50 Years DR, **Manchester, 16 September 2015**

Dilution Refrigerator with cryogenic cycle circulation and adsorption pumping

Vladimir Mikheev, Oxford

Compact self contained Cryofree continuous Dilution refrigerator down to 30mK

(Oxford Instruments 2006-2008)

List of participants:

Alvin Adams ,
Tim Foster
Rod Bateman,
Paul Noonan
Vladimir Mikheev

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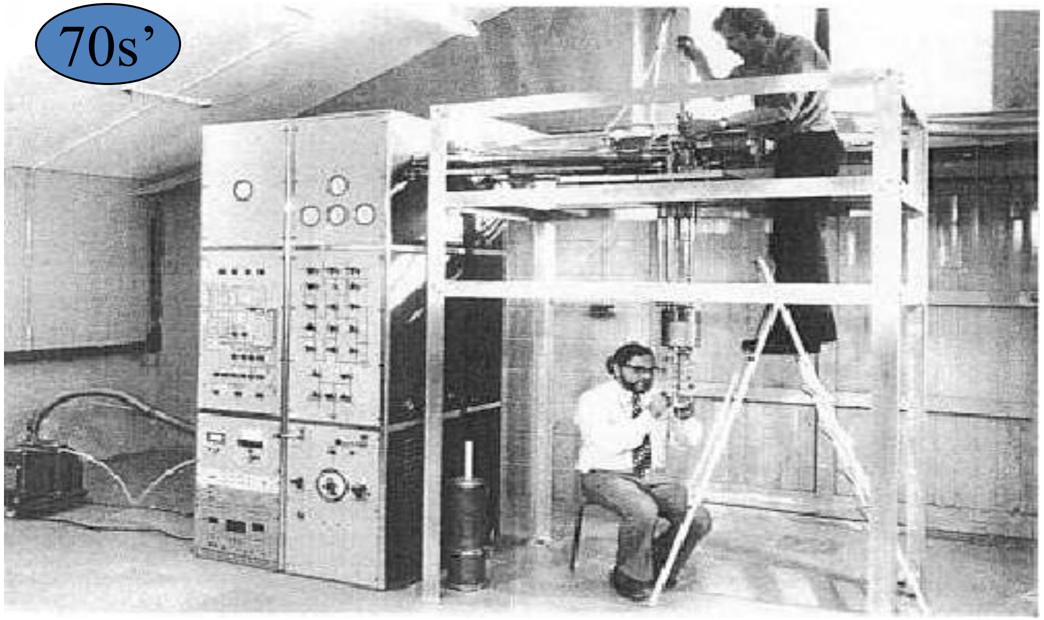
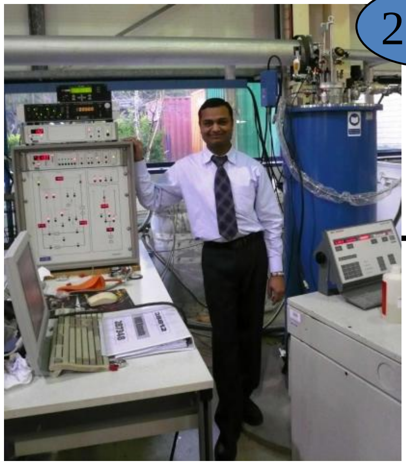
Size Evolution for DR at OI

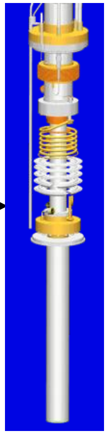
70s'



80s'

2000





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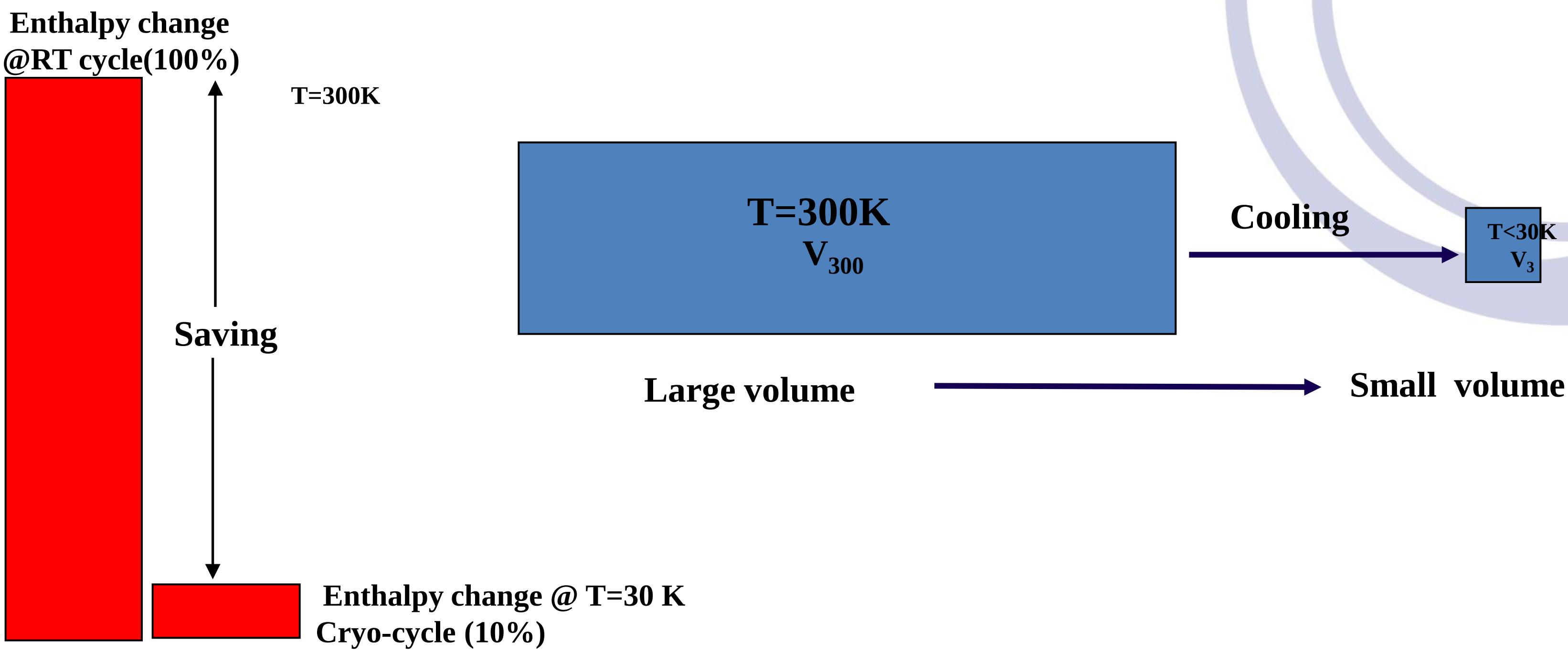
The way to further miniaturization of Dilution refrigerators is in Developing Cryogenic cycle of He3 circulation. **Why?**



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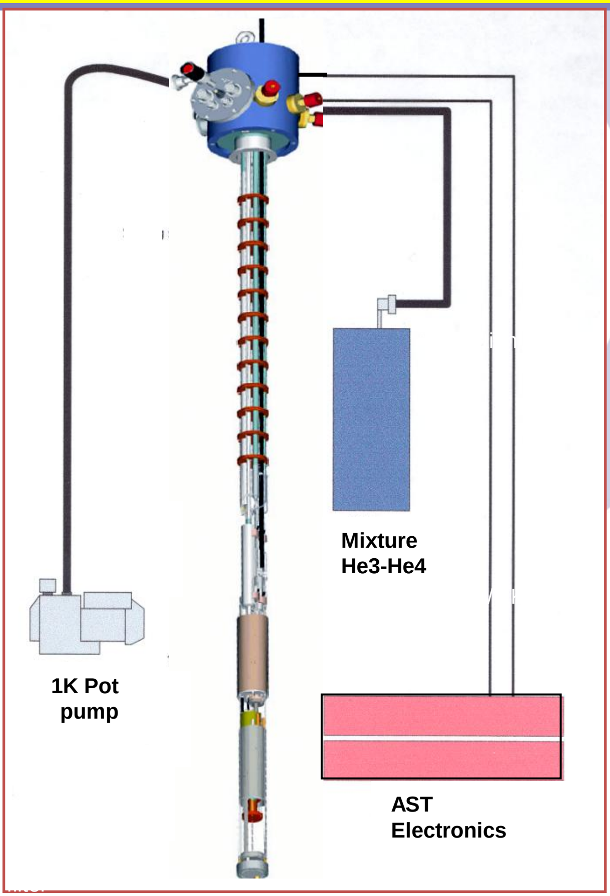
Dilution Refrigerators with cryogenic circulation of He3 at Oxford Instruments since 1997

- The first example is **AST Minisorb top loaded in liquid He4.**
- **Compact DR,--16 mK, quick turn around (<3 hrs from RT)**

AST Minisorb Issues:

- **Two cryo-valves ,**
- **A number of high value impedances,**
- **1K Pot external pump.**



- ***No external pumps,***
- ***No cryo-valves,***
- ***No impedances***
- ***New technology - Cryofree Technology***

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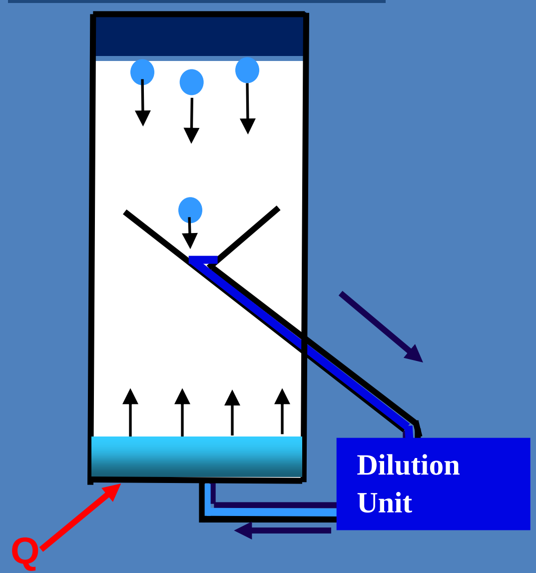
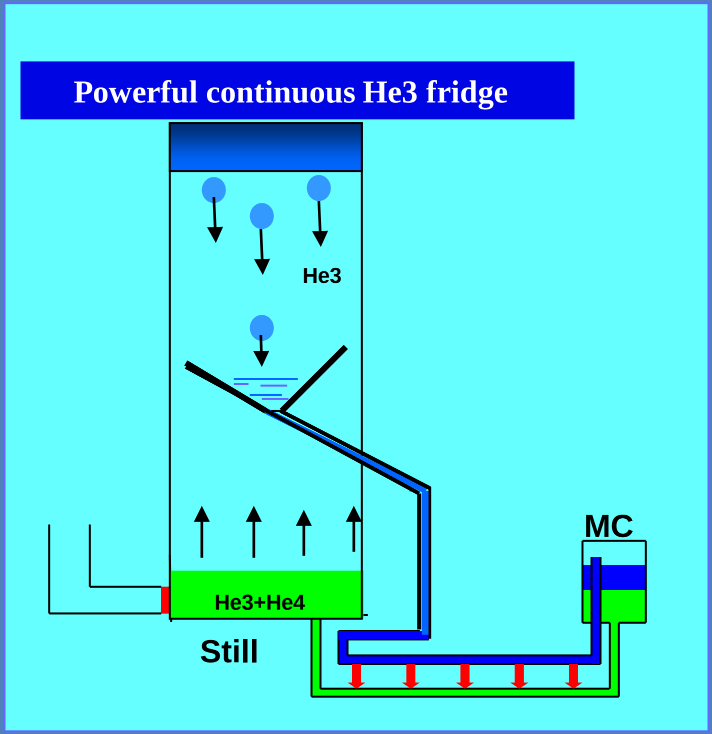
Cryogenic cycle of He3 circulation

How to arrange
Cryogenic circulation?

Heat Pipe effect





Continuous He3-He4 Dilution refrigerator

Pre-History:

- **H.London,G. Clarke, E.Mendoza Phys.Rev. 128,1992, 1962**
- **V Edelman , Cryogenics 12.385.1972 (T~60mK @ Single shot operation)**
- **A. Aroyan, R.Amamchan et al (preprint, Erevan) T~0.2K, attempt of continuous**
- **V Sobolev, V Syvokon at al.1992, Cryogenics ICEC Supplement (12mK continuous)**
- **Yu Bunkov, J Niekky at al.. ~1992 QFS (95-96)(12mK, continuous)**
- **V Edelman (with Institute Photonic, Berlin) 2006, (T~50mK, Single shot)**

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The two main functions at the operation DR refrigerators:

1. **Condensation of gas**

2. **Circulation of gas or liquid.**

The key thing is to produce a liquid He4 or He3, (liquefaction)

What is the best way of He3 liquefaction? 1Kpot?

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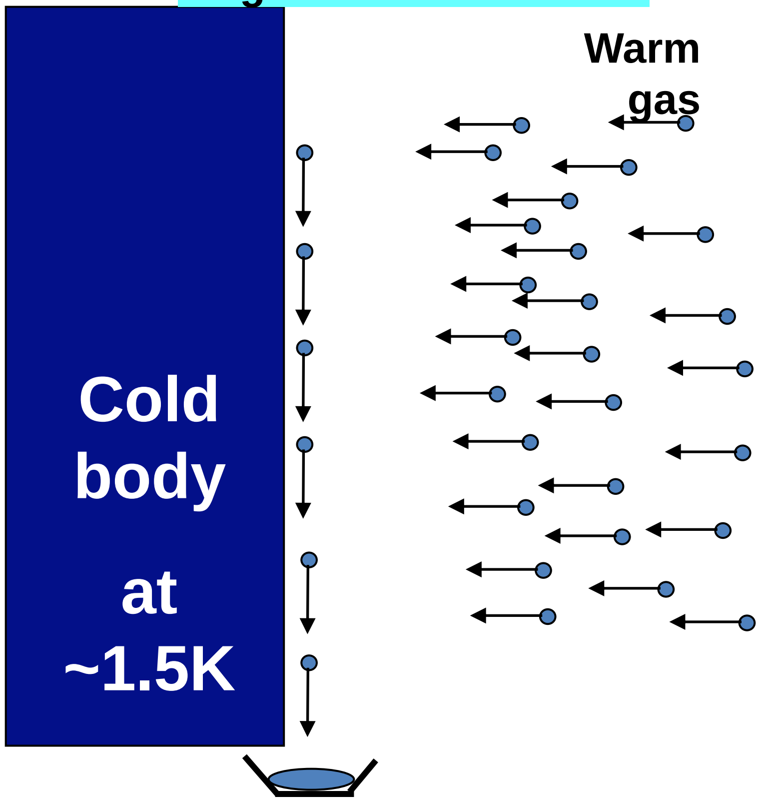
Condensation on the cold surface (1K Pot method)

$P_{gas} > P_{cond}(T)$



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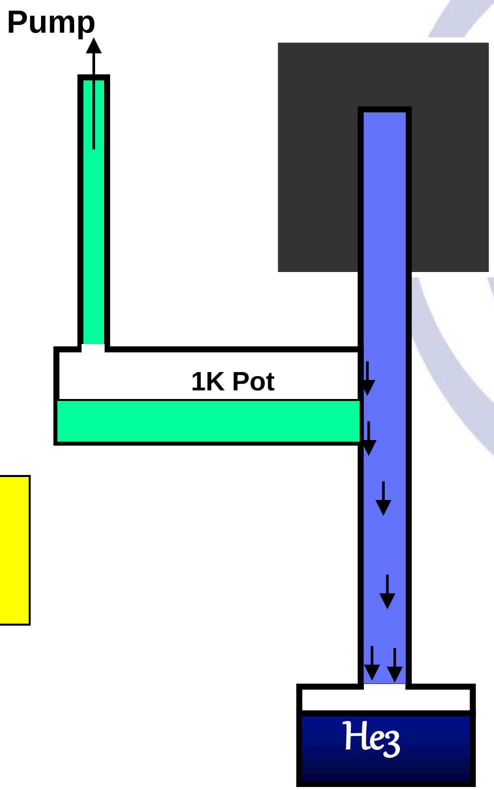

- Condensation on the cold surface requires:
- (1K Pot + N/V_{or} (Z) + External Pump)

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- Liquefaction of He3 by adiabatic expansion gas is easier
- Creating the “rain”of liquid He3 or He4 at the pressure drop

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Adiabatic expansion in atmosphere

Creating the "rain"

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$PV = mRT$ **Ideal Gas**

Reversible adiabatic process

$$P_1V_1T_1 \xrightarrow{S = const} P_2V_2T_2$$

$$\Delta S = c_v ln(\frac{T_2}{T_1}) + R ln(\frac{V_2}{V_1}) = 0$$

$$(\frac{T_2}{T_1})(\frac{V_2}{V_1})^{R/c_v} = 1$$

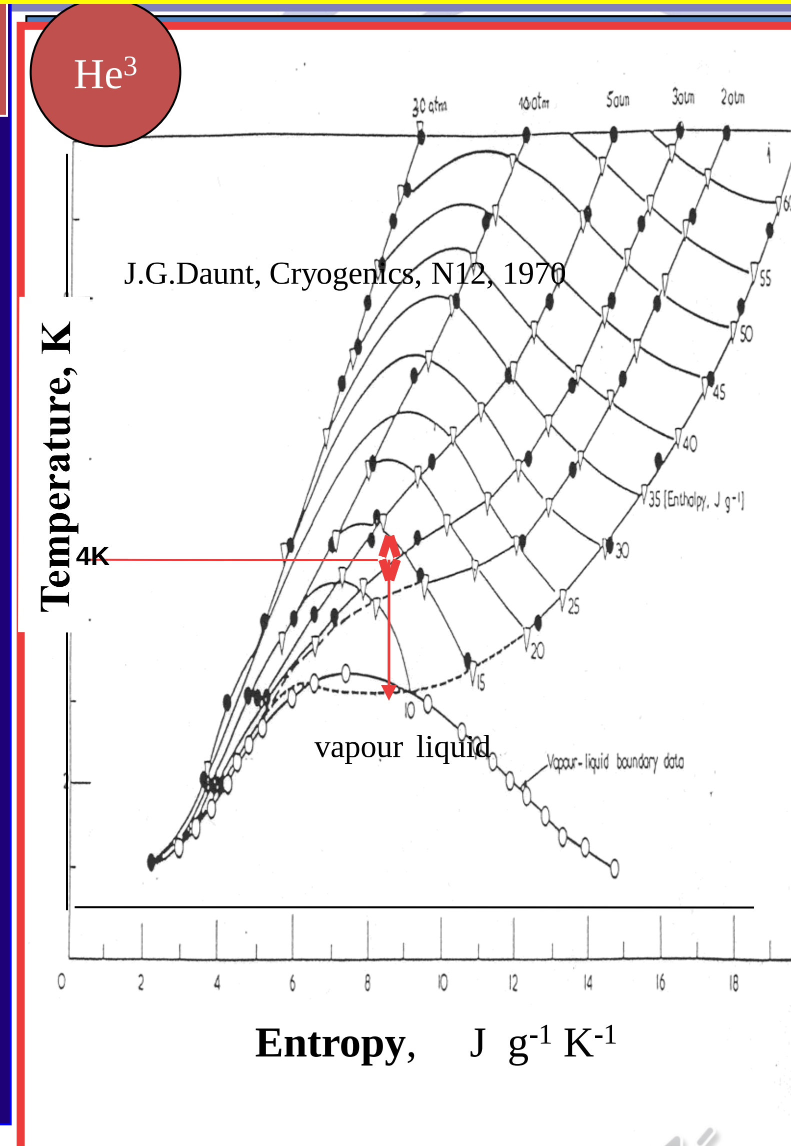
He3

$$(\frac{T_2}{T_1}) = (\frac{P_2}{P_1})^{(\gamma - 1)/\gamma} \qquad \gamma = c_p/c_v = 5/3$$

$$\boxed{T_2 = T_1(\frac{P_2}{P_1})^{0.4}}$$

Example: $T_1 = 4.2K; P_2/P_1 = 1/3$

$T_2 = 2.7K < T_{condens}$



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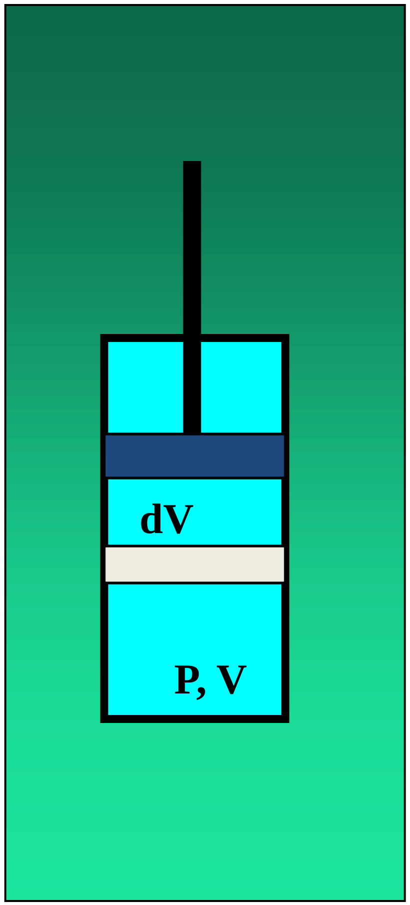
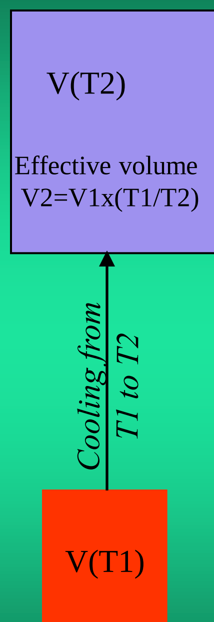
From mechanical expanders to non- mechanical way of expansion

Piston expander

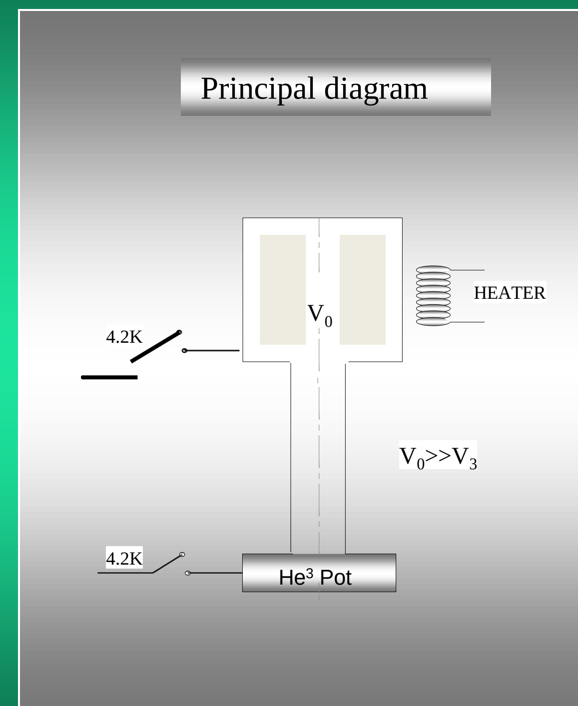


Expansion by cooling of reservoir



Efficiency of single expansion
at Low Temperatures
V2/V1 ~20
if T_1=85K and T2=4.2K

Single expansion by F.Simon, 1932 (method of L.Cailletet , 1877) Troitskii (1980)



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• Cryomech PT 403 Cold Head

•Electrical Connectors

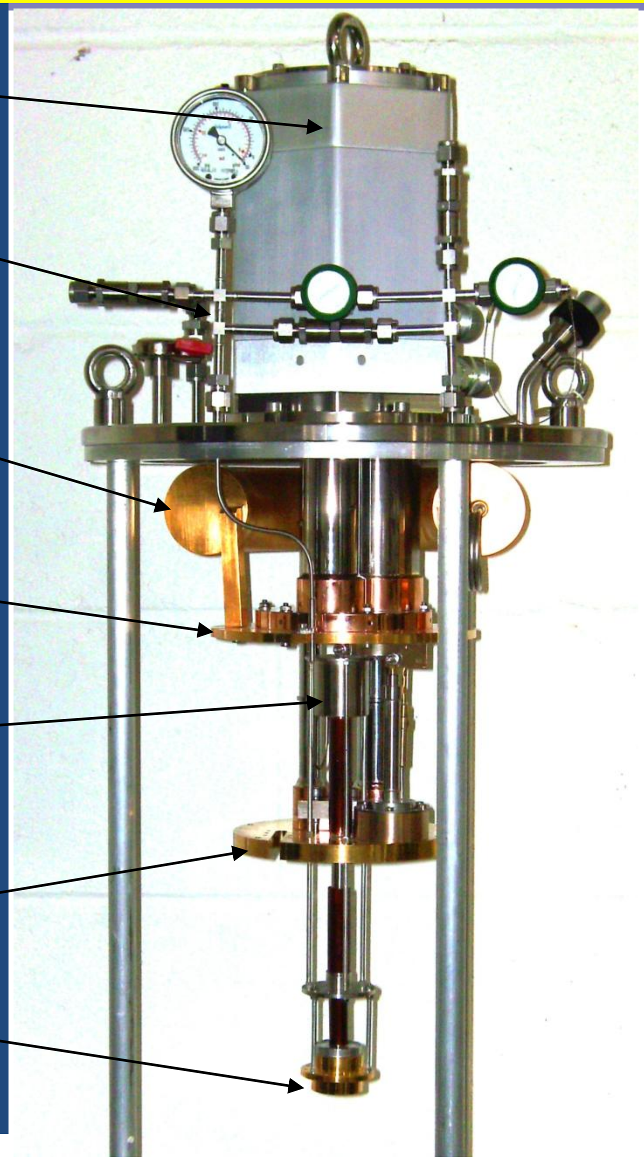
•^{3}He Cold Dumps

•PTR first stage thermal link & shield connection

•Adsorption pump
•Heat switch

•PTR second stage thermal link & shield connection

•He^3 Pot and sample region at <280mK for 2-3 days



General view of He^3 system with PT403, 1 phase, air cooled compressor

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Novel self contained continuously operating Dilution Refrigerator down to mK range (Ox.Inst. 2006)

Key features:

- **Continuous Cryogenic Circulation – CCDR**
- **No External Pumps**
- **No Gas Handling System, - whole gas mixture is inside the Fridge**
- **No liquid cryogens is used, even no cold traps and cold spots on the system**
- **Low Power Single Phase Air cooled compressor (PTR<250mW@4K)**
- **Push button operation, with computer control.**

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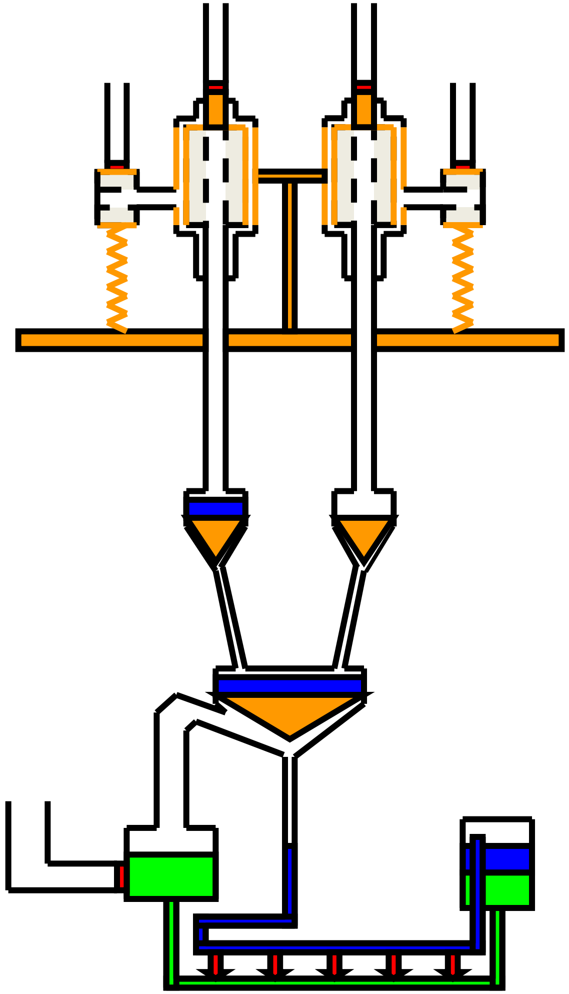
Principal Diagram of CCDR



Continuous operation

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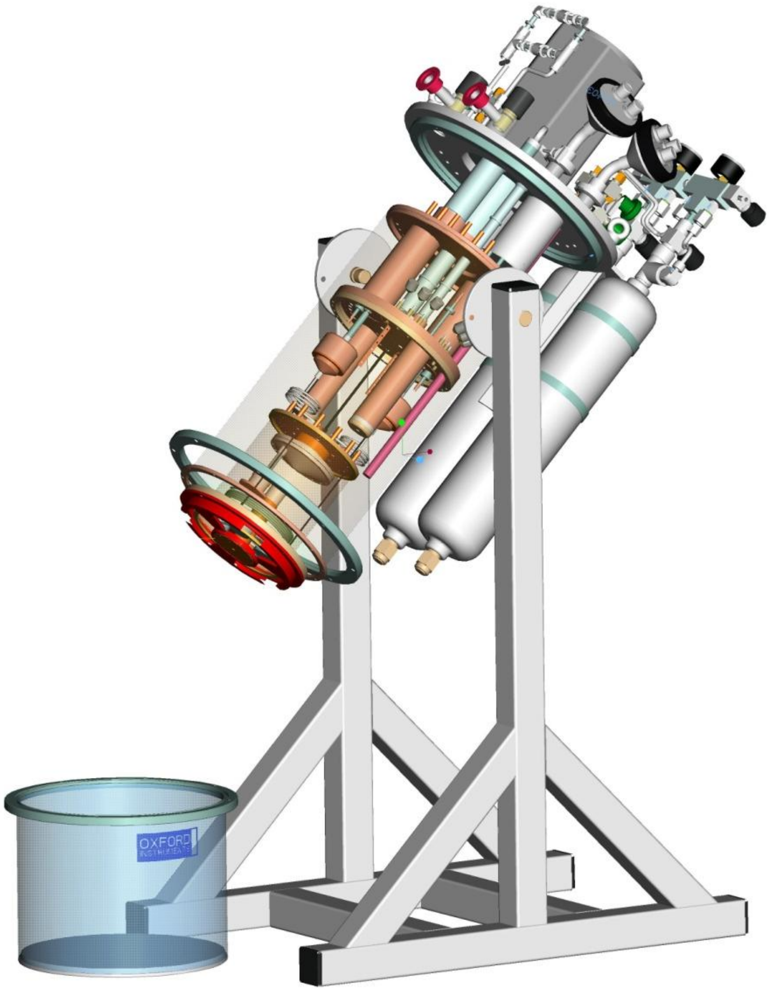

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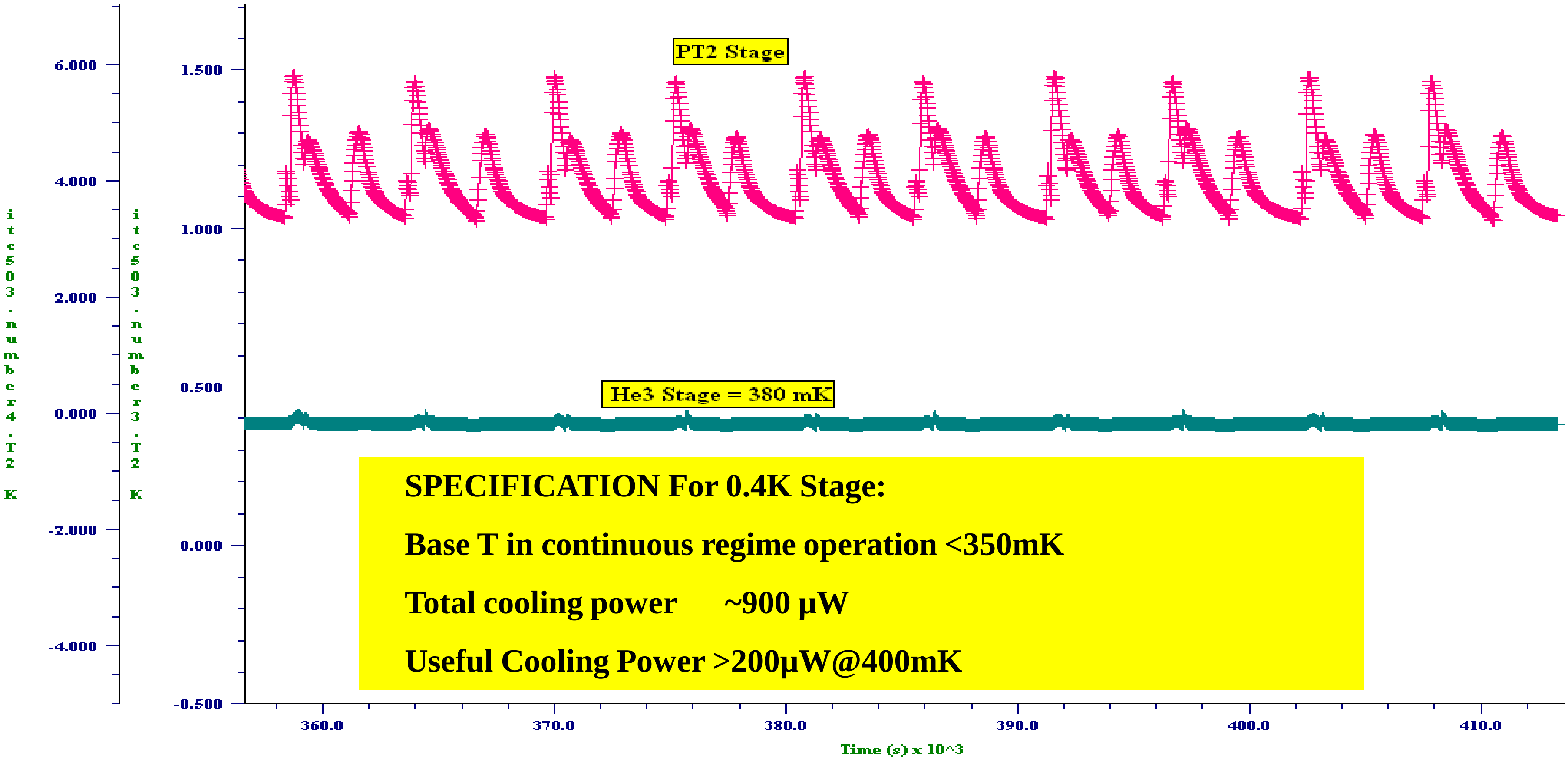
Cryofree Continuous operation of He3 0.4K Stage for Triton-DR



SPECIFICATION For 0.4K Stage:

Base T in continuous regime operation <350mK

Total cooling power ~900 µW

Useful Cooling Power >200µW@400mK

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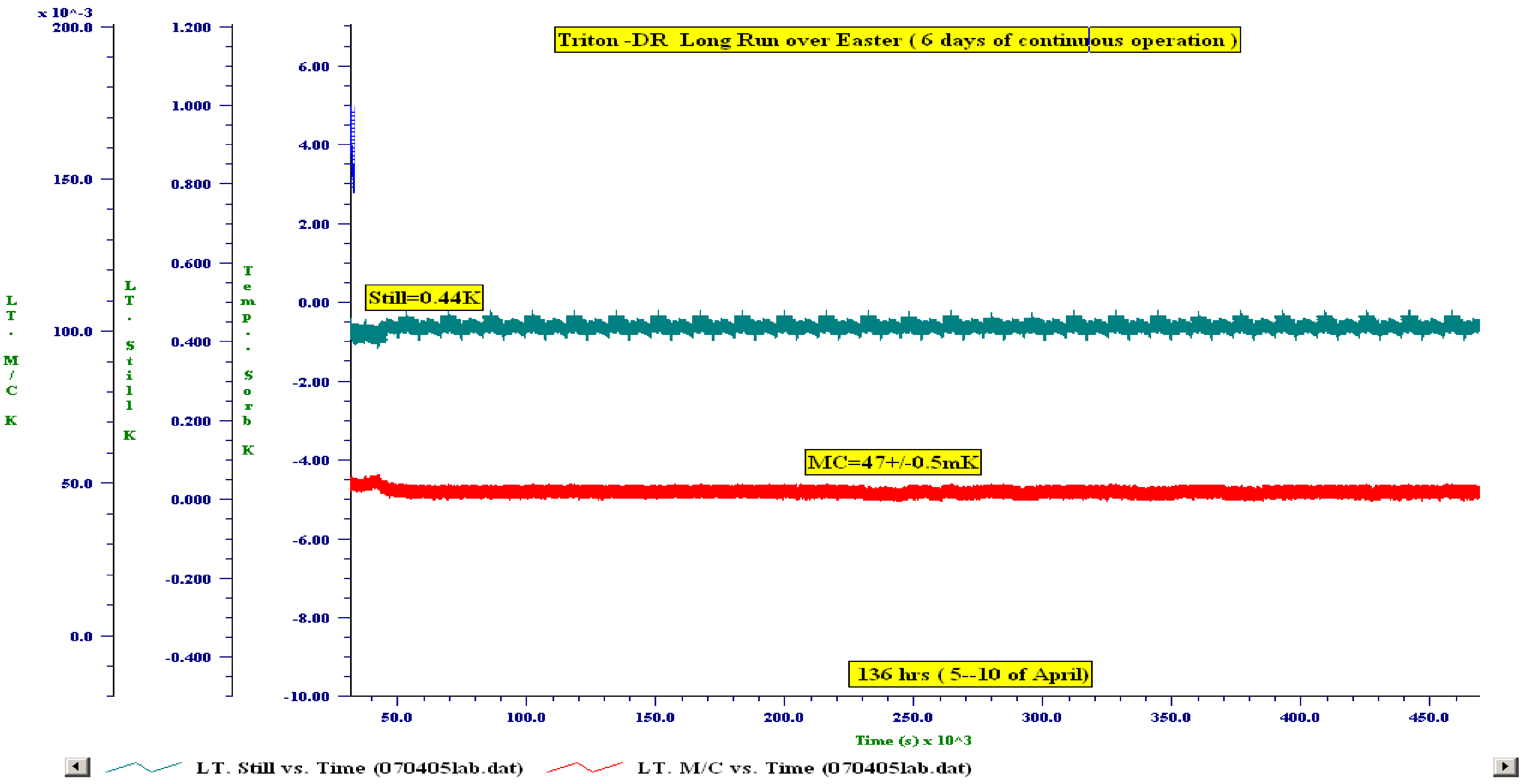
6 days of continuous operation

Cryogen free Dilution refrigerator Triton^{TM}DR



Specification

***CCDR specification*:**

Base Temperature 20-50mK

Cooling power @ 350 mK

for thermal dumping all heat leaks………> 200μW

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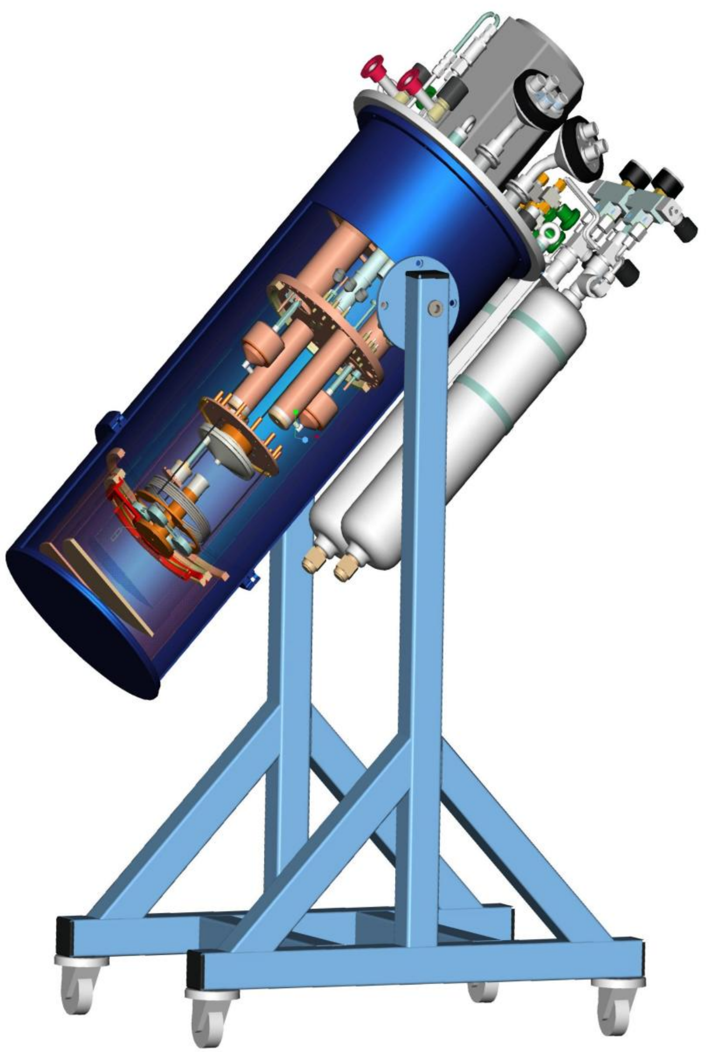
Cryogenic Cycle of He3 Circulation presents new type of self contained Dilution refrigerators



- **Cryogen Free (no liquid cryogen service, no cold traps)**
- **Continuous operation, at temperature down to 20mK so far**
- **Very compact, no external pumps, no gas handling system**
- **Simple T-control, Femto power MC temperature control**
- **True turnkey; plug in the wall, stand-alone control system with PC user interface via Ethernet (done from Oxford to Goteborg University)**
- **Low vibration (due to small PTR)**
- **Large sample space and easy sample change, creates opportunity to interface cryostat to a wide range of applications and opens ULT to a wider audience in the scientific community**
- **ULT will be re-invented and de-mystified…**

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Thank you for your attention

Any questions?

50 Years of Dilution Refrigeration!

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Demand of Cooling Power of DR

2 options

Standard solution

High cooling power DR at Mixing Chamber

CCDR solution

Additional powerful ULT below platform 0.8K and reduced demand on cooling power at Mixing Chamber

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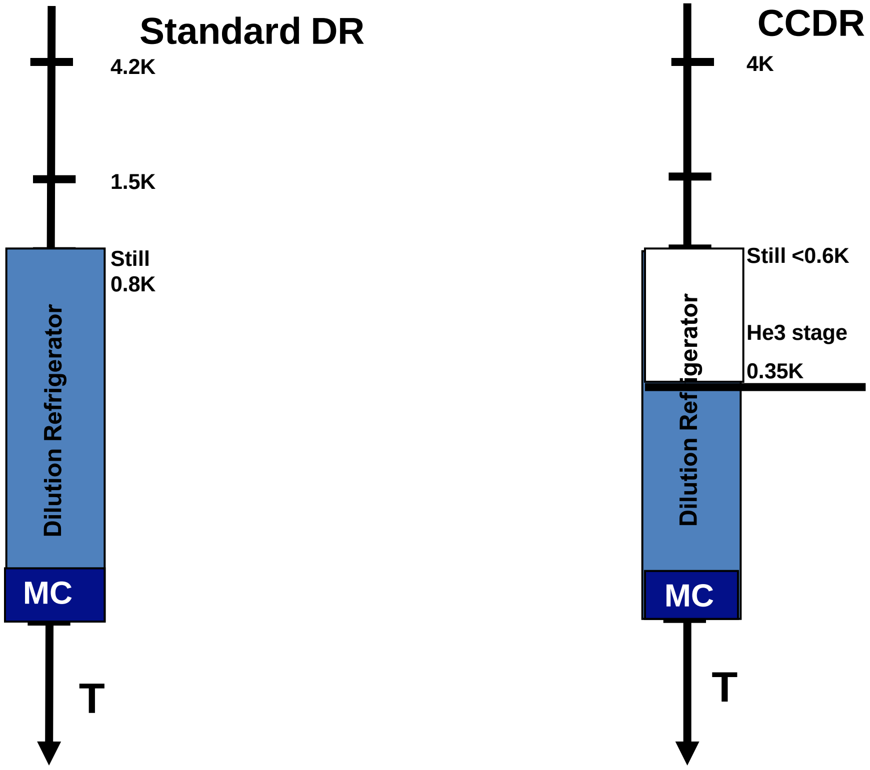

$$\frac{\dot{Q}_{standard}}{\dot{Q}_{CCDR}} \approx \left[\frac{0.8K}{0.35K}\right]^{\geq 2}$$

> 5 for metals

>25 for Insulators

Cooling Power of DR

Required for:

- MC temperature low T, stability , heat withdrawal from customer's experimental interventions, large sample
- Dumping all heat leaks coming from services : wiring, cables, Drivers, optical access lines, additional instrumentation (SQUID)

Base Temperature is Lowest temperature on MC at $Q_{heat\ load} = Q_{cooling\ power\ on\ MC}$

Heat Load

Heat transfer through materials at Low temperatures

$$\dot{Q} = \frac{S}{L} \int_{T_{MC}}^{T_d} k(T)\, dT$$

$T_{MC} << T_d$

Metals, k~T

Conduction electrons,

$$\dot{Q} = \frac{S}{2L} T_2{}^2 dT$$

Insulators/Phonons

$K \sim T^3$; @ $T < \Theta_D/10$

$$\dot{Q} = \frac{Sb}{4L} T_2{}^4 dT$$

Control System

Triton™- *DR*

- **FPGA (field programmable gate array) based algorithms**
- **Automated cycle, stand-alone operation**
- **Femtopower™ technology for MC T-sensor**
- **User interface via ethernet from anywhere**
- **Password security option**