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Vacuum Systems and Cryogenics

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October 2019

Introduction

Cryogenics: the science & engineering of phenomena that occur at temperatures below 120 K

Cryostat: a component or system designed to maintain equipment or material at cryogenic temperatures

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

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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

Roles of Vacuum in Cryogenics

- Thermal Insulation
- Cryopumping
- Pumped Systems - providing cooling below a liquid’s normal boiling point
- Pumping and Purging
- Leak checking
- Safety Issues

Thermal Insulation of Cryostats
Three Ways to Transfer Heat

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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

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

- Such vessels are frequently called dewars
- Thermos bottles are a simple example of this approach

James Dewar's First Vacuum Flask

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.
    - 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} torr 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} torr before cooling, lower pressures are better but there may be operational tradeoffs

Outgassing and Getters

All material outgases 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

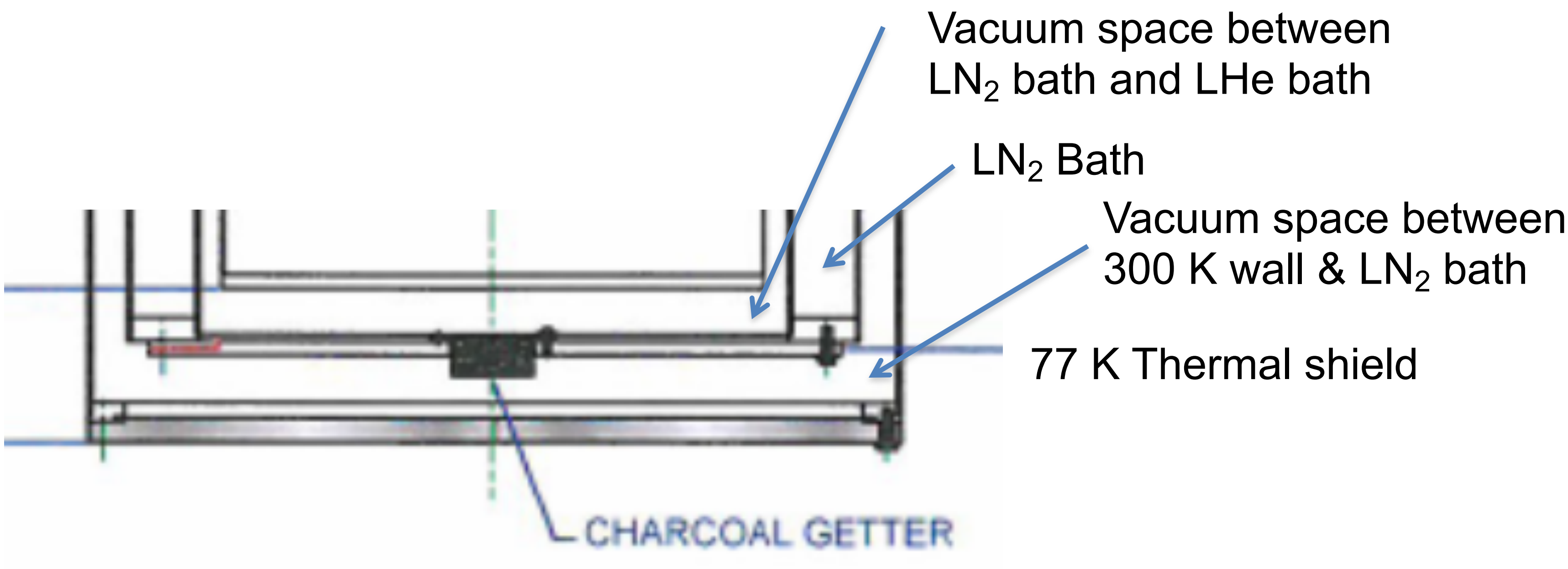
In cryogenic systems, getters may be useful in removing residual gas and passively managing small leaks

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

Simple Example of Vacuum Insulation



Note: vacuum spaces are typically common between different temperature levels

What's Really Needed is a Vacuum System !

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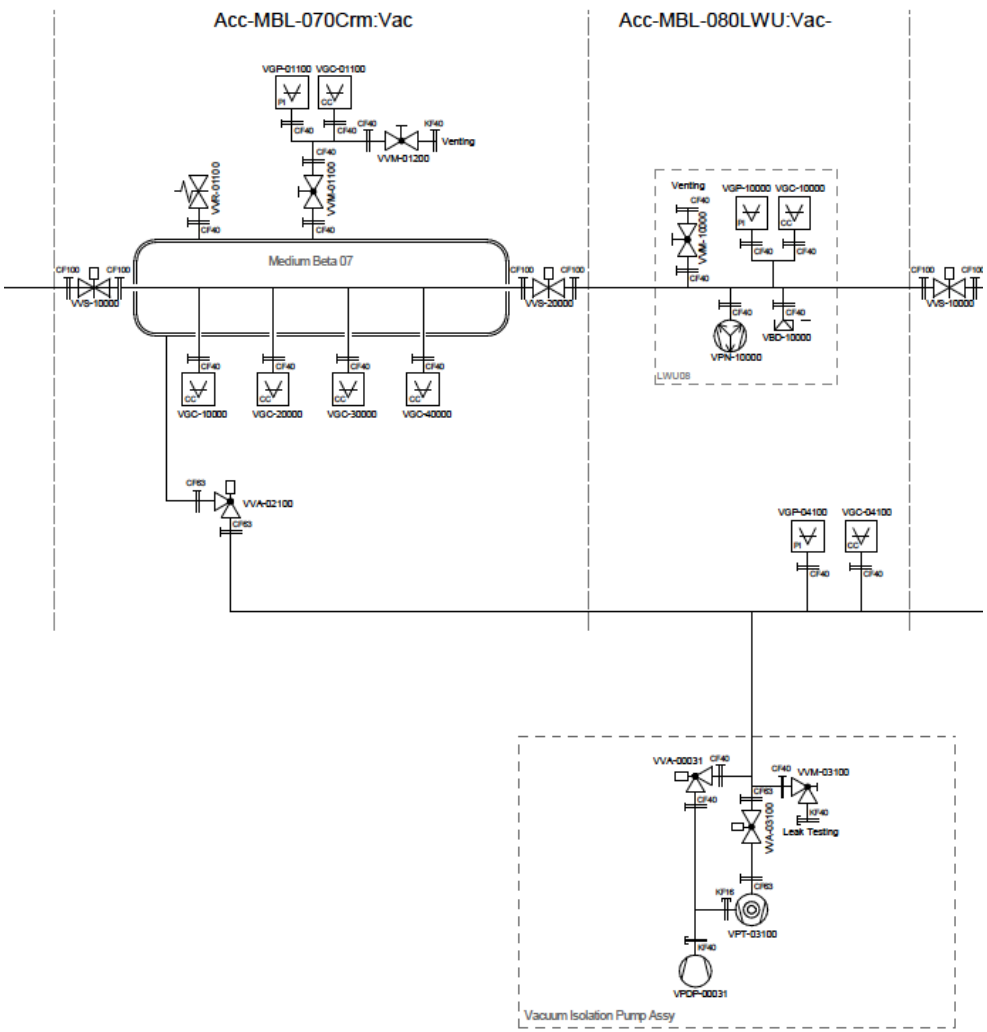


Note:

1) Vacuum gauges
2) Relief valves
3) Sufficient valves to alllow changing of valves or pumps
4) Ports for venting, pumping, purging and leak testing.
5) A control system is also required

Cryopumping

- All components of air will freeze at low enough cryogenic temperatures
- Thus, a cryogenically cooled surface will can be used to create a vacuum in an enclosed space. This is particularly efficent in removing nitrogen, oxygen, water vapor and hydrocarbons.
- There are a number of advantages to cryopumping:
    - Cleanliness (no pump oil)
    - Low or no vibration
    - Very high pumping speeds
    - Ability to pump large and unusually shaped enclosures

Cryopumping

- Depending on application, cryopumps operate at 80 K or below
- Cooling can be provided by stored cryogenic liquids, small cryocoolers or large cryogenic refrigeration plants
- Cryopumping is heavily used in the semiconductor processing industry

Example of a Cryopump

Note ITER has roughly 20 kW of cooling at 4.7 K for cryopumping

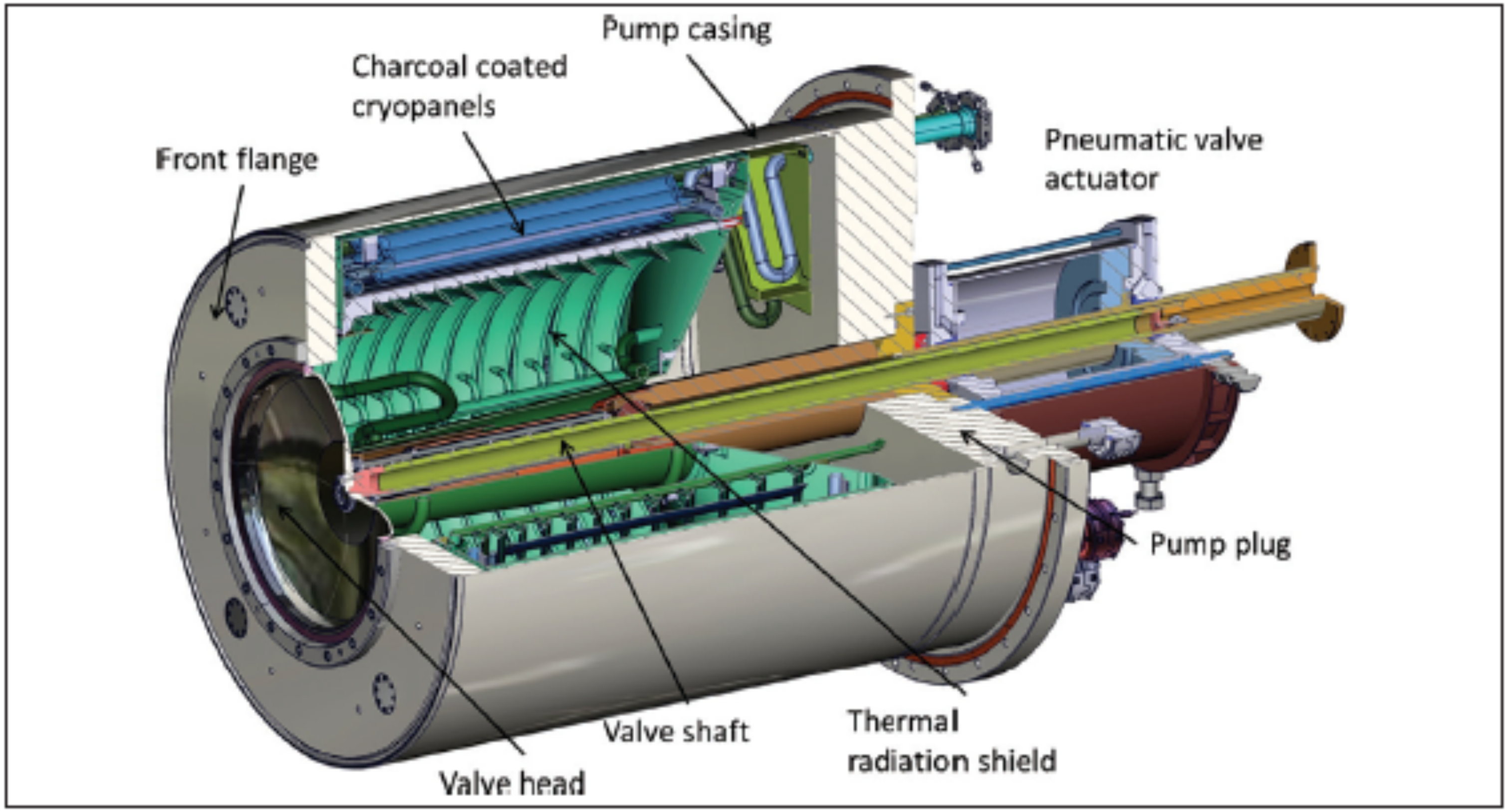
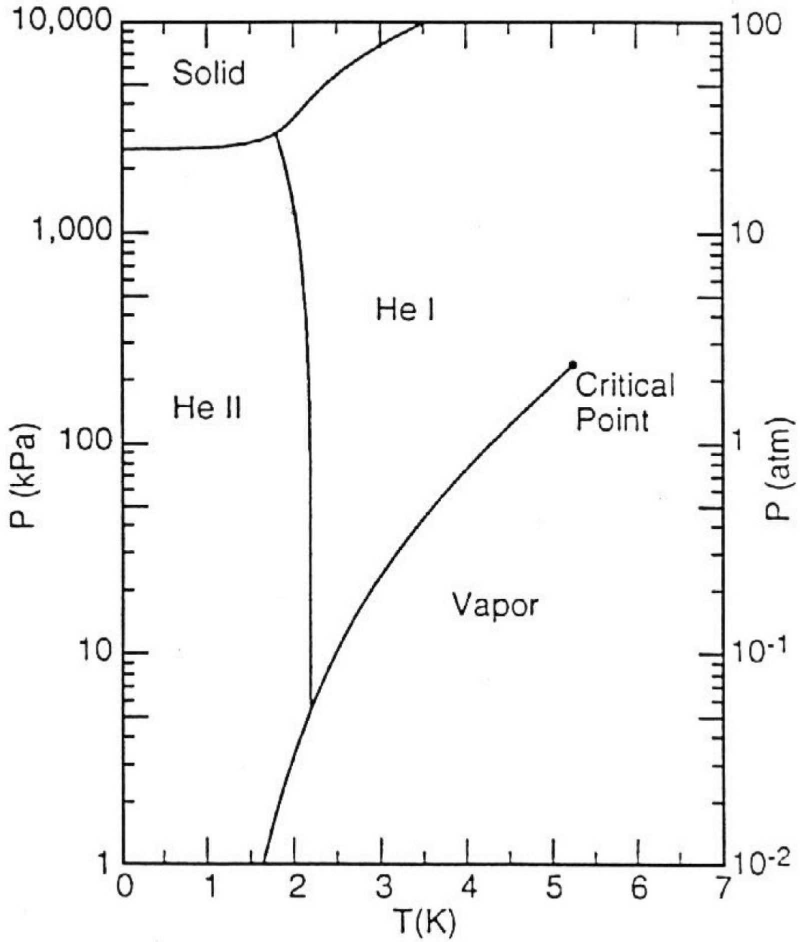


Figure 1: Cutaway view of the ITER torus cryopump. Image reprinted from M. Dremel et al., "The New Build to Print Design of the ITER Torus Cryopump," *Fusion Engineering and Design*, October 2013 (doi.org/10.1016/j.fusengdes.2013.02.026), with permission from Elsevier.

Pumped systems - not vacuum but subatmospheric

- A common way to reach temperatures below 4.2 K (NBP of helium) is to pump on the helium reducing its local pressure and thus its local saturation temperature.
- This can be done with other cryogenic fluids as well but most others will quickly reach their freezing point. Helium remains a liquid down to 0 K.
- This technique will work with ^{4}He down to about 1.3 K. It can be extended down to 200 mK using pumped ^{3}He

P-T Diagram for Helium



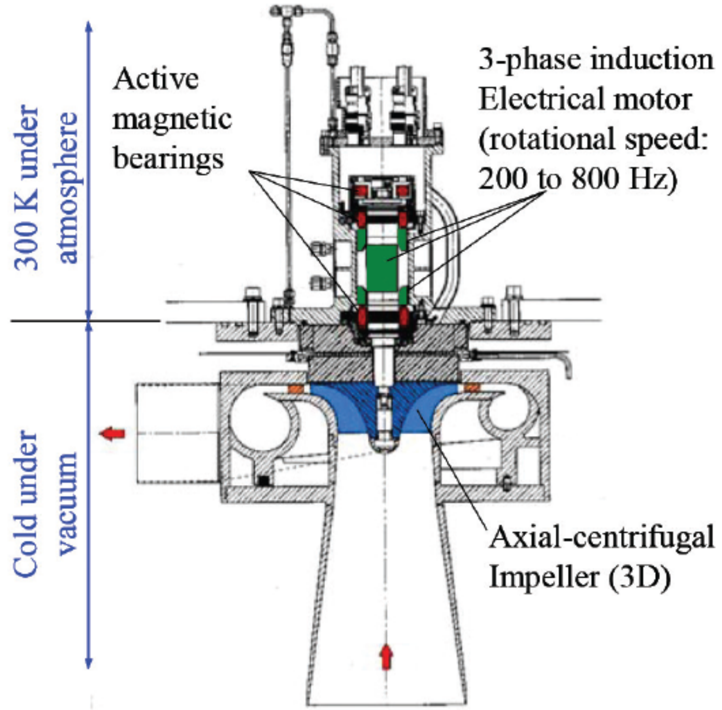
Pumped systems

- For small systems this pumping is done via room temperature vacuum pumps.
- Disadvantages:
  - Long lengths of large diameter subatmospheric pumping lines
    - May result in leaks & contamination of the helium
    - Expensive
  - Loss of cold helium for precooling

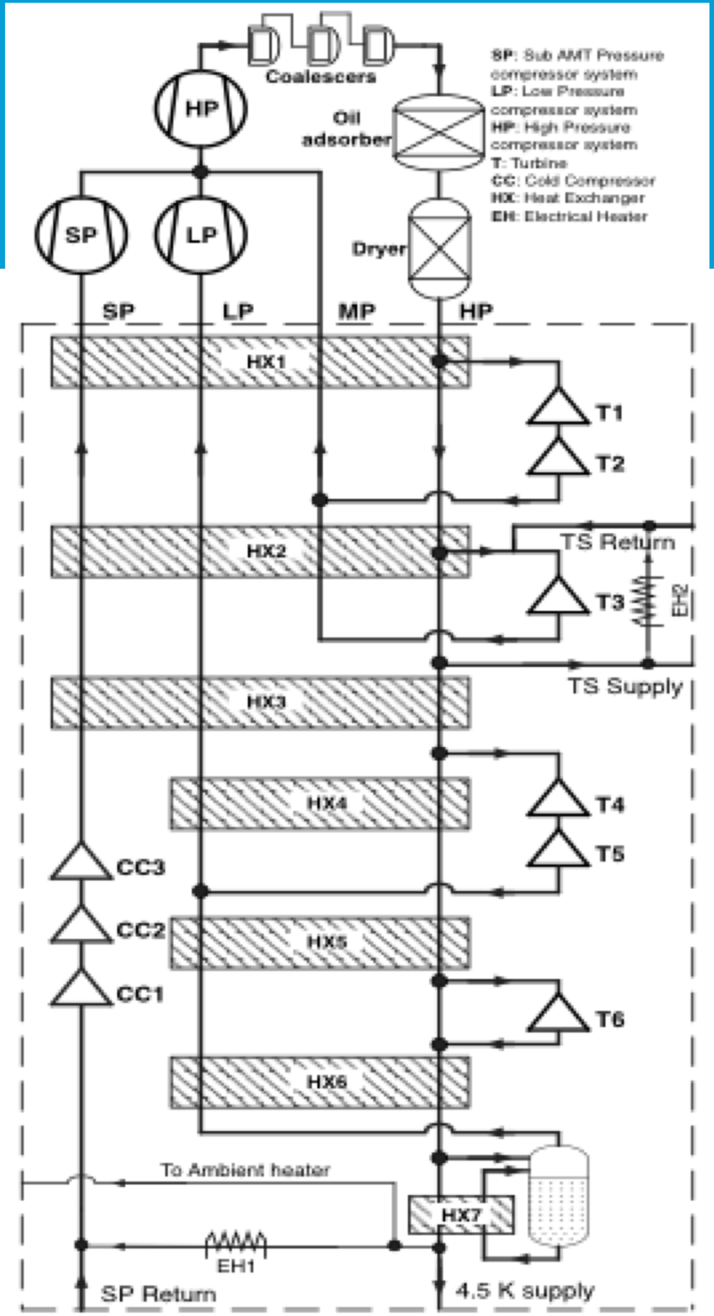
Pumped systems

- For big systems we use cold compressors to pump off the vapor and reduce the helium pressure and temperature
- These are sophisticated turbomachines that act as cod vacuum pumps.
  - Advantages:
    - Cold is recovered for use in the refrigeration cycle
    - Piping outside of cold box operates at near 1 bar. Thus smaller diameter, cheaper and less prone to air inleak

Pumped systems – Cold Compressor Example



Cold Compressors
in ESS Accelerator Cryoplant



Production of Subatmospheric He II in an ESS Cryomodule

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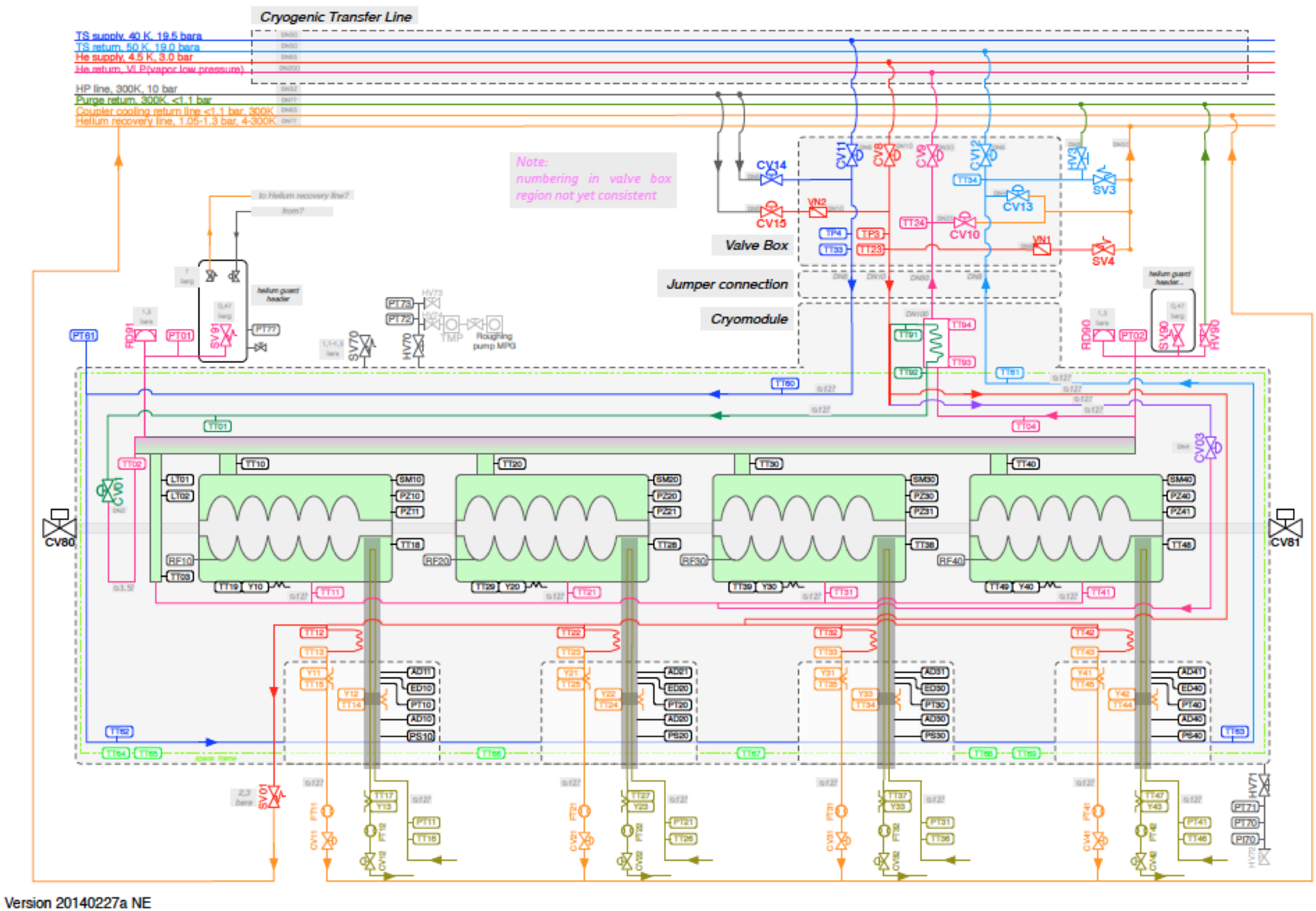

He II @ 2 K produced at each CM

Pumping and Purging

- All cryogenic systems start with air inside them. All the components of air including water vapor and CO_2 will freeze at cryogenic temperatures interupting the operation of the cryogenic system.

- Thus before starting any cryogenic system that has exposed to air the system has to be pumped down to about 10^{-3} mbar and then back filled with helium gas. This pump and purge cycle is typically repeated 5 – 10 times to ensure a clean system. <u>Note that vacuum spaces are pumped down but not backfilled with helium to avoid affecting later leak tests.</u>

- This process requires that any cryogenic system have pumping ports and access to both vacuum systems and pure helium gas.

Leak Detection & Cryogenics

- Pipes and equipment containing cryogenic fluids have to be vacuum leak tight.
- Leaks in cryogenic systems can cause:
  - Spoiling of vacuum insulation with resulting heat leaks
  - Loss of cryogenic fluid
  - Cooling of materials not designed for cryogenic temperatures
  - Possible overpressures with resulting safety issues (see below)
- The gold standard is for the system be checked by a He leak detection process. Allowable leak rates are typically 10^{-5} mbar*l/s
- Such testing is frequently provided by the vacuum group

Safety in Cryogenic Vacuum Systems

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- Even leak tested cryogenic systems may develop leaks.
- There is a very large volume expansion (factor of 700 or higher) between a cryogenic liquid at its normal boiling point and the resulting gas at room temperature and pressure. This can lead to very high pressures, explosive failures and resulting injury.
- To avoid this, ALL vacuum systems containing cryogenic equipment must have pressure relief devices (relief valves, burst discs or lift plates) to prevent excessive pressure rise in the vacuum system.
- Such devices must be properly sized to meet the wost case accidents.
- Review, documentation and inspection of such pressure relief systems is vital to safe operation.

Example of Vacuum Space Pressure Relief

ESS CDS Vacuum Shell

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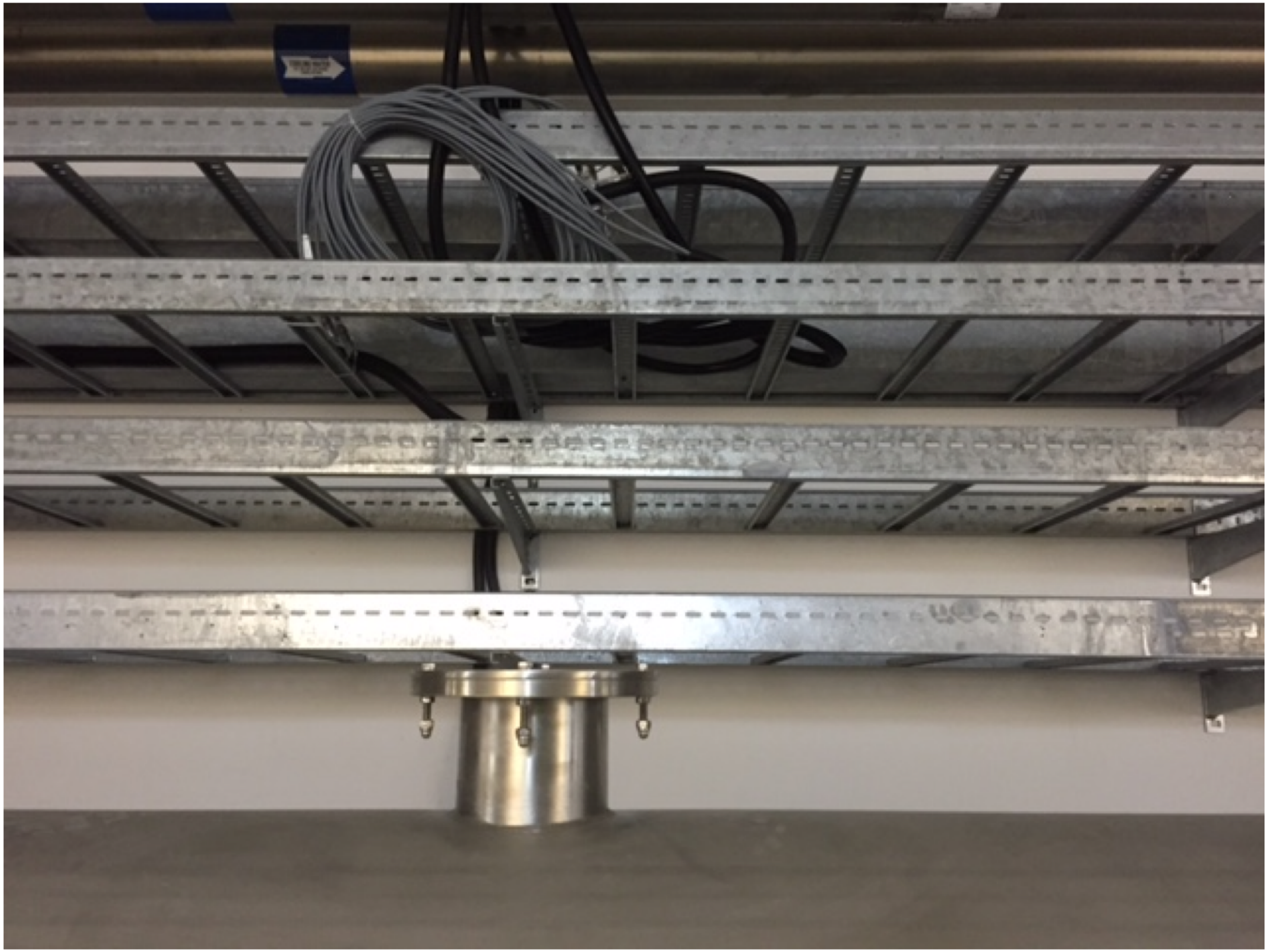

Summary

- Vacuum technology plays a vital role in cryogenic systems.
- Cryogenics also contributes to vacuum systems through the use of cryopumps.
- Vacuum and cryogenic systems are best designed together from the start including safety issues.
- Cryogenic engineers require vacuum expertise or access to vacuum expertise at all stages of a project: design, construction, installation and operation.