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Cryogenic Systems II
Part 2: Keeping Cold

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www.europeanspallationsource.se
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Cryostats and Cryomodules

- What is a cryostat?
  - A device or system for maintaining objects at cryogenic temperatures.
- Cryostats that contain SRF systems are frequently known as a cryomodules. Design approaches are the same
- Cryostat design involves many subtopics:
  - 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

Cryostat Requirements

- Maximum allowable heat leak at various temperature levels
  - This may be driven by the number of cryostats to be built as well as by the impact of large dynamic heat loads (SCRF or target cryostats)
- Alignment and vibration requirements
  - Impact of thermal cycles
  - Need to adjust alignment when cold or under vacuum?
  - Alignment tolerances can be quite tight (TESLA: +/- 0.5 mm for cavities and +/- 0.3 mm for SC magnets)
- Number of feed throughs for power, instrumentation, cryogenic fluid flows, external manipulators
- Safety requirements (relief valves/burst discs)
- Size and weight
  - Particularly important in space systems
- Instrumentation required
  - Difference between prototype and mass production

Cryostat Requirements

- Ease of access to cryostat components
- Existing code requirements (e.g. TUV or ASME)
- Need, if any, for optical windows
- Presence of ionizing radiation or magnetic fields
  - Magnetic shielding is a important part of SRF cryomodules
- Expected cryostat life time
- Will this be a one of a kind device or something to be mass produced?
- Schedule and Cost
  - This should be considered from the beginning

All Design is Compromise

Cryostat Materials

- Materials for cryostats must function properly at cryogenic temperatures
- Material properties change greatly as a function of temperature between 300 K and cryogenic temperatures – such variations must be taken into account in the cryostat design
- Typical materials for cryostats include:
  - Austenitic stainless steels
  - Aluminum
  - Copper
  - G-10 (Fiber reinforced plastic)
  - Glass
  - Quartz (for viewing ports)
- As will be seen, the location of materials used in a cryostat is optimized to reduce heat leak.

Thermal Insulation of Cryostats
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

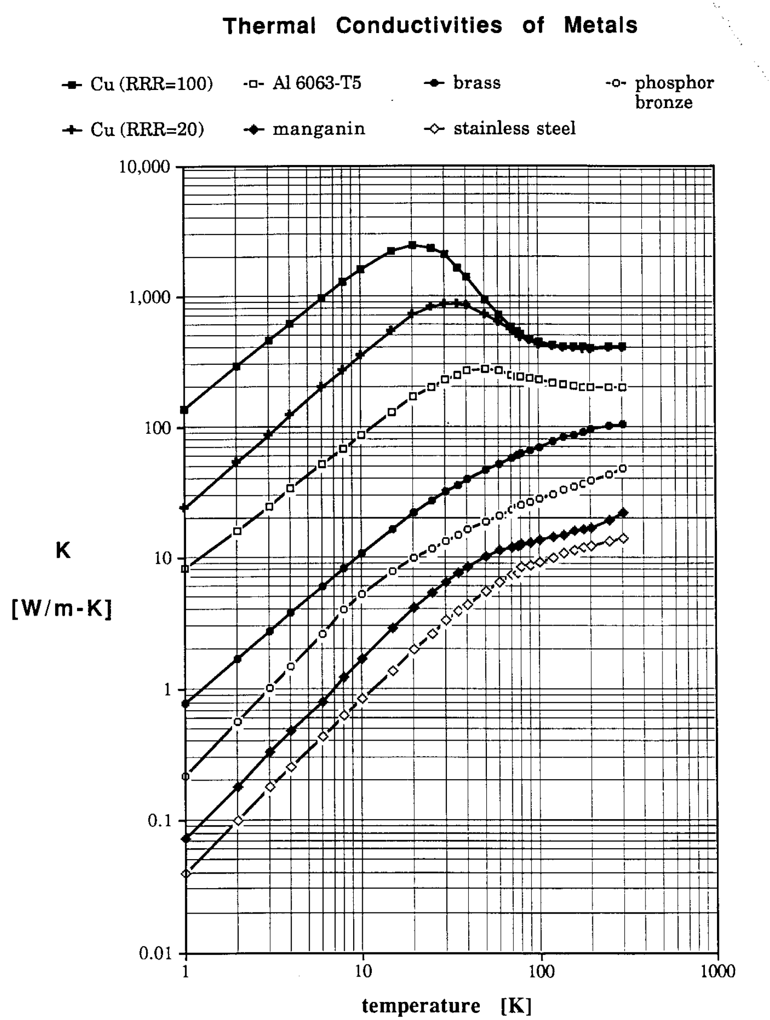
- Fundamental Equation – The Fourier Law in one dimension

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

- 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
    - You still have heat leak from 300 K to this intermediate temperature but remember Carnot, It's more thermodynamically efficient to remove heat at higher temperatures

Thermal Conductivities of Metals



Variation of Thermal conductivity with temperature can be addressed with Thermal Conductivity integrals
See backup slides

From Lakeshore Cryotronics

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 – though not always, more later
  - Thermos bottles are a simple example of this approach

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} torr 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 materials 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 (such as activated charcoal or silica gel) 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

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 $\sigma = 5.67\text{x}10^{-8}\ \text{W/m}^2\text{K}^4$

  – Real world Assumptions:
    - Emissivity (ε) << 1 and independent of wavelength (grey body)
    - Two parallel infinite plates: Radiative heat flux (W/m²)

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

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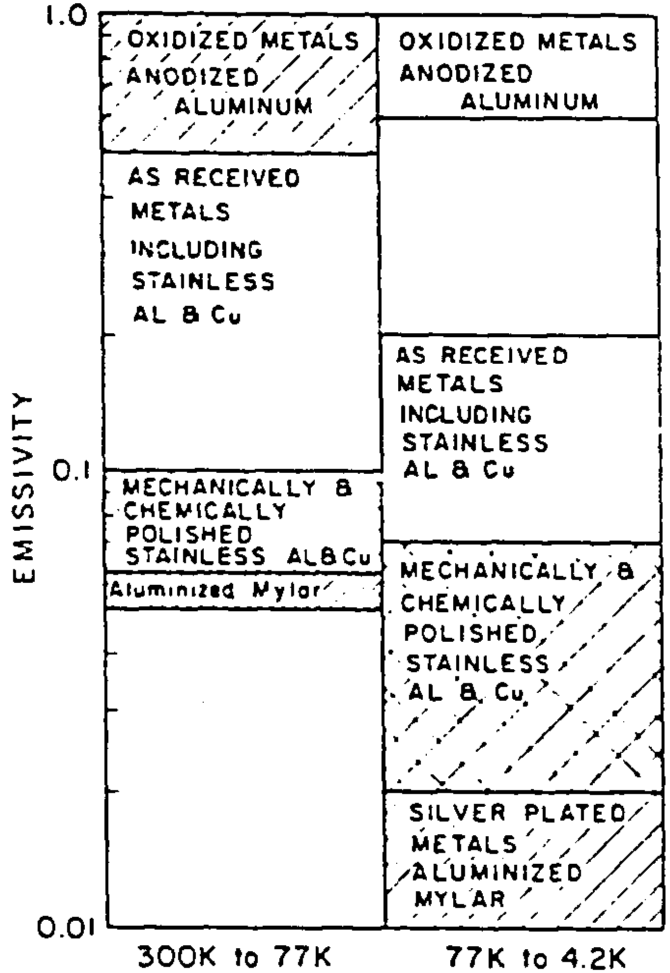
» Two long concentric cylinders or concentric spheres (1 represents the inner cylinder): the radiative heat flux (W/m²) on the inner cylinder is

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

Thermal Radiation Shields

- Uncooled thermal radiation shields placed in a vacuum space between the warm & cold surfaces also help reduce the thermal radiation heat leak
- It can be shown (with the grey approximation and equal emissivities) that with N shields thermal radiation heat transfer is given by:

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

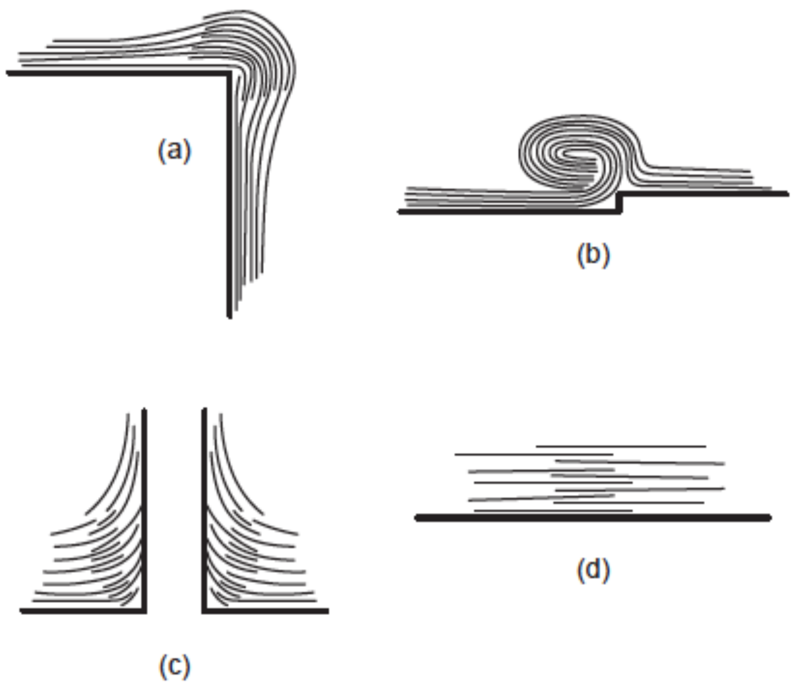
This is the motivation behind Multilayer Insulation

MultiLayer Insulation

- Also referred to as superinsulation
- Used in the vacuum space of many cryostats (10^{-5} torr or better for best performance) – can be used instead of or with actively cooled thermal shields or baths
- Consists of highly reflective thin sheets with poor thermal contact between sheets.
  - Made of aluminized Mylar (or less frequently Kapton)
  - May include separate non conducting mesh
  - May use Mylar aluminized on only one side and crinkled to allow only point contacts between sheets
  - Frequently perforated to allow for better pumping
- Can be made up into blankets for ease of installation
- Don't pack MLI too tightly. Doing so will cause increased conduction heat leak negating the value of the MLI

MultiLayer Insulation

- Great care must be taken with seams, penetrations and ends.
  - Problems with these can dominate the heat leak



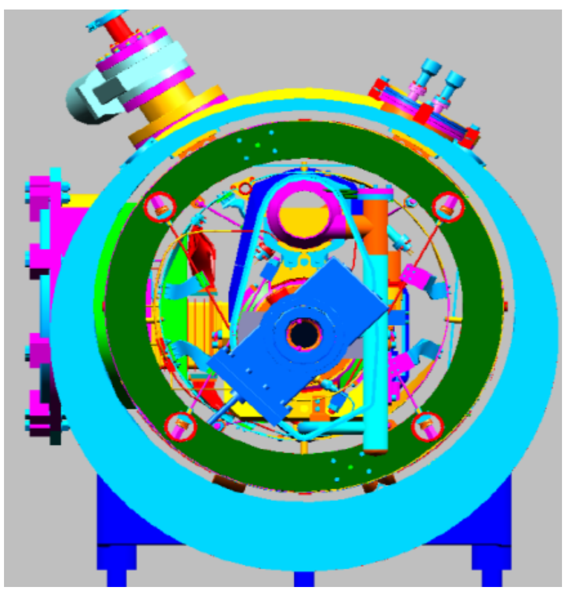
MLI Example from LHC cryostats

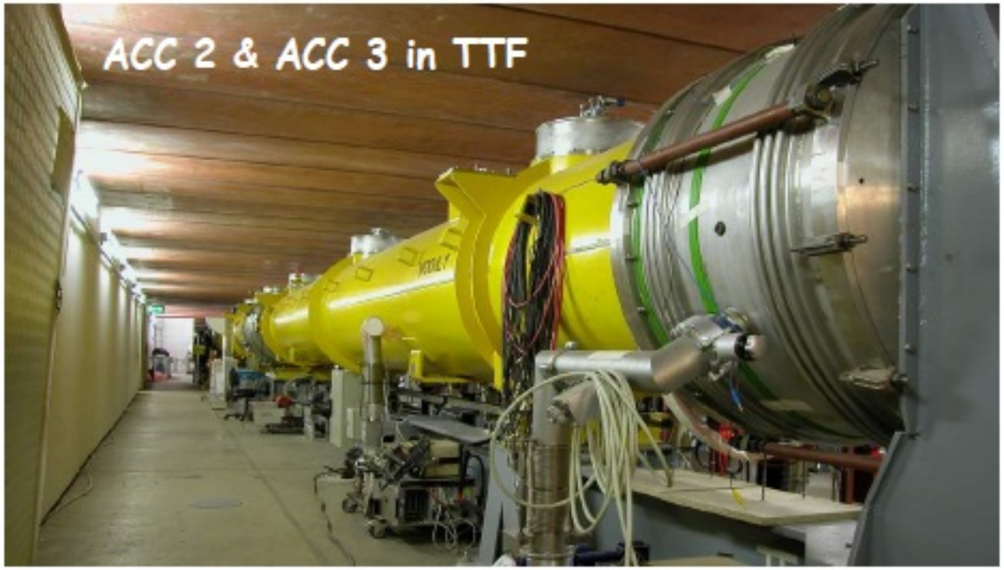


“SERIES-PRODUCED HELIUM II CRYOSTATS FOR THE LHC MAGNETS: TECHNICAL CHOICES, INDUSTRIALISATION, COSTS”
A. Poncet and V. Parma
Adv. Cryo. Engr. Vol 53

Cryomodule Examples: Elliptical Cavities

- Due to the cavity shapes and the general efficiency of using cylinders as pressure/vacuum vessels, these systems are almost always cylindrical in geometry
  - Cold Masses are loaded in from the ends
  - Cryogenic piping connections go out the ends
  - Common design features with accelerator magnet systems
  - Can be further divided into "Space Frame" designs" & "Internal Transfer Line" designs



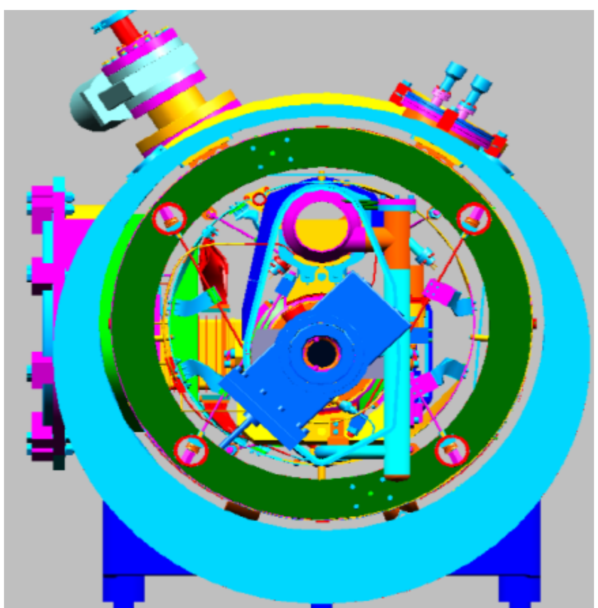


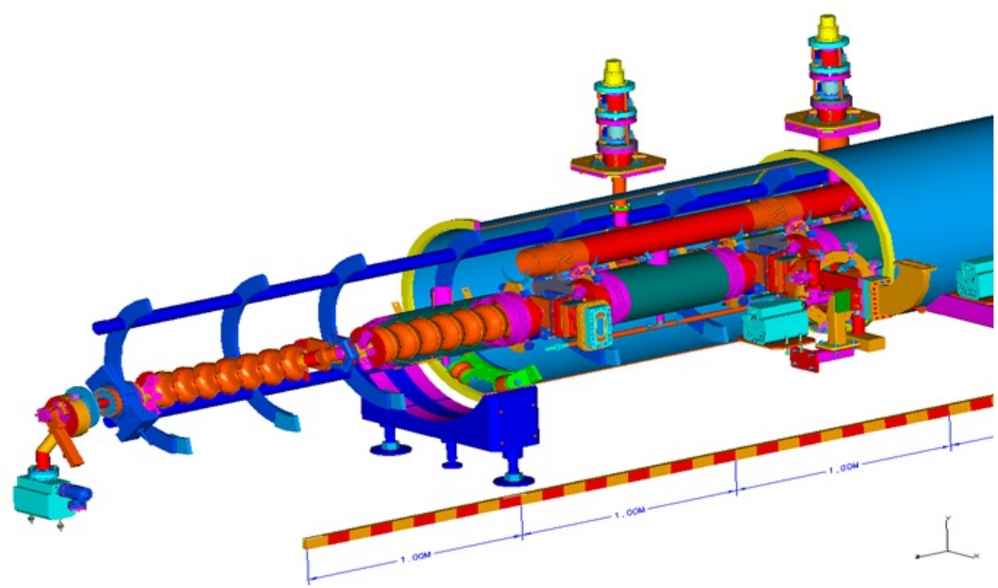
Space Frame Based Designs

- Cold Mass Components are installed into a Space Frame that is inserted into a cylindrical vacuum vessel.
- Space Frame may also contain thermal shield and MLI systems
- Generally alignment is done warm and system is designed to not require realignment once cold
- Very suitable for systems in which the cryo segmentation is done per module with a parallel transfer line
- Higher cost and heat loads tend to limit this approach to small & medium sized machines (~ 50 CMs)
- Examples include: ESS, SNS and Jlab 12 GeV Upgrade

JLab 12 GeV Upgrade Cryomodule

- Based on successful SNS design - a total of 10 CMs were needed
- Cavities at 2.1 K, thermal shield at 50 K – no s/c magnets present
- Cold Mass tied to space frame via nitronic rods
- Space frame rolls into vacuum vessel
- Despite extensive SNS experience, design changes (mainly in cold mass) were required after 1st prototype – *value of prototyping*





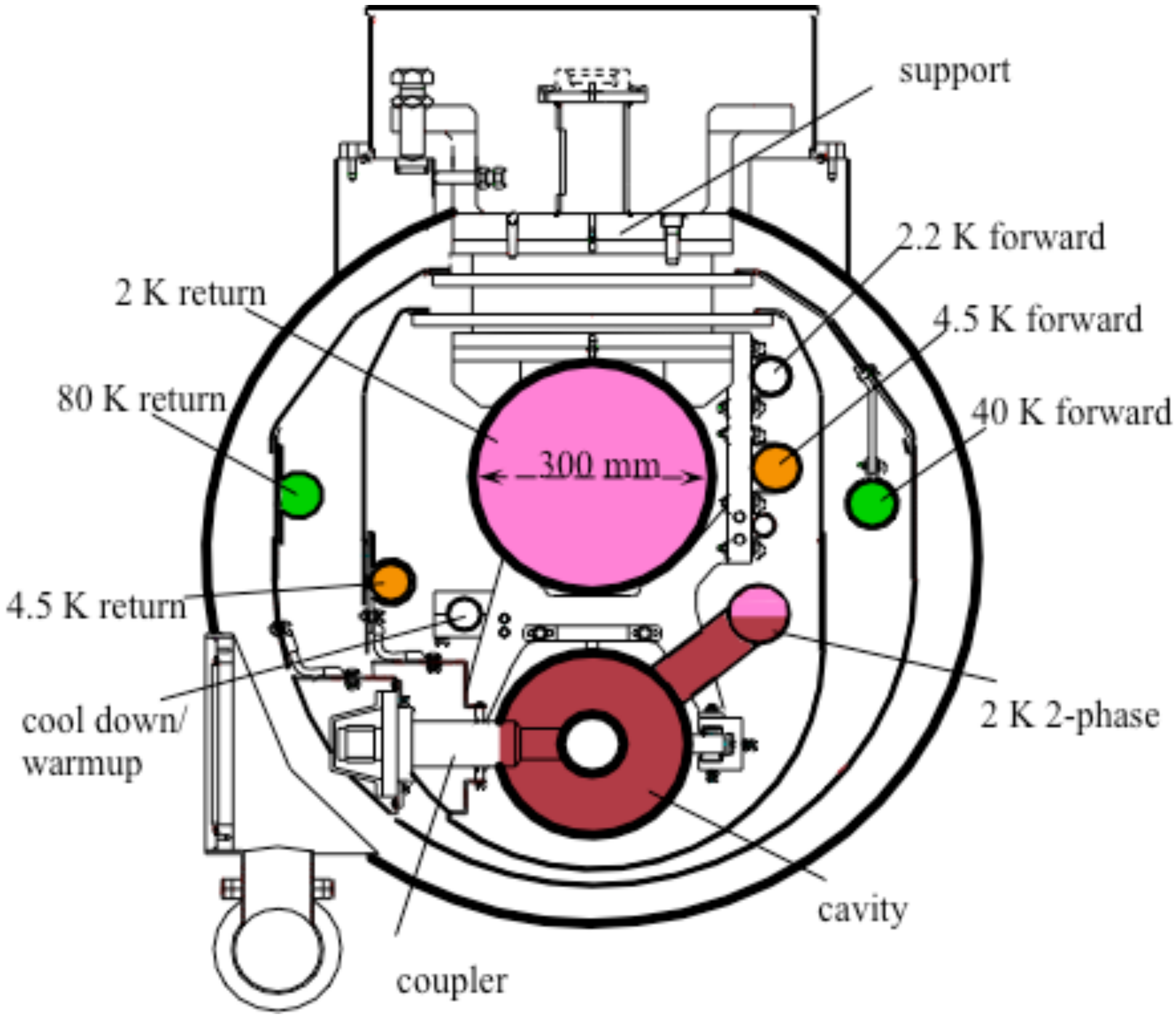
Internal Transfer Line Based Designs

- Cryogenic distribution piping is contained with cryomodules - limited external transfer lines
- Approach commonly used where infrequent cryo-segmentation is desired
- Lower static heat leak & lower cost
- More difficult maintainability (larger number of CMs to thermal cycle)
- Suitable for systems containing large numbers of cryomodules (ILC, XFEL, LCLS II)
- Designs frequently use large diameter distribution lines as the structural backbone for the cold mass

ILC Cryomodule Design

- Based on extensive TESLA development program
- Cavities at 2 K, thermal shields at 5 K and 40/80 K, s/c magnets at 4.5 or 2 K
- Design uses large GRP (whose size is dictated by allowable pressure drop) as the structural backbone for the cold mass
- FRP posts connect GRP to vacuum vessel
- Alignment is done warm. System is designed to keep alignment when cooled
- Design drivers
  - ~ 2000 cryomodules required
  - Low heat leak and low cost
  - Infrequent cryo-segmentation
  - Ease of mass production
- Significant amounts of prototyping (FLASH)
- 3 generations of design with continuous improvement
- Design being used on XFEL and LCLS II (with mods)

3rd Generation ILC Cryomodule



Cryomodules with QWR and HWR Cavities

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- Low to medium beta cavities typically used in heavy ion machines IISAC-II, (TRIUMF) ATLAS Upgrade (ANL), RAON & FRIB (MSU)
- Due to cavity geometry, particularly the QWRs, these cryomodules have a rectilinear geometry
- The designs can be further divided into "Top Supported" or "Bottom Supported" Designs
- Cryogenic lines go out either the top or bottom of assembly
- So far only used in systems where cryo-segmentation is at the individual CM level – external transfer line

Top Down Designs

- All components are suspended from a top plate via metallic rods
  - Length between top plate and connection to cavity mounting beam can be maximized to reduce heat leak
- System is lowered into a simple bath tub style vacuum vessel
- Possibility of better vibration response (longer path between floor and cavity
- Cryogenic and other feedthroughs go through the top plate though coupler and tuner feedthroughs may be through the side or bottom
- Most common type of HWR/QWR cryomodule

ALTAS Upgrade Cryomodule

- Top down design similar to IISAC-II but separate cavity & isolation vacuum – thus clean room assembly needed but higher performance cavities possible
- 7 QWR plus 1 solenoid all at 4.5 K

"Commissioning of the ATLAS Upgrade Cryomodule", P.N. Ostroumov et al. *Proceedings of HIAT09* (2009)

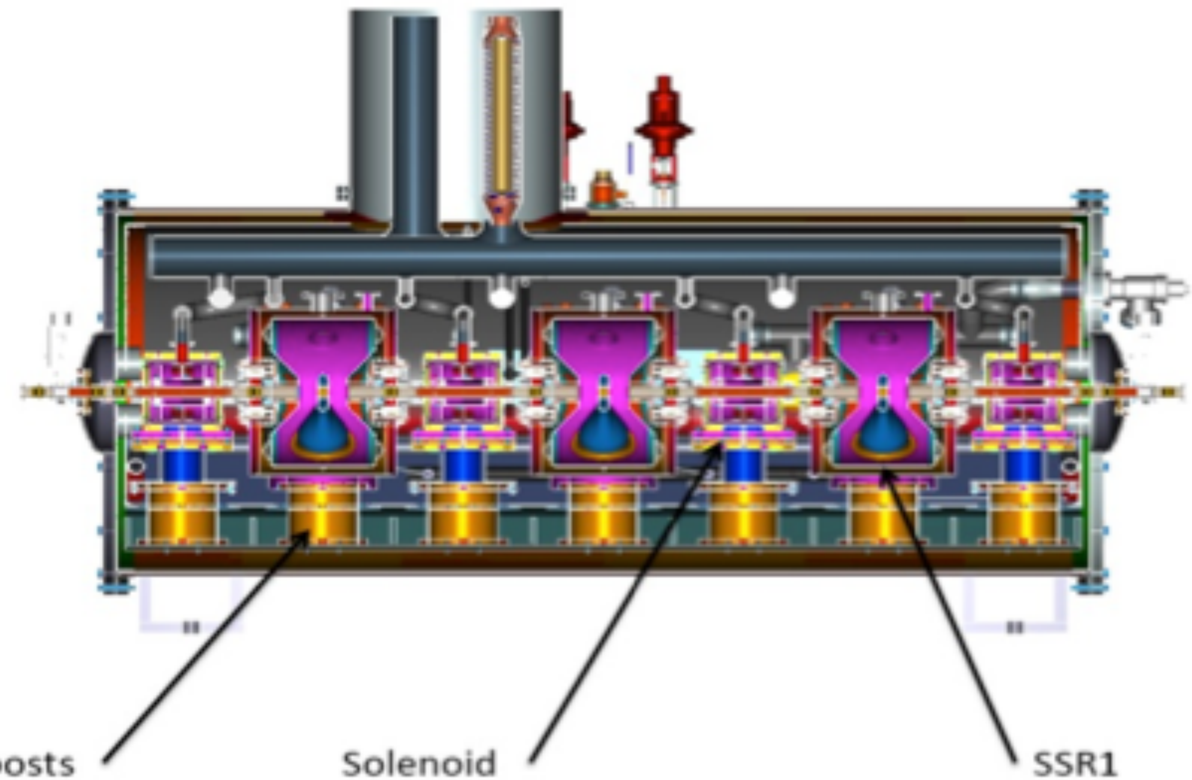
Bottom Supported Design

- Here the components, instead of being hung from the top plate, are supported by FRG posts from a bottom plate.
- Vacuum vessel lid is lowered down on top (FRIB) or slid into a cylindrical vacuum chamber (Fermilab SSR)

Example of Bottom Support in a Cylindrical Geometry

Proposed Fermilab Single Spoke Resonator

Each component has its own support post – very "stiff design"



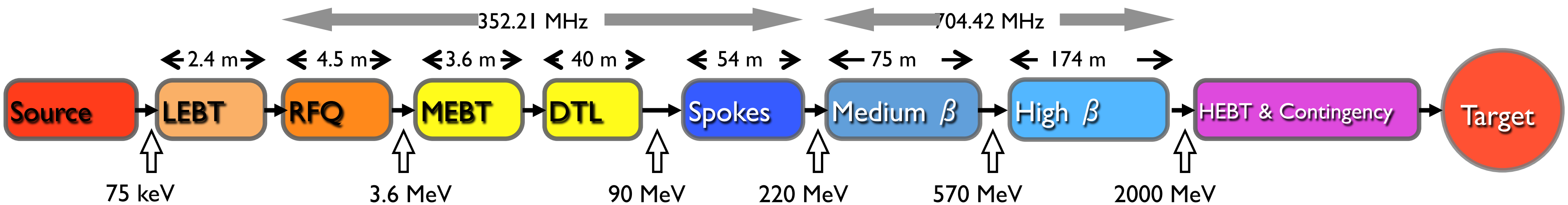
Applications of Cryogenics at ESS

- Cooling for the cryomodules (2 K, 4.5 – 300 K and 40 K)
- Cooling for the Target supercritical H_2 Moderator (16.5 K)
- Liquid Helium and Liquid Nitrogen for the Neutron Instruments
- Cooling for the cryomodule test stand (2 K, 4.5 – 300 K and 40 K)
- This is accomplished via 3 separate cryoplants

Accelerator Cryogenics

- Bulk of acceleration is carried out via 3 classes of SRF cavities: Spoke, Medium (β = 0.67) Beta Elliptical and High (β = 0.86) Beta Elliptical
- No superconducting magnets in the accelerator. There are some in the instruments
- Cavities operate at 2 K with a 40 – 50 K thermal shield
- Inner power coupler cooling from 4.2 K to 300 K
- Accelerator lattice permits an 14 additional cryomodules to compensate for lower than expected cryomodule gradients (Stage 2)

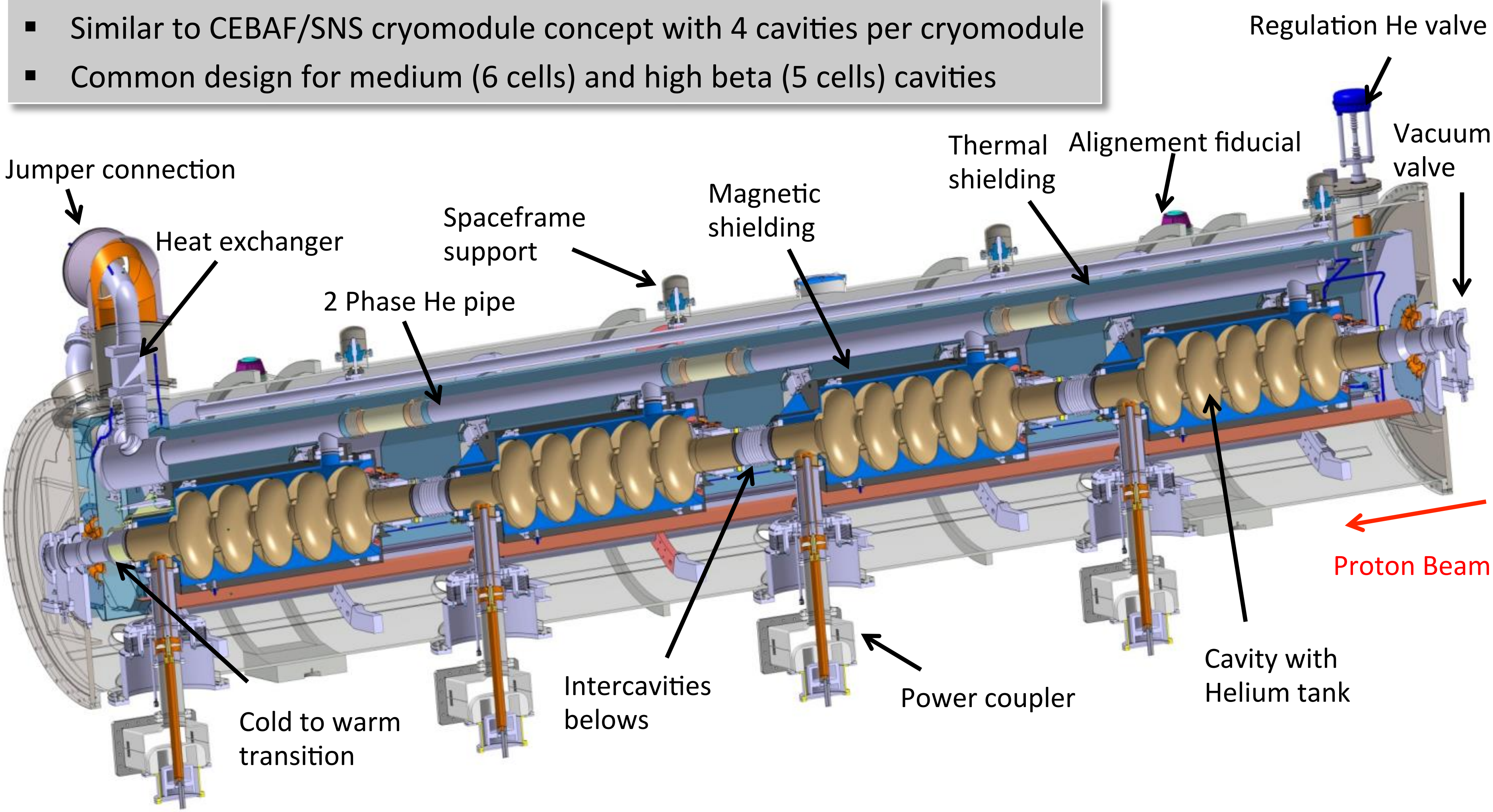
ESS Linac



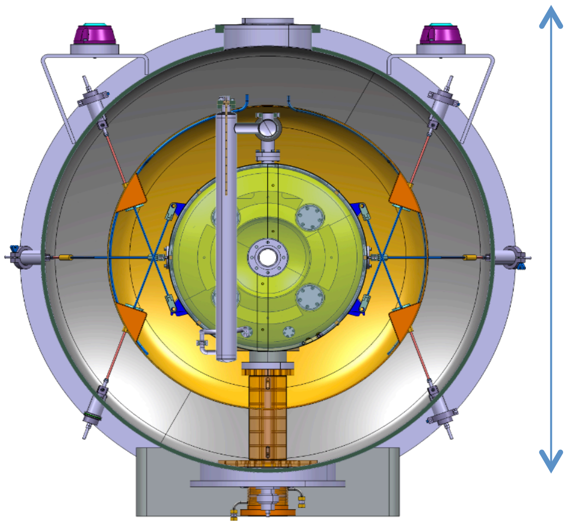
	Energy (MeV)	No. of Modules	No. of Cavities	β_g	Temp (K)	Cryo Length (m)
Source	0.075	1	0	–	~300	–
LEBT	0.075	–	0	–	~300	–
RFQ	3.6	1	1	–	~300	–
MEBT	3.6	–	3	–	~300	–
DTL	90	5	5	–	~300	–
Spoke	220	13	2 (2S) × 13	0.5 β_{opt}	~2	4.14
Medium β	570	9	4 (6C) × 9	0.67	~2	8.28
High β	2000	21	4 (5C) × 21	0.86	~2	8.28
HEBT	2000	–	0	–	~300	–

Elliptical Cavities & Cryomodule (See C. Darve's Talk)

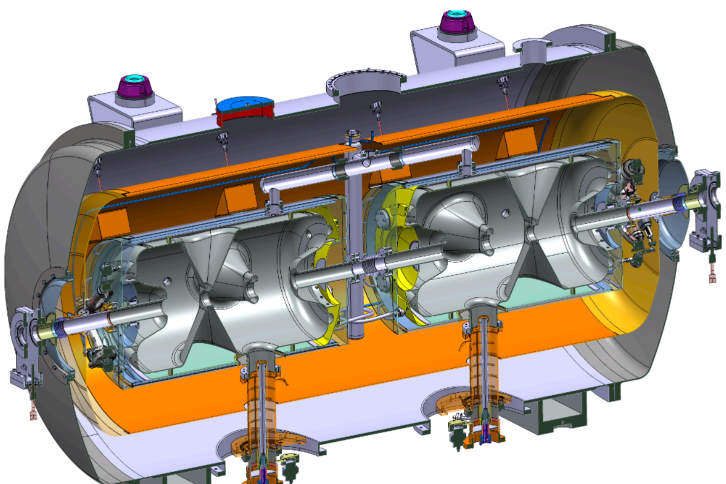
- Similar to CEBAF/SNS cryomodule concept with 4 cavities per cryomodule
- Common design for medium (6 cells) and high beta (5 cells) cavities



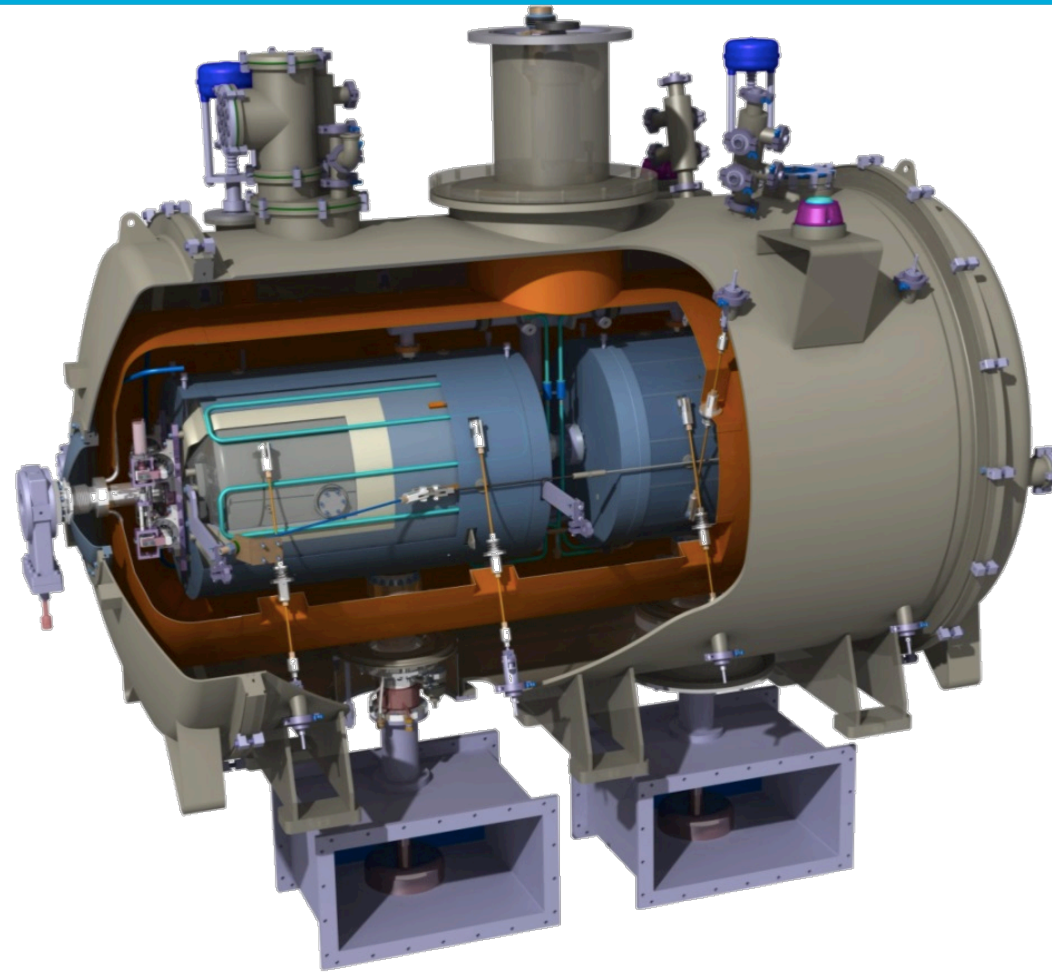
Spoke cavity string and cryomodule package (See C. Darve's Talk)



Diameter
1350 mm



2900 mm



ESS Accelerator Cryoplant (ACCP)

- Provides cryogenic cooling to Cryomodules
  - 13 Spoke and 30 Elliptical (Stage 1)
  - Sized to allow an additional 14 Elliptical Cryomodules for design contingency (Stage 2)
- Allows for number of operating modes
- Connected to the cryomodules via a cryogenic distribution system
- High availability and turn down capability are important features
- Compressor heat is absorbed by Lund District Heating System (unique ESS feature)

Accelerator Cryoplant (ACCP) Capacities

Operation modes		2 K Load, W			4.5 K Load		40-50 K, W
		Isothermal	Non-isothermal	Total	4.5 K, W Total	Liquefaction, g/s	Total
Stage 1 2019-2023	Nominal	1852	627	2478		6.8	8551
	Turndown	845	627	1472		6.8	8551
	Standby				1472	6.8	8551
	TS Standby	-	-	-	-	-	8551
	Maximal Liquefaction	Loads in standby mode plus maximum liquefaction rate at rising level into the storage tank					
Stage 2 2023-…	Nominal	2226	824	3050		9.0	11380
	Turndown	1166	824	1990		9.0	11380
	Standby				1990	9.0	11380
	TS Standby	-	-	-	-		11380
	Maximal Liquefaction	Loads in standby mode plus maximum liquefaction rate at rising level into the storage tank					

ACCP – Contract Award to Linde Kryotechnik AG in December 2014

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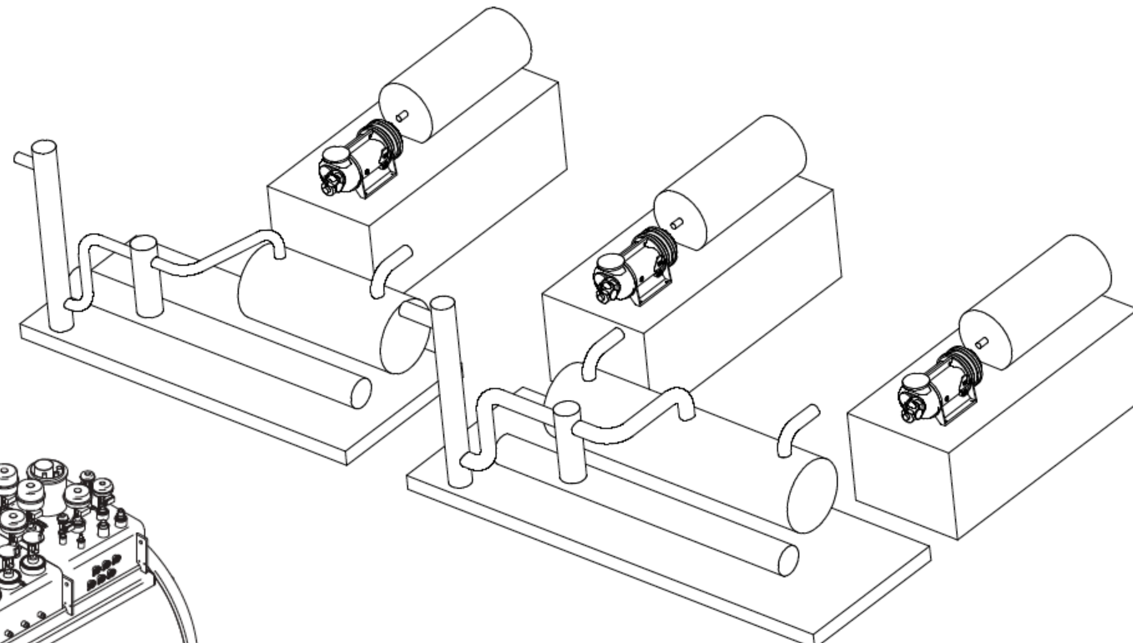
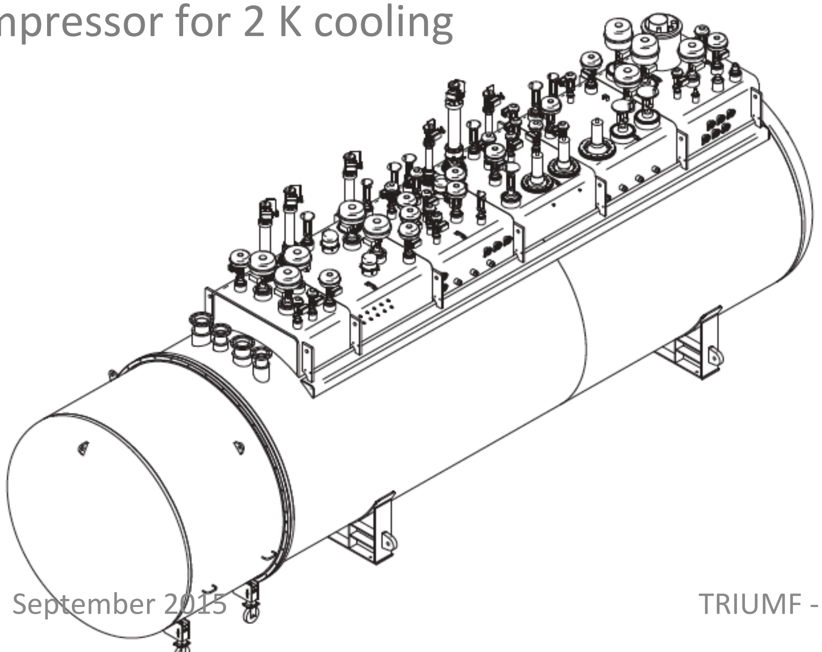
Compressor System:
Three identical machines for SP→MP, LP→MP and MP→HP compression, hot standby compressor is under discussion



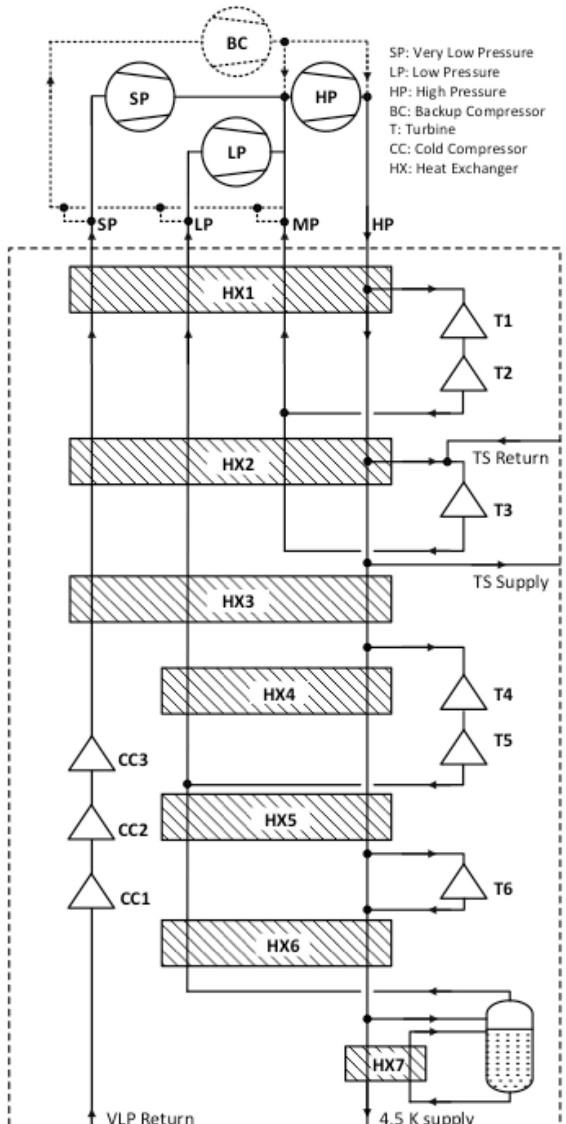
System uses 3 cold compressors + 1 warm sub-atmospheric compressor for 2 K cooling



One Coldbox comprising 6 expansion turbines, 3 cold compressors, in-built acceptance test equipment

Kick Off Meeting was held on May 8
PDR-1: Sept 2 -3

Simplified Flow Schematic from Linde for ACCP



Note:

1) No LN_2 Precooling

2) Last stage of subatmospheric pumping is warm

Cryogenic Distribution System

- Allows warm up and cool down of one or more cryomodules w/o affecting remaining cryomodules
- Connection between distribution line & cryomodule is done via fixed connections
- Separate isolation vacuums in the distribution lines and cryomodules
- Operating modes defined
- Conceptual design complete
- Provided as an In Kind Contribution by IPN Orsay (France) and WrUT (Poland)
- Cryogenic Distribution System must be complete and

Linac CDS – function and layouts

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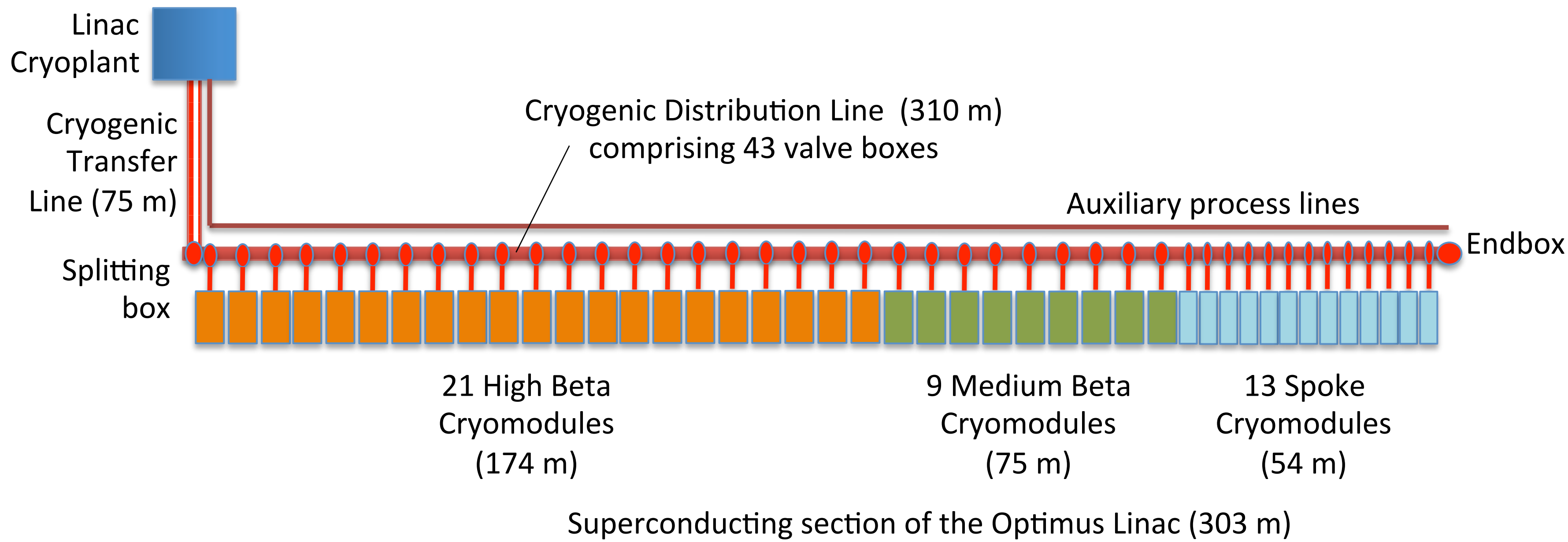
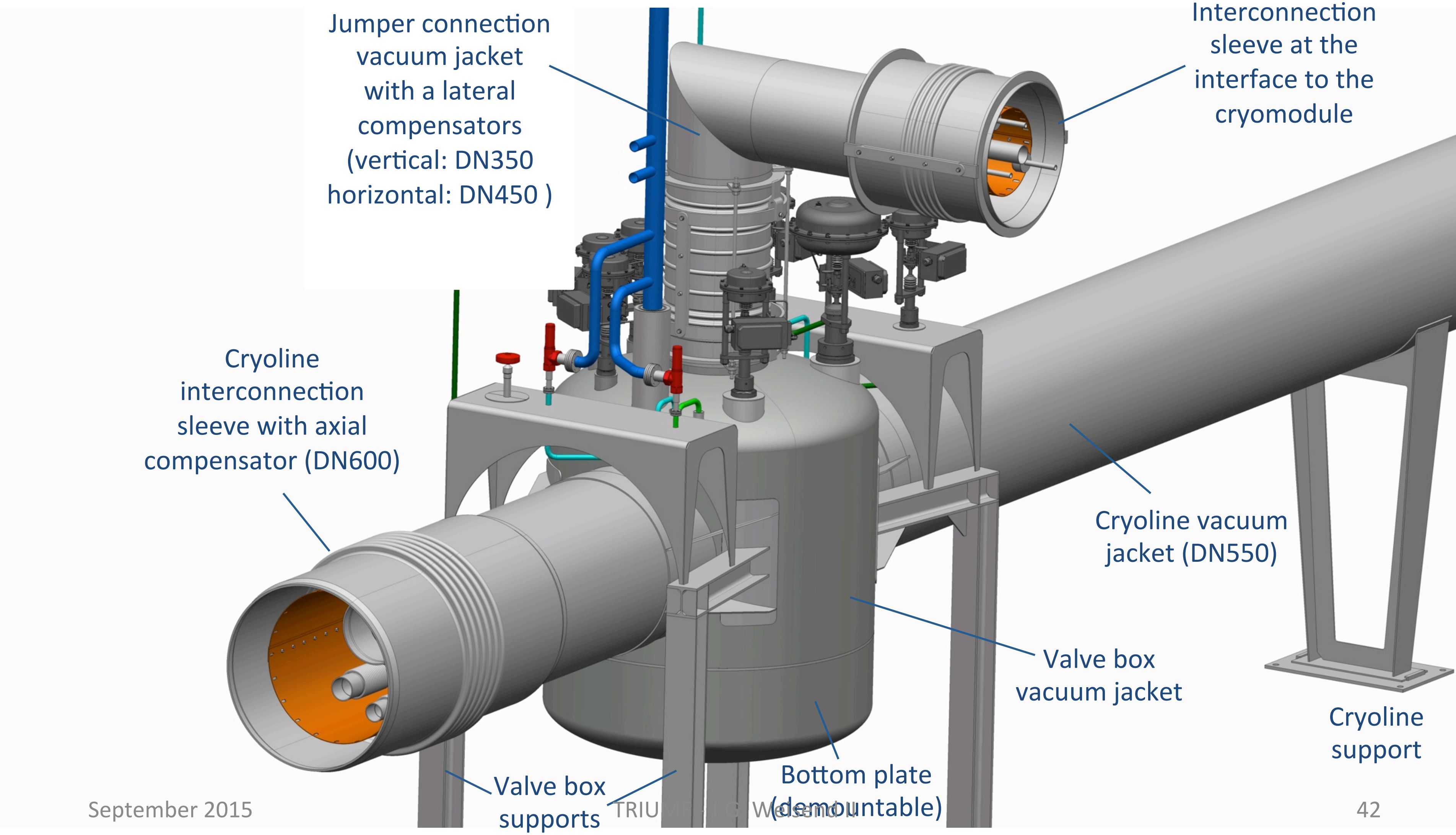
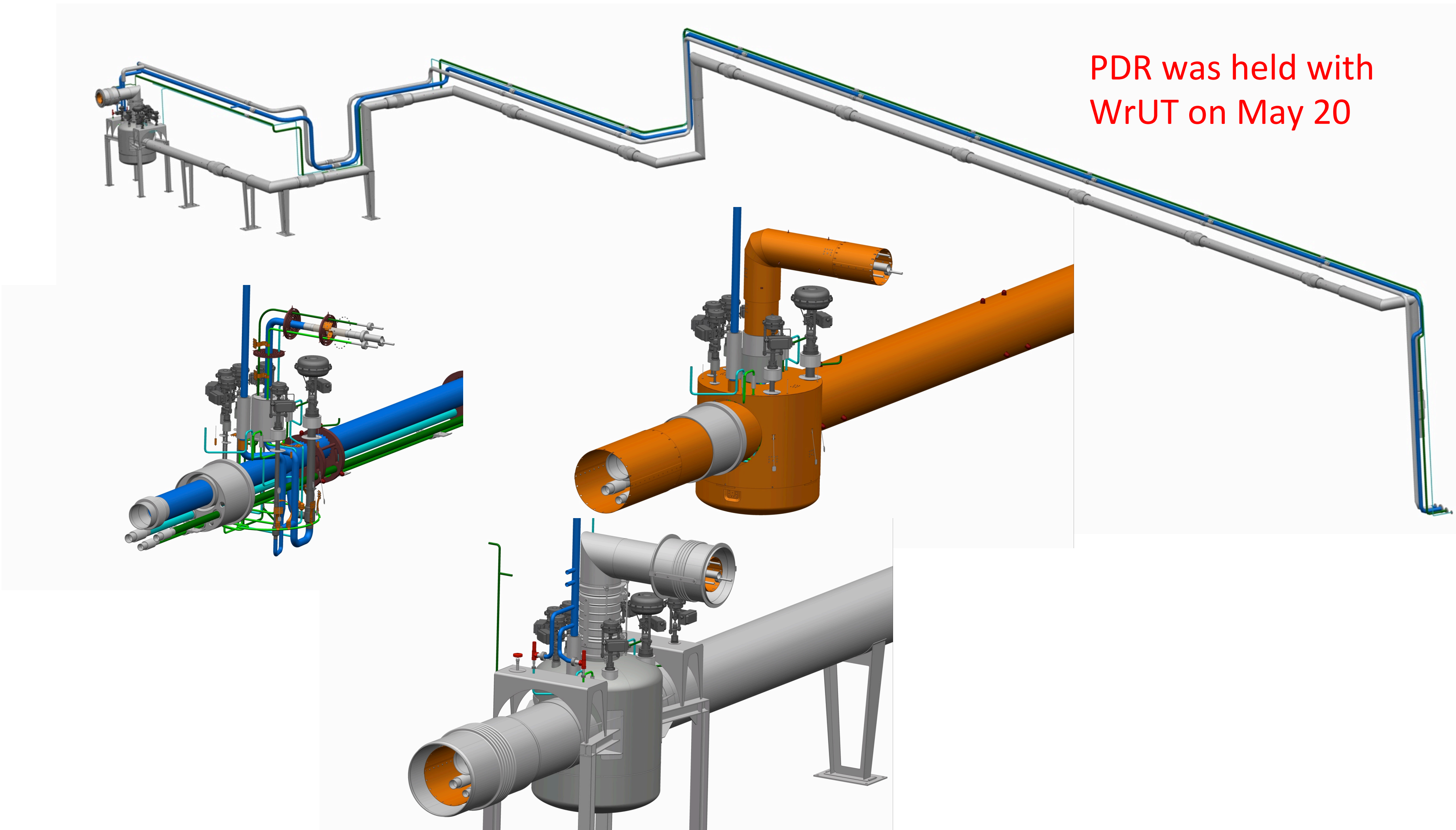
Cryogenic System of the Optimus Linac



Valve box – vacuum jacket



CDS – In kind Agreements with IPNO and WrUT

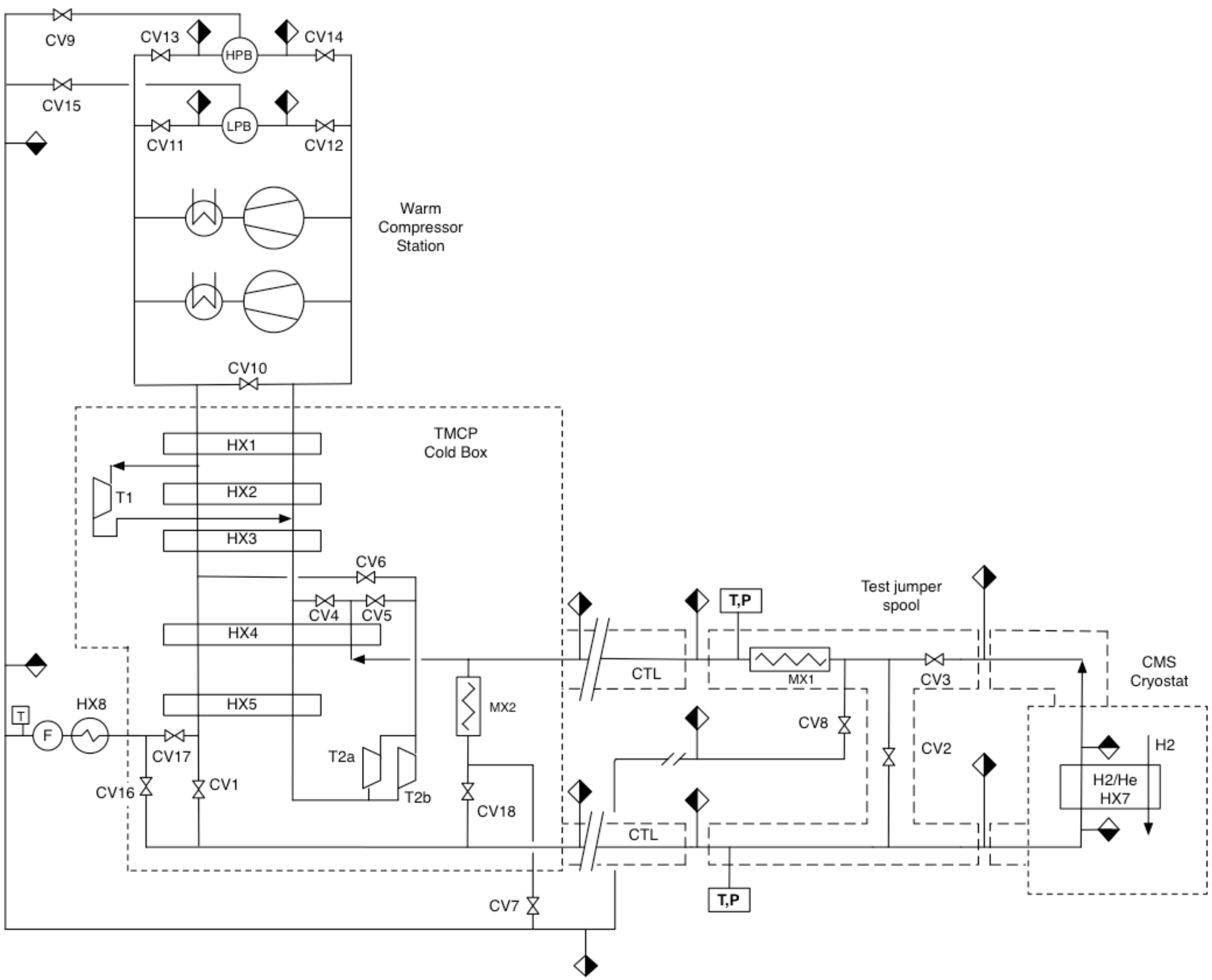


PDR was held with WrUT on May 20

Target Moderator Cryoplant – Substantial Load Increase

- Heat Load at 15 K increased from 20 kW to 30.3 kW due to moderator re-design (higher brightness, more neutrons)
- Impact on space requirements, utilities, interference with other cryoplants and budget (minimal impact on schedule) – technical solutions are currently worked out
- Tight collaboration with FZ Jülich, TU-Dresden and Hans Quack
- Plant will likely be ordered in Q4 2015 /Q1 2015
- Request for Proposals was released just this week.

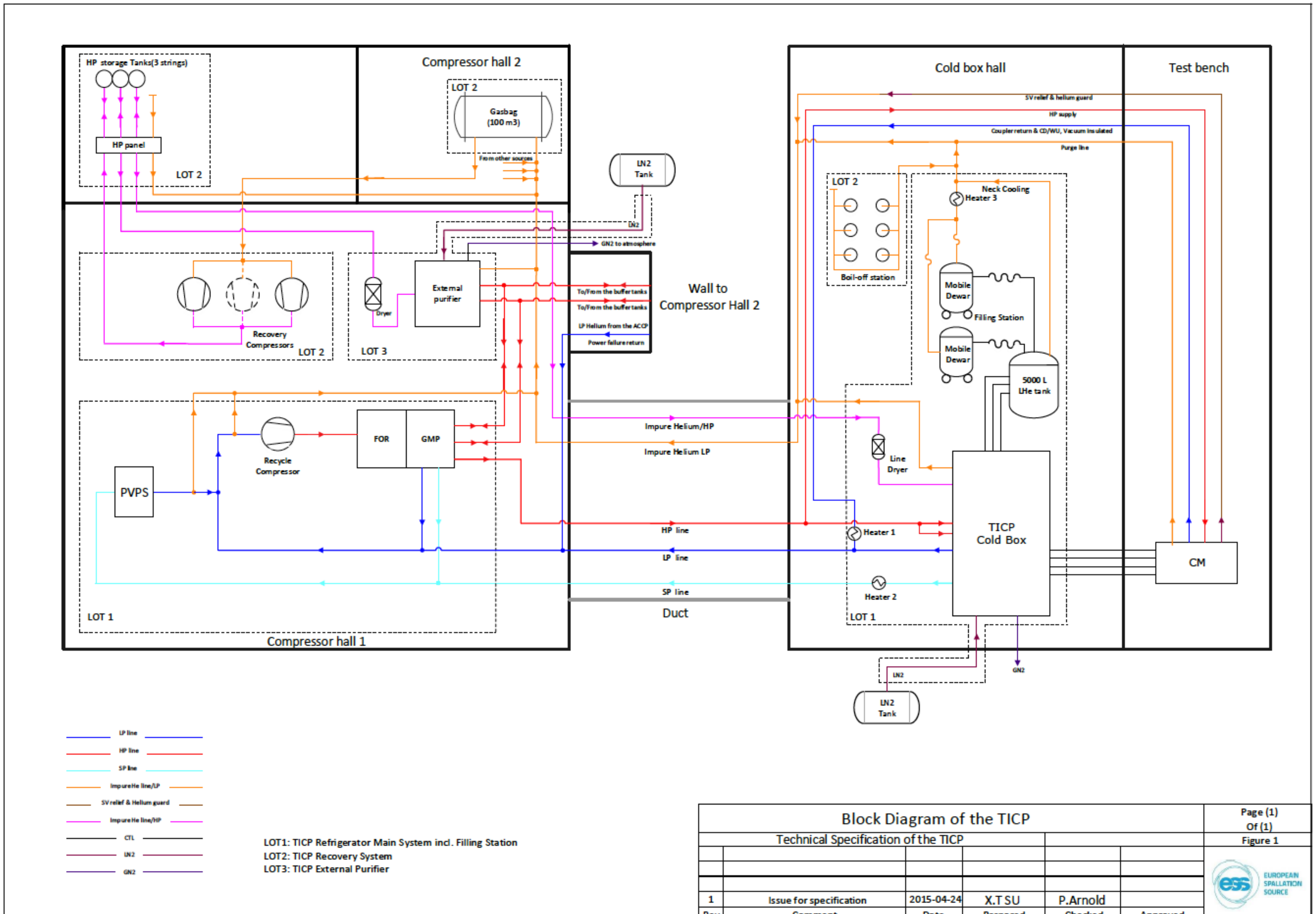
Target Moderator Cryoplant



Test & Instruments Cryoplant (TICP)

- Provides cooling for Cryomodule Test Stand
- During Science Operations, also provides LHe for sample environments and Science Instruments
- TICP provides for CM testing: 76 W at 2 K, 422 W at 40 K and 0.2 g/s of liquid helium
- Sub-atmospheric operation via warm vacuum pumps
- During Science Operations, the TICP shall provide more than 7500 liters of LHe per month
- A recovery system is being built to recover all He gas from instrument halls and return it for purification and liquefaction.
- We expect to order this plant in Q4 2015

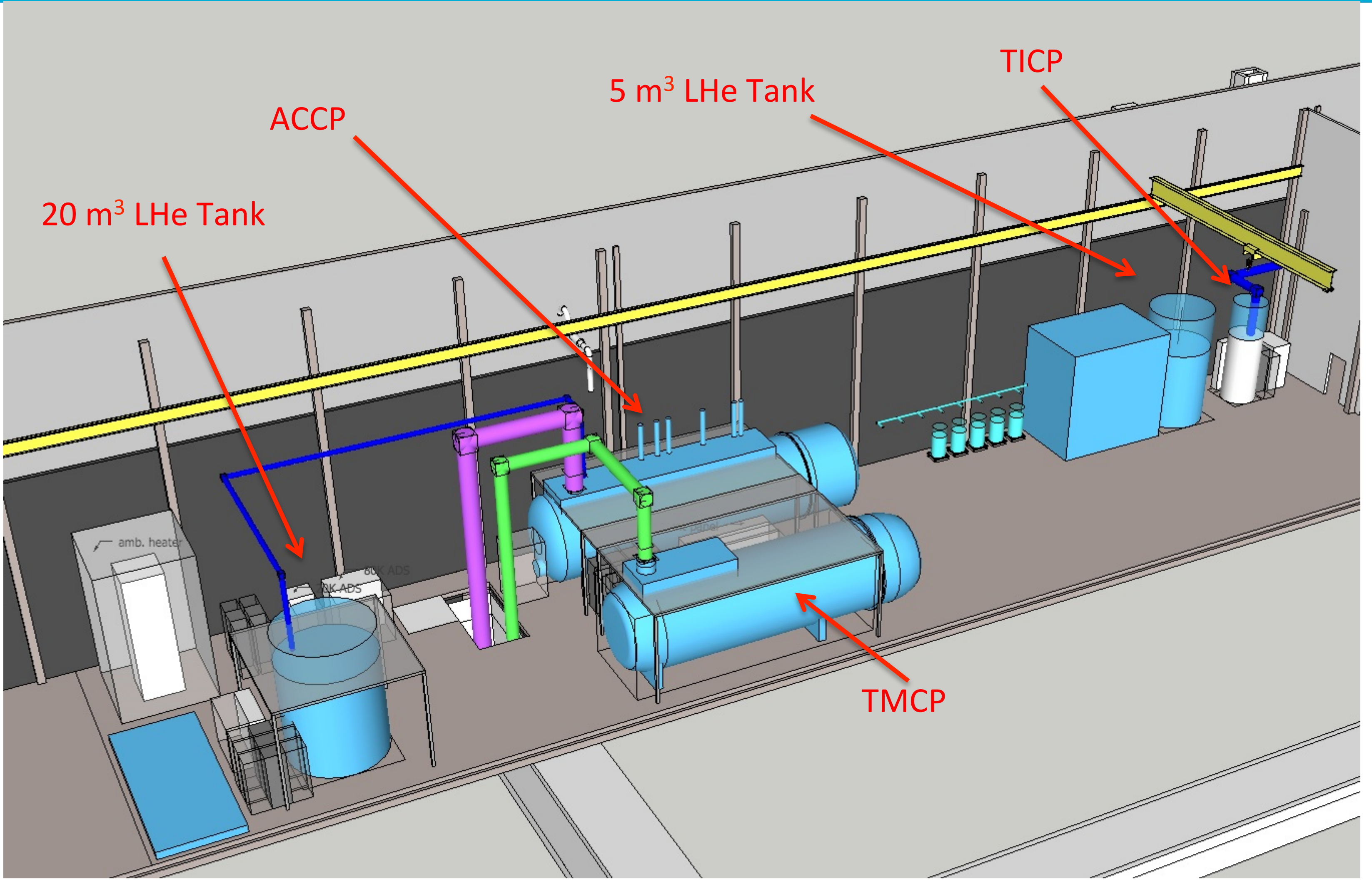
Test & Instruments Cryoplant (TICP)



Helium Recovery and Storage

- The ESS goal is to recovery, purify and reuse as much He as possible
- ACCP and TICP cryoplants will share a common gas system while TMCP has separate storage that can be cross connected
- The system will include a separate cryogenic purifier
- Systems will be provided by IKC or separate contracts
- Expected He Storage Capacities:
  - LHe
    - 20 m^3 (Includes storage for second fill of linac)
    - 5 m^3 (Backup for Instruments He)
  - GHe (20 Bar)
    - 1000 m^3 - sufficient to hold all the linac inventory
  - GHe (200 Bar)
    - 12 m^3 - Instrument He storage

Plant arrangement in the Cold Box Building



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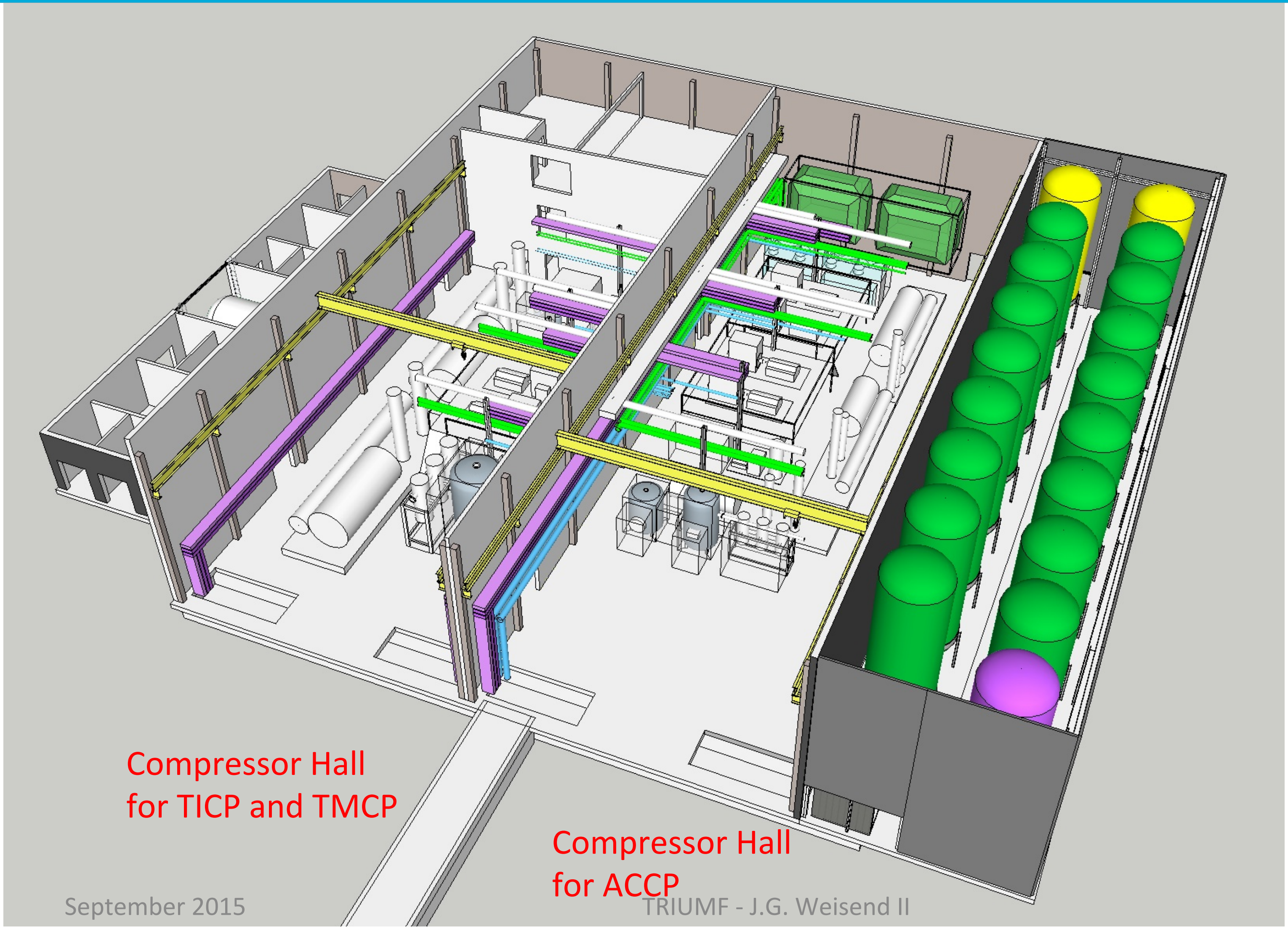
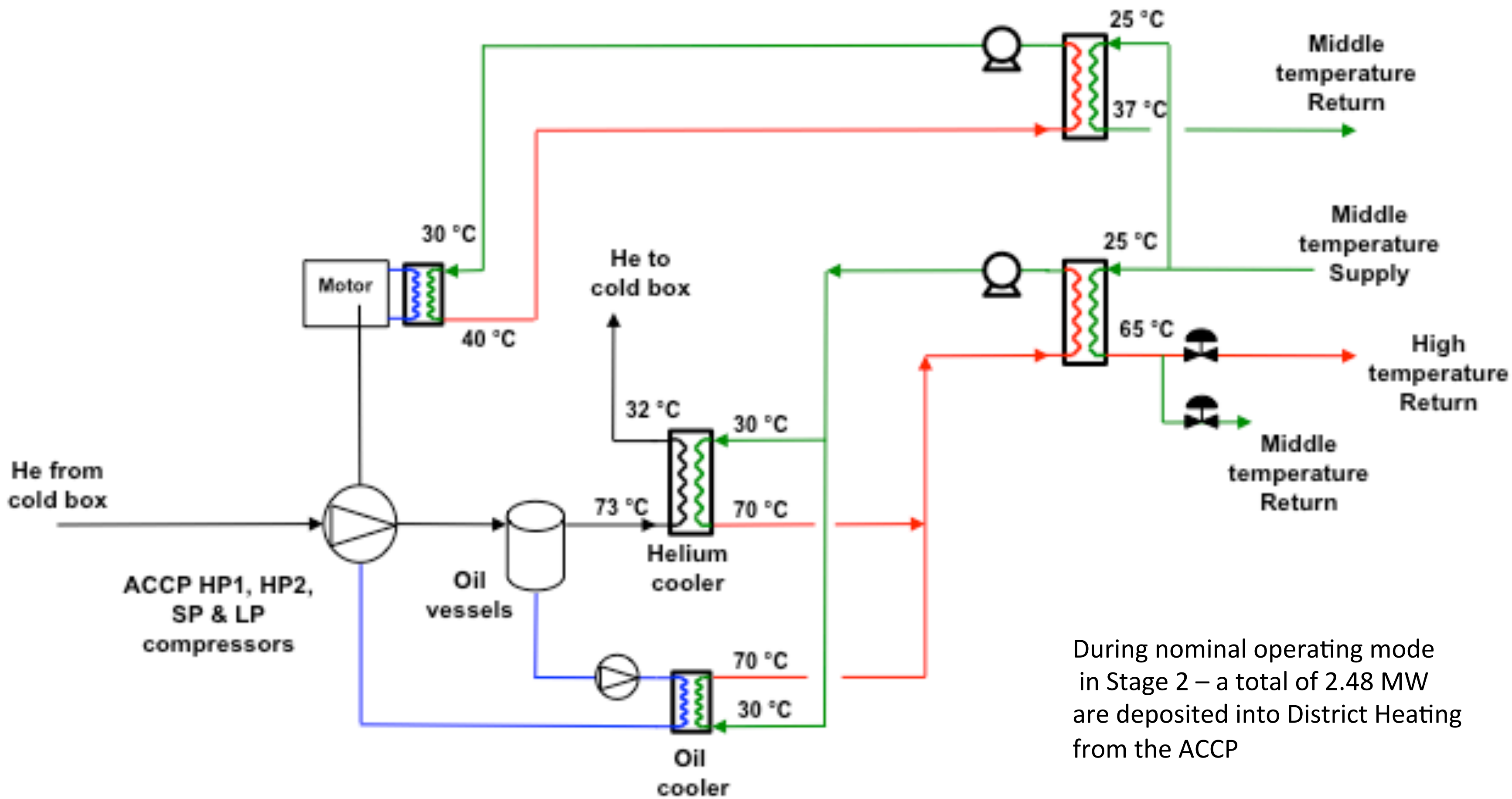
Plant arrangement in the Compressor Building



Compressor Building Foundation Work on Site Started in August 2015

Energy Recovery from ACCP Compressors



During nominal operating mode in Stage 2 – a total of 2.48 MW are deposited into District Heating from the ACCP

Summary

- Cryogenics will play a major role in ESS and affects the accelerator, target and instruments projects
- Work is well underway
  - A very skilled team has been assembled
  - Conceptual designs and technical specifications are complete or under preparation
  - Required buildings and utilities have been defined and are under detailed design
  - Accelerator Cryoplant order has been placed (Kick off meeting was held on May 8)
  - PDR for the WrUT portion of the CDS was held on May 2015
  - Additional cryoplant orders will be placed in Early 2016

Back Up Slides

Thermal Conductivity Integrals

- The strong temperature dependence of K makes heat transfer calculations difficult
- The solution is frequently to use thermal conductivity integrals
- The heat conduction equation

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

Is written as:

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

Thermal Conductivity Integrals

- G is the geometry factor

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

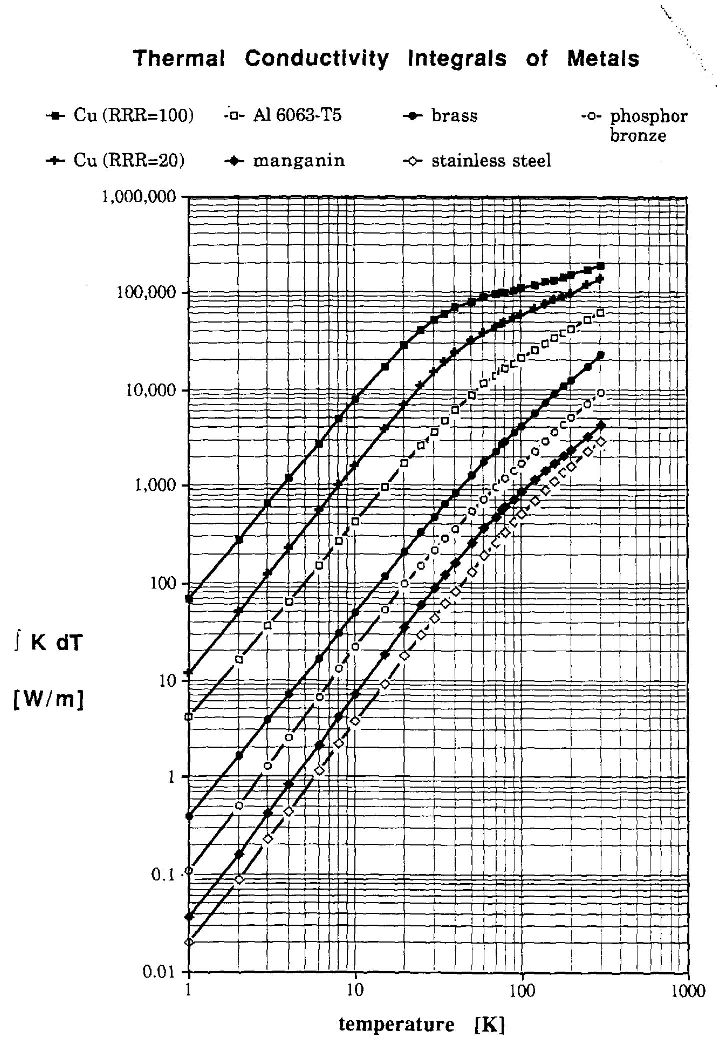
- θ is the thermal conductivity integral

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

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 of Metals



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

Thermal Conductivity Integrals of Metals & Nonmetals