Fundamentals of Cryomodule Design and Cryogenics

SRF 2019 Tutorial Lecture

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my colleagues at DESY MKS and in particular Serena Barbanotti and Kay Jensch
DESY MKS-1 supported me to compile this tutorial

HELMHOLTZ SPITZENFORSCHUNG FÜR GROSSE HERAUSFORDERUNGEN

Disclaimer

It is impossible to explain all fundamental aspects of cryomodule and cryogenic design in a 1:30h lesson.

I‘ll try to give some practical hints for you to start in this field.

WARNING ! This is not academic ! This is not complete !
In this lesson you‘ll learn about the practical approach of a physicist and work package leader of several projects in the past. Several statements will be not exact but ‚handwaving‘ - this might help you for your future projects. Do not use this in examinations at university !

Here I‘ll refer sometimes to basic design types ‚J-Lab type‘ and ‚TESLA-type‘ and I will show some examples from the ESS and XFEL projects. Just because I‘m a bit familiar with these concepts.

Of course there are many more exciting projects underway and many more excellent cryomodule designs available !!!

I‘ve copied material from CEA Saclay,ESS,ELBE, Air Liquide, Linde Kryotechnik and others.

Summary of this tutorial

- Basic specifications
- Basic cryogenic distribution scheme
- RF cryomodule specifications
- Choice of cavity operation temperature
- Liquid Helium cooling – limitations
- Cryomodule thermal insolation fundamentals
- Cryomodule mechanics fundamentals
- Cryomodule assembly
- Cryomodule transportation issues
- Cryomodule testing
- Cryogenic Helium supply – basic specifications
- Helium refrigerator fundamentals
- Subatmospheric systems for T<=2K (warm Helium pumps / cold compressors)
- Helium bath pressure stability and stabilisation of RF load changes
- Topics which are not covered
- If time is left: example XFEL cryogenic system

Concept of this tutorial

Cryomodule design and Cryogenics are closely linked to each other
-> I'll jump between both topics !

Startpoint: There is the decision to use superconducting RF technology in your lab.

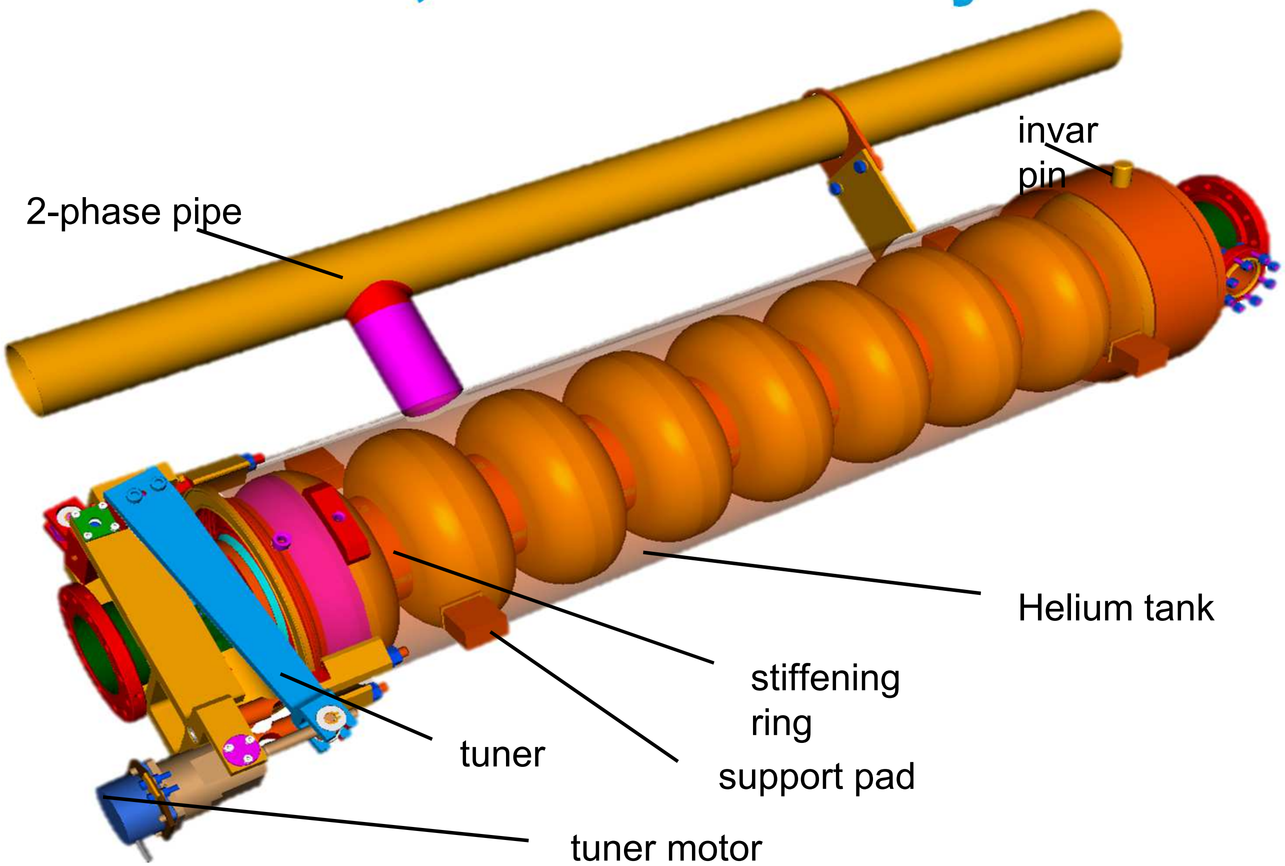
You have some knowledge of SRF technology.

You are put in charge for the fabrication of the cryomodules and the cryogenic supply and operation.

We' try to identify the fundamentals and find the main technical path to conduct this project.

You may interrupt me and ask questions whenever you want !

The object we have to operate
9-cell 1.3GHz ‚TESLA' cavity as an example



ELBE Rossendorf
MESA
FLASH
XFEL
LCLSII
…..

Basic Specifications

These basic specs will mainly determine the decisions for your project !

What particles will you accelerate ?

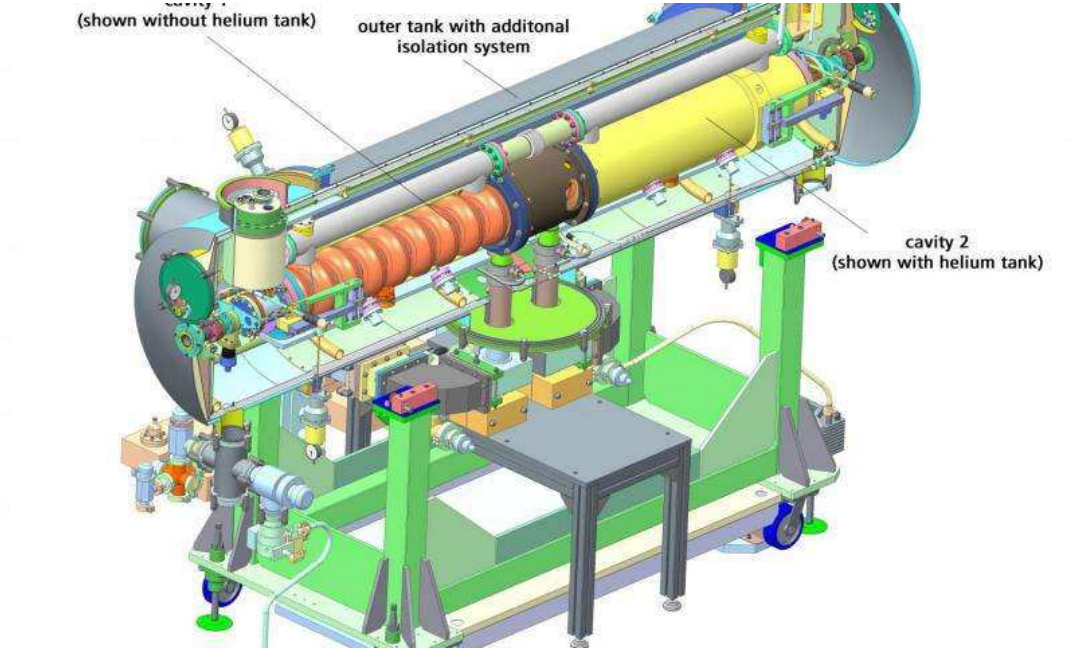
Electrons
Elliptical β=1 cavities , uniform structure in general, long chain of identical cryomodules
Examples: TESLA-technology, FLASH, XFEL, LCLSII, SHINE…………
-> Only one main type of cryomodule ‚simple' cryogenic distribution system

Protons (or other heavy particles)
Variety of different cavities: spoke, low-, medium, high β and a nonuniform structure in general, individual cryomodules
Examples: J-Lab/CEBAF,SNS, ESS…
-> several separated individual cryomodules ‚complex , cryogenic distribution system

Will you operate in pulsed - or cw-mode operation ? ERL ?
-> will determine fraction of dynamic/ static cryogenic loads and additional loads (RF couplers…etc.)

Basic Specifications

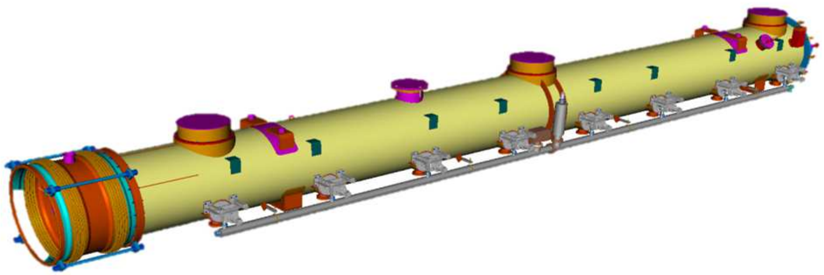
Use of SRF single separated cryomodules in a ‚warm' accelerator.
Examples ELBE,MESA….. many others



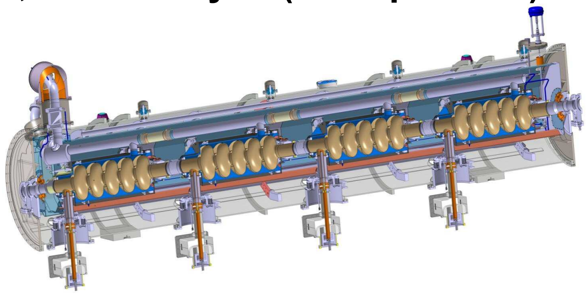
Cryomodule – Basic Specs

Large scale applications

‚TESLA' –Style (example XFEL)



‚J-Lab' –Style (example ESS)

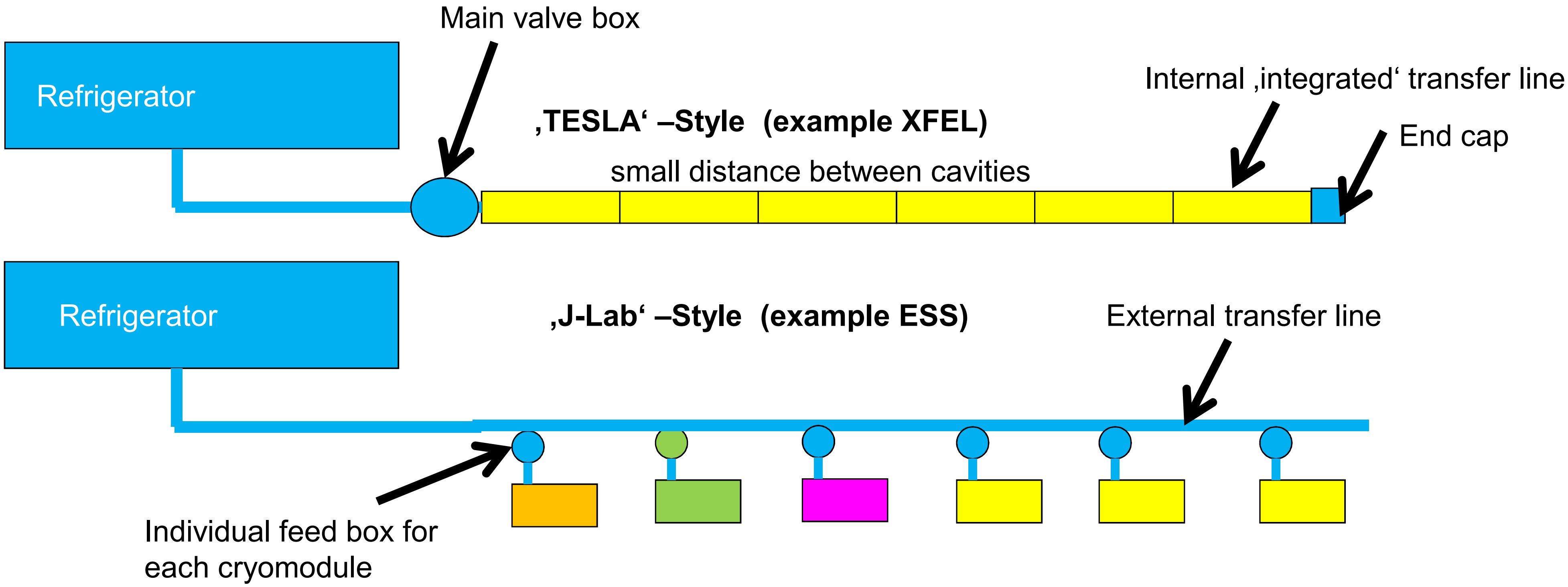


All different cryomodules share some fundamental features:

1. Mechanically support the superconducting RF cavities, allowing thermal shrinkage of parts from 300 K to liquid helium temperatures without introducing stresses during cool down and warm up
2. Guarantee the cavity string alignment
3. Supply the cavity string with liquid Helium
4. Thermally isolate the cavity string from the 300 K environment
5. Bring high power RF to the cavity string (coupler)

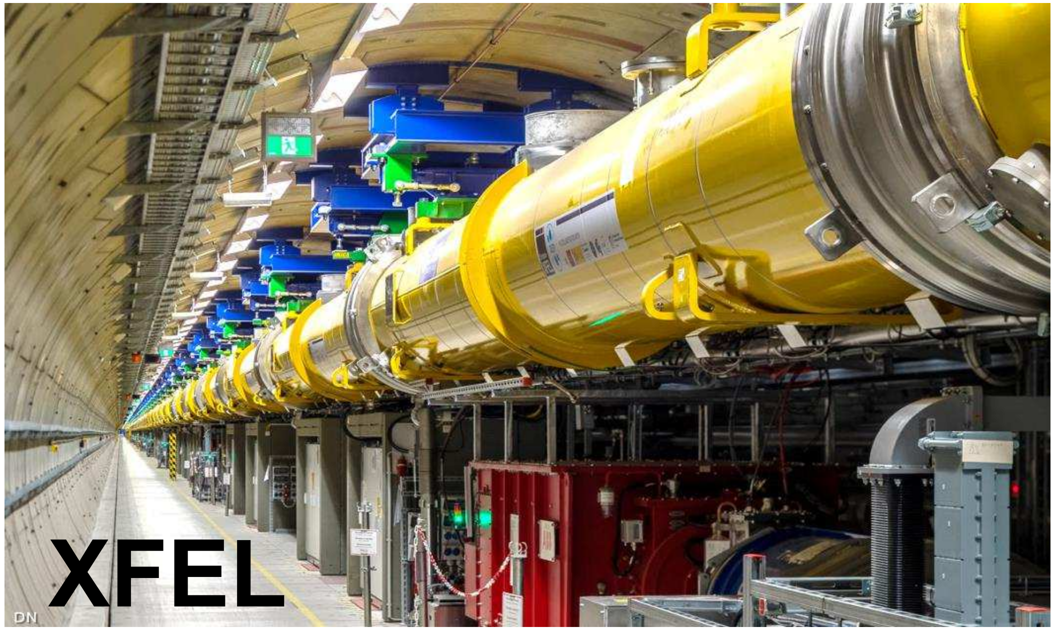
Cryogenic distribution

A very much simplified structure is shown here.
Later more detailed schemes will be shown.

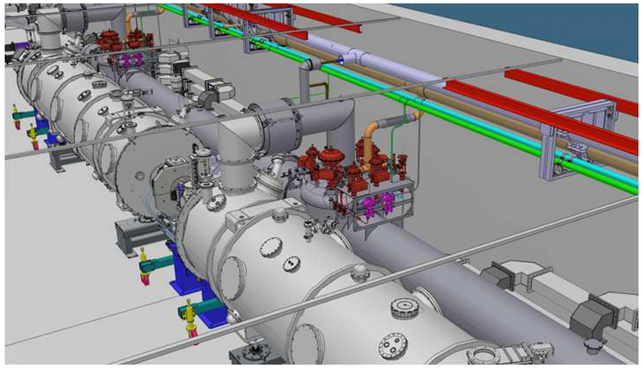


Cryogenic distribution

Cryomodul design and cryogenic distribution are closely related !



100% **welded** process tube connections
No direct feedthroughs into helium process areas



Flanged interconnections may be used

Cryomodule – Specs

Leading physics specs:

, - **Accelerator requirements** – acceleration, beam performance, beam current, alignment, microphonics
- Leads to RF performance and RF sub-systems specs
- Leads to vacuum and cryogenic specs
- Leads to mechanical specs

'More Practical' specs (MUST BE CONSIDERED from the START !):

- Design suitable for serial production (if applicable)
- Transportation requirements
- Legal requirements: risk analysis, pressure vessel code, radiation safety….
- Costs

Cryomodule – Sub-systems

,

Cryomodule 'Stakeholders'

- **RF Systems** (tuners, LLRF, couplers, wave guides…)
- **Vacuum systems** (beam, insulation, coupler (optional))
- **Cryogenic systems** (Helium circuits, thermal intercepts, valves…)
- **Additional systems** (e.g. superconducting magnets, laser, HOM absorber…))
- **Mechanical design** (alignment, vacuum vessel, cold mass, magnetic shielding…)
- **Accelerator system integration & interfaces** (sensors, cabling, controls…)

Cryomodule – parts list

Cryomodule = sub-unit of an accelerator, which contains (list may be un-complete):

- RF cavities (one or more)
- Helium vessel for RF cavities
- RF main couplers for the cavities
- Mechanical tuners for the RF cavities
- Piezo tuner for the cavities (optional)
- HOM couplers (optional)
- HOM absorbers (optional)
- Magnetic shielding
- Cryogenic thermal shield (one or two)
- Helium process tubes for all involved cooling circuits (1-3 circuits)
- Vacuum systems: beam vacuum, insulation vacuum and coupler vacuum (optional)
- Internal support structures
- Outer vacuum vessel
- Superconducting magnets and current leads (optional)
- Instrumentation (for all sub-systems)

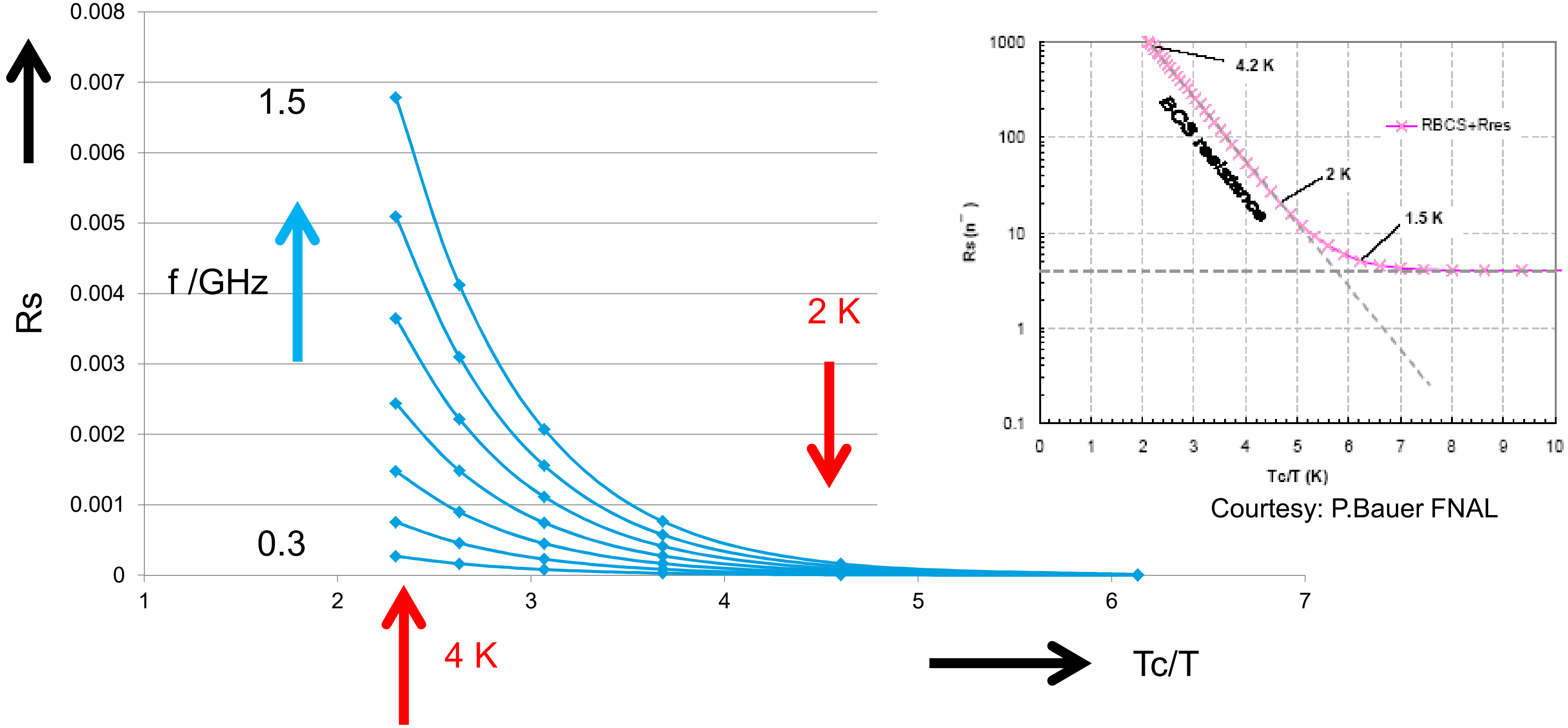
Each part needs an individual tutorial !

Details depend on your particular application !

Choice of Cavity Operation Temperature

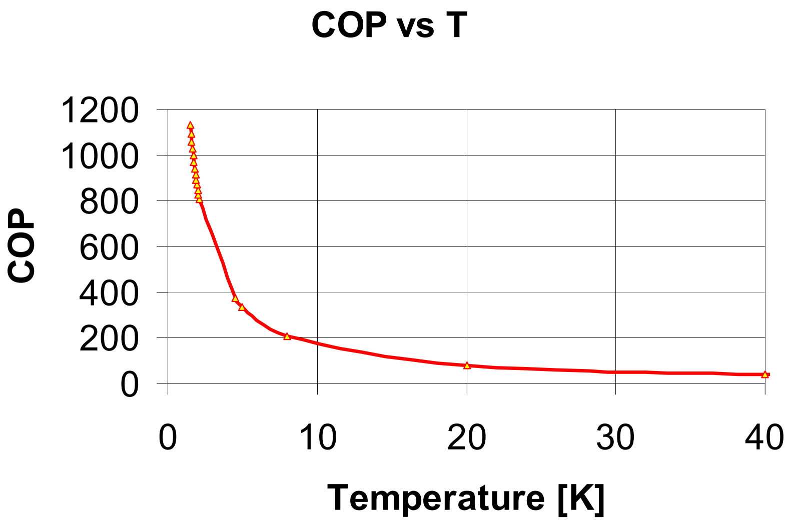
BCS Treatment of RF surface resistance Rs for Nb:

Fit approximation Rs ~ f^2 * (1 /T) * EXP (-a/T) + Ro   f – frequency, T-Temperature, Ro – residual res.
a – fit constant



Courtesy: P.Bauer FNAL

Choice of Cavity Operation Temperature

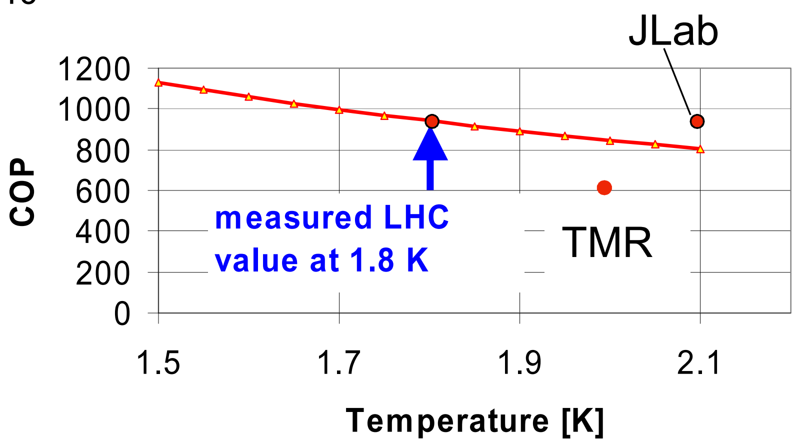


Coefficient of Performance

COP_{real}=1/(K * η CARNOT) = primary power/usable power

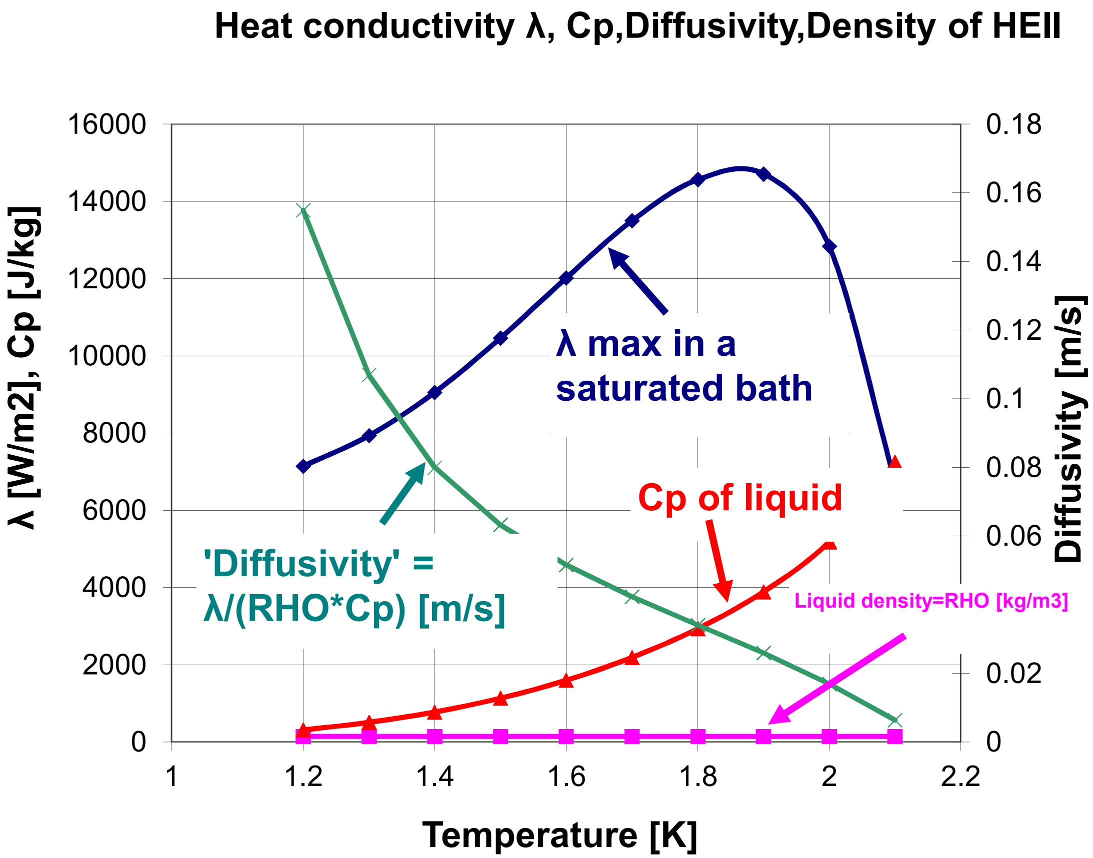
η CARNOT = T/(300 -T)

K= 0.176 (from LHC measurements at 1.8 K)



Choice of Cavity Operation Temperature

The large heat conductivity of HeliumII can be used for liquid bath cooling



Choice of Cavity Operation Temperature

For the time being only Nb bulk material is suited for superconducting cavities -> $T < T_c = 9.2K$

For RF frequencies < (?) 1 GHz liquid helium at atmospheric pressure might be the choice T = 4.2K

For RF frequencies > 1GHz **liquid Helium II cooling below the λ-point** = 2.17 K is the choice

In theory: Rs BCS (T) will dominate η Carnot until the residual resistance is reached at about 1.5 K
-> the lower the operation temperature the better down to about 1.5K

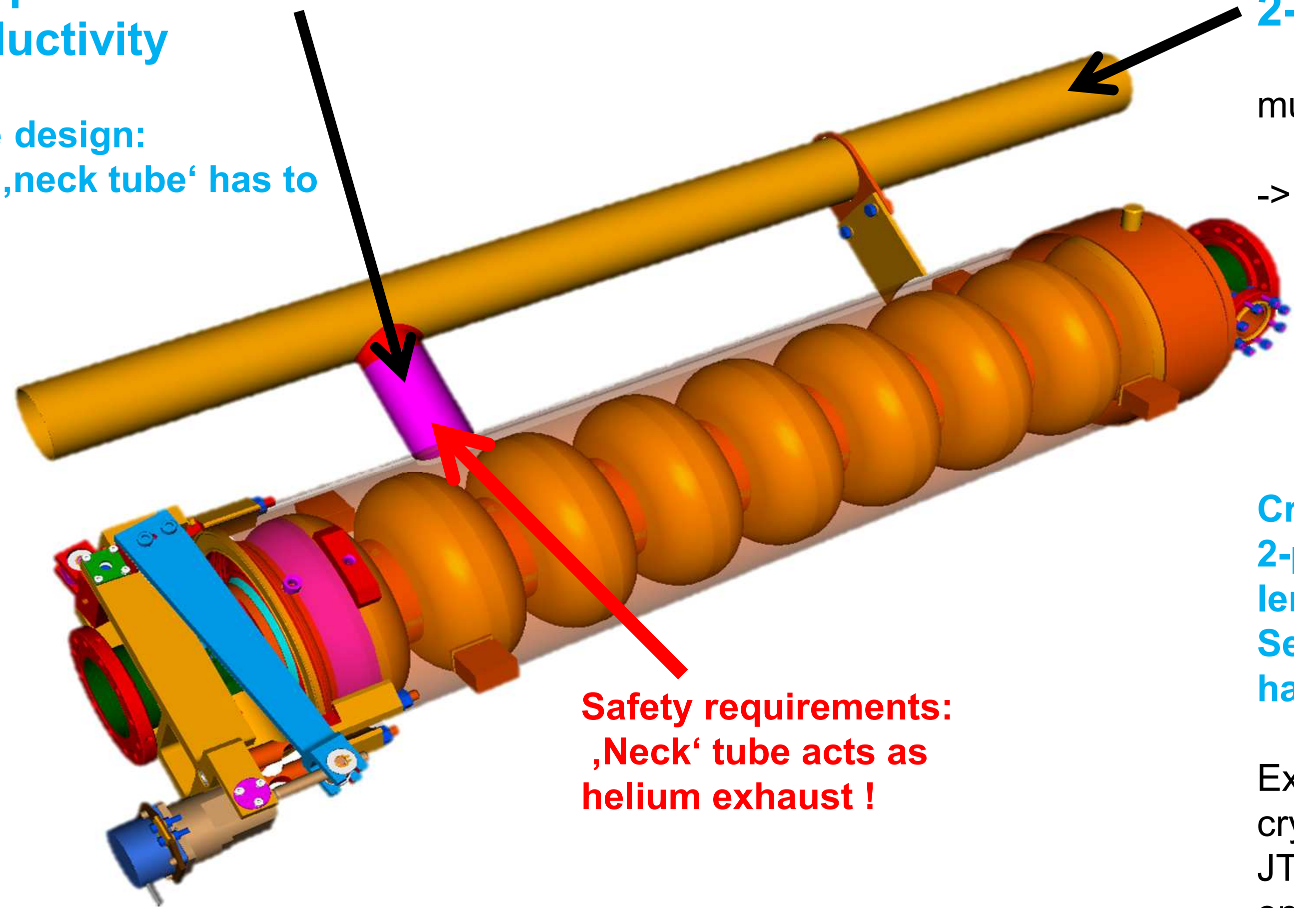
In reality: the 2K Carnot efficiency is only one part of the overall primary power budget in addition there are operational aspects (operation of additional cold compressor stages etc.)
-> for practical reasons the operation temperature is 2K (XFEL,LCLSII,ESS…)
-> ELBE is operating at 1.8K

Thermal shield temperatures: result from general cooling requirements and refrigerator efficiency
thermal shield at about 20K – 40K supply temperature is mandatory
additional 5K circuit may be required for coupler and HOM cooling (active or passive)

Cryogenic heat load limitations

Limit of liquid Helium II heat conductivity

Cryomodule design:
Diameter of ‚neck tube‘ has to be adapted.



Safety requirements:
‚Neck‘ tube acts as helium exhaust !

2-Phase Helium II Flow

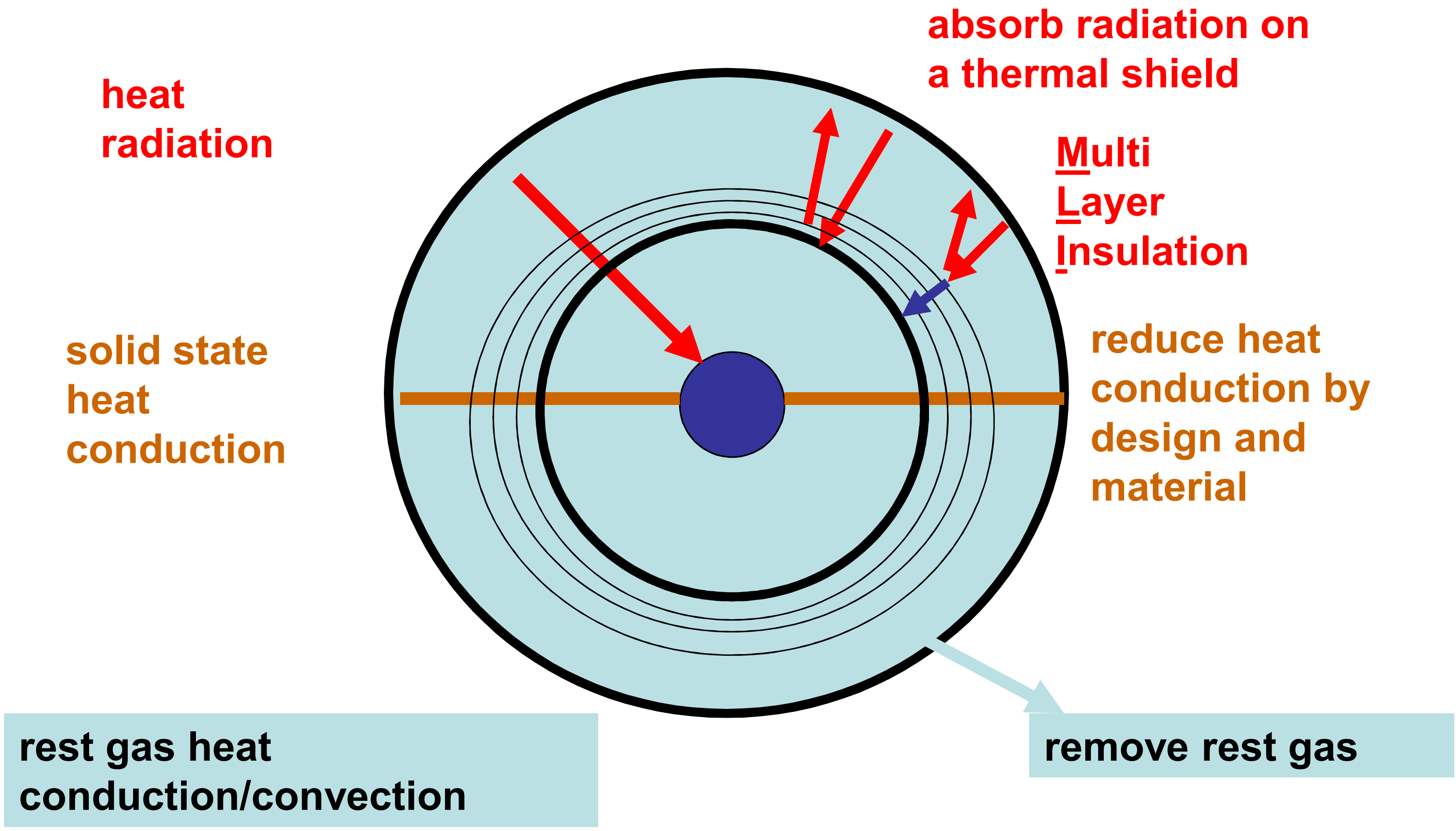
mutual friction of vapor and liquid

-> stratified flow required to avoid instabilities and fluctuations

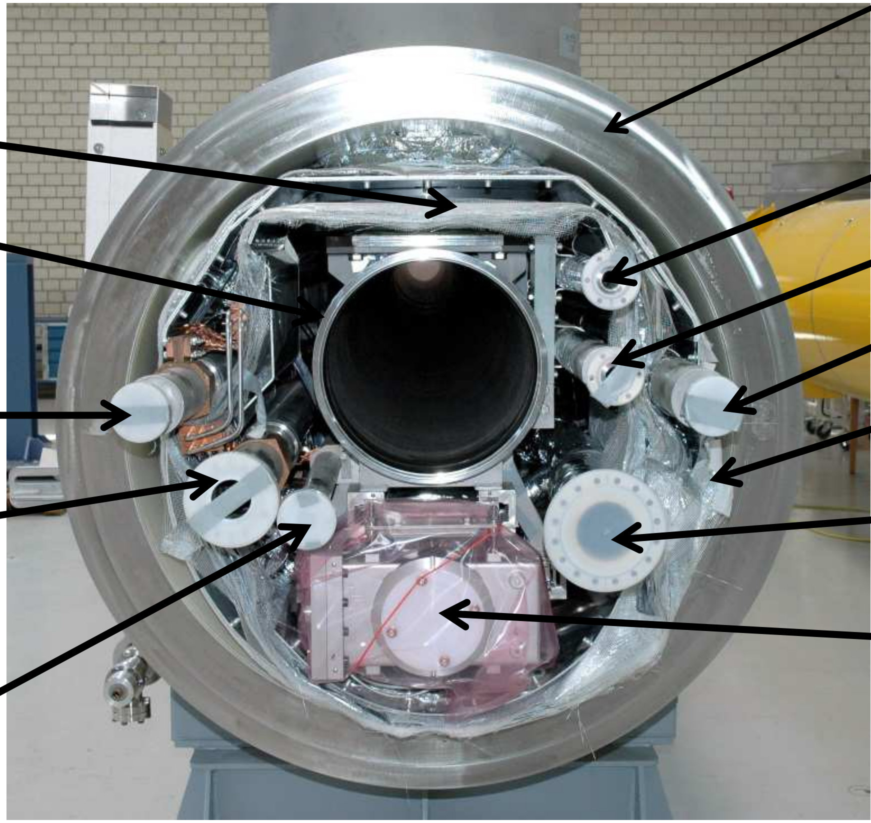
Cryomodule design:
2-phase tube diameter and length have to be adapted.
Section length and JT-valves have to be matched.

Example: each LCLS II cryomodule is equipped with a JT-valve. In contrast : at XFEL one JT-valve serves 12 cryomodules.

Cryomodule fundamentals: thermal insulation



Cryomodule fundamentals: thermal insulation
Example: XFEL cryomodule



Cryomodule fundamentals: thermal insulation

Some Fundamentals of Thermal Insulation: MLI impressions

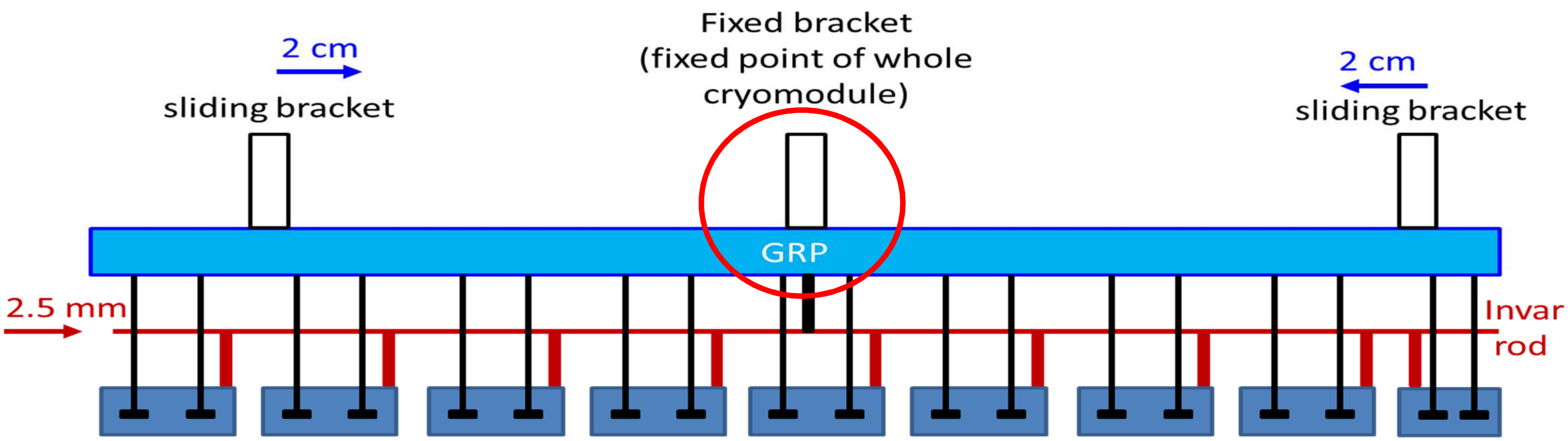
spacer
glas fiber
net

(vitrolan)

Figure 61: Two layers of super insulation on cold mass

Cryomodule fundamentals: mechanical design TESLA type (example XFEL)

The longitudinal position of cavities and main RF couplers is almost decoupled from thermal shrinkage:

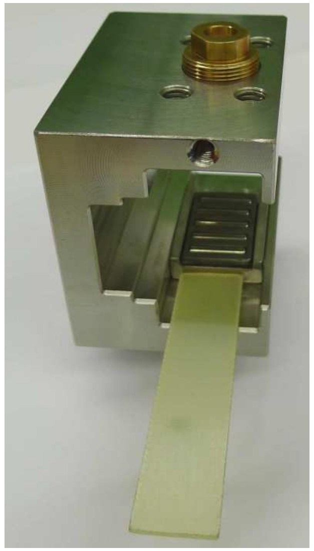


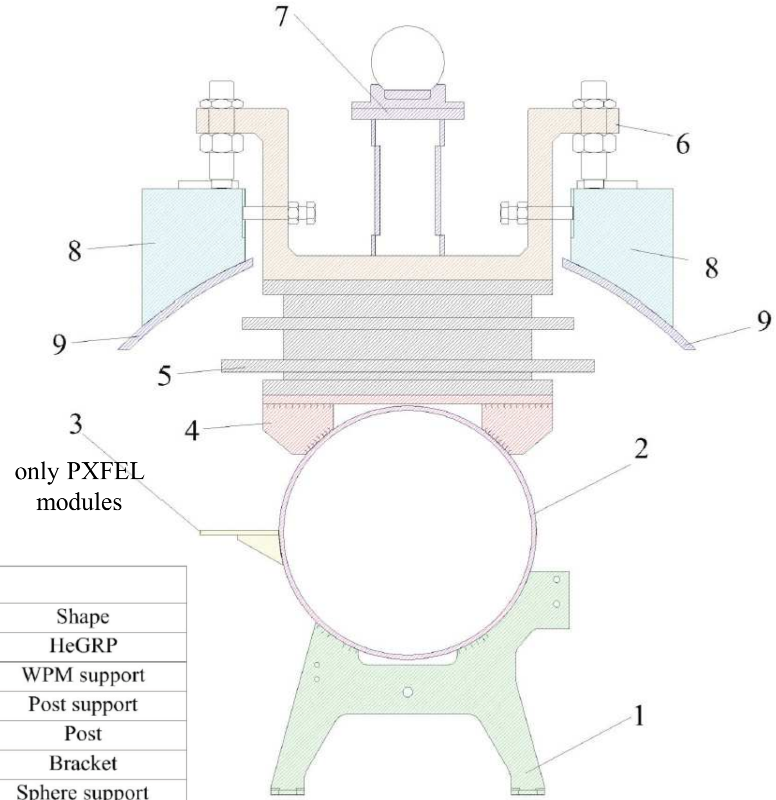
Invar rod, 300 K -> 2 K shrinkage 0.4 mm/m: 6 m -> about 2.5 mm

GRP, stainless steel, 300 K -> 2 K shrinkage 3.1 mm/m: 6 m -> about 2 cm

Cryomodule fundamentals: mechanical design (example XFEL)

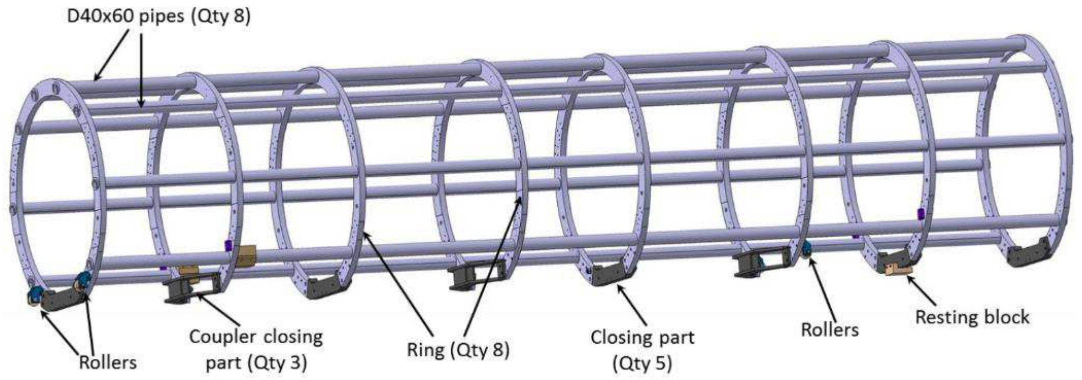
Cavity string support system with rollers: very low friction



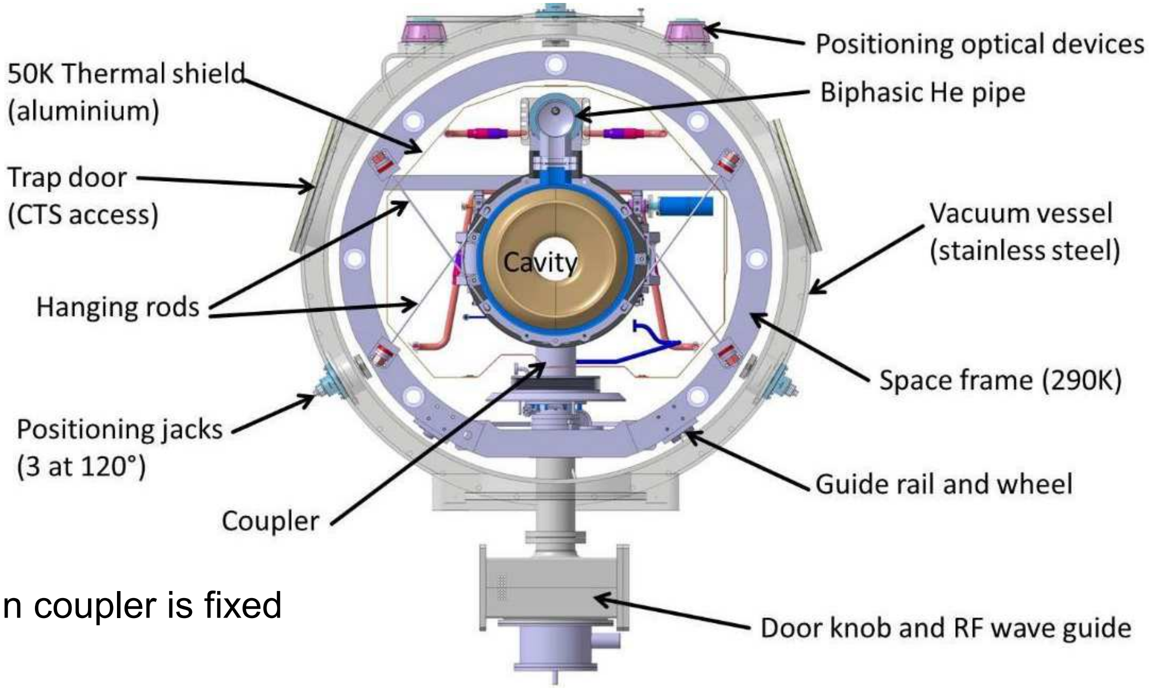


1	Shape
2	HeGRP
3	WPM support
4	Post support
5	Post
6	Bracket
7	Sphere support
8	Post nozzle
9	Vacuum vessel

Cryomodule fundamentals: mechanical design ESS type



Spaceframe (Aluminium) stays at 300K



Pre-loaded hanging rods fix the position of the cavity string

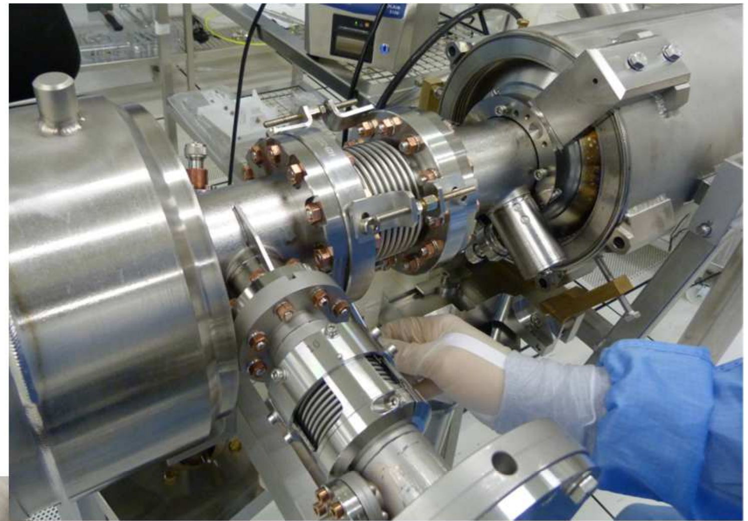
Courtesy of N.Bazin CEA Saclay

Position of the main coupler is fixed

Cryomodule fundamentals: clean room assembly

Cavity string

Cold RF coupler assembly

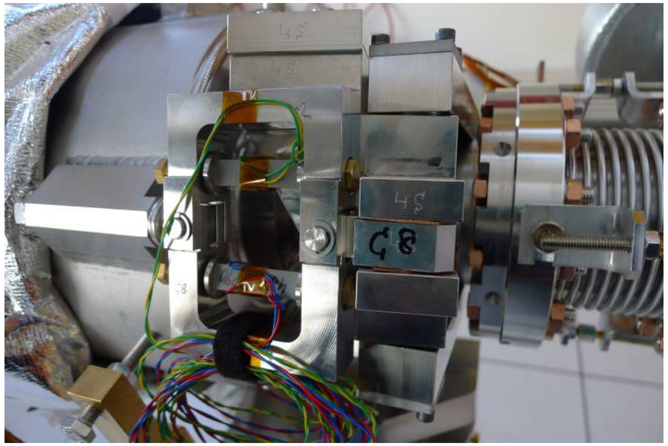


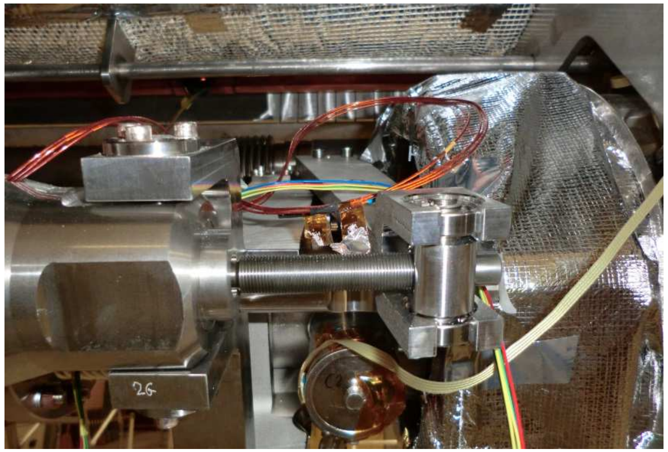
Inter-cavity connection

Images courtesy of C. Madec

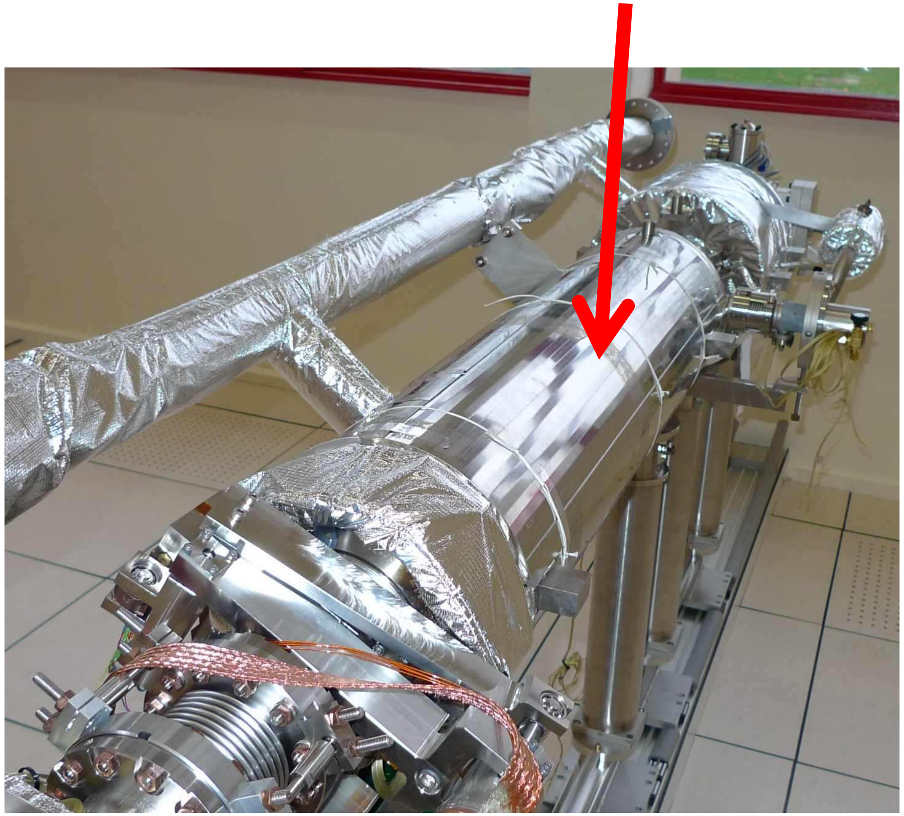
Cryomodule fundamentals: outside clean room assembly

- Installation of MLI, tuner, piezo, magnetic shield



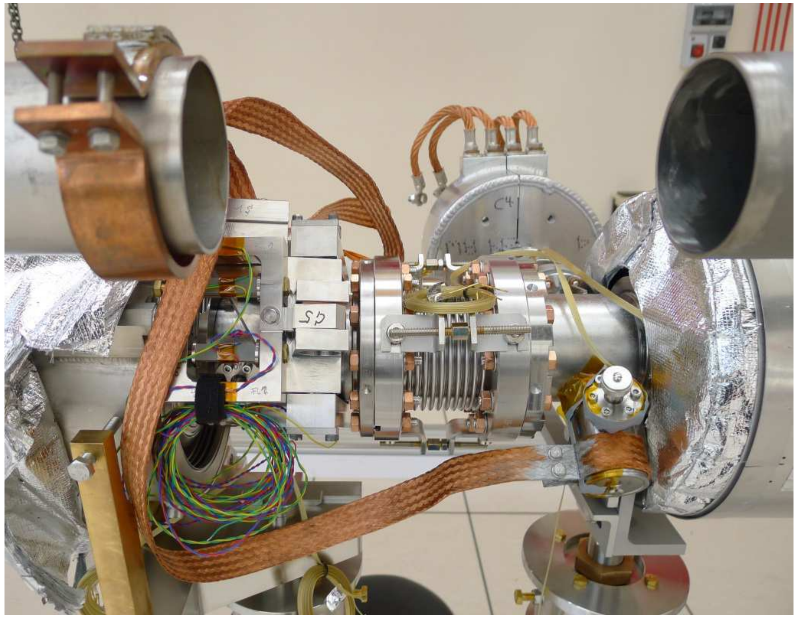


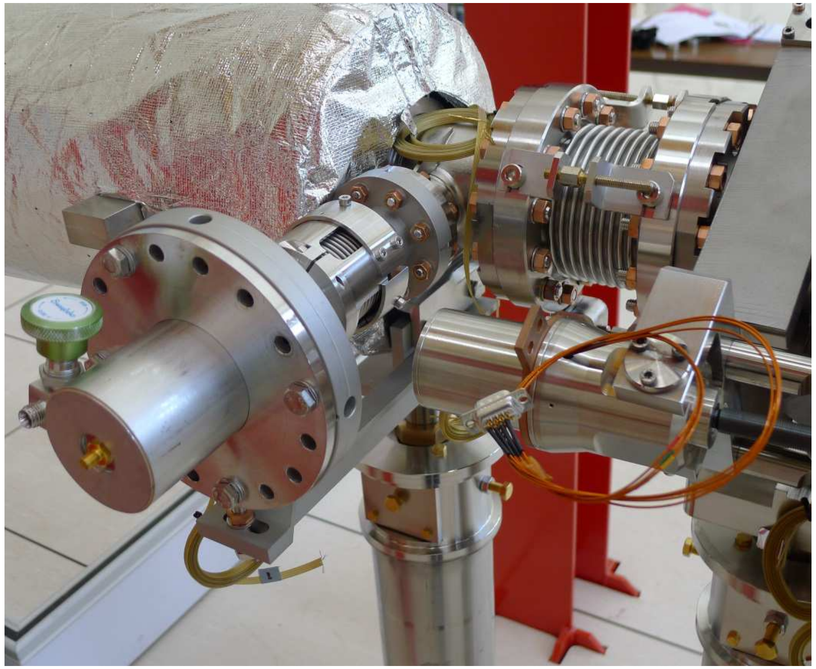
Design of magnetic shielding is mandatory for the operation of high Qo cavities !!!



Cryomodule fundamentals: outside clean room assembly

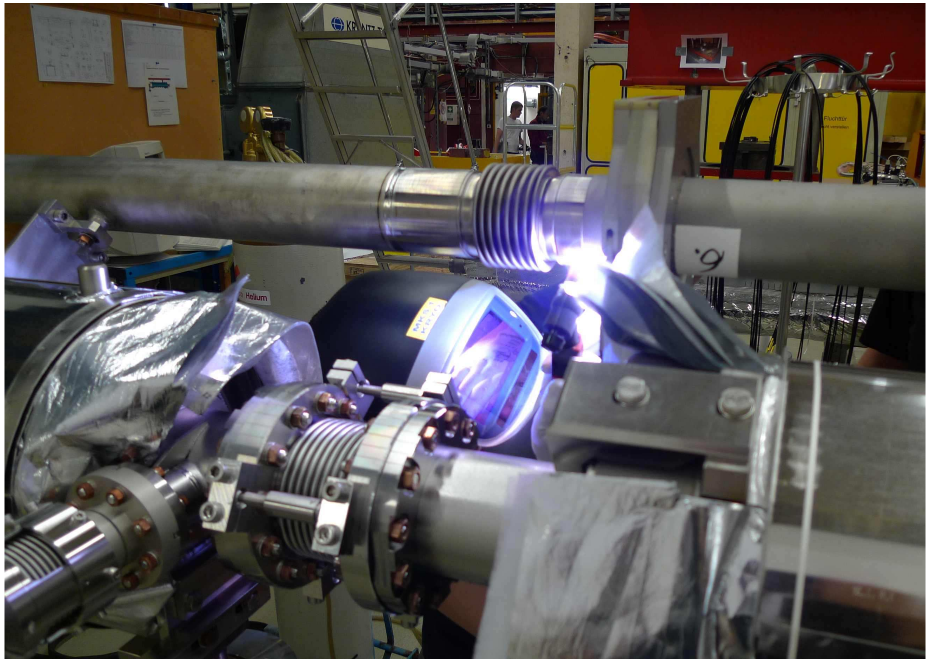
- Cables and thermal intercepts





Cryomodule fundamentals: outside clean room assembly

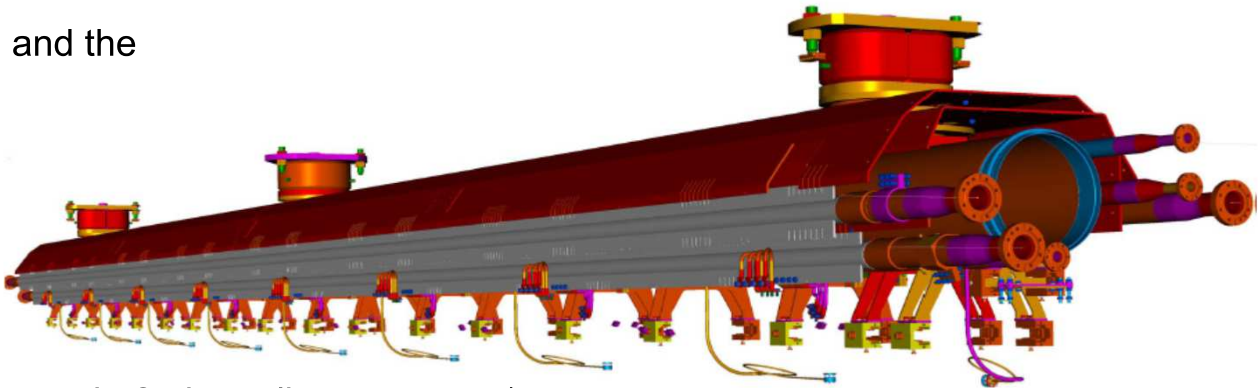
- Welding of the 2-phase pipe



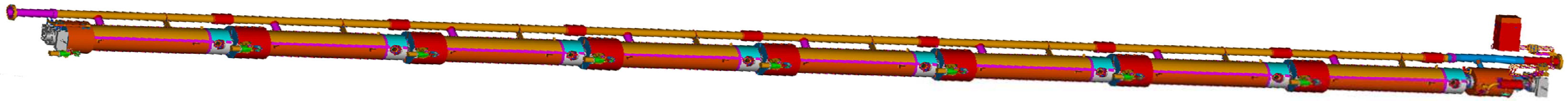
Inside a cryomodule (example XFEL)

A cryomodule has 3 main components

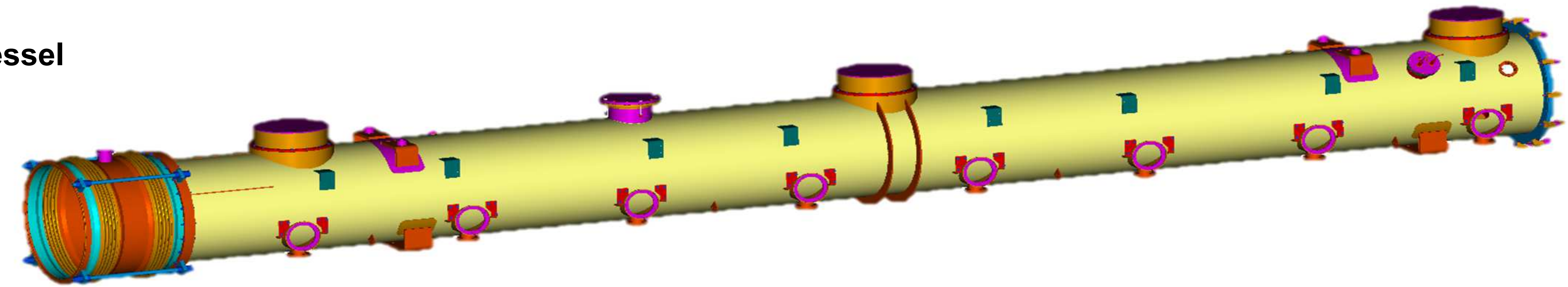
- **Cold mass**: includes all the service pipes, and the cavity string support structure



- **Cavity string**: 8 SCRF cavities (with helium tank, 2 phase line, tuner, …), 1 quadrupole and 8 couplers



- **Vacuum vessel**



Example: XFEL cryomodule assembly of cold mass

Cavity string is attached to cold mass

Tool to slide complete cold mass into vacuum vessel

Cryomodule fundamentals: Transportation !!!

Suited locking devices are required. Mechanical resonance frequencies have to be identified.
Acceleration and mechanical shocks have to be monitored. Also cavity vacuum has to be monitored.

Cryomodule fundamentals: Tests

Unloading of the cryomodule after transport

Cryomodule preparation area

Cryomodule test stand

Cryomodule test stand – module inside

Cryomodule test stand – front view

Refrigeration – Specs

Helium bath cooling for RF cavities established ? -> pressure stability (!!!)

Two phase flow issues ? -> process tube diameter, segmentation

Accelerator tunnel inclined ? -> process tube diameter, segmentation, special mechanical requirements

Heat loads for different temperature levels: -> cavity cooling + thermal shield circuits

Additional active cooling required for RF couplers, HOM adsorbers etc. ? – additional process circuits

Any special cooling requirements ? Fast cool-down ? -> refrigerator capacity, additional valves

Restrictions for cool-down /warm-up procedures ? -> additional valves in distribution system

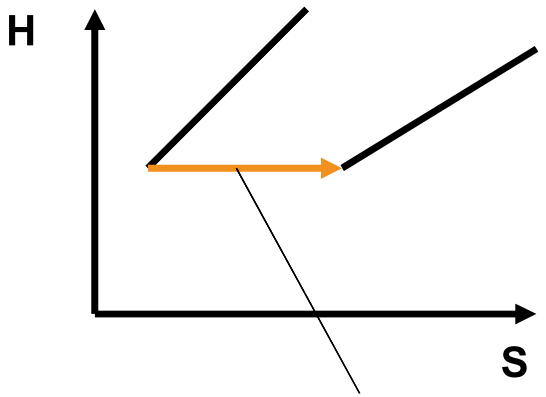
Availability specification from your project ? -> defines the overall layout and the overhead

Redundancy required ? -> yes !

Safety requirements (accelerator tunnel !) -> risk analysis

Some Helium Refrigerator Cycles

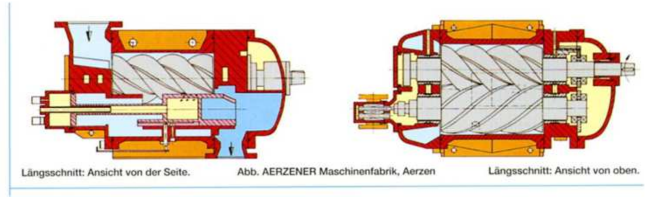
Simple LINDE cycle

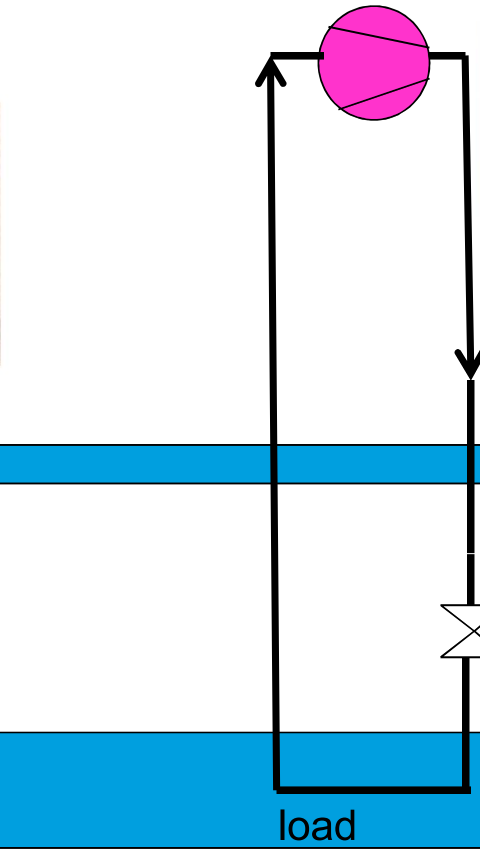


Ideal Joule-Thomson Expansion = **Isenthalpic** Expansion   Δ H=0

Carl von Linde 1842-1934

Screw Compressor



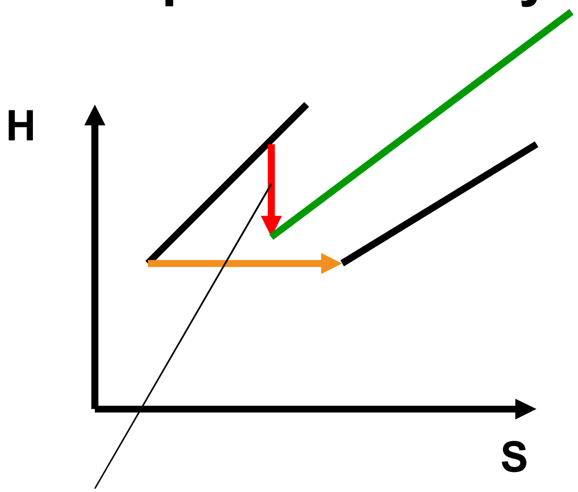


Heat Exchanger

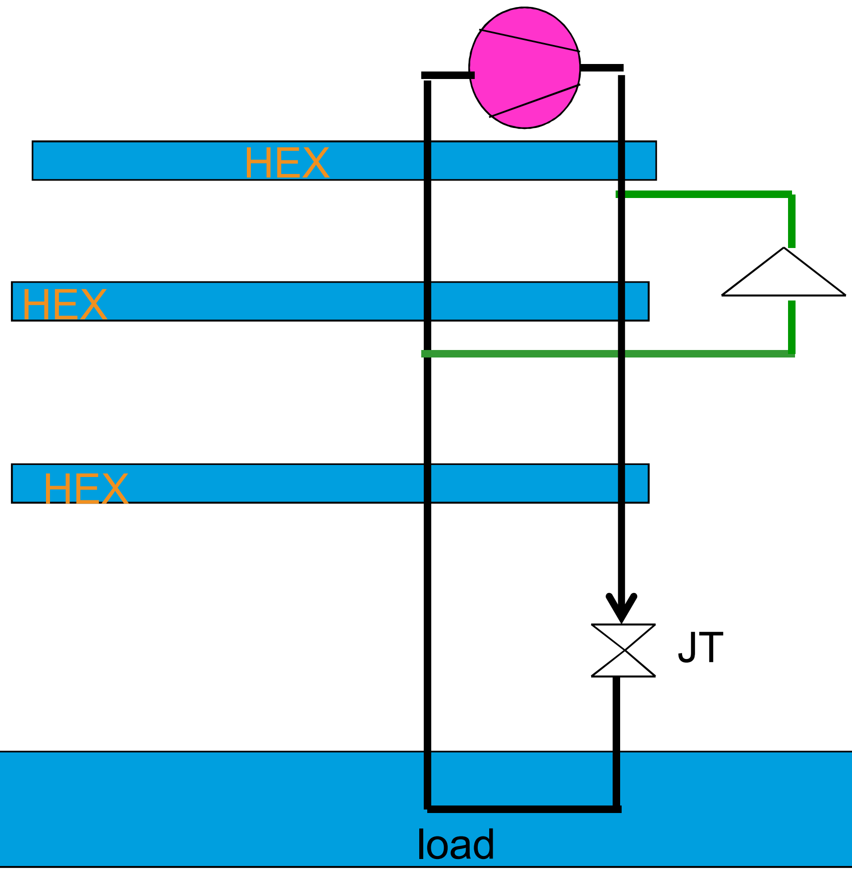
Joule-Thomson Valve

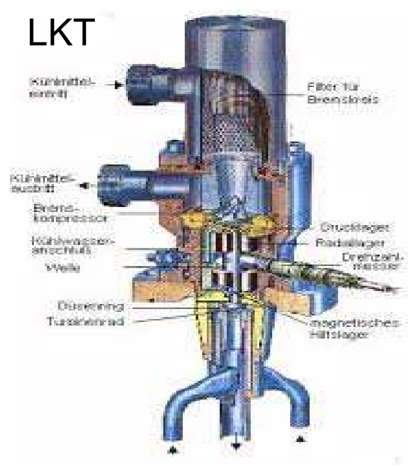
Some Helium Refrigerator Cycles

Simple Claudet Cycle



Ideal Turbine Expansion = **Isentropic** Expansion $\Delta S=0$



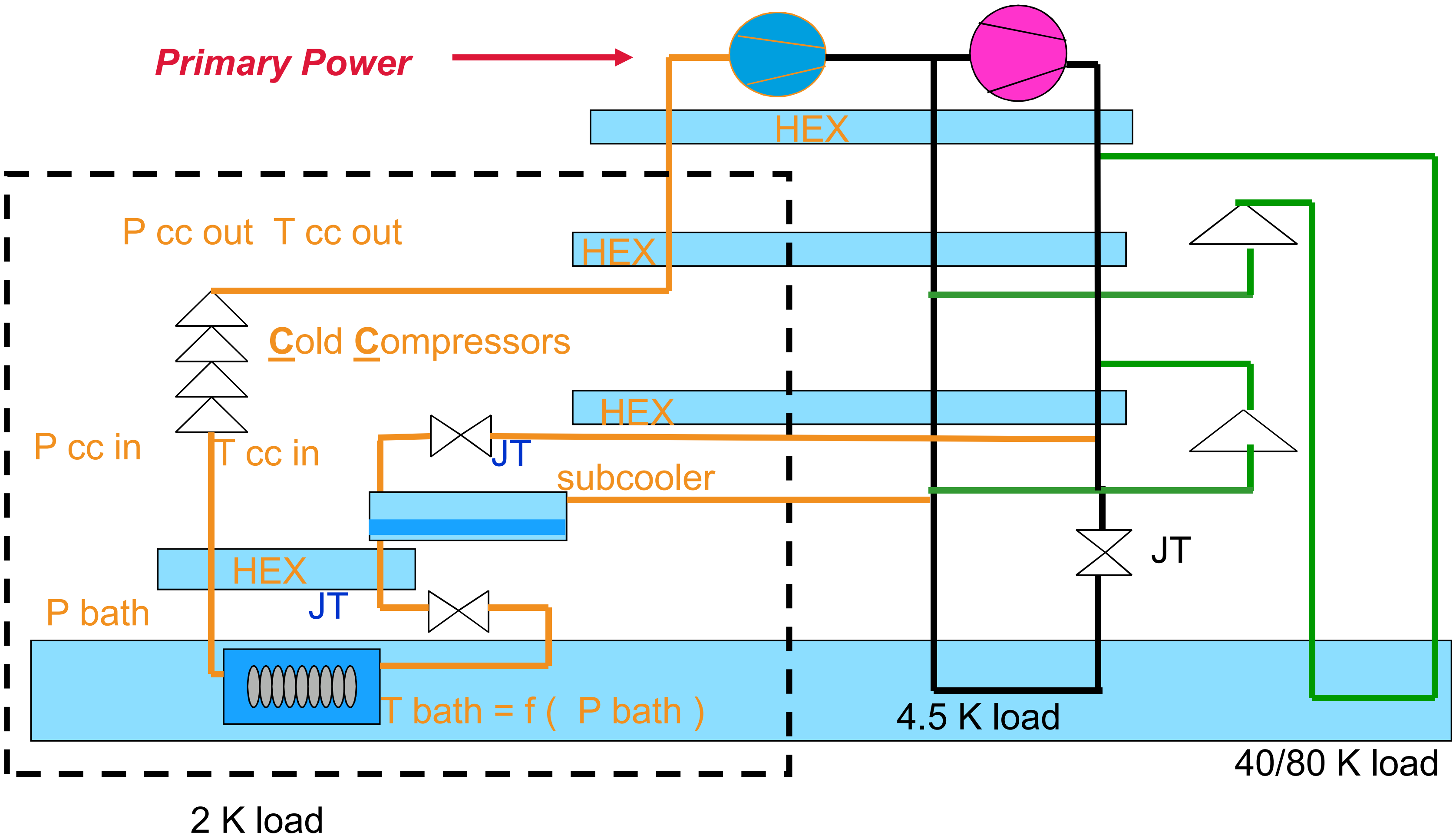


Expansion

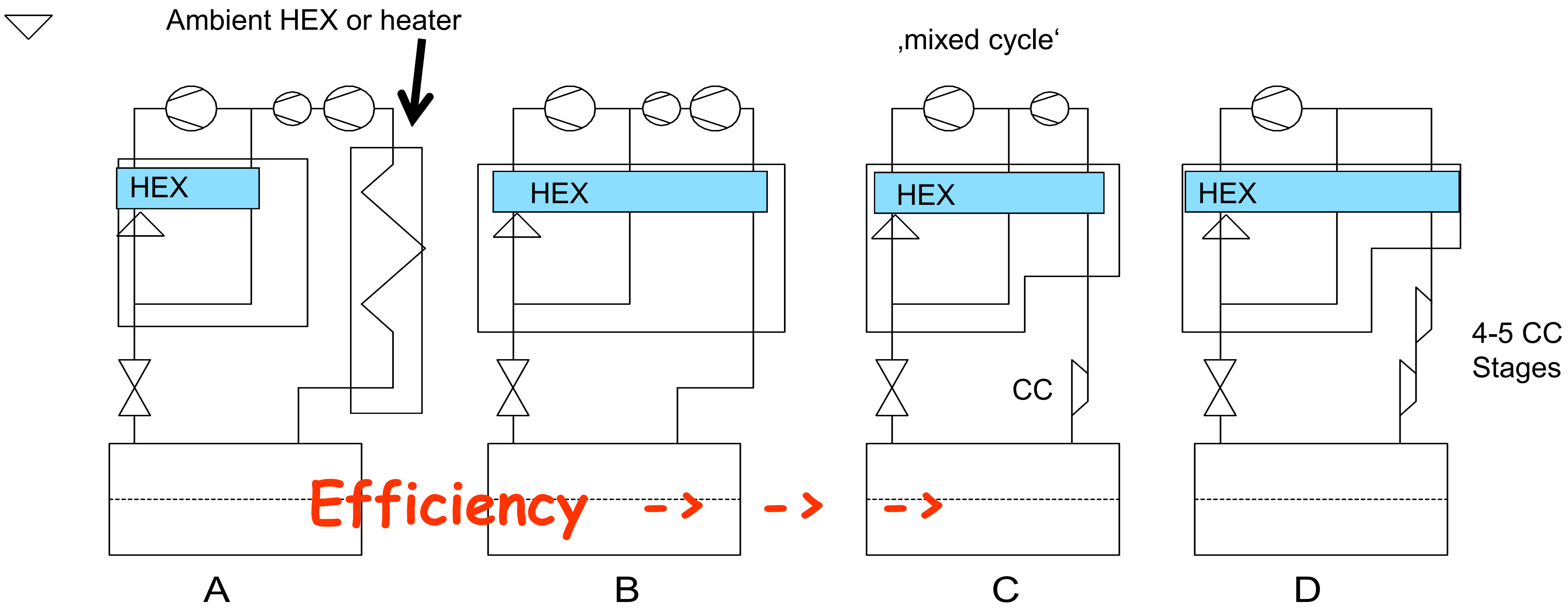
Machine

(Turbine)

Simplified 2 K Helium Refrigerator + Shield Cooling



Refrigerator layout: options for sub-atmospheric operation



A – Only the heat of evaporation of the helium is utilized.

B – The low pressure stream is warmed up in a heat exchanger inside the refrigerator cold box.

C – The cold low pressure stream is precompressed by a cold compressor.

D – The precompression is realized by several stages of cold compression.

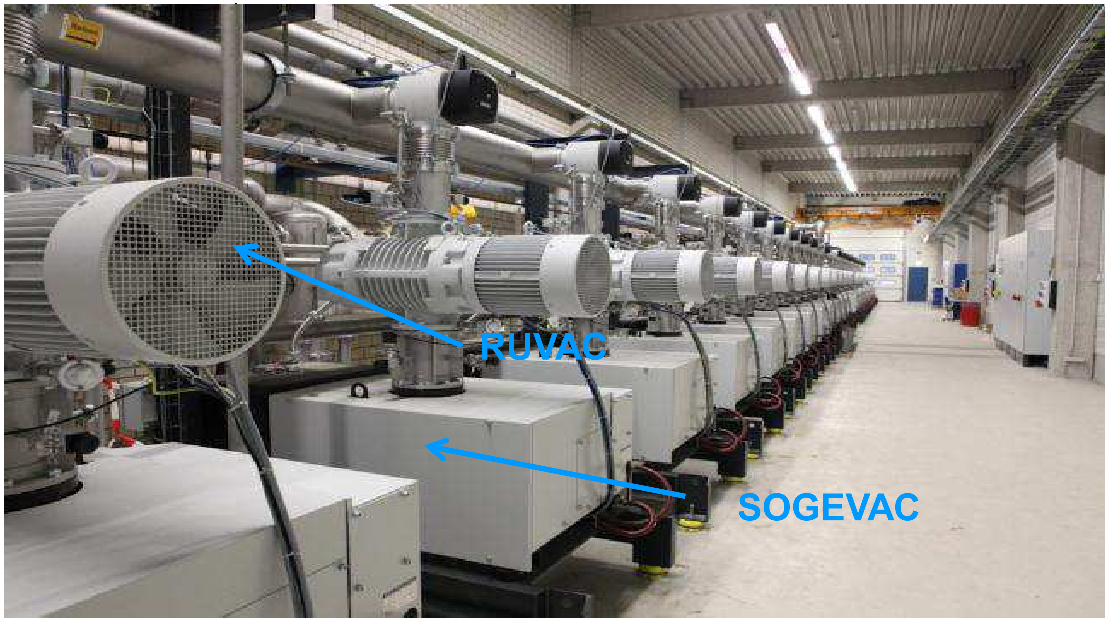
Example XFEL-AMTF : ‚warm‘ Helium pumps

2 sets of compressors for 2K operation at AMTF (2 x 20 g/s helium at 20 mbar)

1 set = 13 x parallel (WS 2001 RUVAC roots blower + SOGEVAC SV750B)

– simple, (robust)**, modular, redundant**

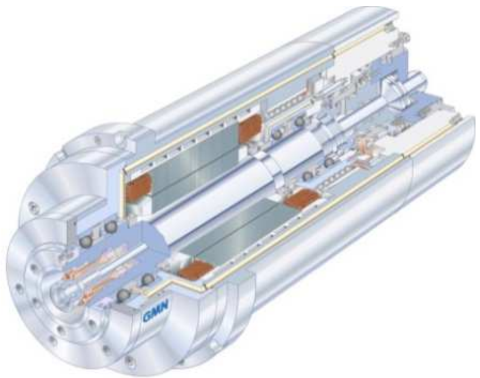
Manufacturer: Oerlikon Leybold

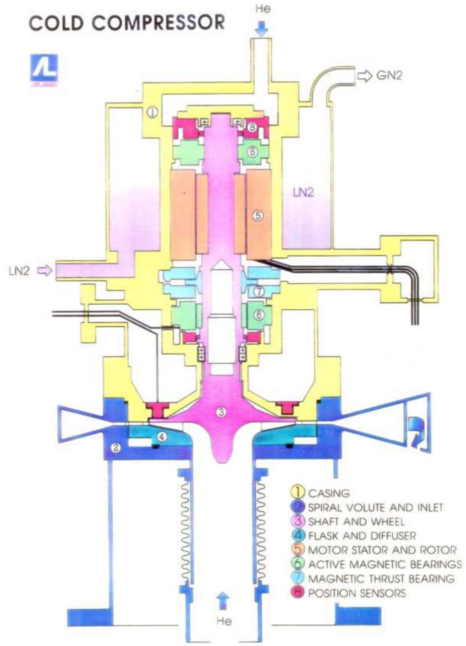


Also serve as a back-up to compensate static XFEL-linac 2K heat loads

Examples: Cold Compressors (‚CC‘)

Ceramic bearings
ELBE/XFEL/ ESS
Linde Kryotechnik

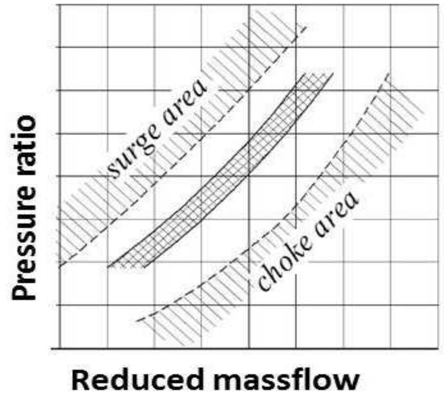




Active magnetic bearings
J-Lab ‚LCLSII / Air Liquide

‚Turbo-compressors: mass flow and pressure ratio coupled

- very narrow operation range
- very sensitive to p,T,m variations
- need continous ‚feed‘ of helium mass flow (at suited P,T)



Pressure ratio: (P_{out}/P_{in}) per Cold-Compressor Stage

Reduced massflow: $m_{red,\,ist} = \frac{m_{ist}}{m_{design}} \times \frac{p_{design}}{p_{ist}} \times \sqrt{T_{ist}/T_{design}}$

Helium bath pressure stability

The resonant frequency of high-Qo cavities is sensitive for Helium bath pressure variations !

XFEL 1.3GHz 9-cell cavities : 40 Hz / mbar frequency shift

Proper pressure regulation is required ! Example XFEL: +/- 1% at 2K /31 mbar specified

Example XFEL-linac:

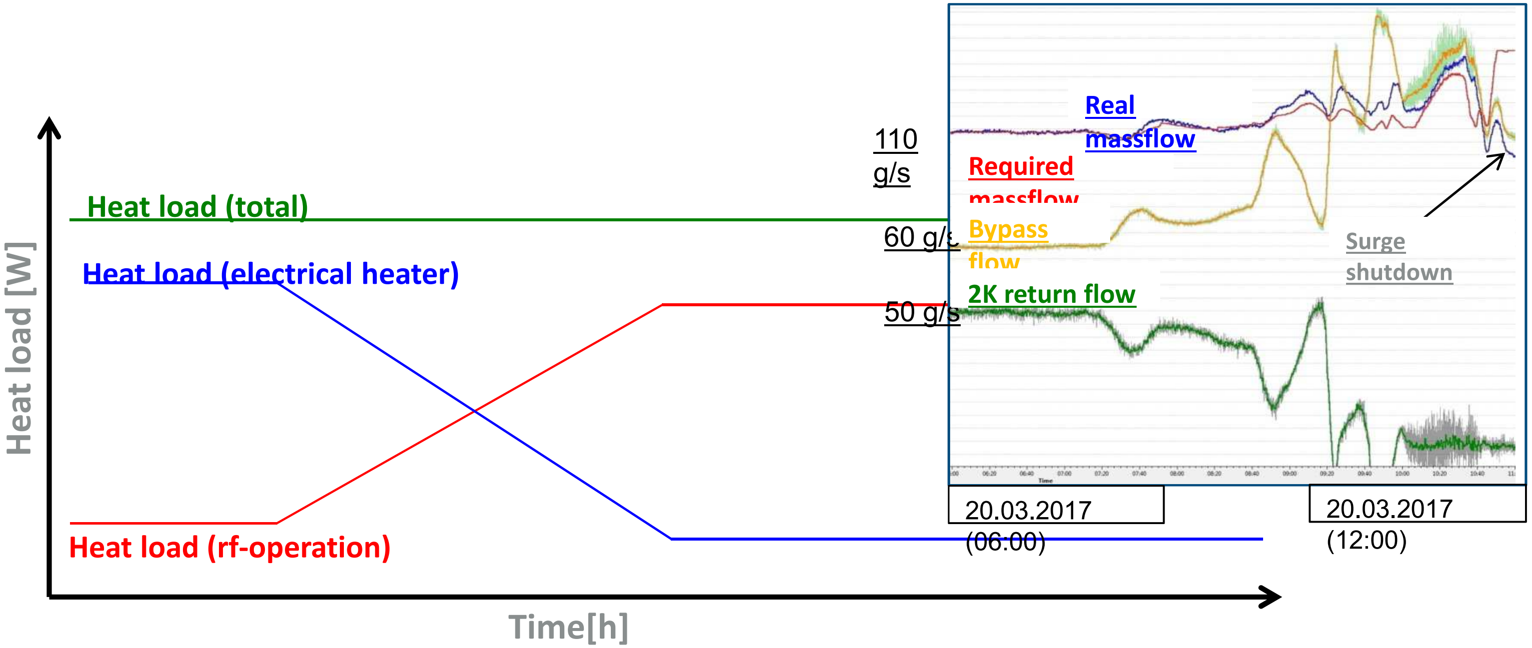
Pressure stability of about +/- 0.3 % achieved.

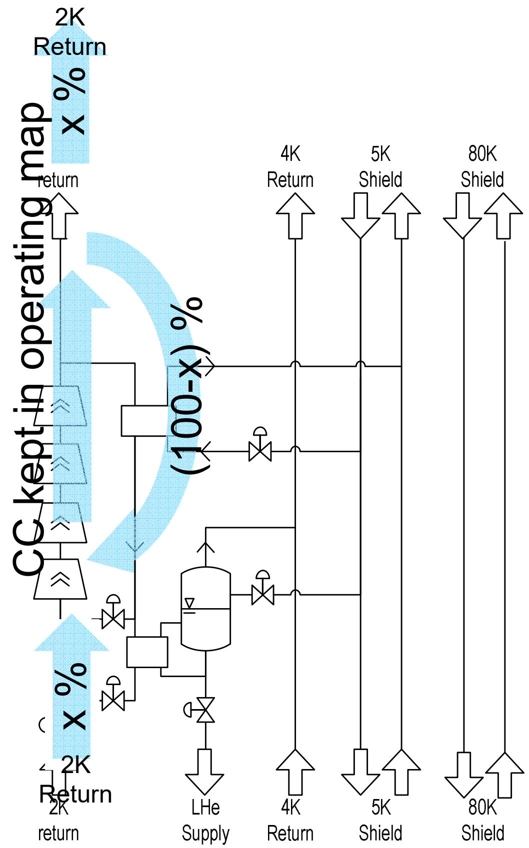
Regulation of RF load changes

RF load changes cause 2K Helium vapor mass flow changes.
CC regulation has to compensate the RF load changes.

by electrical heaters in the Helium bath (complementary) -fast

- by frequency regulation of CC within the narrow operation range (+ mixed cycle) -slow
- by bypass operation (in case of XFEL refrigerator plant)-slow



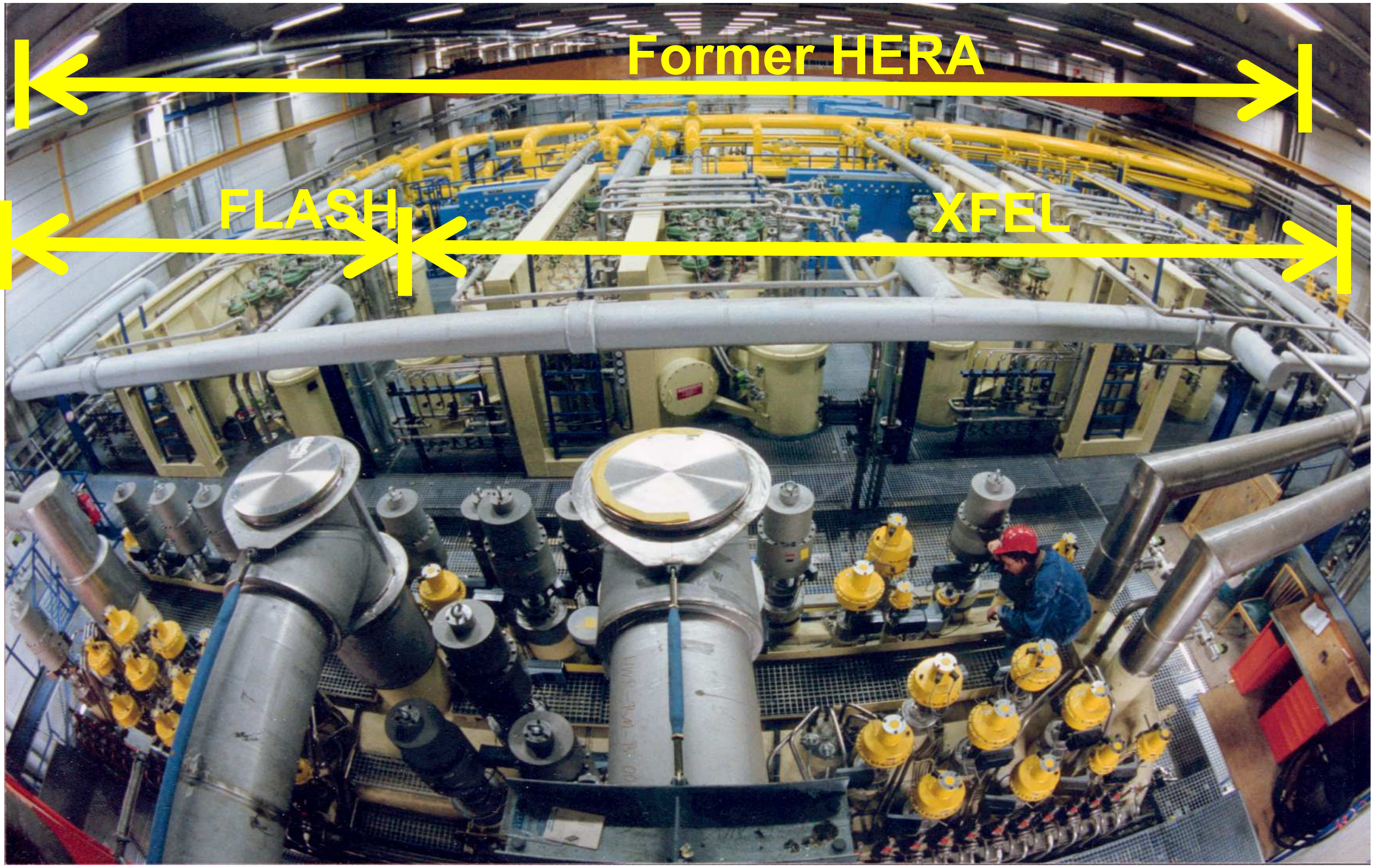


CC bypass operation

Cryogenic fundamentals –topics not covered

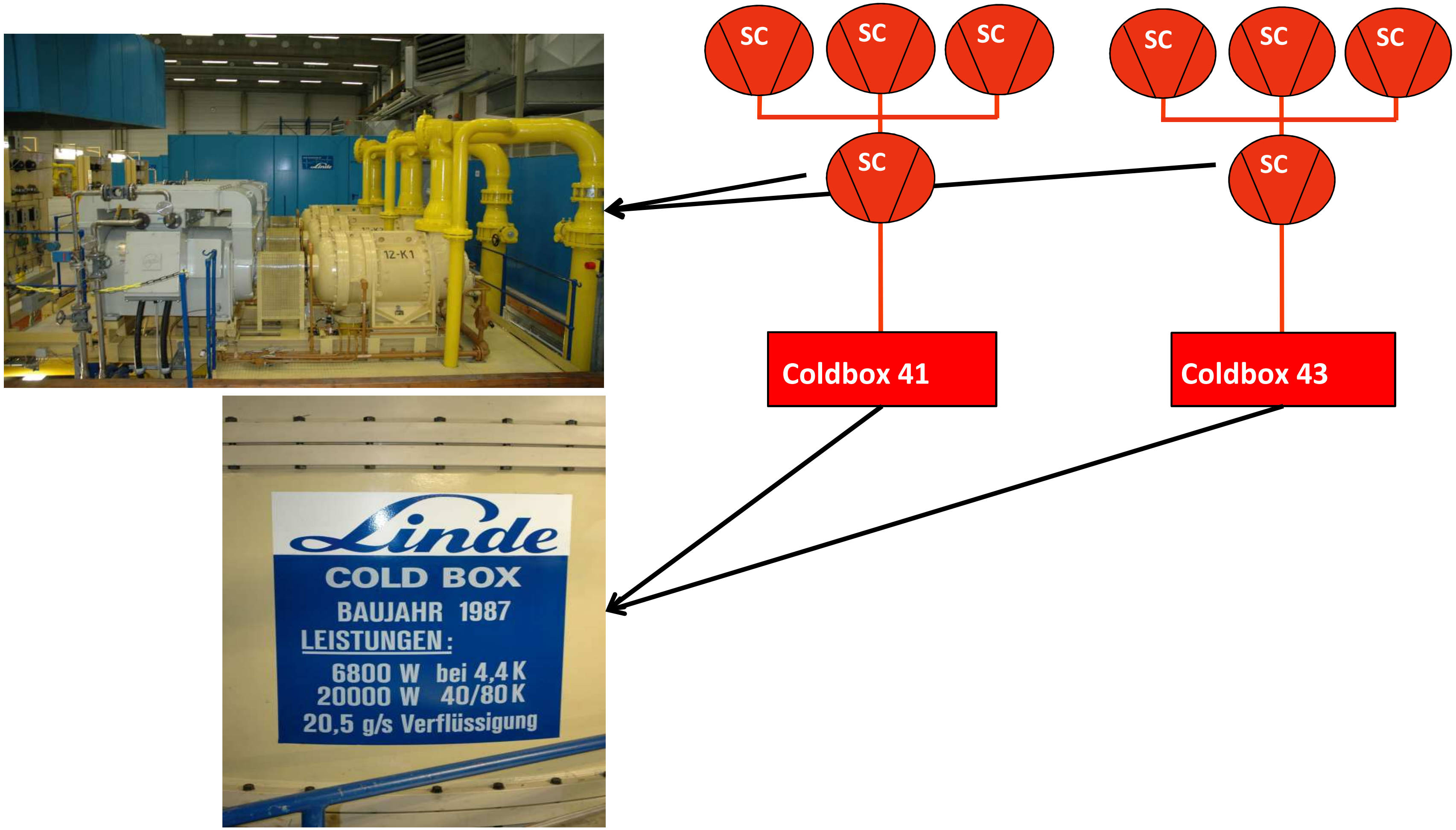
- Safety layout of the cryogenic system
- Helium gas management, storage and purification
- Helium guards for the subatmospheric systems
- Redundancy
- Restart of CCs under subatmospheric conditions
- Cool-down/ warm up
- Thermoacoustic oscillations
- …what else ?

XFEL cryogenic system
Overview



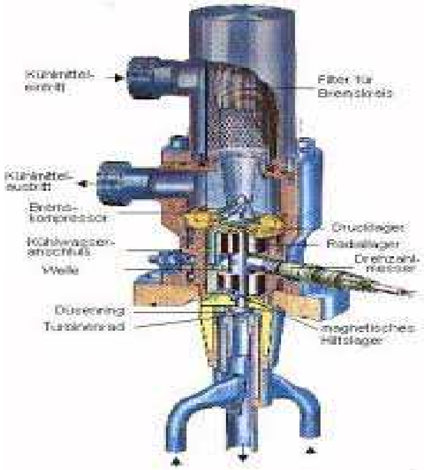
XFEL cryogenic system
Overview

XFEL-Subplant 41 XFEL-Subplant 43

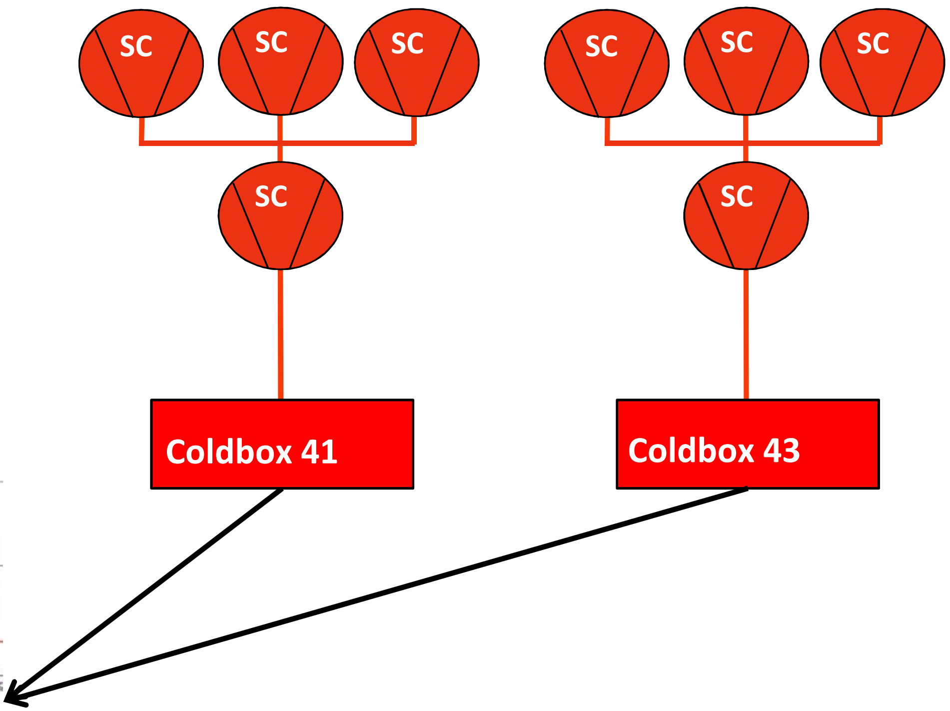


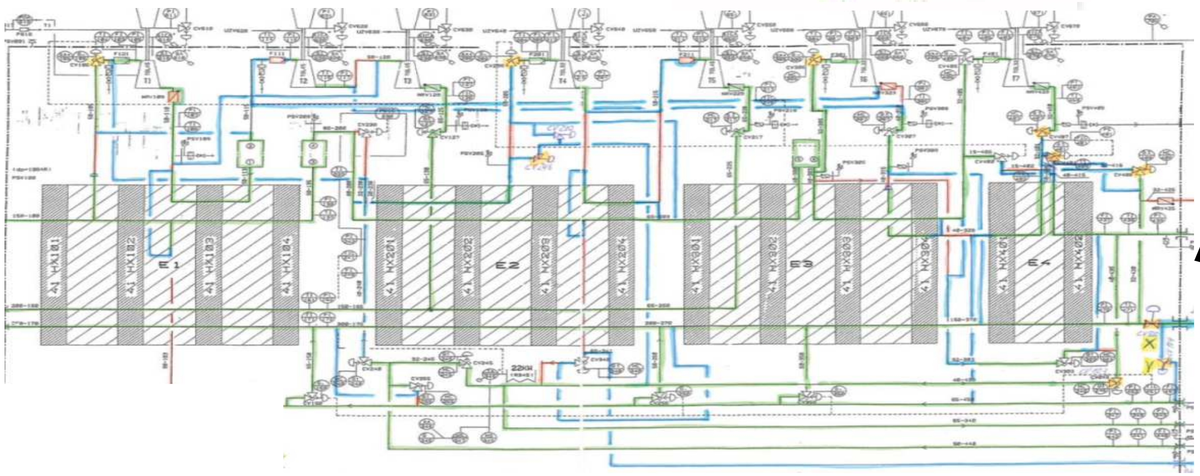
XFEL cryogenic system
Overview

7 Expansion Turbines
Linde Kryotechnik

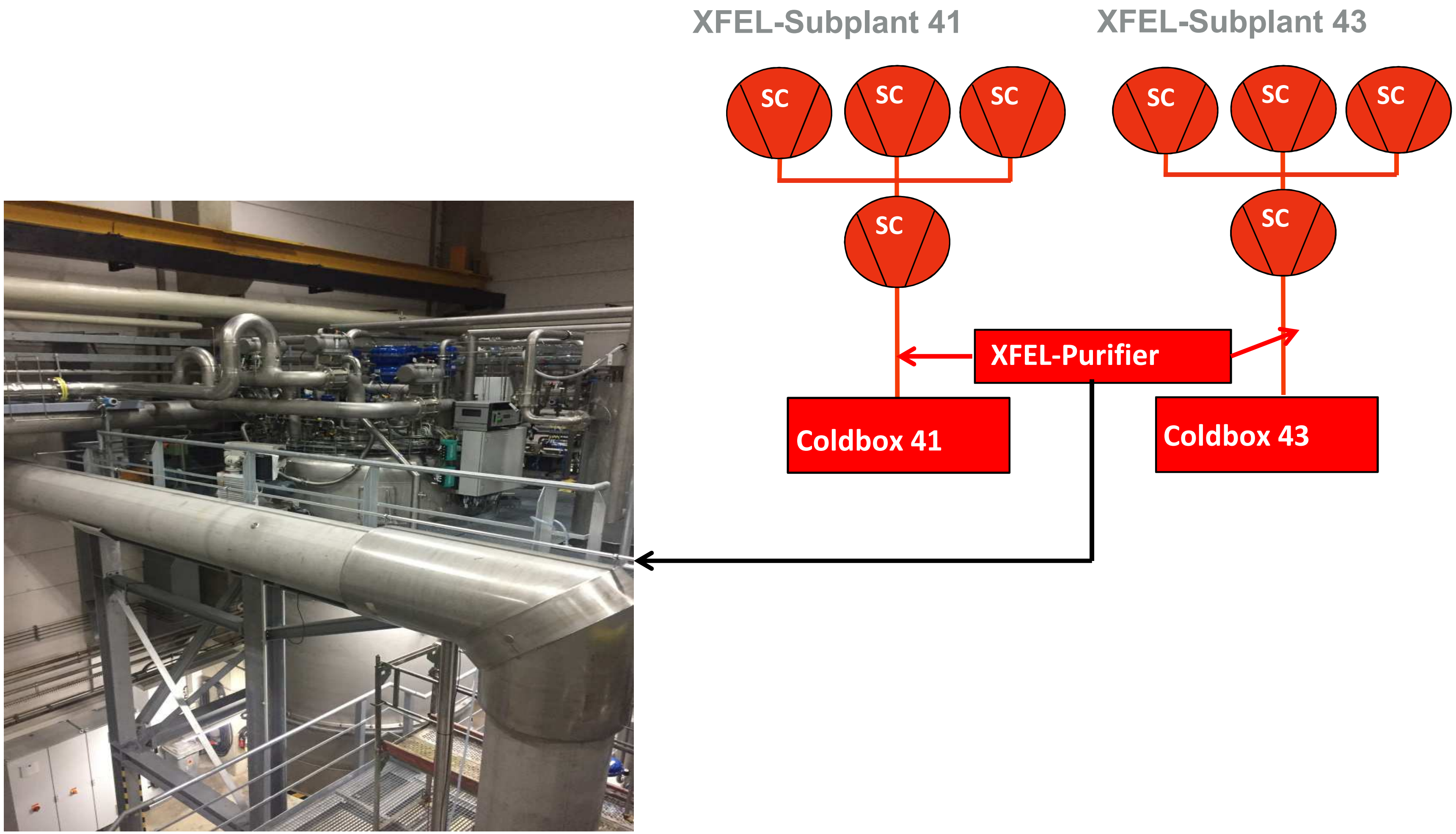


XFEL-Subplant 41 XFEL-Subplant 43

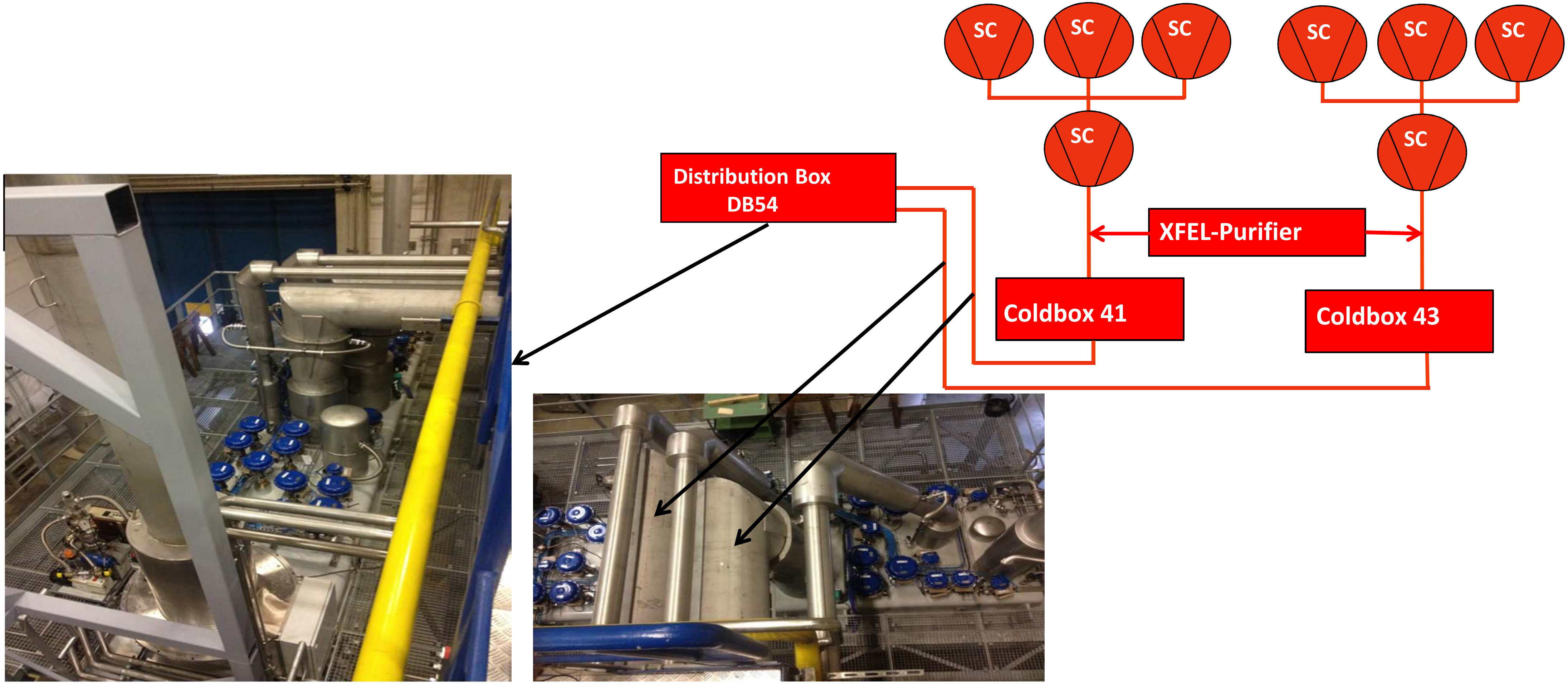




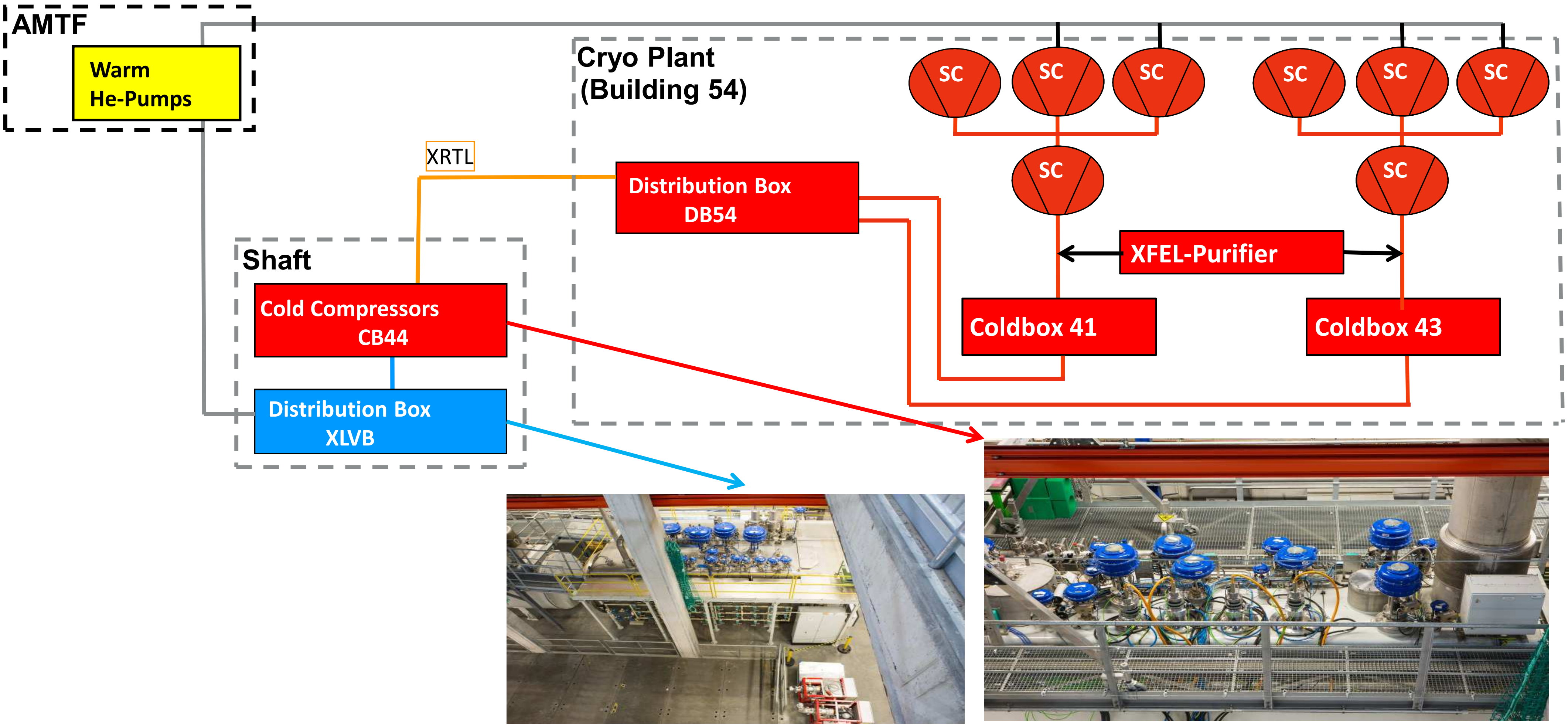
XFEL cryogenic system
Overview



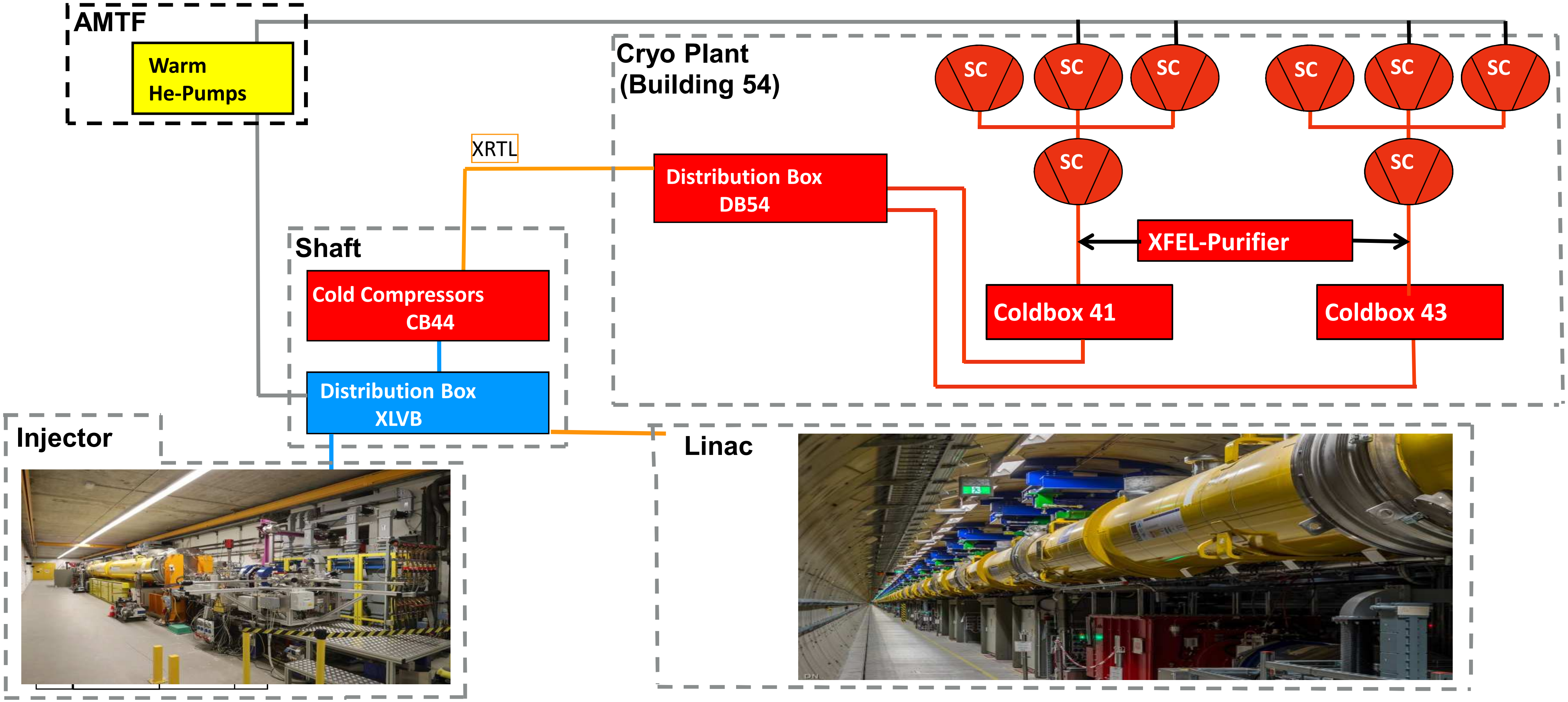
XFEL cryogenic system
Overview



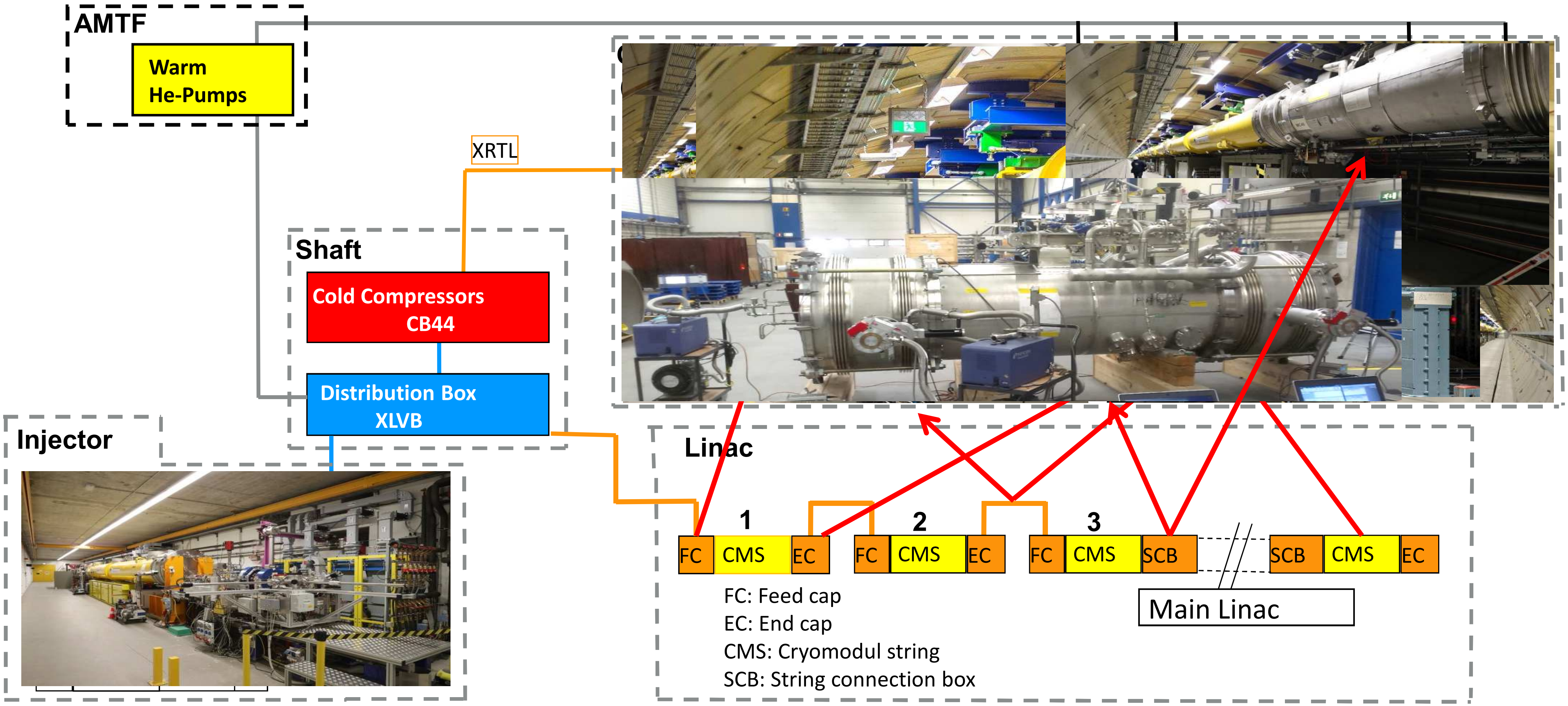
XFEL cryogenic system
Overview



XFEL cryogenic system
Overview



XFEL cryogenic system
Overview



Summary of this tutorial

- **Basic specifications**
- **Basic cryogenic distribution scheme**
- **RF cryomodule specifications**
- **Choice of cavity operation temperature**
- **Liquid helium cooling – limitations**
- **Cryomodule thermal insulation fundamentals**
- **Cryomodule mechanics fundamentals**
- **Cryomodule assembly**
- **Cryomodule transportation issues**
- **Cryomodule testing**
- **Cryogenic helium supply – basic specifications**
- **Helium refrigerator fundamentals**
- **Subatmospheric systems for T<=2K (warm helium pumps / cold compressors)**
- **Helium bath pressure stability and stabilisation of RF load changes**
- **Topics which are not covered**
- **If time is left: example XFEL cryogenic system**

Thank you for your attention !

Feel free to contact me:
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