Some Fundamentals of Cryogenic and Module Engineering

with regard to SRF Technology

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Overview

- First part: Some theory
- Second part: More practical aspects
  (cryomodule design considerations)

Too much items….. and still incomplete…..

But let‘s see how far we can proceed………

My sources:

- LINDEKRYOTECHNIK AG Switzerland, H.Herzog
- AERZEN Compressors Germany
- AIR LIQUIDE France
- WEKA Valves Switzerland
- VDI-Seminars Germany
- AD-Pressure-Vessel-Code
- ASME Code
- My colleagues from INFN, FNAL, Cornell-University, J-LAB, KEK, BESSY, DESY and Steve van Sciver
- others

First part: tutorial objectives

after this part, we should remember:

- The meaning of ‚***cryogenic***‘
- Carnot refrigerator efficiency
- ‚***COP***‘ of a refrigerator
- Some Helium refrigerator cycles
- Some ‚quantum properties‘ of matter at low temperatures
- Some useful Helium II properties
- Some typical cooling cycles
- Some fundamentals of thermal insulation

Cryogenic Fundamentals

Why is ‚Cryogenic' separated from ‚usual' cooling engineering ?

Use of ‚conventional' superconductors like Nb requires cooling

at liquid helium temperatures

Due to basic thermodynamic laws, the efficiency of refrigerators is quite low at these temperatures (‚Carnot cycle') – the cooling is very expensive !

-> excellent thermal insulation is required

-> refrigerators should work very efficient to come closer to the Carnot cycle

-> we have to deal with ‚quantum properties' of matter at these temperatures:

decrease of specific heat, heat transfer, superconductivity, superfluidity……

-> helium is the only coolant (low heat of vaporization, leak tightness, purification techniques….)

-> careful engineering is needed: choice of materials, welding procedures, quality control, pressure vessel code requirements……..

Definition: ‚CRYOGENIC‘

Traditional (you can find in textbooks) : T < 120 K

[My personal view: T < 77 K   (LN2 cooling is no ‚real‘ cryogenic)]

Physicist view : temperatures were characteristic quantum states of matter dominate   (Cp -> 0, Helium II, conventional superconductivity…..)

HERE: The engineering, which is required to specify, design, construct and operate cooling systems and cryostats for superconducting RF cavities at liquid Helium temperatures.

Basic laws of thermodynamics

1. Energy conservation
2. Entropy can never decrease spontaneously in a closed system: $0 \leq \Delta S$ - corresponds to

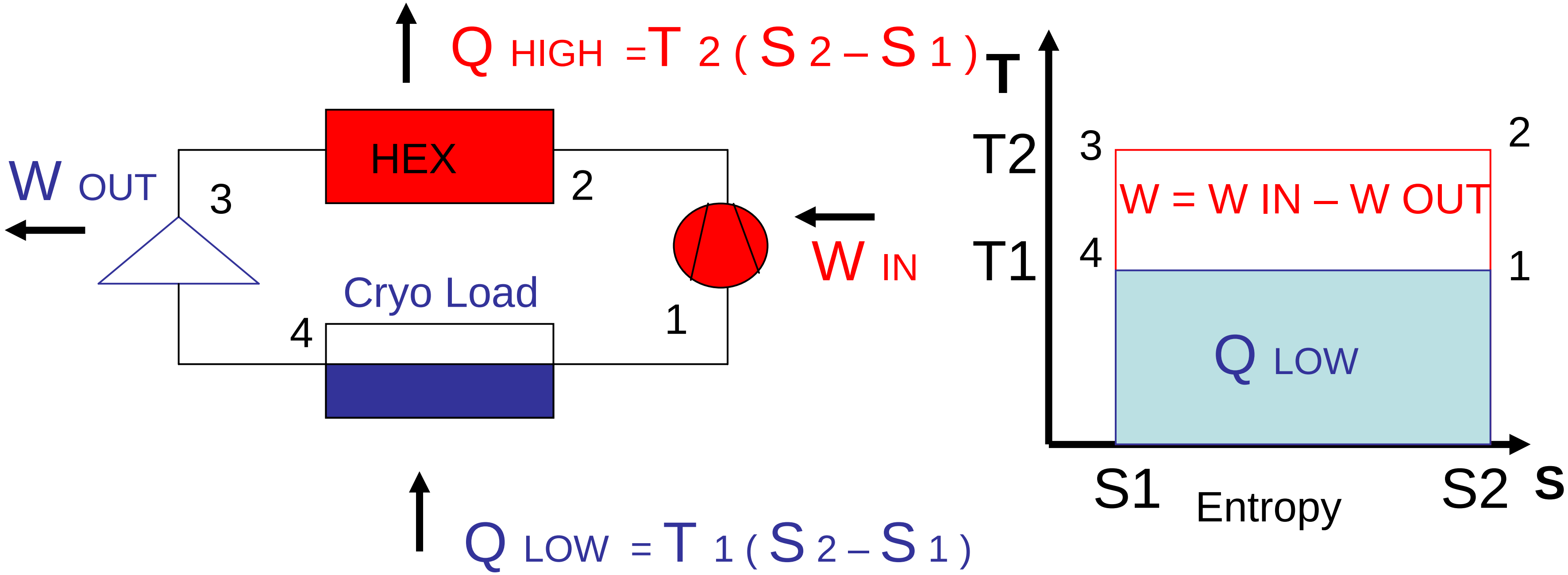
‚The Carnot Cycle is the most efficient cycle that exist‘

3. S -> 0 for T -> 0 for an ideal crystal

corresponds to Cp -> 0

(Engineers forget zero-point energy)

Carnot Refrigeration Cycle

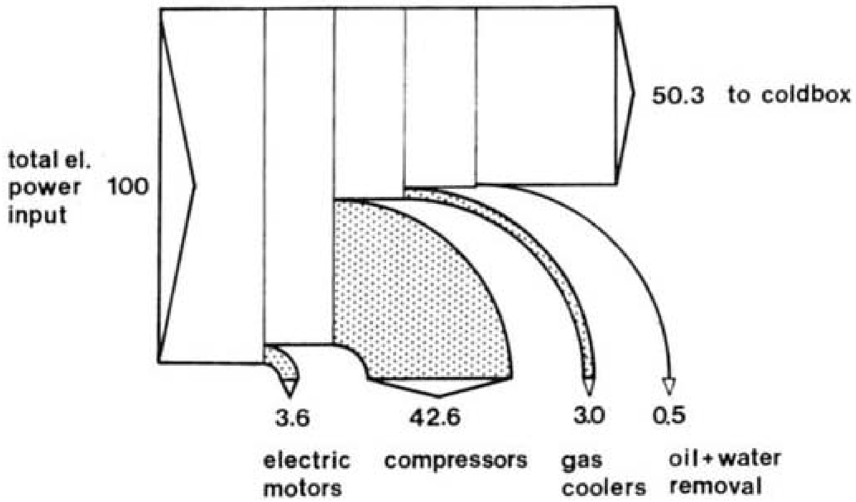


$$\eta_{Carnot} = \frac{\text{Useful Refrigeration}}{\text{Work Input}} = \frac{Q_{LOW}}{Q_{HIGH} - Q_{LOW}} = \frac{T_1}{T_2 - T_1}$$

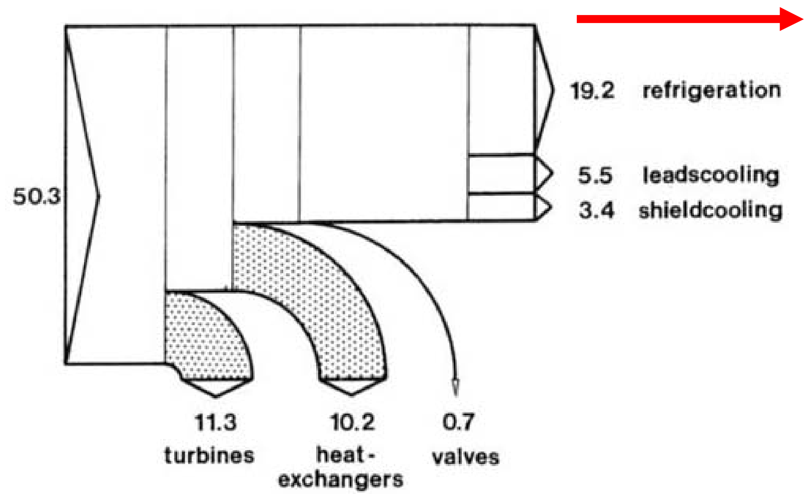
COP = Coefficient of Performance = 1/ η Carnot

Sources of Irreversibility

(B.Ziegler, LINDE)



Carnot Cycle

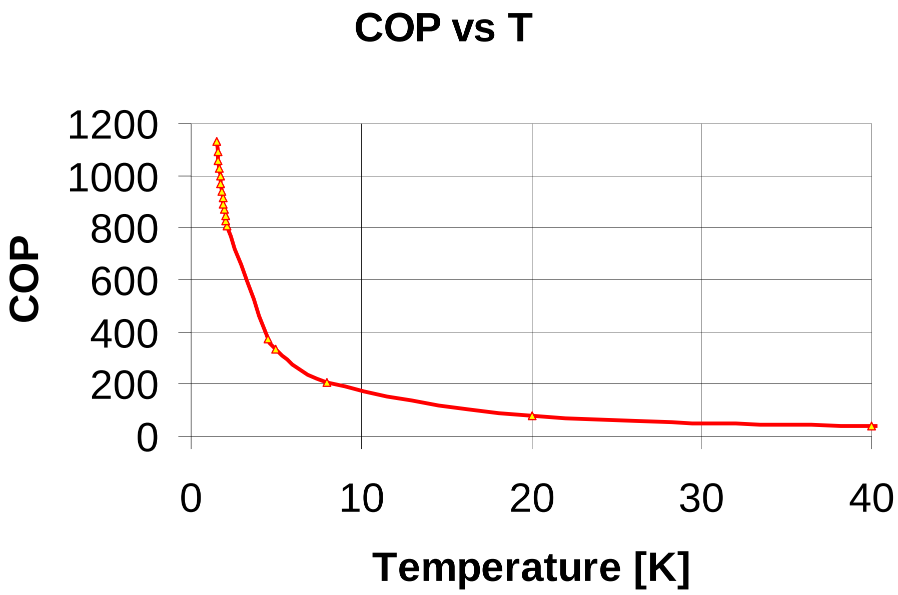


Some Refrigerator COPs

1 W useful refrigeration at 2 K = 870 W Primary Power !!!

Refrigeration Temperature	Carnot 1/η IDEAL WORLD	XFEL-Spec REAL WORLD	% Carnot
2 K	149	870	17
5 K	79	220	36
40 K	7	20	33

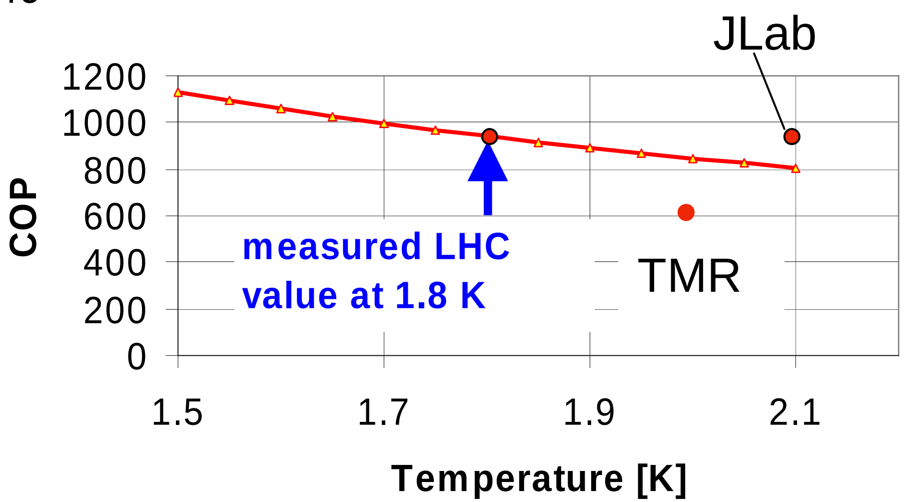
Coefficient of Performance



COP_{real}=1/(K * η CARNOT)

η CARNOT = T/(300 -T)

K= 0.176 (from latest LHC measurements at 1.8 K)



Why do we care about COPs ?

Cooling at liquid helium temperatures T < 5 K is very expensive !

Large SRF facilities (JLAB,SNS, ERLs, XFEL,ILC…..) need Megawatts of primary power supply.

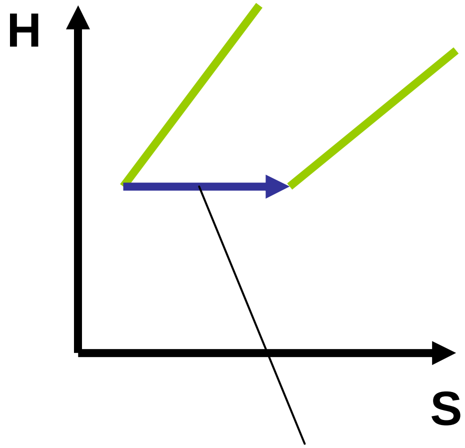
Excellent thermal insulation is mandatory !

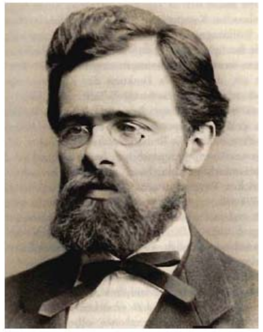
Already at about T> 40 K the situation is much more relaxed !

-> Direct heat loads as much as possible to temperature levels above 40 K (Radiation, HOM-loads, solid state thermal conduction…..)

Some Helium Refrigerator Cycles

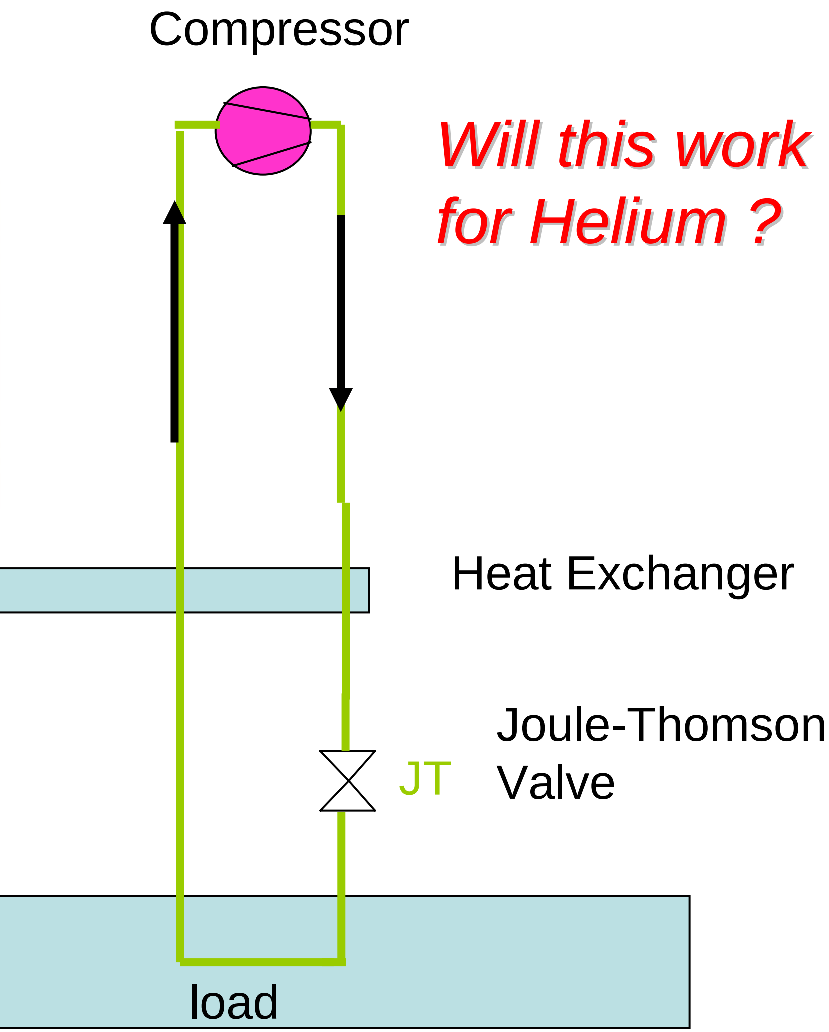
Simple LINDE cycle





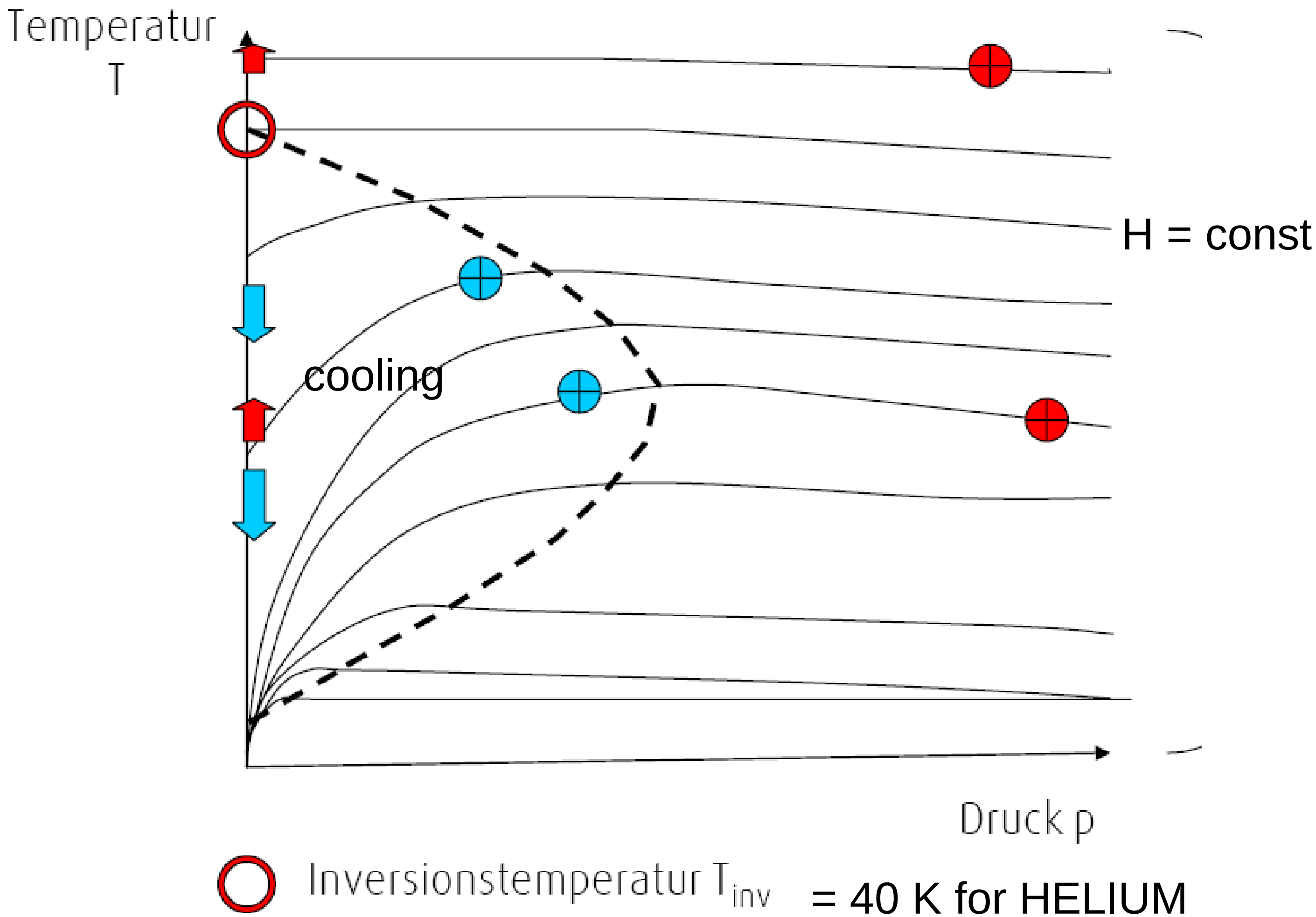
Carl von Linde 1842-1934

Will this work for Helium ?



Ideal Joule-Thomson Expansion =
Isenthalpic Expansion $\Delta H=0$

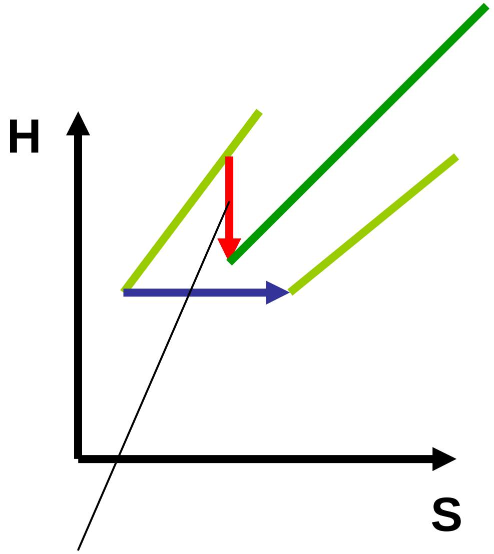
Joule-Thomson Expansion: Inversion Curve



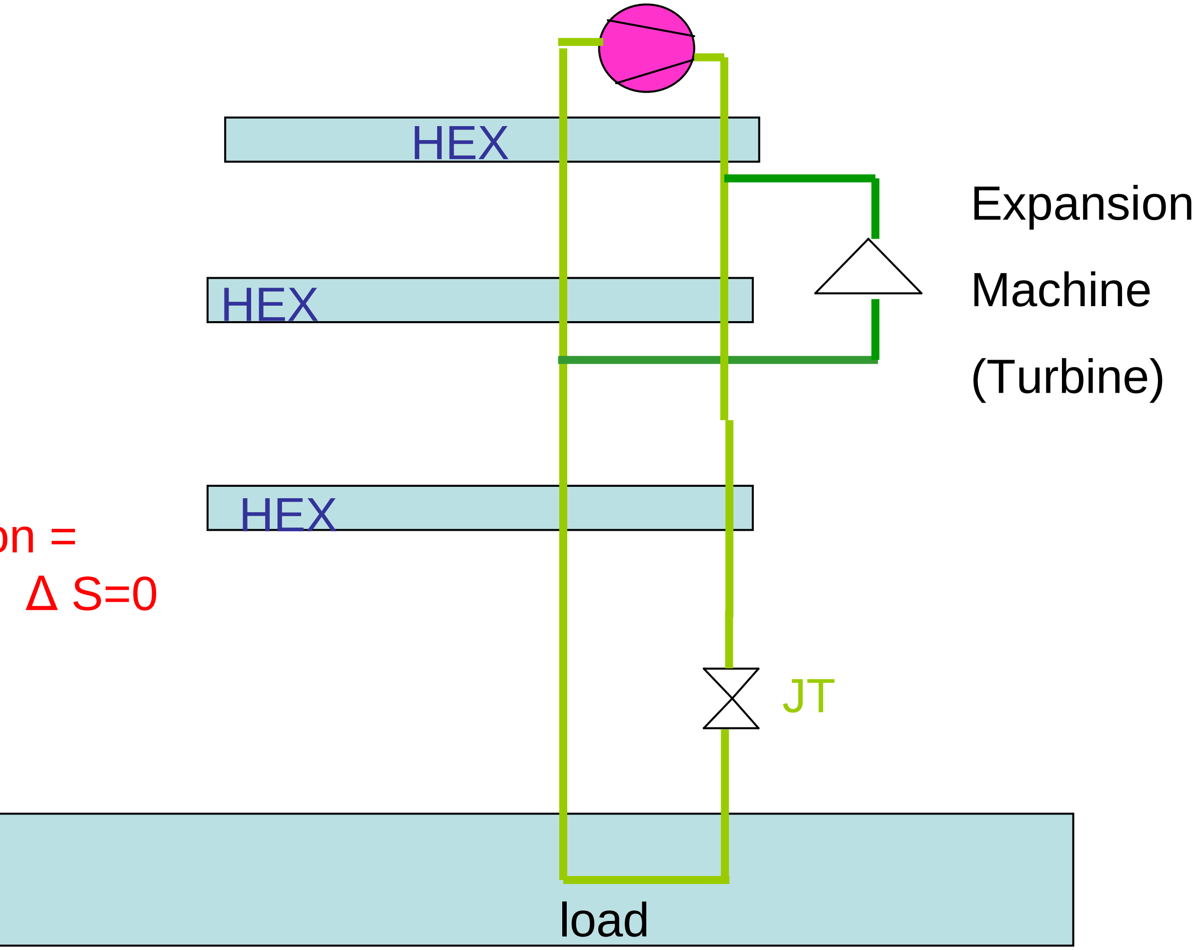
= 40 K for HELIUM

Some Helium Refrigerator Cycles

Simple Claudet Cycle

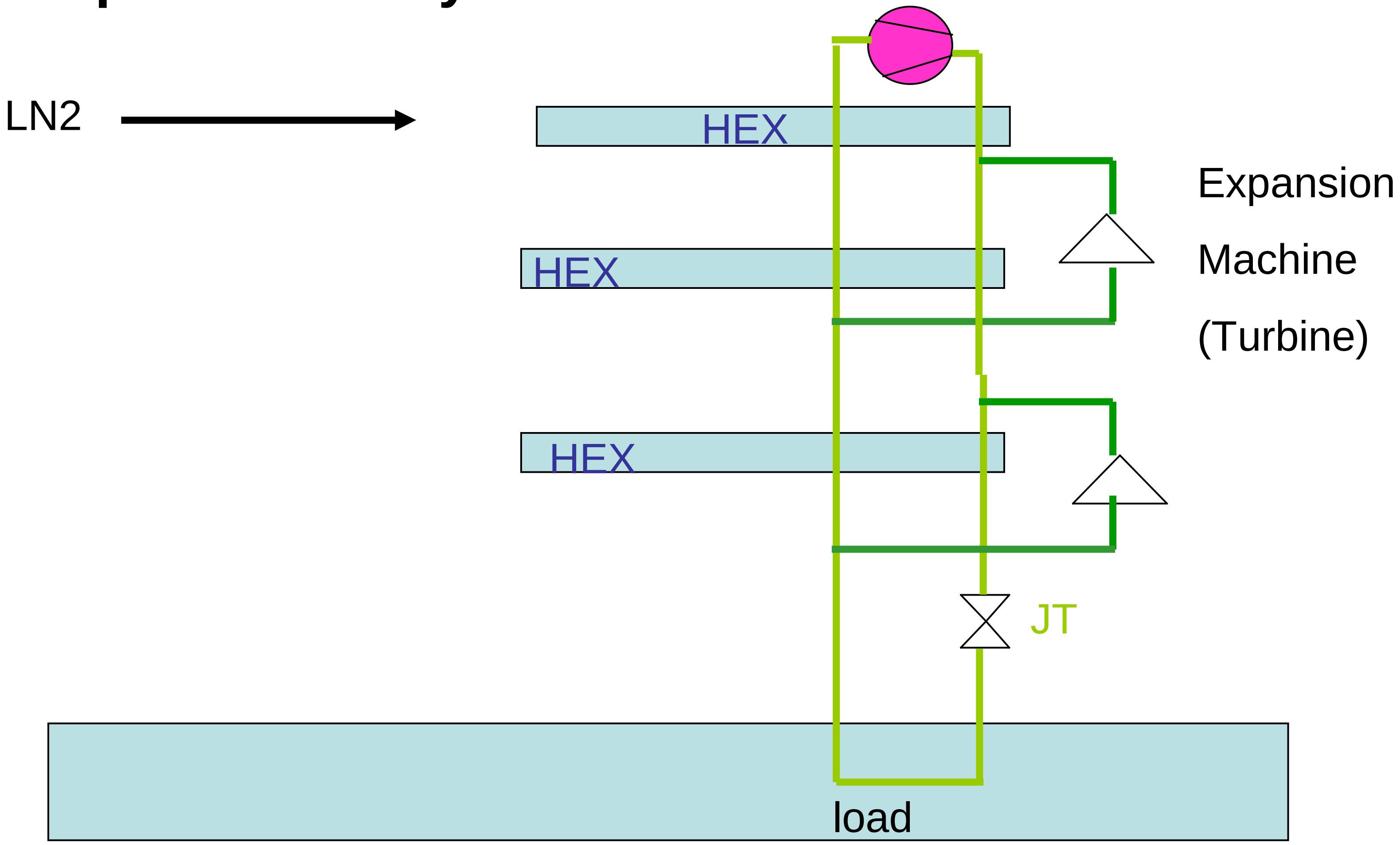


Ideal Turbine Expansion =
Isentropic Expansion Δ S=0



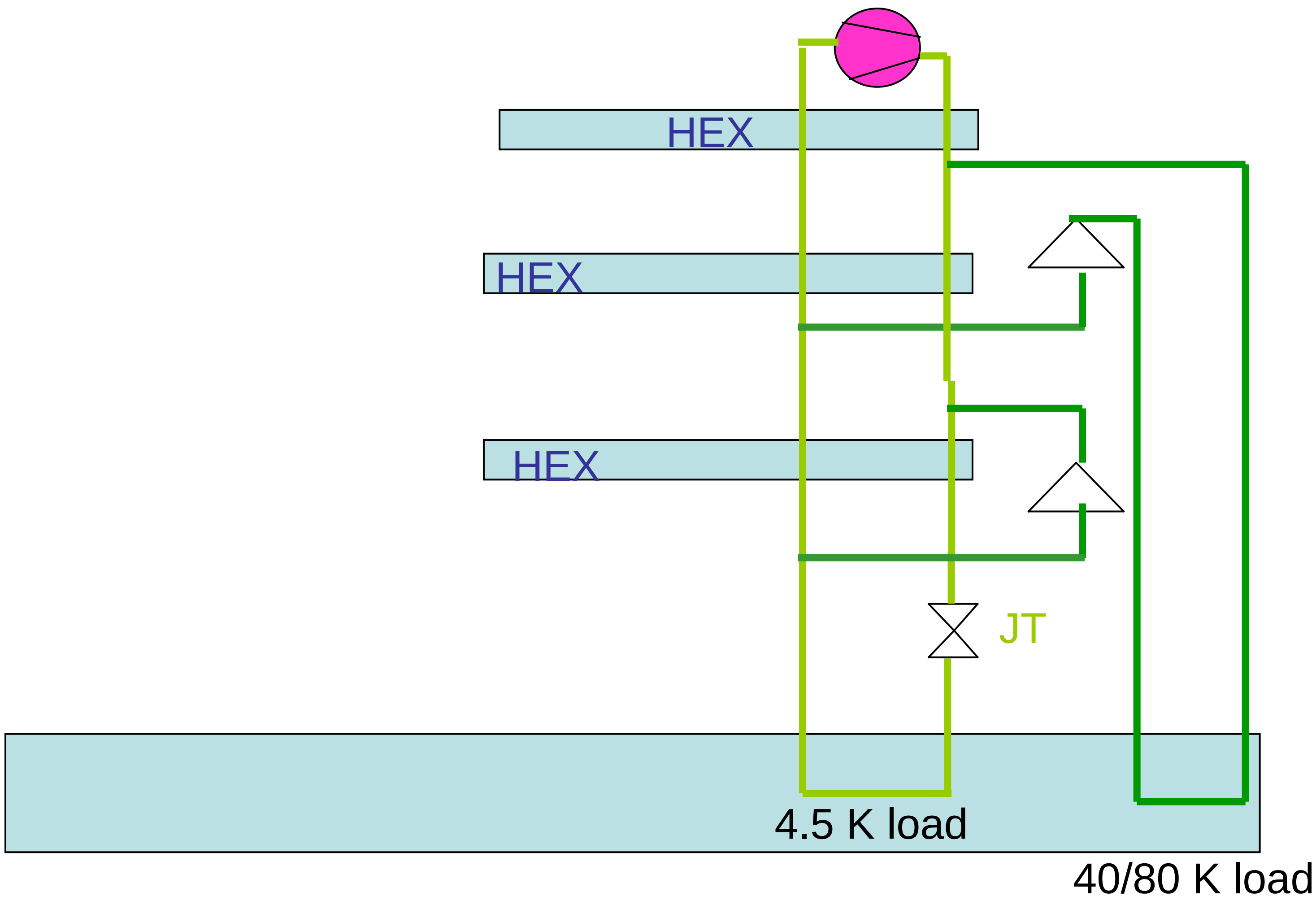
Some Helium Refrigerator Cycles

Simple Collins Cycle



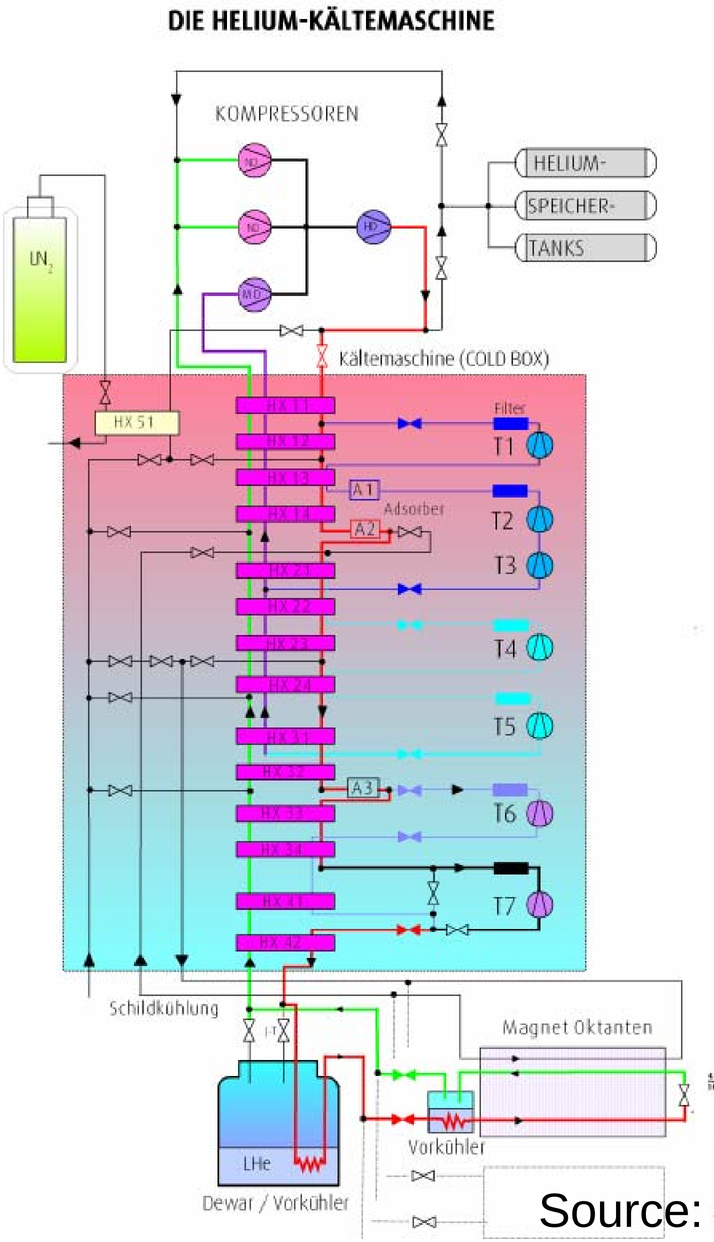
Some Helium Refrigerator Cycles

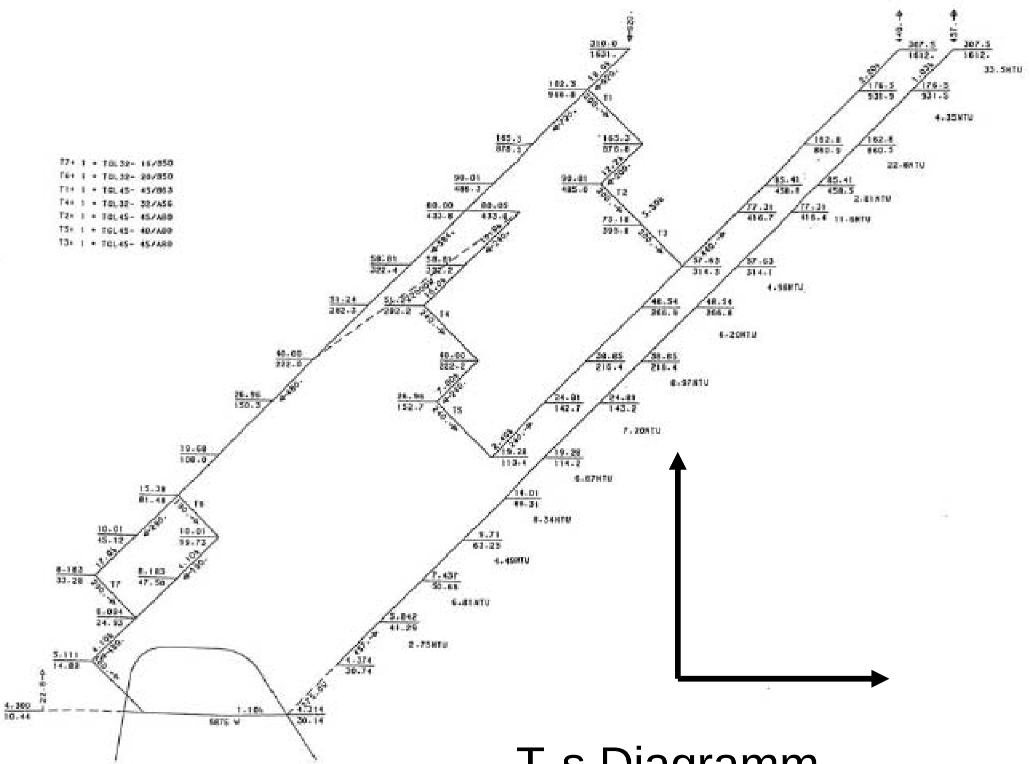
Simplified 4.5 K Helium Refrigerator + Shield Cooling



EXAMPLE:

HERA Cryo Plant



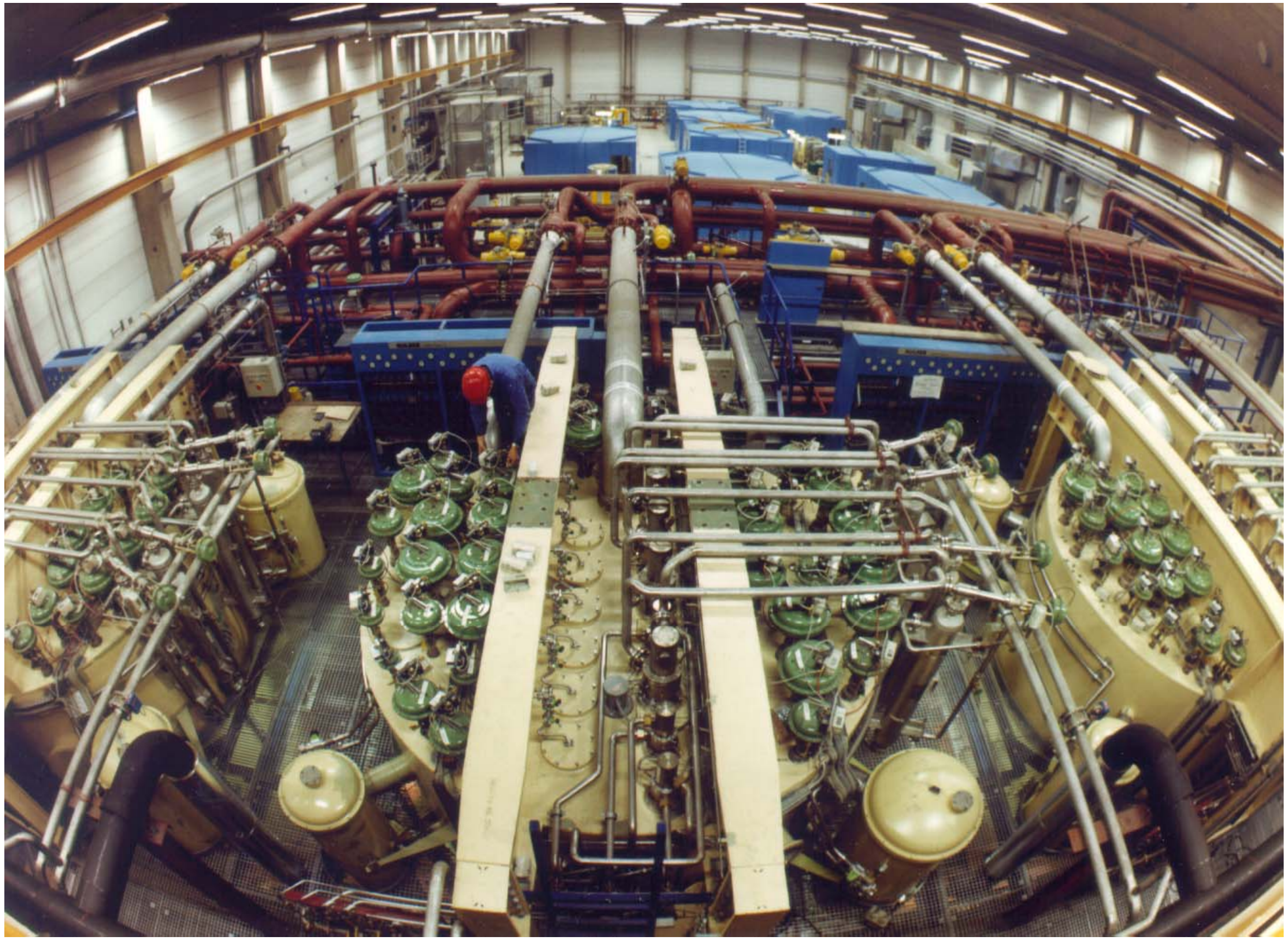


T-s Diagramm

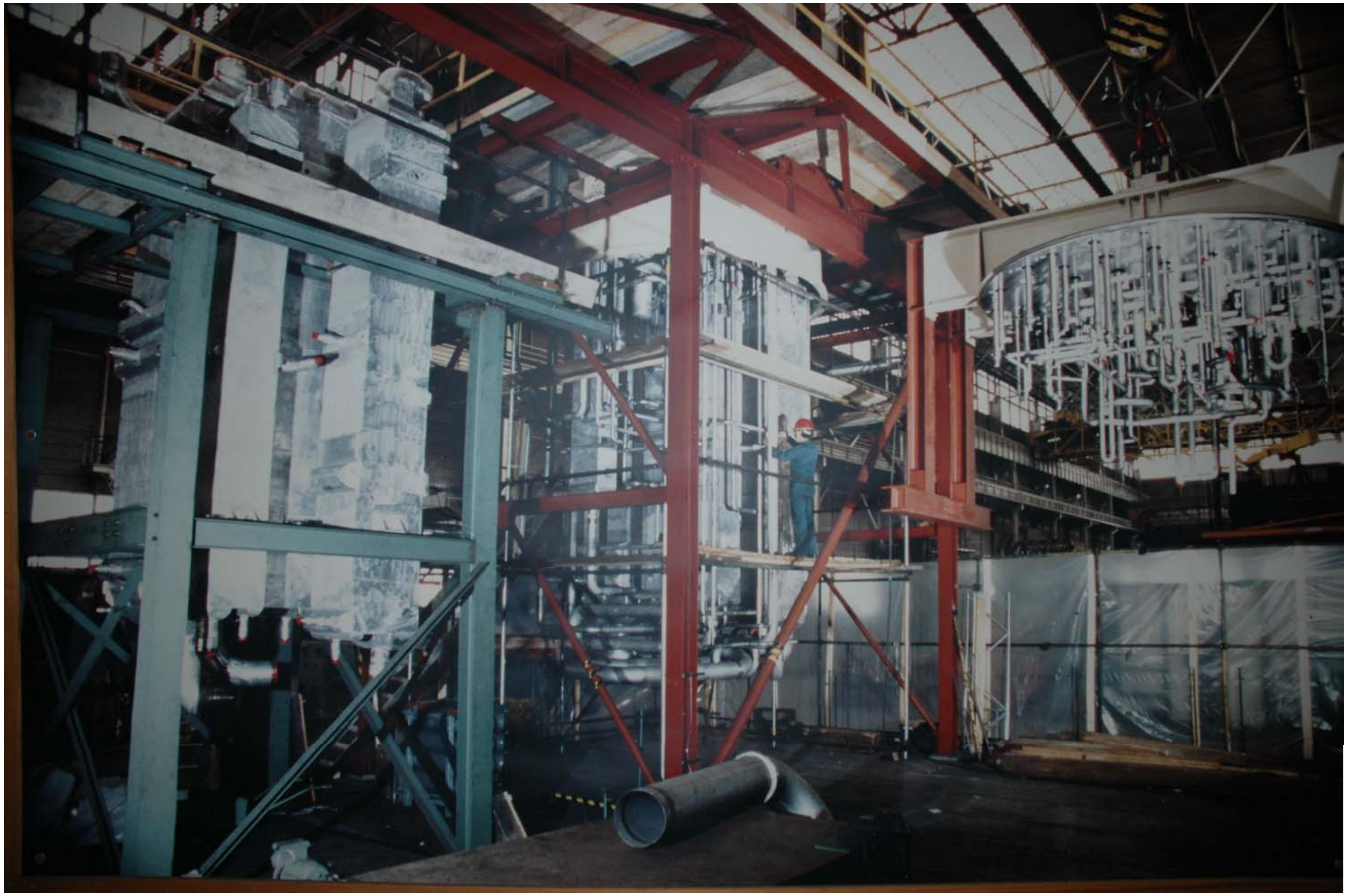
of cryogenic process

Source: + H. Herzog, 08.05.2007

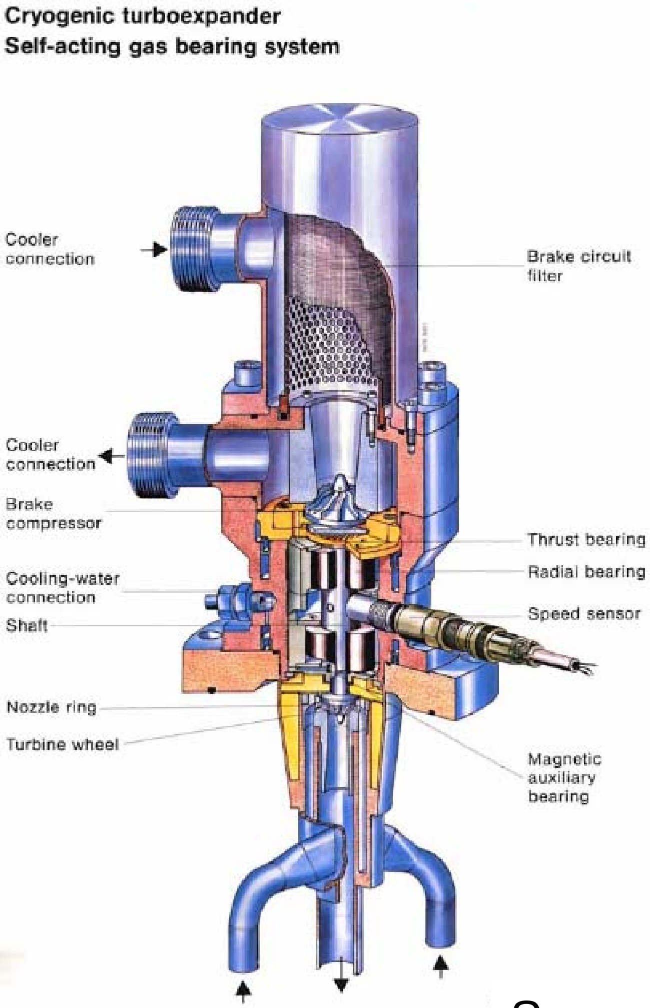
Example: HERA Cryo Plant

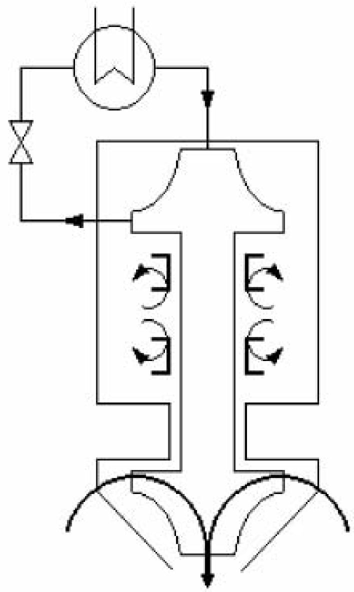


Inside HERA Cold Boxes



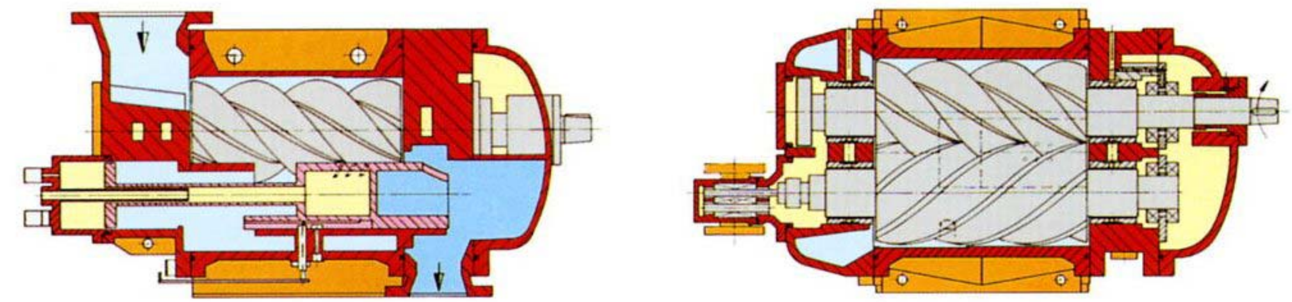
Cryogenic Turboexpander





Source: LINDEKRYOTECHNIK AG

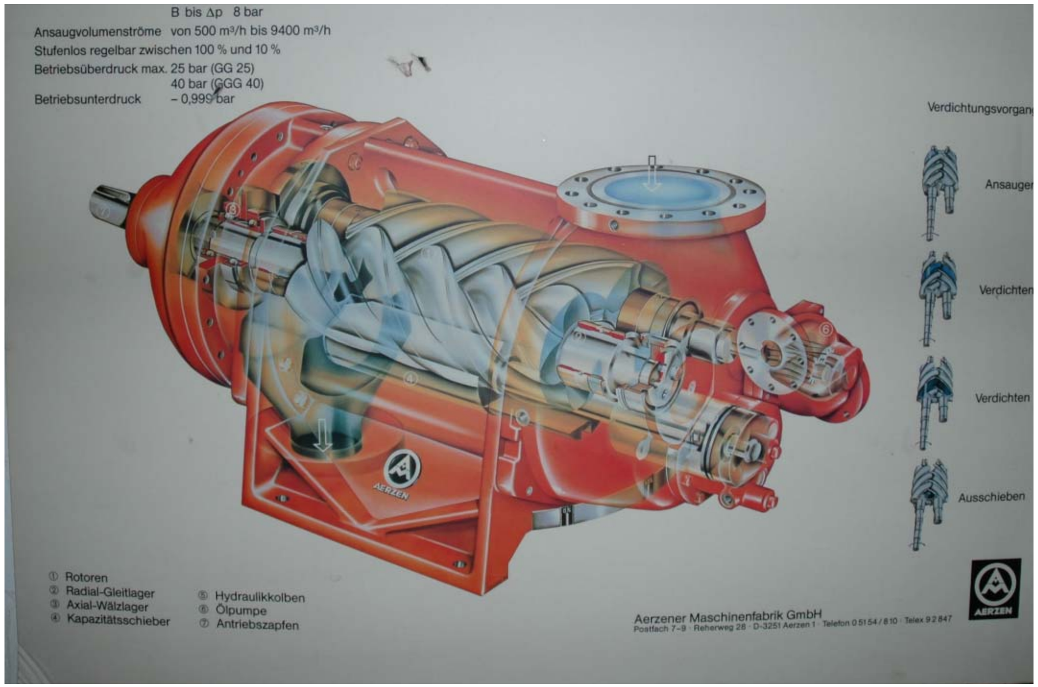
Screw-Compressors



Längsschnitt: Ansicht von der Seite. Abb. AERZENER Maschinenfabrik, Aerzen Längsschnitt: Ansicht von oben.

Source:

AERZEN



HERA-Screw Compressors

LP + MP

HP

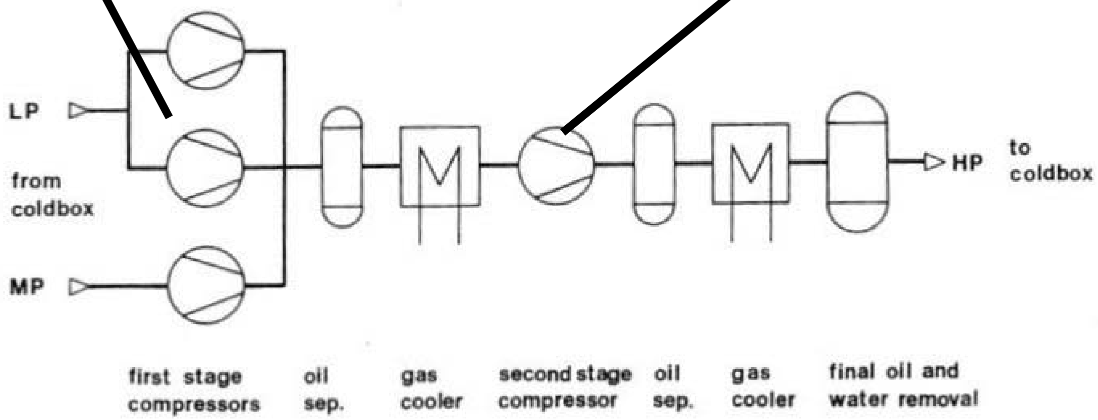
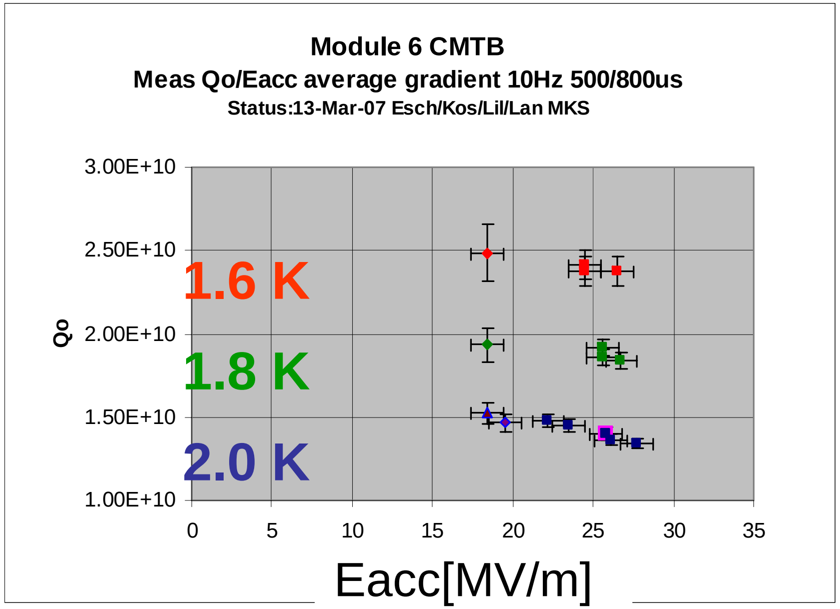


Fig. 2. HERA refrigerator: compressor flowsheet

‚Choice of operation temperature for a sc cavity'

Qo

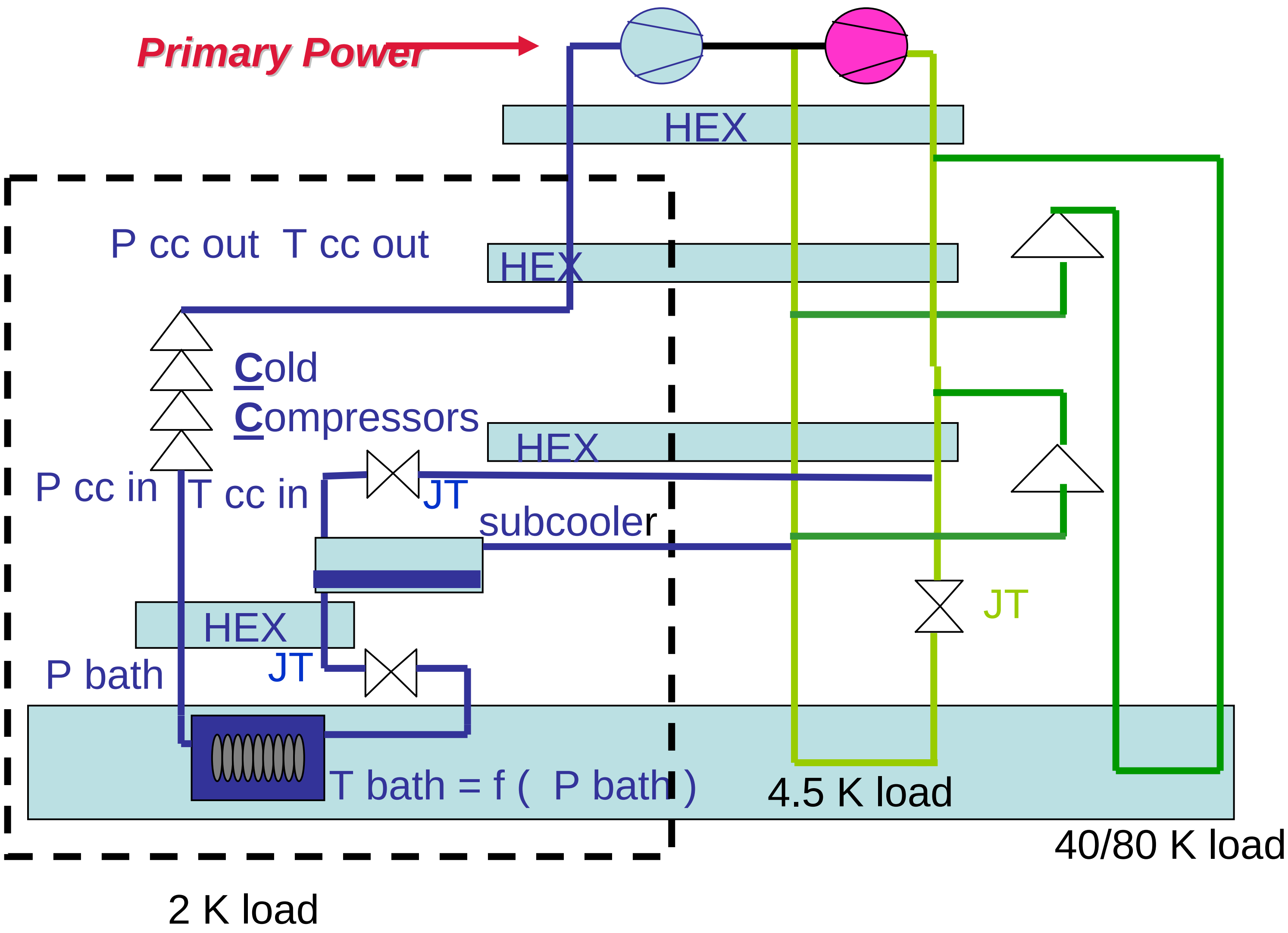


(Courtesy of R.Lange et al. DESY MKS)

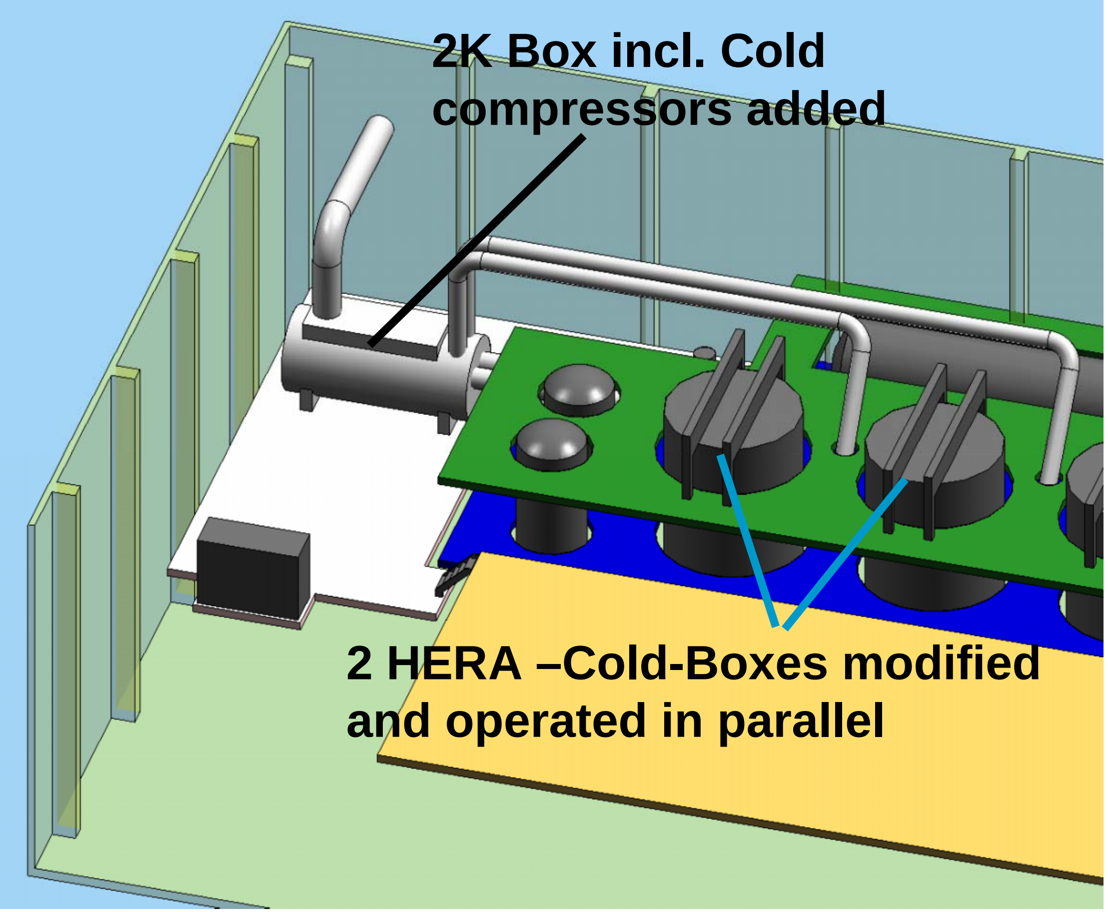
Qo versus Eacc measurement for a complete TTF-cryomodule type III

(similar to XFEL-prototype)

Simplified 2 K Helium Refrigerator + Shield Cooling

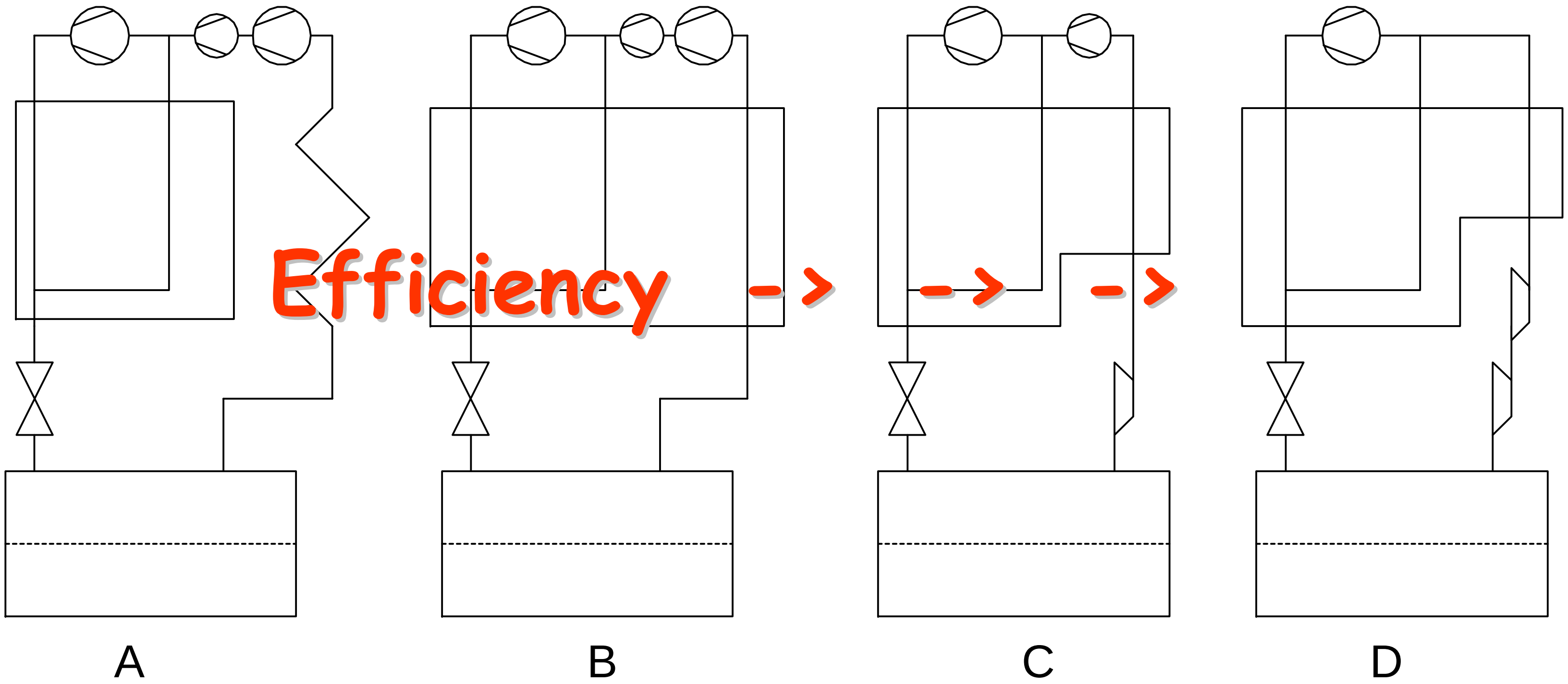


The 20-year old HERA cryogenic plant will be up-graded to the 2 K- XFEL-cryogenic plant



Source: LINDE KRYOTECHNIK AG

Options to Produce Temperatures below 4.4 K, i. e. Evaporation of Helium at Reduced Pressures



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 coldcompressor.

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

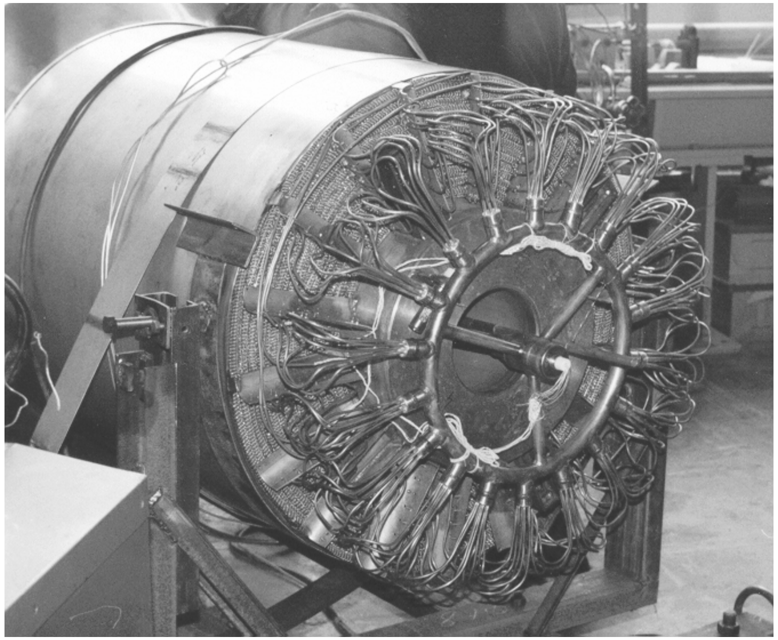
Option A example: warm helium compressors for FLASH-linac/TTF supply at DESY

4 rotary vane pumps + 3 stages of roots blowers
10 g/s helium flow compression: 10 mbar -> 1.05 bar
(two identical sets of compressors for linac and TTF)

Option B: use of heat exchanger
Example: FLASH linac at DESY

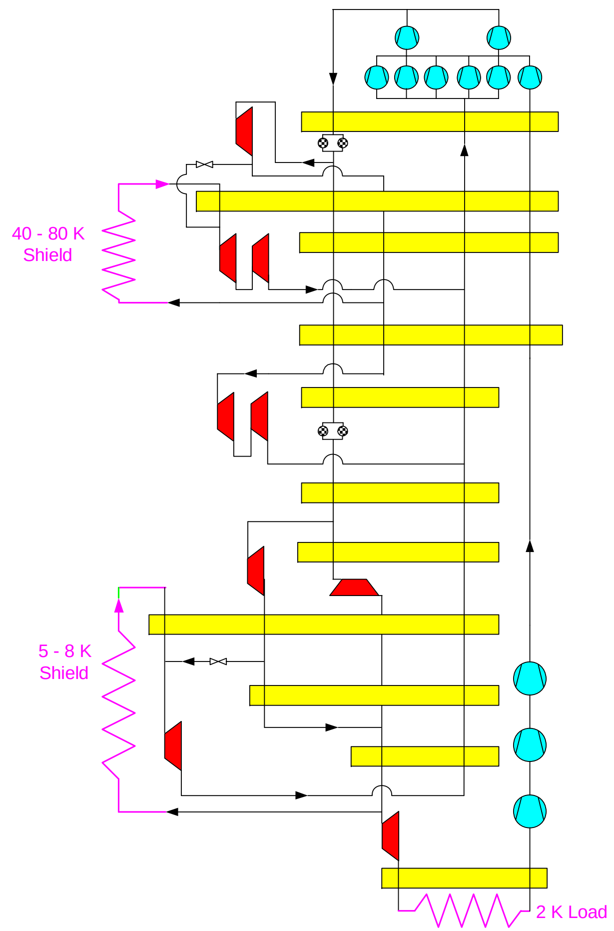
External low pressure heat exchanger (IHEP,Russia)
counter-flow heat exchanger:

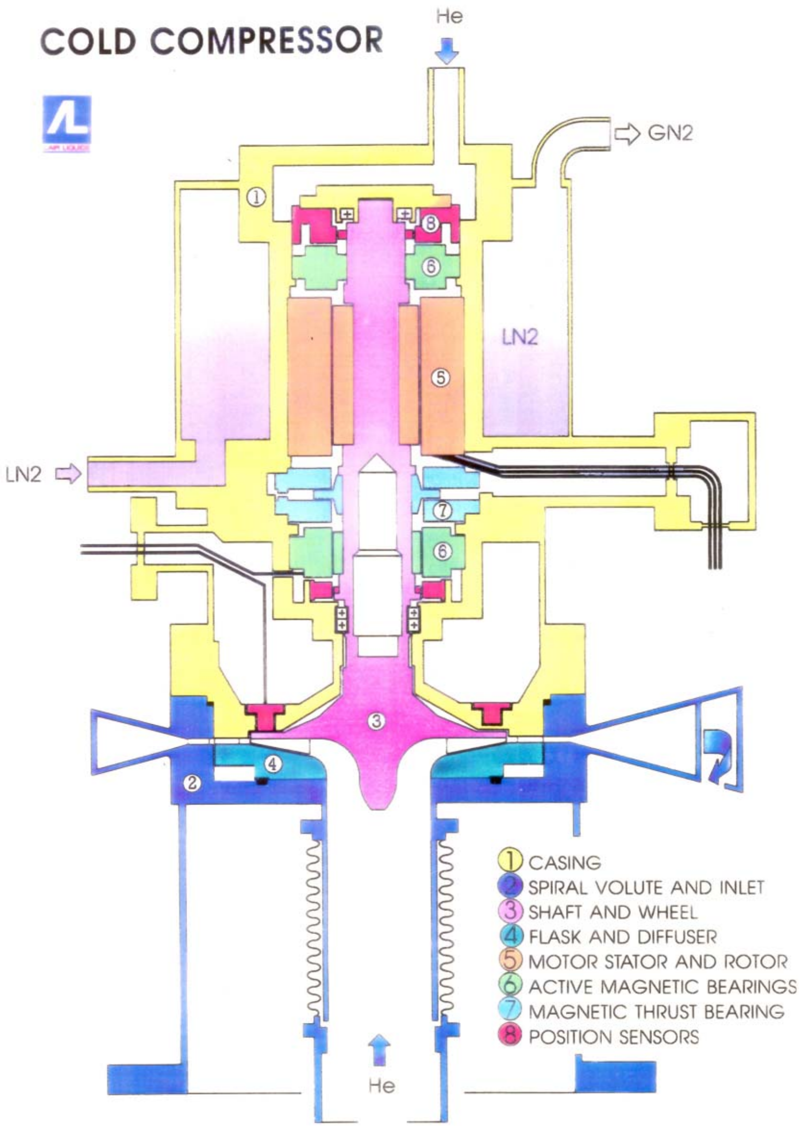
3,5 K / 31 mbar -> 280 K / 29 mbar
7,5 K / 12 bar <- 300 K / 12 bar



Option C/D
Example: TESLA Model Refrigerator

- layout by TU-Dresden
- advice from CERN
- discussion with industry
  - component number and size, flow rates, power consumption
- flow scheme
- 8 screw compressors
- 9 turbines
- 3 cold compressors





Example of a cold compressor with active magnetic bearings used at Tore Supra, CEBAF and Oak Ridge

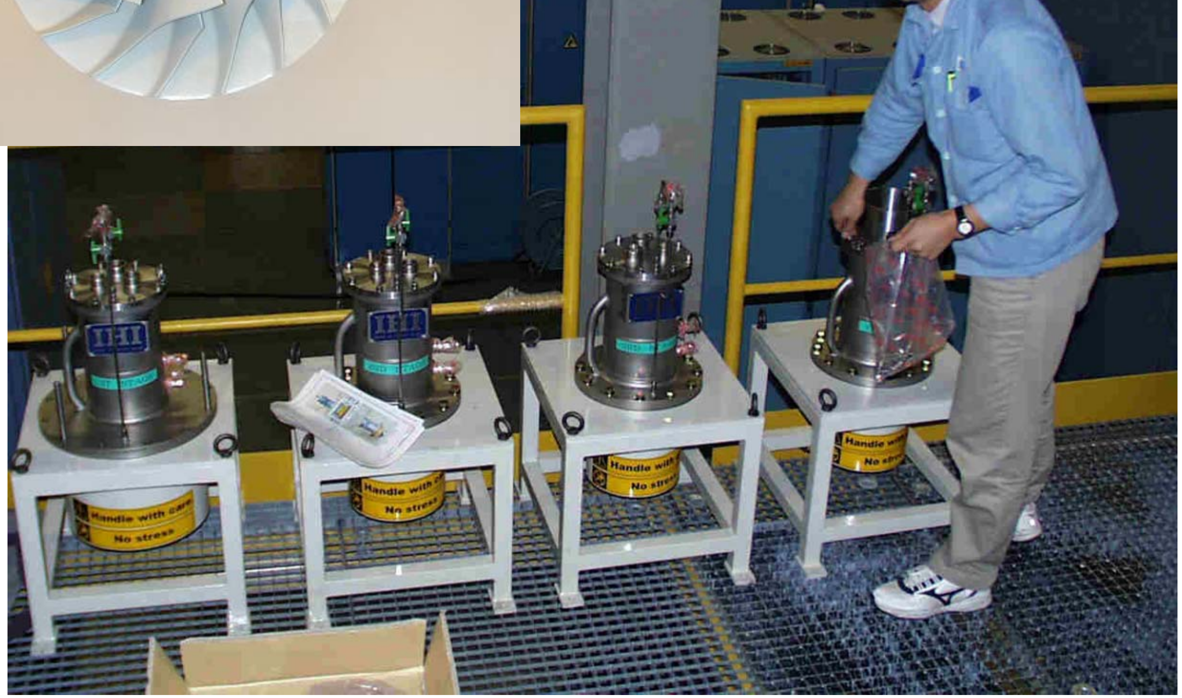
Source: Air Liquide

Cold Compressor Cartridges of 2.4 kW @ 1.8 K Refrigeration Units

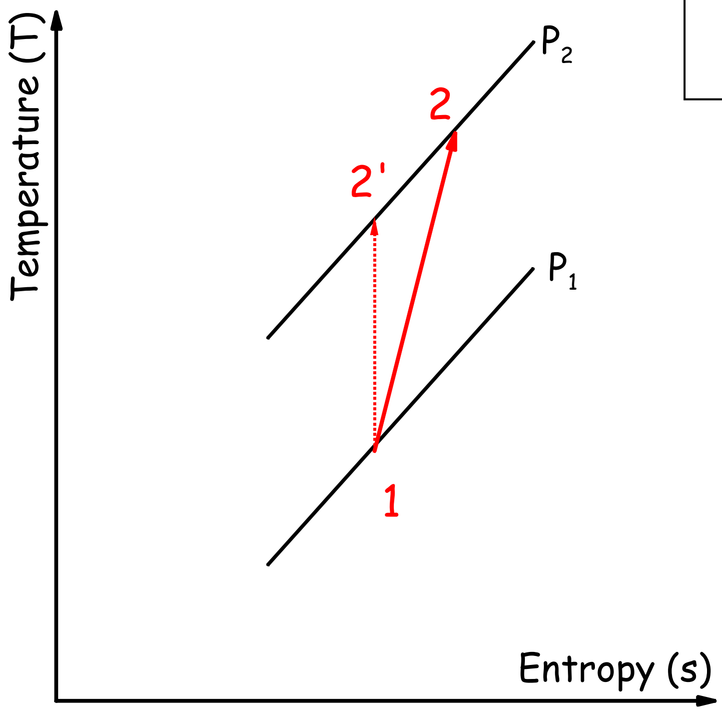
IHI-Linde

Cold compressor impeller

1st stage

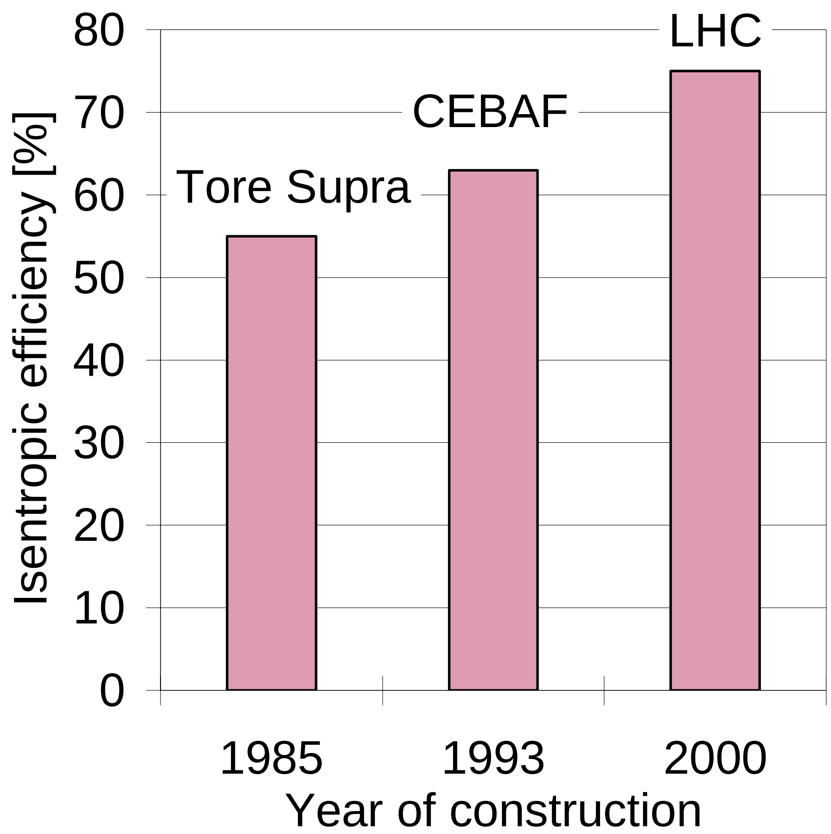


The four-stage LHC cold compressors



$$\eta_{is} = \frac{H_{2'} - H_1}{H_2 - H_1}$$

Development of the Efficiency of Cold Compressors



‚Quantum Properties‘ of Matter at low T

Many physical effects can be characterized by a typical Excitation Energy ΔE

The probability of excitation is about ~ EXP (- $\Delta E / k_B T$)

For T -> ∞ all states are excited.

For T -> 0 condensation in the ground state

ΔE = binding energy -> condensation of matter , liquifaction of gases

$\Delta E = \hbar\omega$ phonons in solids -> specific heat, thermal conductivity

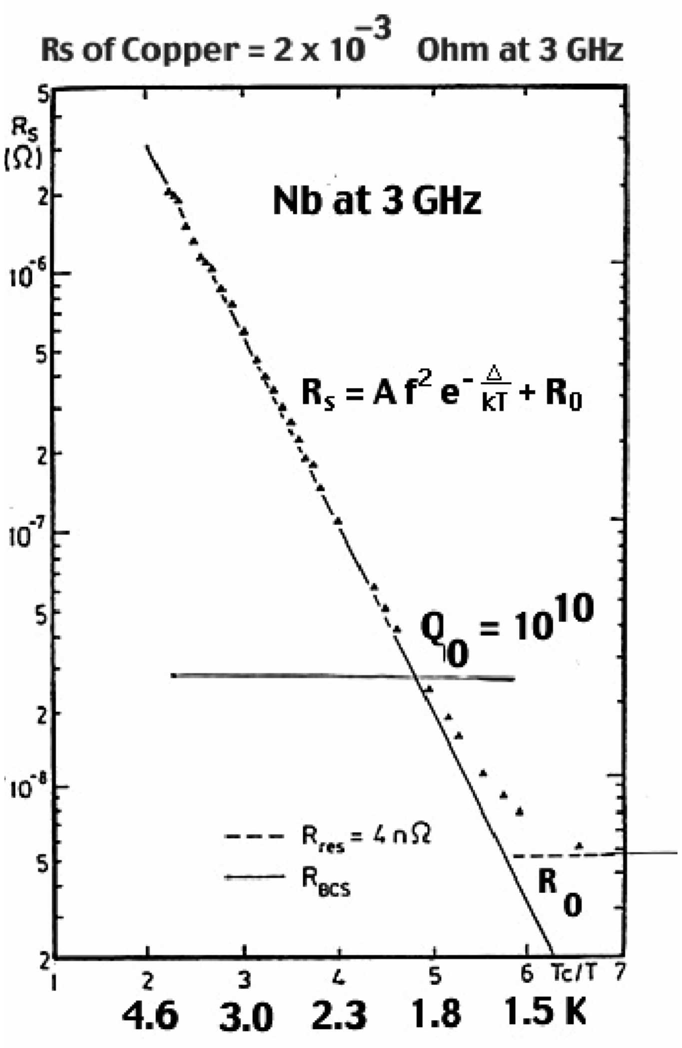
ΔE = superconducting energy gap -> superconductivity

ΔE = band gap of semiconductors -> electrical resistance

Other effects are not disturbed by thermal energy at low T like:

Helium II phenomena (Bose condensation), Kapitza-Effect,…

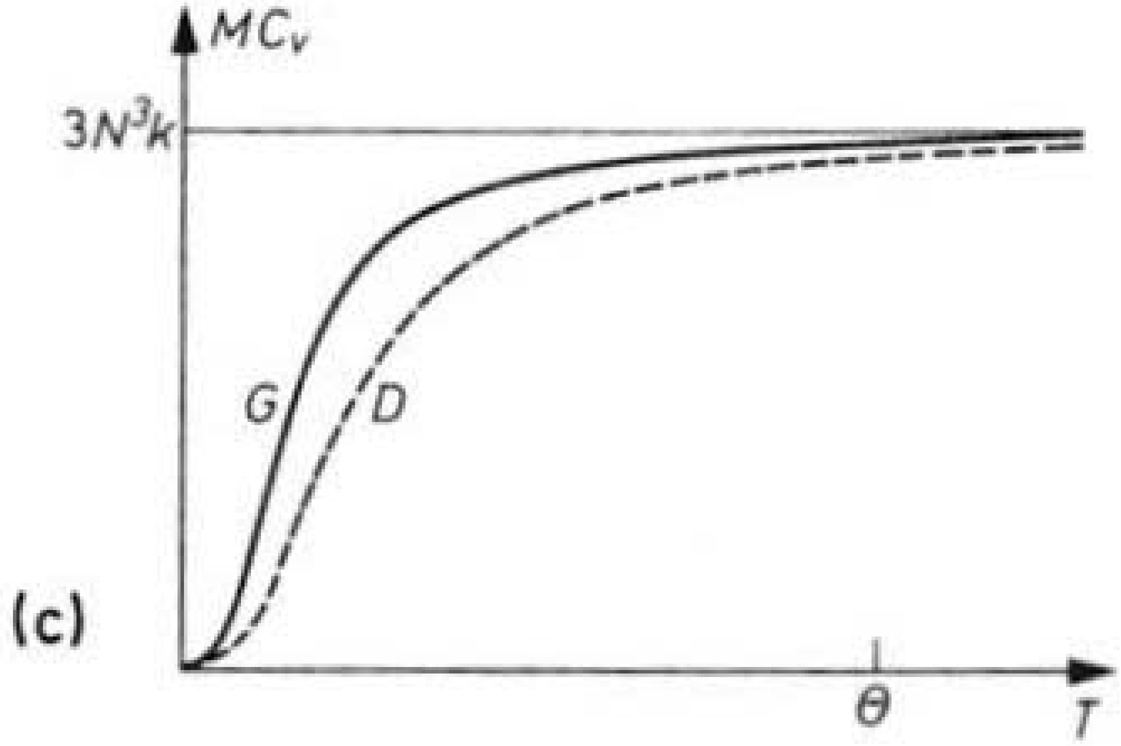
That‘s why we have this SRF workshop…..



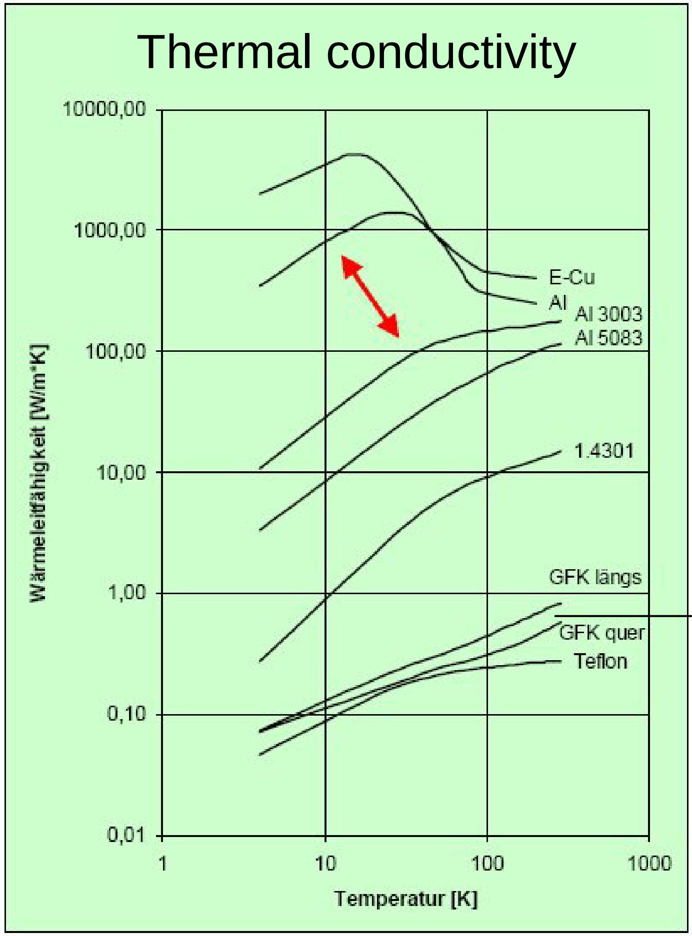
Measurement of the superconducting surface resistance at 3 GHz

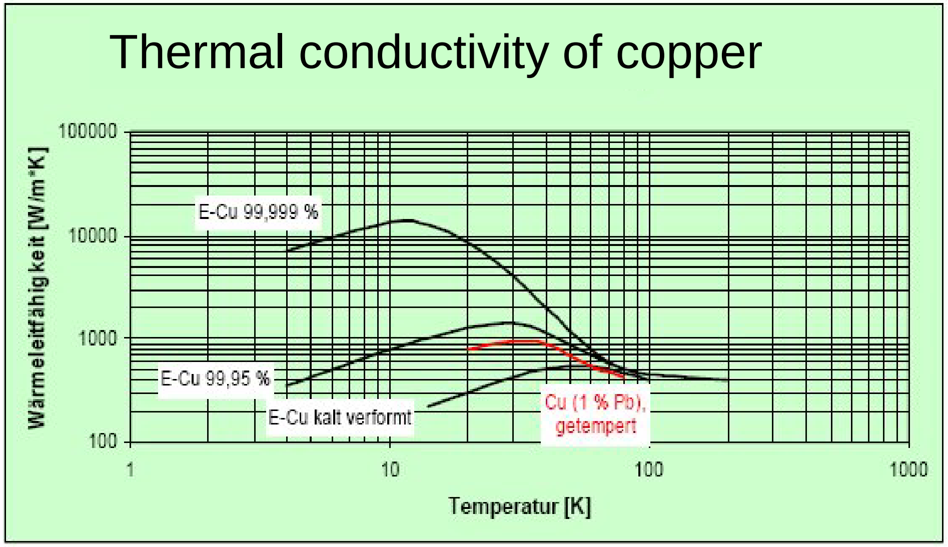
Nb/Cu : reduction of Rs by nearly 6 orders of magnitude

Quantum Properties of Matter at Low Temperatures
Specific Heat of Solids



Thermal Conductivity of Solids at Cryogenic Temperatures





Glas fiber re-inforced epoxid

Thermal contraction of solids

Thermal Stress

Δ L/L

Plastics > 2%

Steel 0,3%

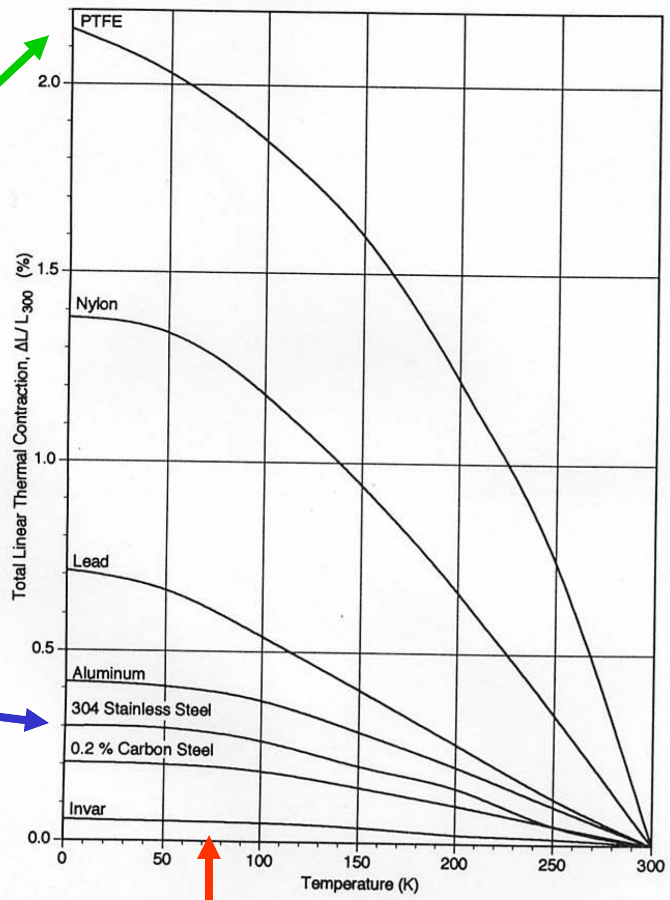
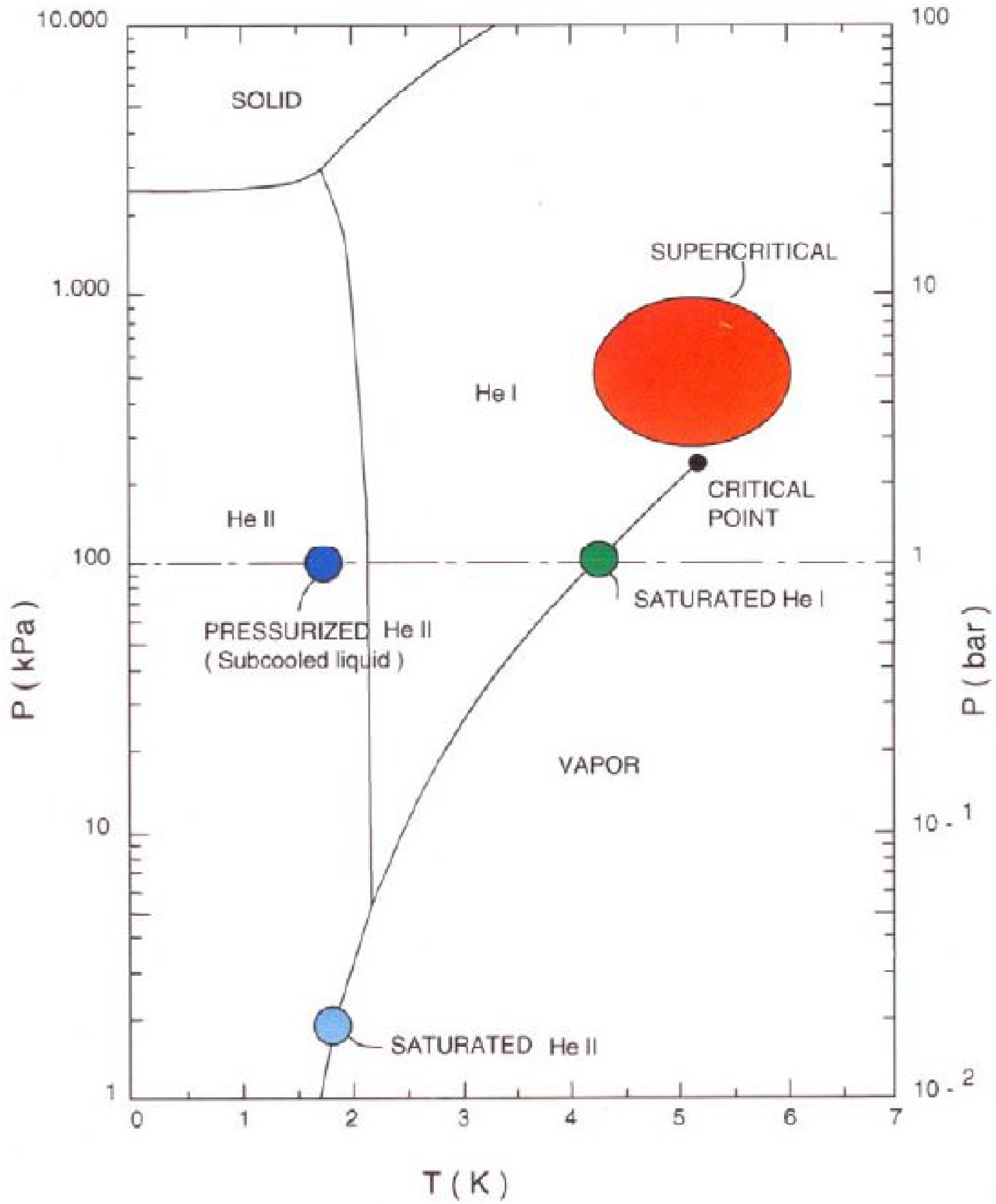


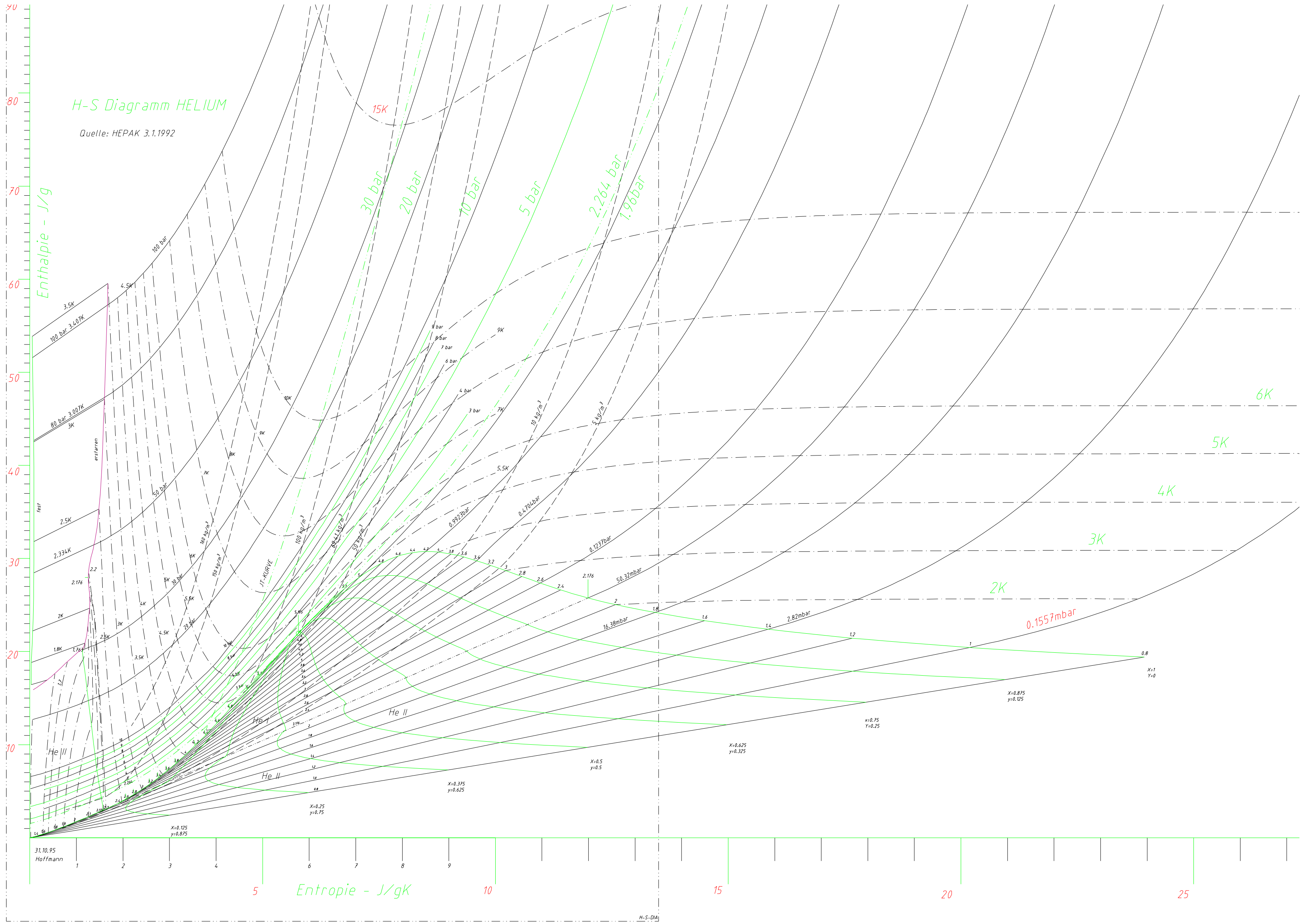
Fig. 4.2. Plots of linear thermal contraction of some common materials as a function of temperature,[3] showing the total contraction at a given temperature as the temperature is lowered from 300 K to that temperature. PTFE = Polytetrafluoroethylene.

77K

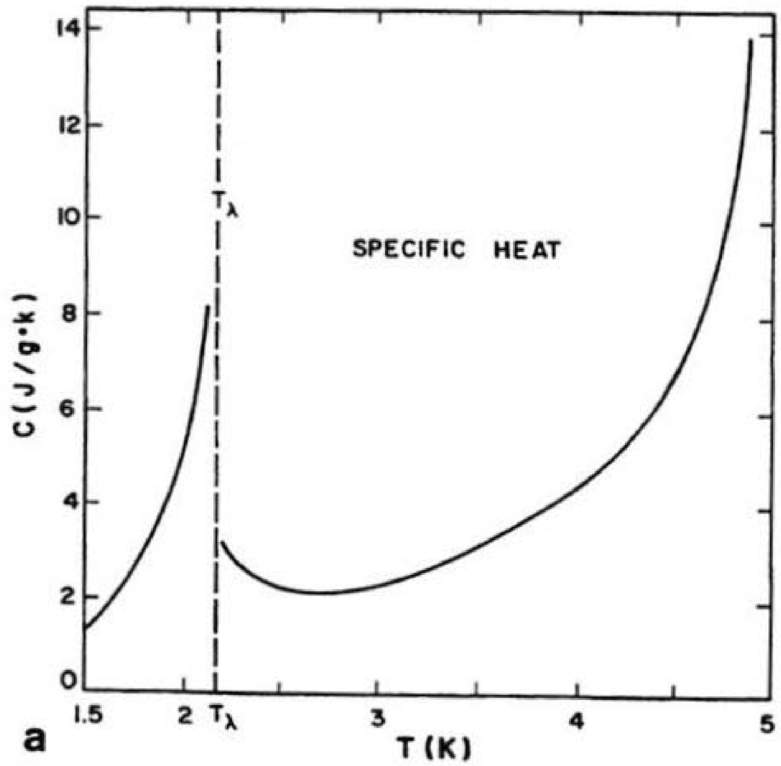
PHASE DIAGRAM OF HELIUM



Other View: H-S-Diagramm of Helium (Source: HEPAK)



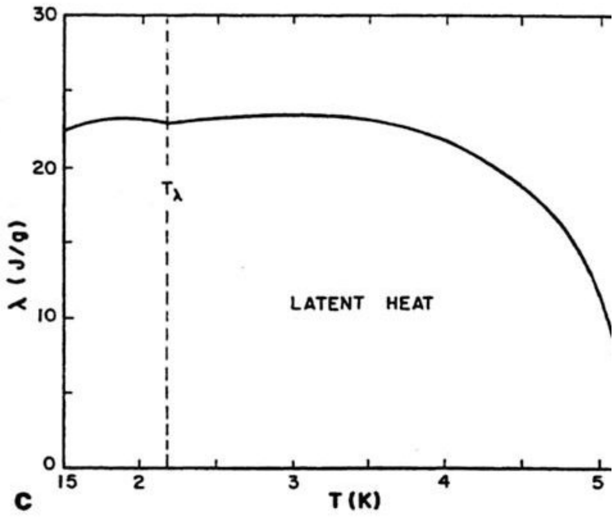
Quantum Properties of Matter at low T
Specific Heat of liquid HELIUM



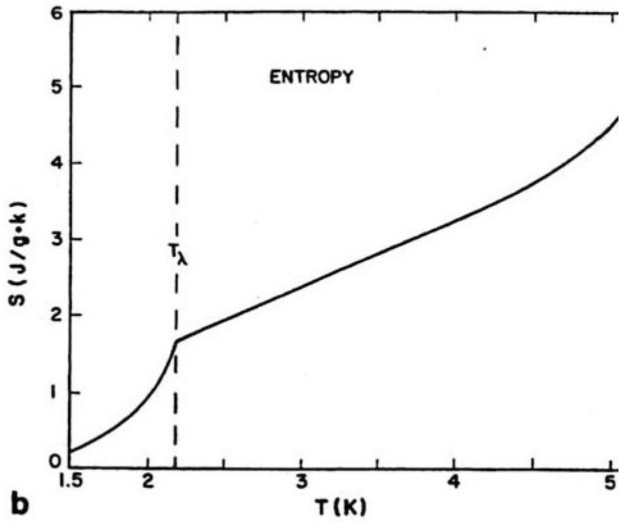
. Specific heat of liquid helium at saturated vapor pressure.

Much larger than specific heat of solids at these temperatures !

Quantum Properties of Matter at low T
Latent Heat and Entropy of liquid HELIUM



. Latent heat of vaporization of liquid helium.

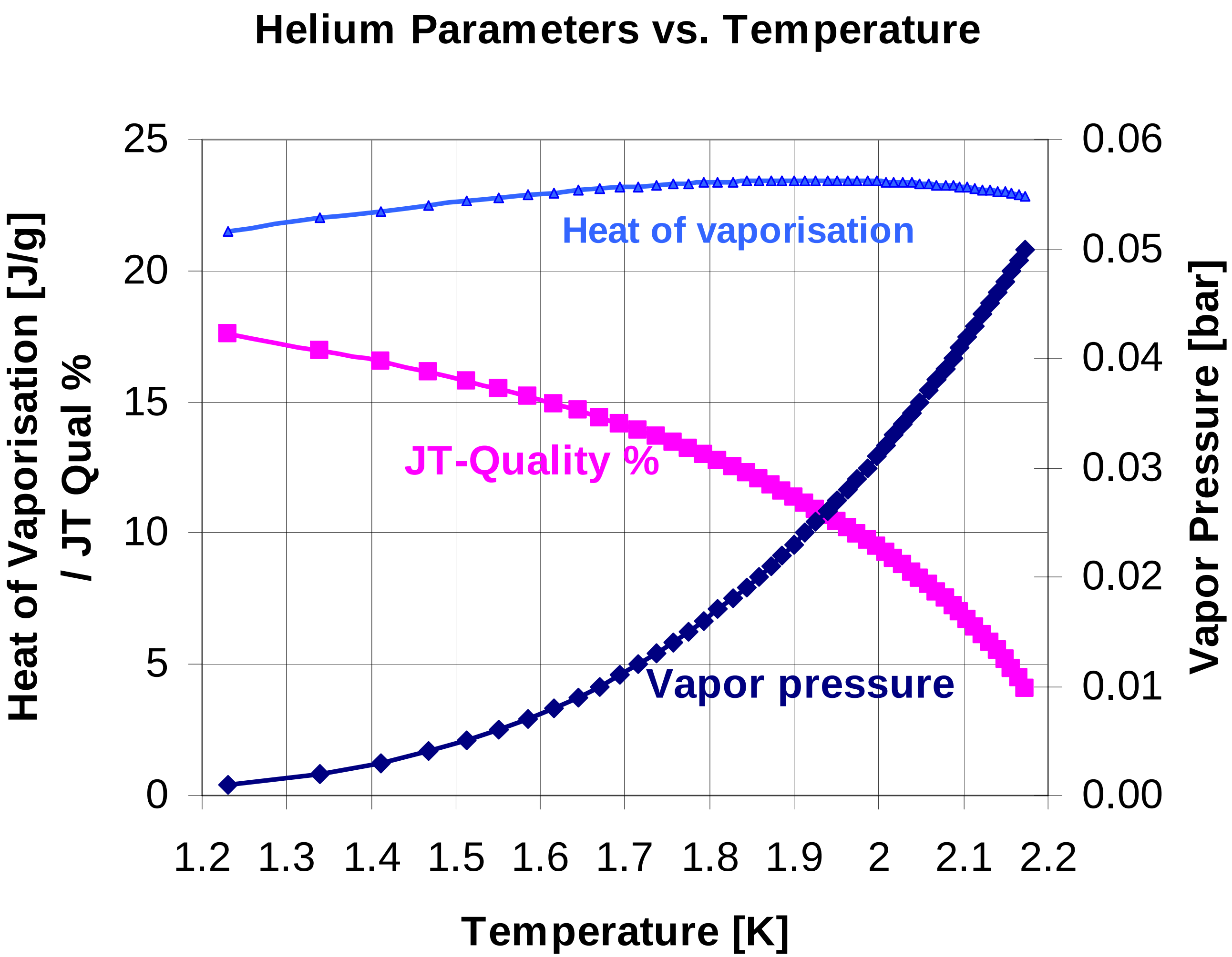


Entropy of liquid helium at saturated vapor pressure

Phase Transition HE I -> HE II ‚second kind‘ phase transition

(no latent heat)

Helium II parameters = f(T)



Definition of Lambda max in a HEII bath

Heat conductivity in HeII — **$q^{m} = f(T) \cdot dT/dx$**

T-Temperature, x-length

$m \approx 3$

f(T) Germany = $f^{-1}(T)$ USA

$$q_{max} \cdot L^{1/3} = \left[\int_{T1}^{T2} f(T)\, dT \right]^{1/3}$$

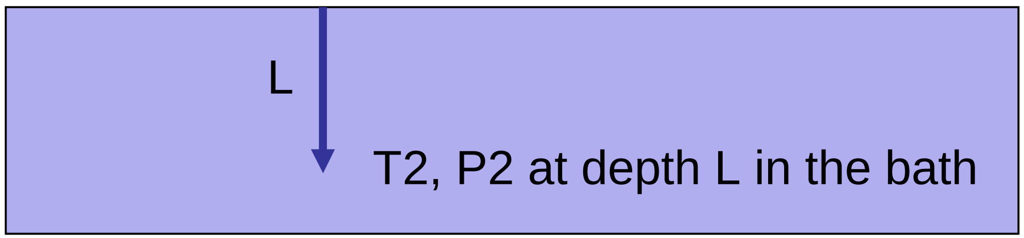
T1 = F (P1) **Temperature function of vapour pressure**

T2 = F (P1 + Δ P)

$\Delta P = \rho \cdot L \cdot g$ **ρ = density of liquid** **g=9.81 m/s2**

L= depth in bath

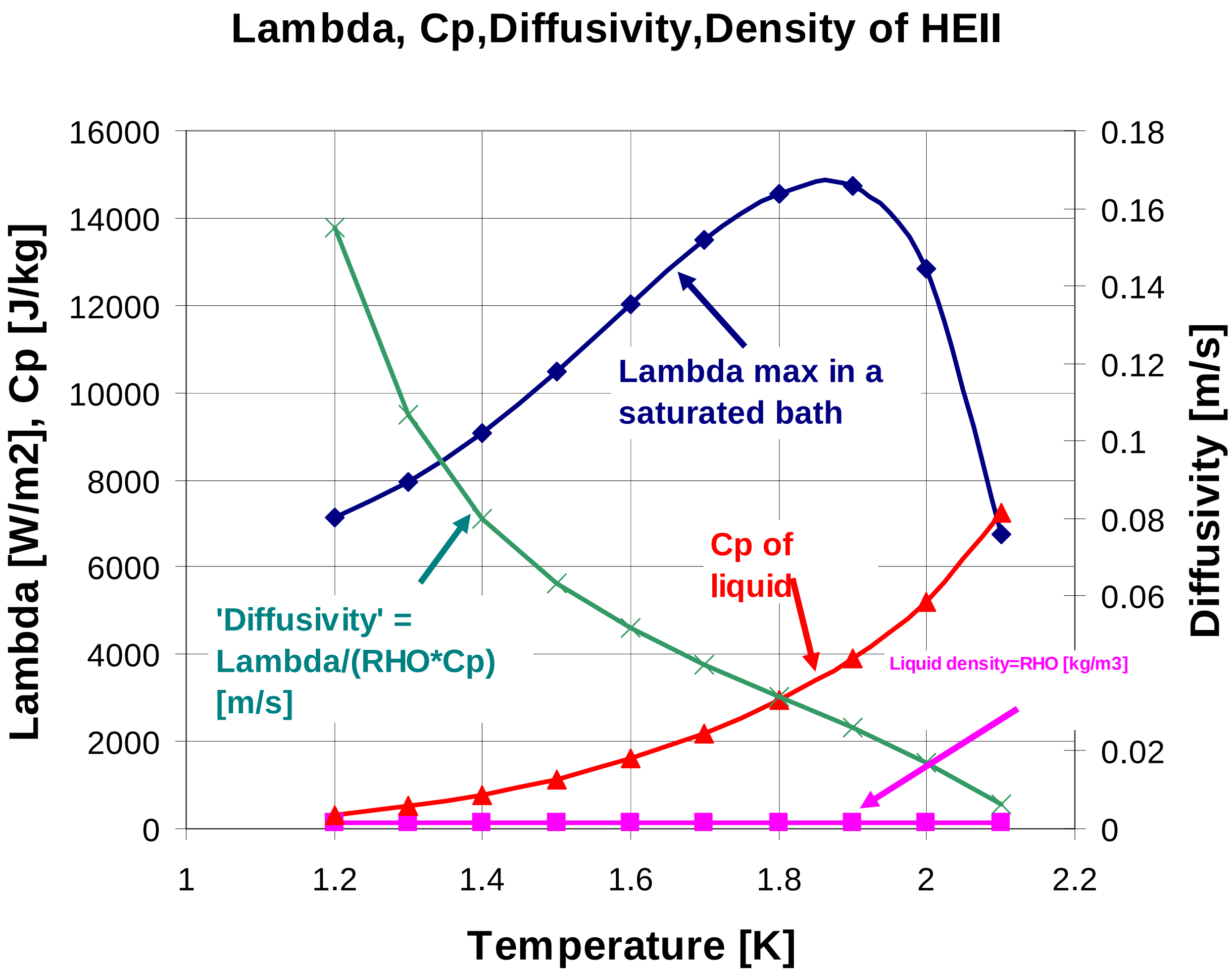
T1, P1 at liquid surface



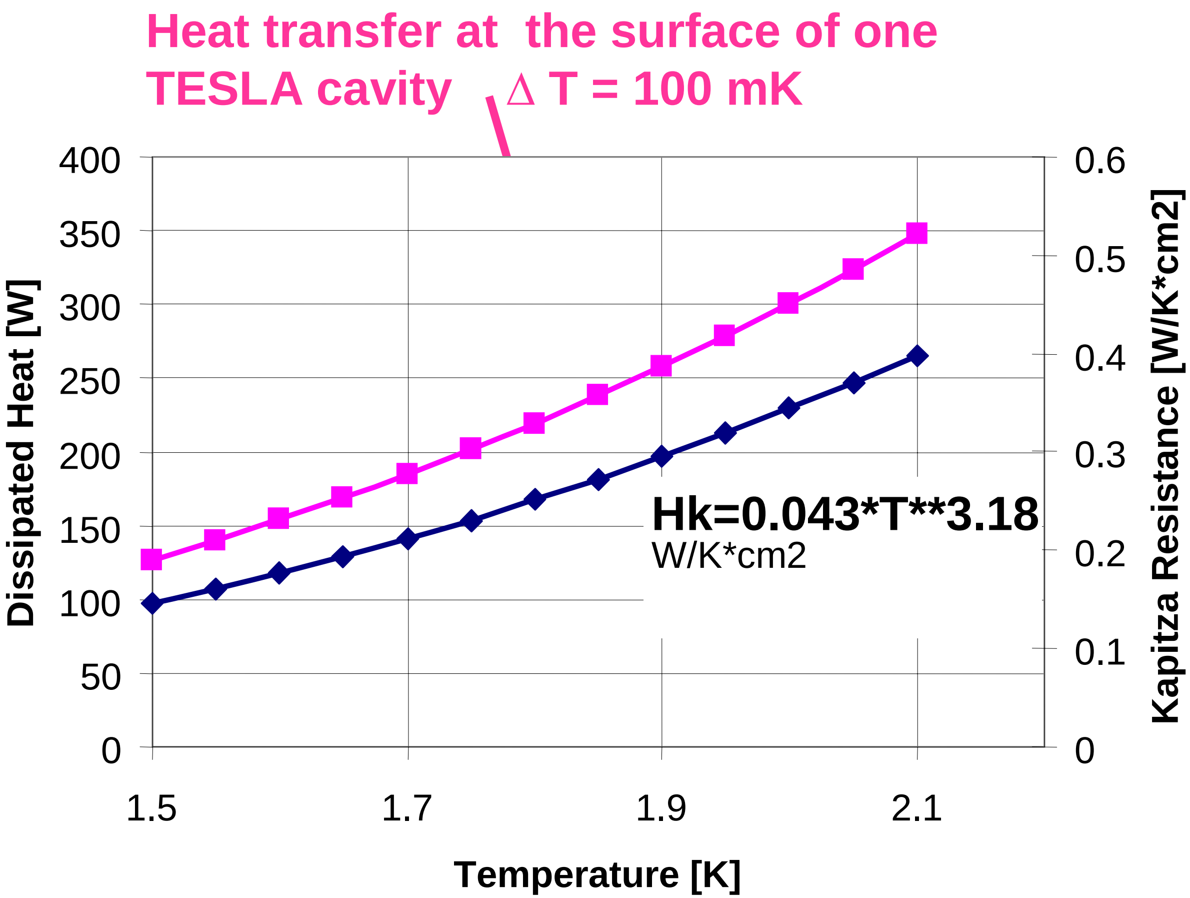
T2 must not be exceeded to avoid bubbles !

Helium II parameters = f(T) (cont.)

Design



Kapitza Heat Transfer
Solid Surface to Helium II

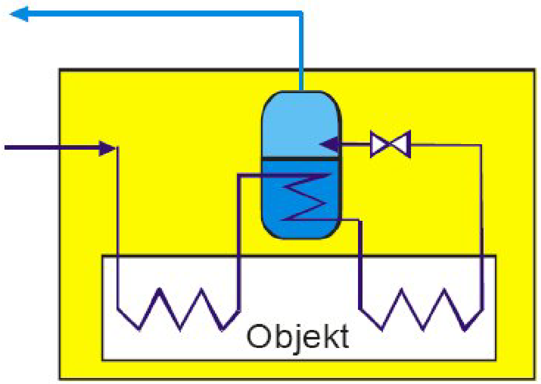


For

Niobium

Some Cooling-Cycles:

Forced 1-phase Helium I Cooling



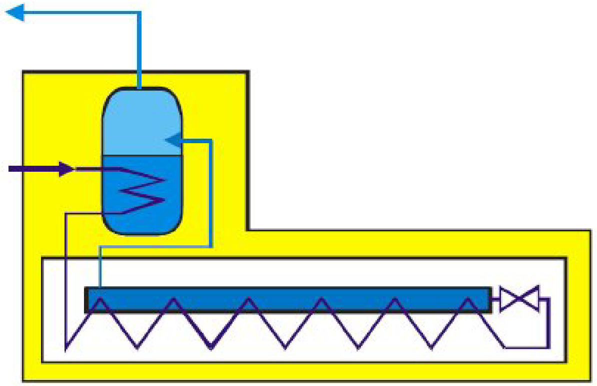
SC Quadrupoles in

TTF-Cryomodules

+ = simple

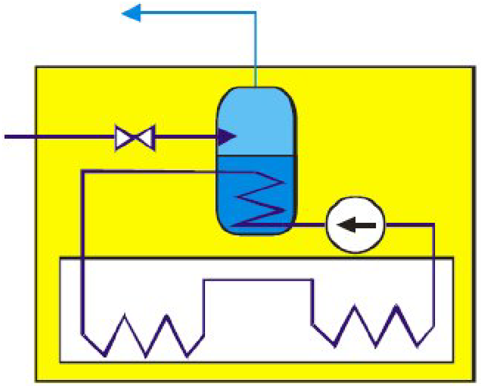
-= large mass flow

excess liquid



HERA Accelerator SC Dipoles

++ = homogeneous cooling of sc coils at constant temperature



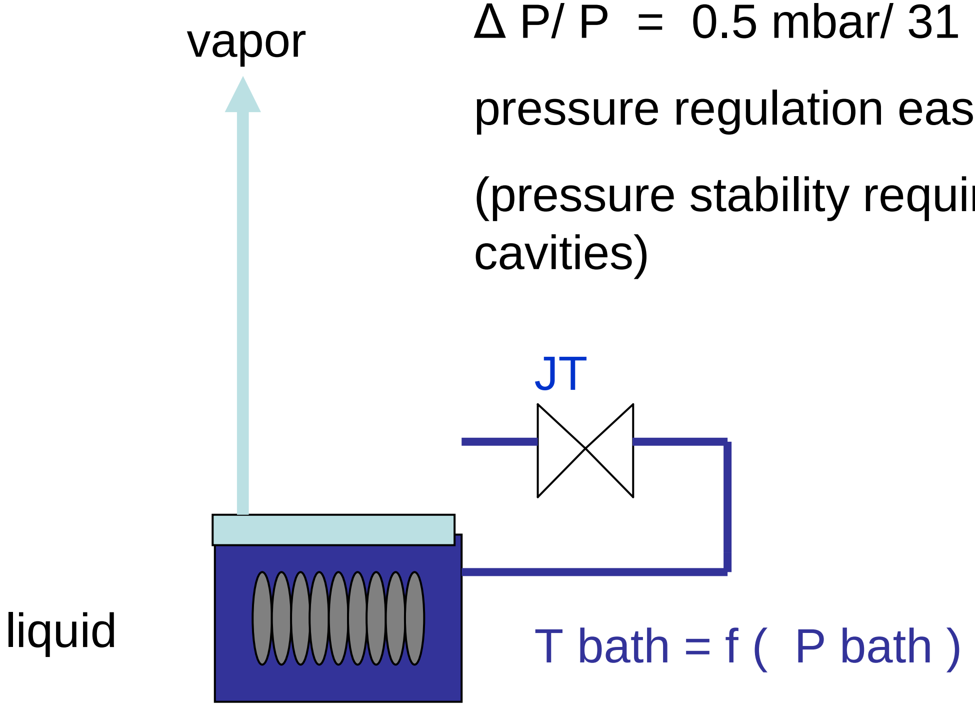
HERA Accelerator Lumi-up-Grade SC Magnets

+ = no excess liquid

-= large mass flows

extra pump

Some Cooling cycles: Bath cooling



Advantages: very simple

$\Delta P / P$ = 0.5 mbar/ 31 mbar = 0.016

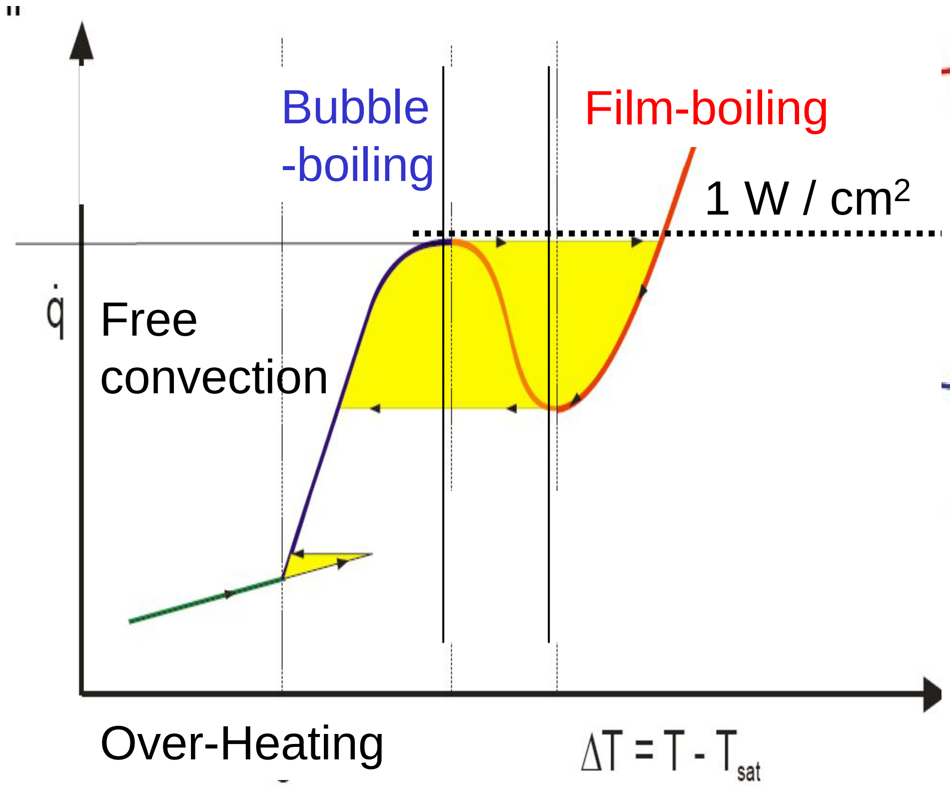
pressure regulation easy

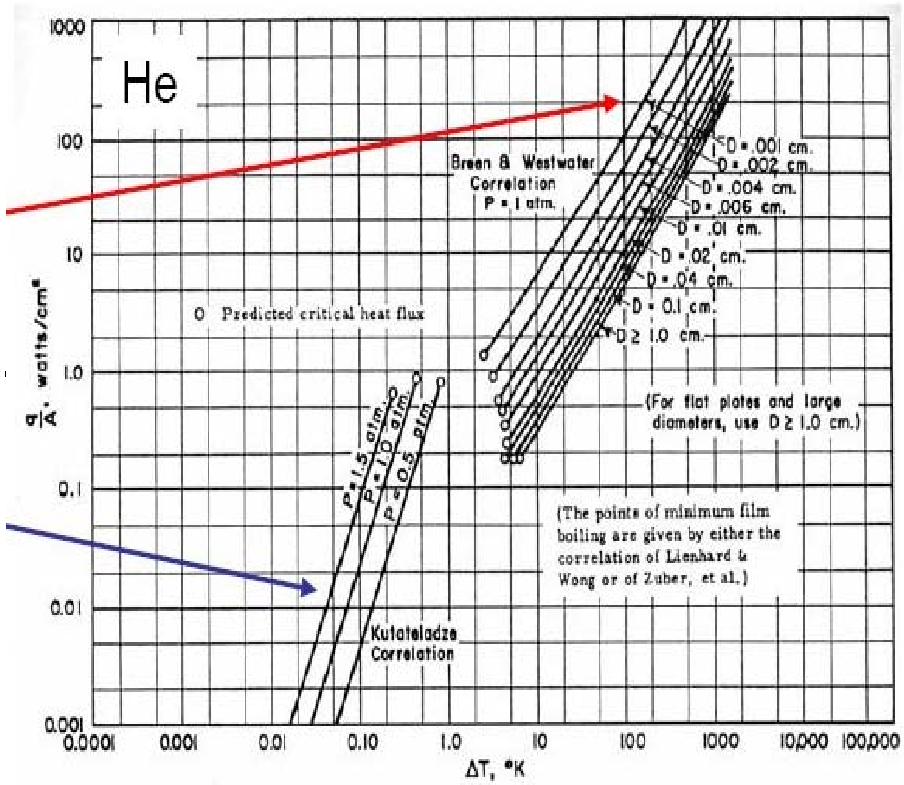
(pressure stability required for TESLA cavities)

Heat Transfer to a Bath of Helium I

Remember: Helium II bath 1 W/cm2
maximum heat flow density

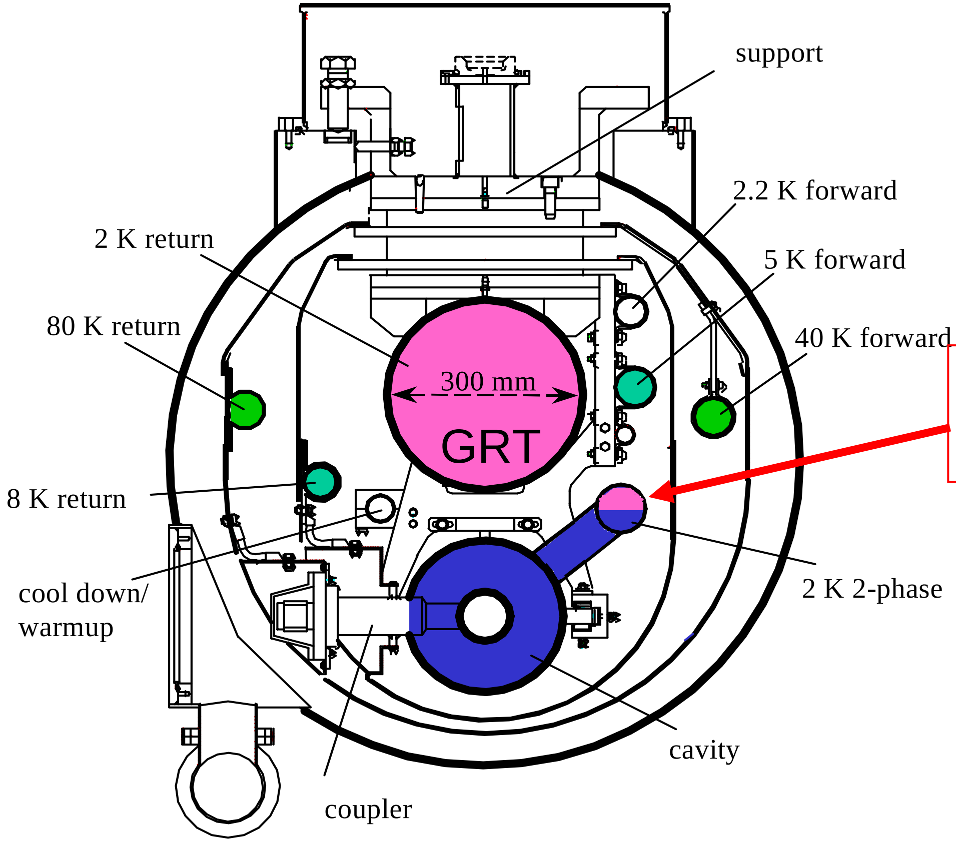
INSIDE the bath !





Layout of XFEL-linac cryogenic: Helium II bath cooling

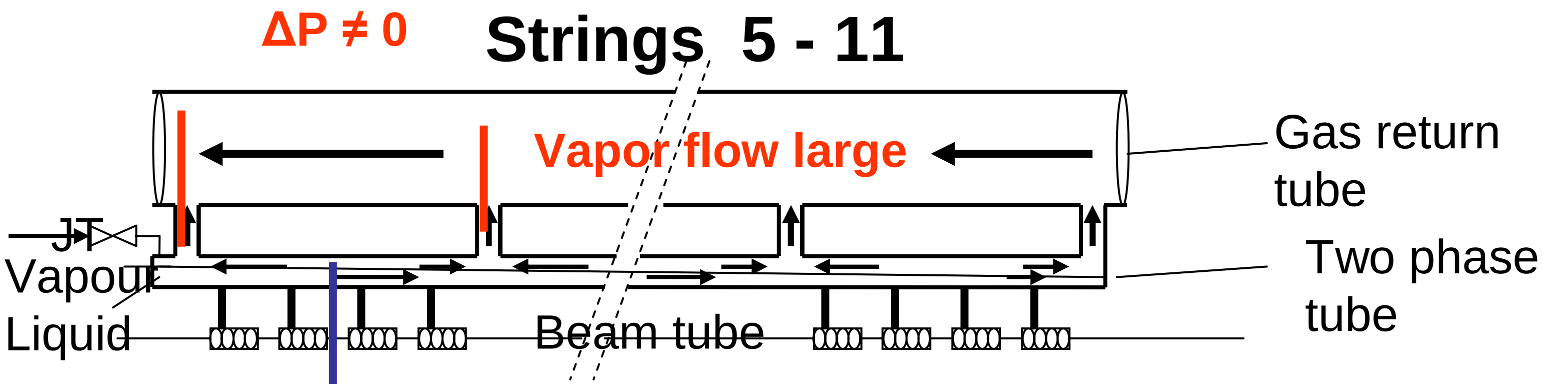
About 1000 1.3 GHz sc cavities will be cooled in a 2K Helium II bath

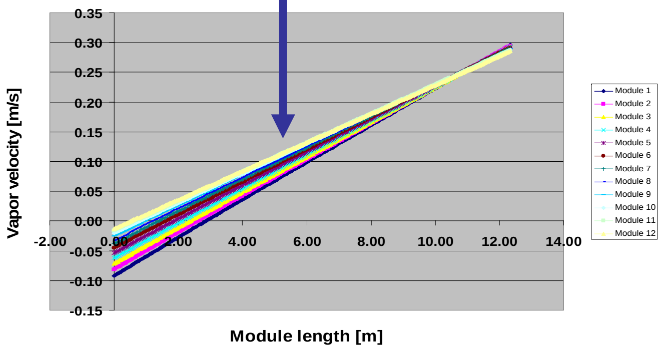


Two phase He II flow involved

Disadvantage:
Complex 2-phase flow conditions

Example: Situation at the start of the XFEL-linac
(refrigerator side)

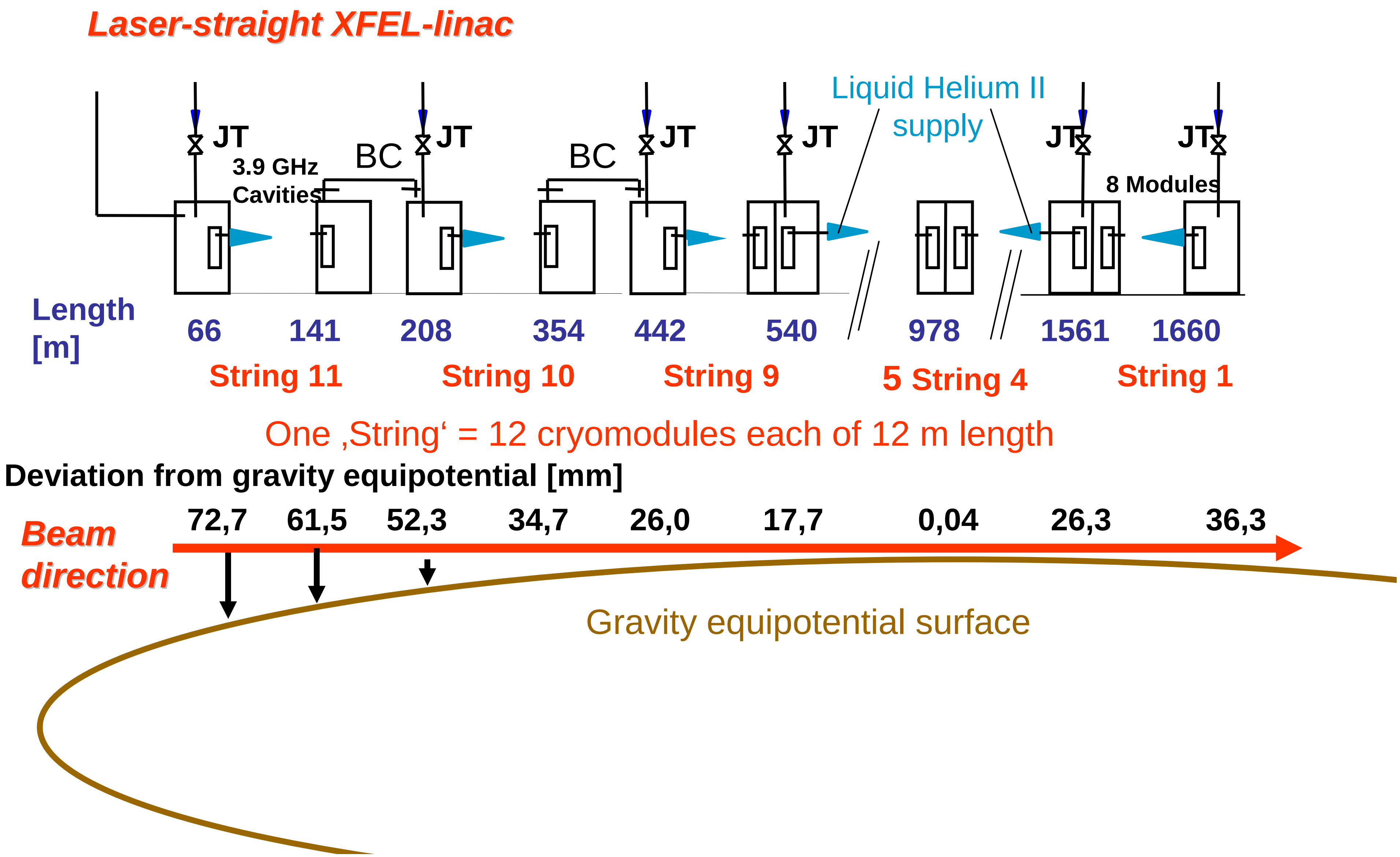




Vapor flow velocity in 2-phase tube

String 10

Disadvantage: 2-phase flow affected by gravitational forces

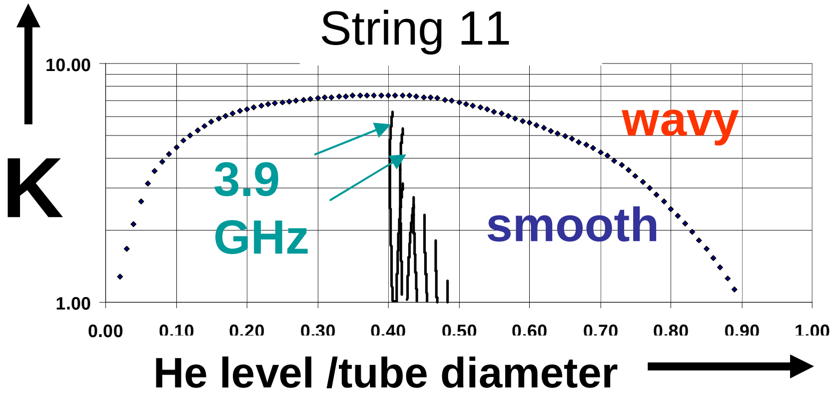


Two phase Helium II flow:
for the XFEL-linac we want stratified-smooth flow

Design operation of XFEL: 2 K, 20 GeV, 23.6 MV/m 15 W/cryomodule

$$K = \left[(\rho l * \rho g * VGS2 * VLS) / ((\rho l - \rho g) * g * \mu * \cos(\beta)) \right]^{1/2}$$

String 11



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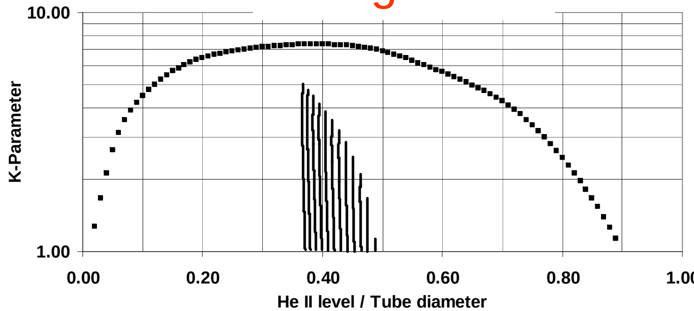

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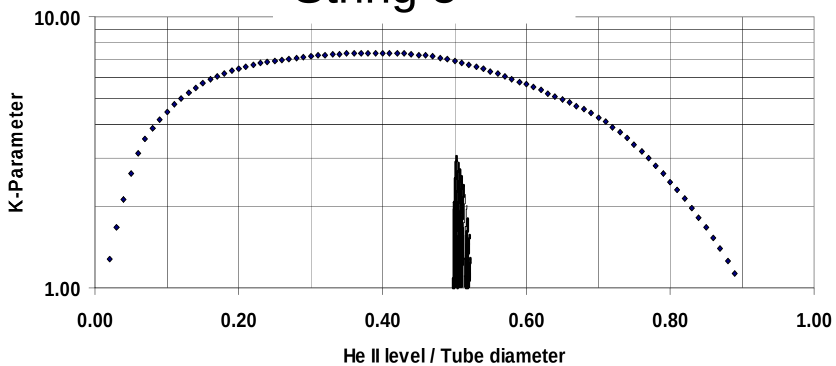
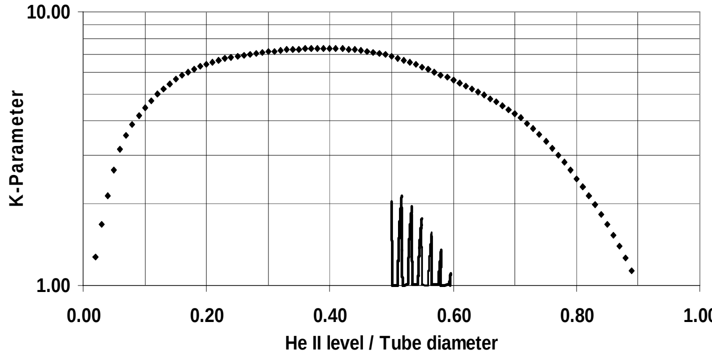
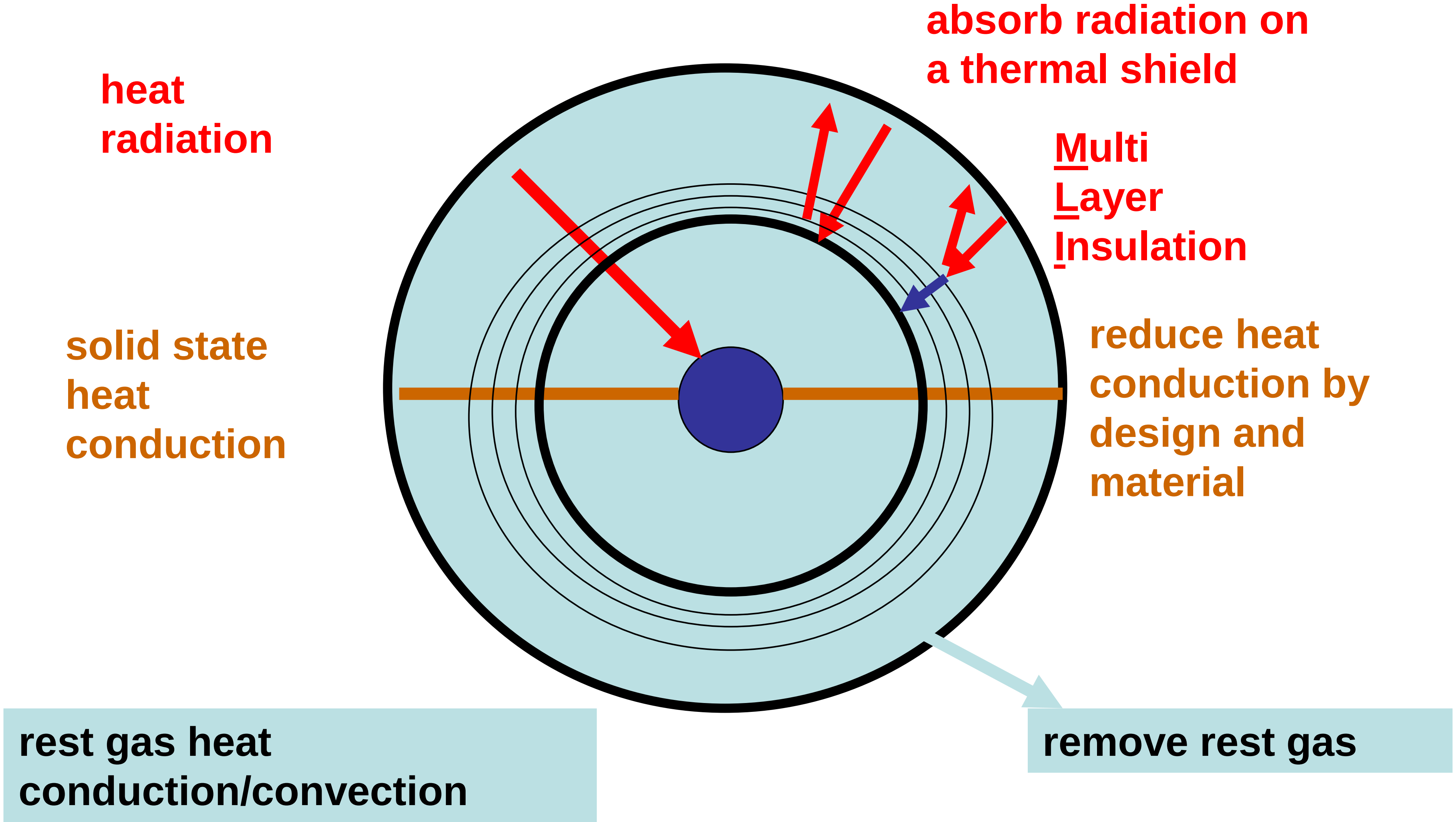


String 1



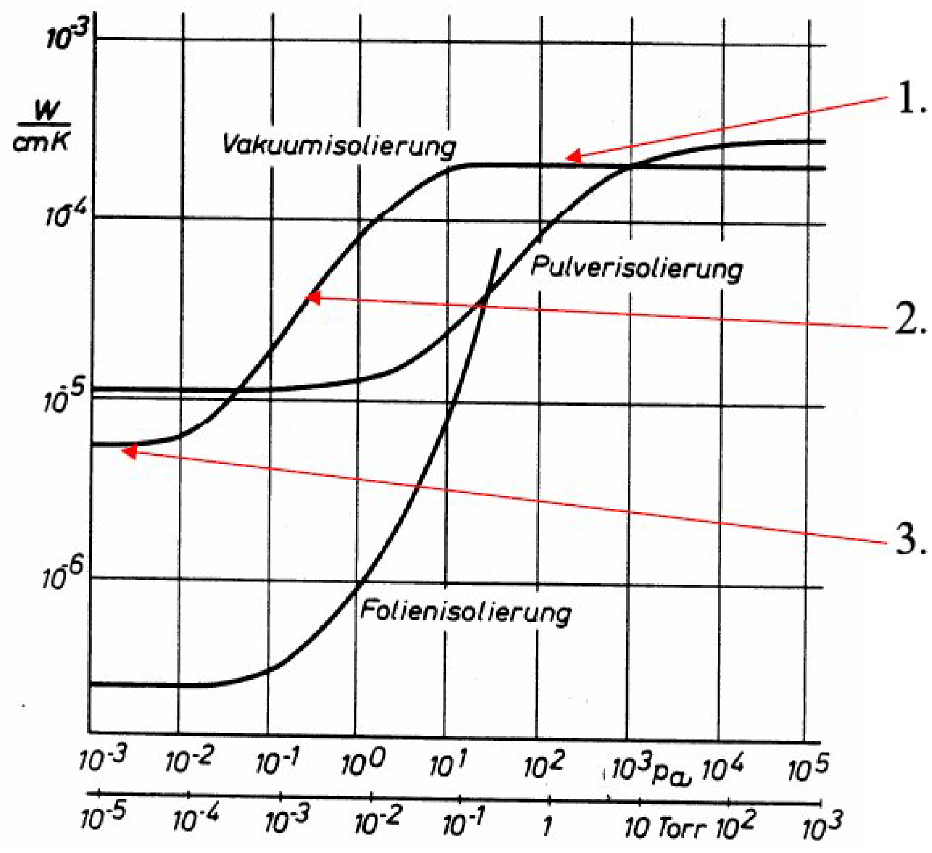
2-ph-flow conditions for cryomodules in different sections of the XFEL-linac

Some Fundamentals of Thermal Insulation



Some Fundamentals of Thermal Insulation: vacuum

heat conductivity



1. **Λ/s << 1: viscous**

2. **Λ/s ≈ 1: Knudsen**

3. **Λ/s >> 1: molecular**

Λ = mean free path of gas molecules

S = cryostat dimension

Some Fundamentals of Thermal Insulation: MLI

Multi Layer Insulation = ‚ Superinsulation‘

to limit heat conduction between the MLI-layers:

avoid direct contact of layers, make vacuum pumping possible

MLI-materials:

Aluminum foil

Plastic foil : Mylar   Al – coated (one or both sides)

vacuum pumping may be enhanced by small holes in foil

space between foils required to limit heat conduction:

use of ‚wrinkled‘ foils or spacer layers

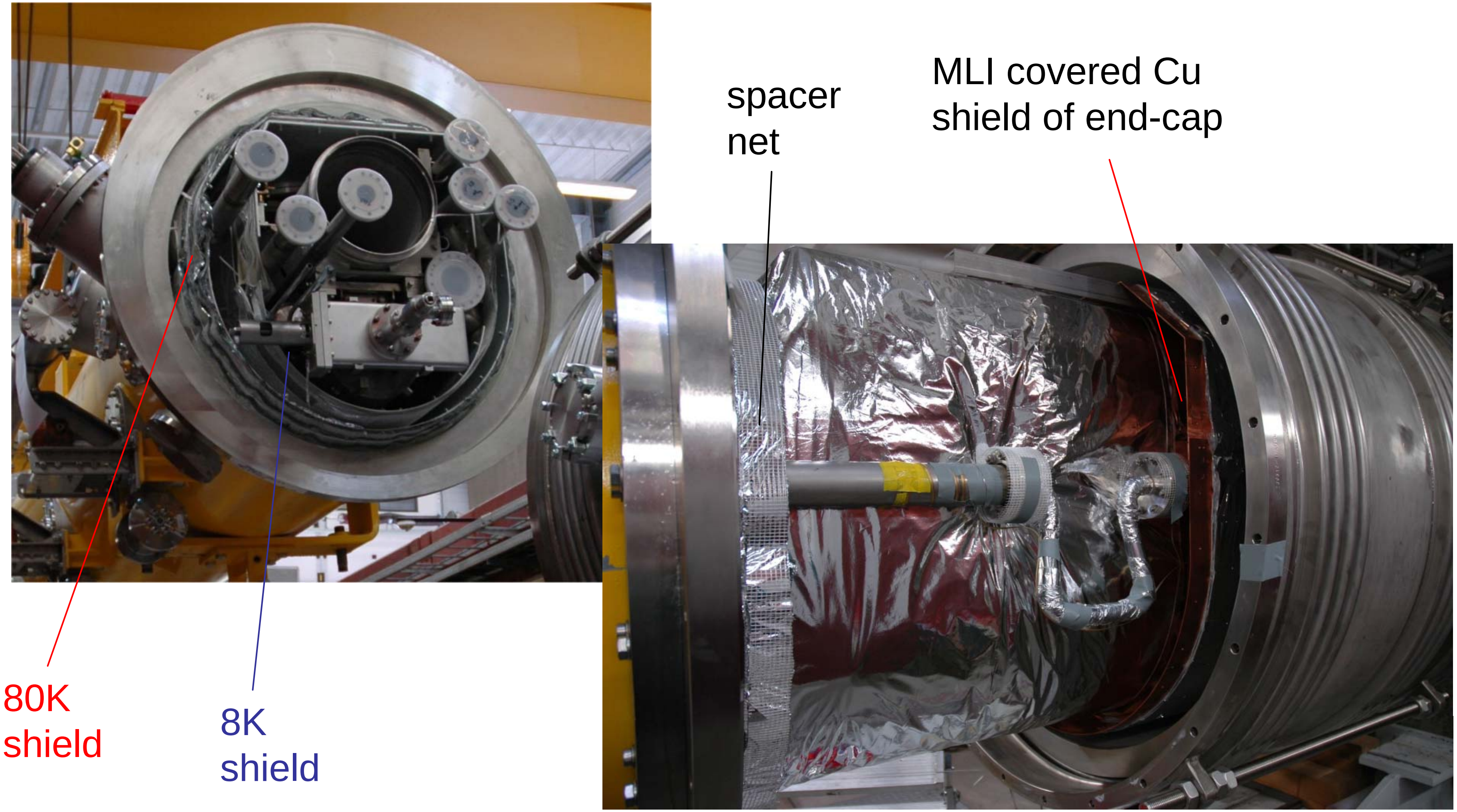
spacer materials: glas-paper, glas fiber net, paper,……

Some Fundamentals of Thermal Insulation: MLI impressions

spacer
glas fiber
net

(vitrolan)

Some Fundamentals of Thermal Insulation: TESLA Cryomodule MLI impressions



Module connection to end-cap

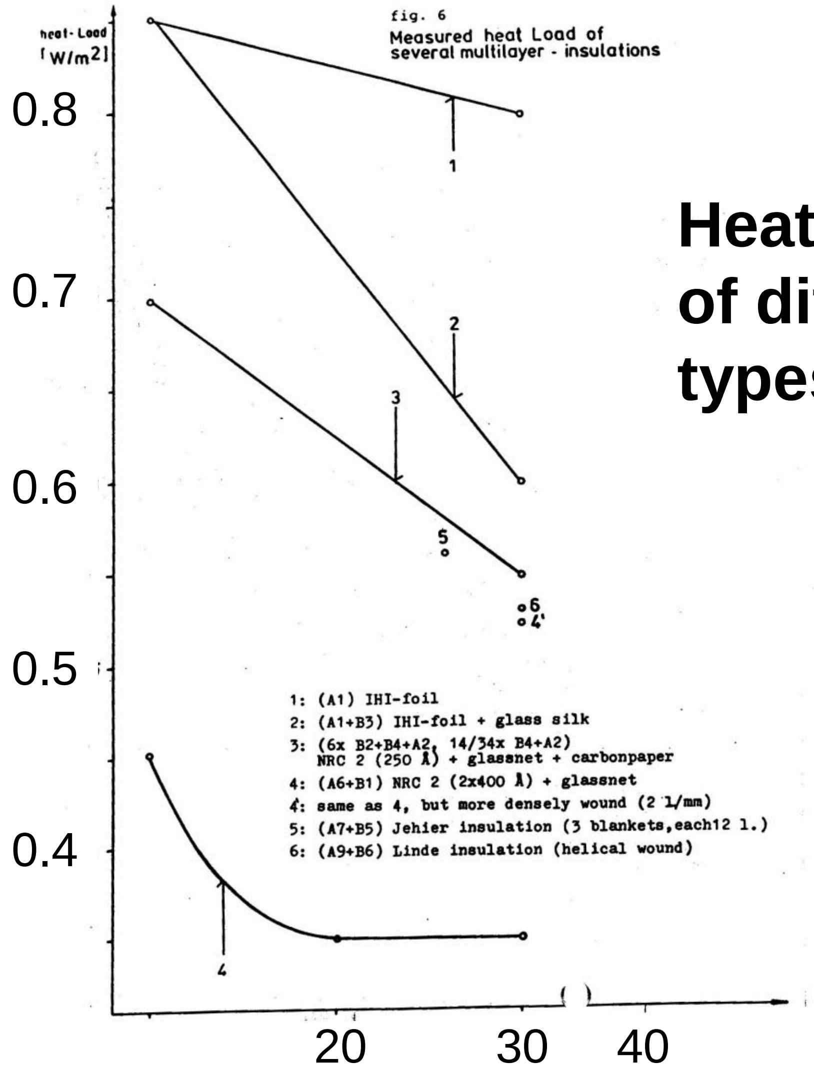
Some Fundamentals of Thermal Insulation: MLI

heat conduction

W/m2

For design:

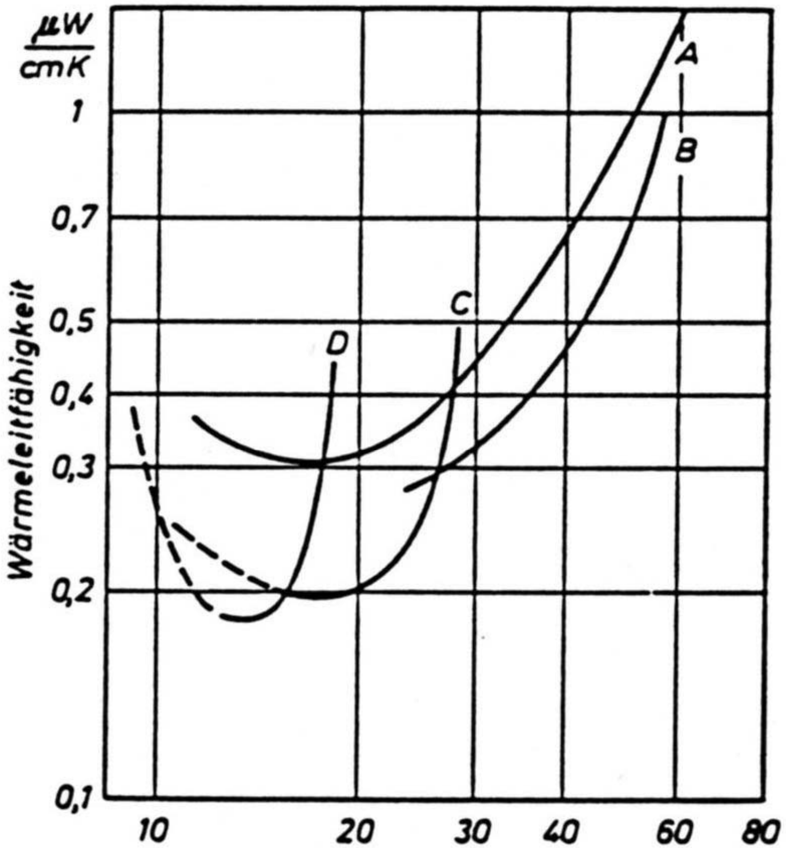
1 W/m2



number of layers

Heat conduction of different MLI types

Some Fundamentals of Thermal Insulation: MLI



MLI Layers / cm

Heat conductivity of different MLIs vs.

Density of layers

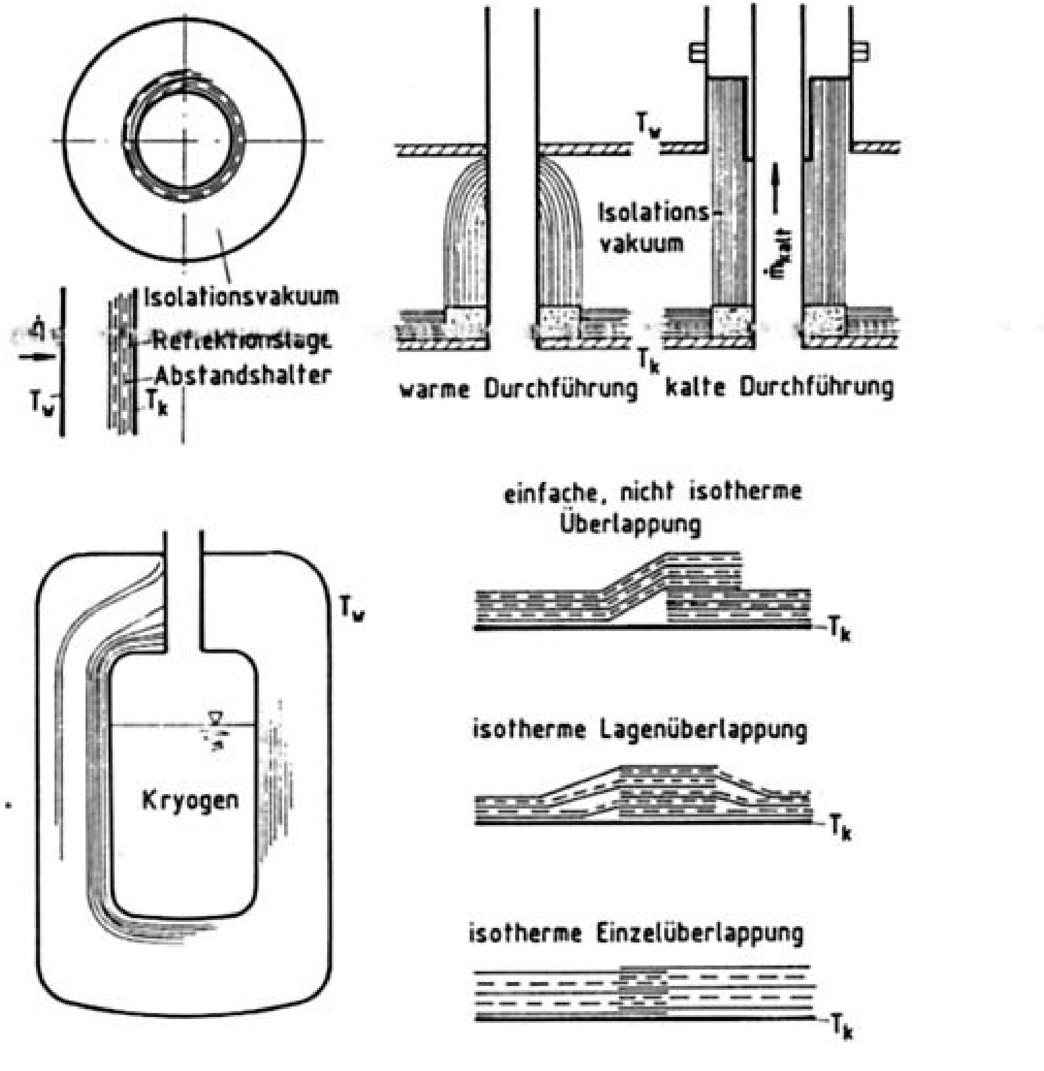
A: AL coated plastic foil

B: AL glas-fiber spacer

C: AL glas-fiber spacer tissue

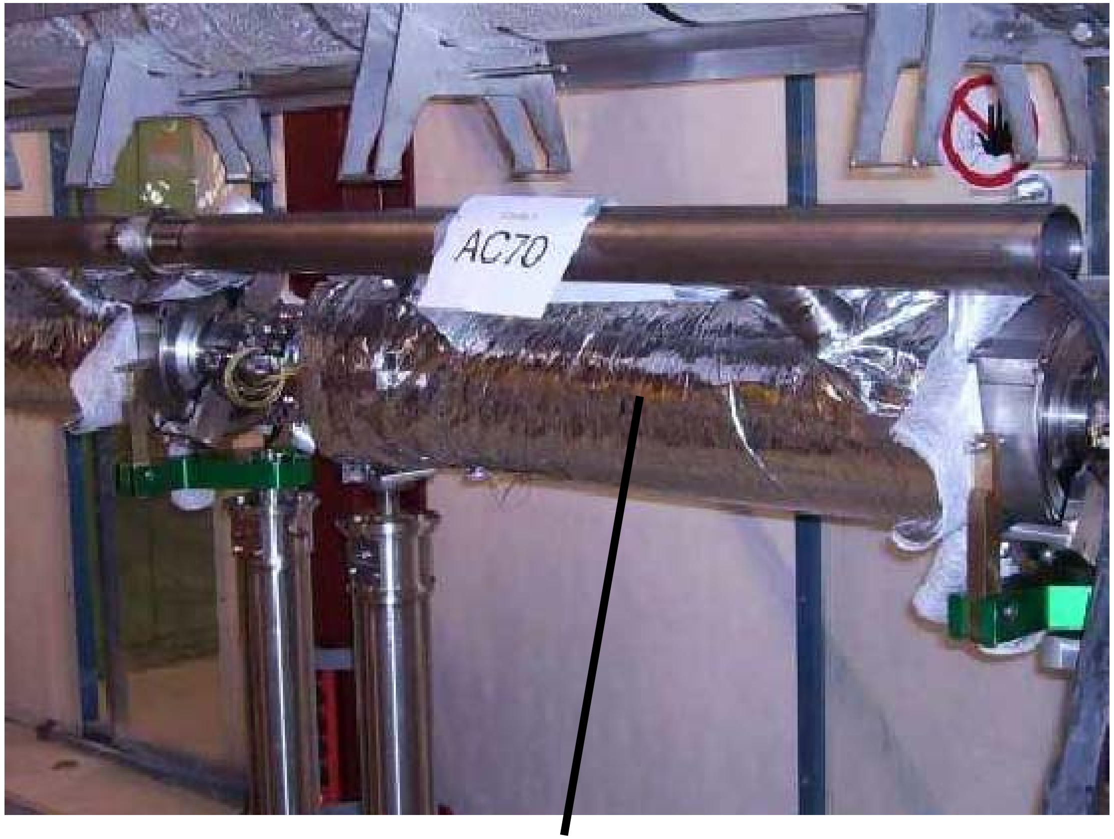
D: AL glas-fiber paper spacer

Some Fundamentals of Thermal Insulation: MLI



Some Fundamentals of Thermal Insulation: MLI

(see safety section)



2 K Helium Vessel of TESLA Cavity

Note:

All helium process areas inside the cryostat should be covered with about 5-10 layers of MLI to limit the impact of insulation vacuum loss !

Heat input caused by the break down of Insulation vacuum:

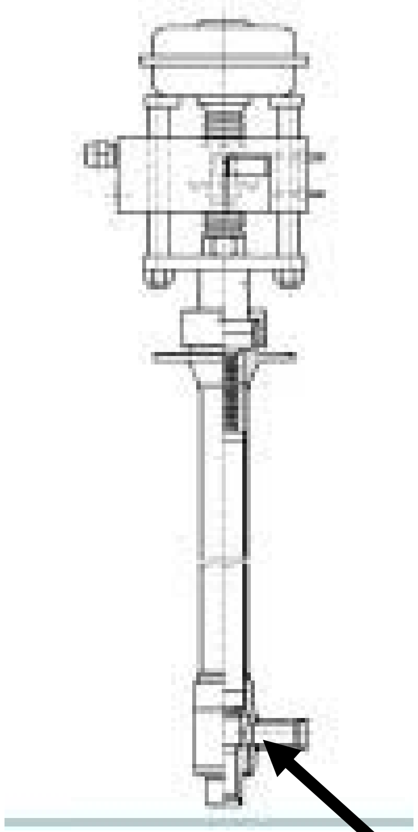
40kW / m2 without MLI

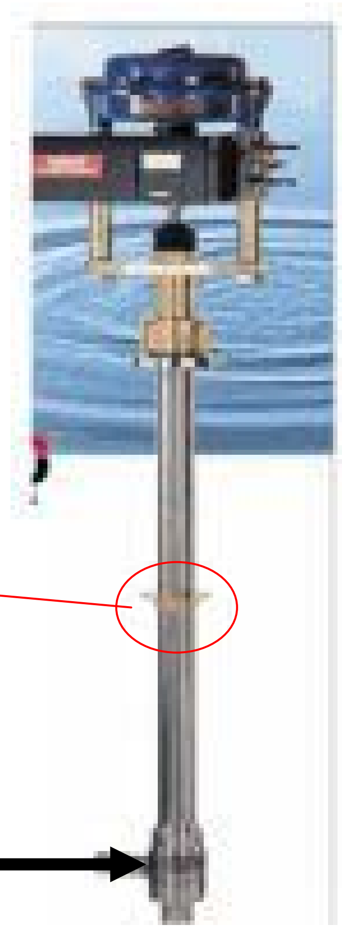
6kW/ m2 with MLI

… in addition the Helium vessel get their magnetic shielding

Single parts of magnetic shield and assembly of magnetic shielding

Some Fundamentals of Thermal Insulation: cryogenic valves





Thermal intercept

Desy ‚philosophy': NO metal/metal sealings !!!

Use of plastic seals like Vespel SP1 (polyimid)

WEKA AG, Schürlistrasse 8, CH-8344 Bäretswil, Switzerland
Tel.: ++41 (0)1 939 29 59 / Fax: ++41 (0)1 939 29 59 / E-Mail: info@weka-ag.ch

Specification: **Valve Sizing Formulas (k_v-Value)**

The calculation for the k_v-value is standardized in DIN/IEC534. For a provisional, simplified sizing for control valves the following basic formulas are usable.

p1	upstream pressure, in bara	ρ	specific grafity, in general and for liquids, in kg/m^3
p2	downstream pressure, in bara	ρ_G	specific grafity of gases at 273K and 1013mbar, in kg/m^3
Δp	pressure drop, in bar	Q_G	volumetric flow for gases at 273K and 1013mbar in m^3 / h
Q	flow of liquids, in m^3/h	T_1	temperature in K, upstream
W	flow in kg/h	υ_1	specific volume of vapor at p_1 and T_1, in m^3/kg
		υ_2	specific volume of steam/vapour at p_2 and T_2, in m^3/kg
		υ^*	specific volume of steam/vapour at $p_1/2$ and T_1, in m^3/kg

Liquid Service:

m^3 / h	kg / h
$kv = Q\sqrt{\frac{\rho}{1000 * \Delta p}}$	$kv = \frac{W}{\sqrt{1000 * \rho * \Delta p}}$

Gas Service:

subcritical flow i.e. $p_2 > p_1/2$ and $\Delta p < p_1/2$	
m^3 / h	kg / h
$k_v = \frac{Q_G}{519}\sqrt{\frac{\rho_G * T_1}{\Delta p * p_2}}$	$k_v = \frac{W}{519}\sqrt{\frac{T_1}{\rho_G * \Delta p * p_2}}$

critical flow i.e. $p_2 < p_1/2$ and $\Delta p > p_1/2$	
m^3 / h	kg / h
$k_v = \frac{Q_G}{259.5 * p_1}\sqrt{\rho_G * T_1}$	$k_v = \frac{W}{259.5 * p_1}\sqrt{\frac{T_1}{\rho_G}}$

Vapour / Steam Service:

subcritical flow i.e. $p_2 > p_1/2$ and $\Delta p < p_1/2$	critical flow i.e. $p_2 < p_1/2$ and $\Delta p > p_1/2$
kg / h	kg / h
$k_v = \frac{W}{\sqrt{1000}}\sqrt{\frac{\upsilon_2}{\Delta p}}$	$k_v = \frac{W}{\sqrt{1000}}\sqrt{\frac{2 * \upsilon^*}{p_1}}$

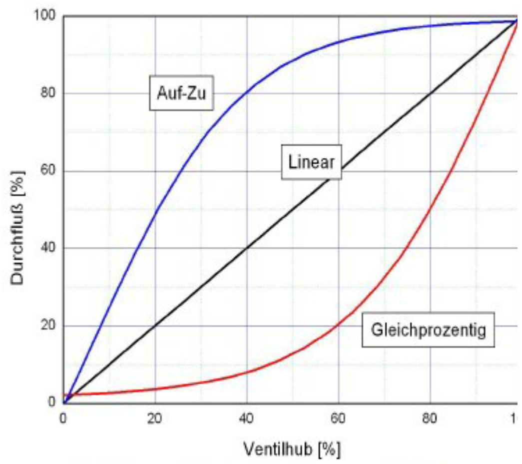
Definition of Kv-value:

volume flow of water

[m3/h] at Δ P = 1bar

and T 278 K -313 K

(Cv= 1,17 Kv USA)



First part: tutorial objectives

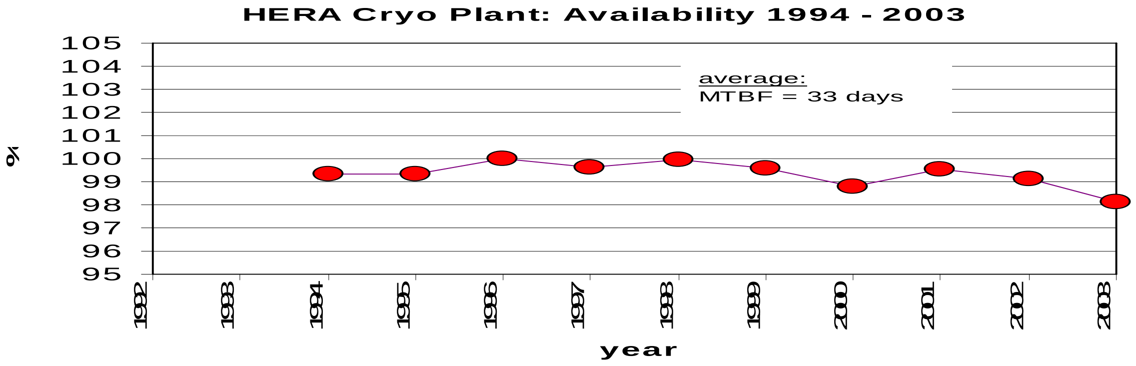
after this part, we should remember:

- The meaning of ‚***cryogenic***‘
- Carnot refrigerator efficiency
- ‚***COP***‘ of a refrigerator
- Some Helium refrigerator cycles
- Some ‚quantum properties‘ of matter at low temperatures
- Some useful Helium II properties
- Some typical cooling cycles
- Some fundamentals of thermal insulation

Second part: tutorial objectives

after this part, we should remember:

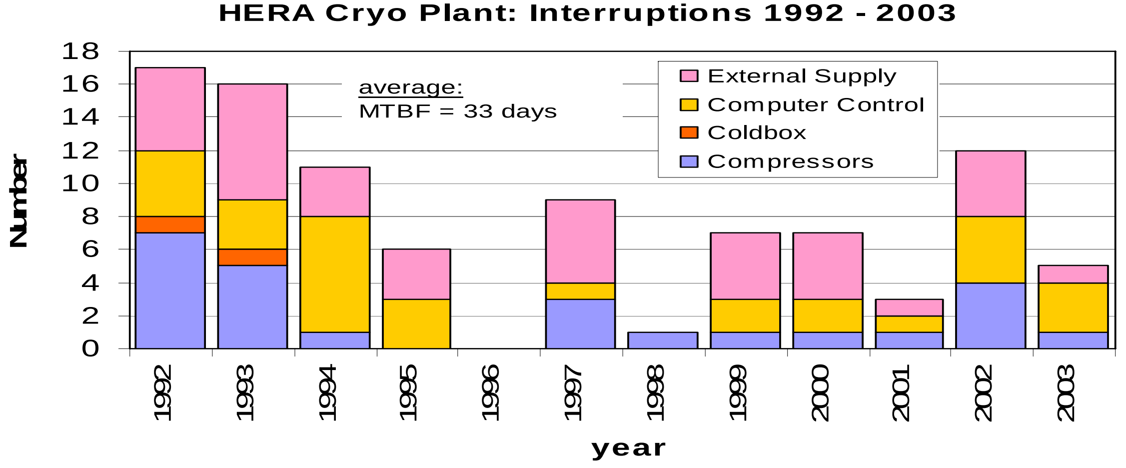
- Measures to increase refrigerator availability
- Helium management considerations
- Suited materials for cryogenic temperatures
- Cryogenic safety aspects
- Basic cryomodule design considerations
- Pressure vessel regulations
- Quality control measures
- Example: TESLA style cryomodule design

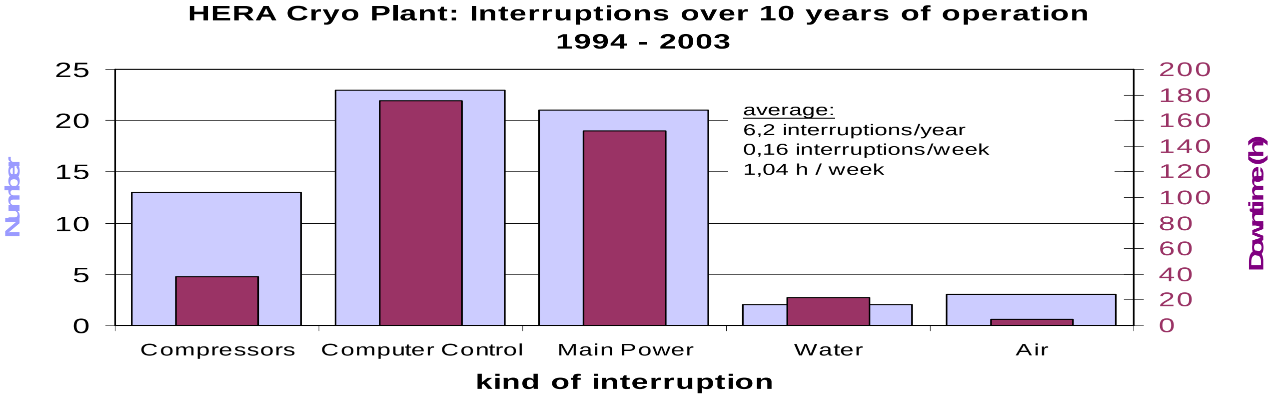


Availability

99.6 %

(utilities excluded)





Is there an availability increase by the installation of a complete redundant refrigerator ?

Availability increase by redundant refrigerators?

Rating	Source of unavailability	Example	**Multiple** refrigerators ... ?
1	External utility failures	Electrical power, cooling water, instrument air failure	would bring no advantage
2	Blockage by frozen out gaseous impurities	Air and/or water vapor	provide somewhat larger tolerance
3	Operational problems	Controls, instrumentation, operators	would be detrimental, because of higher complexity of the system
4	Single component failure not leading to total plant shutdown	Electrical motor burnout, compressor bearings, leaking oil pump seal, turbine bearing trouble	would bring no advantage over component redundancy within a single refrigerator
5	Catastrophic component failure leading to plant shutdown	Loss of insulation vacuum, rupture of heat exchanger, oil spill into cold process piping	would have a positive effect

Redundant compressors and low temperature adsorbers

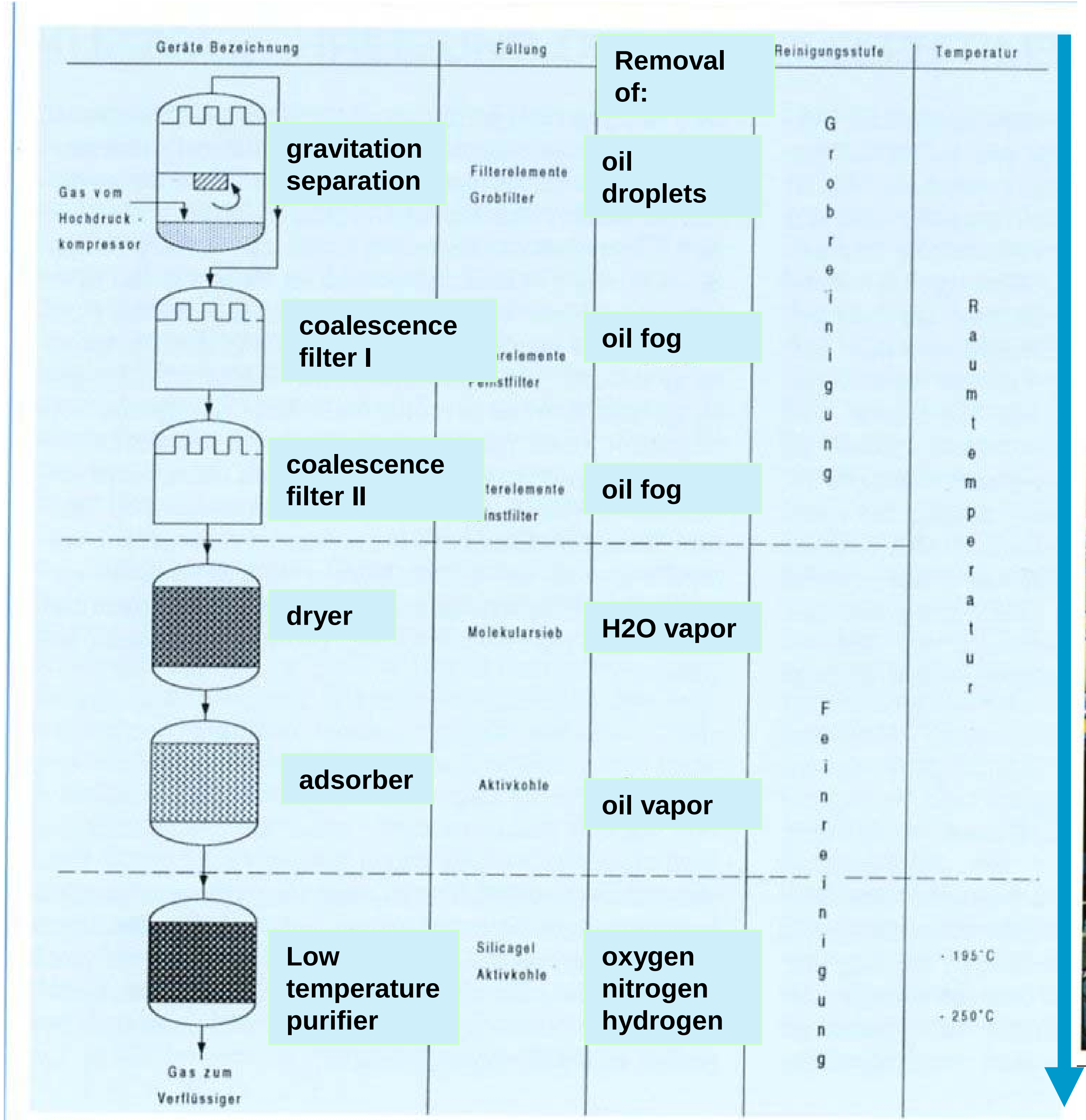
Easy exchange of turbines and cold compressors

Helium Process Gas Management

Helium gas storage tanks

Liquid Helium storage dewar

Helium process gas purification



HD Coalescence Filter

Helium Dryer

Adsorber

Suited materials for low temperatures

Low temperature embrittlement

Causes overloaded components to fracture spontaneously rather than accommodating the stress by plastic deformation

Appropriate steels for low temperature use are listed in the Technical Rules for Pressure Vessels AD-Merkblatt W10 /European harmonized technical rules /ASME-code (USA) . (In general, materials with face-centered cubic (fcc) crystal structure as copper, nickel, certain copper nickel alloys, zircon and titanium are suitable for cryogenic applications.)

.

European Harmonized Rules
Stainless steels for the use at low temperatures
DIN EN 13445-2
B.2.2.4 Lowest material temperature for austenitic stainless steels Apply also for 2K !
(material spec corresponding to ASTM type AISI may differ !)

Material spec	DIN EN number	ASTM type AISI	T_M (in ° C)
X1NiCrMoCu 31-27-4	1.4563		-270
X1CrNiMoN 25-22-2	1.4466		
X1CrNi 25-21	1.4335	310 L	
X2CrNiMoN 17-13-3	1.4429	316 LN	
X2CrNiMoN 17-11-2	1.4406		
X2CrNiMoN 18-12-4	1.4434		
X2CrNiMo 18-15-4	1.4438	317 L	
X2CrNiN 18-10	1.4311	304 LN	
X2CrNiMo 18-14-3	1.4435	316 L	
X2CrNi 19-11	1.4306	304 L	

Cryogenic safety aspects:

Preventive Measures

Against Pressure Build-up

Redundancy

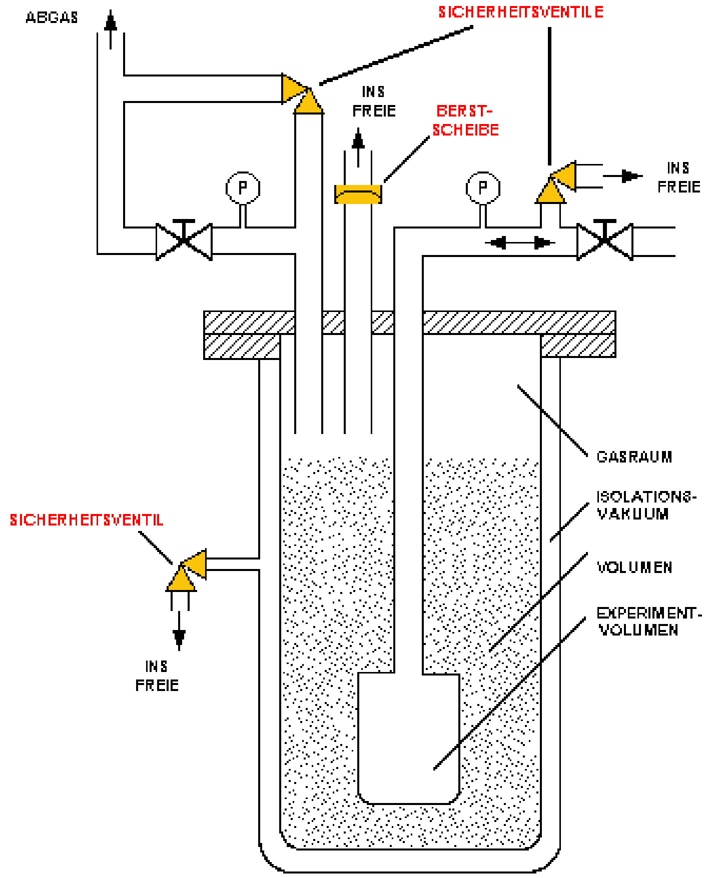
i.e. more safety devices than required

double safety devices

and

Diversity

i.e. safety devices based on different mechanisms



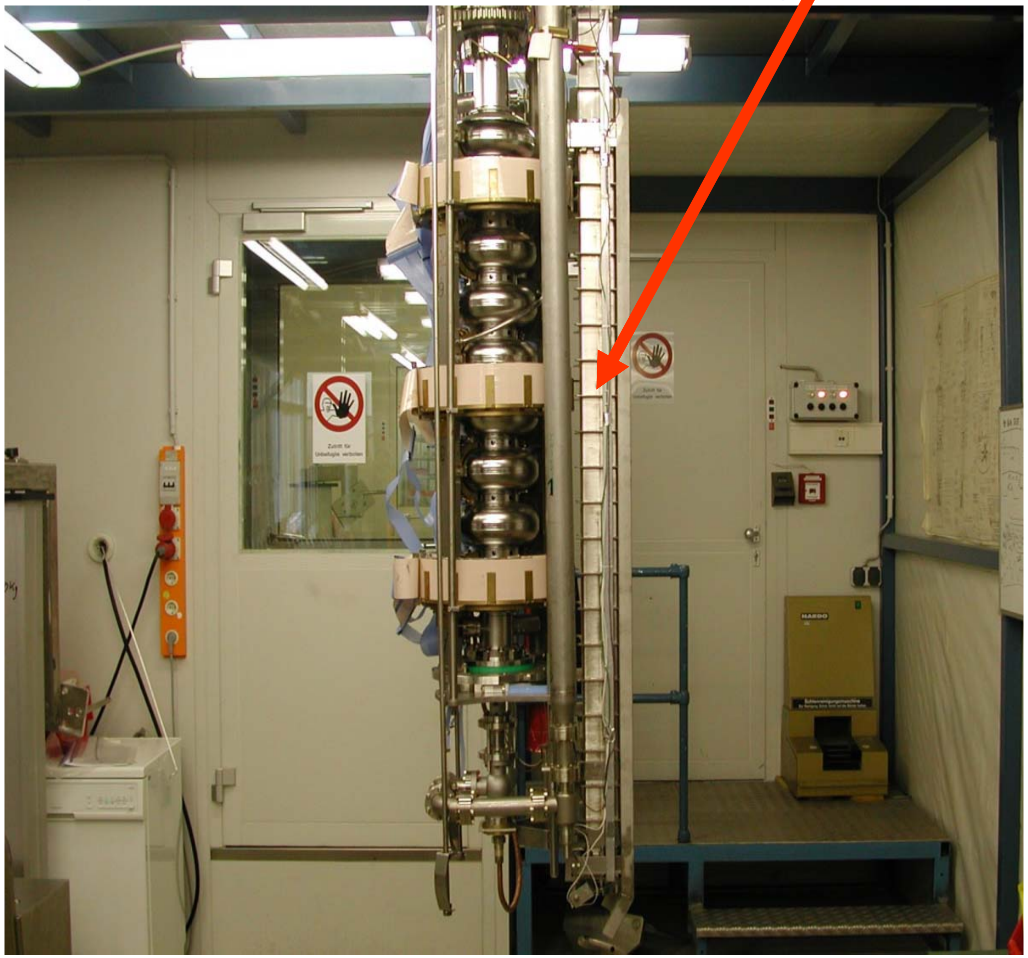
Cryogenic safety aspects

Pressure Build-up by Evaporation

Large air leak into the wave guide of an insert
-> Evaporation of about 2.6 kg/s mass flow through safety valve

Heat input caused by the break down of Insulation vacuum:

40kW / m2 without MLI
6kW/ m2 with MLI

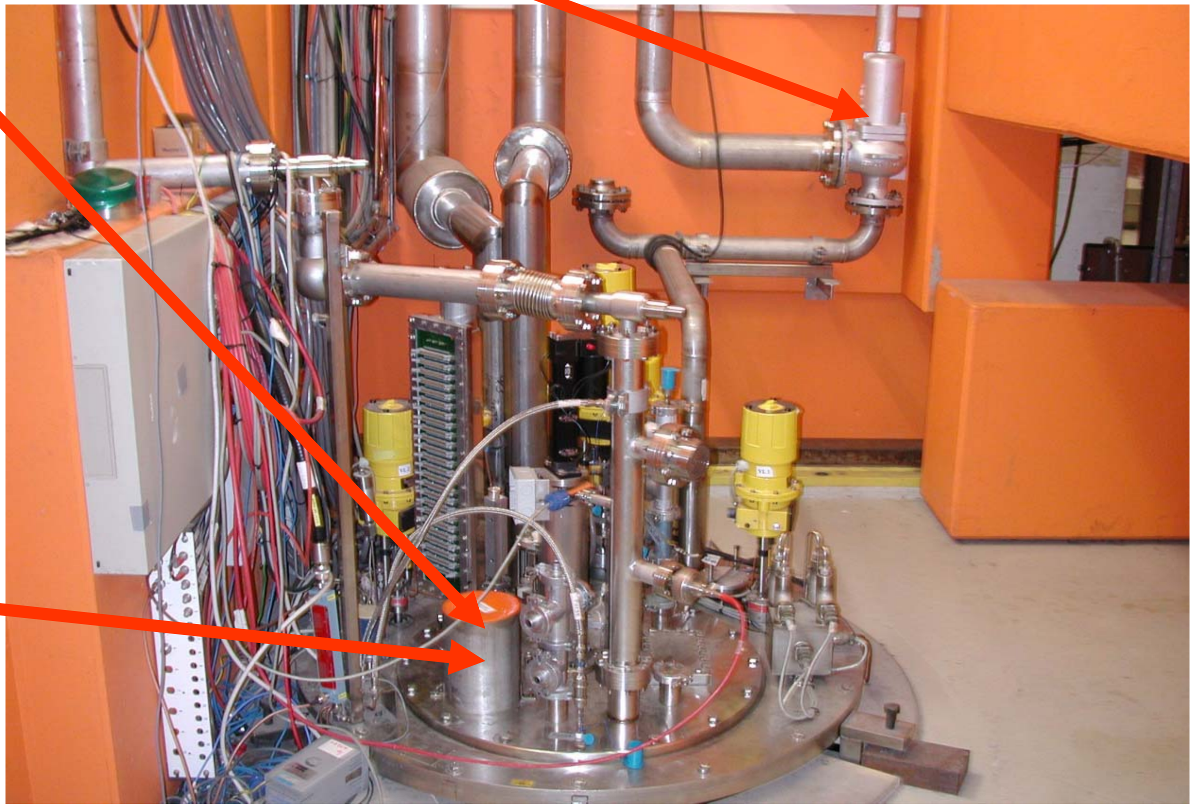


Bernd Petersen DESY –MKS1
Bernd.Petersen@desy.de

Cryogenic safety aspects

Preventive Measures against PressureBuild-up

Release Flap + Safety Valve



Caution in the

Vicinity

Of

Release devices !

Safety aspects: Calculation of venting conditions

According to ASME Code CGA S.1.3-1995

$$m = \frac{Q}{v * \text{sqrt}(dh / dv)_P}$$

$$\frac{\text{sqrt}(v)}{v * \text{sqrt}(dh / dv)_P} = f(T)$$

T=T flow

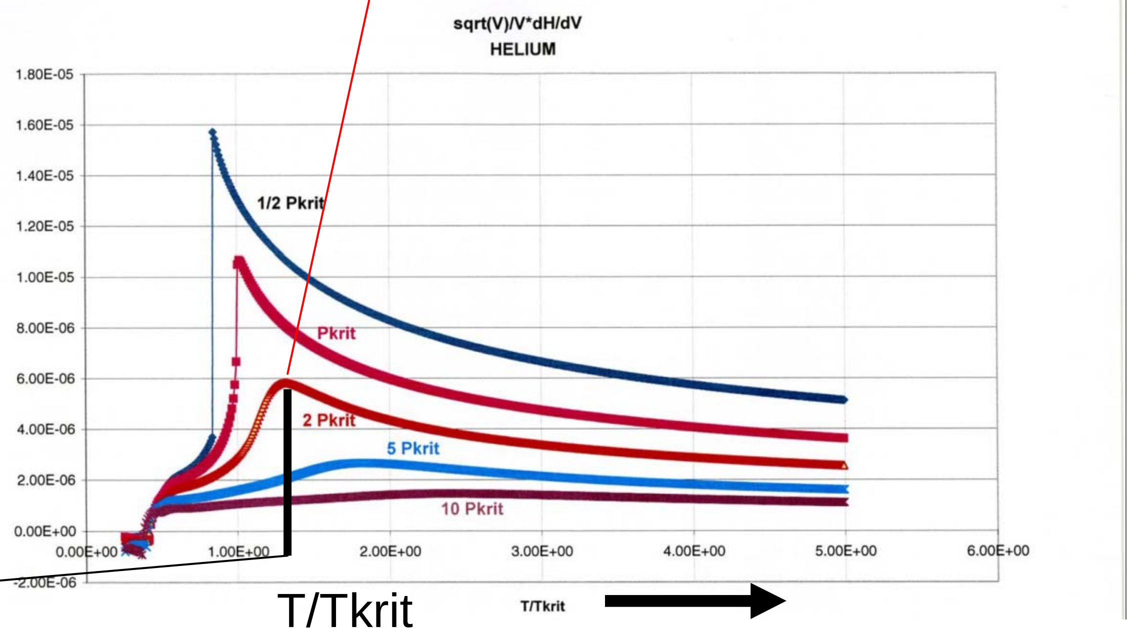
Q – heat input

m – mass flow

V – specific volume

H – specific enthalpy

Maximum at T=T flow



Safety aspects:
Spec of safety valves

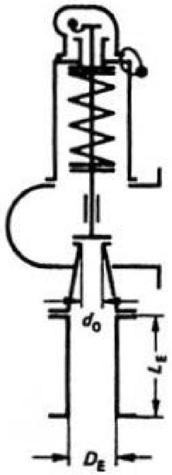


Figure 1

0.4 Gases and vapours

0.4.1 The general relation for the dimensioning of the ninimum cross-section of flow is as follows

$$A_0 = \frac{q_m}{\psi \cdot \alpha_w \sqrt{2 \frac{p_0}{v}}} \quad (2)$$

where:

A_0 = minimum cross-section of flow in mm²

q_m = mass flow to be discharged in kg/h

p_0 = absolute pressure in the pressure chamber in bar

v = specific volume of the medium in the pressure chamber in m³/kg

α_w = the outflow coefficient allotted in the context of component testing

ψ = outflow function

For subcritical pressure ratios $\frac{p_{a0}}{p_0} > \left(\frac{2}{k+1}\right)^{\frac{k}{k-1}}$

$$\psi = \sqrt{\frac{k}{k-1}} \cdot \sqrt{\left(\frac{p_{a0}}{p_0}\right)^{\frac{2}{k}} - \left(\frac{p_{a0}}{p_0}\right)^{\frac{k+1}{k}}} \quad (3)$$

For supercritical pressure ratios

$$\psi = \psi_{max} = \sqrt{\frac{k}{k+1}} \cdot \left(\frac{2}{k+1}\right)^{\frac{1}{k-1}} \quad (4)$$

where

p_{a0} = absolute counter pressure in bar

k = isentropic exponent of the medium in the pressure chamber

10.4.2 In the case of industrial gases and vapours, the specific volume is calculated from the general relation

$$v = \frac{R_1 \cdot T \cdot Z}{p_0} \quad (5)$$

Source: AD pressure vessel code

Safety aspects: procedure

Method used by DESY MKS:

Calculate heat input Q

Find T flow (by ASME code)

Calculate mass flow at T flow (by ASME code)

Calculate sv dimensions (by AD code)

Safety Valve in action………

Basic cryomodule design considerations (1)

Task : design a cryomodule for SRF accelerator operation

- Operation mode : pulsed or cw ???
- Fraction of dynamic and static loads ?
- RF operation frequency   -> choice of operation temperature
- beta = ??? -> general cavity and cryostat design
- RF main coupler loads -> thermal intercepts
- HOM loads -> design of couplers and absorbers
- ERL machines -> active cooling of HOM absorbers may be required
- Tuners -> warm or cold (extra feedtroughs required ?)
- Magnetic shielding of cavities
- Focusing sc magnets included ? Current leads design….
- Alignment requirements
- Environment -> expected radiation level, tunnel ?...........
- Single individual cryostat or serial production for large accelerator ?

Basic cryomodule design considerations (2)

Task : design a cryomodule for SRF accelerator operation

Some ‚formal' aspects:

- Generate a design concept
- Concept for cooling and heat load estimate
- Risk analysis -> choice of technical rules & pressure vessel classification
- Risk analysis -> safety concept & equipment
- Pressure vessel code -> design & construction rules
- Pressure vessel code -> choice and control of materials
- Pressure vessel code -> welding procedures & management
- Pressure vessel code -> third party inspection & test procedures
- Quality control plan (in addition to pressure vessel code)
- Design, construction & prototyping
- Testing, testing,testing……………
- Transfer to industrial construction
- Testing, testing,testing….-> pre-series -> serial production

Basic cryomodule design considerations (3)

Task : design a cryomodule for SRF accelerator operation

Some formal Rules, laws, regulations which have to be obeyed in the EU

INCOMPLETE !

- European Pressure Equipment Directive (Richtlinie 97/23/EG für Druckgeräte)
- Richtlinie über elektrische Betriebsmittel (73/23EWG)
- Geräte- und Produktsicherheitsgesetz (GPSG)
- Betriebssicherheitsverordnung (BetrSichV)
- Qualitätsmanagementsysteme DIN EN ISO 9001, August 1994
- European Harmonized Standards like Europäische Norm EN 13445, etc.

Basic cryomodule design considerations (4)

<u>Task : design a cryomodule for SRF accelerator operation</u>

Some ‚technical' aspects:

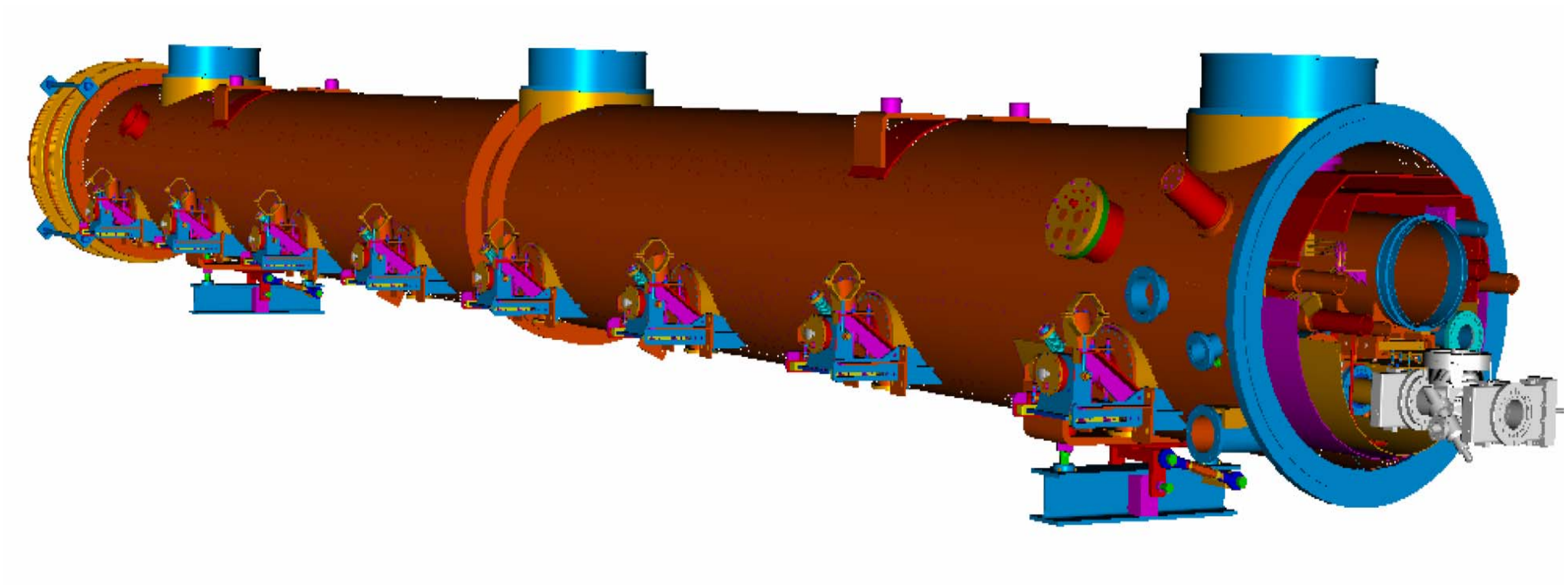
- By the way: the cavities have to work -> include clean room requirements from the start for all related components
- Quality insurance procedures: helium leak tests of each and every helium process components required (before, during and after assembly)
- Helium leak testing at a rate of 10^{-8} mbar/l*sec (or better) for the individual componets at ambient temperatures will avoid ‚cold-leaks' in the order of better than 99%
- DESY ‚philosophy': no direct feedthroughs from helium process areas to insulation vacuum for accelerator cryostats !!!!
- Structural tests (like X-raying of welds) can NOT replace helium leak checks (and vice versa) !!!!!
- Welding additives must be qualified for low temperatures -> strict certification of welding procedures & welders; strict quality control organization and management

Example: TESLA-style cryomodule design (INFN Milano/Italy)

Designed for large accelerators -> low costs per length accelerator

-> ‚easy' and cheap assembly

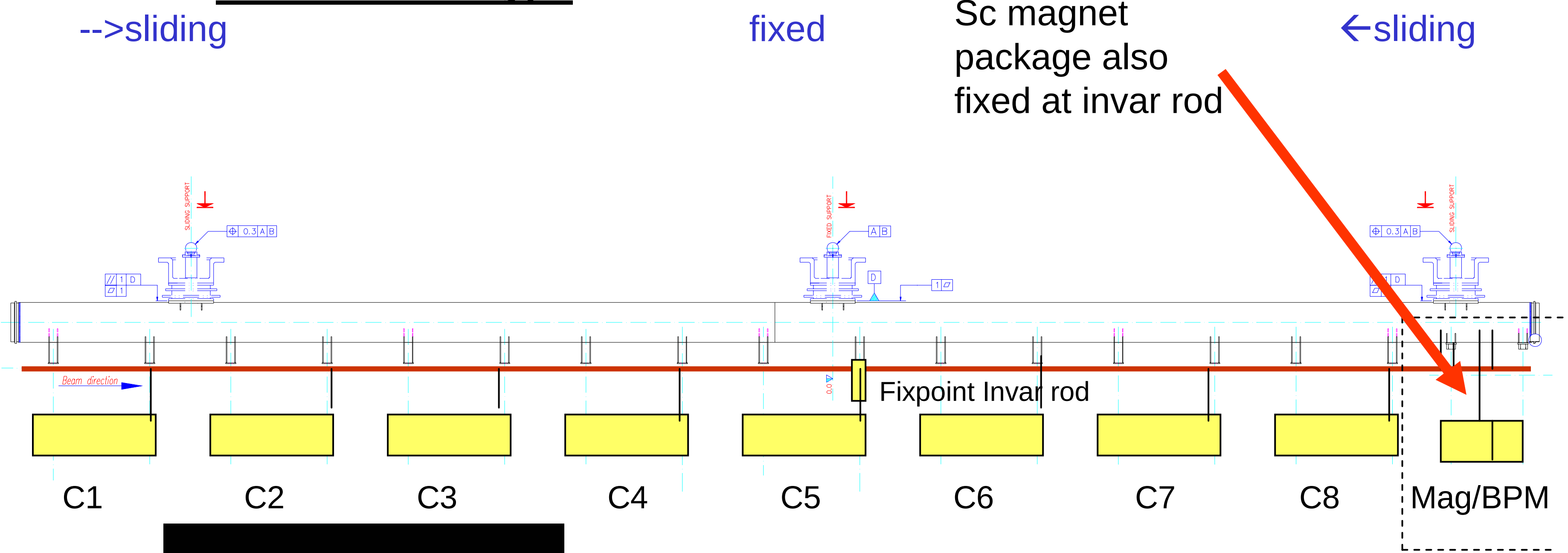
-> serves as a ‚generic design' for other projects:ERLs,XFEL,ILC…..

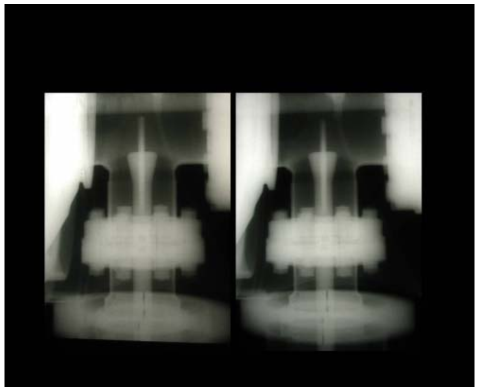


Example: TESLA-style cryomodule design

Positions of cavities and Couplers are fixed

<u>XFEL module type</u>





X-ray of coupler position at 300 K and 2K

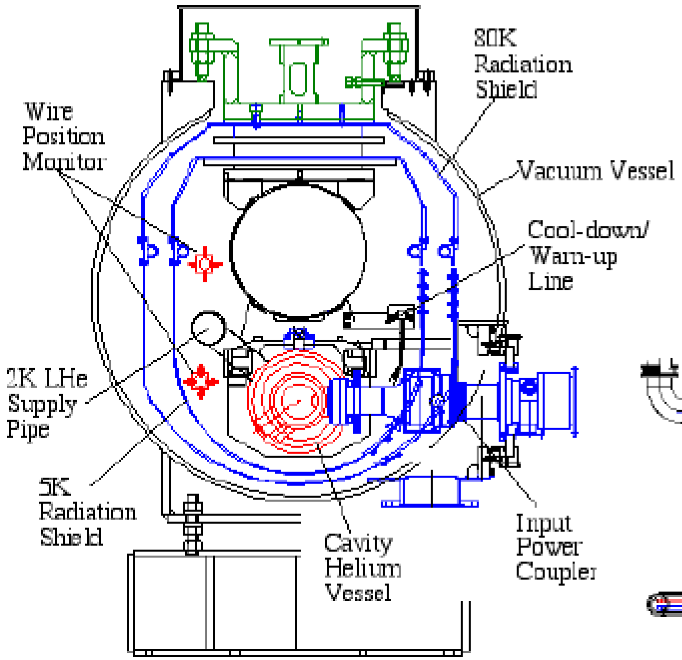
TESLA-style module design: 3 design steps

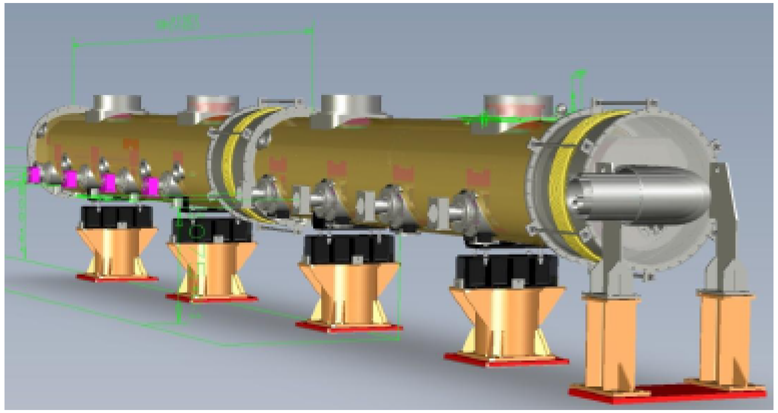
In use for FLASH-linac user facility at DESY

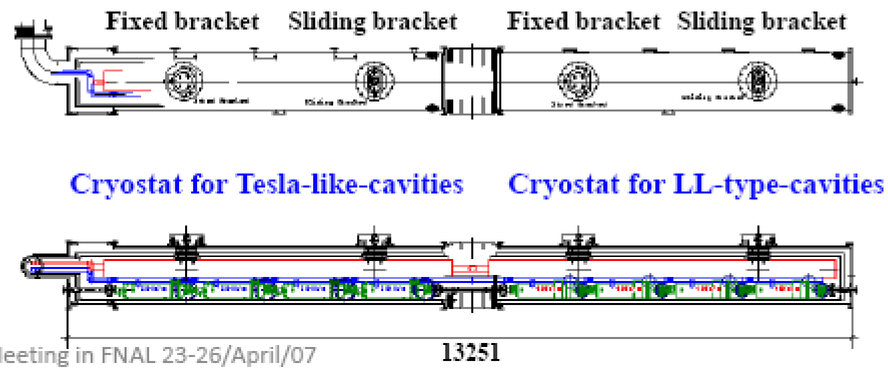
Prototype for XFEL-linac cryomodules (only minor modifications)

Design of the KEK-STF Cryomodule

- The design of the cross section of the KEK-STF cryomodule is based on the **TTF-III** cryomodule.
- Two cryomodules for the TESLA-like-cavities and the LL-type-cavities are connected with the vacuum bellows, and the total length of the vacuum vessels is 13.25 meter.
- Each cryostat is designed to have four cavities.



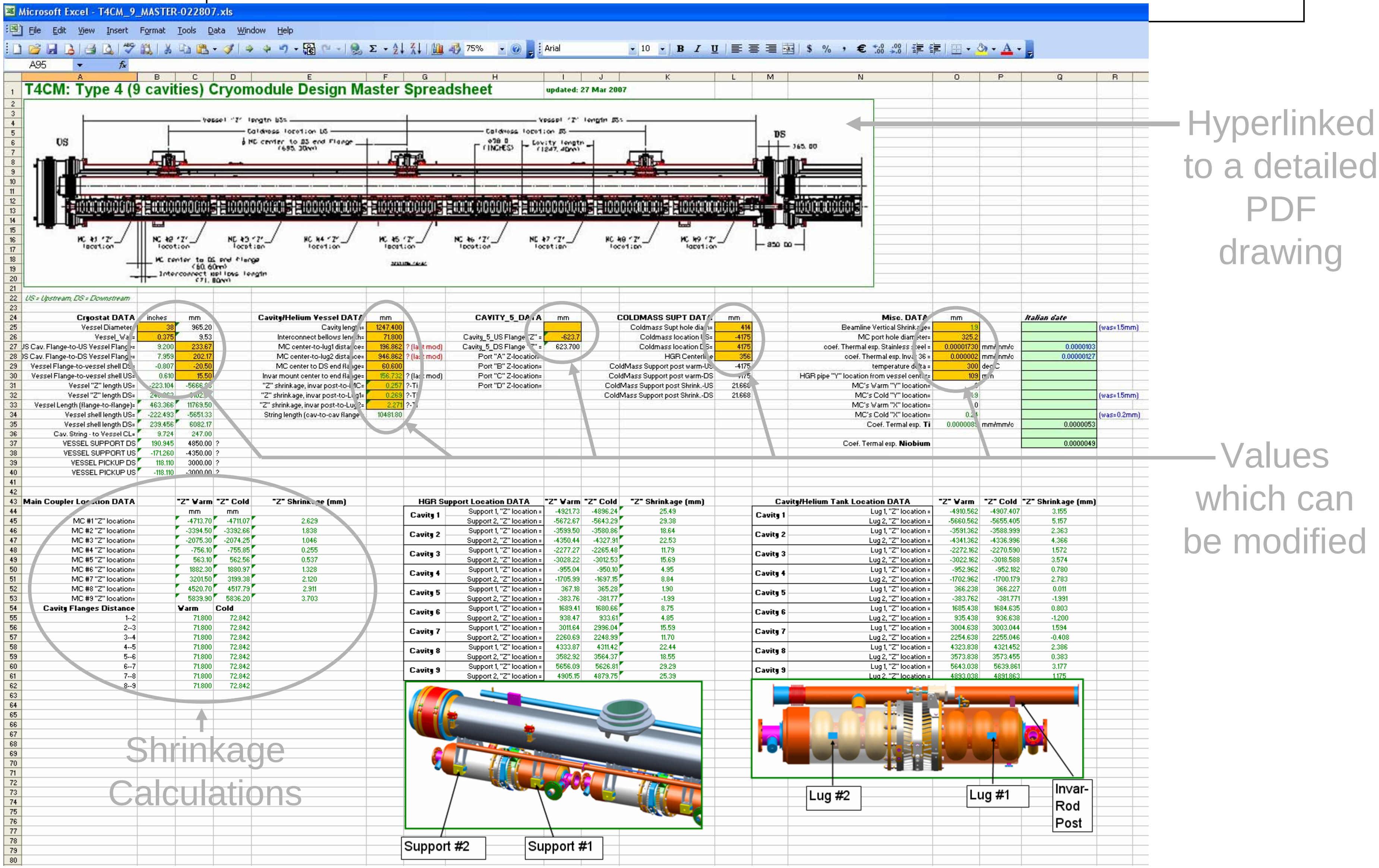




(courtesy of N. Ohuchi et. al KEK)

T4CM Design. The Master Spreadsheet

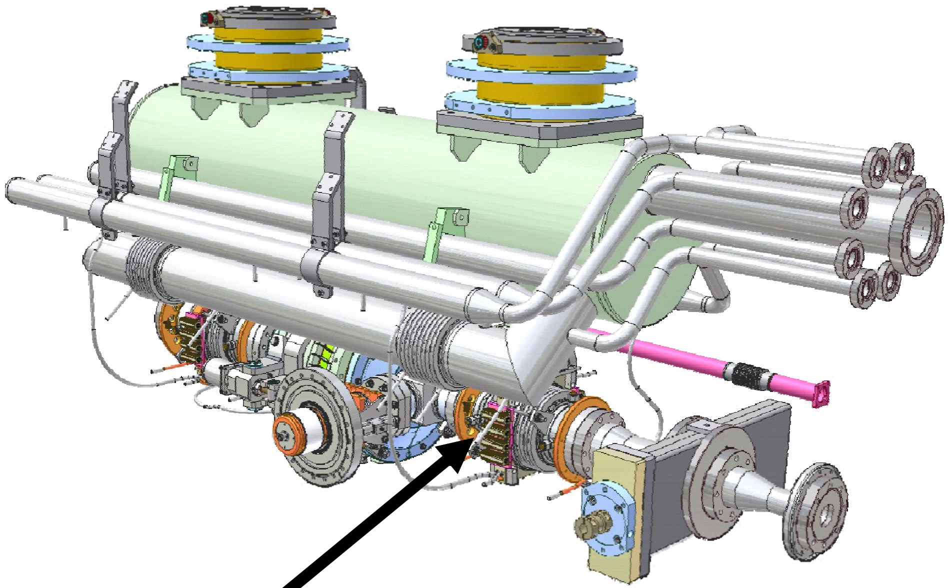
(courtesy of Don Mitchell and Youri Orlov FNAL)



Cornell University ERL Injector Cryostat

(courtesy of Eric Chojnacki)

Design changes for for ERL use (cw-operation, large HOM loads)



HOM absorber

Second part: tutorial objectives

after this part, we should remember:

- Measures to increase refrigerator availability
- Helium management considerations
- Suited materials for cryogenic temperatures
- Cryogenic safety aspects
- Basic cryomodule design considerations
- Pressure vessel regulations
- Quality control measures
- Example: TESLA style cryomodule design

Thank You !