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Accelerator Cryogenics
An Introduction

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Outline

- Introduction
- Production of Cold
  - Refrigerators & liquefiers
  - Carnot efficiency
  - Coefficient of performance
- Maintenance of Cold
  - Cryostats and cryomodules
  - Basic heat transfer mechanisms and guidelines for design
  - Example cryostat (ESS Elliptical cavity CM)
- Summary

Introduction

- Cryogenics : the science and technology of phenomena occurring below 120 K
- Cryogenics plays a major role in modern particle accelerators
  - Enables superconductivity
    - Beam bending and focusing magnets (1.8 K – 4.5 K)
    - Magnets for particle identification in large detectors (4.2 – 4.5 K)
    - Superconducting RF cavities for particle acceleration (1.8 K – 4.2 K)
  - Allows dense pure liquids
    - LAr calorimeters (87 K)
    - LH_2 moderators, targets and absorbers (20 K)

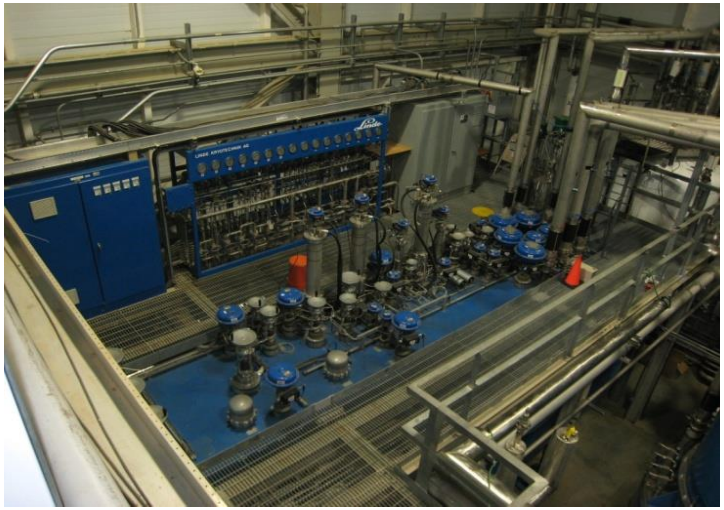
Introduction

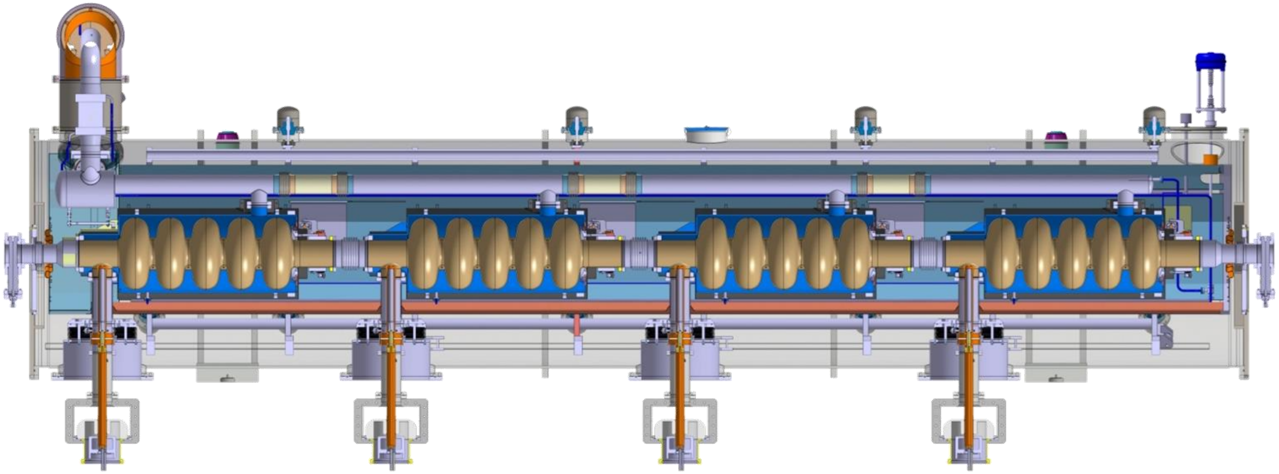
- Since the Tevatron (1983) accelerator cryogenic systems have become larger, more reliable, more efficient, industrialized and much more widespread
- Cryogenics is found in all types of accelerator applications including: HEP accelerators, light sources, heavy ion machines, neutron sources and ADS
- This lecture will give an overview including examples of several key aspects of cryogenic engineering related to accelerators. But there is much more to learn.
- I will discuss how we get equipment to cryogenic temperatures and keep it at those temperatures in accelerators.

Introduction

LHC
Magnets

SNS
4 K
Cold
Box





ESS Cryomodule

Introduction

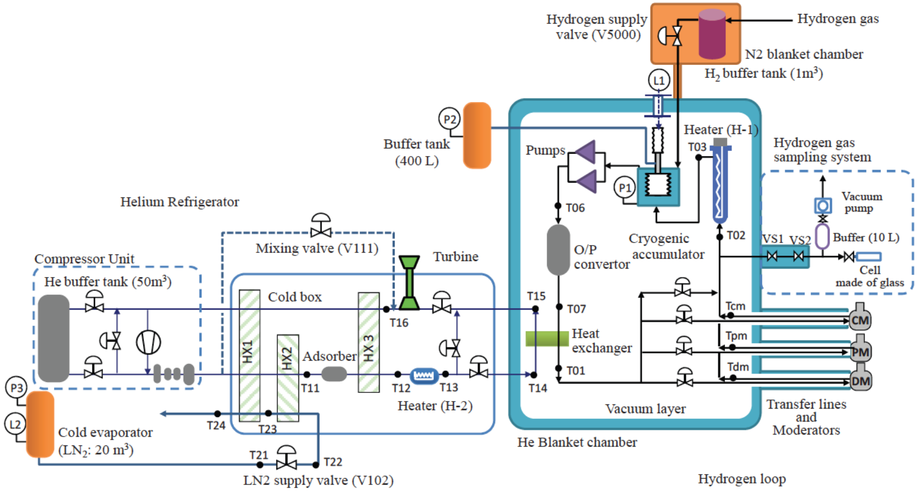


FIGURE 1. Schematic view of the J-PARC cryogenic hydrogen system for a spallation neutron source.

JSNS LH_2 Moderator (6.5 kW @ 16 K)

ATLAS
Magnets
At CERN

Catching Cold

- There are really only a few ways in which to make a pure fluid such as helium colder
  - Cause the fluid to do work by making it expand against a piston or turbine while keeping it thermally isolated from the outside environment Isentropic Expansion
  - Transfer heat from the fluid to a colder surface
  - Cause the fluid to do “internal work” by expanding it through a valve while keeping it thermally isolated Isenthalpic Expansion or Joule-Thomson expansion
  - Once the fluid is a liquid, reduce the pressure above the fluid below atmospheric pressure thus reducing the saturation temperature

- All modern cryogenic plants do the first 3. Ones that provide cooling below 4.2 K also do the last item

Collins Cycle

Cycle consists of :

1) Compression of Helium to ~ 16 Bar with cooling back to 300 K + oil removal

2) Cooling of high pressure gas with LN_2

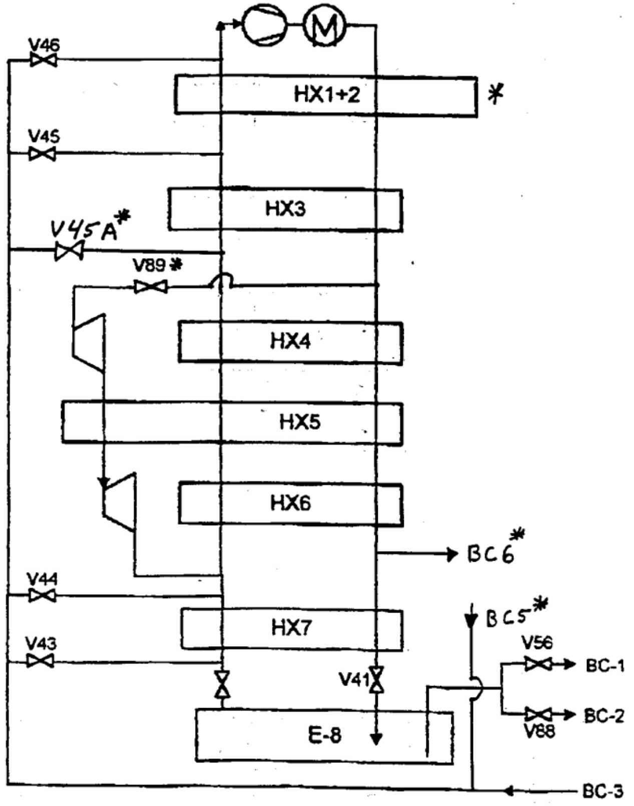
3) Isentropic expansion via 2 or more expansion engines

4) Cooling of high pressure gas by the cold returning low pressure stream

5) Isenthalpic expansion through JT valve

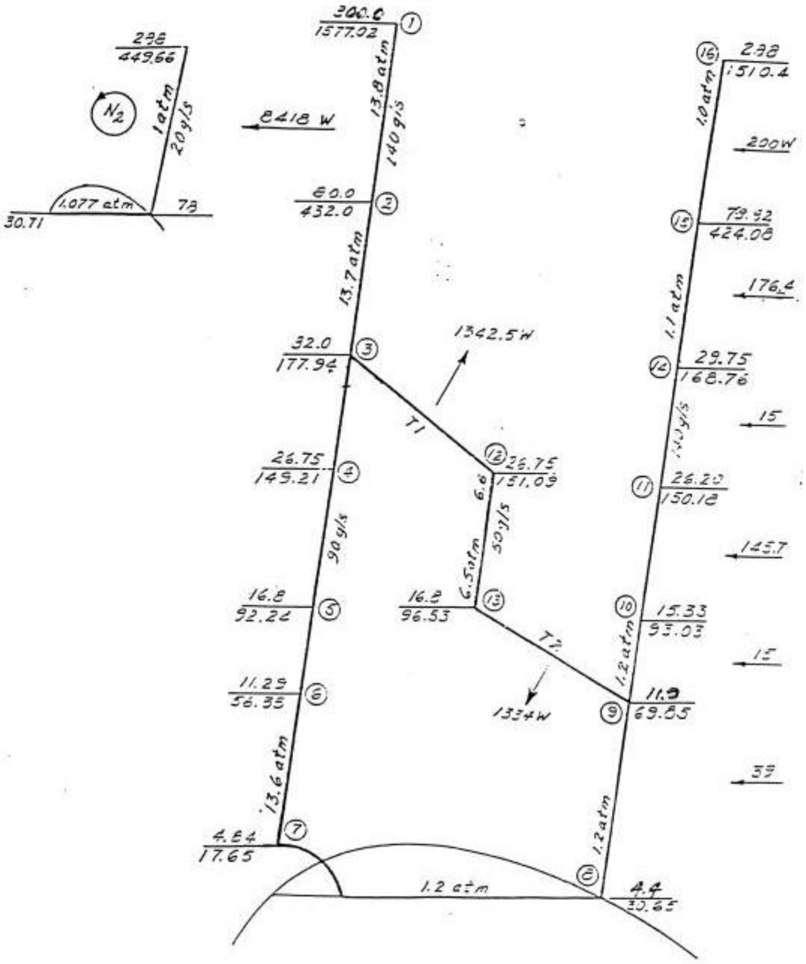
6) Return of gas to compressors at just above 1 Bar

CTI 4000 Refrigerator
(early 80’s vintage ~ 1.2 kW @ 4.5 K)

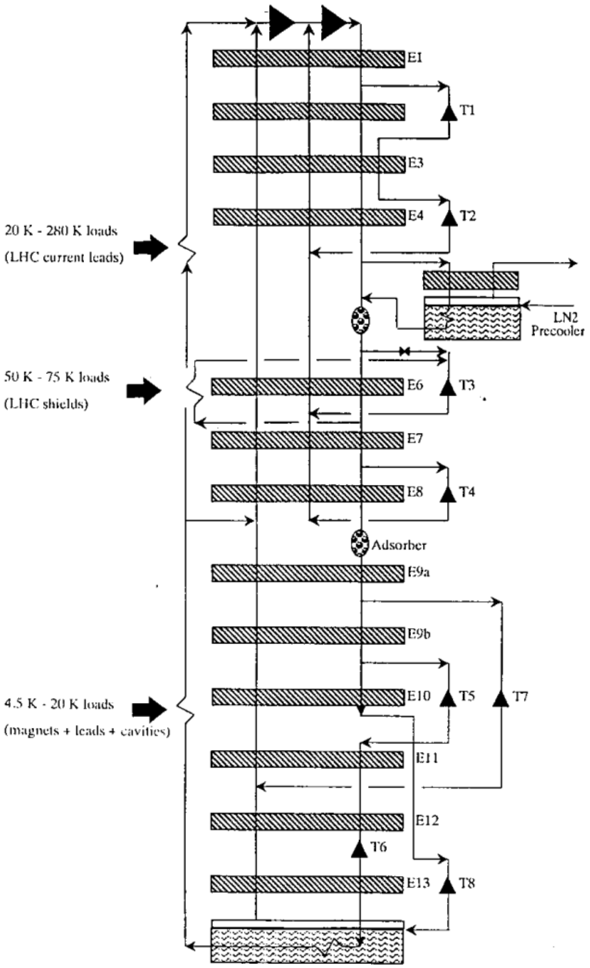


CTI 4000 Upgrade 12 / 2 / 99

* Indicates new or changed component



LHC 4.5 K Refrigeration Plant
18 kW @ 4.5 K – produced in ~ 2004
1of 8 required (4 from Linde, 4 from Air Liquide)



Note:

Large number of expansion turbines – some in series with HP stream

Medium pressure return

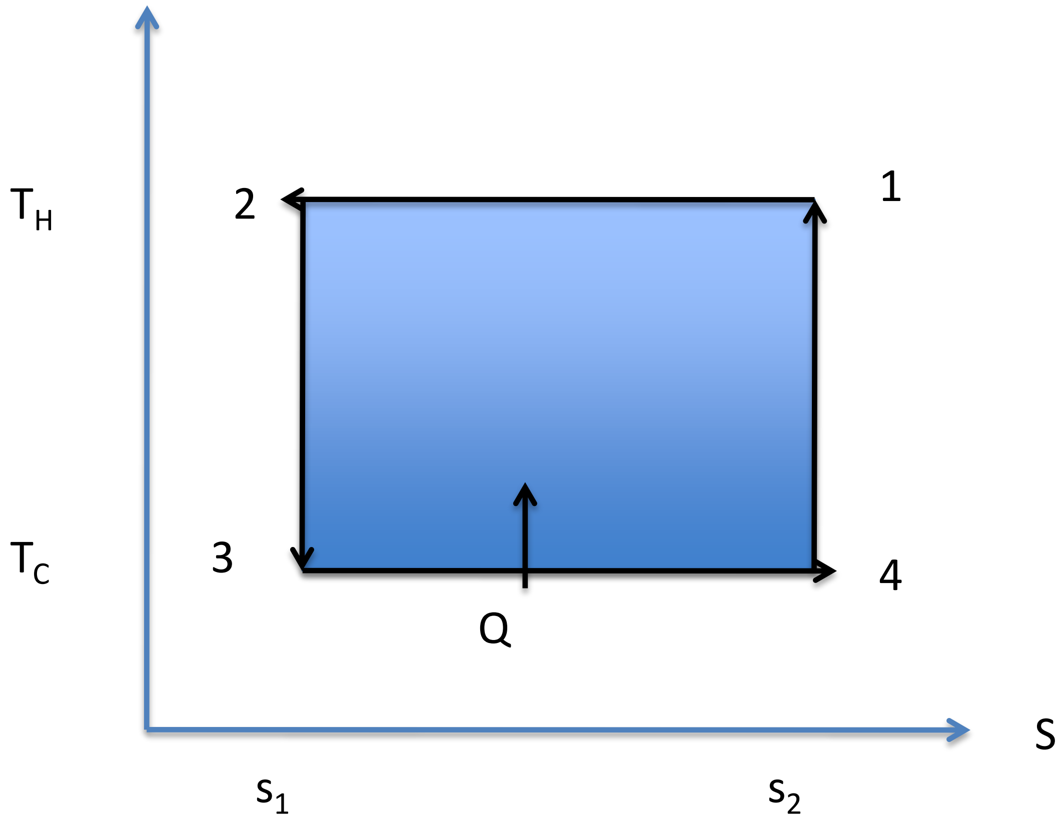
Heat loads at intermediate temperatures

Carnot Cycle

- This is an ideal cycle: all processes are reversible
  - Entropy is only changed by absorbing or removing heat at constant temperature
  - 2^{nd} law of Thermodynamics, in a reversible process dQ = -TdS
- The Carnot Consists of 4 steps
  - Compress the working fluid isothermally at T_H (1-2)
  - Expand the working fluid isentropically from T_H to T_C (2-3)
  - Absorb heat into the working fluid isothermally and reversibly at T_C (3-4)
  - Compress the working fluid isentropically from T_C to T_H (4-1)

  - Note isentropically = reversibly and adiabatically

Carnot Cycle



How do we describe the performance of such a cycle?

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

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

- Minus sign takes into account that the heat absorbed by the cycle is positive while the work done is negative
- 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

Carnot Cycles & the Real World

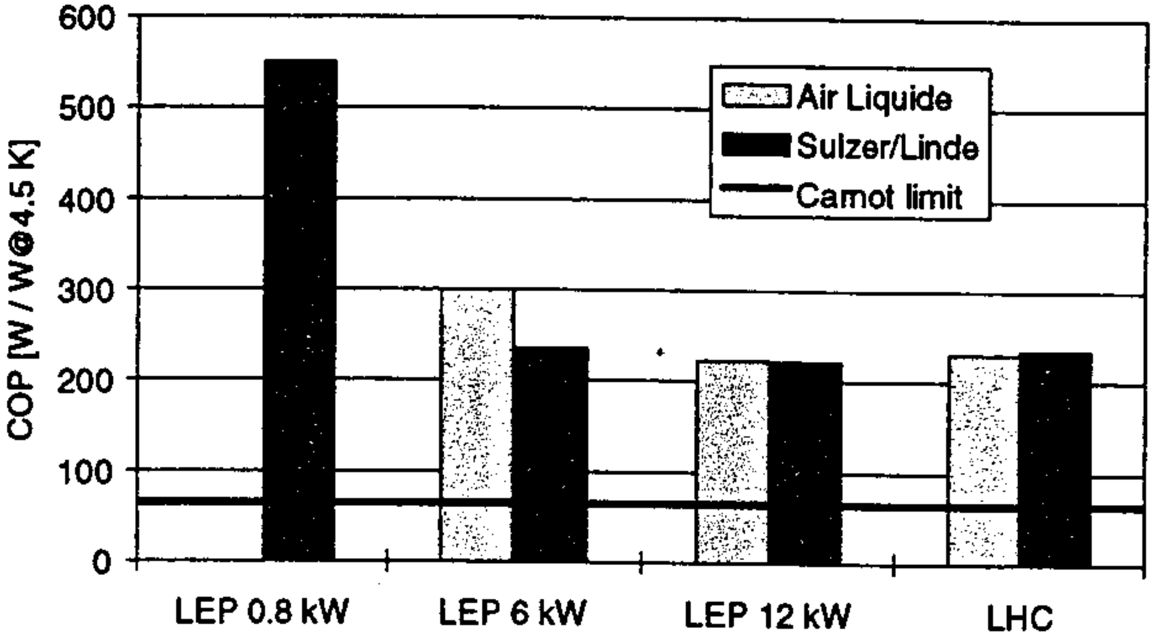
- Can we build a real machine using a Carnot cycle? In a word NO
- Why?
  - Compressing a fluid isothermally is very hard to achieve, Normally the fluid is compressed and then cooled back down to 300 K
  - Expanding or compressing fluid isentropically is basically impossible
  - We can absorb heat into a boiling fluid isothermally but not with out irreversible losses

- How close can we get to Carnot? We define the Figure of Merit (FOM) as:

$$FOM = \frac{COP}{COP_{Carnot}}$$

  - We also speak in terms of “percent Carnot” i.e. FOM of 0.2 is 20% Carnot

The real world is sometimes not kind to cryogenic engineers



These are state of the art helium refrigerators. Note that the best of them (for LHC) runs at about 220 W/W or a FOM of 0.318 or at 32% Carnot

Cryostats, Cryomodules and Dewars

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What is a cryostat?

A device or system for maintaining objects at cryogenic temperatures.

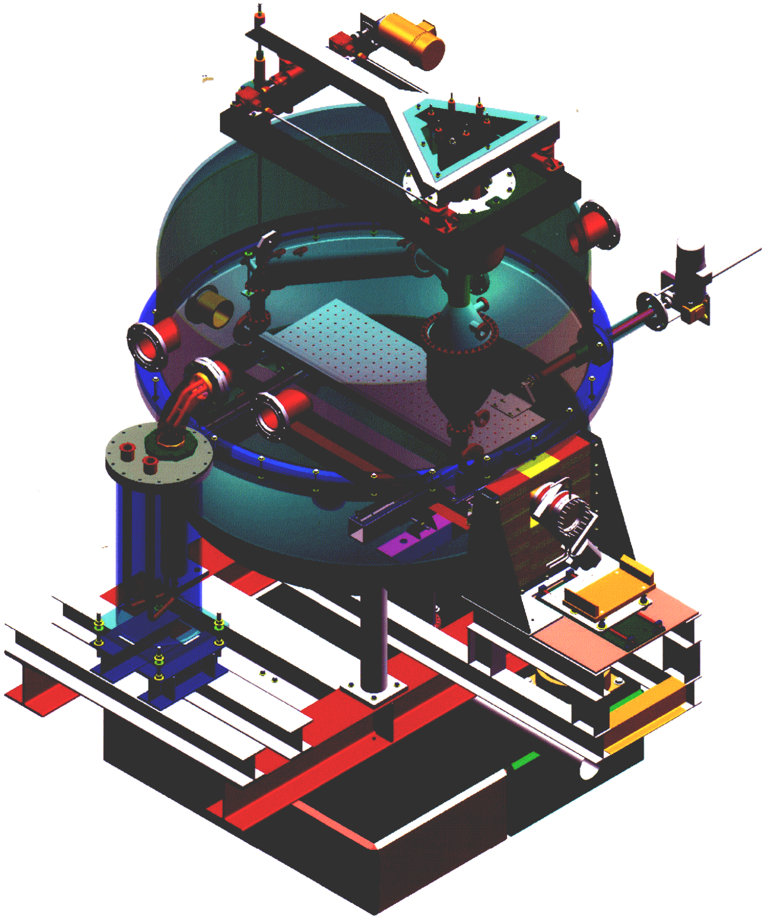
Cryostats that contain SCRF cavity systems are also frequently called *cryomodules*

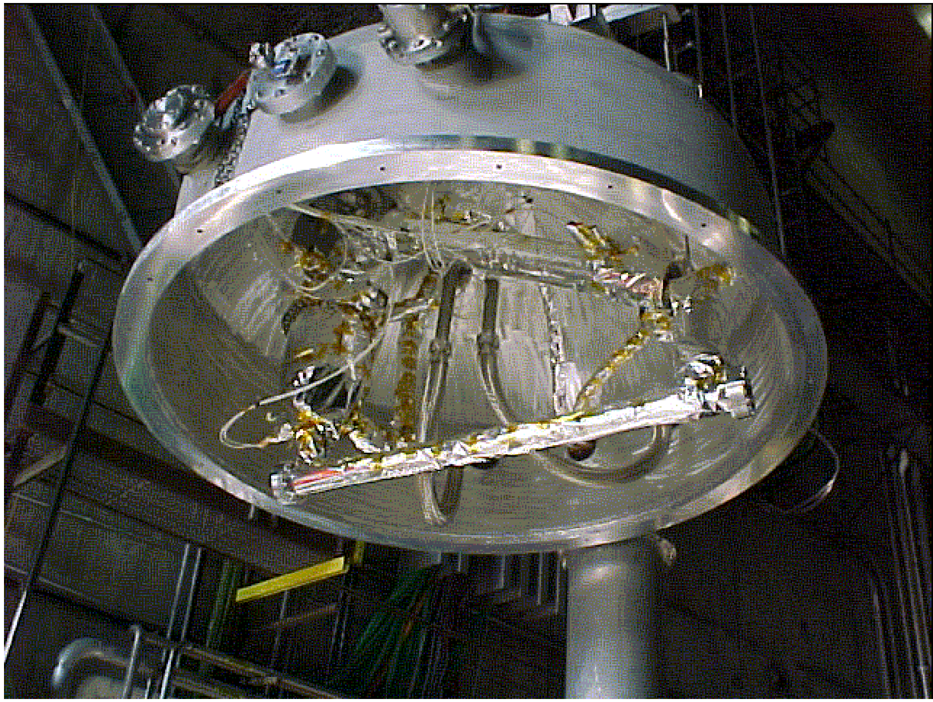
Cryostats whose principal function is to store cryogenic fluids are frequently called *Dewars*. Named after the inventor of the vacuum flask and the first person to liquefy hydrogen

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
- One of the best ways to learn about cryostat design is through examples
- There are many different types of cryostats with differing requirements
  - The basic principles of cryostat design remain the same
  - Before we can do anything else we have to define our requirements

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
- 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

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:

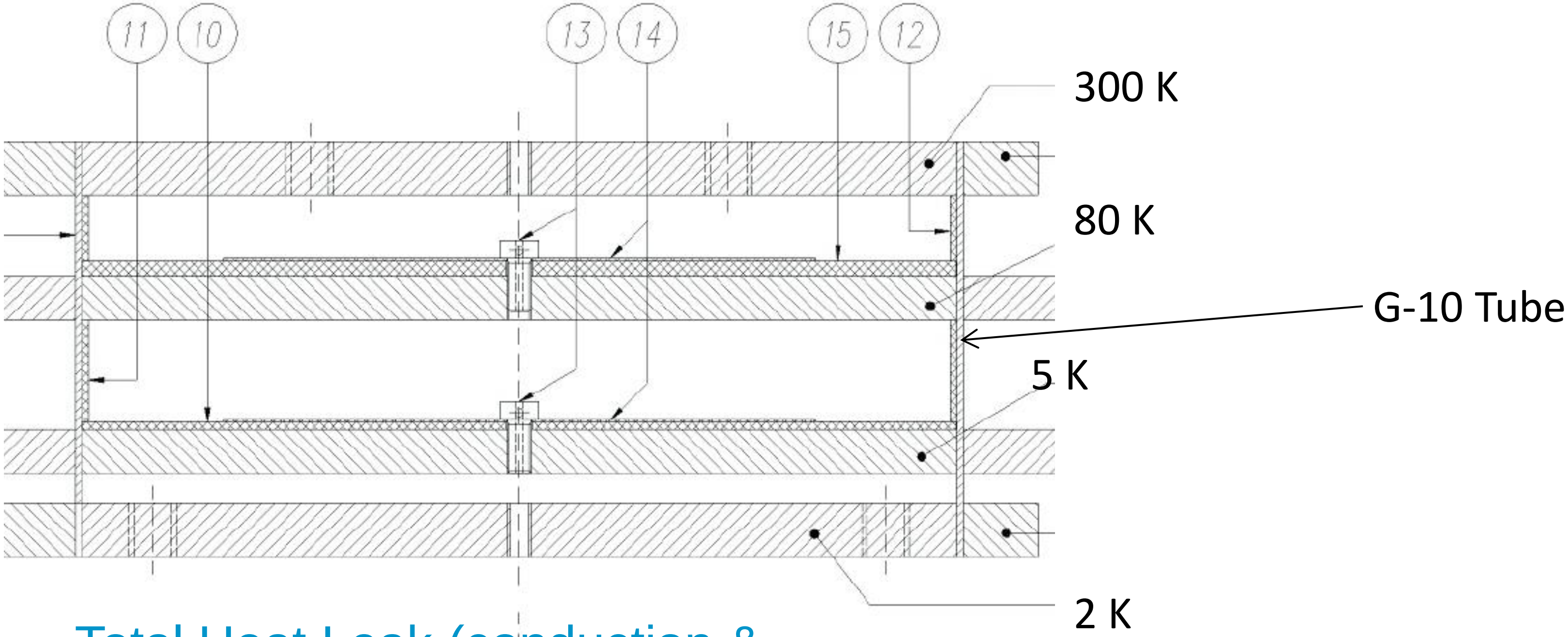
$$Q = -A/L\int_{T_C}^{T_H} K(T)dT$$

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
ILC Cryomodule Support Post

Courtesy T. Nicol - Fermilab



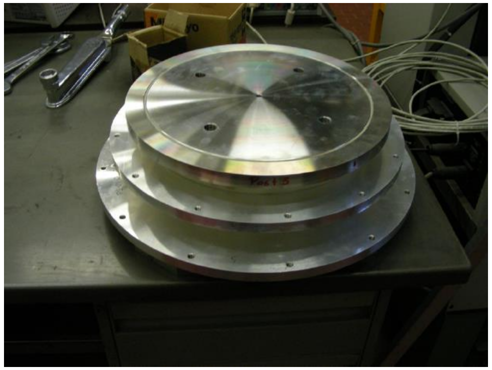
Total Heat Leak (conduction & radiation)

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} mBar If we maintain this level or better we can generally neglect the convection heat leak for most applications.

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} mBar or better range if the system is leak tight and doesn't have significant outgassing

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 $\sigma = 5.67\text{x}10^{-8}$ 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

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

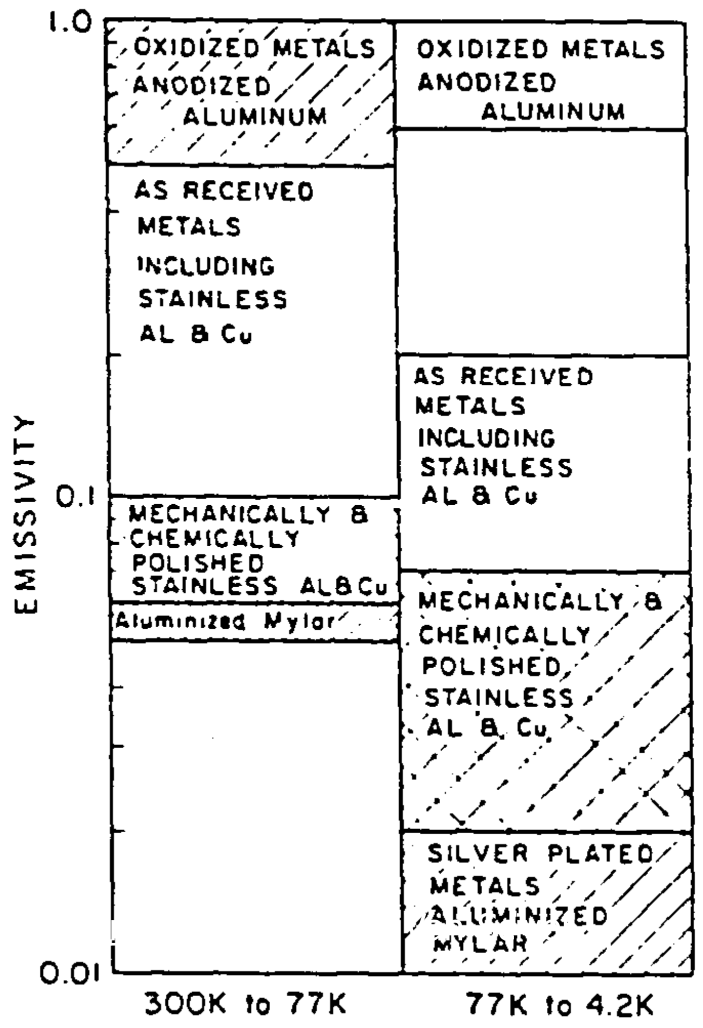
Note as is frequently the case in cryogenics, if the spacing between the cylinders is small compared to the inner radius (i.e. $A_1 \sim A_2$) Eq. C becomes Eq. A

Radiation Heat Transfer

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

We could reduce the emissivity (ε)

- This is done in some cases; using either reflective 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

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

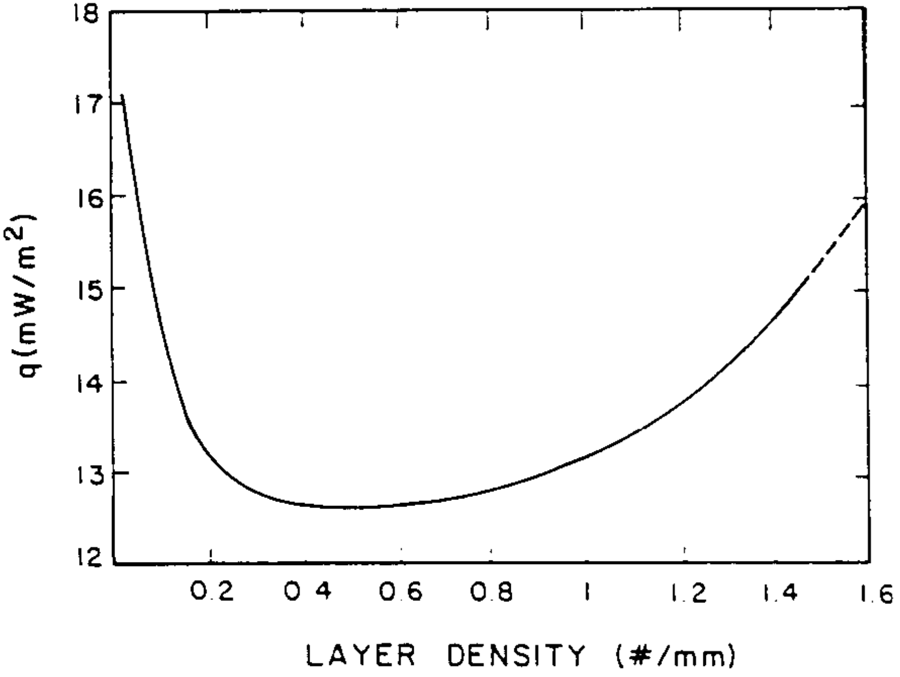
Used in almost all cryostats

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



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

How Are These Principles Used on the ESS Elliptical Cavity Cryomodule Design ?

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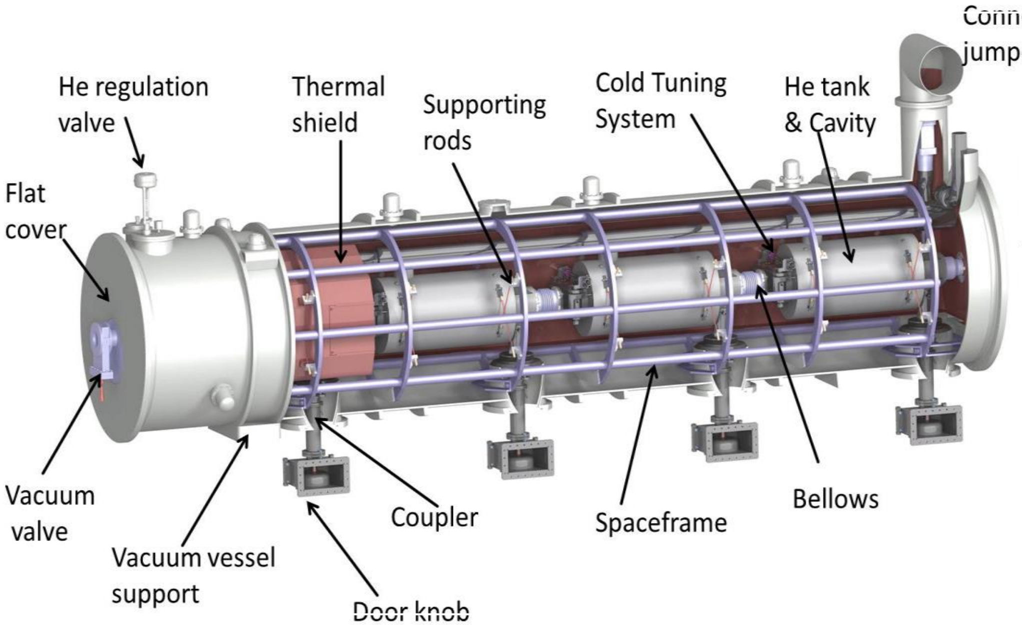
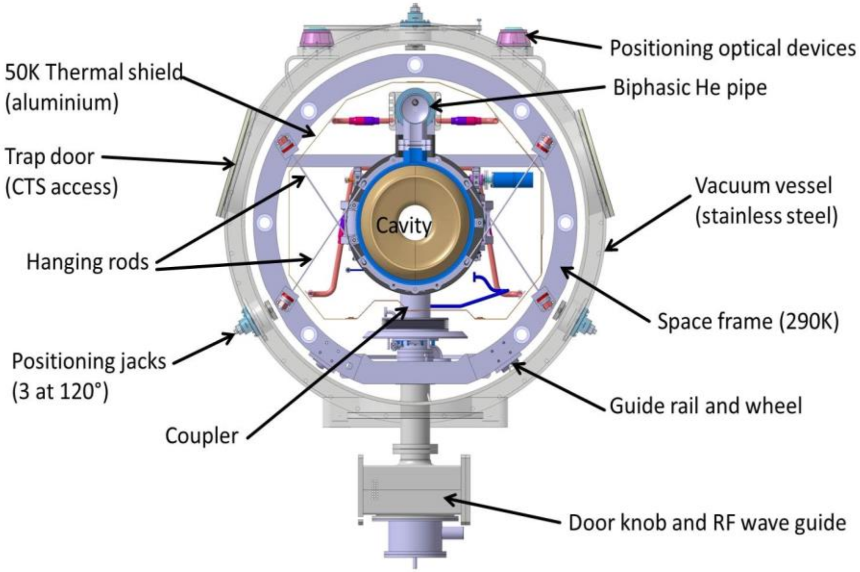
- Similar to CEBAF/SNS cryomodule with 4 cavities per cryomodule

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

There is Much More to Cryogenic Engineering

- This has been just a small sample of cryogenic engineering as applied to accelerators. 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

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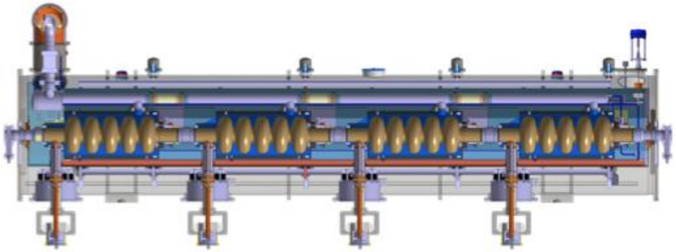
- More than 17 current accelerators use cryogenics in some form and an additional 15 new accelerators using cryogenics are planned between now and 2025 in a wide range of locations: Europe, India, China, Korea, Brazil, USA, Japan
- These future accelerators include some very large installations: FAIR,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

Examples of Future Facilities

Name	Type	Lab	T (K)	Refrigeration Capacity	Status (Start of Operation)
ESS	Accelerator LH2 moderator Instrum. supply	ESS	2.0 40/50 16 4.2	3 kW 11 kW 25 kW 7500 l/month	Construction (2019)
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 @ 2.1 K	Construction (2019) TESLA Tech
FAIR	Accelerator & separator magnets	FAIR/GSI	4 50-80	Up to 37 kW@ 4 K Up 30 kW @ 50-80 K	2 Plants Construction (2019)



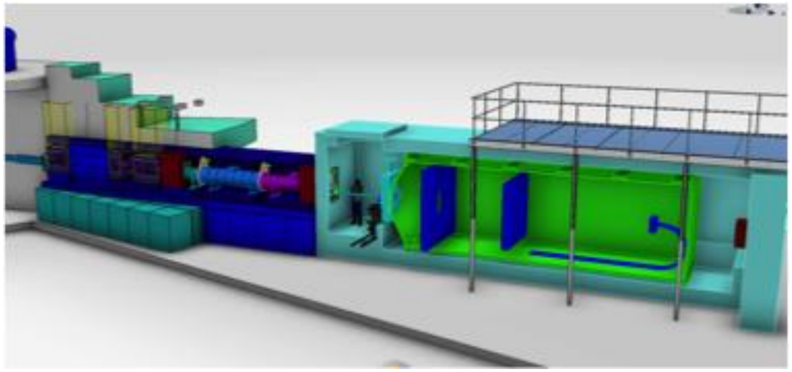
A New Course !

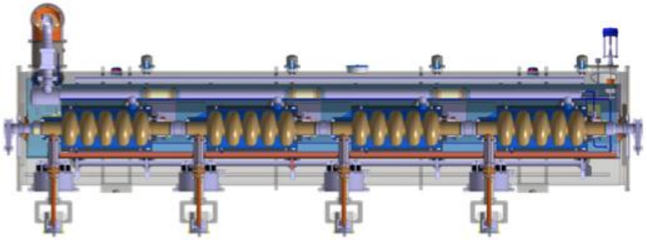
Introduction to ESS [MMT010F]

Höstterminen 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 both in swedish and english go to www.fukurser.lth.se and enter the course code in the search string or contact: Prof. J. Weisend (john.weisend@esss.se)





A New Course !

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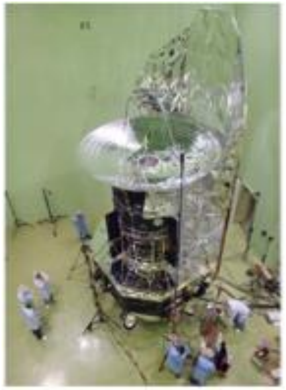
Cryogenic Engineering [MMT020F]

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 Prof. J. Weisend (john.weisend@e



Summary

- Cryogenics is an enabling technology in modern particle accelerators
- Cryogenics is a multidisciplinary field using many aspects of physics and engineering
- The use of cryogenics in accelerators (as well as in other scientific research fields) is growing and additional talent is needed.
- ESS and Lund University are working together to develop a center of excellence in cryogenics in Lund
- Two new classes on ESS and Cryogenics will be presented in the Fall

Back Up Slides

Refrigerators vs. Liquefiers

- Refrigerators are closed cycle systems
  - They provide cooling and can create liquids but all the mass flow is returned to the start of the cycle
  - Such systems are said to have “balanced flow”

- Liquefiers are open cycle systems
  - They provide a liquid which is then drawn off and used elsewhere
  - These have “unbalanced flows” the amount of mass returned to the start of the cycle is less than the amount that started by the mass that was converted to liquid.
  - In order to keep the cycle running this mass would have to be added as room temperature gas.

Refrigerators vs. Liquefiers

- In practice, this distinction is less clear cut
  - Modern cryogenic plants can operate either as refrigerators or liquefiers and in fact, generally operate as a mixture of the two.
  - We talk about refrigeration loads & liquefaction loads
  - A key issue is at what temperature is the boil off gas from a cryogenic liquid returned to the cycle?
    - If brought back at a cryogenic temperature and used to cool incoming warmer gas then this is a refrigeration load
    - If brought back warm and not used to cool incoming warmer gas this is a liquefaction load
- The thermodynamic rules are the same for refrigerators and liquefiers