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Introduction to Closed Cycle Cooling Systems (for MICE)

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Introduction

There are alternatives to standard “wet” cryogenics that use closed cycle cryocoolers.

I was asked to give a short talk on what are cryocoolers, how do they work and their benefits.

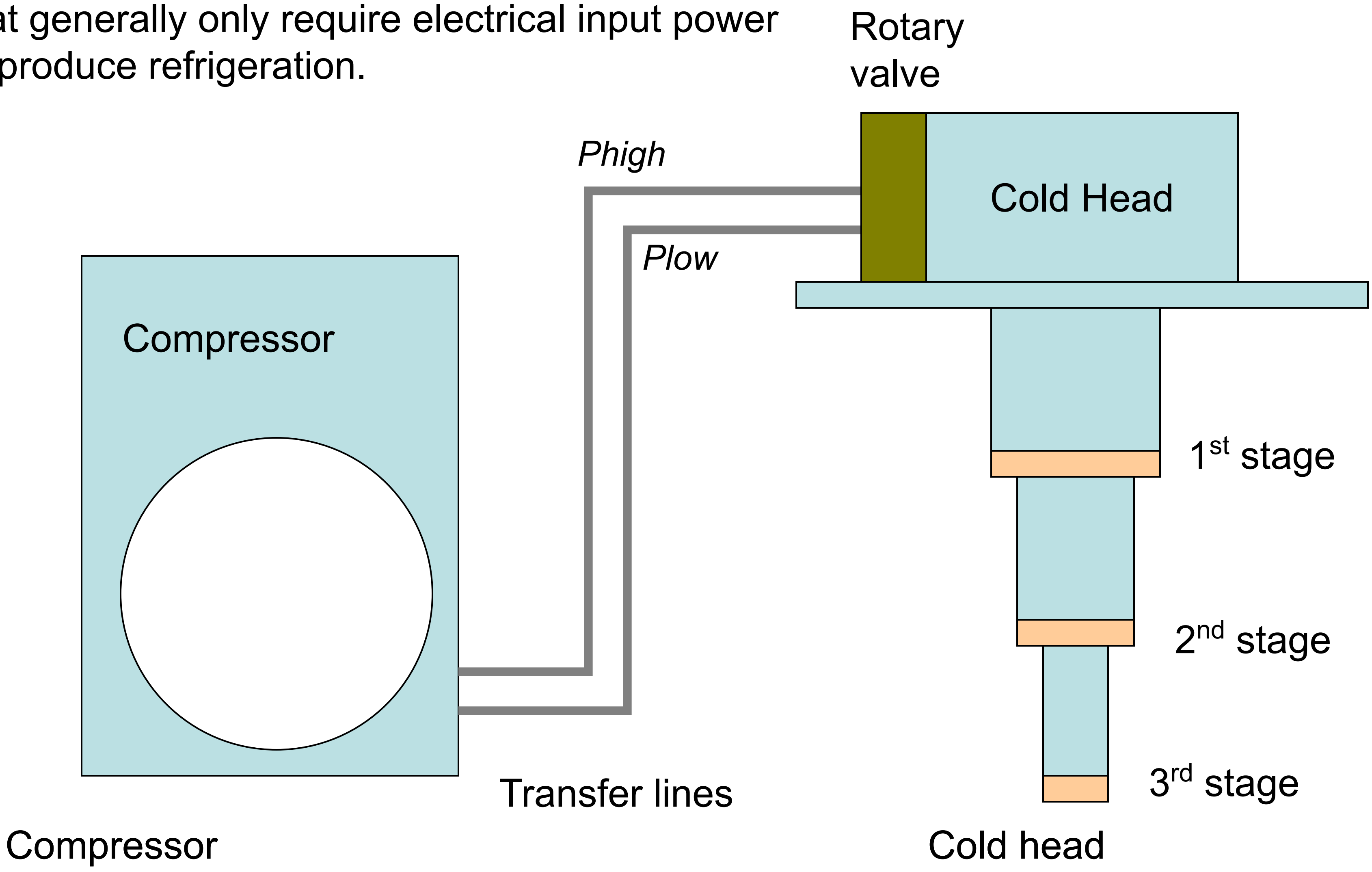
There are many types of closed cycle coolers – for MICE we can concentrate on two:

Gifford McMahon or GM cryocooler

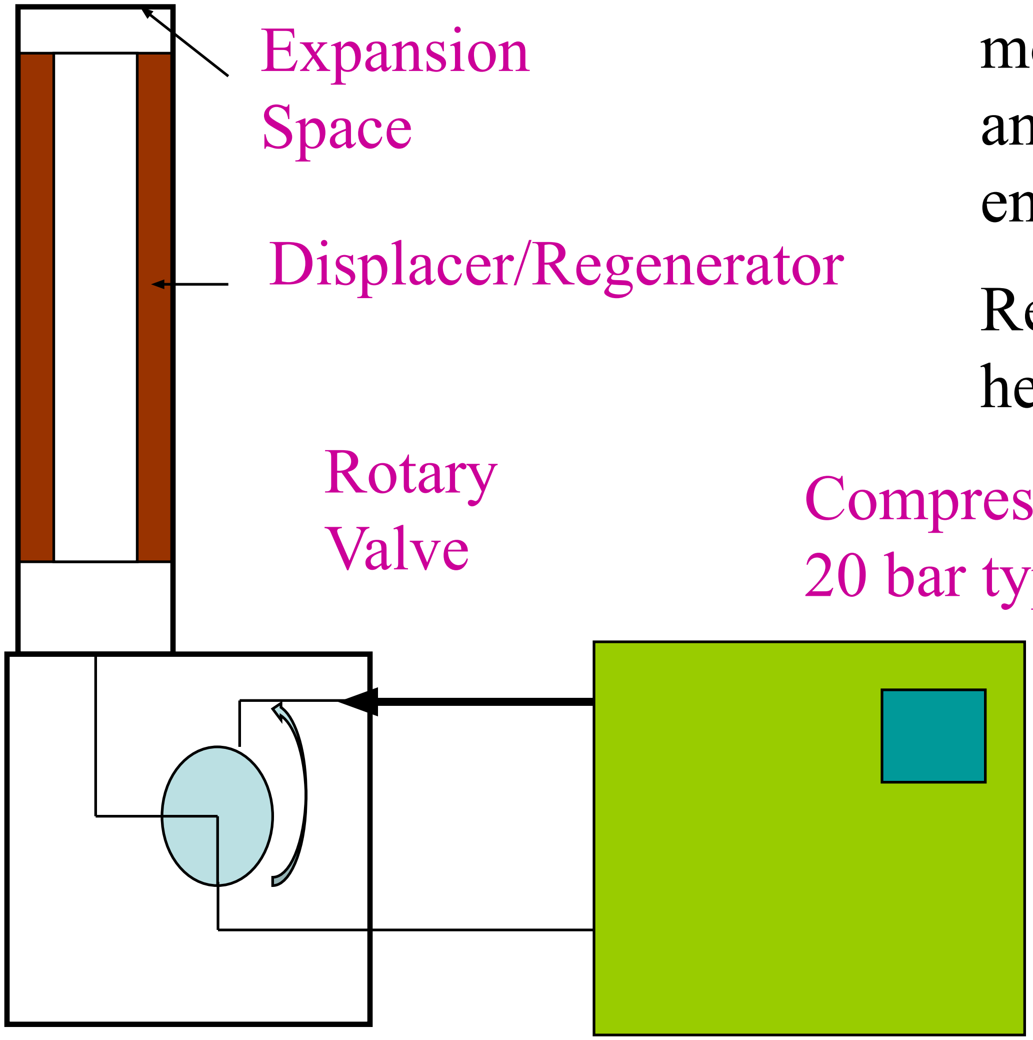
Pulse tube refrigerator

Cryocoolers

Cryocoolers are closed cycle cooling systems that generally only require electrical input power to produce refrigeration.



How do they work ?

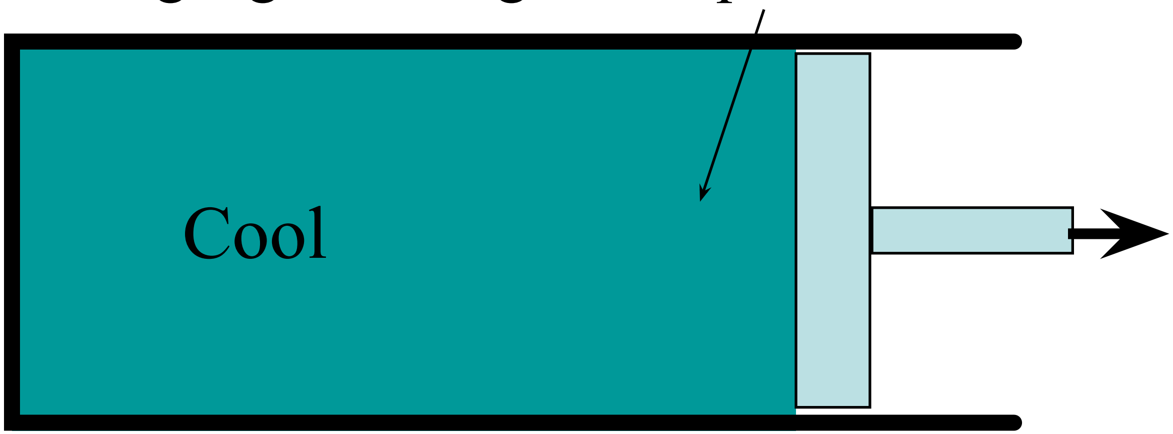


Displacer/Regenerator can move inside the cold head and pushes the gas from one end to the other.

Regenerator is a porous high heat capacity material.

How do they work?

Take a piston in a tube, sealed at one end and containing a gas – if a gas is expanded it cools



When the gas is compressed it heats up. The compressor compresses the gas and removes heat of compression.

Rotary valve alternately connects the cold cold head to the high and low sides of the compressor

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How do they work?

Regenerator /displacer – this shuttles the gas from one end of the cold head to the other so that when the gas is expanded it is always at the cold end.

Compressor - The helium is circulated through the compressor where it is compressed and the heat of compression is removed.

The regenerator acts as a "cold store". After the gas is expanded it passes through the regenerator – exchanges the "cold" with the regenerator material and passes back to the warm end. On the other half of the cycle as the gas goes towards the cold end it is pre-cooled by the regenerator.

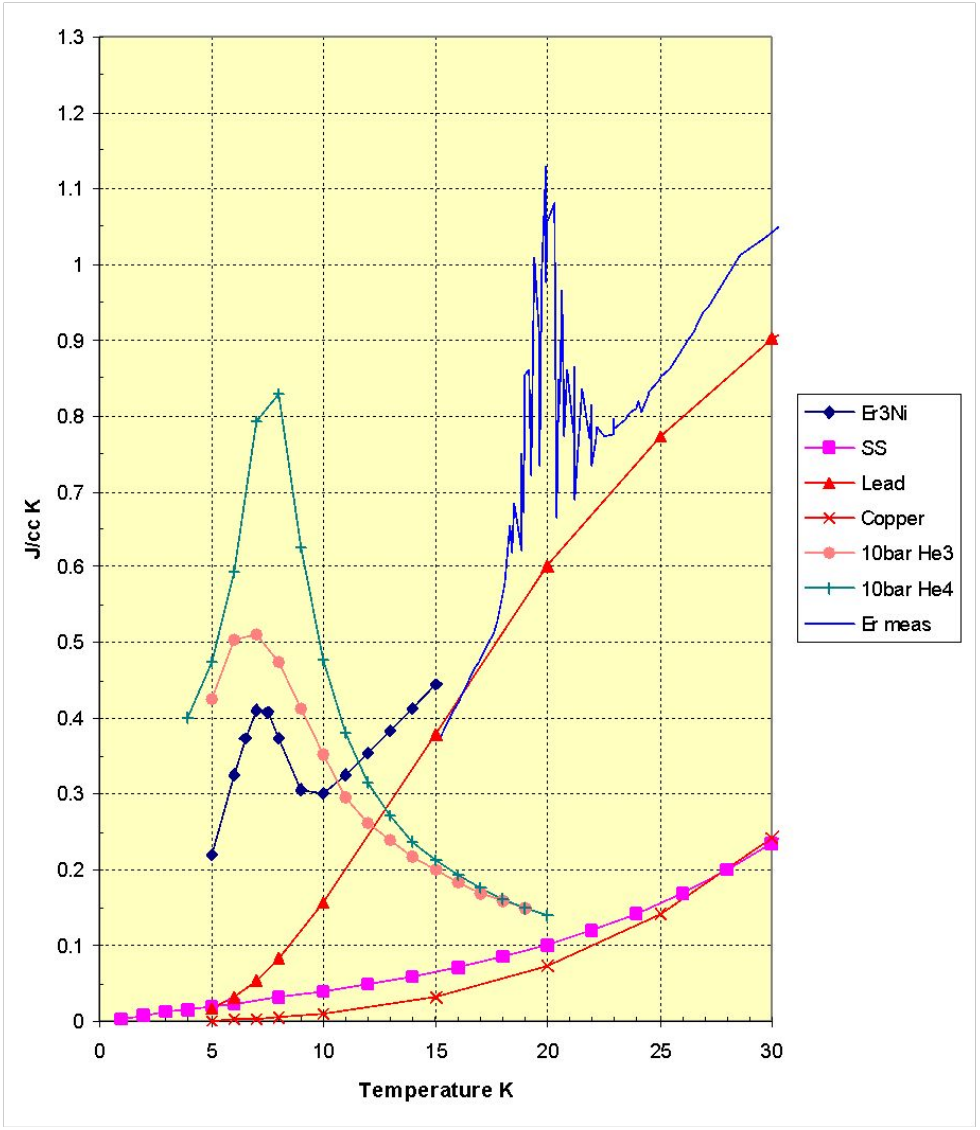
The rotary valve switches the cold head from high pressure feed to low pressure

Regenerator

Modern crycoolers can reach low temperatures because of the work done on regenerators.

The regenerator is the key component that allows low temperatures to be attained.

All low temperature crycoolers take advantage of magnetic transitions which give rise to specific heat anomalies around 4K Er_3Ni is an example.



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Cryocoolers

Cryocoolers can be purchased to operate around 4K

They typically have two or more stages of cooling allowing for interception of heat leaks

The cooling at the intermediate stages is usually many Watts

4K Cryocoolers Specification Chart

Model **SRDK-408DModel** **SRDK-408D**
SRDK-415D

1st Stage Capacity

Watts @ 50Hz 31W @ 40K 35W @ 50K

Watts @ 60Hz 37W @ 40K 45W @ 50K

2nd Stage Capacity

1.0W @ 4.2K 1.5W @ 4.2K

Lowest Temperature 2nd Stage

<3.5K <3.5K

Cooldown Time 2nd Stage

<60min. (4.2K) <60min. (4.2K)

From the Sumitomo web page

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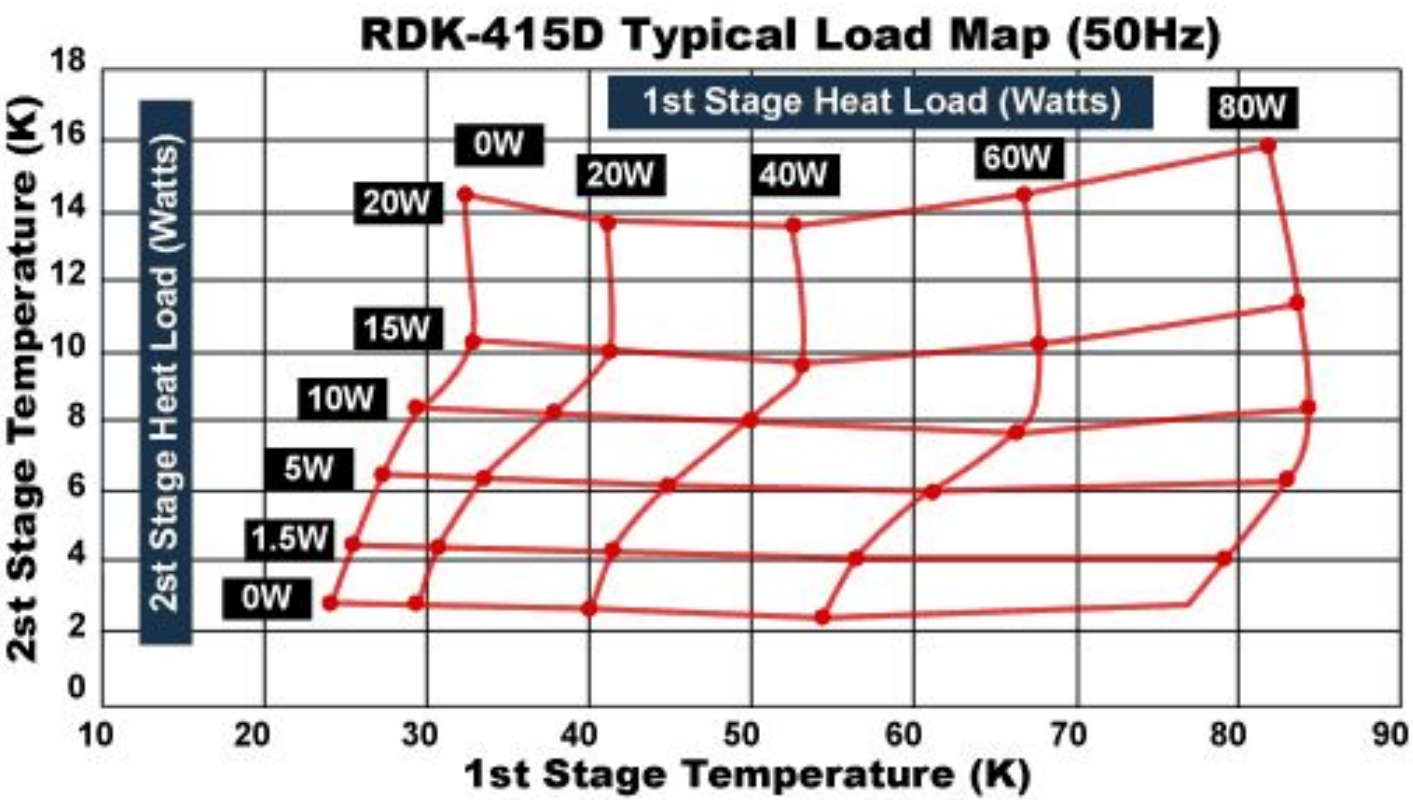
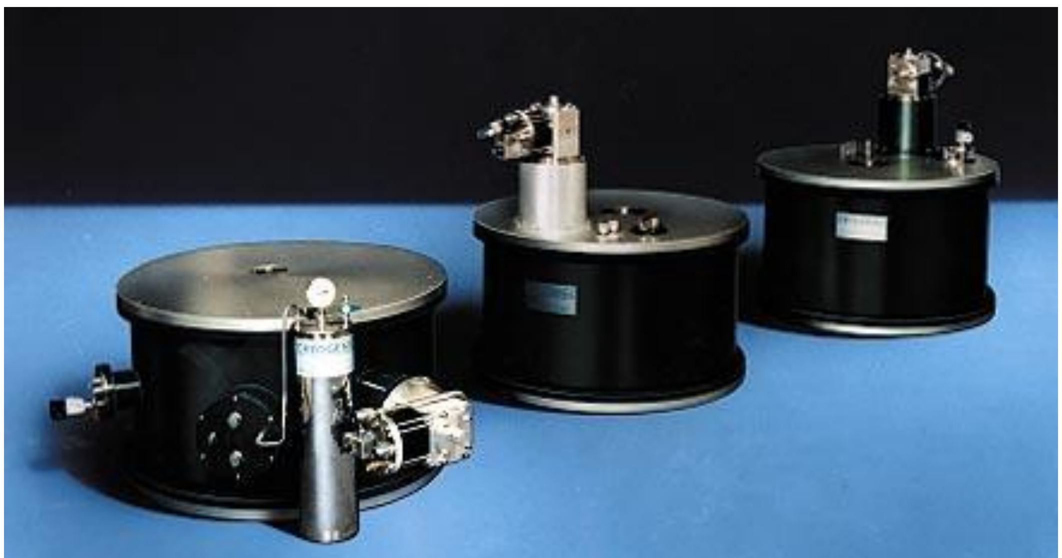


Cryocoolers - examples

Cryocoolers are commonly used to cool small to medium sized magnets.

They are used in magnetic resonance imaging magnets (MRI) in “zero boil-off” systems where the cryocooler is used to re-condense helium back into the bath

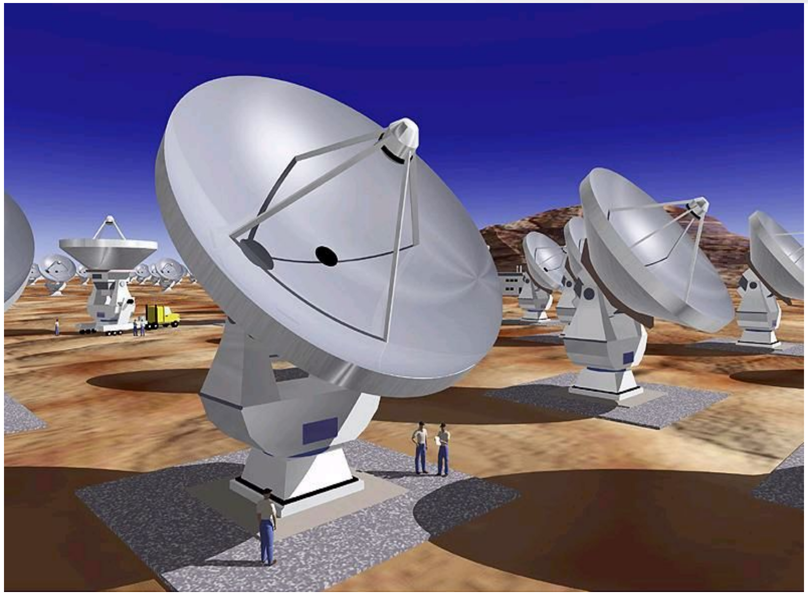
About time they were used in nuclear physics….



Cryogenic (UK) supply magnets up to 15T
Cooled with closed cycle coolers – from Cryogenic web page

A 4K Cold head from the Sumitomo web page

Examples

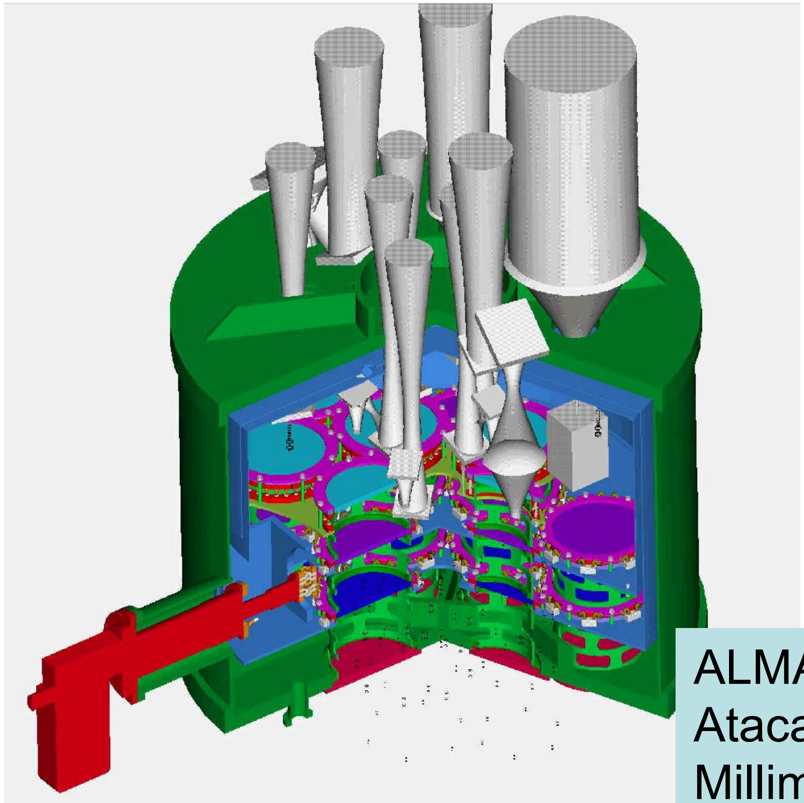


This is a “special” three stage ordered from Sumitomo

1st stage	33W @ 68K
2nd Stage	8W @ 13.7K
3rd Stage	1W @ 4.2K

Cryogenics section is building the low temperature cryostat at the focal plane of the telescope.

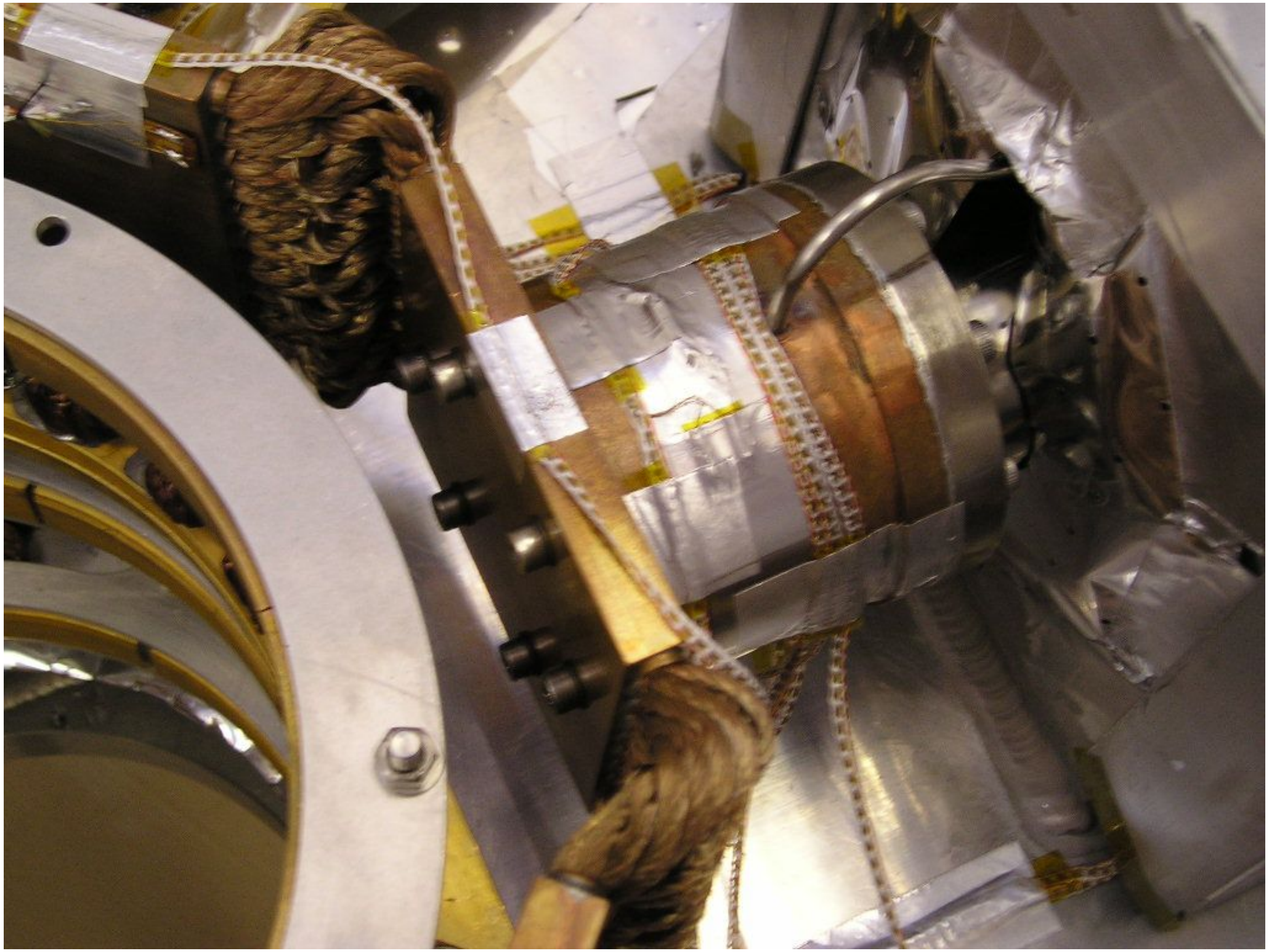
Cryocooler is shown in red



ALMA
Atacama Large Millimetre Array

ALMA Cryocooler

Design requires some heavy engineering on the thermal straps



What do we require ?

Need refrigeration for:

- Decay Solenoid near to ISIS ring
  - Requires supercritical helium
- MICE magnets
  - Require two – phase helium
  - Require shield cooling at 14K
- Hydrogen absorbers
  - Requires helium flow at 14K
- Detectors
  - Requires temperatures < 10K

Actual load at 4K is quite small …..

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Magnets

These are estimates on the likely refrigeration requirements for the MICE system.

Shows that we need a large TCF50 or equivalent refrigerator.

Component list			
Item	14K	4K	
	Watts	Watts	
Absorbers			
All sources	5		
Transfer lines	41	27.4	M Green estimate
Magnet shield cooling			
Couplers x2	30.3	3.2	M Green estimate
Focus magnets x3	21.9	5.2	M Green estimate
Detector mags x2	13.8	2.8	M Green estimate
Current leads	small		
Detectors		30	A Bross 22Jan 2004
Total W	112.00	68.60	
Equivalent 4.4K	35.20	68.60	
Grand total	103.80		
Contingency	30	%	
Budget for	134.94	Watts	

Refrigerators	No pre-cool	With LN2	Power in kW	Cost
TCF 10/CS 121	23	39	82	
TCF 20/DS 220	30	60	122	
TCF 50/FS 440	100	200	272	Around £782k
TCF 20/DSD 241	100			Quote - cost £324k

Relative cost exercise

Cryocooler cost 25 k£

Coil	Heat load at 4K	Coolers	Cost k£
Coupler A	1.6	1	25
Coupler B	1.6	1	25
Focus magnets A	1.7	2	50
Focus magnet B	1.7	2	50
Focus magnets C	1.7	2	50
Detector Magnet A	1.4	4	100
Detector Magnet B	1.4	4	100
Detectors		4	100
Totals	11.1	20	500

To provide same level of refrigeration with a wet system would cost £1.4M - £1.7M

(Both choices will still require a refrigerator for the decay solenoid £324k)

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Absorber

The absorber is a special case as refrigeration is required at 12K for the hydrogen system.

The heat load on the absorber is very low so the requirement can be met from the intermediate stage of a crycooooler.

The cryocooler developed for ALMA has cooling stages at 90K, 12K and 4K.

We can use a helium flow from the compressor of the cryocooler – the only problem here is that the heat exchanger in the absorber will have to withstand 40bar.

If this is not possible then an extra small compressor will have to be used.

Magnets and Detectors

Magnets

Magnets aren't a particular problem as this is a well known technology

Design considerations:

- Use of High Tc superconducting leads
- Heat intercepts off the intermediate stages

Detectors

These are a prime candidate for the use of cryocoolers and IC are already looking at designs incorporating this technology

Issues

Cool-down time for many of the magnets will be long and we may have to incorporate nitrogen pre-cooling loops.

Testing is easier at the host institution and more thorough characterisation will be possible

The implementation will bring considerable cost savings – in most configurations most of the power is used to cool transfer lines

Key Points

a) Staging of MICE will mean that we will have large cryogenic plant standing idle for long periods.

b) Cost - At the present the funding profile for MICE in the UK is not certain. There will be a large cost associated with the purchase of the cryogenic system.

c) Testing - If cryocoolers are used then each of the MICE "modules" can be tested independently and verified before shipping to RAL and integration. For example the detector group are keen on the idea.

d) Design - The cryocoolers can provide intermediate stages of cooling at low temperatures e.g. a three stage cooler could provide 3.8K, 14K and 90K. Can use high Tc current leads to minimise heat loads.

e) May be a pre-cooling issue – we will need to cool down the magnets in a day or two.

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Summary

Proposal:

- RAL provide only refrigeration for the decay solenoid
- Providers of MICE modules should provide their own refrigeration in the form of closed cycle cooling systems
- RAL will provide facilities for pre-cooling magnets to 80K via Nitrogen cooling

END