



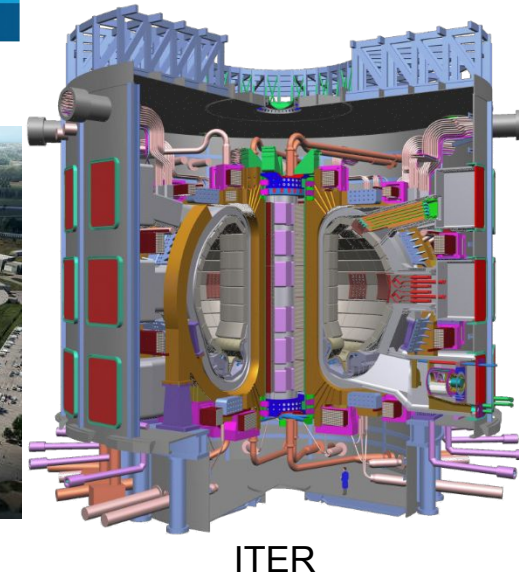
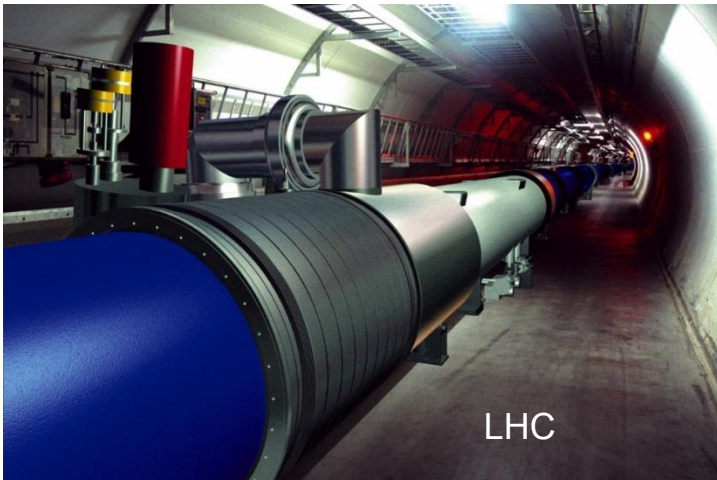
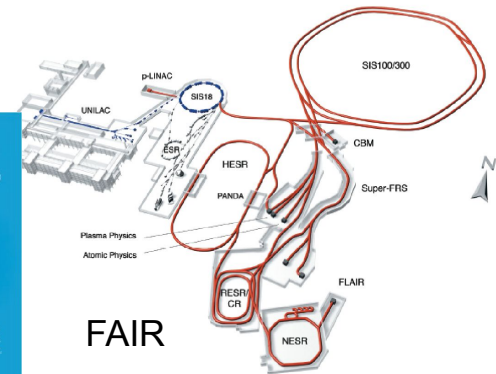
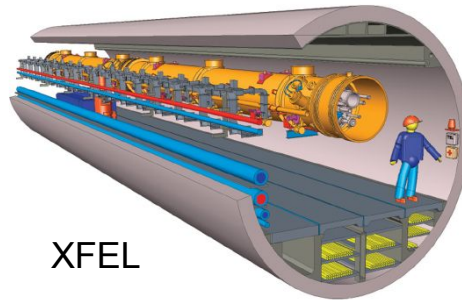
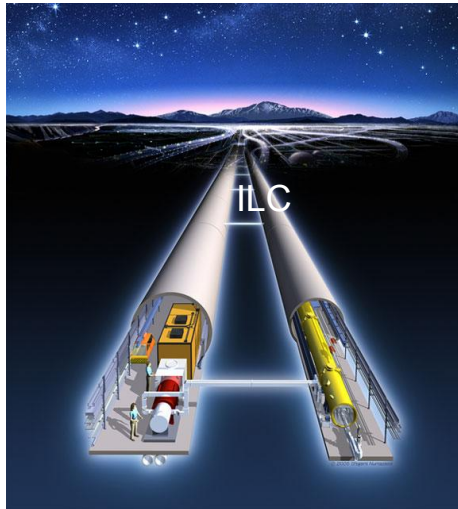
Wrocław University of Science and Technology

Development, design and construction of cryogenic distribution systems for FAIR accelerators

Jaroslav Polinski, Maciej Chorowski.

WUST, Wrocław, Poland

Helium cryogenics is a must in „Big Science”

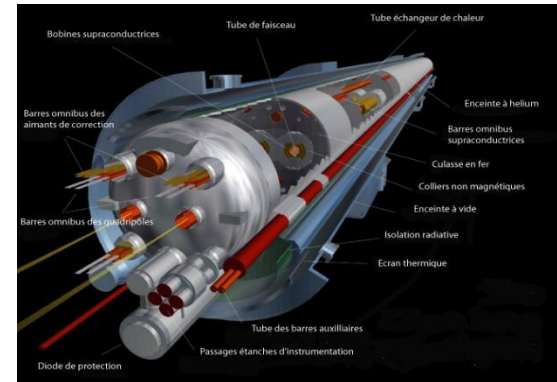
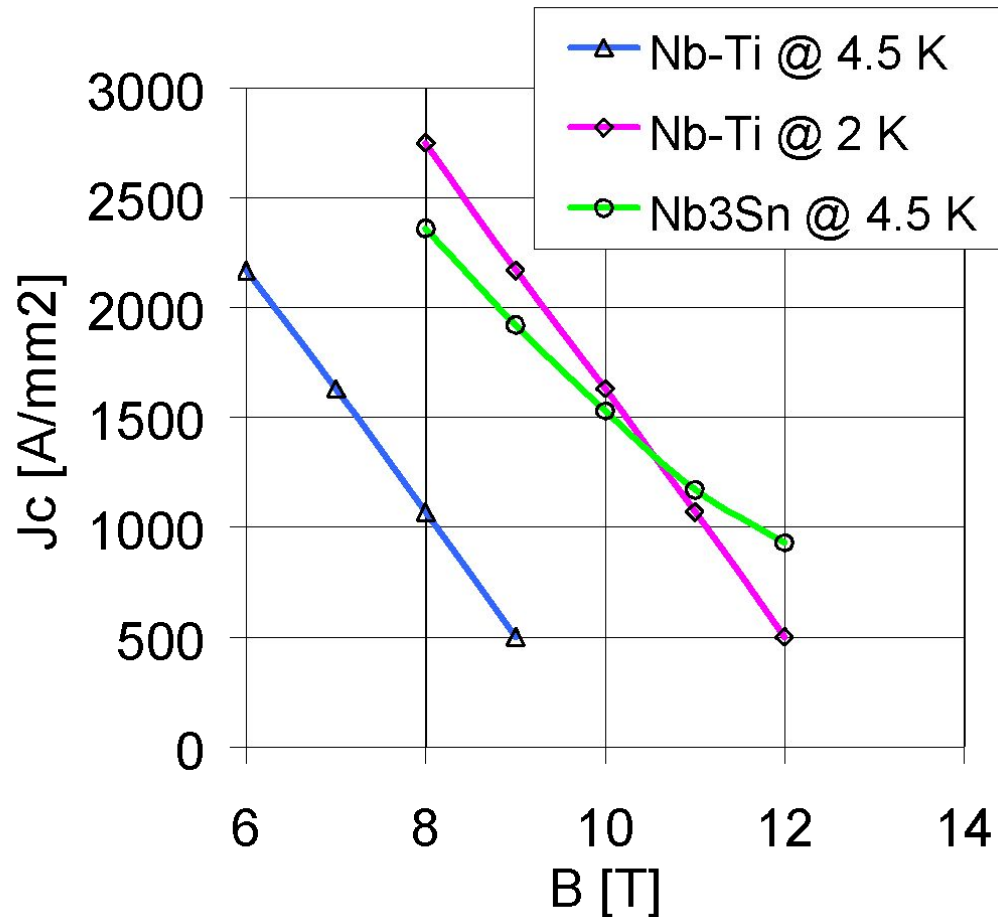


Helium cryogenics and inventory in chosen projects

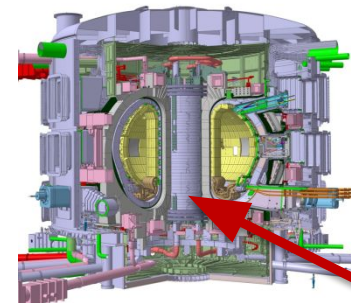
Installation, location, status	Type	Helium inventory
LHC, CERN, Geneva, under operation	pp collider	136 ton
FAIR, GSI, Darmstadt, early stage of construction	ions accelerator	11 ton
XFEL, DESY, Hamburg, advanced stage of construction	free electron laser	5 ton
W7-X, Max Planck Greifswald, commissioned in May 2014	fusion stellarator	2 ton
ITER, Cadarache, advanced stage of construction	fusion tokamak	24 ton
ILC International Linear Collider, conceptual design (Japan?)	e+ e- lin. Collider	100 ton
FCC Future Circular Collider, first idea proposed (CERN?)	pp collider	500 ton

Why Helium and Helium II (superfluid) Cryogenics ?

Critical current density of superconductors



LHC NbTi magnets are cryostated with pressurized IIHe @ 1,8 K



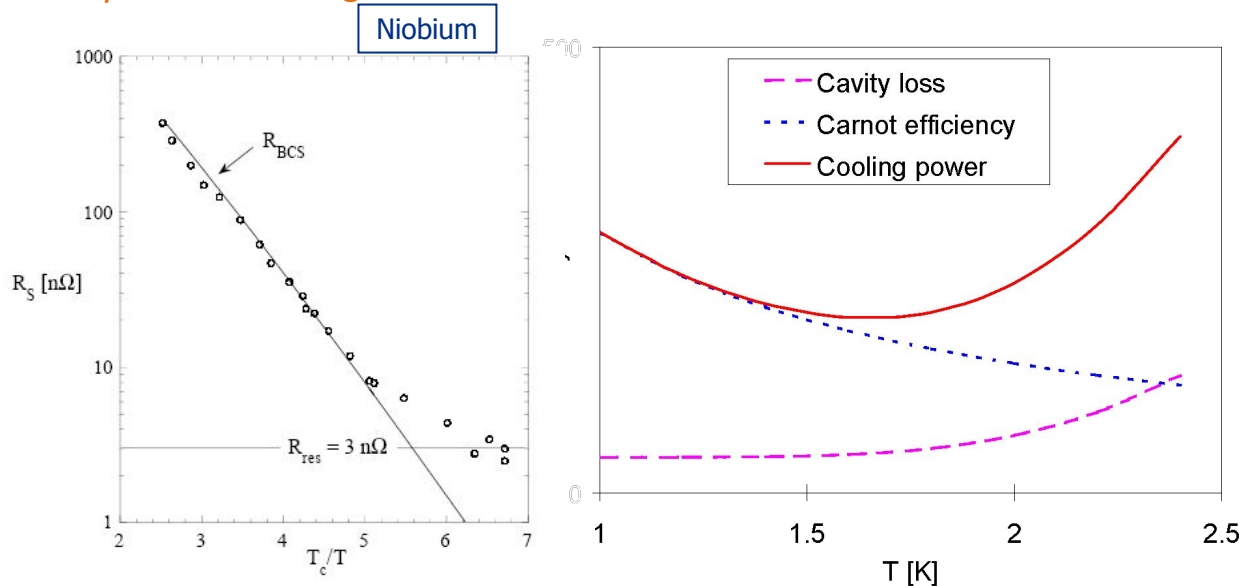
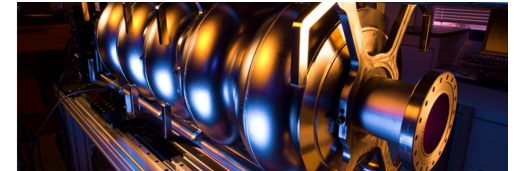
ITER Nb3Sn central solenoid is cryostated with supercritical He @ 4,5 K



Why Helium and Helium II (superfluid) Cryogenics ? Optimization of operating temperature for superconducting RF cavity

- BCS theory $R_{\text{BCS}} = (A \omega^2 / T) \exp (-B T_c / T)$
- For practical materials $R_s = R_{\text{BCS}} + R_0$
- Refrigeration (Carnot) $P_a = P (T_a / T - 1)$

⇒ depending upon ω and R_0 , optimum operating temperature for superconducting cavities

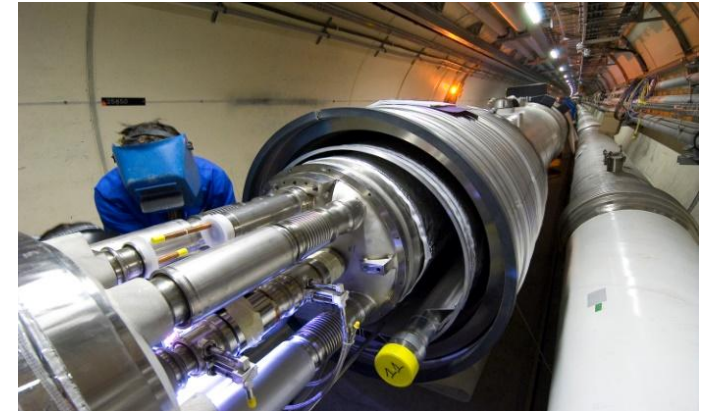
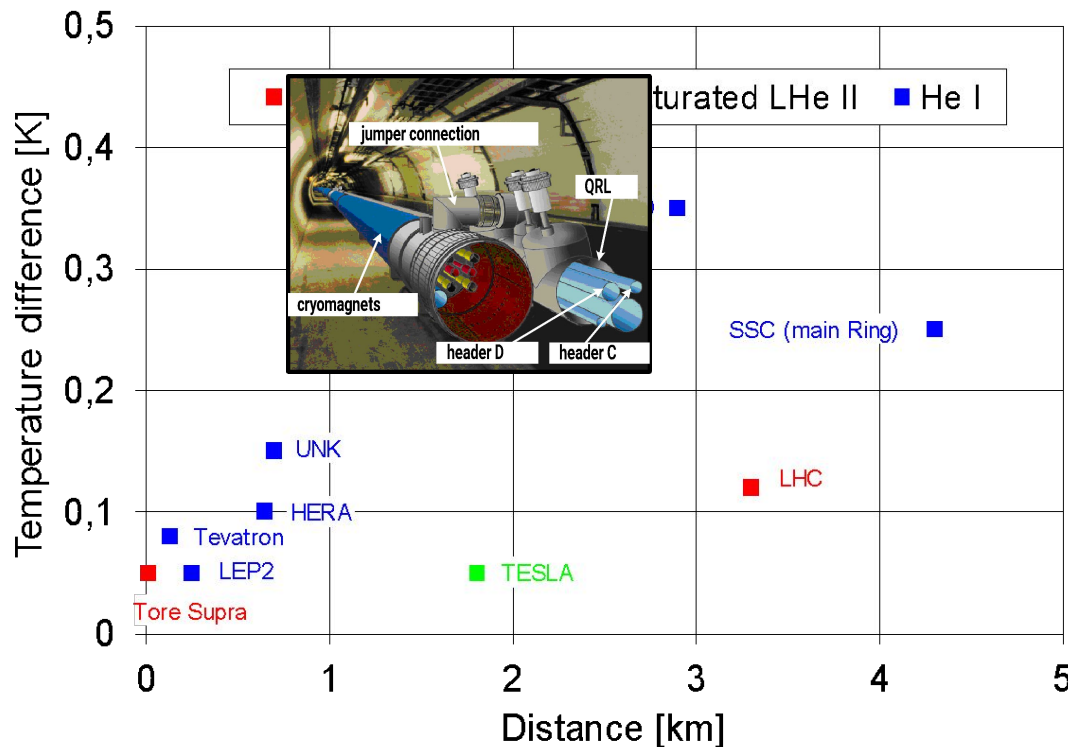


Optimal operation temperature for Nb superconducting RF cavity is below 2 K.

RF Cavities are cryostated with saturated II He



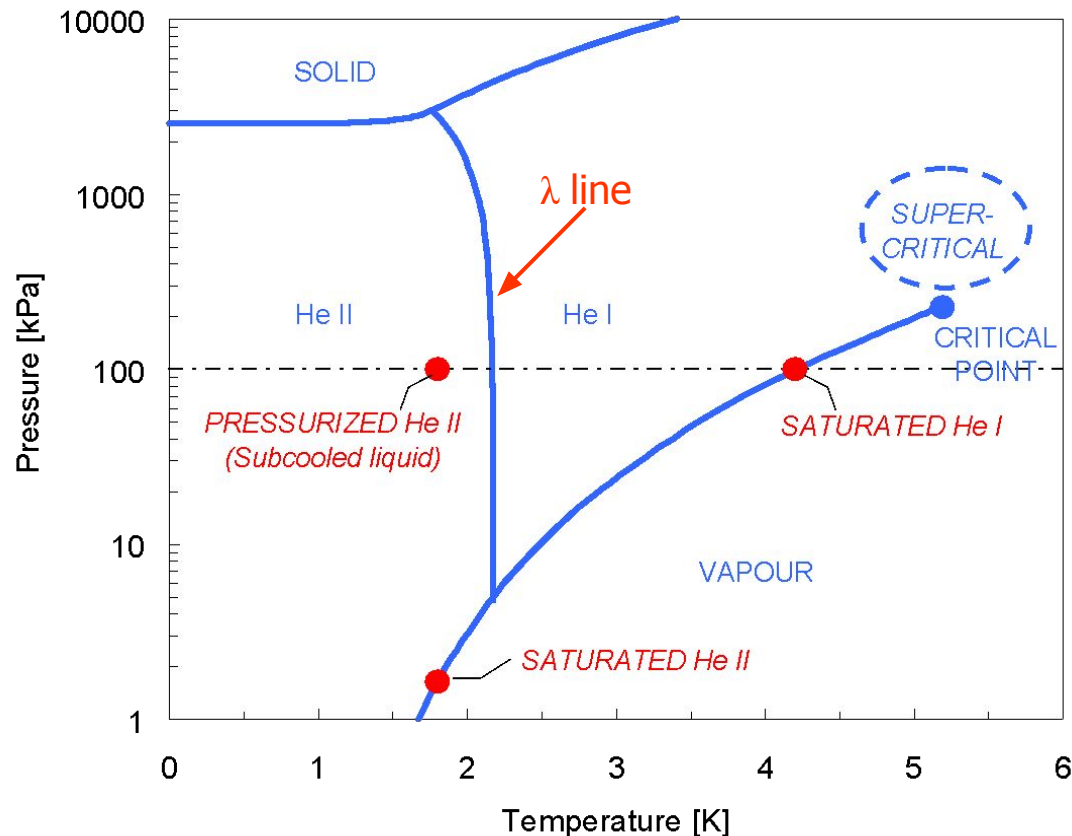
Why Supercritical Helium? Transport of refrigeration in large distributed cryogenic systems



To avoid two-phase flow helium is transported in supercritical state at the distance up to 3.3 km (LHC sector length)



Phase diagram of helium



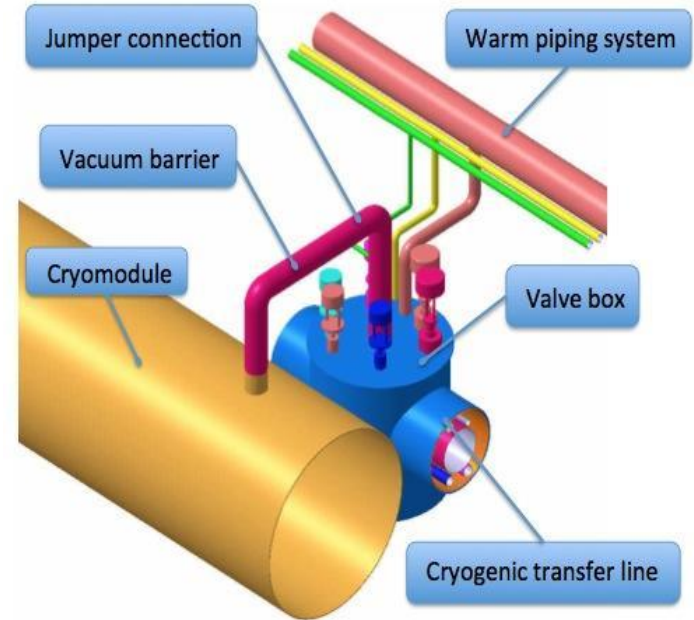
„Big Science” cryogenic systems make extensive use of practically all thermodynamic states of cold helium:

- Supercritical
- Saturated He I
- Saturated He II
- Pressurized He II
- Low pressure vapour



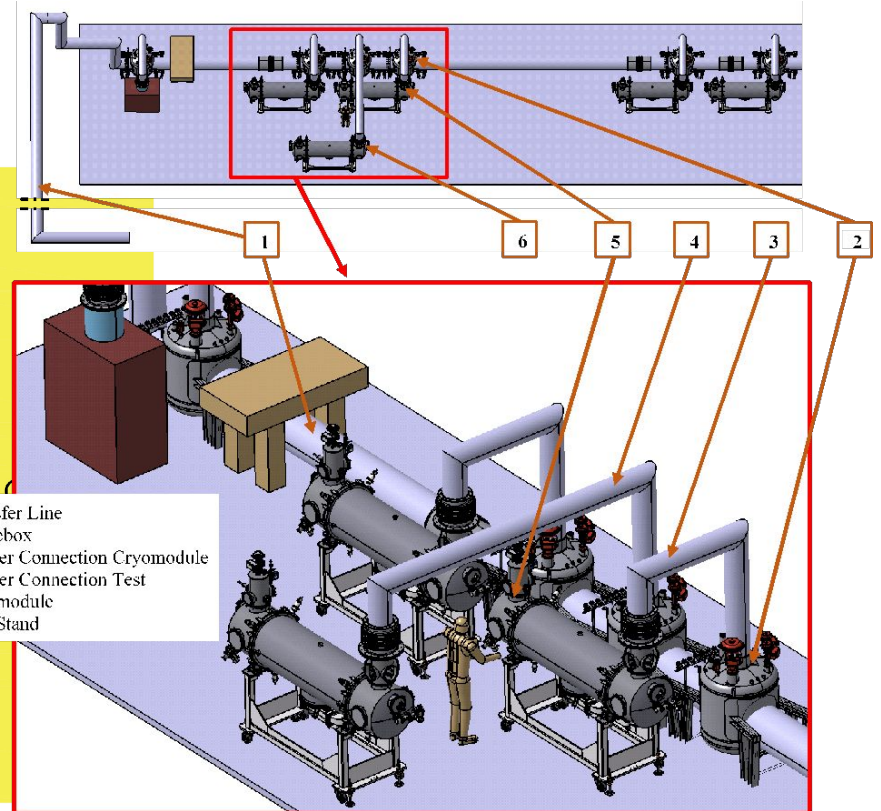
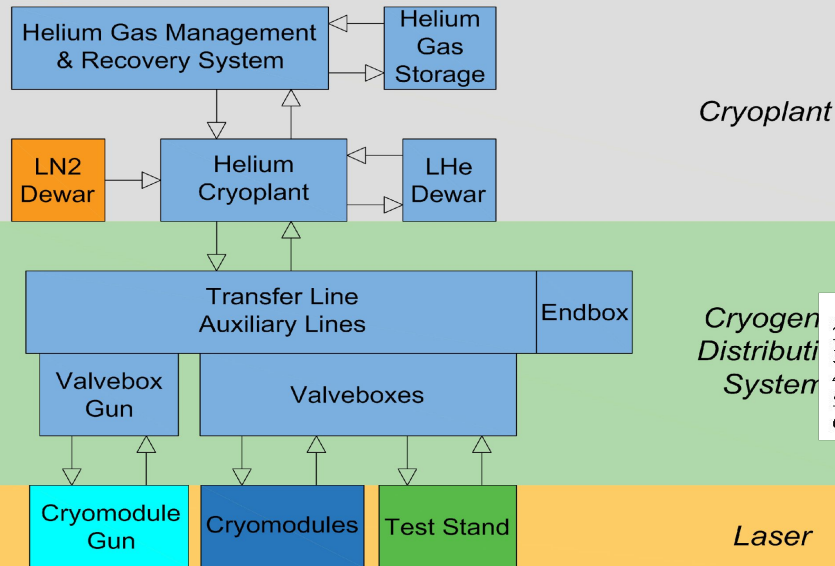
Cryogenic Distribution System CDS

- Connects a cryoplant with cryomodules, magnets, helium inventory tanks
- Transfers helium in both directions
- Allows cool down, cryostating, warm up a machine
- Guarantees safe operation in all operating modes (including failure modes)
- Main components of CDS are: transfer lines, valve boxes, jumper connections, warm piping systems



Exemplary Cryogenic Distribution System – POLFEL

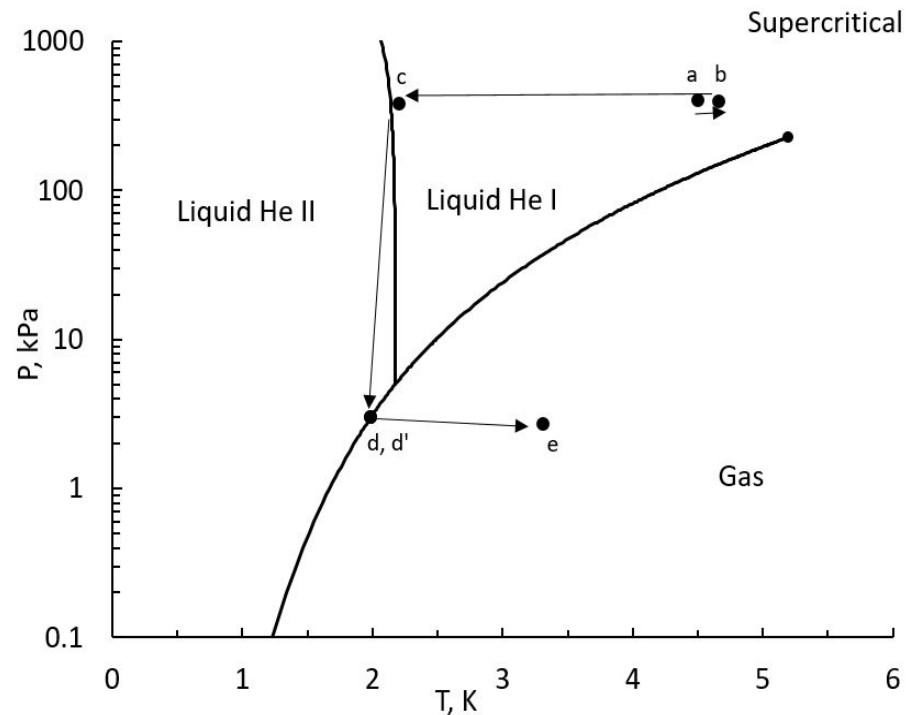
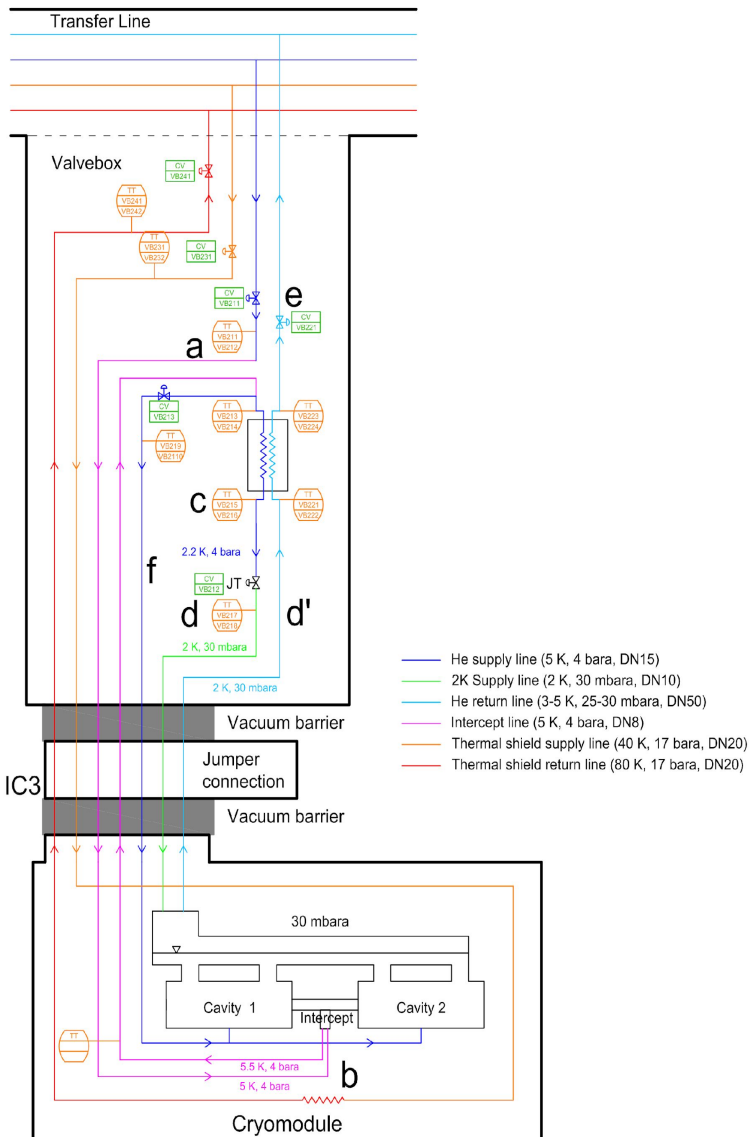
PolFEL (Polish Free Electron Laser) will be the first Free Electron Laser (FEL) facility operating in Poland and Eastern Europe.



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Flow scheme of POLFEL Valve Box with corresponding T-s diagram Take notice of thermodynamic processes occurring in Valve Box/Cryomodule

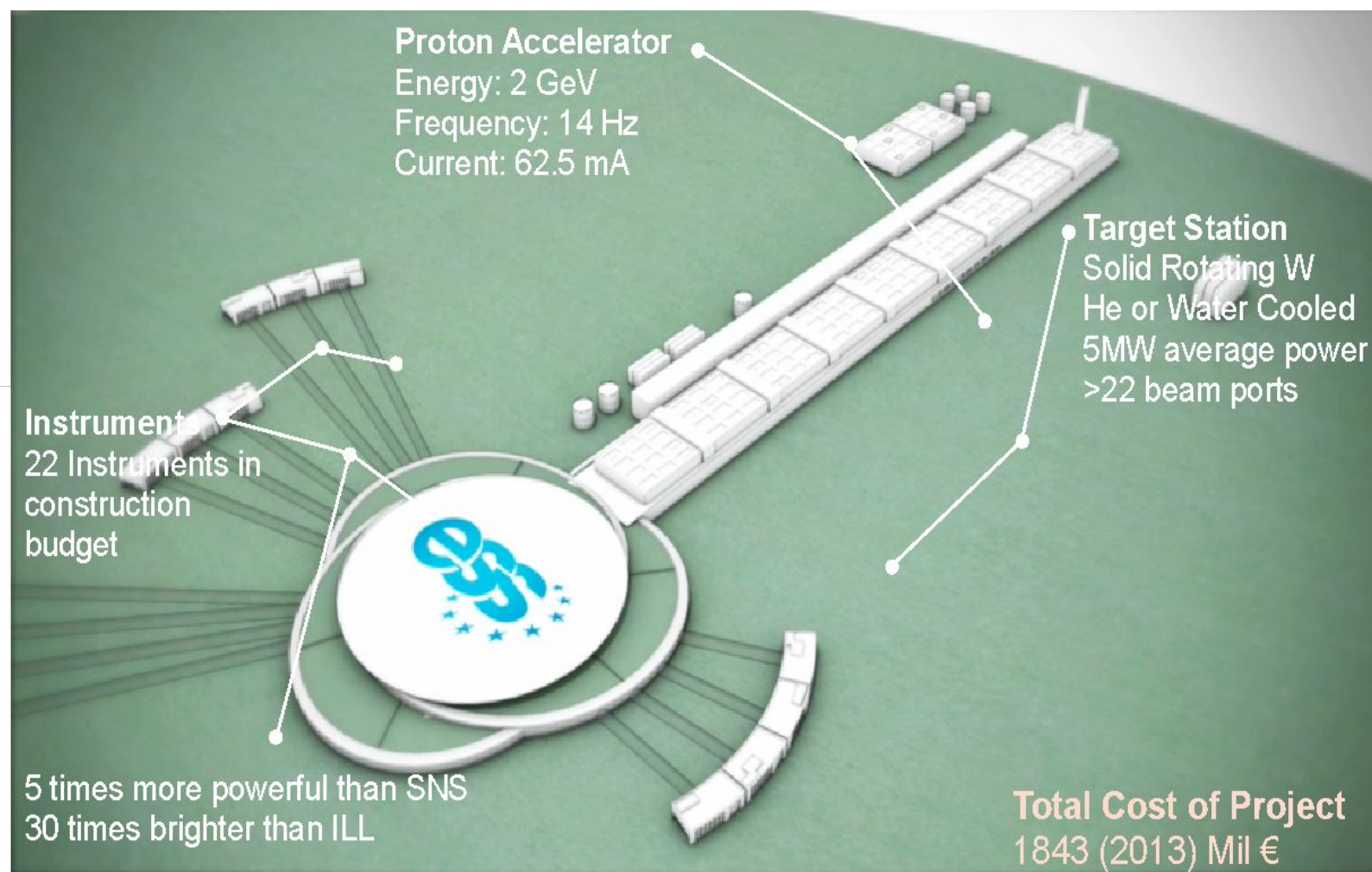




WUST participation in the Polish In-Kind contributions to the large scientific facilities

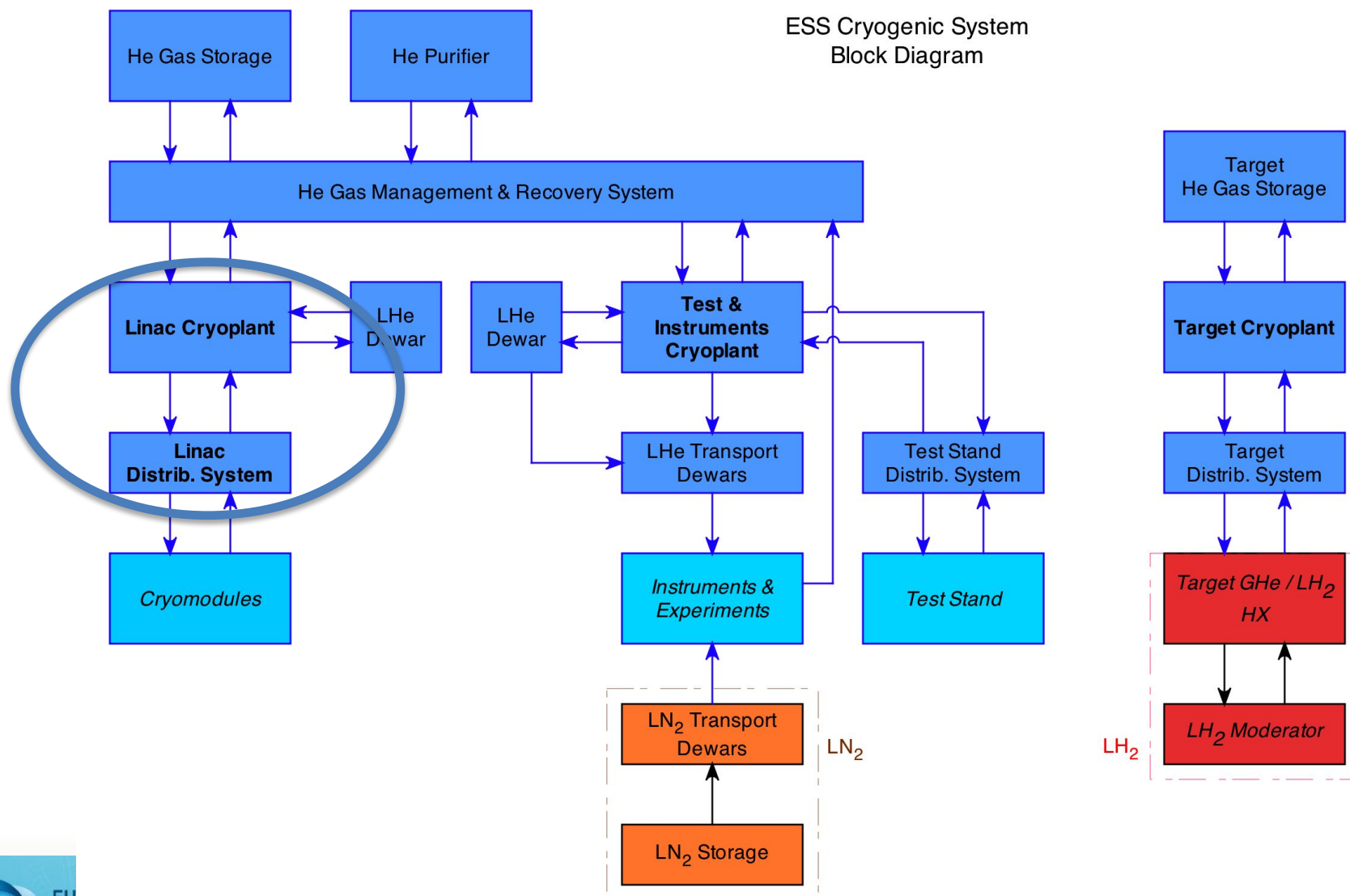
- **European Spallation Source (ESS, Lund, S)**
- **Facility for Antiproton and Ion Research - FAIR (GSI, Darmstadt, DE)**

European Spallation Source - ESS



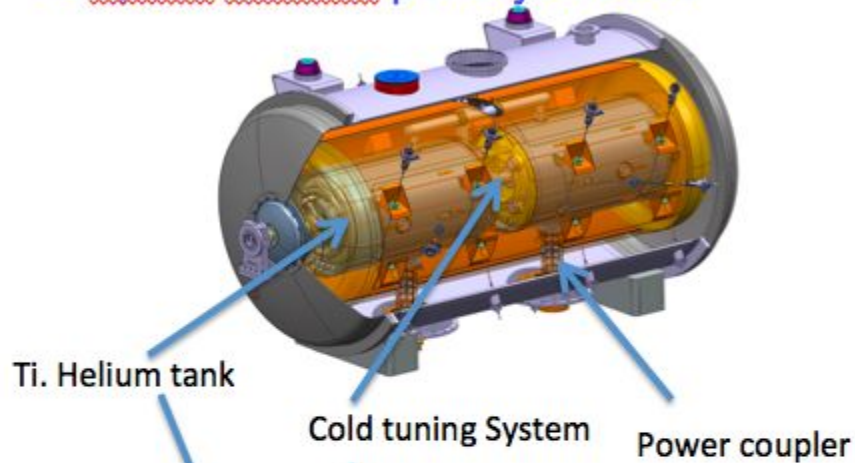
ESS Cryogenics System

ESS Cryogenic System
Block Diagram

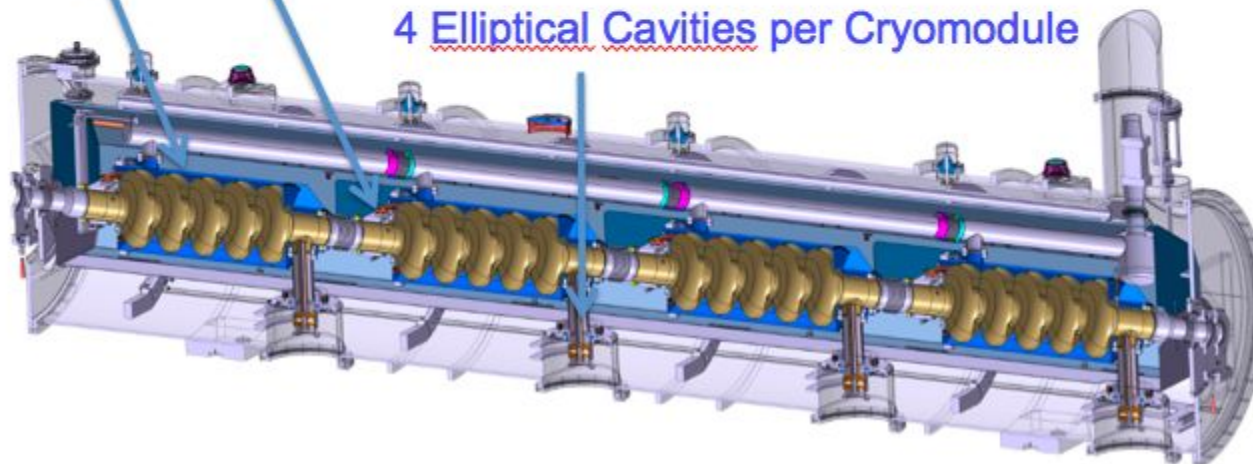


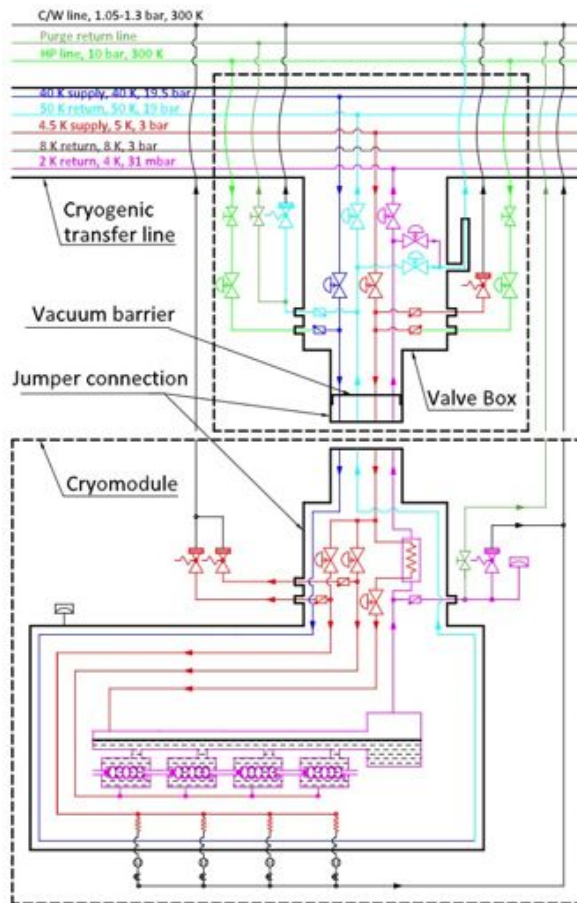
ESS Linac Cryomodules

2 Spoke Cavities per Cryomodule



4 Elliptical Cavities per Cryomodule

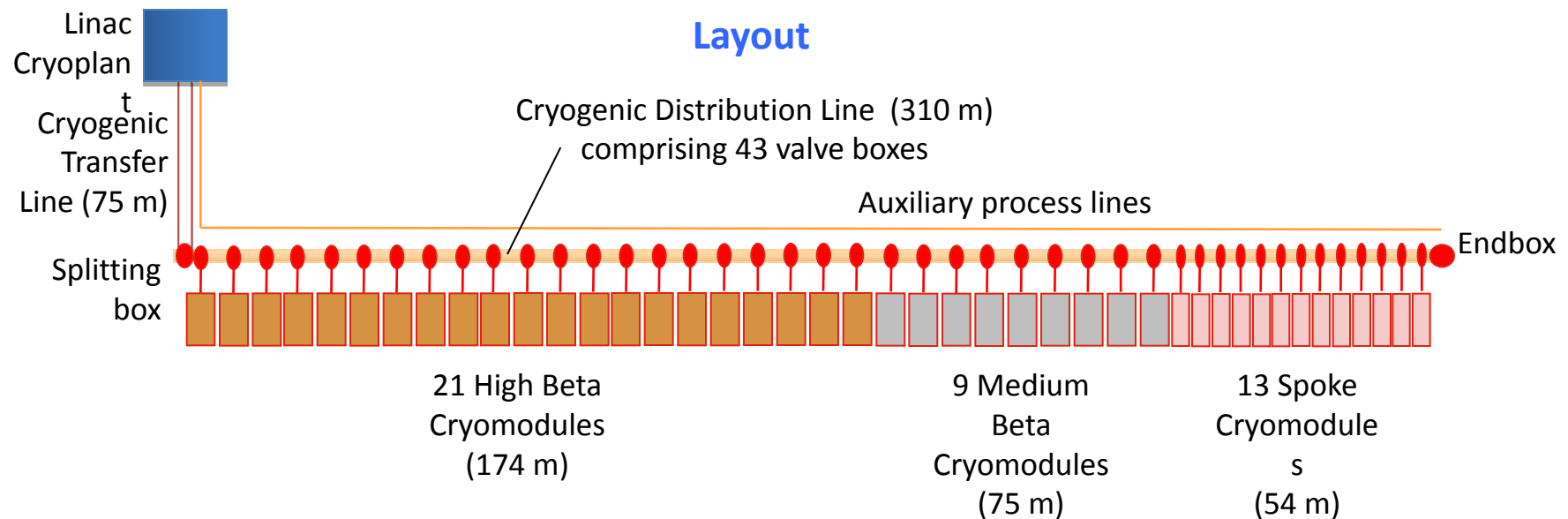




Accelerator Cryogenics

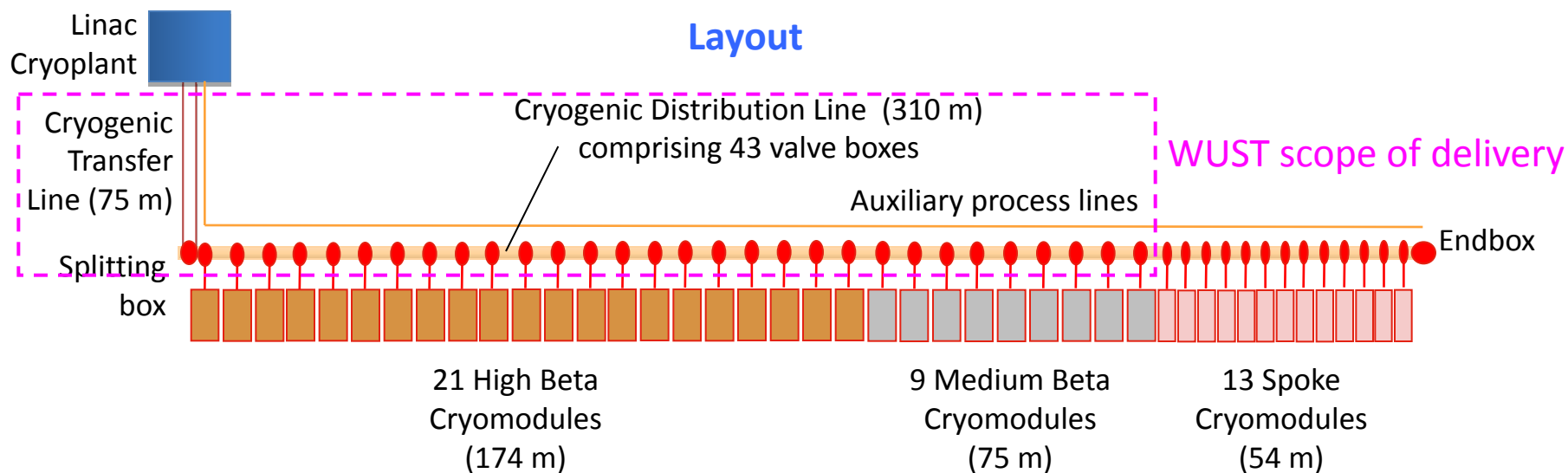
- Distribution system delivers single phase supercritical Helium at 4.5 K & 40 K
- 2 K helium produced at each cryomodule
- Sub atmospheric vapor pumped off to cryoplant
- 4.5 K – 300 K cooling of couplers

ESS Linac Cryogenic Distribution System



Cryogenic Distribution System for the ESS linear accelerator is intended for delivering the cooling power from the linac cryoplant to the cryomodules by means of the constant flows of supercritical and cold gaseous helium, at 4.5 K and 40 K, respectively.

ESS Linac Cryogenic Distribution System

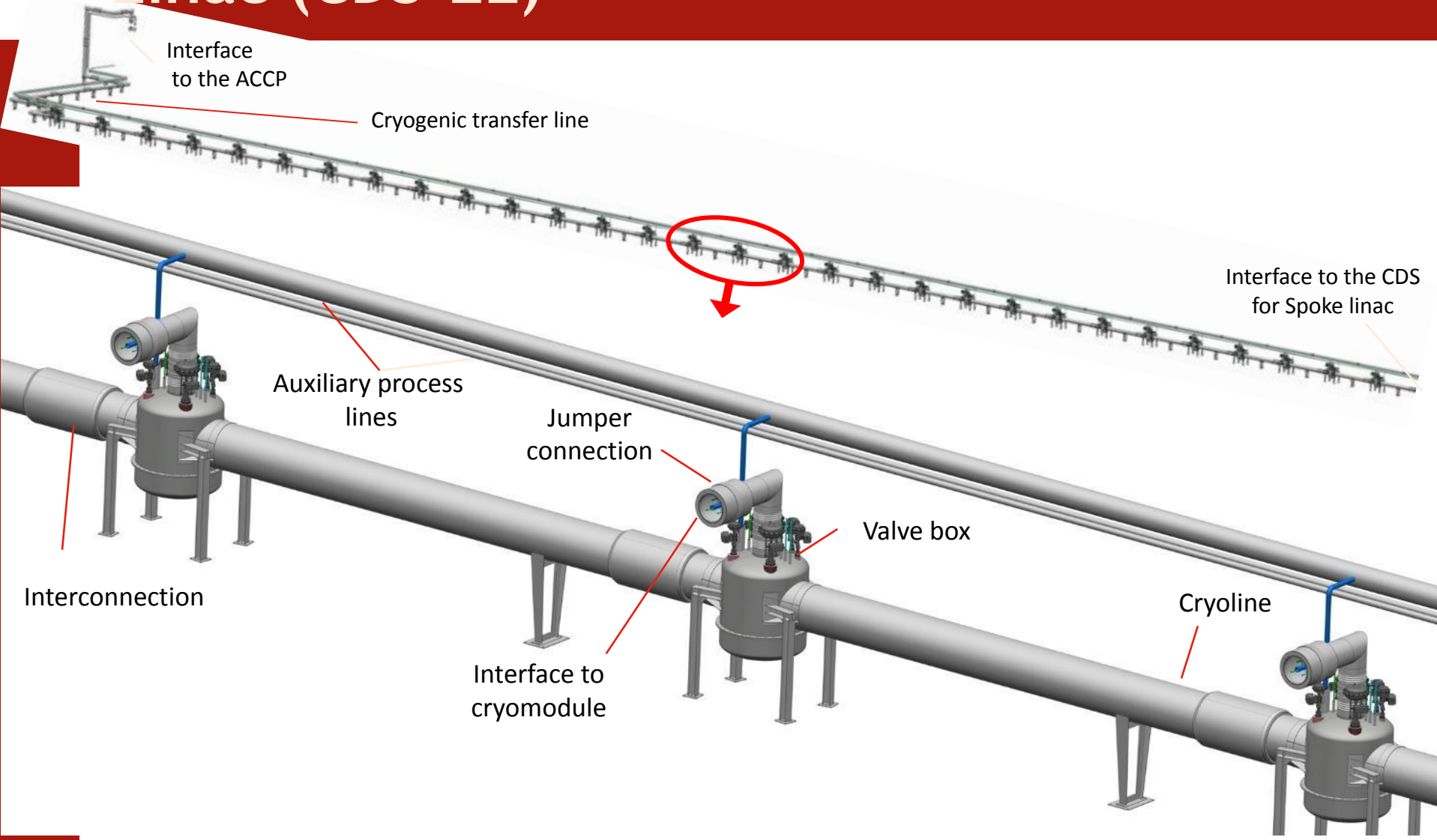


WUST scope of the delivery includes: design, production, installation and commissioning of CDS-EL, that comprises:

- 4 channel Cryogenic Transfer Line – 75 m
- Cryogenic Distribution Line for elliptical part of the ESS Linac, comprises 30 Valve boxes, total length 255 m
- 4 Auxiliary process lines



Cryogenic Distribution System for Elliptical Linac (CDS-EL)





ESS CDS production at Kriosystem LTd, PL



ESS Distribution Cryogenics System installed in the tunnel



Test stand allowing optimization of the main system

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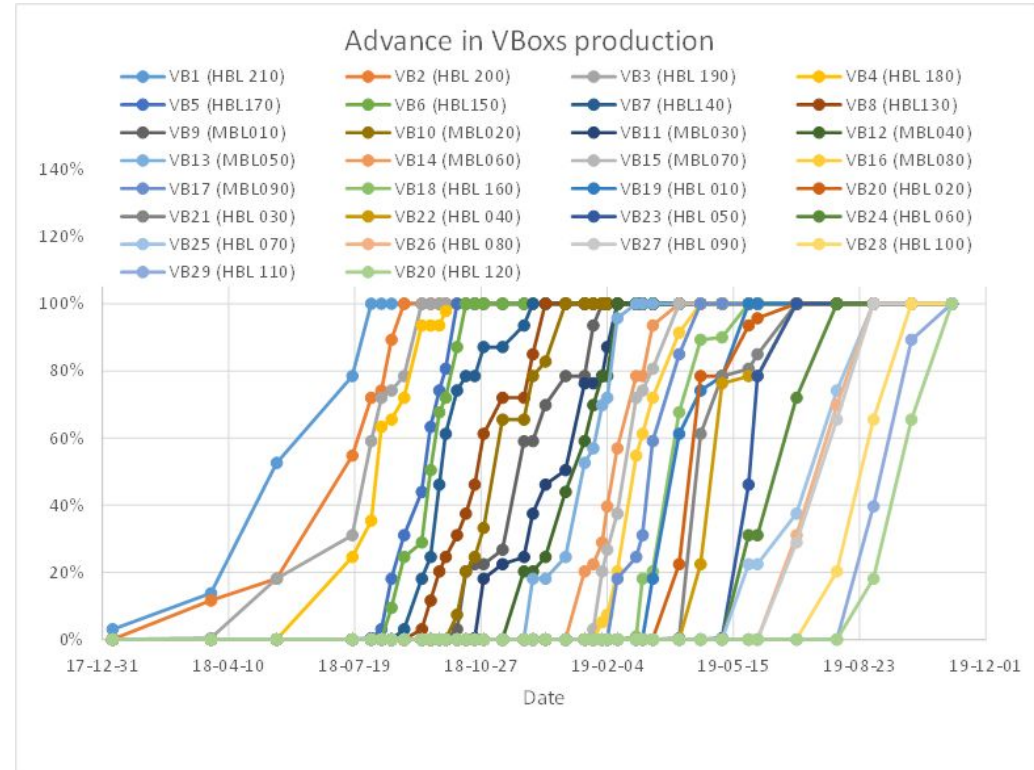


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Industrialization of the CDS valboxes production



The production rate accelerated from 6 monthes (first valve box) to three weeks (average)



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Challenges in design, construction and operation of CDS

- Mechanical design compromising allowable heat balance with mechanical stability
- Risk analysis and coping with failure modes
- Industrialization of the production, CDS is the first system installed in the tunnel
- Vacuum sectorization
- Control systems
- And many others

Cryogenic Distribution System – definitely not „Just Piping”

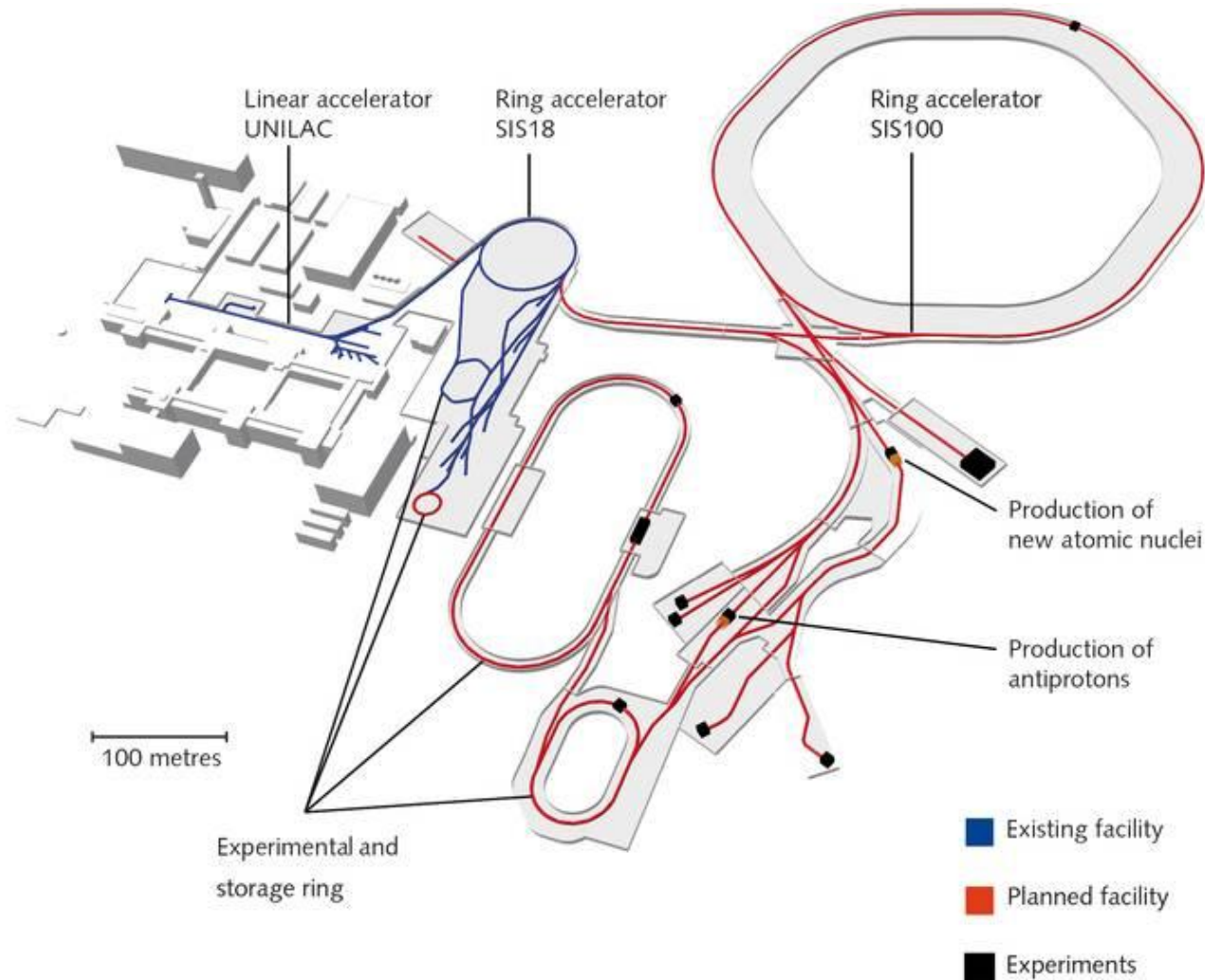


WUST participation in the Polish In-Kind contributions to the large scientific facilities

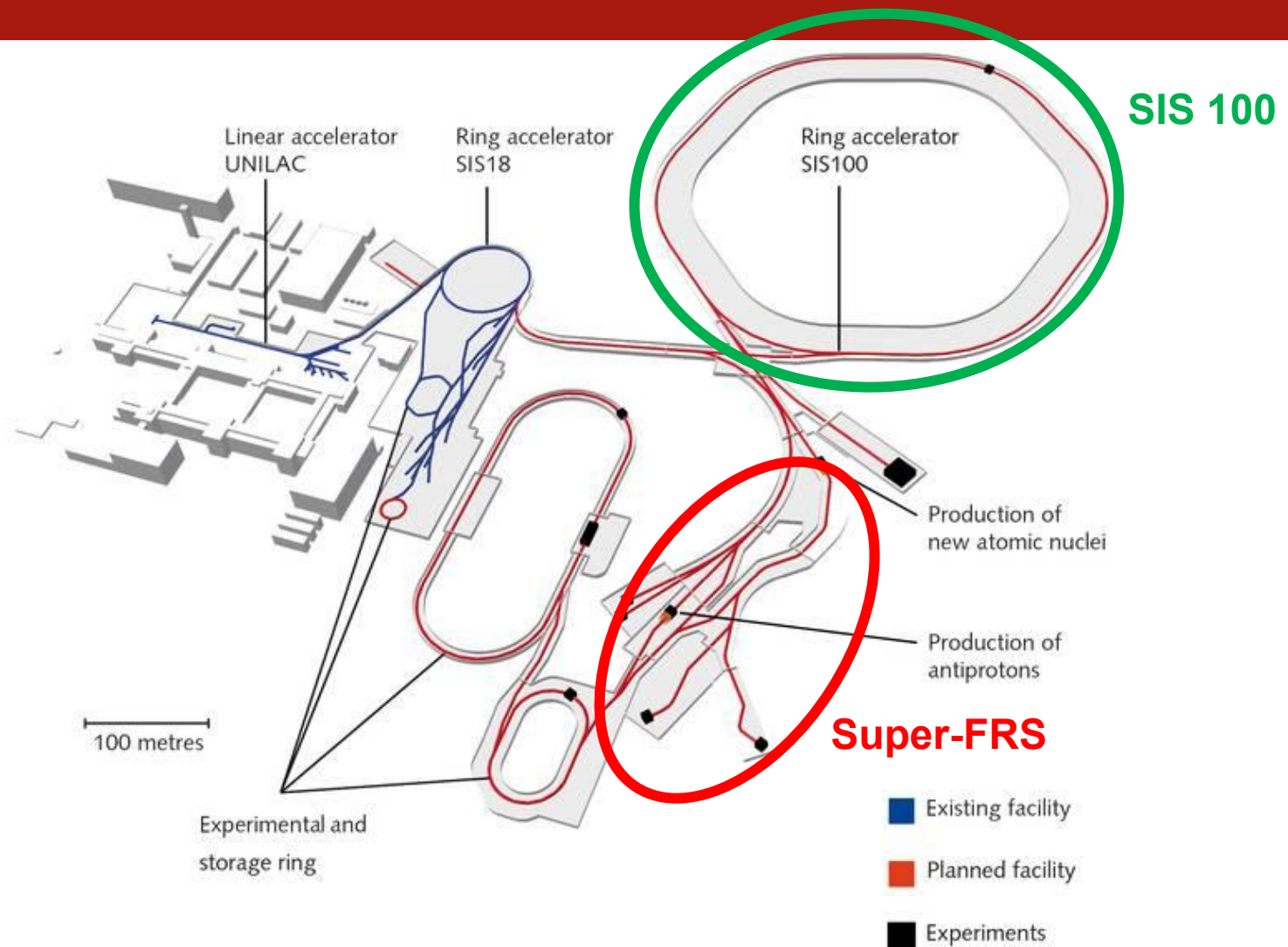
European Spallation Source (ESS, Lund, S)

- Facility for Antiproton and Ion Research - **FAIR** (GSI, Darmstadt, DE)

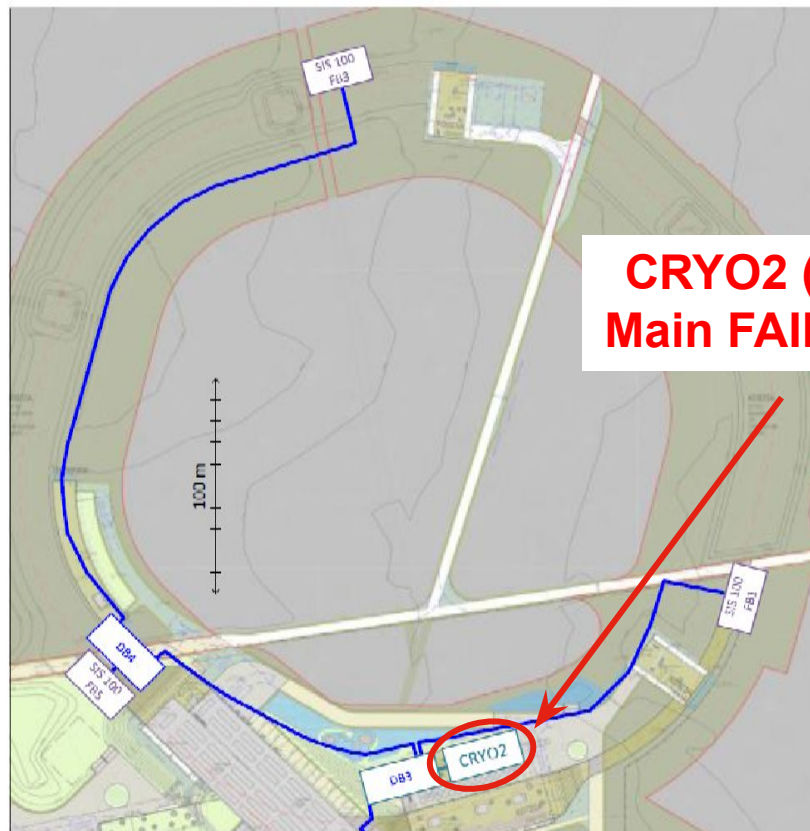
Outline of the FAIR accelerator complex



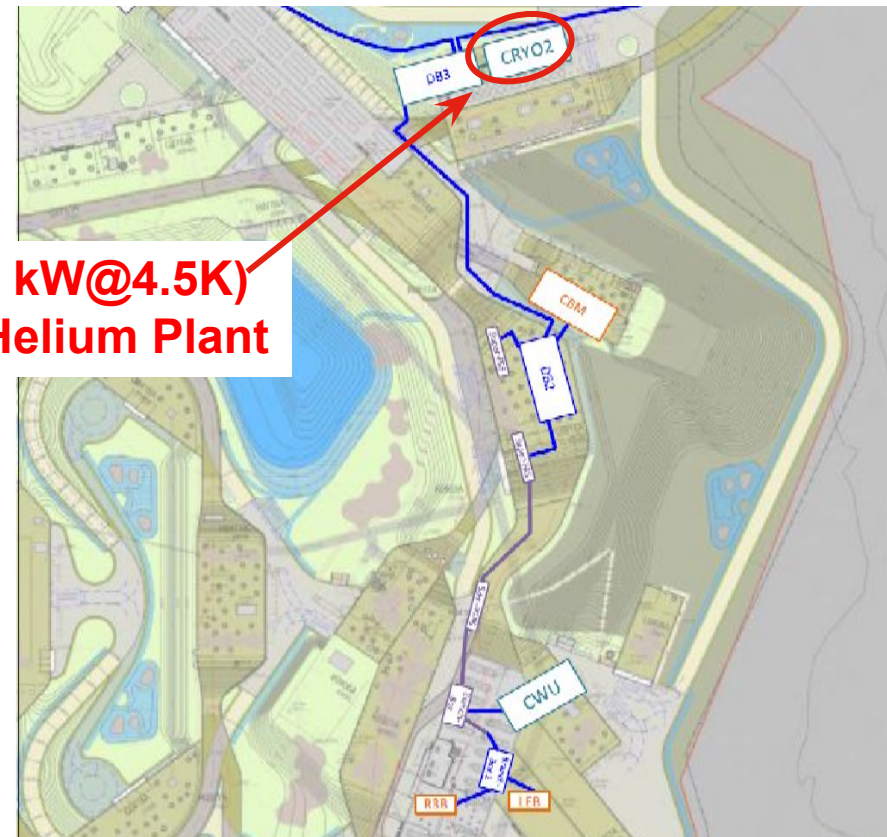
Outline of the FAIR accelerator complex



FAIR Cryogenic System layout



Cryo System for SIS100



Cryo System for Super-FRS

Challenges in design, construction and operation of cryogenic system for superconducting accelerators

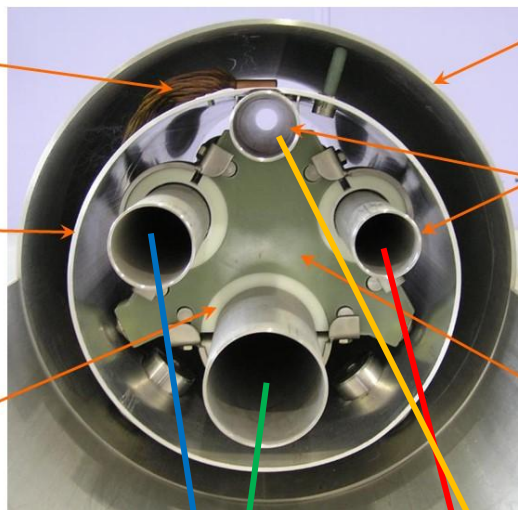
- Shall allow for the safe, stable, and robust cryogenic operation of the superconducting magnet/RF cavities
- Shall allow realization of different operation modes, from cool-down preparation, through cool-down at required temperature drop rate, to nominal operation,
- Require proper material and control instrumentation selection in view of mechanical, thermal, vacuum and radiation resistance properties,
- Require high-efficiency thermal insulation systems for reduction of the Helium Plant operation costs and for the system operation stability,
- Require mechanical design that compromising allowable heat balance with mechanical stability,
- Require over-pressure safety system, based on the active (sensors -> control system-> control valves) and passive (self-activated safety valves, PRDs) elements
- Industrialization of the production, CDS is often the first system installed in the tunnel
- ...

Cryogenic Transfer Line

Thermal bridge
between radiation
shield and
80 K process pipe
(Copper)

Radiation shield
(Aluminium alloy
Al6060)

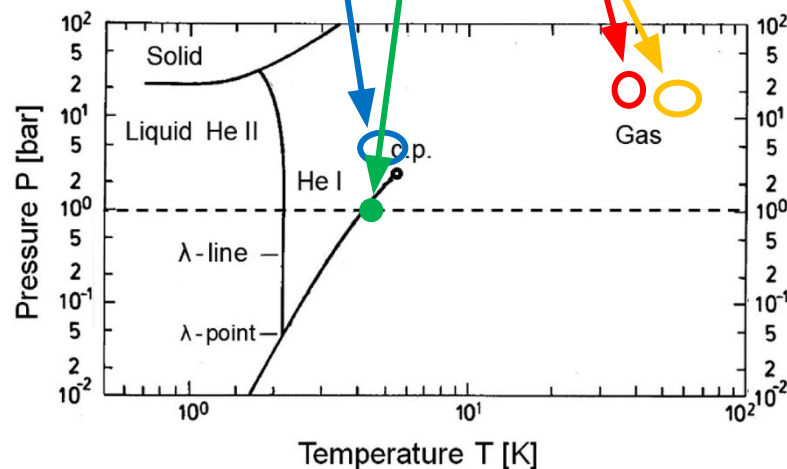
Spacer
(Glassboard)



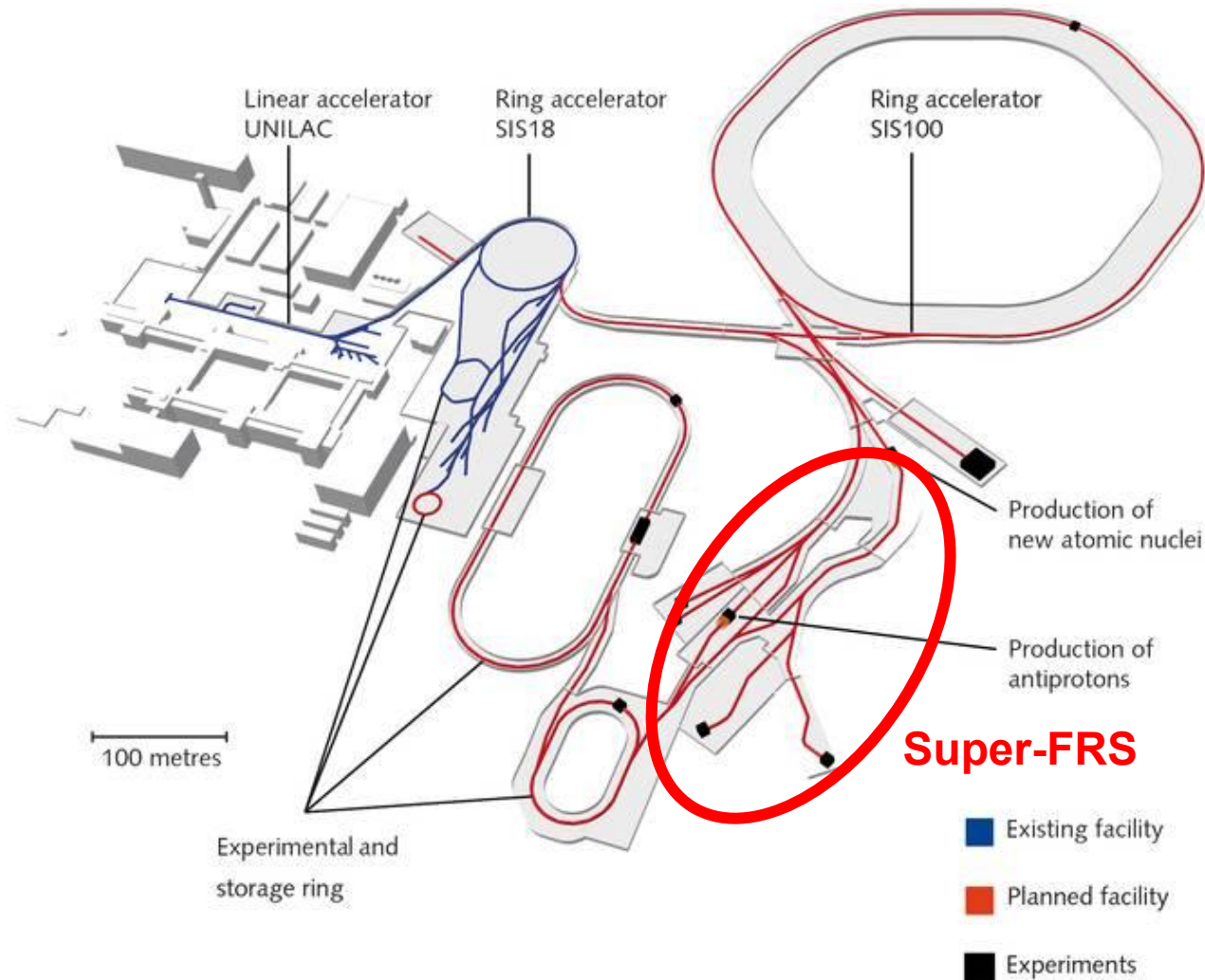
Vacuum vessel
(Austenitic Stainless
steel 304, 1.4301)

Process pipes
(Austenitic Stainless
steel 304L, 1.4306)

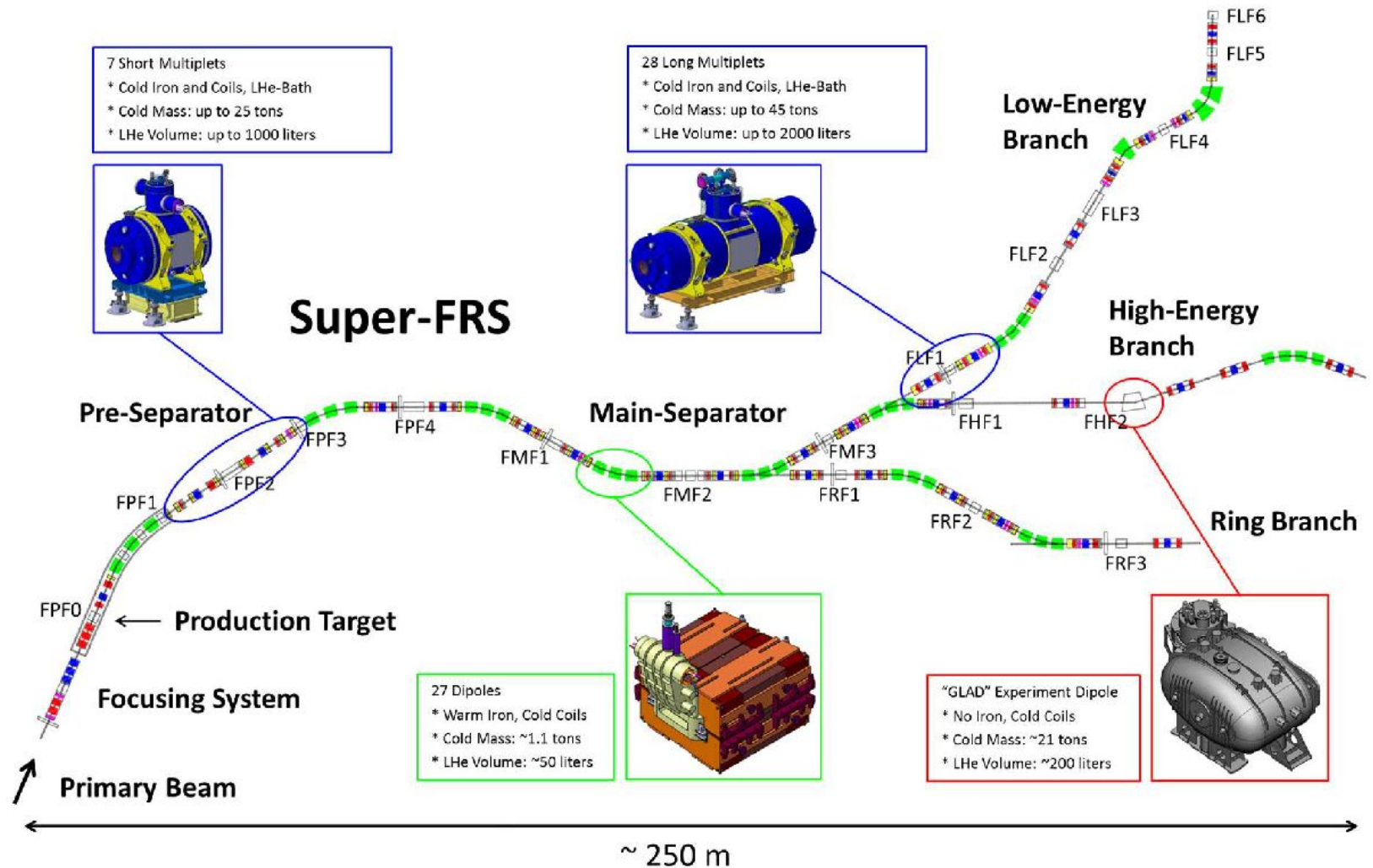
Sliding support
(Epoxy G-10)



Outline of the FAIR accelerator complex

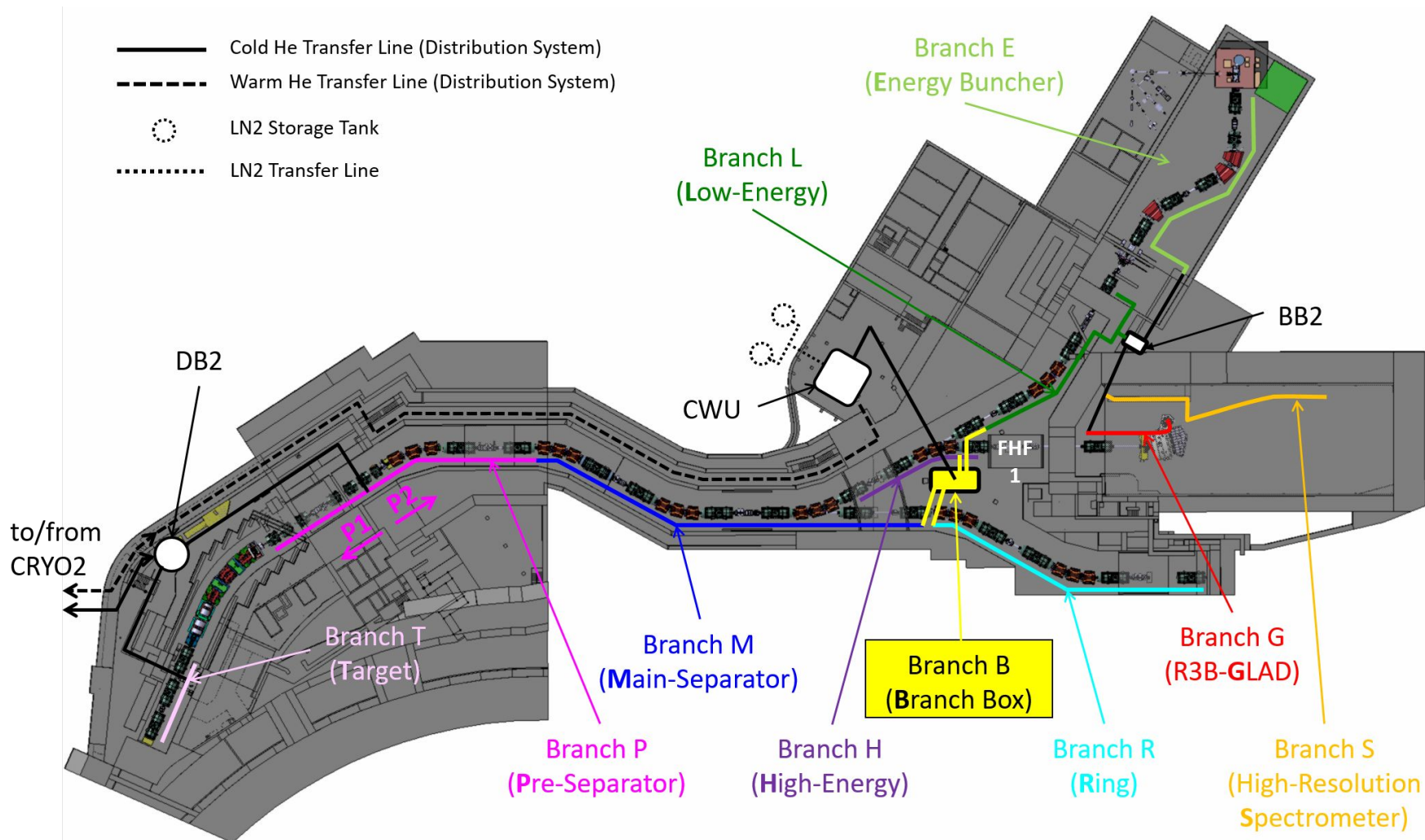


Outline of the Super-FRS



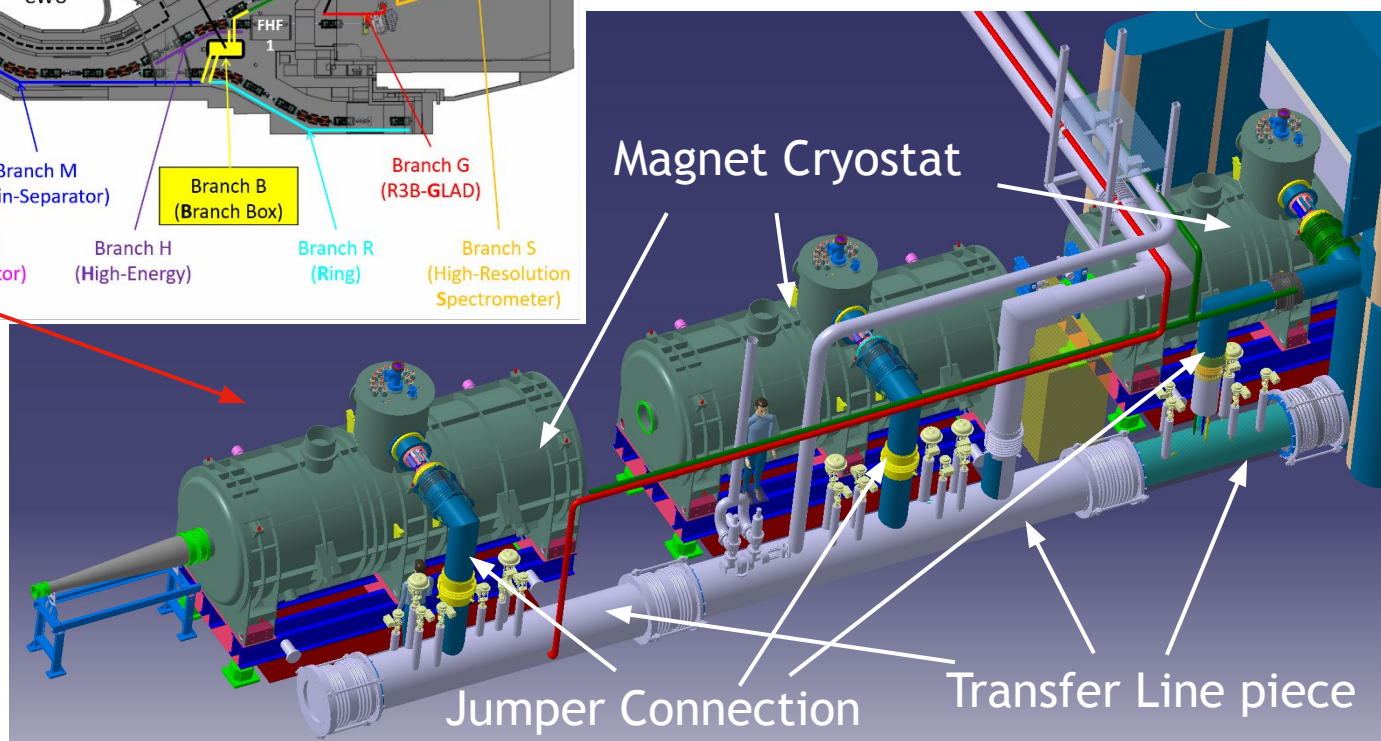
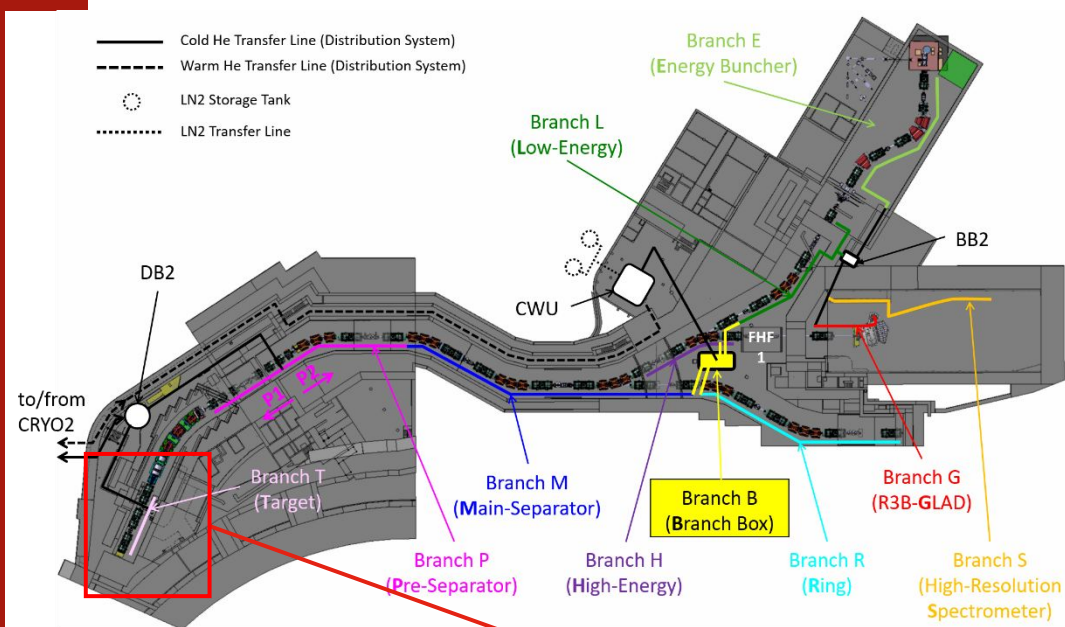


Layout of the S-FRS Local Cryogenics





S-FRS Local Cryo Branch's initial conceptual layout



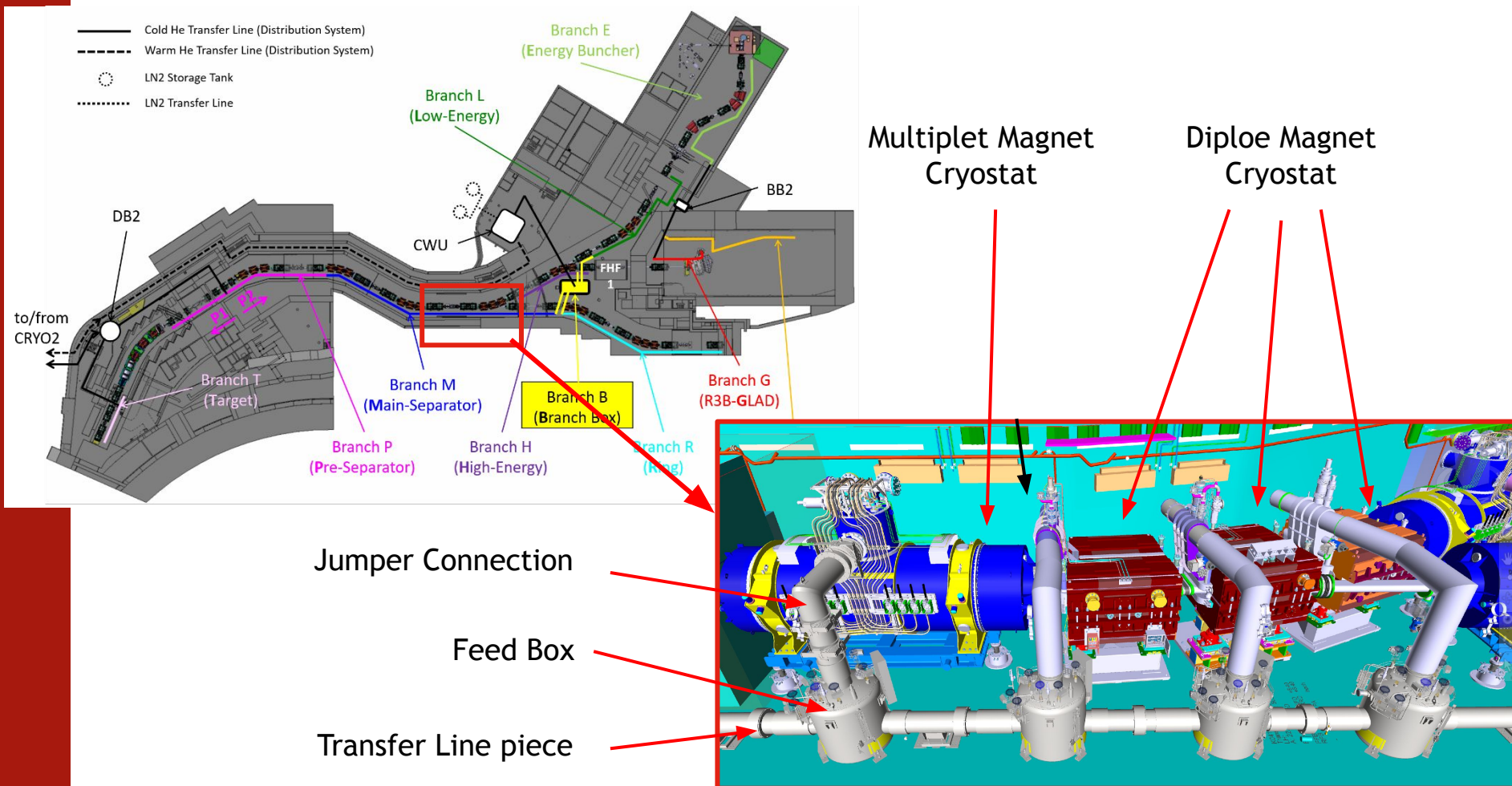


Disadvantages of S-FRS Local Cryo initial conceptual layout

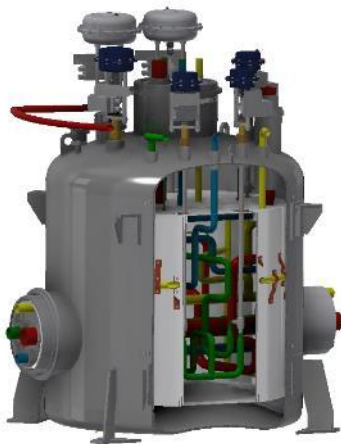
- Requires unique design of the Transfer Line piece for each individual magnet cryostat,
- Very complex, single production and logistic processes,
- High risk of technical mistakes,
- Lack of flexibility in the system installation sequence.



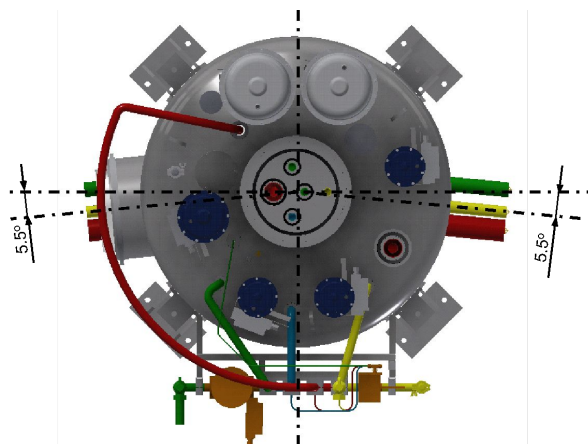
S-FRS Local Cryo Branch's final conceptual layout



Super-FRS Local Cryogenics Component types



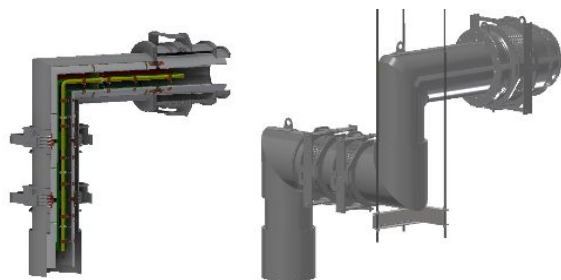
Standard and Branch End Multiplet FBs
0 degree Dipole FBs
(2 types - 38 pcs)



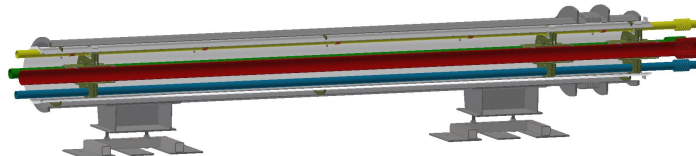
11 and 9.5 degree Dipole FBs
(3 +1 types, 24 pcs)



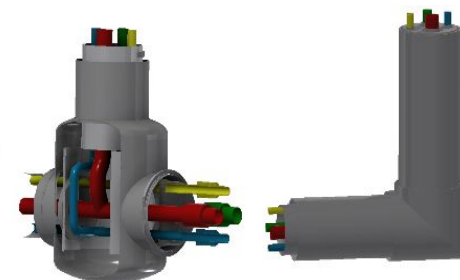
End Box
(2 types, 6 pcs)



1L and 3L Jumper Connections
(15 types, 62 pcs)

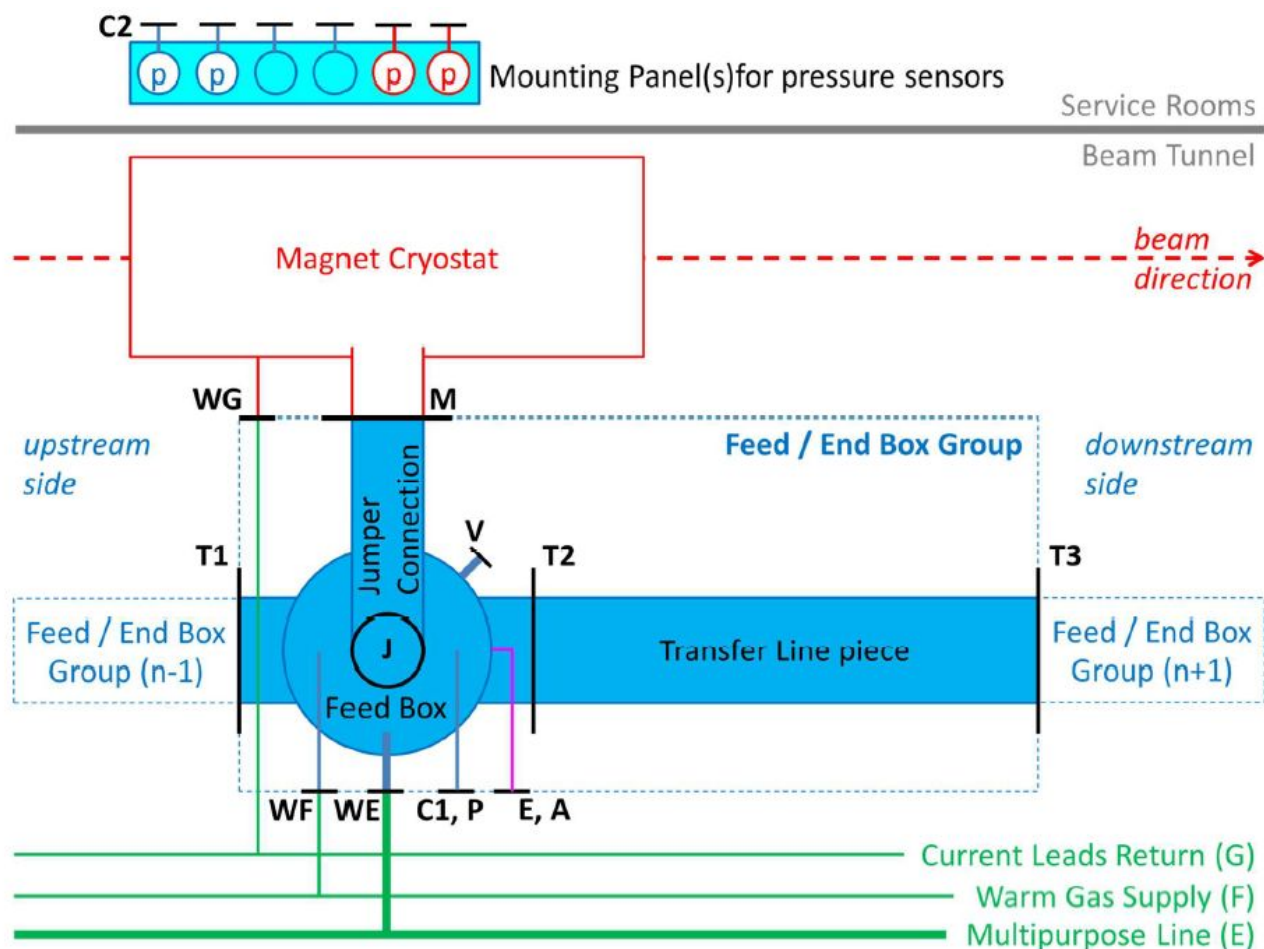


4-ch Transfer Line pieces
(9 type, 44 pcs)

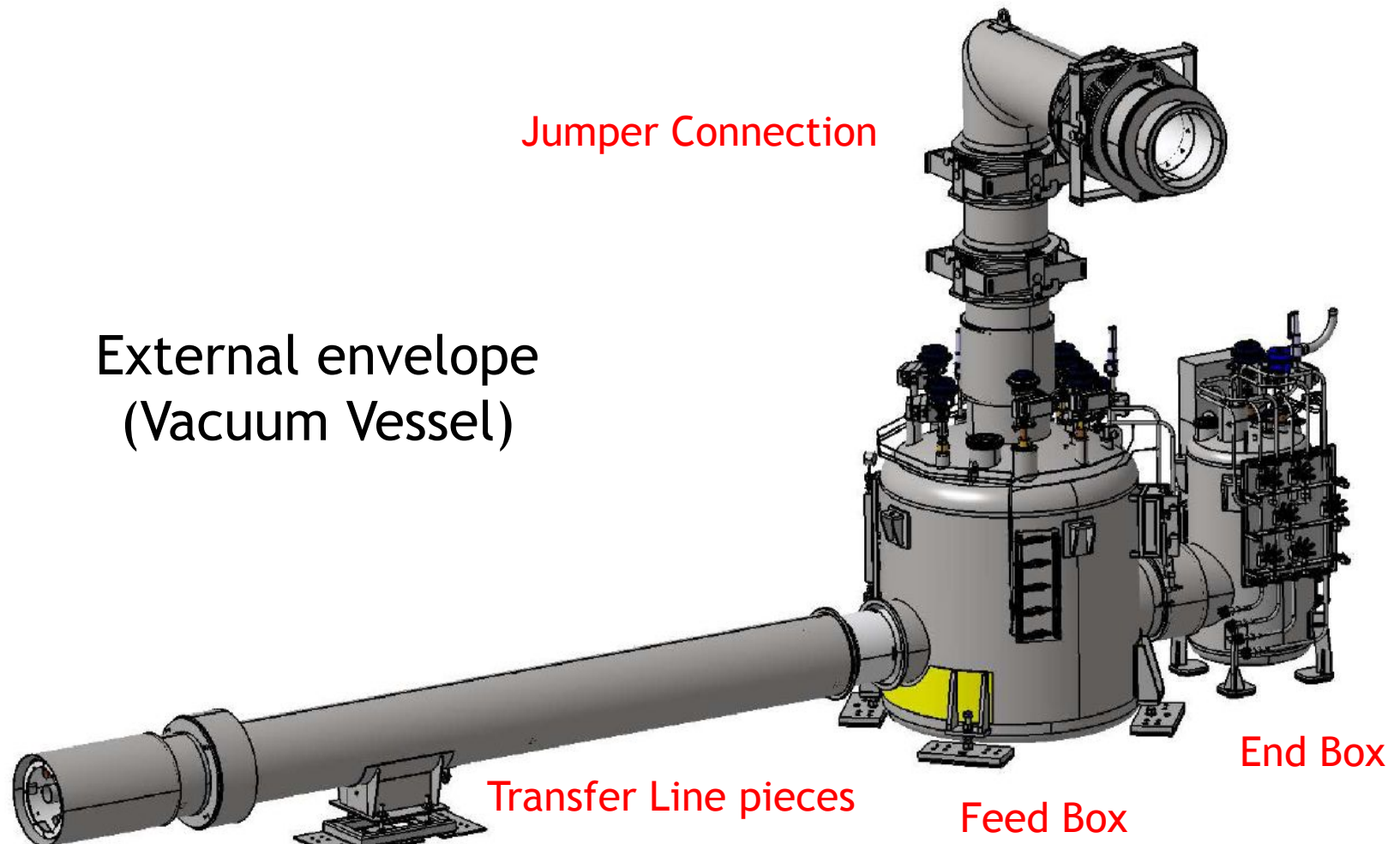


Complex TLs: T and L-conn.
(2+2 type, 5+5 pcs)

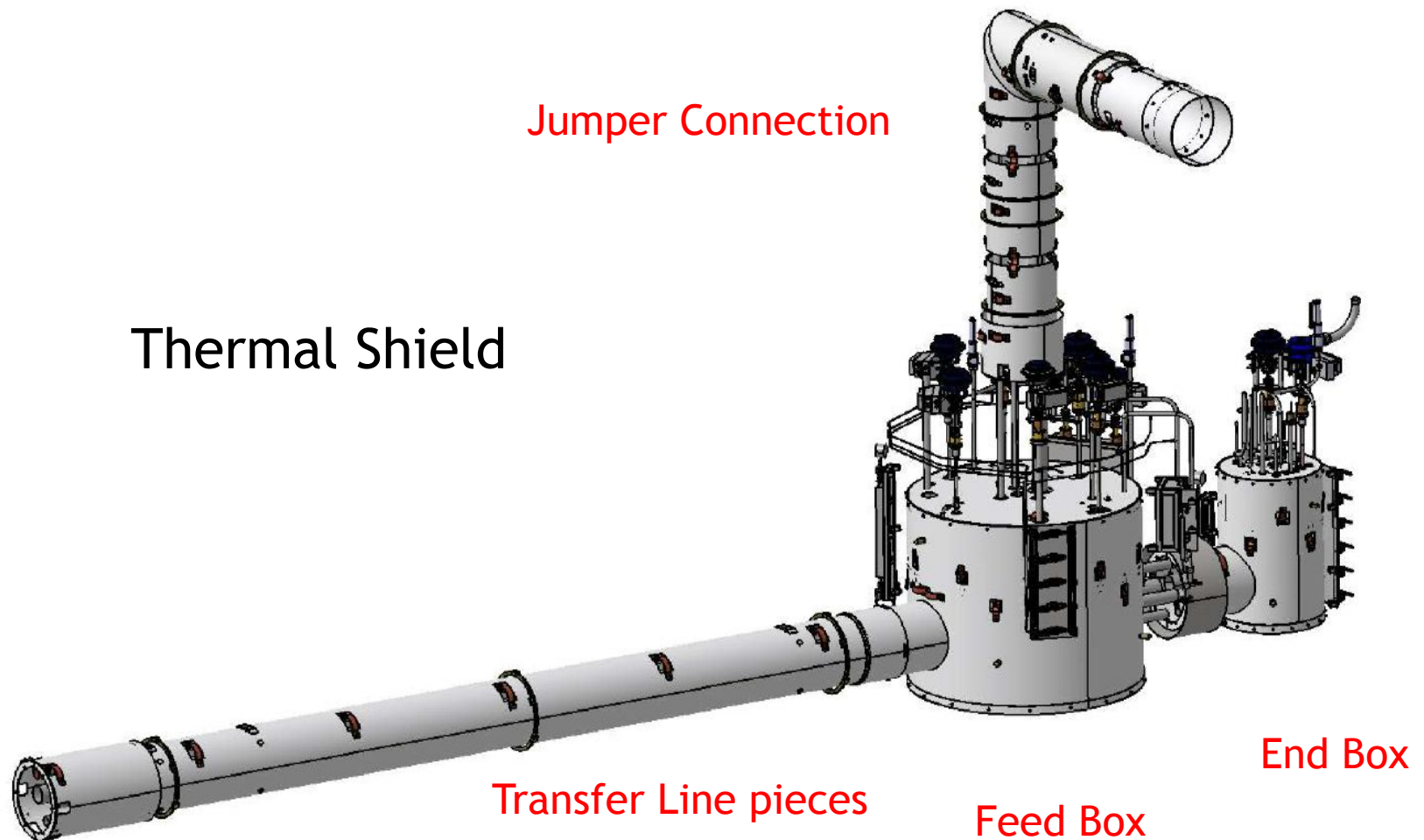
S-FRS Local Cryo - scheme of Feed/End Box group



Feed Box Group design

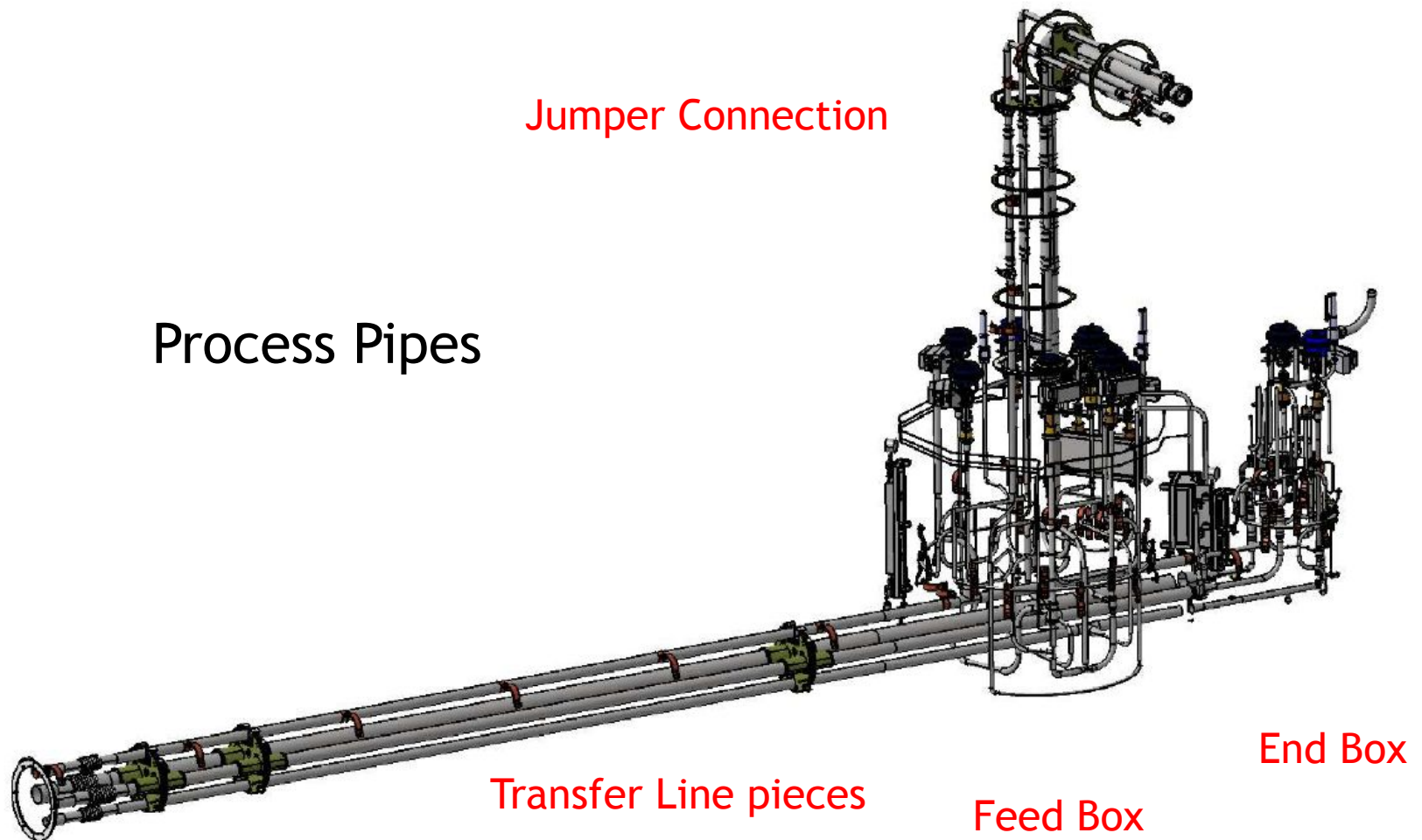


Feed Box Group design





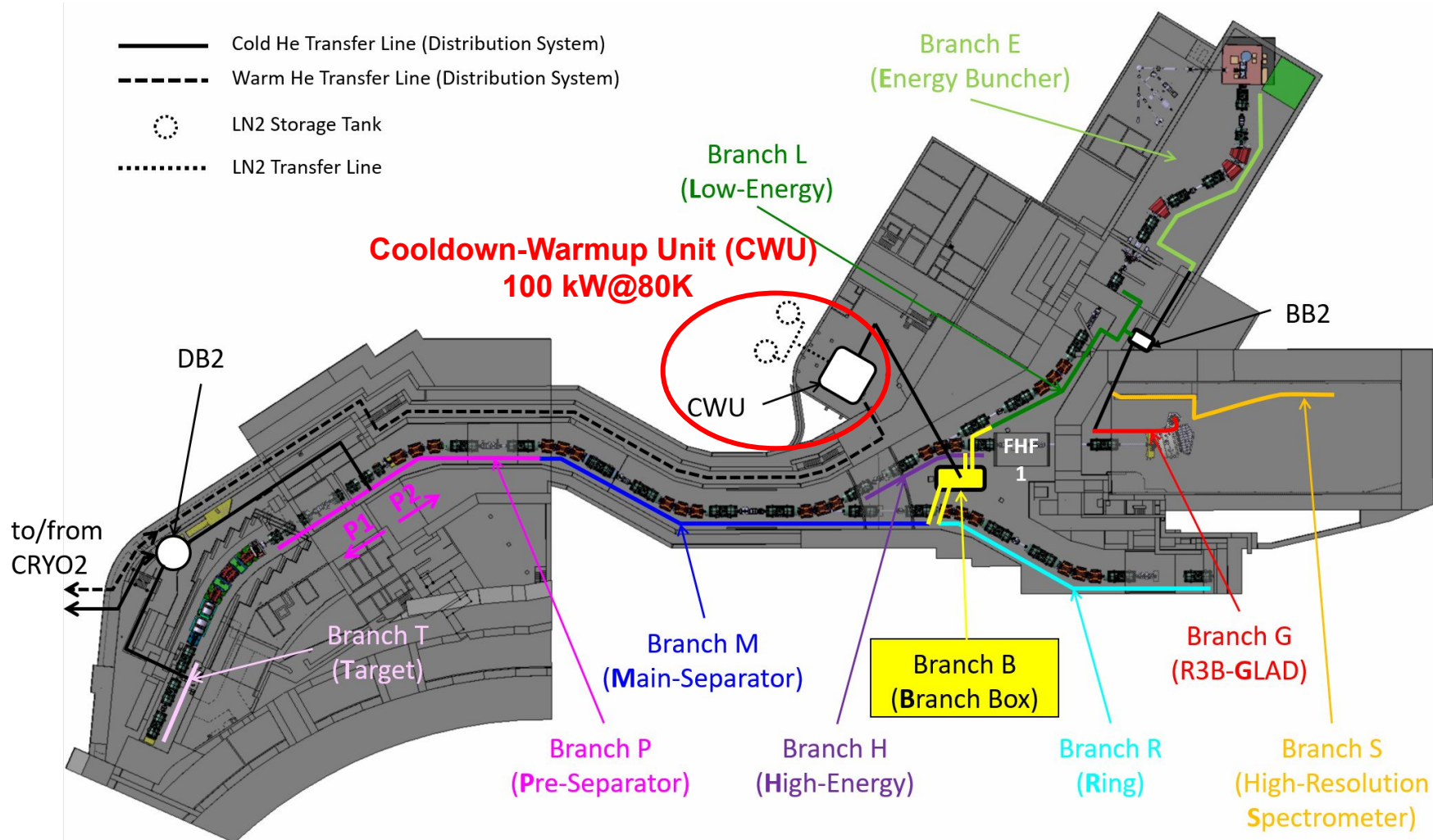
Feed Box Group design



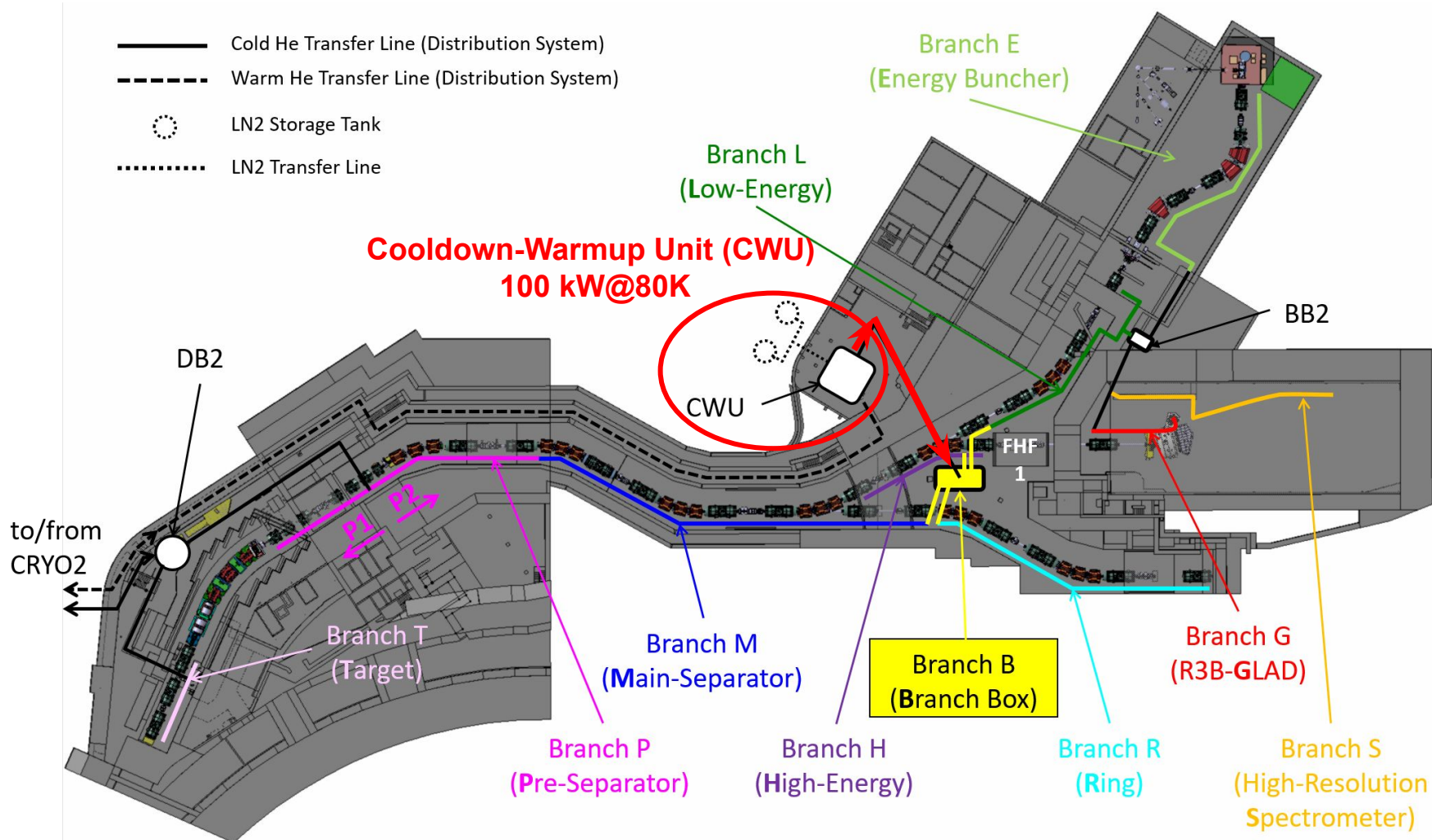
S-FRS Local Cryogenics operation modes

- Cooling down of the magnet cryostats,
- Filling of the magnet vessels with LHe ,
- LHe bath temperature and liquid level stabilization during powering of the magnets,
- Magnet quenches and other hazardous events,
- Warming up/cooling down of all or group of Branches,
- Warming up/cooling down of individual cryostats
- ... - 17 operation modes in total

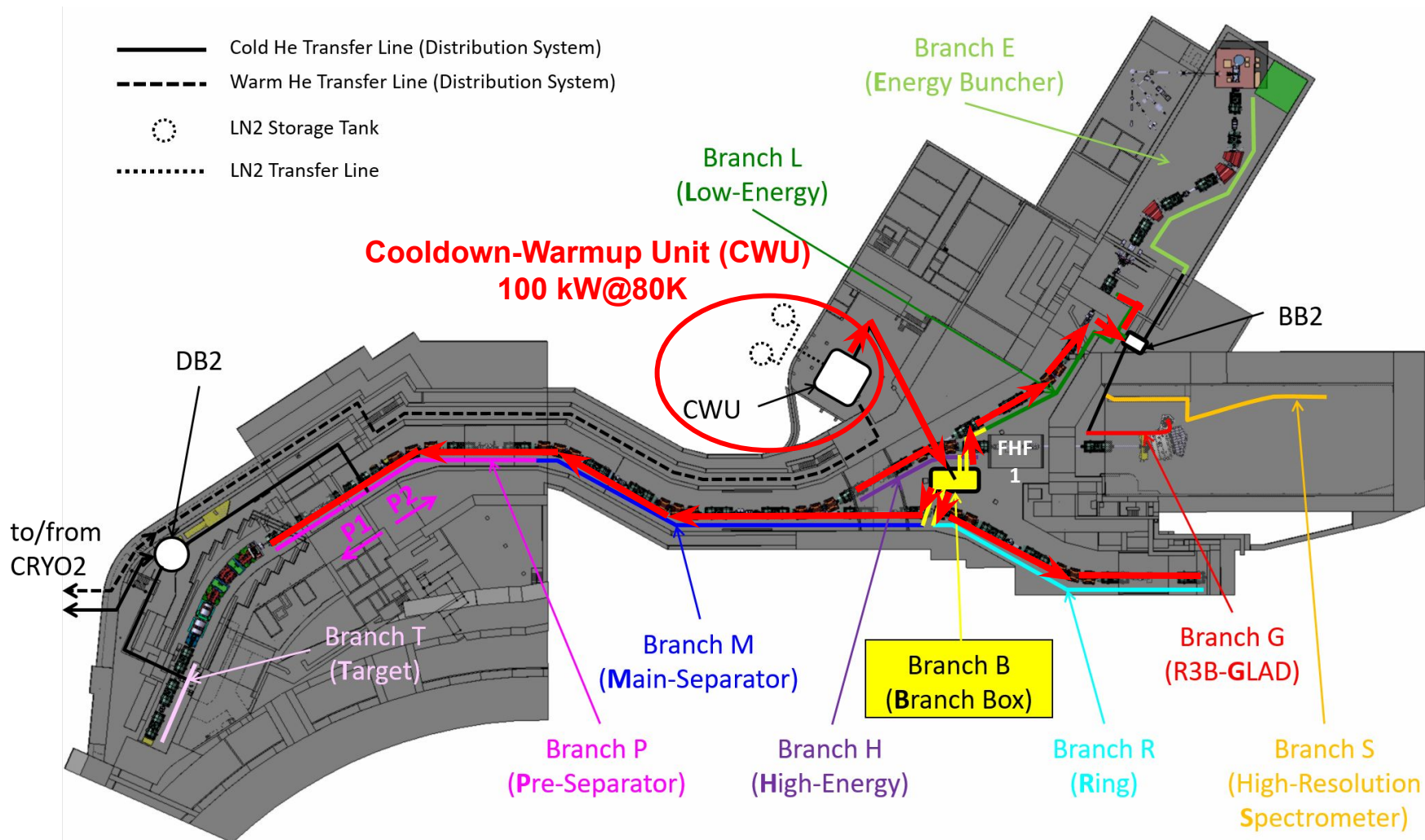
S-FRS Cooldown 300-80K and Warmup (via CWU)



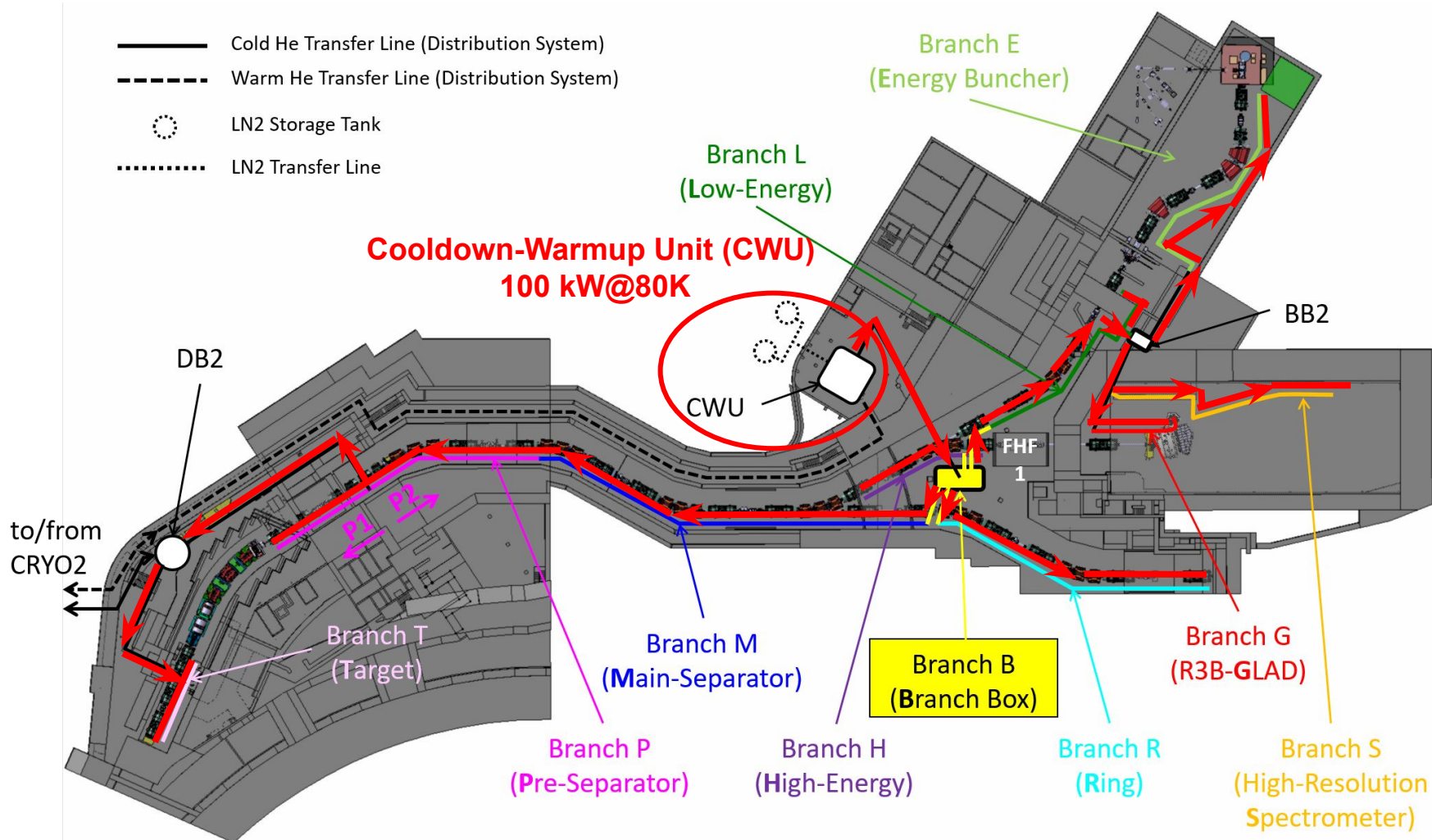
S-FRS Cooldown 300-80K and Warmup (via CWU)



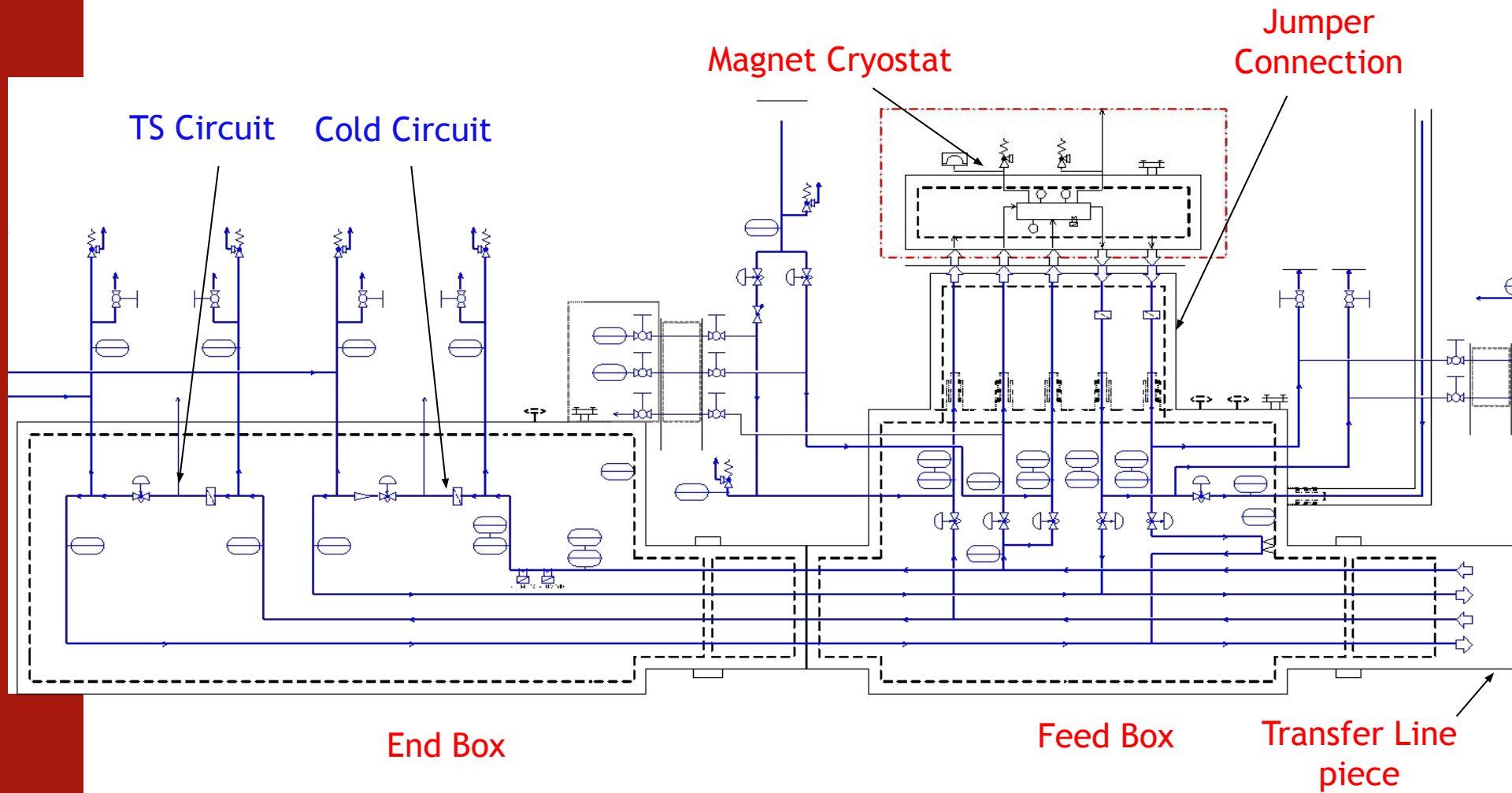
S-FRS Cooldown 300-80K and Warmup (via CWU)



S-FRS Cooldown 300-80K and Warmup (via CWU)

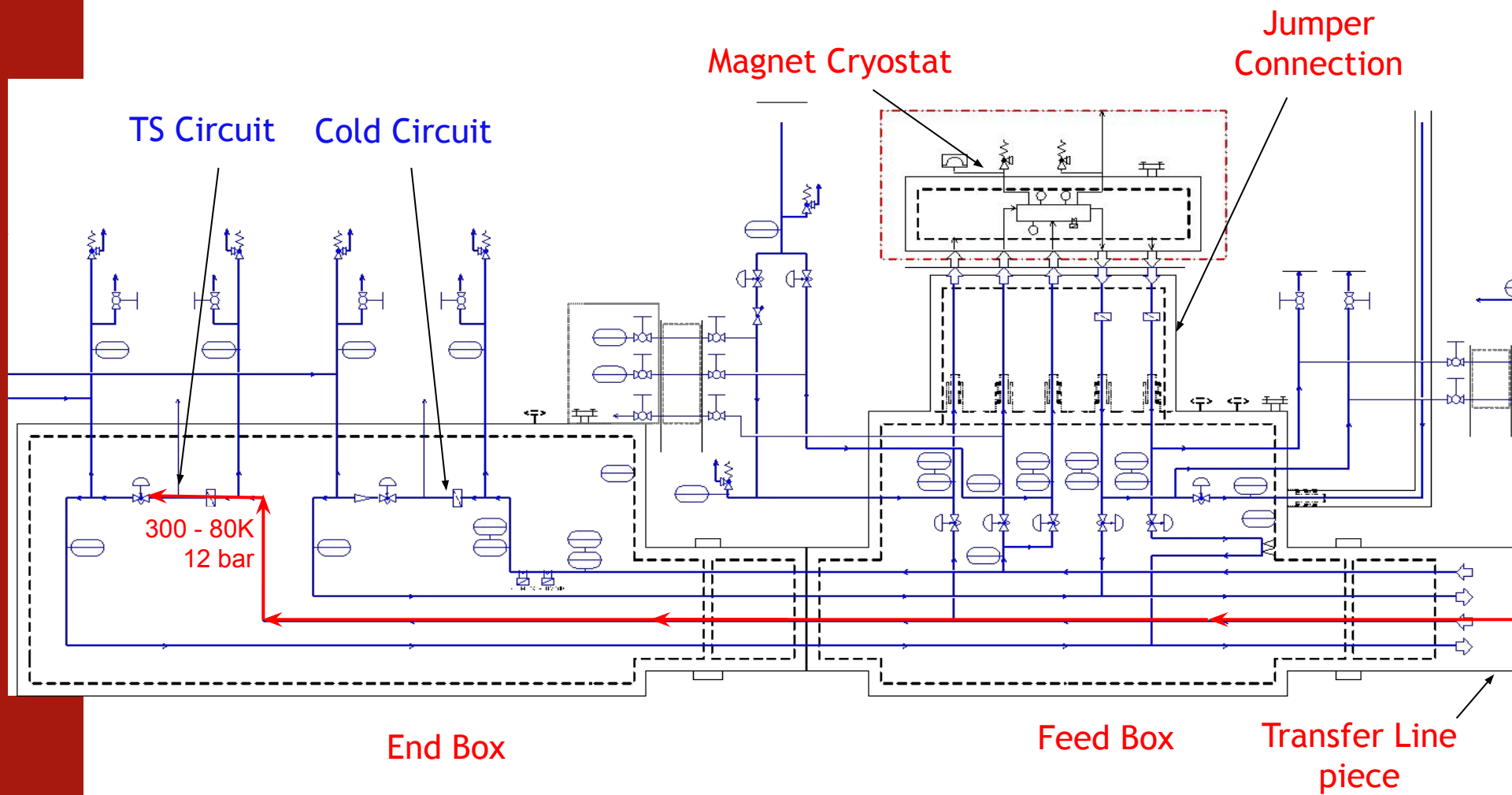


Feed Box Group cool-down phase

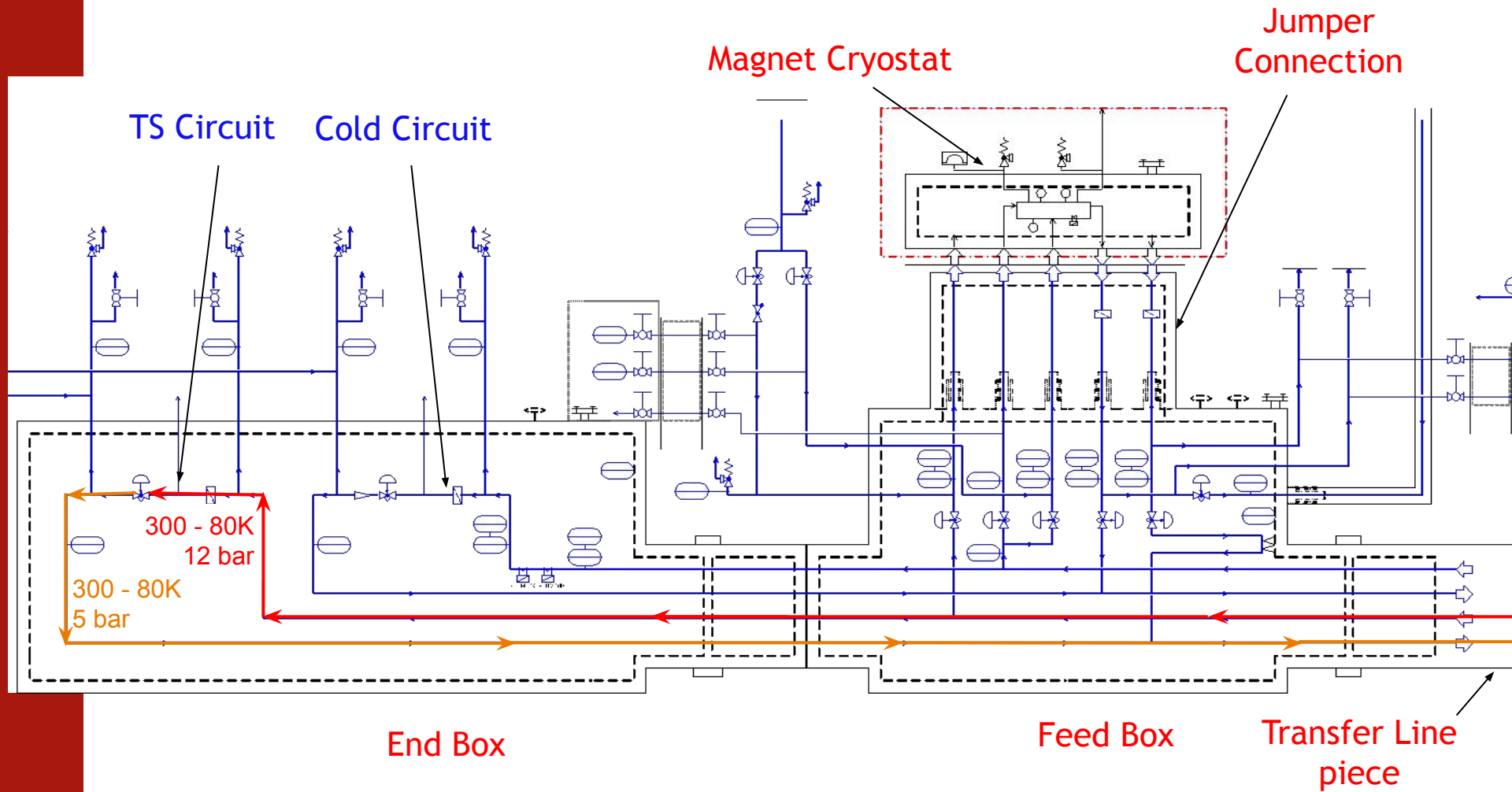




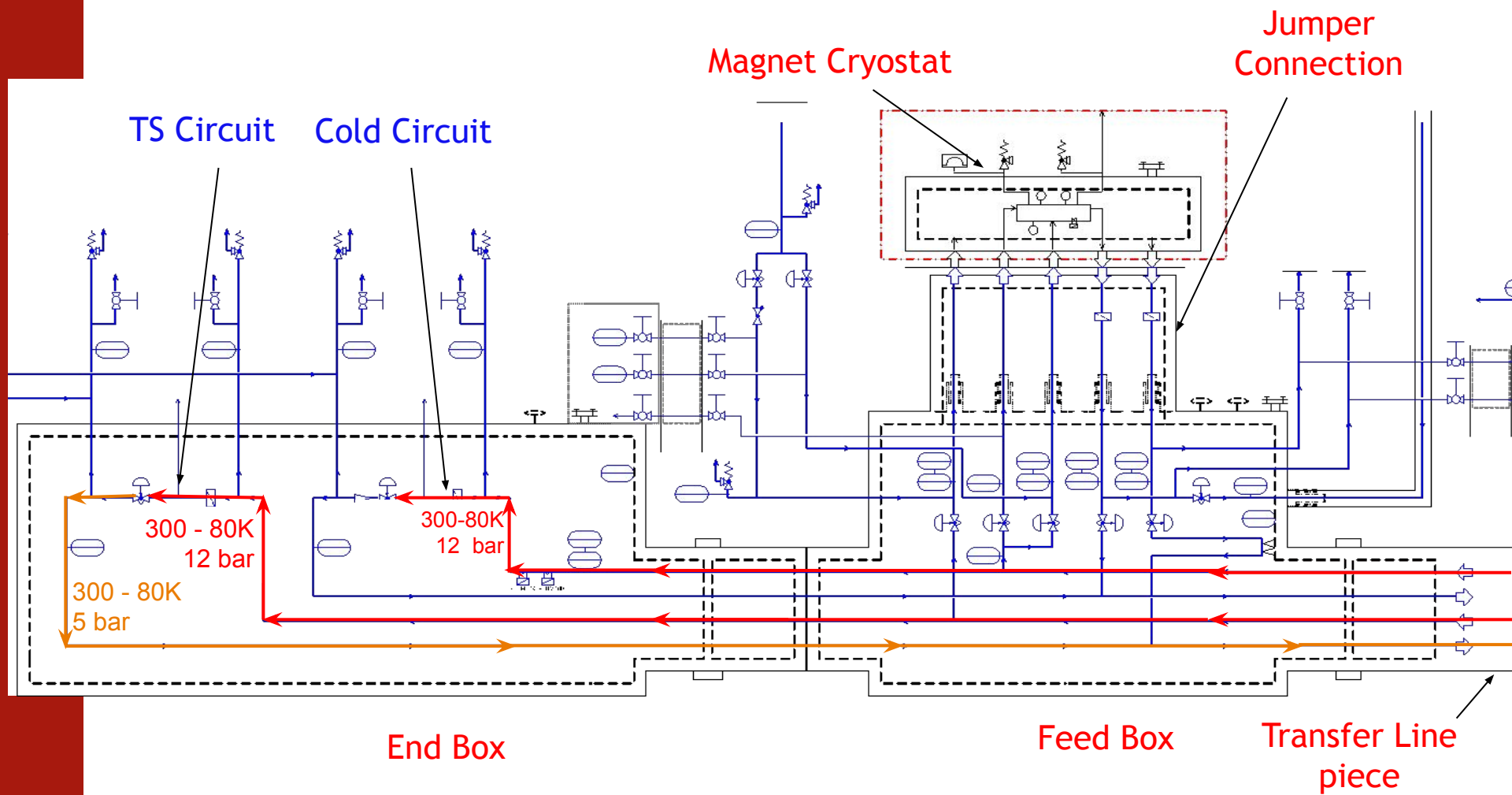
Feed Box Group cool-down phase



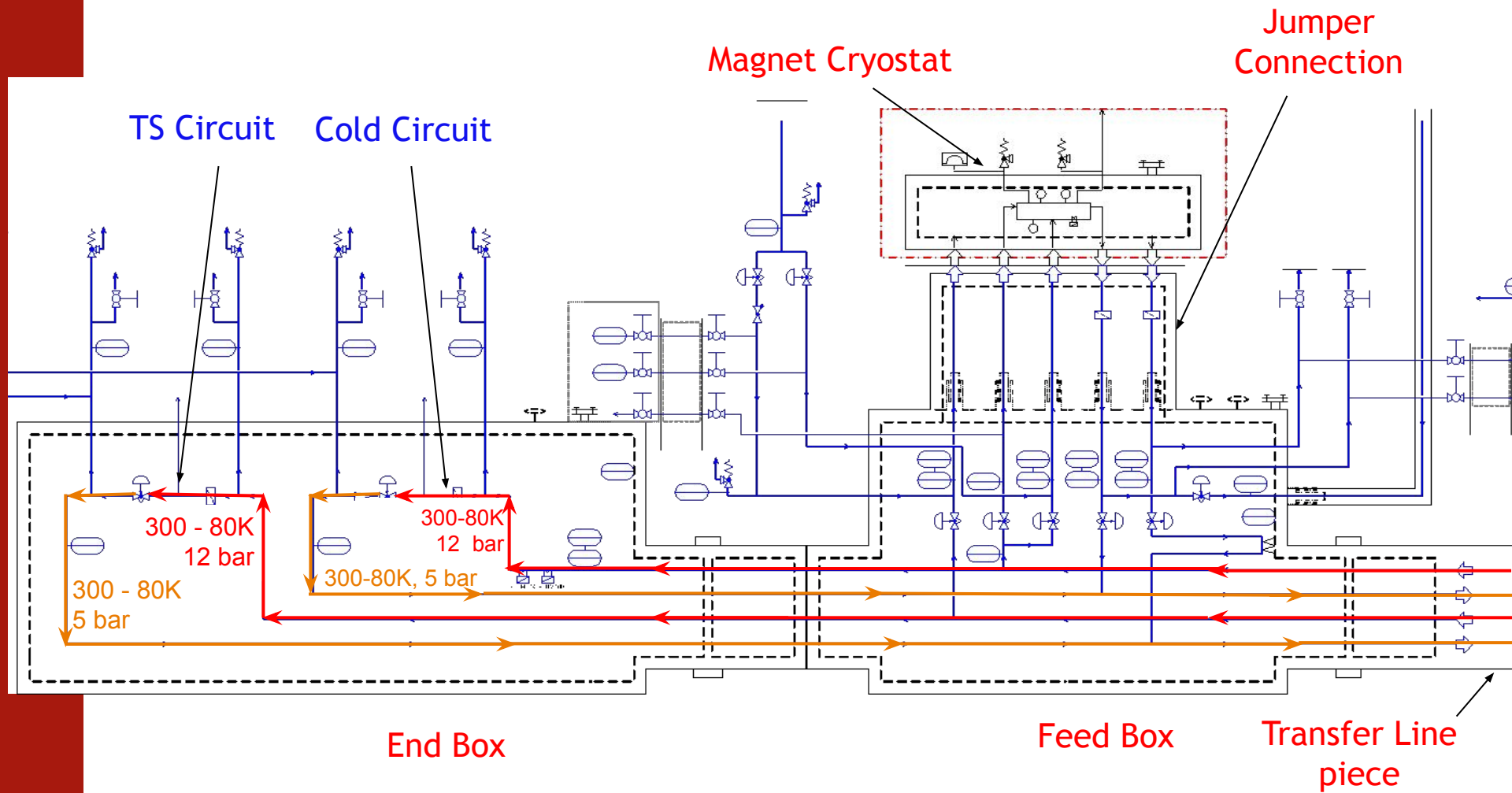
Feed Box Group cool-down phase



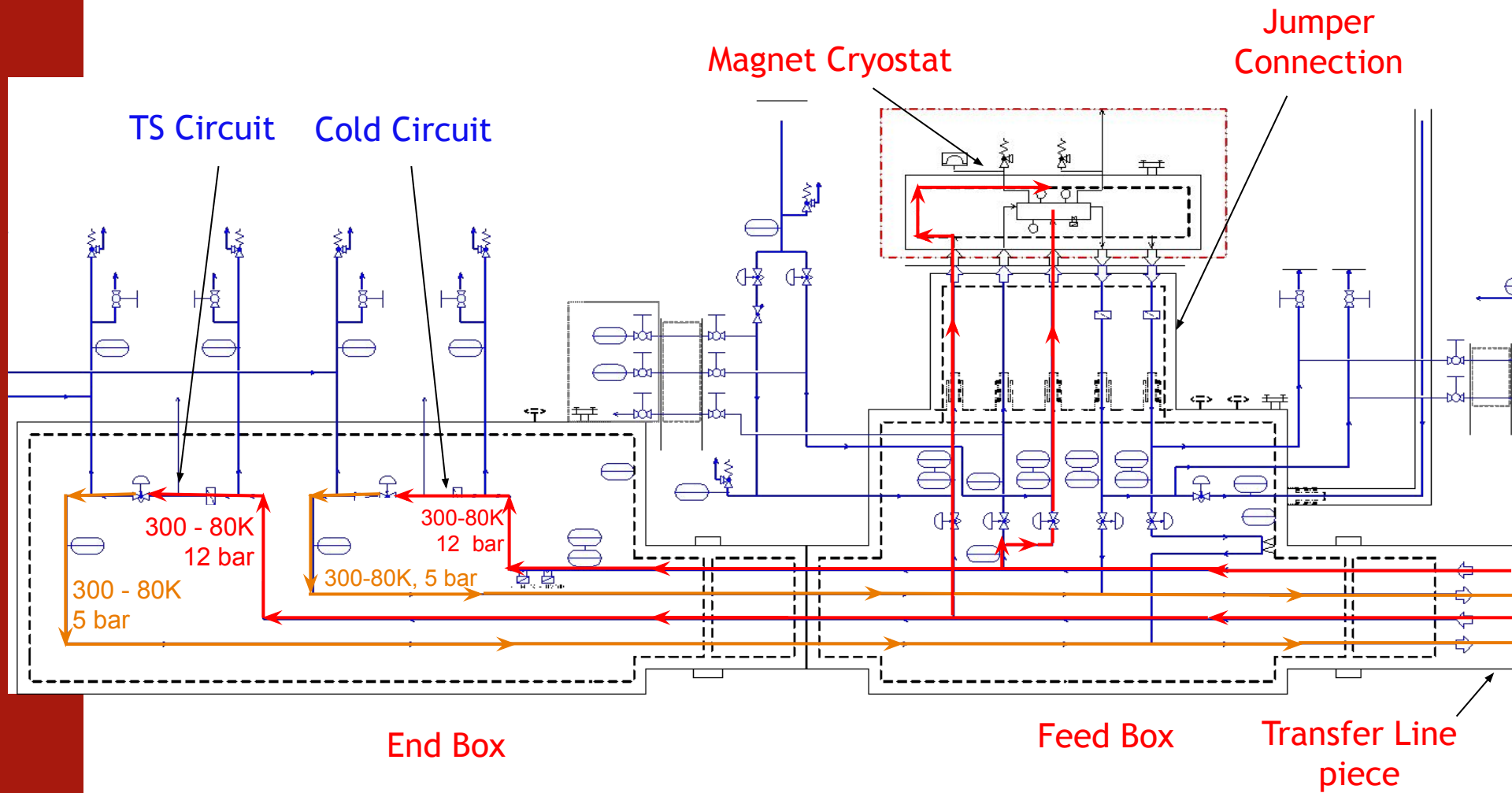
Feed Box Group cool-down phase



Feed Box Group cool-down phase

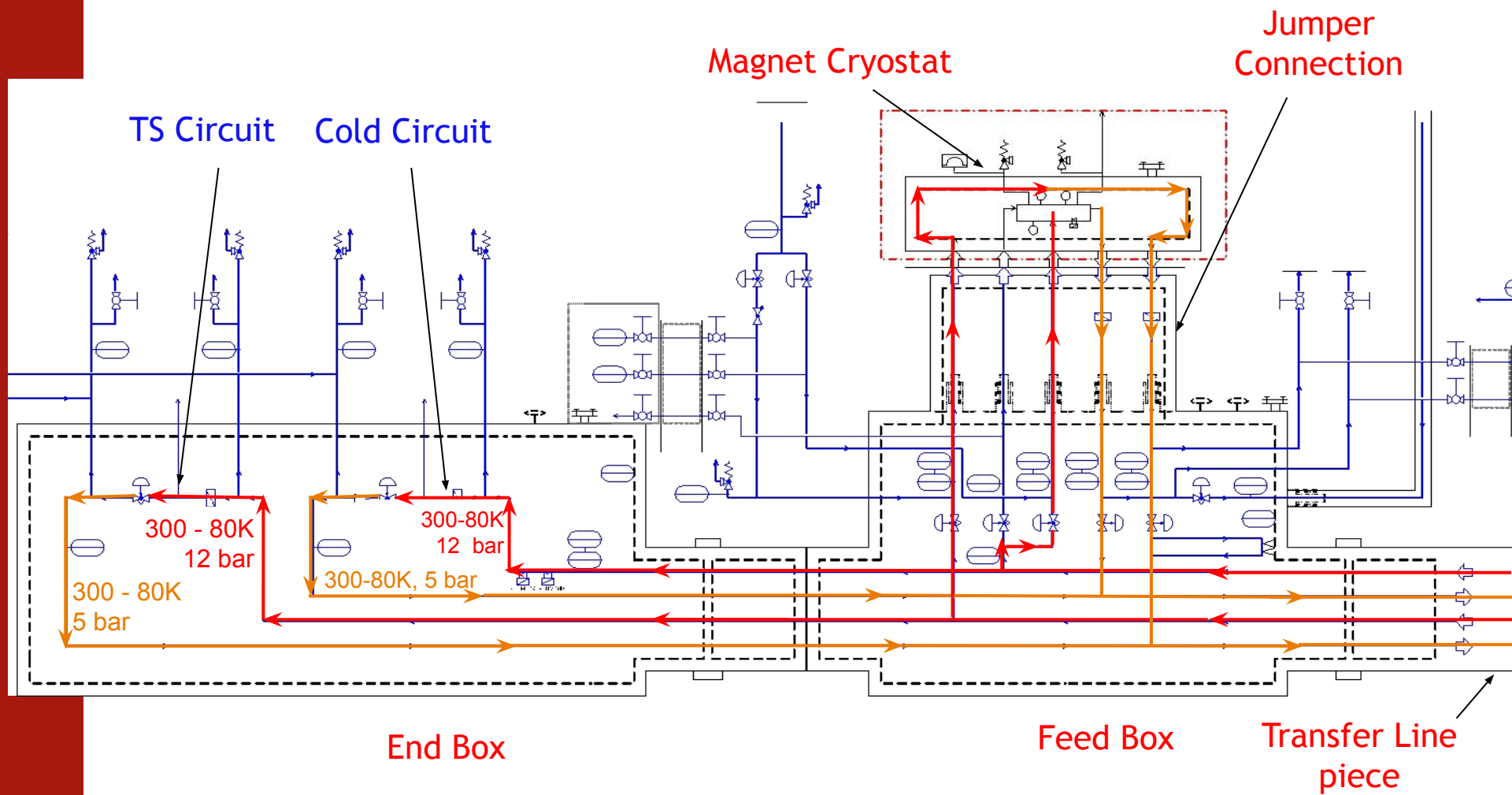


Feed Box Group cool-down phase



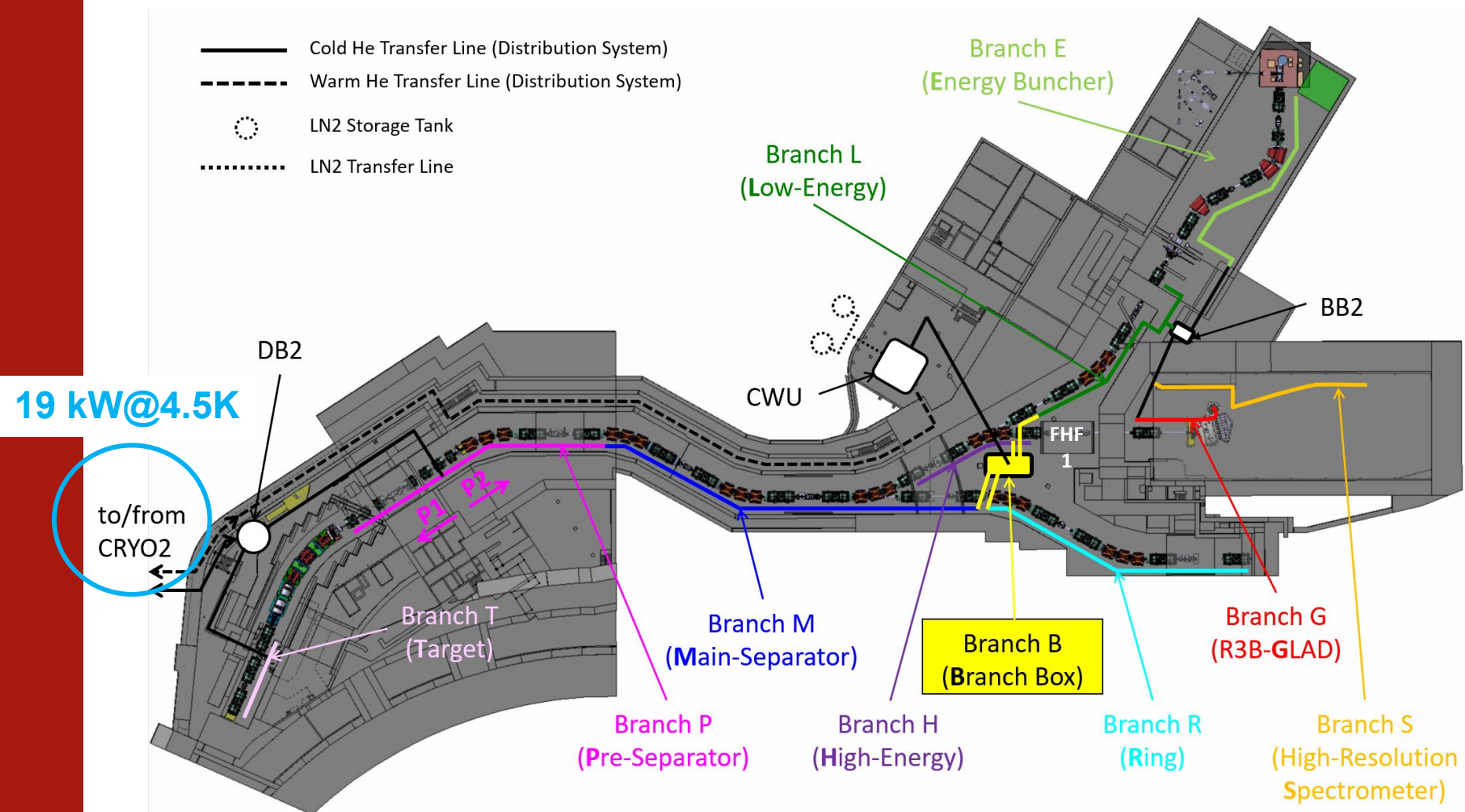


Feed Box Group cool-down phase



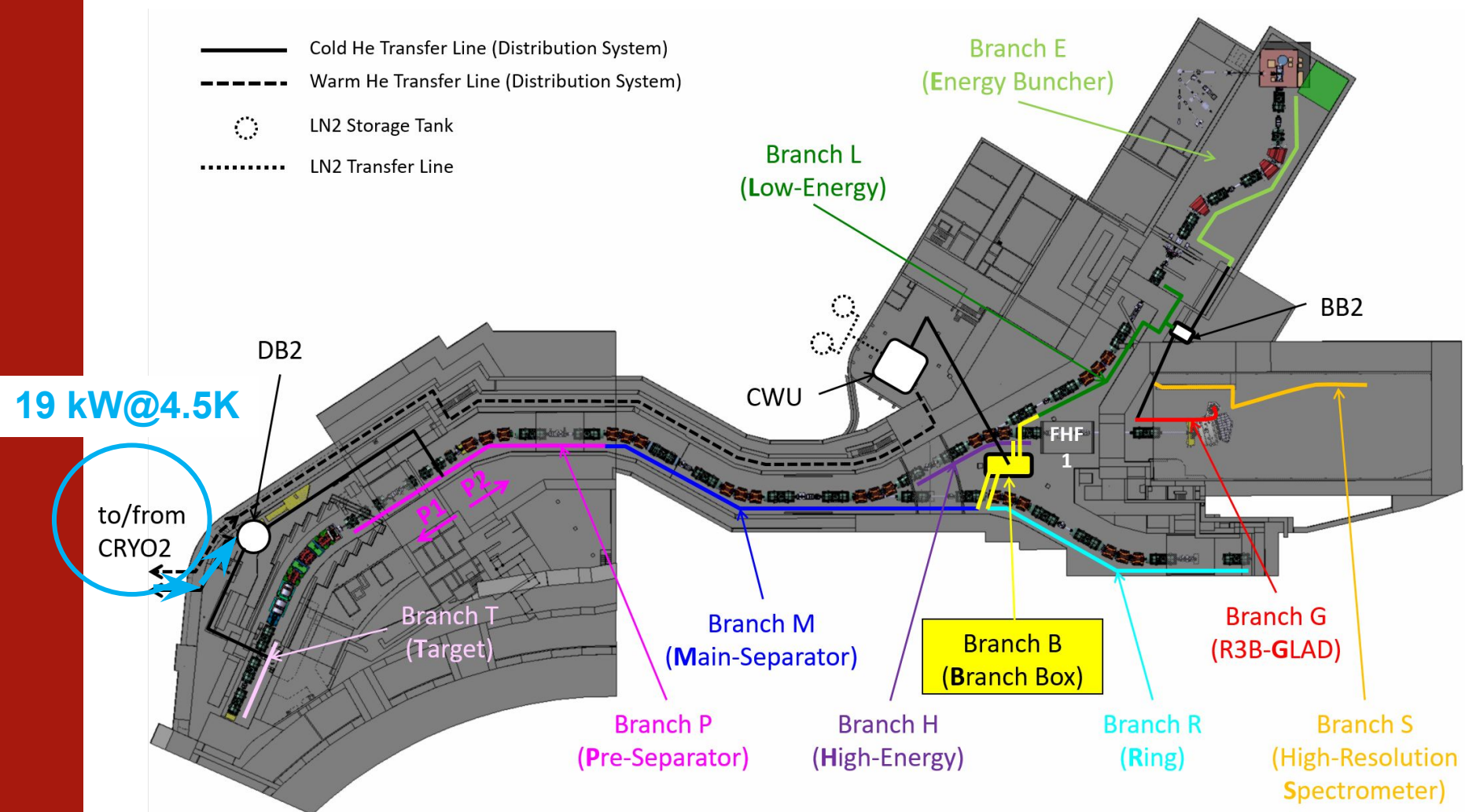


S-FRS Cooldown 80-5 K and Nominal Operation (via CRYO2)



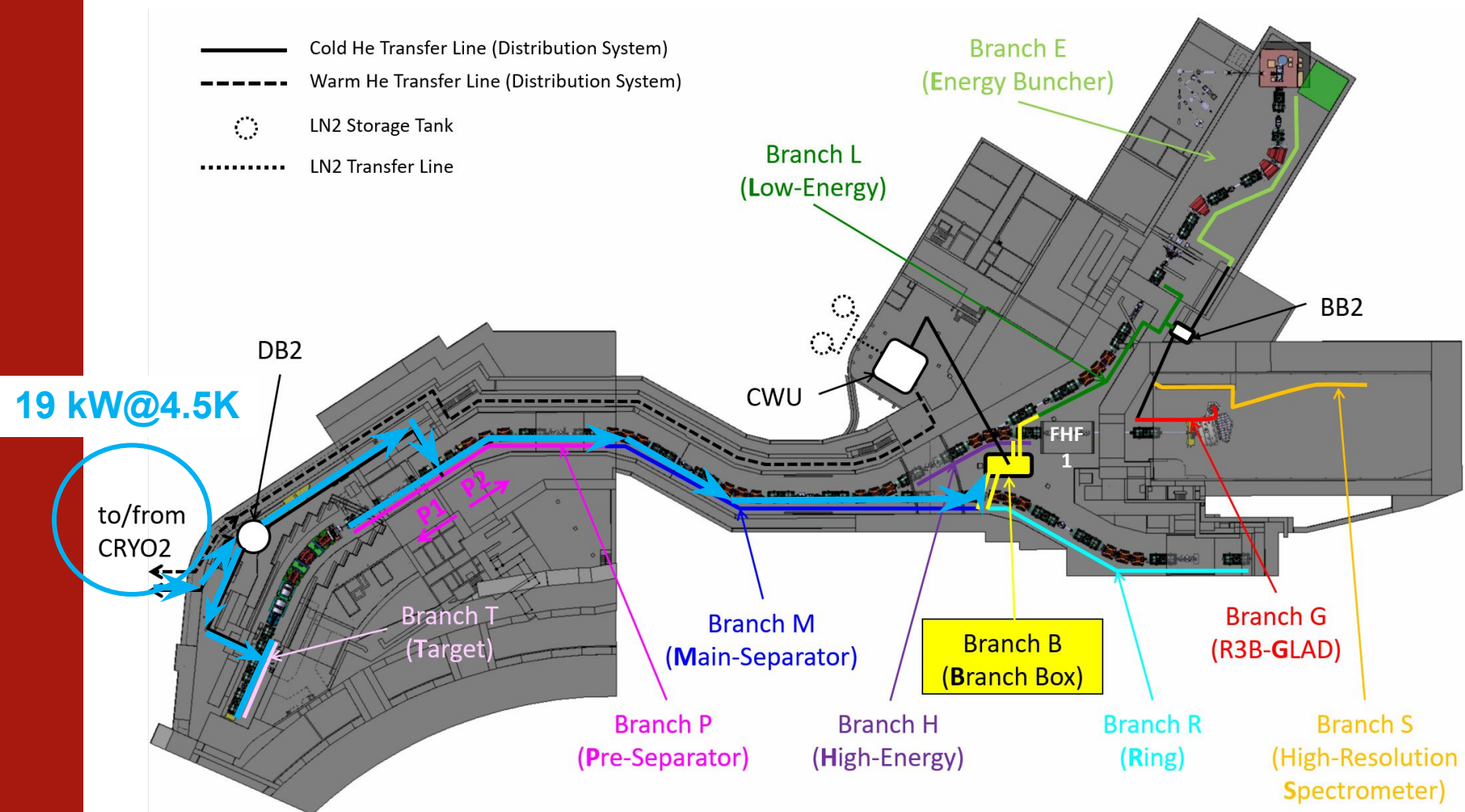


S-FRS Cooldown 80-5 K and Nominal Operation (via CRYO2)



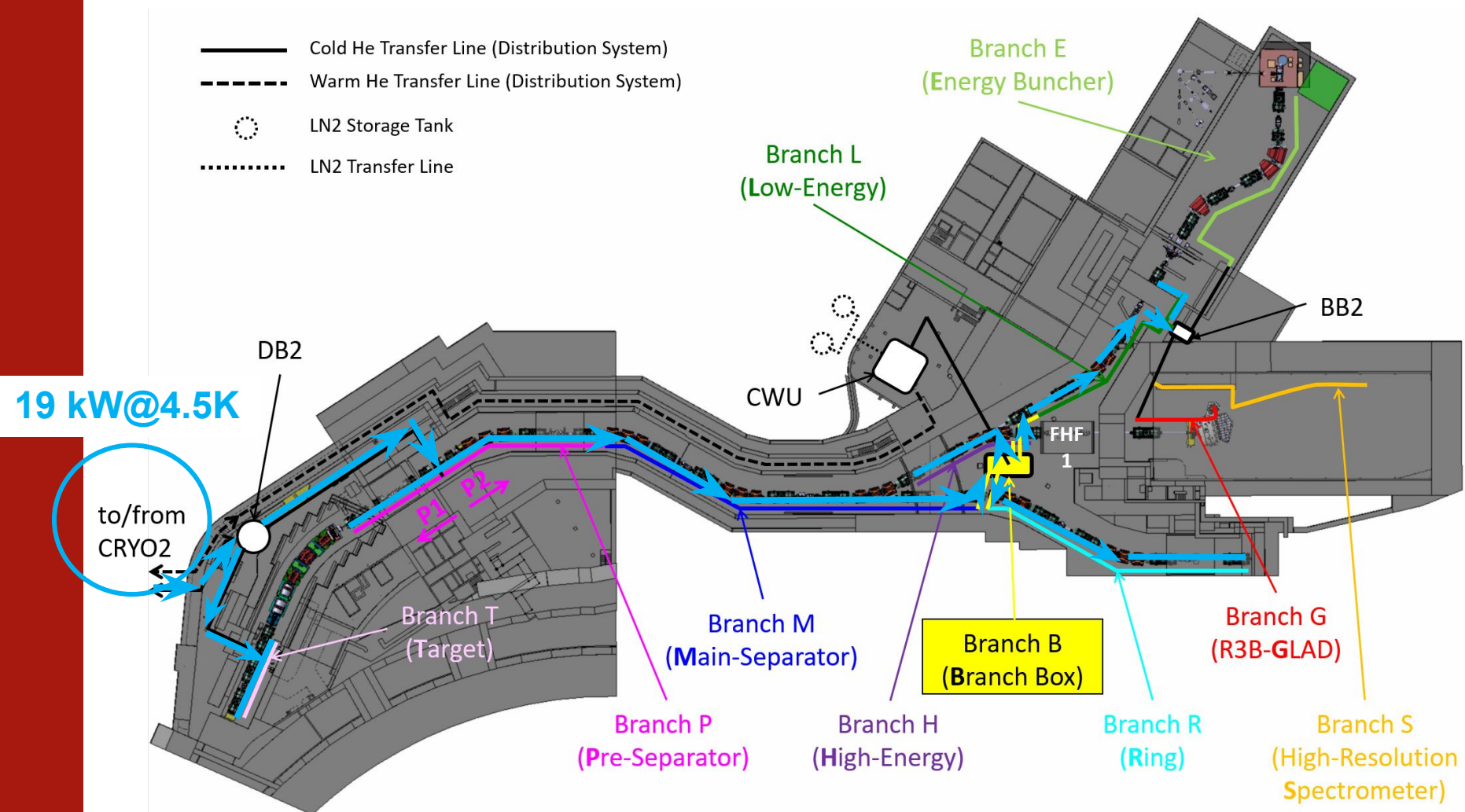


S-FRS Cooldown 80-5 K and Nominal Operation (via CRYO2)

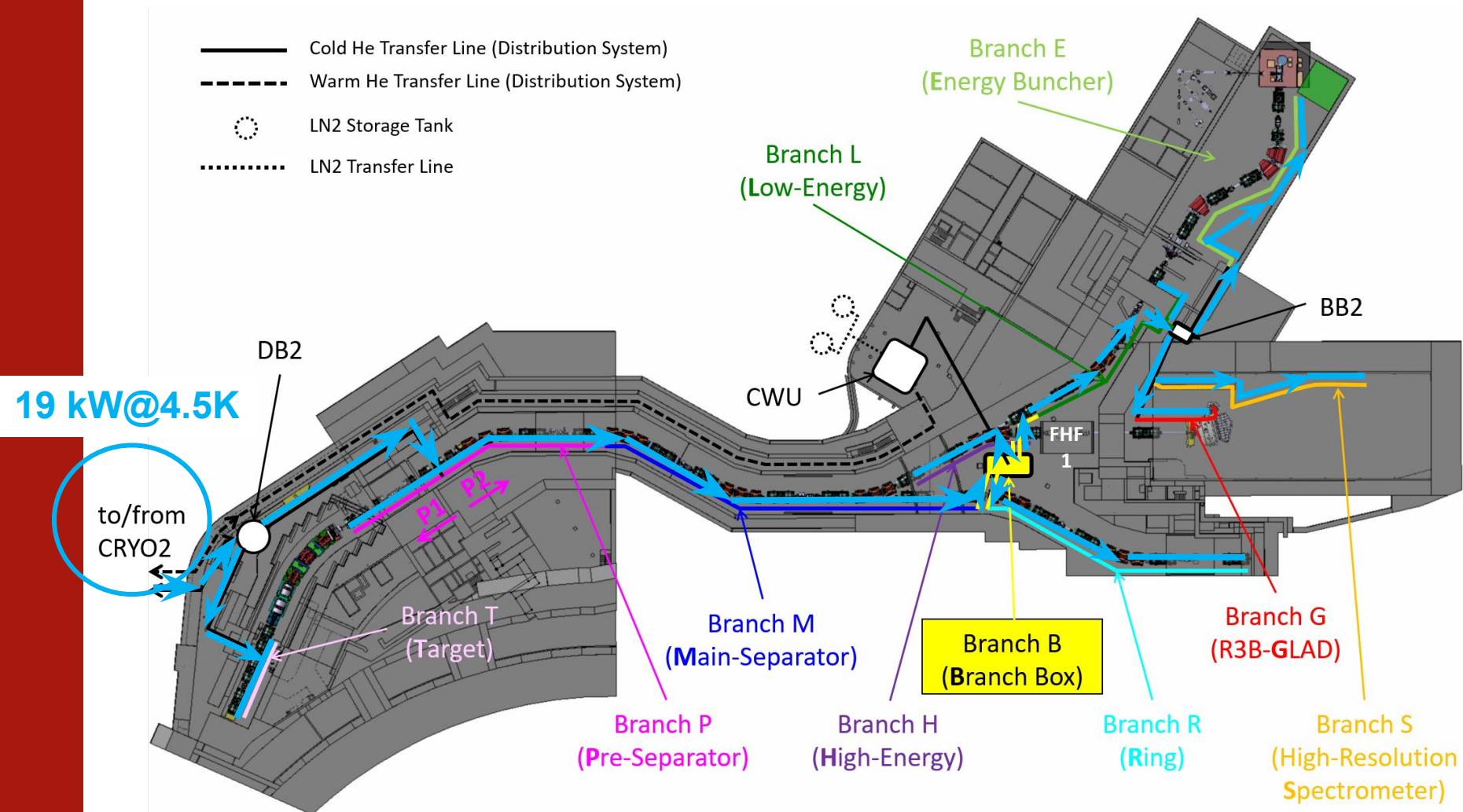




S-FRS Cooldown 80-5 K and Nominal Operation (via CRYO2)

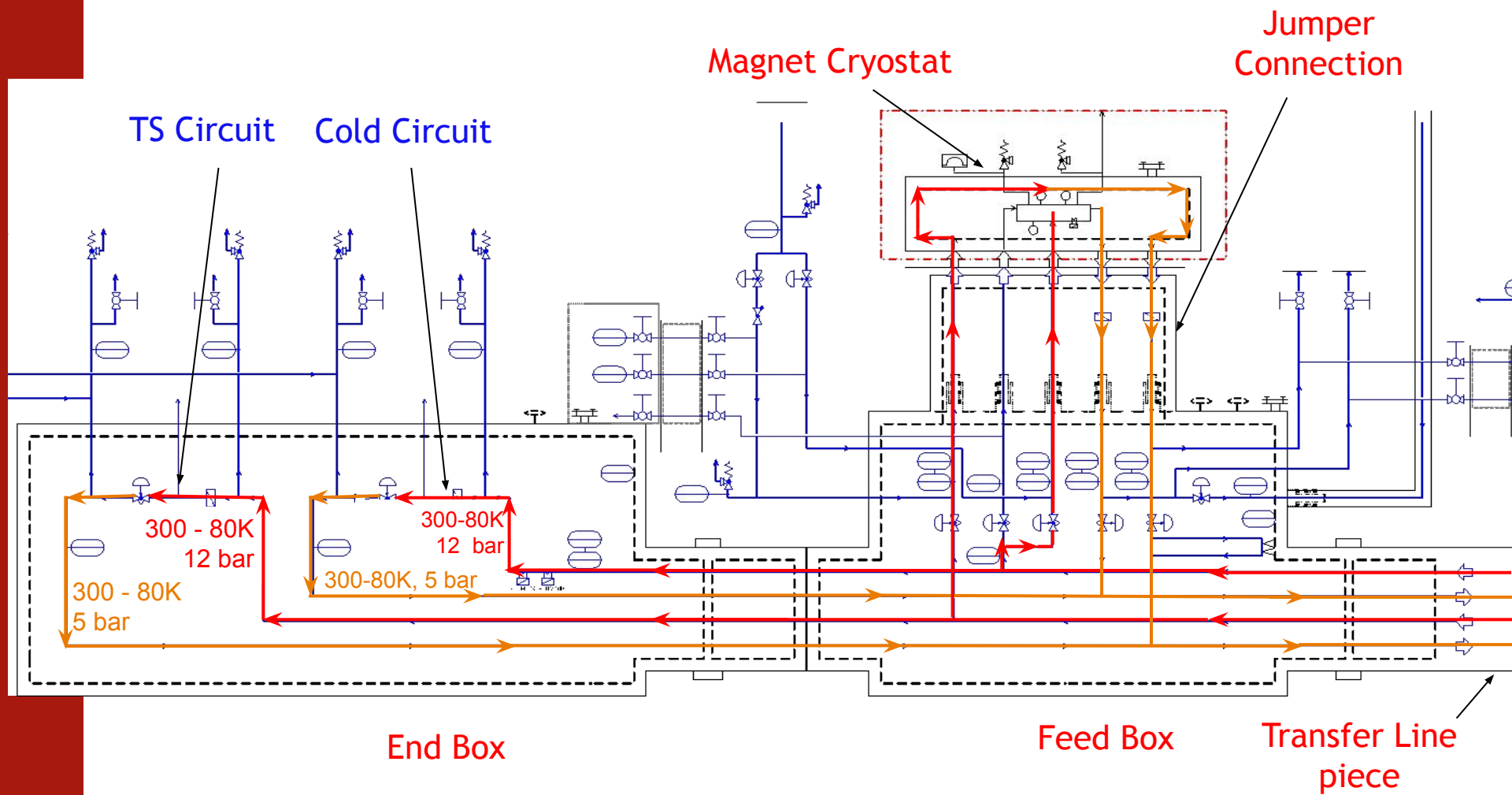


S-FRS Cooldown 80-5 K and Nominal Operation (via CRYO2)

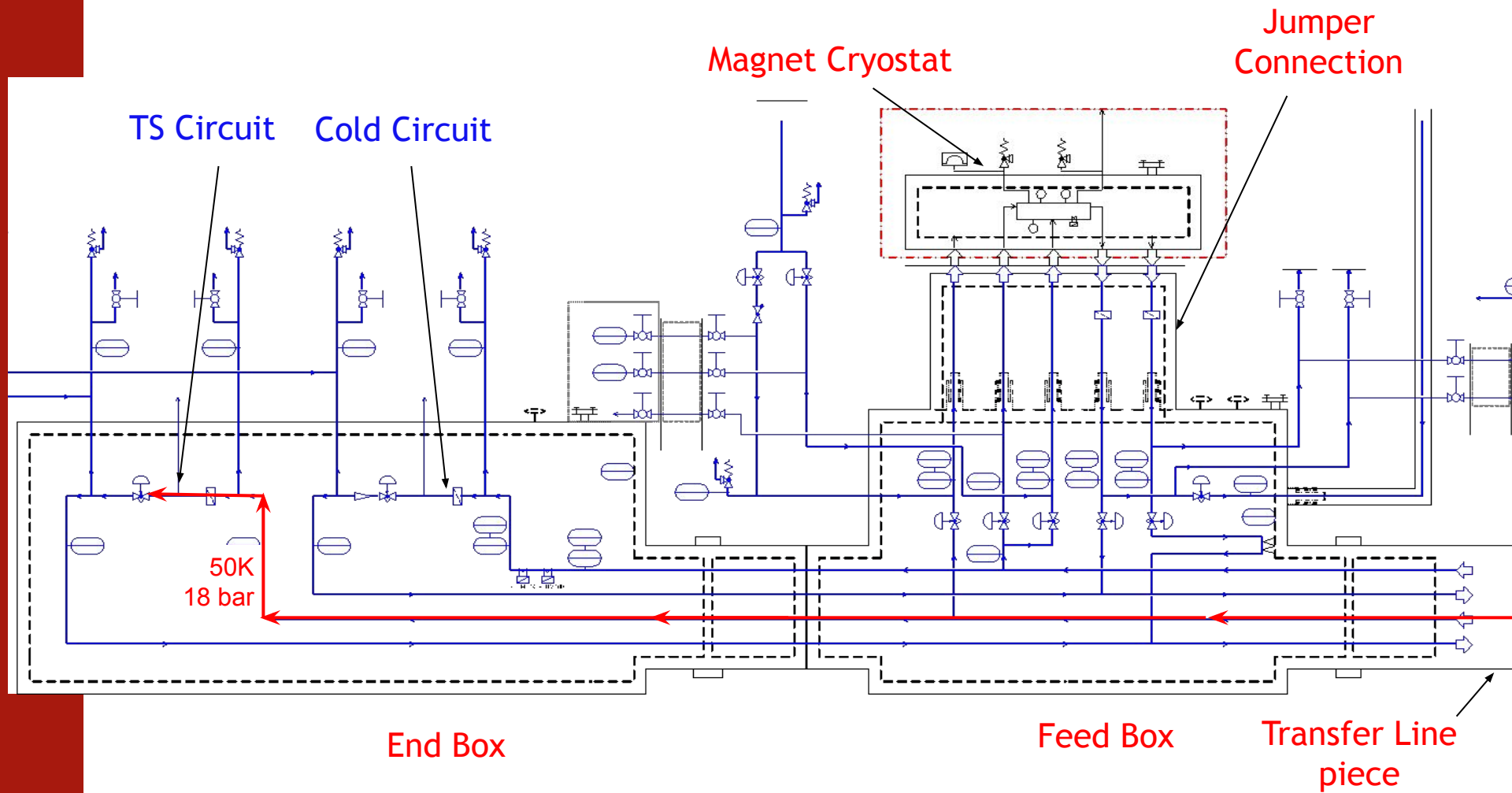




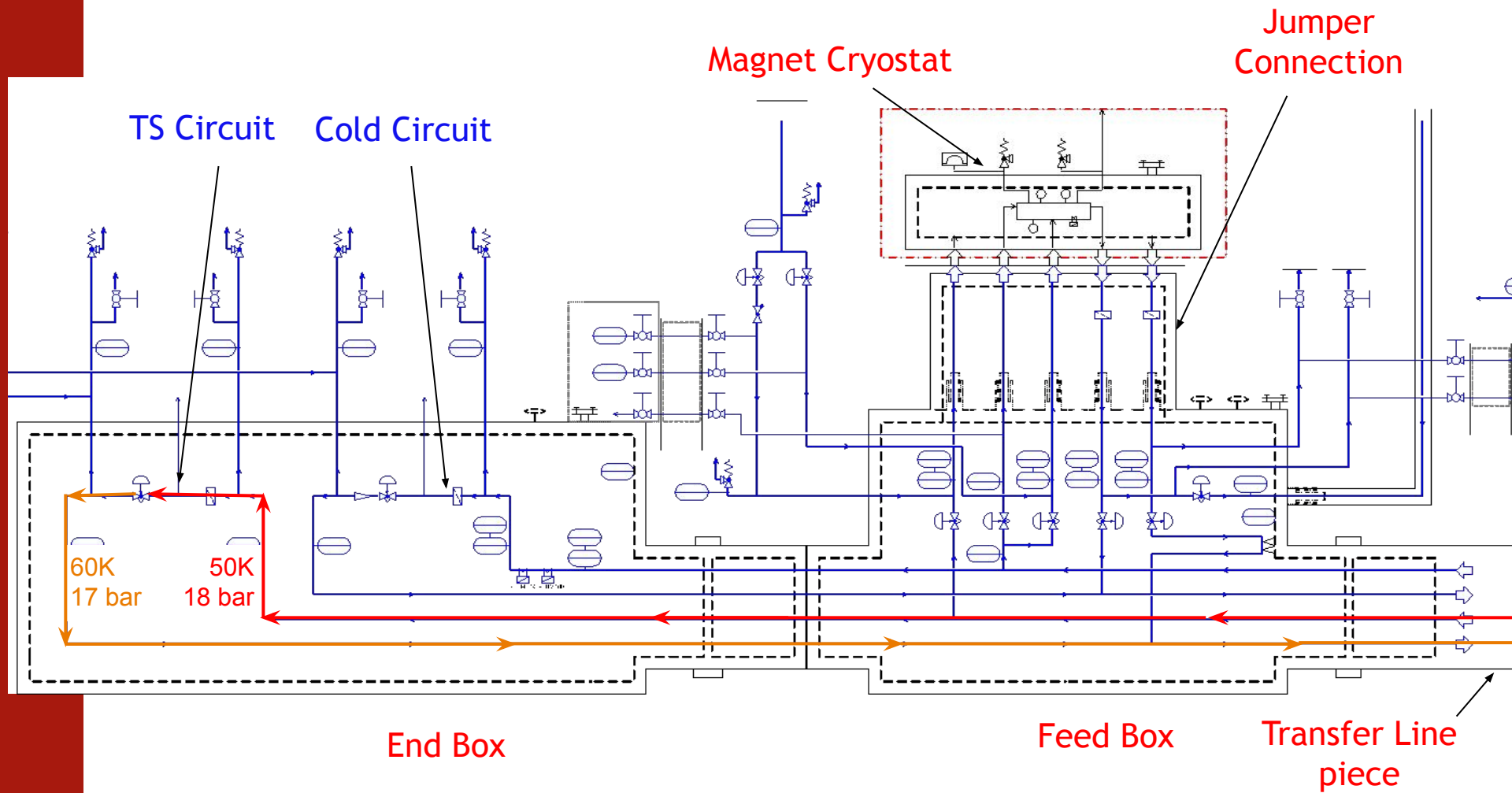
Feed Box Group cool-down phase



Feed Box Group nominal operation

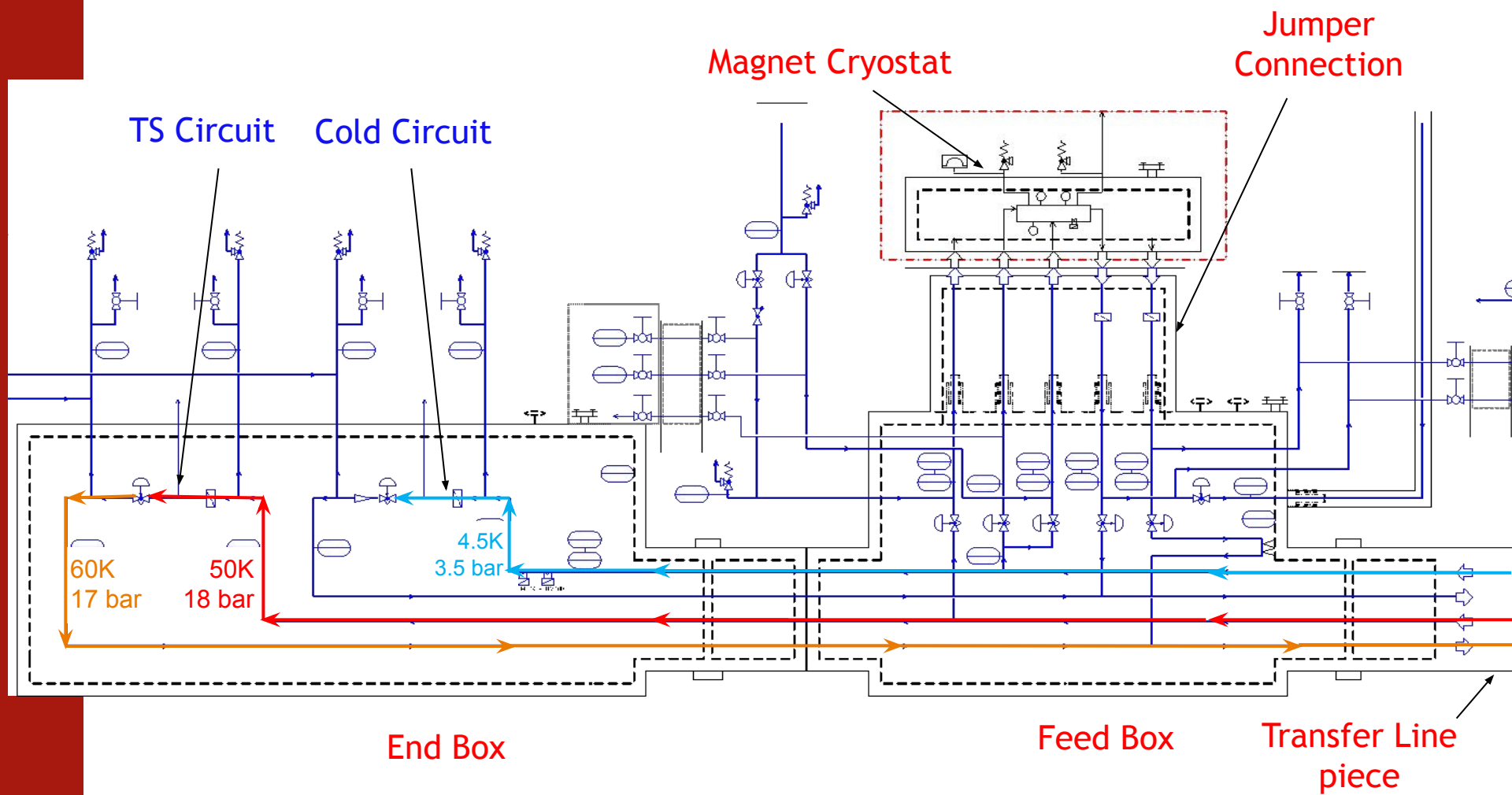


Feed Box Group nominal operation

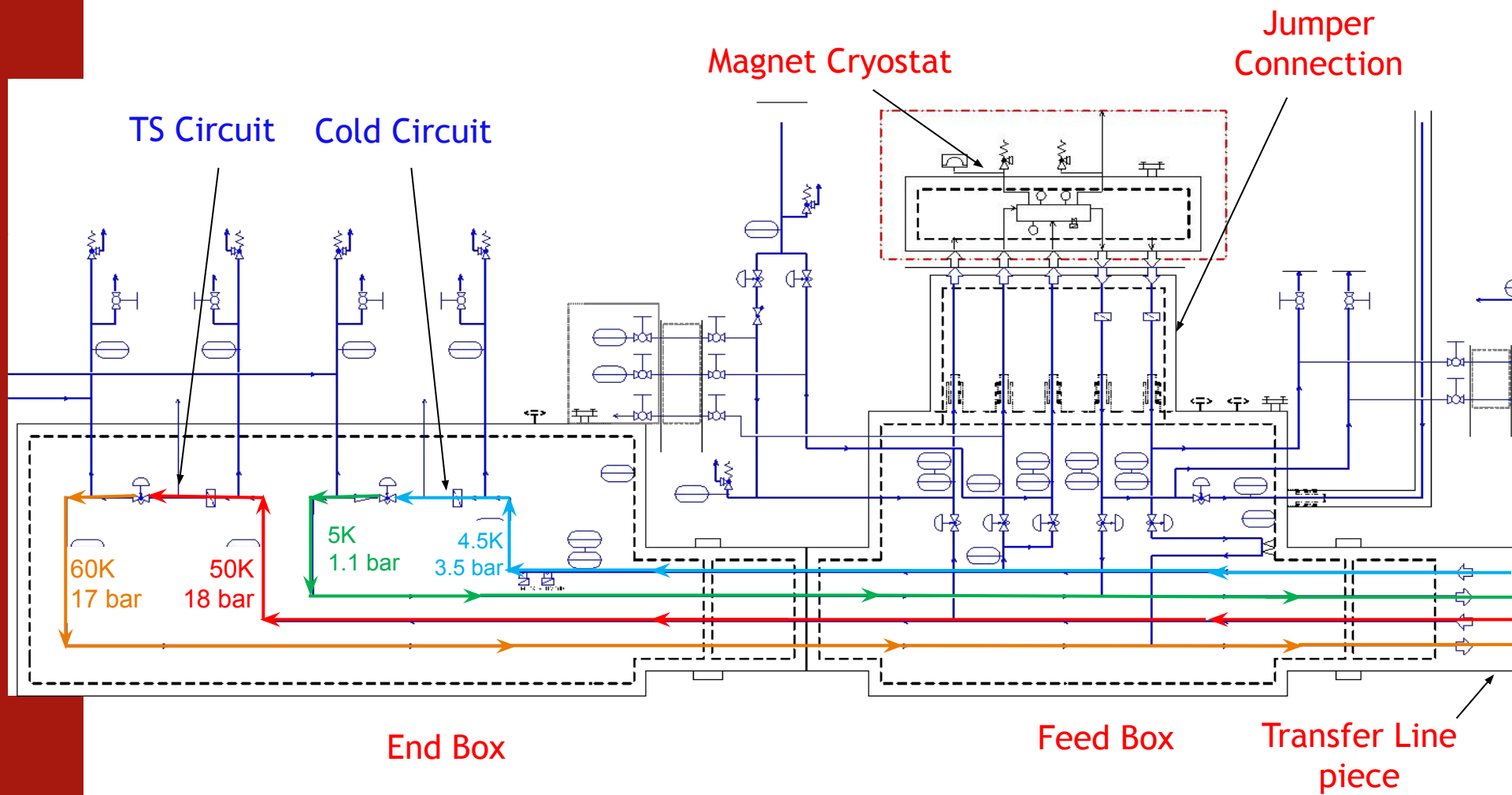




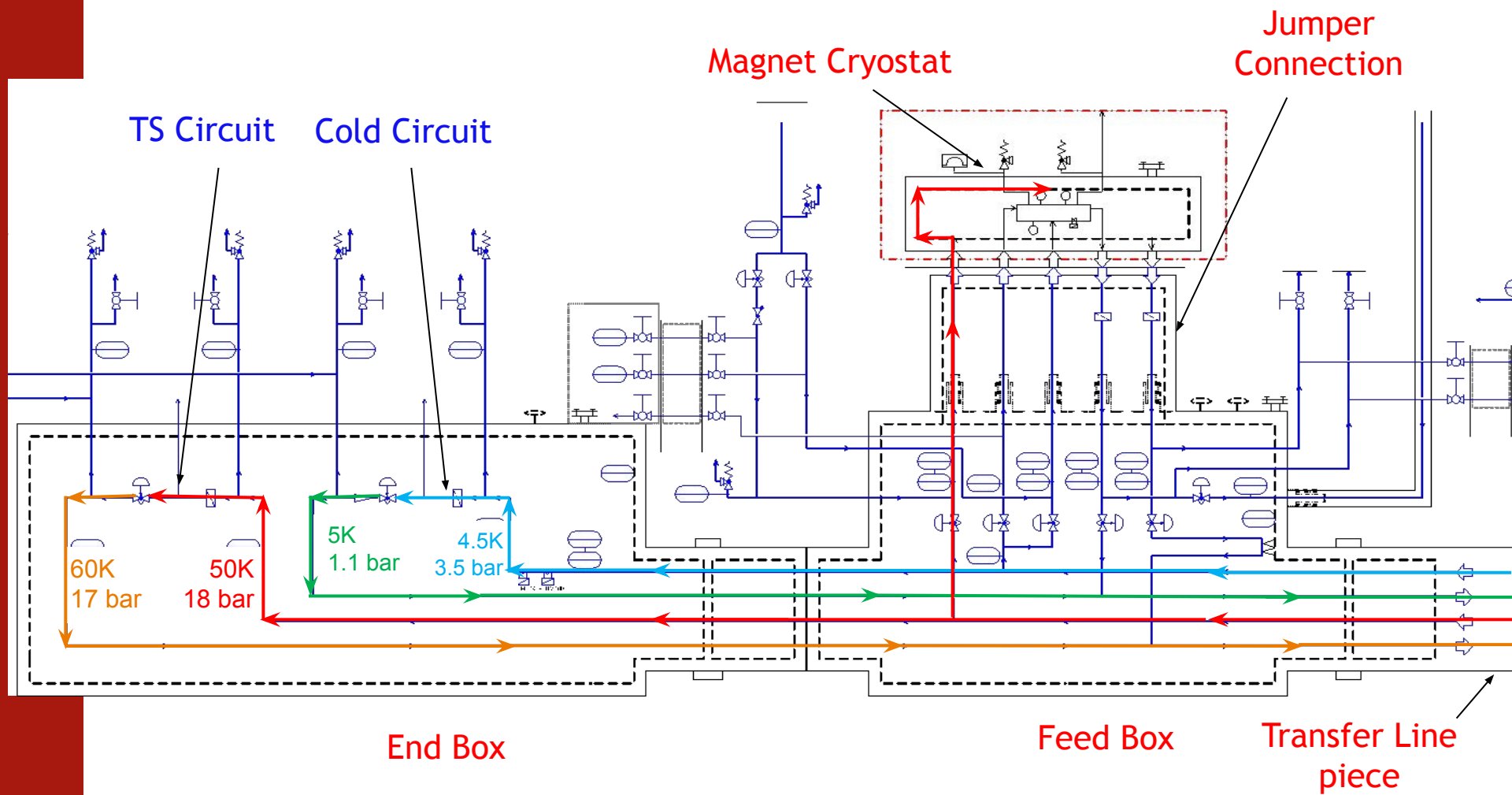
Feed Box Group nominal operation



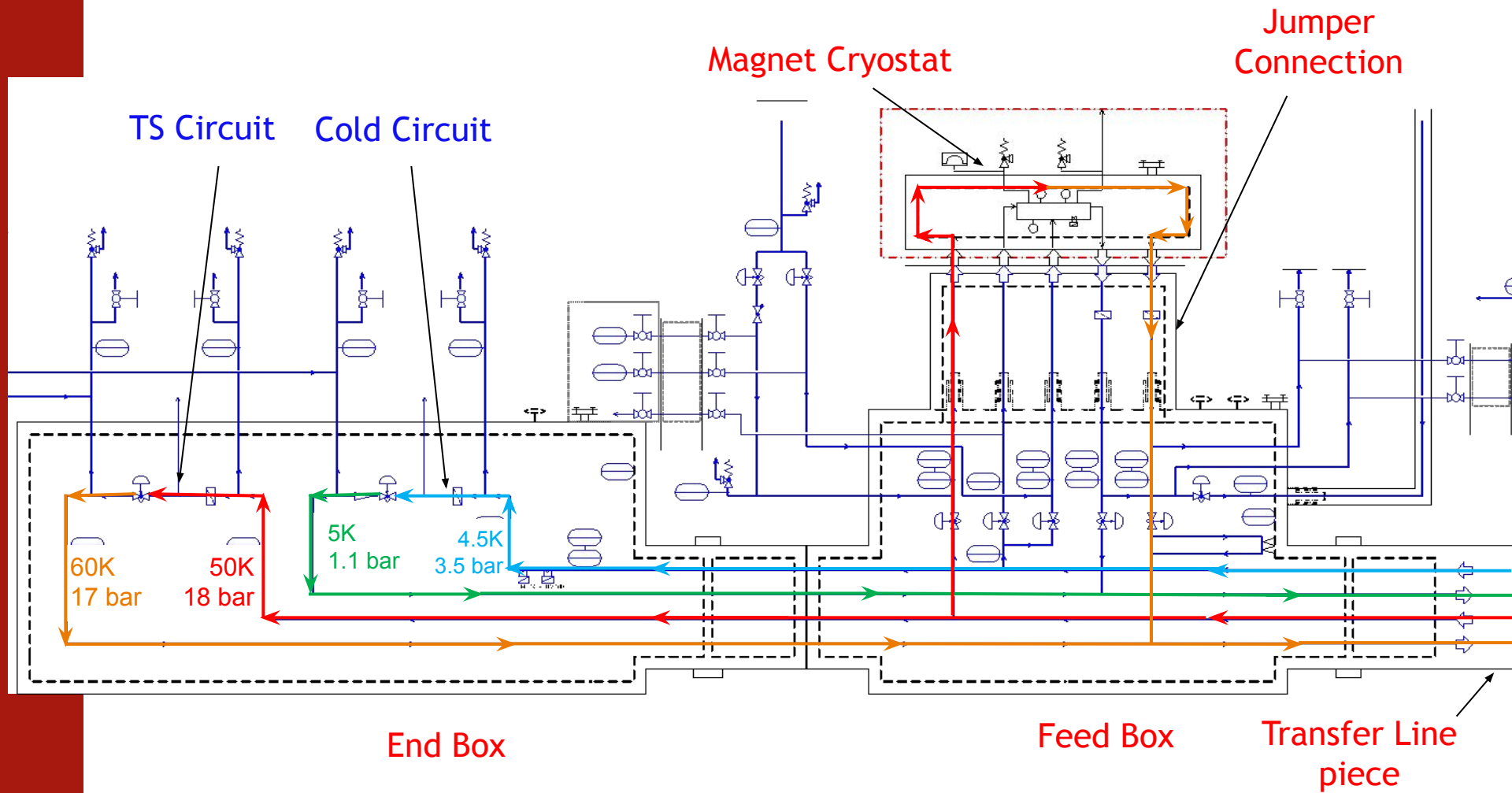
Feed Box Group nominal operation



Feed Box Group nominal operation

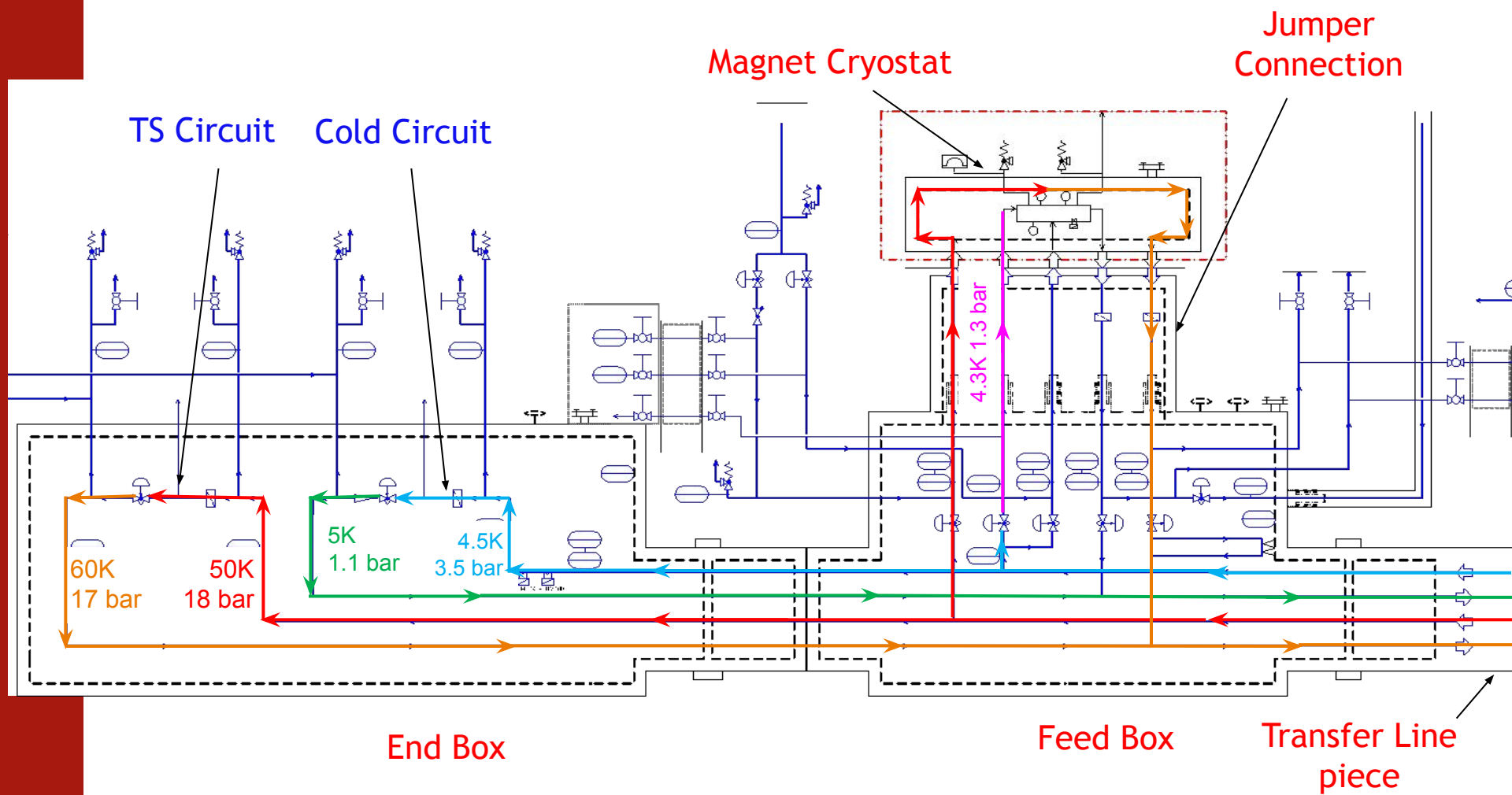


Feed Box Group nominal operation

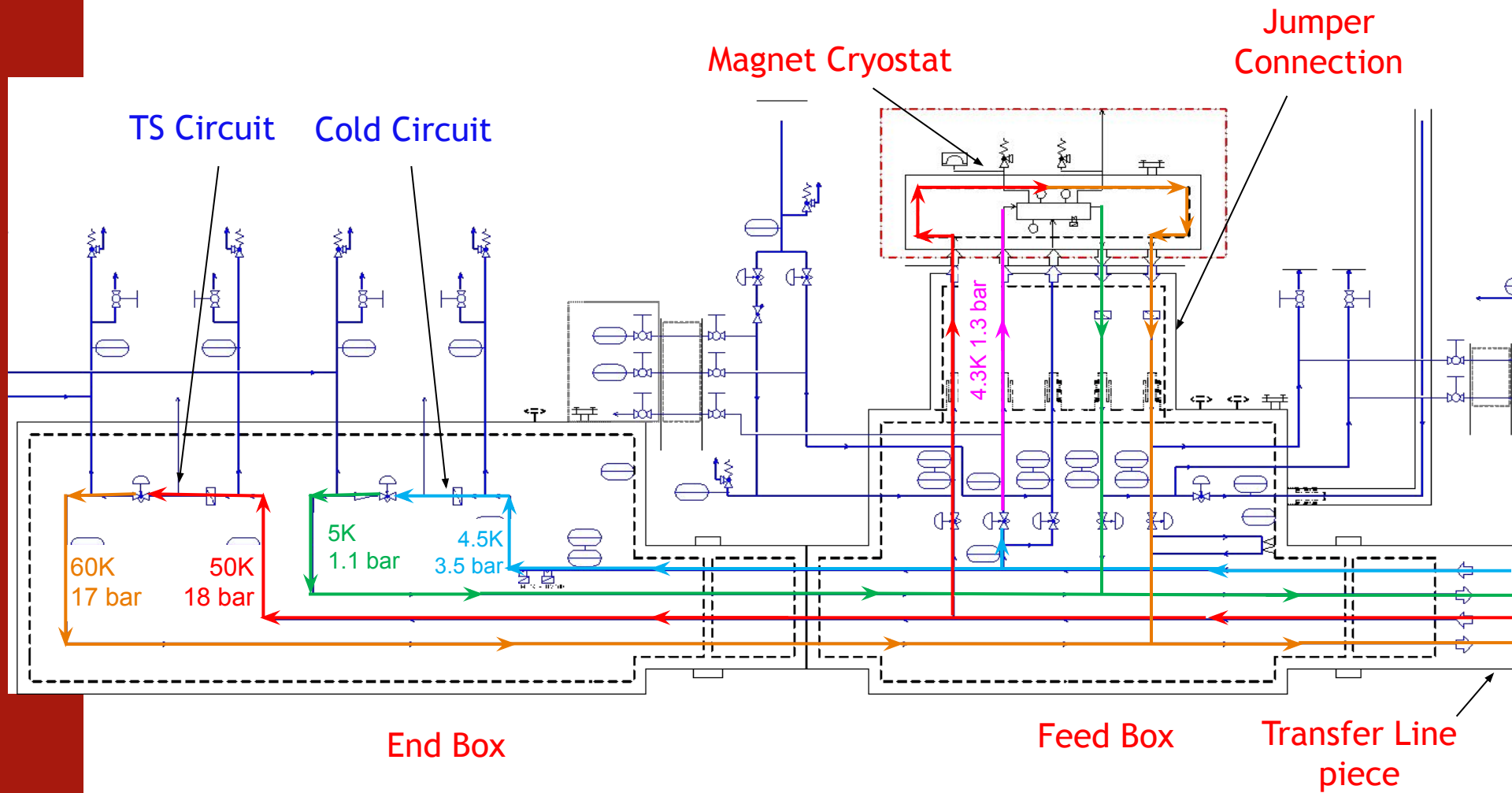




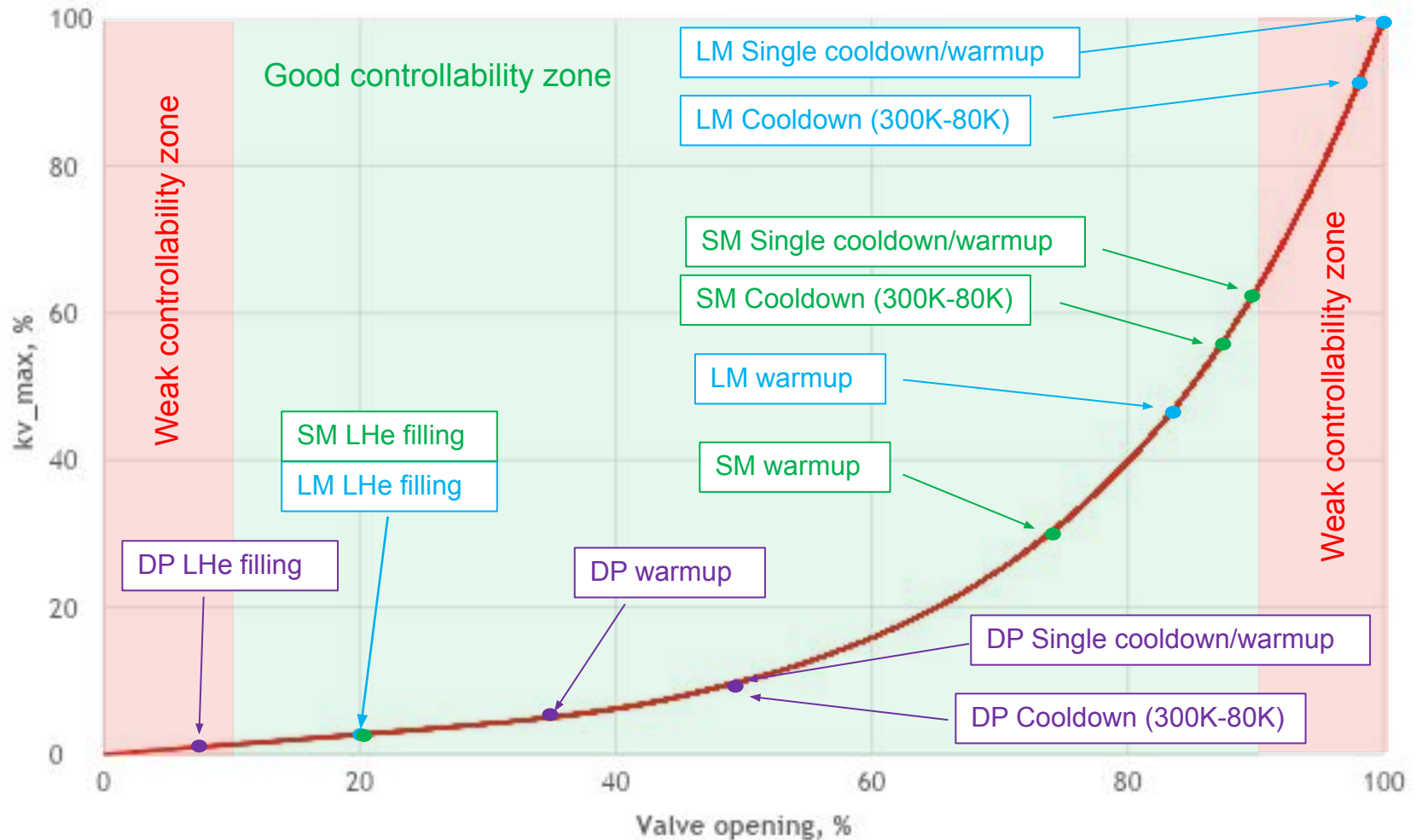
Feed Box Group nominal operation



Feed Box Group nominal operation

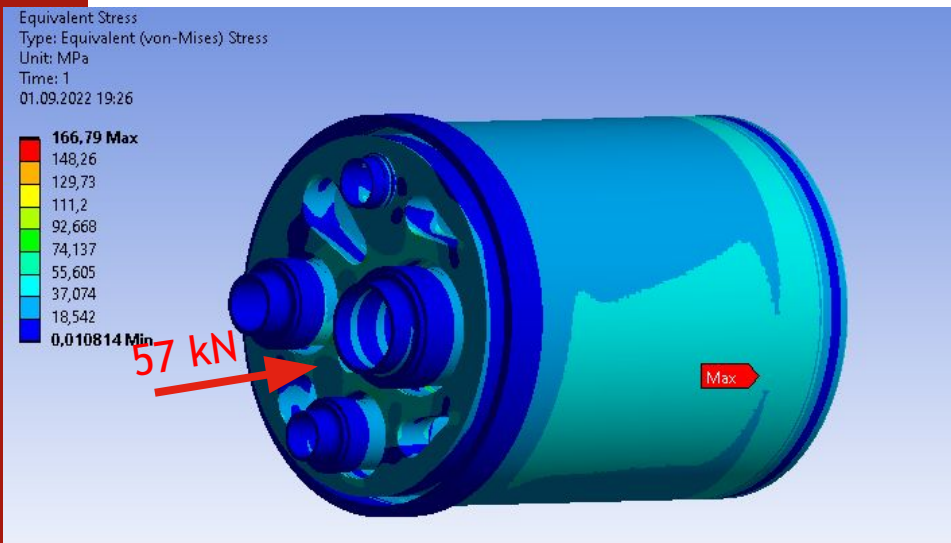


QNP102 valve sizing results

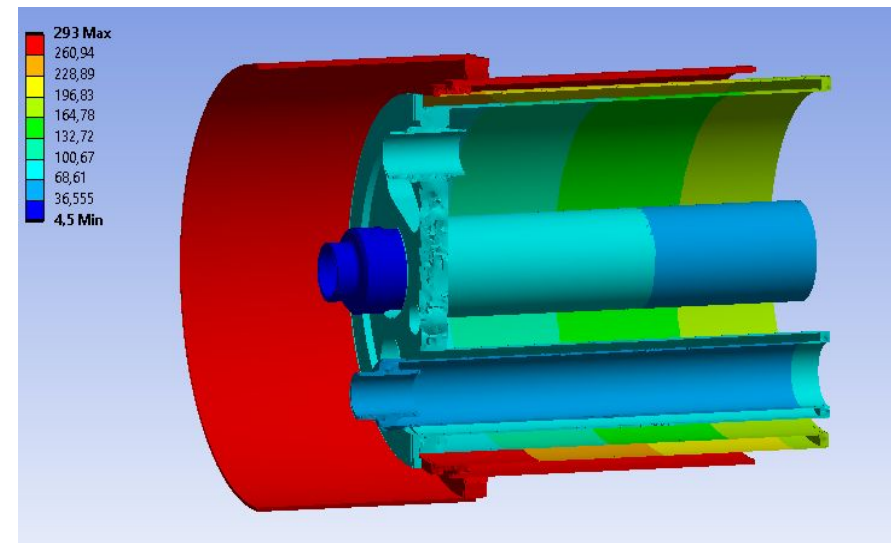


Structural analysis

Thermo - mechanical optimization - Fix supports



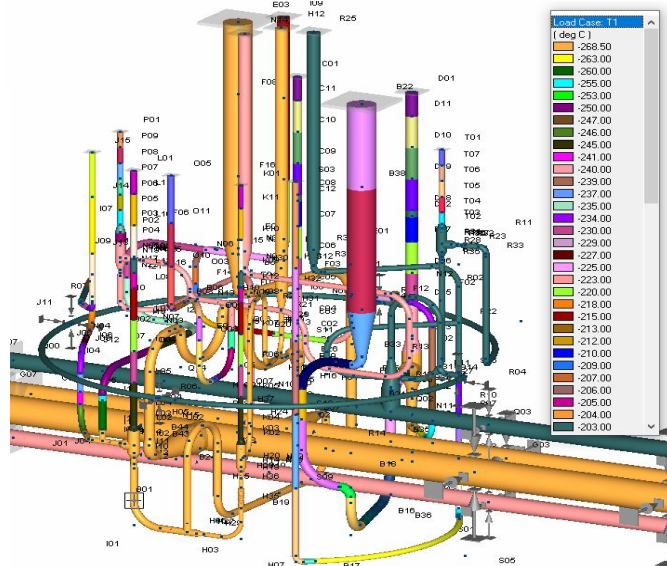
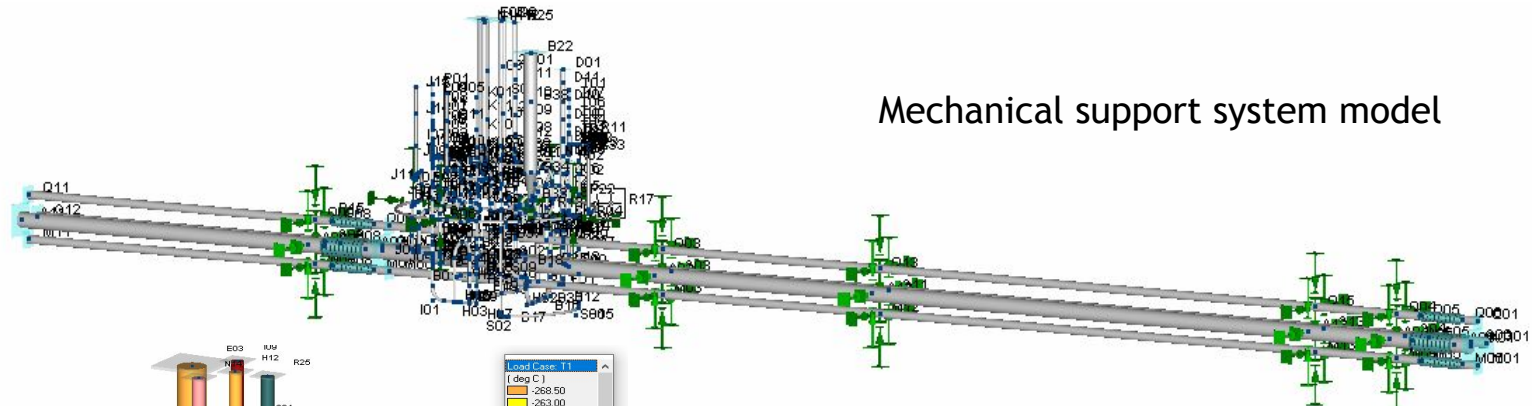
Stress distribution
15 load cases analysed



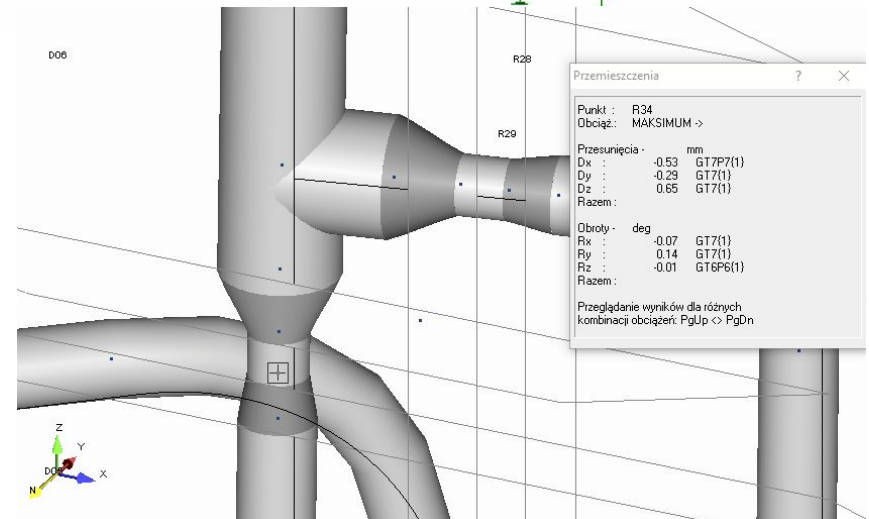
Temperature distribution

Hydraulic system - flexibility analysis

Mechanical support system model



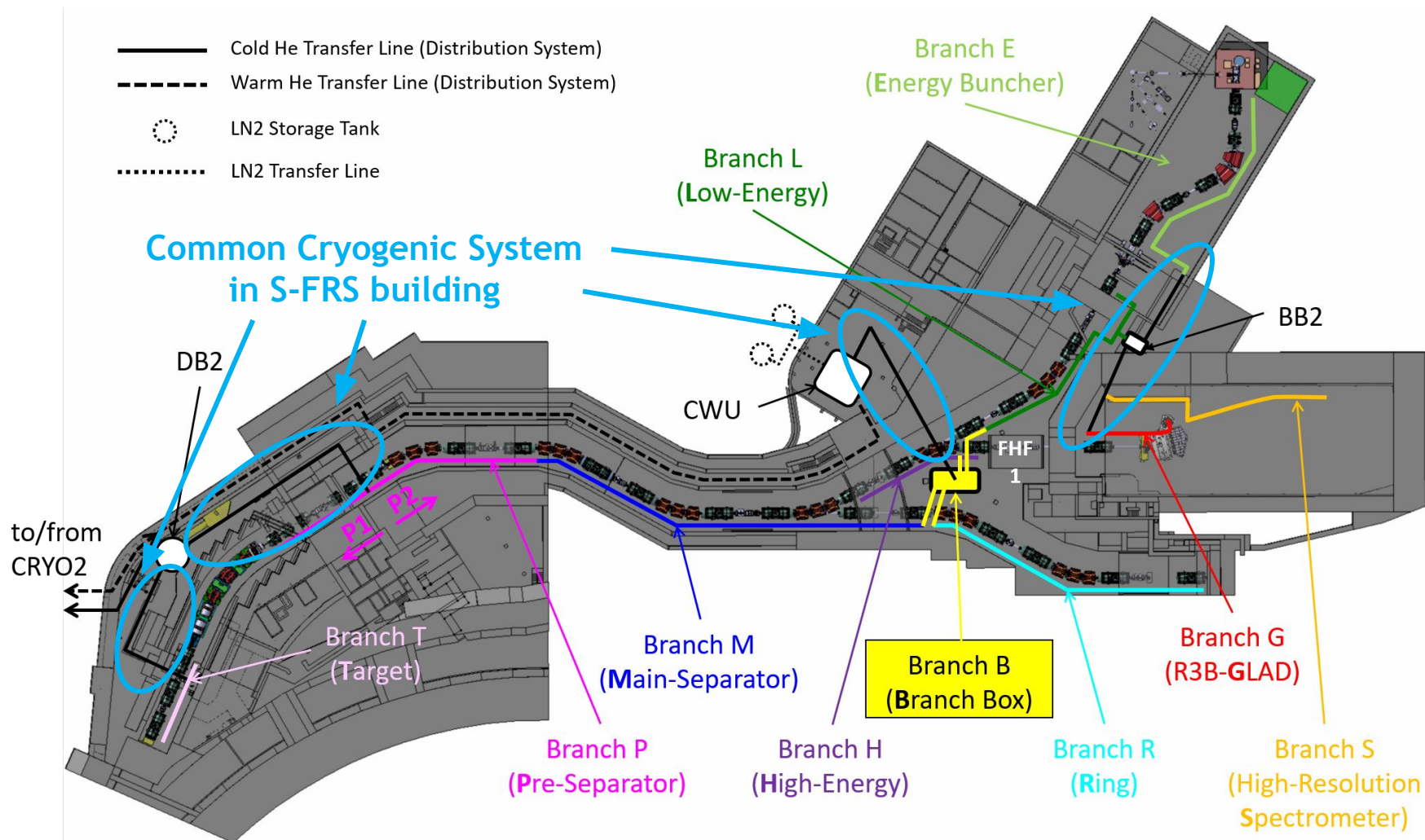
Thermo-mechanical model
(7 load cases analyzed)



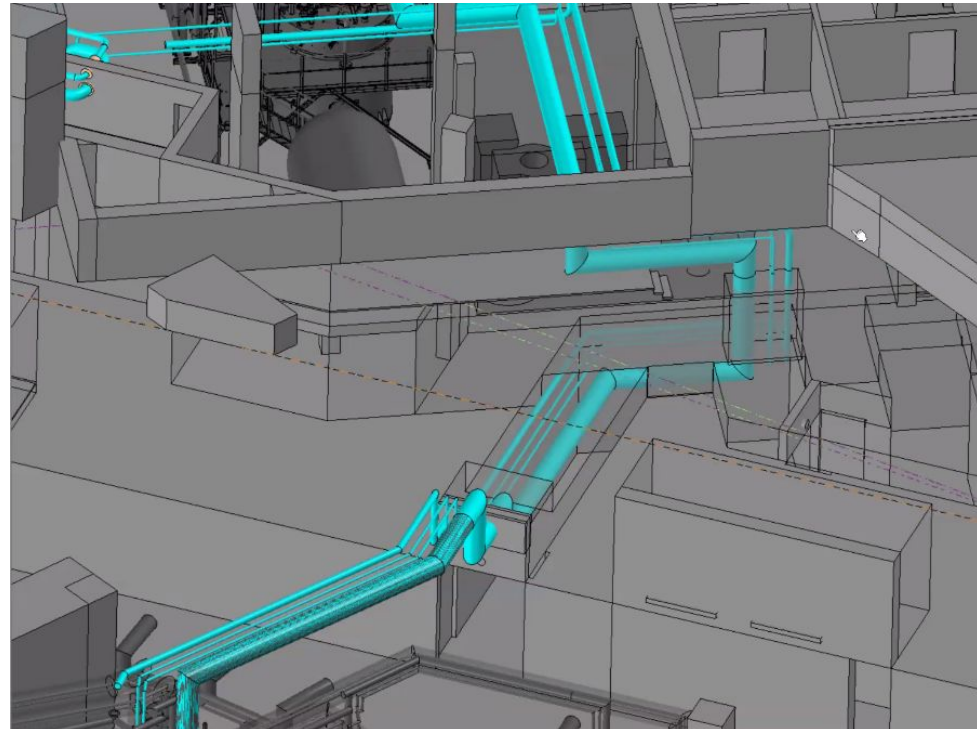
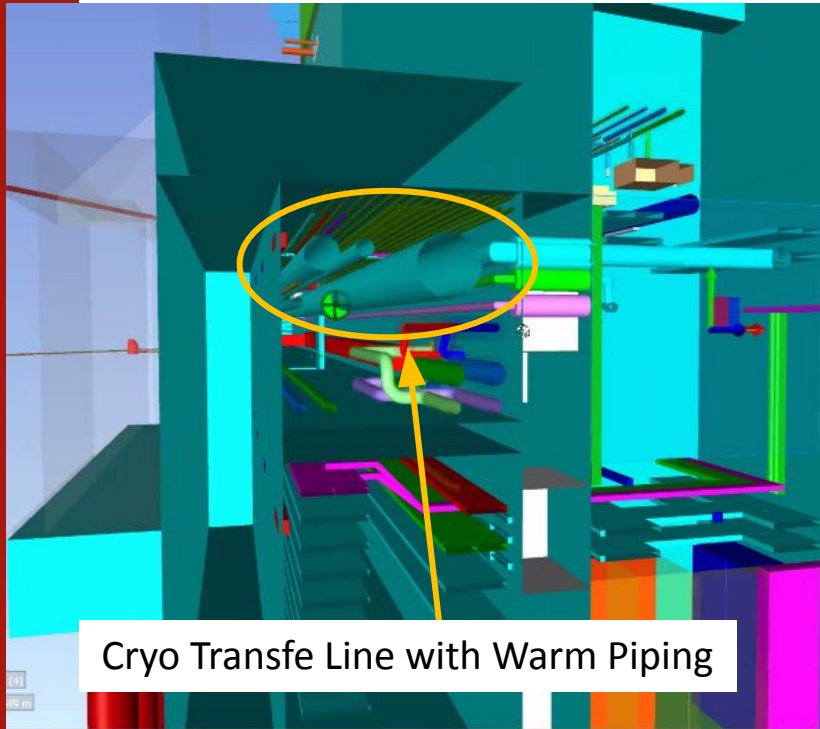
Control Valve head displacement



Layout of the S-FRS Common Cryogenic System



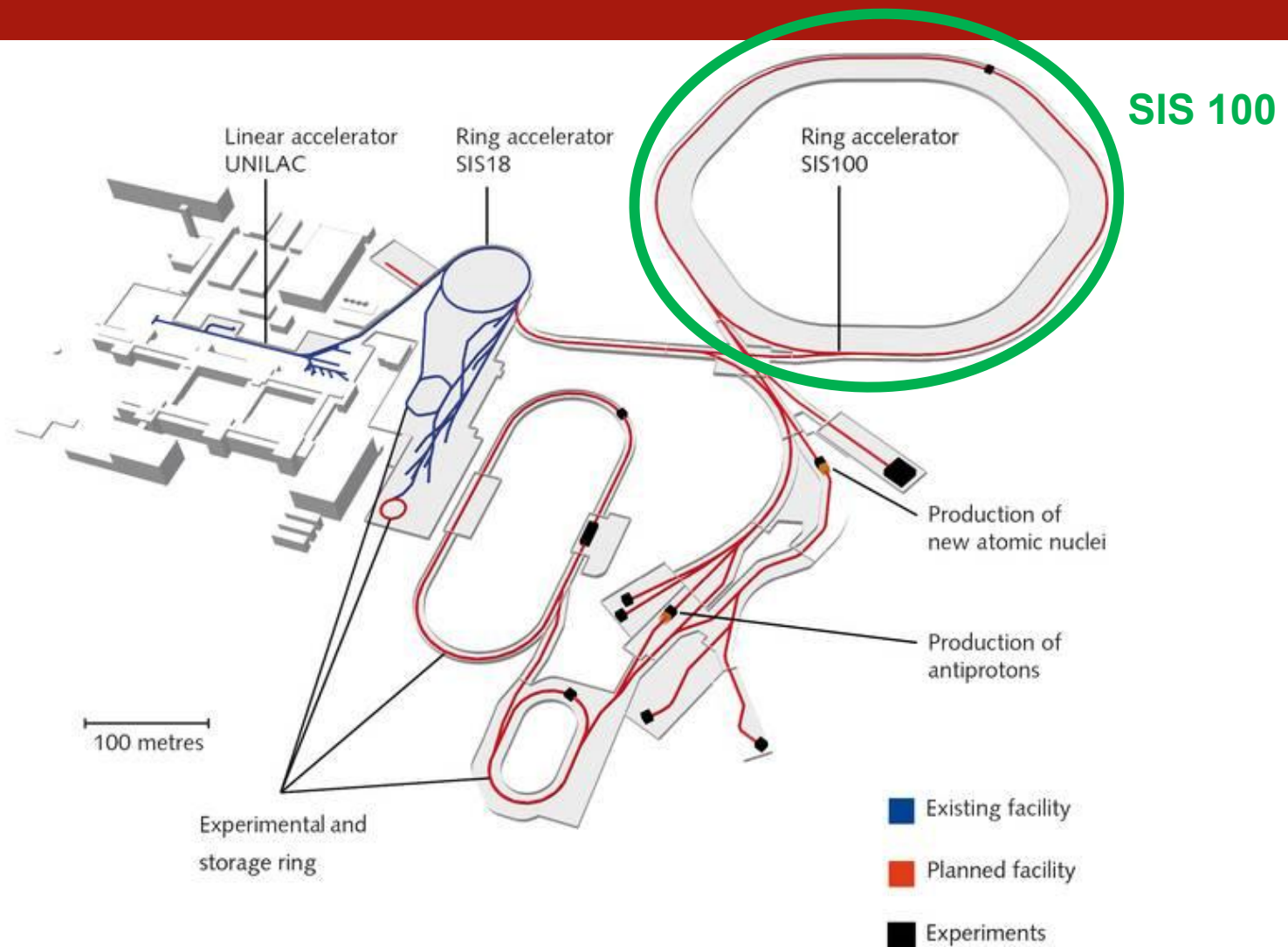
Common Cryo in S-FRS building



Very constricted space:

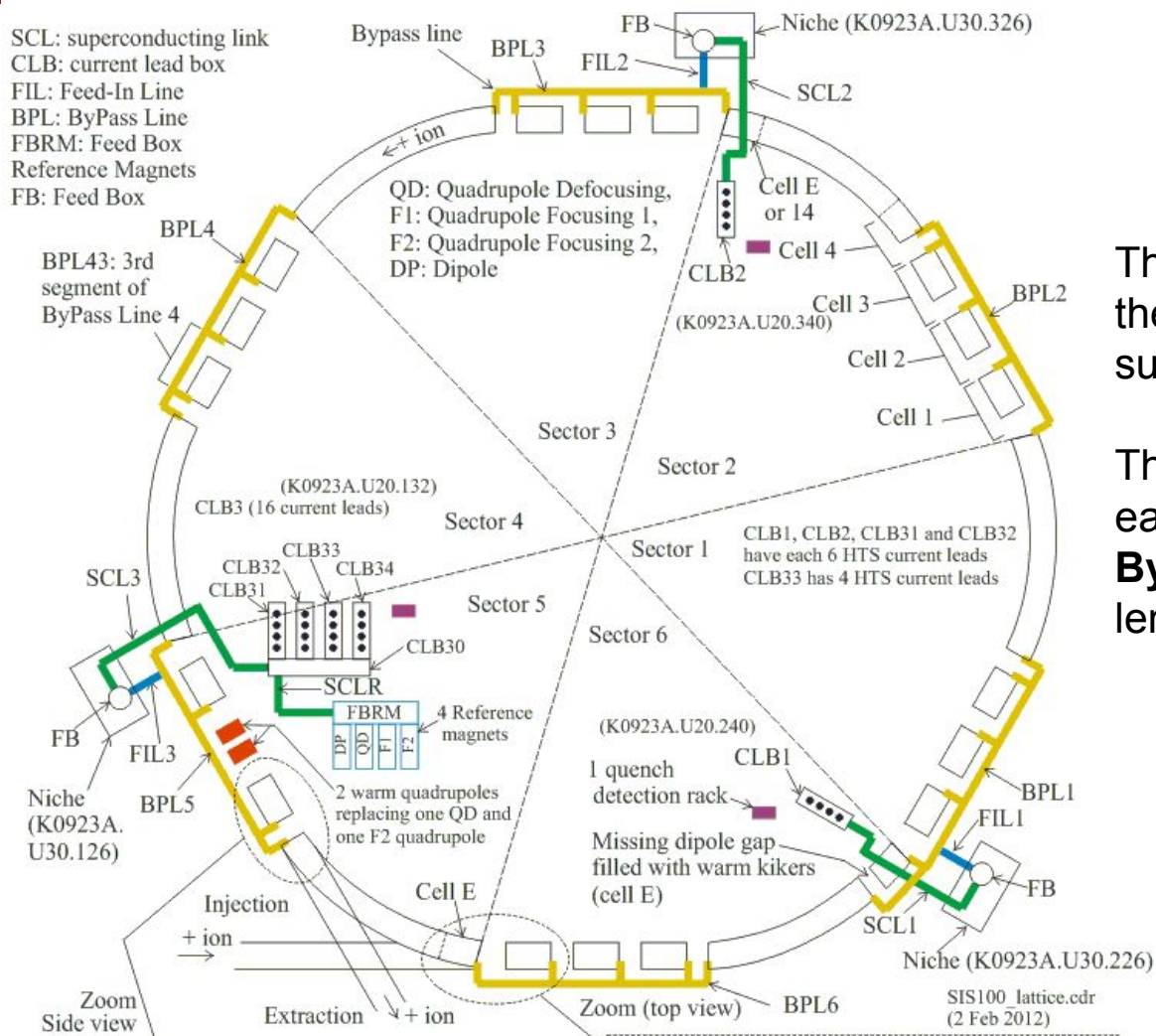
- Small space for transporting system components in the building -> a large number of TL modules with short lengths -> can lead to high heat loads
- A large amount of installation work,
- The transfer of loads (other than weight) from the Common Cryo to the building structure is not allowed

Outline of the FAIR accelerator complex





Local cryogenic system of FAIR SIS100



The SIS100 ring is composed of the six Cold Arcs containing superconducting magnets.

The Cold Arcs are connected to each other by six **Cryogenic Bypass Lines (BPL)** of total length 288 m.

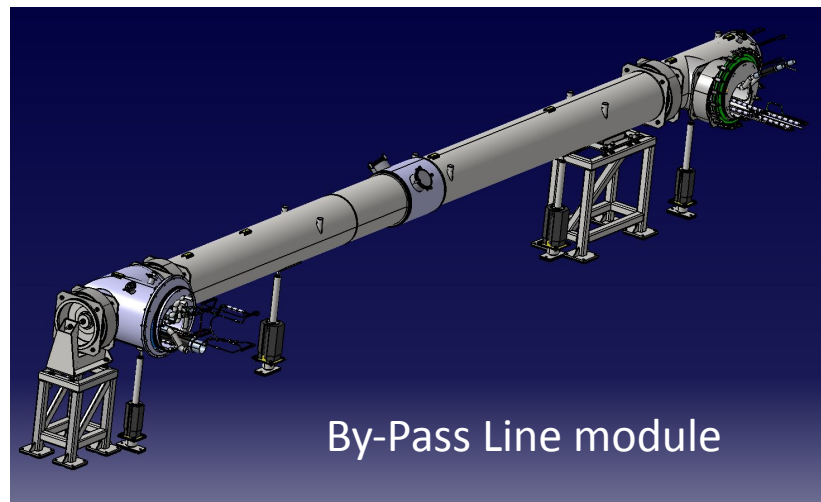
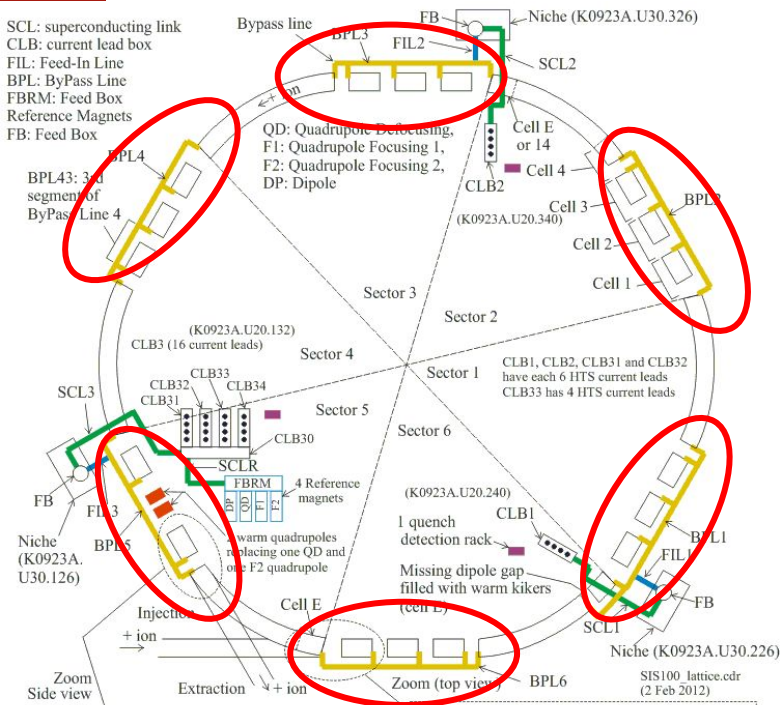


SIS100 Local Cryogenic System purpose

- Provides liquid and gaseous helium to all the magnets of SIS100
- Distributes electric AC current for power and control of magnets by four pairs of superconducting bus bars
- Secures all the magnet process pipes against excessive pressure
- Separates the magnets from external pressure forces
- Measure and control the helium flow through the process pipes



Local cryogenic system of FAIR SIS100



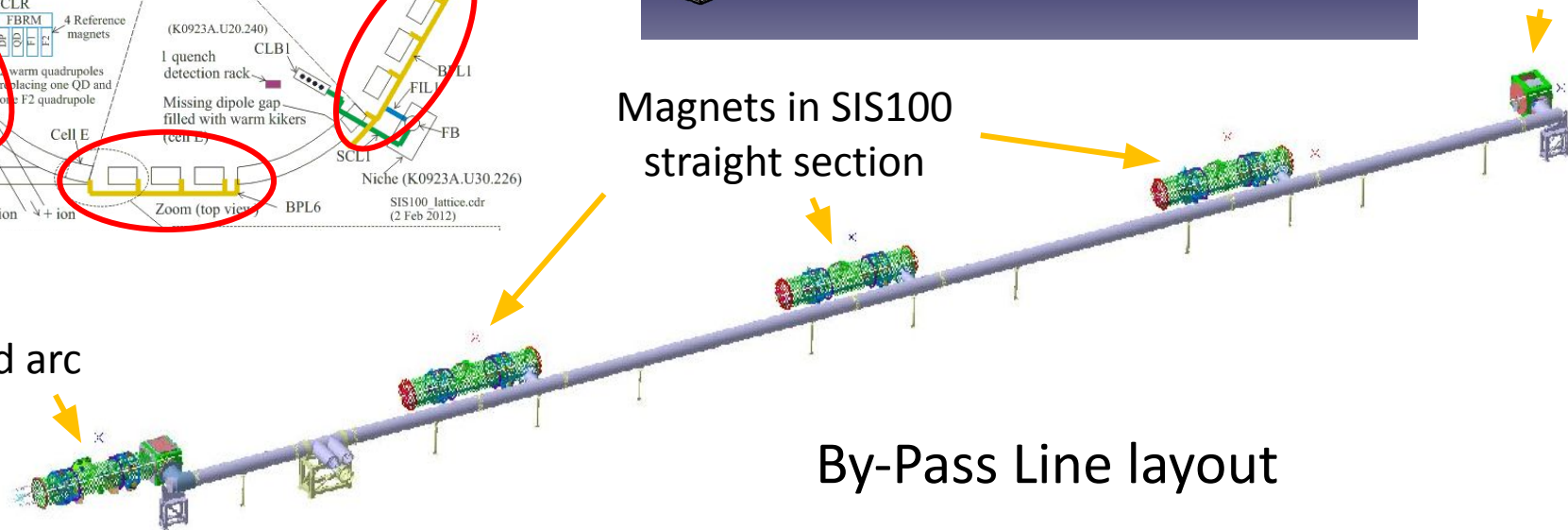
By-Pass Line module

Cold arc

Magnets in SIS100
straight section

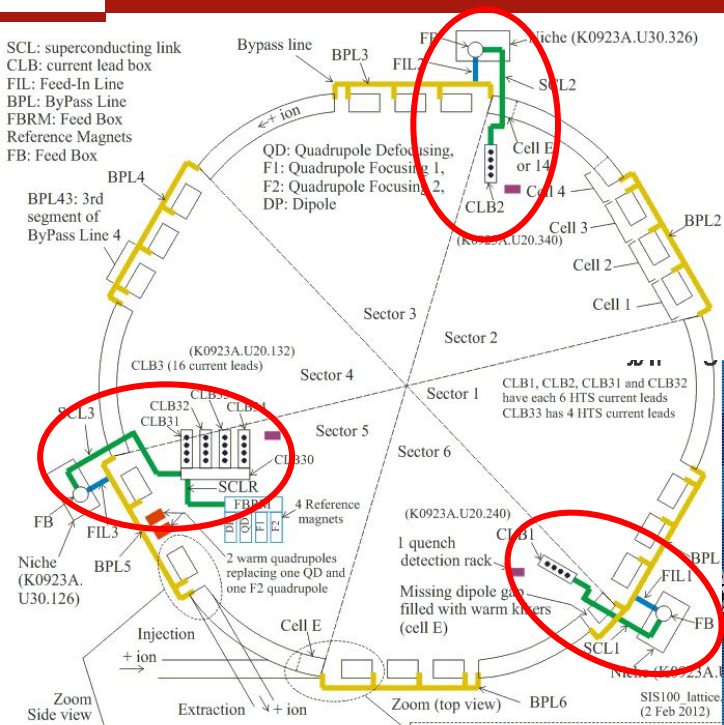
Cold arc

By-Pass Line layout

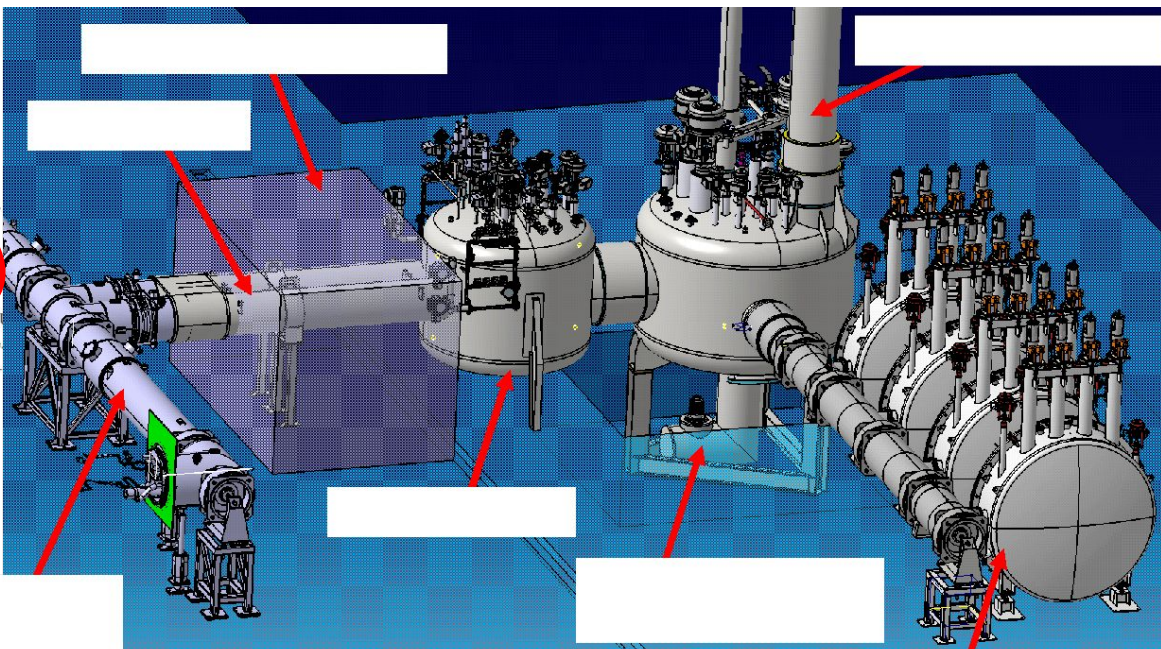




Local cryogenic system of FAIR SIS100

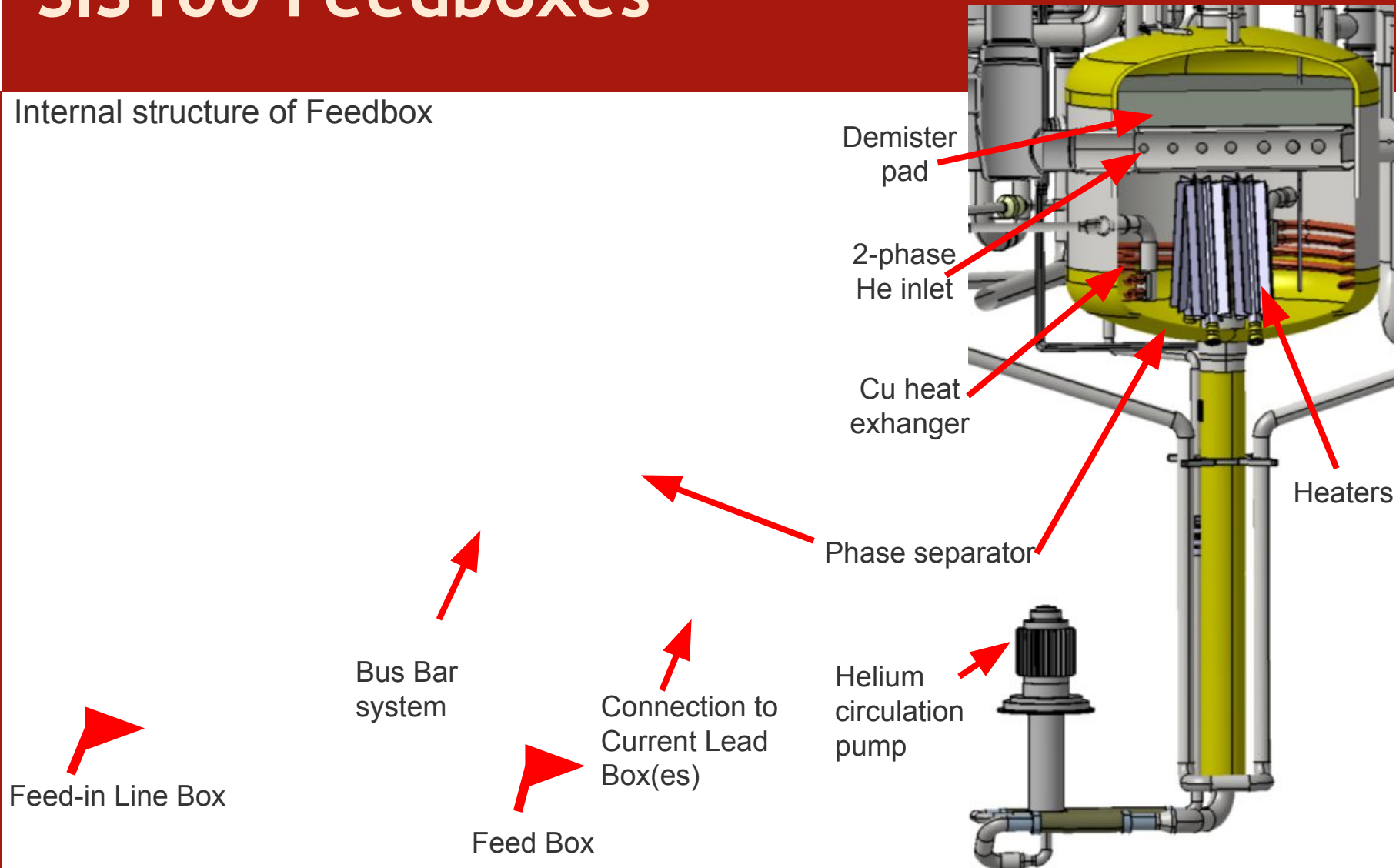


Feed Box + Current Lead Boxes



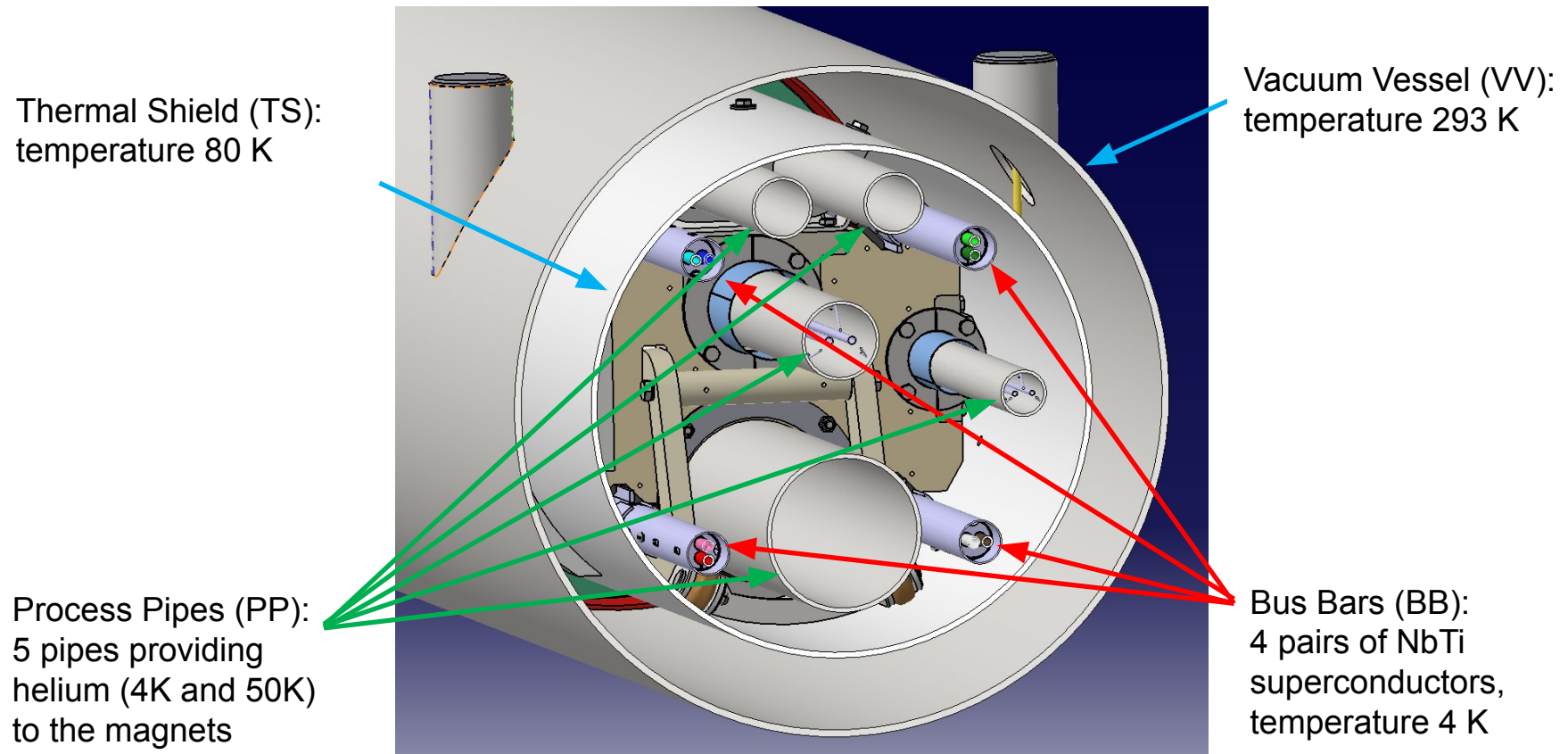
SIS100 Feedboxes

Internal structure of Feedbox



BPL design - internal structure

Cross-section of the Cryogenic Bypass Line

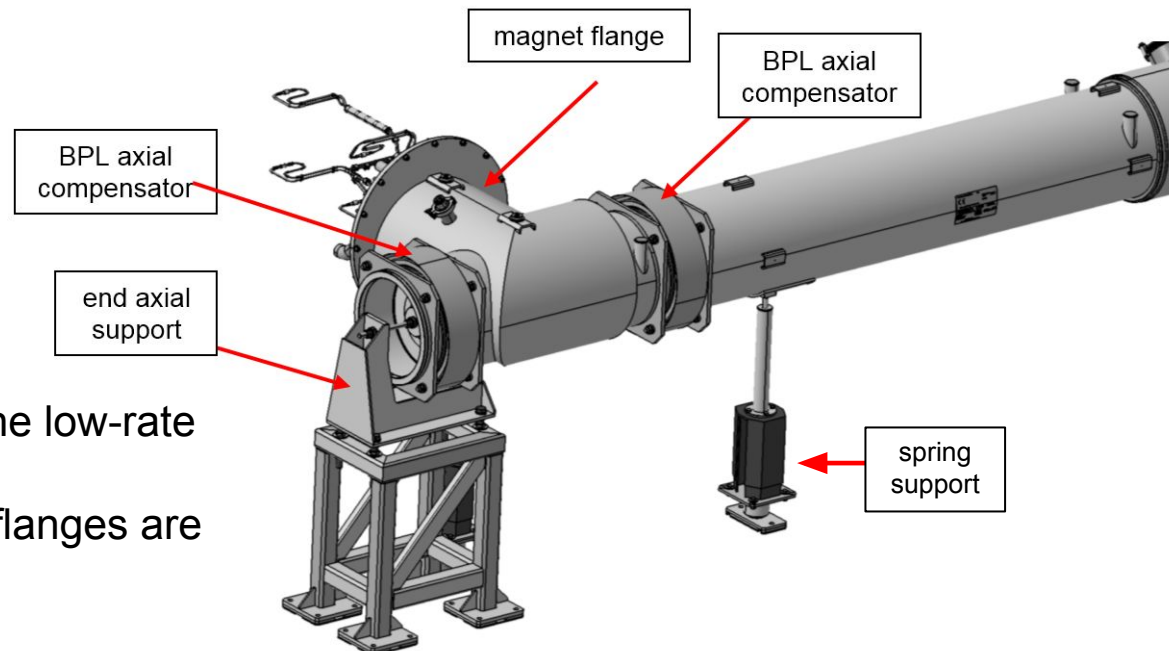


BPL design - floating external supports

The position of the single magnet has to be adjusted with tolerance 0.1 mm on the whole 1.1 km long SIS100 ring. For proper operation, it is crucial to avoid exerting of any significant forces on the magnets.

Simultaneously, many forces are applied to the system:

- external air pressure
- forces due to thermal contraction of the process pipes
- pressurized helium inside (nominal pressure 20 bar)



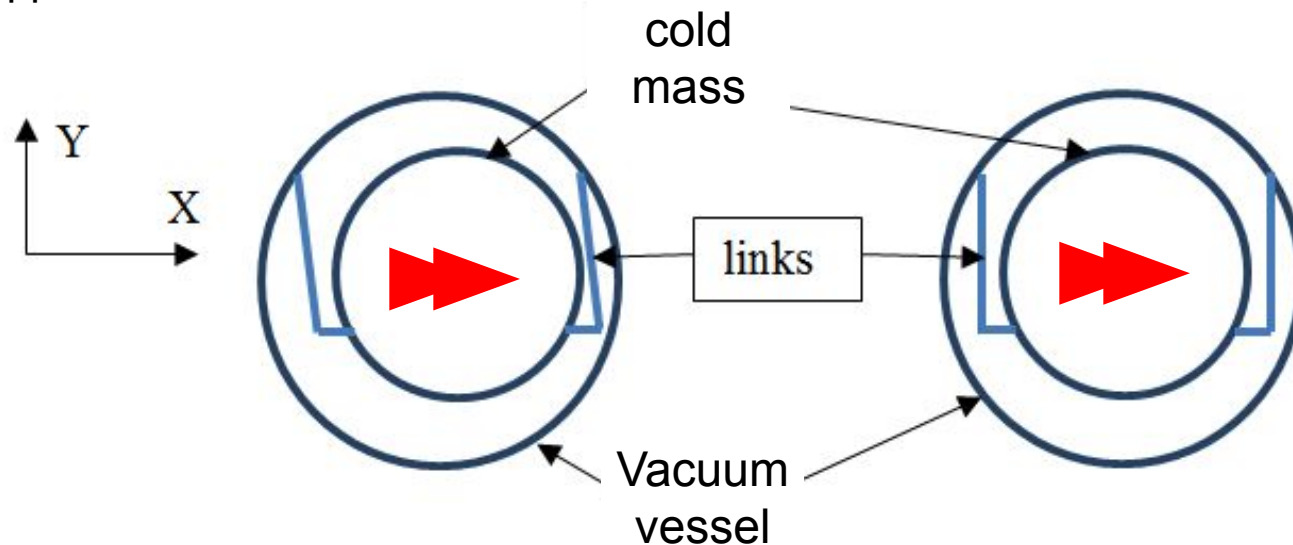
Whole line is suspended mainly on the low-rate springs, segments are separated by axial compensators. The magnet flanges are the only fixed points for BPL.

BPL design - floating internal supports

In order to avoid application of any significant forces on magnet structure, the innovative internal suspension system has been developed.

In BPL it is necessary to allow not only a movement of cold mass along pipe on sliding supports, but in transversal direction too.

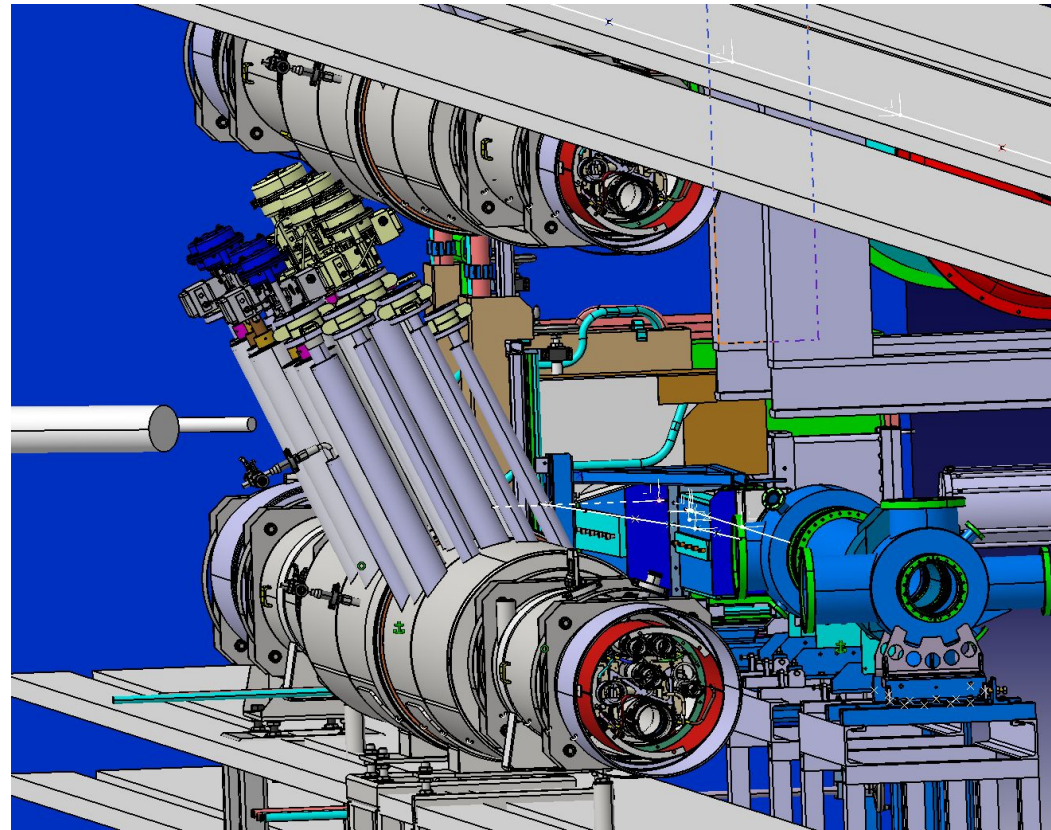
The internal cold mass of the Bypass Line is designed as „floating”, instead of traditional sliding supports.



BPL design - crowded environment

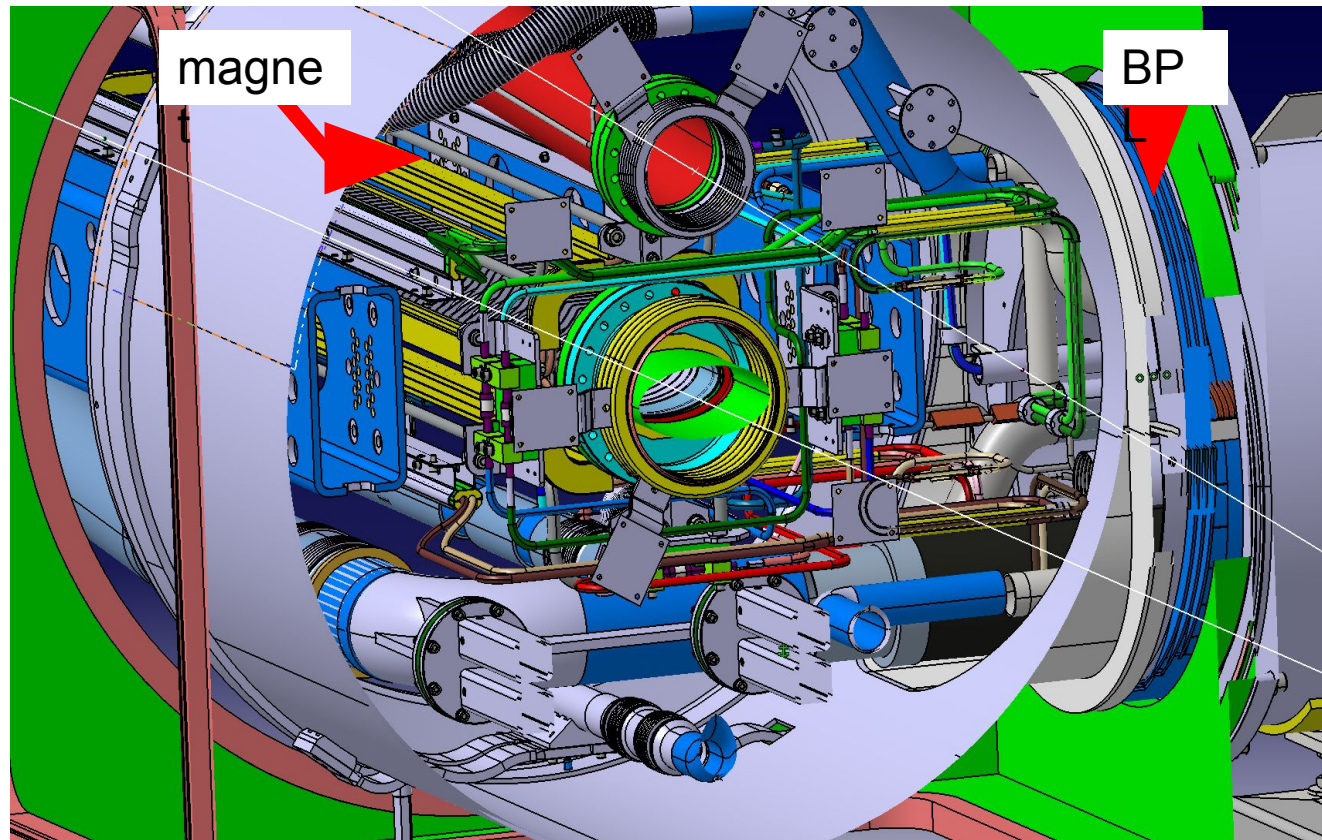
The Bypass Line modules have to fit into existing environment:

- space reservation for BPL was done before design starts and was underestimated
- all other devices have higher priority than BPL - hard to change
- *in situ* assembly procedure very challenging because of limited space of tunnel



Real environment of the End Box BPL module

BPL design - magnet interfaces

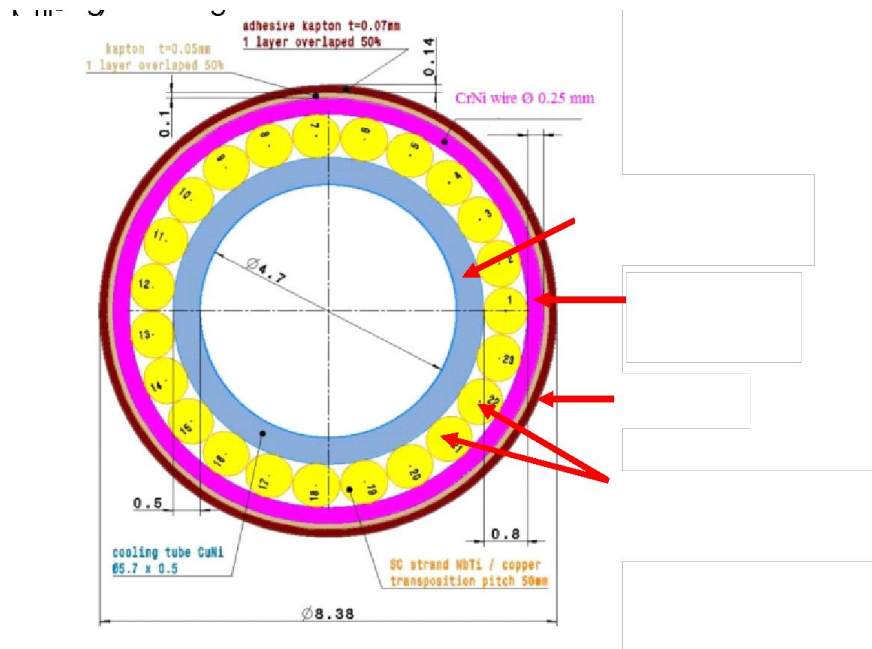


- Magnet design finalized before BPL design
- BPL piping and superconducting busbars have to fit into magnet structure

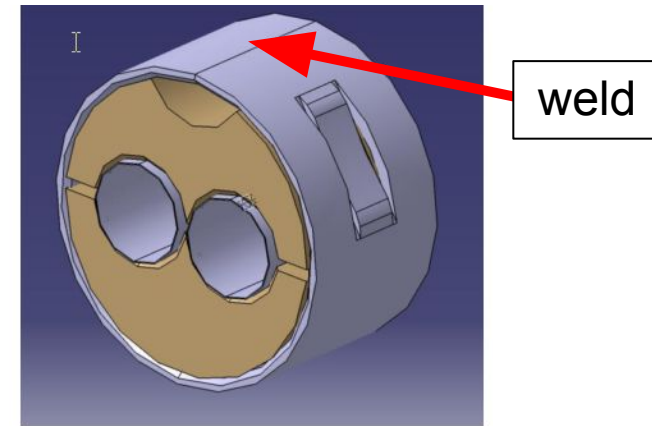
Superconducting cables

Designed Bus Bar clamping system:

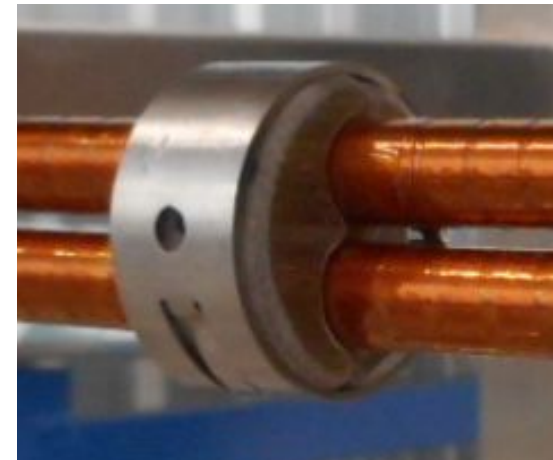
- electrical AC current 13 kA
 - Lorentz force 3.81 kN/m
 - 18 000 clamps on the SIS100 BPL
- > should be simple and cheap!



Cross-section of the superconducting Bus Bar
Nuclotron type - NbTi



The final version of the Bus Bar clamps



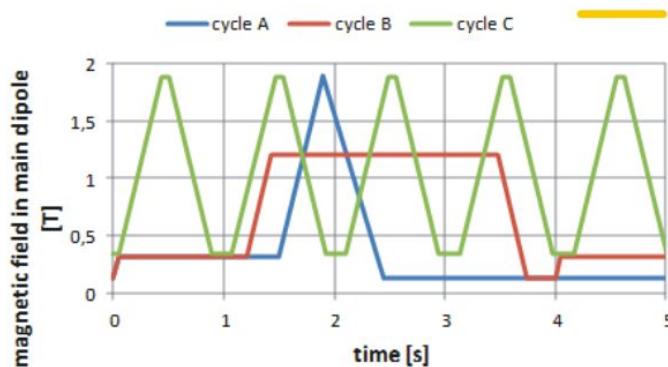
The real BB clamp

Cross-talk between superconductors

For high precision of the magnet control, the **13 kA** AC current in one pair of superconductor is allowed to generate due to electromagnetic cross-talk the maximum **100 mA** current in other pair on the whole SIS100 ring.

Solution:

- Bus Bars in pair clamped together to minimize external electromagnetic field of pair,
- maximized distances between Bus Bar pairs
- optimized orientation of the Bus Bar pairs (twisting)

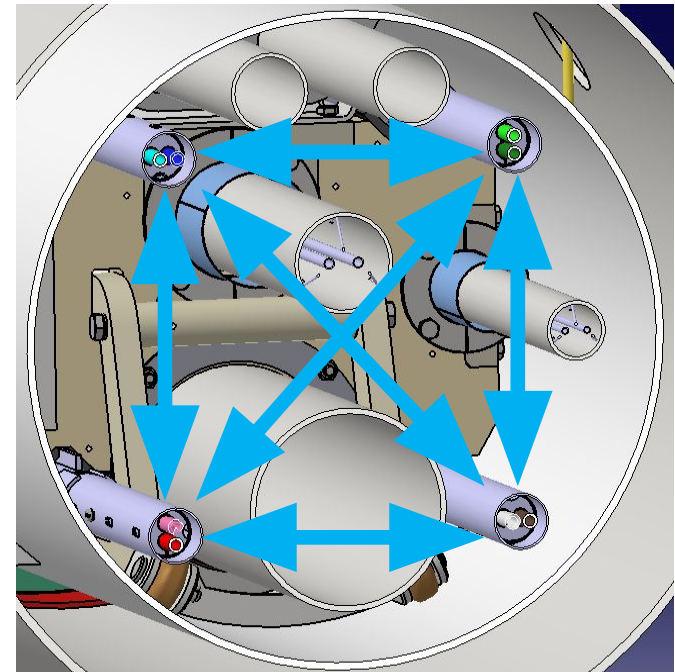


AC current cycles
in Bus Bars

A: Proton cycle (5 s)

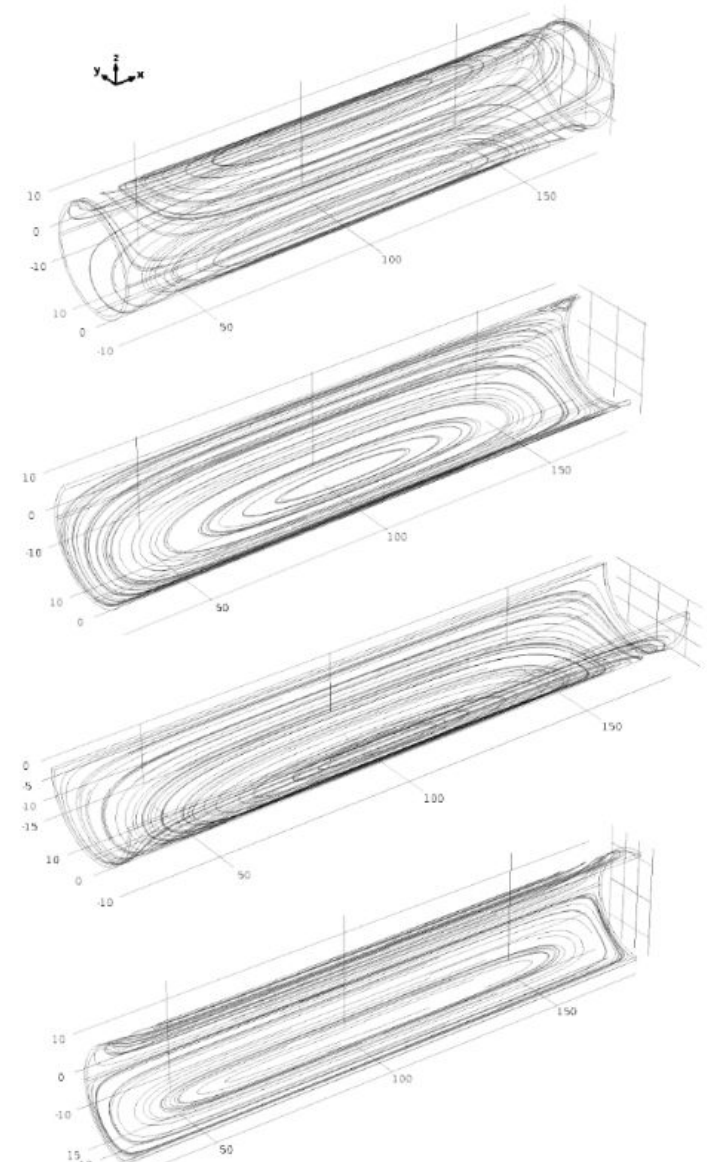
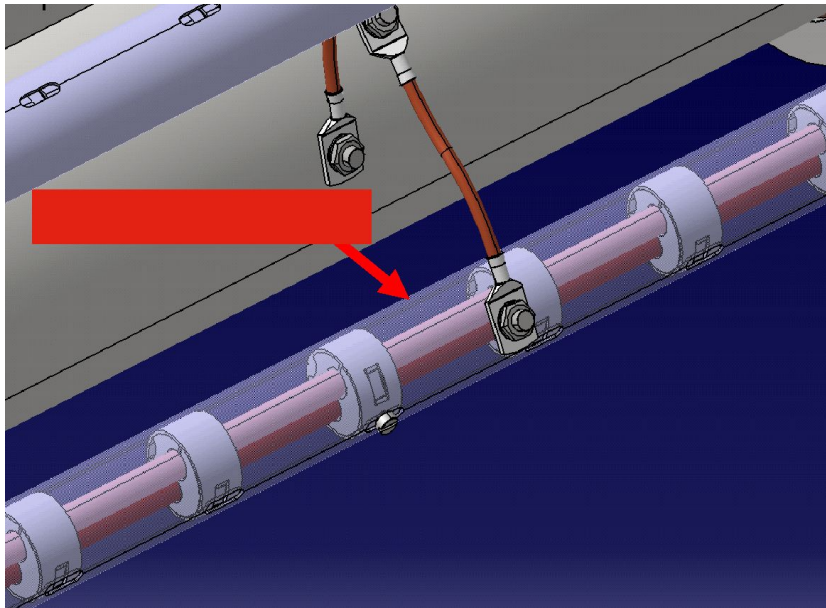
B: RIB cycle U28+ (4 s)

C: triangular cycle U28+ (1.029 s)



Eddy currents

Analysis of heat generation by **Eddy currents** in the Bus Bar mechanical support tube – electromagnetic simulation.



Tomków Ł., Trojanowski S., Ciszek M., Chorowski M., Heat generation by eddy currents in a shell of superconducting bus-bars for SIS100 particle accelerator at FAIR

View of streamlines of Eddy currents for (top to bottom):
full shell, split shell at angle 45 °, 0 °, 90°

Superconducting cables

Thermal compensation system of the Bus Bars to compensate thermal contraction in 12.9 m long module – strongly affected by cross-talk requirements

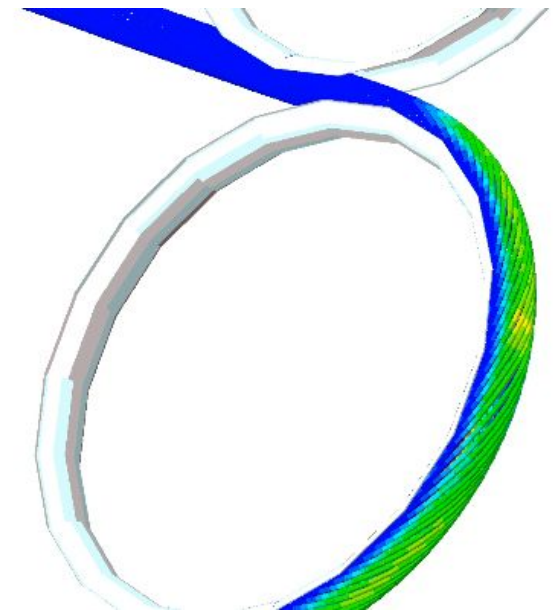
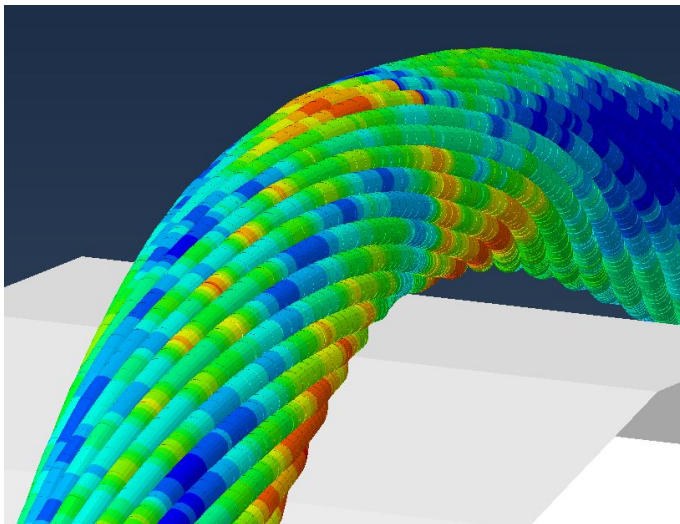
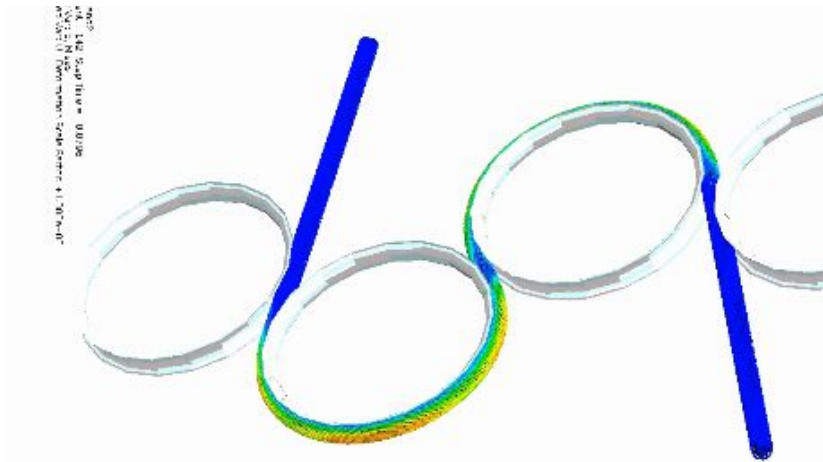


Bus Bars thermal
compensation loop



Bus Bar compensation loop tests at liquid nitrogen

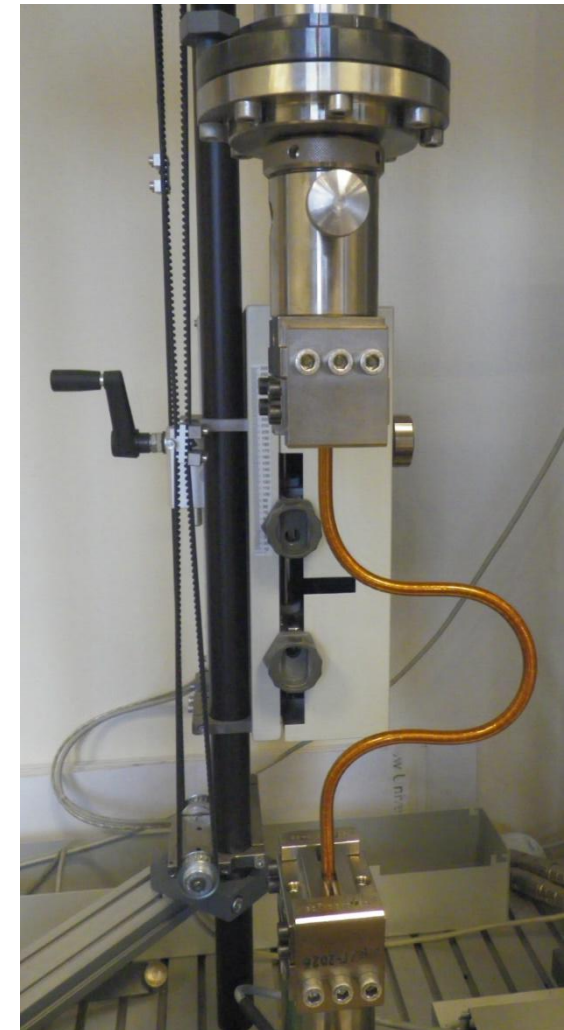
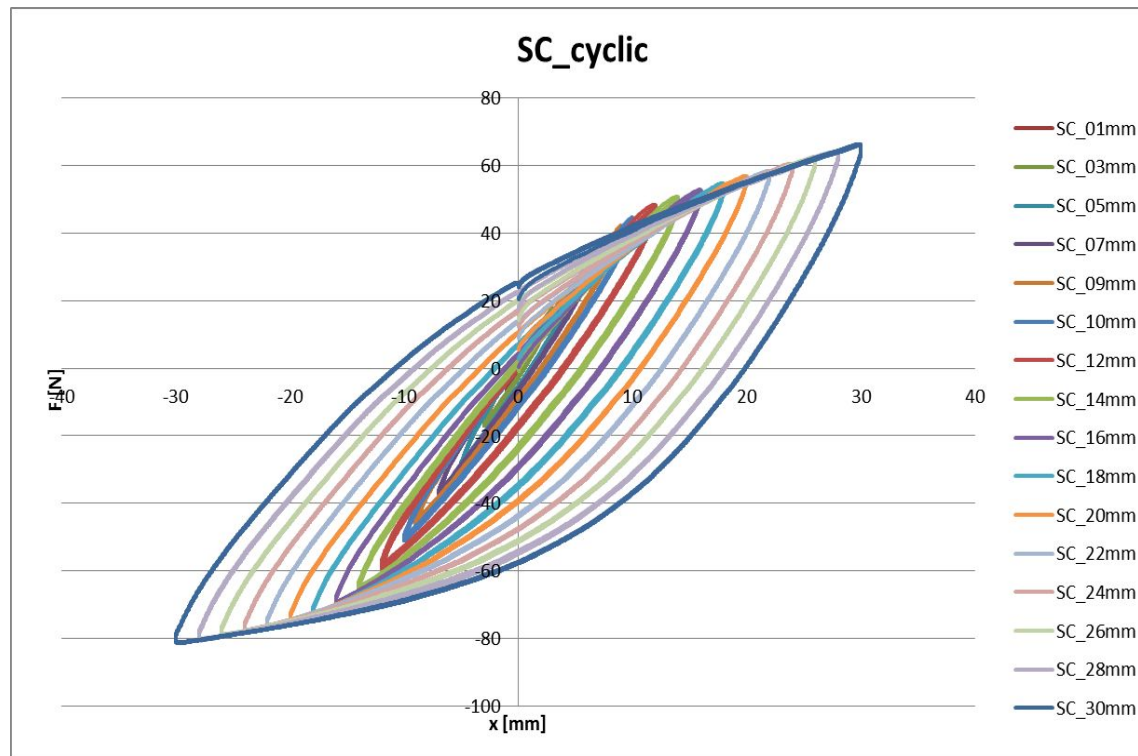
Superconducting cables



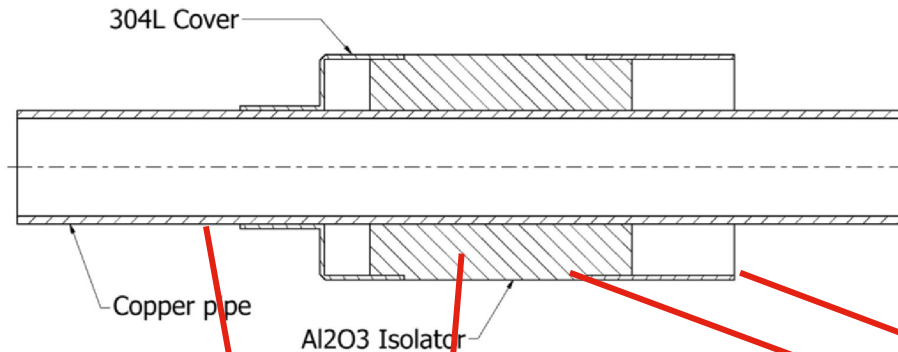
Bending proces of the
superconducting cable
- FEM simulation

Superconducting cables

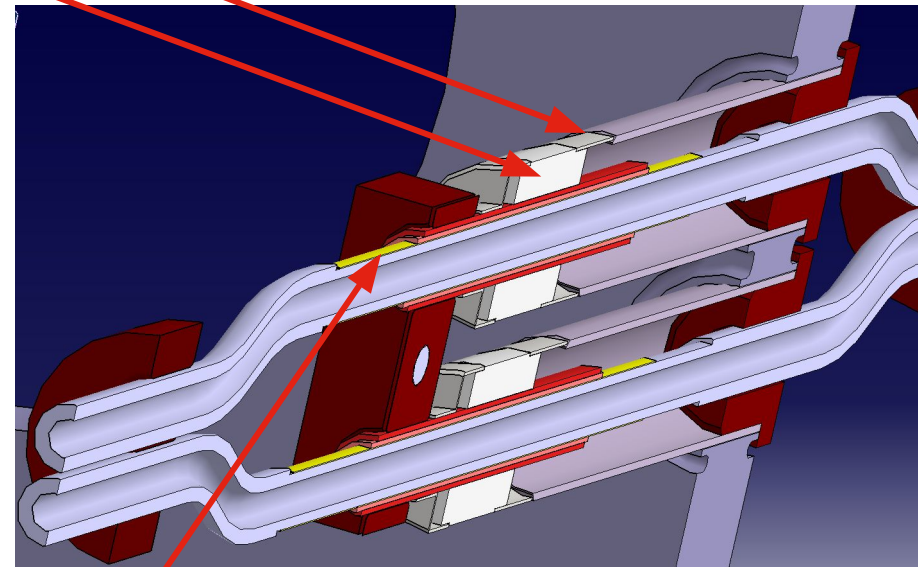
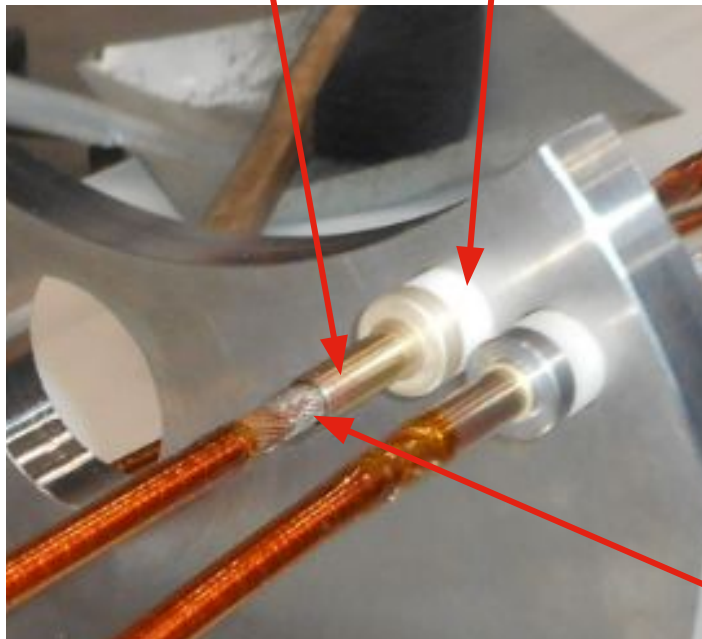
Mechanical hysteresis of the superconducting cable compensation loops has been measured.



Superconducting cables

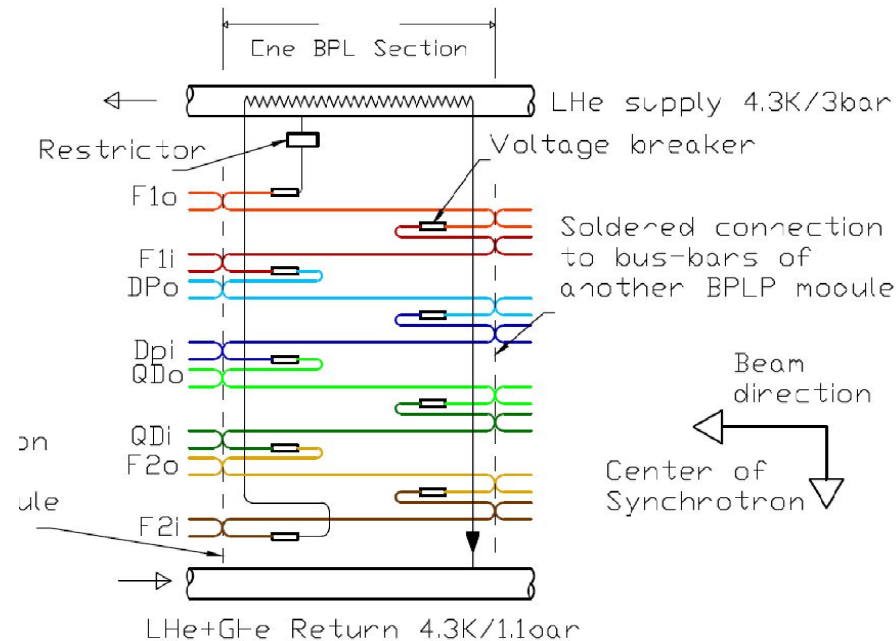


Vacuum Barrier feedthrough
for the Bus Bars



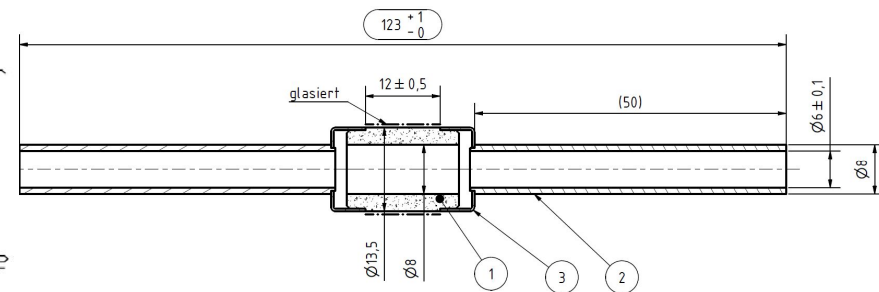
Vacuum-tight solder

Superconducting cables



Flow – electric scheme of Bus Bars in BPL module

In the BPL module, the 8 electrical circuits share a common hydraulic circuit for He flow. **Voltage Breakers** are used to separate the electrical circuits with the continuation of the hydraulic circuit.



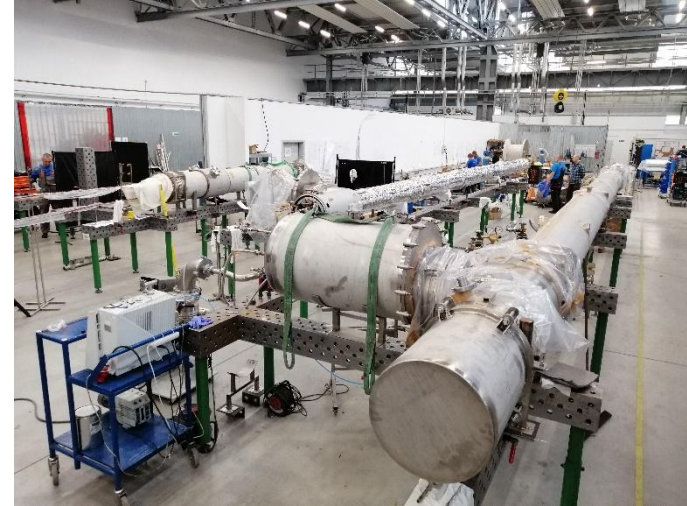
Voltage Breaker design



Voltage Breaker view



Bypass Line - SIS100 production





Summary

- Cryogenic distribution systems (CDSs) are key components of superconducting particle accelerator facilities,
- CDS must enable safe, stable and reliable operation of superconducting devices for a large number of operating modes
- CDS are designed for very low temperatures, high mechanical loads and extremely high radiation operating conditions, and optimized for mechanical stability and limiting thermal loads,
- Local and Common CDSs for the FAIR Super-FRS challenging the complex machine routing and narrow installation space,
- Local CDS for SIS100 includes a superconducting power distribution system, which at the design stage required novel solutions for Vacuum Feedthroughs, Voltage Breakers, electrical and hydraulic connections, as well as electromagnetic analysis and experimental determination of the mechanical properties of the Bus Bars.

Cryogenic Distribution System – definitely not „Just Piping”



Thank you for your attention