Introduction to Cryogenics for accelerators

Serge Claudet

LHC Cryogenic Operations, CERN

CAS

Basics of Accelerator Science and Technology at CERN

Chavanne de Bogis, CH

4-8 Nov 2013

Préambule

Reference

Great thanks to predecessors for this type of exercice, particularly to Ph. Lebrun and his "legacy" of slides

Disclaimer

Being an engineer and new in this domain as "teacher", I will try to share with you some information with emphasis on "applied cases" with a "pragmatic approach" rather than only a theoretical one.

There are plenty of books, previous CAS courses with lot's of formulas and various equations. I leave it to you to check bibliography if this is what you are looking for!

Contents

- Introduction
- Cryogenic fluids
- Heat transfer & thermal insulation
- Cryogenic distribution & cooling schemes
- Refrigeration & liquefaction
- Various complements
- Concluding remarks, references

- **cryogenics,** that branch of physics which deals with the production of very low temperatures and their effects on matter

  Oxford English Dictionary

  2nd edition, Oxford University Press (1989)

- **cryogenics**, the science and technology of temperatures below 120 K

  New International Dictionary of Refrigeration

  3rd edition, IIF-IIR Paris (1975)

Temperature in Celsius (C): unit defined with 0 C (ice) and 100 C (vapour)

Temperature in Kelvin (K): 1 K = 1 C, but 0 K = -273.15 C (absolut zero)

Densification, liquéfaction & séparation des gaz

LNG

130 000 m^3 LNG carrier
with double hull

LIN & LOX

Air separation by cryogenic
distillation

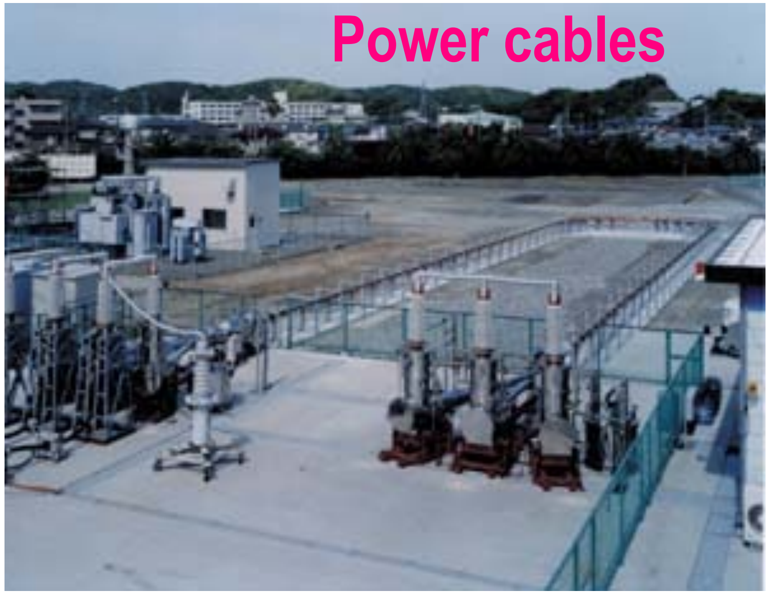
Up to 4500 t/day LOX

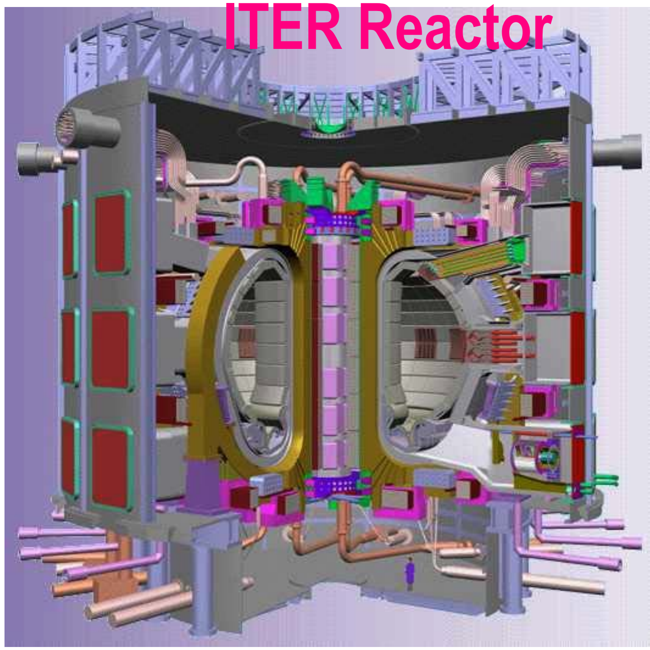
Rocket fuels

Ariane 5

25 t LHY, 130 t LOX

Cooling of superconducting devices





Main reasons to superconducting

For accelerators in high energy physics

- Compactness through higher fields

Capital Cost

$E_{beam} \approx 0.3 \,.\, \mathbf{B} \,.\, r$ [Gev] [T] [m]

$E_{beam} \approx \mathbf{E} \,.\, L$ [Gev] [MV/m] [m]

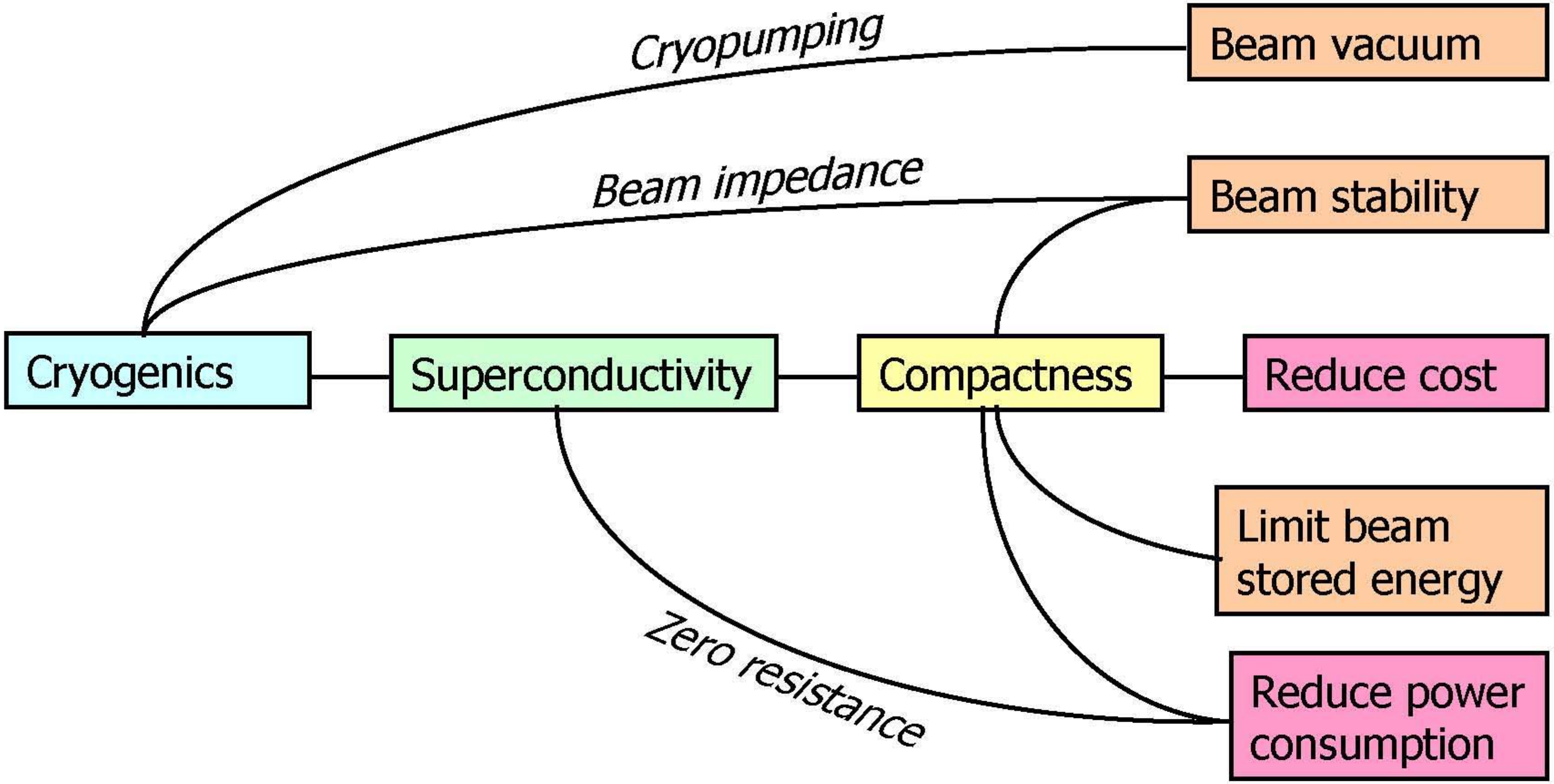
At design stage, working at highest possible temperature is always considered, but often not selected to maximise beam energy …
Cryogenic systems takes longer to recover from failures than conventional ones !
(but there is work on it!)

- Saving operating energy

Operating Cost

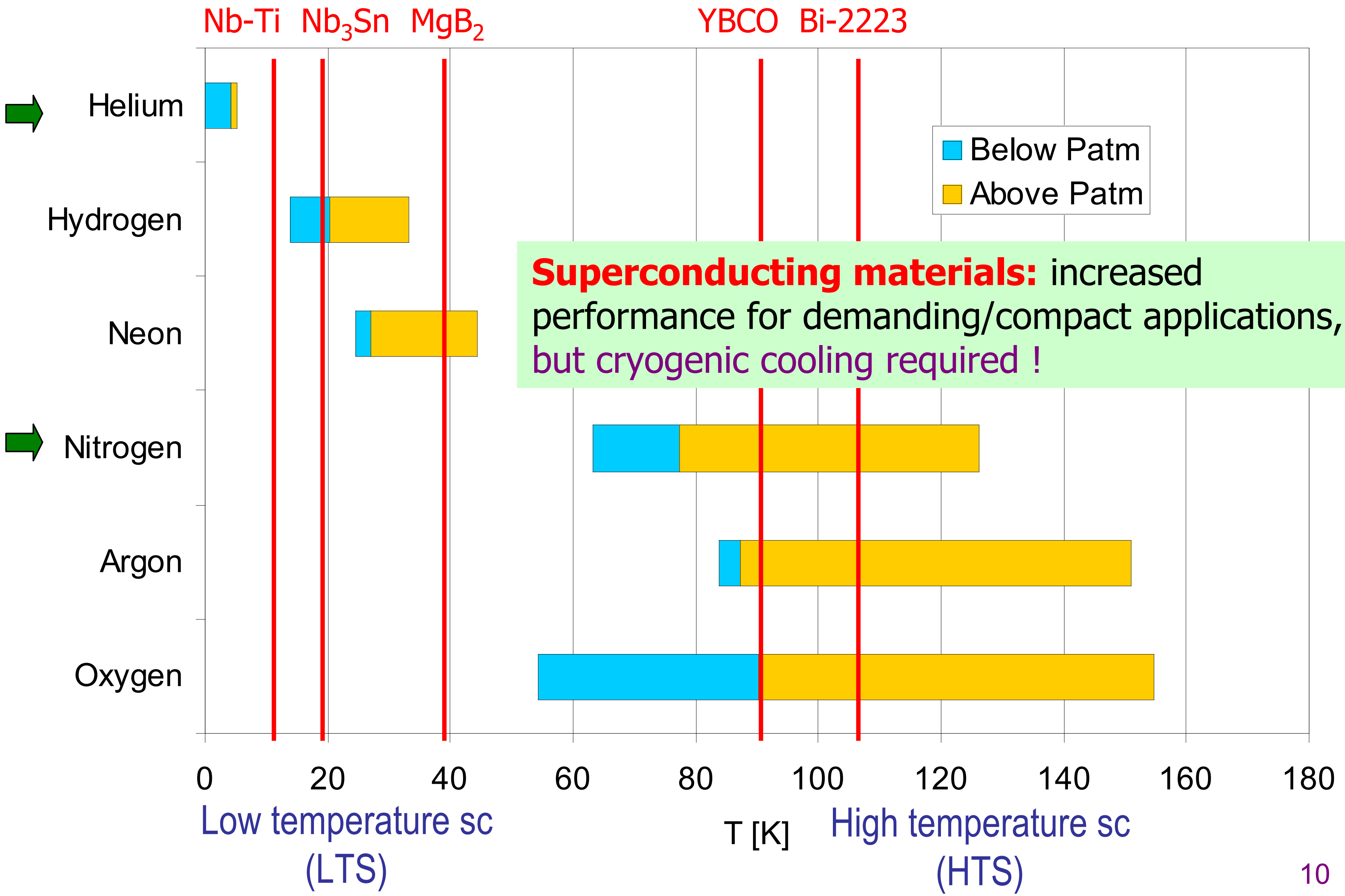
	Electromagnets:	Acceleration cavities
Resistive:	$P_{input} \approx E_{beam}$	$P_{input} \approx Rs.L.\mathbf{E}^2/w$
Superconducting:	$P_{input} \approx Pref$	$R_s \approx R_{BCS} + R_o$
		$R_{BCS} \approx (1/T)\exp(-BT_c/T)$

Rationale for superconductivity & cryogenics in particle accelerators



Contents

Useful range of cryogens, and potential applications



Superconducting materials: increased performance for demanding/compact applications, but cryogenic cooling required !

Characteristic temperatures of cryogens

Cryogen	Triple point [K]	Normal boiling point [K]	Critical point [K]
Methane	90.7	111.6	190.5
Oxygen	54.4	90.2	154.6
Argon	83.8	87.3	150.9
Nitrogen	63.1	77.3	126.2
Neon	24.6	27.1	44.4
Hydrogen	13.8	20.4	33.2
Helium	2.2 (*)	4.2	5.2

(*): λ point

Properties of cryogens compared to water

Property		He	N_2	H_2O
Normal boiling point	[K]	4.2	77	373
Critical temperature	[K]	5.2	126	647
Critical pressure	[bar]	2.3	34	221
Liq./Vap. density (*)		7.4	175	1600
Heat of vaporization (*)	[$J.g^{-1}$]	20.4	199	2260
Liquid viscosity (*)	[μPl]	3.3	152	278

(*) at normal boiling point

Vaporization of normal boiling cryogens under 1 W applied heat load

Power ≈ m′ . Latent_Heat

[W] [g/s] [J/g]

Cryogen	[mg.s^{-1}]	[l.h^{-1}] (liquid)	[l.min^{-1}] (gas NTP)
Helium	48	1.38	16.4
Nitrogen	5	0.02	0.24

Amount of cryogens required to cool down 1 kg iron

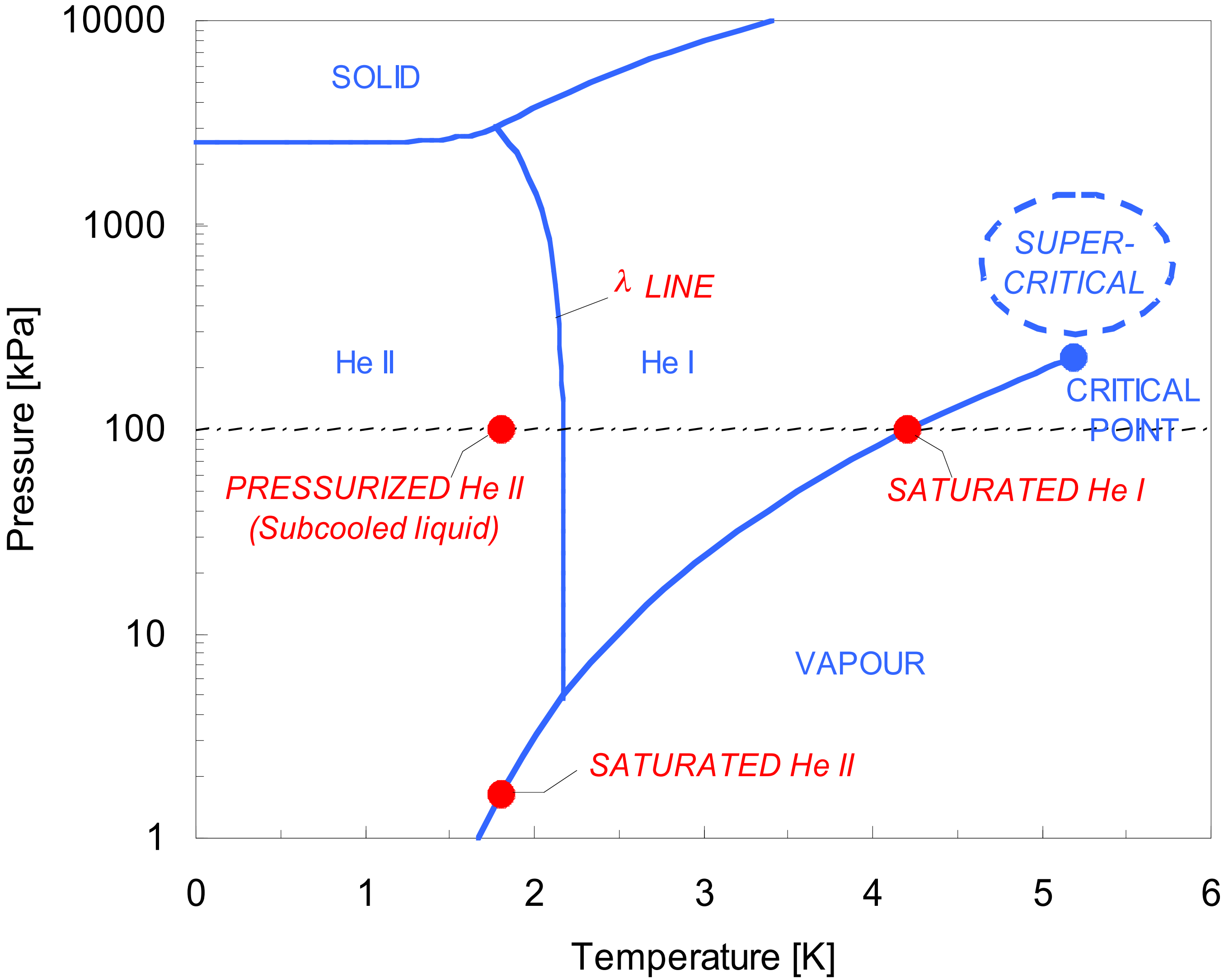
Power ≈ m′ . Latent_Heat
[W] [g/s] [J/g]

Power ≈ m′ . Specific_Heat . ΔT
[W] [g/s] [J/g.K] [K]

+

Using	Latent heat only	Latent heat and enthalpy of gas
LHe from 290 to 4.2 K	29.5 litre	0.75 liter
LHe from 77 to 4.2 K	1.46 litre	0.12 litre
LN2 from 290 to 77 K	0.45 litre	0.29 litre

Phase diagram of helium

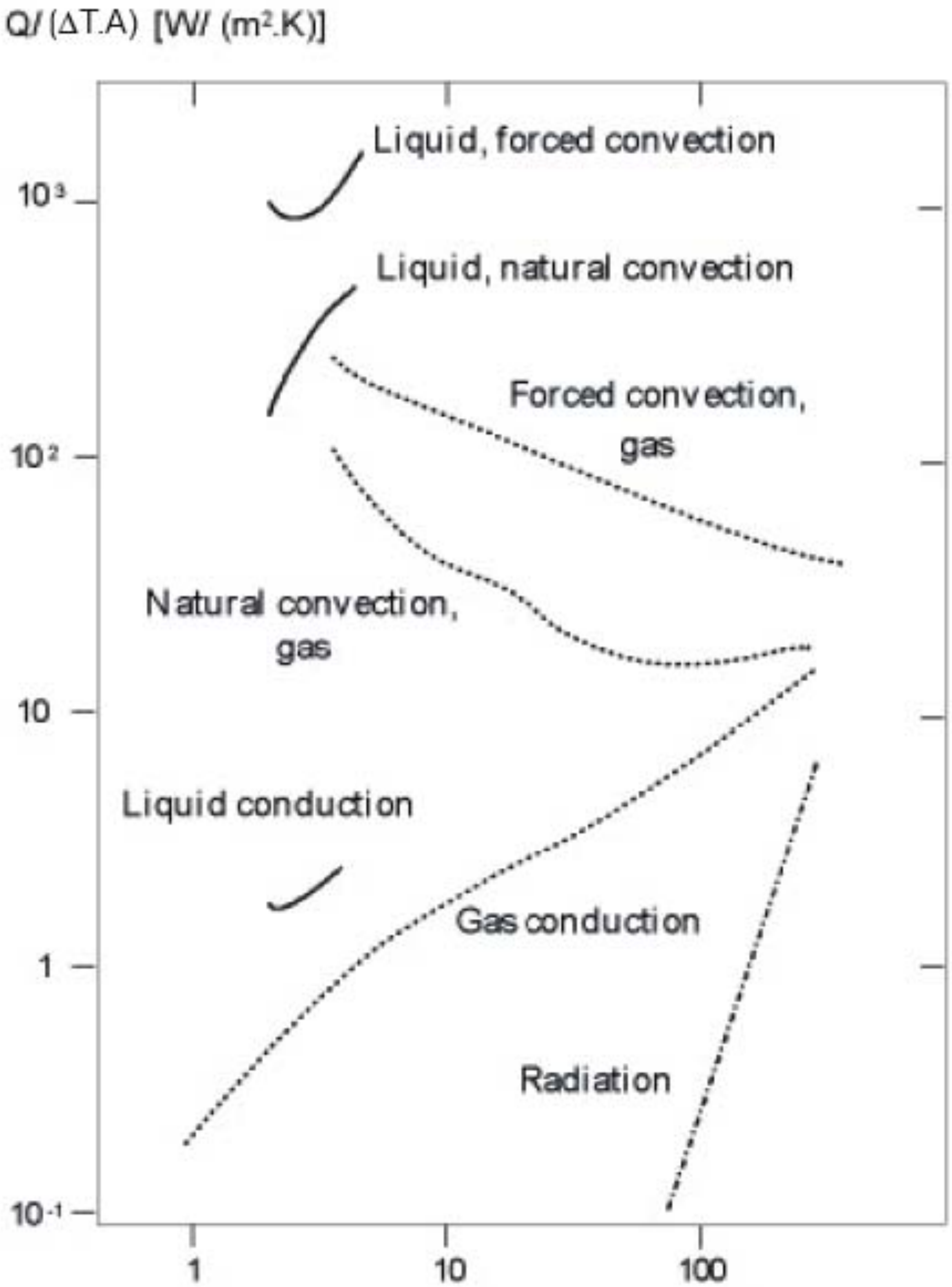


Helium as a cooling fluid

Phase domain	Advantages	Drawbacks
Saturated He I	Fixed temperature High heat transfer	Two-phase flow Boiling crisis
Supercritical	Monophase Negative J-T effect	Non-isothermal Density wave instability
He II	Low temperature High conductivity Low viscosity	Second-law cost Subatmospheric

Contents

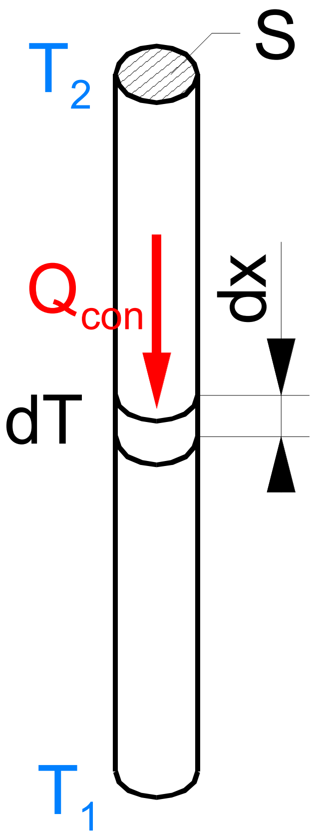
Typical heat transfer coefficients at cryogenic temperatures



3 mechanisms involved:

- Conduction
- Radiation
- Convection

Heat conduction in solids



<u>Fourier's law:</u>

$$Q_{con} = k(T) \cdot S \cdot \frac{dT}{dx}$$

k(T): thermal conductivity [W/m.K]

<u>Integral form:</u>

$$Q_{con} = \frac{S}{L} \cdot \int_{T1}^{T2} k(T) \cdot dT$$

$\int k(T) \cdot dT$: thermal conductivity integral [W/m]

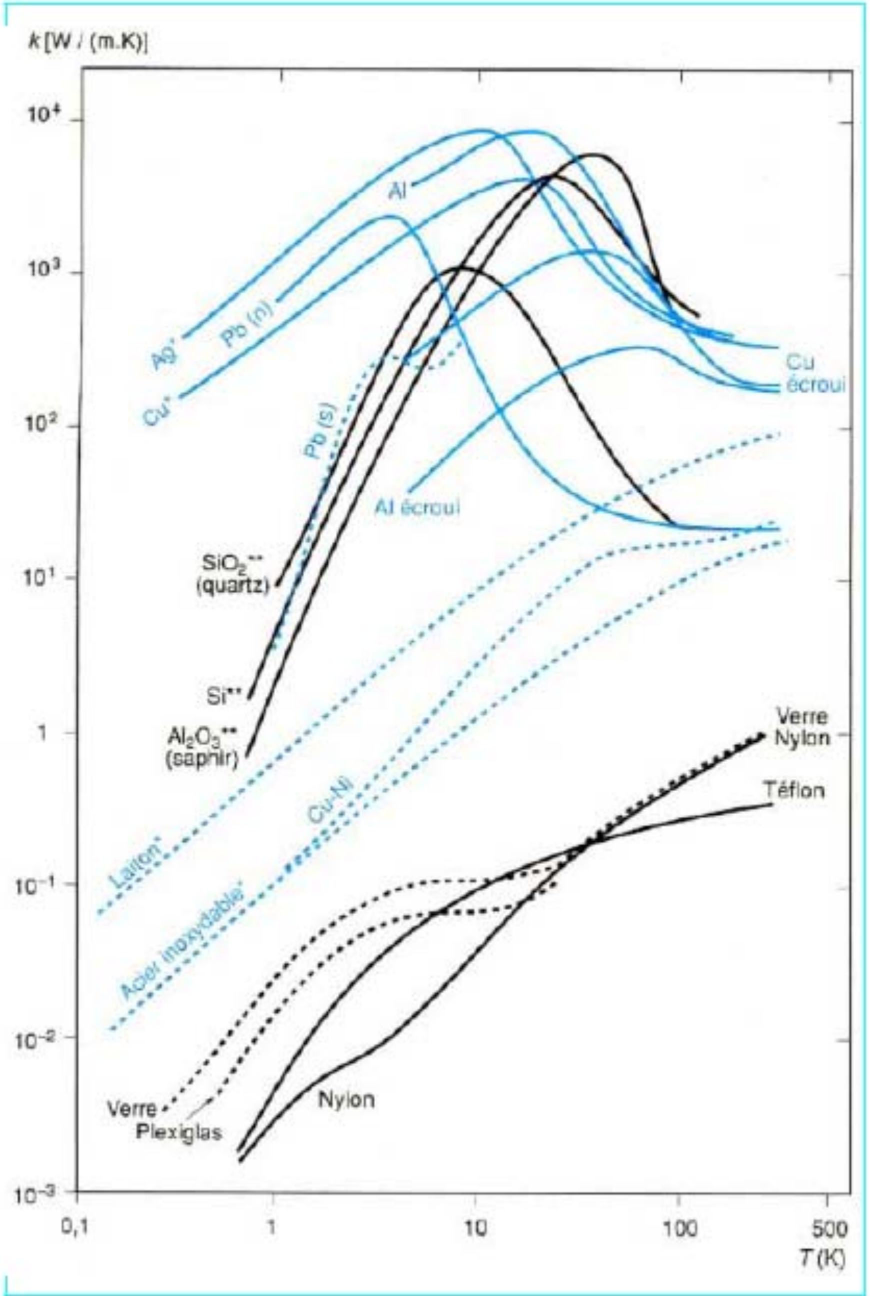
Thermal conductivity integrals for standard construction materials are tabulated

<u>Risks associated with "optimisation":</u>

- small section S: towards limit for material resistance
- long length L: towards limits for mechanical stability
- insulators (large) K: difficulties with transfer of forces

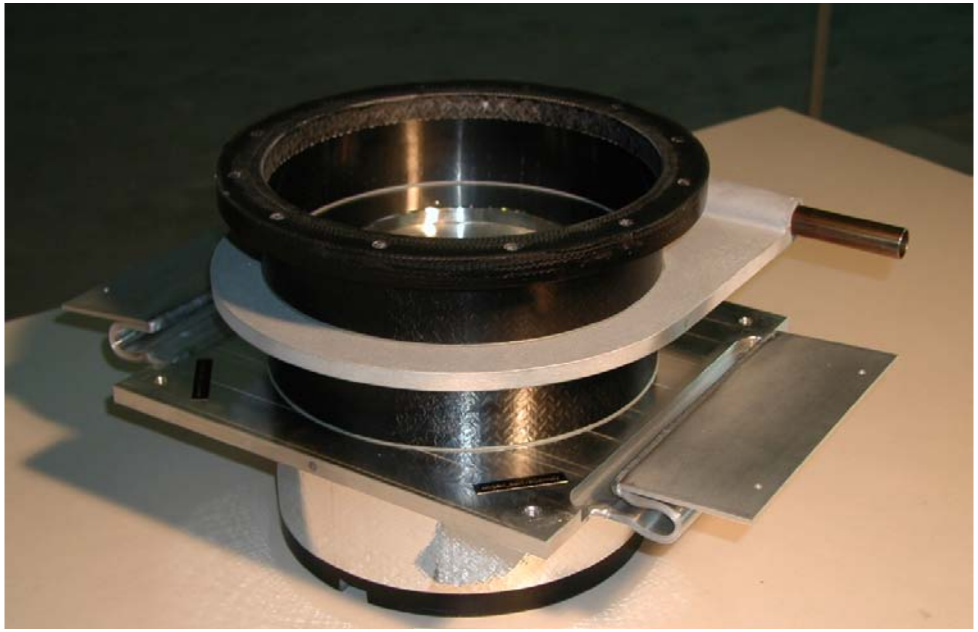
Thermal conductivity integrals, selection of materials [W/m]

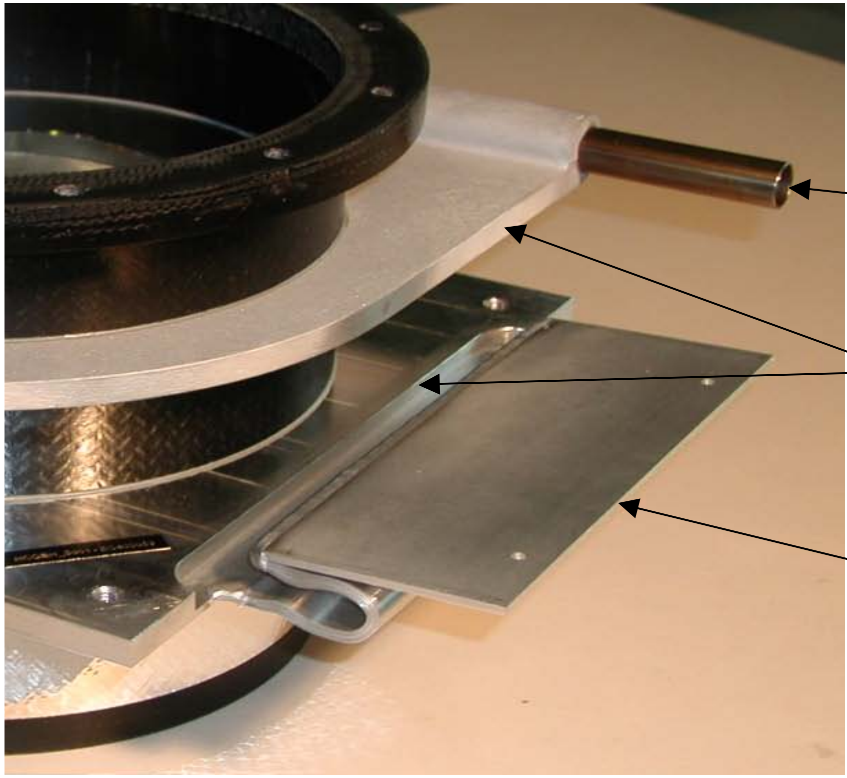
From vanishingly low temperature up to	**20 K**	**80 K**	**290 K**
OFHC copper	11000	60600	152000
DHP copper	395	5890	46100
1100 aluminium	2740	23300	72100
2024 aluminium alloy	160	2420	22900
AISI 304 stainless steel	16.3	349	3060
G-10 glass-epoxy composite	2	18	153



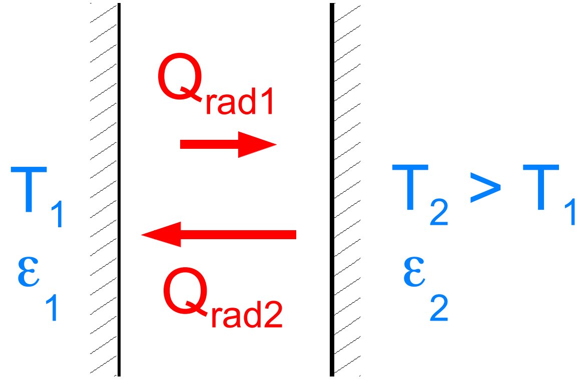
Thermal conductivity of materials at cryogenic temperatures

Non-metallic composite support post with heat intercepts for LHC magnets





Thermal radiation



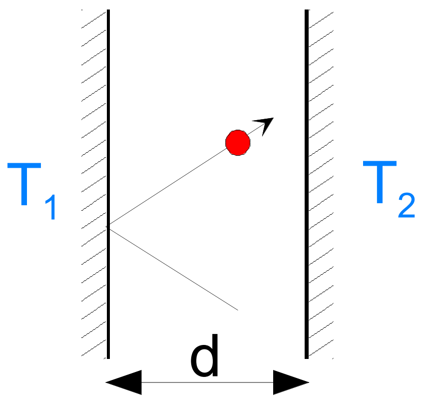
- Wien's law
  - Maximum of black body power spectrum
    $\lambda_{max}.T = 2898$ [μm.K]
- Stefan-Boltzmann's law
  - Black body — $Q_{rad} = \sigma A T^4$
    $\sigma = 5.67 \times 10^{-8}$ W/m^2.K^4
    (Stefan Boltzmann's constant)
  - "Gray"body — $Q_{rad} = \varepsilon \sigma A T^4$
    ε emissivity of surface
  - "Gray" surfaces at T_1 and T_2 — $Q_{rad} = E \sigma A (T_1^4 - T_2^4)$
    E function of ε_1, ε_2, geometry

$E . T^4$

Best would be to have a reflective (high E) "parasol" to intercept T4 …

Emissivity of technical materials at low temperatures

	Radiation from 290 K Surface at 77 K	Radiation from 77 K Surface at 4.2 K
Stainless steel, as found	0.34	0.12
Stainless steel, mech. polished	0.12	0.07
Stainless steel, electropolished	0.10	0.07
Stainless steel + Al foil	0.05	0.01
Aluminium, as found	0.12	0.07
Aluminium, mech. polished	0.10	0.06
Aluminium, electropolished	0.08	0.04
Copper, as found	0.12	0.06
Copper, mech. Polished	0.06	0.02



Residual gas conduction

$\lambda_{molecule}$: mean free path of gas molecules

Best would be to avoid residual gas …

- Viscous regime
  - At high gas pressure $\lambda_{molecule} << d$
  - Classical conduction $Q_{res} = k(T)\ A\ dT/dx$
  - Thermal conductivity $k(T)$ independant of pressure
- Molecular regime
  - At low gas pressure $\lambda_{molecule} >> d$
  - Kennard's law $Q_{res} = A\ \alpha(T)\ \Omega\ P\ (T_2 - T_1)$
  - Conduction heat transfer proportional to pressure, independant of spacing between surfaces
    Ω depends on gas species
  - Accommodation coefficient $\alpha(T)$ depends on gas species, T_1, T_2, and geometry of facing surfaces

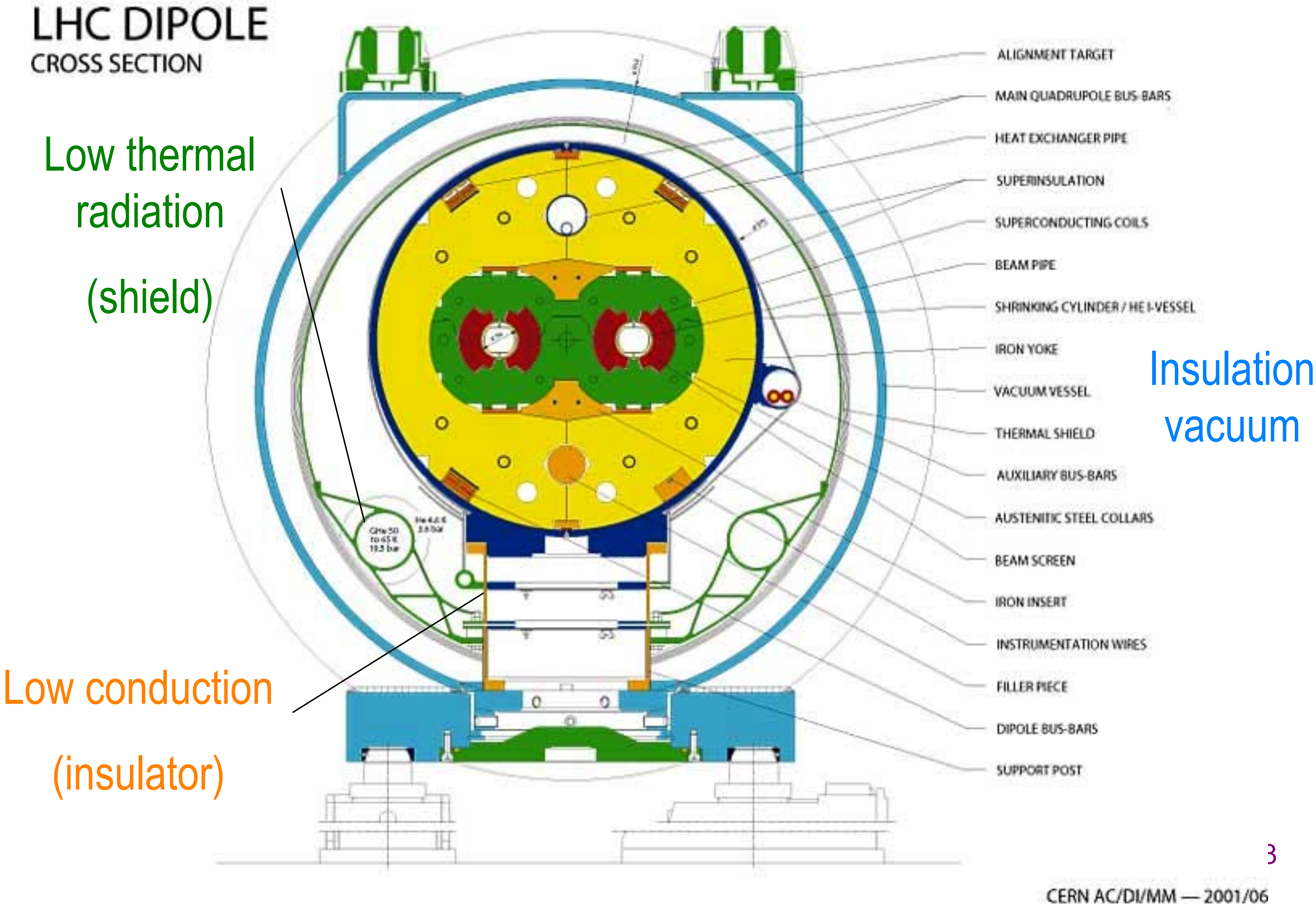
Multi-layer insulation (MLI)

- Complex system involving three heat transfer processes
  - $Q_{MLI} = Q_{rad} + Q_{sol} + Q_{res}$
  - With *n* reflective layers of equal emissivity, $Q_{rad} \sim 1/(n+1)$
  - Due to parasitic contacts between layers, Q_{sol} increases with layer density
  - Q_{res} due to residual gas trapped between layers, scales as 1/n in molecular regime
  - Non-linear behaviour requires layer-to-layer modeling
- In practice
  - Typical data available from (abundant) literature
  - Measure performance on test samples

Typical heat fluxes at vanishingly low temperature between flat plates [W/m²]

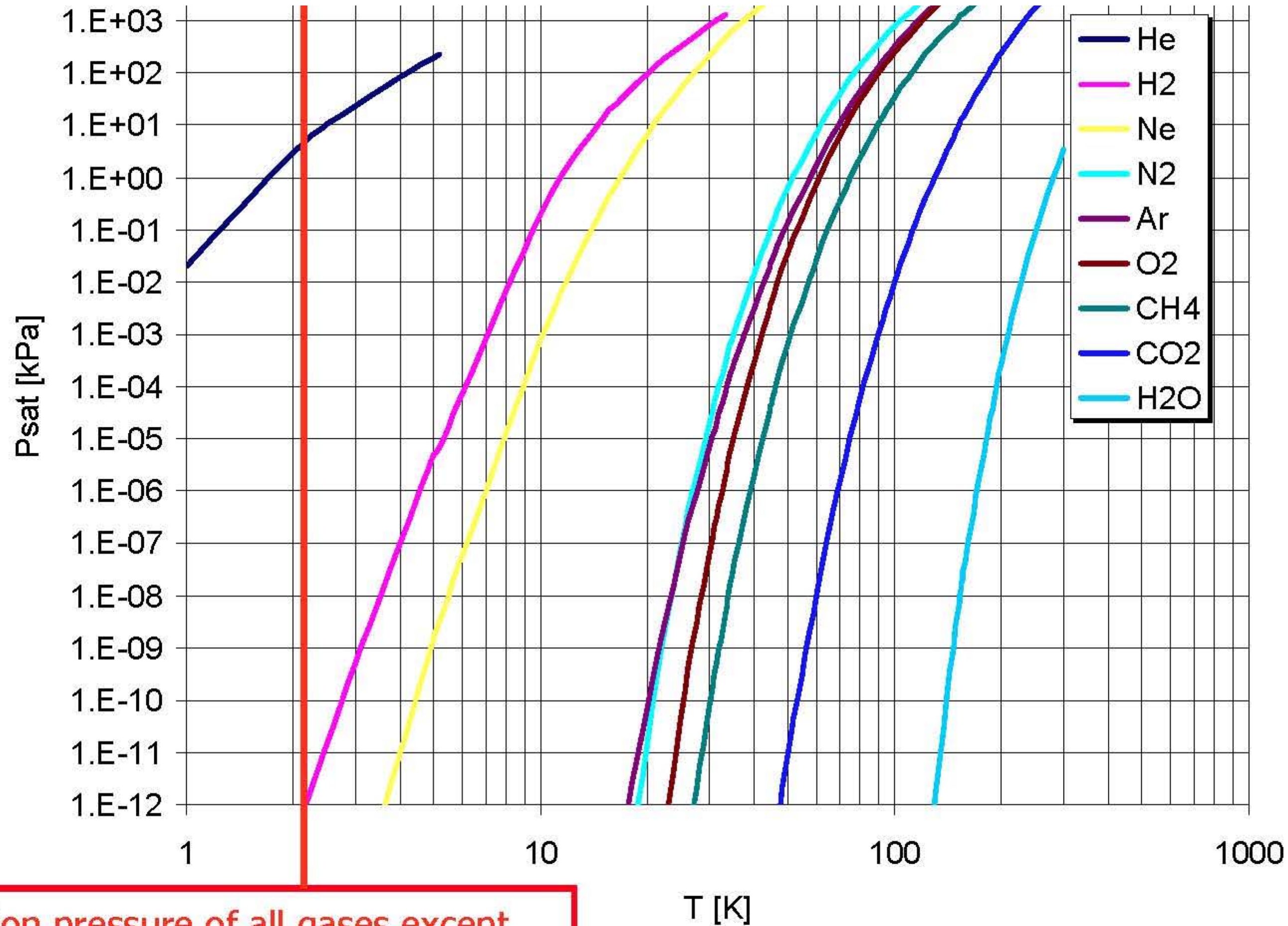
Black-body radiation from 290 K	401	Thermal shields
Black-body radiation from 80 K	2.3	
Gas conduction (100 mPa He) from 290 K	19	Degraded vacuum
Gas conduction (1 mPa He) from 290 K	0.19	
Gas conduction (100 mPa He) from 80 K	6.8	
Gas conduction (1 mPa He) from 80 K	0.07	
MLI (30 layers) from 290 K, pressure below 1 mPa	1-1.5	Super isolation
MLI (10 layers) from 80 K, pressure below 1 mPa	0.05	
MLI (10 layers) from 80 K, pressure 100 mPa	1-2	

Cross section of a LHC dipole



Cryopumping maintains good vacuum

Vapour pressure at cryogenic temperatures



Saturation pressure of all gases except helium vanish at cryogenic temperature

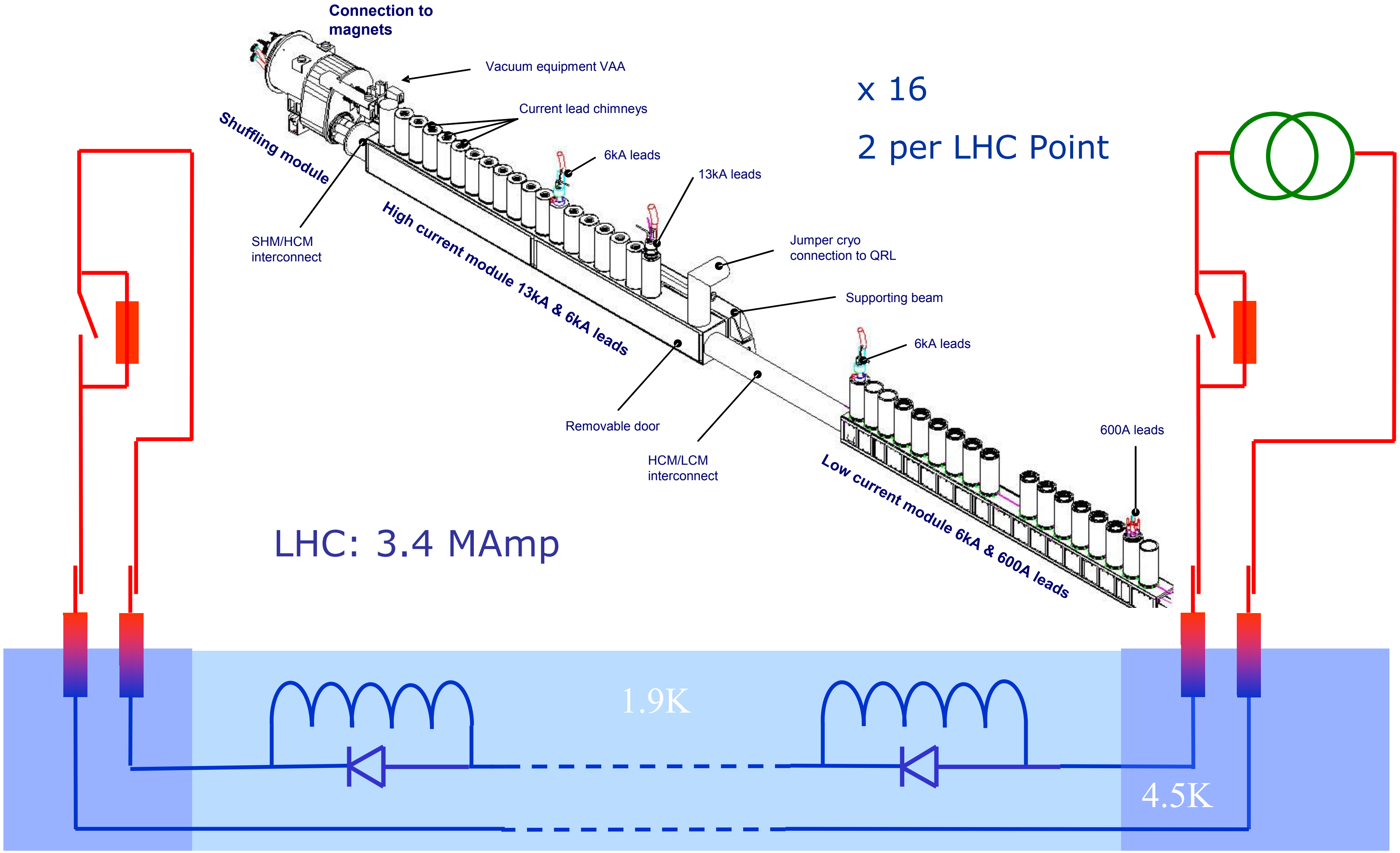
Cryopumping maintains good vacuum

Electrical Feed Box for current leads

x 16

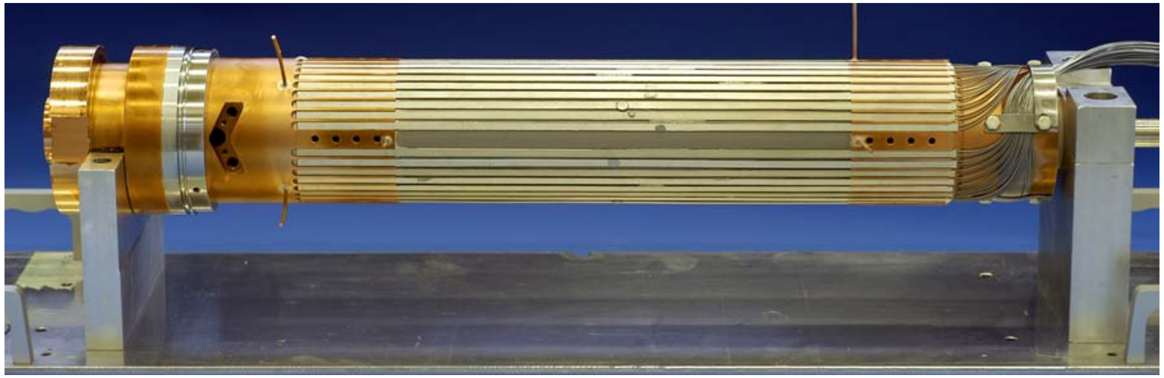
2 per LHC Point

LHC: 3.4 MAmp

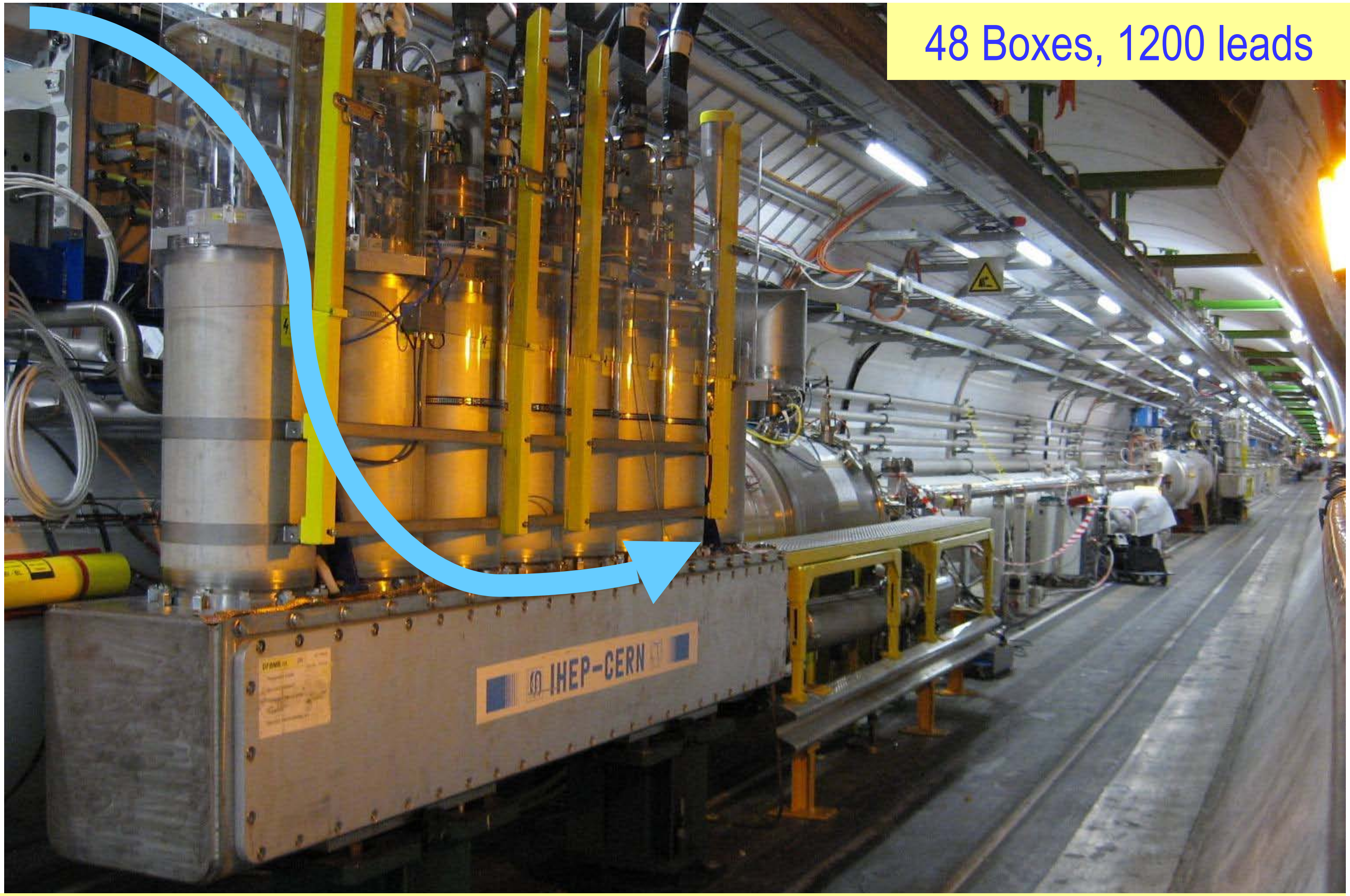


Beating the WFL law: HTS current leads

- The WFL law essentially states that good electrical conductors are also good thermal conductors
- Current leads need good electrical conductors with low thermal conductivity
- Superconductors are bad thermal conductors with zero resisitivity
- Build current lead with superconductor up to temperature as high as possible, i.e. HTS



Electrical feed boxes for current leads



More than 10’000 Amperes per chimney, from room temperature down to 4.5K in about a meter

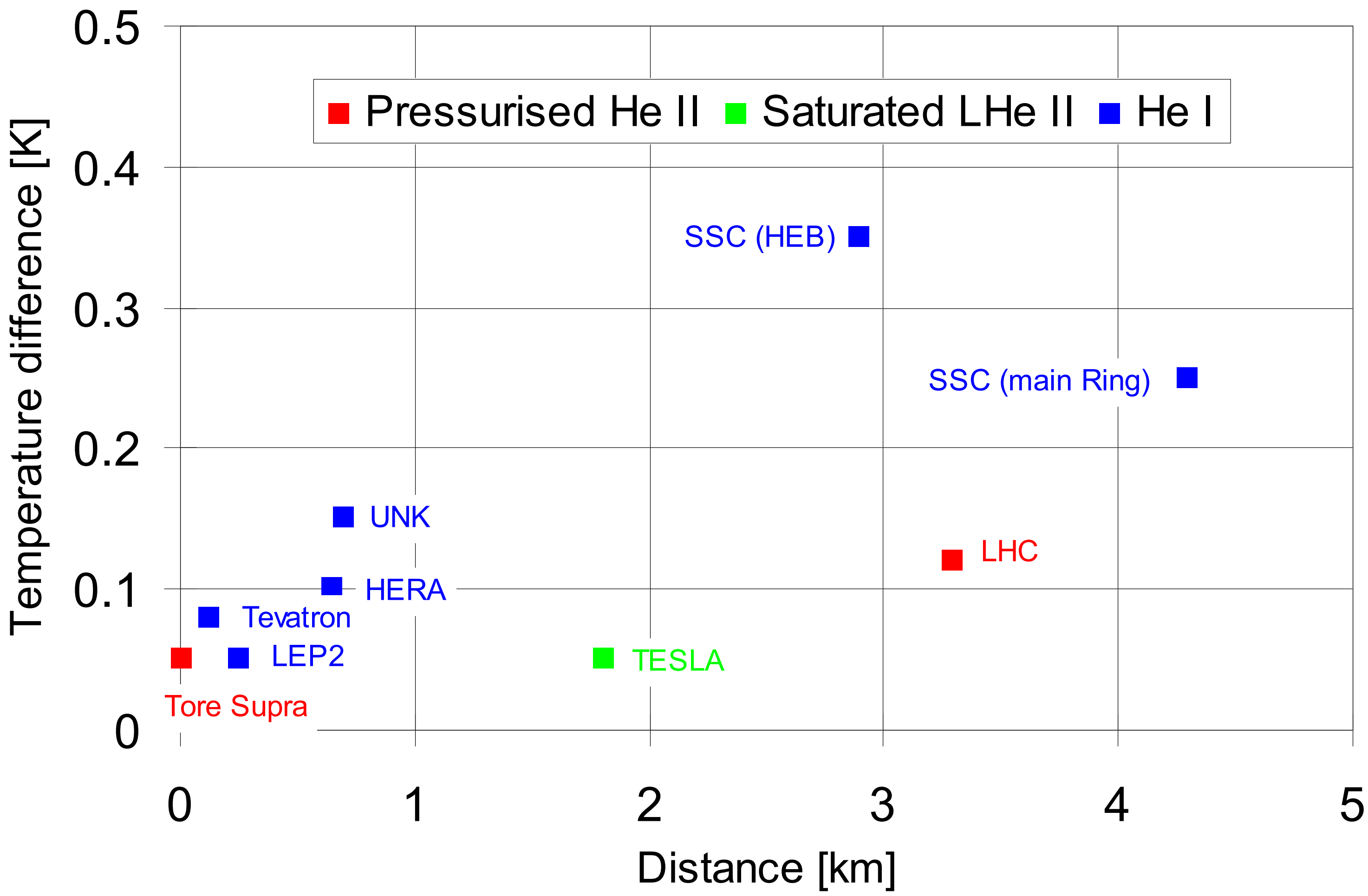
HTS vs. normal conducting current leads

Type		Resistive	HTS (4 to 50 K) Resistive (above)
Heat into LHe	[W/kA]	1.1	0.1
Total exergy consumption	[W/kA]	430	150
Electrical power from grid	[W/kA]	1430	500

For LHC, using HTS allowed to save the equivalent of 1 large 18kW@4.5K refrigerator !

Contents

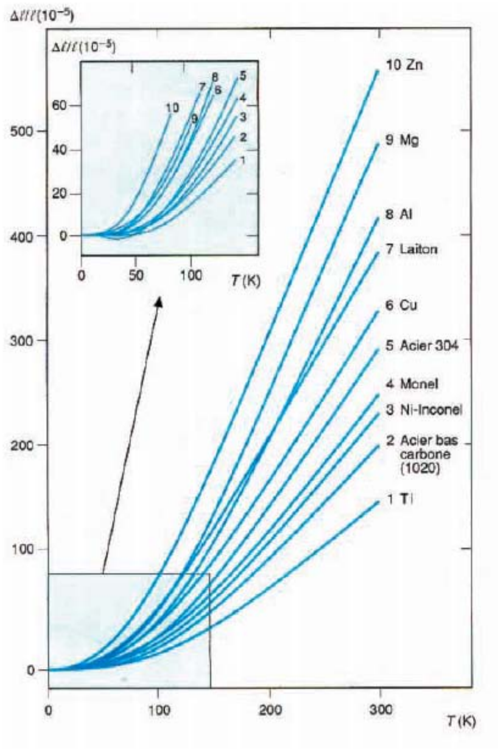
Transport of refrigeration in large distributed cryogenic systems



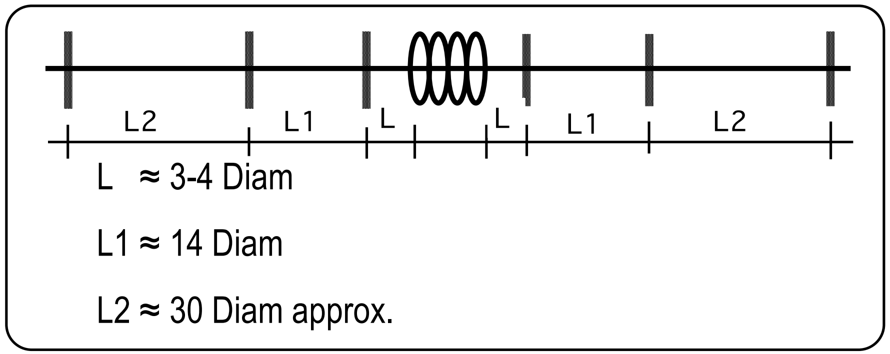
Cryogenic distribution scheme: design issues

- Monophase vs. two-phase
  - temperature control
  - hydrostatic head & flow instabilities
- Pumps vs. no pumps
  - efficiency & cost
  - reliability & safety
- LN_2
  - cooldown and/or normal operation
  - capital & operating costs of additional fluid
  - safety in underground areas (ODH)
- Lumped vs. distributed cryoplants
- Separate cryoline vs. integrated piping
- Number of active components (valves, actuators)
- Redundancy of configuration

Thermal contraction for cryo lines



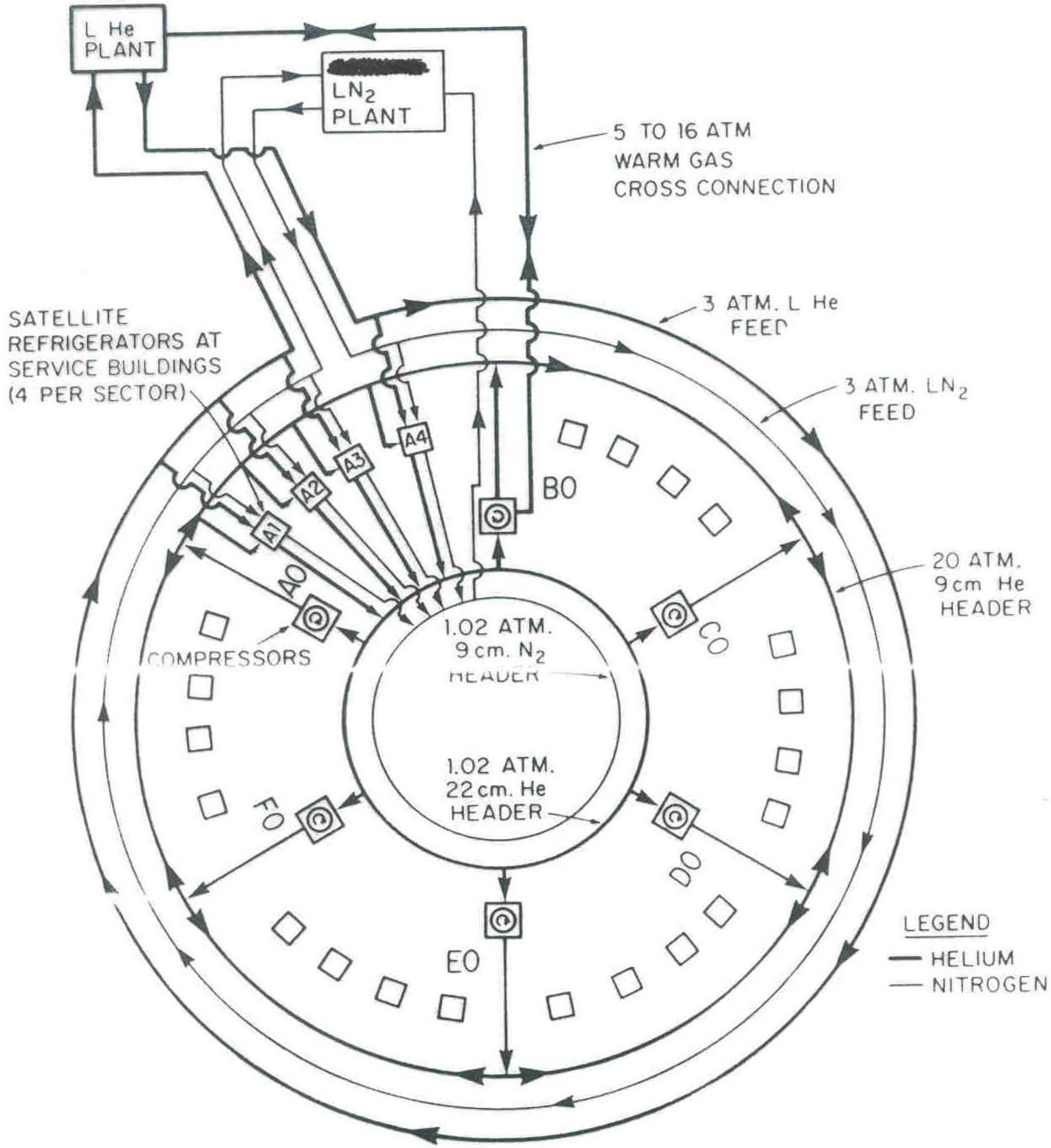
3 mm / m of thermal contraction
=> Compensation required !

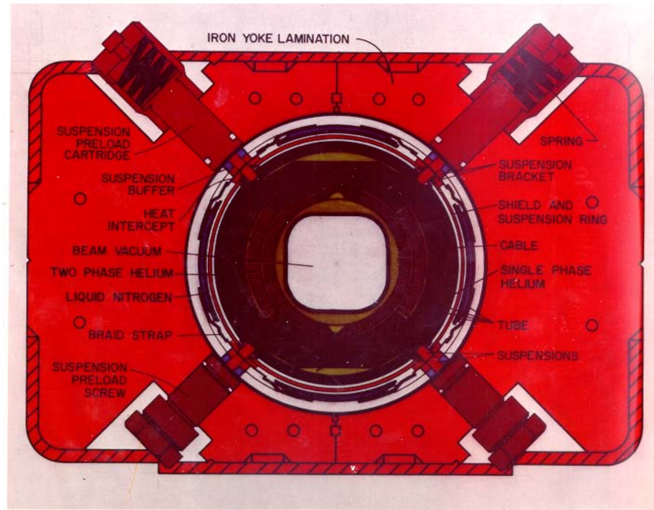


Thermal compensation

This is THE delicate part in the design of a cryogenic line, as thermal performance can only be considered once the line withstand mechanical forces !!!

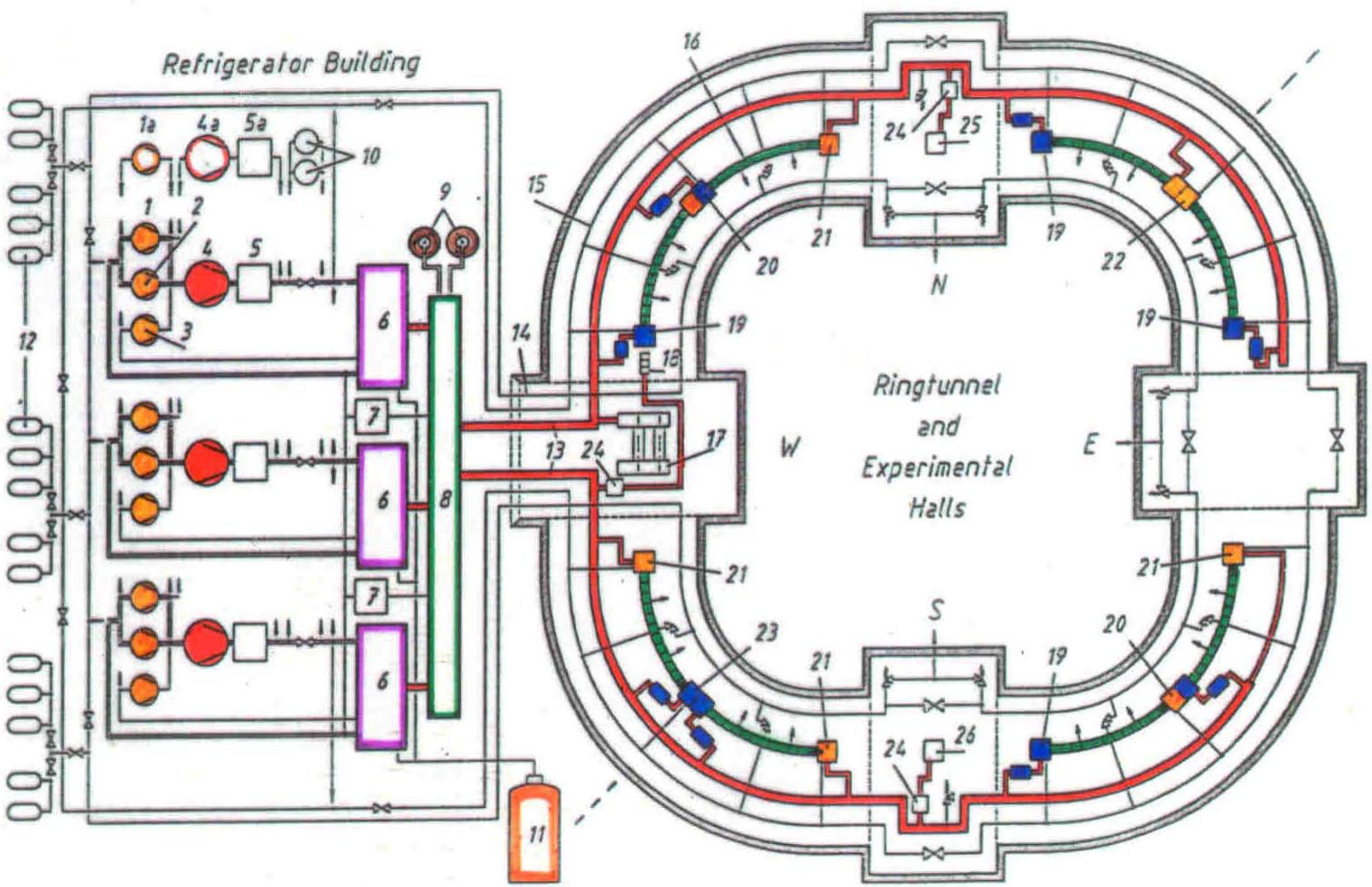
Tevatron distribution scheme



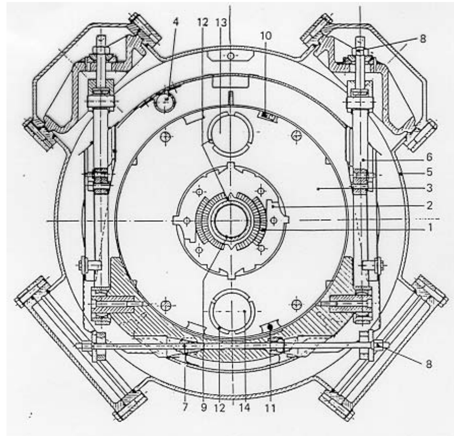


Central helium liquefier, separate ring cryoline and satellite refrigerators

HERA distribution scheme

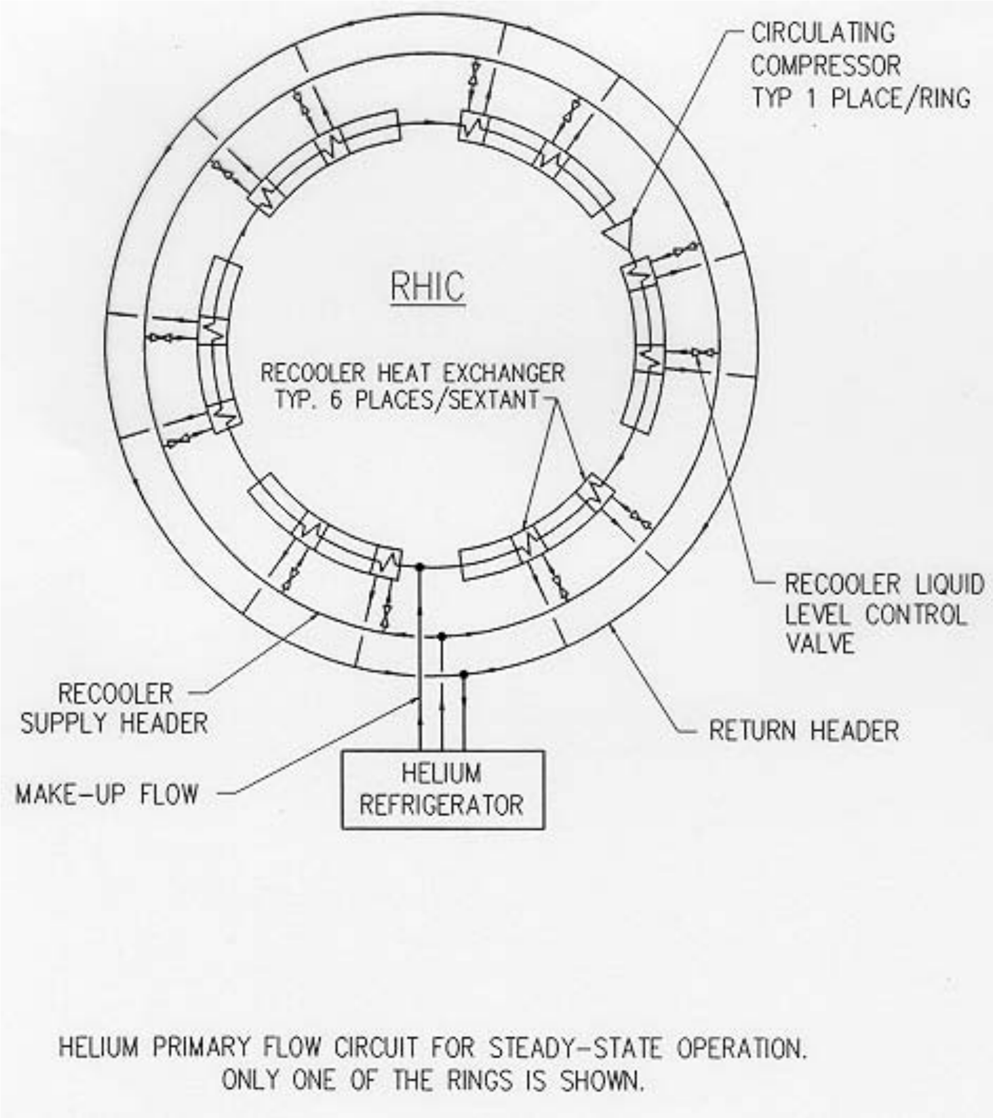


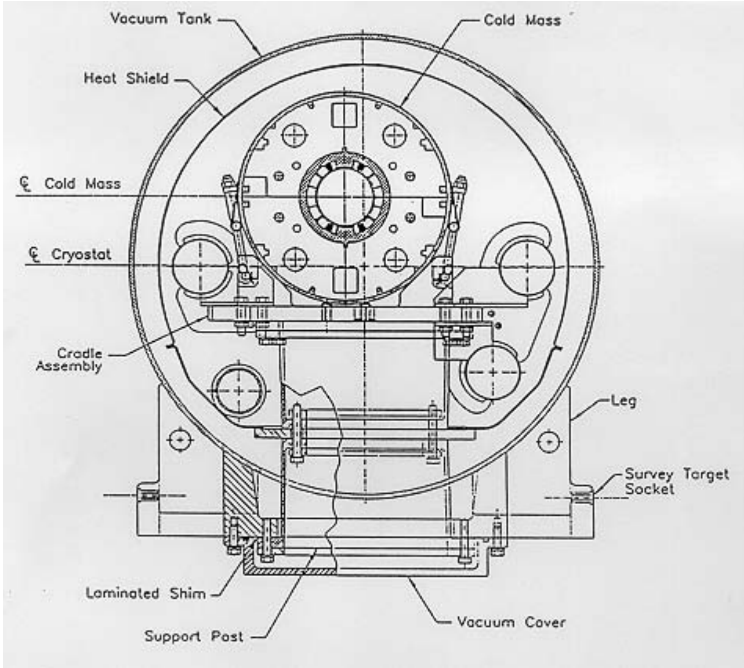
Refrigeration 4.3 K	6775 W	total mass flow	0.871 kg/s
Refrigeration 40/80 K	20000 W	Primary power	2845 kW
Current lead flow	20.5 x 10^{-3} kg/s	Specif. power consumption	281 W (300 K)/W (4.3 K)



Central cryoplant and separate ring cryoline

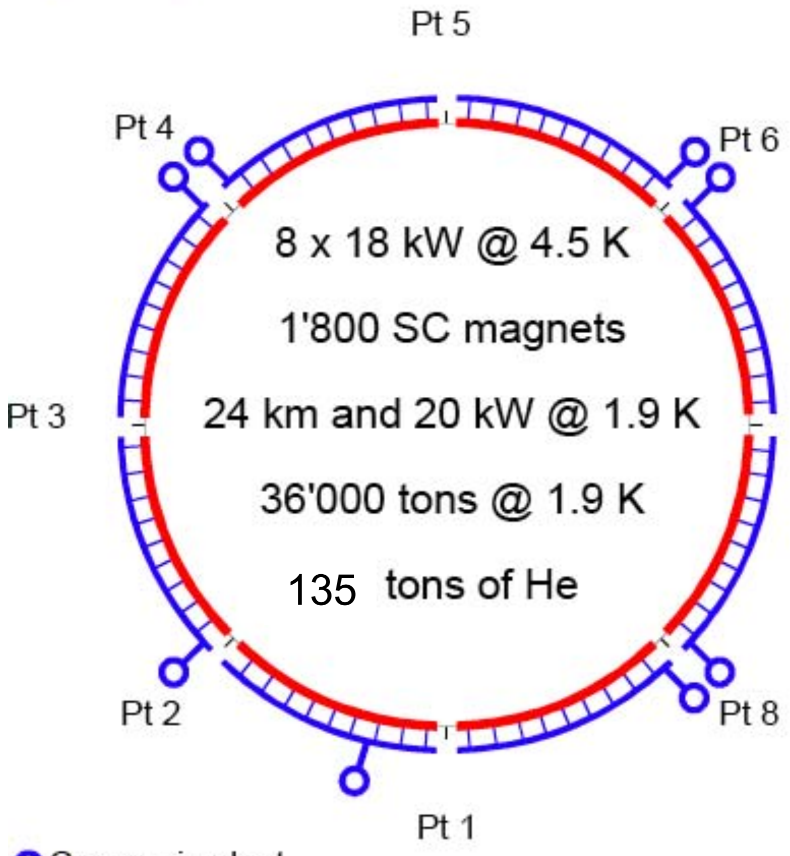
RHIC distribution scheme

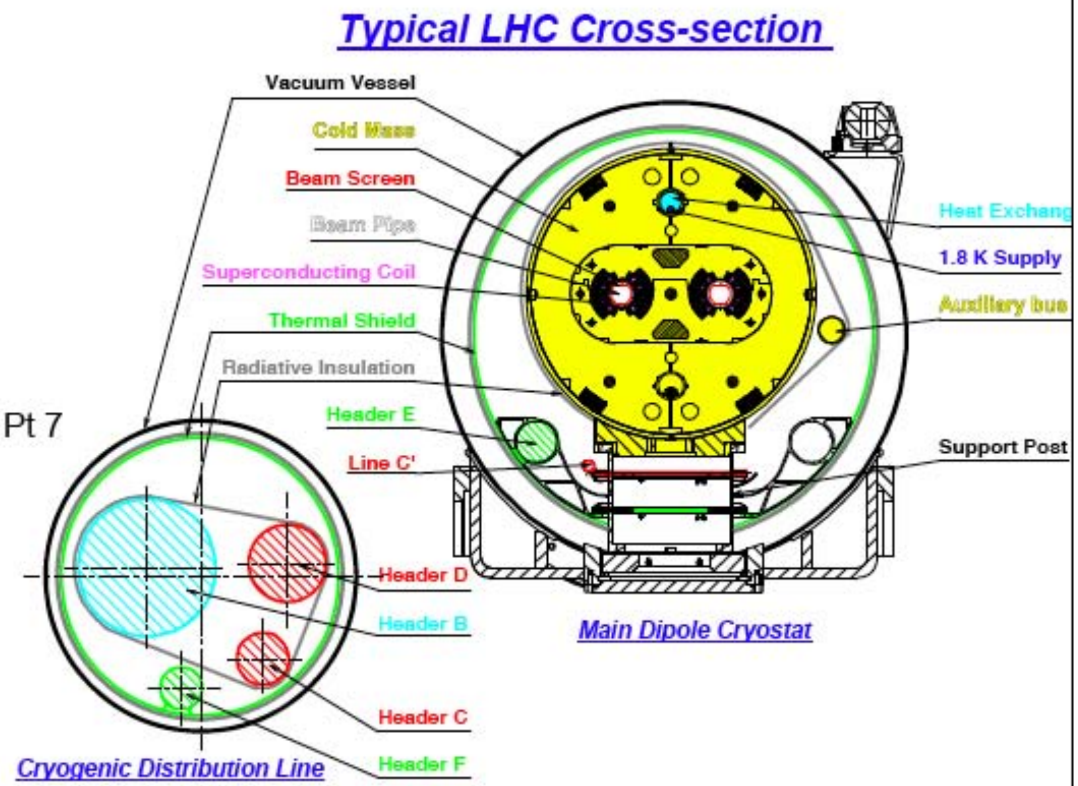




Central cryoplant and piping integrated in magnet cryostat

LHC distribution scheme



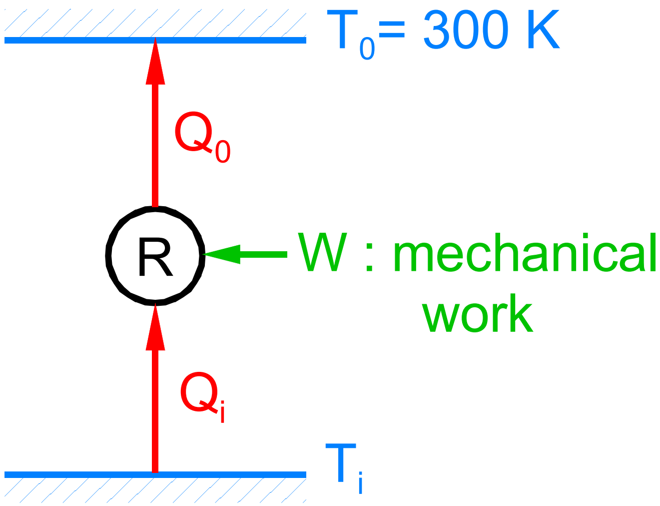


Cryoplants at five points,
separate ring cryoline,
107 m long strings

Superconducting Linac (Tesla_based)

Contents

Thermodynamics of cryogenic refrigeration



First principle [Joule] $Q_0 = Q_i + W$

Second principle [Clausius] $\frac{Q_0}{T_0} \geq \frac{Q_i}{T_i}$

(= for reversible process)

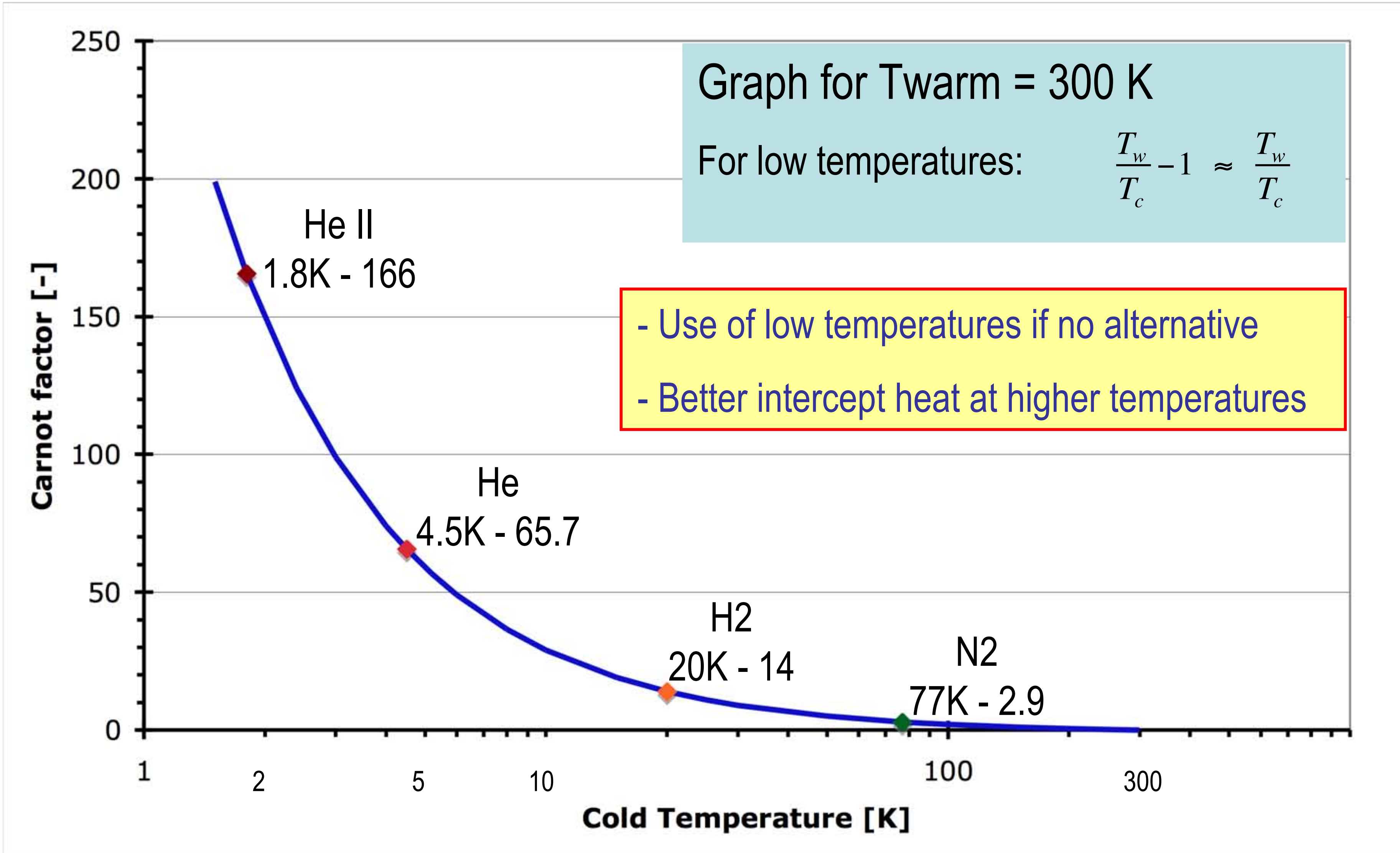
Hence, $W \geq T_0 \cdot \frac{Q_i}{T_i} - Q_i$ which can be written in three different ways:

① $W \geq T_0 \cdot \ddot{A}S_i - Q_i$ introducing entropy S as $\ddot{A}S_i = \frac{Q_i}{T_i}$

② $W \geq Q_i \cdot \left(\frac{T_0}{T_i} - 1\right)$ ← Carnot factor

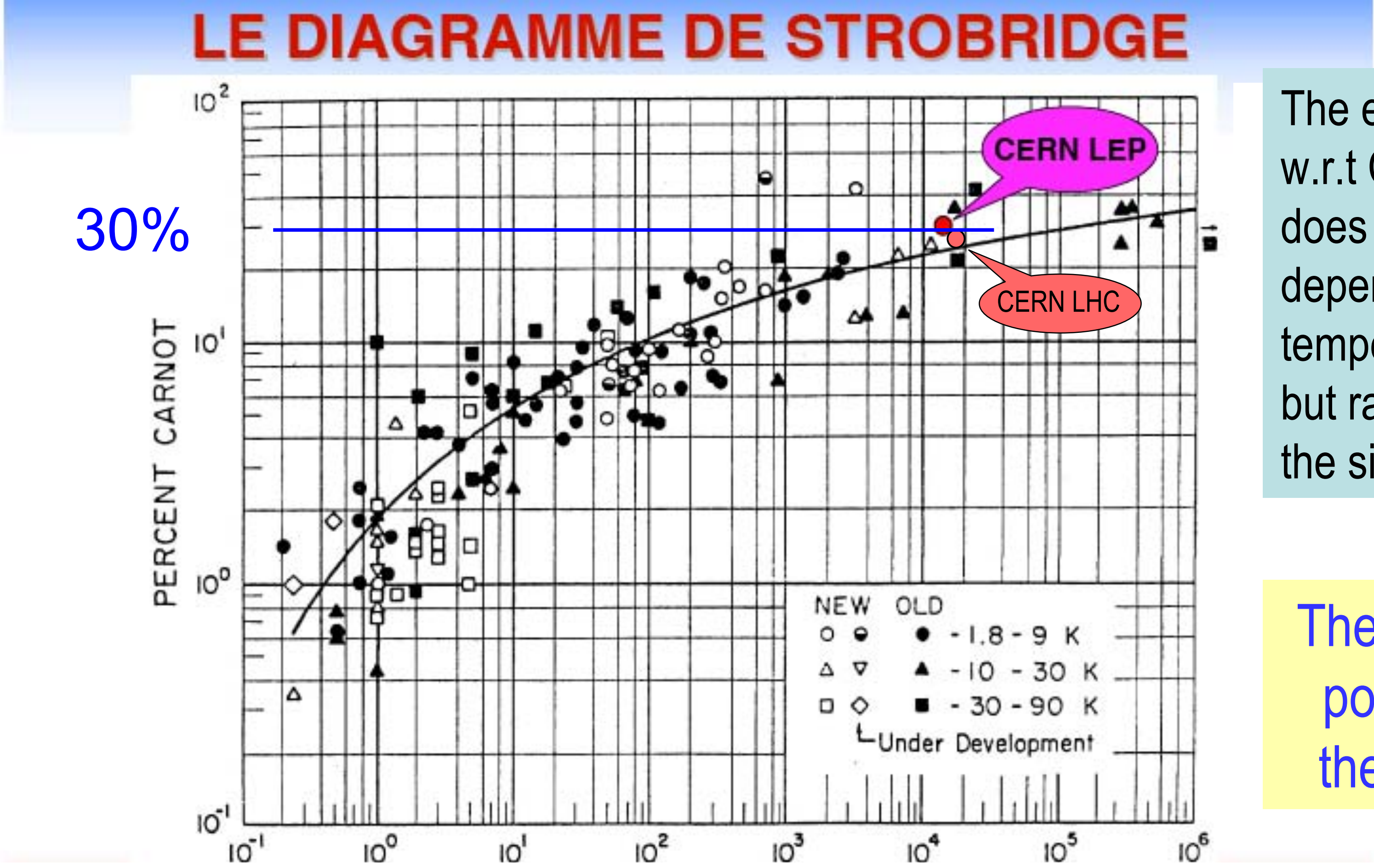
③ $W \geq \ddot{A}E_i$ introducing exergy E as $\ddot{A}E_i = Q_i \cdot \left(\frac{T_0}{T_i} - 1\right)$

The Carnot Factor



Helium refrigerators

Power Input ≈ Power@cold x Carnot / %w.r.tCarnot



Capacity [Watts]

The efficiency w.r.t Carnot does not depend on the temperature, but rather on the size

The largest possible, the best !

Minimum refrigeration work

Consider the extraction of 1 W at 4.5 K, rejected at 300 K
The minimum refrigeration work (equation 2) is:

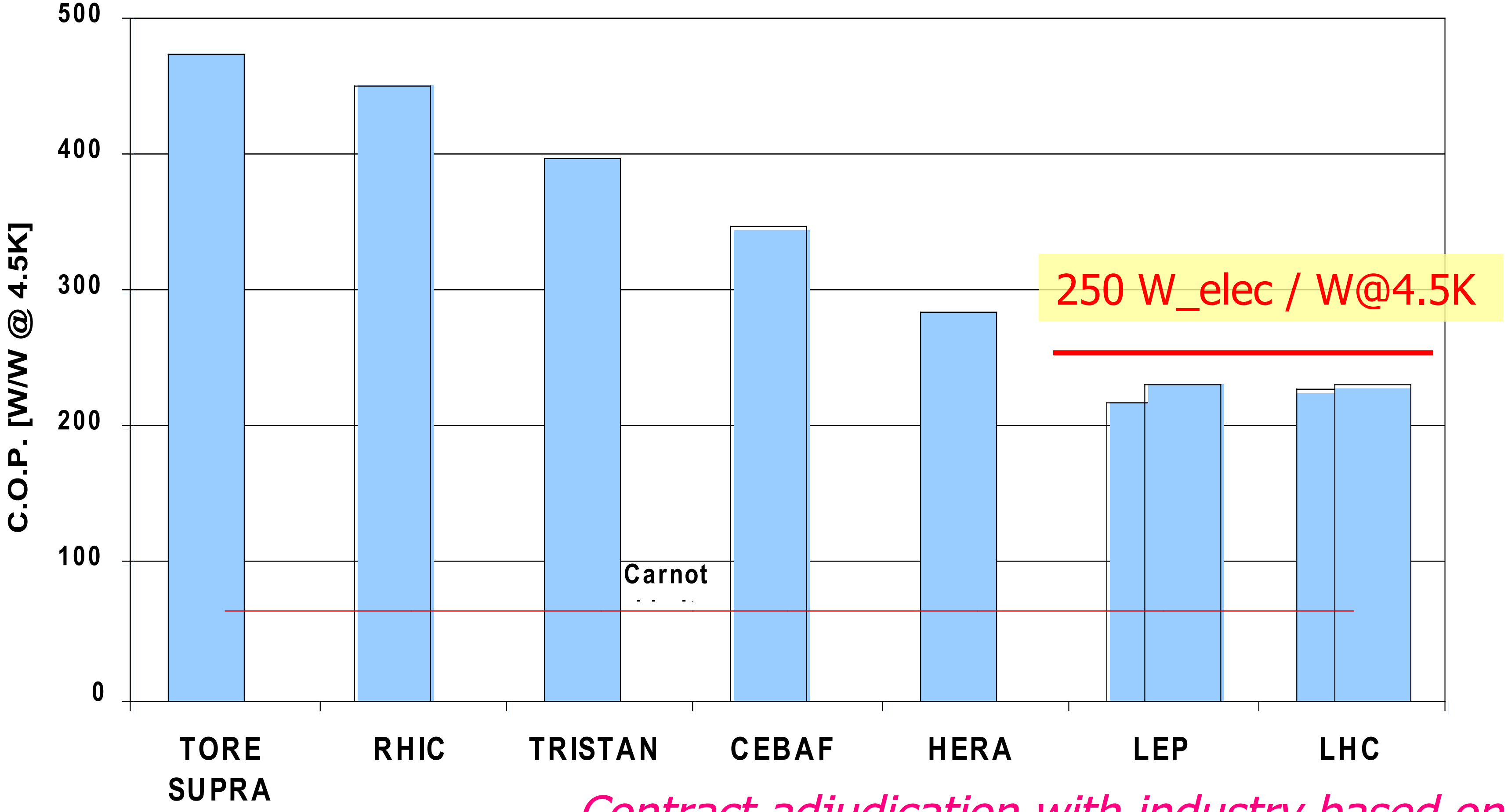
$$W_{min} = Q_i \cdot \left(\frac{T_0}{T_i} - 1 \right) = 1 \cdot \left(\frac{300}{4.5} - 1 \right) = 65.7 \ \ W$$

In practice, the most efficient helium refrigerators have an efficiency of about 30% w.r. to the Carnot limit.

$$\Rightarrow \ W_{real} = \frac{W_{min}}{ç} = \frac{65.7}{0.3} = 220 \ \ W$$

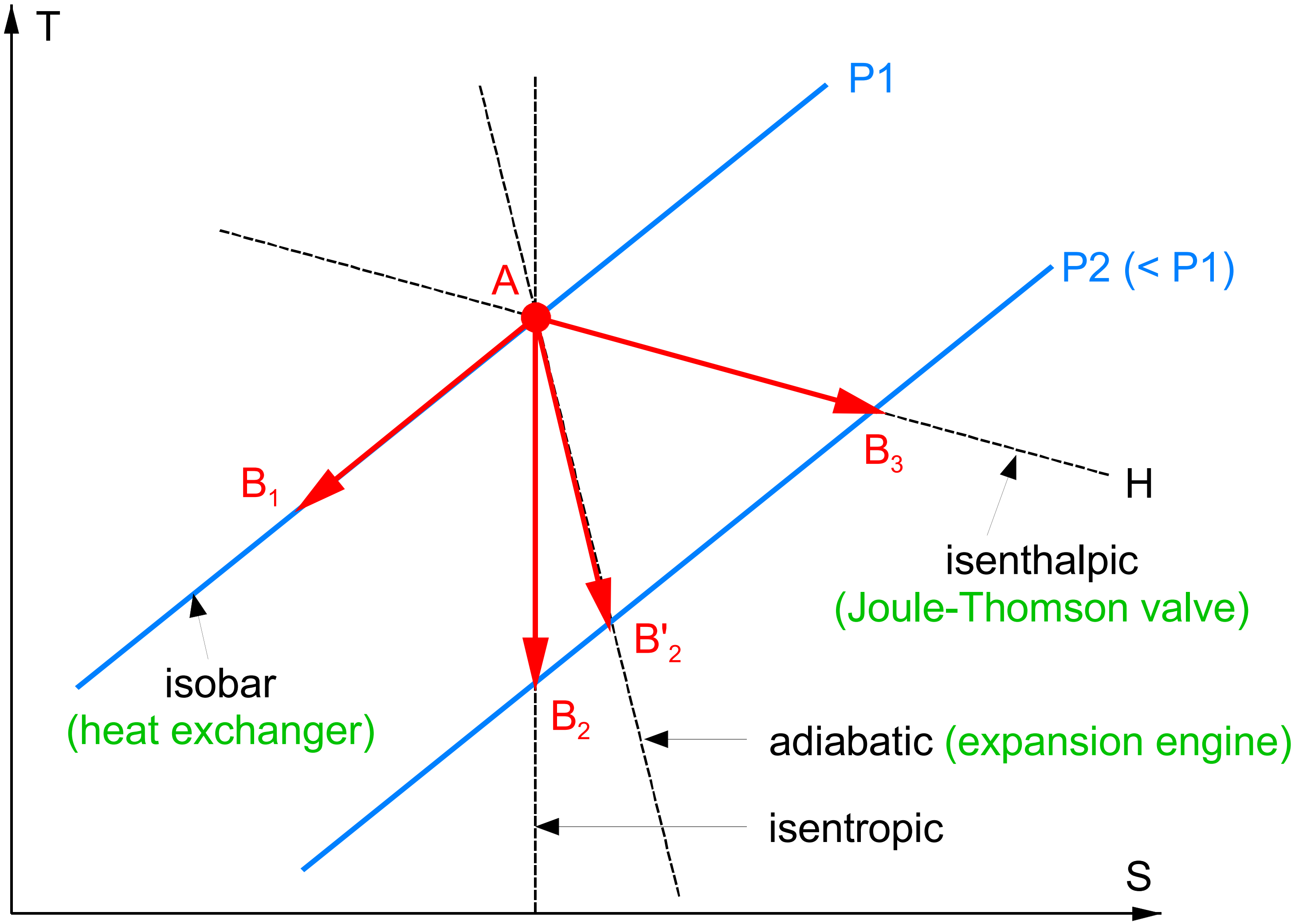
C.O.P. of large cryogenic helium refrigerators

Time (left to right) is not the only factor for improvement

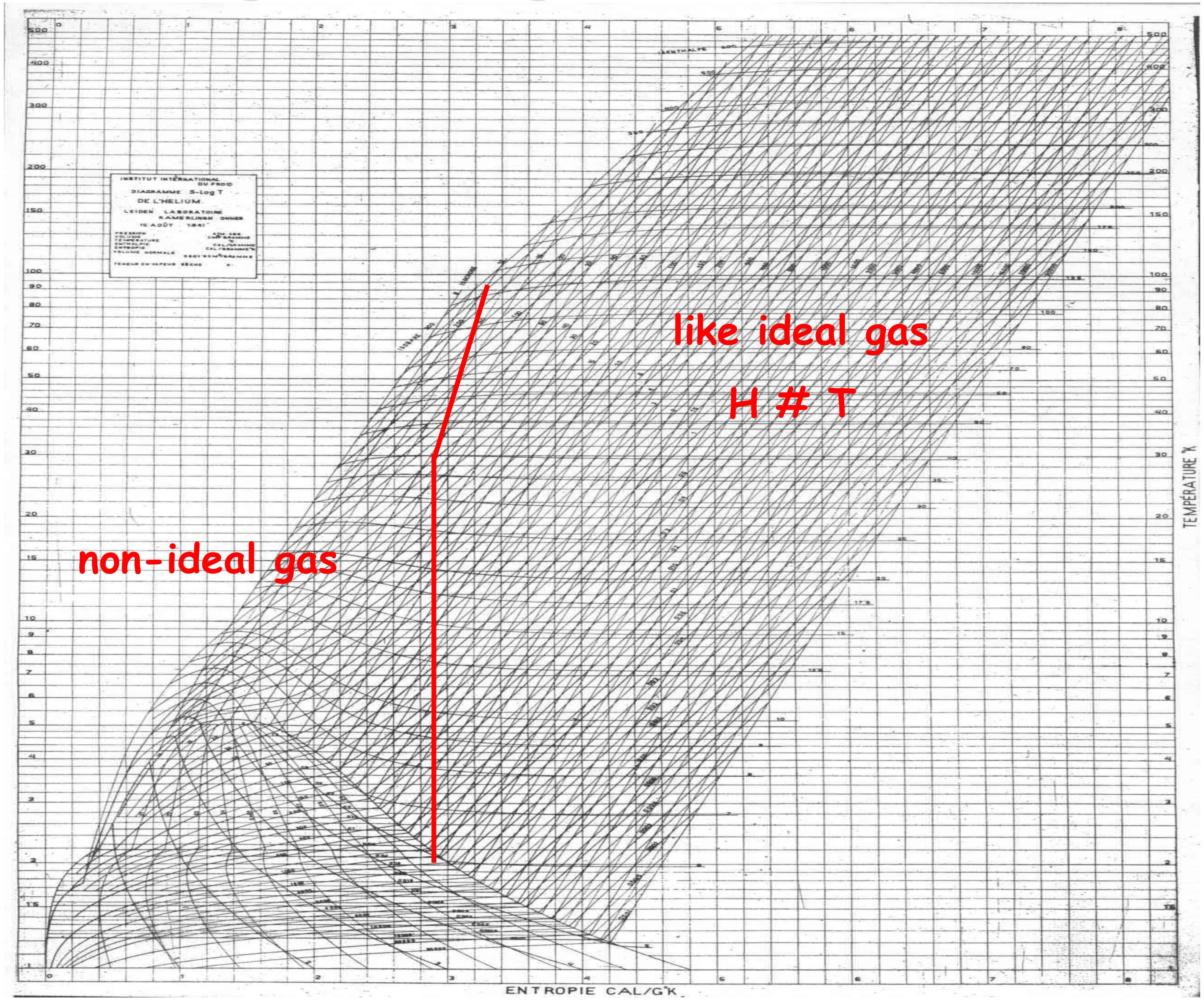


Contract adjudication with industry based on Capital+Operation(10yrs) costs

Elementary cooling processes on T-S diagram



Log T-s Diagram for Helium

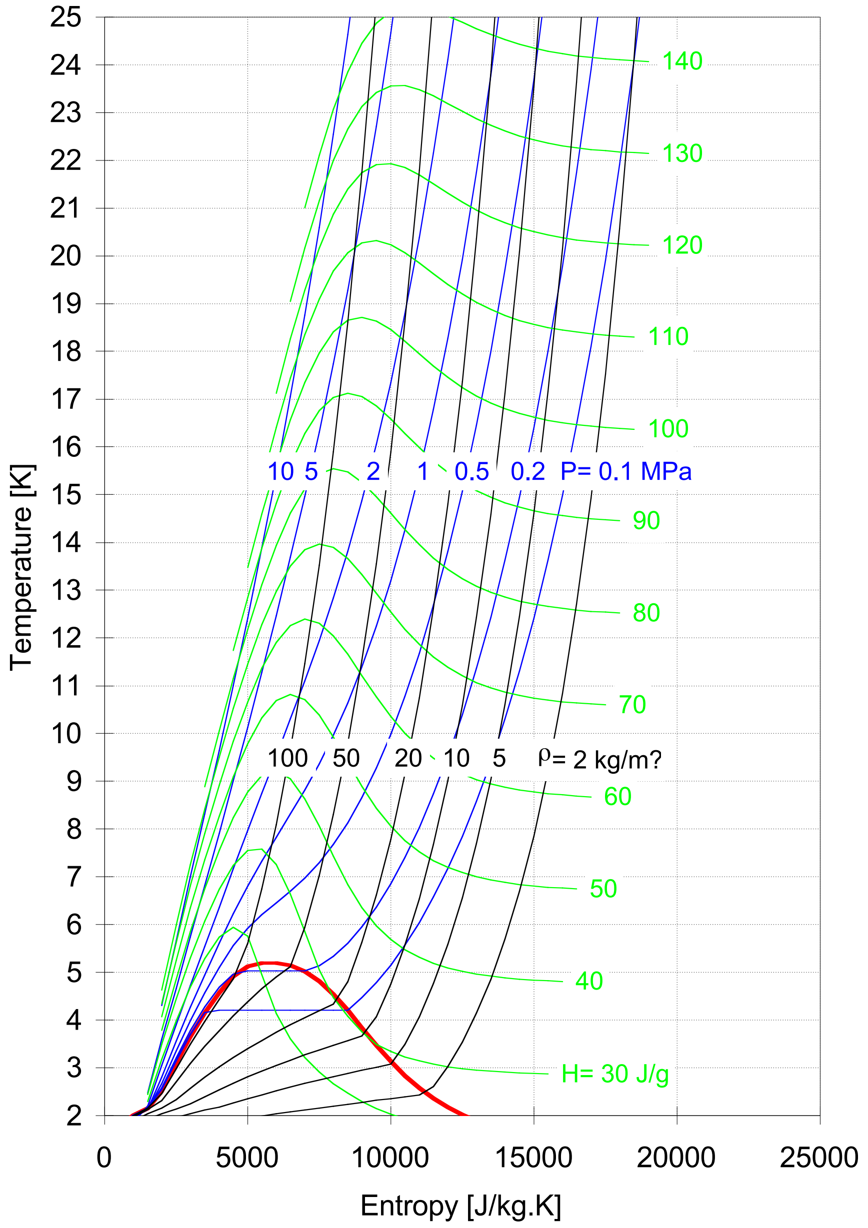


Maximum Joule-Thomson inversion temperatures

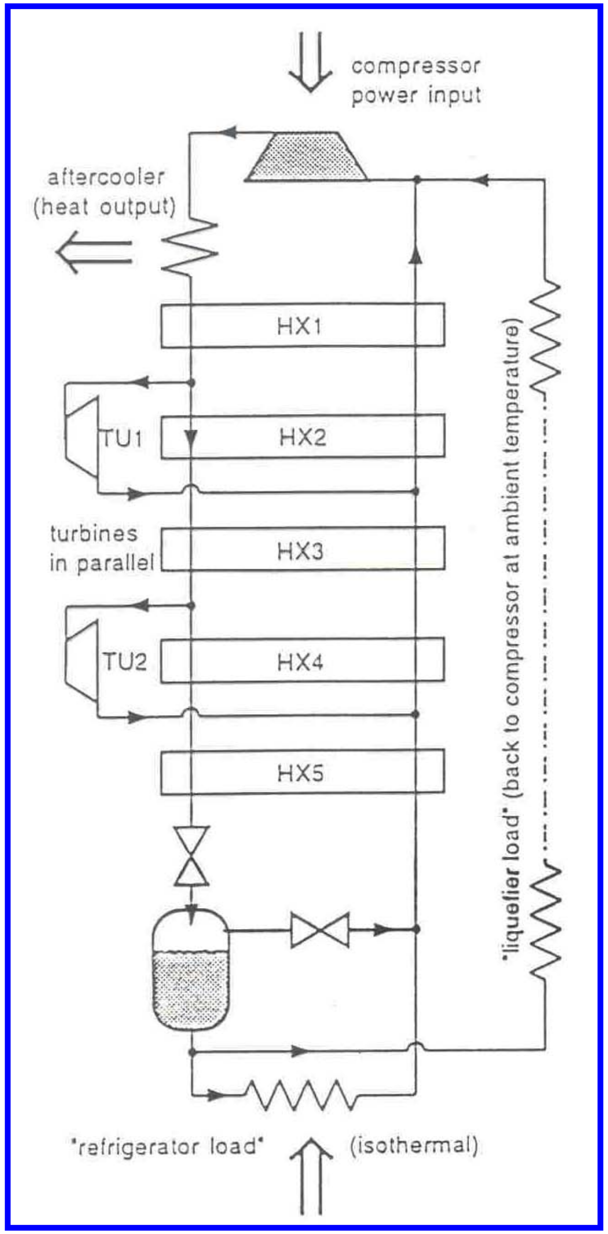
Cryogen	Maximum inversion temperature [K]
Helium	43
Hydrogen	202
Neon	260
Air	603
Nitrogen	623
Oxygen	761

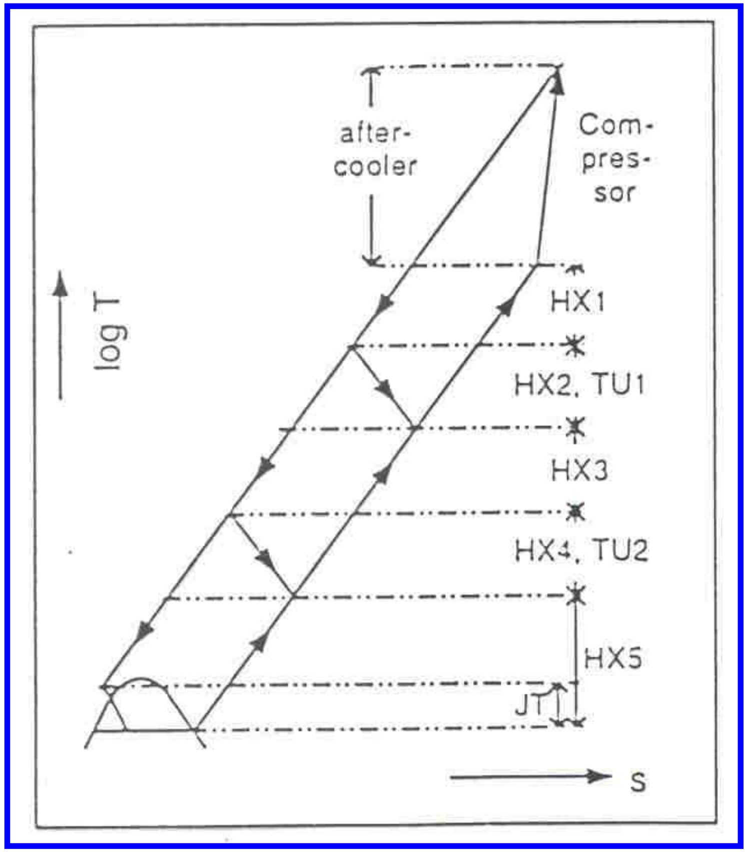
While air can be cooled down and liquefied by JT expansion from room temperature, helium and hydrogen need precooling down to below inversion temperature by heat exchange or work-extracting expansion (e.g. in turbines)

T-S diagram for helium (non-ideal part)

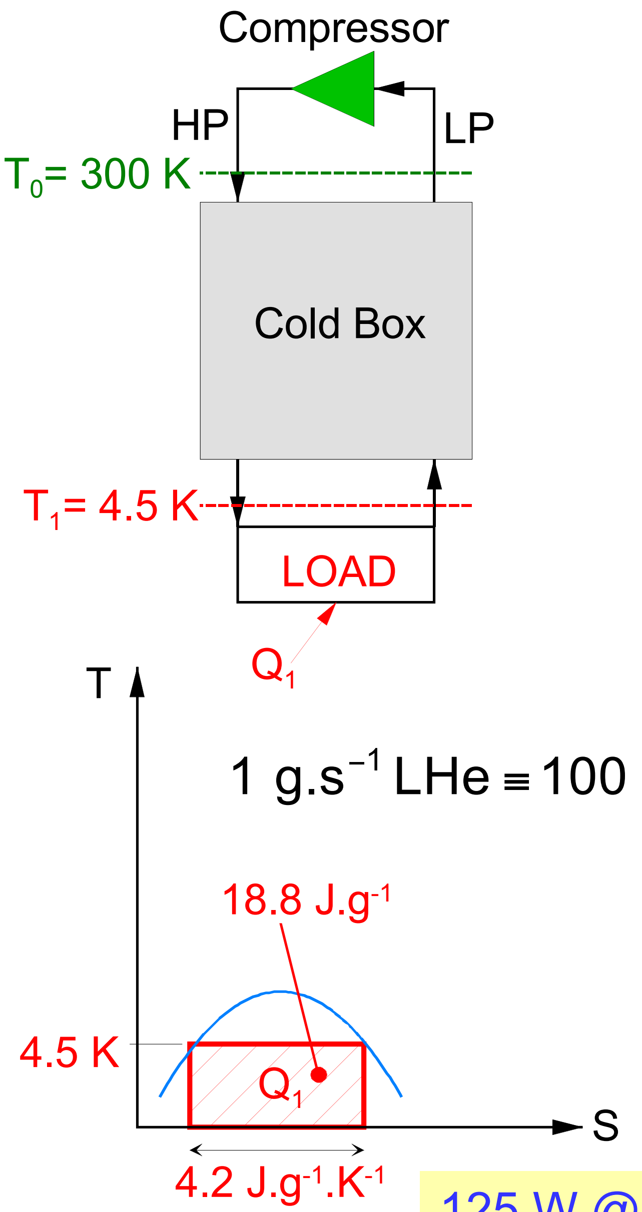


Two-stage Claude cycle

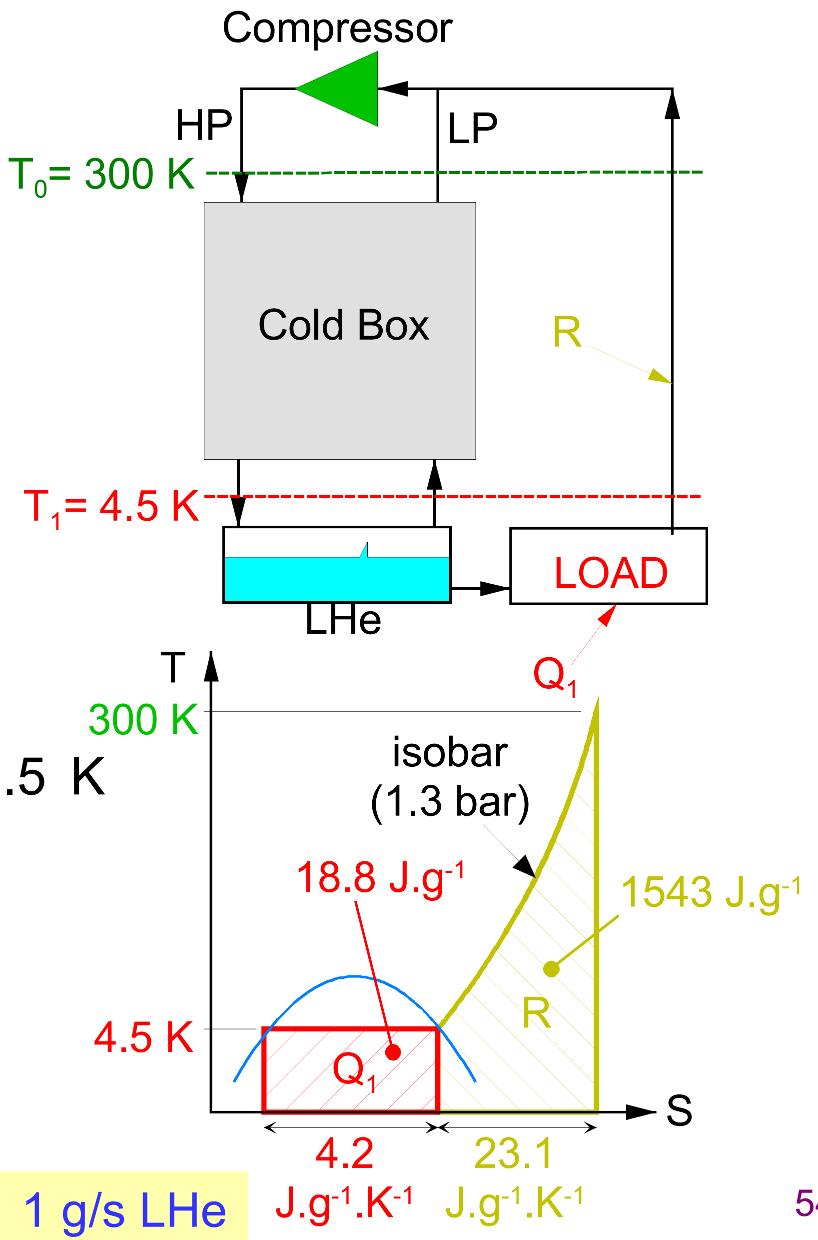




Refrigerator



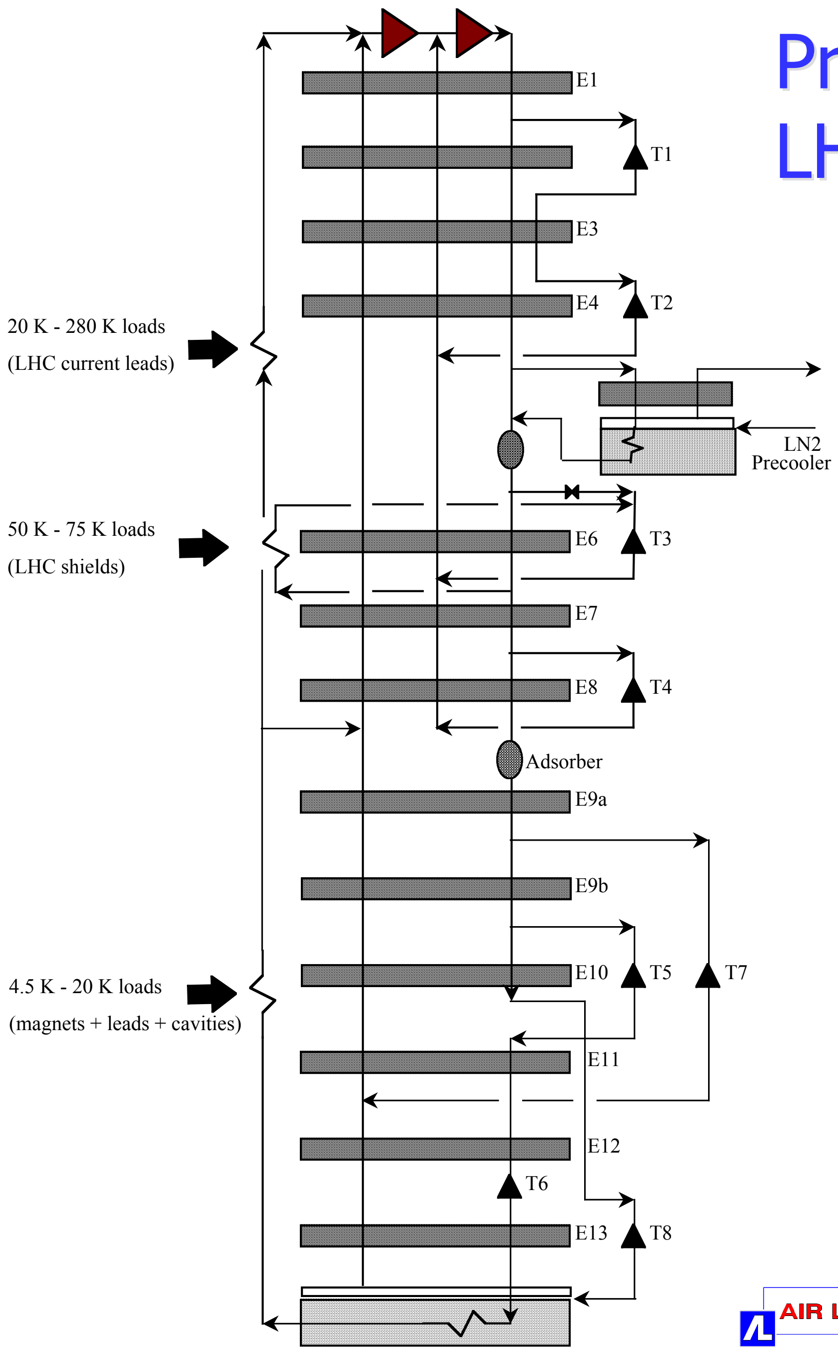
Liquefier

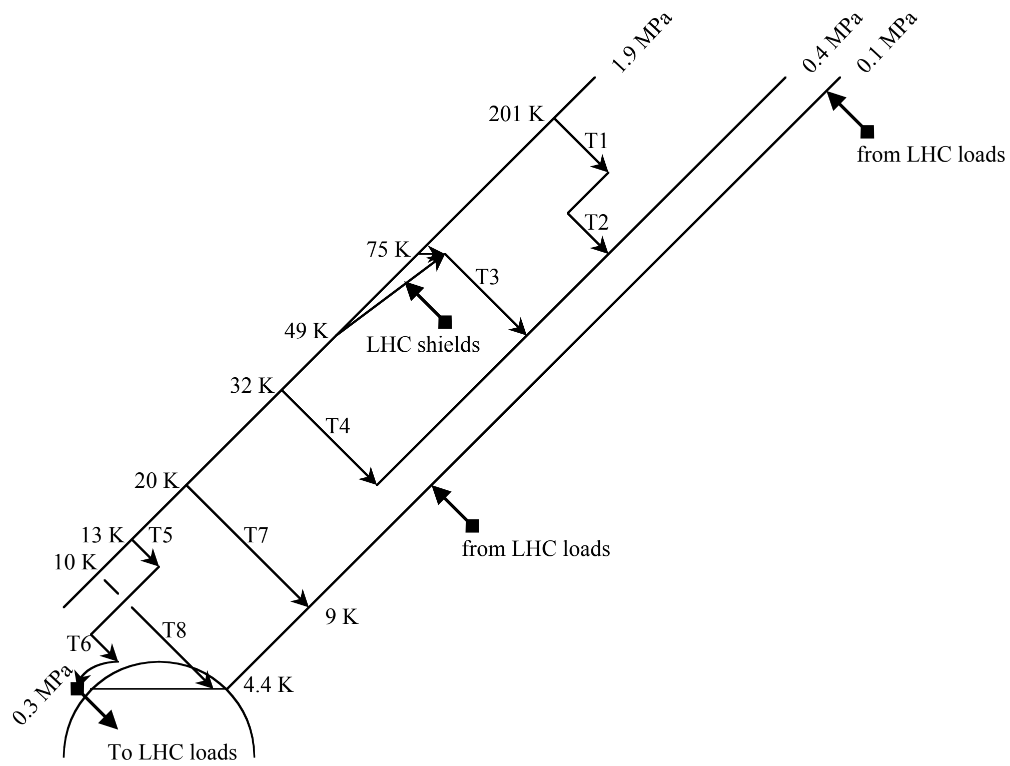


$$1\ \text{g.s}^{-1}\ \text{LHe} \equiv 100\ \ \text{W @ 4.5 K}$$

125 W @ 4.5K ≈ 1 g/s LHe

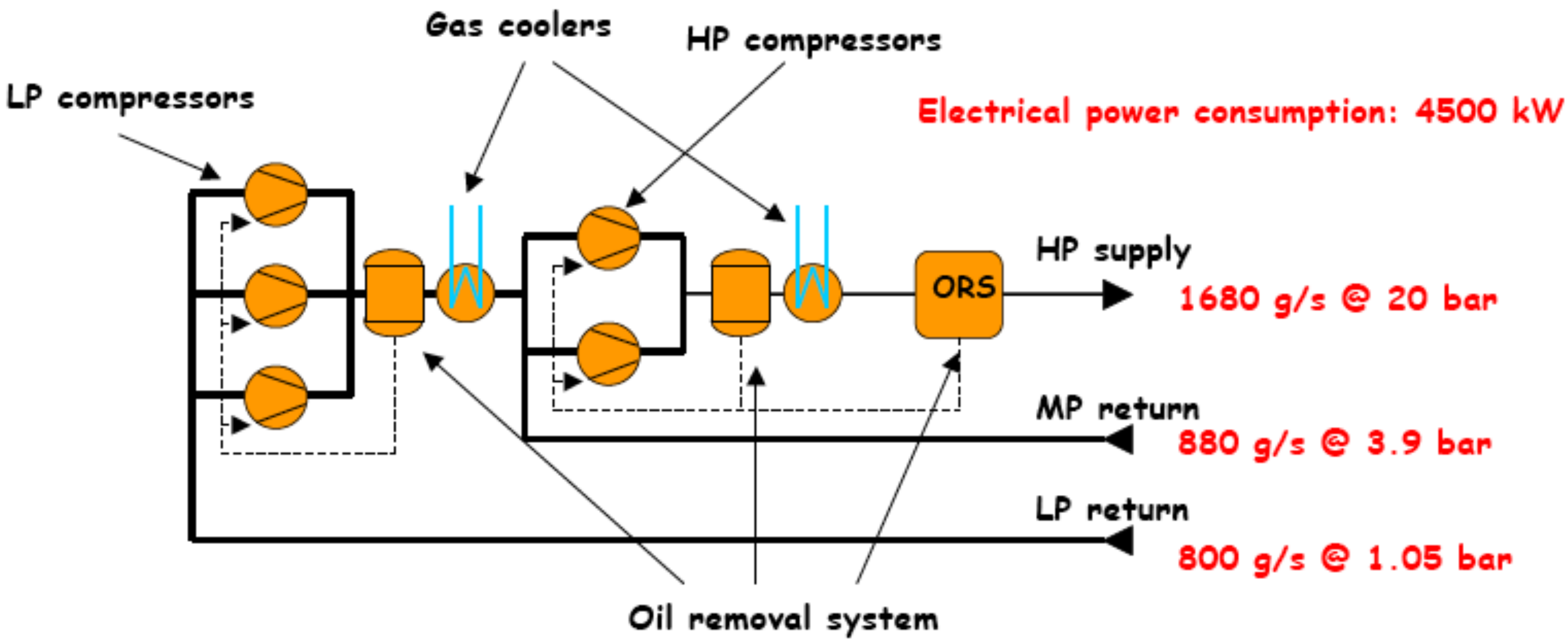
Process cycle & T-S diagram of LHC 18 kW @ 4.5 K cryoplant





Process diagram, LHC compressors 18 kW @ 4.5 K

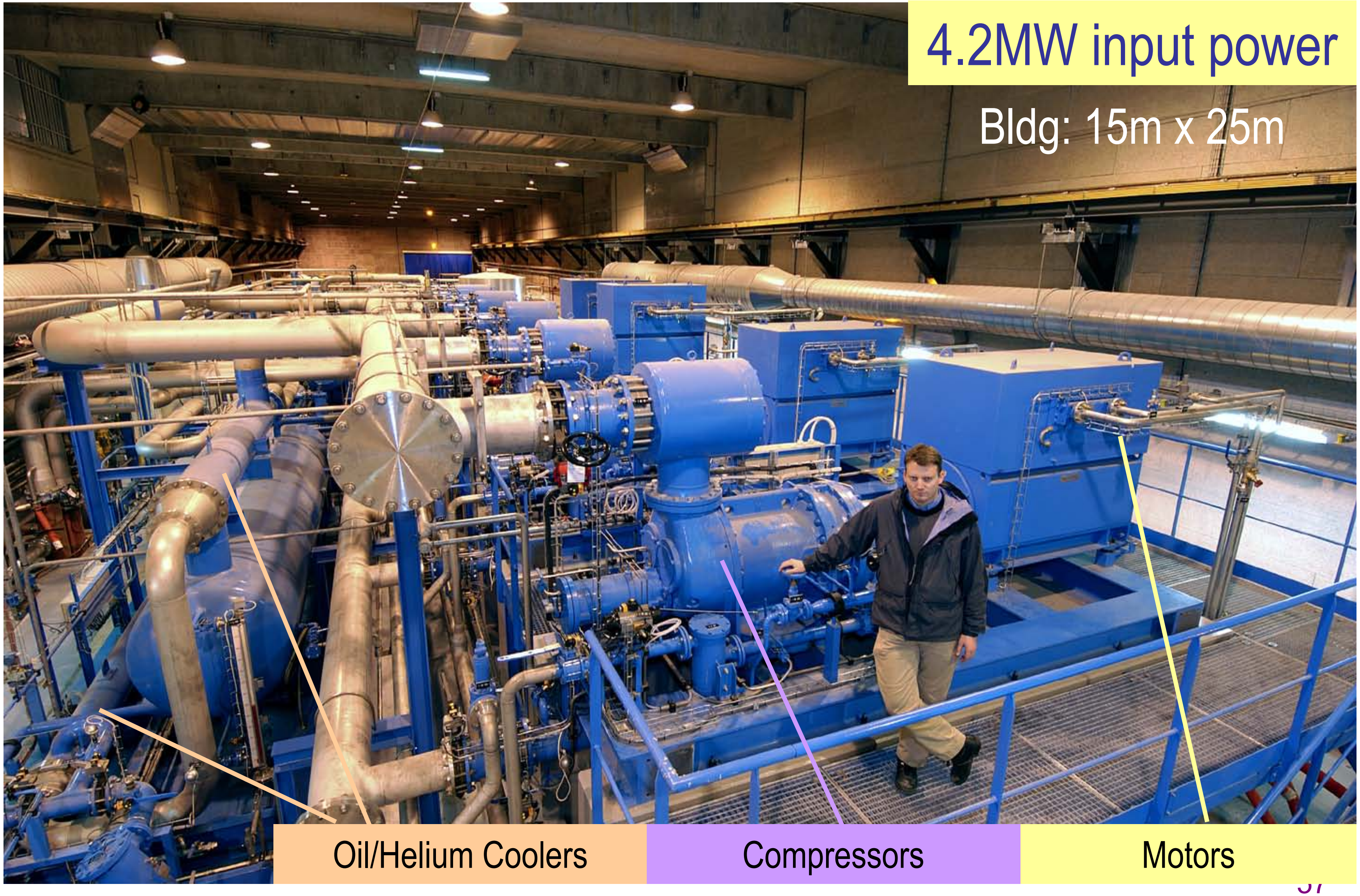
Oil lubricated screw compressors, water cooled, oil separation included



Machine derived from industrial refrigeration (or compressed air)

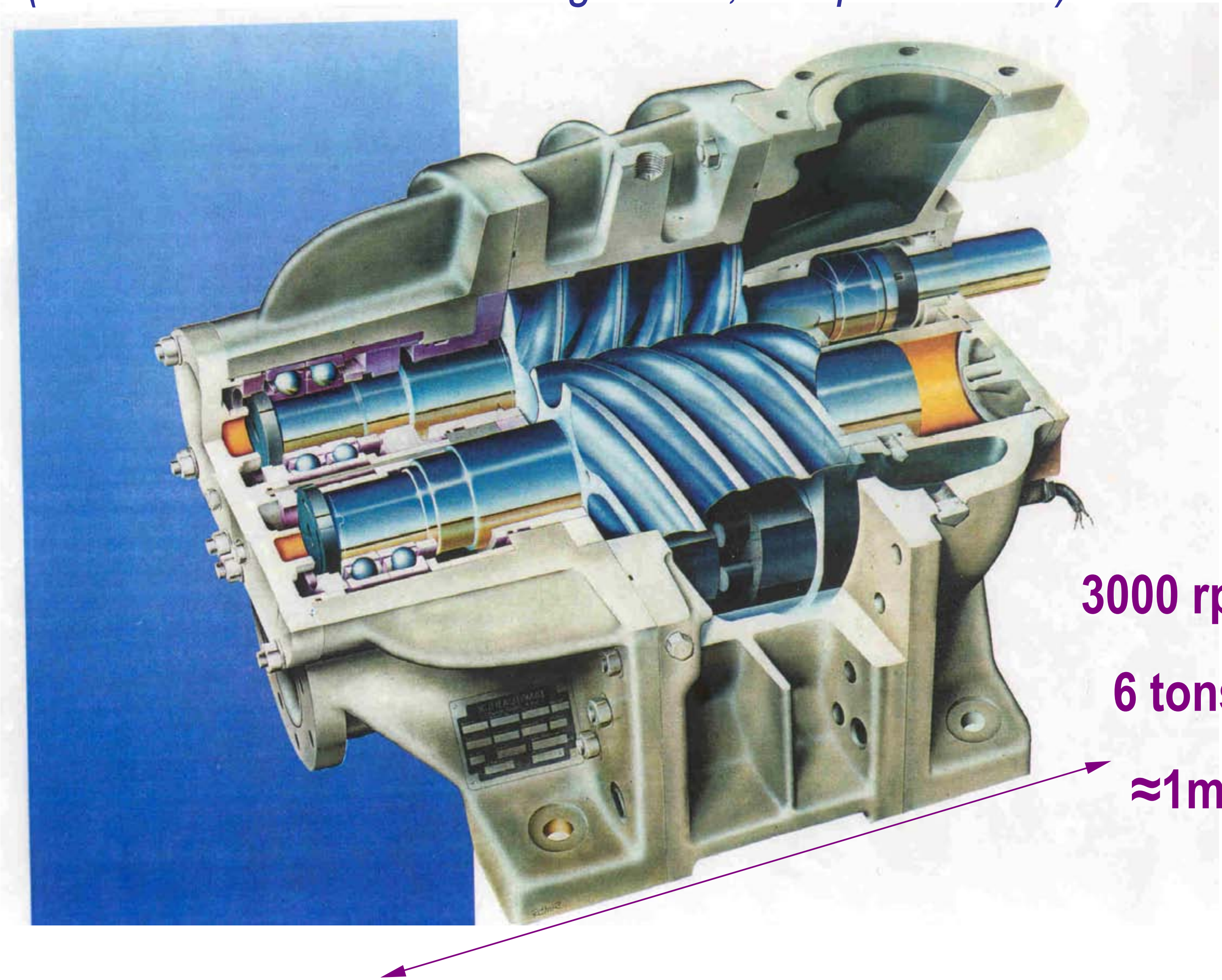
No more piston (high PR, low flow), not yet centrifugal (high flow, low PR)

Compressor station
of LHC 18 kW@ 4.5 K helium refrigerator



Oil-injected screw compressor

(derived from Industrial refrigeration, compressed air)

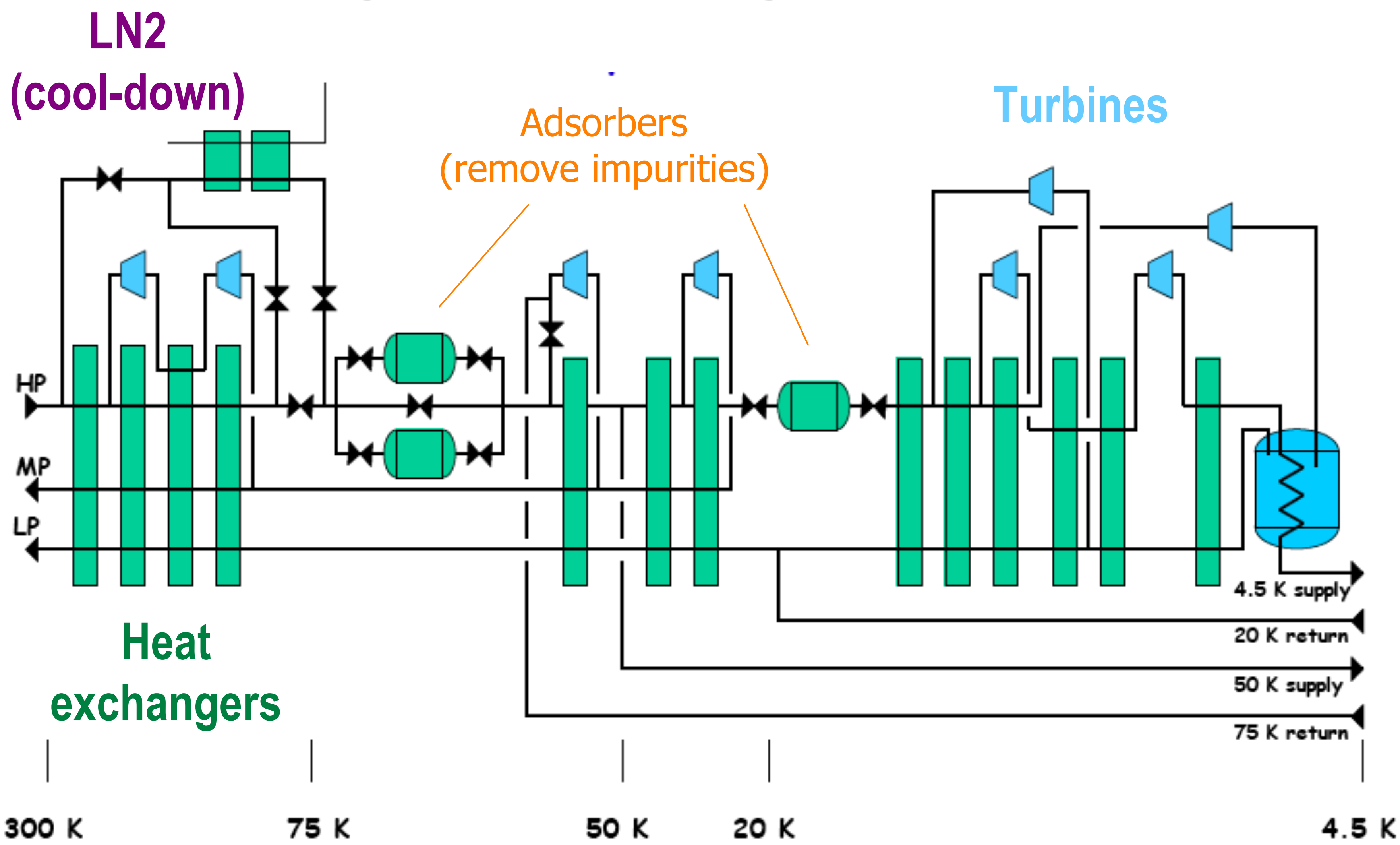


3000 rpm

6 tons

≈1m

Process diagram, LHC refrigerator 18 kW @ 4.5 K



LHC 18 kW @ 4.5 K helium cryoplants

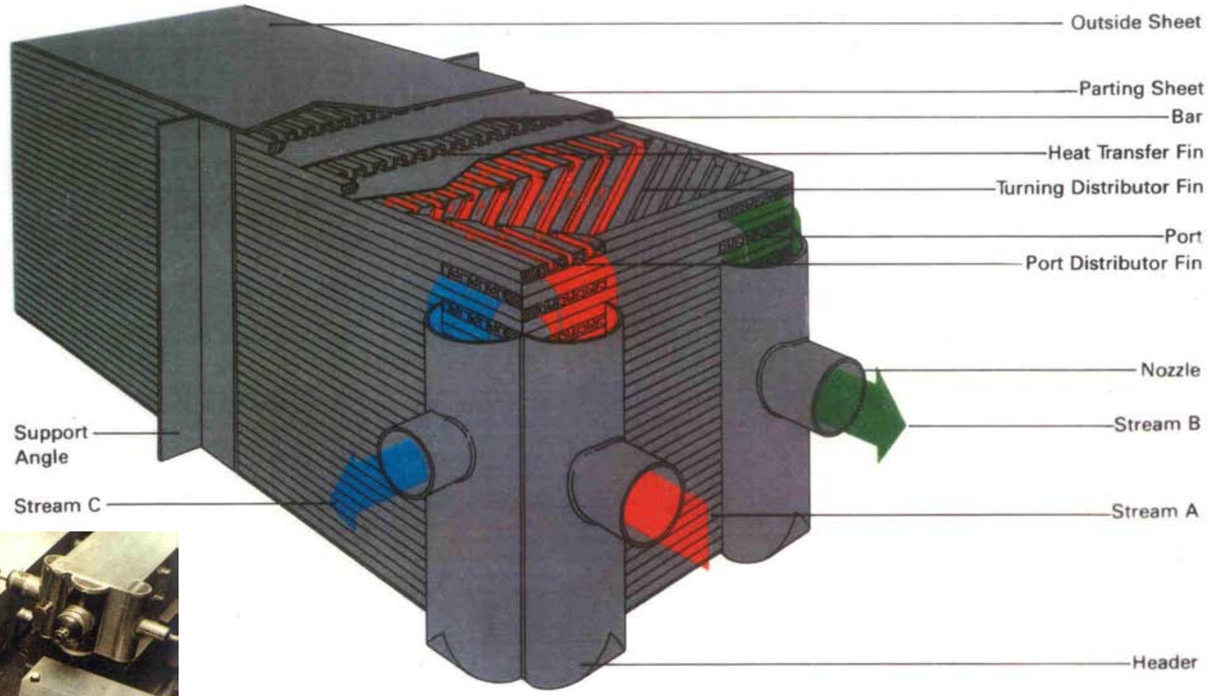
33 kW @ 50 K to 75 K, 23 kW @ 4.6 K to 20 K, 41 g/s liquefaction

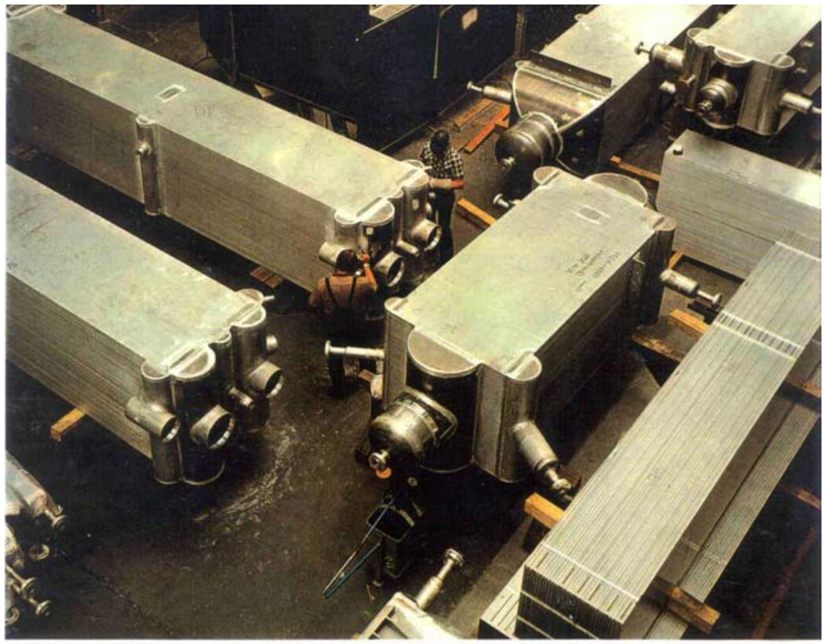
Diameter: 4 m
Length: 20 m
Weigth: 100 tons
600 Input/Output signals

Air Liquide

Linde

Brazed aluminium plate heat exchanger



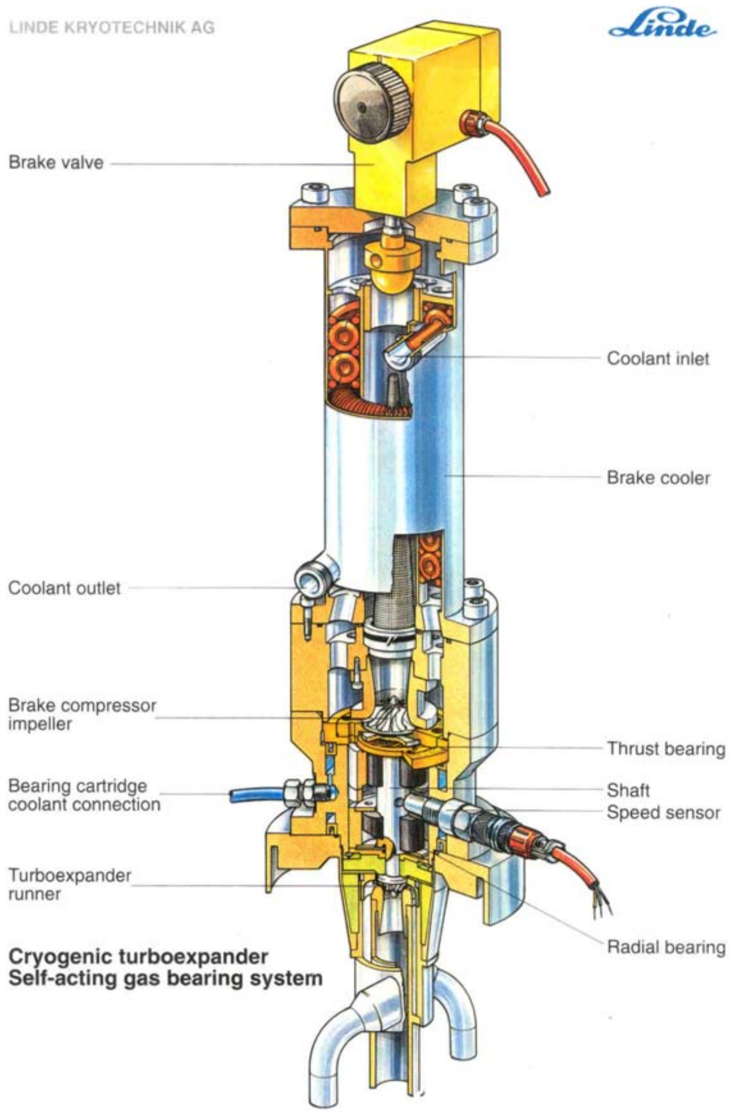


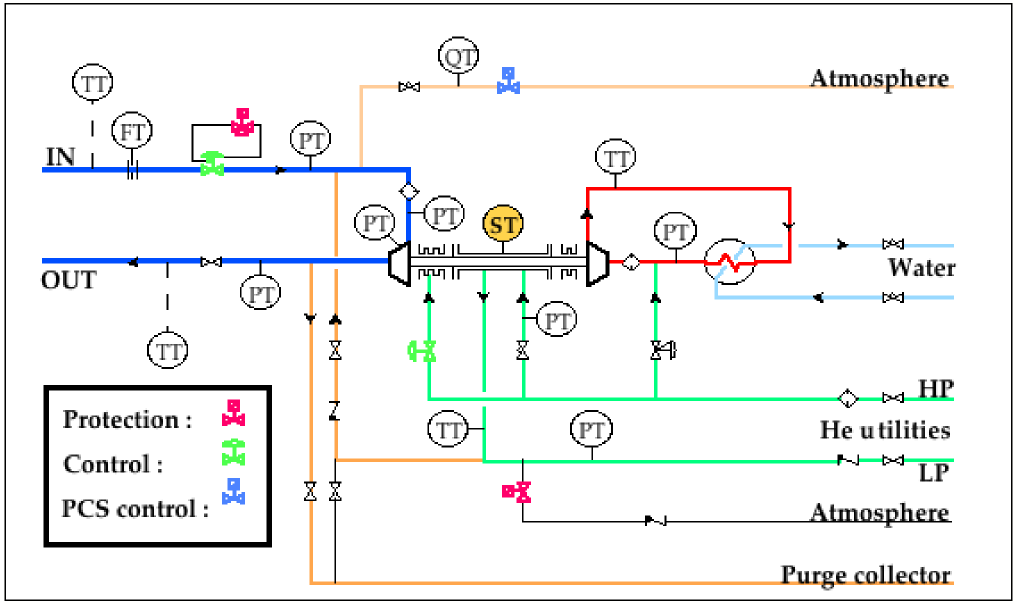
Largest used: 1.4 m x 1.4 m x 8 m

(10 tons)

Cryogenic turbo-expander

Specific technology "contact free" gas bearings operated at 120'000 rpm



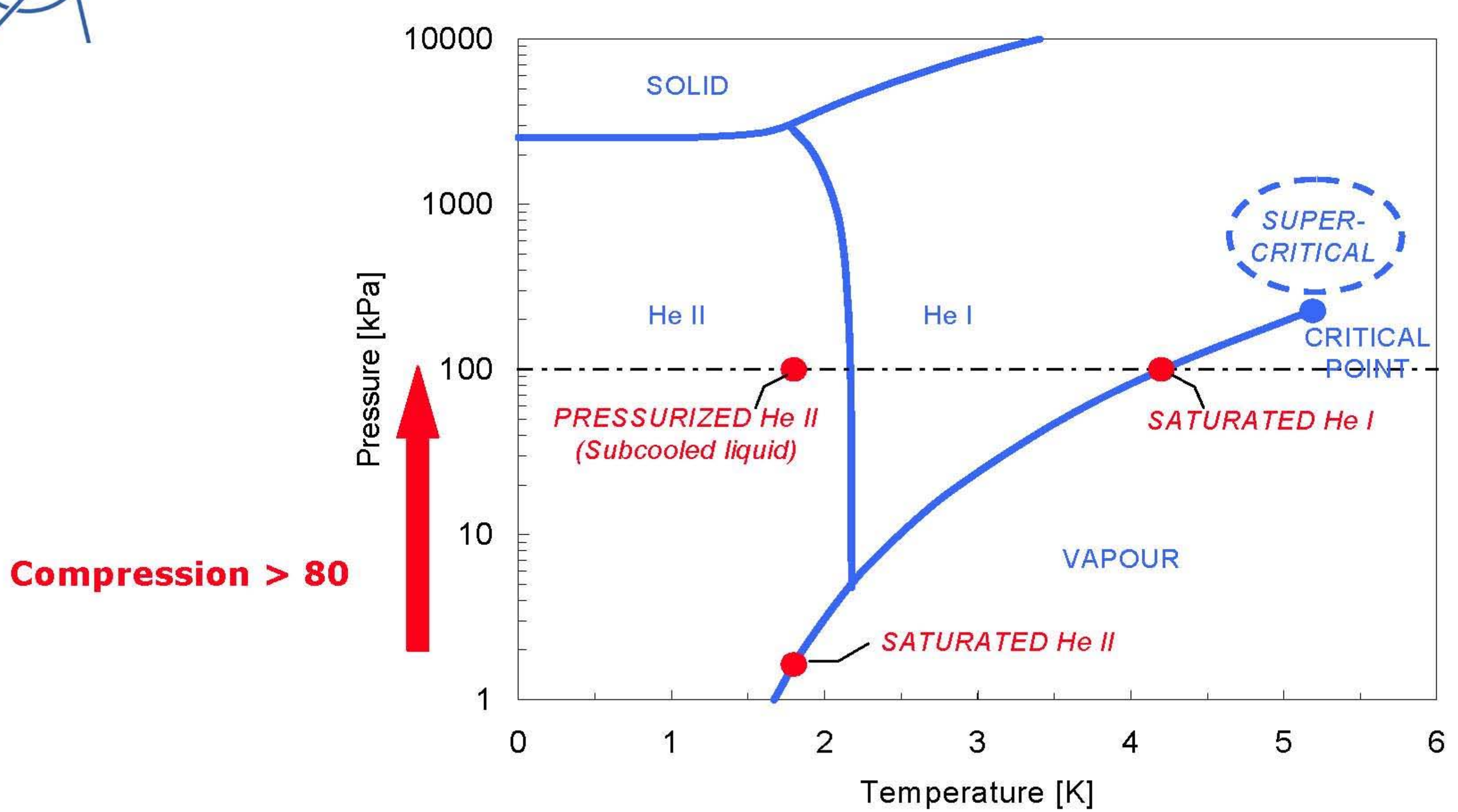


Wheel diameter: 5-15 cm

Shaft length: 20 cm

Rotation: 60'000 to 150'000 rpm

Challenges of power refrigeration at 1.8 K

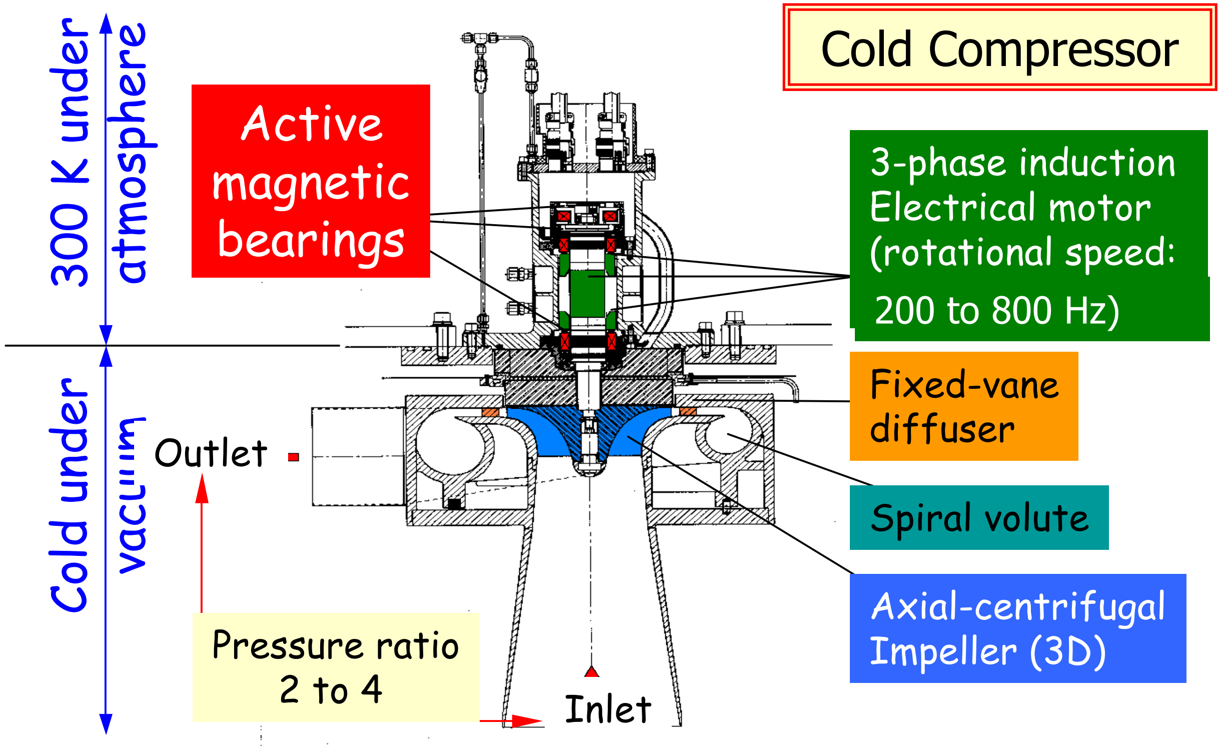


- Compression of large mass flow-rate of He vapor across high pressure ratio

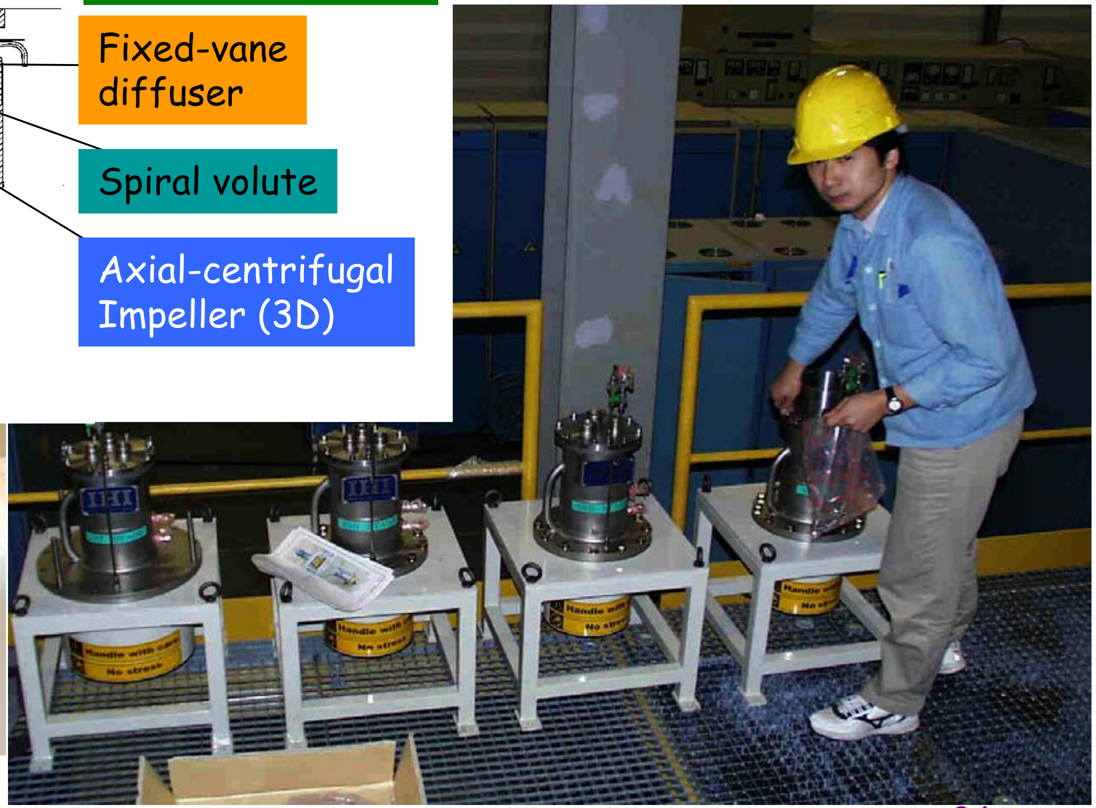
$\Rightarrow$ intake He at maximum density, i.e. cold

- Need contact-less, vane-less machine $\Rightarrow$ hydrodynamic compressor
- Compression heat rejected at low temperature $\Rightarrow$ thermodynamic efficiency

1.8K Units with cold compressors (x8)



Specific technology to allow large capacity below 2K



Contents

Bulk Liquid & Gaseous cryogen storage solutions

Deliveries in Liquid form:

- 60 trucks LN2 to cool a LHC sector to 80K (14 days-1'200t)

- 20 trucks for external storage of helium (4 months - 90tons)

250m3 Gaseous He

(20B - 850kg He)

How to deal with impurities

- Any liquid or gas other than helium would solidify during the cooling process. This could block the helium flow or degrade moveable components (valves, turbines)

- Typical treatment applied for: Water, air (N_2 and O_2), H_2 (adsorption on porous medium like activated charcoal, molecular thieve)

Recommendation:

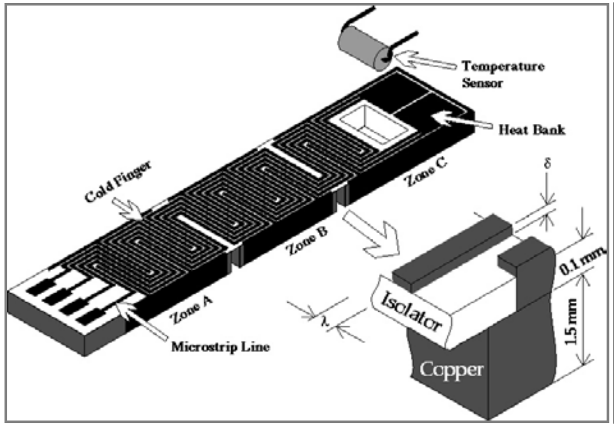
⇒ evacuation of air once circuits are leak-tight (pur helium)

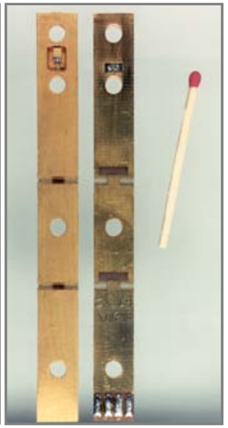
⇒ on-line treatment of what could remain or arrive during operation, with target of fraction of ppm(v)

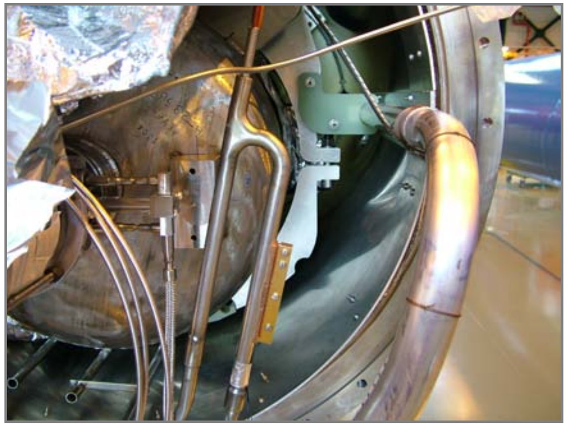
Thermometry

Industrial instrumentation whenever possible, specific developments when necessary

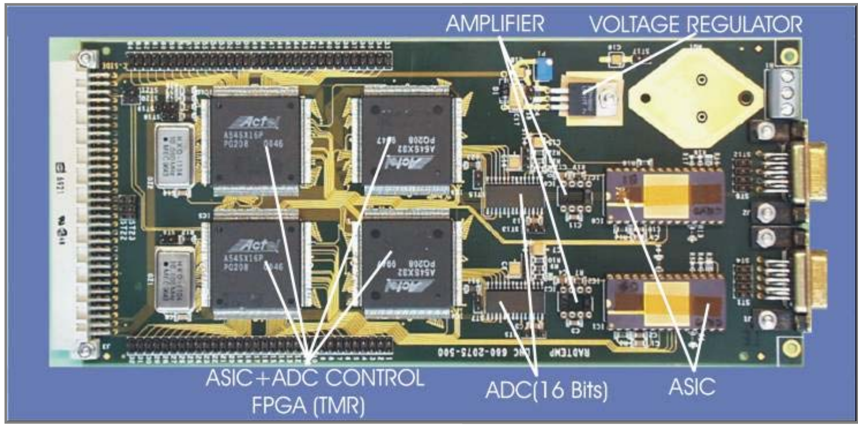
6'000 units, +/- 10 mK @ 2K in LHC radiation conditions

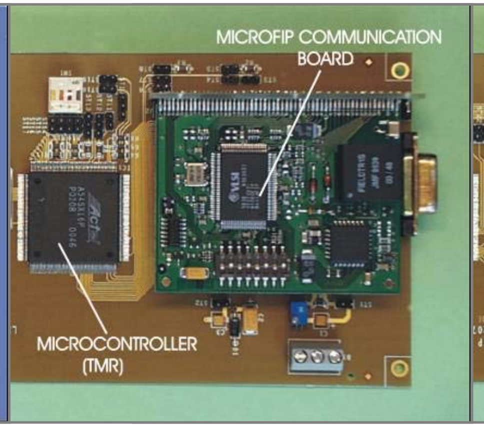




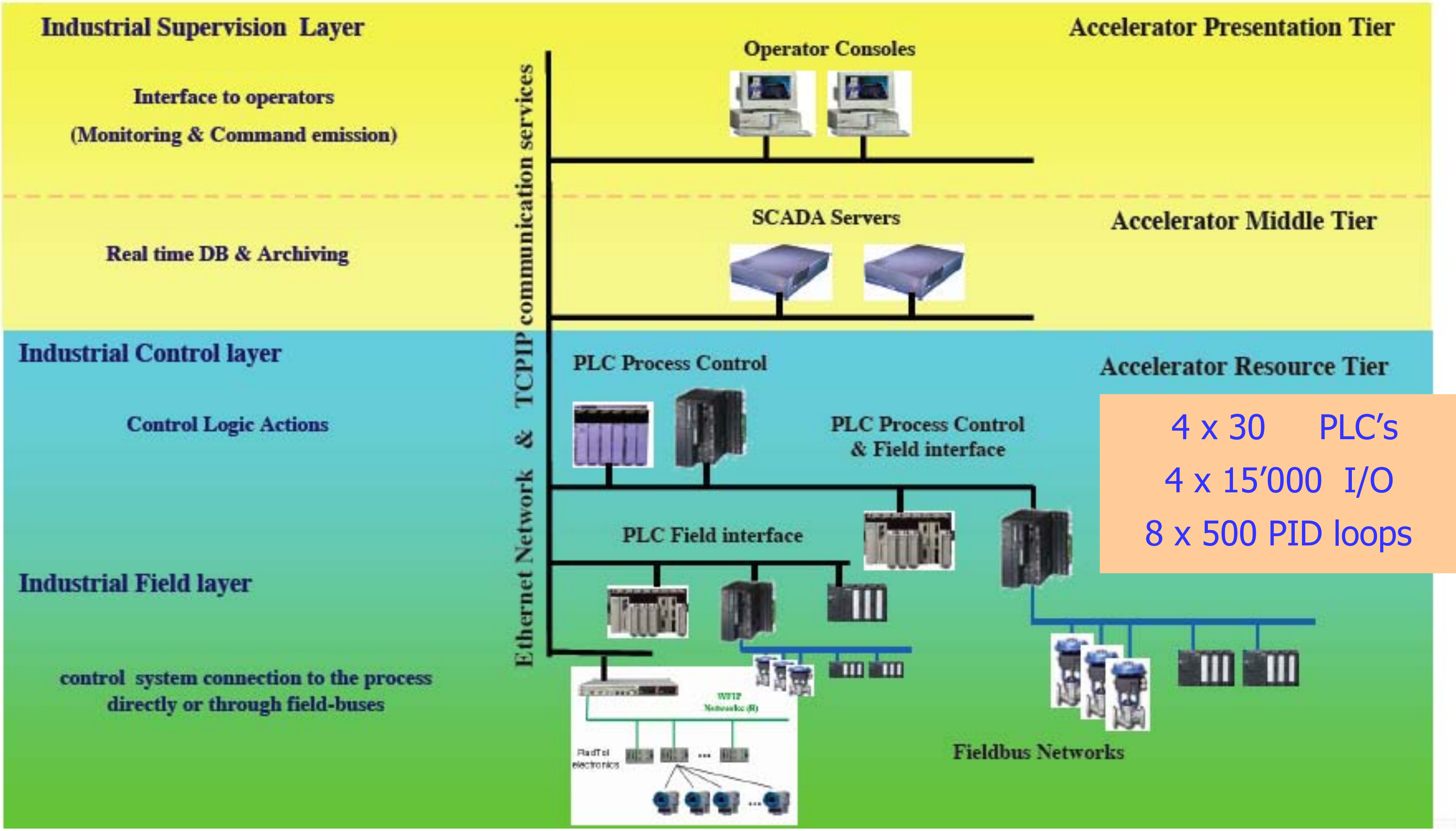


From 'sensor' to 'thermometer' with signal processing





Industrial Control Architecture



Cryo operator in Cern Central Control room

Shift 24/7

Fully automated, supervised by a single operator

Safety notes

- Major risks associated with cryogenic fluids at low temperatures:
  - Asphyxia: Oxygen is replaced by a pure
  - Cold burns: in case of contact with cold surfaces
  - Explosion: pressure rise in case of warm-up at constant volume (1l Liq≈ 700 l gas)
  - Embrittlement: Thermal contractions, potential fragile at cold
- Be informed about valid standards, like for pressure vessels, safety devices, transport of cryogens, …

Concluding remarks

- Cryogenics serving superconducting systems is now part of all major accelerators and future projects.
- While advanced applications tend to favor “below 2K”, many almost industrial applications are based on “4.5K” and RnD (or demonstrators) continues for “high temperature” applications
- If cryogenic engineering follows well defined rules and standards, there are variants depending on boundary conditions, continents, time of a project…

  I could only recommend that demonstrated experience be evaluated and adapted to specific requirements you may have !

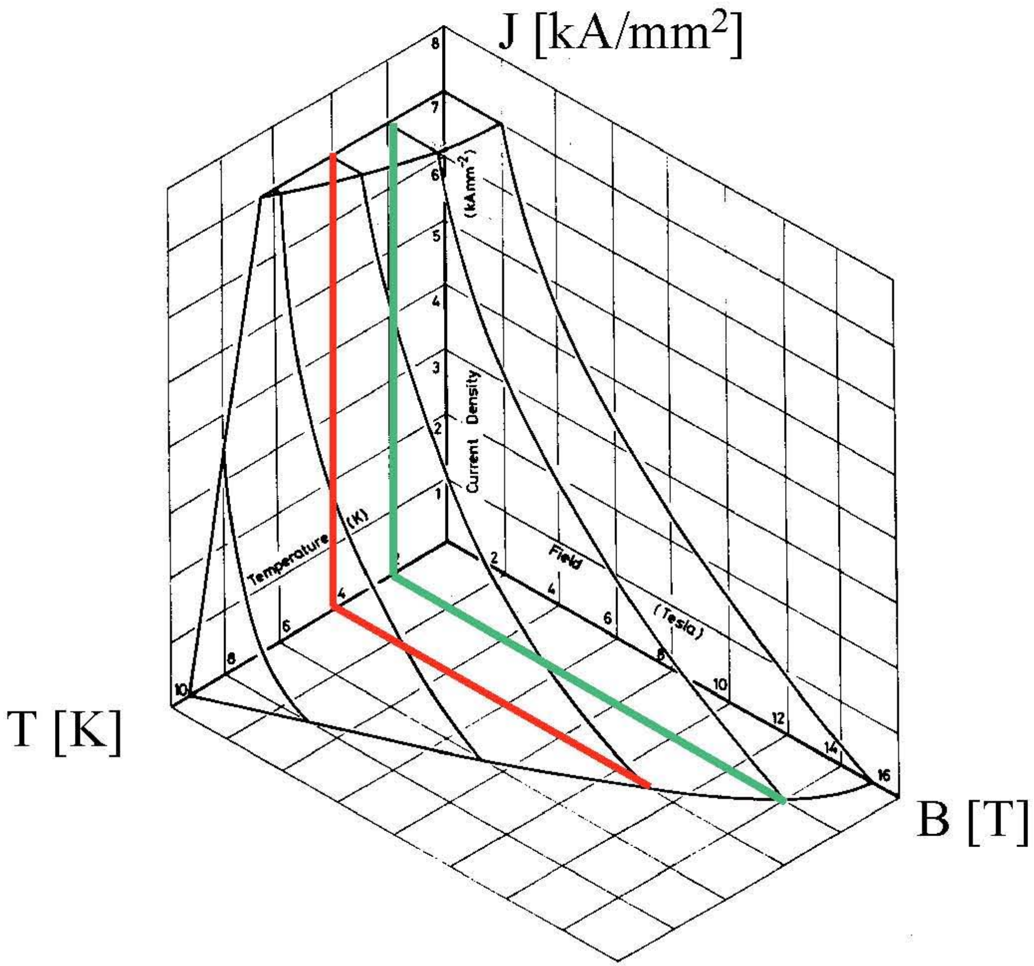
Thanks for your attention,
and hoping you would (now) be more aware with cryogenics !!!

Some references

- K. Mendelssohn, *The quest for absolute zero*, McGraw Hill (1966)
- R.B. Scott, *Cryogenic engineering*, Van Nostrand, Princeton (1959)
- G.G. Haselden, *Cryogenic fundamentals*, Academic Press, London (1971)
- R.A. Barron, *Cryogenic systems*, Oxford University Press, New York (1985)
- B.A. Hands, *Cryogenic engineering*, Academic Press, London (1986)
- S.W. van Sciver, *Helium cryogenics*, Plenum Press, New York (1986)
- K.D. Timmerhaus & T.M. Flynn, *Cryogenic process engineering*, Plenum Press, New York (1989)
- Proceedings of *CAS School on Superconductivity and Cryogenics for Particle Accelerators and Detectors*, Erice (2002) (+2013)
  - U. Wagner, *Refrigeration*
  - G. Vandoni, *Heat transfer*
  - Ph. Lebrun, *Design of a cryostat for superconducting accelerator magnet*
  - Ph. Lebrun & L. Tavian, *The technology of superfluid helium*
- Proceedings of ICEC and CEC/ICMC conferences

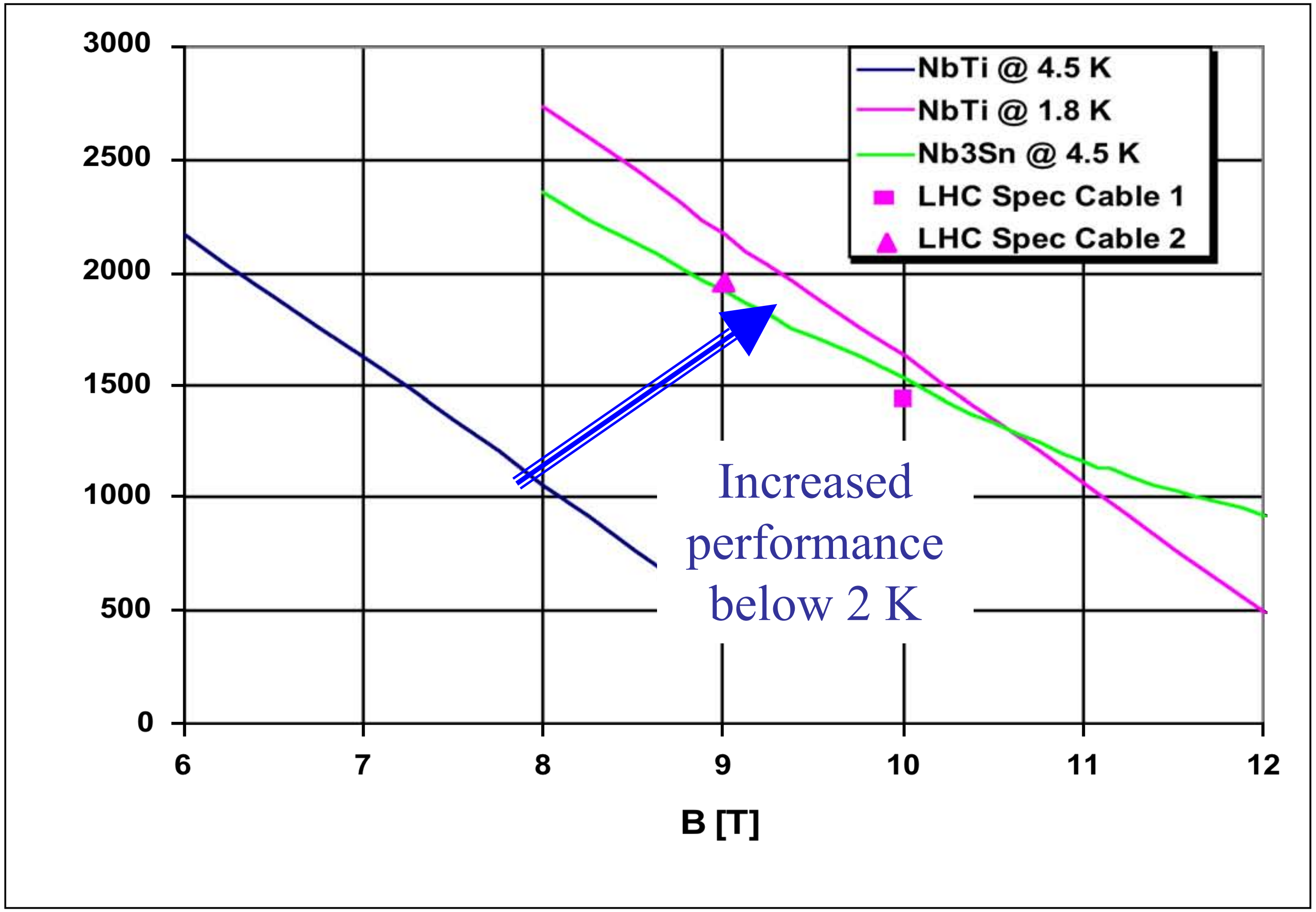
Bonus slides

Operating temperature & performance of superconductors



- Superconductivity only exists in a limited domain of temperature, magnetic field and current density
- Electrotechnical applications require transport current and magnetic field
- Operating temperature of the device must therefore be significantly lower than the critical temperature of the superconductor

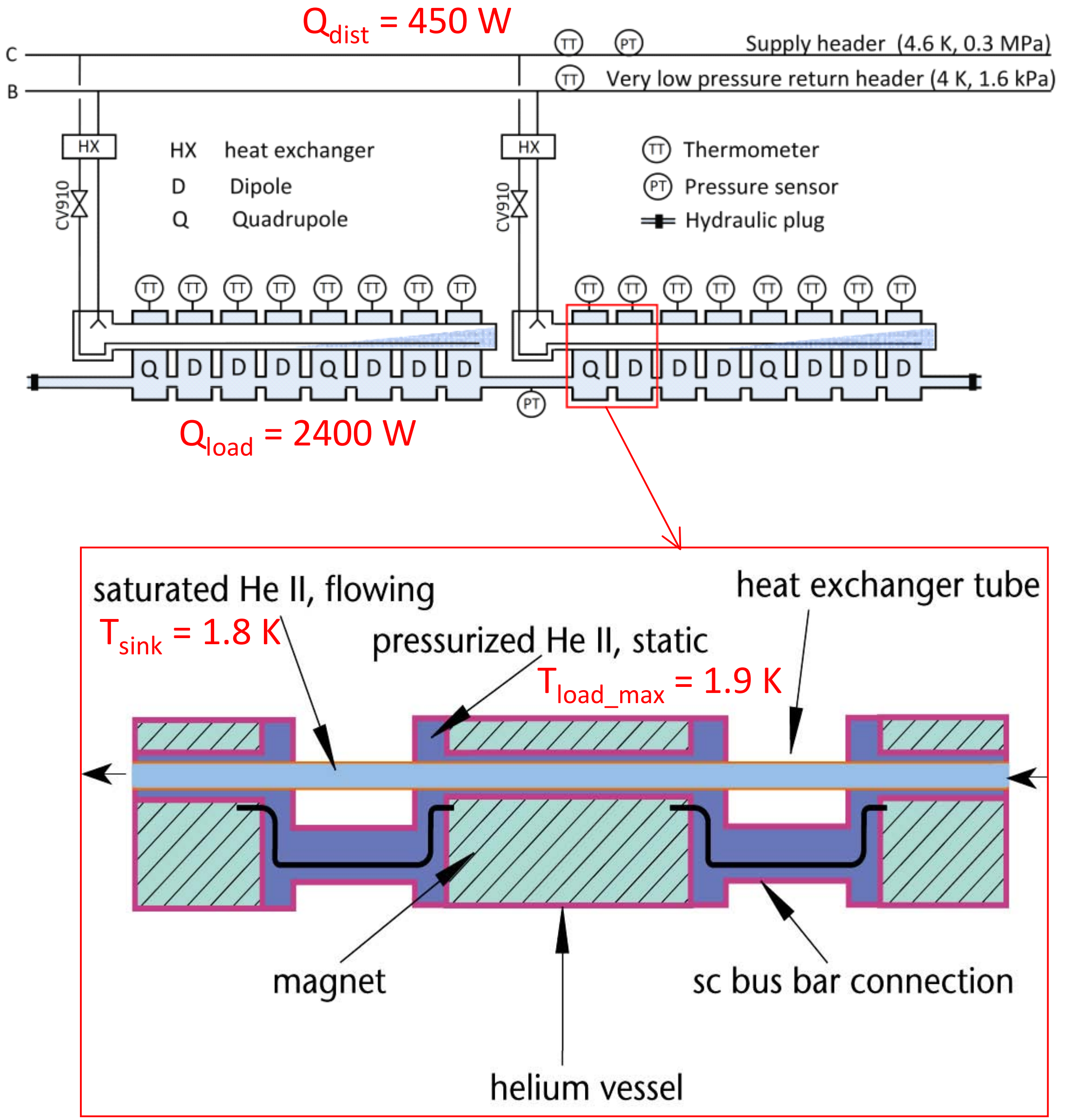
Superconducting magnets



LHC sector cooling scheme

Pressurized/saturated He II

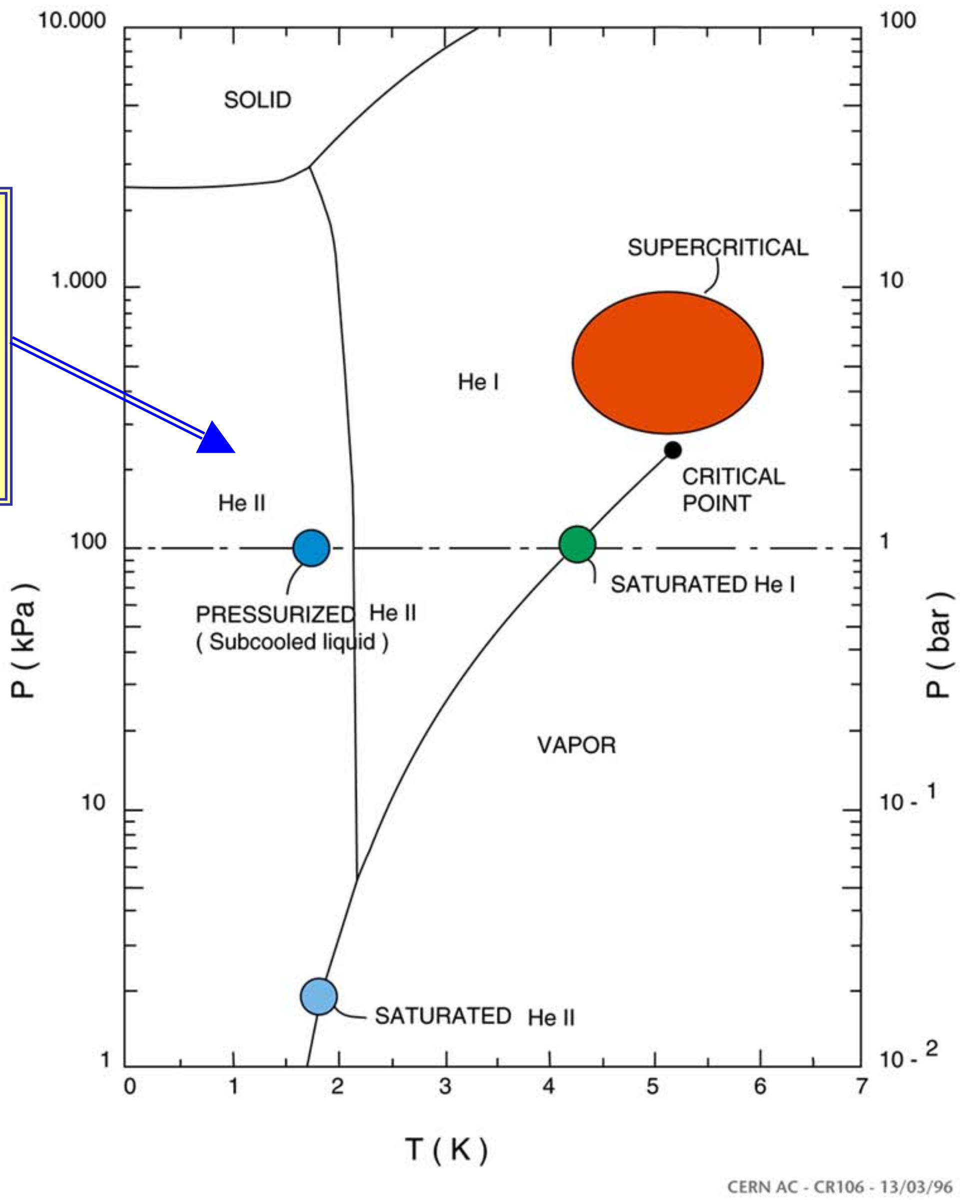
37’500 tons at 1.9 K



Helium phase diagram

Superfluid Helium:

- Lower viscosity
- Larger heat transfer capacity



Basic thermodynamics at low temperature

- Minimum refrigeration work W_{min} to extract heat Q at temperature T and reject it at ambient temperature T_a

$$W_{min} = Q\,(T_a/T - 1) = T_a\,\Delta S - Q$$

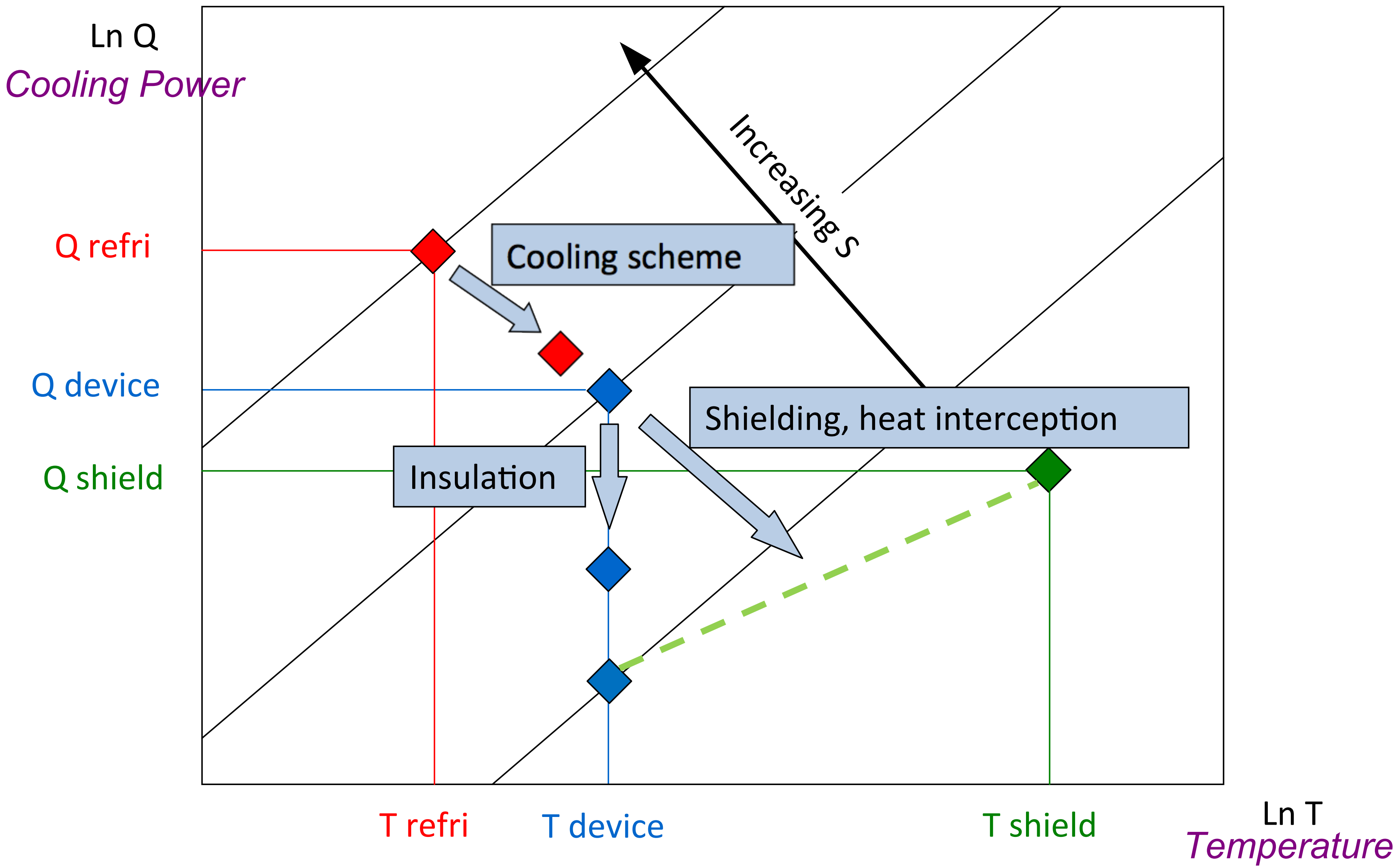
- At cryogenic temperature $T \ll T_a$

$$W_{min} \simeq Q\,T_a/T \simeq T_a\,\Delta S$$

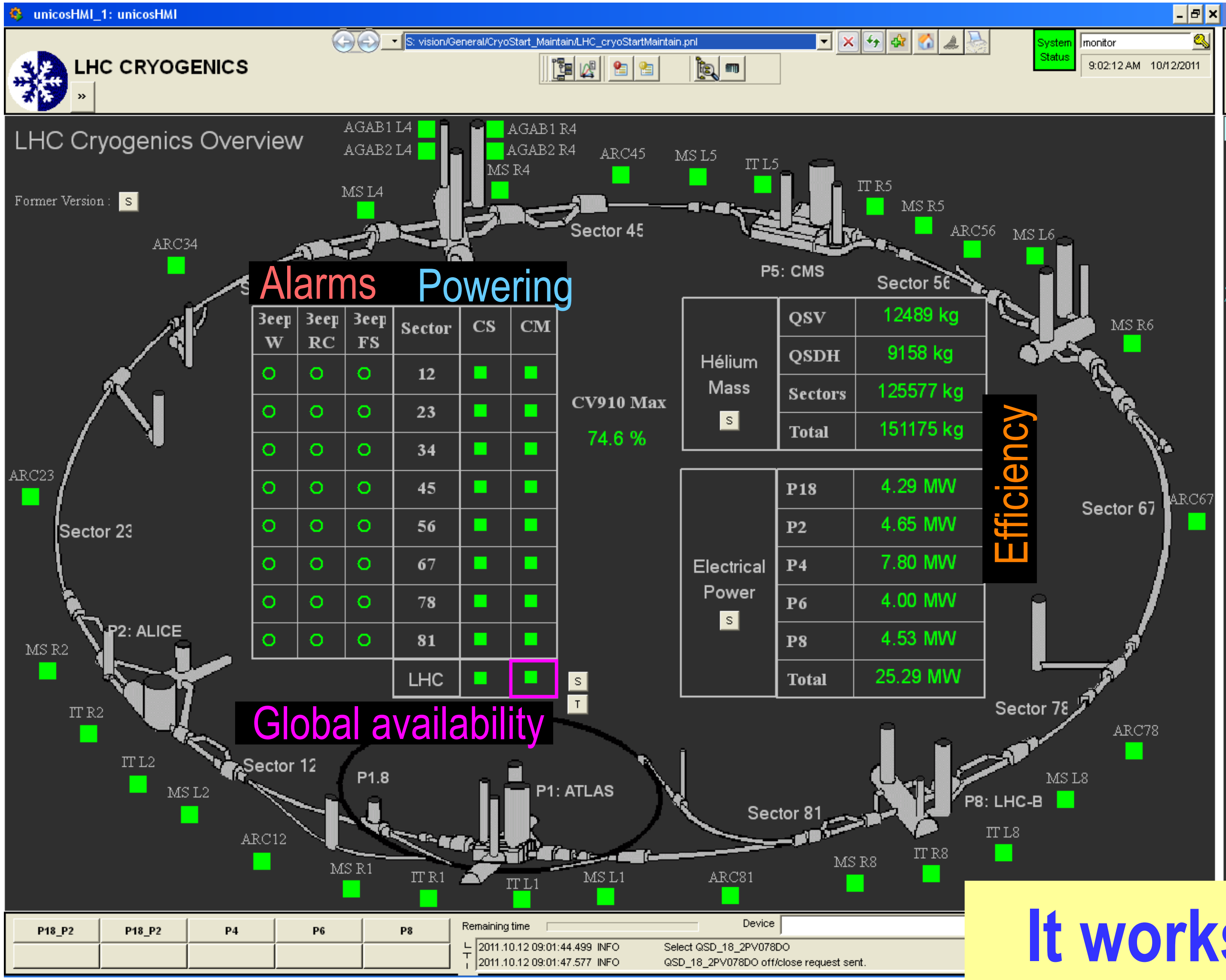
➔ entropy is a good measure of the cost of cryogenic refrigeration

➔strategies minimizing ΔS improve cryogenic design

Cryogenic design strategies

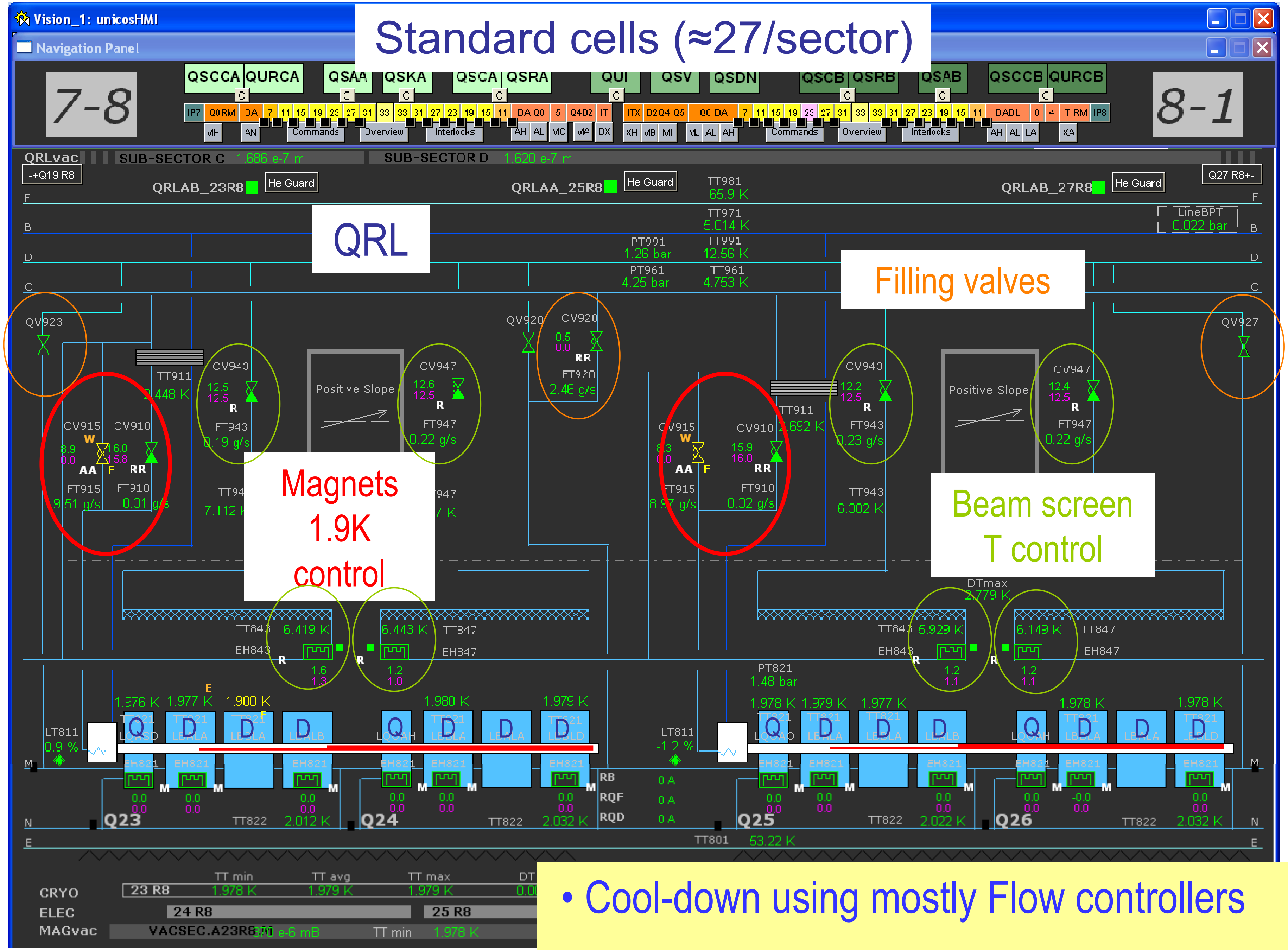


Operation, indicators



It works !!!

Standard cells (≈27/sector)



- Cool-down using mostly Flow controllers
- P, T, L controllers at operating conditions