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Keeping Cool:
Cryogenics, Heat Transfer and Cryostat Design

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Outline

- Introduction to Cryogenics
- Heat transfer, thermal insulation systems and the impact on cryostat design
- Cryostat Examples and Thermal Insulation
    - ESS High Beta Cryomodule
    - TESLA/ILC Cryomodule
    - XRS Cryostat

Introduction

Cryogenics : the science and technology of phenomena occurring below 120 K

Why 120 K?
The temperature below which "permanent gases" start to condense

Fluid	Normal Boiling Point (K)
Krypton	119.8
Methane	111.6
Oxygen	90.2
Argon	87.3
Nitrogen	77.4
Neon	27.1
Hydrogen	20.3
Helium	4.2

But still – Why do we care?

Interesting & useful things happen at cryogenic temperatures

- Separation of air into constituent components for industrial use (oxygen, nitrogen, argon, krypton, neon)
- Liquefaction of gases allows transport at high densities and low pressure (LNG, oxygen, nitrogen, argon , hydrogen, helium)
- Superconductivity permits high field magnets (MRI, particle accelerators, basic research) and possibly electrical power applications (generators, motors, transmission lines). Superconductivity also permits powerful RF cavities for particle acceleration
- Exploration (rocket engines, cosmic background at 3 K)

Separation of air into constituent components for industrial use (oxygen, nitrogen, argon)

Air separation by cryogenic distillation

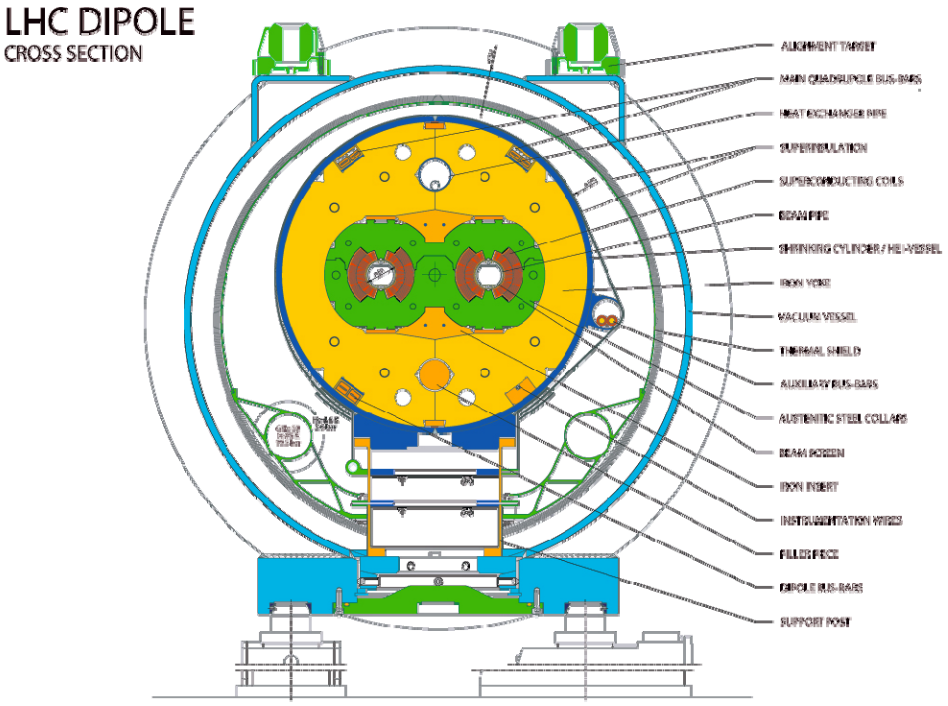
Up to 4500 t/day LOX

Liquefaction of gases allows transport at high densities and low pressure (LNG, oxygen, nitrogen, argon, hydrogen, helium)

130 000 m^3 LNG carrier with double hull

Superconductivity
(enables high field magnets)

Large Hadron Collider (CERN) 9 T magnets operating at 1.8 K (superfluid helium)



CERN AC/DI/MM — 06-2001

Superconductivity
(enables high field magnets)

Magnetic Resonance Imaging (MRI)

Certainly the most common use of superconductivity

Magnets operate in the 1 – 3 T range cooled to roughly 4 – 5 K

Very low loss cryostats

    Use of cryogenics is not obvious to staff or patients

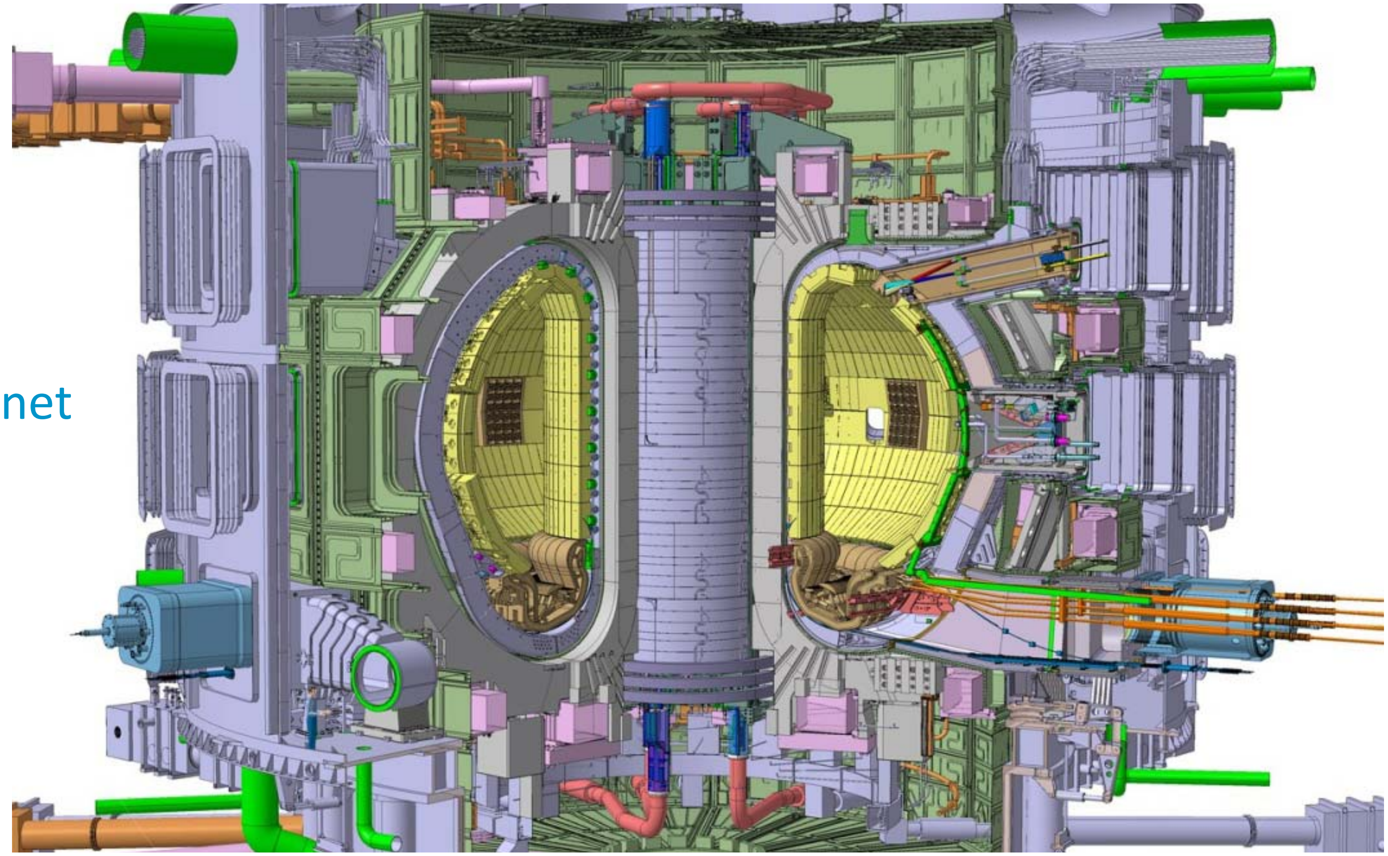
Superconductivity
(enables high field magnets)

ITER Fusion Reactor

Under design & construction in Cadarache, France

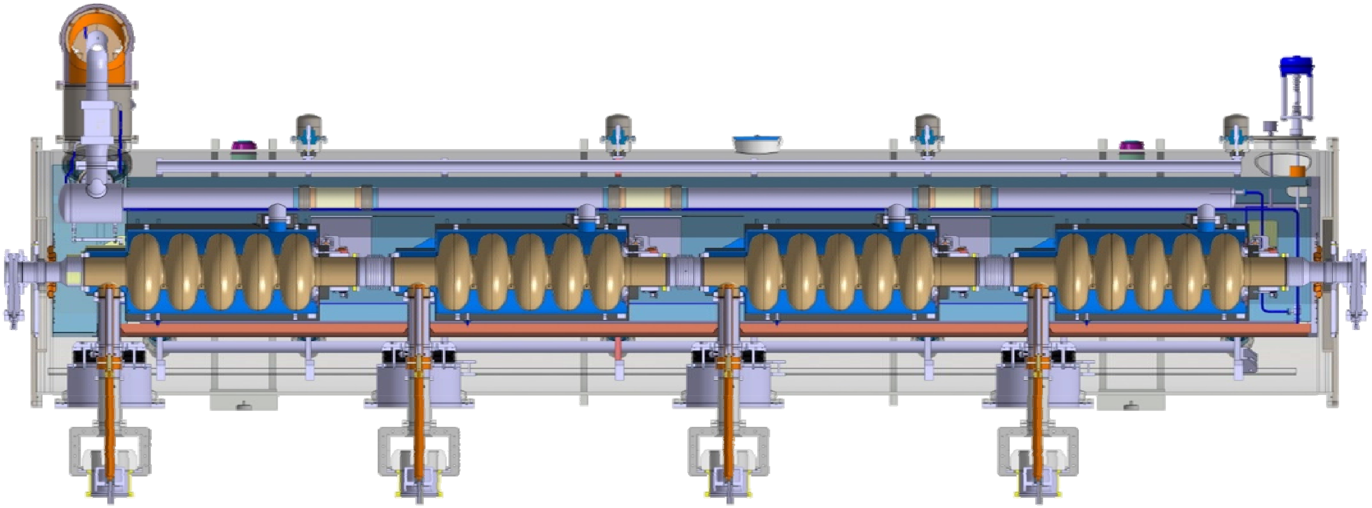
3 separate superconducting magnet systems

3 ~ 25 kW at 4.5 K helium refrigeration plants



Superconductivity (enables powerful RF cavities for accelerators)

ESS Elliptical Cavity Cryomodule



Superconducting RF is Very Popular
(In addition to ESS we have)

Name	Type	Lab	T (K)	Refrigeration Capacity	Comments
CEBAF/12 GeV	Accelerator	JLab	2.1	8.4 kW @ 2.1 K	
SNS	Accelerator H_2 Moderator	ORNL	2.1 20	2.4 kW @ 2.1 K 7.5 kW @ ~ 20 K	
S-DALINAC	Accelerator	TU Darmstadt	2.0	120 W @ 2.0 K	
FLASH	Accelerator	DESY	2.0		TESLA tech
ARIEL (e linac)	Accelerator	TRIUMF	2.0	288 L/h	
ALICE	Accelerator	STFC Daresbury	2	150 W @ 2 K	TESA Tech
CLS	Accelerator	CLS (Canada)	4.5	284 W @ 4.5 K	SRF Cavities
ERL	Electron Linac	Cornell	1.8 5 40-50	7.5 kW @ 1.8 K 6.8 kW @ 5 K 144 kW @ 40-80	Proposed: Prototypes under construction TESLA Tech
XFEL	Electron Linac	DESY	2.0 5 – 8 40-80	2.5 kW @ 2 K 4 kW@ 5 -8 K 26 kW @ 40-80 K	Construction (2017) TESLA Tech
LCLS II	Accelerator	SLAC	2.1 K	4 kW @ 2 K 14 kW @ 35 -55 K 1.2 kW @ 5 – 8 K	Design (2019) TESLA Tech

Exploration (rocket engines)

Ariane 5 Cryogenic Main Stage

Cryogenics and IR Astronomy

IR astronomy is an important window into understanding the universe

- Allows observations of objects through dust clouds etc
- Compliments other observing methods (radio, x-ray, gamma ray, UV, visual)
- Measuring variations in the 3 K background gives information on the formation & evolution of the universe

These are almost always space borne systems operating at temperatures of 2 K or less

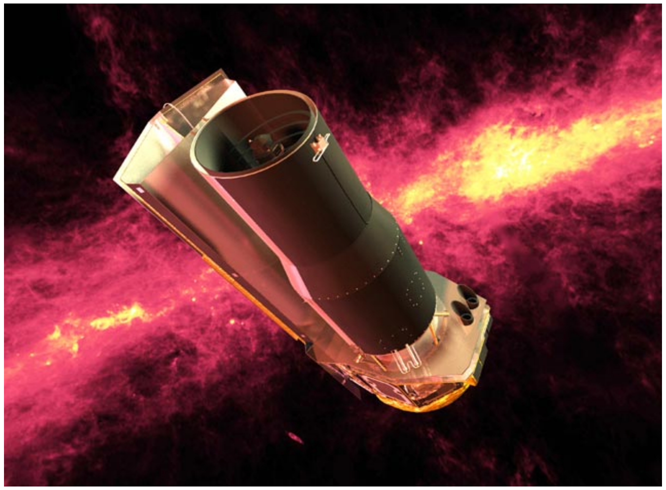
Examples:

- IRAS, Spitzer, COBE, WMAP
- Planck and Herschel (launched in 2009)

Spitzer Infrared Space telescope

(2003 -2009)

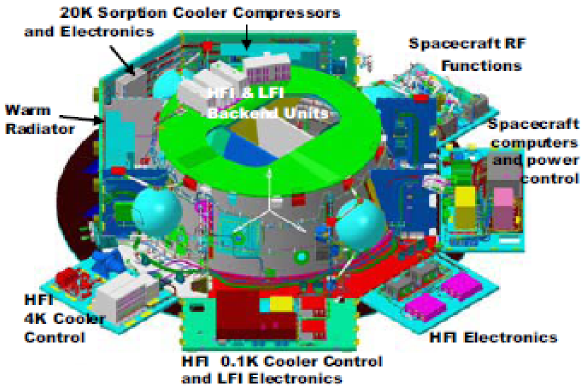
Cooled to 1.8 K via superfluid helium (360 L)



Planck & Herschel Missions (ESA)

Planck

- Surveys the structure of the cosmic background
- Requires temperatures down to 100 mK
- Uses only mechanical coolers
  - Sorption (20 K), JT (4 K) and dilution refrigerator (100 mK)
  - No tanked cryogens



Herschel (mission complete)

- IR observatory similar to Spitzer
- Requires temperatures down to 300 mK
- Contained 2360 L of He II (1.6K)
- ^{3}He Sorption cooler provides 300 mK temperatures

Cryogenics is a major industry

Firms with significant cryogenic activities include:

Air Products – 10 B$ in sales in 2014
Praxair – 11 B$ in sales in 2012
Linde – 16.6 B Euros in sales in 2013
Air Liquide – 15 B Euros in sales in 2013
Siemans – Significant MRI producer
General Electric – Significant MRI producer

Heat Transfer & Cryostat Design

The field of cryogenics has many subtopics, for today I talk only about the relationship between heat transfer and cryostat design, But before I do I want to bring up 2 important background points:

1) Coefficient of Performance

2) Temperature variation of thermal conductivity

Coefficient of Performance & the Carnot Cycle

Coefficient of Performance: the heat absorbed from the cold sink divided by the net work required to remove this heat

$$\mathrm{COP} = -\frac{Q_a}{W_{net}} = -\frac{\left({Q_a}/{m}\right)}{\left({W_{net}}/{m}\right)}$$

For the ideal (and in practice unachievable) Carnot cycle it can be shown that:

$$COP = -{Q_a}/{W_{net}} = \frac{T_C}{T_H - T_C}$$

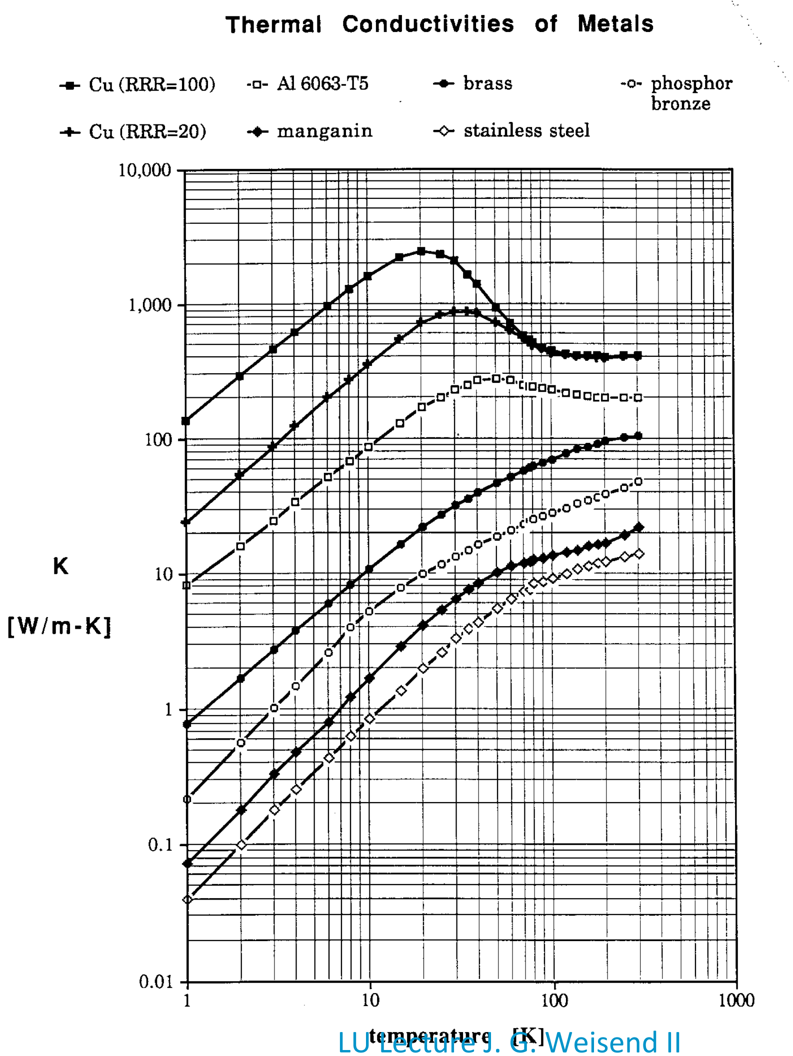
Coefficient of Performance & the Carnot Cycle

- For a plant operating between room 300 K and 4.2 K, the Carnot COP is 4.2/(300 – 4.2) or 0.0142
- The Carnot cycle is the ideal case. It is the best you can do without violating the laws of thermodynamics
- Note that the form of the Carnot COP shows that you have a better COP (thus a more efficient process or refrigerator) if T_C is large
  - It is always thermodynamically more efficient to intercept heat (provide cooling) at higher temperatures
  - This fact drives a lot of cryogenic design
- In practice, we generally discuss the inverse of the COP because this allows us to describe the number of watts of work required to provide 1 Watt of cooling at a given temperature. For a Carnot cycle providing cooling at 4.2 K. This is **70 W/W**
  - People will frequently and incorrectly refer to this as a COP as well

Temperature Variation of Thermal Conductivity

A feature of cryogenics is that given the wide temperature range experienced, material properties are not constant and thus there temperature dependence must be taken into account. This effect is particularly strong with Thermal conductivity.

Thermal Conductivity of Metals



From Lakeshore Cryotronics

Thermal Conductivity Integrals

The strong temperature dependence of K makes heat transfer calculations difficult

The solution frequently is to use thermal conductivity integrals

The heat conduction equation is written as:

$$Q = -G\left(\theta_2 - \theta_1\right)$$

Thermal Conductivity Integrals

G is the geometry factor

$$G = \frac{1}{\int_{x_1}^{x_2} \frac{dx}{A(x)}}$$

θ is the thermal conductivity integral

$$\theta_i = \int_0^{T_i} K(T)dT$$

Thermal Conductivity Integrals

Advantages:

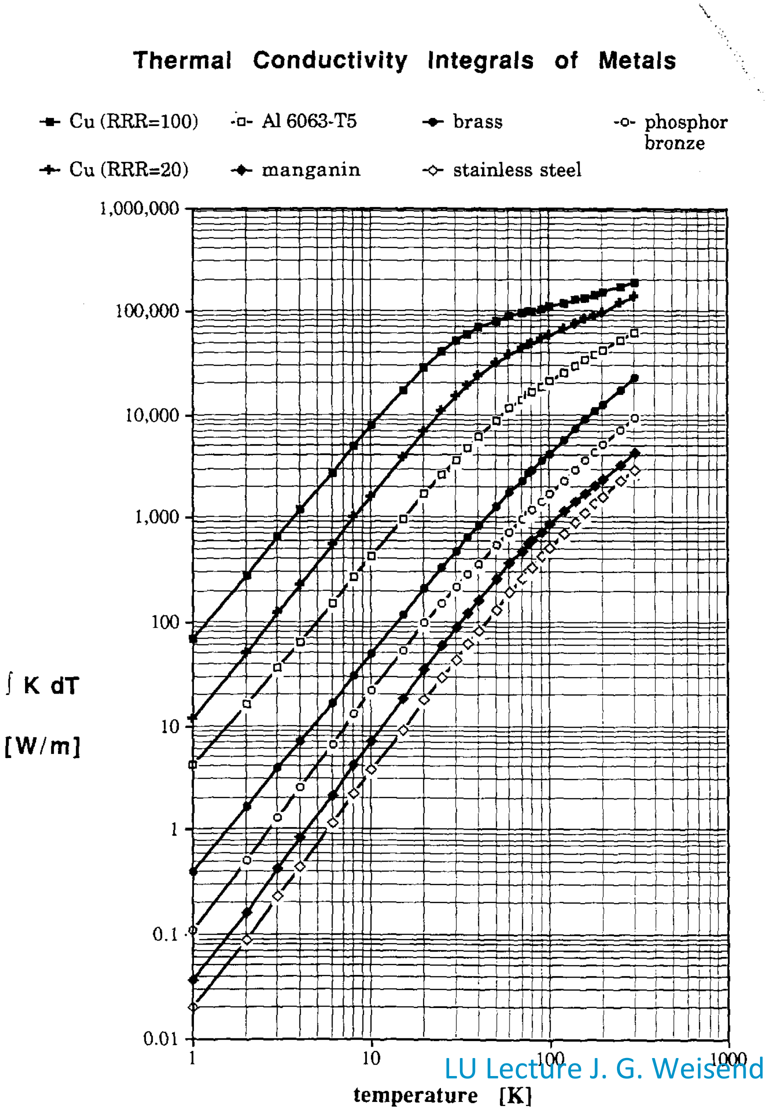
Simple

Only end point temperatures are important. (assuming there are no intermediate heat sinks) The actual temperature distribution is not.

Thermal conductivity integrals have been calculated for many engineering materials

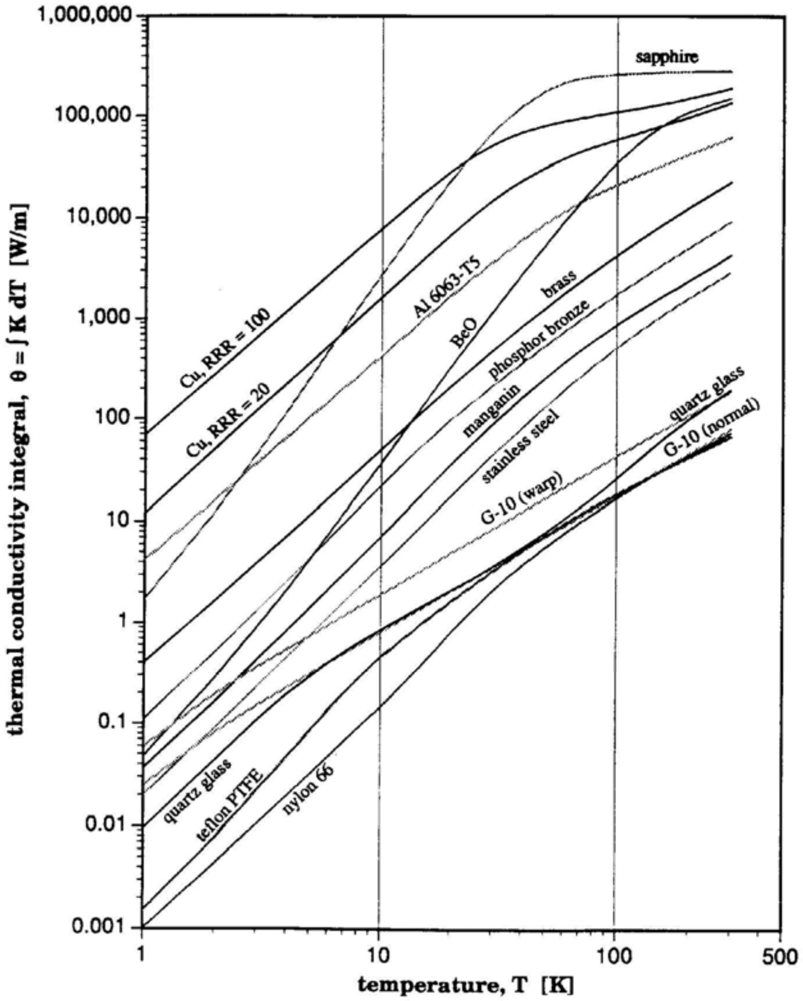
This is quite useful for heat leak calculations

Thermal Conductivity Integrals



From Handbook of Cryogenic Engineering, J. Weisend II (Ed)

Thermal Conductivity Integrals of Metals & Nonmetals



Cryostats, Cryomodules and Dewars

What is a cryostat?

A device or system for maintaining objects at cryogenic temperatures.

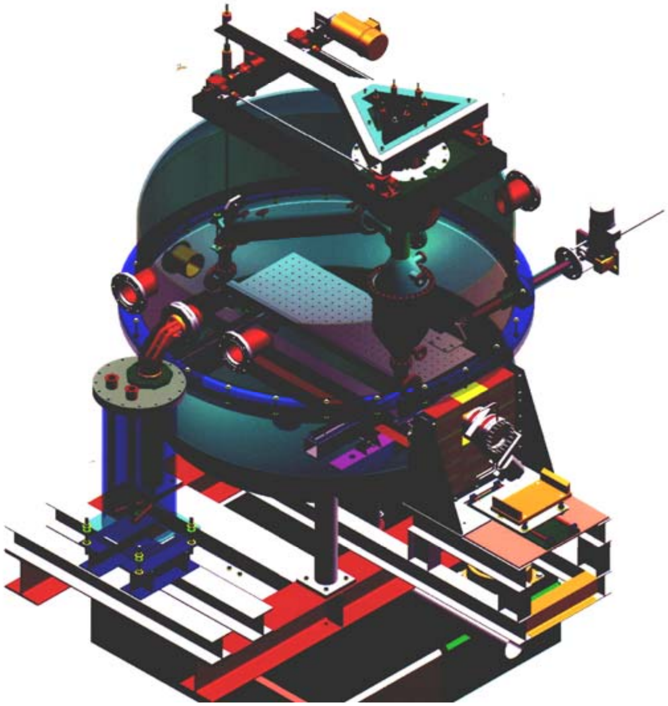
Cryostats that contain SCRF cavity systems are also frequently called *cryomodules*

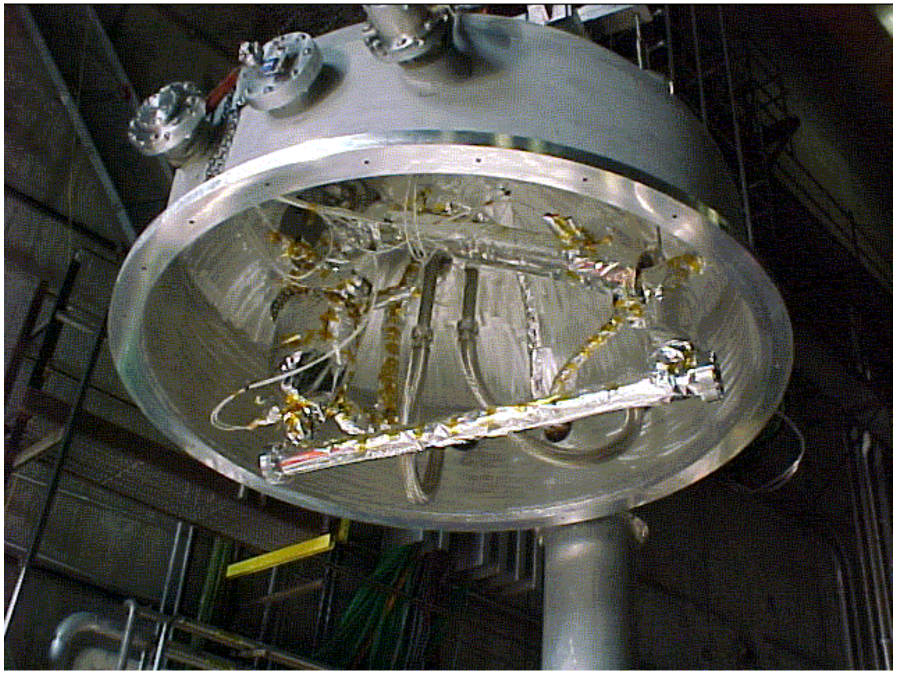
Cryostats whose principal function is to store cryogenic fluids are frequently called *Dewars*. Named after the inventor of the vacuum flask and the first person to liquefy hydrogen

Cryostats

- Cryostats are one of the technical building blocks of cryogenics
- Cryostat design involves many subtopics most of which we don’t have time to cover here:
    - Development of requirements
    - Materials selection
    - Thermal insulation
    - Support systems
    - Safety
    - Instrumentation

E158 LH_2 Target Cryostat





Thermal Insulation

- This is key to proper cryostat design
- The effort and cost expended on this problem are driven by cryostat requirements:
  - Dynamic vs. static heat loads
  - Number of cryostats
  - Operational lifetime & ability to refill cryostats (e.g. space systems)
- Lowest possible static heat leak isn't always the best answer
- Recall It is thermodynamically best to intercept heat leaks at the warmest temperature practical

Three Ways to Transfer Heat

- Conduction
  - Heat transfer through solid material
- Convection
  - Heat transfer via a moving fluid
    - Natural or free convection – motion caused by gravity (i.e. density changes)
    - Forced – motion caused by external force such as a pump
- Radiation
  - Heat transferred by electromagnetic radiation/photons
- There is no such thing as a perfect insulator – though we can design systems with very small heat leaks
- All matter above 0 K radiate heat
  - Remember we can't get to 0 K – 3rd Law of Thermodynamics though we can get vanishingly close
- Heat flows from high temperature to low
  - Heat leaks in, cold doesn't leak out

Conduction Heat Transfer

Fundamental Equation – The Fourier Law in one dimension

$$Q = -K(T)A(x)\frac{\partial T}{\partial x}$$

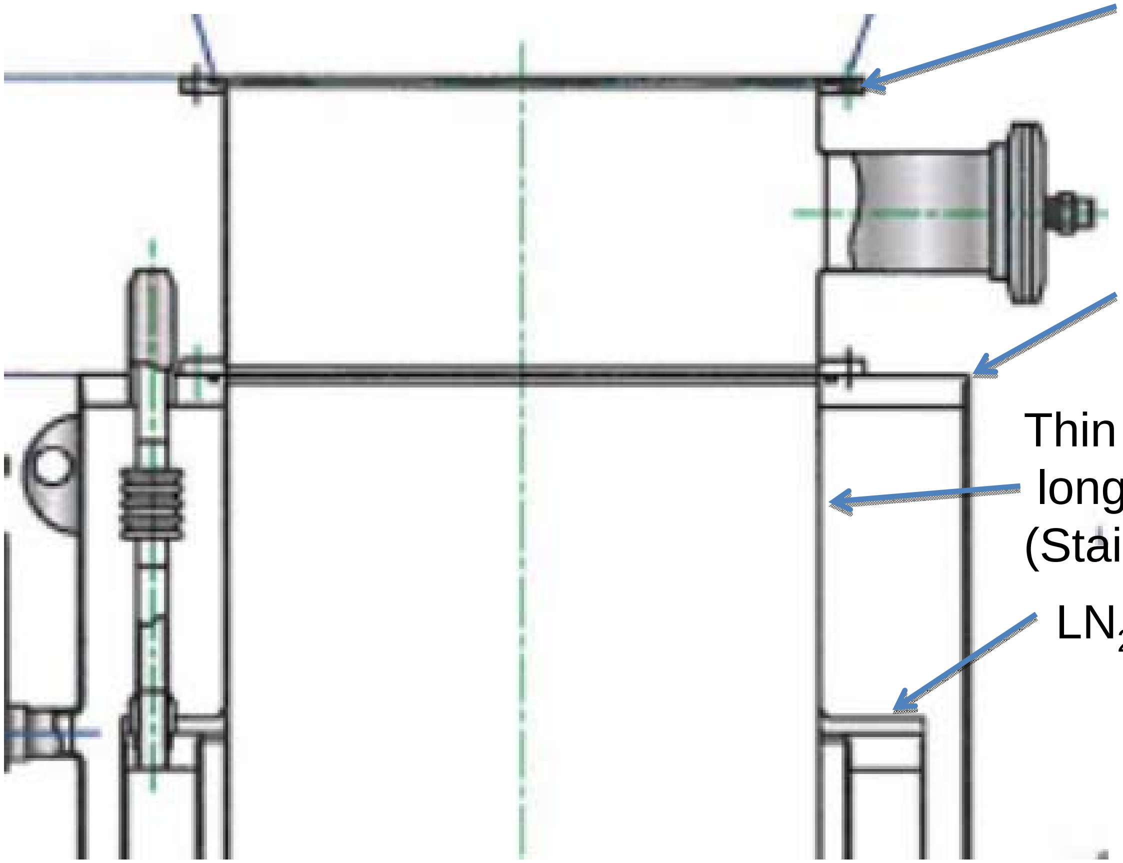
If we assume constant cross section we get:

$$Q = -A/L\int_{T_C}^{T_H} K(T)dT$$

Reduce conduction heat leak by:

- Low conductivity material: make K(T) small
- Reduce cross sectional area: make A small
- Increase length: make L large
- For a given T_C make T_H smaller: i.e. use intermediate temperature heat intercepts

Design Example
Laboratory Cryostat



300 K

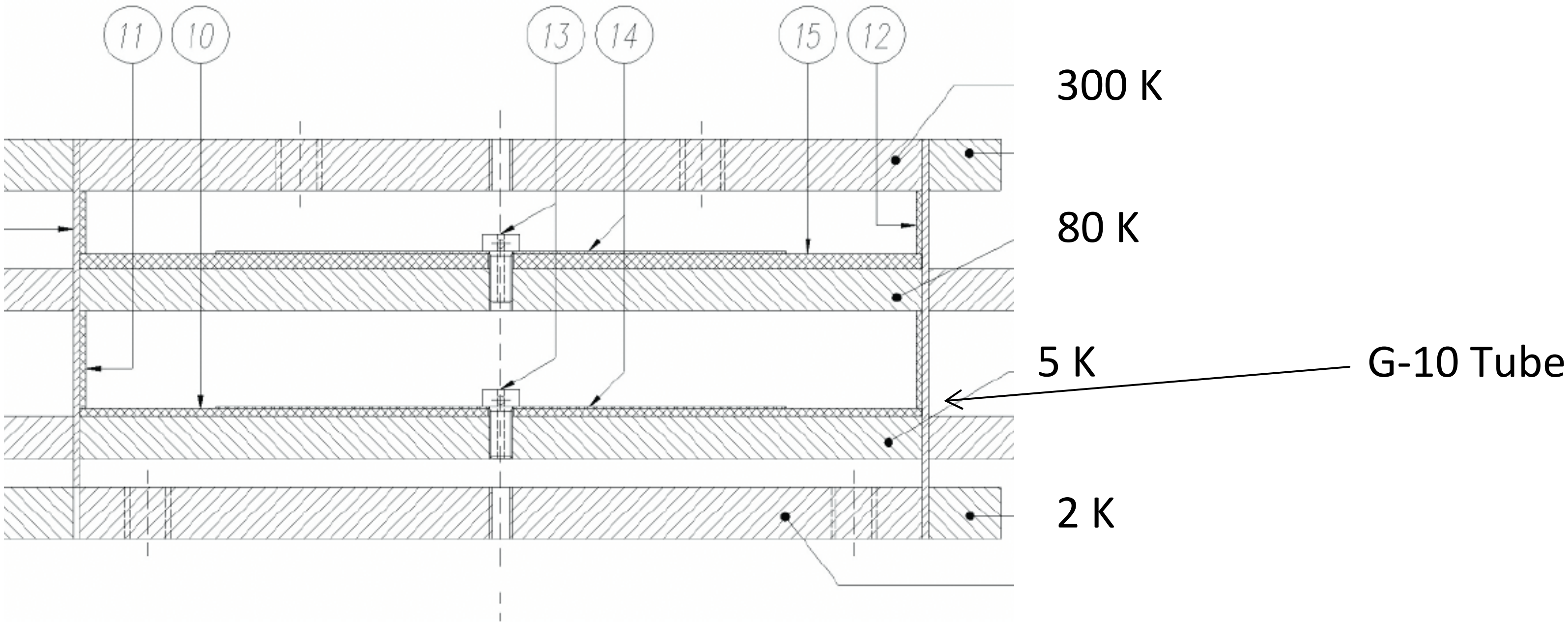
300 K

Thin wall
long length & low K
(Stainless Steel)

LN$_2$ Bath (77 K)

Design Example
ILC Cryomodule Support Post

Courtesy T. Nicol - Fermilab



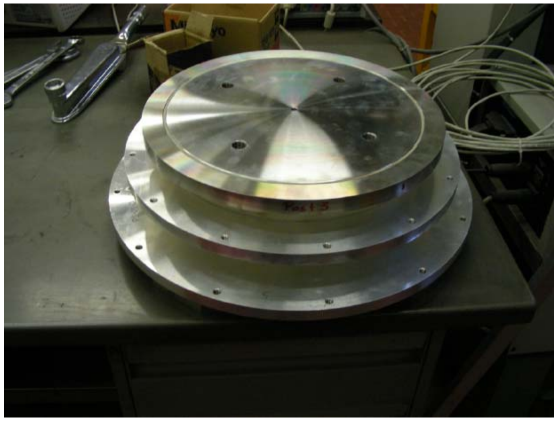
Total Heat Leak (conduction & radiation)

70 K - 10.5 W

5 K - 0.9 W

2 K - 0.03 W

Can support up to 50 kN



Convection Heat Transfer

Fundamental Equation: Newton’s law of cooling

$$Q = hA(T_{surface} - T_{fluid})$$

where h is the heat transfer coefficient and is a function of Re, Pr, geometry etc depending on the situation

In cryogenics we eliminate convection heat leak in cryogenic systems by “simply” eliminating the fluid – vacuum insulation

Using vacuum insulation to create vessels capable of storing cryogenic liquids was first done by James Dewar – who liquefied hydrogen

Vacuum Insulation

How much vacuum is enough?

- This of course depends on the heat leak requirements but generally we want to be below 10^{-5} millibar
- If we maintain this level or better we can generally neglect the convection heat leak for most applications.
  - Cryogenic Engineering, Flynn (1997) has a good discussion of calculating heat leak due to residual gas pressure

Cryopumping

- At cryogenic temperatures almost all common gases condense and freeze onto the cold surface.
- Typically, we'll see that once surface are cooled to ~ 77 K the isolation vacuum will drop to the 10^{-8} millibar or better range if the system is leak tight and doesn't have significant outgassing
- But don't just start cooling with everything at room pressure
  - Heat leak will likely be too high
  - Safety hazards due to enrichment of LOX on cold surfaces
  - Large amounts of condensed gases in vacuum space can lead to other problems including rapid pressure rise upon warming and possible solid conduction
  - Best practice is to be at least 10^{-3} millibar before cooling, lower pressures are better but there may be operational tradeoffs

Outgassing and Getters

All material outgas into a vacuum. This can raise the pressure in a sealed vacuum space

Reduce outgassing by:

- Minimize amount of polymers, wire insulation, FRP etc – difficult
- Keep vacuum surfaces as clean as possible. Remove any oil or cutting fluid, wear gloves etc.

Getters: materials inserted into vacuum spaces to remove residual gas at low pressures

In cryogenic systems, getters may be useful in removing residual gas and passively managing small leaks

Outgassing and Getters

3 types of getters

Adsorbers –gas bonds to surface

- Activated charcoal, silica gel
- Effectiveness increases with decreasing temperature – good for cryogenic systems

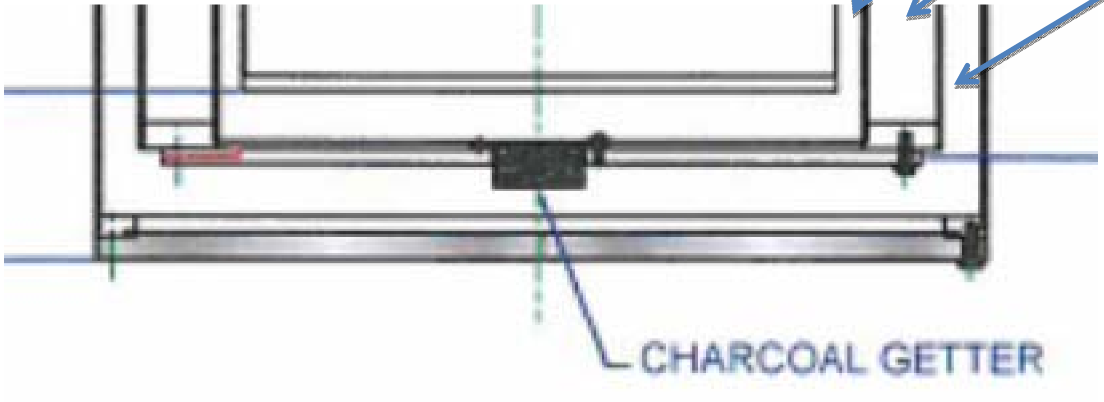
Chemical getters – chemical reaction between material and gas

- Ba & other Alkali metals – not very common in cryogenics

Solution or absorber getters – gas is absorbed in interstitial space of metals

- Ti, Zr, Th works well with H_2, O_2 and N_2
- Much better at room temperature
- Occasional use in room temperature applications in cryogenic systems

Design Example
Laboratory Dewar



Vacuum space between LN_2 bath and LHe bath

LN_2 Bath

Vacuum space between 300 K wall & LN_2 bath

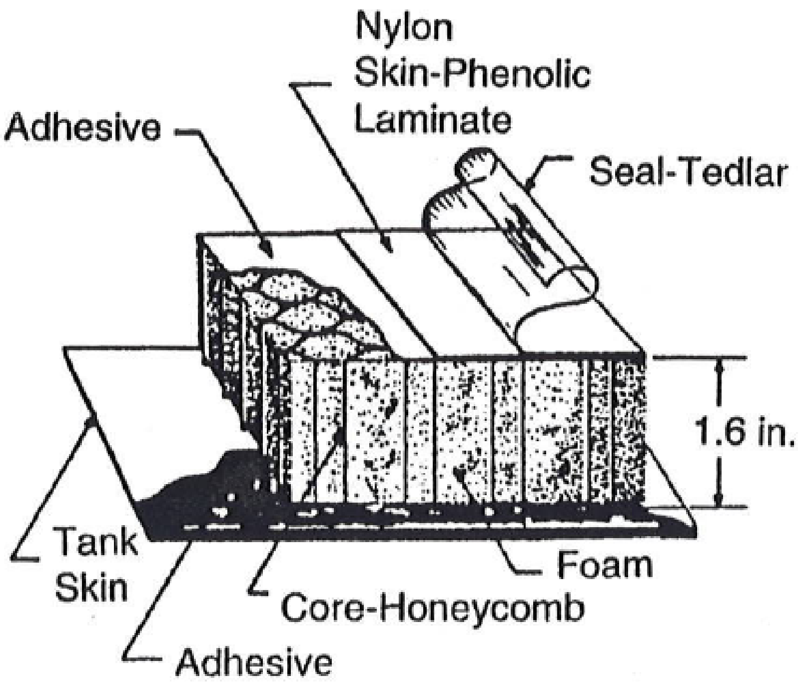
77 K Thermal shield

Note: vacuum spaces are typically common

Foam & Other Insulation Methods

- Not all cryogenic systems use vacuum insulation
- This is particularly true of storage vessels for fluids other than helium
- Reasons for using alternatives to vacuum insulation
  - Cost
  - Weight – Space shuttle main tank
  - Required hold time – related to size
  - Complex vessel shapes
- Some solutions
  - Expanded closed or open cell foams
  - Rock wool, fiberglass or other porous material
- These all require vapor barriers to prevent air from being pulled into the insulation and condensed (can cause both a safety hazard via O_2 enrichment & reduce effectiveness)

Design Example:Complex Foam Insulation System: LH_2 Tank for 2nd Stage Saturn V



From <u>Cryogenic Engineering</u>, Flynn

Allows helium purging of the insulation

Weight ~ 4.15 kg/m^2

Performance: measured effective thermal conductivity (0.86 – 1.1 mW/cm K) at T_{av} = 144 K Note this includes conduction, convection and radiation heat transfer

Radiation Heat Transfer

Frequently the largest source of heat leak to cryogenic systems

Fundamental Equation: Stefan-Boltzmann Law – energy emitted from an ideal black body: $E_b = \sigma T^4$ where $\sigma = 5.67\times10^{-8}$ W/m^{2}K^4

Real world Assumptions:

Emissivity (ε) << 1 and independent of wavelength (grey body)

Two parallel infinite plates: Radiative heat flux (W/m^2)

Eq. A

$$q_r = \left(\frac{\varepsilon_1\varepsilon_2}{\varepsilon_1 + \varepsilon_2 - \varepsilon_1\varepsilon_2}\right)\sigma\left(T_1^{\,4} - T_2^{\,4}\right)$$

Frequently in cryogenic systems $\varepsilon_1 \sim \varepsilon_2 << 1$ then Eq. A becomes:

Eq. B

$$q_r = \left(\frac{\varepsilon}{2}\right)\sigma\left(T_1^{\,4} - T_2^{\,4}\right)$$

Radiation Heat Transfer

Two long concentric cylinders or concentric spheres (1 represents the inner cylinder): the radiative heat flux (W/m^2) on the inner cylinder is

Eq. C

$$q_1 = \left(\frac{\sigma\left(T_1^4 - T_2^4\right)}{1/\varepsilon_1 + \left(A_1/A2\right)\left(1/\varepsilon_2 - 1\right)} \right)$$

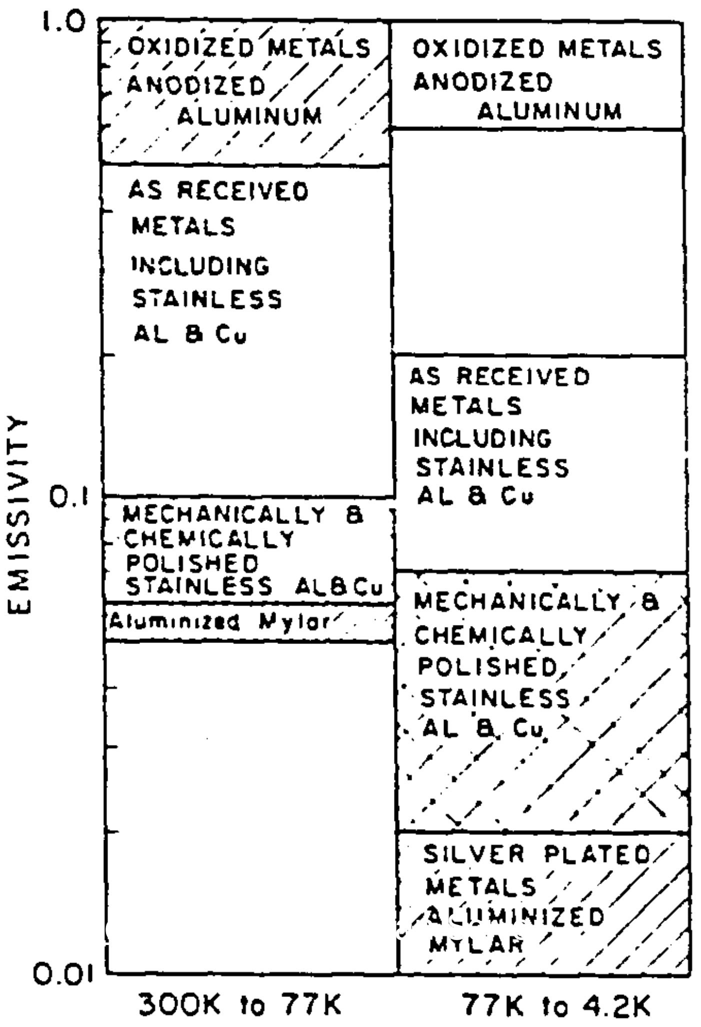
Note as is frequently the case in cryogenics, if the spacing between the cylinders is small compared to the inner radius (i.e. $A_1 \sim A_2$) Eq. C becomes Eq. A

Radiation Heat Transfer

Looking at Eq. A, How do we reduce the heat transfer?

We could reduce the emissivity (ε)

- This is done in some cases; using either tape or silver plating
- Better below 77 K
- It's also part of MLI systems (see below)
- We have to consider tarnishing
- May be labor intensive



Radiation Heat Transfer

Another way to reduce radiation heat transfer is to install intermediate actively cooled radiation shields that operate at a temperature between 300 K and the lowest cryogenic temperature. This has several advantages.

- It greatly reduces the heat load to the lowest temperature level
  - Assume parallel plates with $\varepsilon = 0.2$
  - then from Eq. B q (300 K – 4.2 K) = 46 W/m^2 while q (77 – 4.2) = 0.2 W/m^2
- It allows heat interception at higher temperatures & thus better Carnot efficiency
- Such an actively cooled shield provides a convenient heat intercept for supports, wires etc to reduce conduction heat leak.

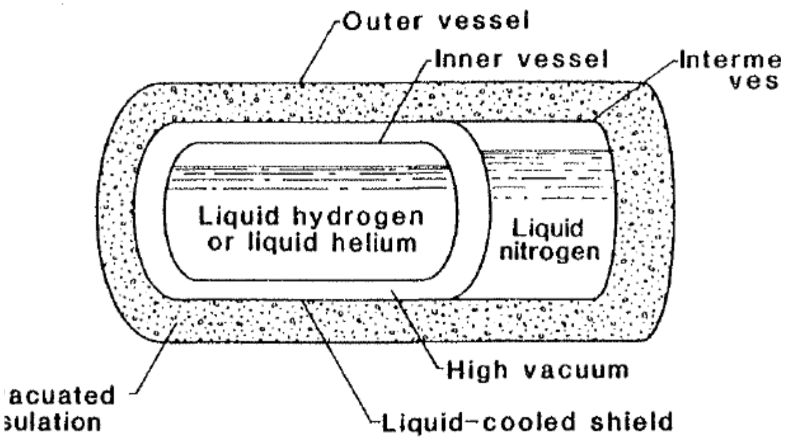
Shields may be cooled by

- Liquid baths (LN_2)
- Vapor boil off from stored liquid – common in LHe storage dewars
- Cooling flows from refrigeration plants
- Conductive cooling via small cryocoolers

Radiation Heat Transfer

LN_2 bath surrounds inner LHe or LH_2 bath

Baths are separated by a vacuum insulation space



Shield is cooled by boil off gas from stored cryogen

Spacing of cooling tubes on shield may be calculated by: $\Delta T = qL^2/2kt$

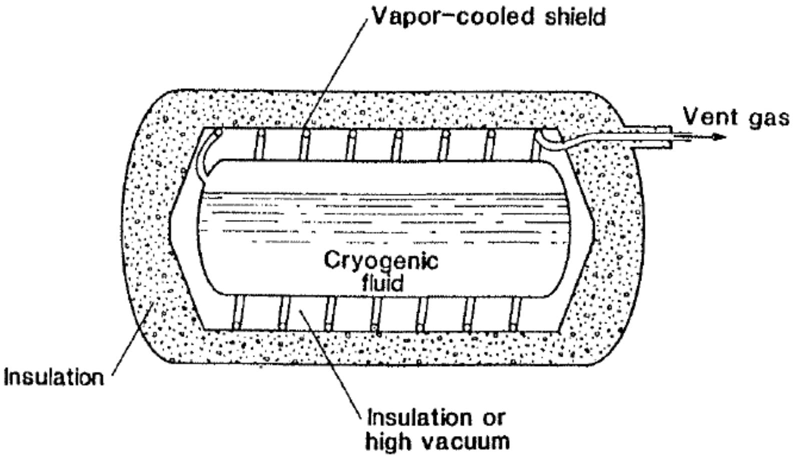
ΔT = max allowable temperature difference between any point on shield and tube

q = heat flux on shield

k = shield thermal conductivity

L = ½ max tube spacing

t = shield thickness



From Cryogenic Engineering, Flynn

Radiation Heat Transfer

Use Multilayer Insulation (MLI) or "superinsulation" inside the vacuum space to reduce heat leak

$$q = \frac{\varepsilon}{(N+1)2}\sigma\left(T_H^4 - T_L^4\right)$$

Multilayer Insulation

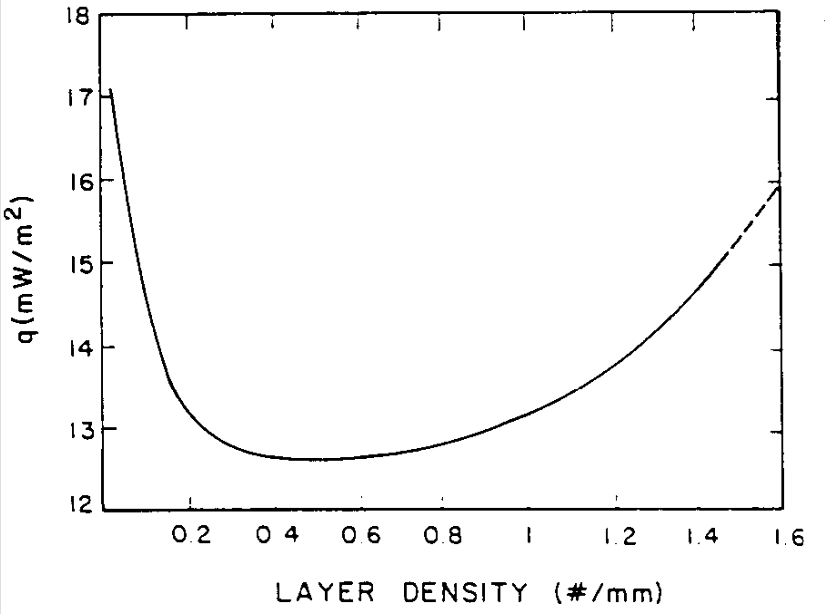
Used in almost all cryostats

Consists of highly reflective thin sheets with poor thermal contact between sheets

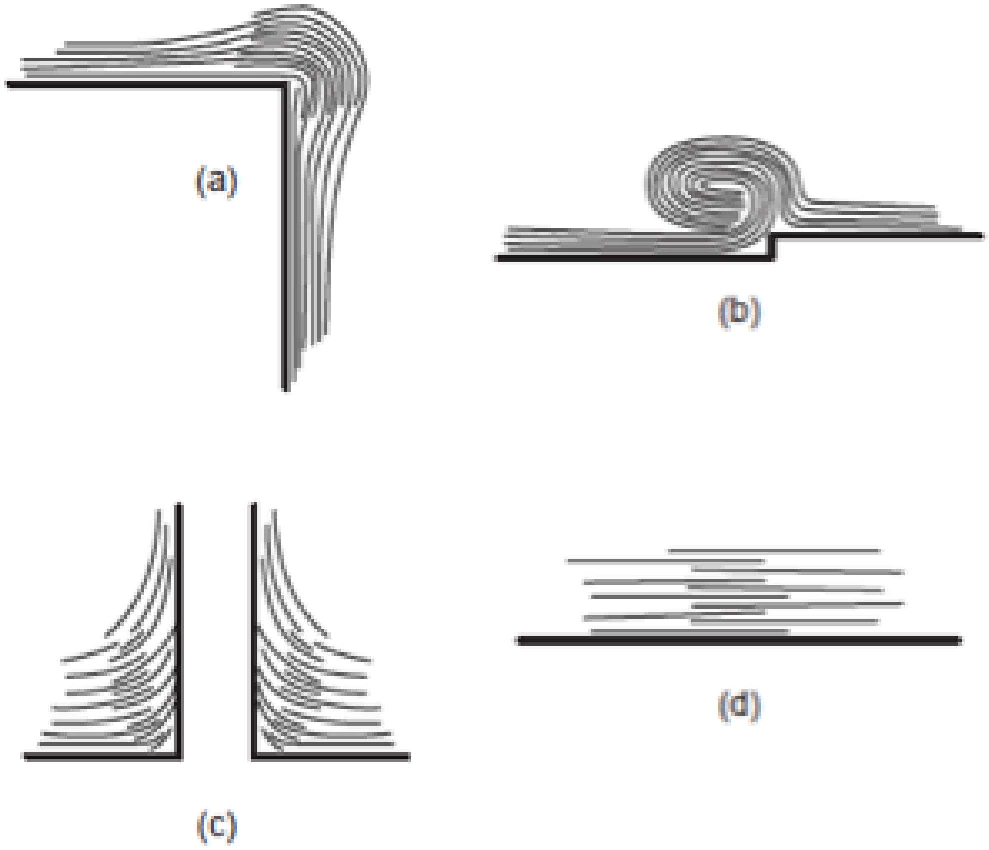
Don't pack MLI too tightly. Optimal value is ~ 20 layers / inch

Great care must be taken with seams, penetrations and ends.

Problems with these can dominate the heat leak



Multilayer Insulation: Proper treatment of Penetrations, overlaps, corners



Example of MLI in LHC Magnets

"SERIES-PRODUCED HELIUM II CRYOSTATS
FOR THE LHC MAGNETS: TECHNICAL CHOICES,
INDUSTRIALISATION, COSTS"
A. Poncet and V. Parma
Adv. Cryo. Engr. Vol 53

Porous Insulation

- Radiation heat transfer may also be reduced by filling the vacuum space between 300 K and cryogenic temperatures with other materials that are low conductivity and block line of sight
- Such materials include:
  - Glass beads or microspheres
  - Perlite powder (made from a volcanic rock)
  - Opaciated powders – copper or other metallic flakes mixed in with other powders to further reduce radiant heat transfer
  - Aerogel
- Advantages:
  - Cheaper
  - Easier to install in complex shapes
  - Better performance than MLI in poor or no vacuum
- Frequently used in large storage and transport dewars

Porous Insulation

The total heat transfer through porous insulation between 2 spheres may be estimated by:

$$W = \frac{\bar{k}\left(T_2 - T_1\right)}{t}\sqrt{A_1 A_2}$$

Where

t = thickness of Insulation

$\bar{k}$ = the mean thermal conductivity

1 = inner vessel and 2 = outer vessel

Mean thermal conductivities may be found in references such as

Cryogenic Engineering by Flynn

Comparison of Thermal Insulation Approaches
(6 inch thick insulation in all cases)

	Total Heat Flux (W/m^2)	
Type of Insulation	**300 K to 77 K**	**77 K to 20 K**
Polystyrene Foam (2 lb/ft^3)	48.3	5.6
Gas Filled Perlite powder (5 – 6 lb/ft^3 filled with He)	184.3	21.8
Perlite powder in vacuum (5 – 6 lb/ft^3)	1.6	0.07
High Vacuum (10^{-6} torr $\varepsilon = 0.02$)	9	0.04
Opacified powder (Cu flakes in Santocel)	0.3	-
MLI	0.03	0.007

Increasing Cost & Complexity

Note better performance of evacuated Perlite over high vacuum between 300 K & 77 K

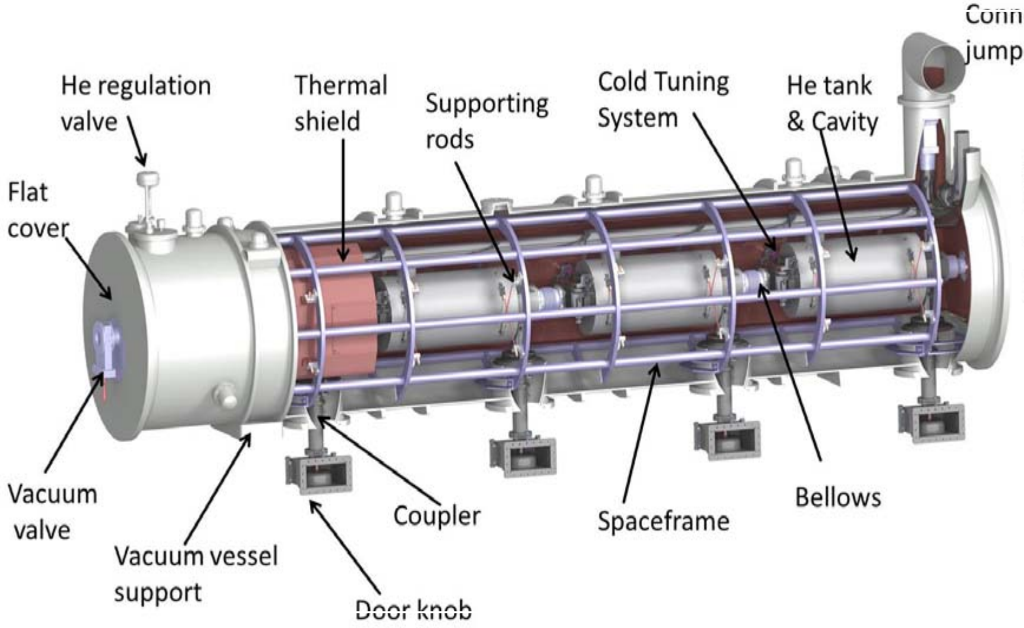
From Cryogenic Systems – Barron
For rough estimates only

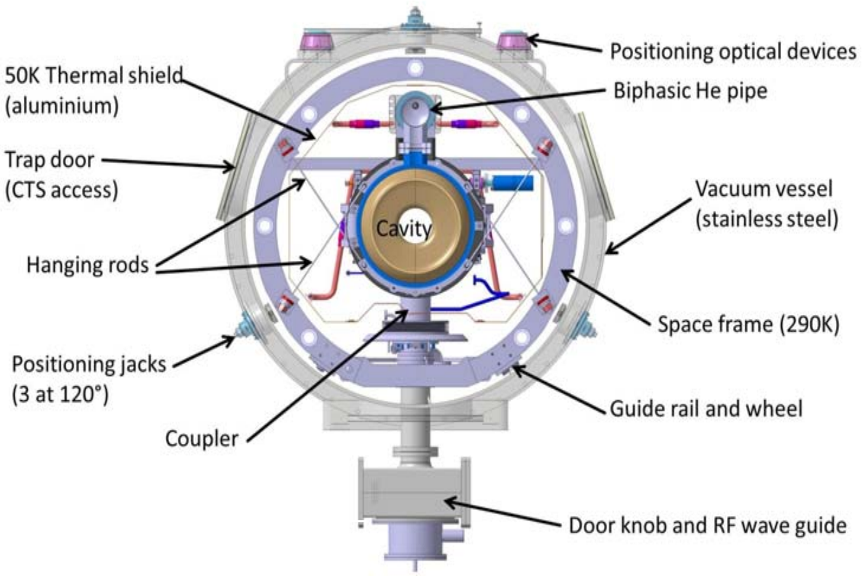
Example #1
The ESS Elliptical Cryomodule

- Similar to CEBAF/SNS cryomodule with 4 cavities per cryomodule

Courtesy P. Bosland CEA

- Common design for medium (6 cells) and high beta (5 cells) cavity cryomodules





- Accelerating gradient:

  for β=0.67 (Medium Beta): Eacc=16.7 MV/m Qo> 5E9 at 2 K
  for β=0.86 (High Beta): Eacc=19.9 MV/m Qo> 5E9 at 2 K

- Maximum operating helium pressure: 1.431 bar

- total length: 6.6 m
- Beam height: 1.5 m

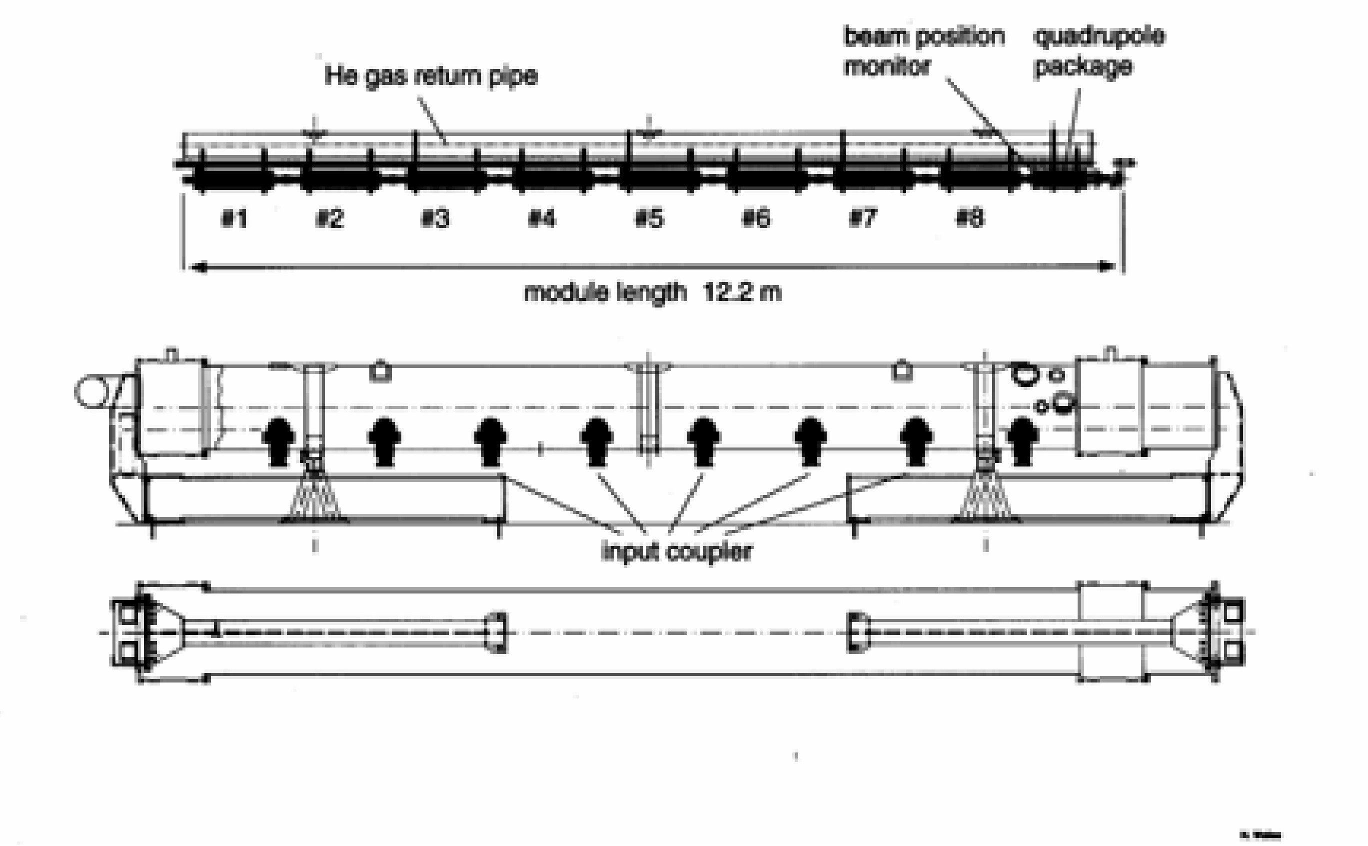
Example #2 International Linear Collider SCRF Cryomodule

- Two 15 km long linacs (250 GeV on 250 GeV)
- 35 MV/m SCRF cavities (1.3 GHz)
- Requires ~ 2000 cryomodules
- Extension of TESLA technology
- Requirements are very similar in many ways to LHC dipoles
    - ILC cryomodules have much higher dynamic heat loads

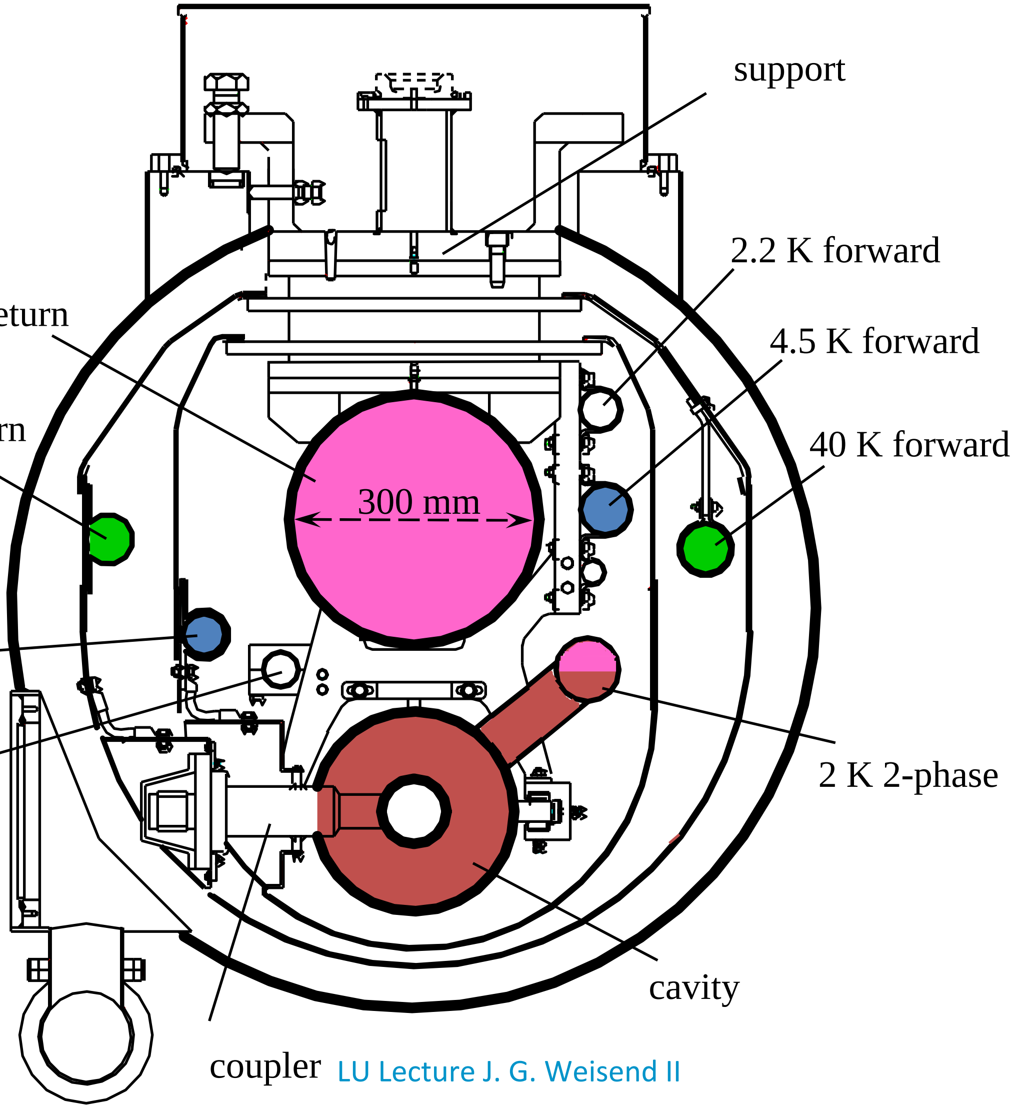
ILC Cryomodule Features

- Eight 9 cell sc cavities + possibly 1 sc magnet package
- Components are tied to 300 mm pipe strongback
- 2 thermal shields (40/80 K and 5 K)
  - 5 K may go away during value engineering
- New design allows semi-fixed couplers
- Design has been extensively tested during the TESLA project
- ILC design is a fourth generation of the TESLA cryomodule

Side View of 1st Generation TESLA Cryomodule (each end of 300 mm tube shrinks 15 mm upon cooldown)



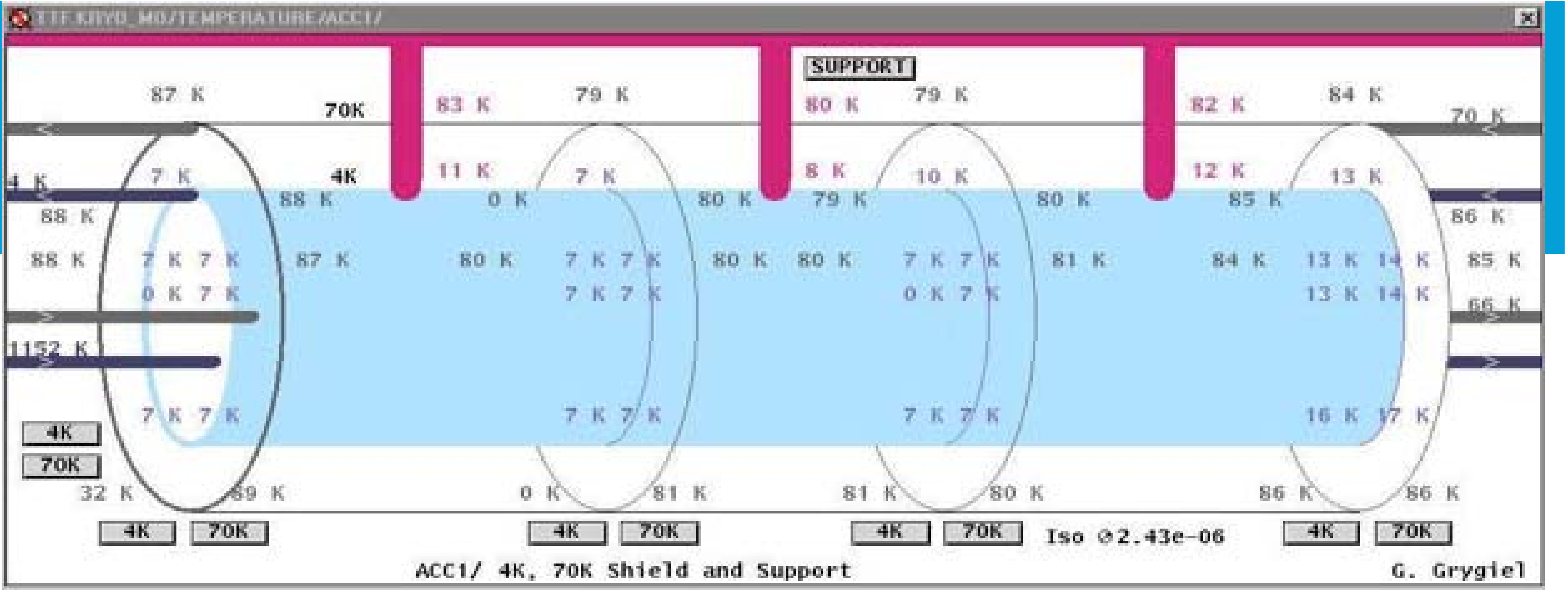
3^{rd} Generation TESLA Cryomodule ILC Prototype

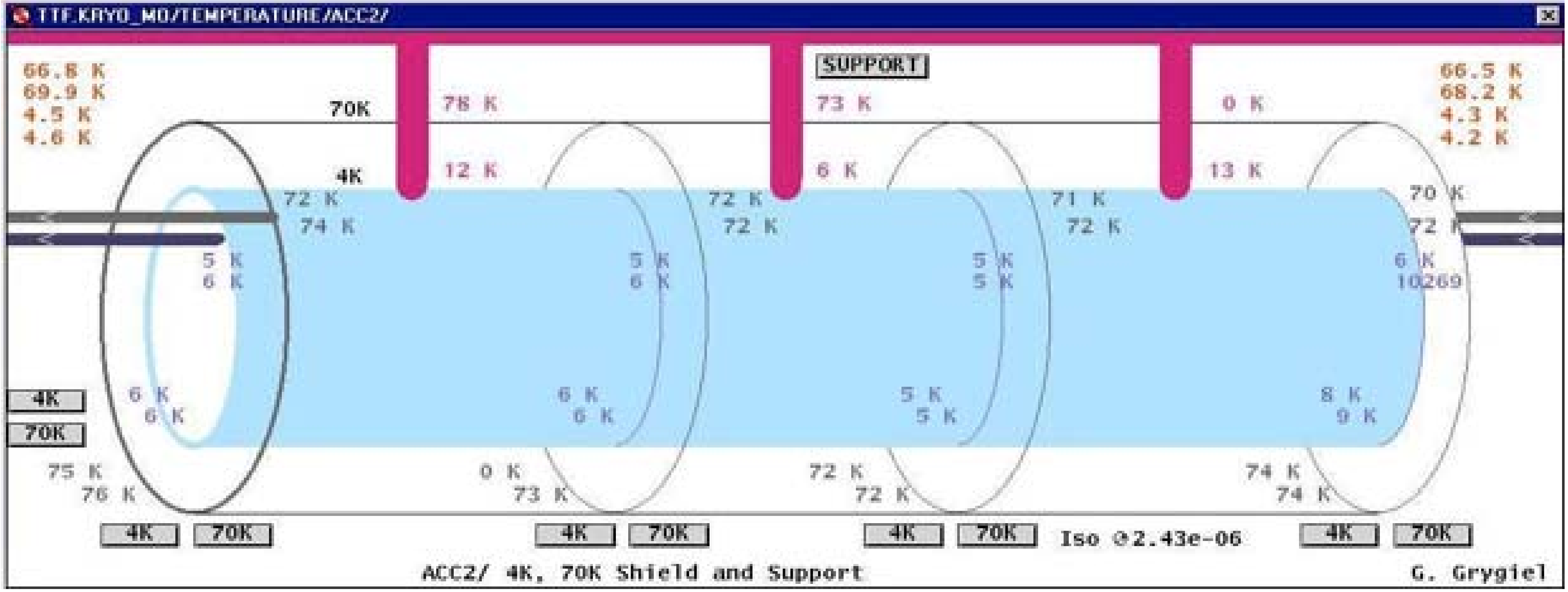


3rd Generation TESLA Cryomodule ILC Prototype

TESLA Static Heat Leak Measurements (note total 2 K heat load is ~ 7 W)

Temperature Level	Predicted Heat Leak (W)	Measured Heat Leak (W) Cryomodule #1 (alone)	Measured Heat Leak (W) Cryomodule #1 (with #2)	Measured Heat Leak (W) Cryomodule #2
70 K	**76.8**	**90**	**81.5**	**77.9**
4.5 K	**13.9**	**23**	**15.9**	**13**
2 K	**2.8**	**6**	**5**	**4**


TTF.KRYO_M0/TEMPERATURE/ACC1/
SUPPORT
87 K
70K
83 K
79 K
80 K
79 K
82 K
84 K
70 K
4 K
7 K
4K
11 K
7 K
8 K
10 K
12 K
13 K
88 K
88 K
0 K
80 K
79 K
80 K
85 K
86 K
88 K
7 K 7 K
87 K
80 K
7 K 7 K
80 K
80 K
7 K 7 K
81 K
84 K
13 K 14 K
85 K
0 K 7 K
7 K 7 K
0 K 7 K
13 K 14 K
66 K
1152 K
7 K 7 K
7 K 7 K
7 K 7 K
16 K 17 K
4K
70K
32 K
89 K
0 K
81 K
81 K
80 K
86 K
86 K
4K 70K
4K 70K
4K 70K
Iso ⌀2.43e-06
4K 70K
ACC1/ 4K, 70K Shield and Support
G. Grygiel


TTF.KRYO_M0/TEMPERATURE/ACC2/
SUPPORT
66.8 K
69.9 K
4.5 K
4.6 K
70K
78 K
73 K
0 K
66.5 K
68.2 K
4.3 K
4.2 K
4K
12 K
6 K
13 K
72 K
74 K
72 K
72 K
71 K
72 K
70 K
72 K
5 K
6 K
5 K
6 K
5 K
5 K
6 K
10269
4K
70K
6 K
6 K
6 K
6 K
5 K
5 K
8 K
9 K
75 K
76 K
0 K
73 K
72 K
72 K
74 K
74 K
4K 70K
4K 70K
4K 70K
Iso ⌀2.43e-06
4K 70K
ACC2/ 4K, 70K Shield and Support
G. Grygiel

Example #3: Space Cryostat
The X-Ray Spectrometer (XRS)

- Mission life time is dependent on the supply of He II (1.3 K) in the cryostat. In order to achieve the 2.5 year life time, the heat leak must be < 800 μW
- Additional design drivers:
  - Size and weight
  - Use of an ADR requiring a superconducting magnet – sensors need 0.065 K
  - A costly one of a kind device

Solutions to Minimize Heat Leak

- All heat leaks (even 10 μW) are important
- Solid Ne (17 K) dewar surrounds He dewar to reduce radiation and conduction heat leak
- Low emissivity materials used: polished Al, gold plating and aluminized mylar
- HiT$_c$ superconductors used for magnet leads
- All other wiring is optimized for minimum heat leak
- Helium tank suspended by graphite/epoxy straps optimized to meet launch loads
- Radiation baffles in vent and fill lines plus devices to prevent superfluid film flow in vent line

“Thermal Design of the XRS Helium Cryostat”, S. Breon et al., Cryogenics 36:10 (1996)

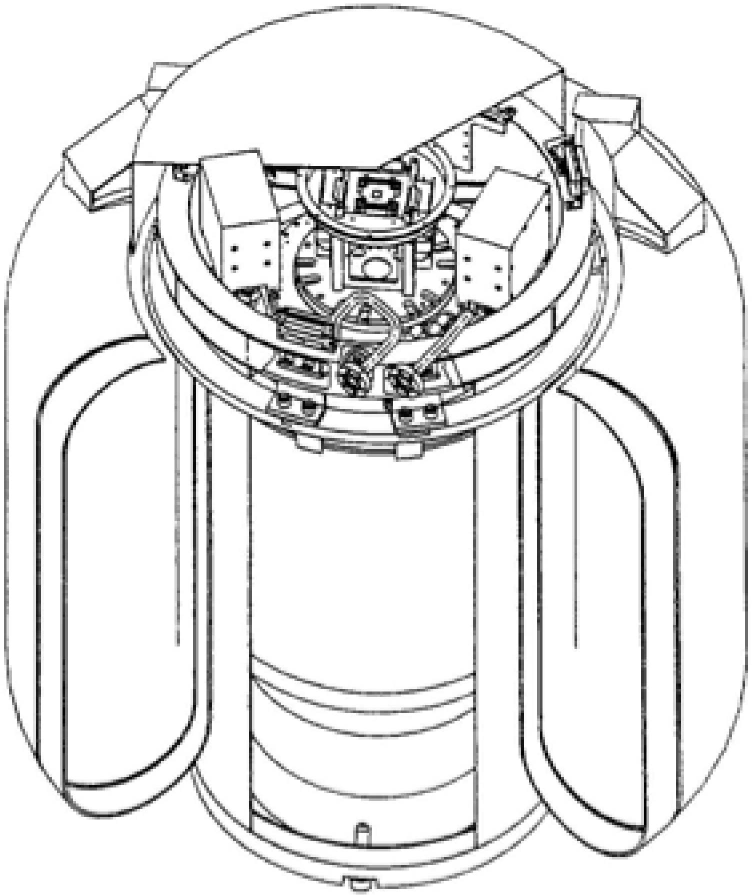
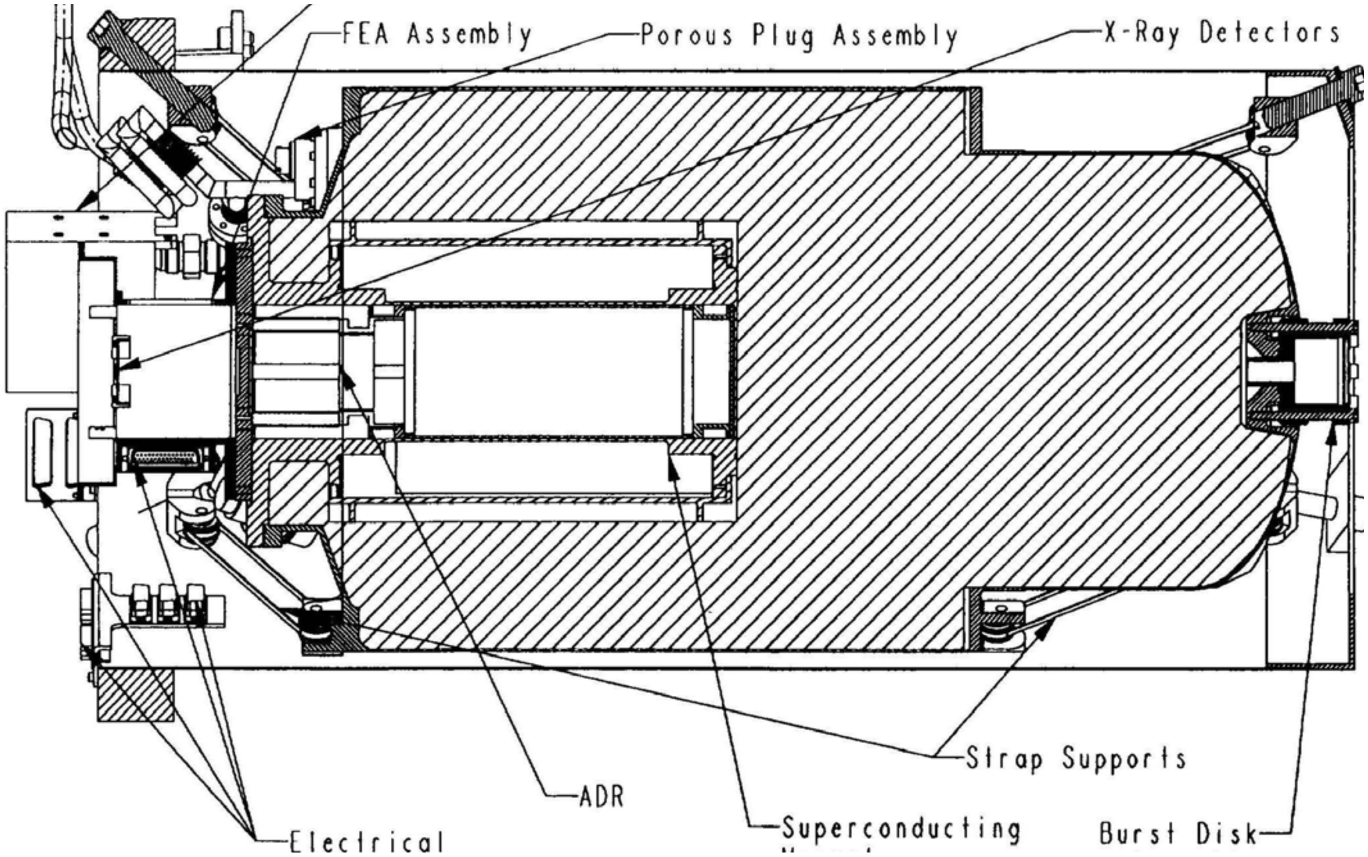


Figure 1 XRS configured for Astro-E. Hybrid cyrogenic system provides cooling stages at 17 K (solid neon), 1.3 K (superfluid helium) and 0.065 K (ADR). JFETs in FEA are at 80–120 K

“Thermal Design of the XRS Helium Cryostat”, S. Breon et al., Cryogenics 36:10 (1996)



XRS Cryostat

Analytical heat leak models and full scale thermal measurements at the component, subsystem and helium insert level were carried out.

Measured heat leak to the helium insert (on the ground) was ~ 629 μW

There is Much More to Cryogenic Engineering

This has been just a small sample of cryogenic engineering Other topics include:

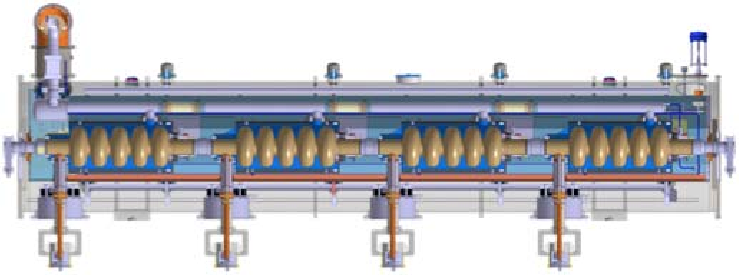
- Properties of Cryogenic Fluids
- Cryogenic Properties of Materials
- He II (superfluid helium)
- Safety in Cryogenics
- Instrumentation
- Cryogenic Distribution Systems
- Cryogenics below 1 K
- Use of Small Cryocoolers
- Vacuum Systems
- High Temperature Superconductor Applications
- Superconducting Magnets and RF Cavities

The Use of Cryogenics in Accelerators is Growing

More than 17 current accelerators use cryogenics in some form and an additional 15 new accelerators using cryogenics are planned between now and 2025 in a wide range of locations: Europe, India, China, Korea, Brazil, USA, Japan

These future accelerators include some very large installations: FAIR, XFEL, ESS, LCLS II, ILC

The need for trained staff in this area is an issue and Lund University is in the early stages of developing a center of excellence in cryogenics including classes (senior undergraduate/graduate), research projects and collaborations with ESS and possibly Maxlab



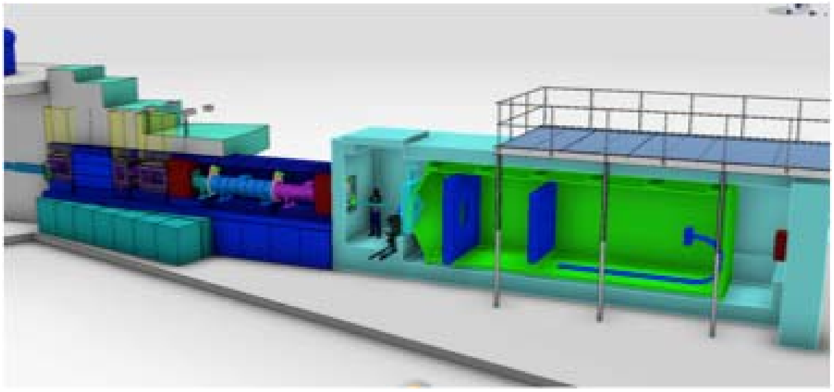
A New Course !

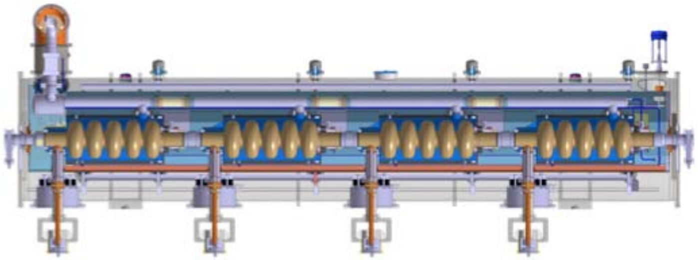
Introduction to ESS

Hötterminen 2015 - Läsperiod 1

The European Spallation Source (ESS) will enable transformative advances in materials science. ESS is currently one of the largest European Science projects under construction. In order for ESS to meet its scientific goals, extensive contributions from a variety of engineering disciplines are required. The goal of this course is to introduce the student to the specialized applications of mechanical, electrical and software engineering required to make ESS a success. An overview of the basic project management activities required for a large scale project such as ESS will also be presented. Lectures will presented by the engineers and scientists carrying out the work, who are world leaders in their area of expertise.

For further details contact: Prof. J. Weisend (john.weisend@esss.se)





A New Course !

Cryogenic Engineering

Hötterminen 2015 - Läsperiod 2

Cryogenics is the science and engineering of phenomena that occur at a temperature below 120 K. Cryogenics is the basis for a multi-billion industry and is a key enabling technology in such areas as the production and use of industrial gases, liquefied natural gas, space exploration, high energy physics, fusion energy and magnetic resonance imaging. It is an important technology for the European Spallation Source (ESS) Project. This class emphasizes the engineering aspects of cryogenics including: cryogenic properties of materials, air separation, refrigeration, liquefaction, cryostat design, cryocoolers, instrumentation, cryogenic safety and the properties of cryogenic fluids. Extensive examples will be drawn from current activities in both industry and research (including ESS). The class will consist of lectures and a design project using real world problems.

For further details contact: Prof. J. Weisend (john.weisend@esss.se)

Summary

- Cryogenics is an important field that supports research, industry, medicine and exploration
- An important topic in cryogenics is the proper design of cryostats that maintain equipment at its operating temperature
- While the application may seem exotic, the basic rules of heat transfer apply to cryogenics and drive the design of cryostats
- Two new classes are starting at LTH in the Fall of 2015
  - Introduction to ESS
  - Cryogenic Engineering