The nEDM Project: A new cryogenic measurement of the electric dipole moment of the neutron

David Haase

NC State University and

The Triangle Universities Nuclear Laboratory

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Overview

- Motivation for EDM measurements
- Description of the nEDM experiment
- Cryogenic issues in the nEDM project

Local collaborators –

NC State - Bob Golub, David Haase, Paul Huffman, Albert Young, Ekaterina Korobkina, Chris Swank, David Kendellen, Graham Medlin

Duke - Mohammad Ahmed, Haiyan Gao, W. Zheng, Y. Zhang

Other institutions include ORNL, Caltech, UIUC, U. Va., MIT, Boston U., UC Berkeley, Harvard, ASU, U. Ky., LANL, IU, Miss. St., Simon Fraser

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Physics Motivation



- *Significant discovery potential in search for EDMs*
  - If particle EDMs are observed in the next round of experiments, a new source of CP violation will have been discovered.
  - Such CP violation could play a role in explaining the observed excess of matter over anti-matter in the Universe.
  - The neutron is a key component of understanding new CP violation should it be observed in any EDM.
  - EDM searches will continue to be compelling even after LHC produces new physics results.

Context with other EDM Searches

- Three classes of observable EDMs that presently provide complementary constraints at similar levels of precision:
  - paramagnetic atoms and molecules (i.e. thallium)
  - diamagnetic atoms (i.e. mercury)
  - neutron
- Paramagnetic systems are primarily sensitive to the EDM of the unpaired electron.
- Diamagnetic systems are considerably more complicated; they depend on a combination of parameters
  S[$g_{\pi NN}$, d_N],C_S,C_P,C_T, d_e.
- Neutron EDM has no additional atomic and much simpler nuclear physics to deal with, and one can compute the dependence of d_n on CP-odd sources at the quark-gluon level.

Overview of nEDM @ SNS

- Our goal is to measure the neutron electric dipole moment with a sensitivity of $\boldsymbol{d_n < 4 \times 10^{-28}\ e\cdot cm}$ (90%)
  – *the current experimental limit is* $\boldsymbol{d_n < 3 \times 10^{-26}\ e\cdot cm}$ *(Institut Laue Langevin)*

- Collaborative effort based at Oak Ridge National Laboratory (ORNL), that includes 21 institutions and more than 67 individuals.

NSAC Subcommittee Recommendation – 2011

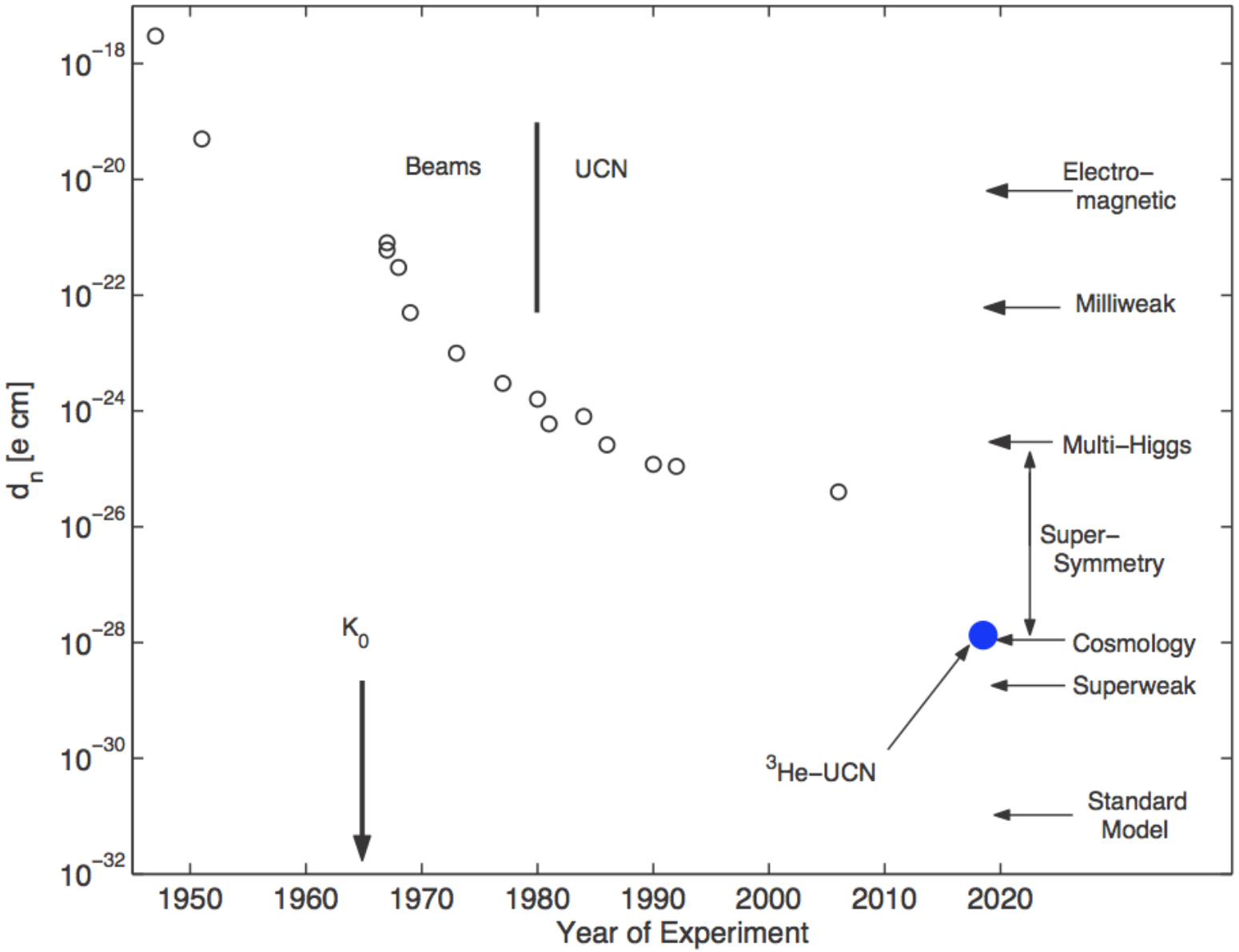
"The subcommittee finds that the scientific motivation for EDM searches remains as compelling as ever. **In particular, a measurement with sensitivity at the anticipated reach of the US nEDM experiment (~4 x 10^{-28} e-cm) would have a profound impact on nuclear physics, particle physics and cosmology, even in the event of a negative result.**"

Report to the Nuclear Science Advisory Committee, Submitted by the Subcommittee on Fundamental Physics with Neutrons, December 1, 2011

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Goal Relative to Existing Measurements

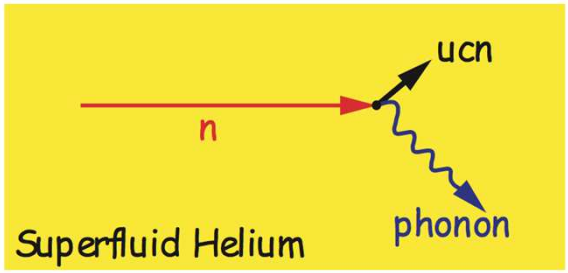


International Efforts

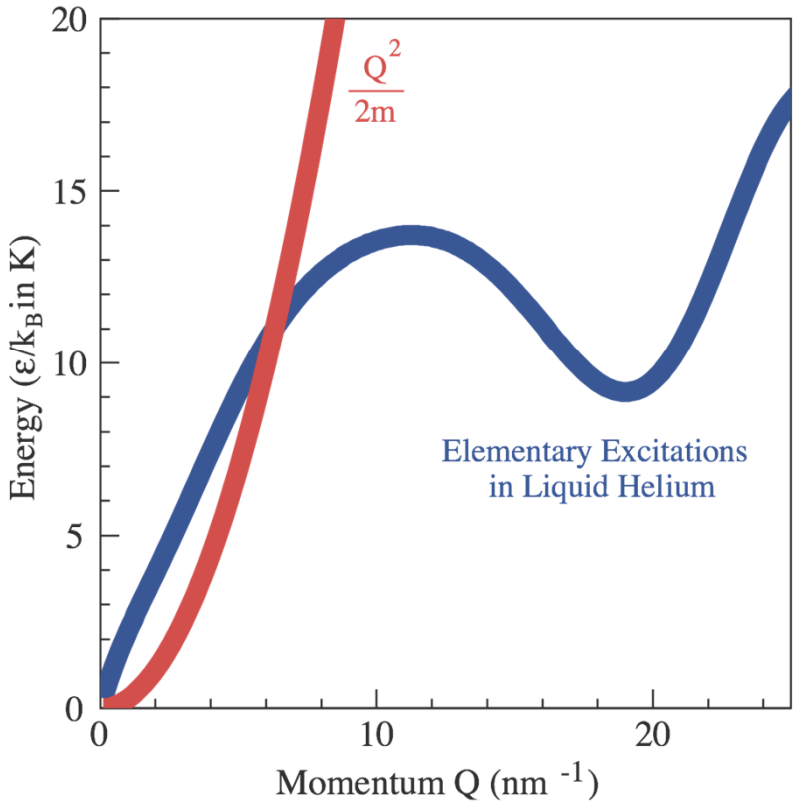
Exp	UCN source	cell	Measurement techniques	Γ_d (10^{-28} e-cm)
ILL CryoEDM	Superfluid ^{4}He	^{4}He	Ramsey technique for | External SQUID magnetometers	Phase1 ~ 50 Phase 2 < 5
PNPI – ILL	ILL turbine PNPI/Solid D_2	Vac.	Ramsey technique for | E=0 cell for magnetometer	Phase1<100 < 10
ILL Crystal	Cold n Beam	solid	Crystal Diffraction	< 100
PSI EDM	Solid D_2	Vac.	Ramsey for ⅂, external Cs & ^{3}He magnetometer. Possible Xe or Hg comagnetometer	Phase1 ~ 50 Phase 2 < 5
SNS EDM	Superfluid ^{4}He	^{4}He	^{3}He capture for | ^{3}He comagnetometer SQUIDS & Dressed spins	< 4
TRIUMF	Superfluid ^{4}He	Vac.	Under Development	< 10
JPARC	Solid D_2	Vac.	Under Development	< 5
Munich FRMII	Solid D_2	Vac.	Under Development	< 5
NIST	Crystal	Solid	R & D	~ 5 ?

Superthermal Production of UCN

- 8.9 Å (12 K or 0.95 meV) neutrons can scatter in liquid helium to near rest by emission of a single phonon.



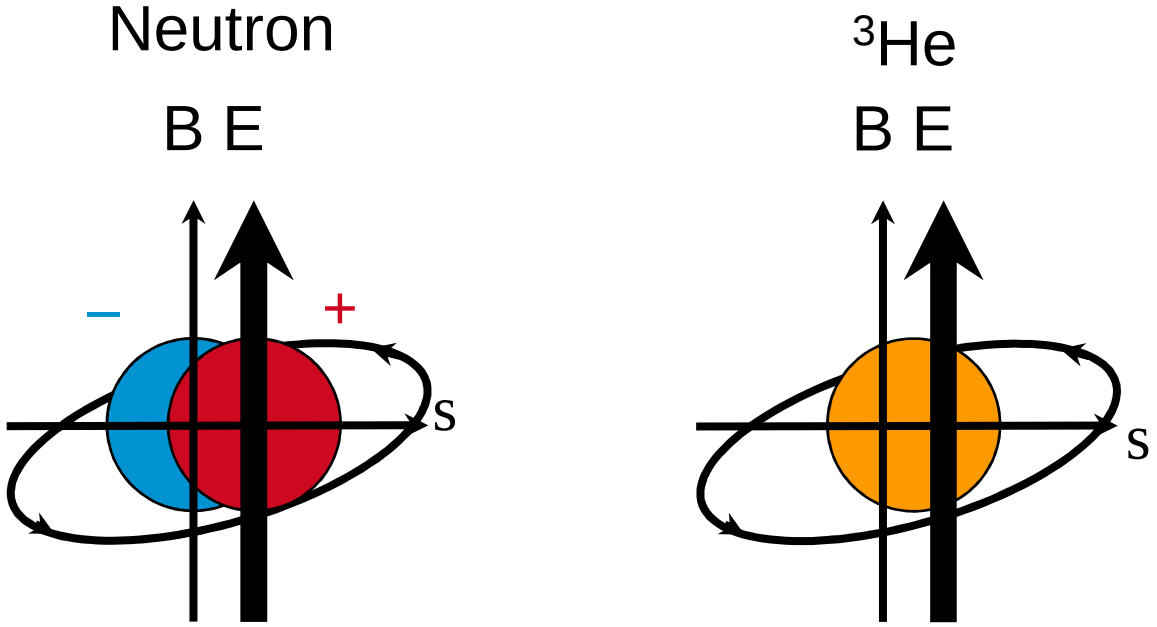
- Upscattering (by 12 K phonon absorption)
- ~ Population of 12 K phonons
  ~ $e^{-12\ K/T_{bath}}$



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Golub and Pendlebury, Phys. Lett. **53A**, 133 (1975)

Co-Magnetometry



$f_n = \gamma_n B \pm 2\, d_n E$

$f_3 = \gamma_3 B$

$\gamma_3 = 1.1\ \gamma_n$

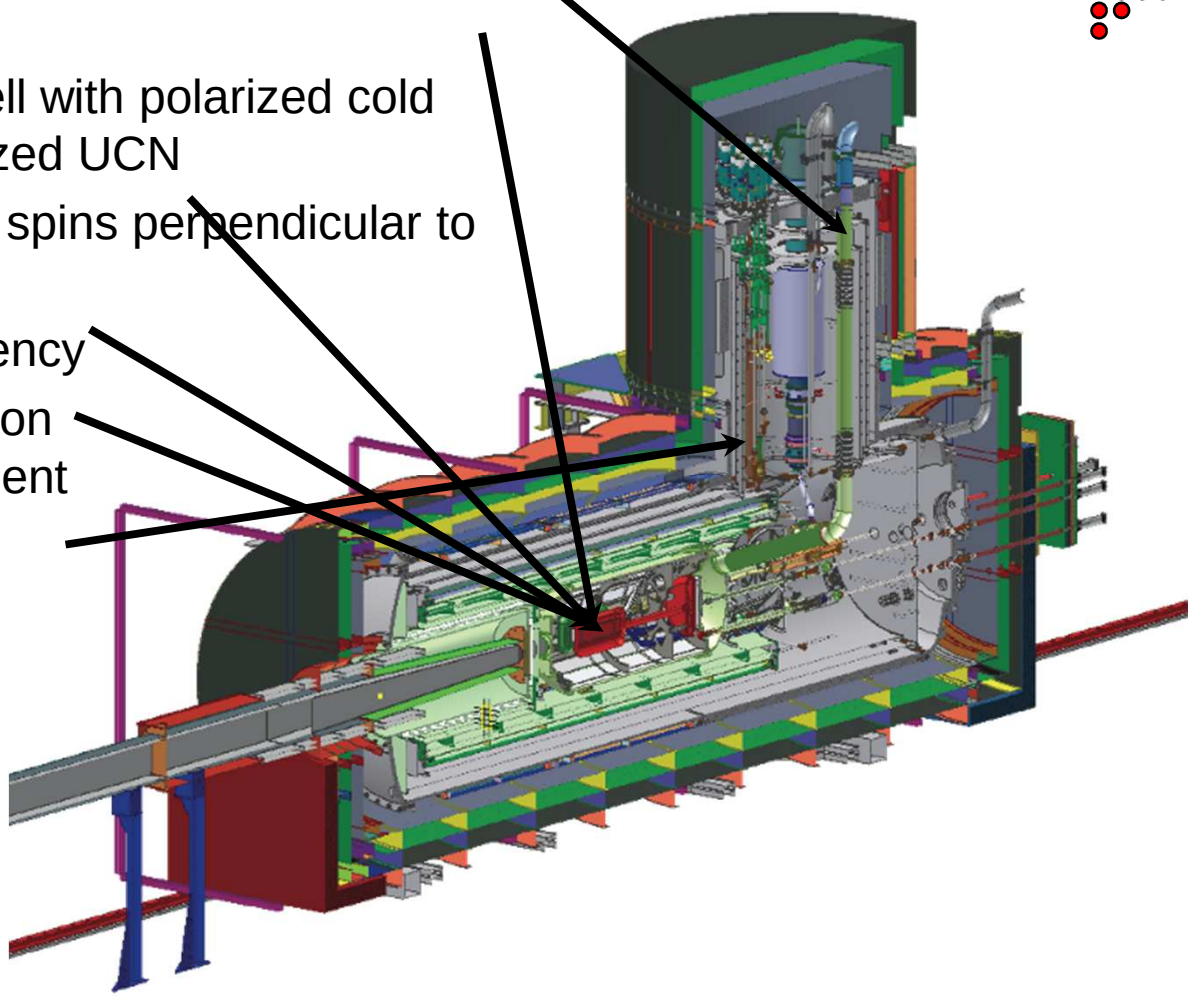
- Look for a difference in precession frequency
  $f_n - f_3 = (\gamma_n - \gamma_3)\, B \pm 2\, d_n E = (0.1\ \gamma_n)\, B \pm 2\, d_n E$
- Detect precession of ^{3}He magnetization by SQUIDS which serves as a direct magnetometer ($d_{3He} << d_n$)

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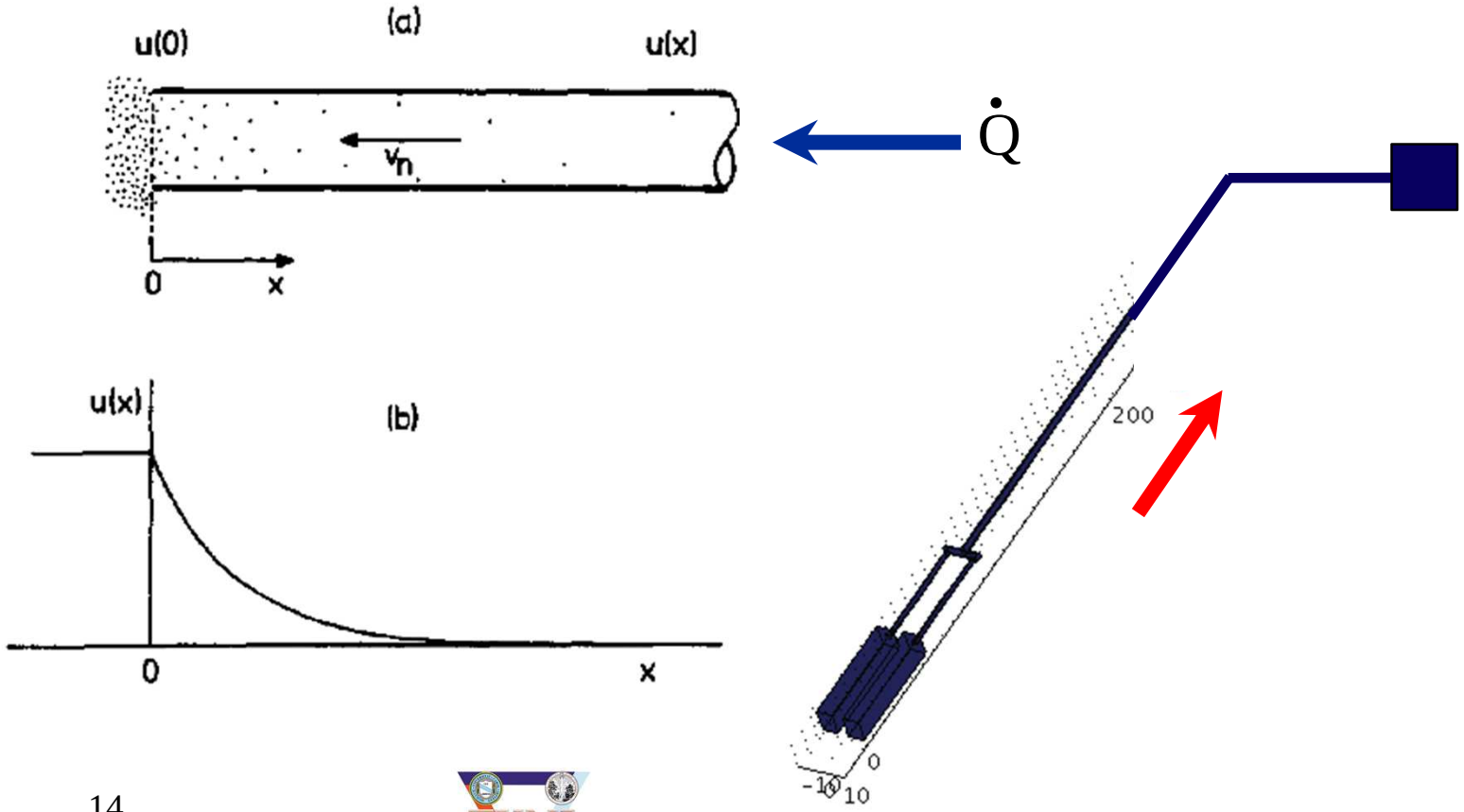
Measurement Cycle

- Load collection volume with polarized ^{3}He atoms
- Transfer polarized ^{3}He atoms into the measurement cell
- Illuminate measurement cell with polarized cold neutrons to produce polarized UCN
- Apply a π/2 pulse to rotate spins perpendicular to B_0
- Measure precession frequency
- Remove reduced polarization ^{3}He atoms from measurement cell
- Repeat (periodically reversing B and/or E)



^{3}He Transport - Heat Flush Technique

- Used to move ^{3}He around in the apparatus
- Source of our isotopically pure ^{4}He



McClintock, Cryogenics **18**, 201 (1978)

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Cryogenic Systems

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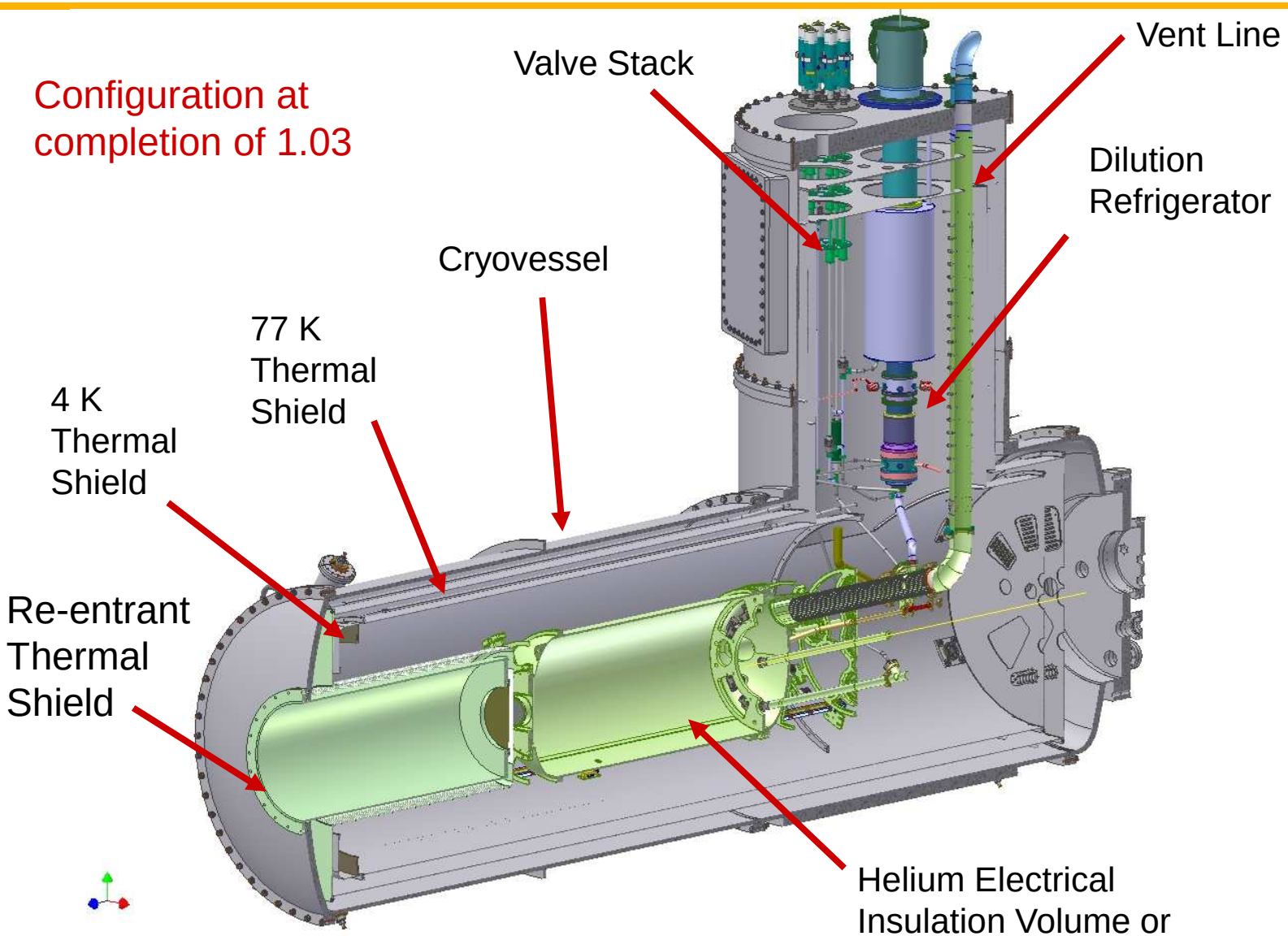
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Cryogenic Issues

- Cooling 1000 liters of superfluid helium to 0.25 K
- Injection of polarized ^{3}He atoms into liquid helium
- Heat flush of polarized ^{3}He into the target volumes
- Heat flush removal of depolarized ^{3}He from the target volumes
- Purification of the liquid ^{4}He to $X_3 \sim 10^{-12}$
- Construction using non-magnetic, non-conducting and non-activating materials
- Long-term operation, reliable cooldowns and acceptable maintenance and trouble-shooting

WBS 1.03

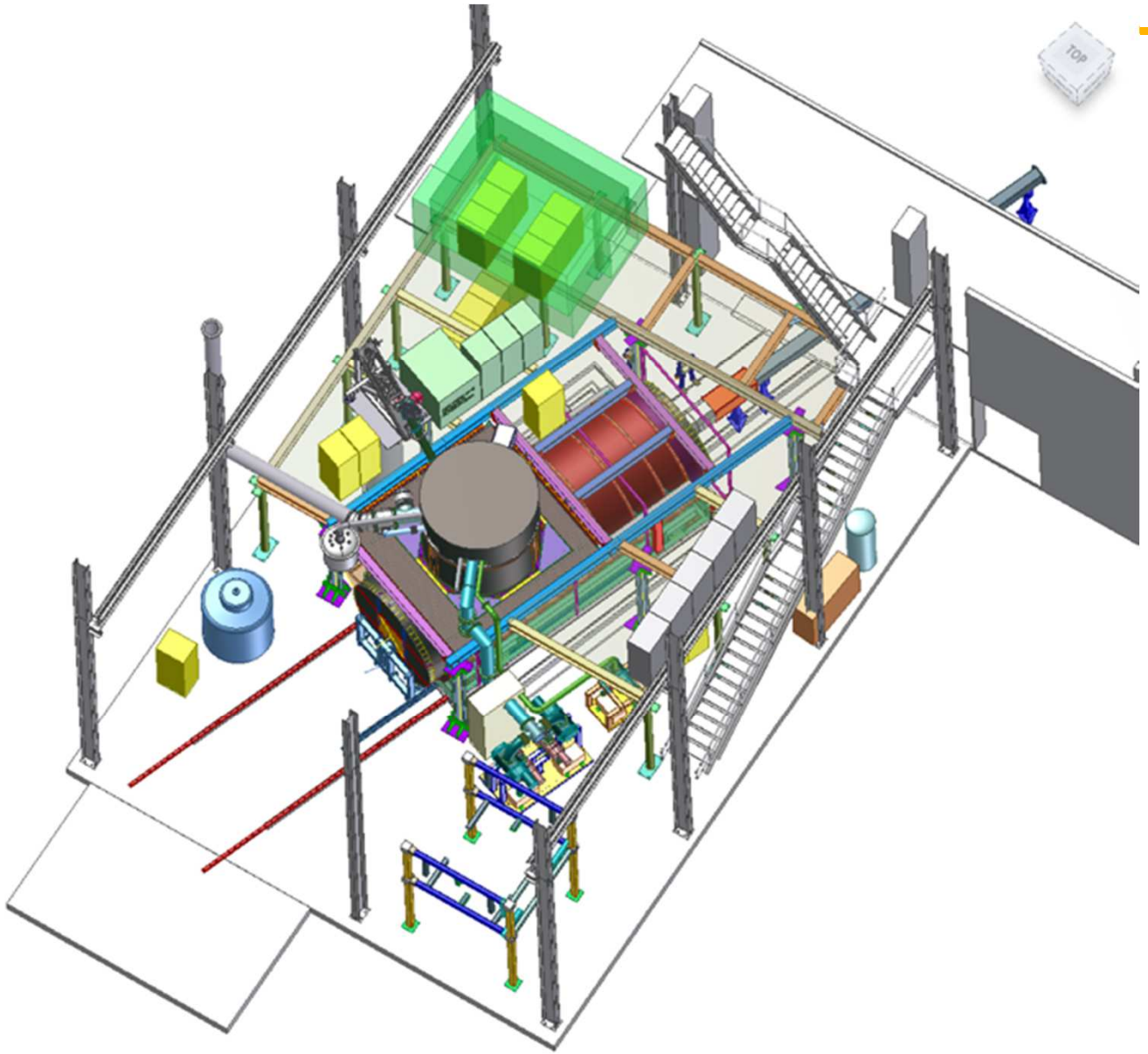
Configuration at completion of 1.03



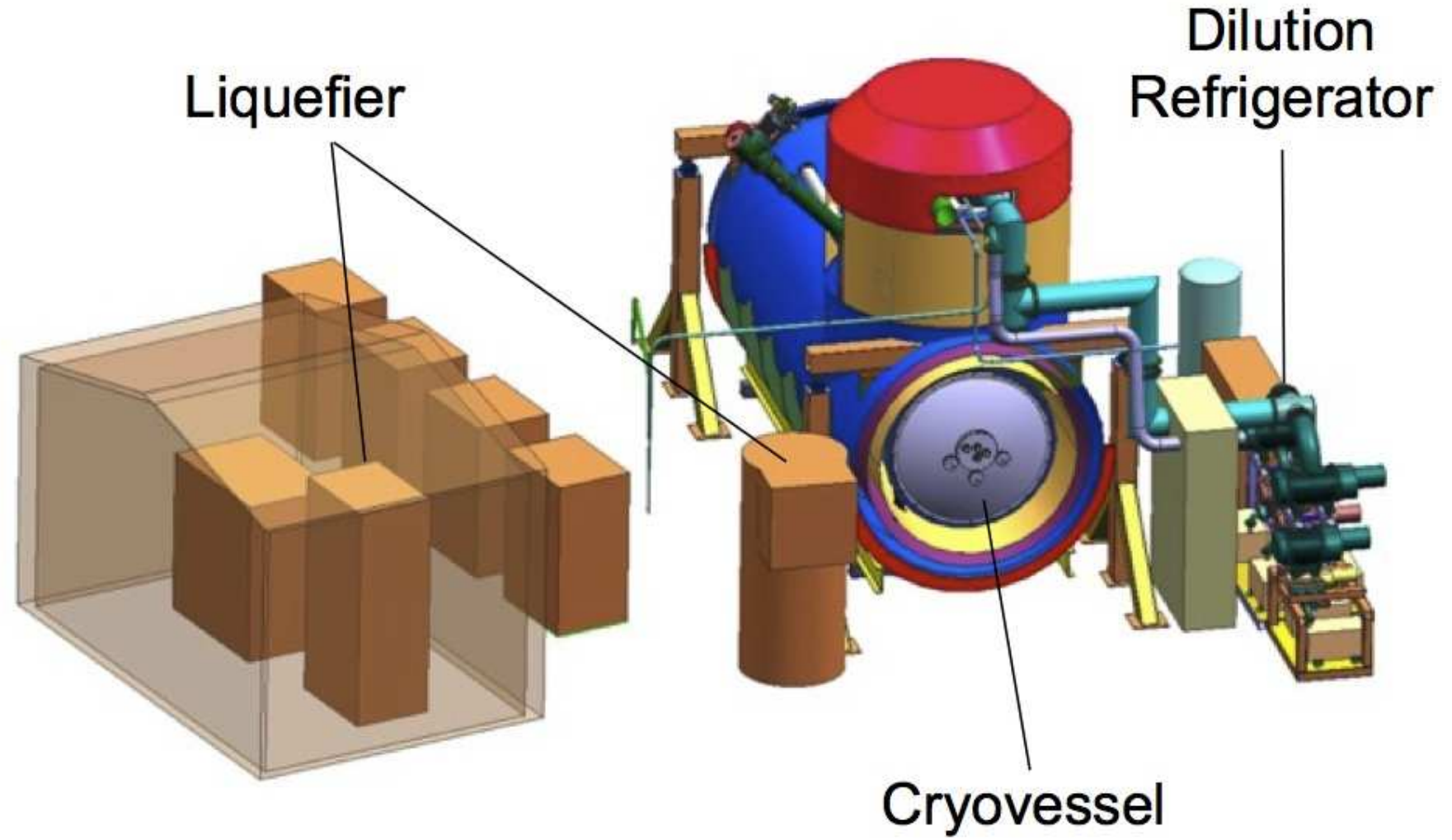
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Global View



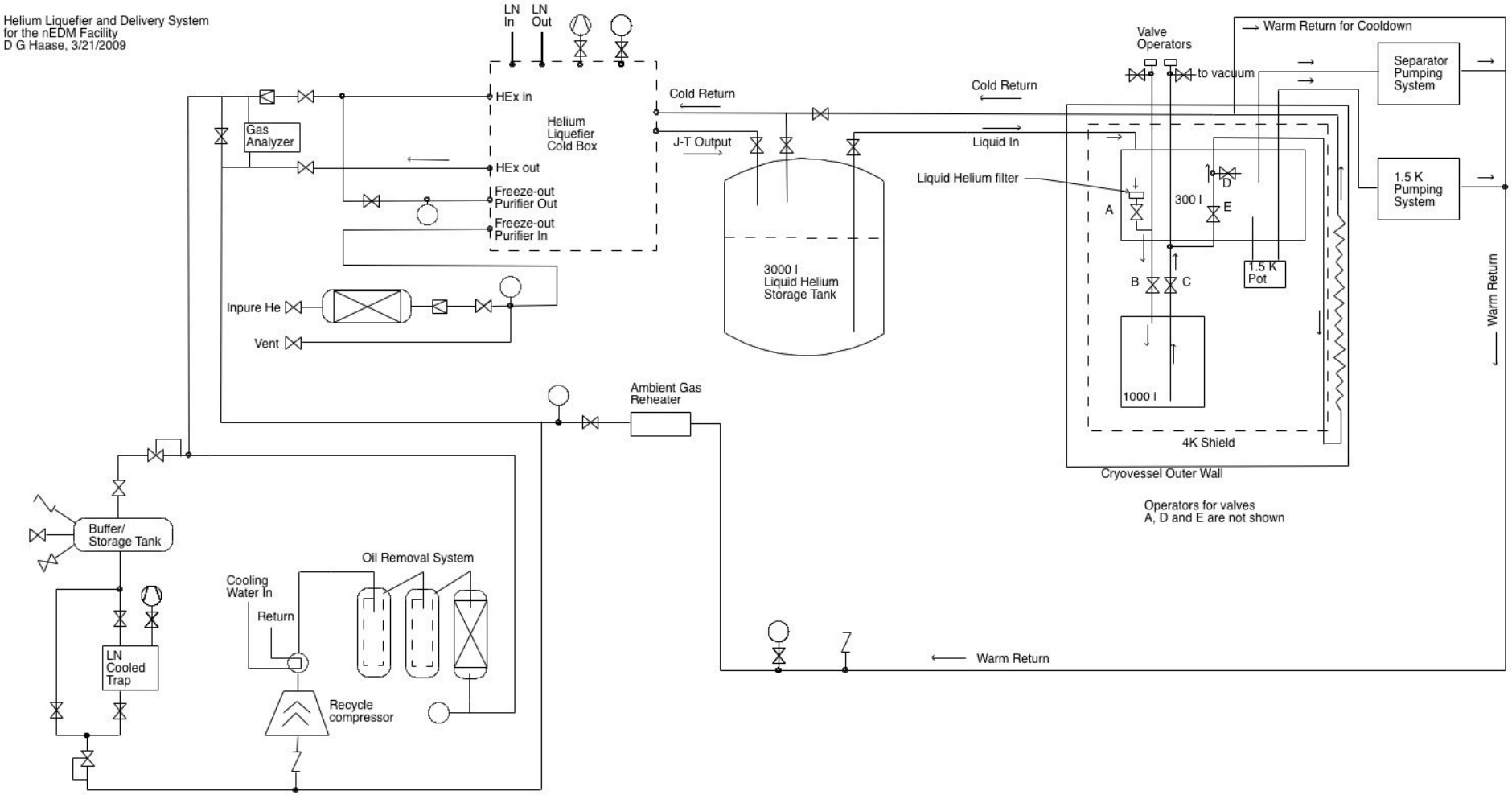
Refrigerators



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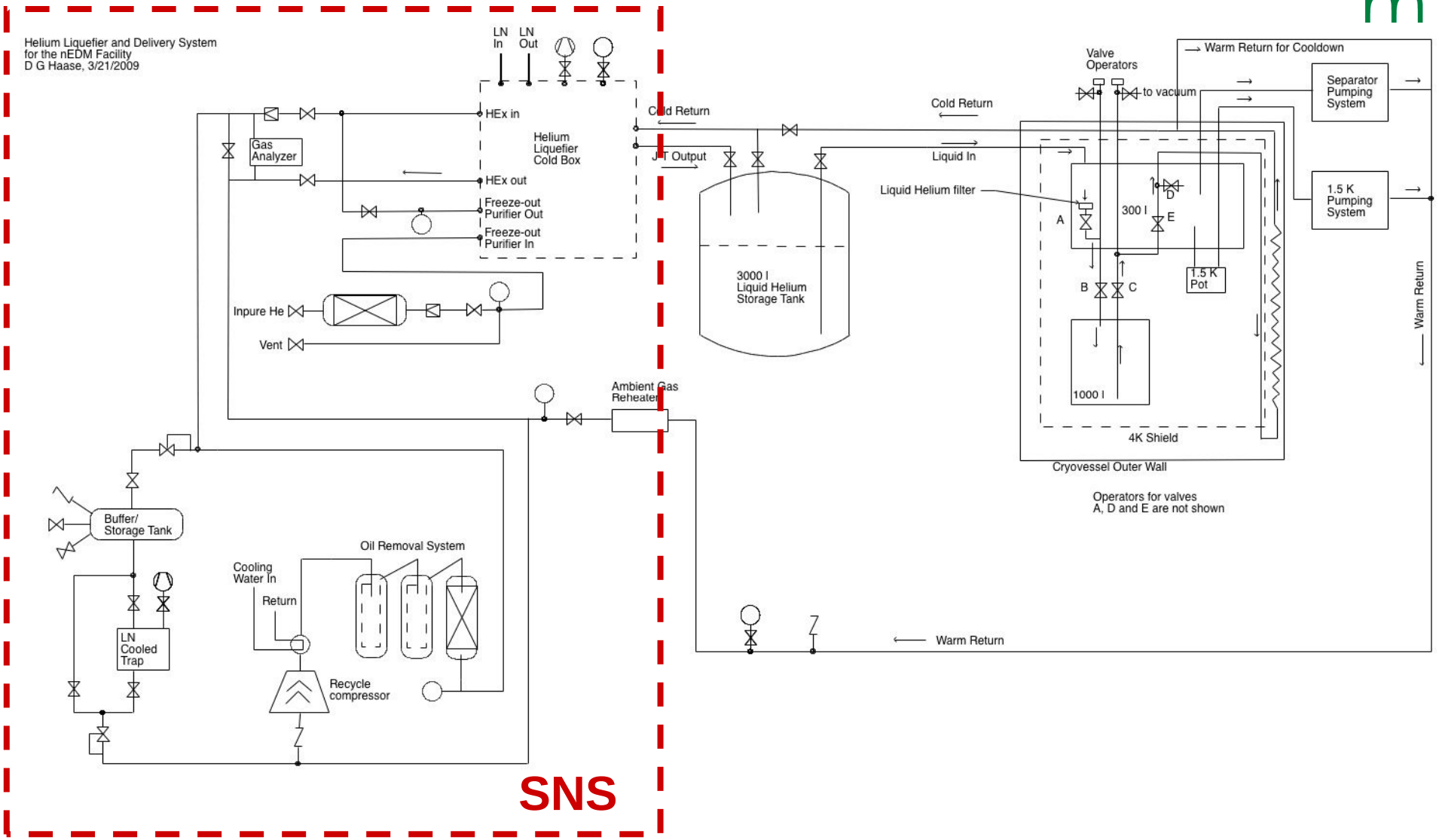
Helium Liquefier



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Helium Liquefier

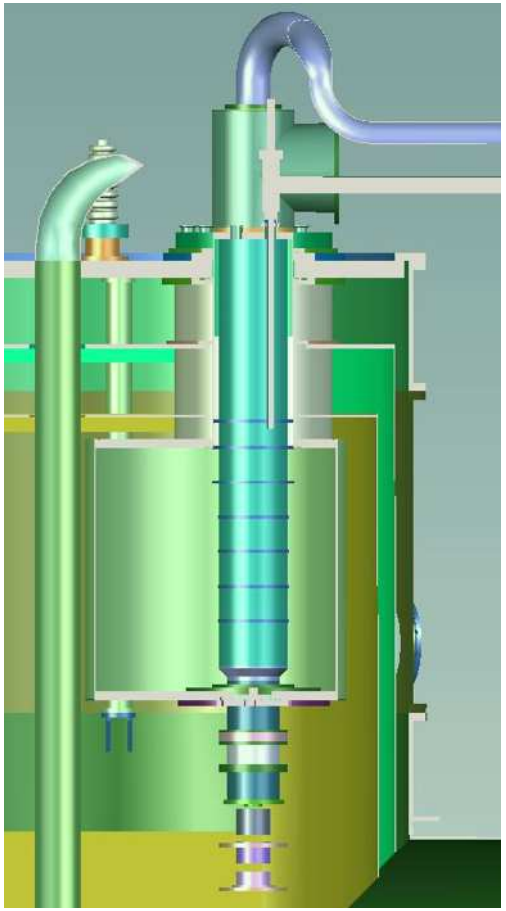


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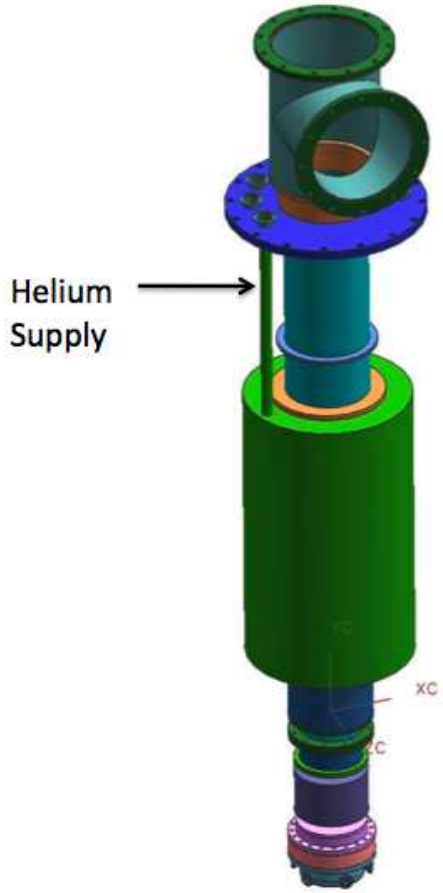
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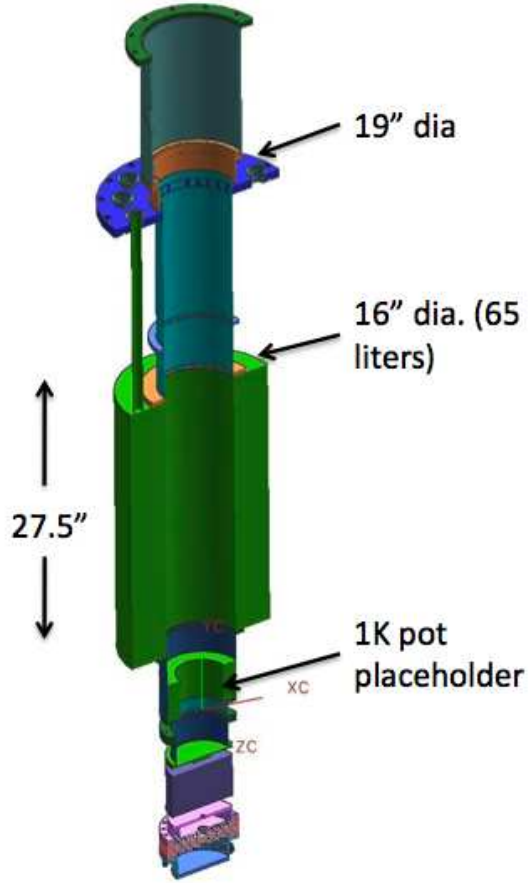
Revisions of the Dilution Refrigerator

Old



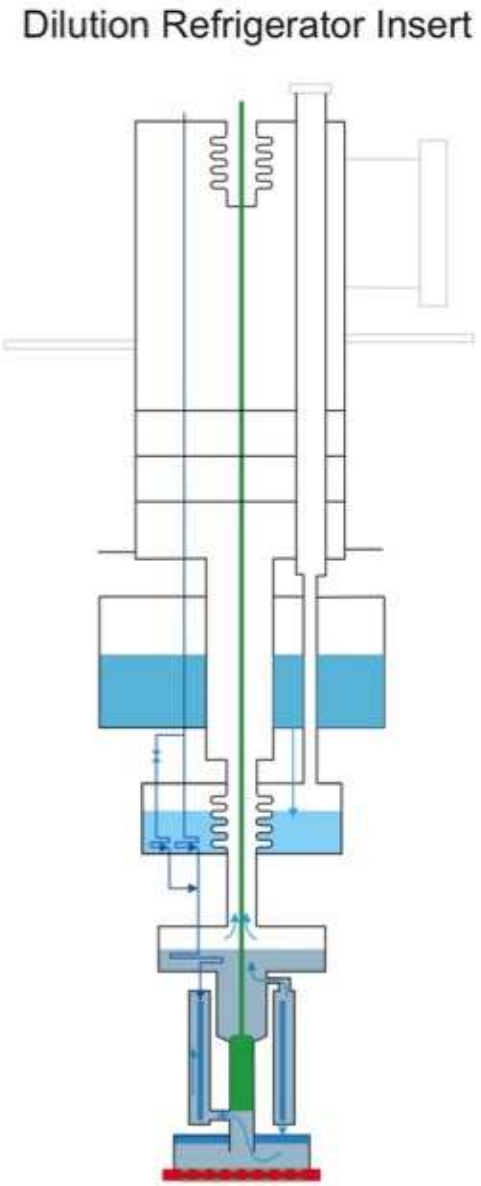
New





Dilution Refrigerator

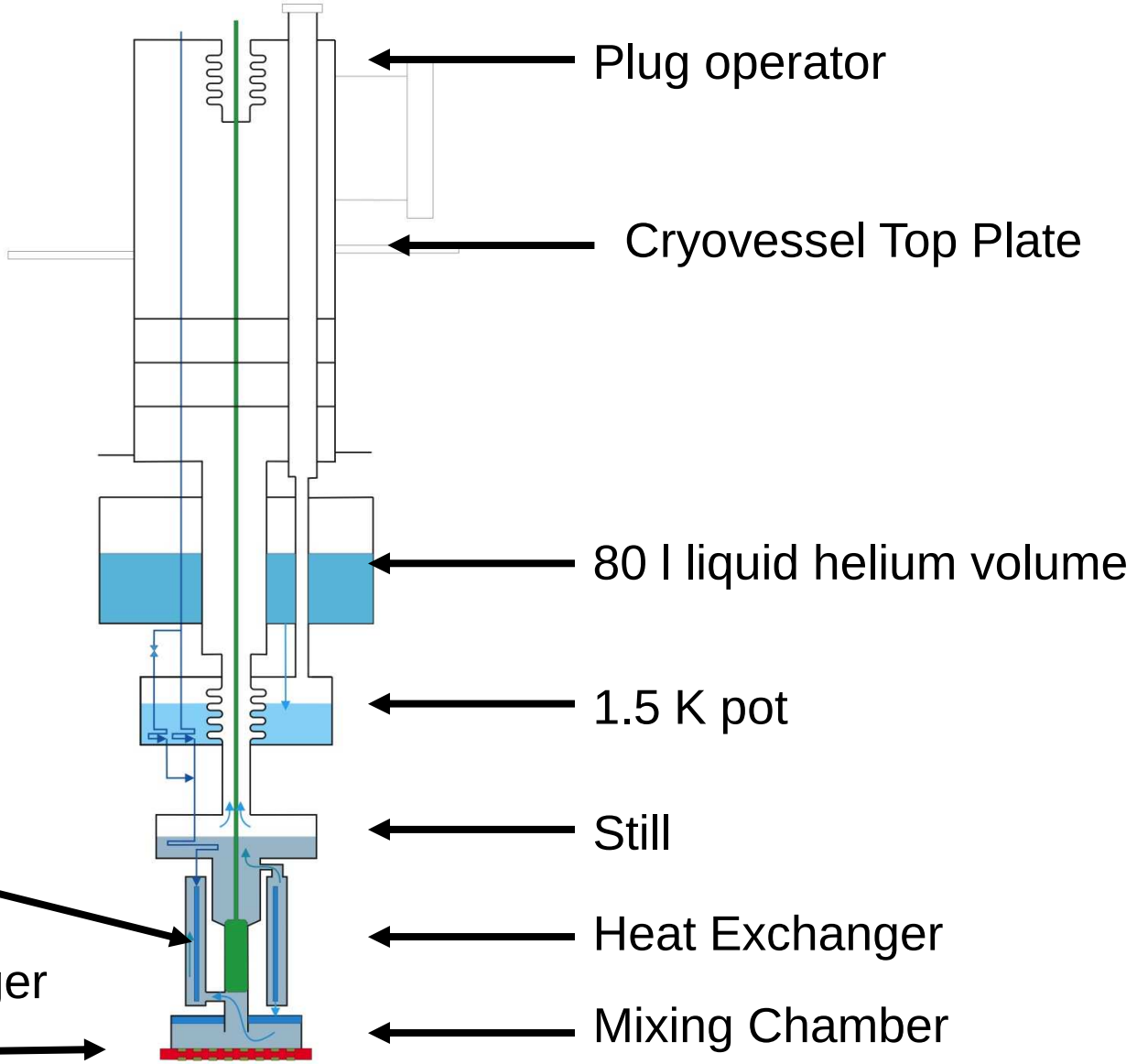
- Increase cooling power during cooldown
- Reduction of LHe entrainment volume to 80 l
  - Becomes part of DR installation
  - Reduces complexity of previous design
  - Removes large vacuum seal and metal
  - Allows simpler pre-installation testing



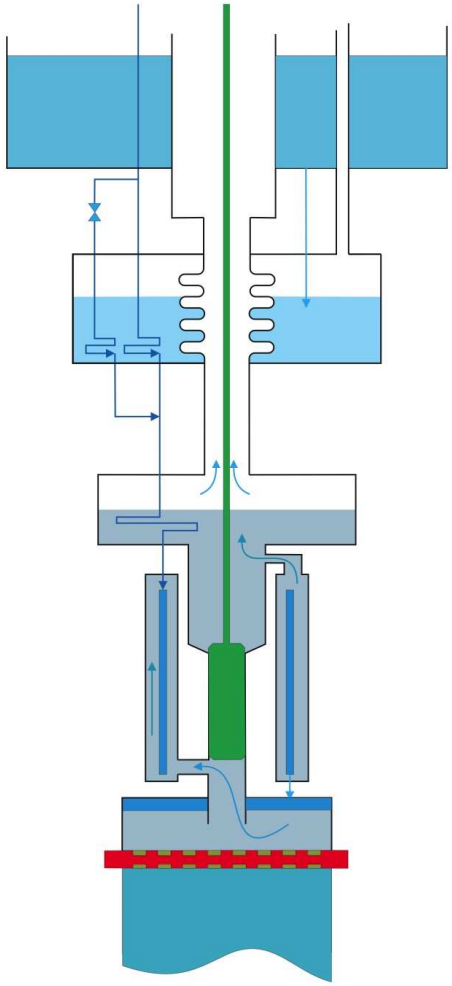
D. Haase and W. Yao

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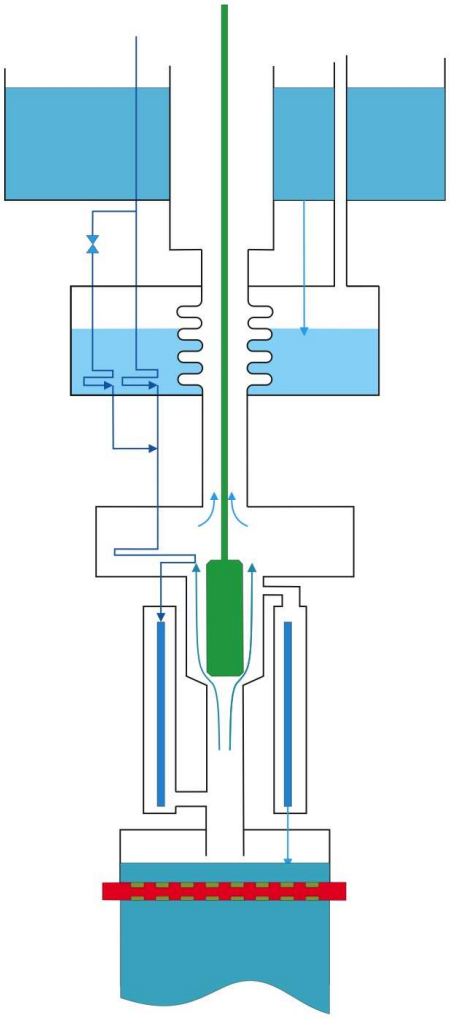
Dilution Refrigerator Insert



Work as a Dilution Refrigerator



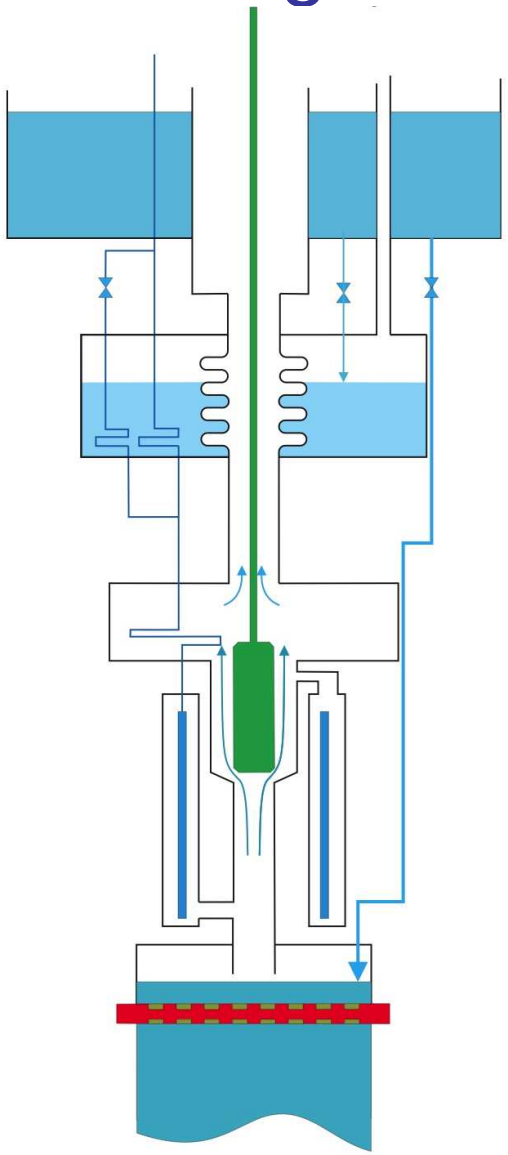
Work as a Helium 3 pot



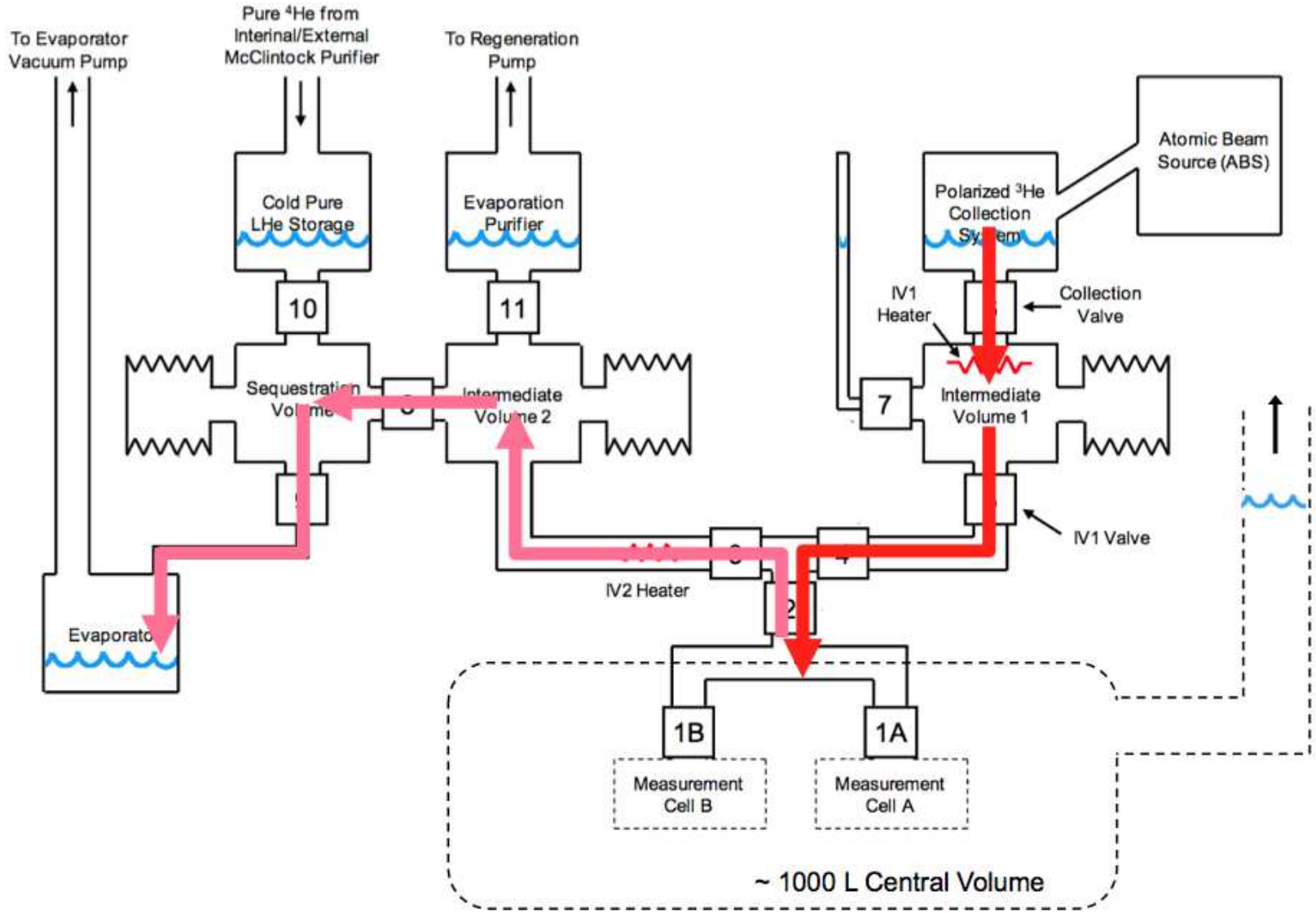
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Operation as ^{4}He refrigerator



^{3}He Volumes and Transfer

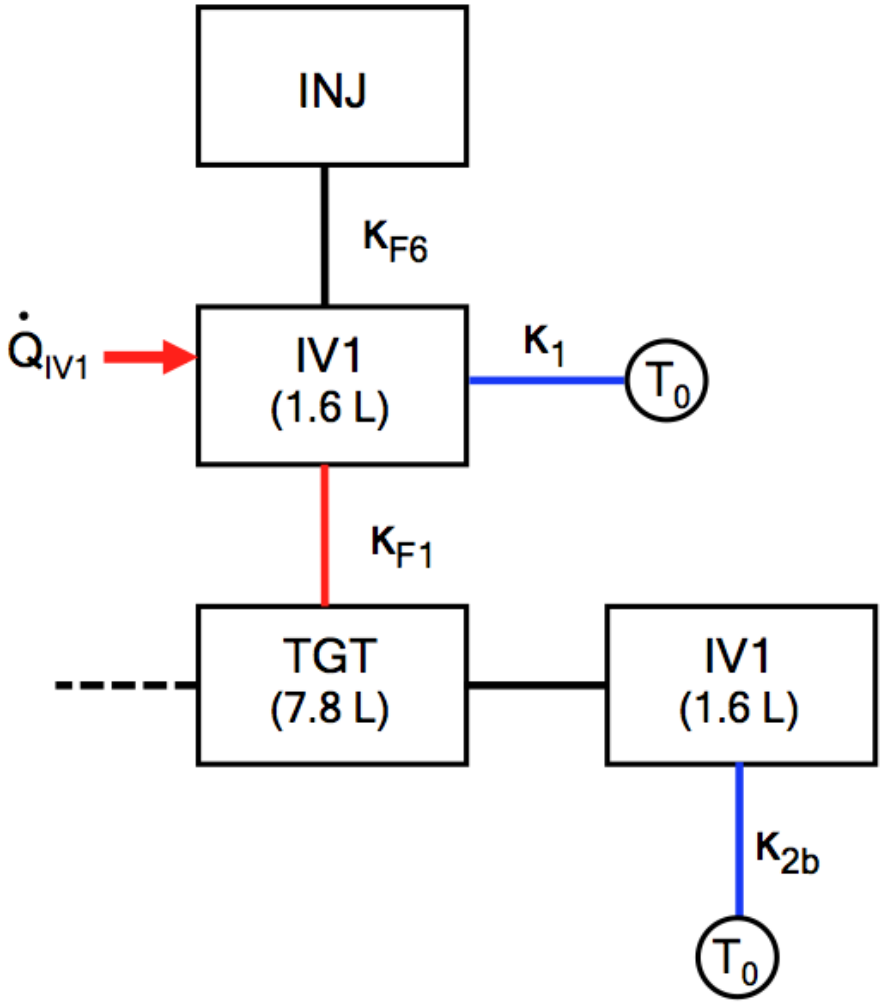


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D. Beck and D. Kendellen

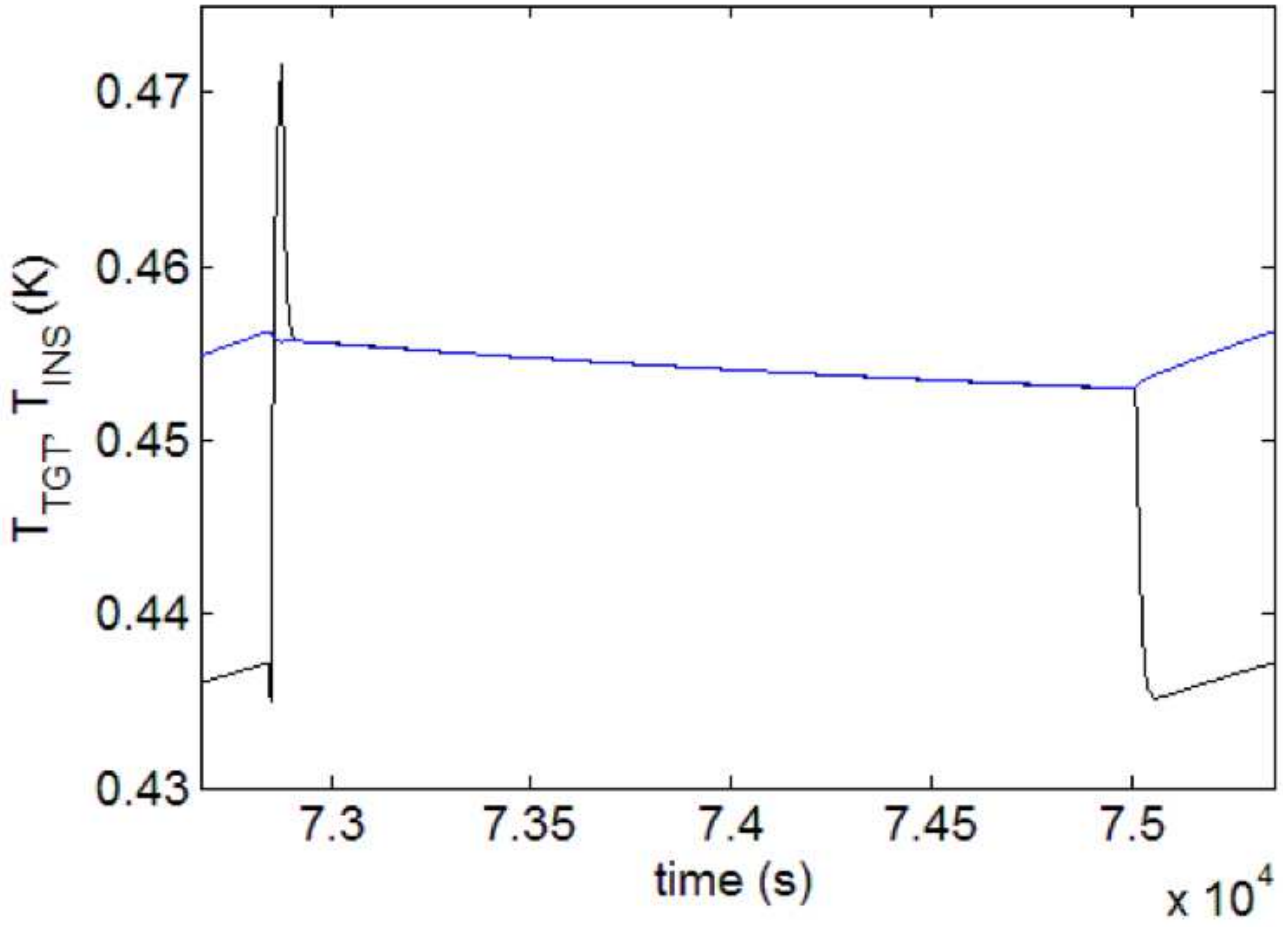
Thermal Modeling of ^{3}He Cycles



$$C_{IV1}\frac{dT_{IV1}}{dt} = \dot{Q}_{IV1} - \kappa_1(T_{IV1} - T_0) - \kappa_{F1}(T_{IV1} - T_{TGT}) - \kappa_{F4}(T_{IV1} - T_{IV2}) - \kappa_{F6}(T_{IV1} - T_{INJ})$$

$$\dot{Q}_{TOT} = \kappa_1(T_{IV1} - T_0) + \kappa_{2b}(T_{INS} - T_0) + \ldots$$

Thermal Modeling of ^{3}He Cycle

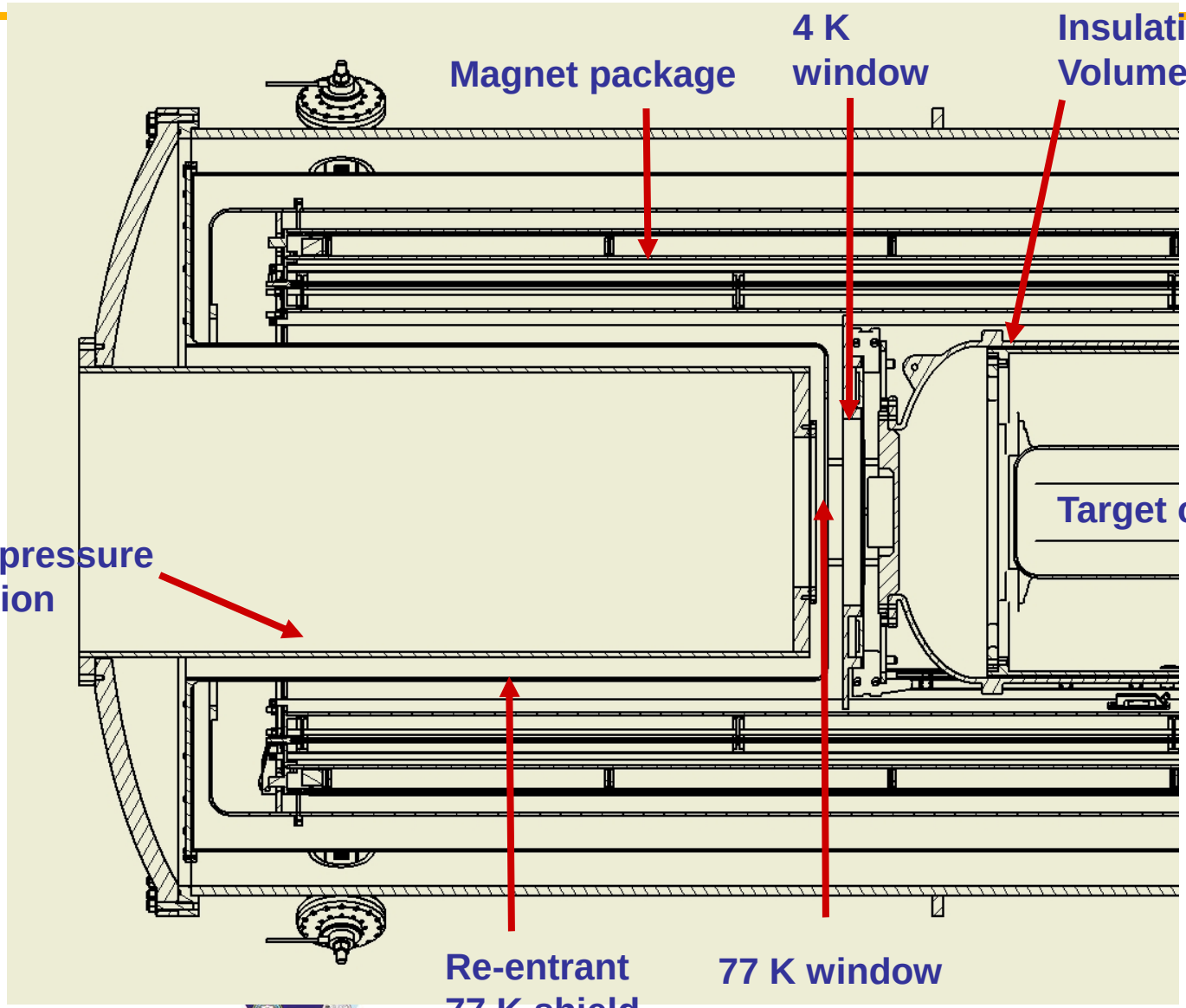


$$\dot{Q}_{TOTIN} \approx 26 \text{ mW}$$

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Cryovessel re-entrant thermal shields

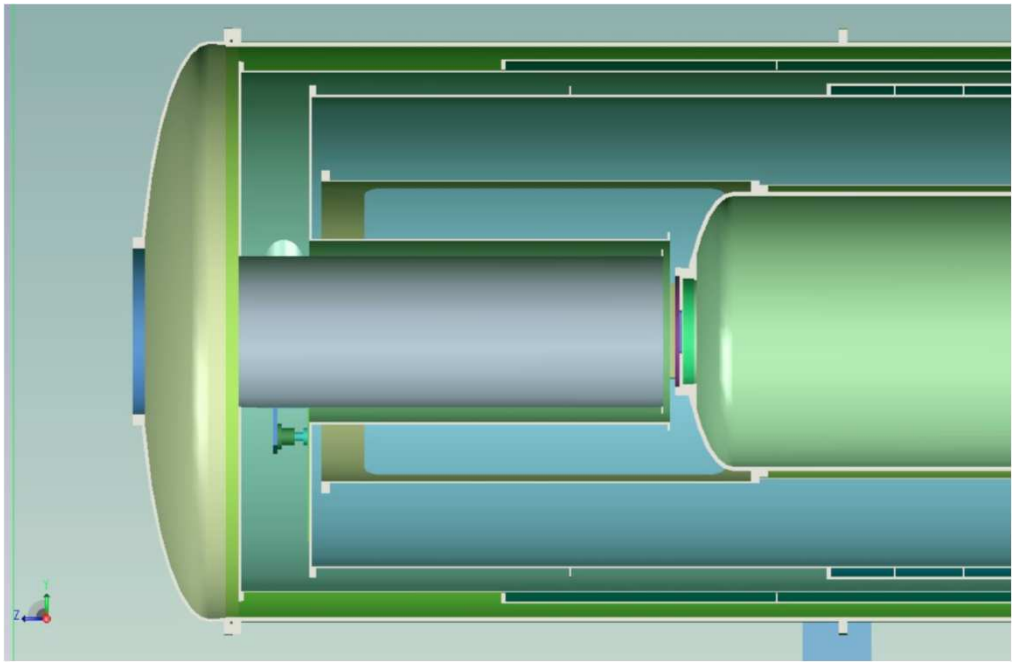


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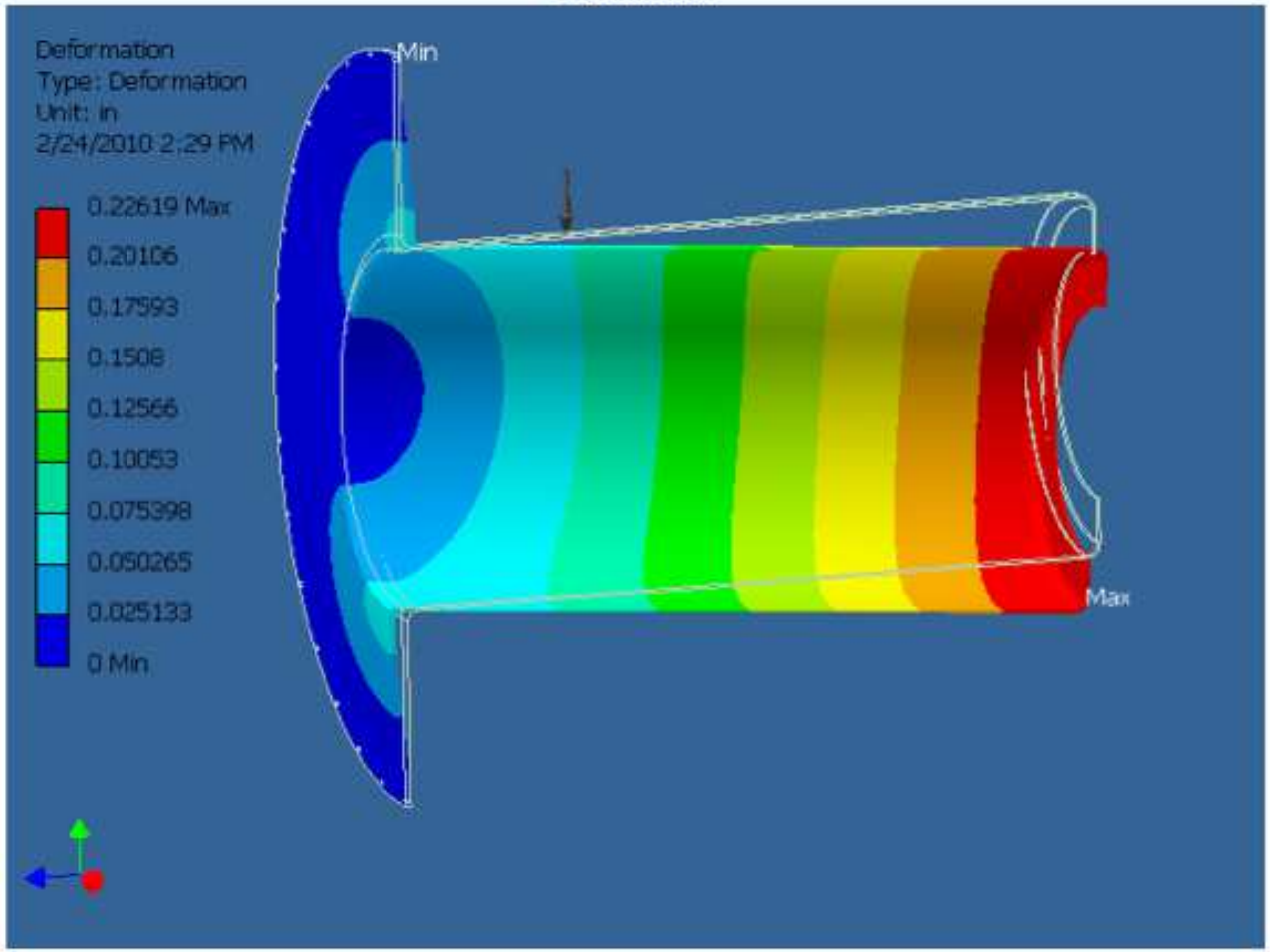
Reentrant Thermal Shield

- Problem of radiative heat flow from shield to magnet package. Also radiative shielding for Central Volume
- Patterned mylar from VAST Films, Ltd. Aluminized hexagons 2 mm circumference separated by 80 μm. $2-$5/sq.ft.



Cryovessel re-entrant thermal shields

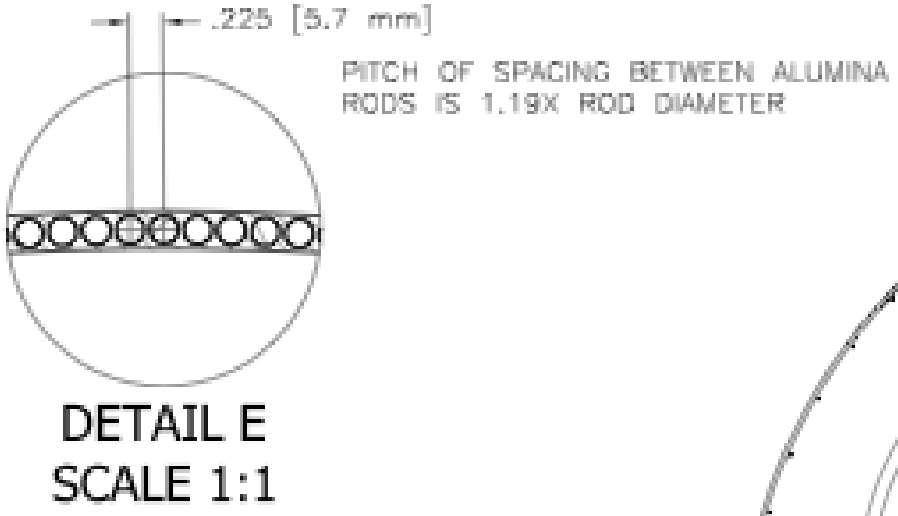
FIGURE 4
Deformation

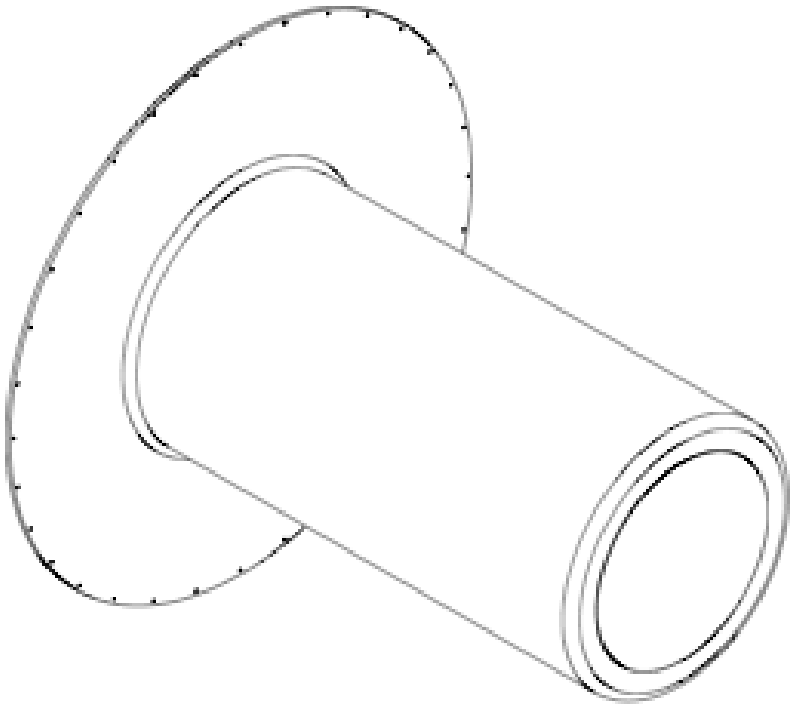


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Cryovessel re-entrant thermal shields





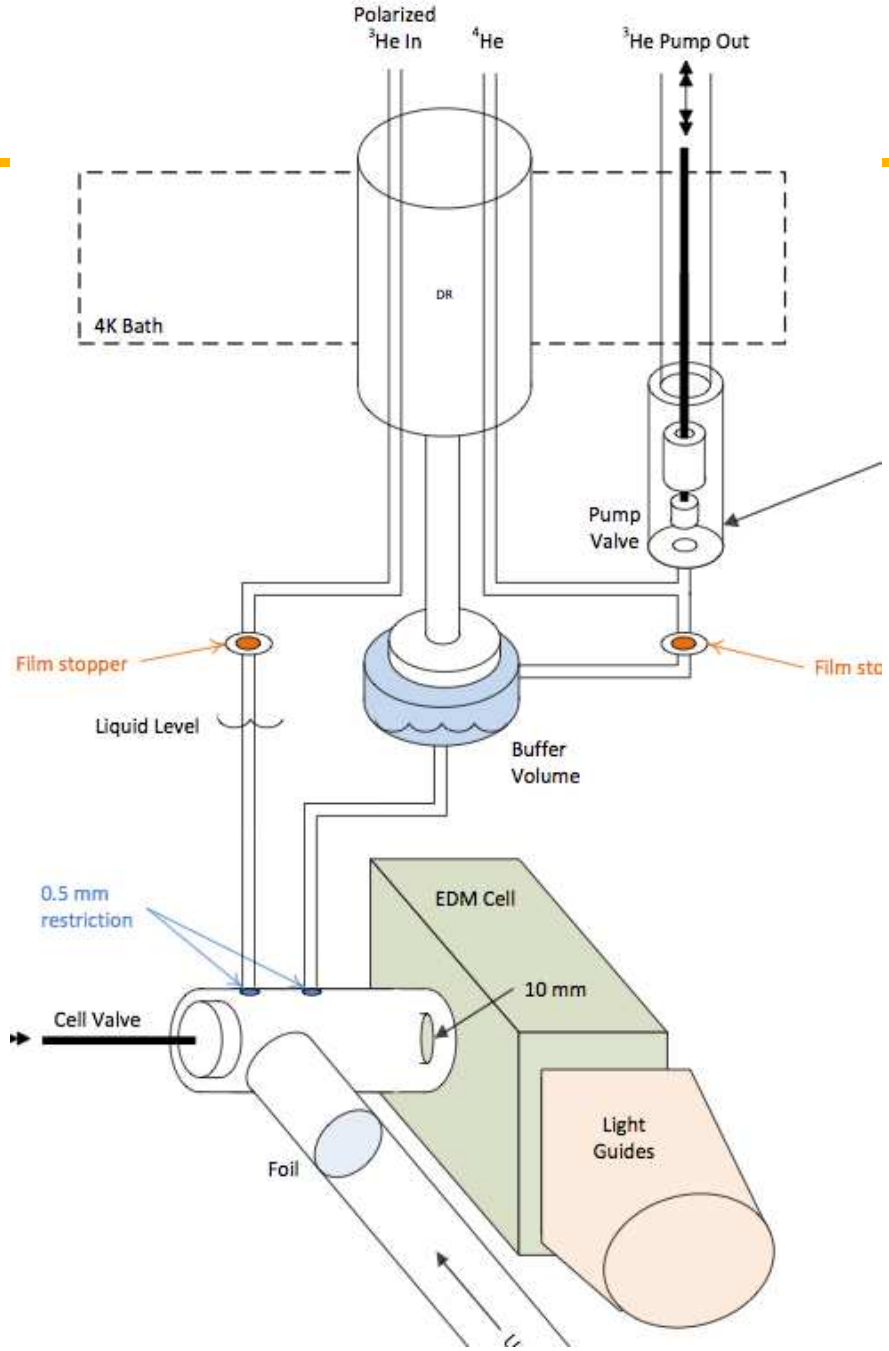
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Current nEDM activities

- Medium Scale High Voltage Tests (LANL)
- Tests of Electrode Coating Materials (IU and LANL)
- ^{3}He Injection Process (UIUC and Harvard)
- nEDM Test Facility at PULSTAR (NCSU, UK)

Test Facility at PULSTAR

- Capture neutrons
- Measure n decays
- Optimize cell coatings
- Inject and remove ^{3}He



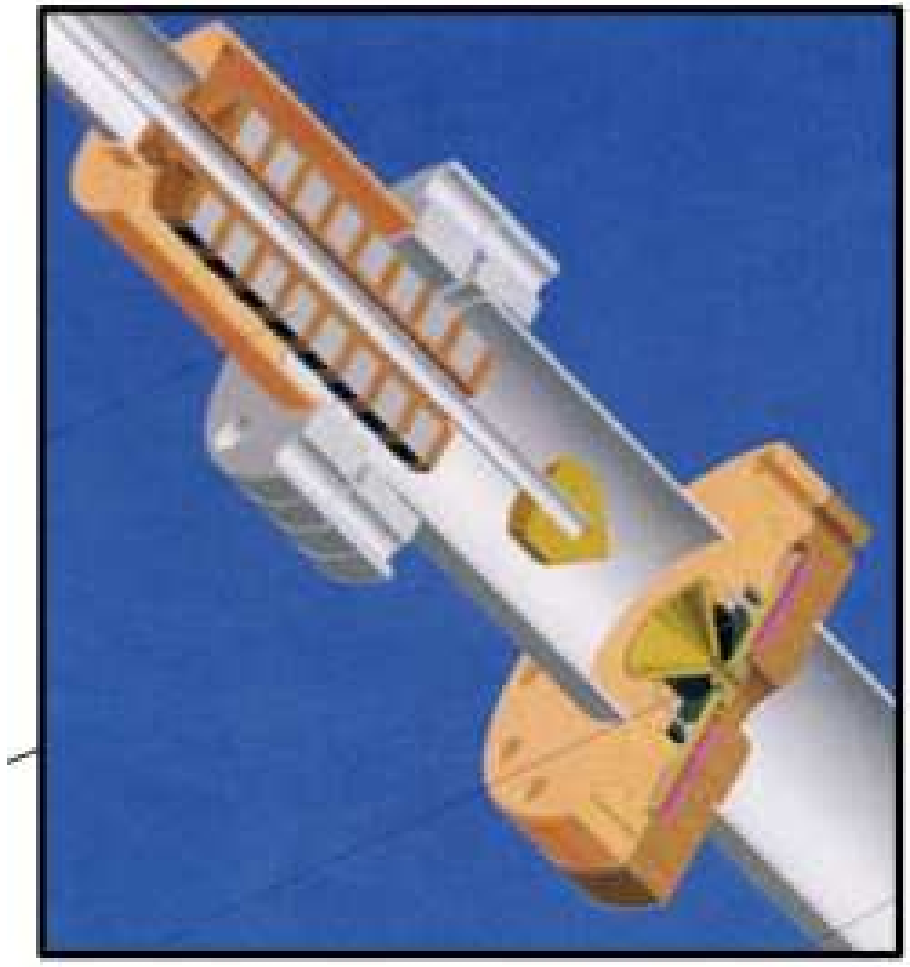
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Operating Cycle

- Dissolve polarized ^{3}He into the sample cell from a storage volume. $X_3 \sim 10^{-10}$
- Perform experimental measurements
- Remove ^{3}He by pumping with a charcoal adsorption pump
- When the pump surface is fully covered, close off the charcoal volume and regenerate by heating to ~ 20 K

Charcoal Adsorber and Valve
(W. Yao)

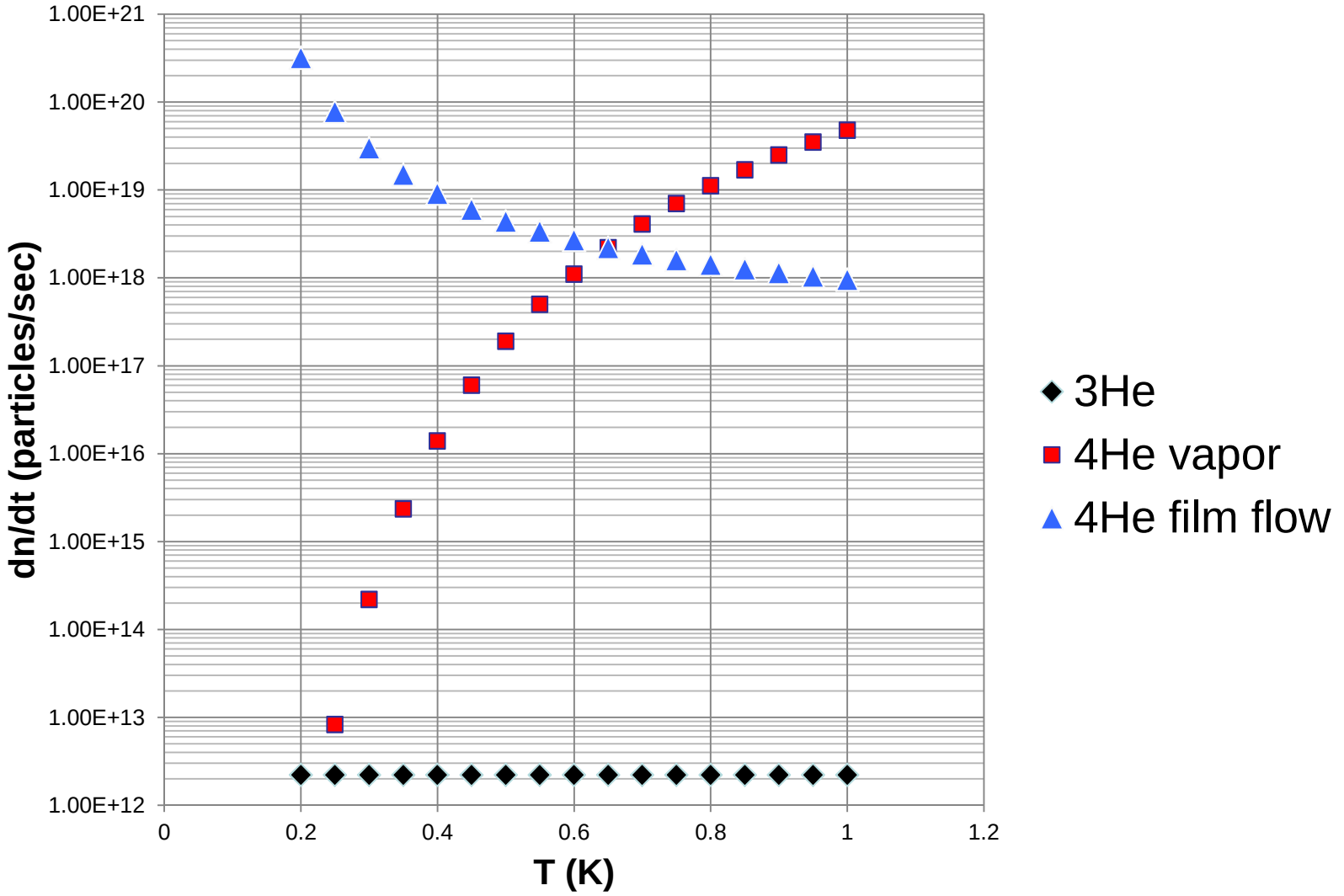


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Calculations of ^{3}He and ^{4}He Removal

- Approach – calculate orifice diameter required to remove the ^{3}He within 16 hours.
- Then use that geometry to calculate flow rates for ^{4}He through effusion and through film flow
- Compare rates to choose an optimum temperature for the purification
- An ideal situation would be to purify near the operating temperature and also extend the lifetime of the charcoal adsorber before regeneration

Gas Flow Rates vs Temperature



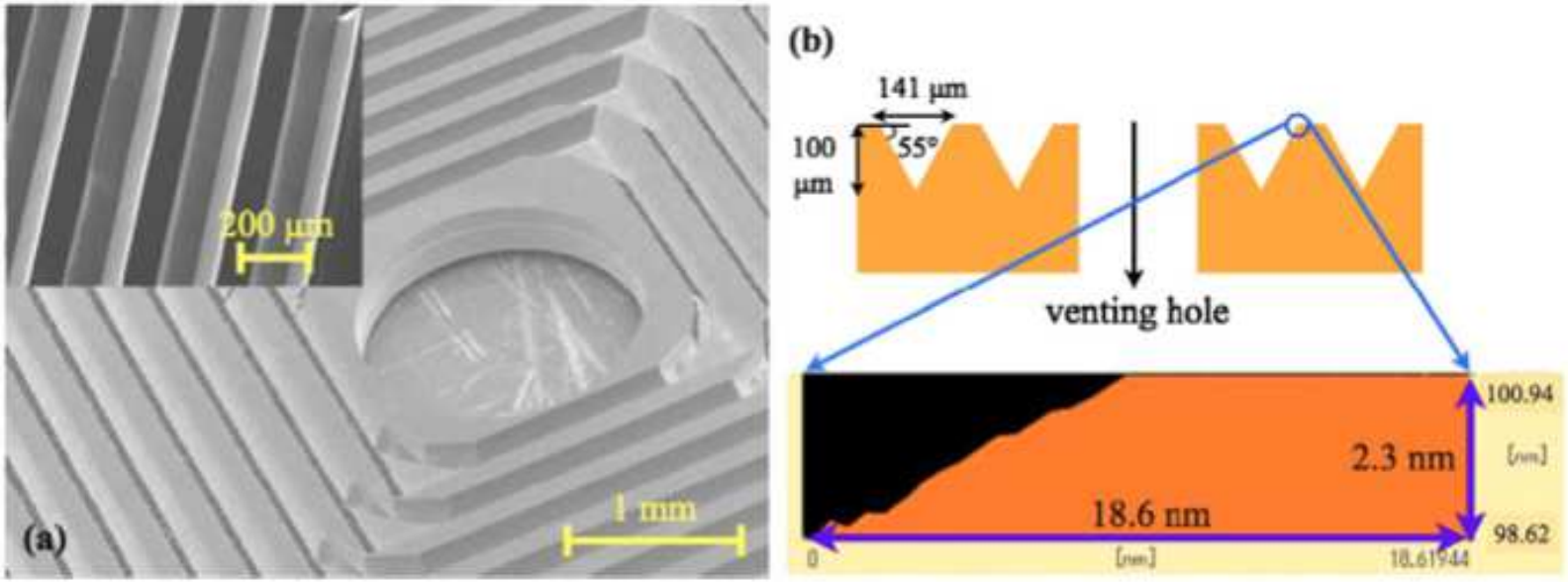
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Suppression of ^{4}He Collection

- Deal with it – large charcoal adsorber and regular regeneration cycle
- Traditional film burner – causes a heat load of 0.1 to 1 mW
- Film “pinner” using sharp edged etched Si chip, which could also be used on fill line

Etched Silicon Film Suppressor



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K. Ishikawa et al. / Cryogenics 50 (2010) 507–511

Processing of Etched Silicon

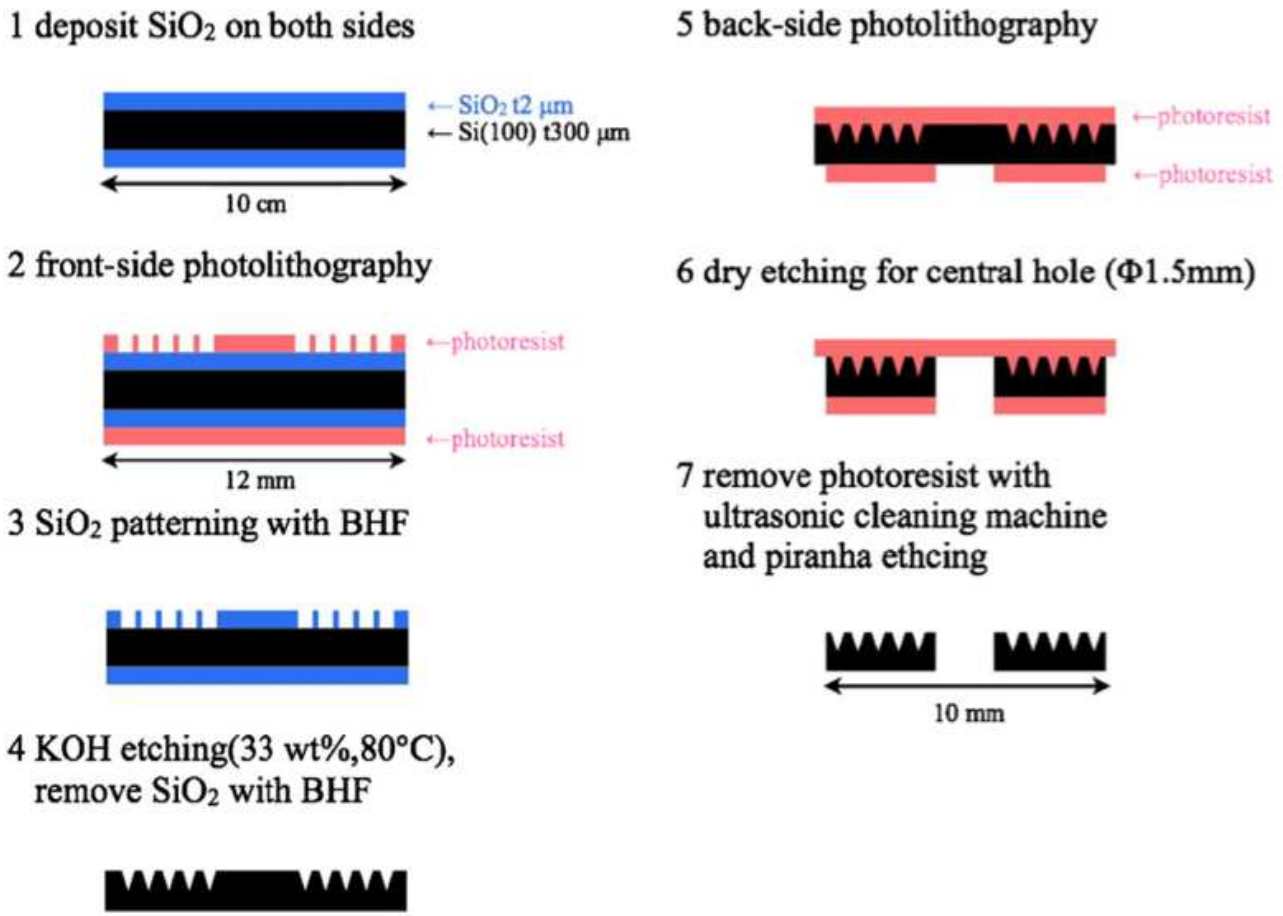


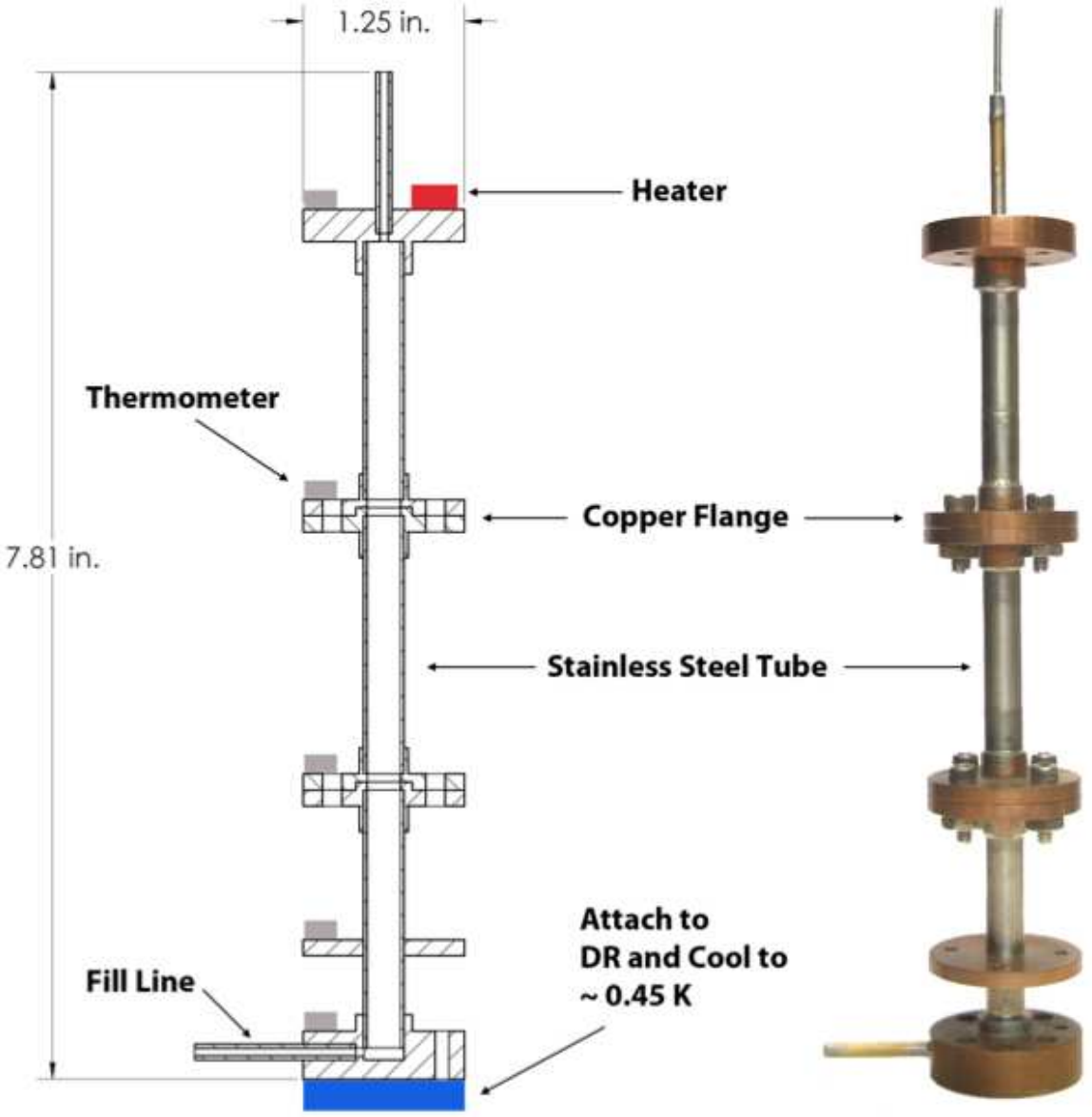
Fig. 3. Process flow for the production of knife edge devices. Cross-sectional views of the wafer are shown.

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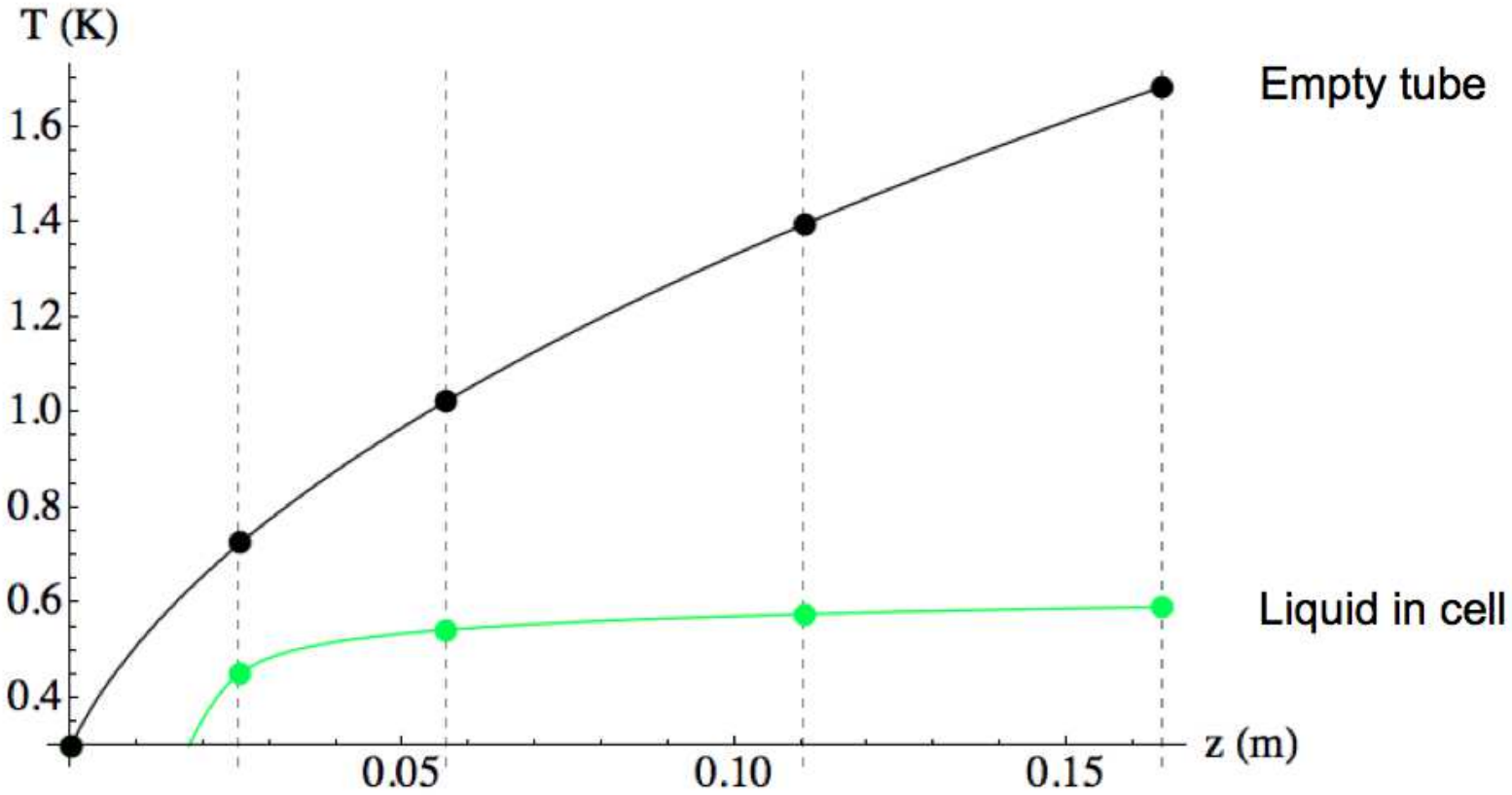
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K. Ishikawa et al. / Cryogenics 50 (2010) 507–511

^{4}He film flow measurements



^{4}He film flow measurements



T_0 = 0.3 K, h = 0.7″, $\dot{Q}$ = 20 μW

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Dilution Refrigerator at NCSU





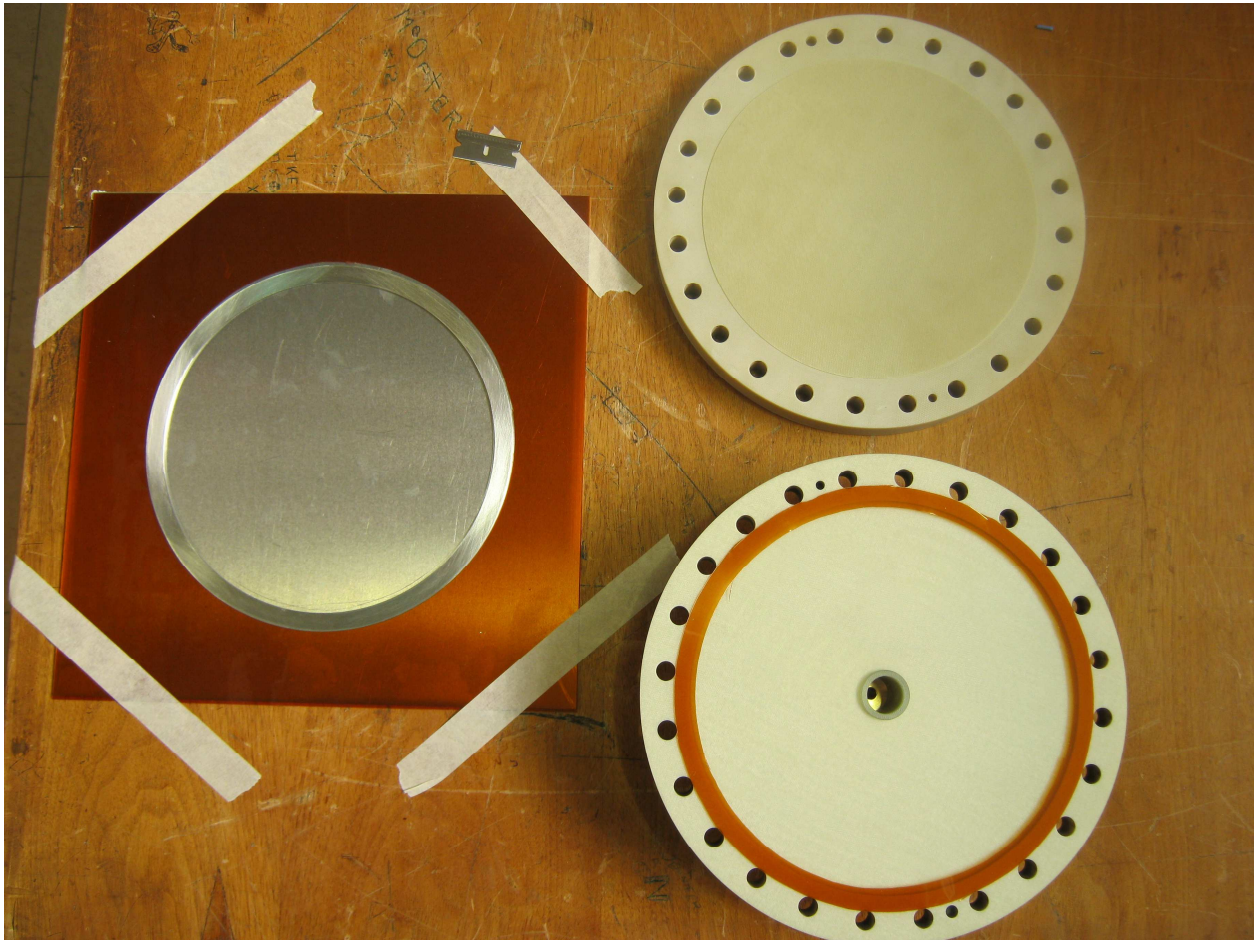
Molded composite fixture



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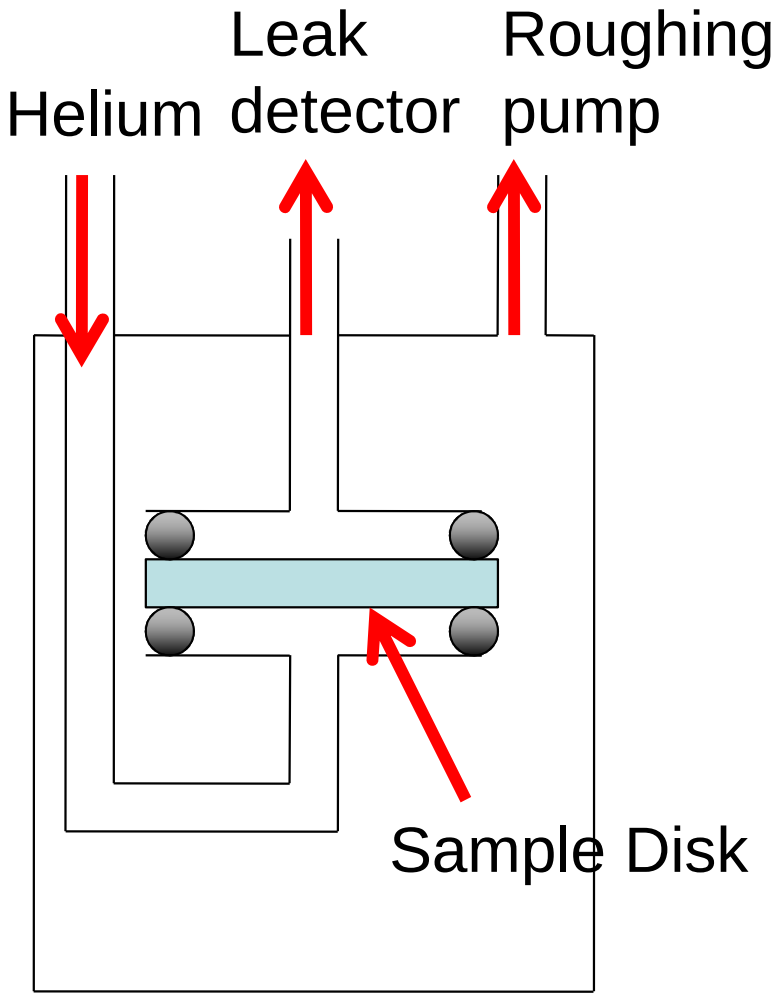
G-10 Test Volume and Kapton Seal



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Room temperature diffusion test system

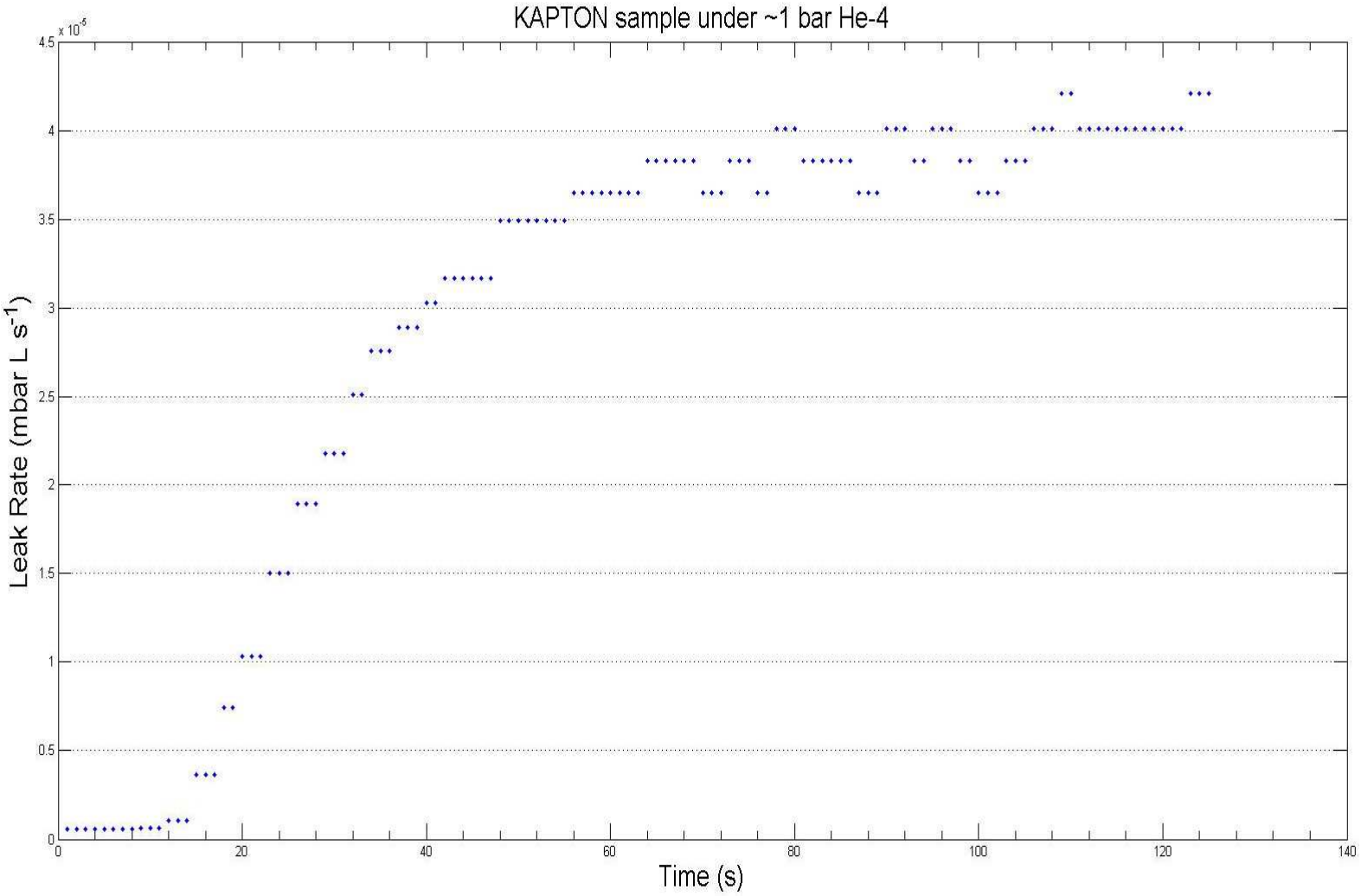




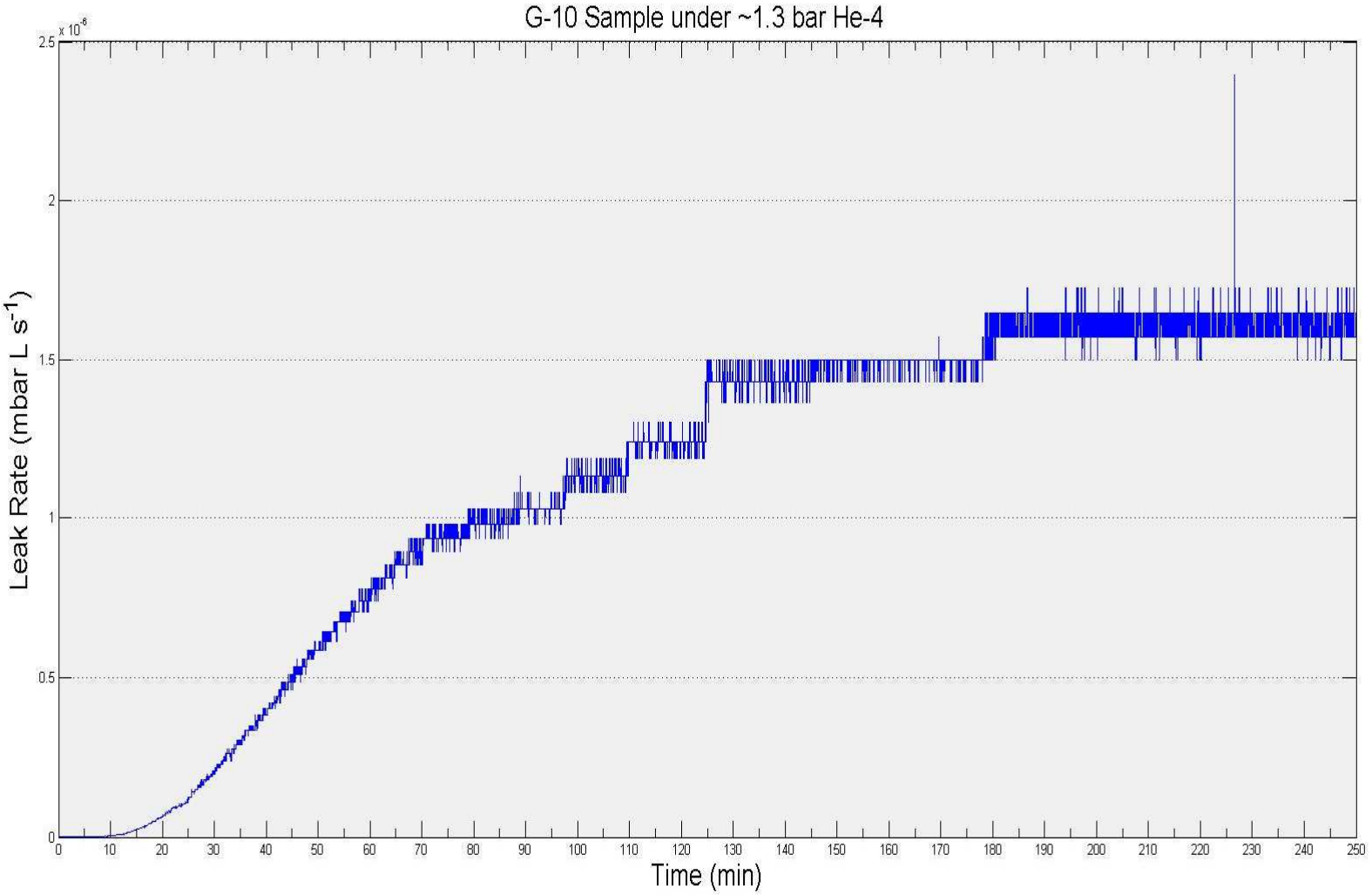
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Diffusion through 5 mil Kapton



Diffusion through G-10 (31 mil) at room temperature



Summary

- "…**the US nEDM experiment (~4 x 10^{-28} e-cm) would have a profound impact on nuclear physics, particle physics and cosmology, even in the event of a negative result.**"
- In the interim period the highest priority is confirming that the high voltage specifications can be met
- Additional R&D to prepare for full-scale efforts
- Project management status has been changed – to great advantage
- We look forward to return to construction, installation and testing



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Cryogenic Test Facility at NCSU





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Medium Scale High Voltage Tests

- Building smaller-scale test facility (~10 cm electrodes).
- Close oversight by the ITC
- Questions to be addressed
  - electrode material selection
  - pressurization requirements
  - acrylic cell and coatings
  - leakage current
  - SQUID survivability

