INTRODUCTION TO HELIUM REFRIGERATION FOR SUPERCONDUCTING DEVICES

HELIUM REFRIGERATION CYCLES

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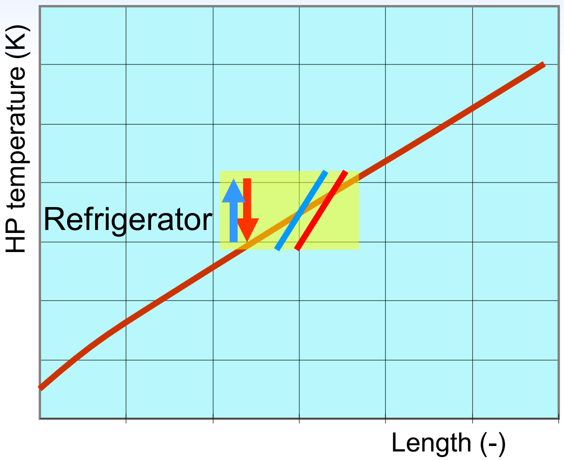
CRYOGUY

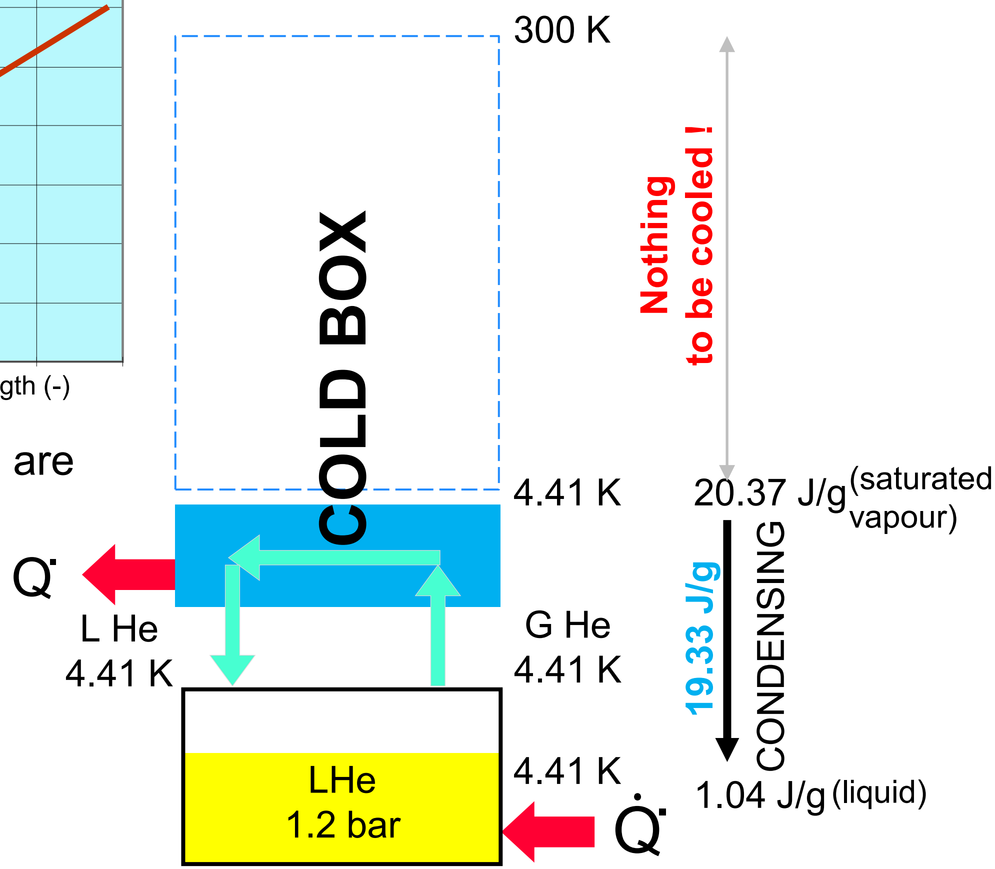
REFRIGERATION AND LIQUEFACTION

OPERATING MODES (1)

PURE REFRIGERATION



The heat exchangers are **balanced**.



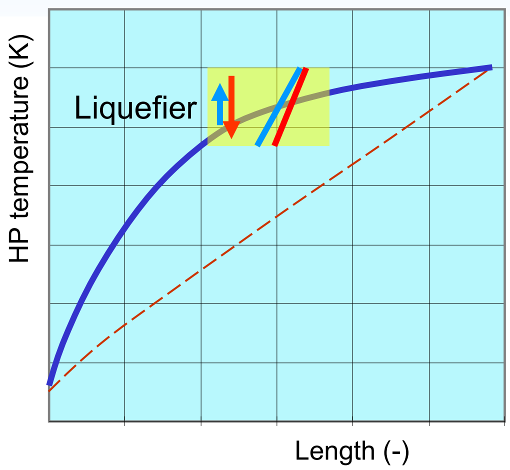
Only **little energy** has to be extracted from helium vapour to condense it.

But it is to be done **at low temperature.**

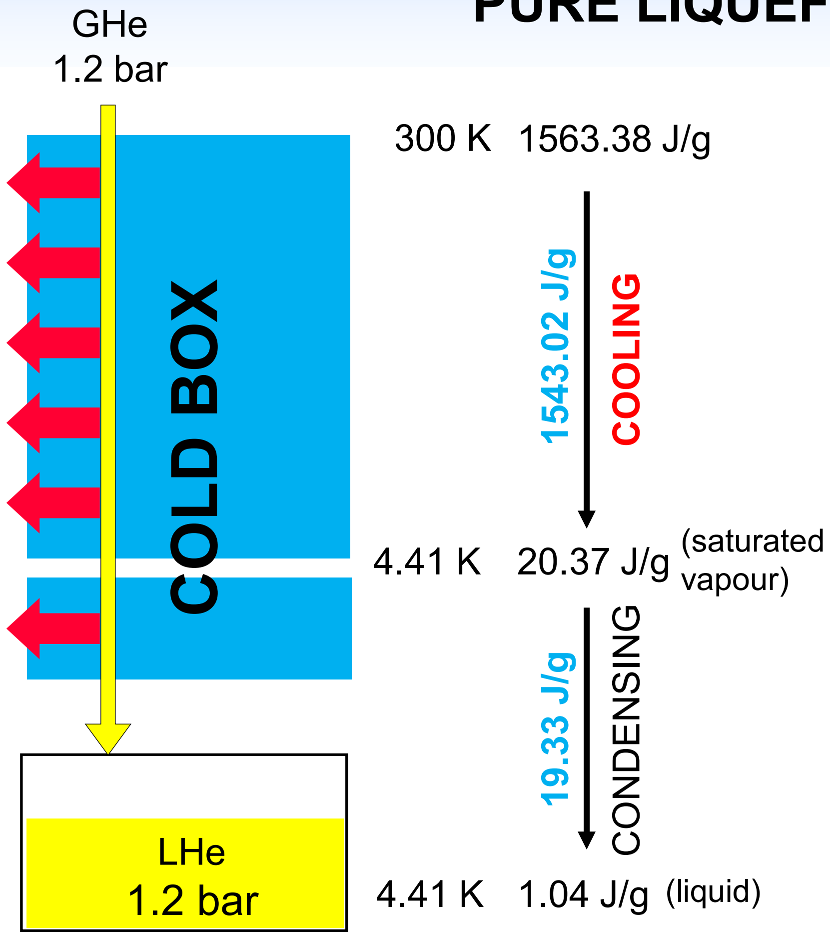
Operation in a pure isothermal refrigeration regime is expressed by the power that is absorbed at the operating temperature. Example : 100 W at 4.5 K

OPERATING MODES (2)

PURE LIQUEFACTION



The heat exchangers are **unbalanced**.



A big amount of energy is to be extracted from helium **at all temperatures** between 300 and 4.4 K to cool it.

And, finally, **little energy** has to be extracted from helium vapour to condense it.

Operation in a pure liquefaction regime is expressed by the liquid helium quantity that is liquefied within one unit of time. Example : 3 (g/s) or ~90 L/h.

HOW TO FEED ELECTRICALLY A SUPERCONDUCTING COIL?

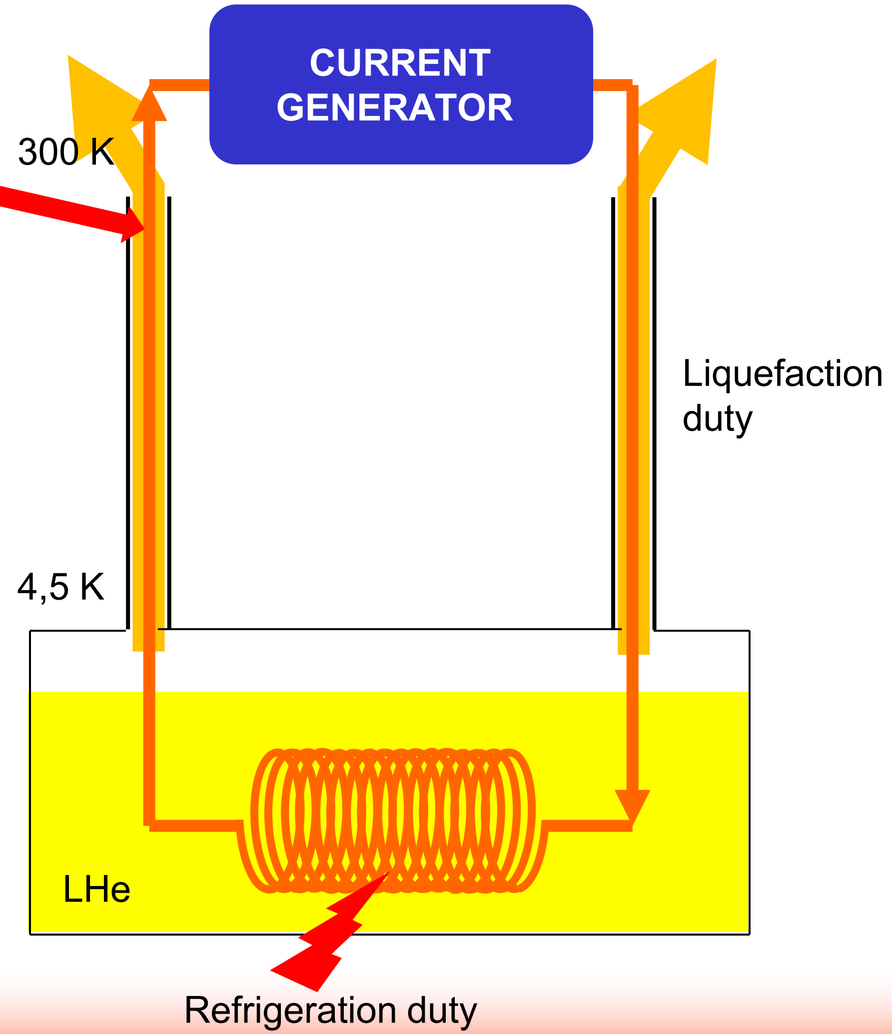
High current (tens of kilo Amps)

The conductor must have a good electrical conductivity and a large cross section.

But, consequently, it has a good thermal conductivity !

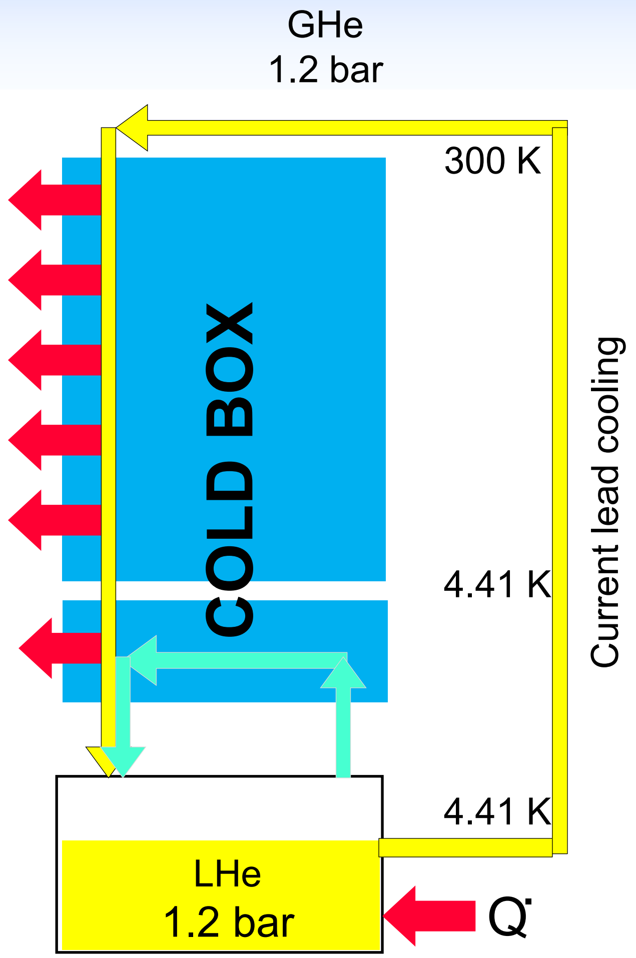
Therefore, a high heat in leak between 300 and 4 K.

Solution : heat that is generated by Joule effect into the conductor is transferred to cold helium circulating from cold to warm end.



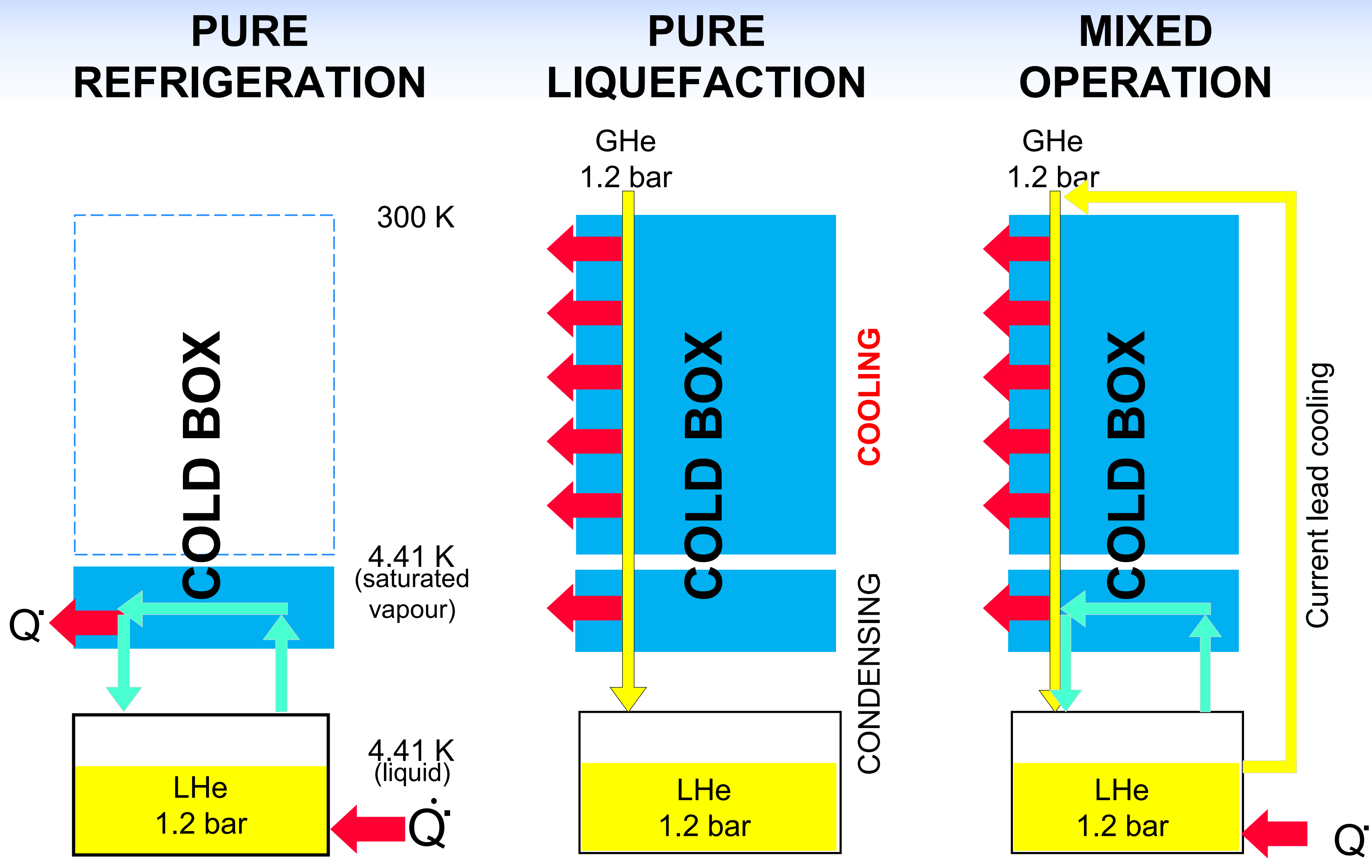
OPERATING MODES (3)

MIXED OPERATION



Operation in a mixed regime is expressed by the cryogenic power that is absorbed at the operating temperature and the liquid helium quantity that is liquefied within one unit of time.
Example : 300 W at 4.5 K + 3 g/s

THE THREE OPERATING MODES



CALCULATION OF THE CARNOT POWER

FOR AN ISOTHERMAL OPERATION

(Vaporization of a liquid : constant temperature)

$$\dot{W}_{Carnot} = \frac{T_w - T_c}{T_c} = \frac{T_w}{T_c} - 1$$

FOR A NON-ISOTHERMAL OPERATION

(Heating or cooling a gas : temperature changes)

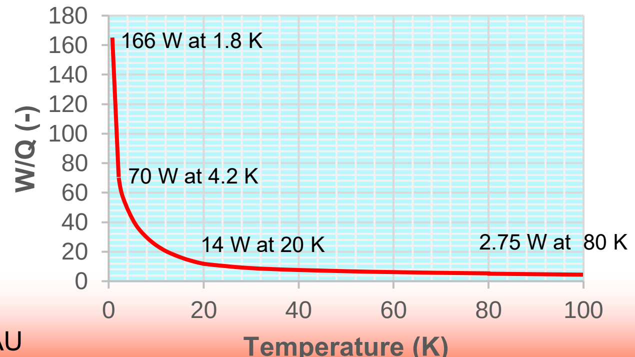
$$\dot{W}_{Carnot} = \dot{m} \times [(T_w \times \Delta s) - \Delta h]$$

Examples :

Carnot power, to get 1 W at 4.2 K

$$\frac{300}{4.2} - 1 = 70.43 \text{ W}$$

Roughly inversely proportional to the temperature ratio



Carnot power to liquefy 1 g/s of helium

$$\dot{W}_{Carnot} = 1 \times [300 \times (31.612 - 3.56) - (1573.51 - 9.94)] = 6852 \text{ W}$$

6852 / 70 = ~100

1 g/s ⟷ about 100 W

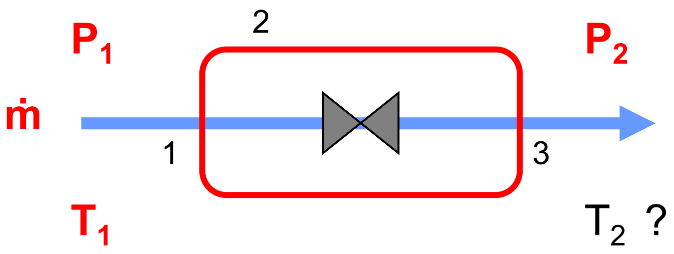
Theoretical equivalence liquefaction/refrigeration

To be used ONLY for SMALL moves from refrigeration to liquefaction load or conversely !

FREE EXPANSION

A SIMPLE EXAMPLE

Assumption : gas velocity is negligeable



Because the system is in a steady state !

Balance :

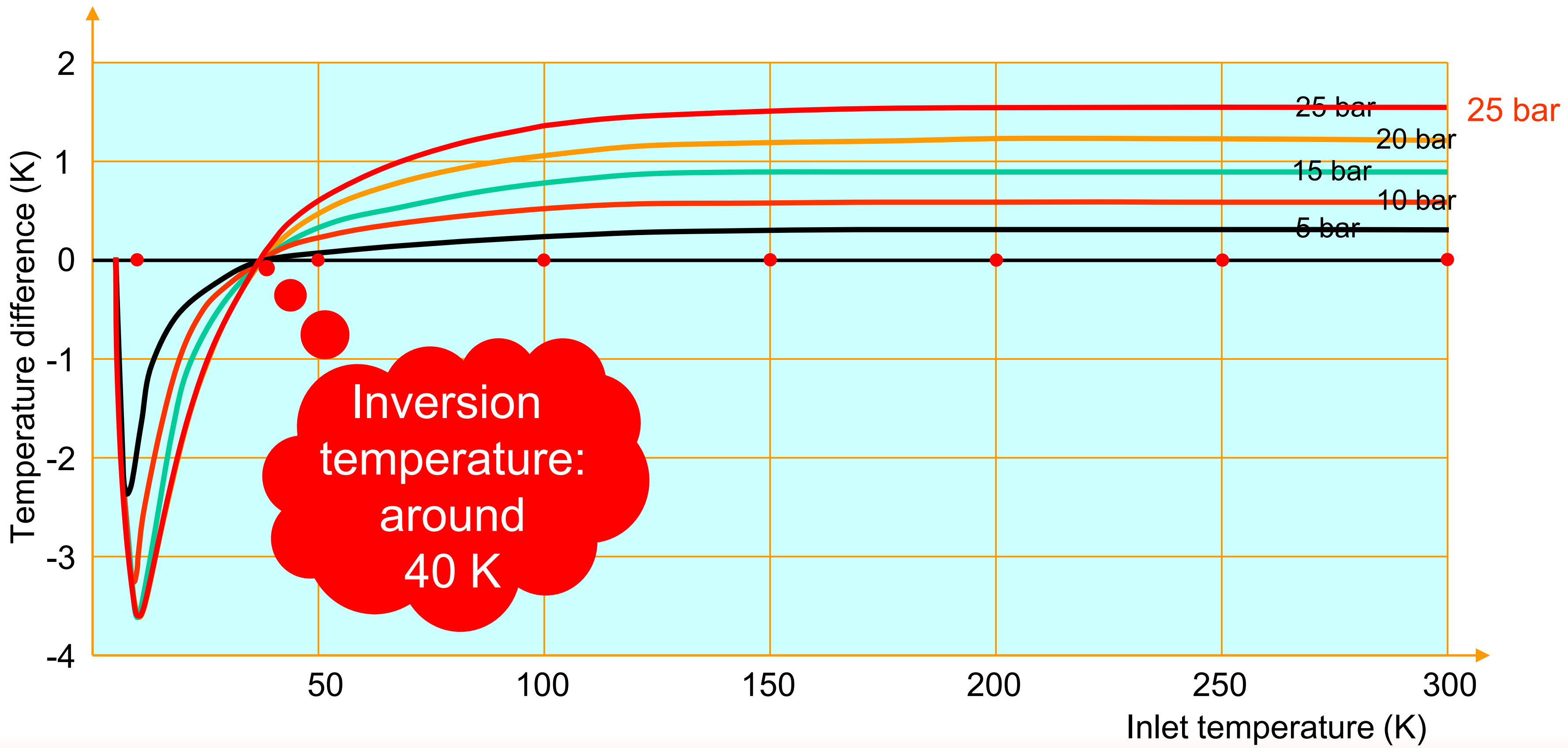
$\dot{m} \times h_1 - \dot{m} \times h_2 = 0$

$h_2 = h_1$

P_1	and	T_1	+ REFPROP	⇒	h_1
15.0 bar		300.00 K			1567,89 J/g
$\dot{m}$					
10.0 g/s					
$h_2 = h_1$					
P_2	and	h_2	+ REFPROP	⇒	T_2
1.0 bar		1567.89 J/g			300.88 K

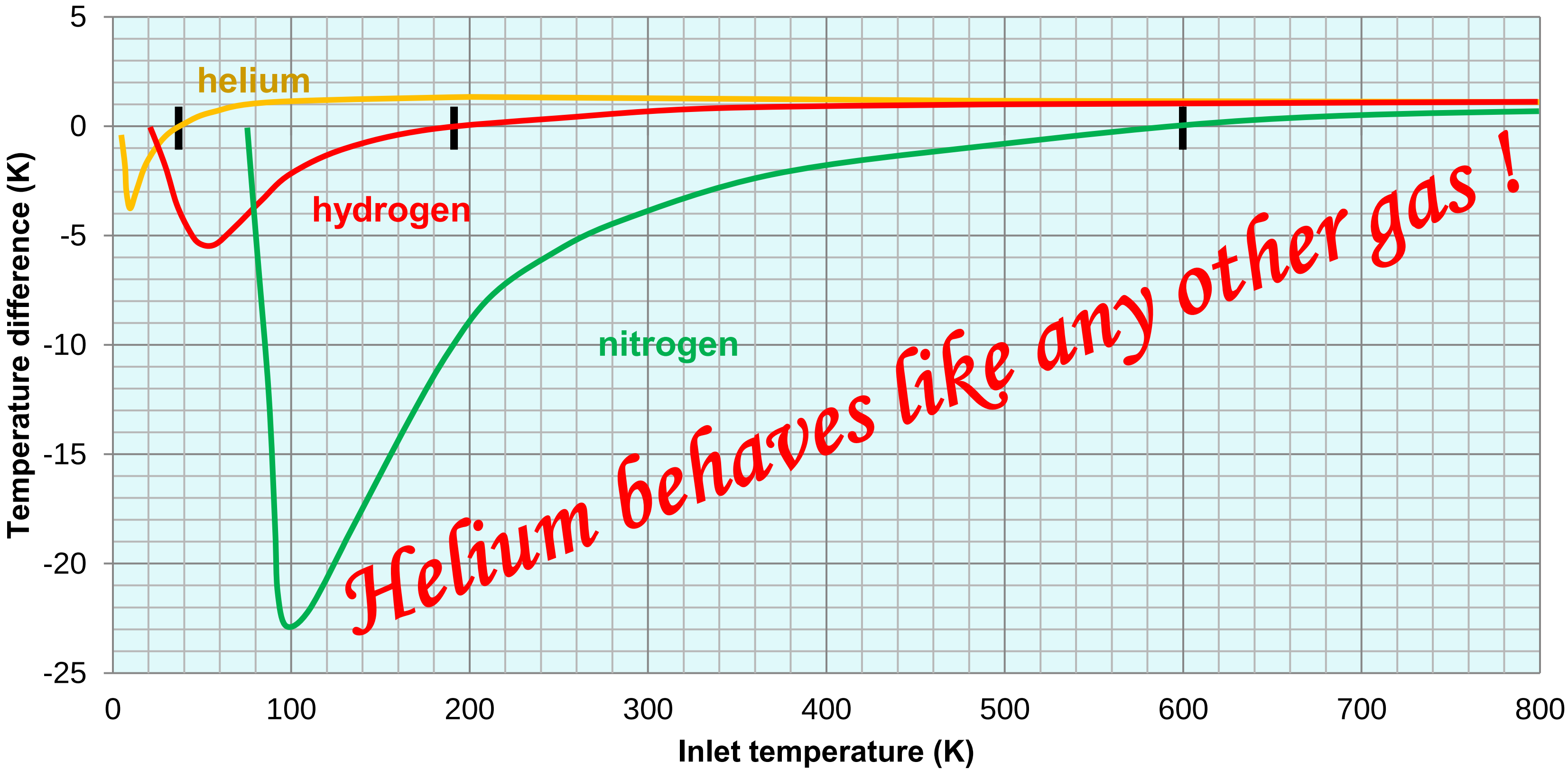
JOULE THOMSON EXPANSION OF HELIUM

Temperature difference obtained by expansion of helium gas through a valve, from various pressures down to 1.0 bar, depending on the inlet temperature.

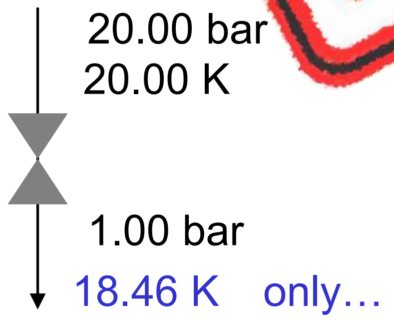


JOULE THOMSON EXPANSION OF VARIOUS GASES

Temperature difference obtained by expansion of various gases through a valve, from 20 bar to 1 bar, depending on the inlet temperature.

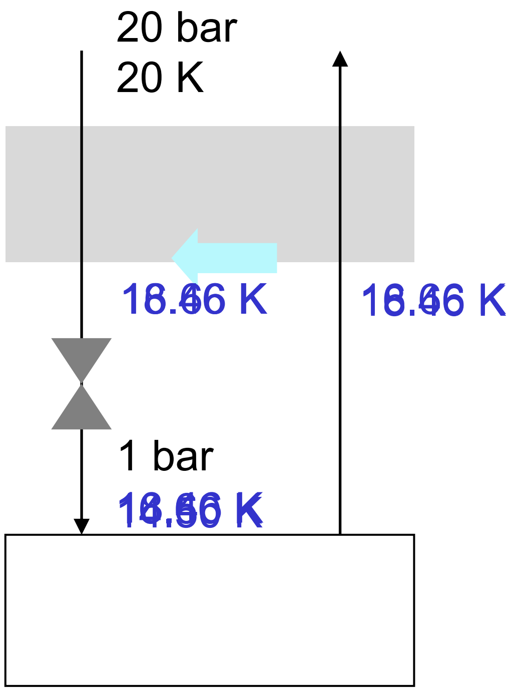


THE ISENTHALPIC EXPANSION



Liquefaction of helium is not possible by only simple expansion when starting from 20 K.

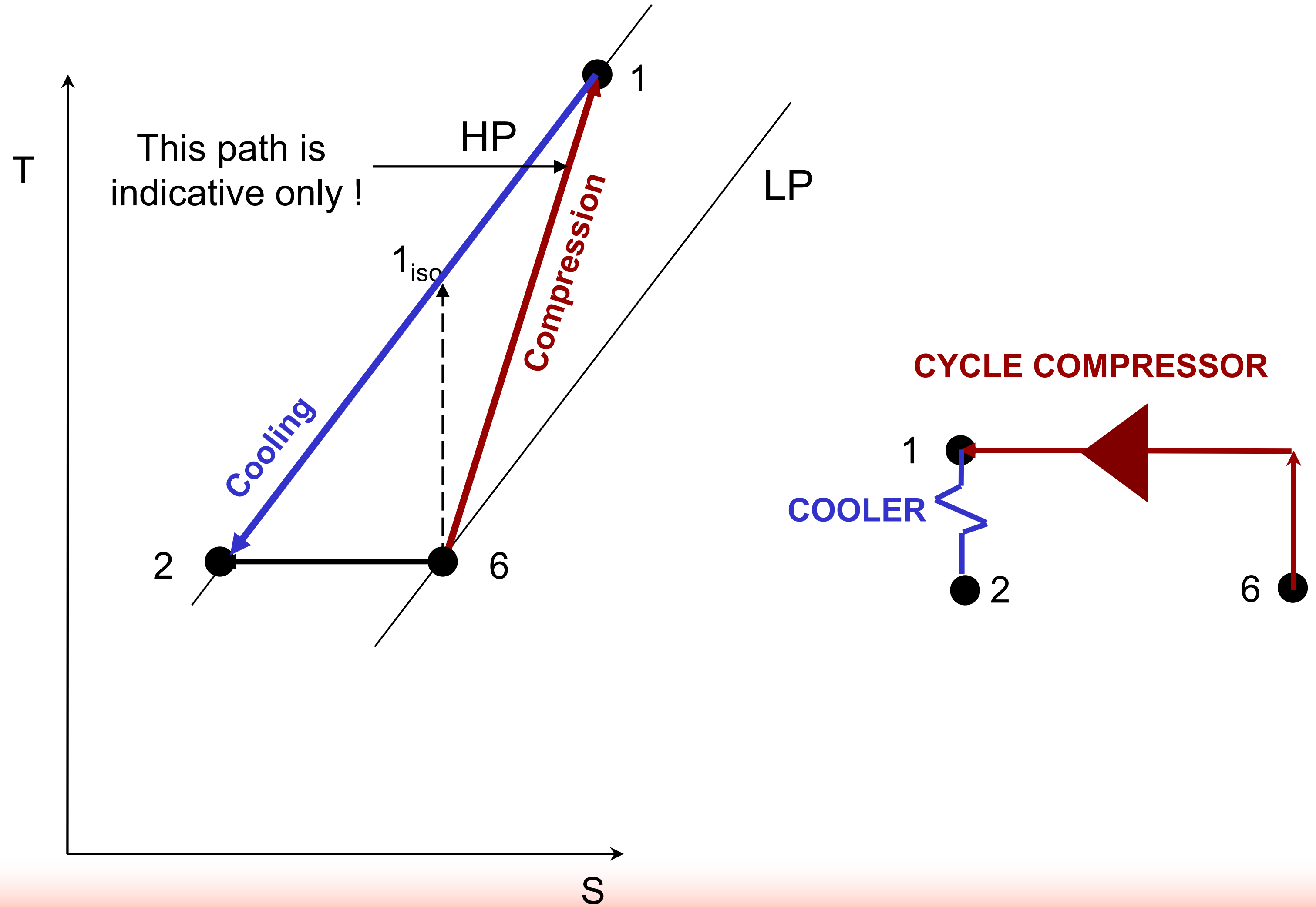
Why not use the cold expanded helium to "pre-cool" high pressure helium before expansion?



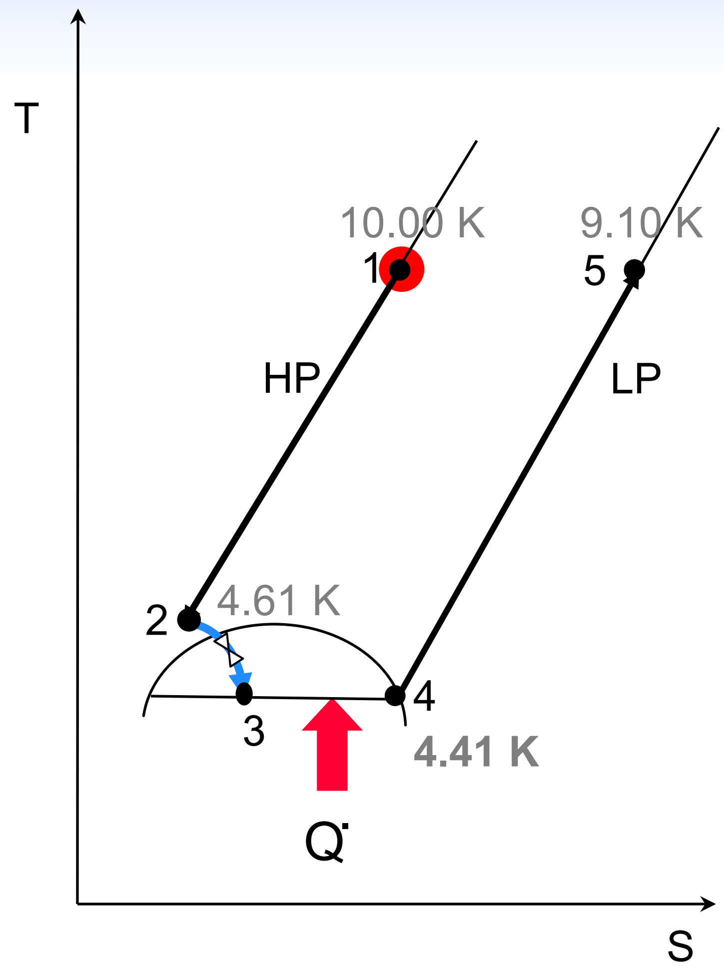
This is a **Joule-Thomson** cycle!

Un peu plus de cinématique

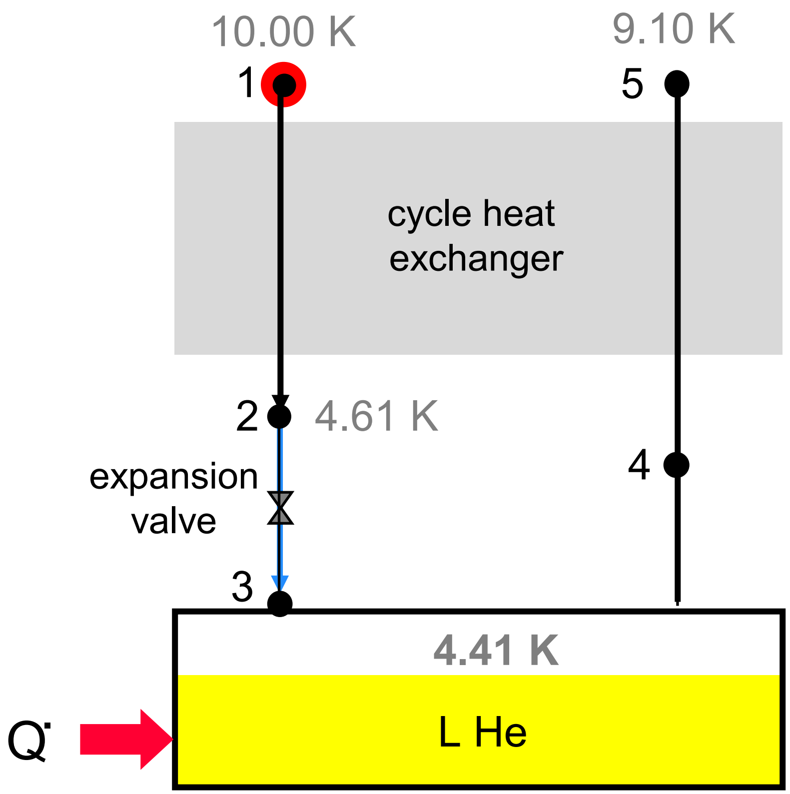
COMPRESSION, ON THE T-s DIAGRAMME



THE JOULE THOMSON CYCLE



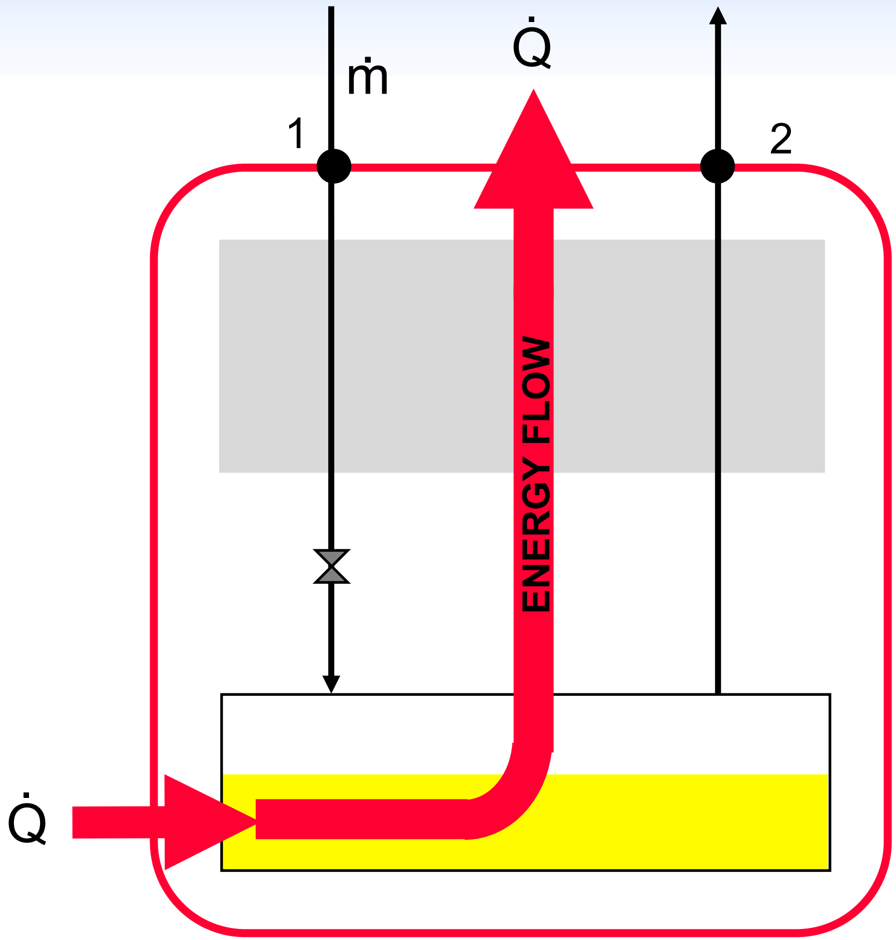
Temperature-Entropy diagram



Flow diagram

THE JOULE THOMSON CYCLE

Refrigerator



Because the system is in a steady state !

Balance :

$$(\dot{m} \times h_1) + \dot{Q} - (\dot{m} \times h_2) = 0$$

$$\dot{Q} = (\dot{m} \times h_2) - (\dot{m} \times h_1)$$

$$\dot{Q} = \underbrace{\dot{m} \times (h_2 - h_1)}$$

Power IN ($\dot{Q}$)

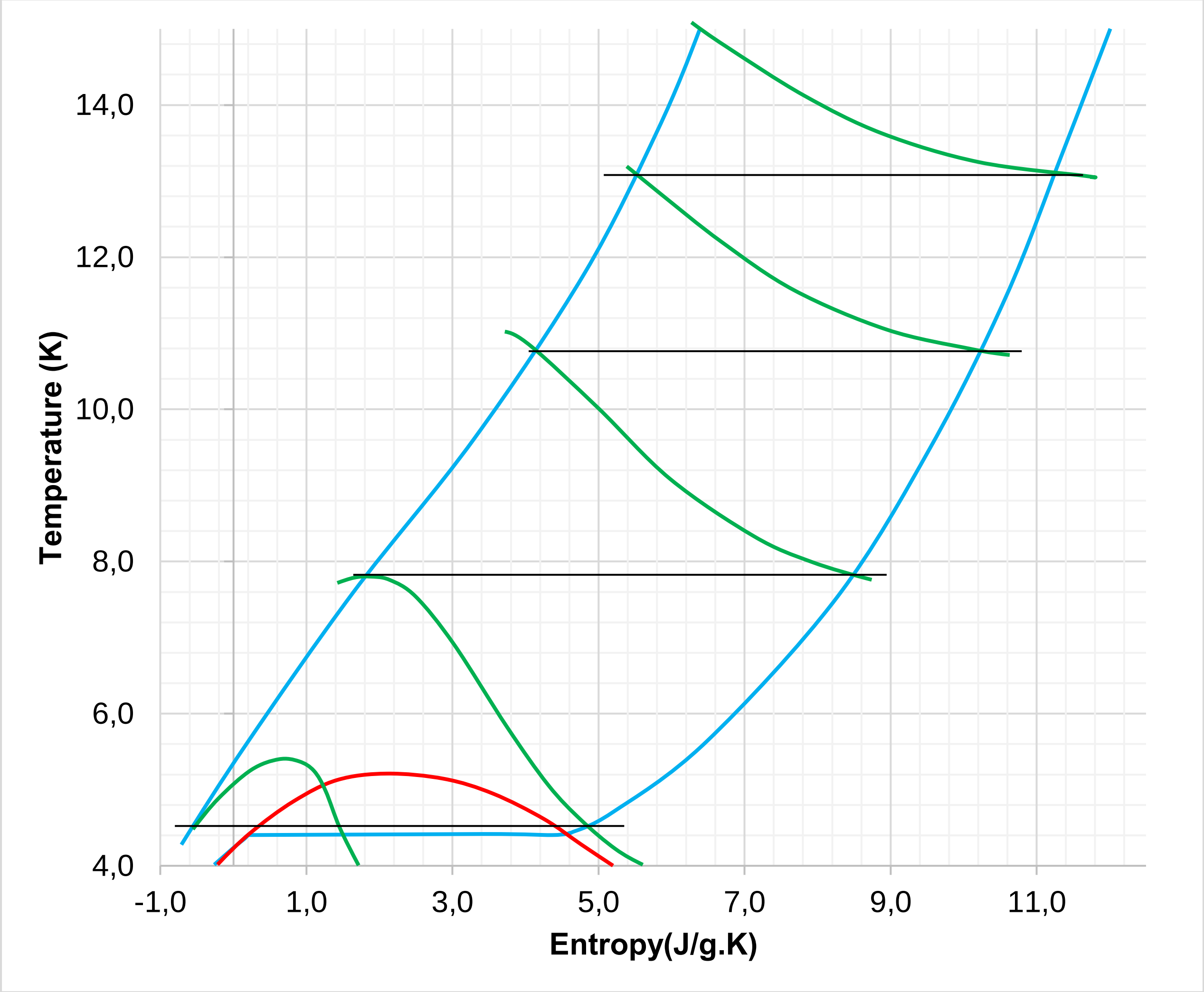
Power OUT ($\dot{m} \times (h_2 - h_1)$)

$$\dot{m} = \frac{\dot{Q}}{h_2 - h_1}$$

The Joule Thomson cycle is kind of a "**power belt**" circulating energy from any place to the warm end.

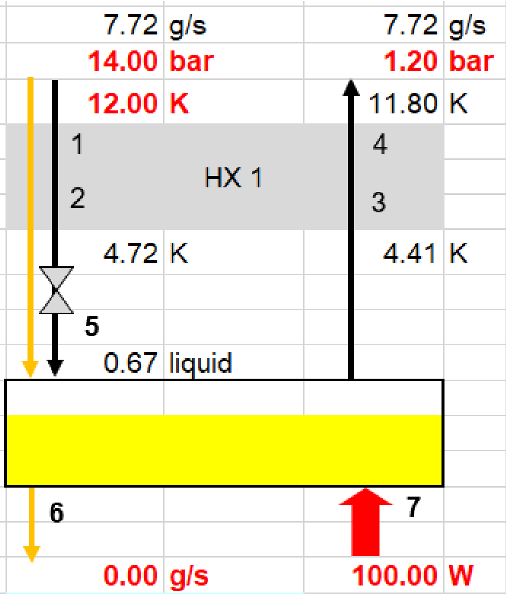
THE JOULE THOMSON CYCLE

COOL-DOWN



THE JOULE THOMSON CYCLE

"Refrigerator"

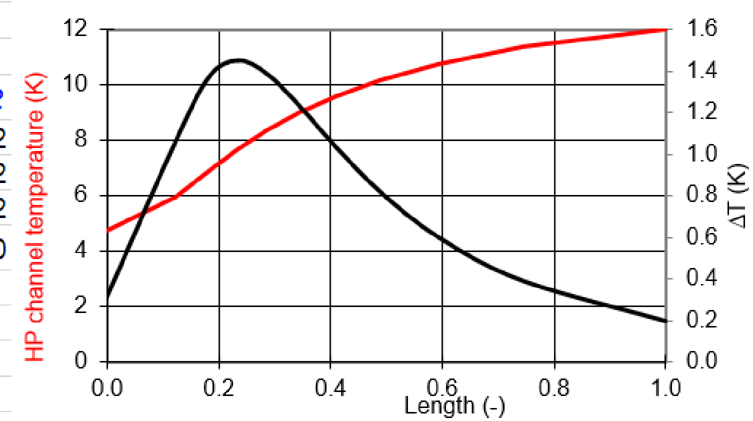


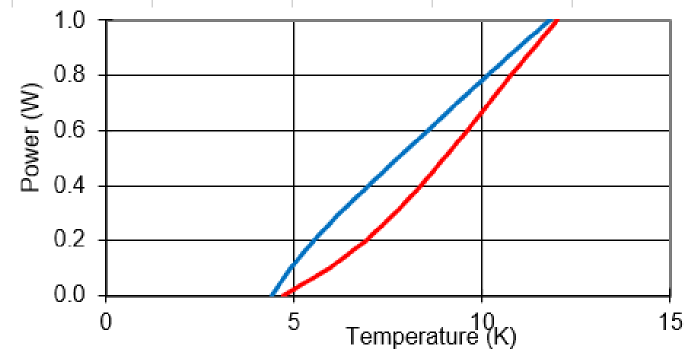
ΔT_w	0.20	K
$\dot{Q}$	343	W
MTD	0.74	K
UA	464	W/K
ΔT_c	0.32	K

	P (bar)	T (K)	h (J/g)	ṁ (g/s)
1	14.00	12.00	51.81	7.72
2	14.00	4.72	7.41	7.72
3	1.20	4.41	20.37	7.72
4	1.20	11.80	64.77	7.72
6	1.20	4.41	1.04	0.00

THERMAL BALANCE	
Warm end	-100.00
Liquefaction	0.00
Refrigeratior	100.00
Balance	0.00

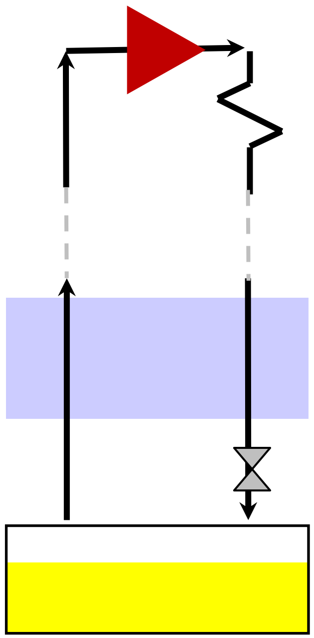
399.82 W	1	JT cycle	4	-499.82 W
	1	He	6	
100.00 W	7			





A REFRIGERATION CYCLE

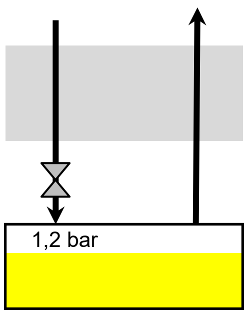
4 STEPS

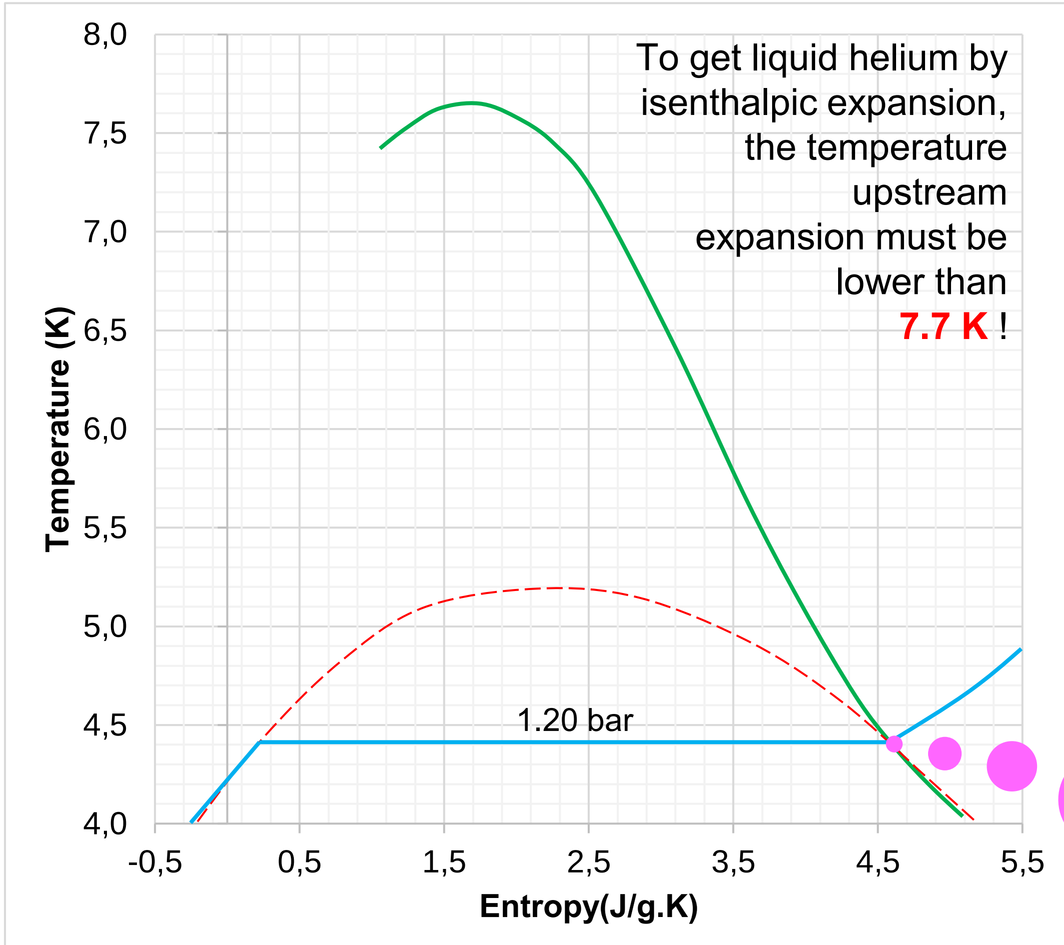


- 1 Compression, **HEATS the warm source**
- 2 Cooling by Heat Exchange,
- 3 Expansion, **COOLS the cold source**
- 4 Warming-up by Heat Exchange.

JOULE THOMSON EXPANSION

THE FIRST DROP OF LIQUID HELIUM





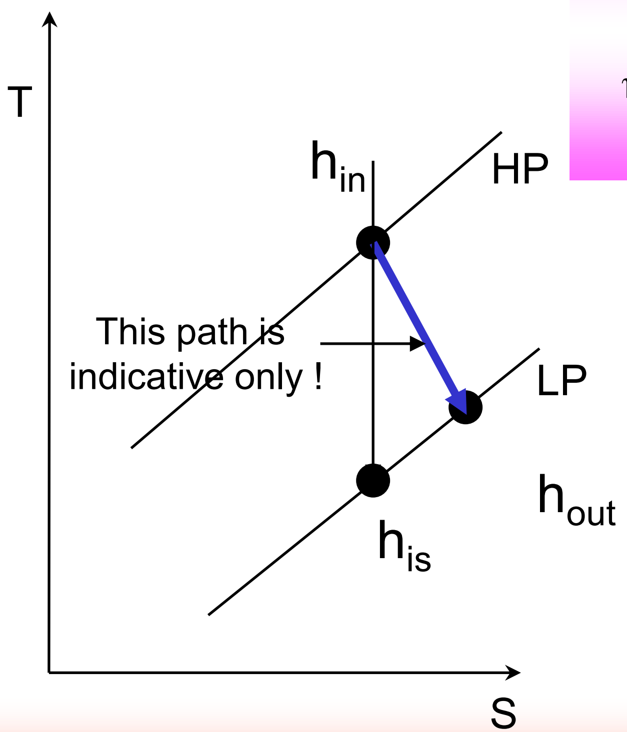
The first LHe drop appears **HERE !**

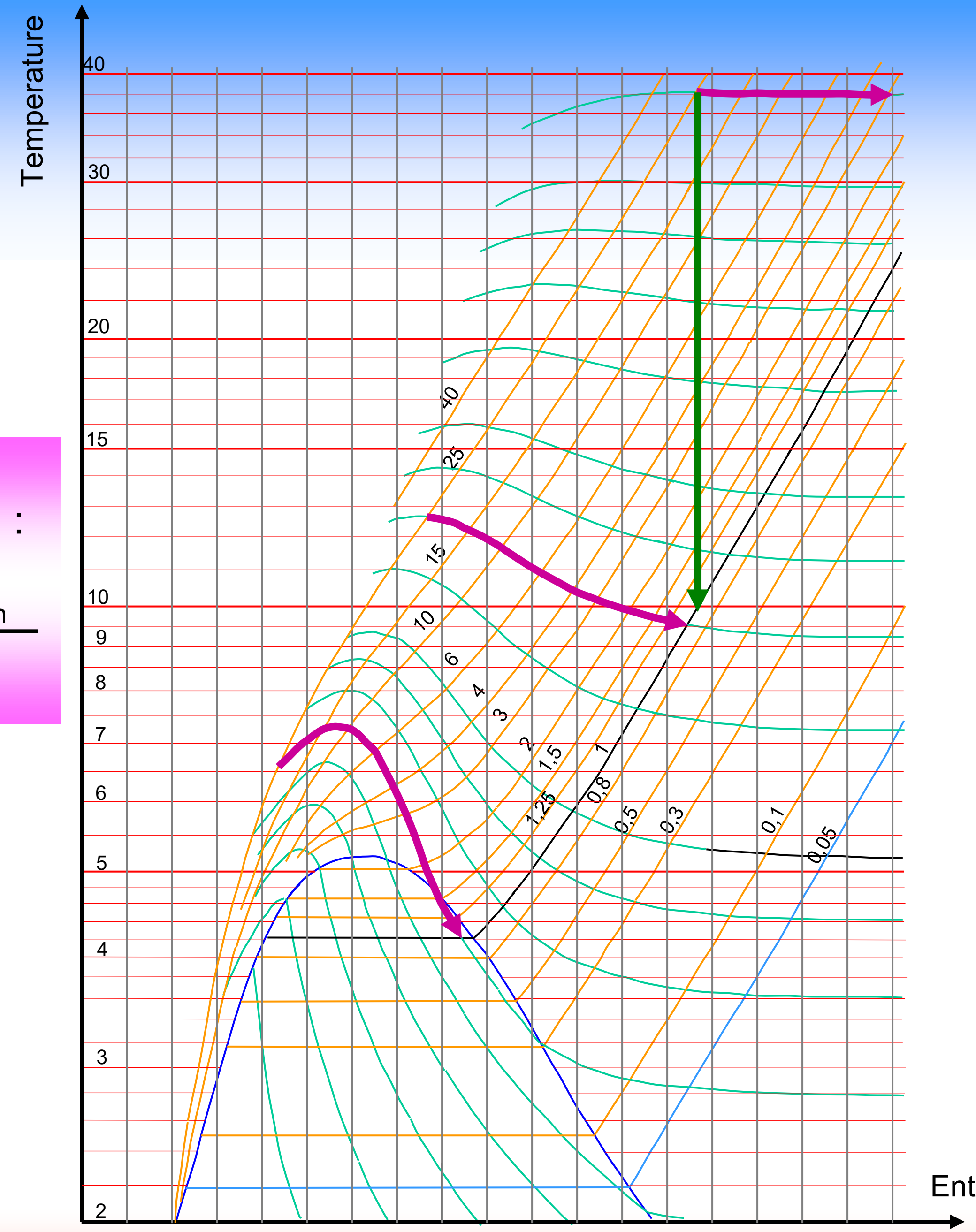
THE ISENTROPIC EXPANSION

Also said :
« with external work »

Isentropic effectiveness :

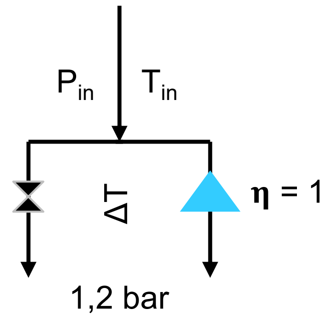
$$\eta_{is} = \frac{h_{out} - h_{in}}{h_{is} - h_{in}}$$





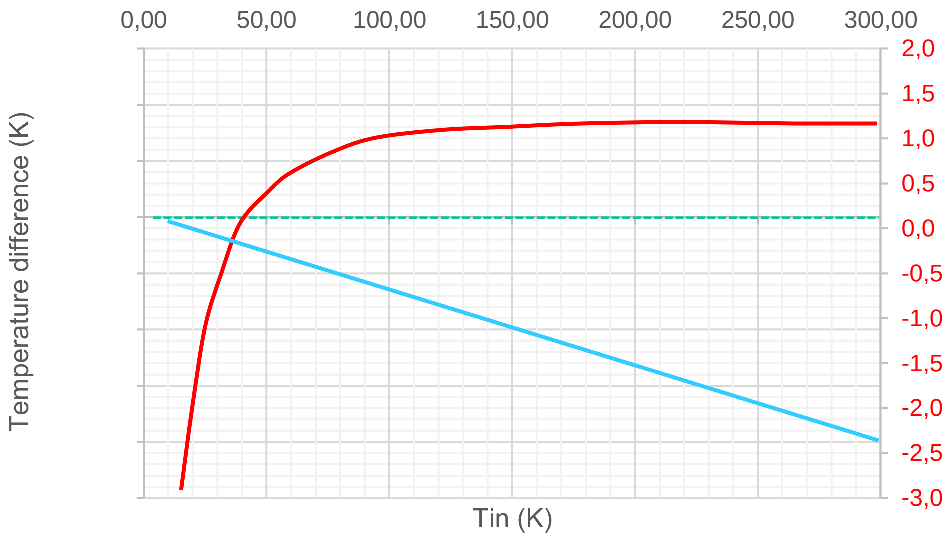
VARIOUS EXPANSIONS

Let's compare various ways of expanding helium :



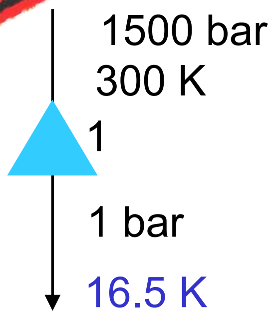
Through a valve (*isenthalpic expansion*)

Through an expander (expansion with external work or *isentropic expansion*)



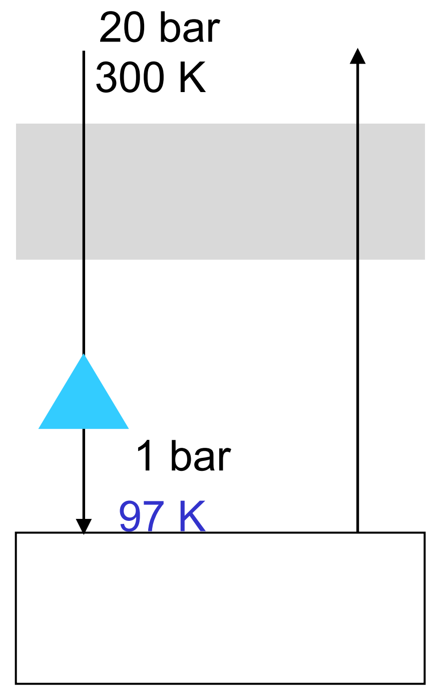
Isentropic effectiveness : $\eta_{is} = \dfrac{h_{out} - h_{in}}{h_{is} - h_{in}}$

THE ISENTROPIC EXPANSION OF HELIUM



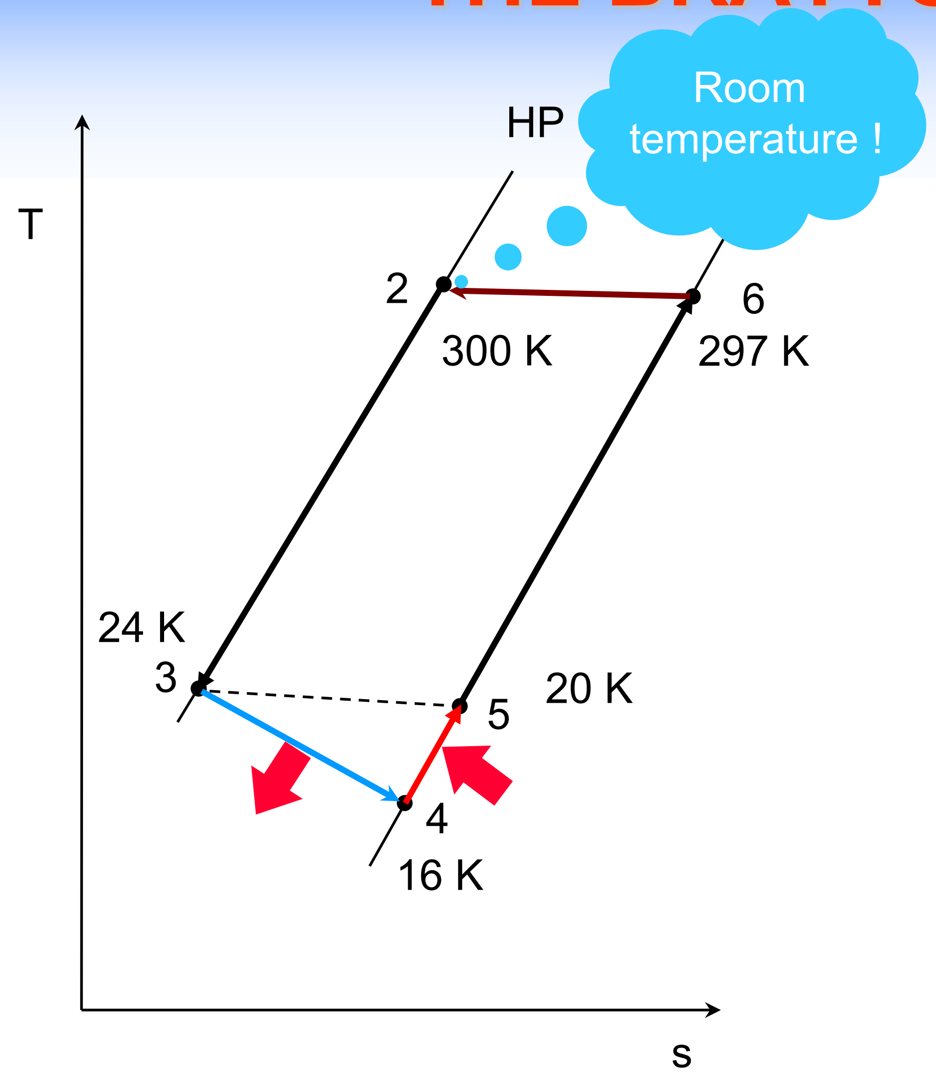
Liquefaction of helium is not possible by simple isentropic expansion only.

Why not use the cold expanded helium to "pre-cool " helium before expansion?

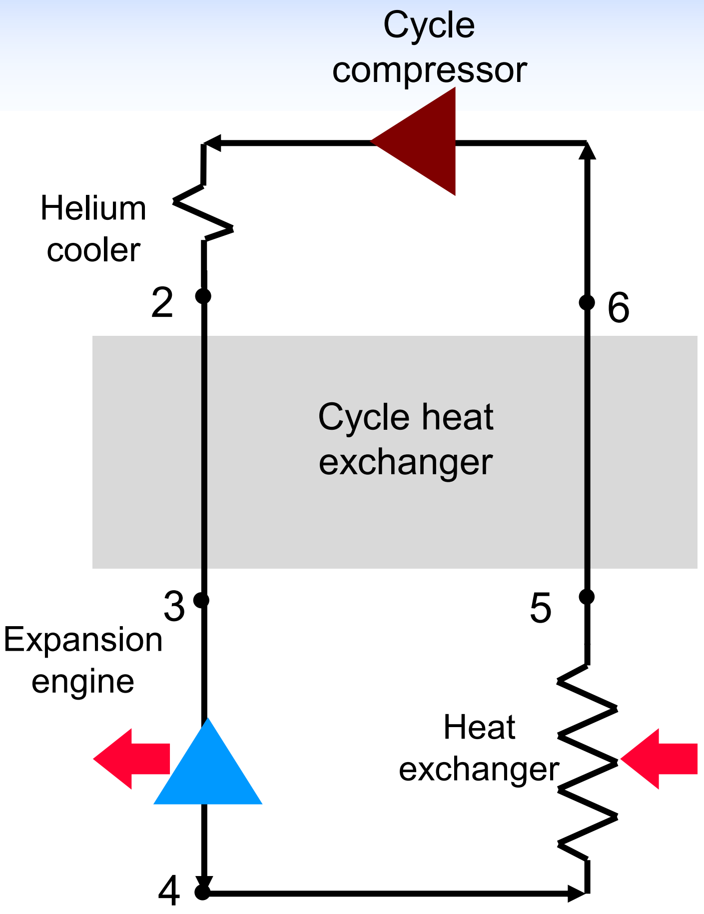


This is a **Brayton** cycle!

THE BRAYTON CYCLE



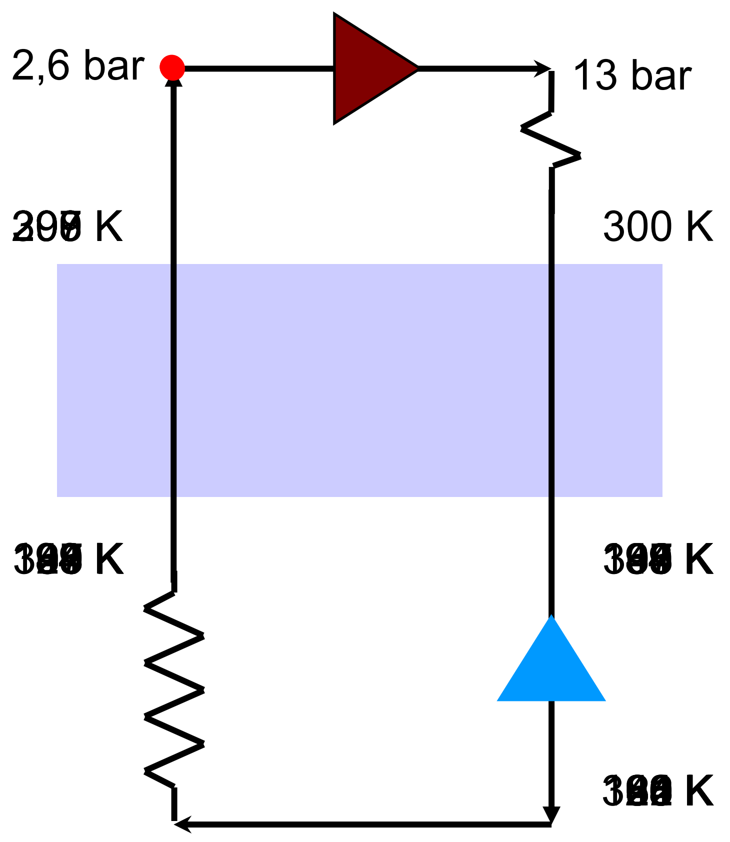
T-s DIAGRAM



FLOW DIAGRAM

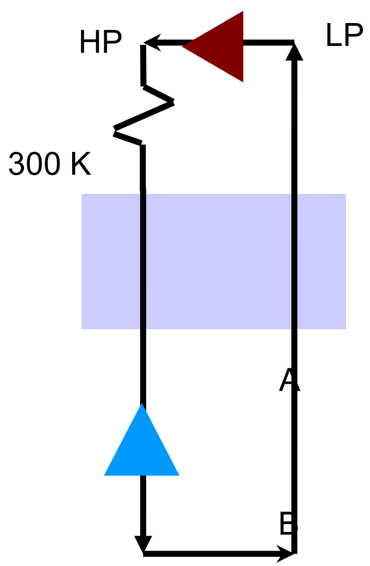
THE BRAYTON CYCLE

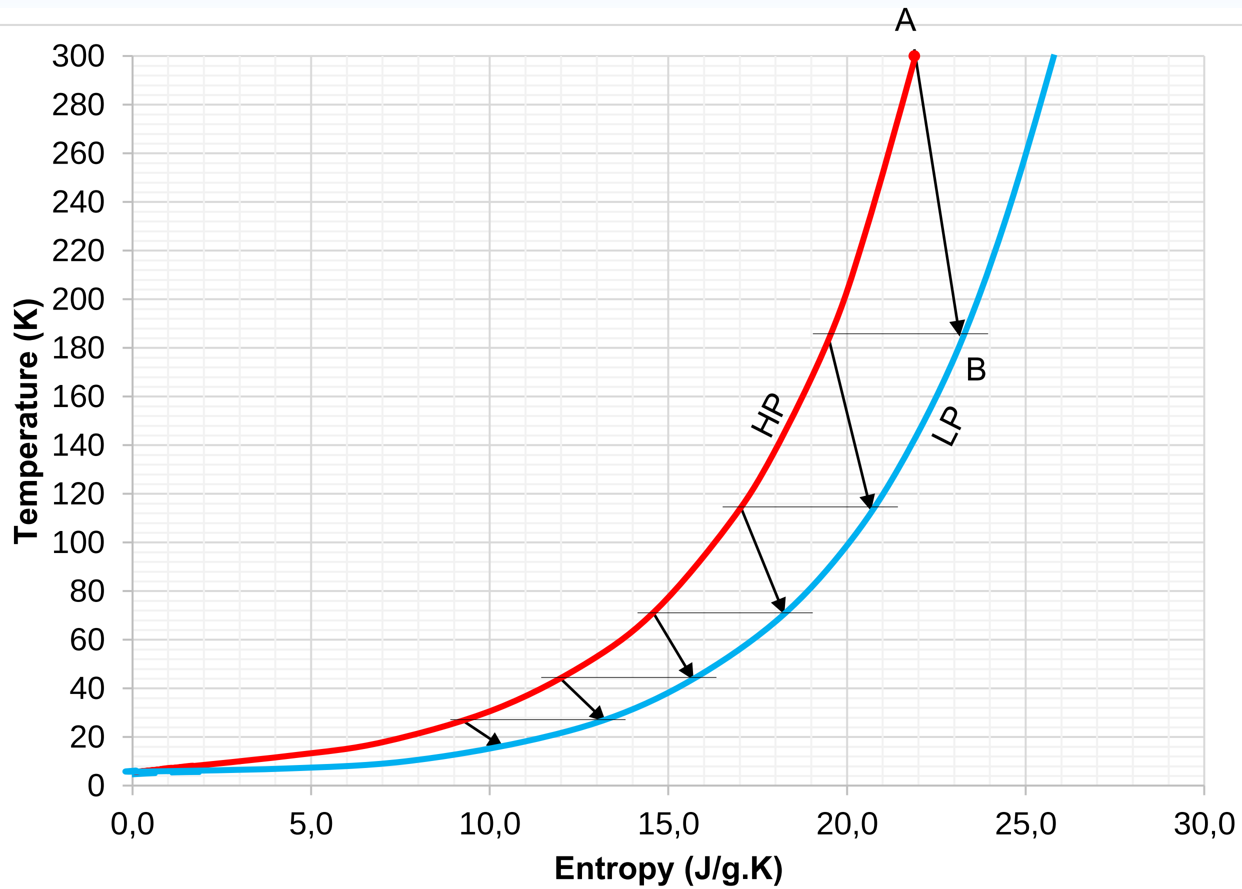
COOLING DOWN KINEMATICS



THE BRAYTON CYCLE

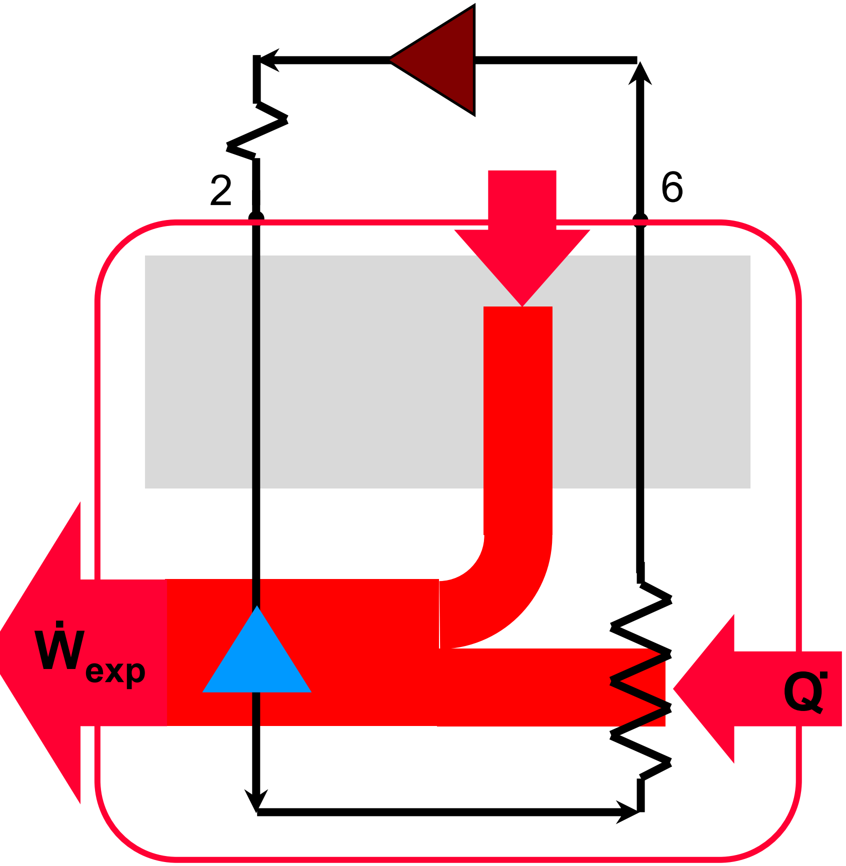
COOL-DOWN





THE BRAYTON CYCLE

"Refrigeration"



Balance :

$$(\dot{m} \times h_2) - \dot{W}_{exp} + \dot{Q} - (\dot{m} \times h_6) = 0$$

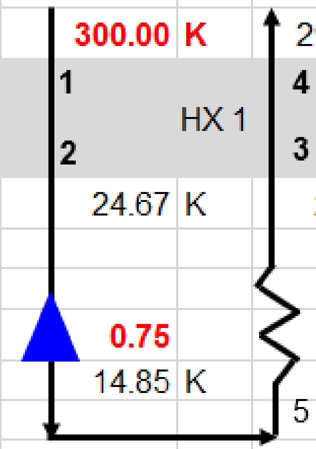
$$\dot{Q} + \dot{m} \times (h_2 - h_6) = \dot{W}_{exp}$$

Warm end + W :
Energy IN

Turbine :
Energy OUT

THE BRAYTON CYCLE

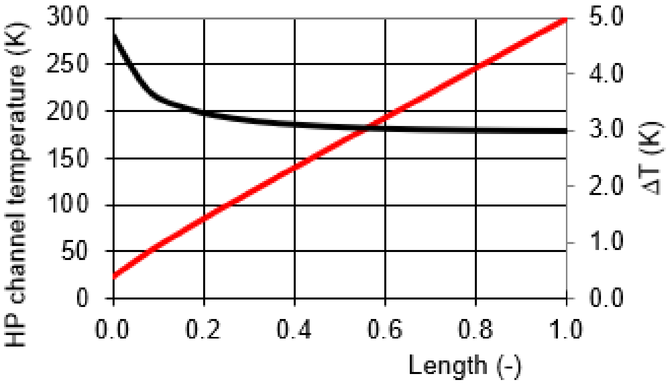
"Refrigeration"

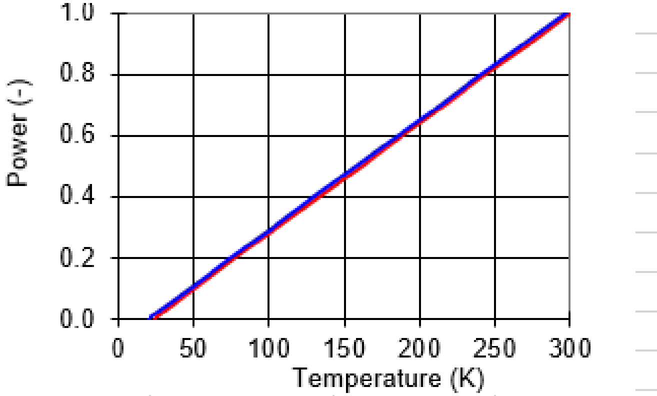


ΔT_w	3.00	K
$\dot{Q}$	51821	W
MTD	3.21	K
UA	16146	W/K
ΔT_c	4.67	K
$\dot{W}_{exp}$	-1736	W

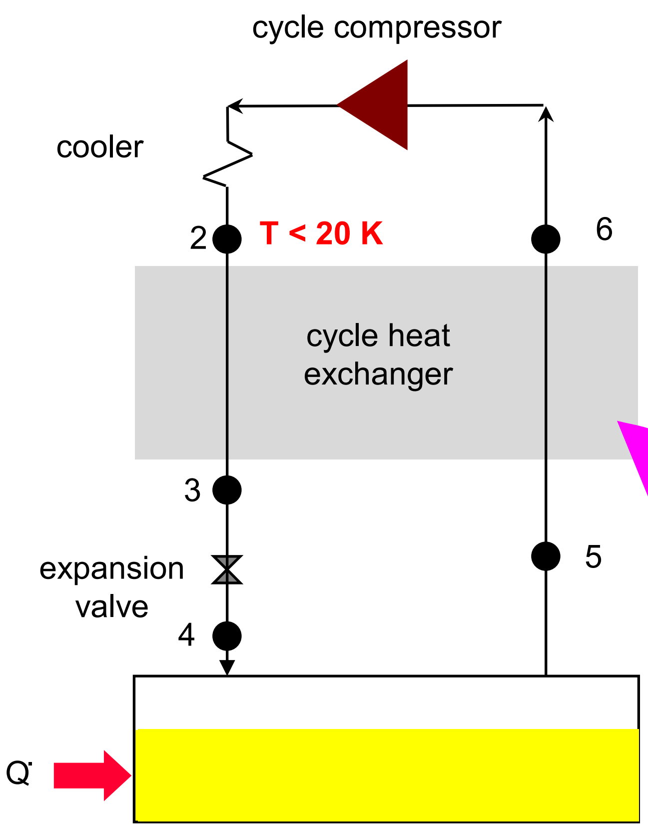
	P (bar)	T (K)	h (J/g)	ṁ (g/s)
1	18.00	300.00	1568.87	35.96
2	18.00	24.67	127.70	35.96
3	3.00	20.00	107.22	35.96
4	3.00	297.00	1548.39	35.96
2	18.00	24.67	127.70	35.96
5	3.00	14.85	79.41	35.96

THERMAL BALANCE	
Warm end	736.26
Turbine	-1736.26
Refrigeration	1000.00
Balance	0.00

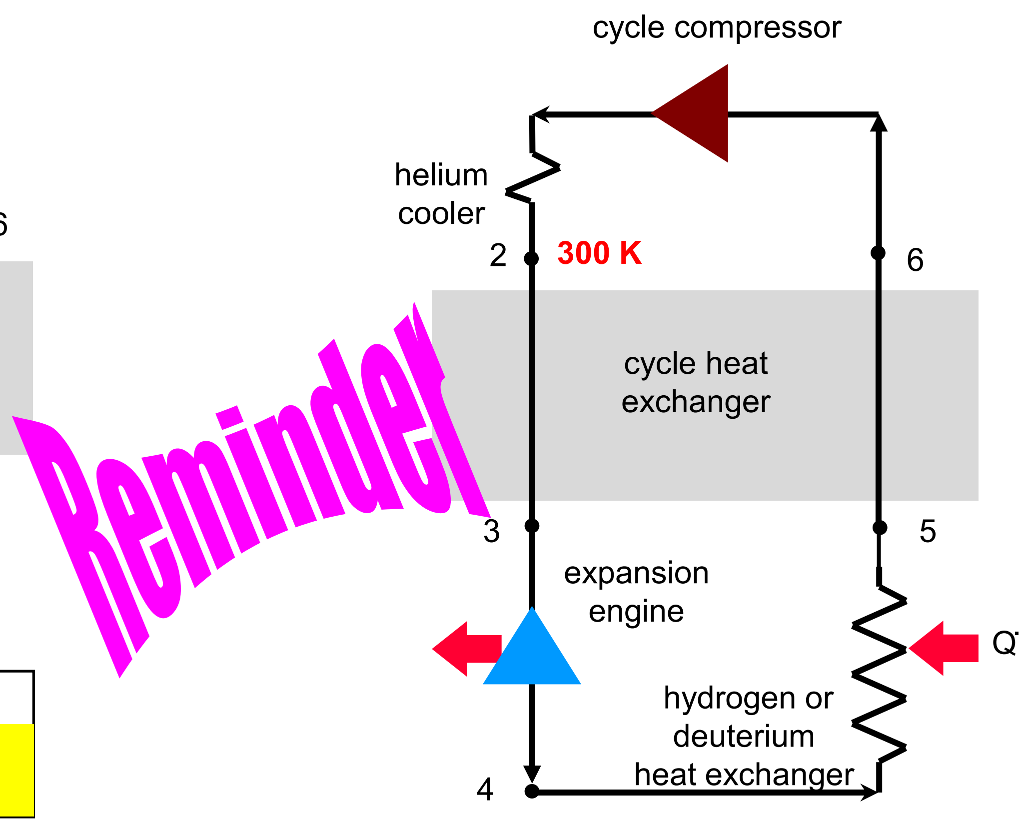




The Joule Thomson and the Brayton cycles are the fundamental bricks of any liquefaction or refrigeration cycle !

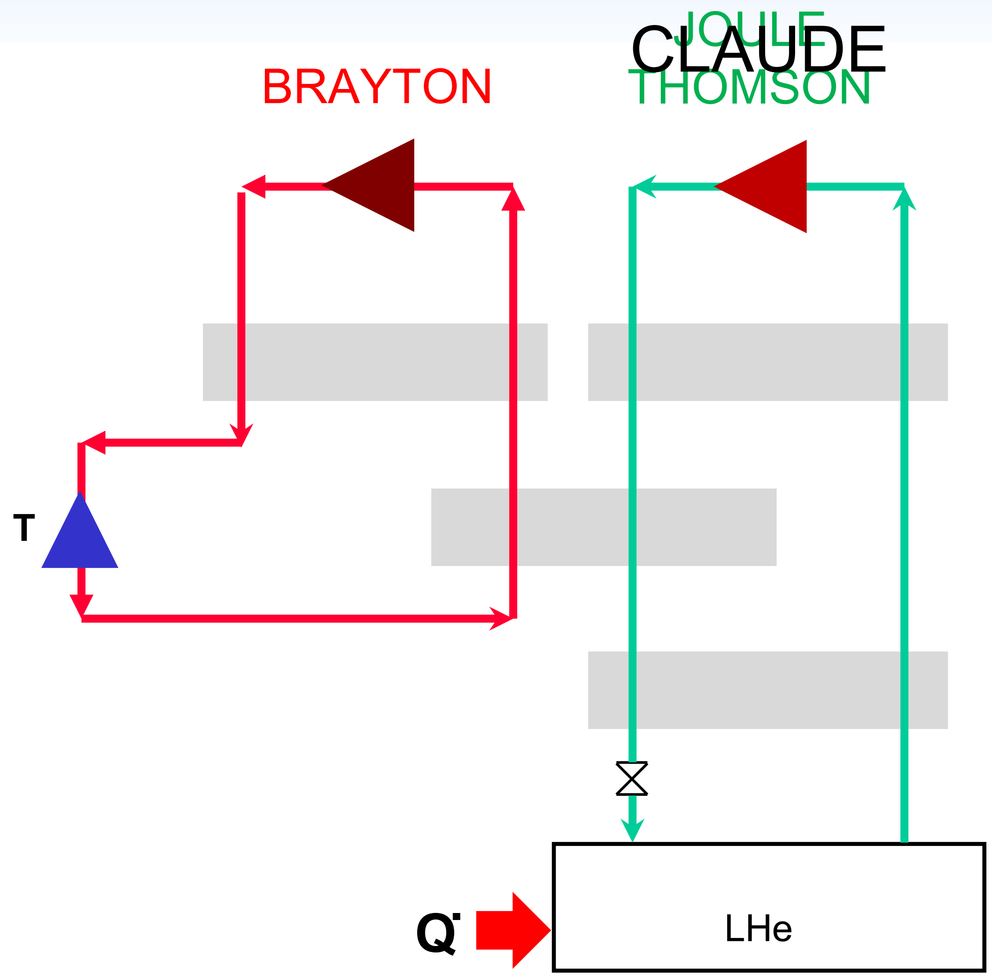


The Joule Thomson cycle

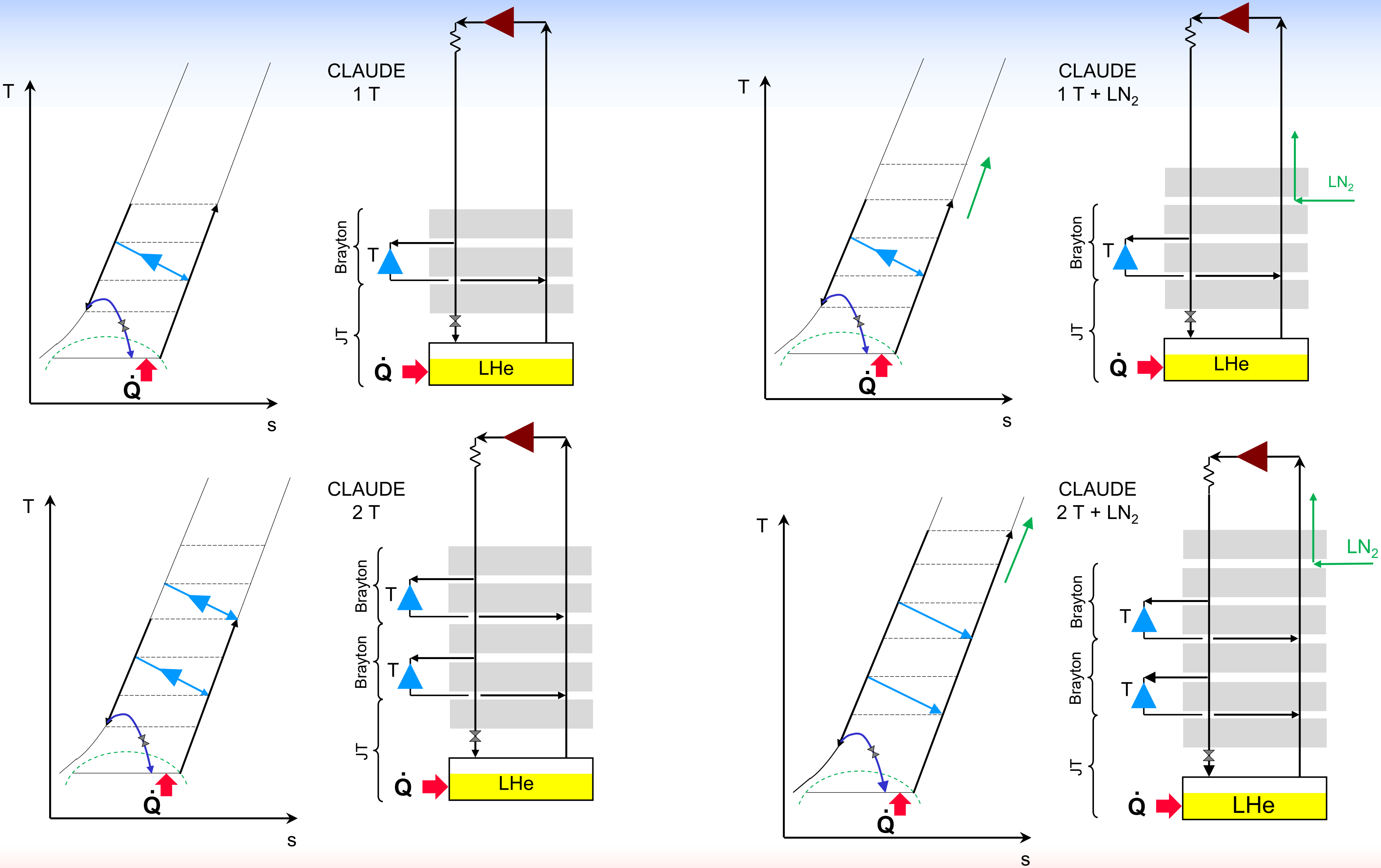


The Brayton cycle

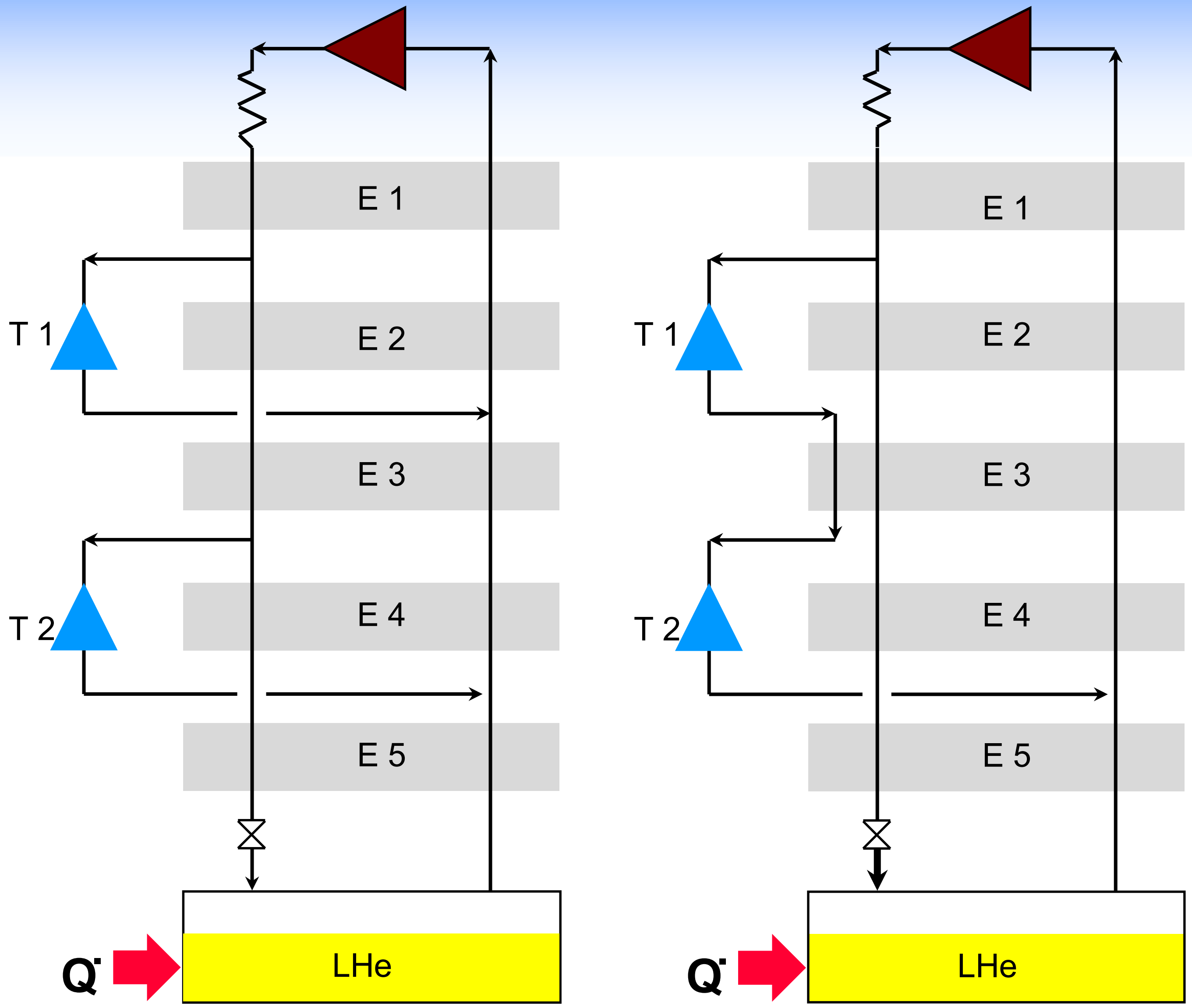
THE CLAUDE CYCLE 1 turbine



CLAUDE CYCLES



Turbines in parallel or in series ?



Turbines in a series arrangement are submitted to a lower expansion ratio, therefore, their effectiveness is higher.

Remark : the pressure between the turbines stabilises at a value that allows the same mass flow rate to be processed by both turbines.

EQUIVALENT POWER OF A REFRIGERATOR

A LEP refrigerator provides :

- 10000 W at 4.5 K
- 13 g/s of LHe at 1.3 b (4.5 K)
- 6700 W between 55 and 75 K

Is there a way to compare this refrigerator to another one ?

We can compare the entropic equivalent powers.

"Equivalent power"

EQUIVALENT POWER OF A REFRIGERATOR

$$\dot{W}_{Carnot} = \frac{T_w}{T_c} - 1$$

Inputs in **bold red**

Room temp.	**300**	(K)	Shields	Isothermal	Liquid	
Power		(W)	**6700**	**10000**		
T in		(K)	**55**	**4,5**	**4,5**	
T out		(K)	**75**			
P in		(bar)	**18**		1,30	
P out		(bar)	**17,5**			
Mass flow		(g/s)	63,69		**13**	
Carnot power		(W/W)	25639	656667	85656	767961
Carnot power at		4,5	K			65,67
Equivalent at	**4,5**	K	390	10000	1304	11695
Absorbed power				(W)		**2665000**
Specific power				(W/W)		227,9
Carnot yield						0,288

$$\dot{W}_{Carnot} = \dot{m} \times [(T_w \times \Delta s) - \Delta h]$$

EVALUATION OF THE PERFORMANCE OF A REFRIGERATOR

Example : the LEP refrigerators

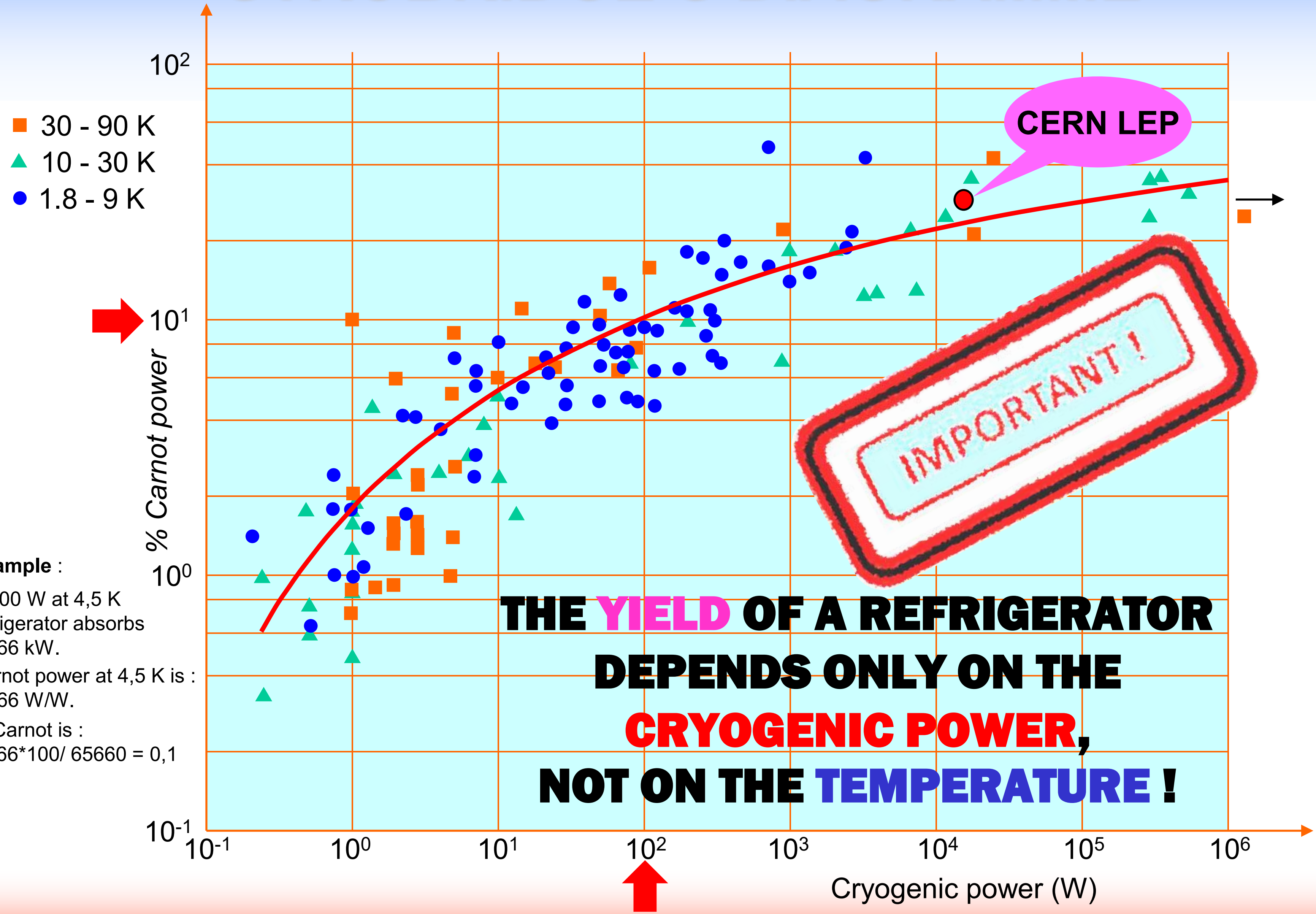
(the equivalent power at 4.5 K is 12 kW)

Ideal power (Carnot)	768000 W
Actual power absorbed by the compressors	2665000 W

$$\text{Efficiency (compared to Carnot)} = \frac{\text{Ideal power (Carnot)}}{\text{Actual power absorbed by the compressors}} = \frac{768000}{2665000} = 0.29$$

$$\text{Coefficient of performance (COP)} = \frac{\text{Actual power absorbed by the compressors}}{\text{Equivalent power}} = \frac{2665000}{12000} = 222 \text{ W/W}$$

STROBRIDGE'S DIAGRAMME



Example :

A 100 W at 4,5 K refrigerator absorbs 65.66 kW.

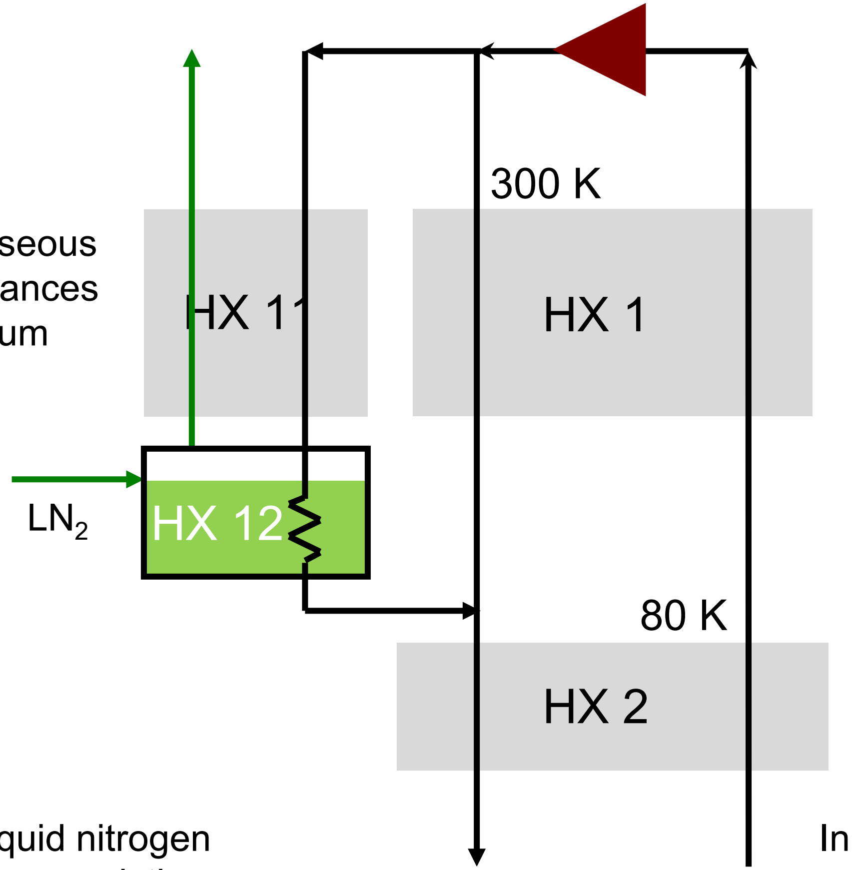
Carnot power at 4,5 K is : 65.66 W/W.

% Carnot is : 65.66*100/ 65660 = 0,1

THE YIELD OF A REFRIGERATOR DEPENDS ONLY ON THE CRYOGENIC POWER, NOT ON THE TEMPERATURE !

SEPARATE NITROGEN HEAT EXCHANGER ARRANGEMENT

In HX 11, the gaseous nitrogen flow balances the liquefied helium flow.



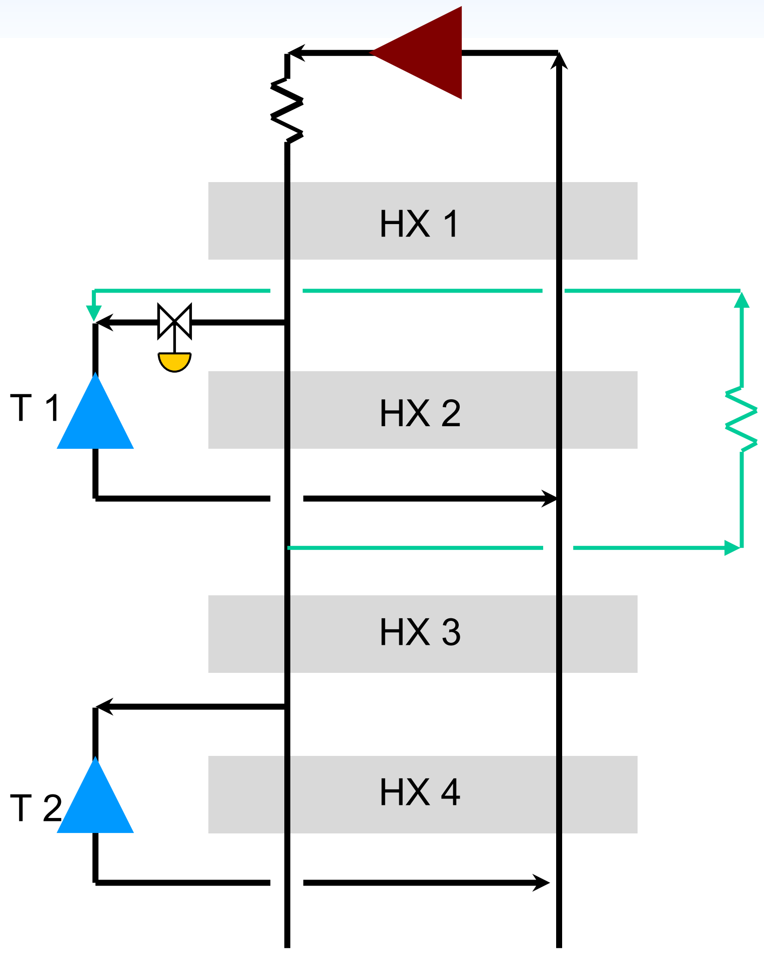
In HX1, the high pressure and low pressure flows are balanced.

A possibility to add a liquid nitrogen pre-cooling capability to an existing liquefier.

In a **refrigerator** mode, no risk of solidifying nitrogen in case of an important low pressure flow.

CIRCULATING IN SHIELDS (5)

The optimal solution !



HIGH POWER REFRIGERATION

After what we have learned about basic refrigeration cycles, how to design an efficient cycle for a high power?

GENERAL RULES (1)

THERMODYNAMICS

Please Mr CARNOT : have a big number of cooling stages

Expand all the available mass flow rate down to the lowest possible pressure.

Have the smallest but reasonable temperature differences in the heat exchangers.

Operate each machine at its highest effectiveness (if possible).

But, combine operating conditions of the various machines in order to reach the highest **global** refrigerator yield.

GENERAL RULES (2)

COMMON SENSE

Fight against any pressure drop:

- In the refrigerator and distribution cold circuits,

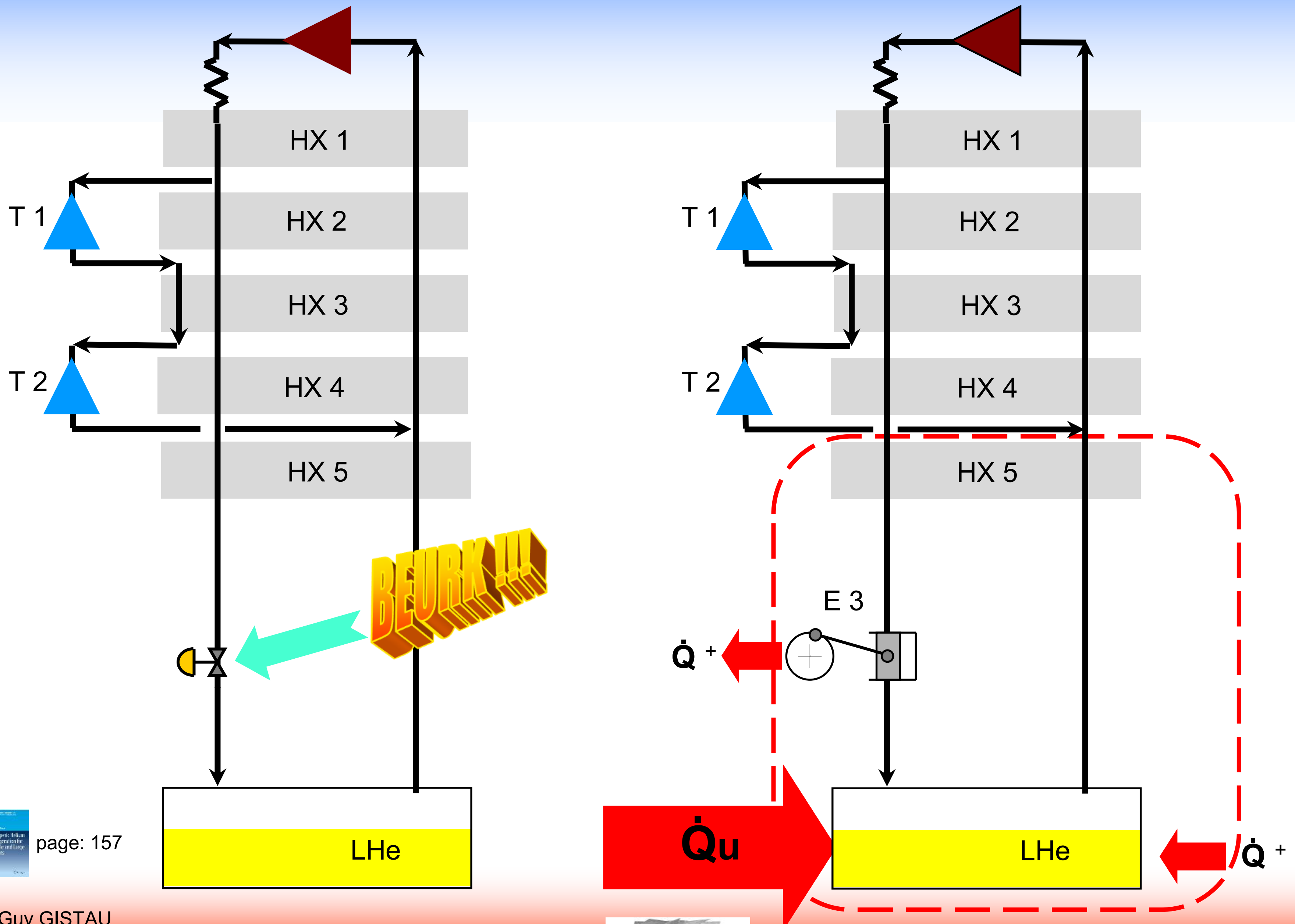
  (Even worse if a cryogenic circulator is used)

- In the refrigerator and distribution thermal shield circuits.

This is the “refrigerator guy” duty.

But the “refrigerator guy” has also to have an eye on the “customer” circuits in order to be sure that their sizing will result in acceptable pressure drops.

THE “JT” EXPANSION



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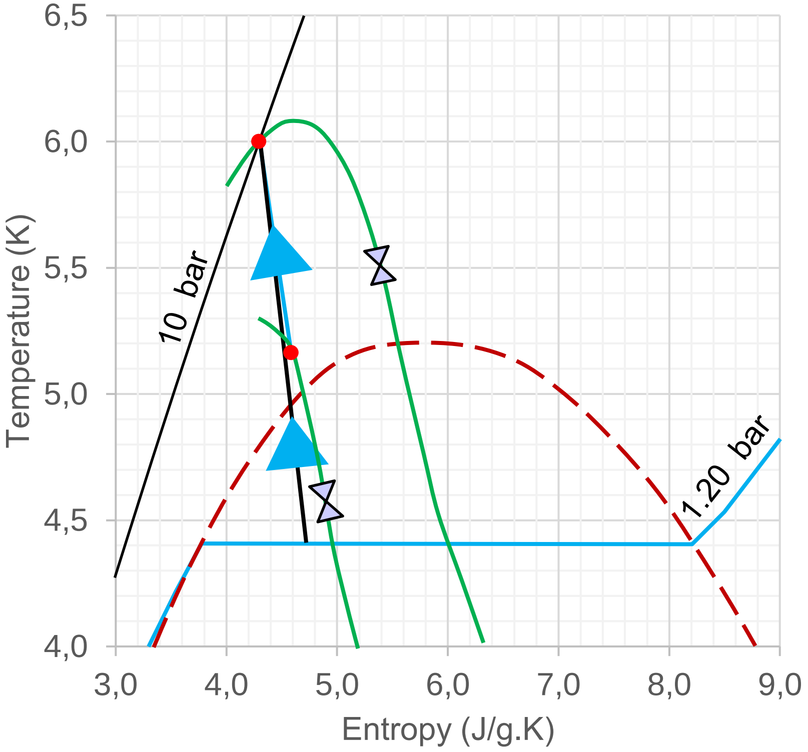
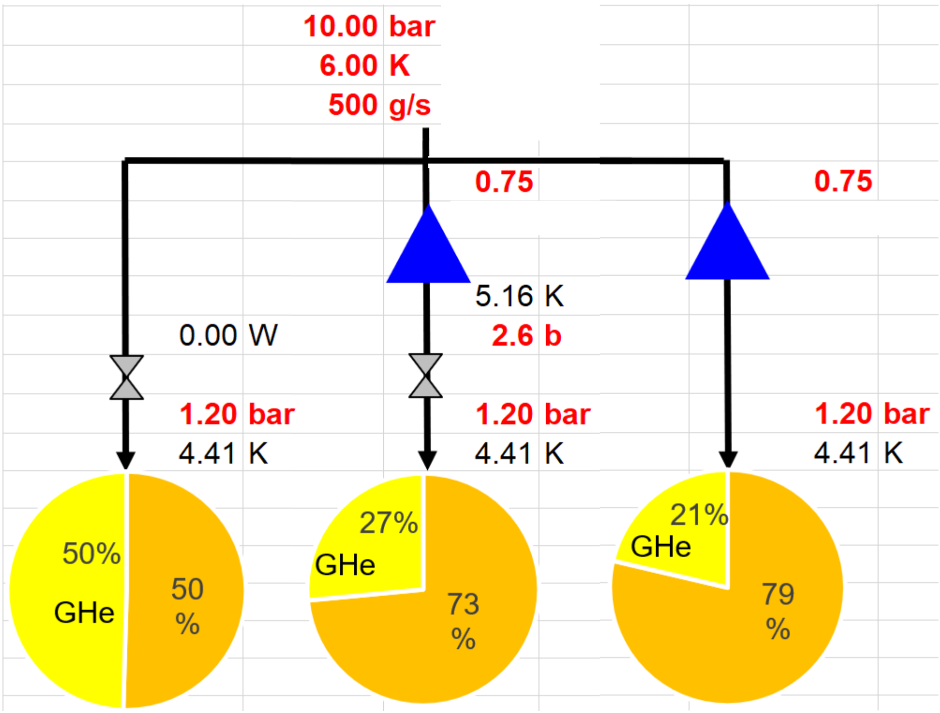
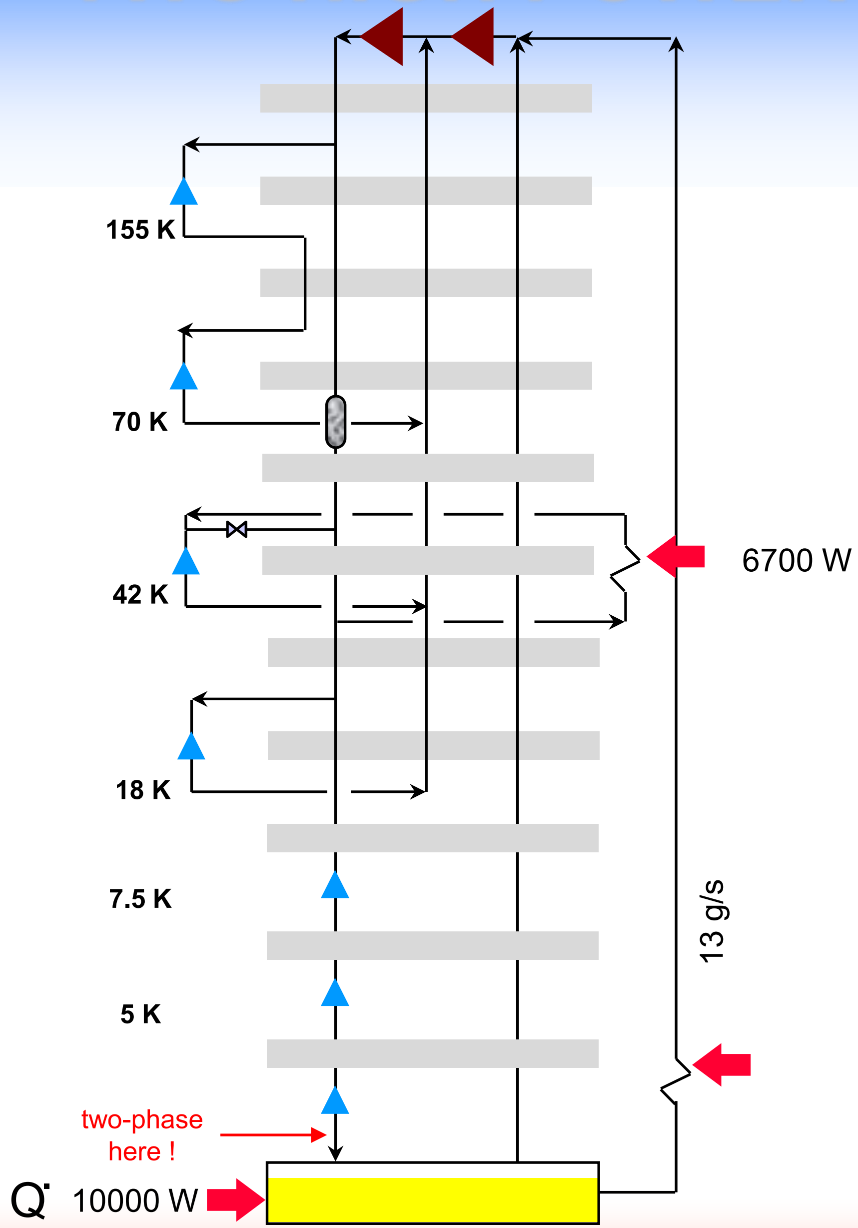
INTEREST OF A TURBINE EXPANDING INTO LIQUID

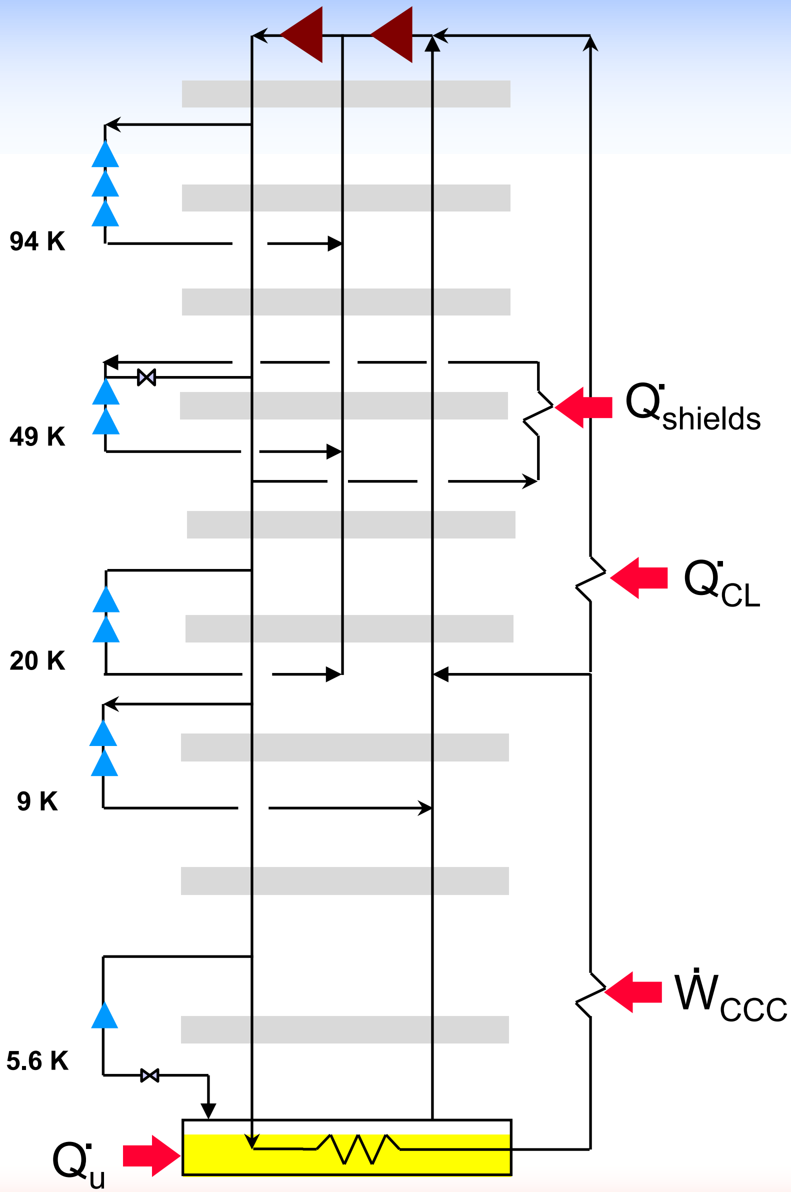




TWO HIGH POWER REFRIGERATORS



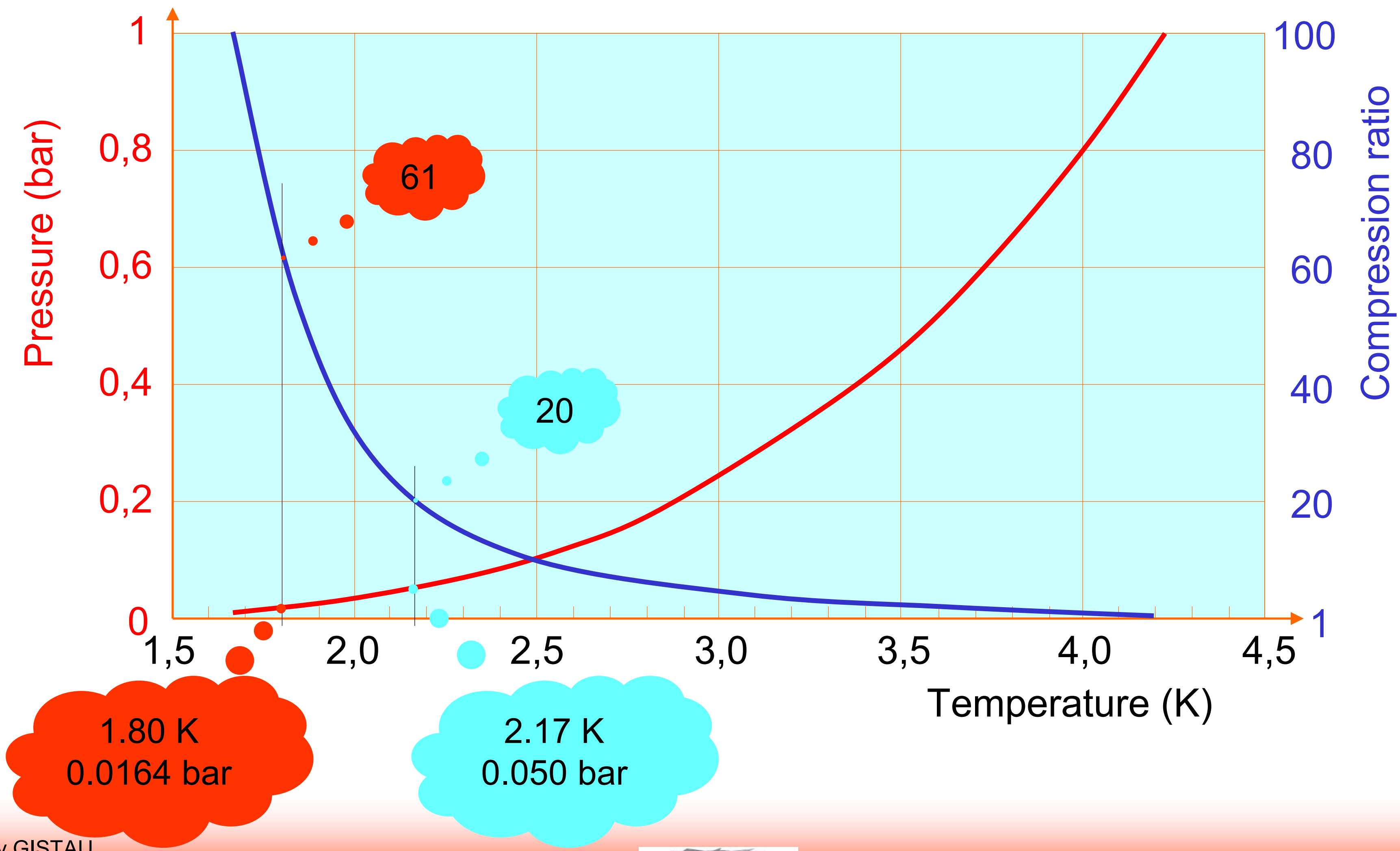
AIR LIQUIDE (LEP)



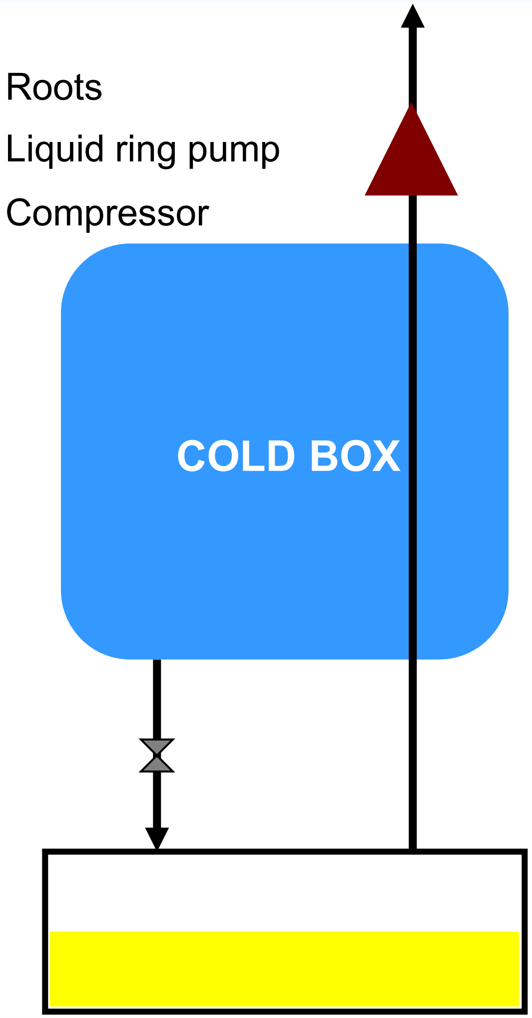
LINDE (LHC)

REFRIGERATION
AT TEMPERATURES LOWER THAN 4.5 K

LHe SATURATED PRESSURE



PUMPING ON LIQUID HELIUM



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The easiest way.

The most efficient in a pure thermodynamical way.

−

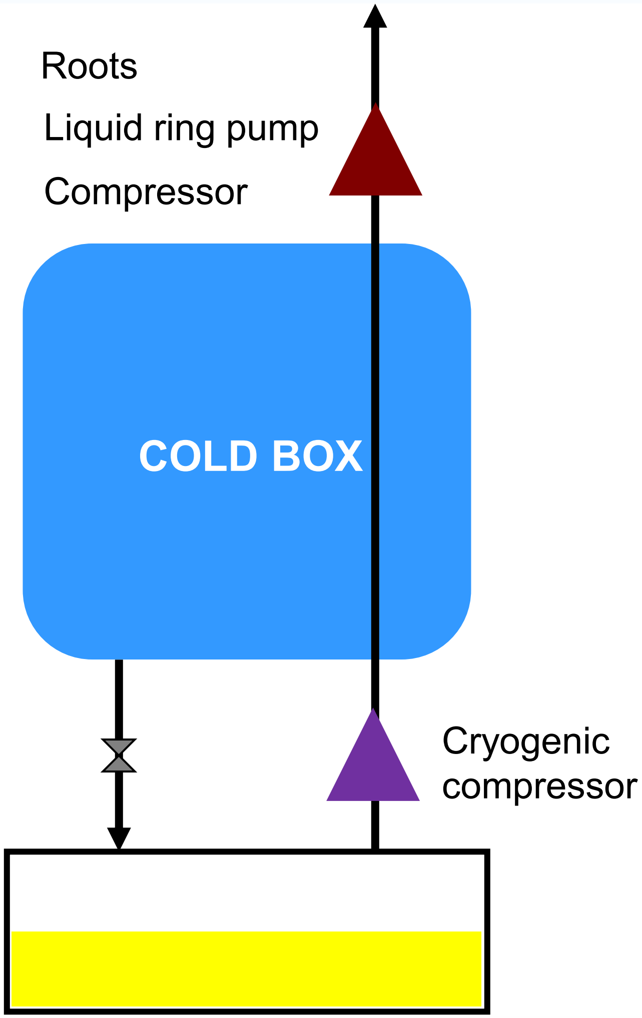
The machine volume flow rate can be very large if high power and/or low temperature.

If low temperature, the heat exchanger is very unefficient : heat losses are large.

If low temperature, the machine is not very efficient.

Possible air leaks into the circuits.

PUMPING ON LIQUID HELIUM



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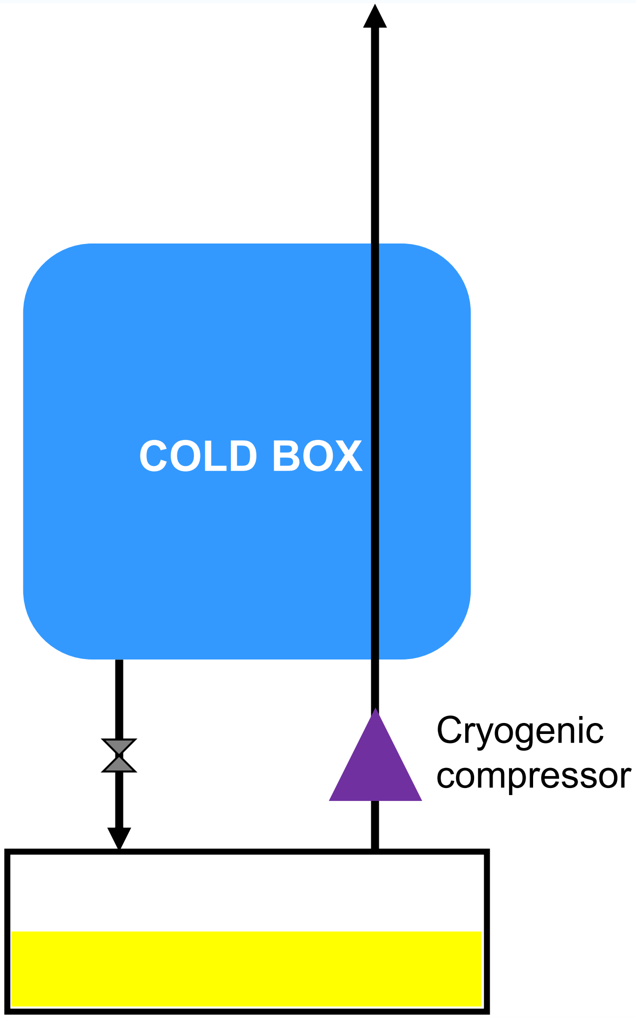
The room temperature machine volume flow rate is reasonable, even if high power and/or low temperature.

The refrigerator has to take care of the cryogenic compressor heat load BUT the cryogenic compression ratio is lower .

−

Possible air leaks into the circuits.

PUMPING ON LIQUID HELIUM



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No more air leaks into the circuits.

−

The refrigerator has to take care of the cryogenic compressor heat load.

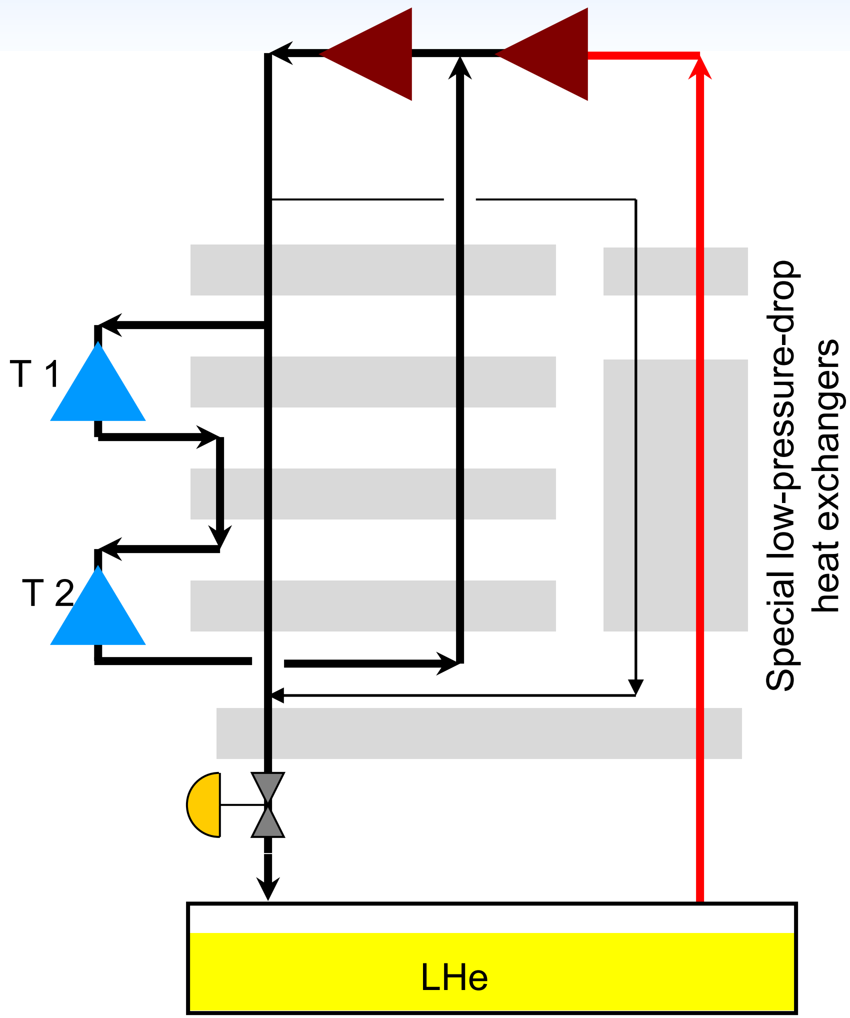
If low temperature, the heat load of the cryogenic compressor is large.

SUB-ATMOSPHERIC SURPRESSOR

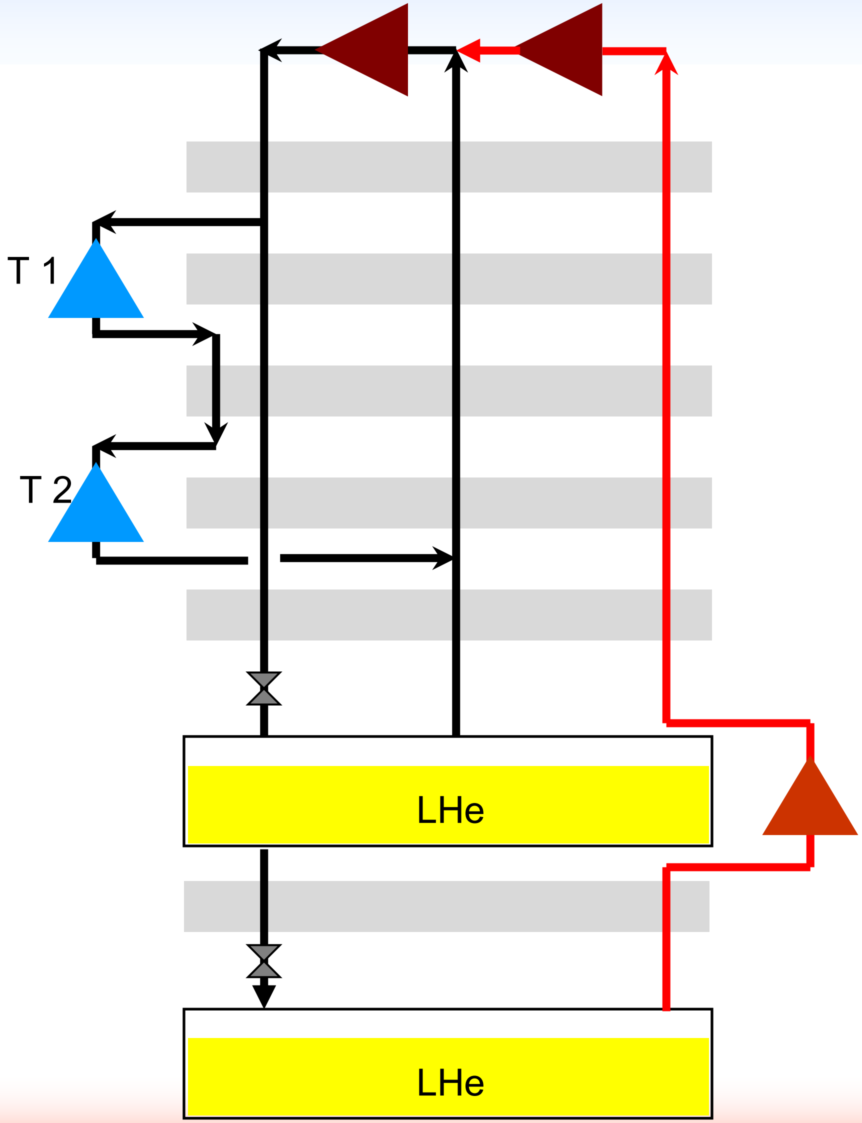
Remember !

It is not possible to have an efficient low-pressure-drop
heat exchanger.

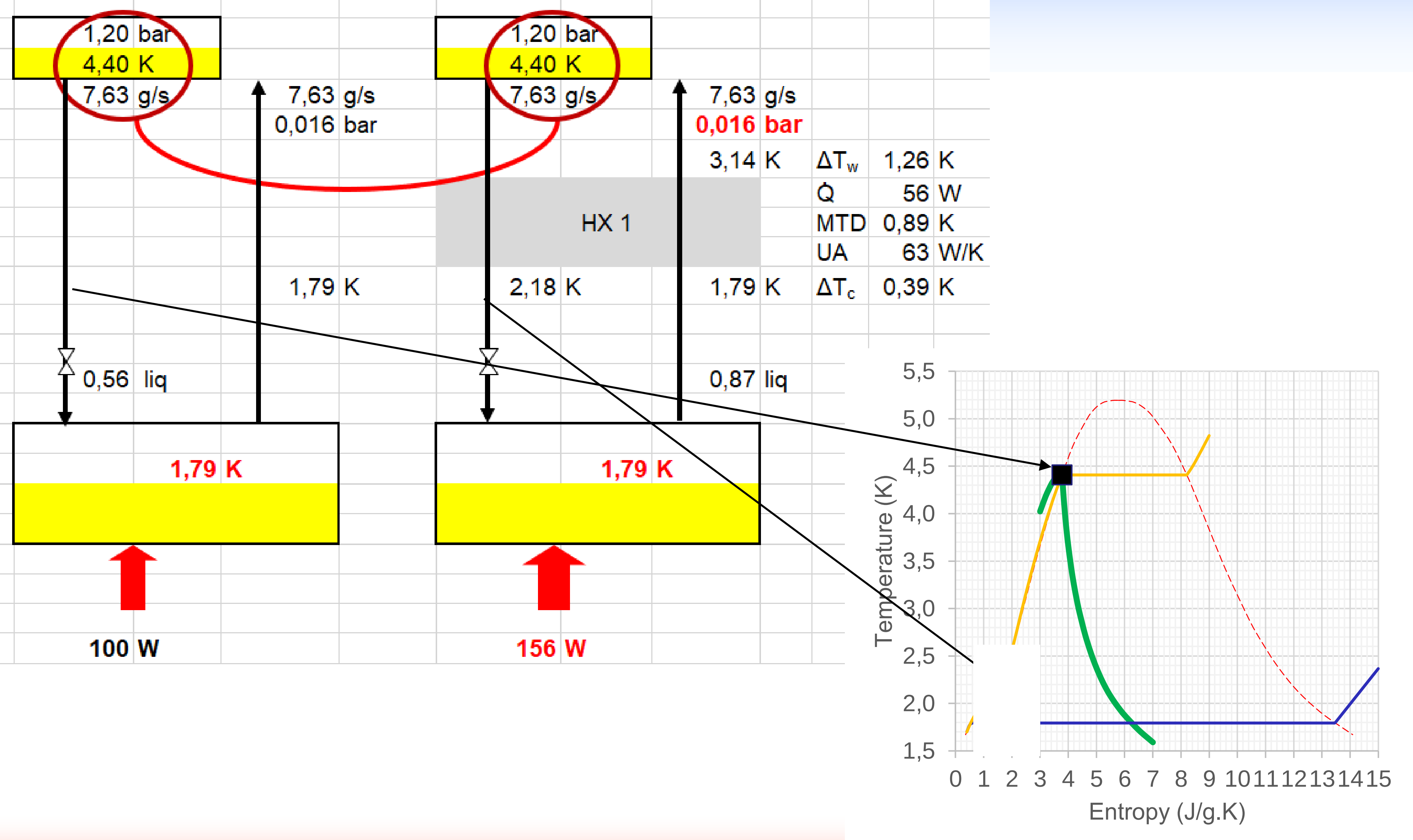
Low-pressure-drop means low heat exchange coefficient.



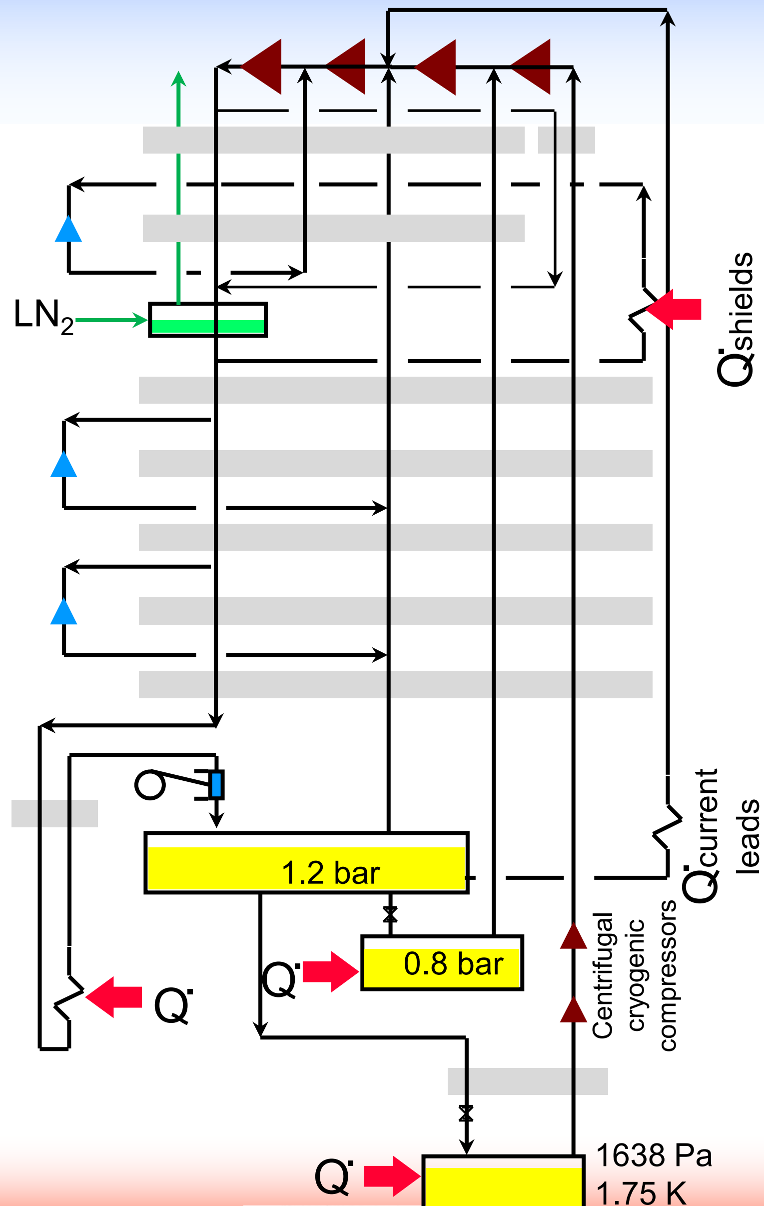
MIXED PUMPING



NECESSITY OF THE JT HEAT EXCHANGER

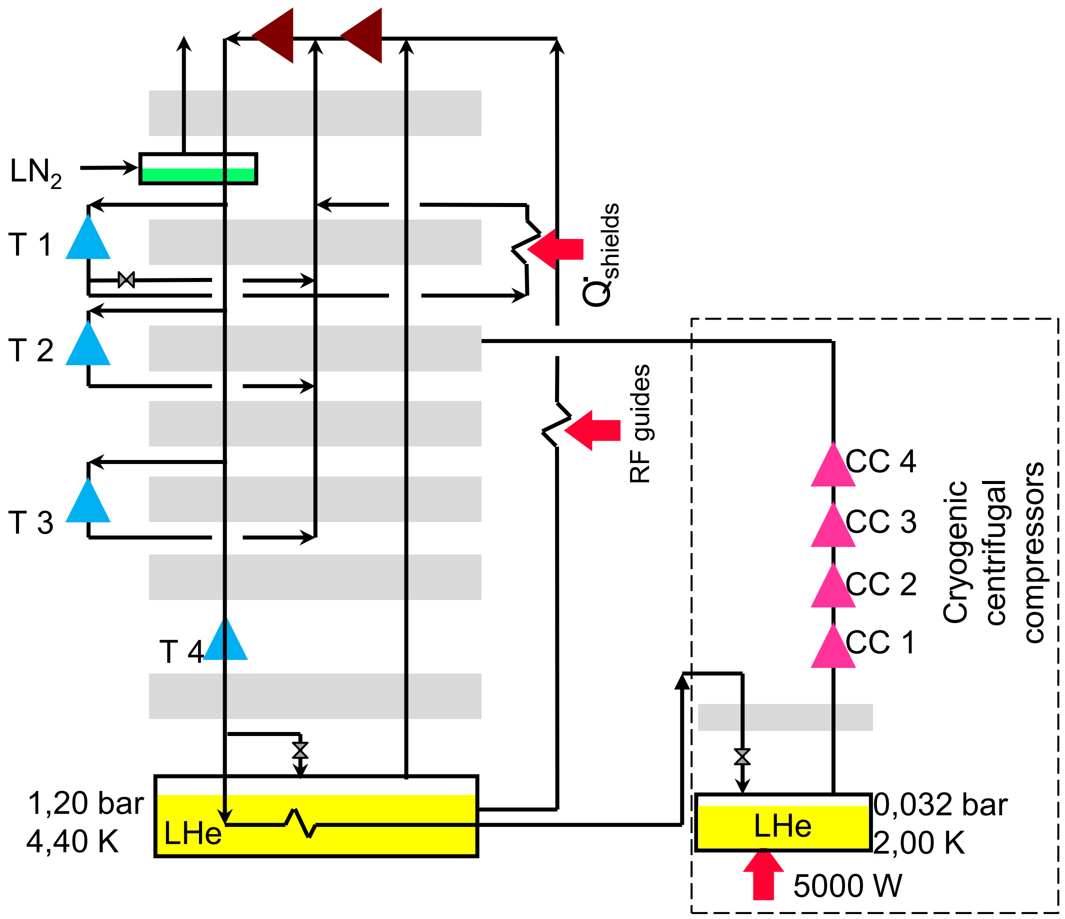


TORE SUPRA (WEST) REFRIGERATOR



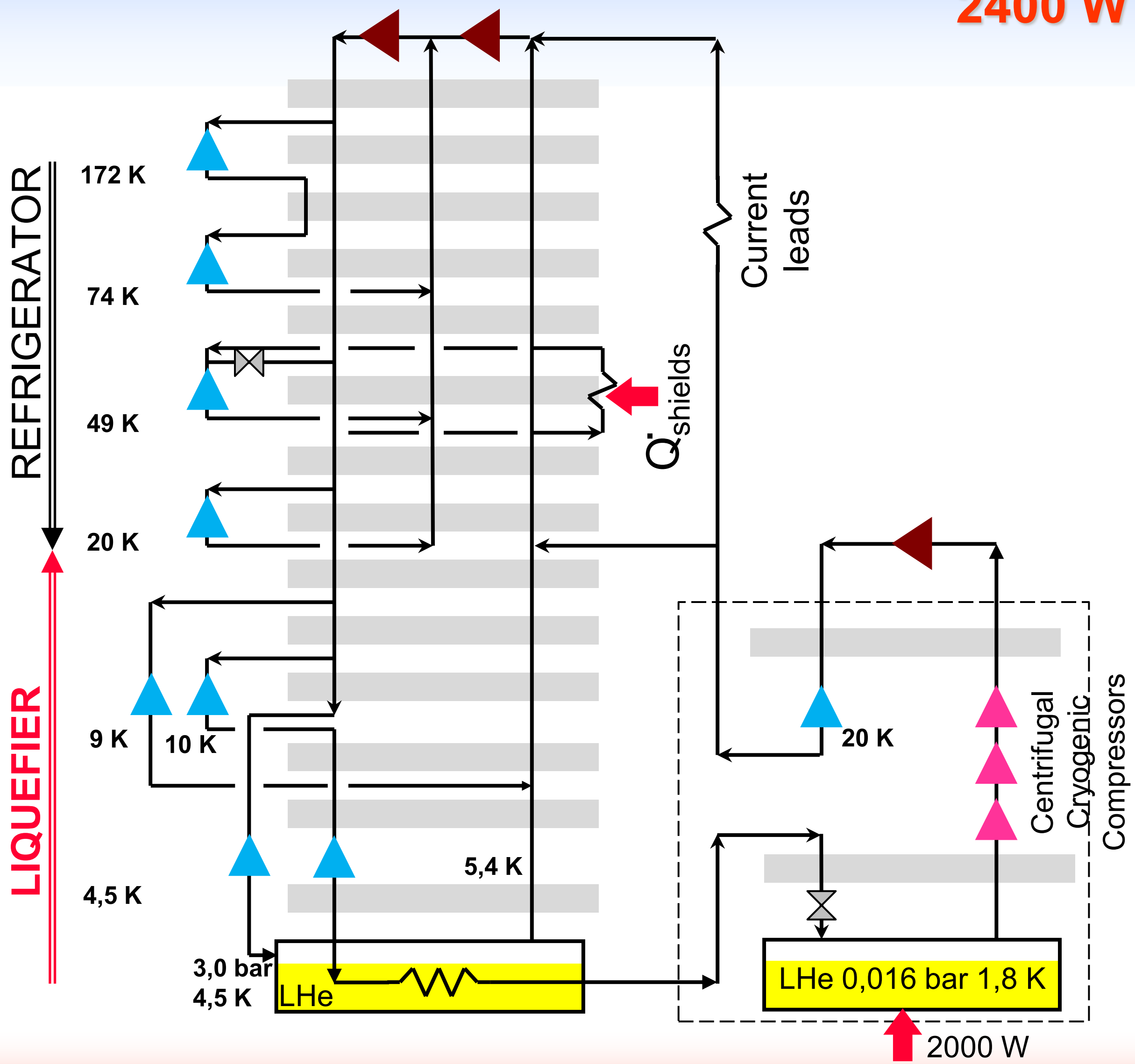
CEBAF REFRIGERATOR 5.0 kW at 2.0 K

5000 W at 2.0 K



A LHC REFRIGERATOR, 2.4 kW at 1.8 K

2400 W at 1.8 K



CRYOGUY