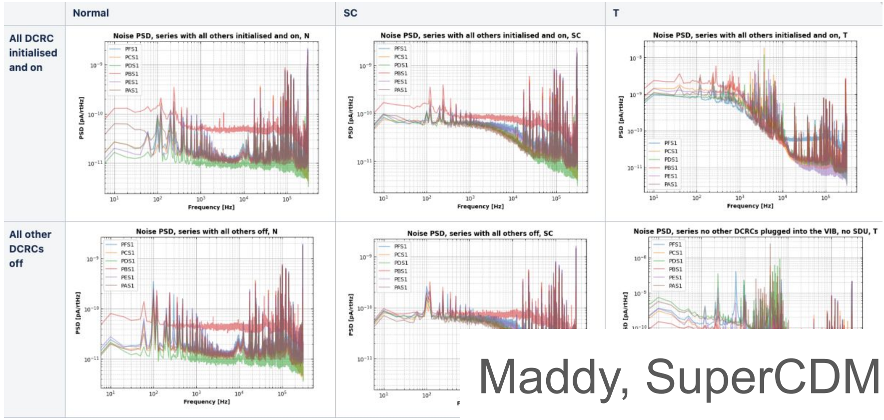
Battle with noise: Cooling it down..

Lecture prepared with input from
Doug Pinckney, Adam Mayer, etc.

Noise…

- Noise is often one of the limitations of particle detectors
- Especially true for lots of rare event search experiments
- Understanding & minimizing noise is a constant topic of the field…



Maddy, SuperCDMS

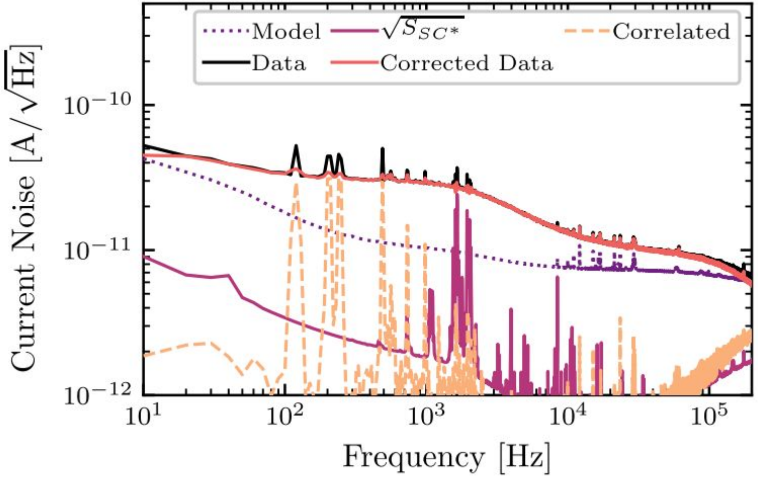


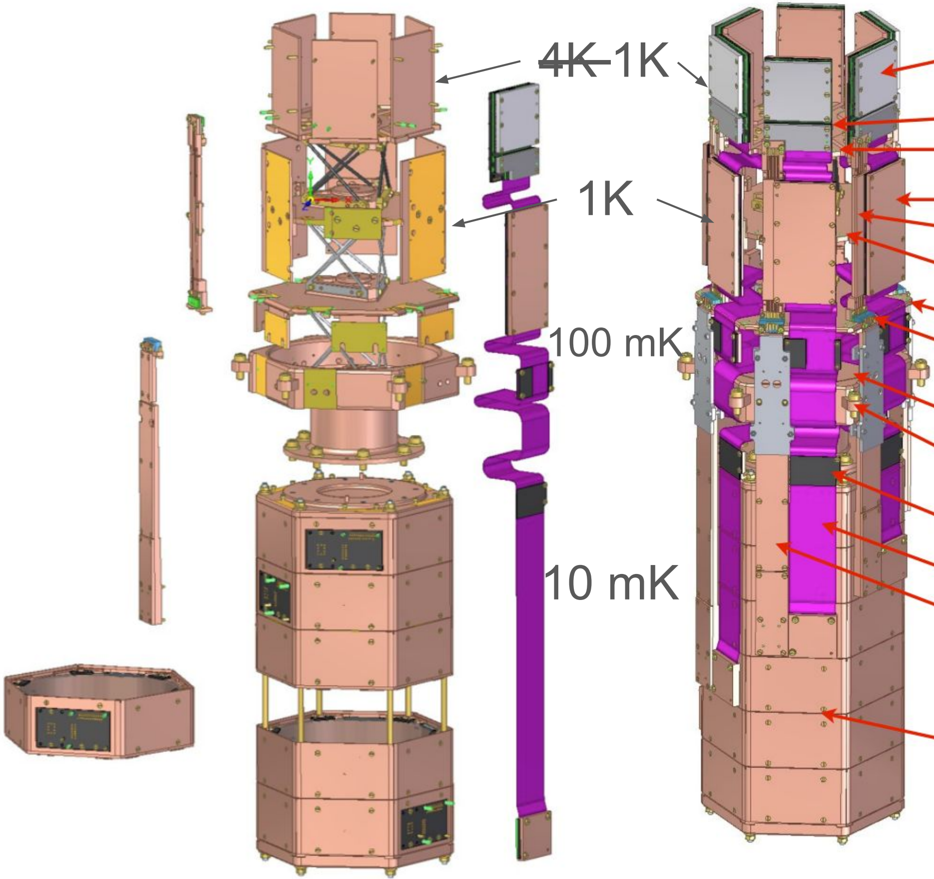
FIG. 6. Measured noise (black solid), modeled voltage-coupled noise (purple solid), correlated noise (yellow dashed), measured noise with voltage-coupled and correlated components subtracted (orange solid), and theoretical noise model (purple dots) shown for $R_0 \approx 15\% R_N$. The environmental noise model explains the peaks in the measured spectrum, but there is still a discrepancy between the environmental-noise-corrected data and the noise model.

AIP Advances 1 August 2020; 10 (8): 085221 https://en.wikipedia.org/wiki/Noise_%28electronics%29

Types of noise we often deal with

- Johnson–Nyquist noise
    - $\boxed{v_n = \sqrt{4k_BTR\Delta F}}$
    - Irreducible noise
    - From electron random motion
- Shot noise
    - $i_n = \sqrt{2Iq\Delta B}$
    - From “when the charge carriers (such as electrons) traverse a gap”
- Flicker noise (1/f noise)
    - Power vs frequency looks like 1/f
    - Not discussed today
- One general method of reducing noise: **cool it down**

SuperCDMS Tower



connector to cable to 300K

LH stiffener w/HEMTs

LH stage

ST stiffener w/SQUIDs

Vacuum Coax Assembly (Upper)

ST stage

CP stage

Vacuum Coax Upper/ Lower Connector

CP stiffener w/R_{sh}

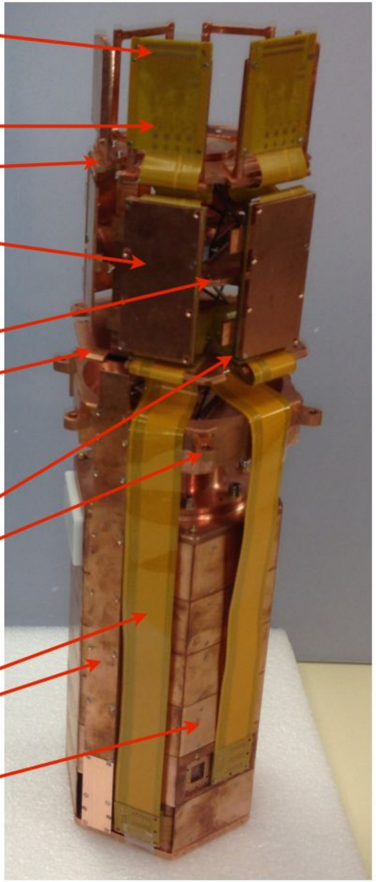
MC stage

MC stiffener/heat sink

Vertical Flex Cable

Vacuum Coax Assembly (Lower)

detector packages



Some basic material properties

- Need to always consider material properties when cooling them down
    - Heat capacity (specific heat)
    - Thermal conductivity
    - Thermal expansion (contraction in cold)
    - Critical temperature for superconductors

Specific Heat (c)

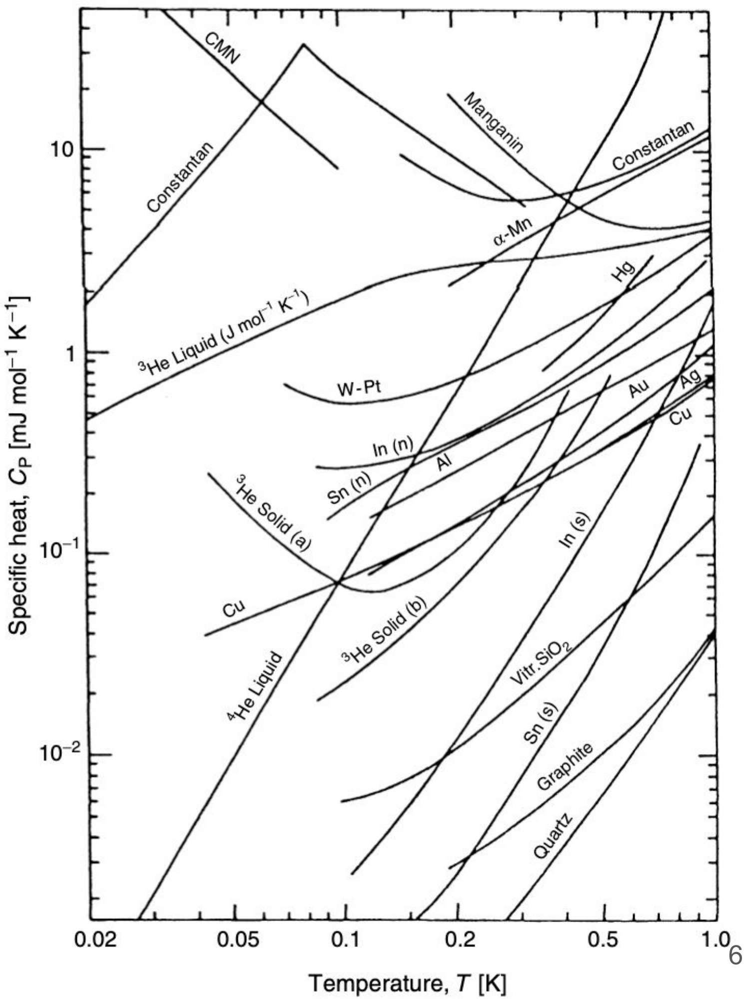
- Energy required to change a unit mass of a material’s temperature

- Heat capacity (C) factors in the particular sample’s mass

- At low temperature (T << Debye Temp.), C follows a power law whose exponent describes what is holding the heat

  - C ~ T - Electrons

  - C ~ T^3 - Phonons



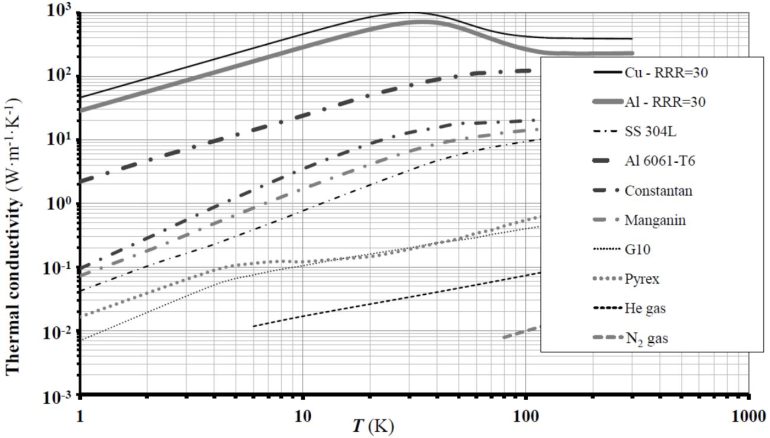
Thermal Conductivity (k)

- How easy is it to put power through a material

$$\dot{q} = \dot{Q}/A = -\kappa \nabla T \qquad \dot{Q} = \frac{A}{L}\int_0^L \dot{q}\,dx = \frac{A}{L}\int_{T_1}^{T_2} \kappa(T)\,dT$$

- A steady-state power across a material sustains a temperature difference
- Limiting conductance can sometimes be the “boundary” from “acoustic mismatch” = “Kapitza Resistance”
- Also a power-law for T << Debye Temp.
- k ~ T - Electrons $\dot{Q} = \frac{A\kappa_0}{2L}(T_2^2 - T_1^2)$

  … for small ΔT $\dot{Q} \simeq \frac{A\kappa_0}{L} T \Delta T = \frac{A}{L}\kappa_e(T)\Delta T$
- k ~ T^3 - Phonons $\dot{Q} = \frac{Ab}{4L}(T_2^4 - T_1^4)$
- k ~ T^4 - Electron-Phonon coupling
- $\dot{Q} = \kappa V (T_{phonon}^5 - T_{electron}^5)$



Wiedemann-Franz Law

- For **metal**, thermal conductivity is closely related to electrical conductivity
  - Both are determined by the flow of electrons

$$\kappa/\sigma = L_0 T \qquad L_0 = (\pi k_B/e)^2/3 = 2.44 \cdot 10^{-8} W\Omega/K^2$$

- Electrical conductivity is much easier to measure than thermal conductivity
- Often in metal, both conductivities are limited by scattering on defects
- RRR (Residual Resistivity Ratio) used to characterize “purity” of metal

$$RRR = \sigma_{4K}/\sigma_{300K} = R_{300K}/R_{4K}$$

- Eg. for pure copper
  - Random piece: RRR~10
  - Very pure commercial copper: RRR~50
  - Very pure copper, repeatedly annealed: RRR up to >1000

Cooling Time Constant (τ)

- Combining a material’s heat capacity and it’s thermal conductance to a surrounding “bath”, the temperature evolution is typically exponential with

$$\tau = C/G$$

- Typically, plastics and superconductors below Tc are hard to cool down
- Stainless steel with an extreme aspect ratio can also have a large τ (days-weeks)
- Copper are much easier to cool -- widely used in cryogenic applications
  - Gold is better……

Stainless Steel Time Constant

- HeRALD cell takes weeks to reach equilibrium
- Had a run end due to a poorly thermally anchored stainless steel capillary, couldn't reach below 200 mK
  - A lab down the hall didn't anchor a stainless coax line, same problem

The crime in action…

Thermal Expansion

- Objects change size as they cool down
- Most contraction happens by ~77 K (LN temp) - dunk in LN is a good test
- Plastics contract O(1%), metals contract O(0.1%)
- A joint where stainless steel bolts together copper will loosen while cold, whereas a brass-bolted joint tightens
- It’s common to use spring washers (“Bellevilles”) to counter this

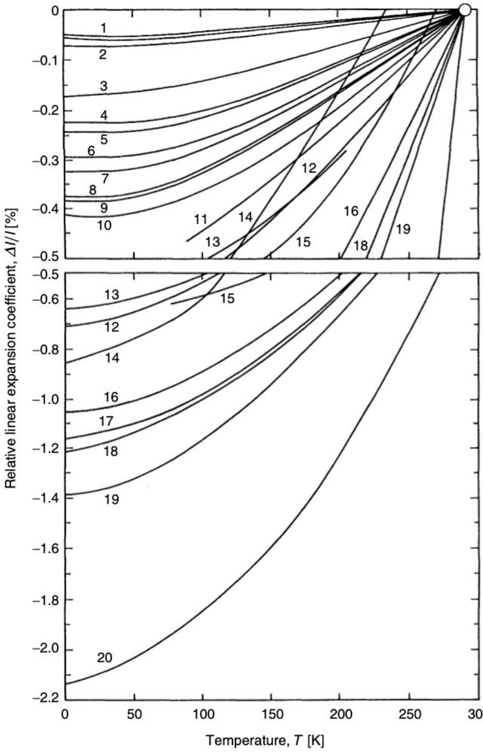
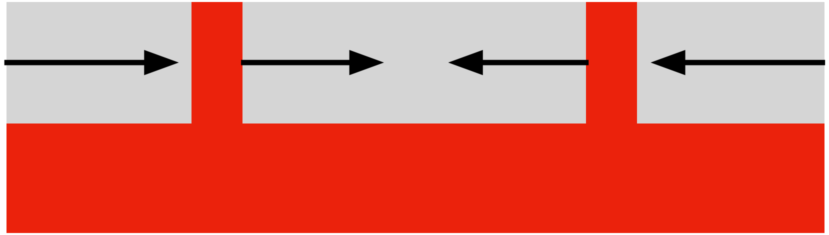
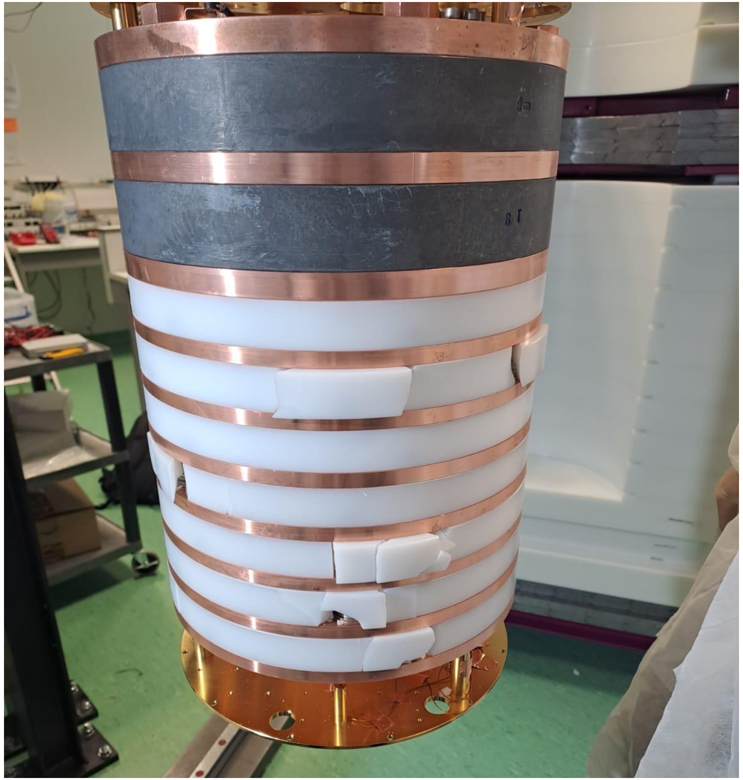


Fig. 3.17. Relative linear thermal expansion coefficient of (1) Invar (upper), Pyrex (lower), (2) W, (3) nonalloyed steel, (4) Ni, (5) $Cu_{0.7}Ni_{0.3}$, (6) stainless steel, (7) Cu, (8) German silver, (9) brass, (10) Al, (11) soft solder, (12) In, (13) Vespel SP22, (14) Hg, (15) ice, (16) Araldite, (17) Stycast 1266, (18) PMMA, (19) Nylon, (20) Teflon [3.76]. Some further data are: Pt similar to (3); Ag between (9) and (10); Stycast 2850 GT slightly larger than (10). The relative change of length between 300 and 4 K is $10^3\Delta l/l = 12, 11.5, 4.4, 6.3$ and 5.7 for Polypropylene, Stycast 1266, Stycast 2850 GT as well as 2850 FT, Vespel SP-22 and solders, respectively [3.44, 3.55, 3.56, 3.76–3.82, 3.114]. Torlon behaves very similar to Stycast 2850FT [3.114]

Shattered Polyethylene

- Shielding for Ricochet Cryostat
- Polyethylene contracted radially while copper screws did not contract
- Tension caused the PE to shatter



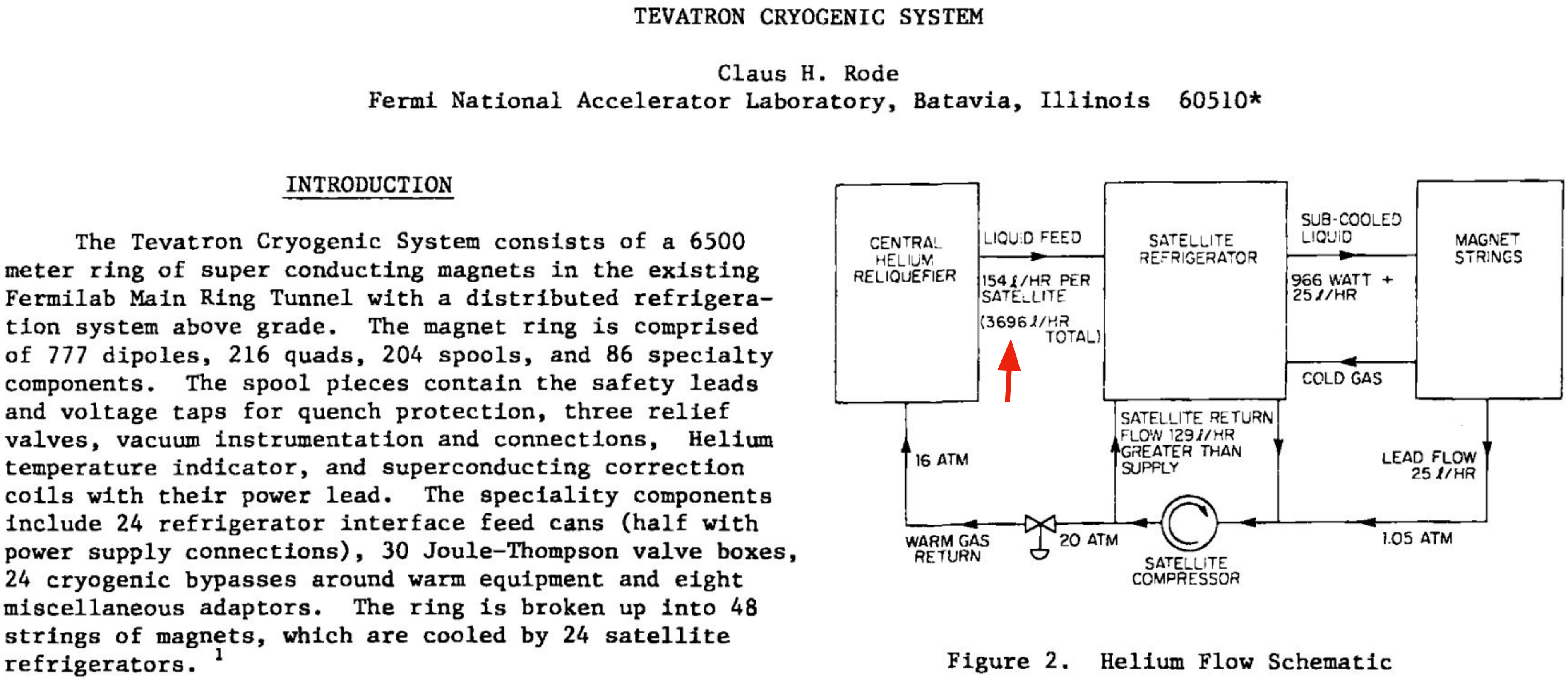


How to cool things down?

- Two different situations above ~4 K vs below ~4 K
- From room temperature to ~4 K:
  - The “wet” way
    - Liquid Nitrogen → 77 K
    - Liquid Helium → 4.2 K
    - (if you’re desperate) Pump on Liquid Helium → ~1 K
  - The “dry” way
    - Gifford-McMahon (GM) cooler → 30K
    - Pulse Tube CryoCooler → 2.5 K
- Below 4K:
  - Dilution Refrigerator
  - Adiabatic Demagnetization Refrigerator

Liquid helium at Tevatron

https://s3.cern.ch/inspire-prod-files-0/01cbdb97a4f5d30ac6f170b64ffb465a



TEVATRON CRYOGENIC SYSTEM

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Fermi National Accelerator Laboratory, Batavia, Illinois 60510*

INTRODUCTION

The Tevatron Cryogenic System consists of a 6500 meter ring of super conducting magnets in the existing Fermilab Main Ring Tunnel with a distributed refrigeration system above grade. The magnet ring is comprised of 777 dipoles, 216 quads, 204 spools, and 86 specialty components. The spool pieces contain the safety leads and voltage taps for quench protection, three relief valves, vacuum instrumentation and connections, Helium temperature indicator, and superconducting correction coils with their power lead. The speciality components include 24 refrigerator interface feed cans (half with power supply connections), 30 Joule-Thompson valve boxes, 24 cryogenic bypasses around warm equipment and eight miscellaneous adaptors. The ring is broken up into 48 strings of magnets, which are cooled by 24 satellite refrigerators.[1]

Figure 2. Helium Flow Schematic

https://en.wikipedia.org/wiki/Pulse_tube_refrigerator

Pulse tube cryocooler

- Overly simplified:
  - When compressor pushing, gas in pulse tube heats up and extra heat gets dumped out via X3
  - When compressor pulling, gas cools down and T_L gets colder

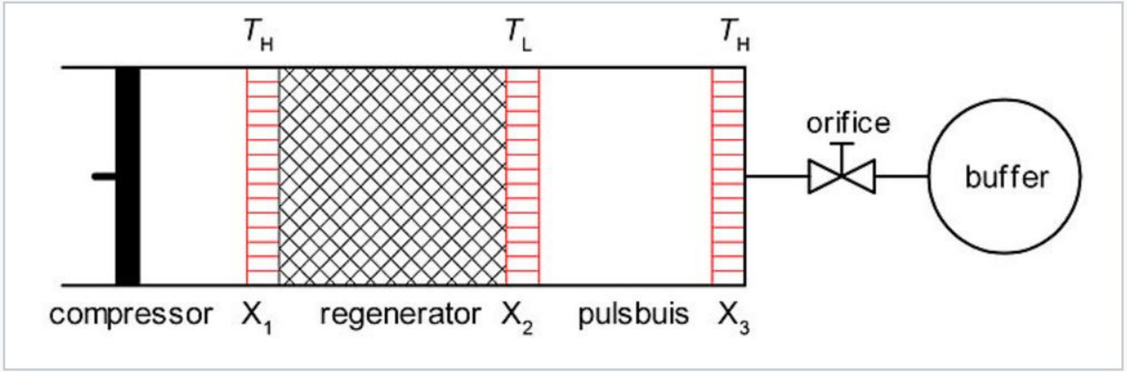
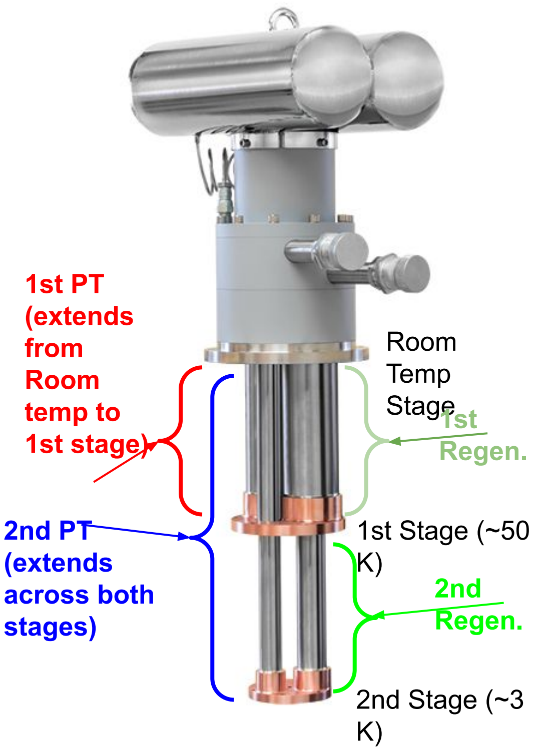


Figure 1: Schematic drawing of a Stirling-type single-orifice PTR. From left to right: a compressor, a heat exchanger (X_1), a regenerator, a heat exchanger (X_2), a tube (often called *the pulse tube*), a heat exchanger (X_3), a flow resistance (orifice), and a buffer volume. The cooling is generated at the low temperature T_L. Room temperature is T_H.

Two stage pulse tube cooler



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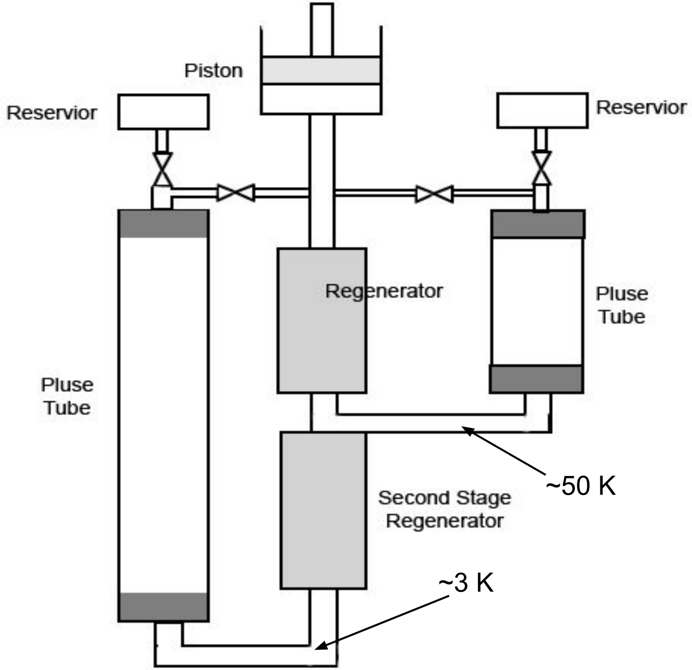
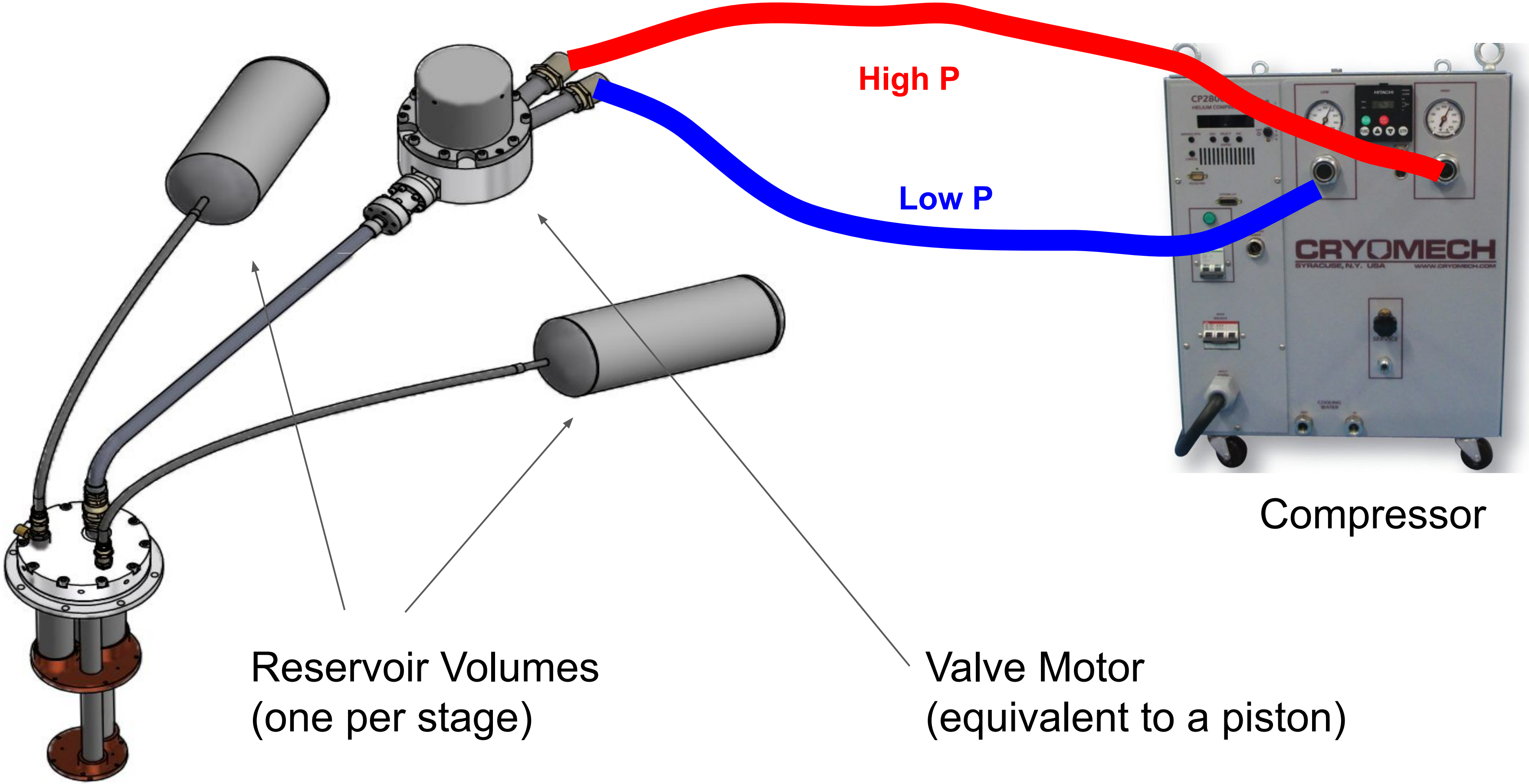




High P

Low P

Compressor

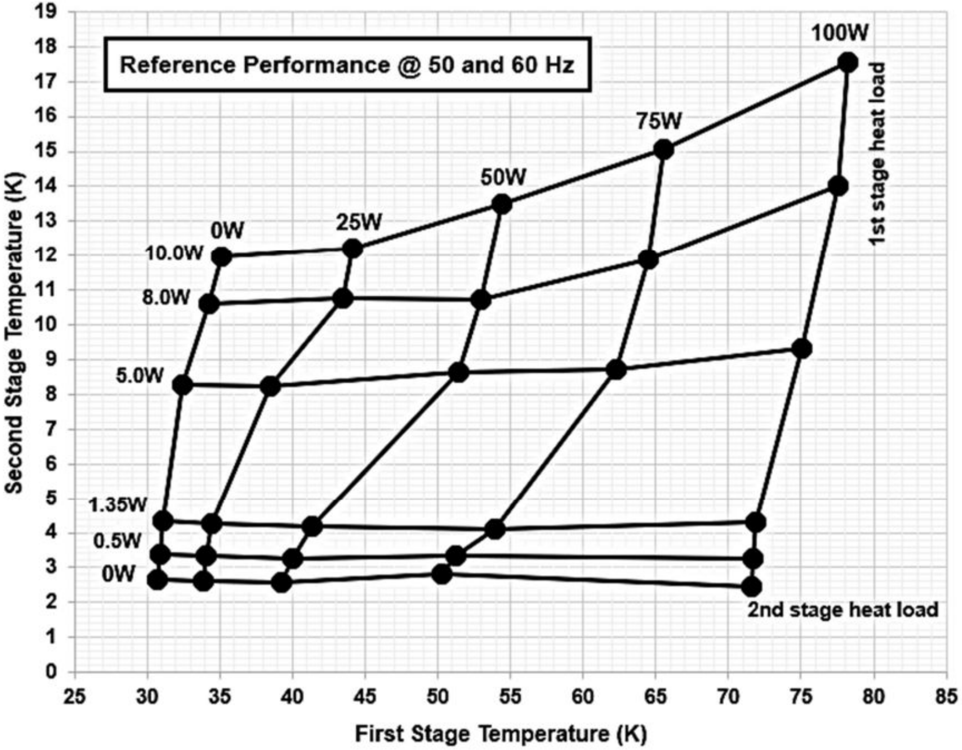
Reservoir Volumes
(one per stage)

Valve Motor
(equivalent to a piston)


KINEDYNE
KINEDYNE
CRYOMECH
CRYOMECH
T-902 Left Tank

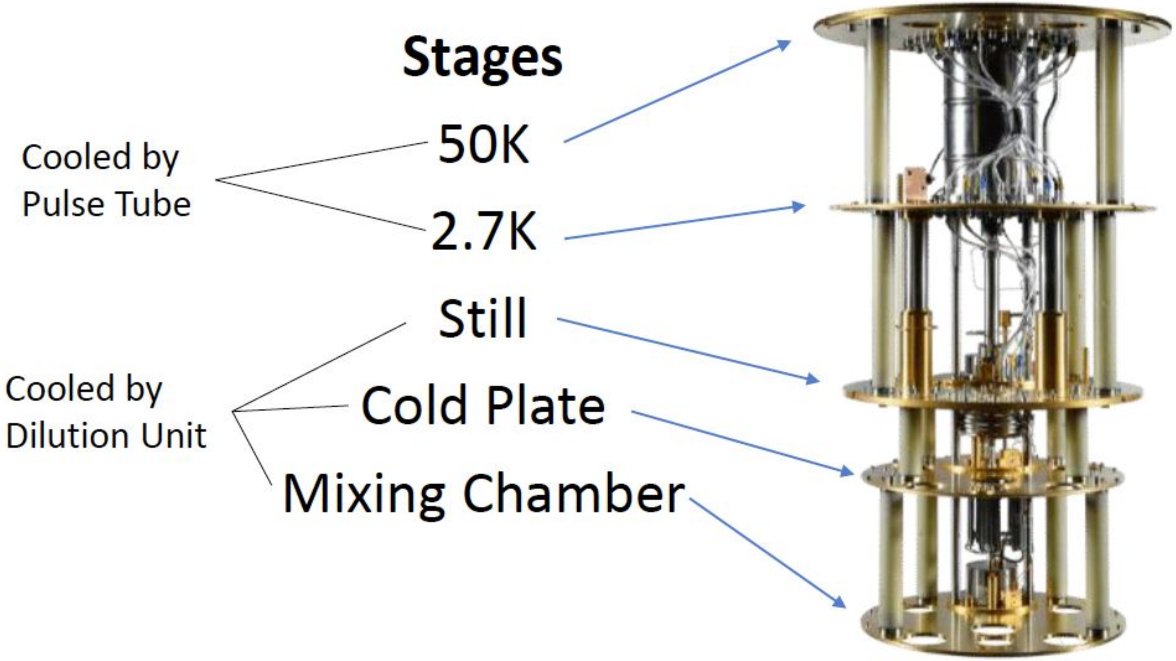
https://bluefors.com/wp-content/uploads/2023/09/PT415-RM-Capacity-Curve.pdf

Cryomech PT415 performance



Materials from Adam & Richard’s
summary, “CUTE training introduction”

Dilution refrigerator



Stages

Cooled by
Pulse Tube

- 50K
- 2.7K

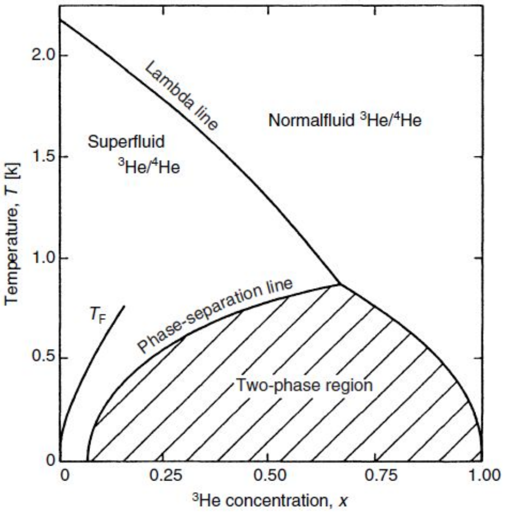
Cooled by
Dilution Unit

- Still
- Cold Plate
- Mixing Chamber

Cryoconcept
Hexa-dry M
(Similar to CUTE)

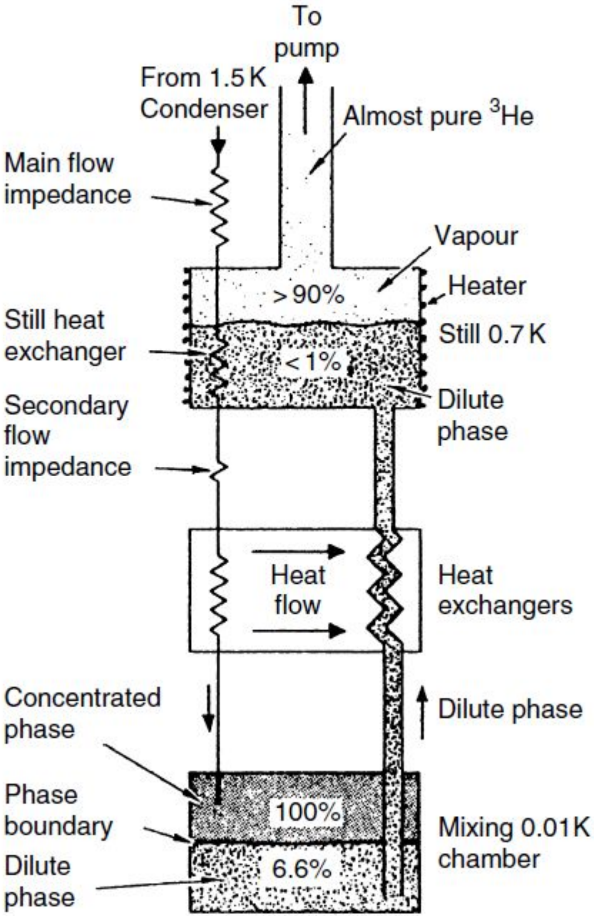
DR fundamentals

- Cooling to milliKelvin temperatures occurs through phase transition of He3/He4 mixture
- Below ~1K, the mixture separates into a He3 concentrated phase (approaching 100% He3) and a He3 dilute phase (approaching 6.6% He3)
- As He3 atoms are pumped from concentrated to dilute phase, the transition is endothermic and absorbs energy from its environment
- Unlike evaporative cooling which drops off exponentially with temperature, this transition drops off quadratically, enabling lower ultimate temperatures

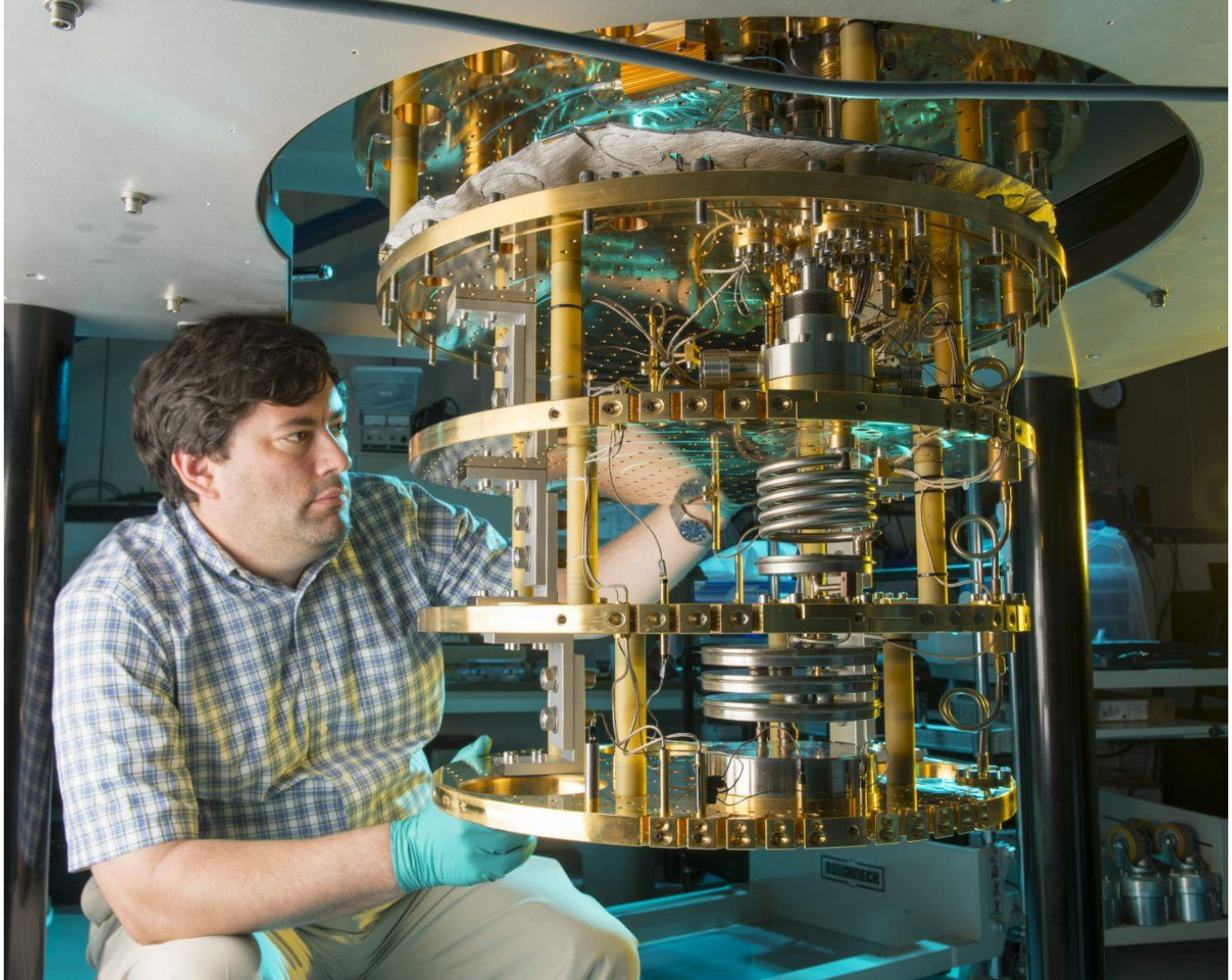


DR fundamentals -- continued

- Condense a mixture of He3/He4
  - Typically ~30% He3 in 65-100 L total
- In steady state, ~100% He3 circulates:
  - Gas He3 is condensed by impedances and precooled through heat exchangers at Still/Cold plate
  - LHe3 arrives in MC in concentrated phase
  - Transition from concentrated to dilute phase causes cooling
  - LHe3 is pumped out of MC dilute phase up to Still by osmotic pressure difference
    - (cools incoming He3 on its way)
  - He3 evaporates (evaporative cooling) and gas is pumped out to circulate
  - He3 concentration in gas phase decreases with increasing Still T above 600 mK

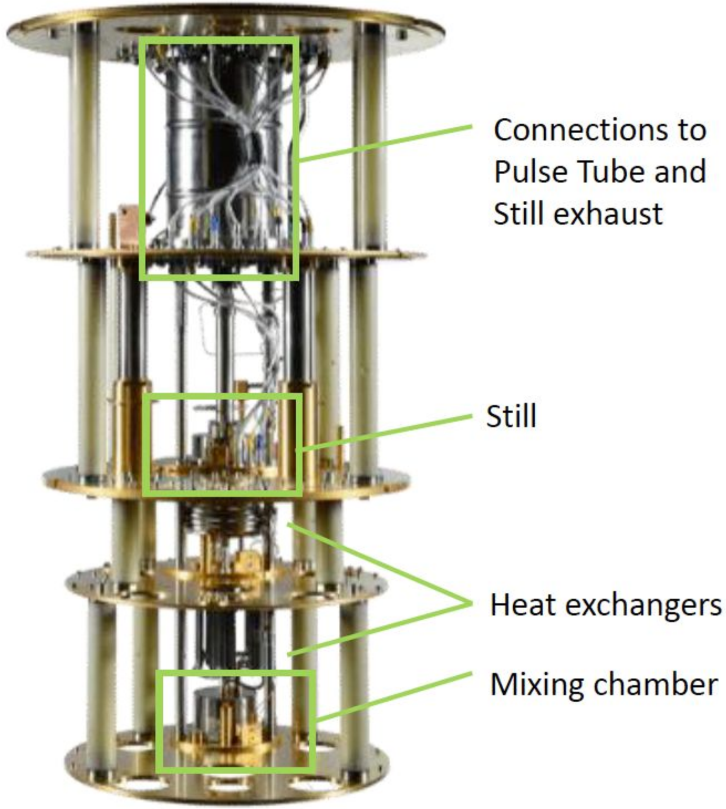


Source: Pobell Chap. 7



Source: Pobell Chap. 7

DR: cooling power budget



- MC cooling power (ideal) proportional to flow rate: $\dot{Q}_{max} = 84\dot{n}_3 T_{mc}^2$
- Still temperature: ideally 600-700 mK
  - Gas pressure too low if too cold
  - He3 fraction too low if too hot
- An art to tune the operation point…

Still runs at 400-900 mK
<10 mW cooling power

CP runs at 60-200 mK
Ill-defined cooling power

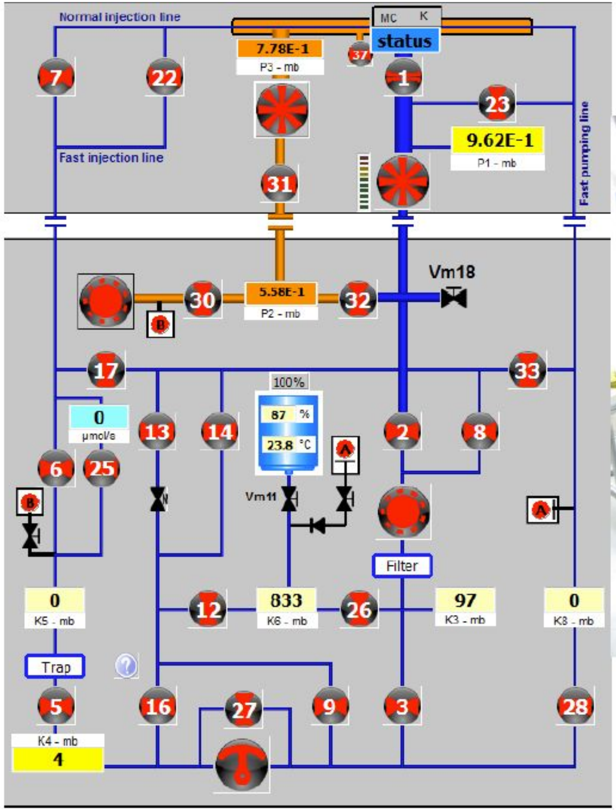
MC runs at 10-100 mK
<200 uW cooling power

DR: cooling power budget

- Imperative to limit how much heat is brought down to cold stages with wiring, support structures, etc.
  - Copper thermal conductivity is ~400 W/m.K
  - E.g. 10 cm typical magnet wire (30 AWG) is 0.255 mm diameter
  - This gives 200 uW for 1K delta T
- Heat sink well at each stage
  - Wrap wire around post and glue with high thermal conductivity materials
- Use thinner wire to decrease cross sectional area (fragile)
- Add thermal loops to increase length (difficult for many wires)
- Use low thermal conductivity wire (increases electrical resistance unless SC)
- **All of the above**

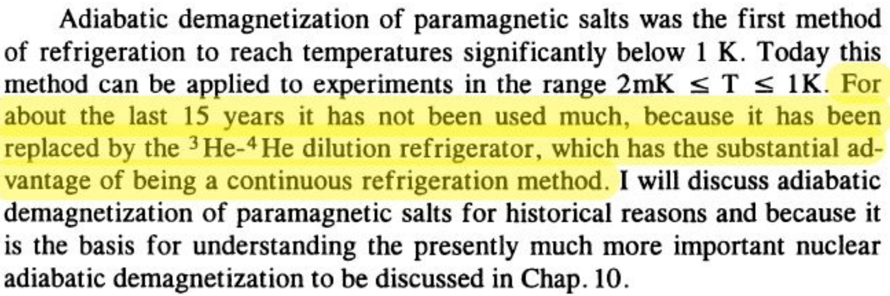
Gas Handling System

- System of pumps and valves to control the circulation of He3/He4 mix
- Different paths used for pre-cooling and condensing/base temperature
  - Fast injection/pumping for pre-cooling
  - Normal injection/turbo for condensing and base temperature
- Includes pumps for achieving high vacuum

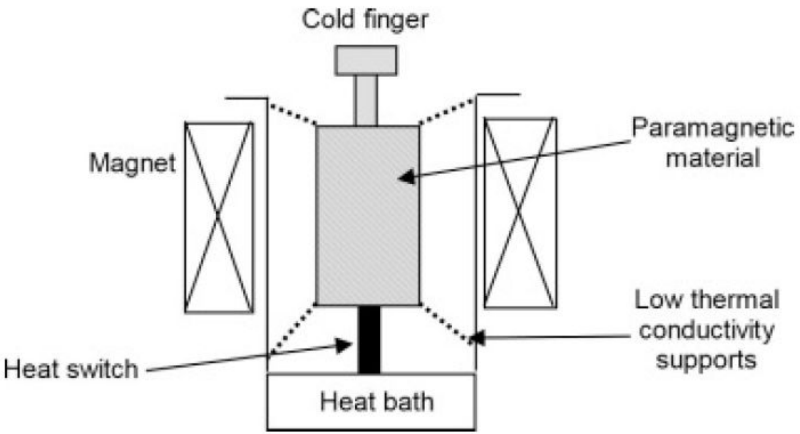


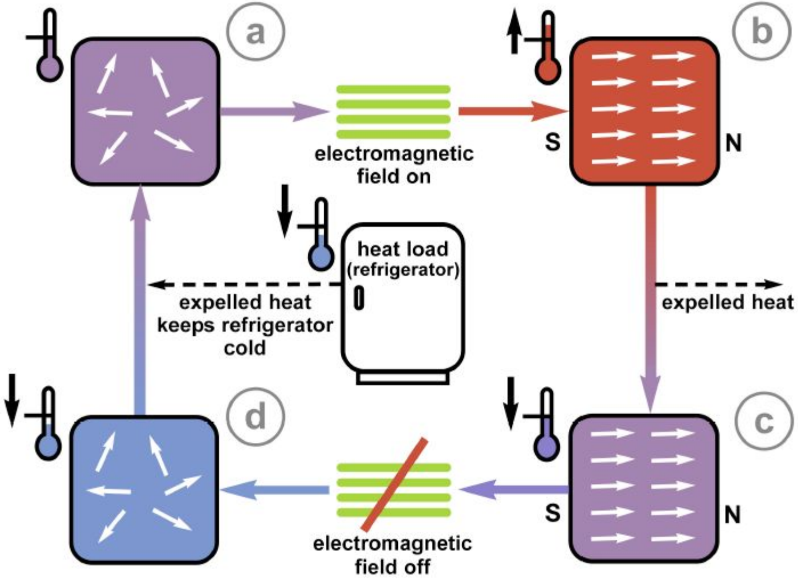
ADR

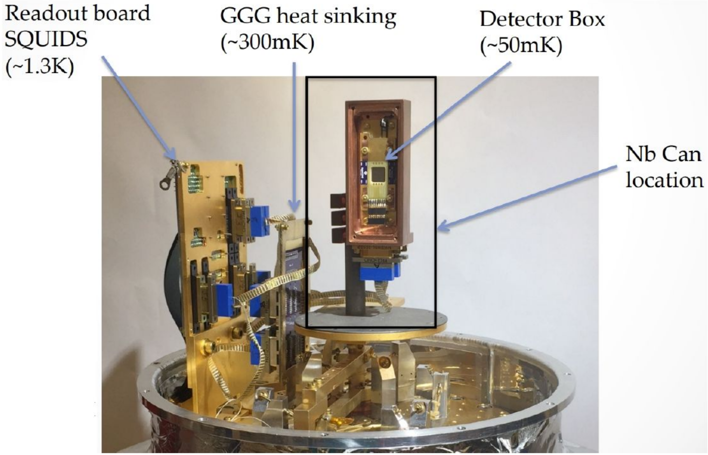
(Pobell, Chap. 9)



Adiabatic demagnetization of paramagnetic salts was the first method of refrigeration to reach temperatures significantly below 1 K. Today this method can be applied to experiments in the range 2mK $\leq$ T $\leq$ 1K. For about the last 15 years it has not been used much, because it has been replaced by the ^{3}He-^{4}He dilution refrigerator, which has the substantial advantage of being a continuous refrigeration method. I will discuss adiabatic demagnetization of paramagnetic salts for historical reasons and because it is the basis for understanding the presently much more important nuclear adiabatic demagnetization to be discussed in Chap. 10.





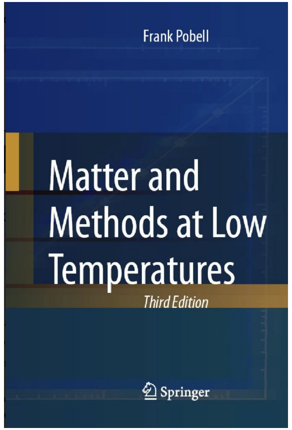


ADR is still in use…

- Despite Pobell disfavors it, ADR is still widely used today
- Much smaller than DR
- No/minimum gas handling, way less prone to leak
- Does not rely on gravity -- can work on rockets, balloons, and satellites
- Disadvantages:
  - Heat switch is annoying
  - Has a big magnet around -- especially bad for devices sensitive to B-field
  - Need to recycle periodically

Some Resources

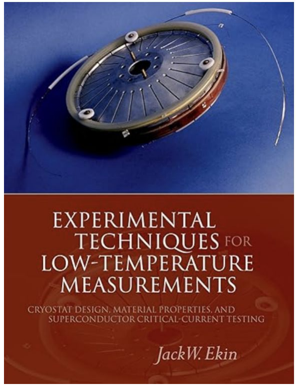
- [Pobell - Matter and Methods at Low Temperature]
- [Ekin - Experimental Techniques for Low-Temperature Measurements]
- [Balshaw - Practical Cryogenics]
- [NIST - Cryogenic Technology Resources]
- [Duthil - Material Properties at Low Temperature]


Frank Pobell

Matter and Methods at Low Temperatures

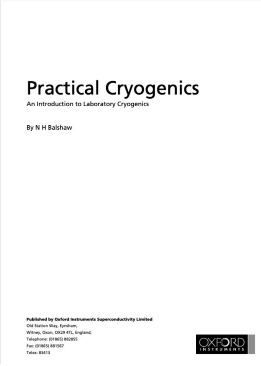
Third Edition

Springer


EXPERIMENTAL TECHNIQUES FOR LOW-TEMPERATURE MEASUREMENTS

CRYOSTAT DESIGN, MATERIAL PROPERTIES, AND SUPERCONDUCTOR CRITICAL-CURRENT TESTING

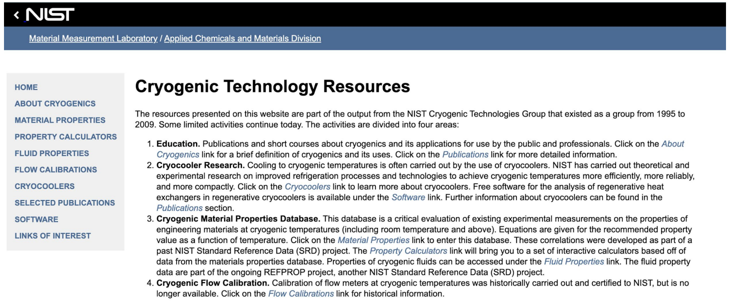
Jack W. Ekin


Practical Cryogenics

An Introduction to Laboratory Cryogenics

By N H Balshaw

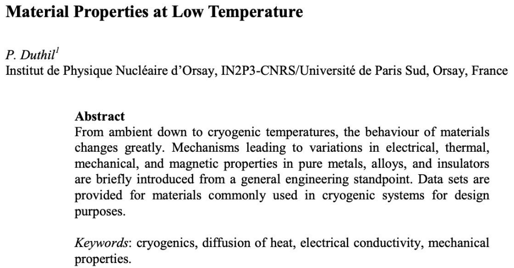
Published by Oxford Instruments Superconductivity Limited
Old Station Way, Eynsham,
Witney, Oxon, OX29 4TL, England,
Telephone: (01865) 882855
Fax: (01865) 881567
Telex: 83413



Cryogenic Technology Resources

The resources presented on this website are part of the output from the NIST Cryogenic Technologies Group that existed as a group from 1995 to 2009. Some limited activities continue today. The activities are divided into four areas:

1. **Education.** Publications and short courses about cryogenics and its applications for use by the public and professionals. Click on the *About Cryogenics* link for a brief definition of cryogenics and its uses. Click on the *Publications* link for more detailed information.
2. **Cryocooler Research.** Cooling to cryogenic temperatures is often carried out by the use of cryocoolers. NIST has carried out theoretical and experimental research on improved refrigeration processes and technologies to achieve cryogenic temperatures more efficiently, more reliably, and more compactly. Click on the *Cryocoolers* link to learn more about cryocoolers. Free software for the analysis of regenerative heat exchangers in regenerative cryocoolers is available under the *Software* link. Further information about cryocoolers can be found in the *Publications* section.
3. **Cryogenic Material Properties Database.** This database is a critical evaluation of existing experimental measurements on the properties of engineering materials at cryogenic temperatures (including room temperature and above). Equations are given for the recommended property value as a function of temperature. Click on the *Material Properties* link to enter this database. These correlations were developed as part of a past NIST Standard Reference Data (SRD) project. The *Property Calculators* link will bring you to a set of interactive calculators based off of data from the materials properties database. Properties of cryogenic fluids can be accessed under the *Fluid Properties* link. The fluid property data are part of the ongoing REFPROP project, another NIST Standard Reference Data (SRD) project.
4. **Cryogenic Flow Calibration.** Calibration of flow meters at cryogenic temperatures was historically carried out and certified to NIST, but is no longer available. Click on the *Flow Calibrations* link for historical information.


Material Properties at Low Temperature

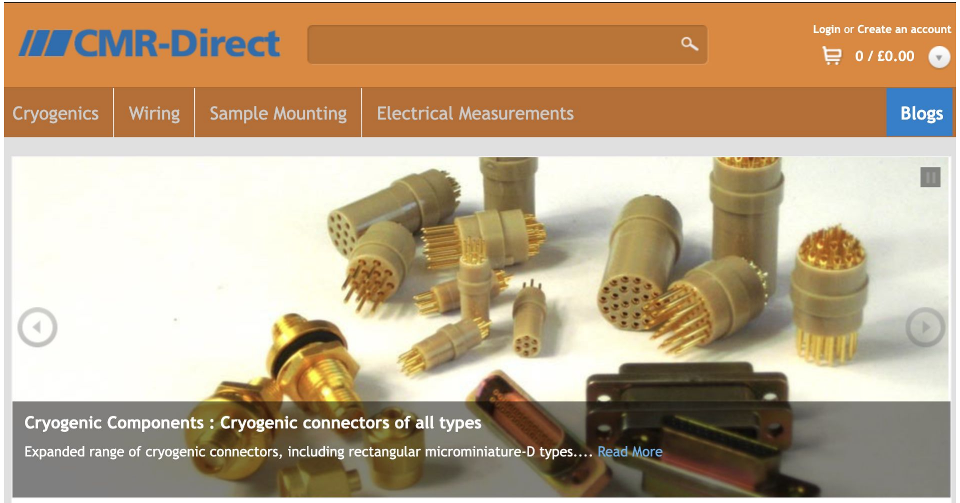
P. Duthil[1]
Institut de Physique Nucléaire d'Orsay, IN2P3-CNRS/Université de Paris Sud, Orsay, France

Abstract
From ambient down to cryogenic temperatures, the behaviour of materials changes greatly. Mechanisms leading to variations in electrical, thermal, mechanical, and magnetic properties in pure metals, alloys, and insulators are briefly introduced from a general engineering standpoint. Data sets are provided for materials commonly used in cryogenic systems for design purposes.

Keywords: cryogenics, diffusion of heat, electrical conductivity, mechanical properties.

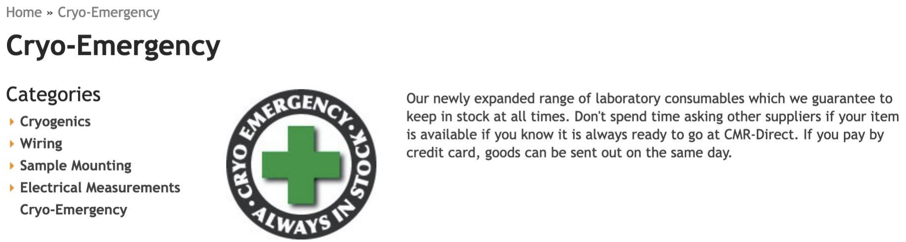
A Bonus Resource - CMR Direct

- All-purpose cryogenic supply shop
- Adhesives, wiring, connectors, etc
- Includes “Cryo-emergency” products, ready to ship immediately
- Helpful product descriptions!
- https://www.cmr-direct.com/



Cryogenic Components : Cryogenic connectors of all types

Expanded range of cryogenic connectors, including rectangular microminiature-D types.... Read More



Cryo-Emergency

Our newly expanded range of laboratory consumables which we guarantee to keep in stock at all times. Don't spend time asking other suppliers if your item is available if you know it is always ready to go at CMR-Direct. If you pay by credit card, goods can be sent out on the same day.