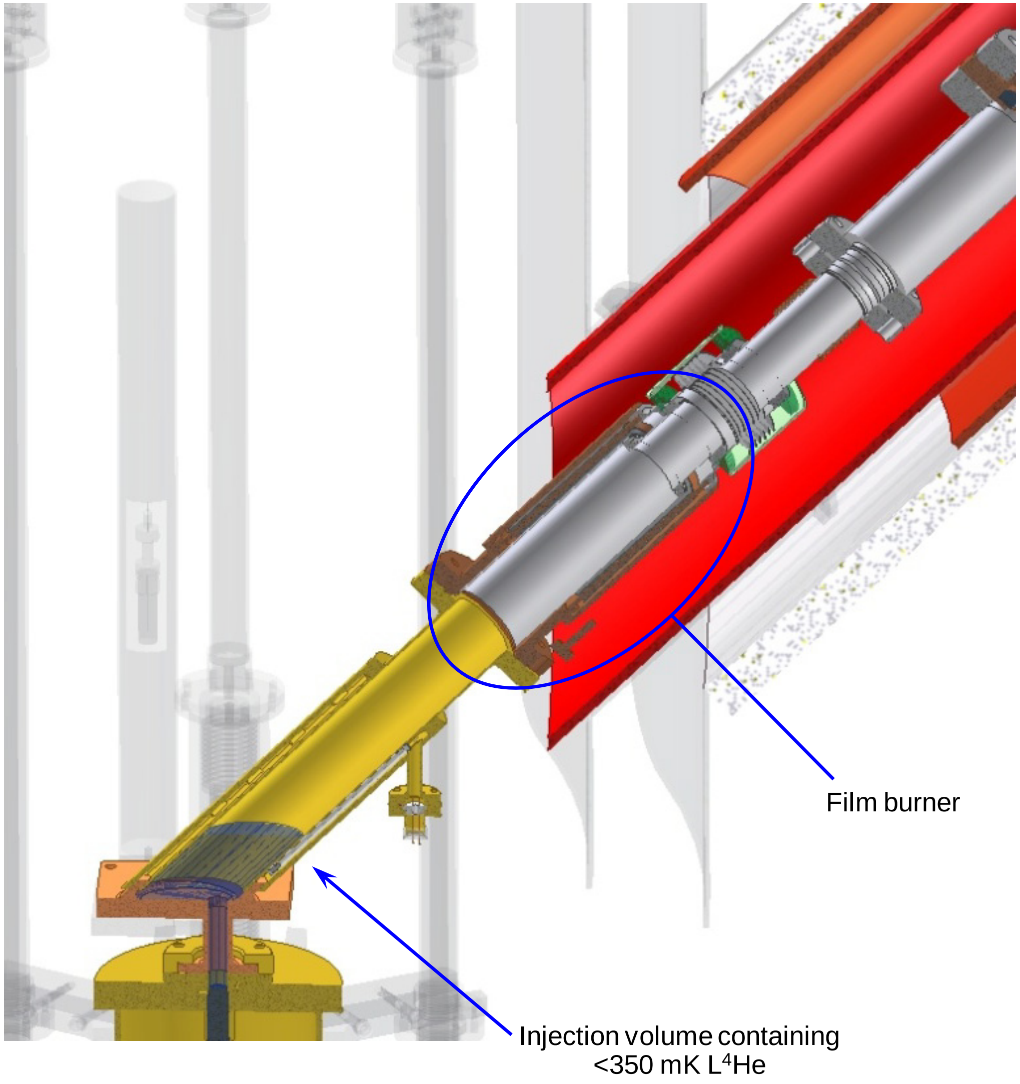
^{4}He Film Control



- A ^{4}He film will be generated on the walls of the beam line immediately above the bulk LHe.
- Evaporation of film into beam line must be prevented.
  - Produces large heat load to injection volume (HeVAC)
  - ^{4}He gas can block the beam (^{3}He- ^{4}He atomic scattering)
- Our approach to film control: a "Film Burner"
  - Evaporate the film with a heater. Then re-condense it where cooling is efficient and gas conductance to beam line is low.
- Film burner advantages :
  - Proven technique
  - Robust and reliable (once it works).
  - No contamination (compared to Cs ring).

Film Control

- Film burner challenges:
  - Efficient cooling is required to remove the heat supplied by the evaporator.
  - The conductance of vapor from evaporated film to the beam line must be small.
  - Operation depends on the details of
    - The heat load
    - The condenser cooling
    - The geometry of the evaporator/condenser



- Difficult to model $\Rightarrow$ a test is needed to prove a given design.

Film Burner Design

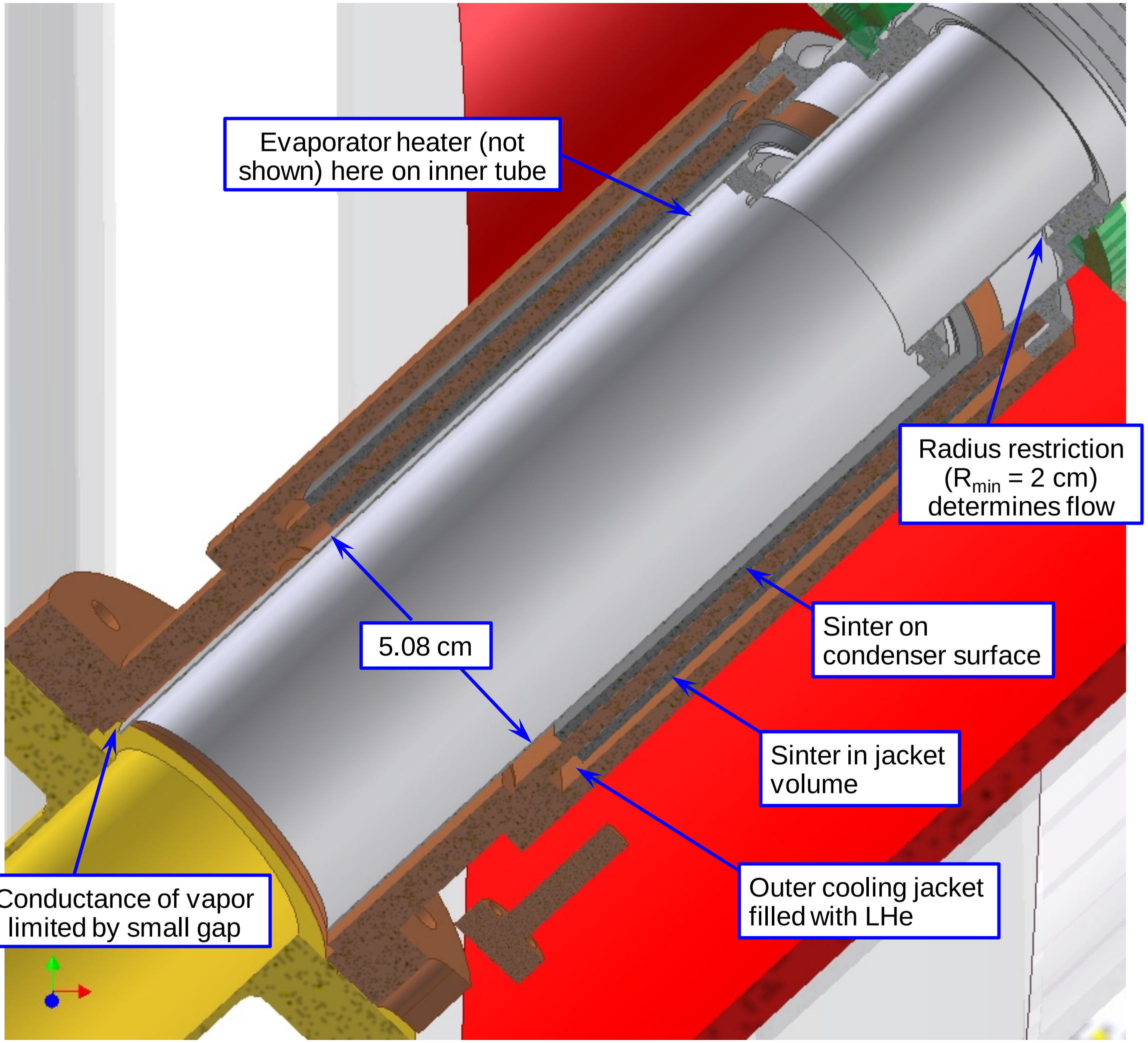
Heater Power Estimate

$v_f \cdot t_f = 1.2 \times 10^{-4}\ \mathrm{cm}^2/\mathrm{s}$

t_f = film thickness (depends on surface)
$\cong 30 \cdot h^{-1/3}$ nm (with h in cm) (10-12 nm)
v_f = film velocity (of order 50 cm/s)

$$P = v_f \cdot t_f \cdot 2\pi R_{\min} \cdot L \cong 4.5\ \mathrm{mW}$$

L = heat of vaporization = 3.02 J/cm^3
R_{min} = minimum (upward) radius = 2.0 cm



- Typical temperature required to vaporize film is 0.7 to 1 K
- To insure full condensation, condenser surface should be at < 0.35 K
- Cooling supplied to outer jacket of condenser by DR Mixer via LHe thermal link
- To overcome Kapitza resistance, sinter is needed on both inner and outer surface of condenser.
- Limiting radius defined at top of film-burner where beam is smallest.

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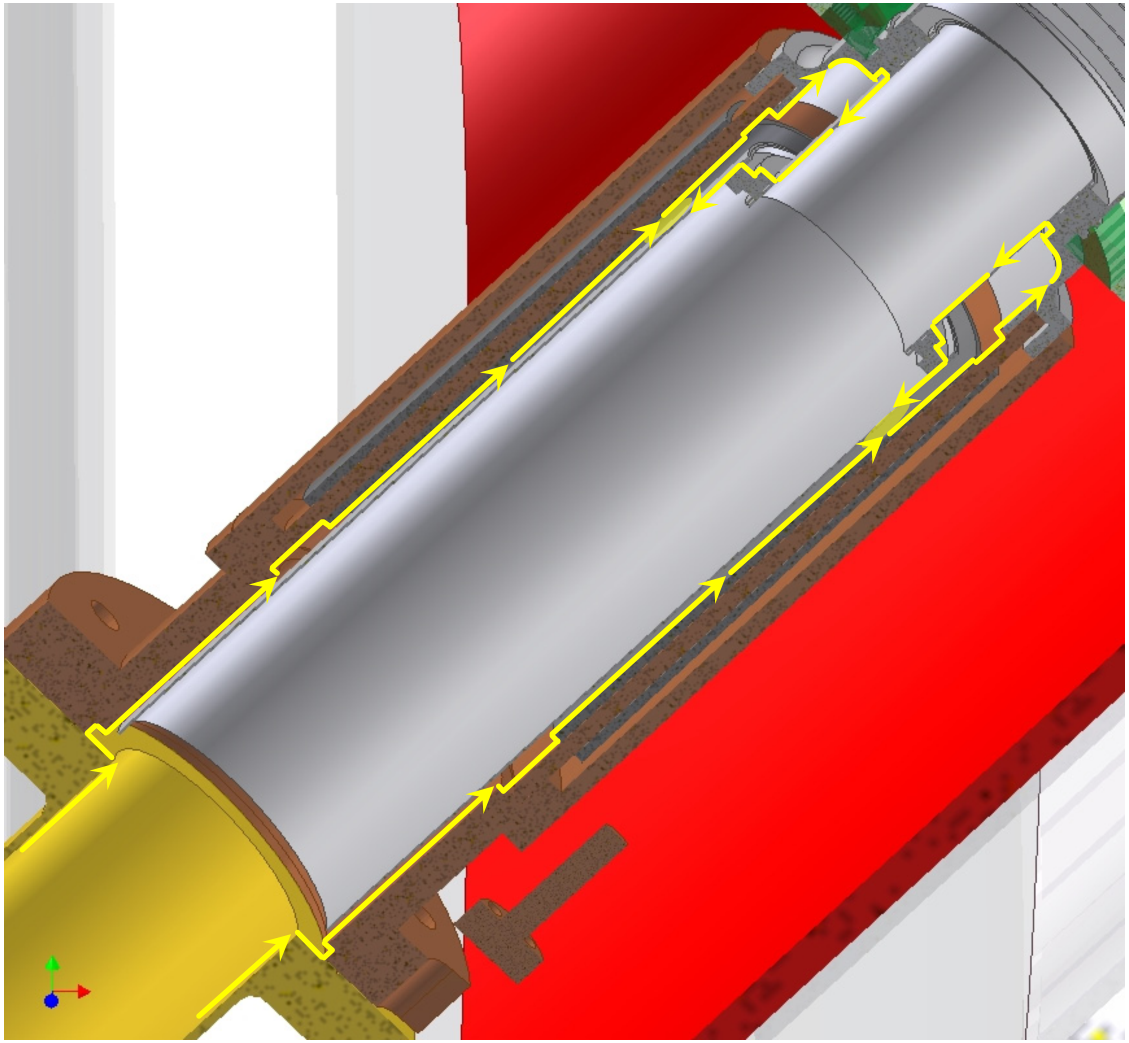

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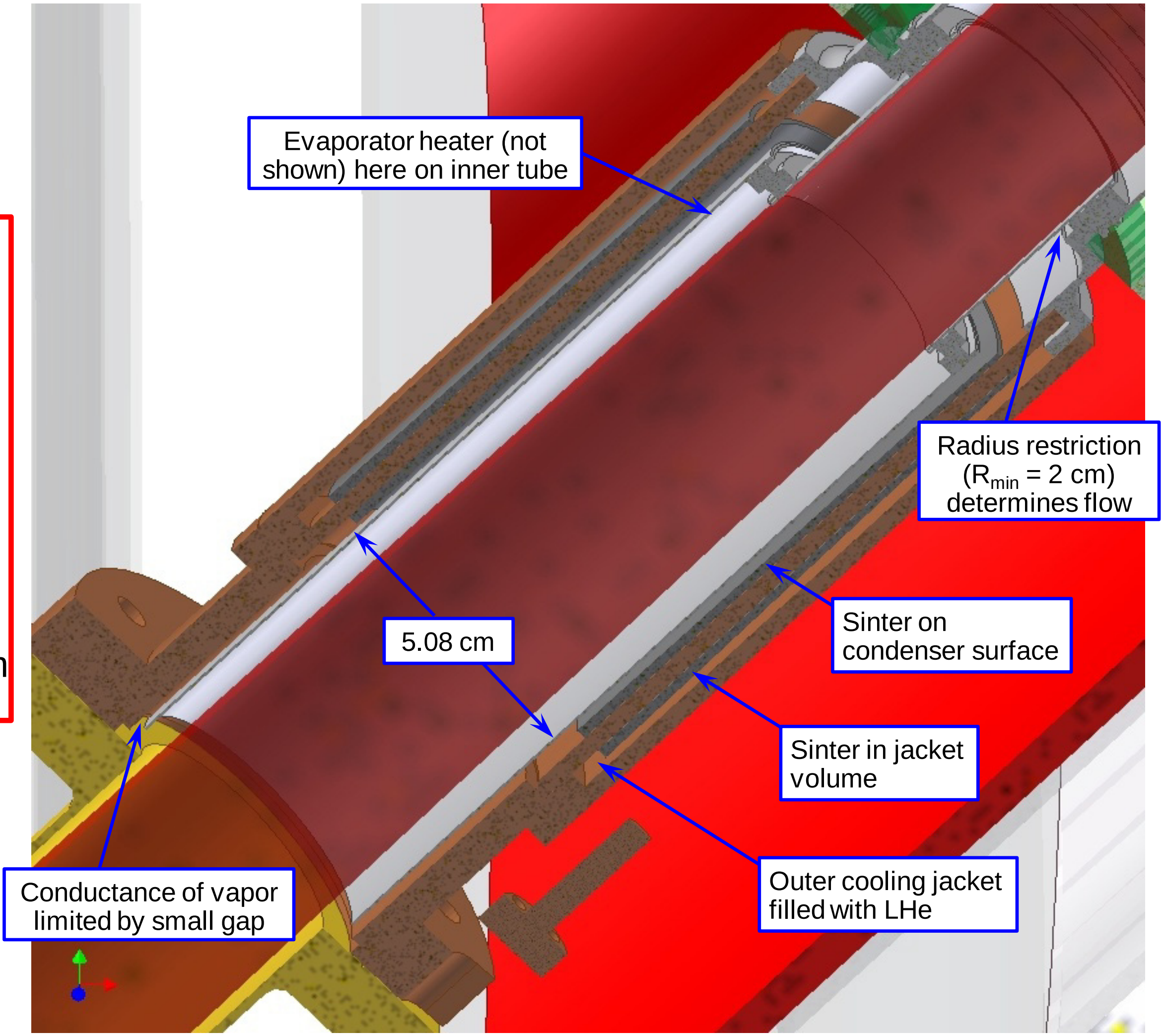

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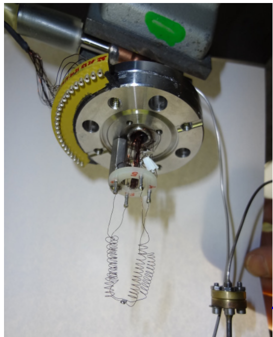
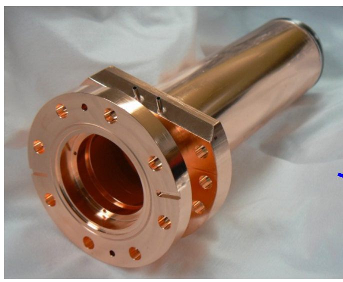
- To overcome Kapitza resistance, sinter is needed on both inner and outer surface of condenser.
- Limiting radius defined at top of film-burner where beam is smallest.
- Diameter is determined by the projected size of the collimated beam

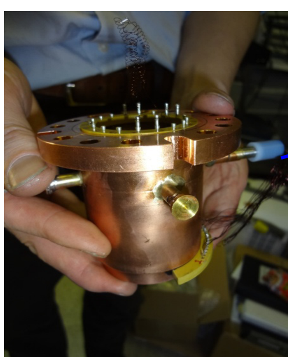
A “Simple” Test of the Film-burner



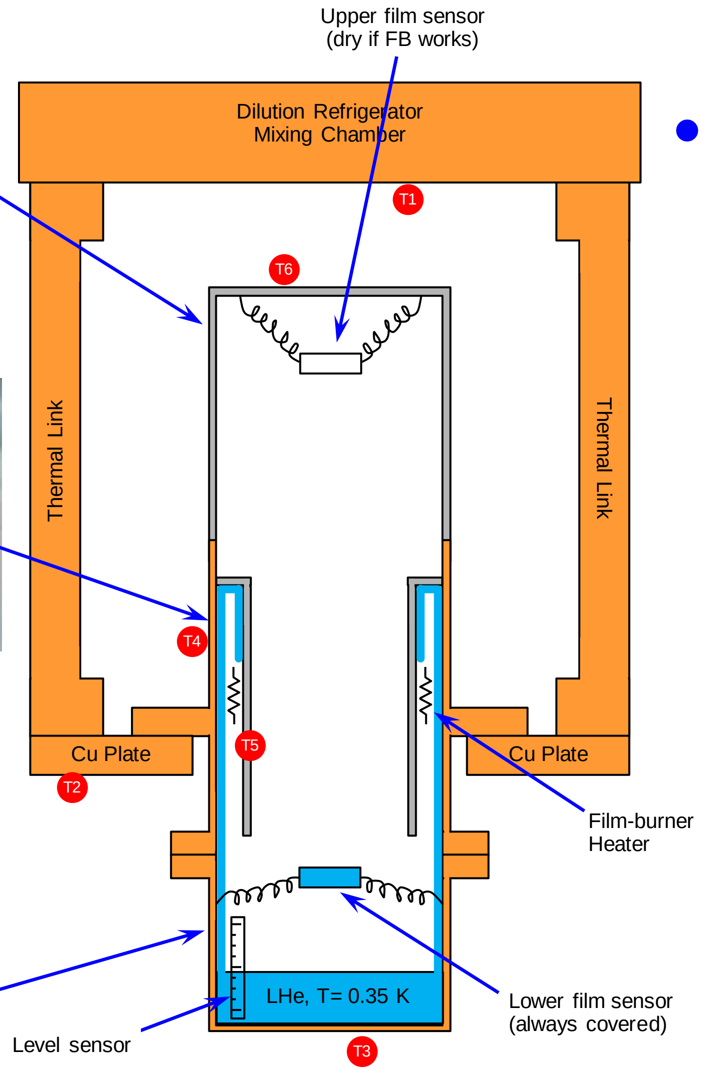
Top flange assembly



The Duke film-burner



Injection volume assy.



- Initial test plan (a.k.a. Phase 1):
  - Using DR in Ike Silvera’s Harvard lab (~8 mW @300 mK)
  - Use existing (but untested) Duke film-burner
    - Cooled with copper thermal links
    - R_{min} = 1.33 cm (2/3 of real FB)
    - P = 3 mW
  - Success: elimination of film above film-burner.

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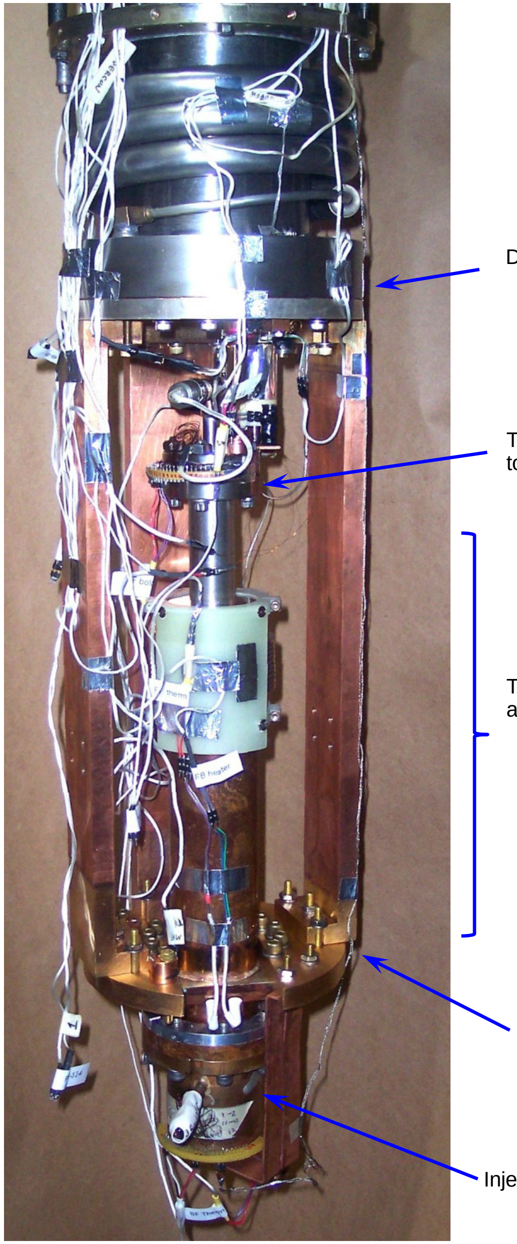

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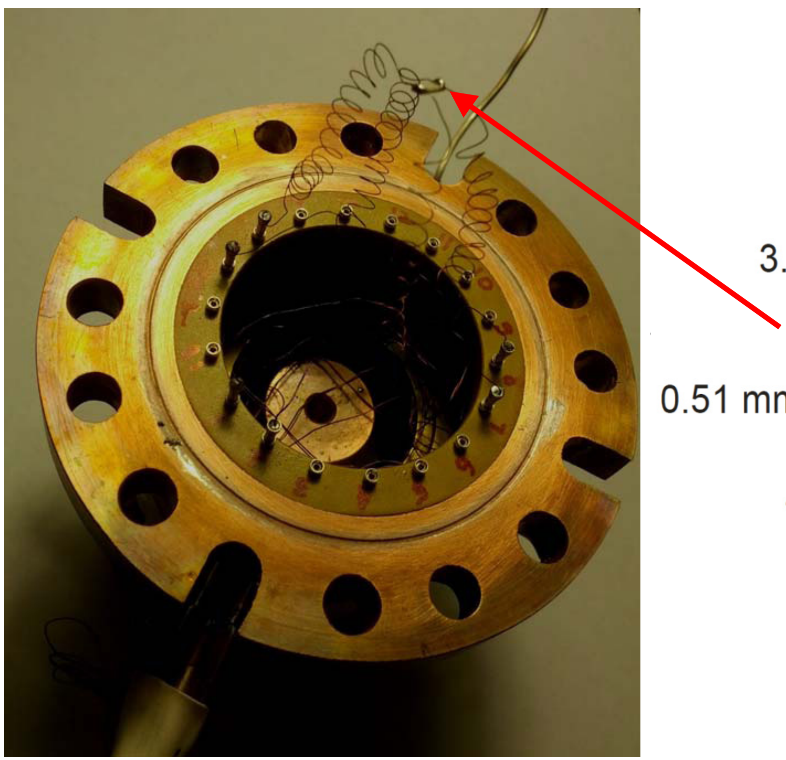
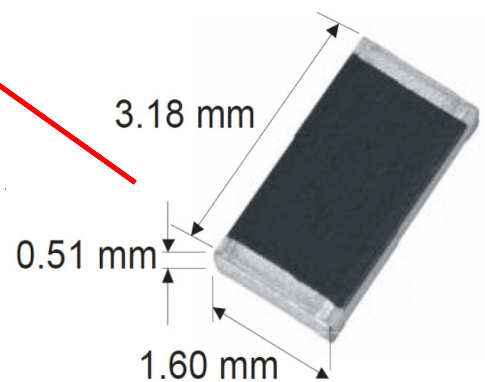
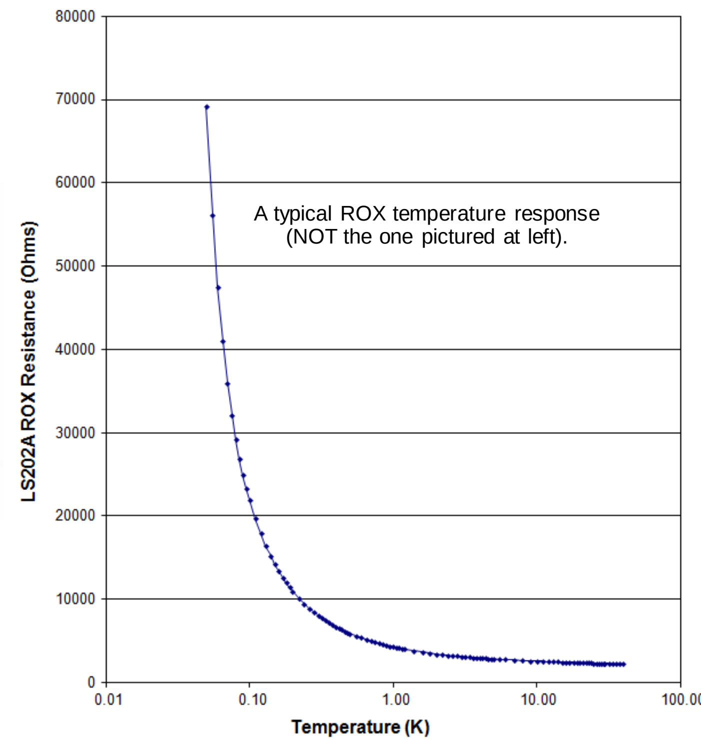
- Progress so far…
  - Commissioning of the DR 1/12 to 3/12
  - Test cool-downs, 6/12 and 8/12
  - Successful test run, 9/12

Helium Film Sensor

- Use a surface-mount RuO_2 resistor as uncalibrated temperature sensor.
  - 10 kΩ at room temperature
  - > 100 kΩ below 50 mK
  - < 1 cent each (we bought 6000!)
- Suspend from fine wires to thermally isolate sensor.
- Two film sensors:
  - On inj. vol. – always covered with film (when LHe is present)
  - On top flange assembly – should not be covered if film burner is working.

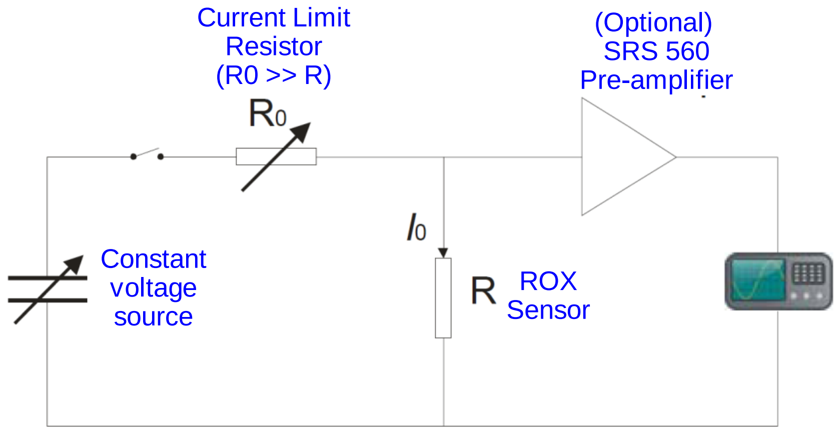


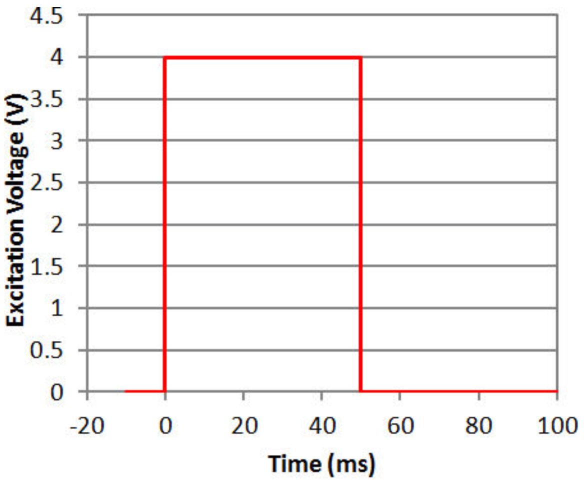


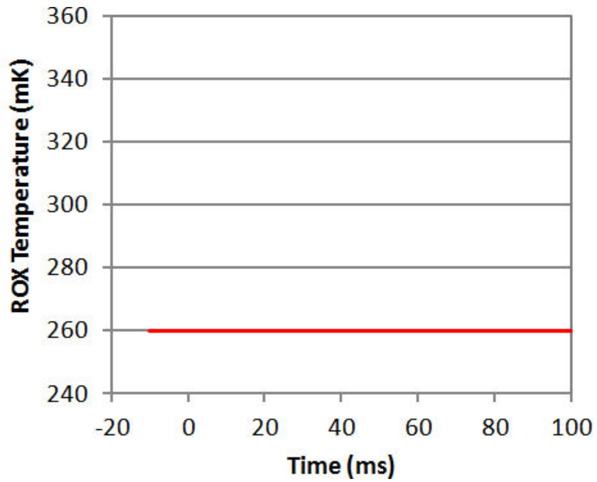


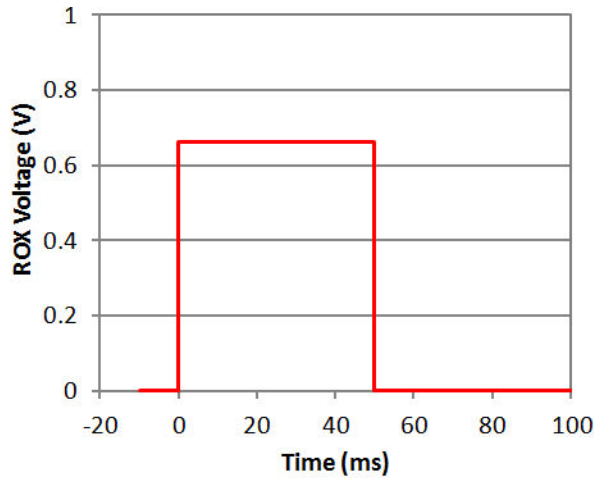
Detecting Superfluid Film

- Procedure for detecting film
  - Abruptly initiate constant current through the ROX
  - Digitize amplified voltage across ROX vs time.
  - No film:
    - If “self-heating” is small, ROX voltage is constant









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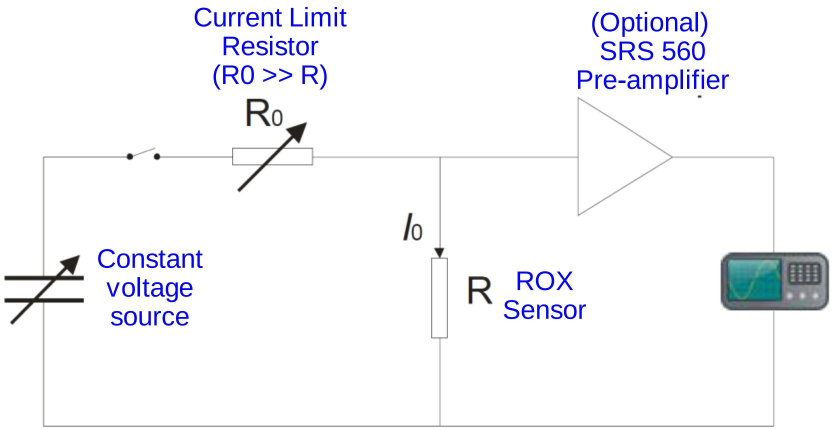

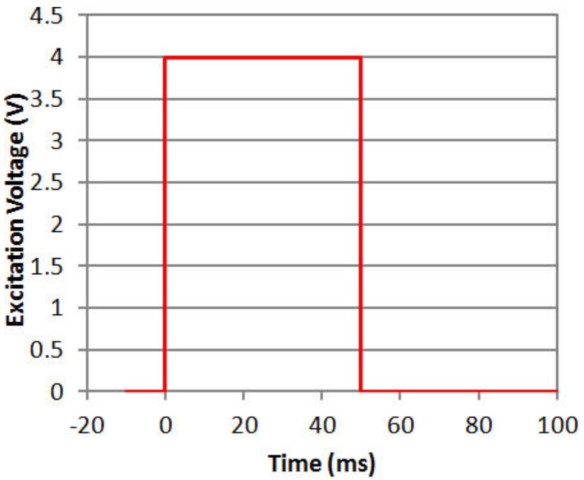

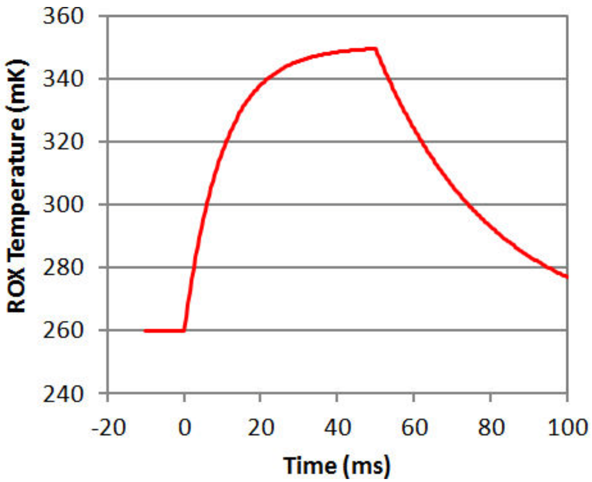

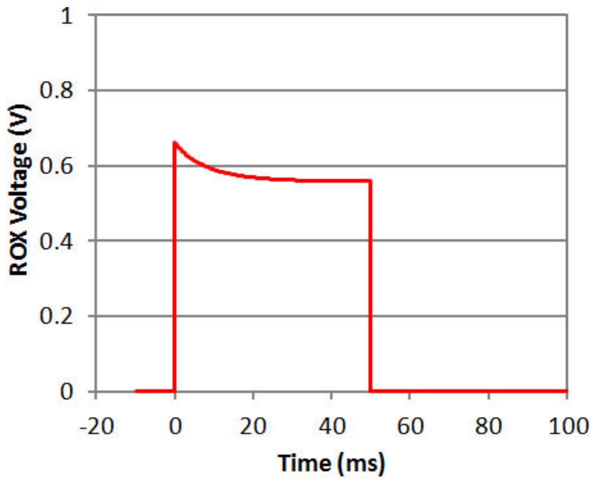

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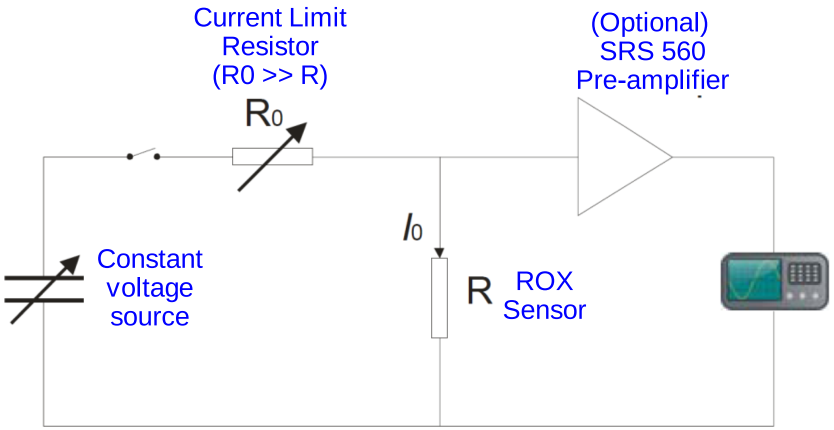

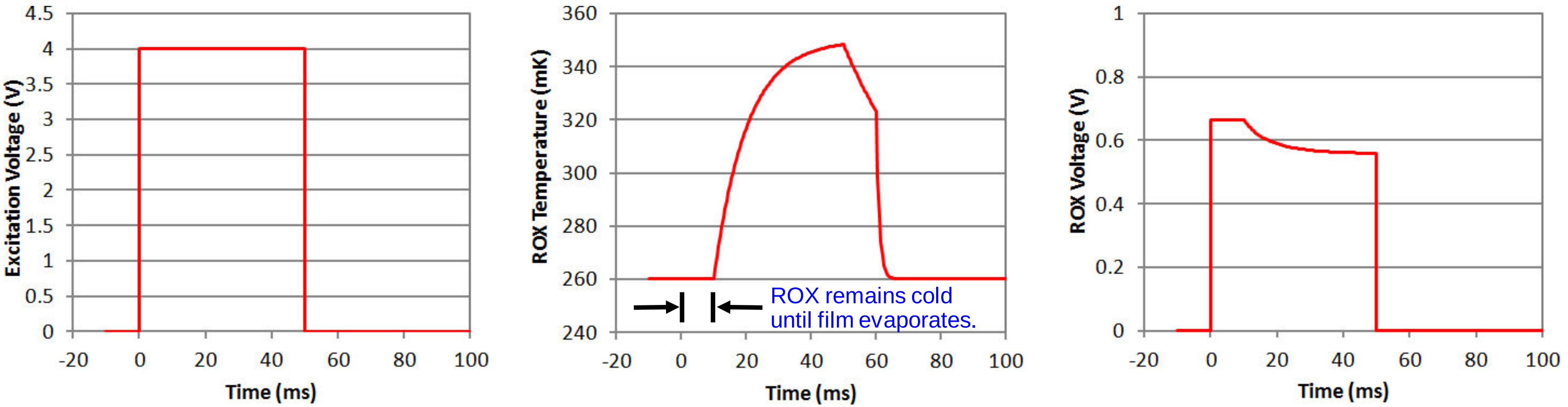

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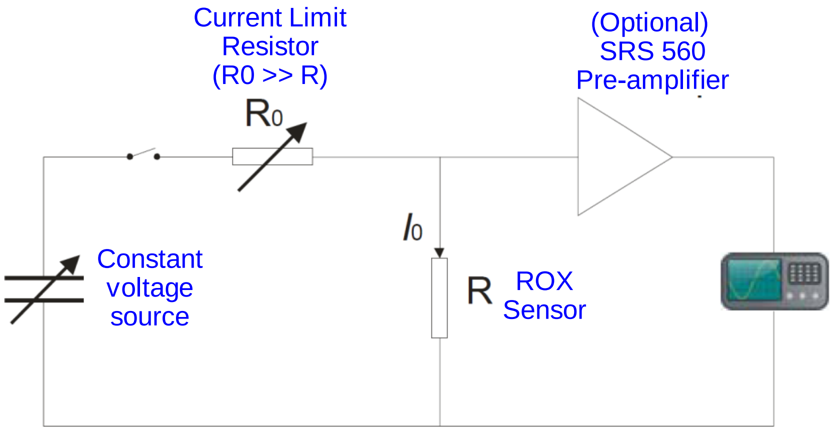

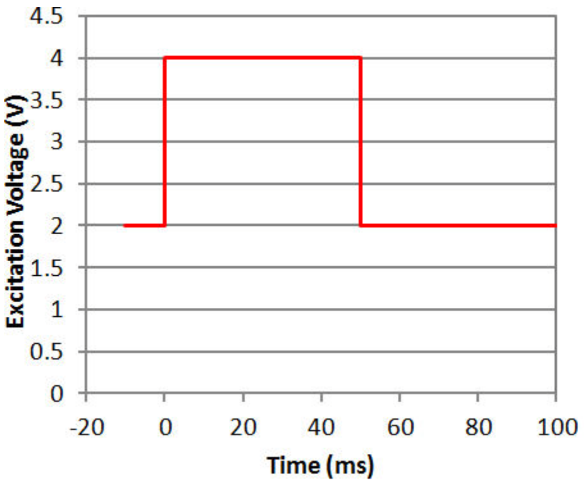

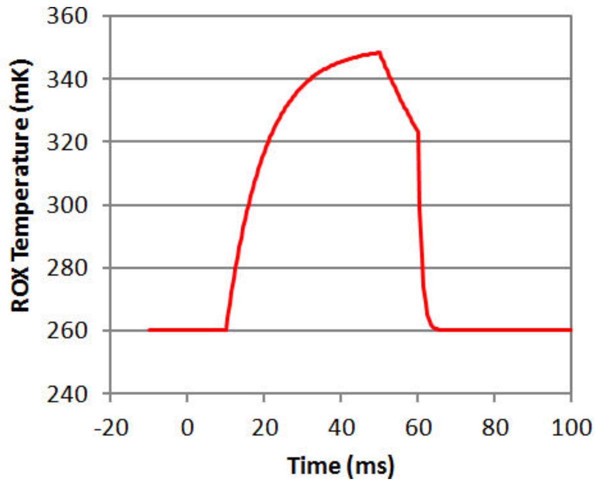

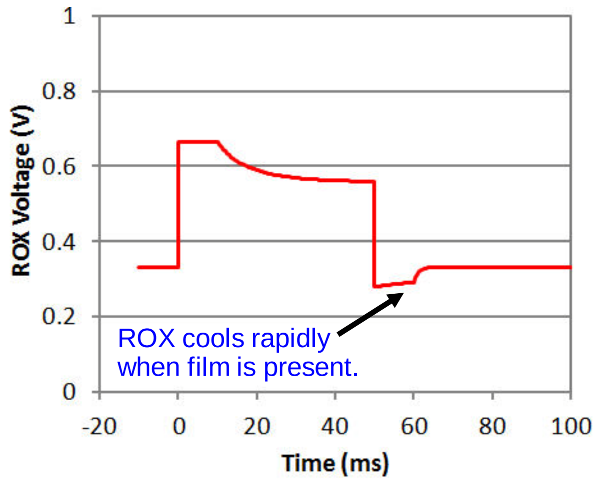

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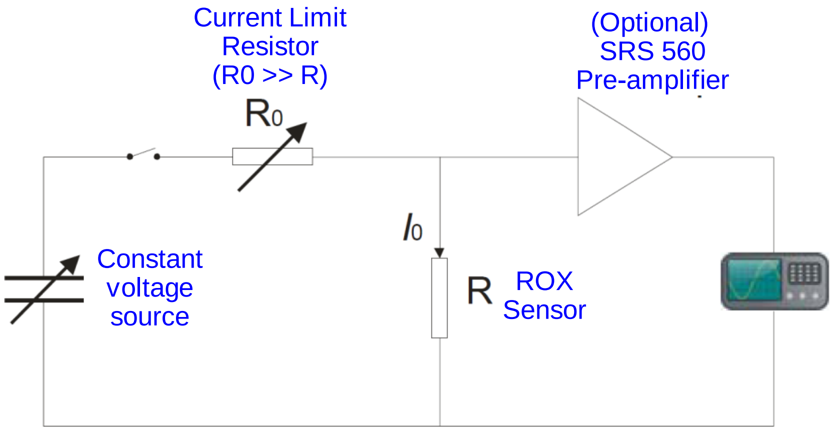

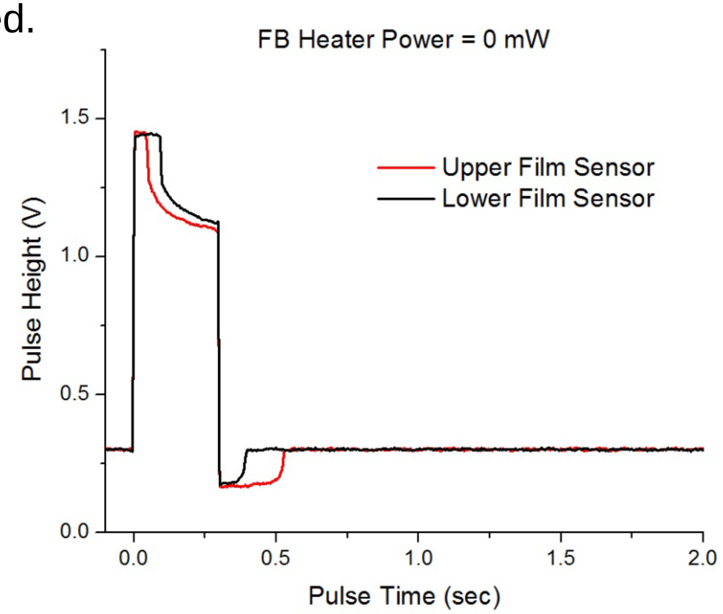

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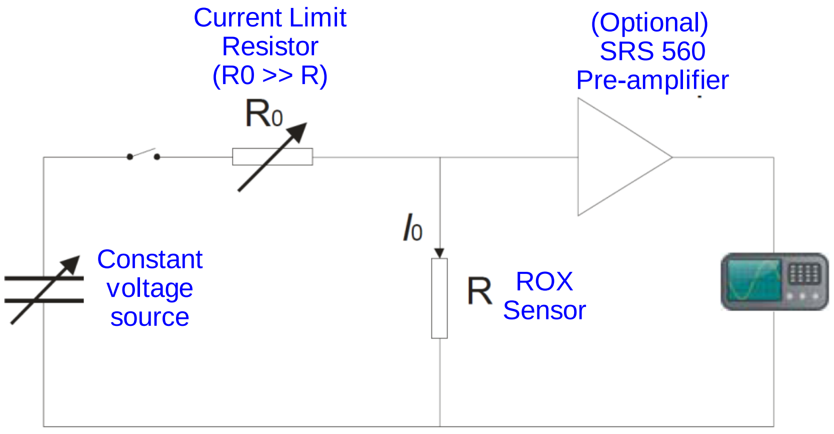

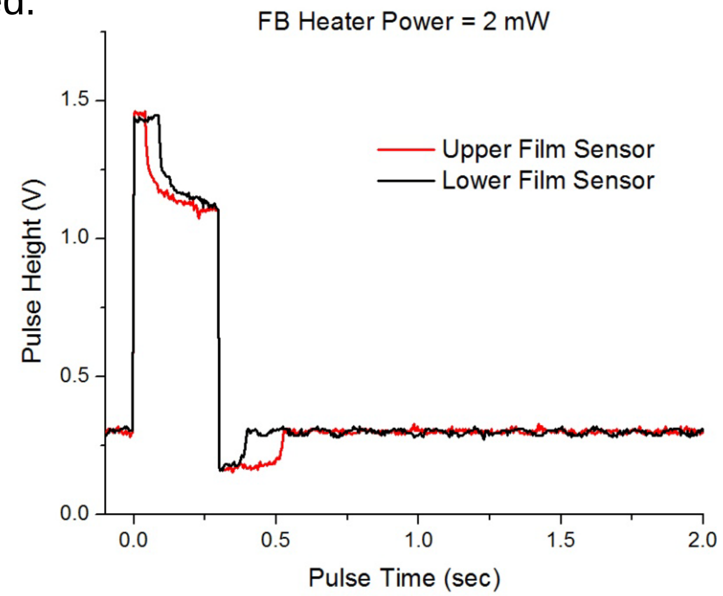

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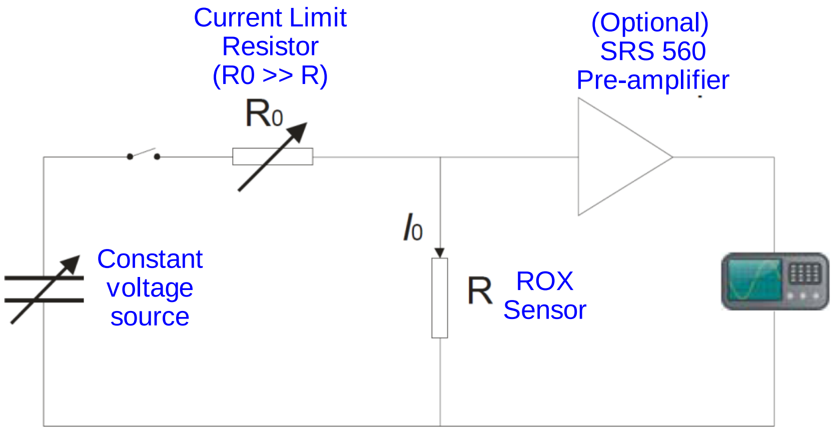

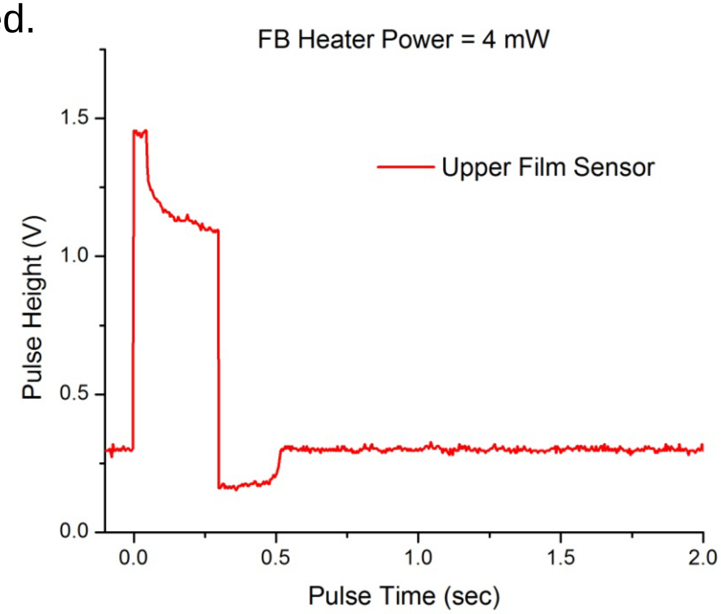

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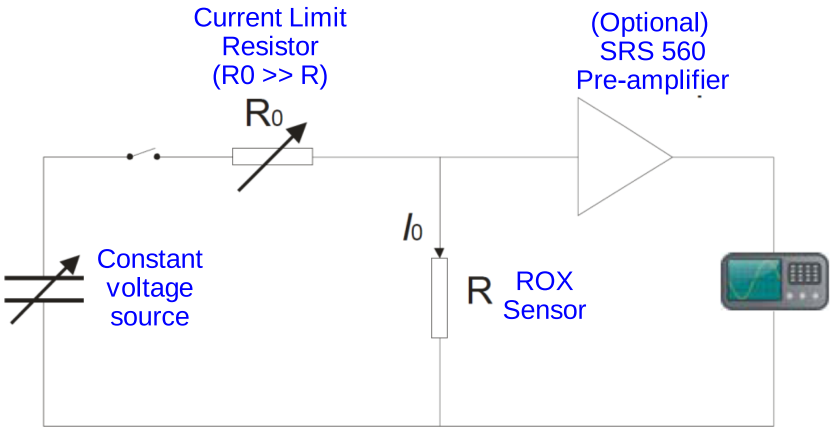

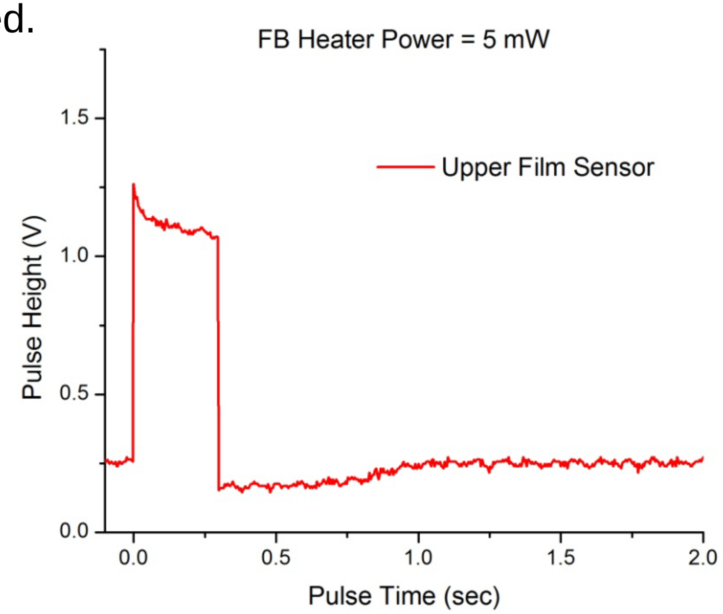

Detecting Superfluid Film

- Procedure for detecting film
  - Abruptly initiate constant current through the ROX
  - Digitize amplified voltage across ROX vs time.
  - No film:
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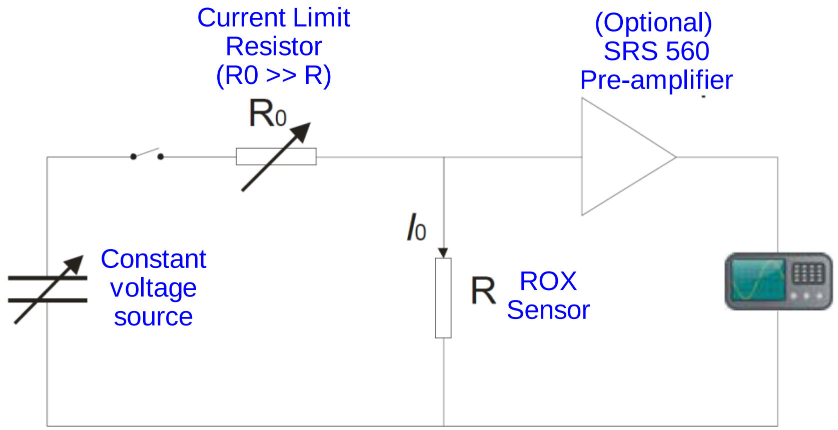

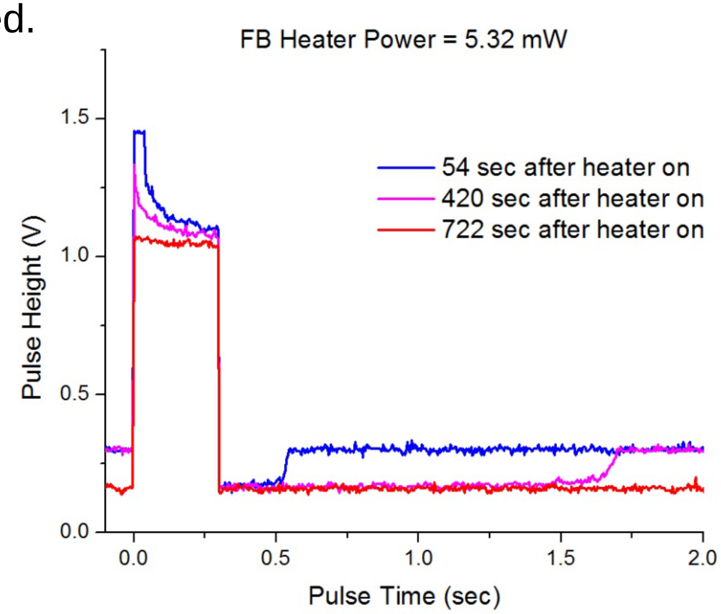

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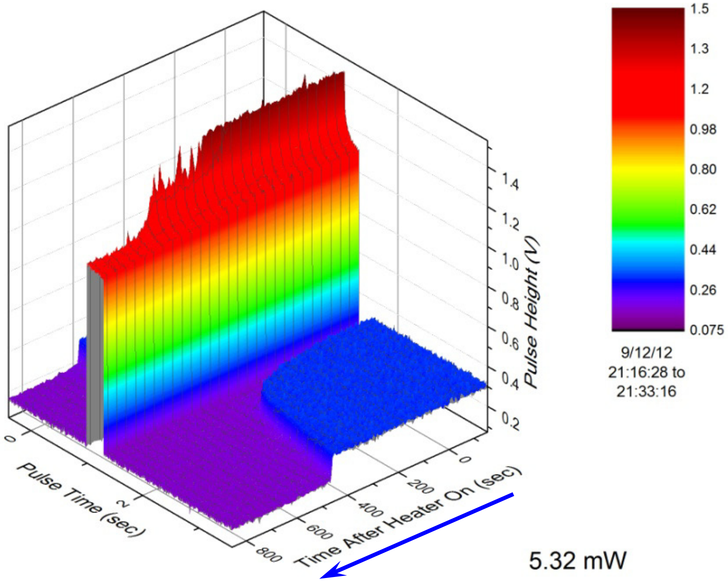

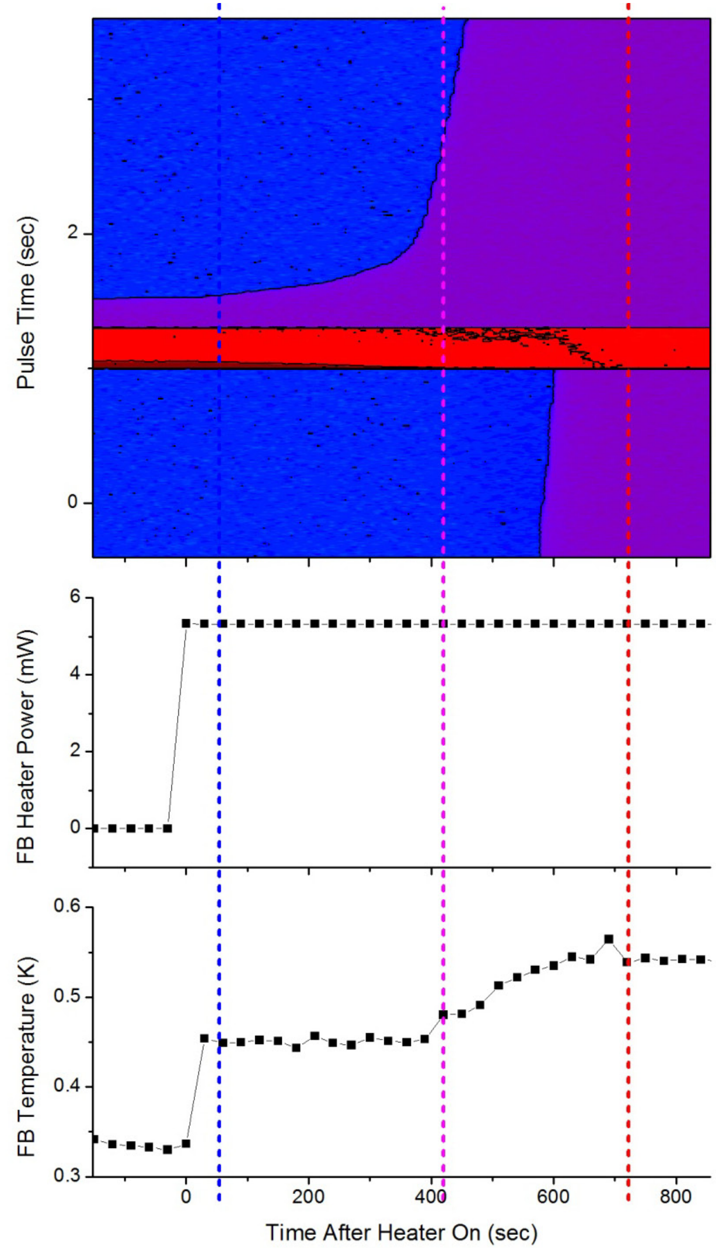

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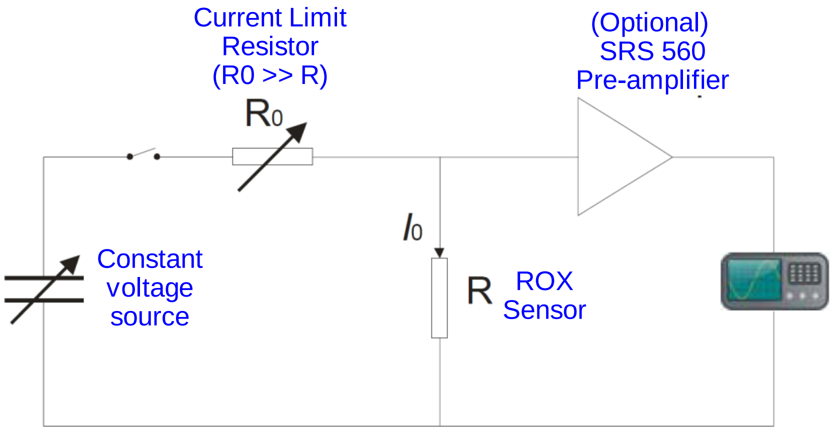
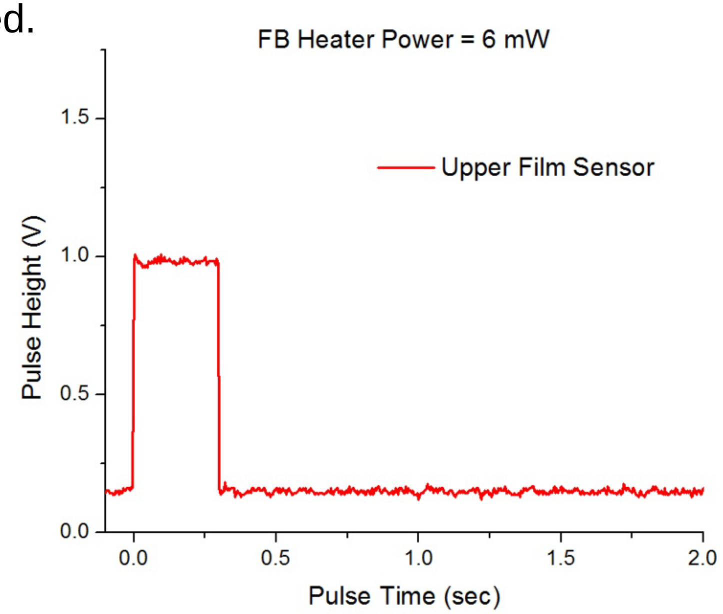
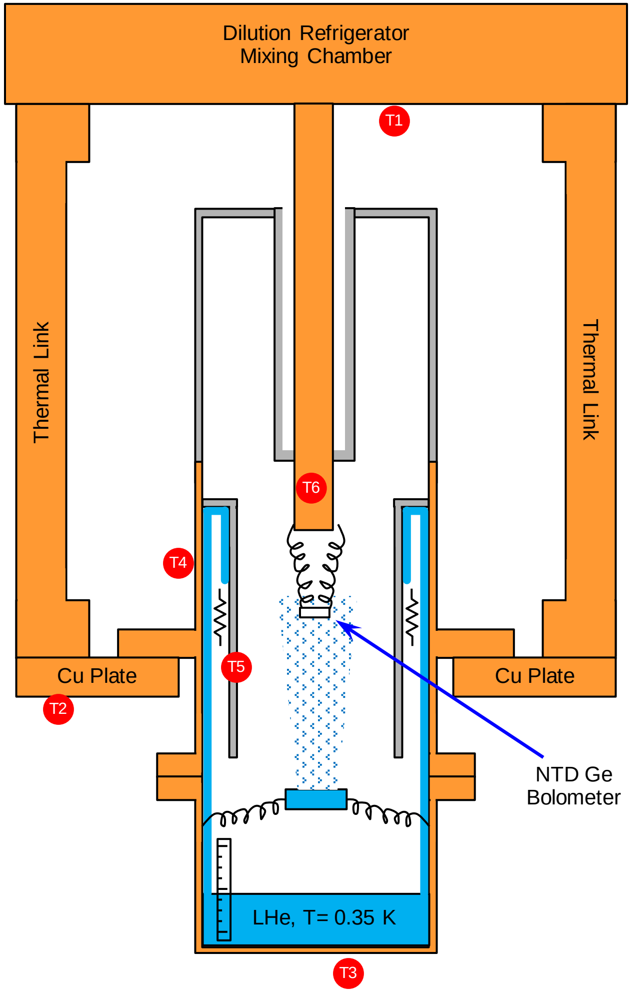




The "Phase 1" Film burner works.

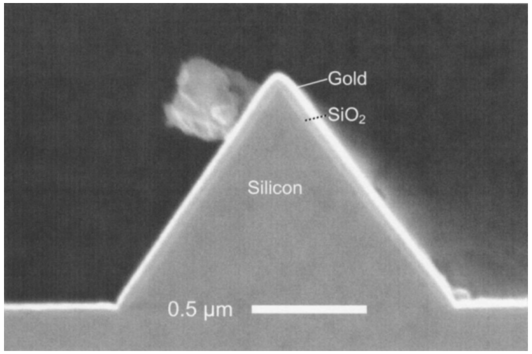
...or does it?

- We can stop the film, but require ~70% more heater power than expected.
  - Surface quality can affect film thickness.
  - Radial "knife edge" may not be smooth
- We don't know that all vapor is recondensed on condensor surface.
  - Test by measuring density of vapor within tube by transmission of ^{4}He atoms
  - Generate a pulsed "beam" of atomic ^{4}He
    - Method pioneered* in Ike Silvera's lab
    - Apply a short heat pulse to small surface (Bolometer) coated with ^{4}He film to evaporate the film
    - Velocities in vapor pulse follow M-B distribution of 0.65-0.8 K
    - Pulse durations from 30-60 μs
  - Pass beam through residual vapor in the "beam line"
    - Flight path $\geq$ 4 inches
  - Detect unscattered beam
    - Measure temperature rise of a neutron transmutation doped (NTD) germanium bolometer chip
    - Measure versus time to get beam velocity dependence
    - Response time is ~40 μs

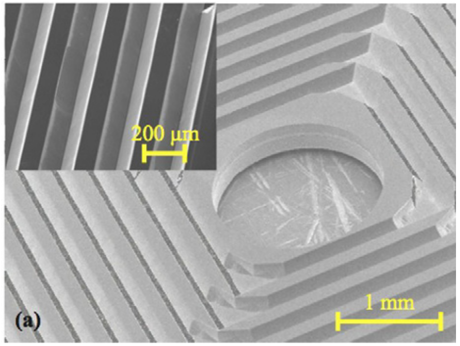


Beyond Phase 1: Phase 2

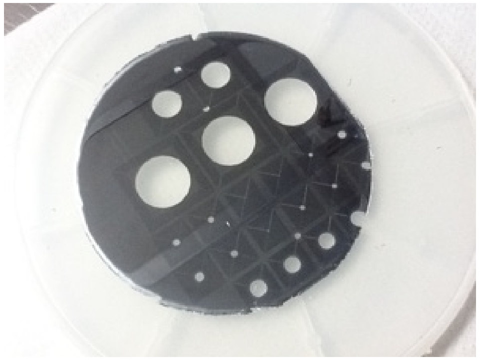
- Realistic dimensions: R_{min} 50% larger)
- Realistic materials: plastic injection volume
- Realistic cooling:
  - LHe thermal link to MC heat exchanger
  - Cooling jacket and 2-sided sinter on condenser
- Change geometry to reduce heat load:
  - Etched Silicon "film thinner"
  - A Series of VERY sharp edges: film thickness reduced due to large surface tension energy at small radius.
  - Edge must be "atomically sharp" (< 10 nm radius).
  - Currently under study at NCSU



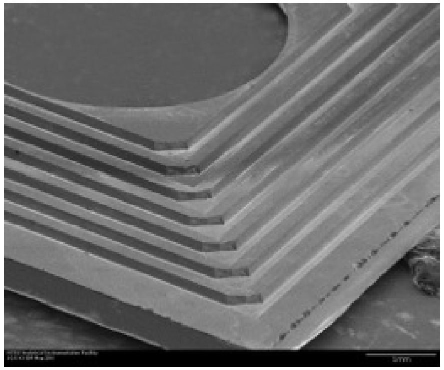
S. J. Spector et al, J. Vac. Sci. Technol. B 216, 2865 (2003)



K. Ishikawa et al, Cryogenics 50, 507 (2010).



Etched 4" wafer at NCSU (D. Haase)



SEM Image of etched wafer (D. Haase)

Backup Slides

Beam Transmission

$$\frac{I_T}{I_0} = \exp\left[\frac{-L}{\lambda_v(T_0)}\right] = \text{Transmission}$$

I_0 = Unattenuated intensity

I_T = Intensity attenuated by gas at T_0

L = Length of scattering region

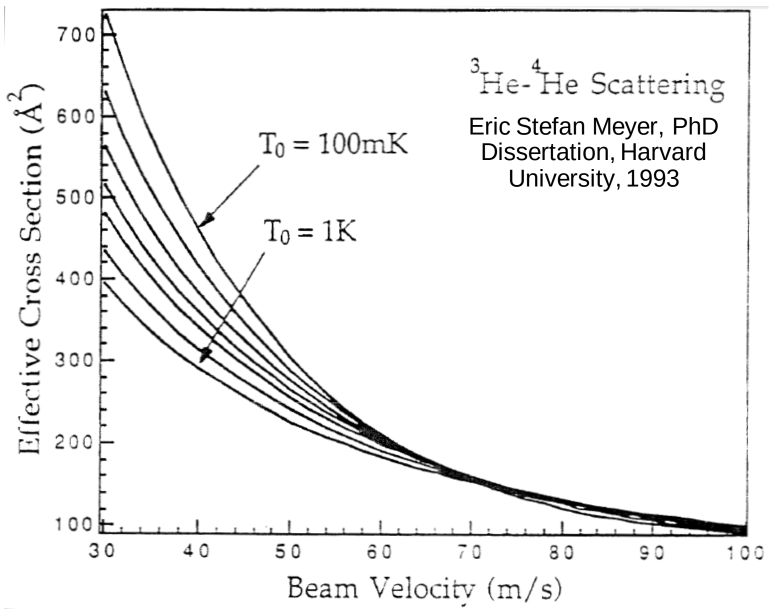
$$\sigma_{eff} = \frac{1}{n \cdot \lambda_v(T_0)}$$

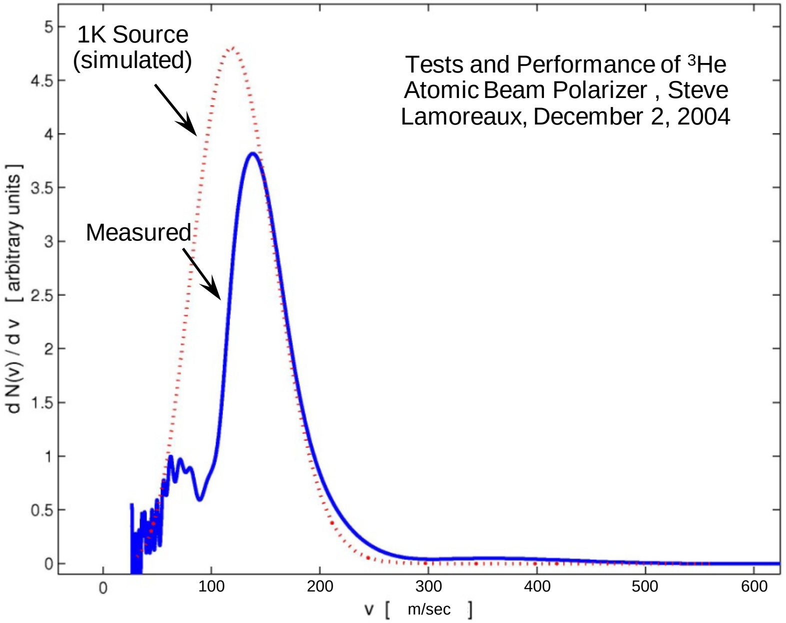
n = target gas density

$\lambda_v(T_0)$ = mean free path of atom with velocity v

T_0 = Target Temperature

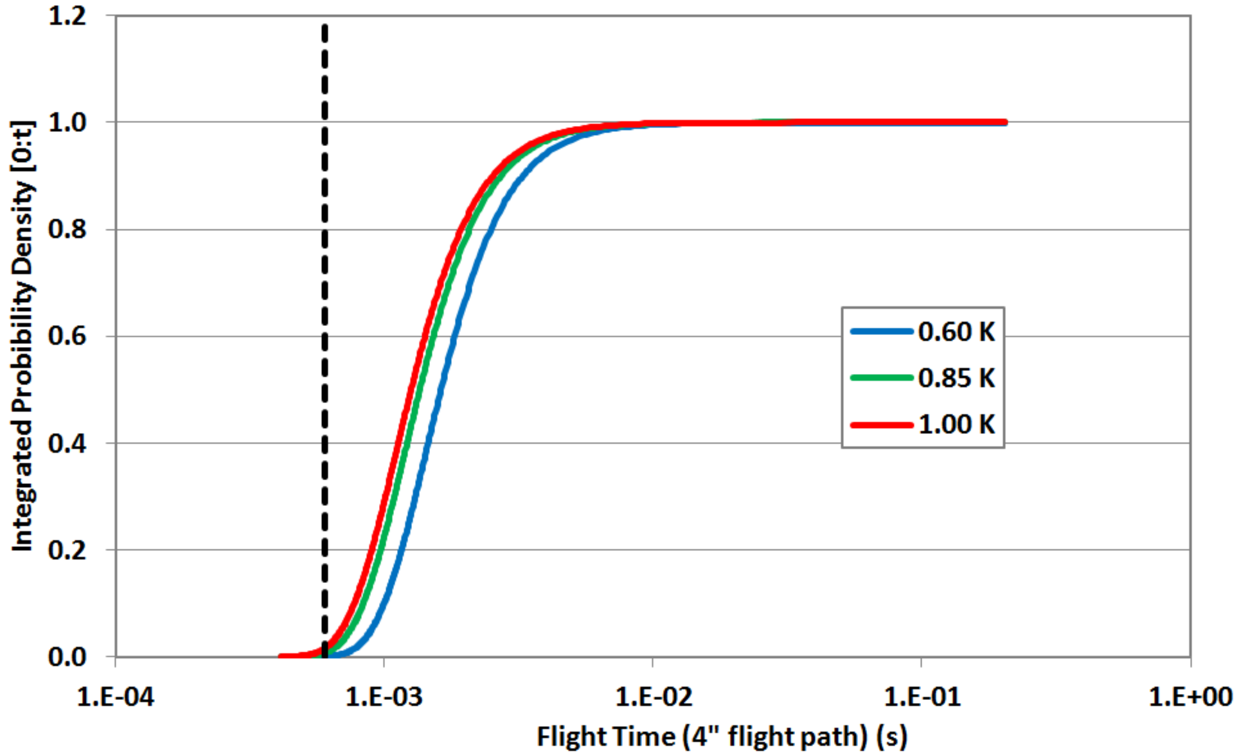
- Most scattering occurs at the low-temperature end of the beam line.
  - Cross section is highest for low target temperature.
  - Density of gas in the beam line goes as 1/T (to first order) so is highest at low temperature
- A realistic simulation of the scattering is underway.



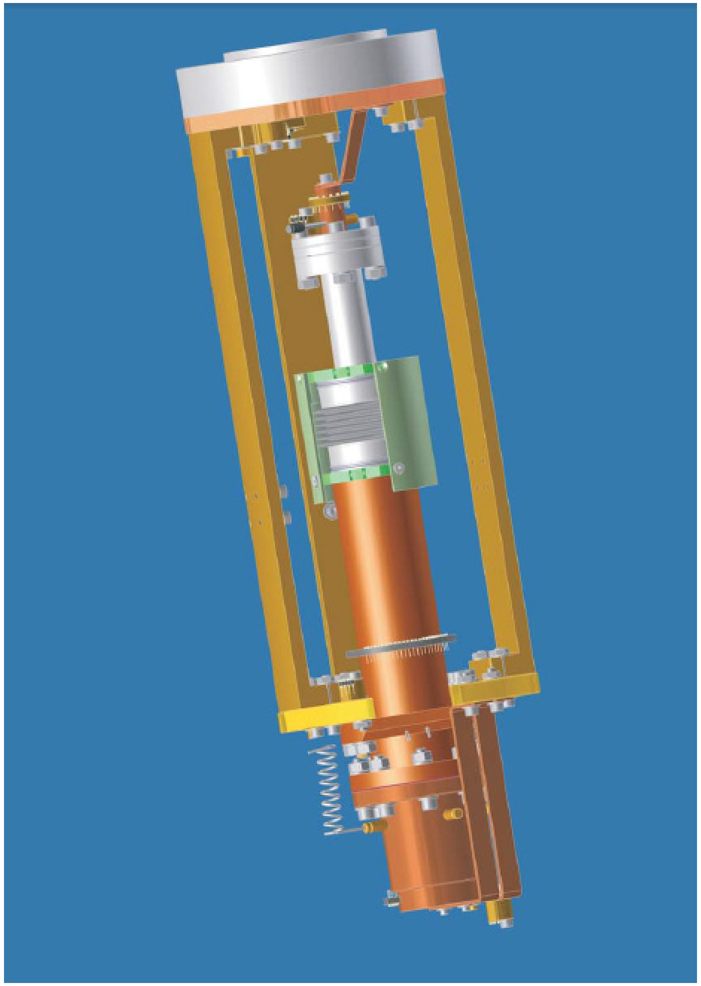


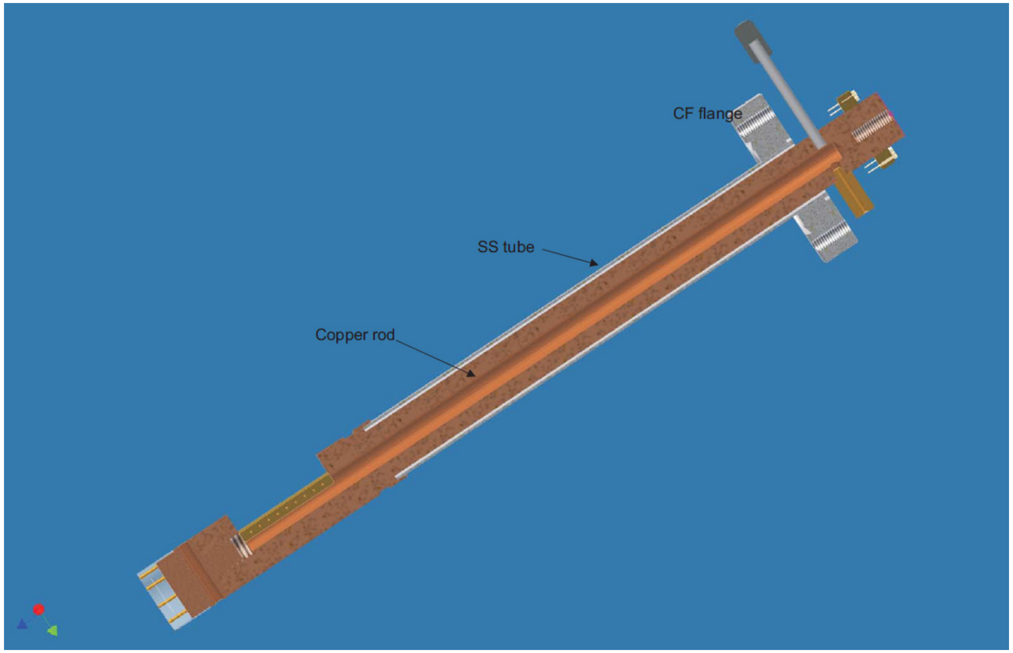
Time-of-flight Resolution

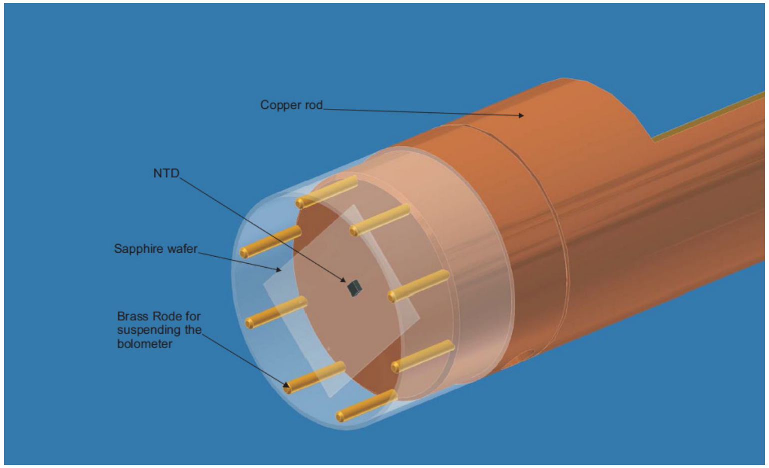
- Want pulse duration ≈ 0.1 × shortest flight time for 10% speed resolution
  - Film evaporates in 30-60 μs
  - Bolometer response is about 40 μs
  - Speed resolution is about 60 μs
  - Lowest flight time should be ~600 μs
- Conclusion: 4” flight path seems OK (lower temp. evaporator and longer flight path would be better)



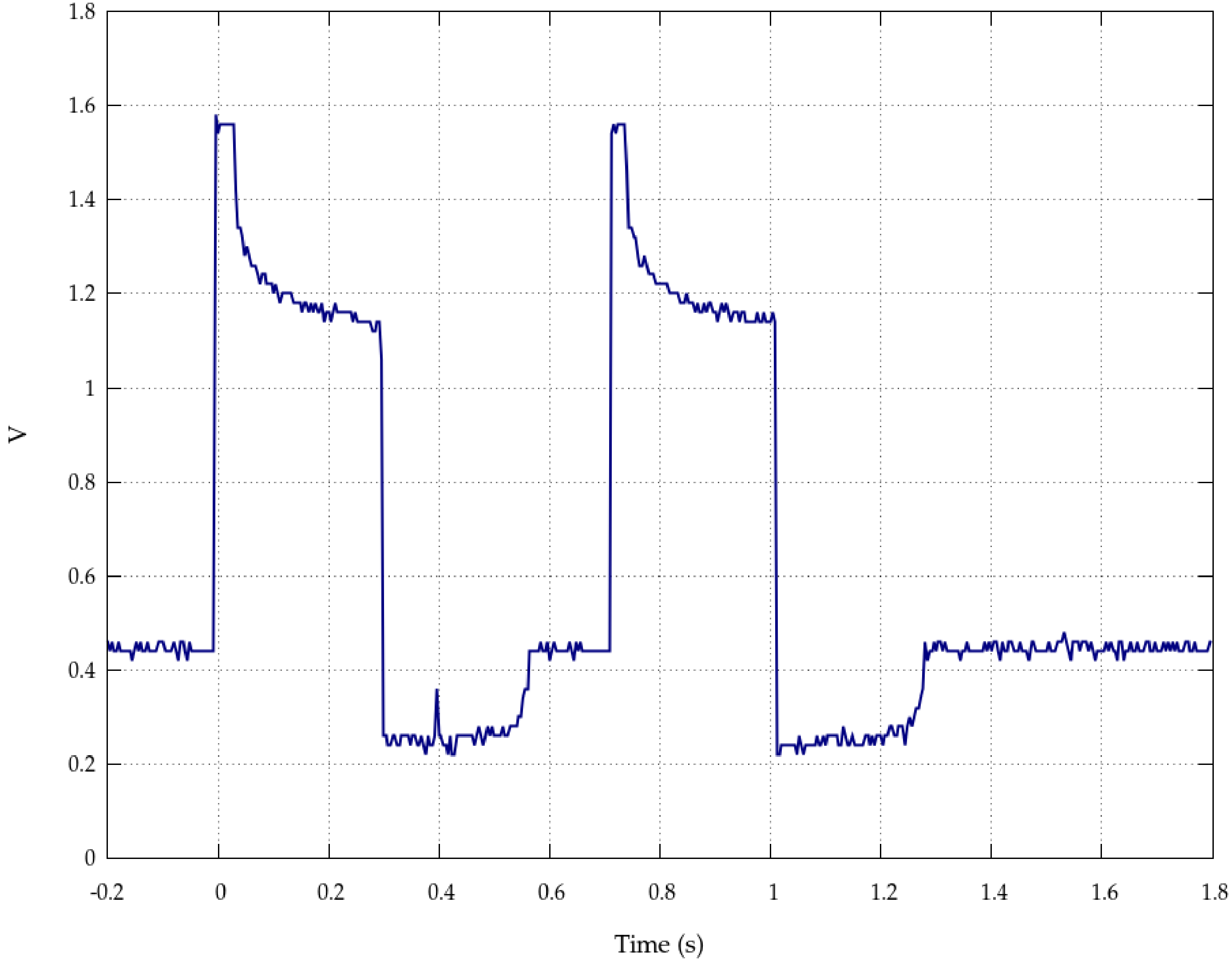
Phase 1 with NTD Ge Cold Finger





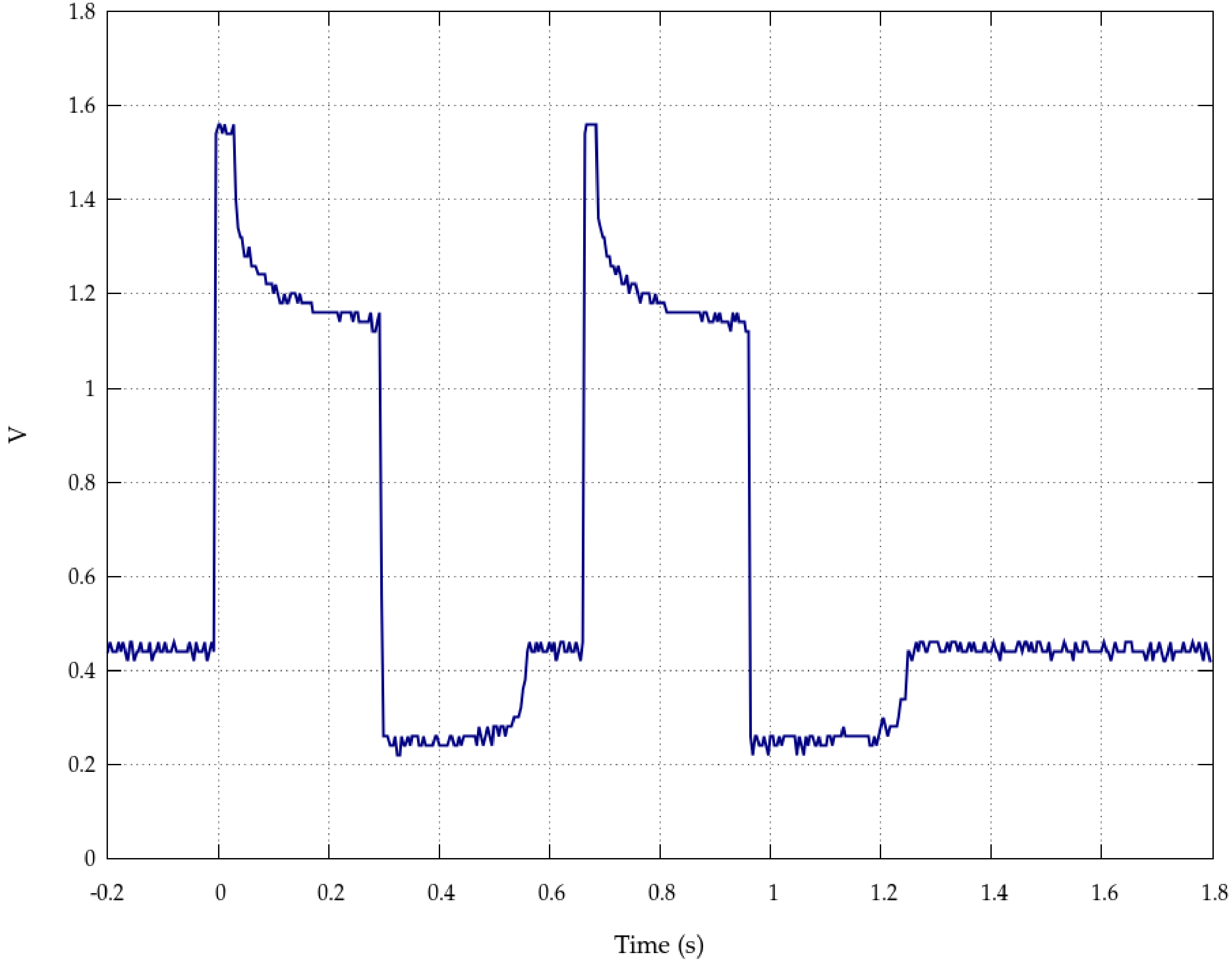


Detecting Superfluid Film



Top ROX, with LHe, 90 mK, 45 kOHm, 4 V pulses

Detecting Superfluid Film



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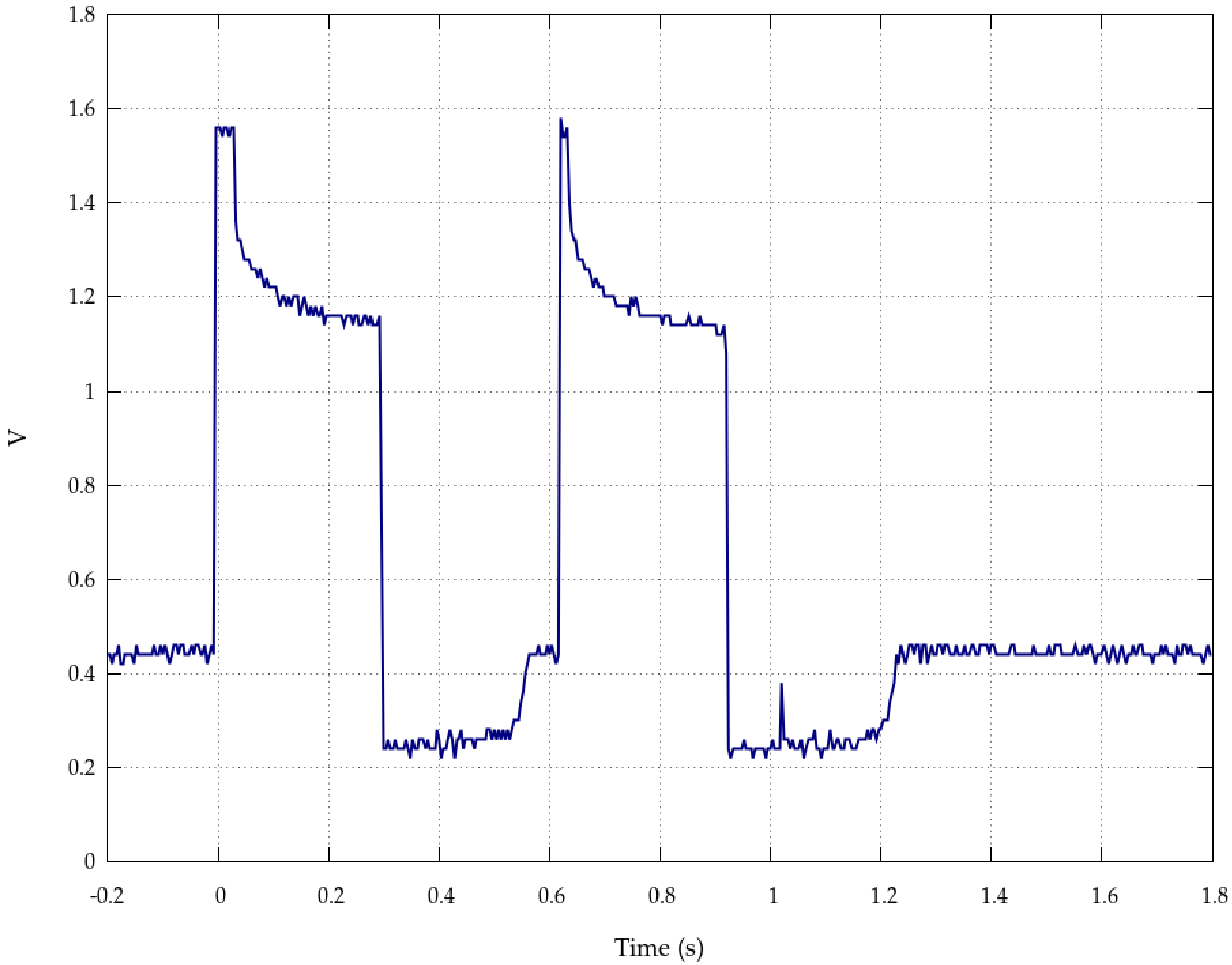

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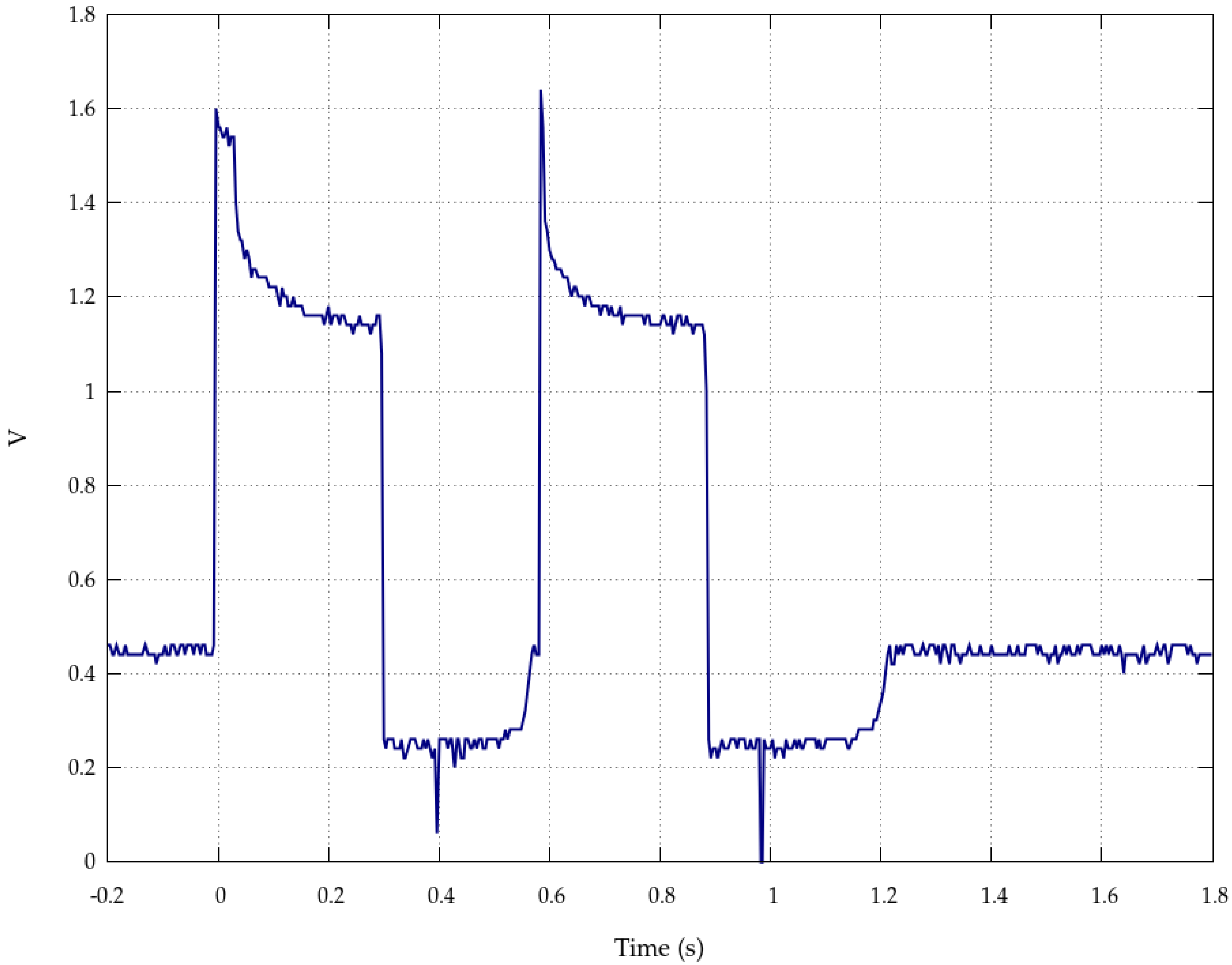

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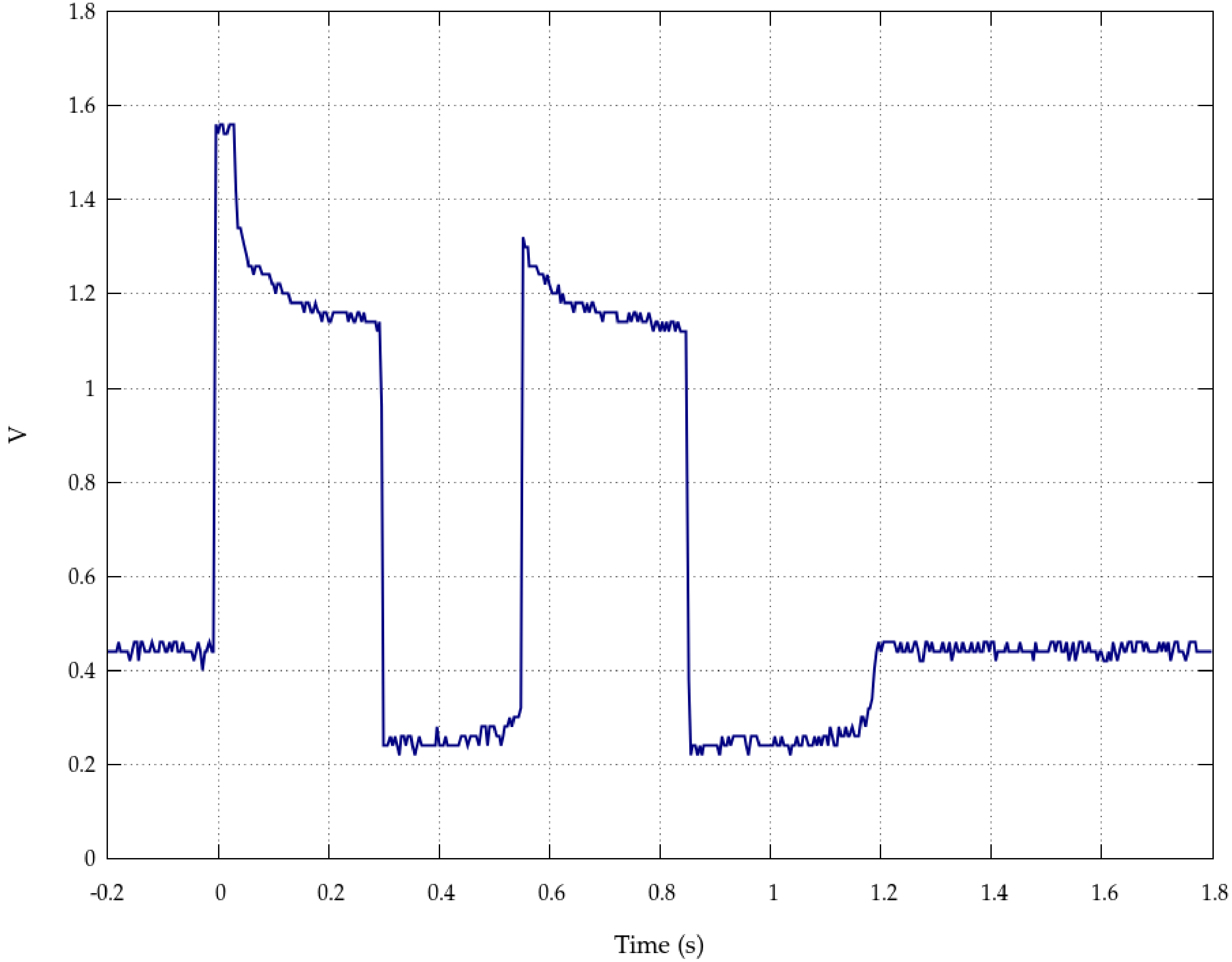

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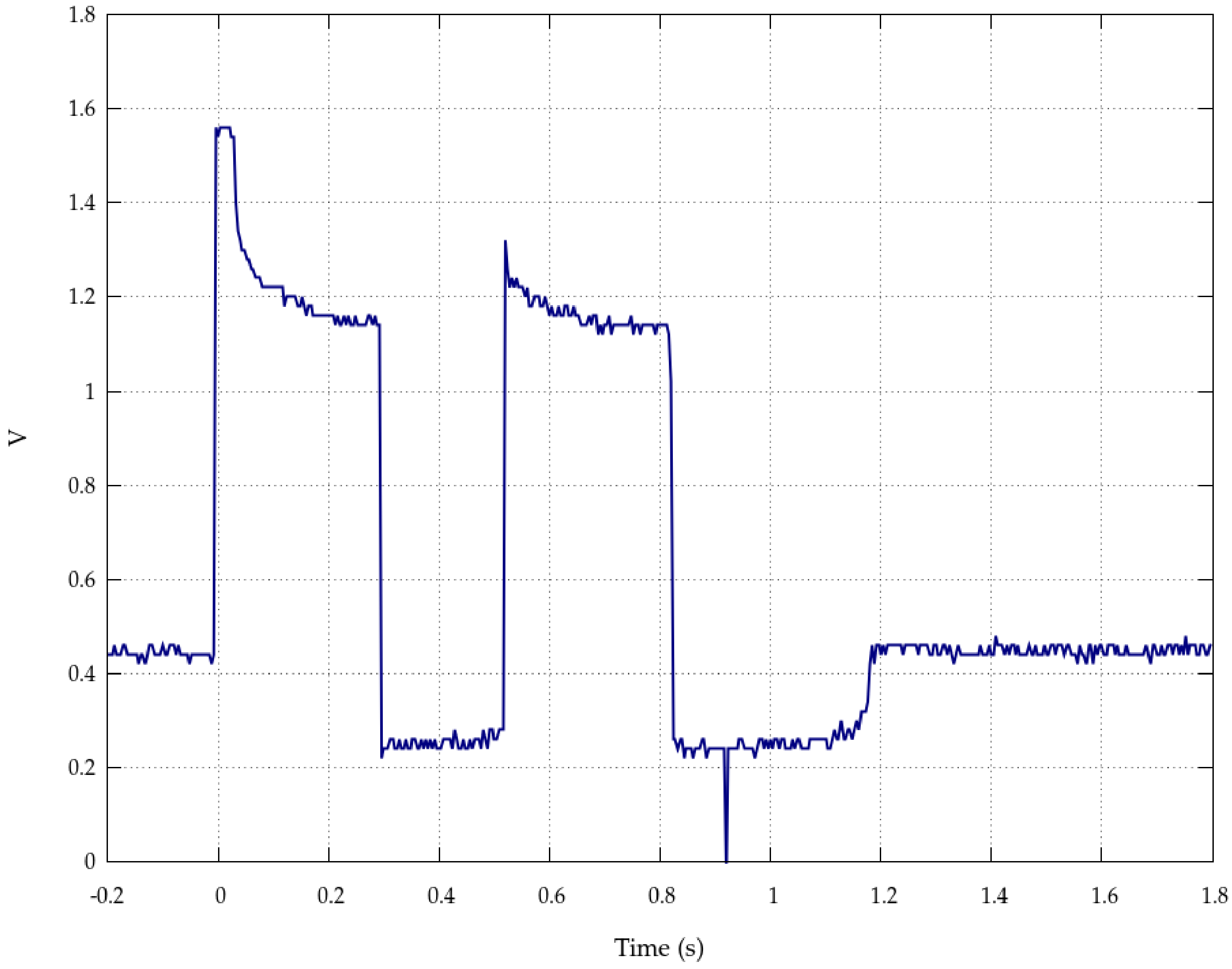

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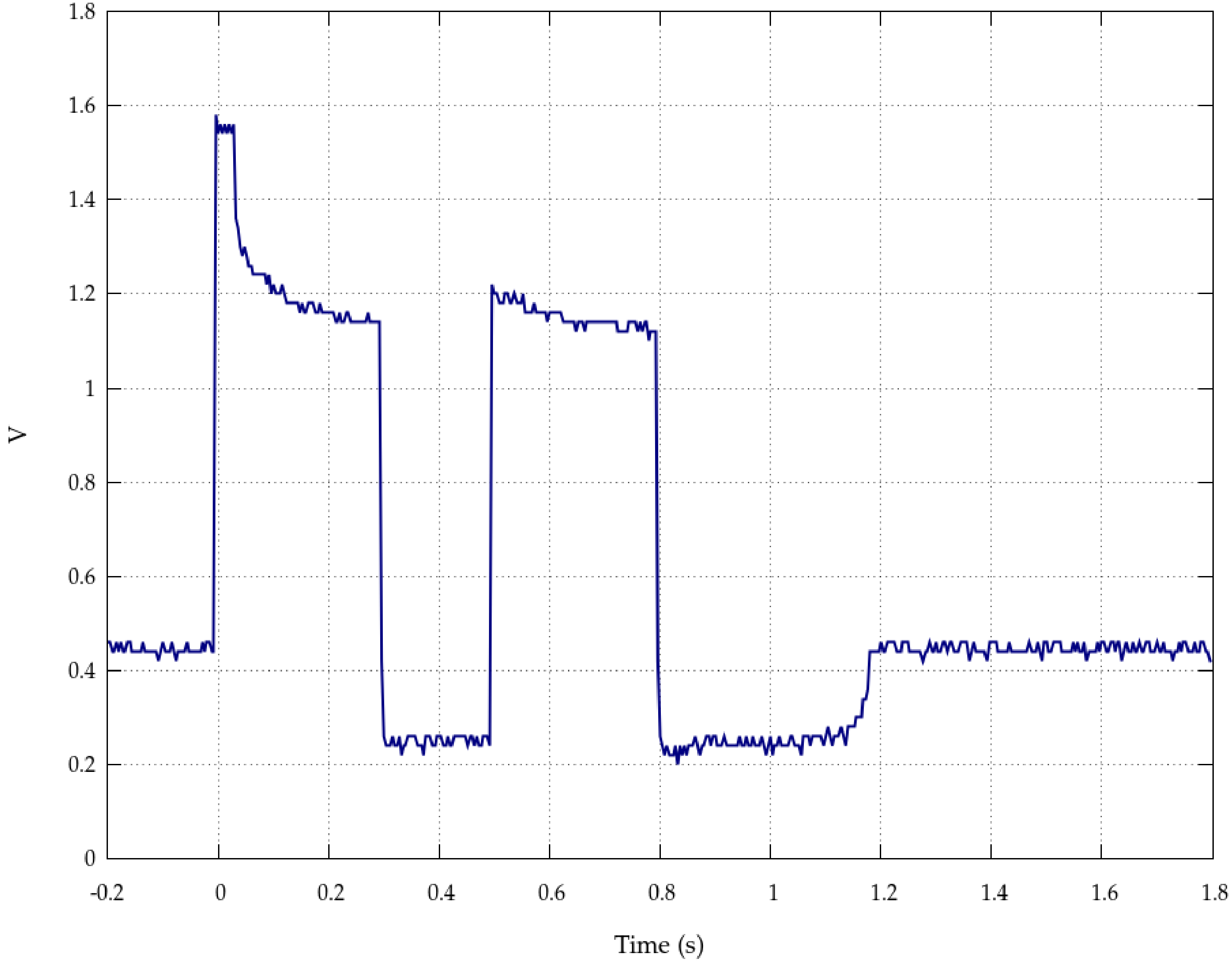

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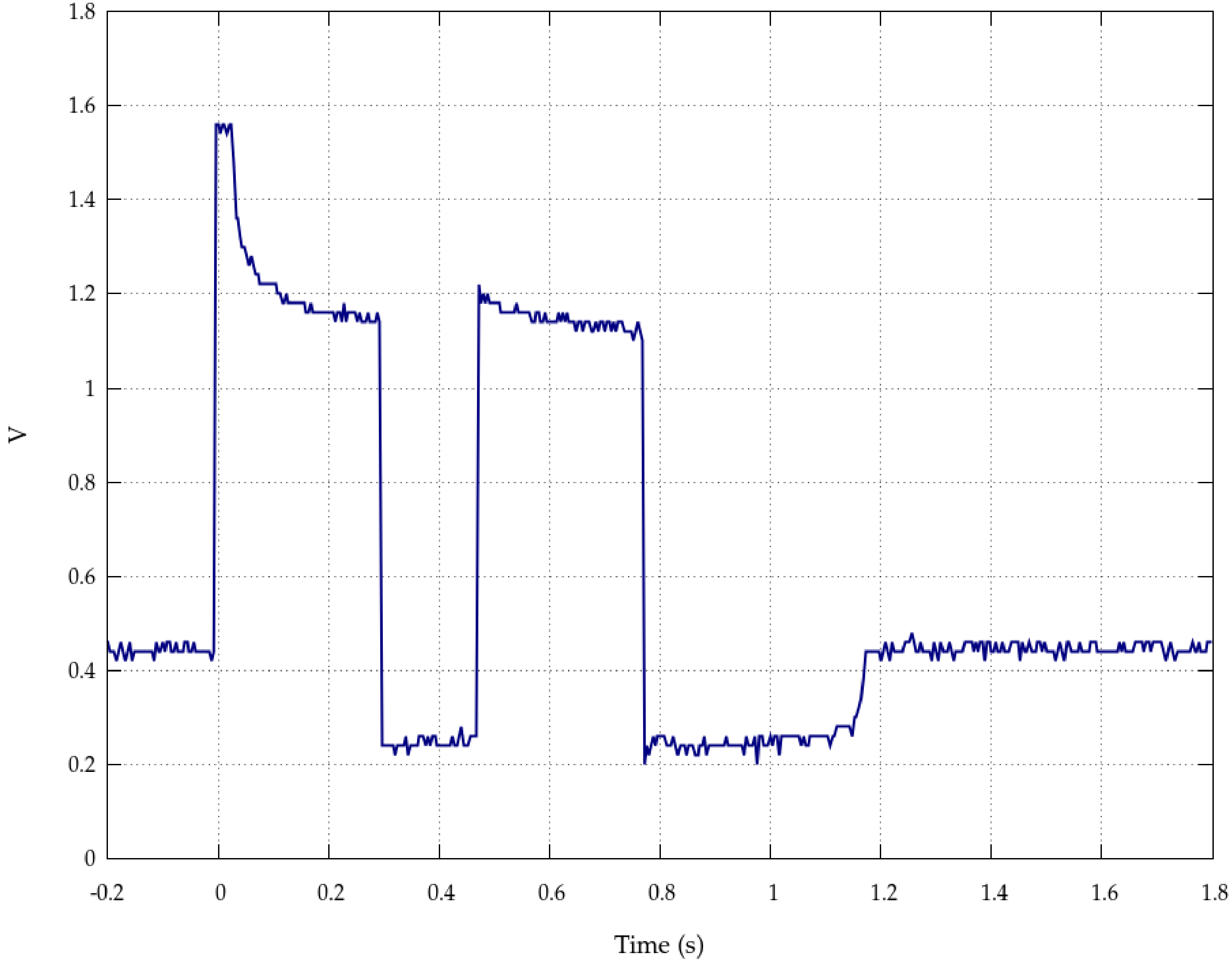

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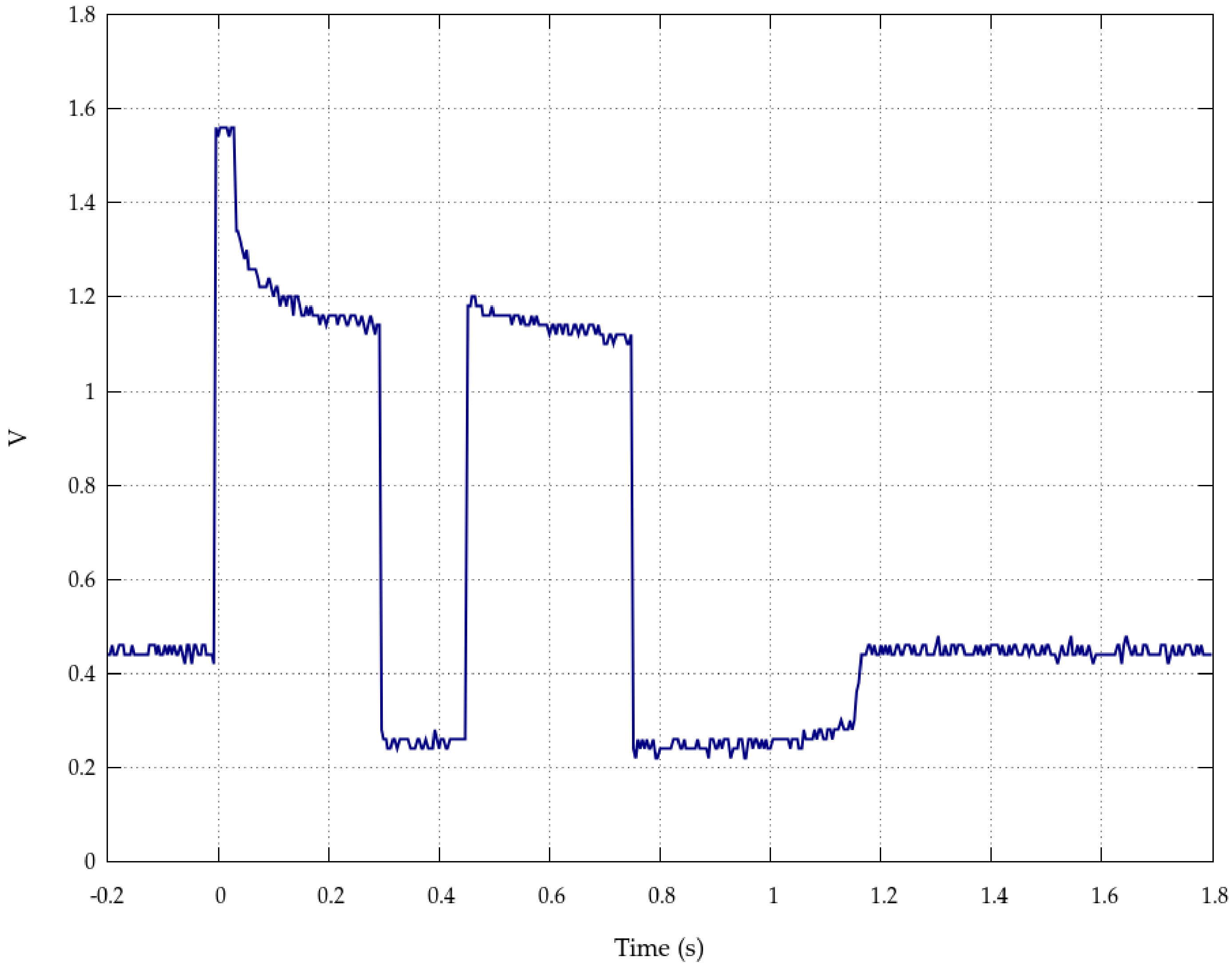

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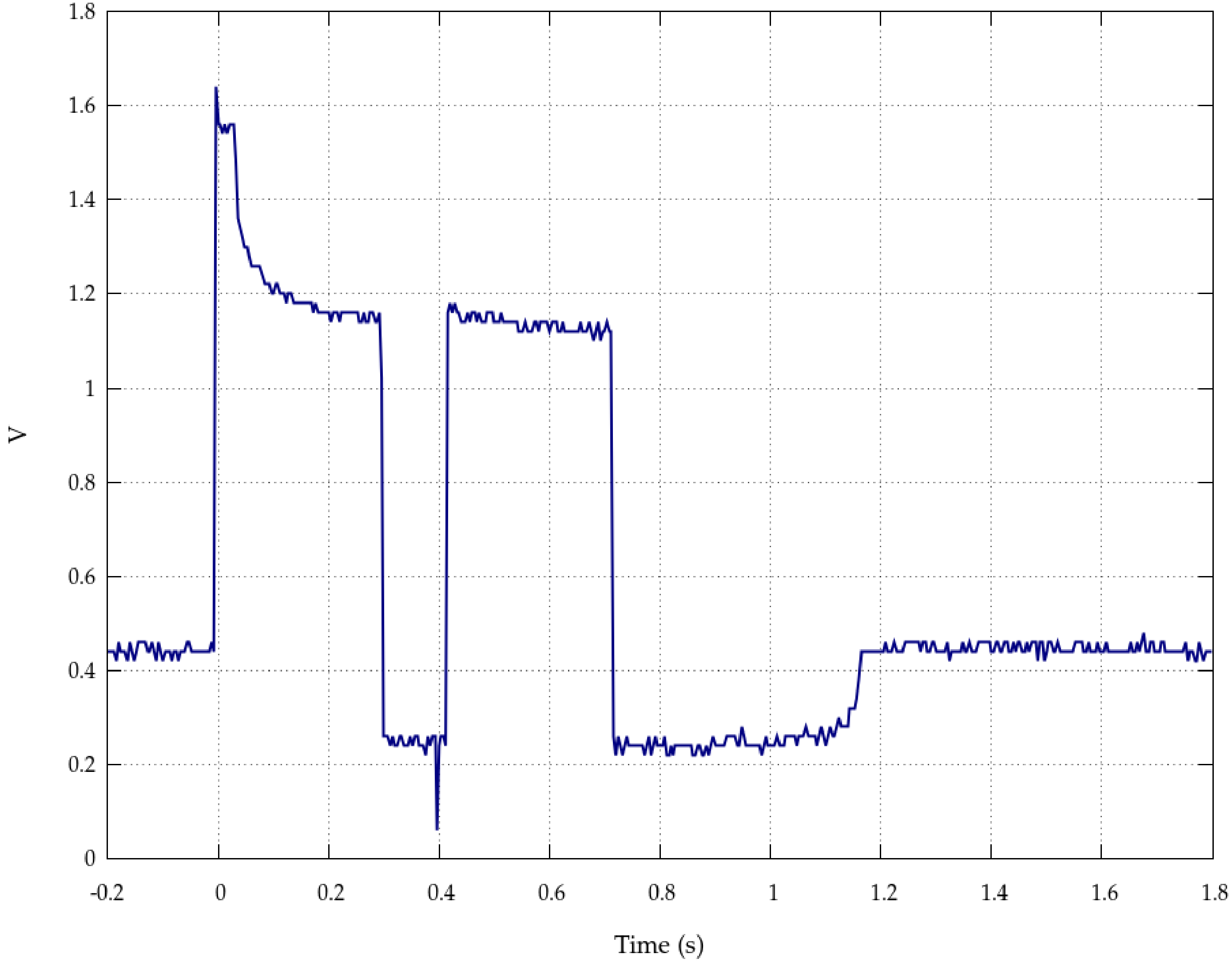
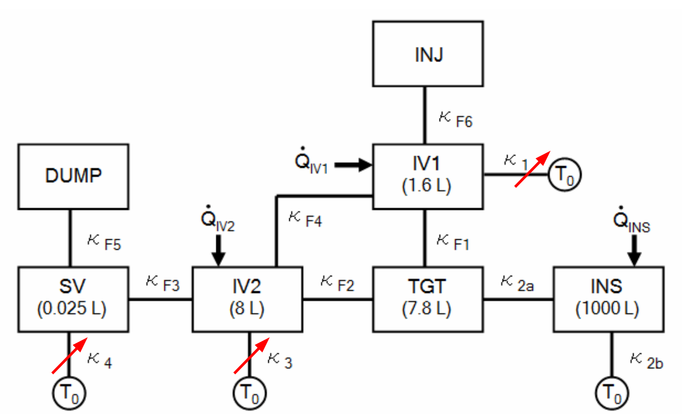


Top ROX, with LHe, 90 mK, 45 kOHm, 4 V pulses

Heat Budget

Subsystem[†]	Source	Amount (mW)	Basis of Estimate
General	Radiative heating to insulation volume and ^{3}He/^{4}He volumes	0.2	Calculation, emissivity = 1
	Mechanical support to 1.5 K	5	Calculation x 5
	Conduction through Electrical Leads	1	Calculation x 5
^{3}He Heat Flush	Heater currents	20	Flow calculations from 3He services group
Purifier	Film Burner	6	Calculation x 2
	Valves	1.5	2 @ 0.75 mW
	Bellows	1.5	1 @ 1.5 mW
Injector	Radiation through injection pipe	2	Calculation x 10
	Film burner	6	Calculation x 2
Light Guides and PMTs	Radiative heating from 8 K	3	Calculation (includes 15 K PMT's) x 2
Valves		10	10 valves @ 1.0 mW
Bellows		6	2 bellows @ 3 mW
Magnets	I^2R Losses, eddy currents	1 5	
Contingency	Project management	20	
Total Heat Load to DR at 0.35 - 0.40 K		**88.2**	

- Heat flush transport is one of the largest sources of heat load.
- A thermal model[‡] of the apparatus and measurement cycle indicates:
  - Closed valves should have low thermal conductance (< 1 mW/K)
  - Adjustable thermal links (ATLs) will reduce the overall heat load

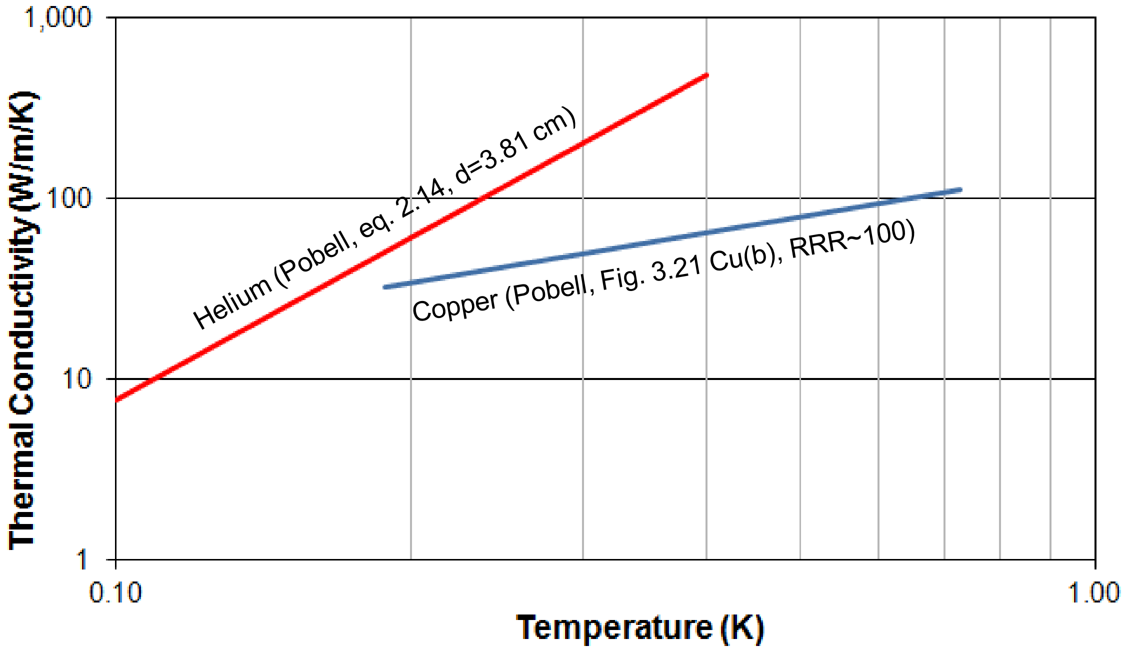


† D. Haase, Heat Budgets and Other Items, a presentation at the June 17-19, 2009 nEDM Collaboration.

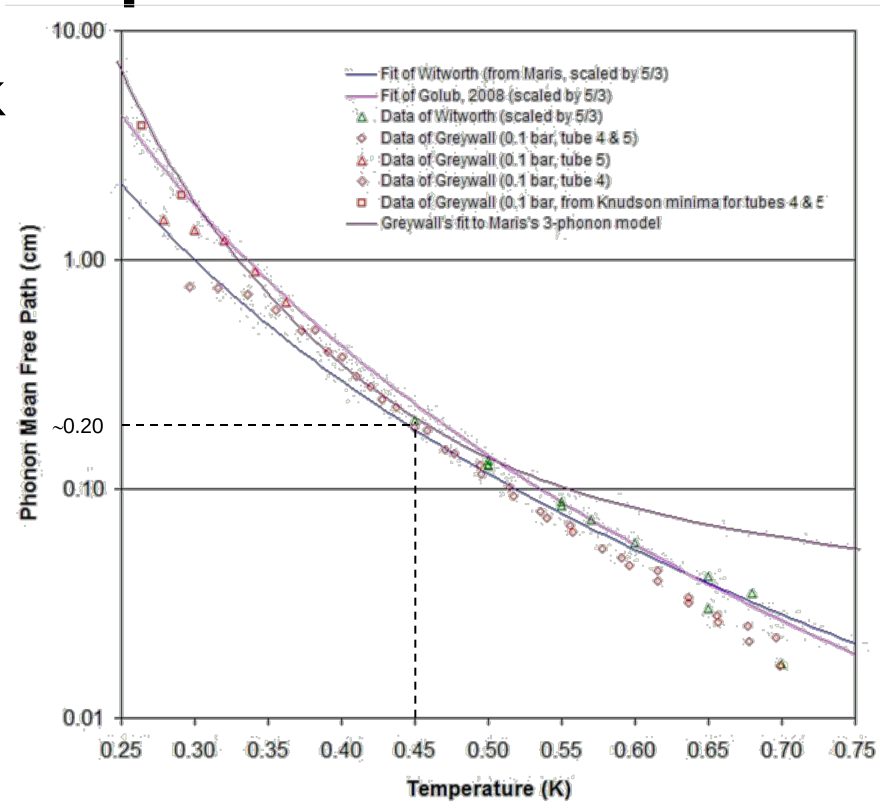
‡ D. Kendellen and D. Haase, An Updated Thermal Model for Cooling the nEDM ^{3}He Services, a Technical Feasibility, February 23, 2010.

Adjustable Thermal Links (and Valves)

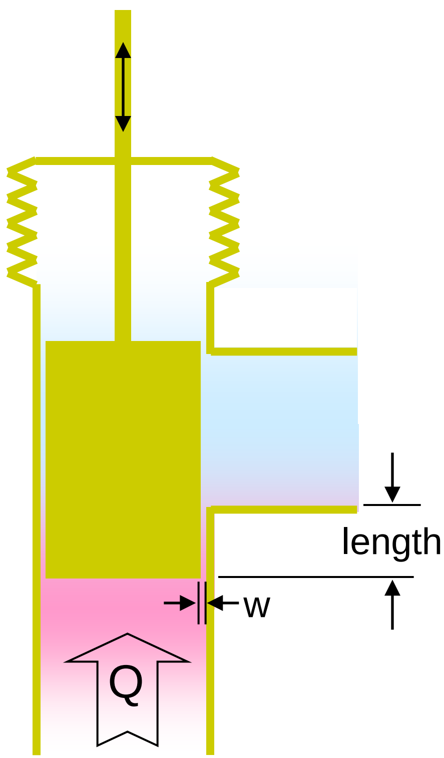
- Bolted joints can have poor thermal conductance (unless care is taken)
- Helium is still a pretty good thermal conductor at 0.45 K
  - Kapitza resistance is not so bad at this temperature
  - Offers the possibility of adjustability (adjustable thermal links)
- ATLs are usful for:
  - Reducing the heat load on DR when components are warmed during heat flush…
  - While allowing rapid re-cooling when the heat flush is over.



ATL Principle of Operation



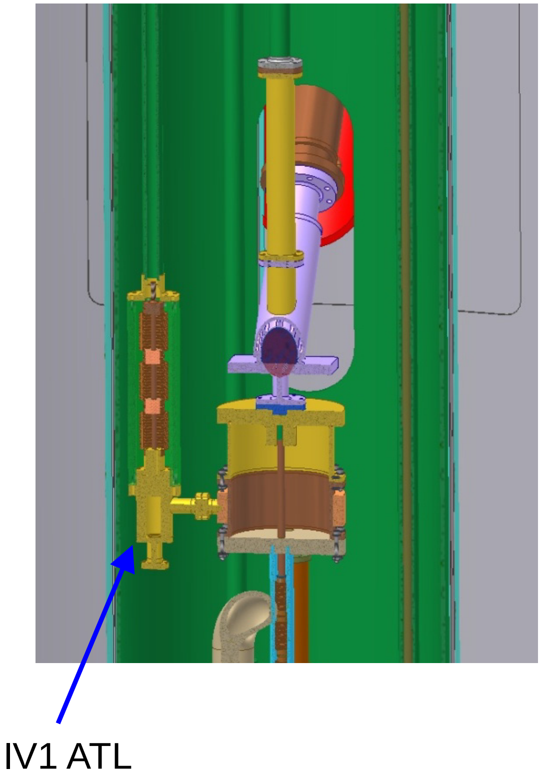
- Heat transport is via phonons for T<0.6 K
- If mean free path of phonons, λ_{ph}, is geometrically restricted, the effective conductivity is reduced.
  - Need typical dimension << λ_{ph}
  - $\lambda_{ph} \approx 0.2$ cm at 0.45K

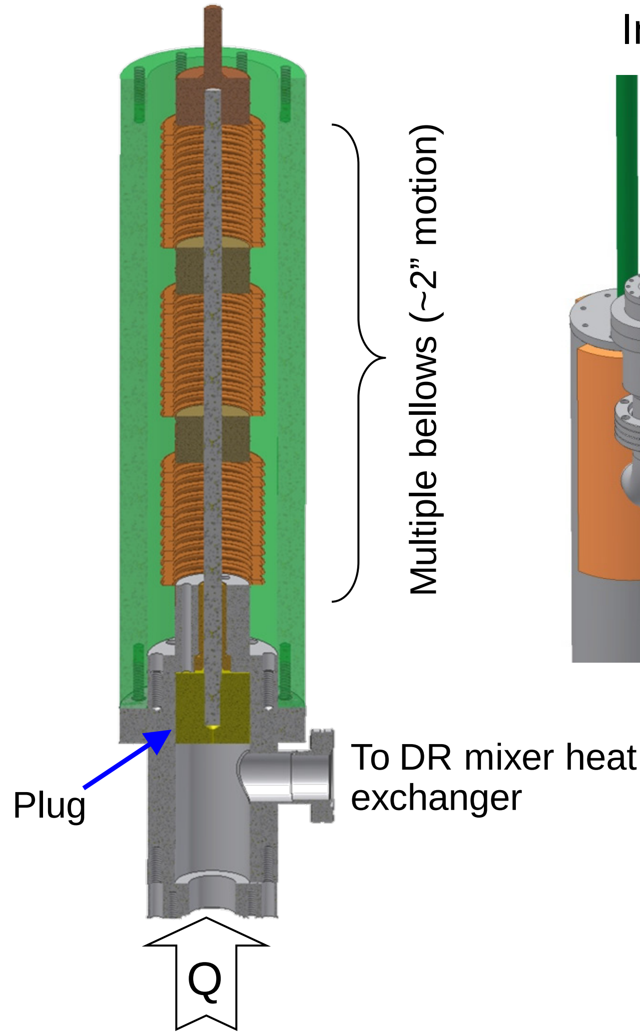


- Create restriction with adjustable-length annular gap
  - Restriction (w) must be ~ a few mils (~50X smaller than λ_{ph})
  - Wall and plug material must have low conductivity compared to LHe

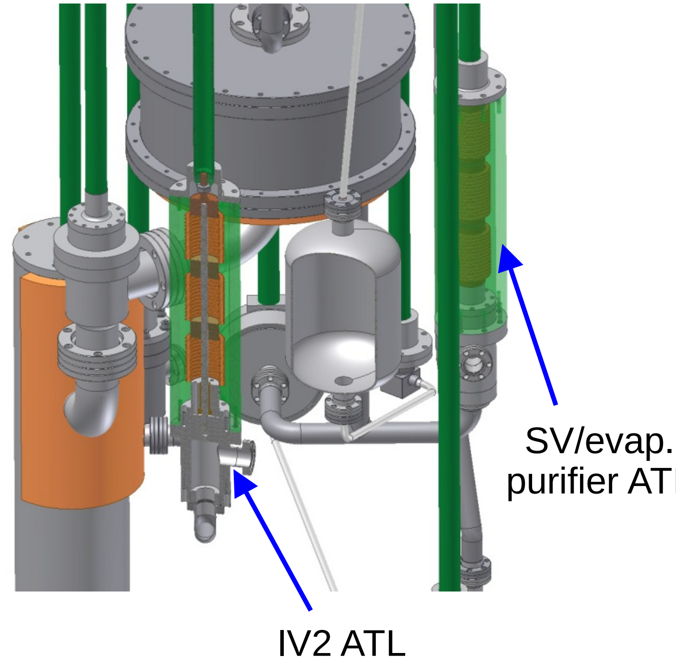
Implementation in the CAD Model

In the Injection Module



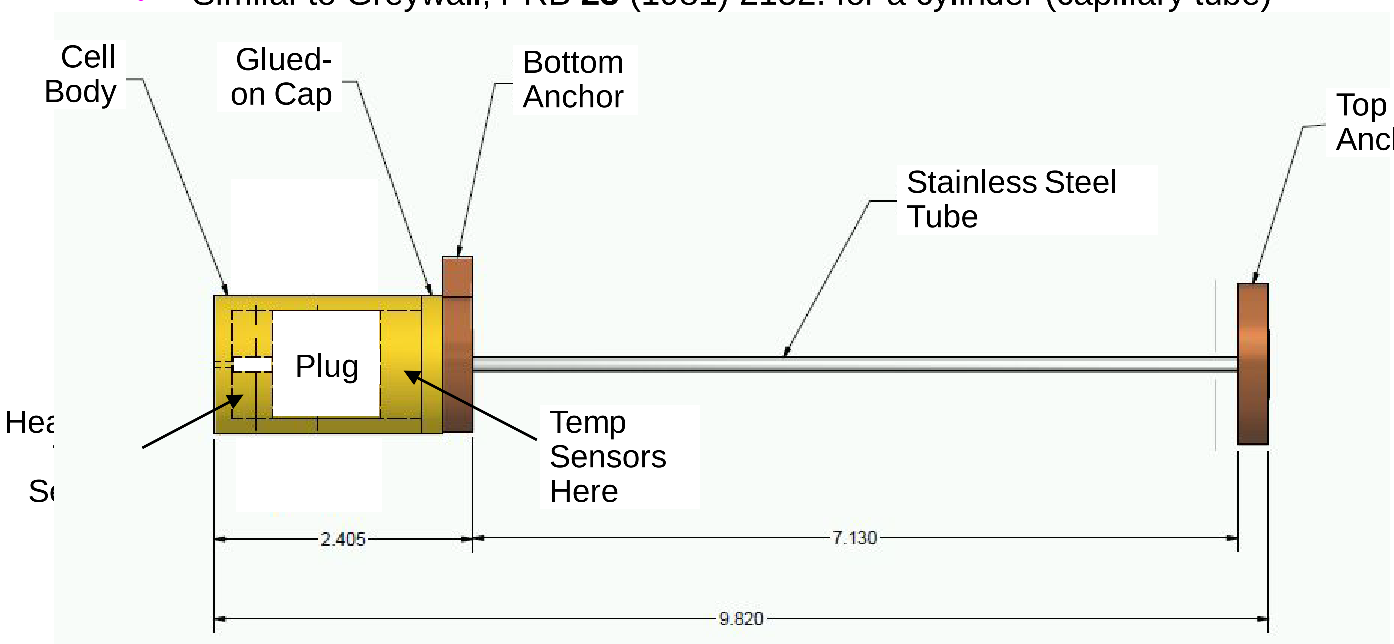


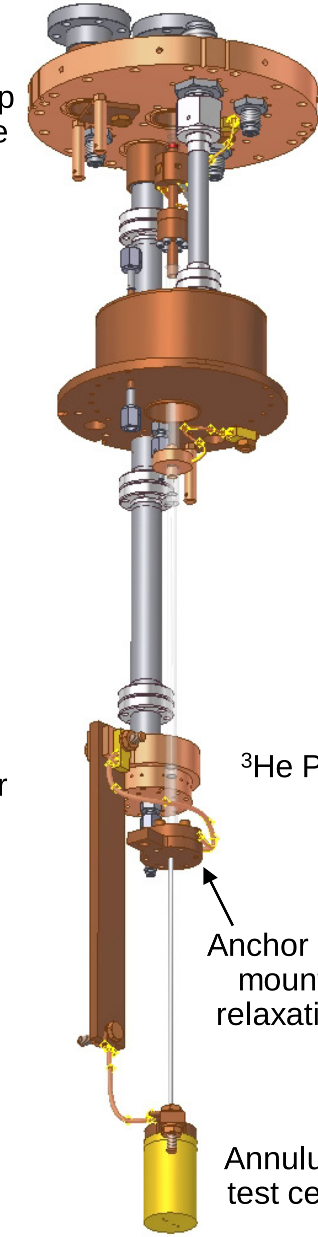
In the Purifier Module



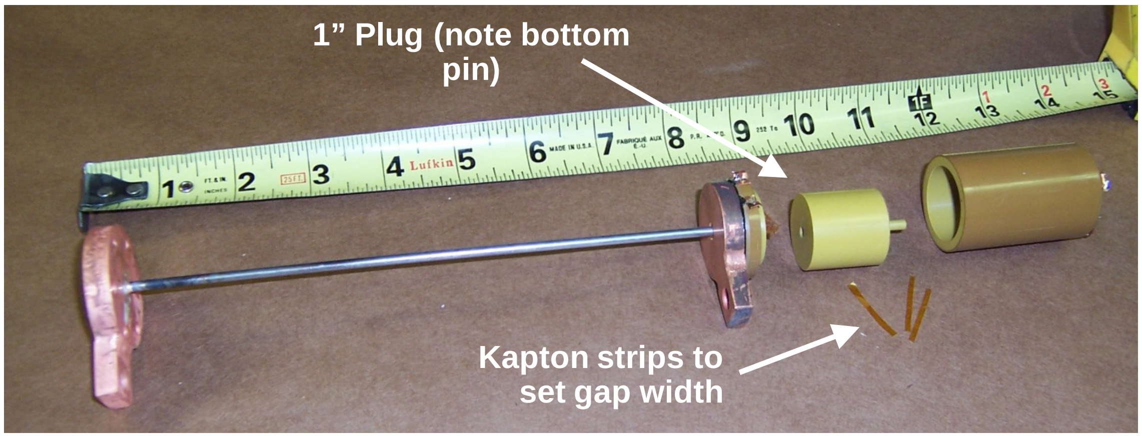
Thermal Conductance of an Annular Gap

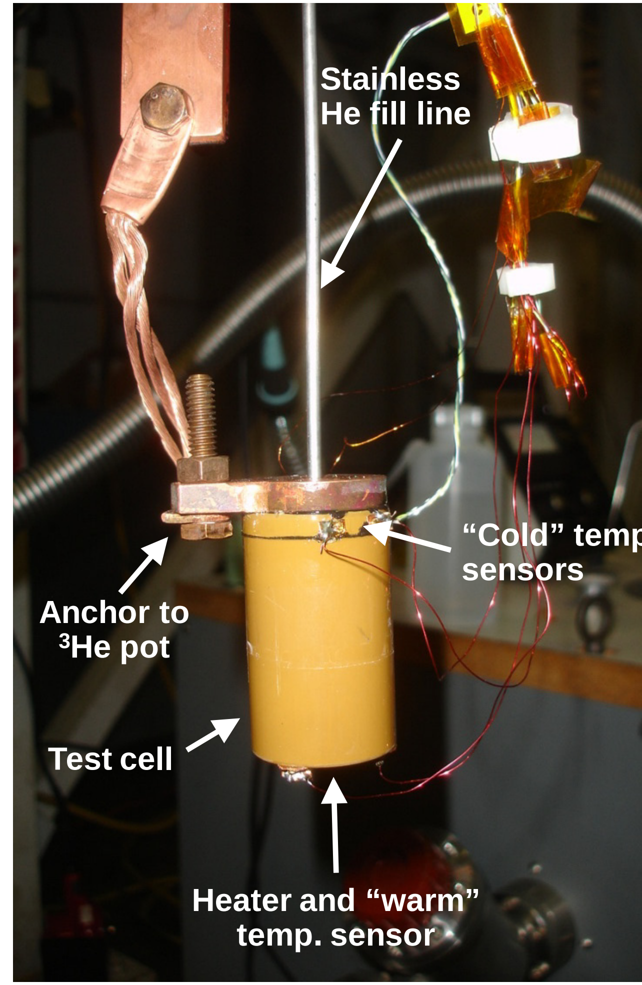
- Proof of principle: geometrically restrict phonon mean free path to reduce thermal conductance of LHe for T < 0.6K
- Measure for:
  - a single length (1”) -- no actuation
  - a single gap width (0.001”)
  - a range of temperatures (~0.4 – 0.6 K)
- Design as simple modification to wall-depolarization apparatus
- Predict behavior following Casimir, Physica (Utrecht) **5** (1938) 495.
  - Similar to Greywall, PRB **23** (1981) 2152: for a cylinder (capillary tube)



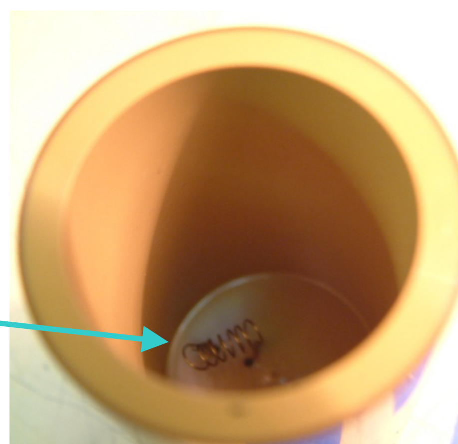


Annulus Thermal Isolation Test

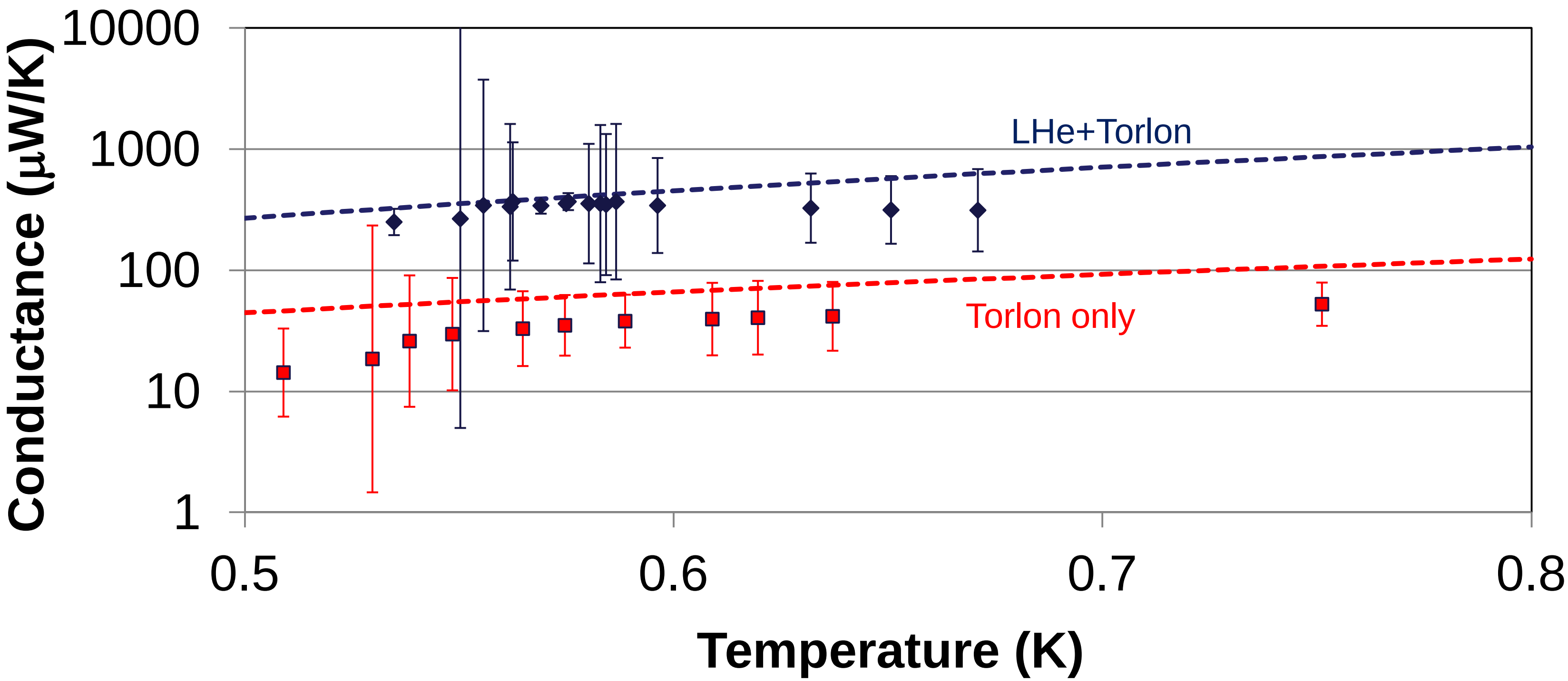




Nichrome heater at bottom of cell



Annulus Thermal Conductance



- Good agreement with prediction (dotted curves)
  - Small discrepancy may be due to sensor calibration error
- Senior thesis project of Andrew (Ian) Chen (now at MIT)

^{3}He Wall Depolarization

- The total longitudinal relaxation time, T_1

$$\frac{1}{T_1} = \frac{1}{T_D} + \frac{1}{T_B} + \frac{1}{T_S}$$

  - T_D = dipolar interaction between ^{3}He atoms -- not an issue at nEDM concentration
  - T_B = B-field gradient effect -- can be controlled with careful design
  - T_S = Surface (wall) effect
- For measurement cell (0.45 K, dTPB in dPS), T_S > 1000 s (“R&D” goal)
- Two separate projects were launched to make the measurements at Duke/NCSU and UIUC:
  - Critical to SNS nEDM method
  - Difficult measurement
  - Involved PhD students at early stage in experiment
    - Qiang (Alan) Ye, Duke
    - Jacob Yoder, UIUC

Measuring ^{3}He Wall Depolarization

- The Method:
  - Cool test cell
    - UIUC: with ^{3}He evaporation fridge.
    - Duke/NCSU: with DR
  - Fill test cell with LHe to some level
  - Polarize ^{3}He at room temperature
    - UIUC: Metastability Exchange Optical Pumping
    - Duke/NCSU: Rubidium Spin-exchange Optical Pumping
  - Open isolation valve
  - ^{3}He to diffuses (is drawn) into LHe
  - Measure polarization vs. time with NMR
  - Repeat for other levels of LHe, concentrations of ^{3}He and Temperatures
- Extrapolate to geometry of nEDM

Duke/NCSU Setup

UIUC Setup

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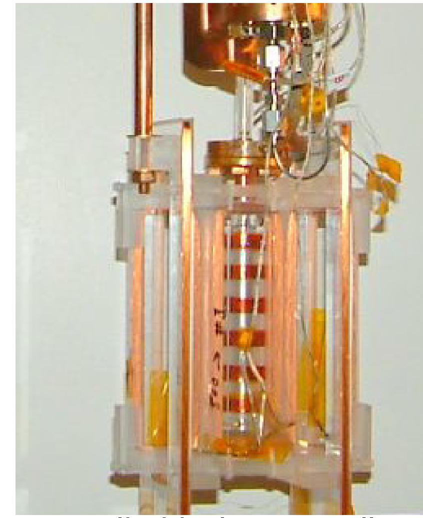
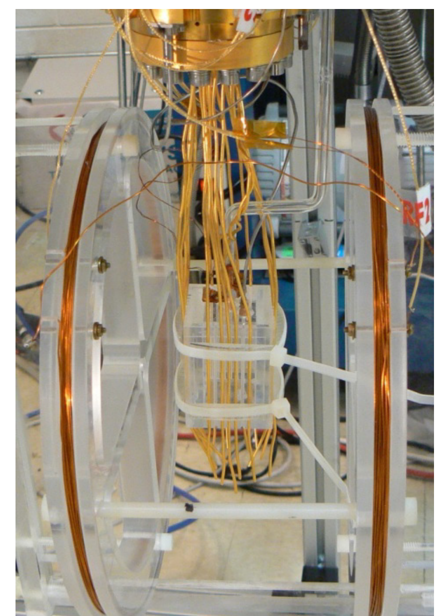


Cylindrical UIUC Cell



Rectangular Duke/NCSU Cell

Extrapolation to nEDM Geometry

- If P_d is the probability per wall bounce of depolarization, can write:

$$N_{\uparrow}(t+\Delta t) = N_{\uparrow}(t) - P_d \cdot \varphi \cdot S \cdot \Delta t$$

$$\varphi = \tfrac{1}{4} \cdot \rho_{\uparrow}(t) \cdot \langle v \rangle = \text{flux of polarized atoms hitting unit area per unit time}$$

$$\rho_{\uparrow}(t) = \frac{N_{\uparrow}(t)}{V} = \text{density of polarized atoms}$$

$$\frac{dN_{\uparrow}}{dt} = -P_d \cdot \tfrac{1}{4} \cdot \langle v \rangle \cdot \frac{S}{V} \cdot N_{\uparrow}(t)$$

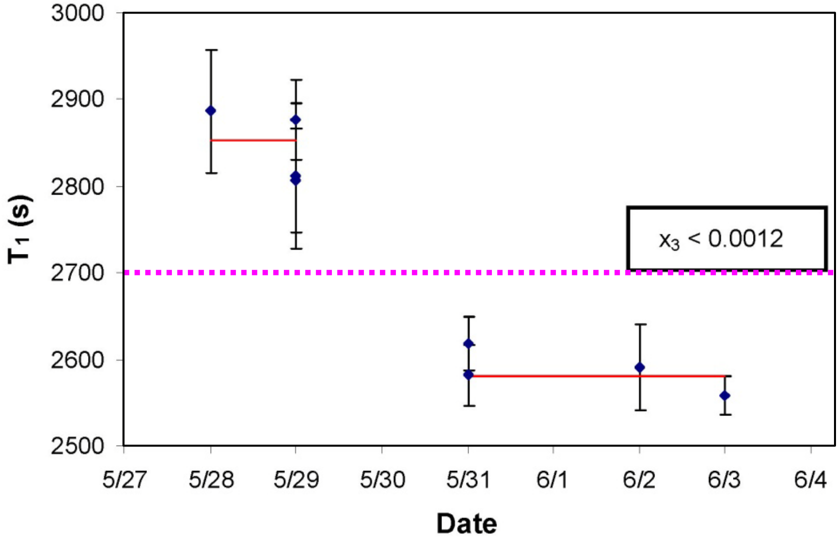
$$N_{\uparrow}(t) = \exp\left(\frac{-t}{T_S}\right)$$

$$\frac{1}{T_S} = P_d \cdot \tfrac{1}{4} \cdot \langle v \rangle \cdot \frac{S}{V}$$

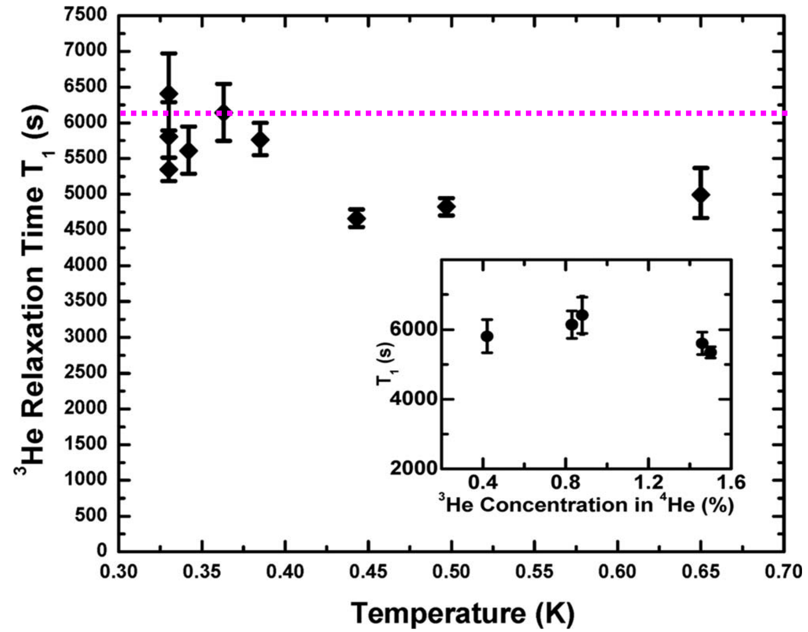
- Knowing P_d, can extrapolate from S/V of test cell to larger nEDM measurement cell.

^{3}He Relaxation Rate Data

J. Yoder Thesis



Ye et al., Phys. Rev. A 80, 023403 (2009)



$$T_s = 2700 \pm 140\ \text{s},\ S/V = 2.96\ \text{cm}^{-1}$$

$$P_d < 1.32 \times 10^{-7}$$

$$T_s^{nEDM} > 16000\ \text{s (at 0.45 K)}$$

$$T_s = 6100\ \text{s},\ S/V = 2.1\ \text{cm}^{-1}$$

$$P_d = 1.0 \times 10^{-7}$$

$$T_s^{nEDM} = 21{,}000\ \text{s (scaled to 0.45 K)}$$

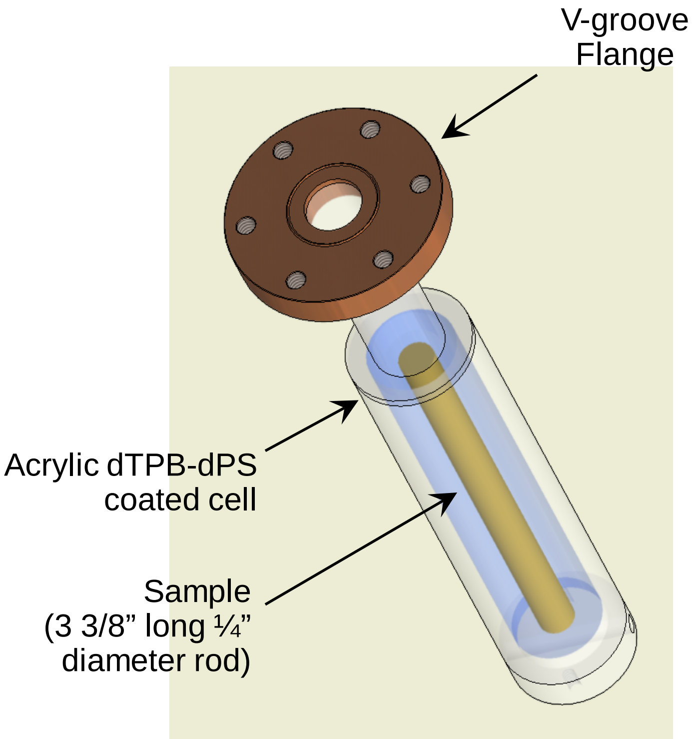
$T_S > 20{,}000$ s

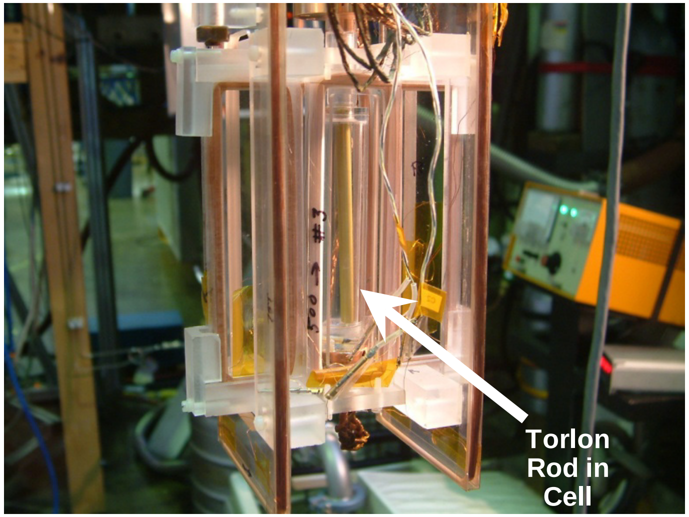
Other Materials

- Improved apparatus to quickly measure T_s on a variety of materials.
  - Use "detachable cell" with low P_d
  - Introduce sample
  - This geometry permits measurements with conductive samples (e.g. Be-Cu)
- Analysis: subtraction method
  - Measure empty cell to find $T_S^{dTPB\text{-}dPS}$
  - Measure with sample to find T_S^{Total}

$$\frac{1}{T_s^{Sample}} = \frac{1}{T_s^{Total}} - \frac{1}{T_s^{dTPB\text{-}dPS}}$$

Material	P_d
Acrylic coated with dTPB-dPS	1.0×10^{-7}
Bare Torlon 4203	$(1.01 \pm 0.08)\times10^{-6}$
BeCu coated with Polyimide	$(7.9 \pm 0.3)\times10^{-7}$
Torlon coated with Polyimide	$(2.5 \pm 0.1)\times10^{-7}$





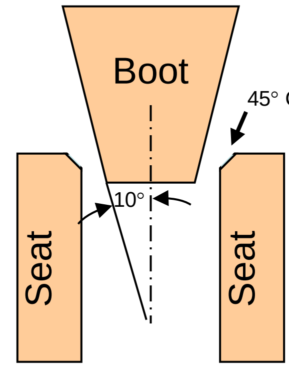
Valves

- There are lots of valves
- The valves (in the most demanding case) must be:
  - Large (1” aperture)
  - Minimal LHe open/closed volume change
  - Non-magnetic (and non-superconducting)
  - “^{3}He friendly” (low wall depolarization probability)
  - Superfluid tight
  - Able to stand off 1 atm
  - Thermally isolating
  - Reliable (> 10,000 cycle lifetime)

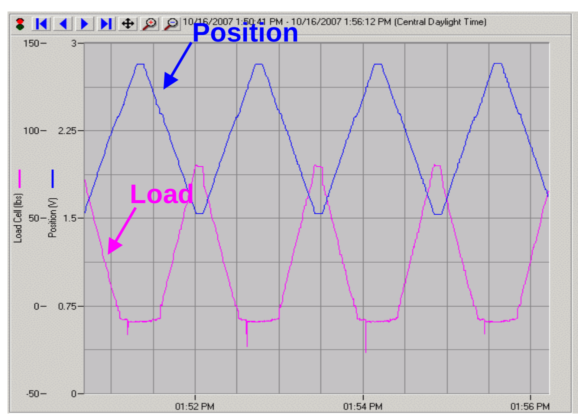
e.g. plastic, ceramic

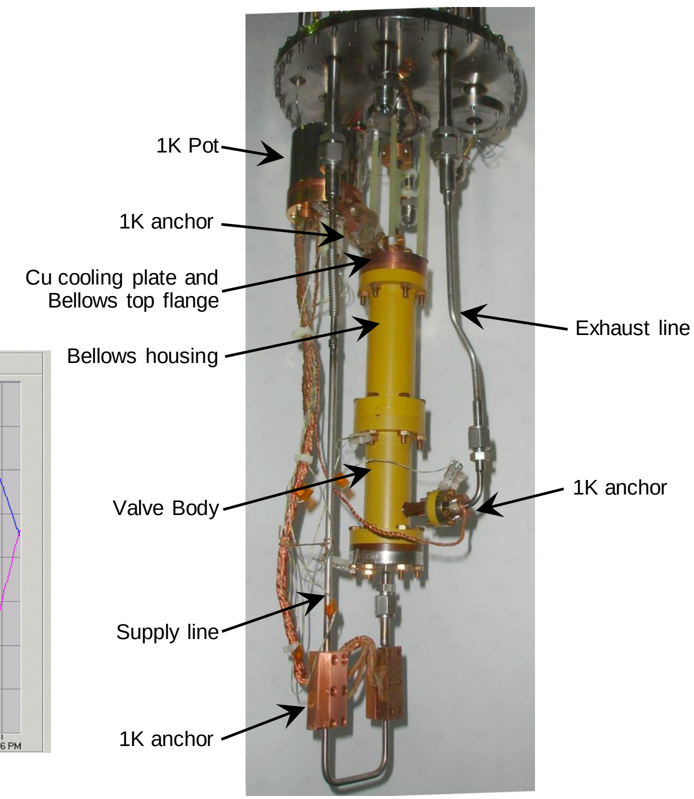
Valve Development

- Demonstration of a working valve is <u>required</u>.
- Our solution:
  - Self-cleaning "Cork-in-bottle seal"
  - High-strength Plastics (Torlon, Vespel)
  - Polyimide-coated BeCu Bellows – hidden by another seal
  - "Australian" V-groove flange seals with Kapton gaskets
  - Low conductance annular gap for thermal isolation

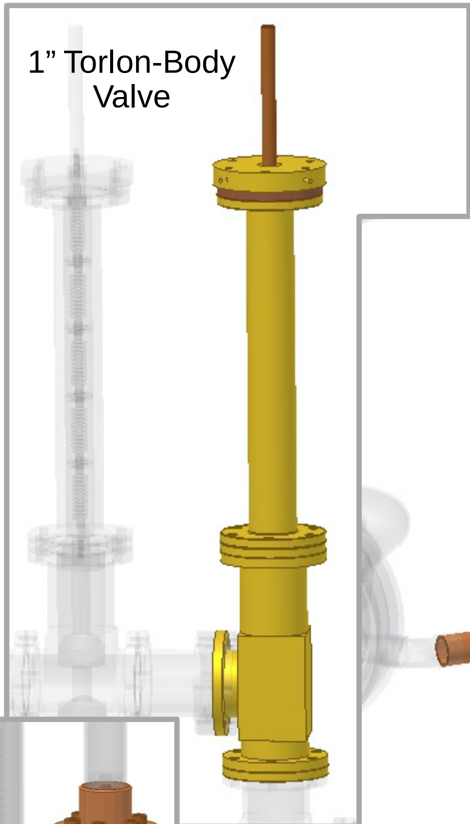


- Test plan:
  - Verify seal design
  - Fabricate a full-sized prototype valve
    - Include all essential features
  - Use reasonable materials
  - Test under realistic conditions
    - LHe II inside at ~1.7 K
    - Vacuum outside
- Tested Successfully
  - 10, 000 Cycles





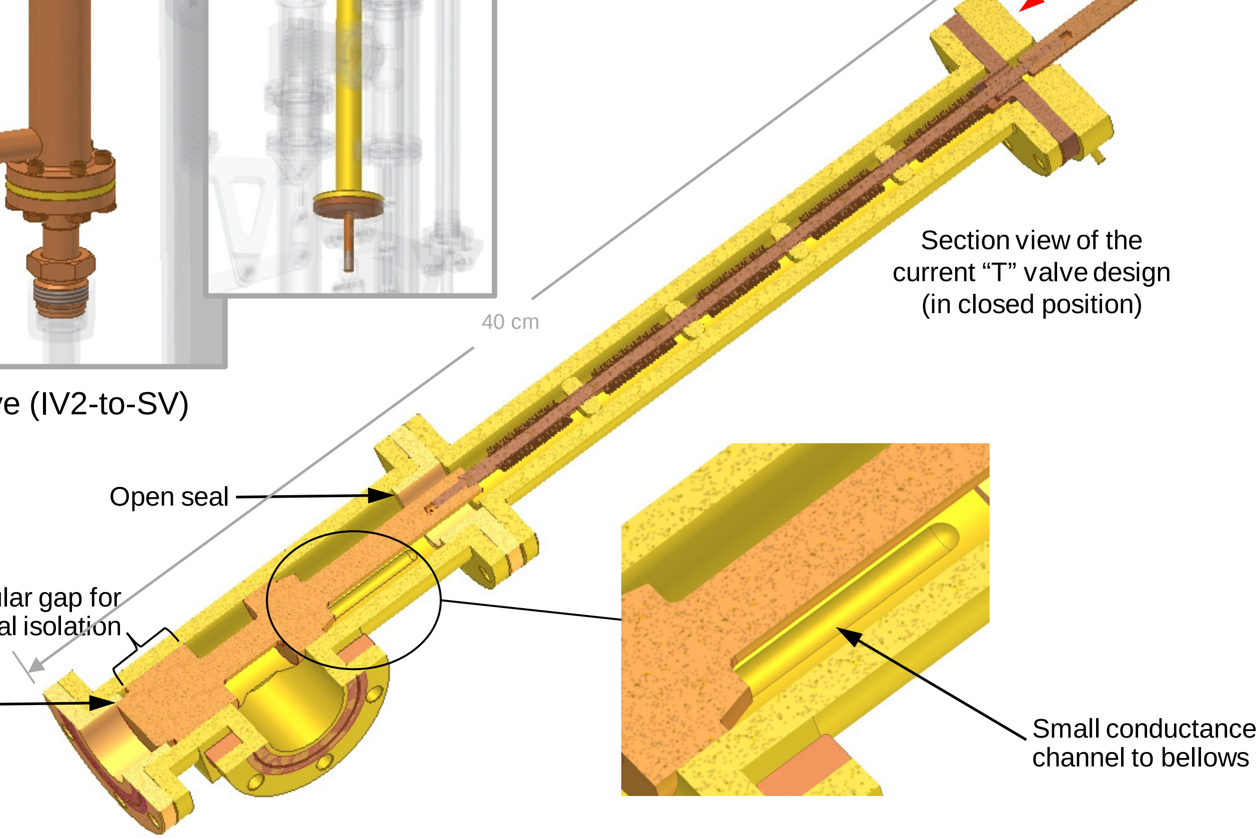
Valve Designs



1/2” Valve (IV2-to-SV)

Injection Volume Valve

Mini Valve



Section view of the current “T” valve design (in closed position)