Cryogenics/ Superconductivity for Accelerator & Liquefaction of Gases

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My First Visit to CHINA (Memorable 15 days)

Jubilant Superconducting Cavity Team after Successful Test at 4. 2 K

ASIAN ACCELERATOR SCHOOL AT BEIJING IN Dec. 1999

In 1999, Helium Liquefier in China with capacity > 50 L/hr was almost not there.

Today China is the potential hub on using LHe for their ambitious Accelerator/ Fusion Programme along with MRI

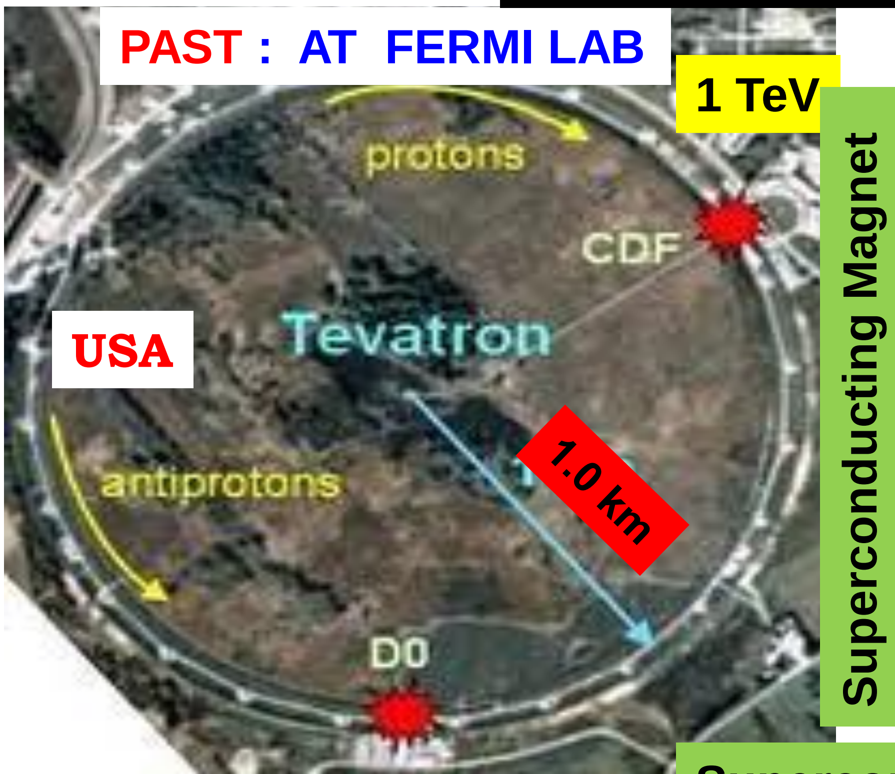
Realization of High Power Accelerator (LHC. ILC) is possible because of Superconductivity & Cryogenics

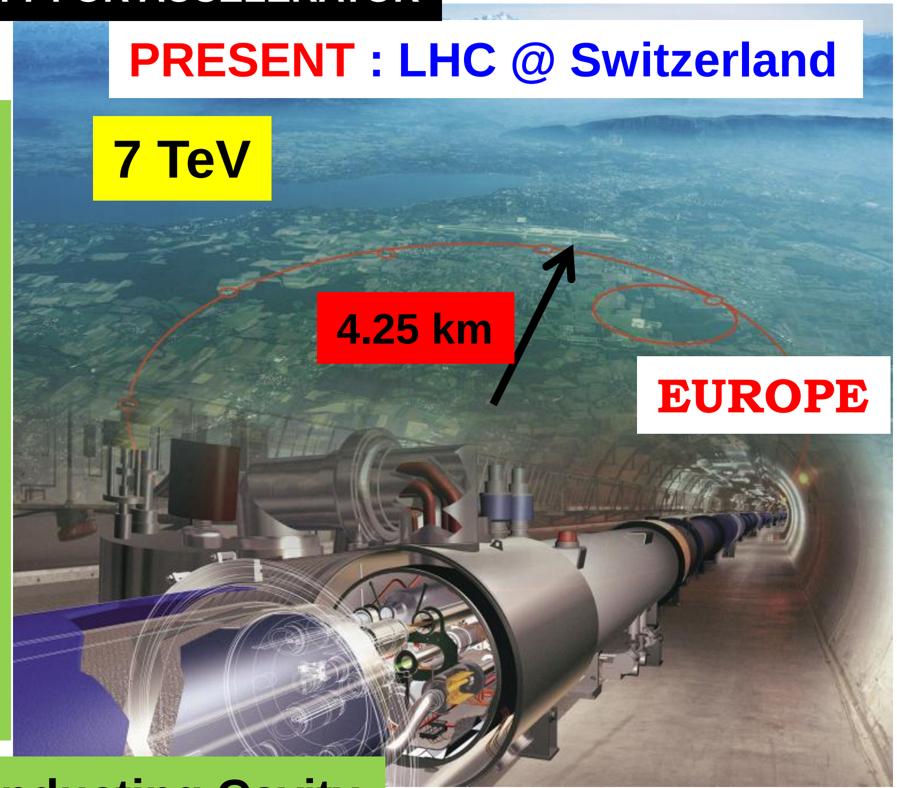
1. Compact Size
2. Low Power Consumption

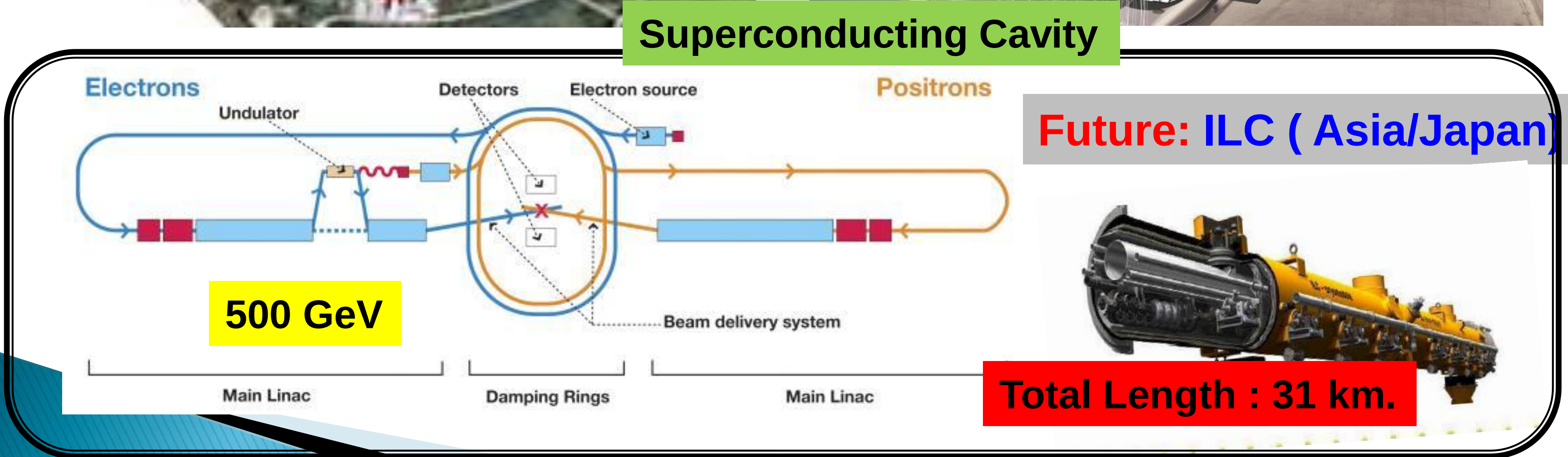
Outline of my Lectures

1. Role of Superconductivity & Cryogenics for Accelerator : Introduction & Definitions :
2. Thermodynamics and Thermodynamic Process for Liquefaction
3. Liquefaction Cycles and their performance Parameters

SUPERCONDUCTIVITY FOR ACCELERATOR







Cryogenics

Greek Word (12 th Century)

- **Icy Cold**
- **Production**

Where is the Boundary for Cryogenic Range : 120 K (- 153 C) ???

In India Cryogenics became a house hold name when Russia declined to Supply Cryogenic Engine with Technology to Indian Space Research Organisation (ISRO)

CE 7.5 Engine

Development of Cryo Engine in India

SUPERCONDUCTIVITY

Superconductivity – The phenomenon of losing resistivity **R=0** when sufficiently cooled to a very low temperature (below a certain critical temperature).

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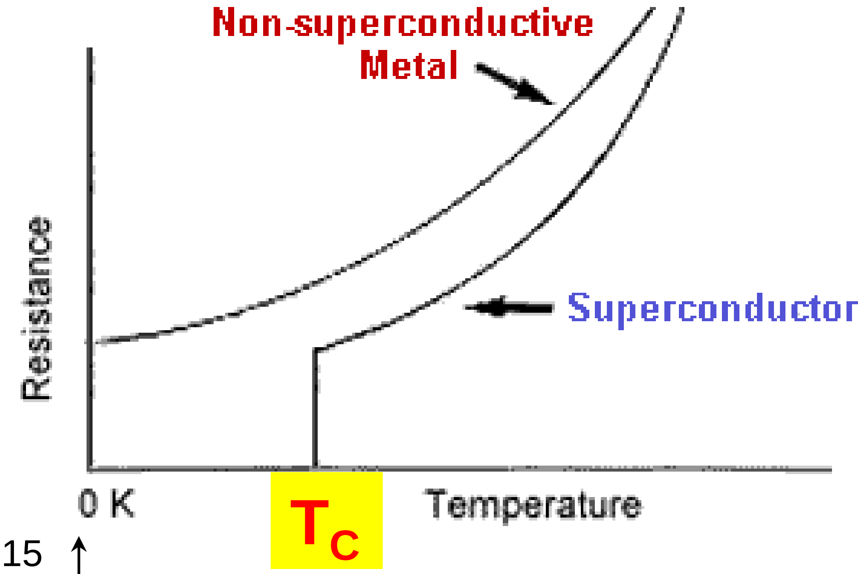
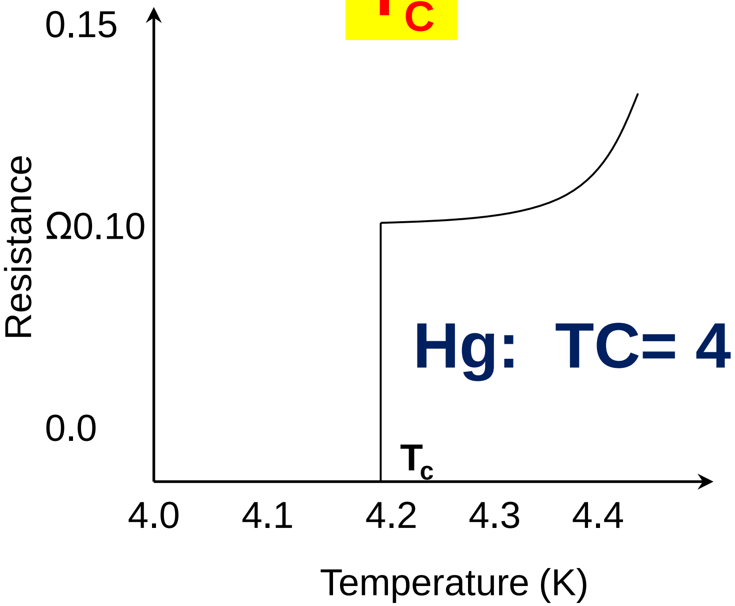


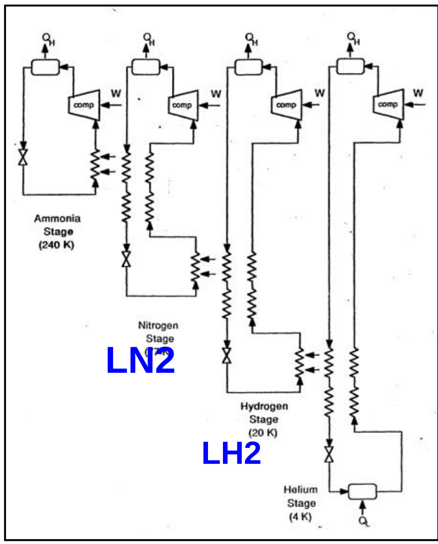


1908 : Heike Kamerlingh Onnes Succeeded in Liquefying Helium

1911 : Discovery of Superconductivity

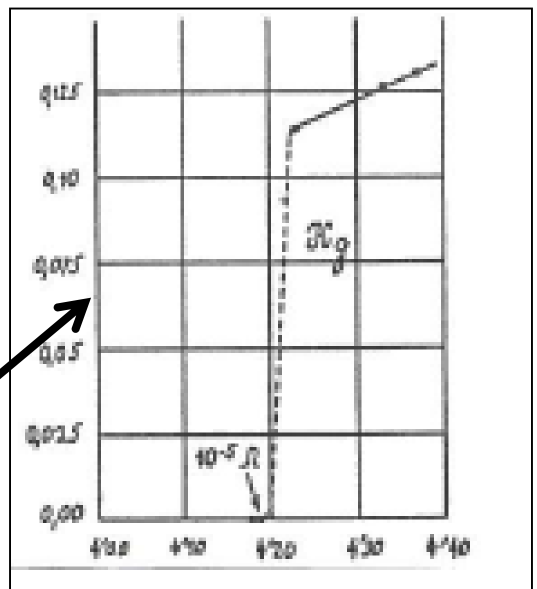
(1853-1926)

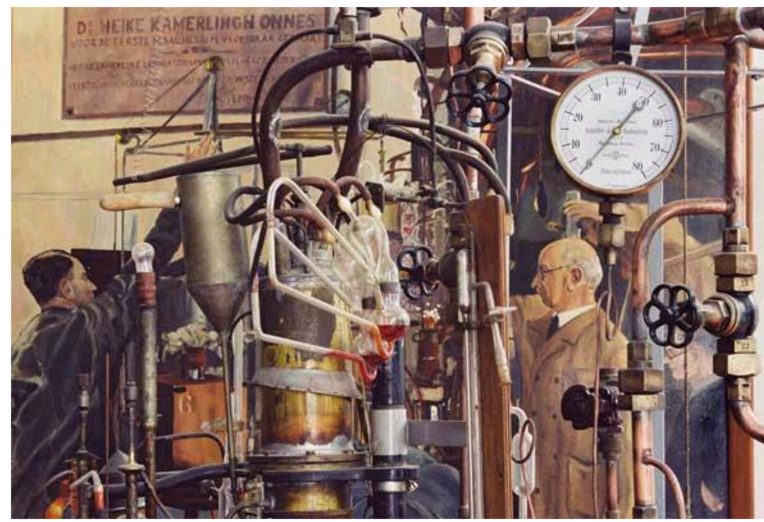
Cascade Helium Liquefier



LHe

FAMOUS R-T PLOT

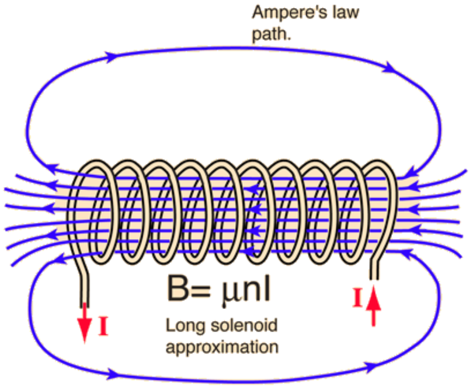




The physics laboratory in Leiden became the "coldest place on earth"

High Energy Physics are the biggest promoter of Superconducting Magnet through Powerful Accelerator (Next to MRI)

High Energy (E) means (High Velocity (v))
Needs high Magnetic Field (B) to bend the ion beam



$$r = \frac{mv}{qB}$$

$$\vec{F} = q\vec{E} + q\vec{v} \times \vec{B}$$

$$BL = \mu NI$$

$$B = \mu \frac{N}{L} I$$

$$B = \mu n I$$

B is proportional to Ampere Turns (nI)

I (Current) is limited in normal Conductor (Cu, Al) because of Joule Heating (I^2R) Power Loss. To compensate we can Increase no of layers (Size !!)

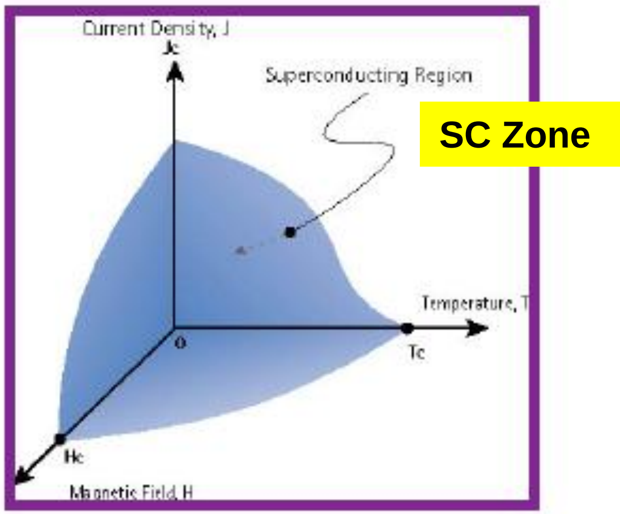
or we can have efficient cooling system/ very high heat Transfer coefficient and surface Area (LN2 Cooling ????)

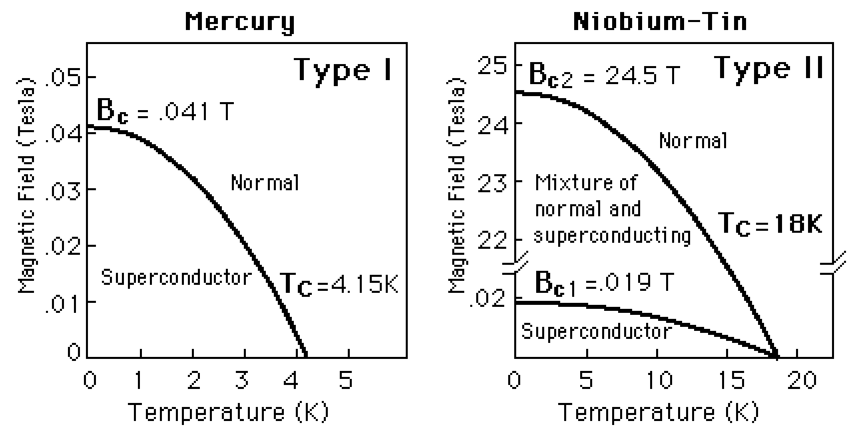
(Possible for High Field Pulsed Magnet)

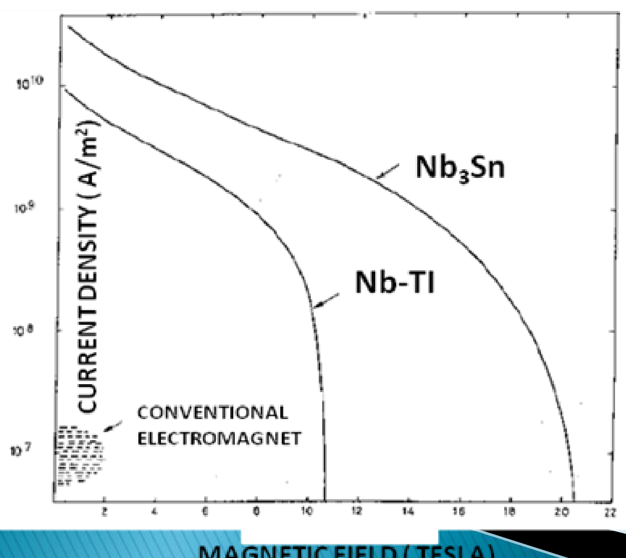
Superconductor (R=0) : No Joule Heating (Except at Joint and Current lead)

Superconductivity Destroyed If any Parameter Exceeds its critical value: And they are Interlinked

$T > T_c$, $I > I_C$, $H > H_c$

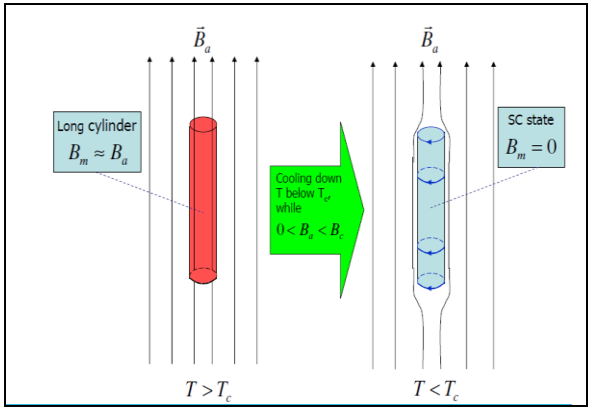






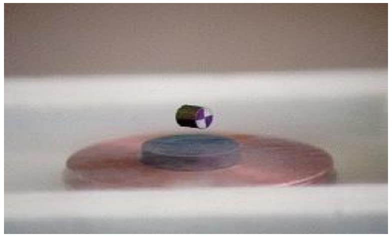
$$H_c(T) = H_c(0)\left[1 - \left(\frac{T}{T_c}\right)^2\right]$$

Another Property of Superconductor (Meissner Effect) : Perfect Diamagnetism : Expulsion of Magnetic Flux



$T > T_C$ $T < T_C$

Magnetic Lavitation



Tokyo- Nagoya : 300 Km
Travel time : 40 Minutes

We all are waiting for Superconducting Maglev train Between Tokyo & Nagoya (2027) 600 Km/hr

Longest Network of Superconductivity & Cryogenics after LHC (CERN) Project

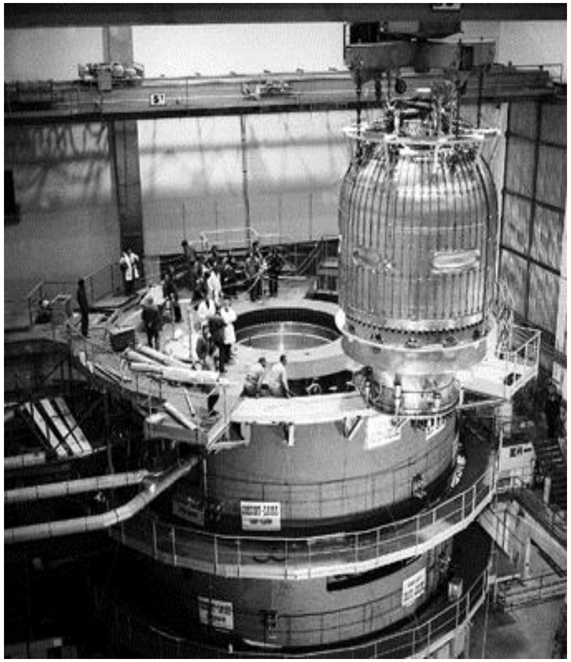
Cryogenics + Nuclear Science

Breakthroughs.

1. ULT through nuclear adiabatic demagnetisation.
2. Polarised targets for nuclear experiments. (Bubble Chamber)
3. High field magnets for Particle Accelerators.
4. Cryogenic detectors for high precision spectroscopy.
5. Superconducting Cavities for Particle Accelerators.
6. Cryopumping for better vacuum in Beam line pipe

Bubble Chamber Filled with Liquid Hydrogen (1956- 1985)
(First Application of Cryogenics in Major Accelerator programmer)

Bubble chamber : Tracks of charged particles by means of a visible string of bubbles that are left by the particles as they fly through a Liquid Hydrogen (Purest Target) at a temperature 24 to 29 K with pressure from 40 Psig to 70 Psig)



BEBC project (1966) giant cryogenic bubble chamber surrounded by a 3.5 T superconducting solenoid magnet that operated at CERN Super Proton Synchrotron (SPS) until 1984

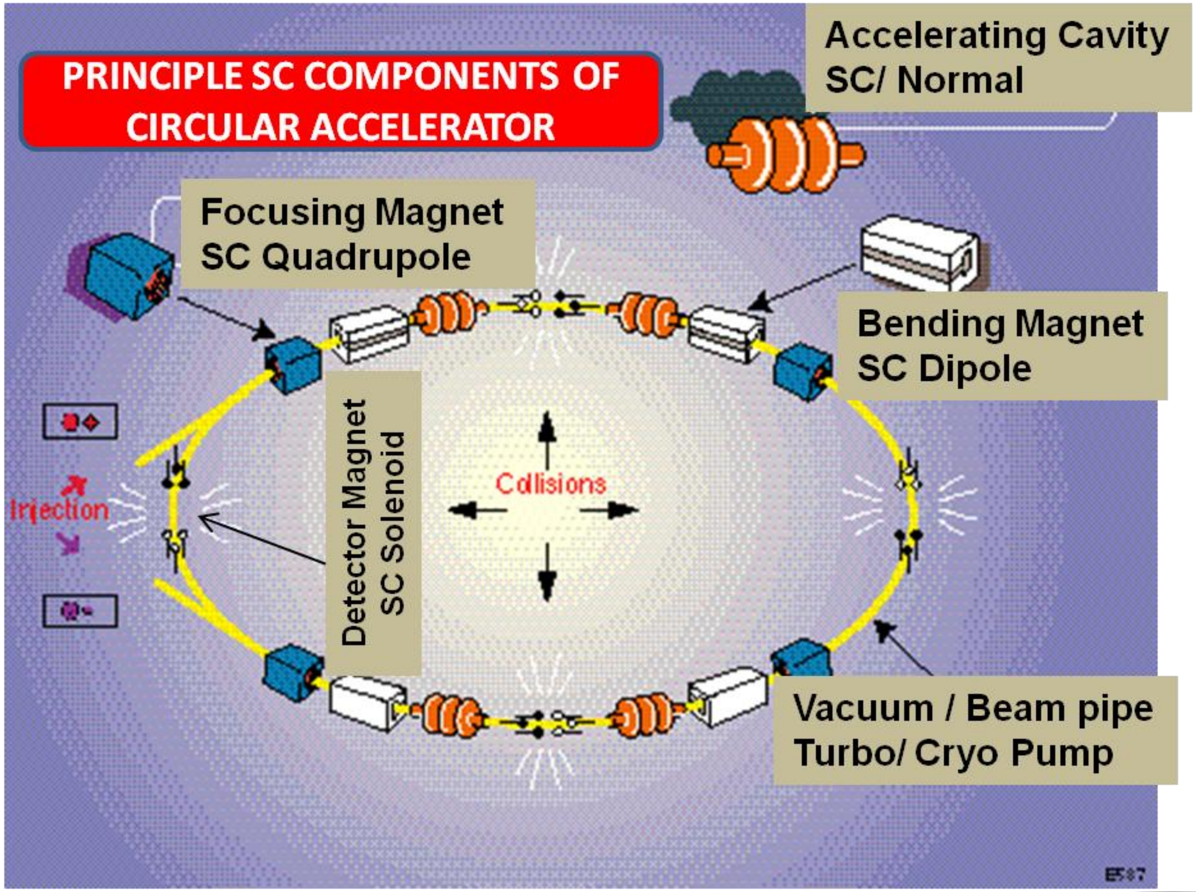
developments in electronics and new wire chamber detectors, brought an end to the bubble-chamber

Remains of the BEBC at CERN Science Museum

Cryogenics - Superconductivity - Accelerator (Brief History)

- 1908 – Kamerlingh Onnes Liquefied Helium (4.2 K)
- 1911 – Superconductivity is Born !!
- 1960 _ Bubble Chamber with Liquid hydrogen
- 1980 – Tevatron , First Accelerator Using SC Magnet (70 Yrs) !!!!
- 1986 – High Temp Superconductors (> 77 K)
- 1988 – Tristan, Japan Accelerator with SC Cavity
- 2005– 2017 : ECR and Spectrometer HTS Magnet with Cryocooler
- 2011 – Commissioning of LHC (Largest Cryogenics)
- 2025 – 30 – International Linear Collider (ILC)/ CepC

MAIN COMPONENTS OF A CIRCULAR ACCELERATOR



1. CAVITIES : ENERGY

2. MAGNETS : GUIDES

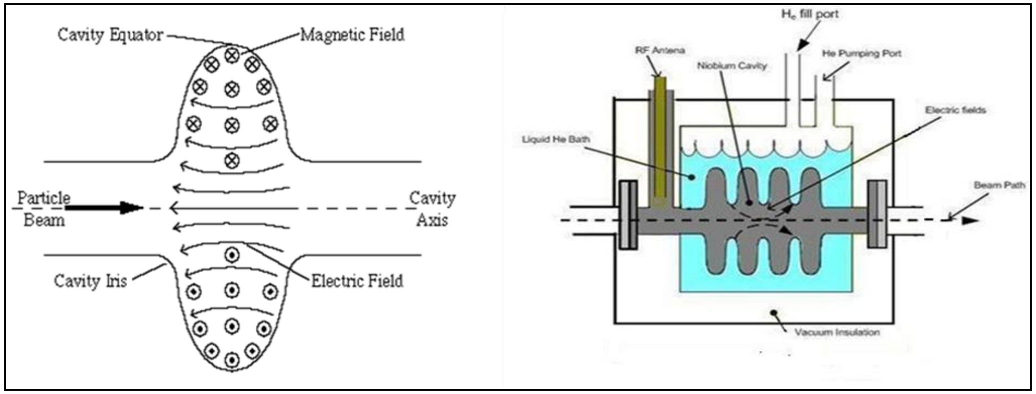
& FOCUSS THE BEAM

3. DETECTOR : DETECTS

NEW PARTICLE

Cavities are the Engine and
Magnets are the Steering

CAVITY



RF POWER FEED TO THE CAVITY (LC CIRCUIT), ELECTRIC FIELD (MV/m) GENERATES (Max at IRIS where Beam Passes)

SURFACE CURRENT ON CONDUCTOR,

HEAT (Loss) ON WALL BECAUSE OF SURFACE RESISTANCE :
COOLING BY WATER / LIQUID HELIUM

HIGHER SURFACE RESISTANCE
MORE HEAT : MORE LOSS

Why Superconducting Cavity?

Unlike DC superconductor, there are resistive power loss in RF superconductor because of Surface Resistance

Resonant cavities have Quality factors, Q, whose value depend on resistive losses.

High Q , Low Loss $$P_d = \frac{\omega U_0 E_{acc}^2}{Q_0}$$

Q is inversely Proportional to Surface Resistance.

$$Q_0 = \frac{G}{R_s}$$

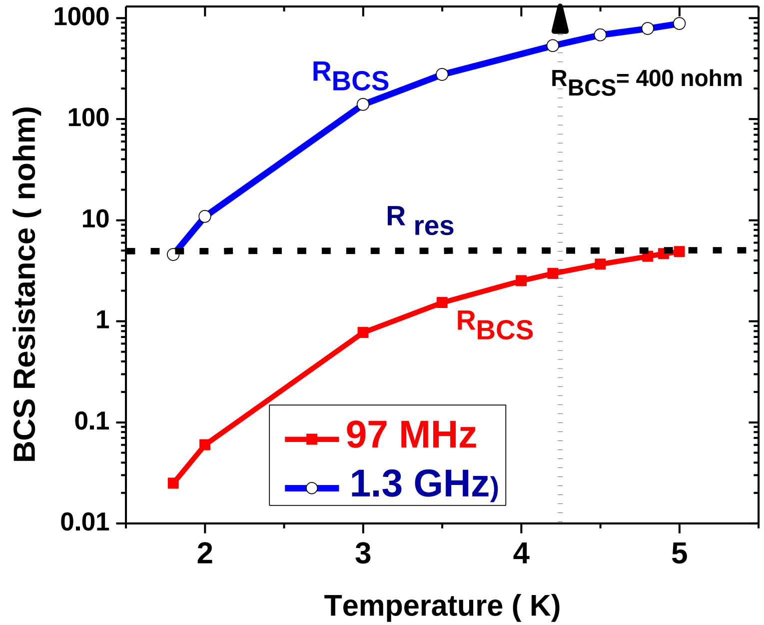
(R_s) Copper/ R_s (Noibium) = 10^5

Surface Resistance

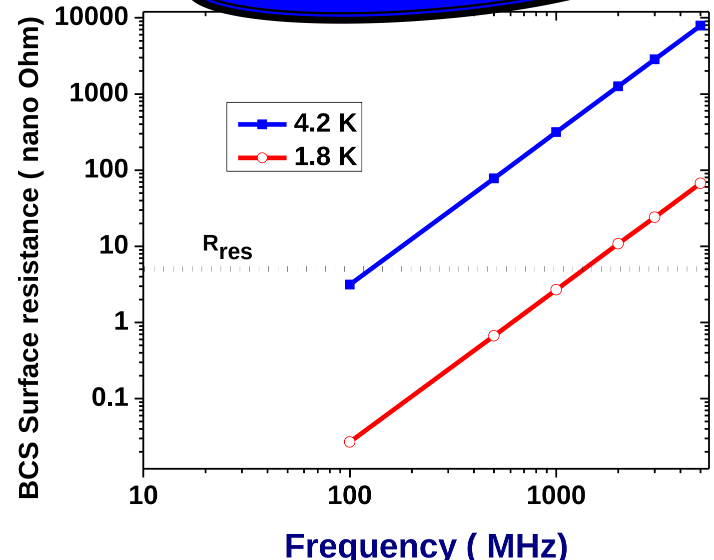
SURFACE RESISTANCE WITH TEMPERATURE (T) & RF FREQUENCY (f)

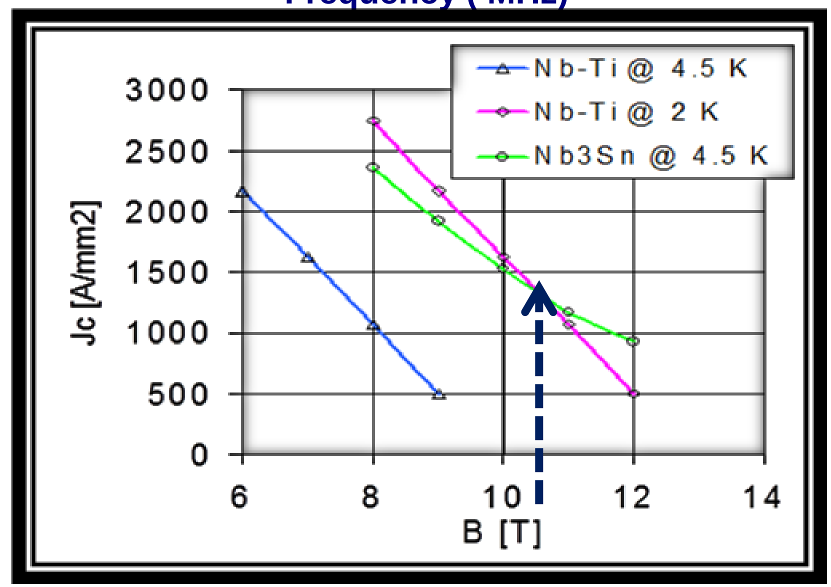
$$R_{BCS} = 2x10^{-4}\left(\frac{f}{1.5x10^{9}}\right)^{2}\frac{e^{-17.67/T}}{T}$$

WHY 2K?



Nb : Tc= 9.2 K

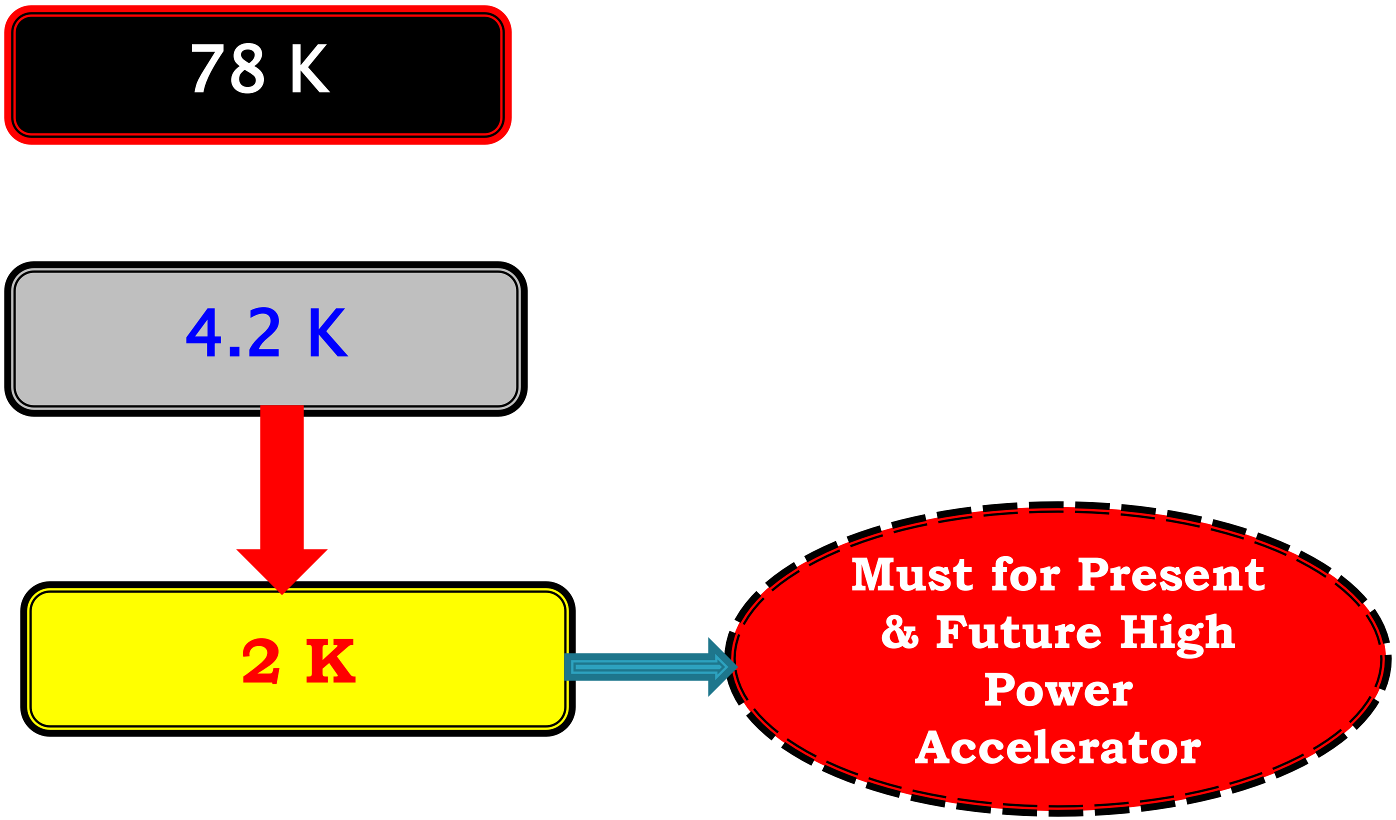




For High Frequency Cavity:
2 K is Choice

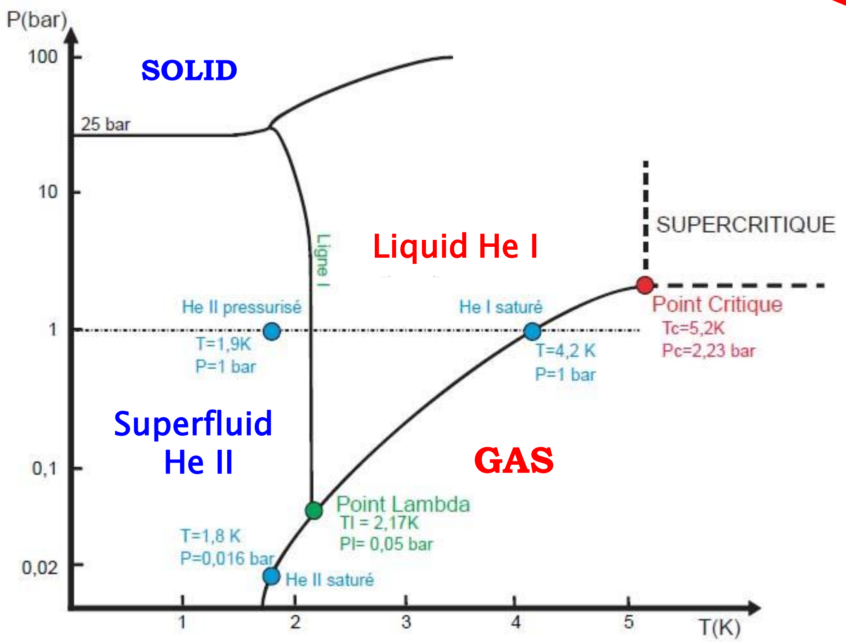
For High Field Magnet :
NbTi at 2 K or Nb_3Sn at 4.2 K

Transition from He I to He II (Superfluid)

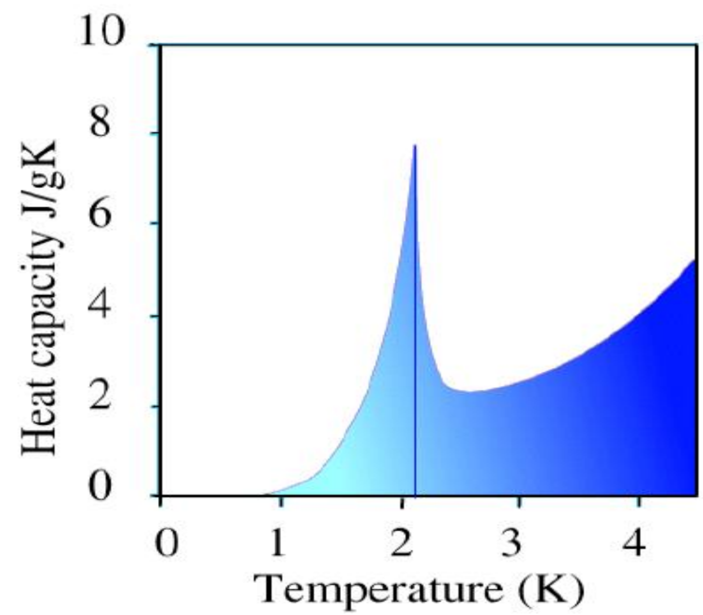


Super-fluidity is the characteristic property of a fluid with zero viscosity which therefore flows without loss of kinetic energy (no Pressure drop)

TRANSITION TO A SUPER-FLUID PHASE BELOW THE λ-point (2.17K)



1. **Low Viscosity**
2. **High Conductivity**
3. **High Specific Heat**

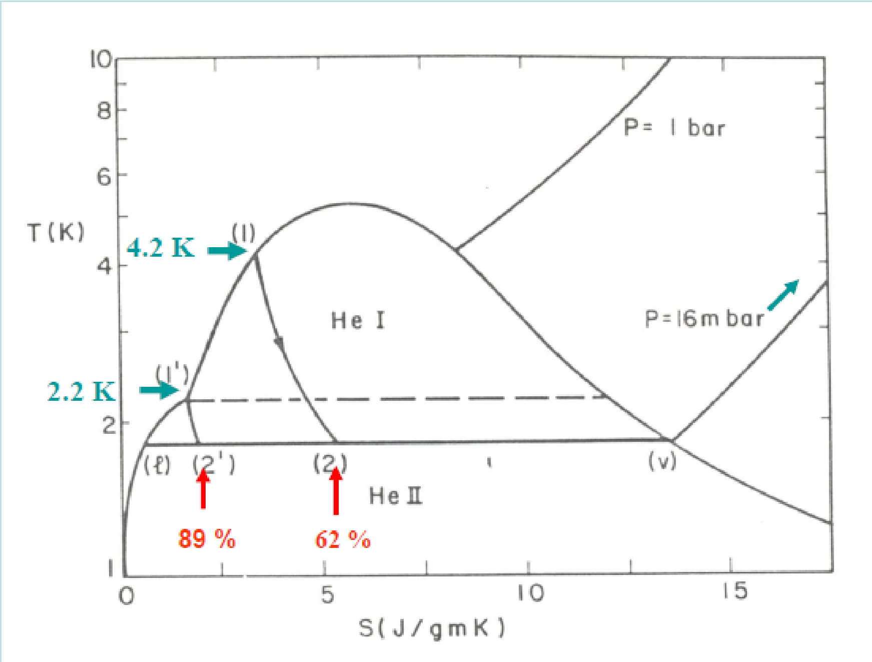


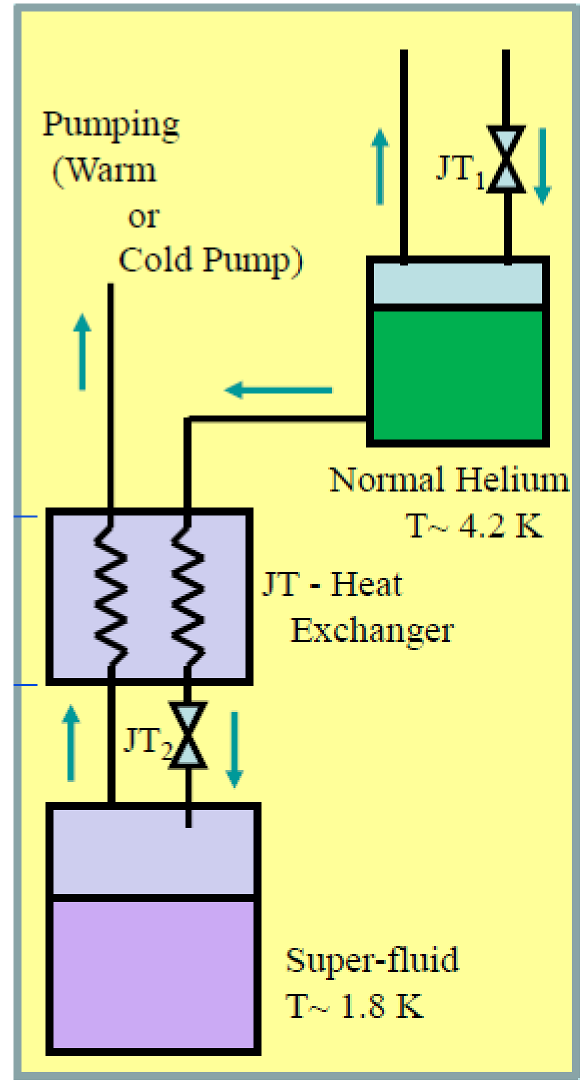
Advantages

1. Super-fluid Helium can easily flow through SC strand /Cable

2. Small temperature rise with a heat input (specific heat)
3. Large Conductivity maintain equal temperature. SC Magnet is stable

Simple 2 K System





An Efficient Heat Exchanger (4.2 –2K) improves the yield from 62% to 89 %

Example : 100 l/hr He I liquefier (400W at 4. 2 K) can have

1. **50- 55 L/hr (38 W) He II without HX**
2. **80-82 L/hr (56 W) He II with HX**

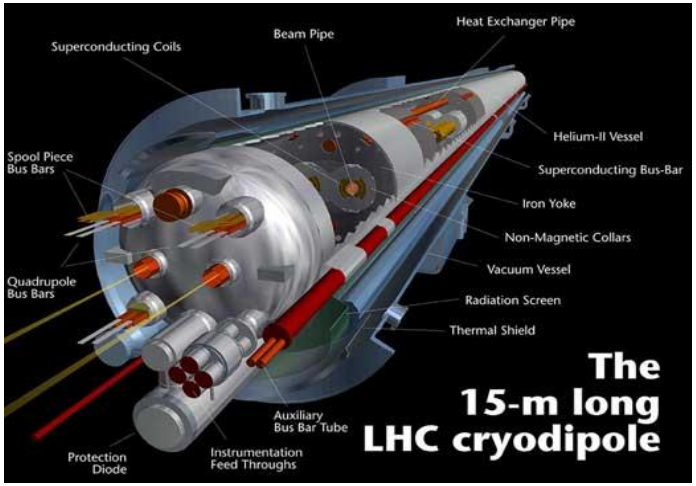
Power Comparison in Cavity

Description	Normal (Cu) Cavity	Superconducting (Niobium)
Eacc (MV/m)	1	1
G, f	17, 97 MHz	17, 97 MHz
Rs	3 milli-ohm	10 nano- ohm
Q_0= G/Rs	6.5 x 10^3	2.1 x 10^9
Power Loss	9000 W @ 300K	0.5 W at 4.2 K
Plug Power	9000 W	150-200 W

Estimated Refrigeration Load for ILC: 210 KW
Total AC Power Consumption : 50MW : Cu Cavity : 500– 1000 MW

Saving: 400 MW

Comparison for CERN LHC

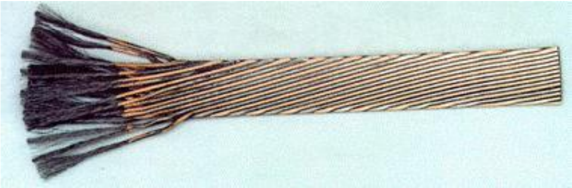


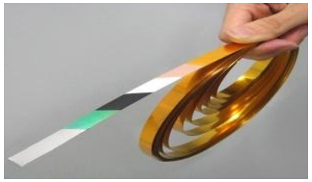
ENERGY : 7 TeV

$$E_{beam} = 0.3 B_{dipole} R$$

DESCRIPTION	SUPERCONDUCTING MAGNET	NORMAL MAGNET
Field	8.3 Tesla	2.1 Tesla
Total Length	27 km	108 km
No of Magnets	1500	6000
Ref. Power	144 kW @ 4.2 K	
Power at Room Temperature	144 x 225 33MW	3300 MW

Practical Superconductor Today





VERY GOOD ELECTRICAL CONDUCTORS ARE NOT SUPERCONDUCTOR (Cu, Ag, Au)

Material	Tc (K)	Hc (T	Application
Pb	7.2	.08T	Cavity
Nb	9.2	0.2	Cavity
Nb-Ti	10	15(T)	Magnet
Nb_3Sn	18	24.3	Magnet
Nb_3Ge	23	38	Magnet
YBCO	93	>100	Magnet & power application
BSSCO	110	>100	Magnet & power application
MgB_2	39		Promising for MRI

Type 1: Pb, Nb — Pure Metal, Clean surface, Easy fabrication, Not high H_C

Type 2: Nb-Ti, Nb_3Sn, Nb_3Ge — **High Hc, Tc Ductile**

YBCO, BSSCO — **High Tc, Jc, High Cost, Brittle**

Now based on T_c, we need different cooling medium that is the criteria To distinguish LTS and HTS

2nd Part will be started with

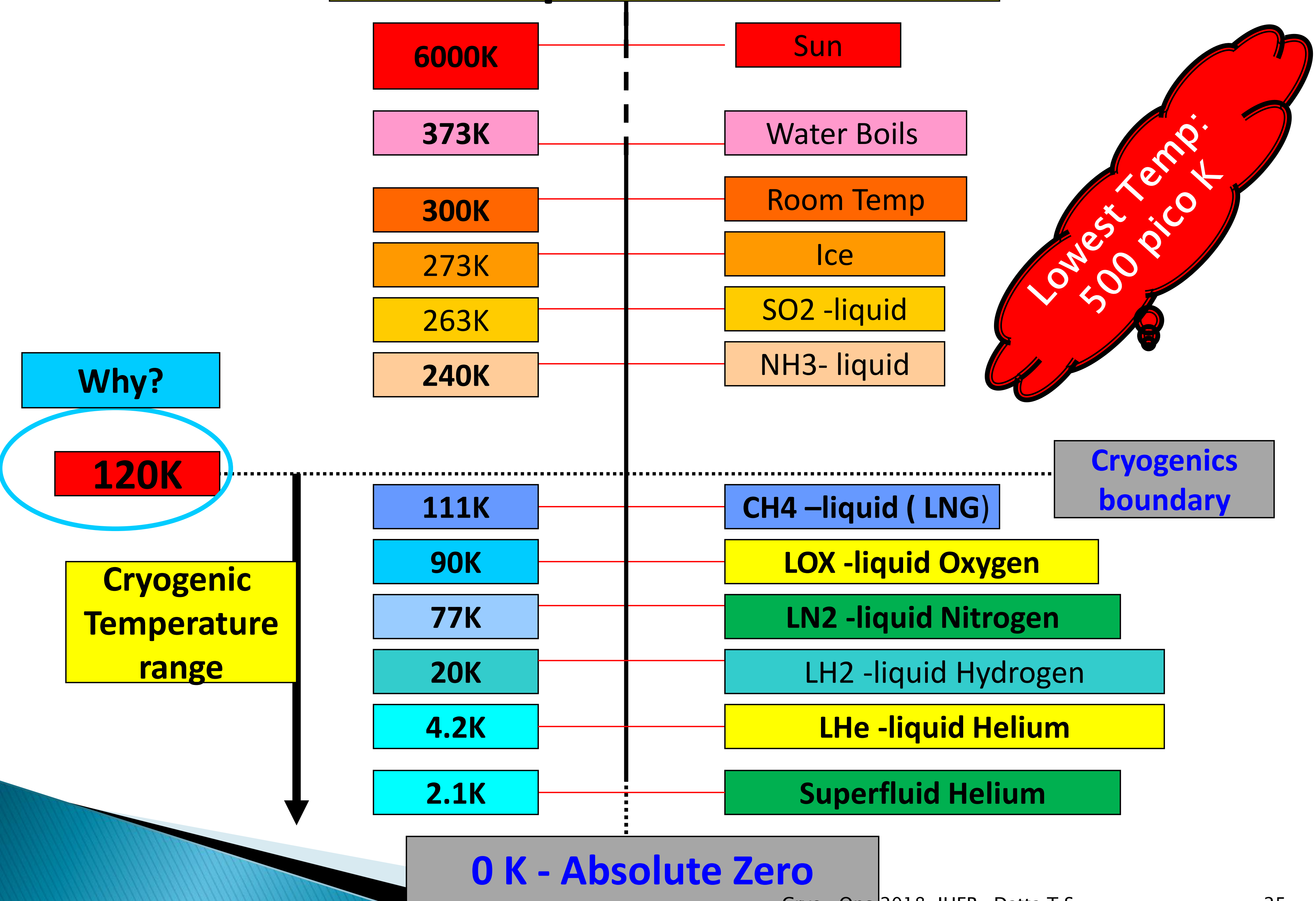
BASIC THERMODYNAMIC PROCESS FOR COOLING

&

Then

How to Liquefy Helium (4.2 K) and Nitrogen (77.4 K)

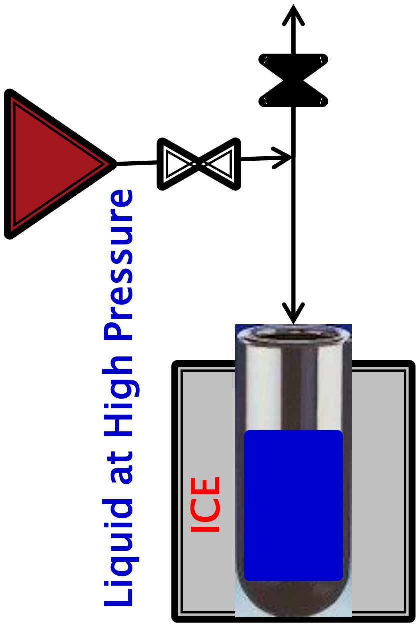
Temperature Scale



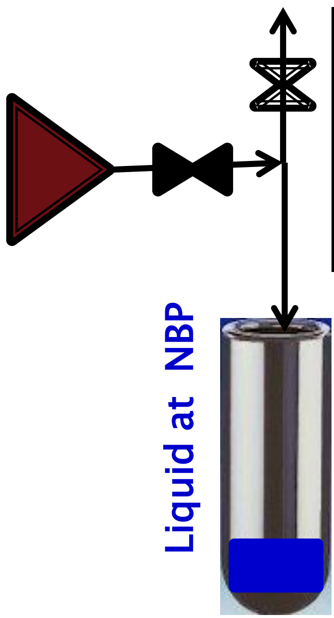
PERMENANT GASES

Laboratory techniques for reducing temperatures and Liquefaction

A. **Liquefaction of gas at high pressure in a thick-walled glass tube surrounded by ice (273 K),**
B. **A rapid expansion of the vapor phase to atmospheric pressure through a valve.**
C. **The temperature of the remaining liquid phase then dropped to its NBP.**



a) Isothermal Compression



b) Rapid Expansion

Ethylene, could be liquefied with a critical temperature of 282 K and a normal boiling point temperature of 169 K,

Methane, Nitrogen, hydrogen, Helium that could not be liquefied by this technique, even with pressures up to 40 MPa, were called “permanent”gases.

CRYOGENIC RANGE

	T(boil)	T(critical)	P(critical)
SO_2	263K	432K	79 Bar
NH_3	240K	405K	115 Bar
C_2H_4	169	282	50
CH_4	112	191K	46 Bar
O_2(LOX)	90K	155K	50 Bar
N_2 (LN2)	78K	126K	34Bar
H_2 (LH2)	20K	33K	13Bar
He(LHe)	4.2K	5.2K	2.2 Bar

Permanent Gas

Tc [SO2/NH3] > 273K (ICE temp)

gas

Pressure

liquid

Tc [N2/He] < 273 K (ICE Temp)

gas

Whatever Pressure ?

No liquid

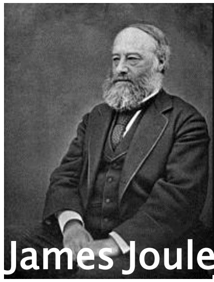
Permanent Gases

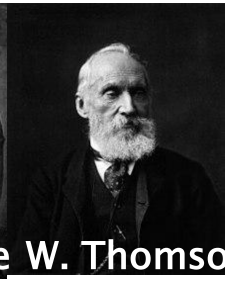
Hence they are called

LNG & LPG ??

Ar, N_2, O_2, Air, Ne, H_2 and He

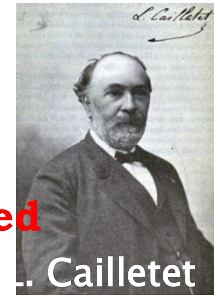
HISTORY ON LIQUEFACTION OF PERMANENT GASES

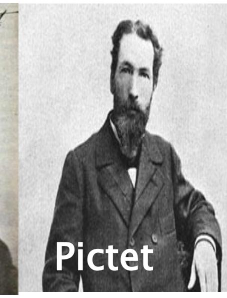




1852

JT Effect Discovered

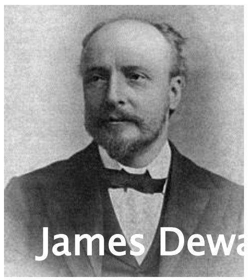





Wroblewski and Olszewski

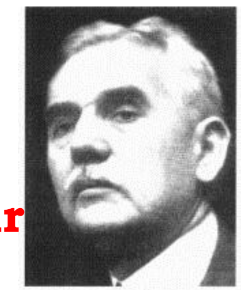
1877- 1883

Oxygen / Nitrogen Liquefied



1898

Hydrogen Liquefied



George Claude

Carl von Linde

1902

Expansion Engine for Air

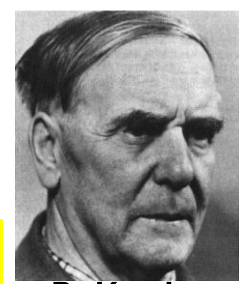
Heike Kamerlingh Onnes

July 10, 2008

Helium Liquefaction

1934

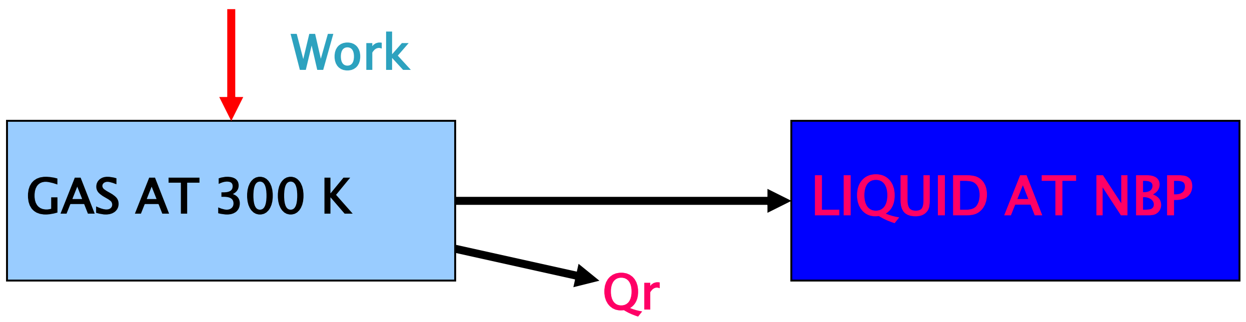
Helium Liquefaction with Claude Cycle



P. Kapitsa

LIQUEFACTION OF PERMANENT GASES

Qr = Sensible Heat + Heat Of Vaporisation



(Qr) = Nitrogen 234 J/ gm (300K to 78 K) + 199 J/gm

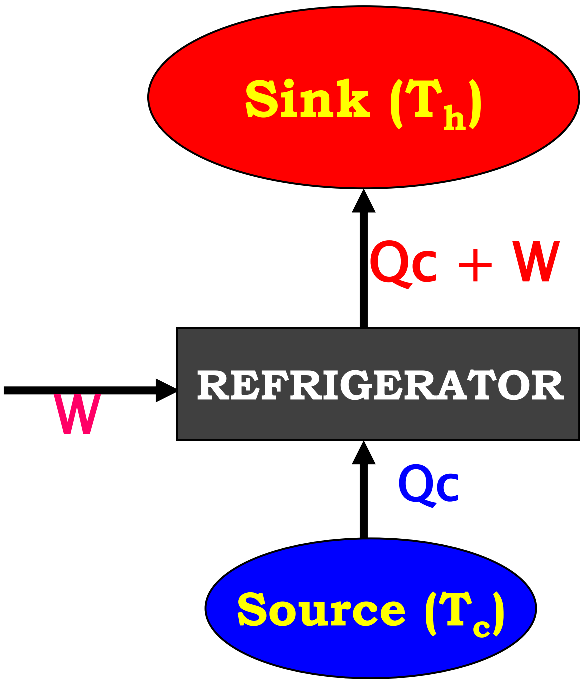
Helium : 1542 J/ gm (300 K to 4.2 K) + 20 J/ gm

Latent Heat

Sensible Heat

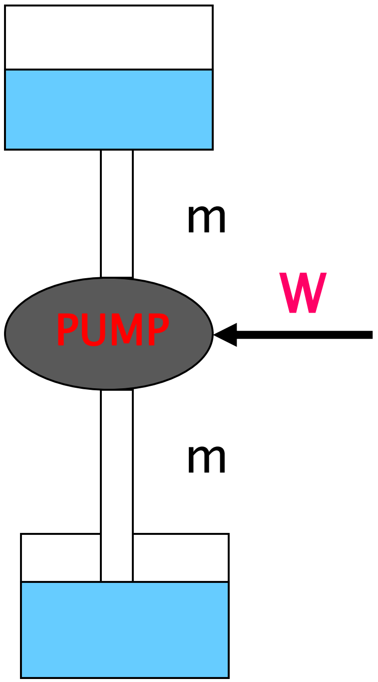
Refrigerator

To Transfer Heat from Source to Sink if Source Temp is less than Sink



Refrigerator is analogues to Water Pump to transfer Heat (Water) from Lower Temp (Lower level) to Higher Temp (Higher Level)

Power required or pump size depends on water capacity (Ref. Load in Watt) and the difference of level (Diff on Temp)

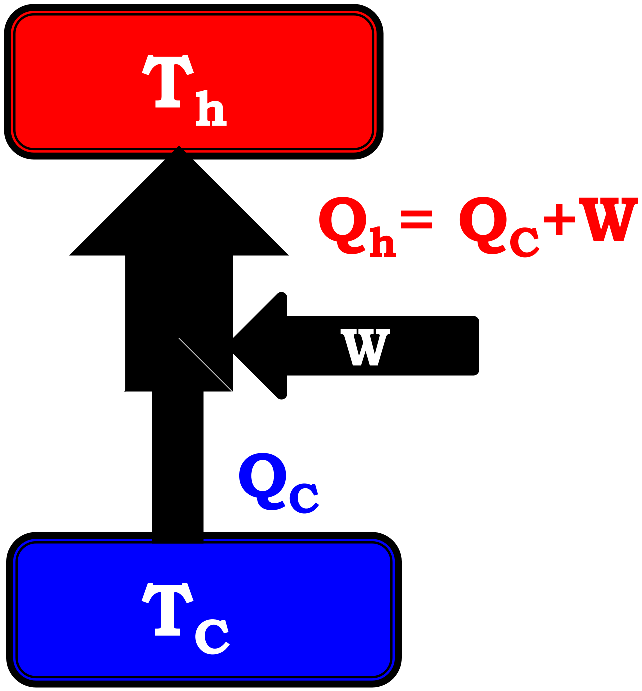


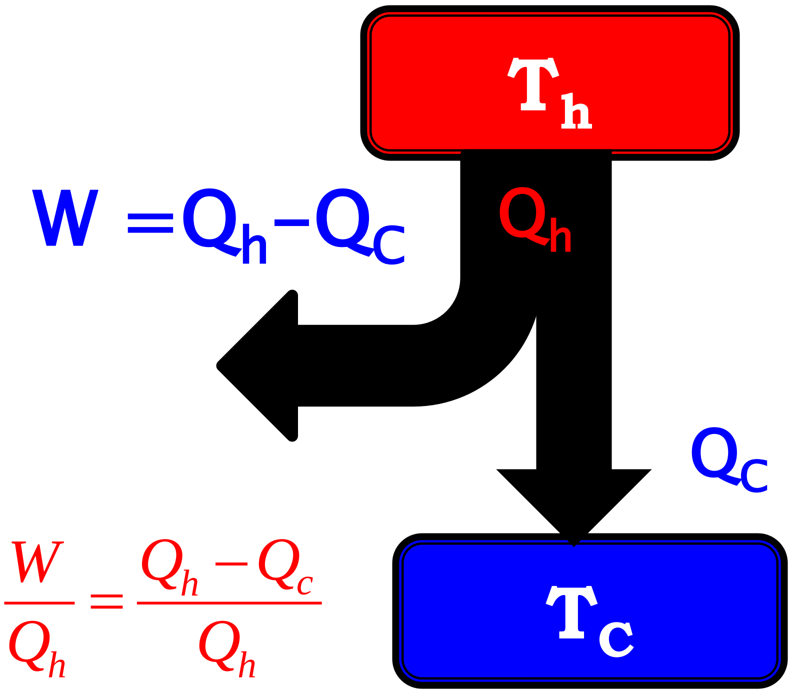
Transfer Amount of Heat energy is different between Source and Sink unlike pump. That embodies the concept the " Quality" of Thermal energy

REFRIGERATOR

HEAT ENGINE

Second Law of Thermodynamics: It is impossible to extract an amount of heat Q_H from a hot reservoir and use it all to do work W .



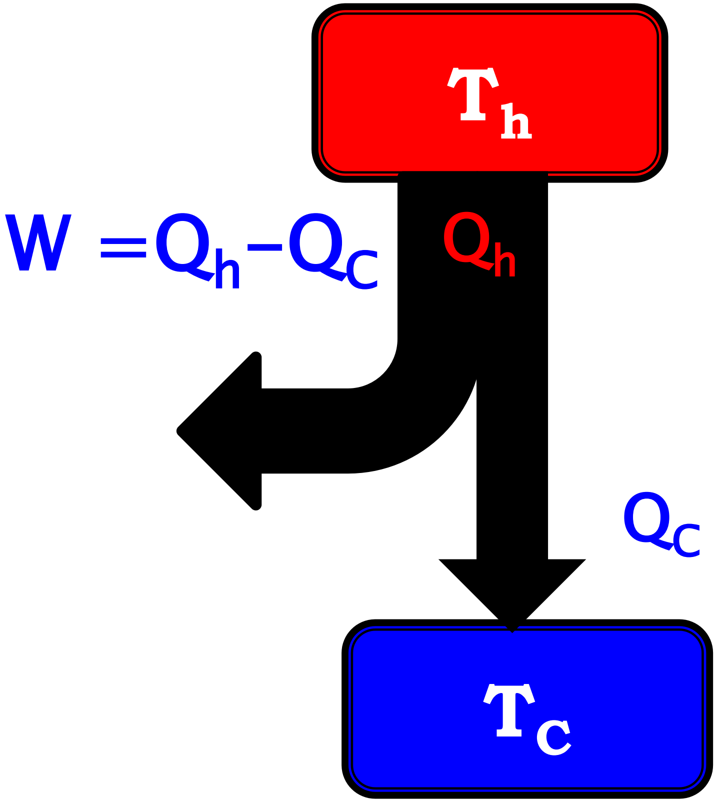


$$\eta = \frac{W}{Q_h} = \frac{Q_h - Q_c}{Q_h}$$

2nd Law of Thermodynamics: It is not possible for heat to flow from a colder body to a warmer body without any input of Work

CARNOT CYCLE is the Most Efficient Cycle to have Maximum Work

$$\eta = \frac{W}{Q_h} = \frac{Q_h - Q_c}{Q_h} = \frac{T_h - T_c}{T_h}$$



Here T_C Is fixed (300 K) and T_h Can be varied . Higher T_h Higher Efficiency.

T_h= 600, η = 50 %
T_h= 1000K , η= 70%

Power (W) required to extract 1 W refrigeration at T_c is : 1/ (COP) = $= \frac{W}{Q_c} = \frac{Q_h - Q_c}{Q_c} = \frac{T_h - T_c}{T_c}$

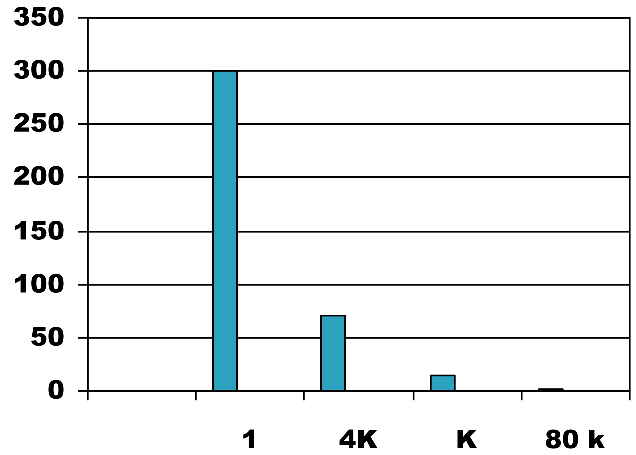
T_h = 300 K T_c vary from 200 K to .000001 K

T_C=200 K , W = 0.5 W

LN_2 : T_c = 78 K , W = 1.68 W

LH_e : T_c = 4.2 K, W = 70 W

T_c = 0.01 W= 30k W



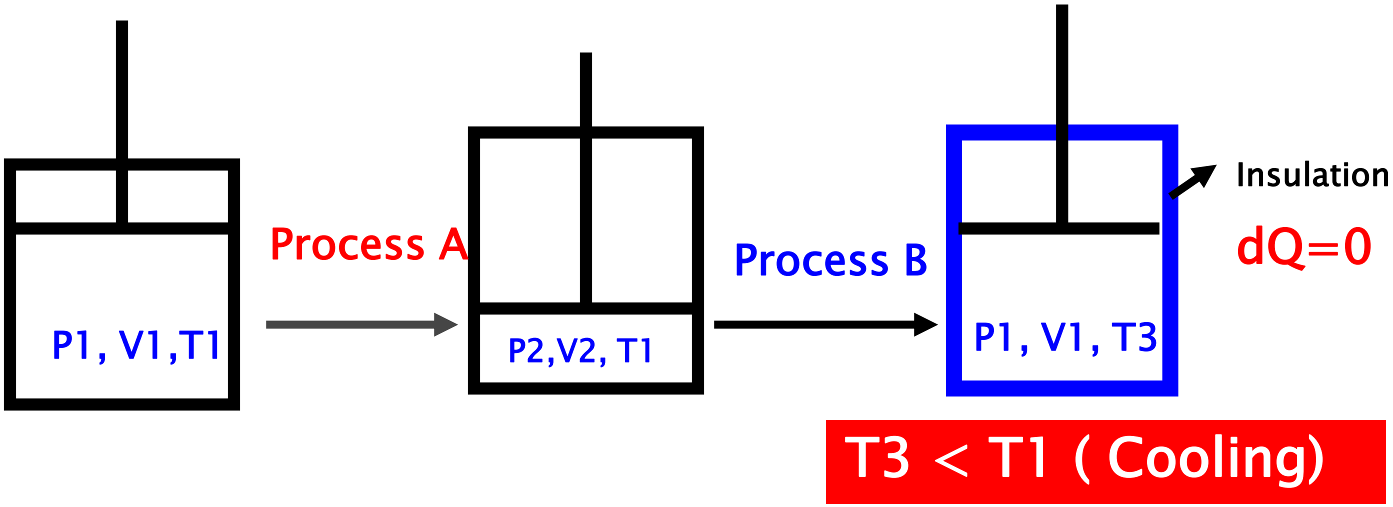
These are Theoretical minimum Power. We have to multiply first with efficiency of the Cycle and then multiply with mechanical efficiency of all Components (Compressor, Heat Exchanger, Expander of refrigerator

Actual work $= W_c/(\eta_{Cycle} * \eta_{Comp})$ Total efficiency may be 10 to 30 % at 4.2 K

Required Plug Power for 1 W refrigeration at 4. 2 K = 500- 225 W

BASIC THERMODYNAMIC PROCESS FOR COOLING

- A. **ISOTHERMAL COMPRESSION (Compressor)**
- **B. ADIABATIC EXPANSION (Turbine)**
- **C. ISENTHALPIC EXPANSION (JT VALVE)**
- **D. ISOBARIC COOLING (Heat Exchanger, Precooler)**



Isothermal compression is achieved with water/ air cooling System.
$W = m. T (R/ M) \ln (P2/P1)$.

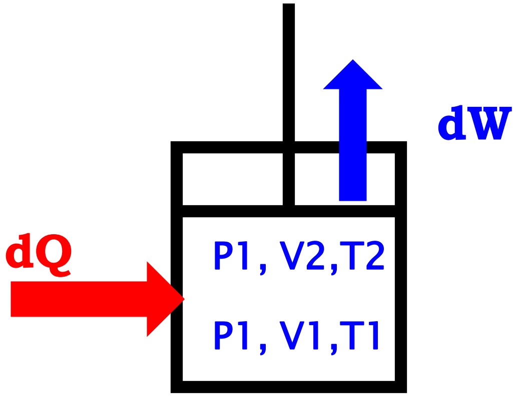
Example : 1 gm/s gas T= 300 K, P2/ P1 = 15

Helium : 1600 W (20 NM^3), N2 = 200W (2. 8 NM^3)

Thermodynamic Parameters

Fundamental :

Pressure (P)
Temperature (T)
Volume (V)
Gas Constant (R)
Work (W)
Heat (Q)
Internal Energy (U)



$$dQ = dU + dW = C_p dT + pdV$$

Other Important Parameters

1. Entropy (S) :

$$dS = \frac{dQ}{T}$$

- **Entropy is a measure of Disorder.**
- **Second Law of Thermodynamics: In any cyclic process the entropy will either increase or remain the same.**

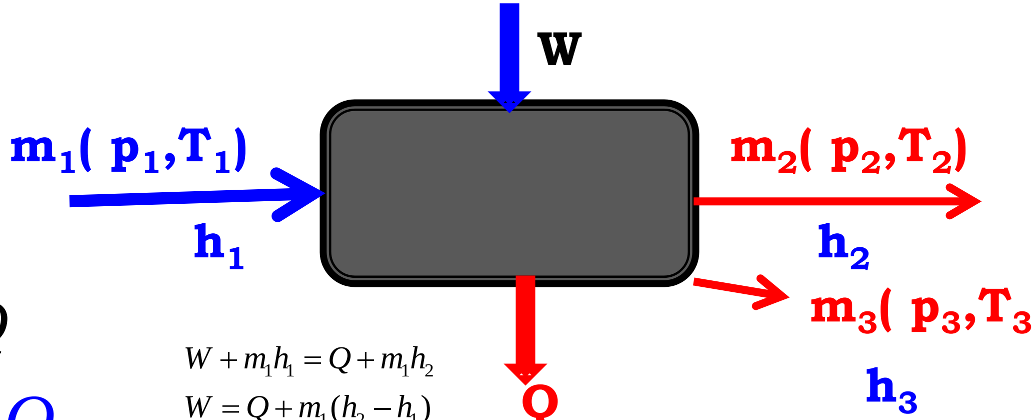
$$\oint ds = \oint \frac{dq}{T} \geq 0$$

2. Enthalpy (h)

- **equivalent to the total heat content of a system. It is equal to the internal energy of the system plus the product of pressure and volume.**

$$dh = du + pdv$$

Energy & Mass Balance



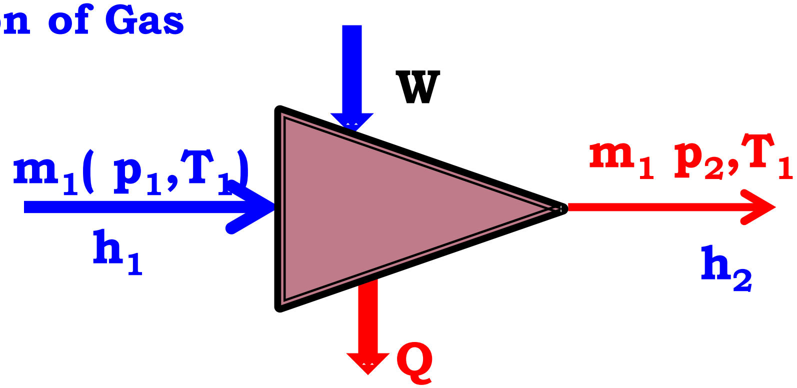
$$m_1 = m_2 + m_3$$

$$m_1 h_1 + W = m_2 h_2 + m_3 h_3 + Q$$

$$W = m_2 h_2 + m_3 h_3 - m_1 h_1 + Q$$

$$W + m_1 h_1 = Q + m_1 h_2$$
$$W = Q + m_1 (h_2 - h_1)$$
$$W = m_1 T_1 (S_2 - S_1) + m_1 (h_2 - h_1)$$

A. Example : Isothermal Compression of Gas



$$W + m_1 h_1 = Q + m_1 h_2$$

$$W = Q + m_1 (h_2 - h_1)$$

$$W = m_1 T_1 (S_2 - S_1) + m_1 (h_2 - h_1)$$

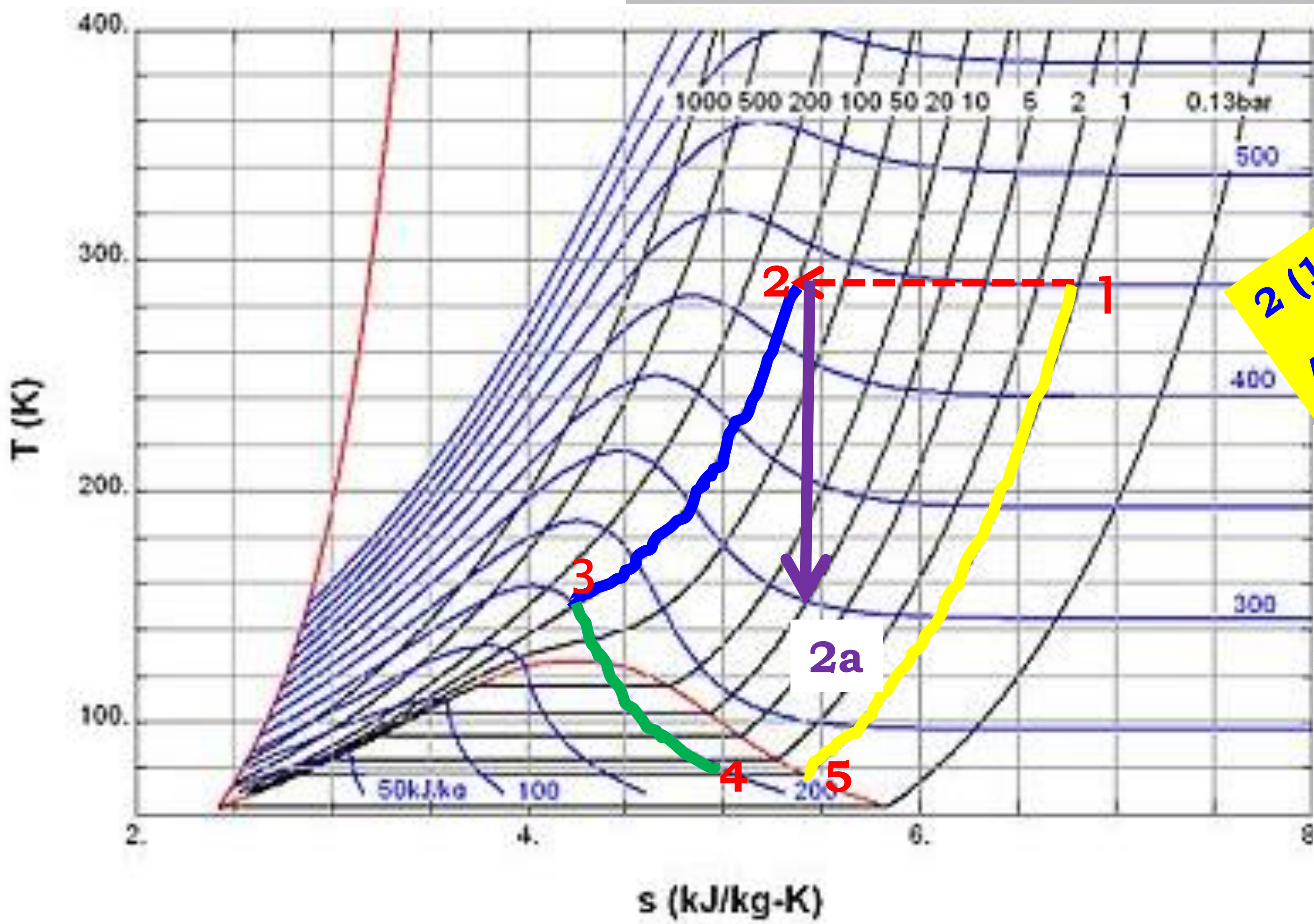
(Temperature, Entropy Chart with enthalpy)

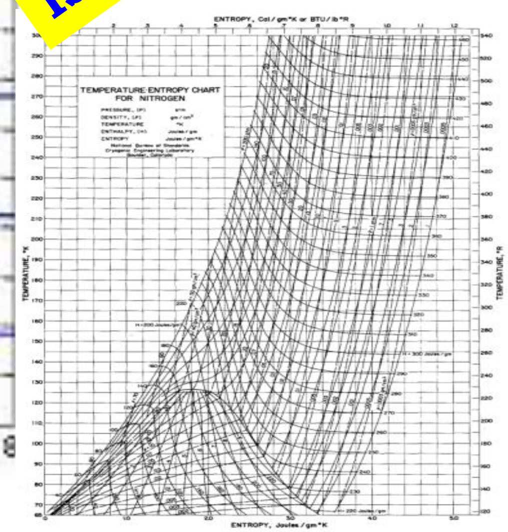
SAMPLE TEMPERATURE- ENTROPY CHART FOR NITROGEN

- Constant Enthalpy Curve (blue)
- Constant Pressure Line (black)
- Liquid Vapour Inter-phase (red)

- 1 (1bar, 280 K)–2 (100, 280) : **Isothermal Compression**
- **2(100,280)-3(100,150) : Isobaric Cooling (HX)**
- **3(100,150) -4(1,78) : Isenthalpic Cooling (JT)**
- **5(1,78) -1(1,280) : Isobaric Heating (HX)**

2 (100, 280)-2a (10-155): Adiabatic Expansion/ Isentropic Cooling





To Liquefy Permanent Gases

Cooling

Isenthalpic (JT)

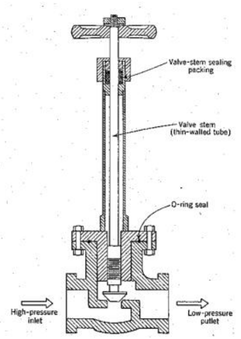
Indirectly By Other Cold Liquid/ Gas (Heat Exchanger

Isentropic

By JT Valve (No External Work But it does internal work)

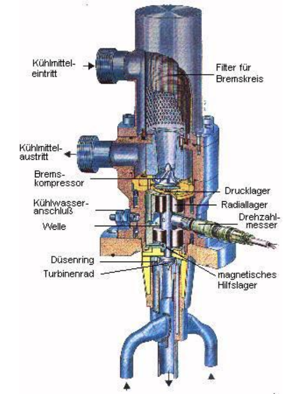
By Expansion Engine/Turbine (Do External Work)

High Pressure to Low pressure



Cooling co- efficient

$$\mu_{jT} = \left(\frac{\partial T}{\delta p}\right)_h \qquad \mu = \left(dT/dP\right)_x \qquad \mu_s = \left(\frac{\partial T}{\partial p}\right)_s$$



μ should be positive
Higher is Better

Isenthalpic /JT Cooling

$$\mu_{jT} = \left(\frac{\partial T}{\delta p}\right)_h = \frac{1}{C_p}\left[T\left(\frac{\partial v}{\partial T}\right)_p - v\right]$$

For an Ideal Gas $pv = RT,\quad \left(\frac{\partial v}{\partial T}\right)_p = R/p = v/T$

$$\mu_{JT} = 0$$

Fortunately Gas does not behave ideally

Real Gas : Vander Wall $\left(p + \frac{a}{v^2}\right)(v - b) = RT$

$$\mu_{JT} = \frac{(2a/RT)\left(1 - b/v\right)^2 - b}{C_p\left[1 - (2a/vRT)\left(1 - b/v\right)^2\right]}$$

Isenthalpic /JT Cooling

$$\mu_{JT} = \frac{(2a/RT)\left(1-\frac{b}{v}\right)^2 - b}{C_p\left[1-(2a/vRT)\left(1-\frac{b}{v}\right)^2\right]}$$

At low specific volumes

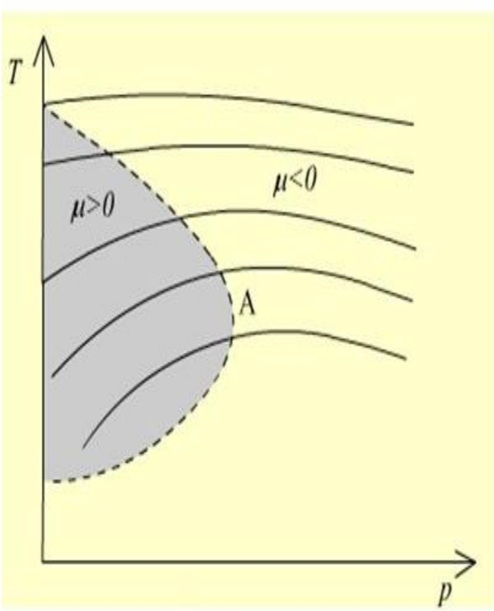
$$\mu_{JT} = \frac{1}{C_p}\left(\frac{2a}{RT} - v\right)$$

When , 2a/RT > v,
Or T < 2a/bR

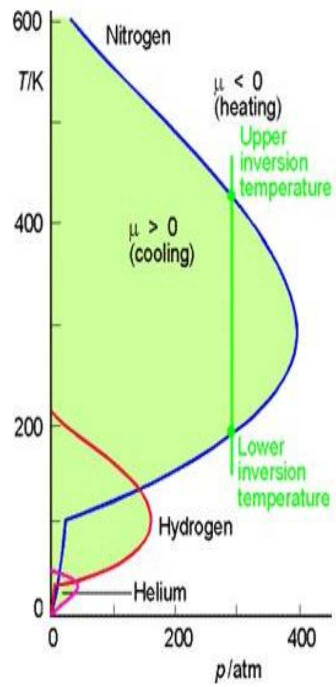
μ_{jT} is Positive , Hence Cooling

When , 2a/RT < v,

μ_{jT} is Negative , Hence Heating



Inversion curve



Inversion curve is represented by all points , where μ_{jT} =0

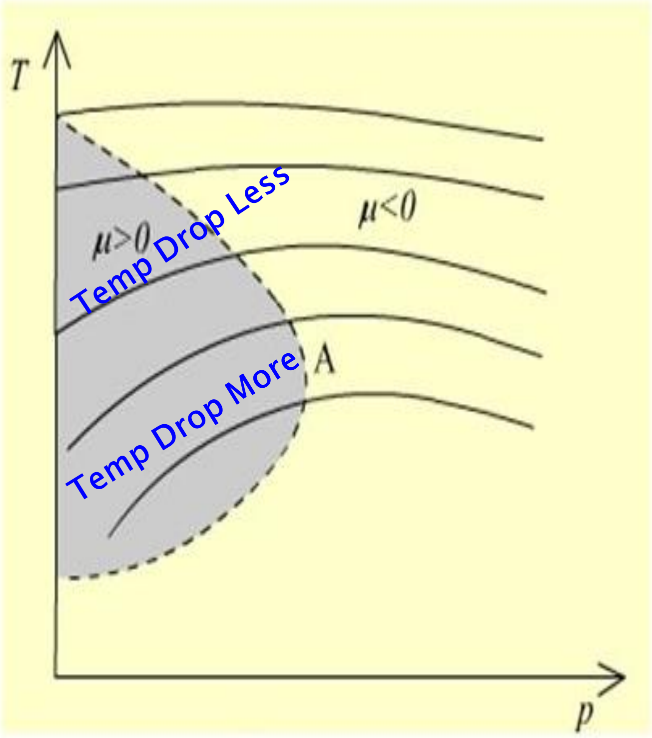
$$T_i = \frac{2a}{bR}\left(1-\frac{b}{v}\right)^2$$

Maximum Inversion Temperature
T_{imax} = 2a/bR
(at p=0 or b/v=0)

Above Max inversion temperature (T_{imax})we will not be able to cool the gas for any set of pressure combination.

Gas	He	H2	Ne	N2	Ar	O2
T_{imax} (K)	45	205	250	621	794	761

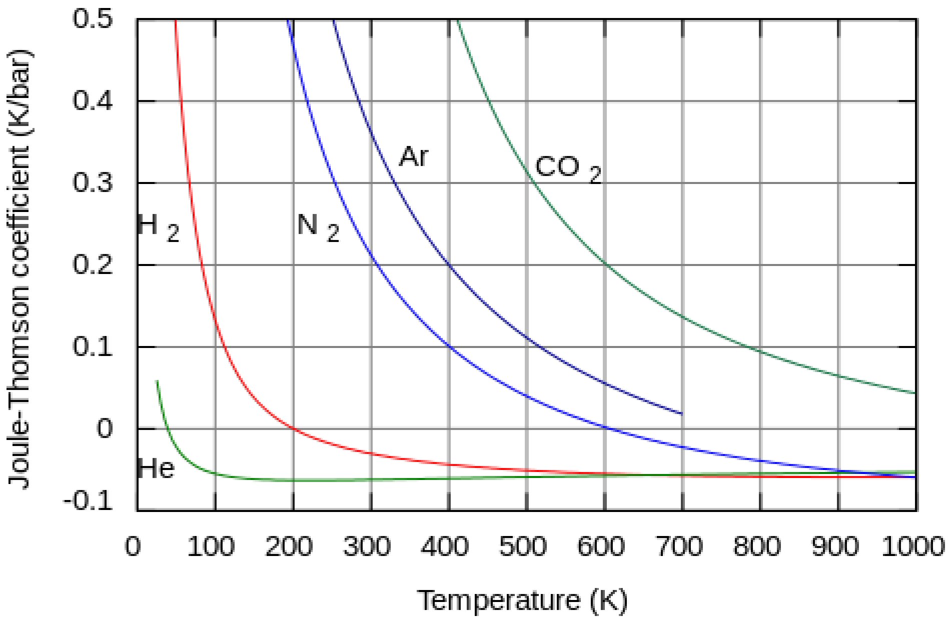
Above RT



Just below their max inversion temperature drop in temperature is not significant and temperature drop increases as we lower the inlet temperature and max above their critical temperature.

That's the reason JT is always incorporated in the last stage of liquefaction cycle. It can also handles liquid gas mixture unlike turbine

Temperature is the measure of thermal kinetic energy (energy associated with molecular motion); so a change in temperature indicates a change in thermal kinetic energy. The internal Energy is the sum of thermal kinetic energy and thermal potential energy. Thus, even if the internal energy does not change, the temperature can change due to conversion between kinetic and potential energy; this is what happens in a free expansion and typically produces a decrease in temperature as the fluid expands



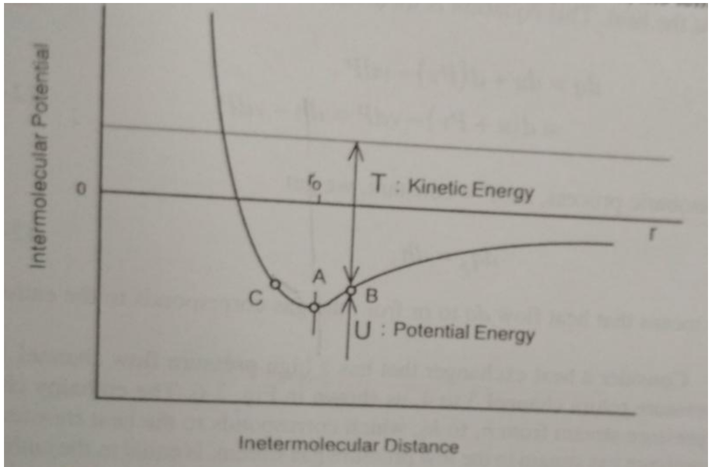


Fig. 2-5 Cooling by Joule-Thomson expansion: microscopic stand point of view.

High pressure to Low pressure
Intermolecular Distance increases

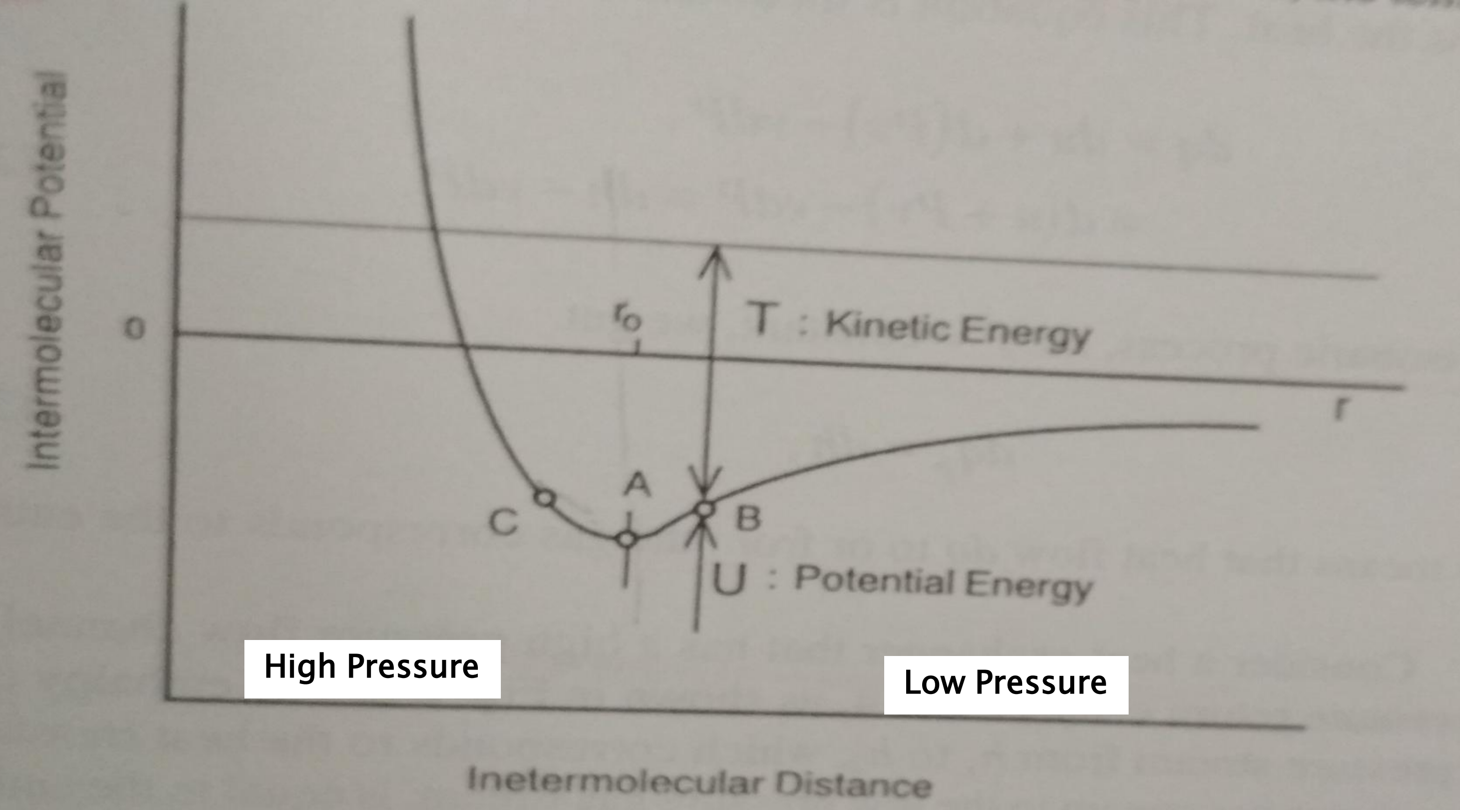


Fig. 2-5 Cooling by Joule-Thomson expansion: microscopic stand point of view.

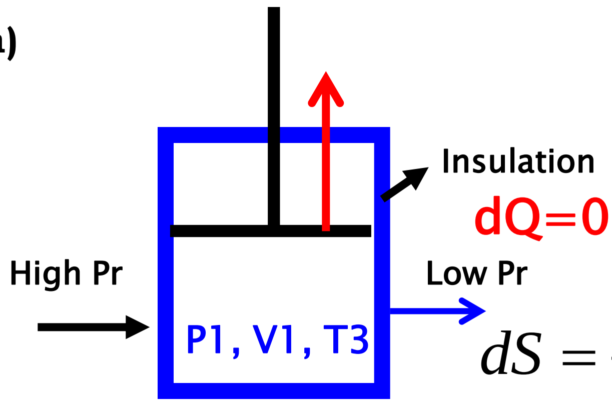
Example :

1. **A to B : Potential Energy increases and hence kinetic Energy decreases. Total energy remains same. Cooling**
2. **C to A : Potential Energy decreases and hence Kinetic Energy Increases. Hence Heating**

Adiabatic Expansion (Isentropic Cooling)

High Pressure Gas does an External work (Lifting Piston) and comes out at low Pressure and low temperature

$$\mu_s = \left(\frac{\partial T}{\partial p}\right)_s = \frac{T}{C_p}\left(\frac{\partial v}{\partial T}\right)_p$$



$$dS = \frac{dQ}{T}$$

$$\left(\frac{\partial v}{\partial T}\right)_p = R/p = v/T$$

$$\mu_s = {}^{v}\!/\!_{C_p}$$

dS=0 (Isentropic)

$$dQ = dU + dW = C_p dT + pdV$$

$$\mu_s > \mu_{JT}$$

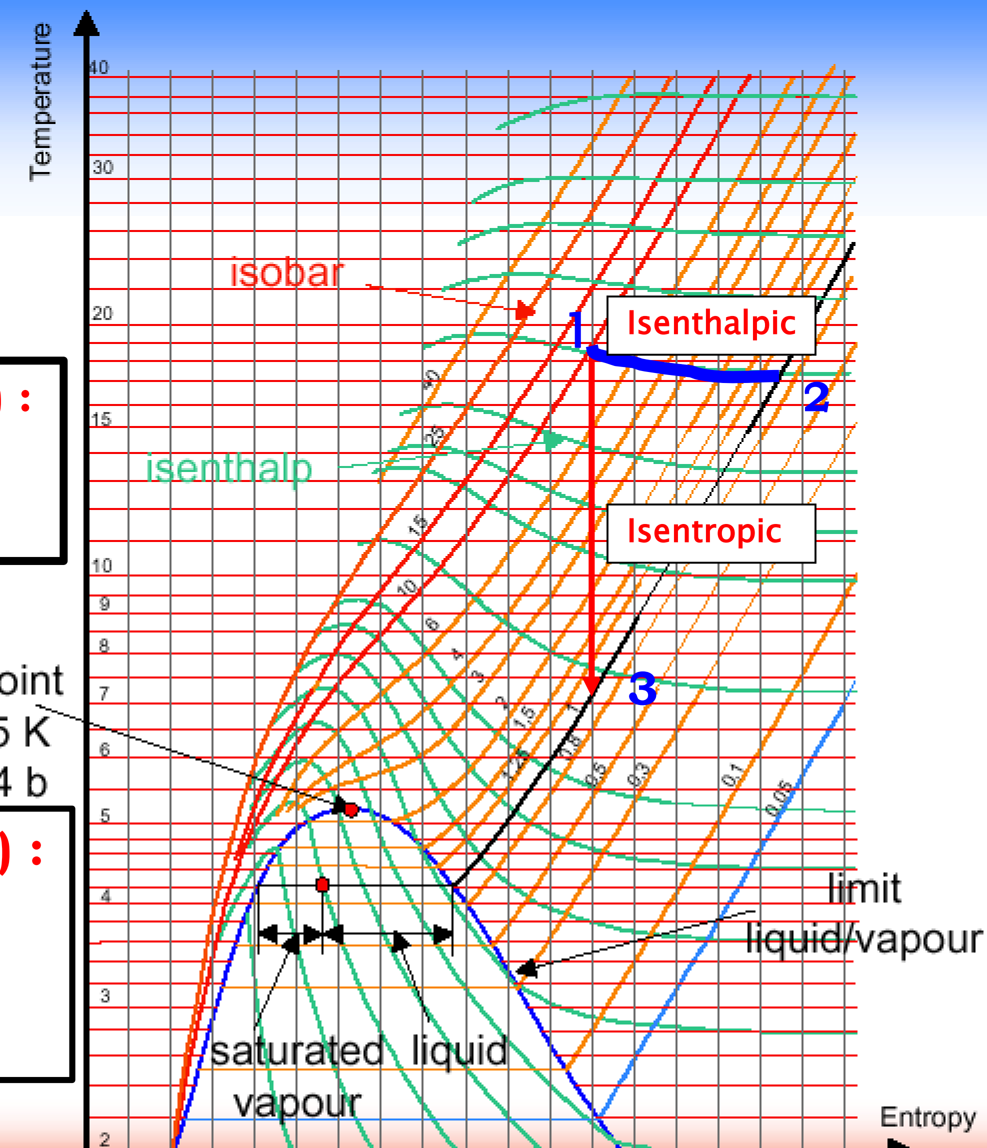
- **Unlike JT Expansion, There will be always cooling effect on adiabatic expansion at any temperature and Pressure**
- **Temperature drop is much higher compared to JT Expansion**

Comparison of Cooling Effect by JT & Isentropic Expansion Through T- S Chart

$(dT)_s >> (dT)_h$

HELIUM

1 (19k, 10 bar) - 2 (17 K, 1 Bar) :
JT Cooling
Drop only 2 K



1 (19k, 10 bar) - 3 (7 K, 1 Bar) :
Isentropic Cooling

Drop 12 K

Adiabatic (Isentropic) Expansion

$$PV^{\gamma} = Cons\tan t \qquad \gamma = \frac{C_p}{C_v}$$

γ = 1.66 (He, Monatomic Gas)
=1.4 (N2, Diatomic Gas)

$$P_1 V_1^{\gamma} = P_2 V_2^{\gamma} \qquad T_2 = T_1 \left(\frac{P_2}{P_1} \right)^{\frac{\gamma - 1}{\gamma}}$$

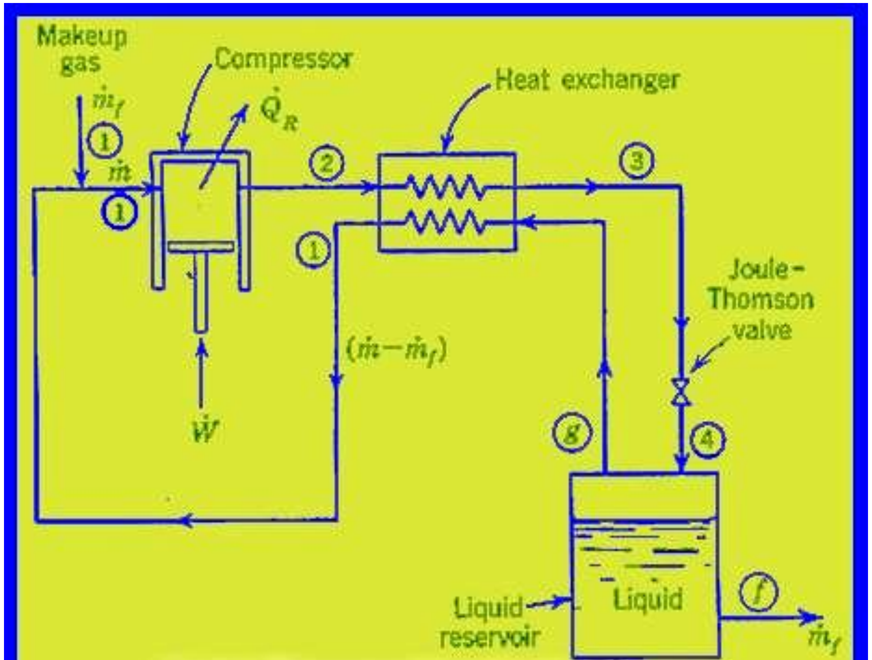
Example : If Helium Gas is Expanded from 220 Psi (p1) to 18 Psi (p2) at Inlet temperature (T1) = 60 K

T_2 = 23.4 K , Actual Case it is 30K

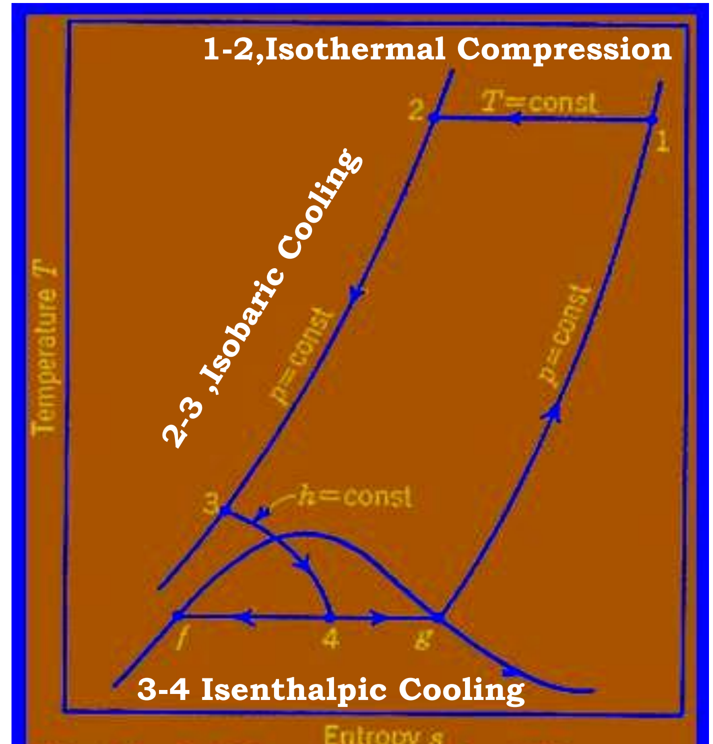
Efficiency = 80 %

Primary Practical Nitrogen Liquefier (Linde- Hampson Cucle)

It is only for those gases whose T_{imax} is above RT



Linde-Hampson liquefaction system.



The Linde-Hampson cycle. The state-points refer to the numbered points in the Linde-Hampson liquefaction system.

$$\frac{\dot{m}_f}{\dot{m}} = y = \frac{h_1 - h_2}{h_1 - h_f} \quad <<1$$

Yield can be increased by Increasing Pressure (lower h2), Other parameters are fixed but at what cost ??

Ideal Thermodynamic Liquefaction Cycle

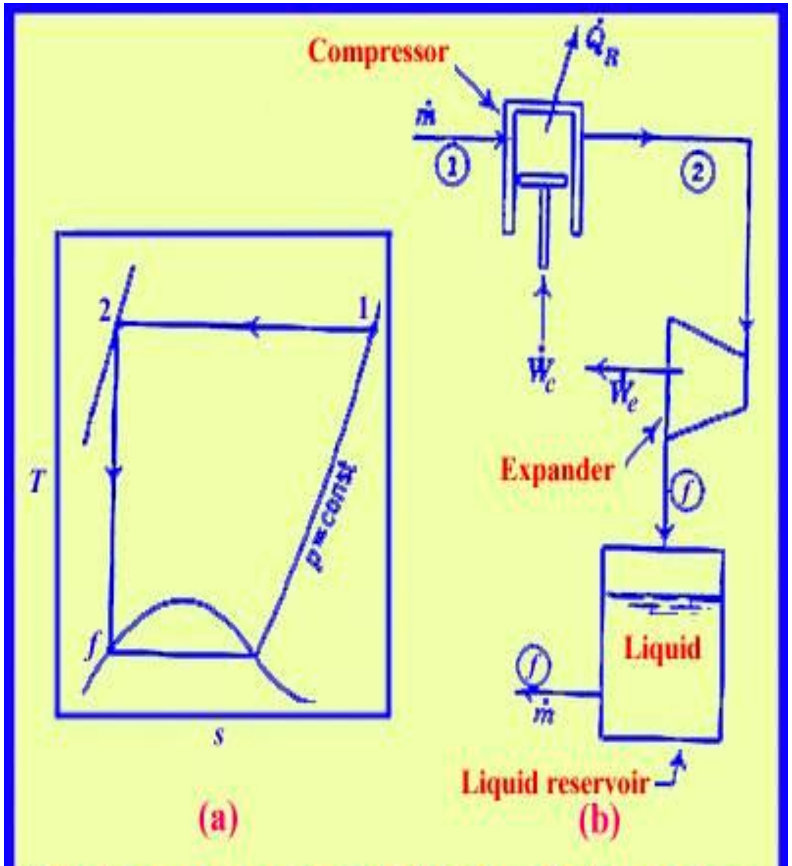
1----2 : Isothermal Compression
2----f : Isentropic Expansion

Not Possible , Why ???

For N_2, if P_1 is I bar, then P_2 must be 700000 Bar (very high pressure) to liquefy all the gases

Not Practical

Liquid Yield (Y) = $m_f/m = 1$



The thermodynamically ideal liquefaction system.

Ideal Work Requirement for 1 Kg Liquid Production
N2 = 768 KJ, He = 6800 KJ,

Value will be used for Comparison

A simple table on liquid yield and work required per unit production of liquid nitrogen for various compressor discharge pressure is presented here

(T_1 = 300 K, P_1 = 1 bar absolute pressure, h_f = 30 J /gm. h_1 = 462 J/ gm)

$$\frac{\dot{m}_f}{\dot{m}} = y = \frac{h_1 - h_2}{h_1 - h_f}$$

$$\frac{W}{m_f} = y\left[T_1\left(S_1 - S_2\right) - \left(h_1 - h_2\right)\right]$$

Pressure (P_2)	h_2	$Y = m_f / m$	W/m_f	FOM
20 bar	454	0.02	12888	0.06
50	448	0.03	9937	0.08
100	438	0.06	7200	0.11
200	425	0.09	5564	0.13

FOM = Ideal Work Required/ Actual Work

We Need Very High Pressure to have Significant Percentage Of Liquid Production on this L- H Cycle

Analysis on Linde- Hampson Cycle

Pressure	Yield mf/m	W/mf (J/ Kg)
100 Bar	0.06	7200

For 10 litre/ hr (8 kg/hr) liquid nitrogen production : Compressor capacity required at 100 bar discharge pressure

$m = m_f \times y$ = 8 kg/hr/0.06 = 133 kg/hr = 106 M^3/hr

Theoretical Power : 7200 kJ/kg x 8/ 3600 = 16 kW ?

Considering the efficiency of Compressor and Heat Exchanger, the Actual power Requirement will be more than Double 40 kW
Power Cost of Liquid nitrogen will be Rs 20/ Litre

Actual Power cost is only Rs 5/ litre
This Cycle is Simple but not Cost Effective

Can we use the same Cycle for Helium Liquefaction ??

LIQUEFACTION OF HELIUM

Max Inversion Temperature for Helium : 45 K (Below RT)

BASIC LINDE- HAMPSON SYSTEM WILL HAVE HEATING EFFECT.

We have to Precool with Liquid Nitrogen (78 k) and Liquid Hydrogen (20 K) prior to JT .

(First Liquefaction of Helium in 1908 : By Precooling L- H)

ALTERNATIVELY : ADDING ONE ADIABATIC EXPANSION PROCESS BY USING A TURBINE : Next

First Helium Liquefier By Kamerlingh Onnes

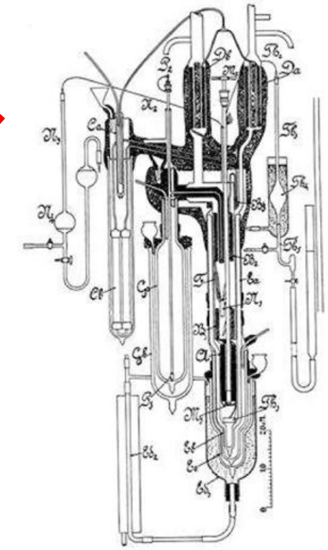
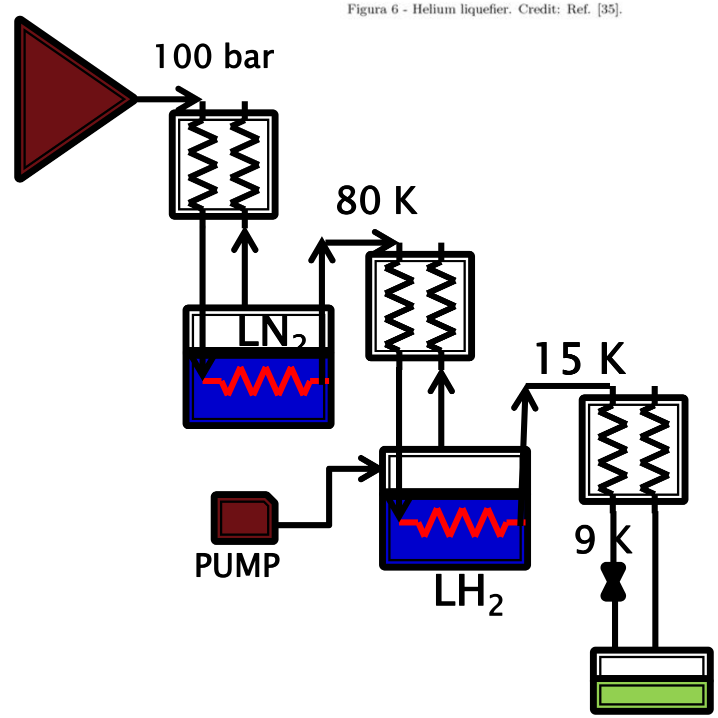
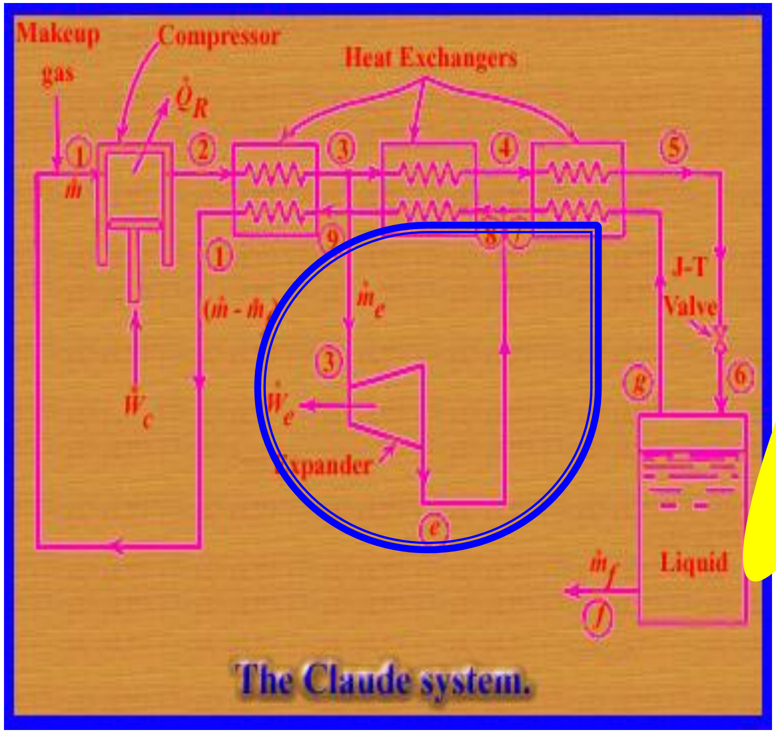


Figura 6 - Helium liquefier. Credit: Ref. [35].

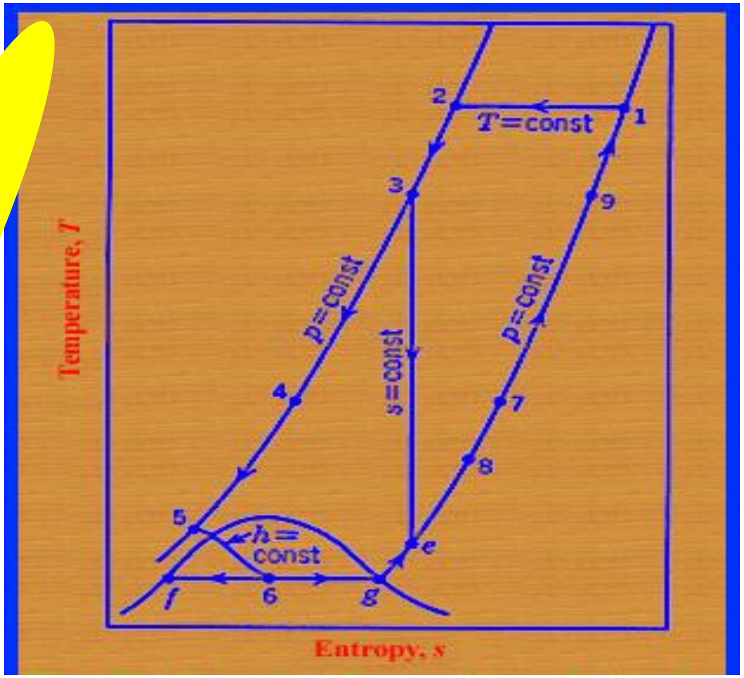


Helium Liquefaction Cycle

One more Process (Isentropic Expansion, 3-e) has been added to precool the gas below Timax prior to JT



Claude Cycle



$$\frac{\dot{m}_f}{\dot{m}} = y = \frac{h_1 - h_2}{h_1 - h_f} + \frac{\dot{m}_e}{\dot{m}}\left[\frac{h_3 - h_e}{h_1 - h_f}\right]$$

Added term enhances the liquid
In addition the work output from the Isentropic process can reduce the total work

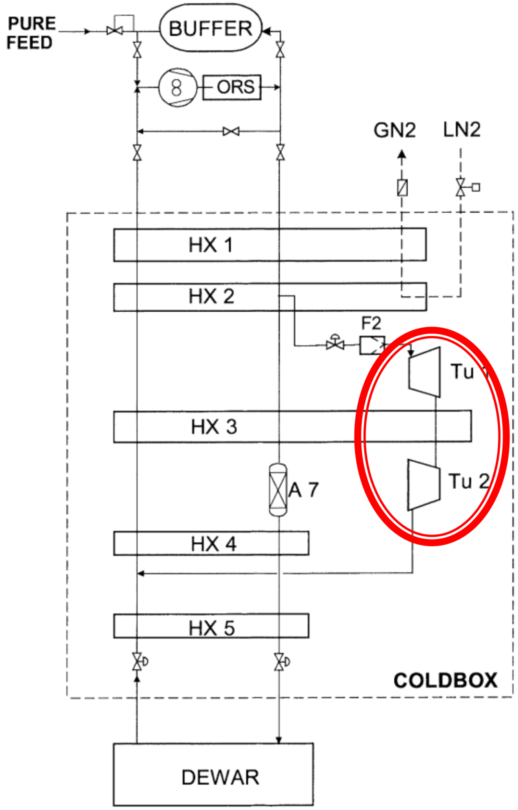
HELIUM LIQUEFIER WITH TURBINE

Capacity can be further enhanced by using two Expander and precooled with liquid Nitrogen. This is called Modified Claude Cucle.

Initial year, isentropic expansion was achieved by Reciprocating Piston type and later Turbine

Standard 1 kW class Refrigerator

300 litres/hr

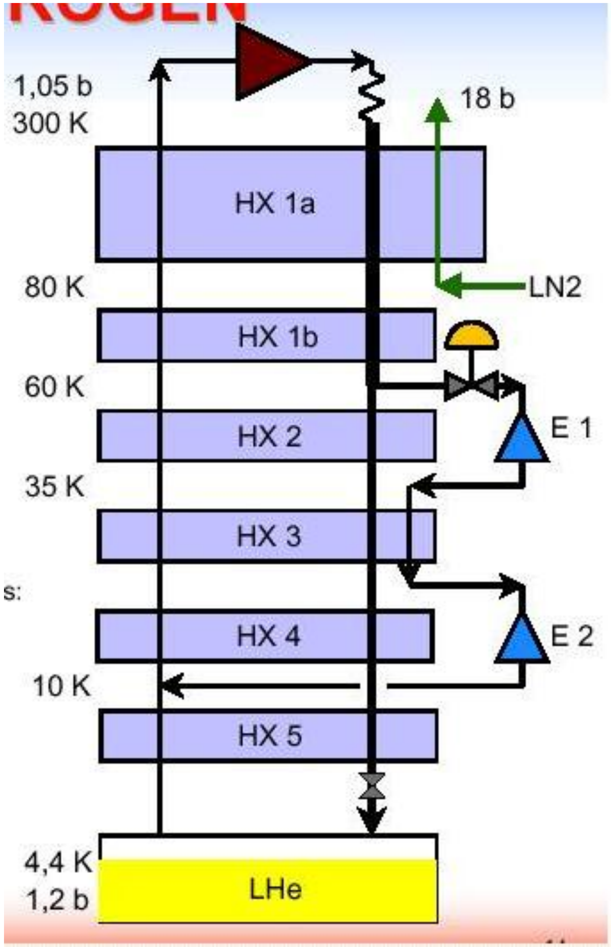


Advantage : Turbines are more reliable than the expansion engines because the latter are susceptible to performance deterioration due to contamination.

Disadvantage : Turbines do having a limited expansion ratio, that is a limited ratio of inlet to outlet pressures.

That was the reason Turbine are used in series rather than parallel for Reciprocating Expander

STANDARD HELIUM LIQUEFIER/ REFRIGERATOR CYCLE



Major Components :
1. Compressor 2. Heat Exchanger
3. Expander 4. JT Valve

Standard 1 kW at 4.3 K Helium Refrigerator needs a Compressor with capacity 100g/s and discharge pressure at 13 bar (g)

Isothermal Operation : Work required

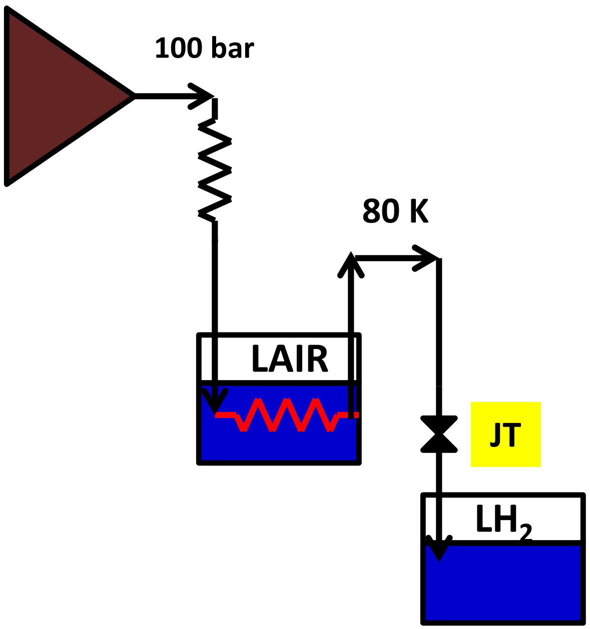
$$W = \frac{m}{M} RT \ln\left(p_2 / p_1\right) = 150kW$$

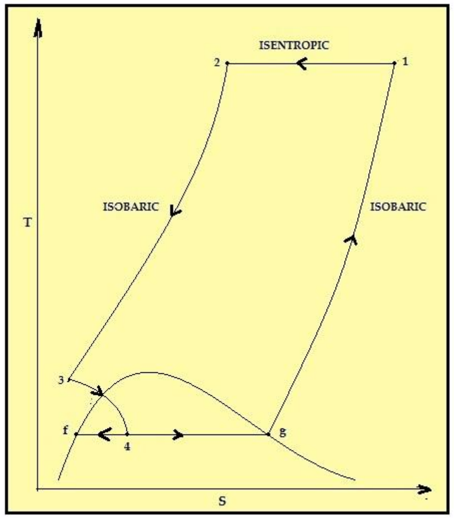
Actual Plug Power ; 300 kW

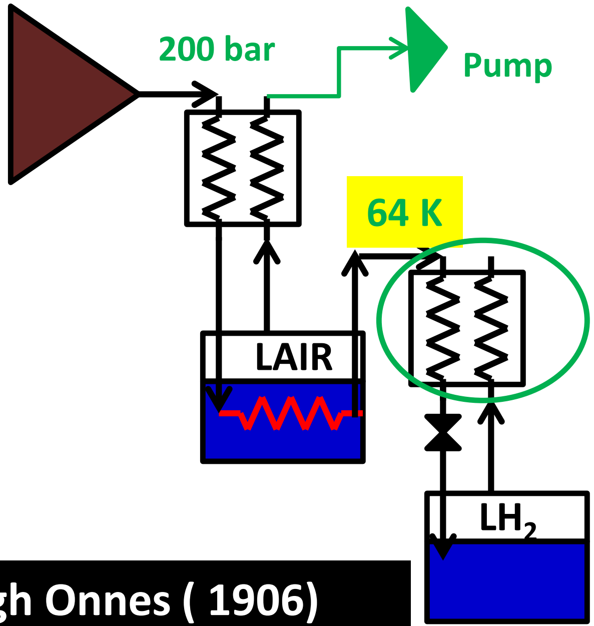
Compressor Efficiency : 49%

Inverse COP = 300 W/ W

Hydrogen Liquefaction







James Dewar (1895)

Liquefaction Rate was : 1.0 L/hr

Kamerlingh Onnes (1906)

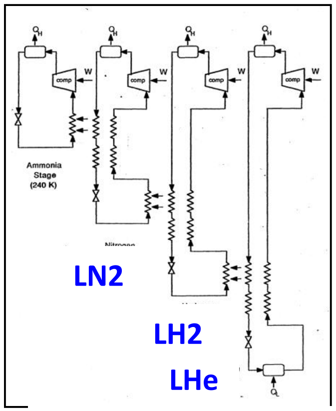
Liquefaction Rate was : 4 L/hr

Production Rate improved

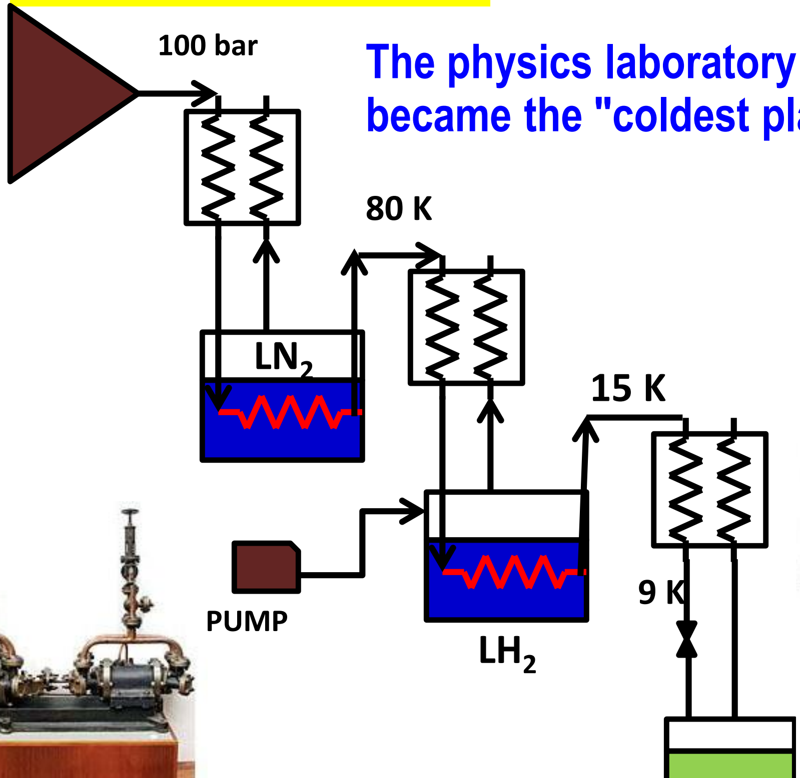
1. **Higher Pressure**
2. **Lower Precooling Temperature**
3. **Using of Last Heat exchanger**

1908 : First Helium Liquefier

(1853-1926)

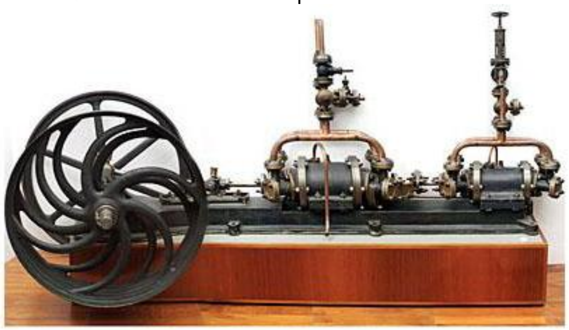


Cascade Helium Liquefier



The physics laboratory in Leiden became the "coldest place on earth”

100 cc Liquid was collected



Cailletet Mercury Compressor

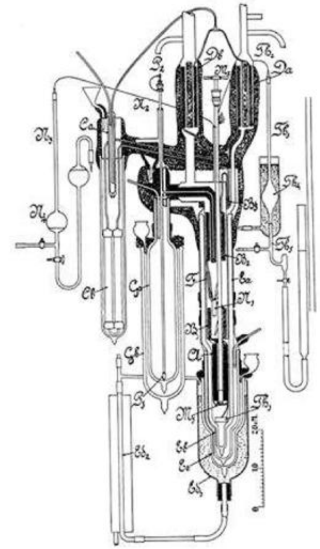


Figura 6 - Helium liquefier. Credit: Ref. [35].

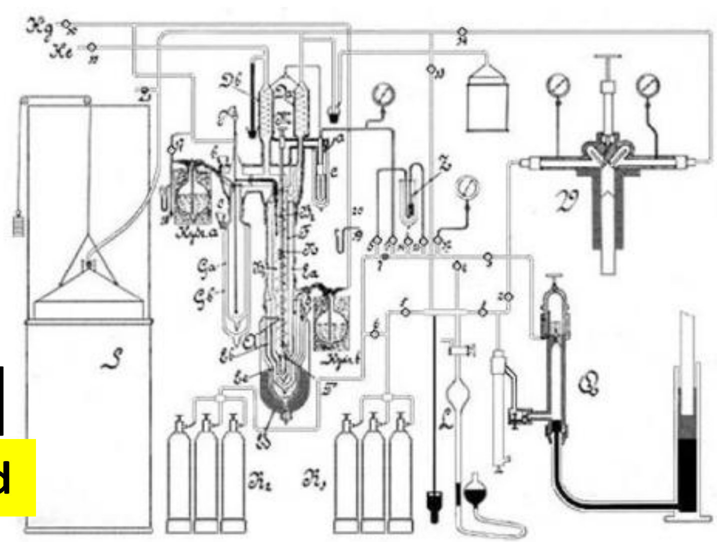
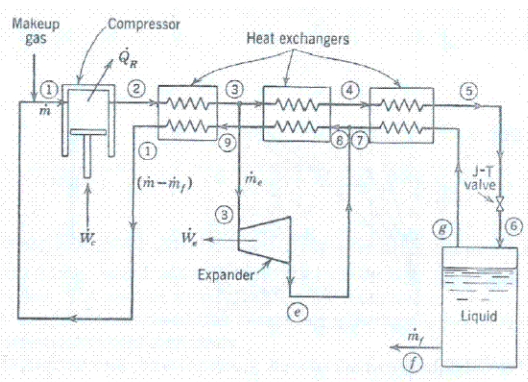


Figura 5 - Helium's cycle in the cascade process. Credit: Ref.[35].

HELIUM LIQUEFIER BASED ON EXPANSION ENGINE

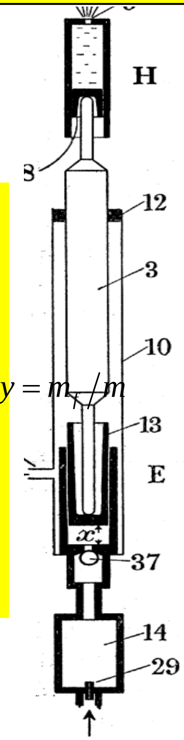
In 1934, Kapitsa Developed a helium liquefier based on the Claude cycle. The reciprocating expansion engine replaced the liquid hydrogen precooling bath

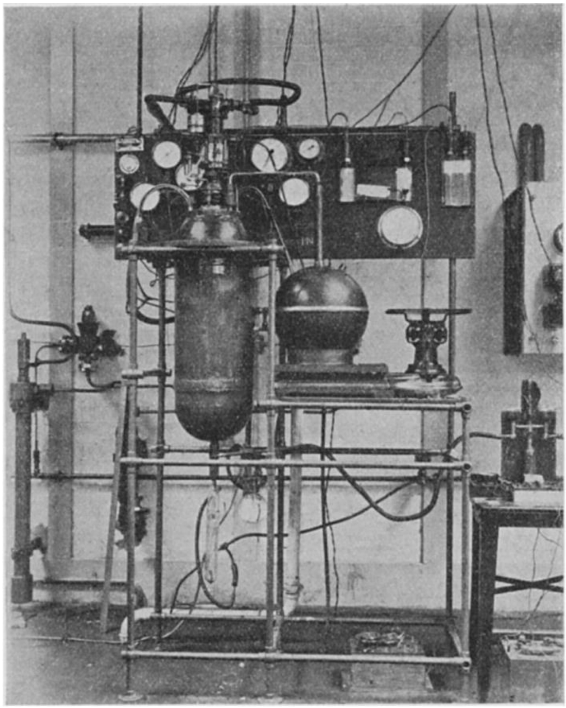


Claude Cycle

100 strokes/ m
Dia : 11 Inches

Kapitsa Expansion Engine





Kapitsa Helium Liquefier

Operating Pressure was only 17 bar against 100 bar
Production rate was 1. 7 liters/ hr against compression of 30 NM^3/hr

Yield, $y = {m_f}/{m} = 0.04$ **Much higher than JT cooling and with low pressure**

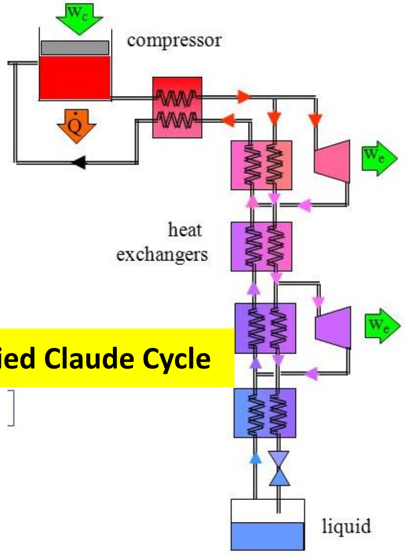
Reported that in 1932 M/S Linde delivered first Commercial Expansion based Helium liquefier to University of Charkov, Ukarine

Collins Helium Liquefier

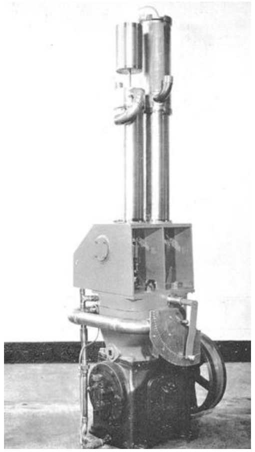
1935, Collins used two reciprocating expansion engines to eliminate the need for both liquid nitrogen and liquid hydrogen precooling.

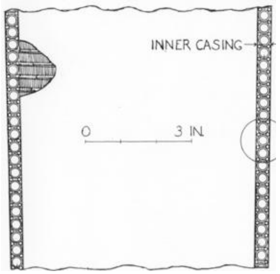
Liquefaction rate ~ 1L/hr.
Discharge pressure 15 Bar, 10 kW Motor

By 1946 Same Collins liquefier was commercially available in the name of ADL Collins Helium cryostat.



Modified Claude Cycle





Collins Fin tube Heat Exchanger

First Expender used for Helium liquefaction
Later it was Modified to have better sealing,
Valves under tension

First Commercial Laboratory Helium Liquefier : 1946

By 1946 Same Collins liquefier was commercially available in the name of ADL Collins Helium cryostat.

ASIA

First Helium Liquefier in Japan (Make ADL ,USA Collins type, Capacity 4 L/hr) was established At Tohoku University (Institute of Material Science) in 1952

In the Same Year (1952) , similar Helium Liquefier was Commissioned at National Physical Laboratory (NPL), New Delhi, India

Dr K S Krishnan along with foreign Delegates from Russia in front of Helium Liquefier at NPL in 1955

1936- 1969 , Linde : VR4 ,VR 8 Helium liquefier of Capacity 3-6 Lhr

Most Popular Helium Liquefier in Low Temperature Laboratories (1965 – 1980)

ADL to CTI 1400

Capacity : 10 litre/hr (single Compressor) : Reciprocating 2 stage; 100 Nm3/hr , Reciprocating Expansion Yield = .08

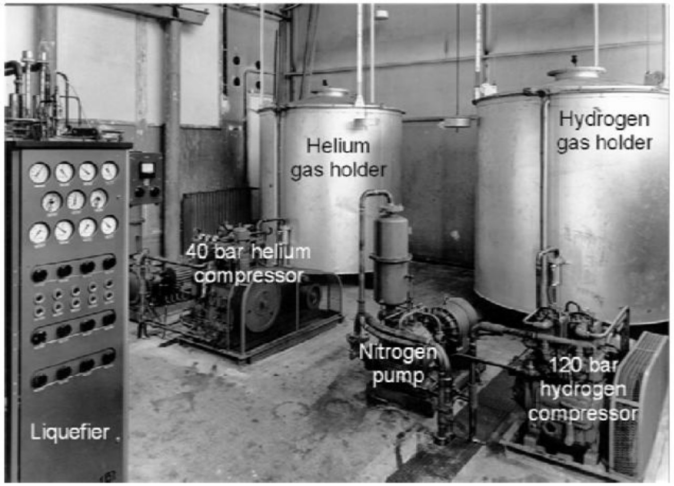
CTI 1410 → KOCH → PSI → LINDE (L 1410)

Automatic Engine speed, Screw Compressor, Modular

Production rate : 10 litres/ hr to 50 litres/ hr

In 1955, Très Basses Températures (TBT) was founded to sell Helium liquefier based on Kamarlingh onnes (Preccoling by LN2 & LH2 and JT)

Capacity : 7 L/ hr



In 1958, Air Liquide bought the activity and of such machines were sold till 1966

HELIUM LIQUEFIER WITH TURBINE

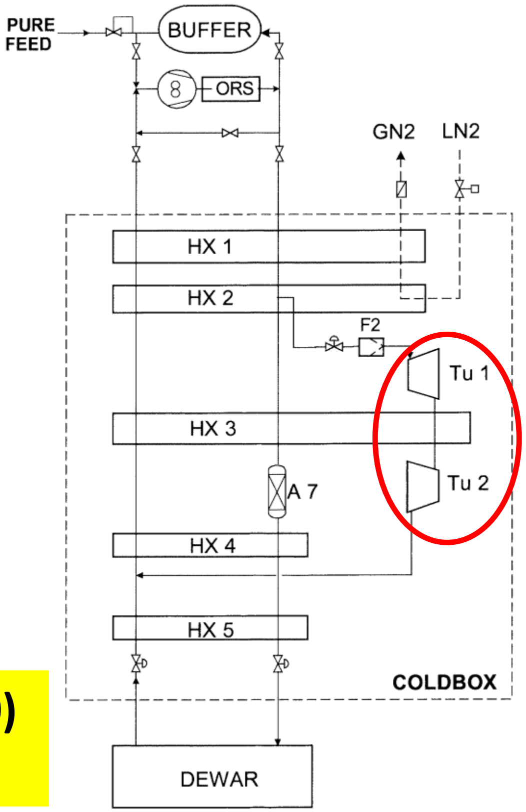
In **1964, Air Liquide** started developing helium cryogenic expansion turbines running on static gas bearings. The **first turbine helium liquefier was sold in 1968**. It produced **35 L/h** and had a liquid nitrogen pre-cooled one-turbine Claude cycle.

Advantage : Turbines are more reliable than the expansion engines because the latter are susceptible to performance deterioration due to contamination.

Disadvantage : Turbines do having a limited expansion ratio, that is a **limited ratio of inlet to outlet pressures.**

That was the reason Turbine are used in series rather than parallel for Reciprocating Expander

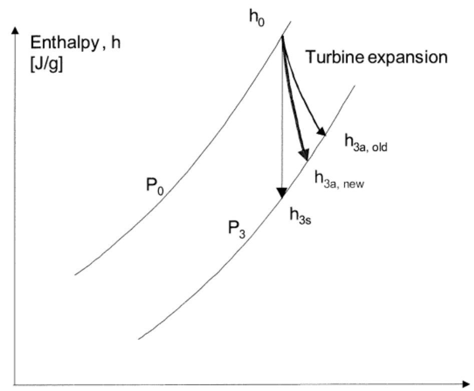
Standard 1 kW class Refrigerator



1969 ,M/s Linde also developed turbine based (TCF 20,50,100) Helium Liquefier

Turbine Efficiency

Over 30 years , efforts are on to enhance the Isentropic Efficiency of Turbine and that in turn increase the production rate



Design case	0	0	1	1
Turbine position	Tu 1	Tu 2	Tu 1	Tu 2
Isentropic efficiency	61%	67%	80.9%	79.3%

Liquefaction rate improved 35 to 50 %

$$\eta_s = \frac{w_a}{w_s} = \frac{h_0 - h_{3a}}{h_0 - h_{3s}}$$

$$y = m_f / m = (h_1 - h_2)/(h_1 - h_f) + x\eta_s (h_0 - h_{3a})/(h_1 - h_f)$$

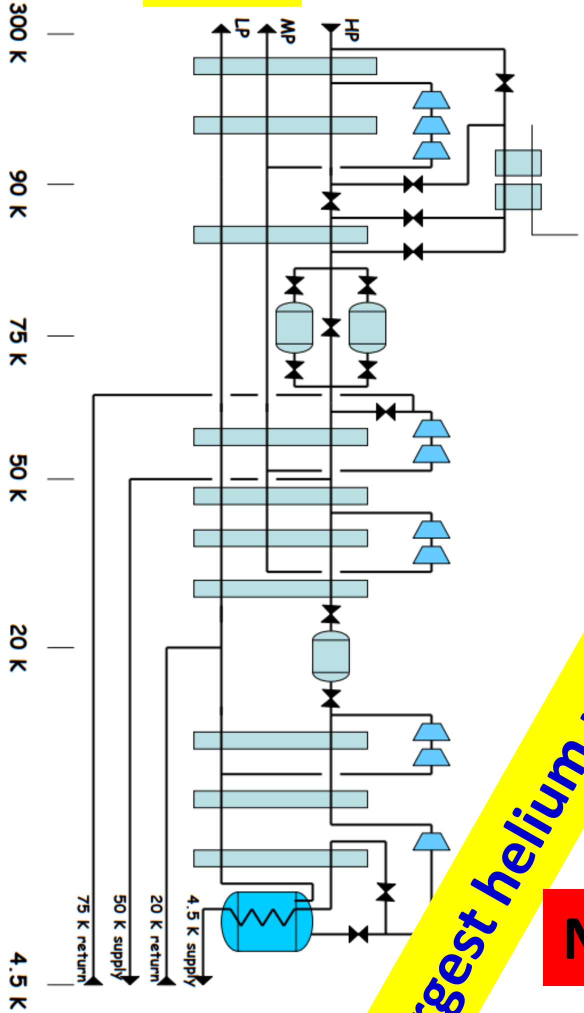
For Higher Capacity refrigerator, medium pressure parallel Turbine will have better efficiency. That also used multi stage compressor with higher Isothermal Efficiency.

TCF to L Model

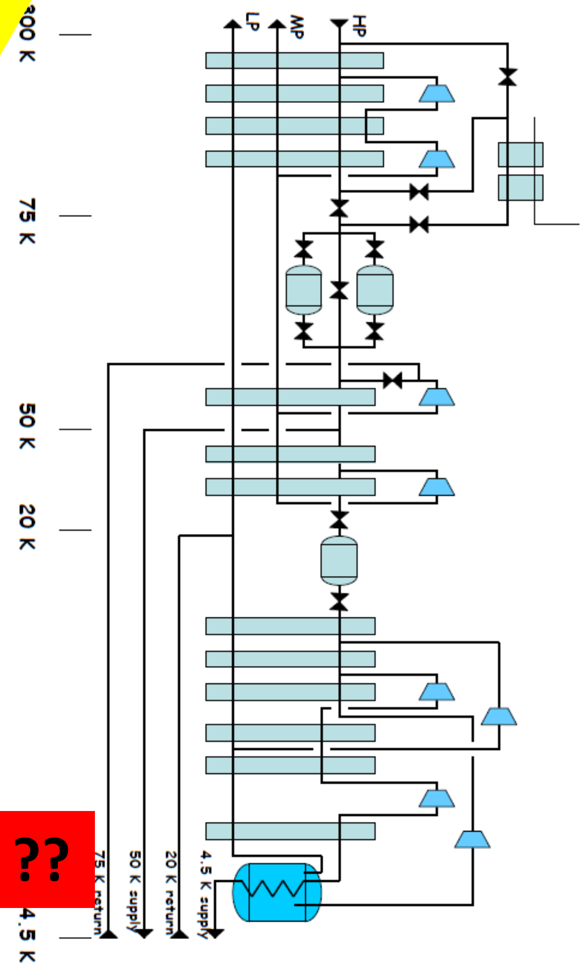
Courtesy to Linde

18 kW at 4.5 K Helium Refrigerator for CERN LHC Project

LINDE



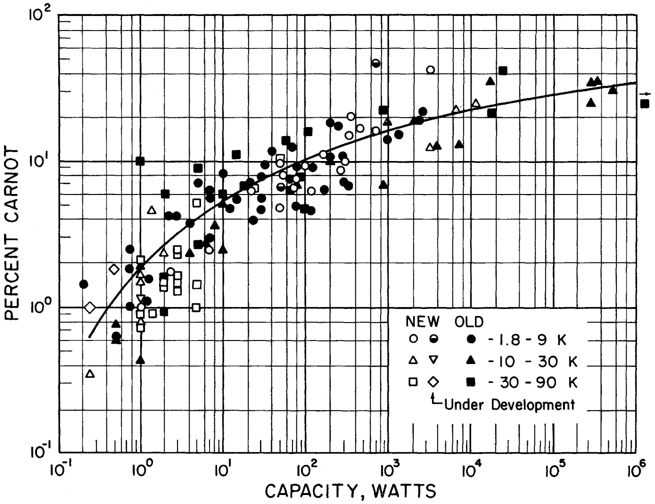
AIR Liquide



Largest helium refrigerator with Single Cold Box

Next 20 / 25kW ??

Strobridge Survey (Efficiency) 1974



GM Cryocooler ; 4 kW for 1W refrigeration at 4.2 K

Laboratory Scale Helium Refrigerator (~ 100 W) :
700 W for 1 W

Medium Range 1kW Class (300 W for 1W Range)

Large Helium Refrigerator (18 kW for CERN :
225 W for 1 W

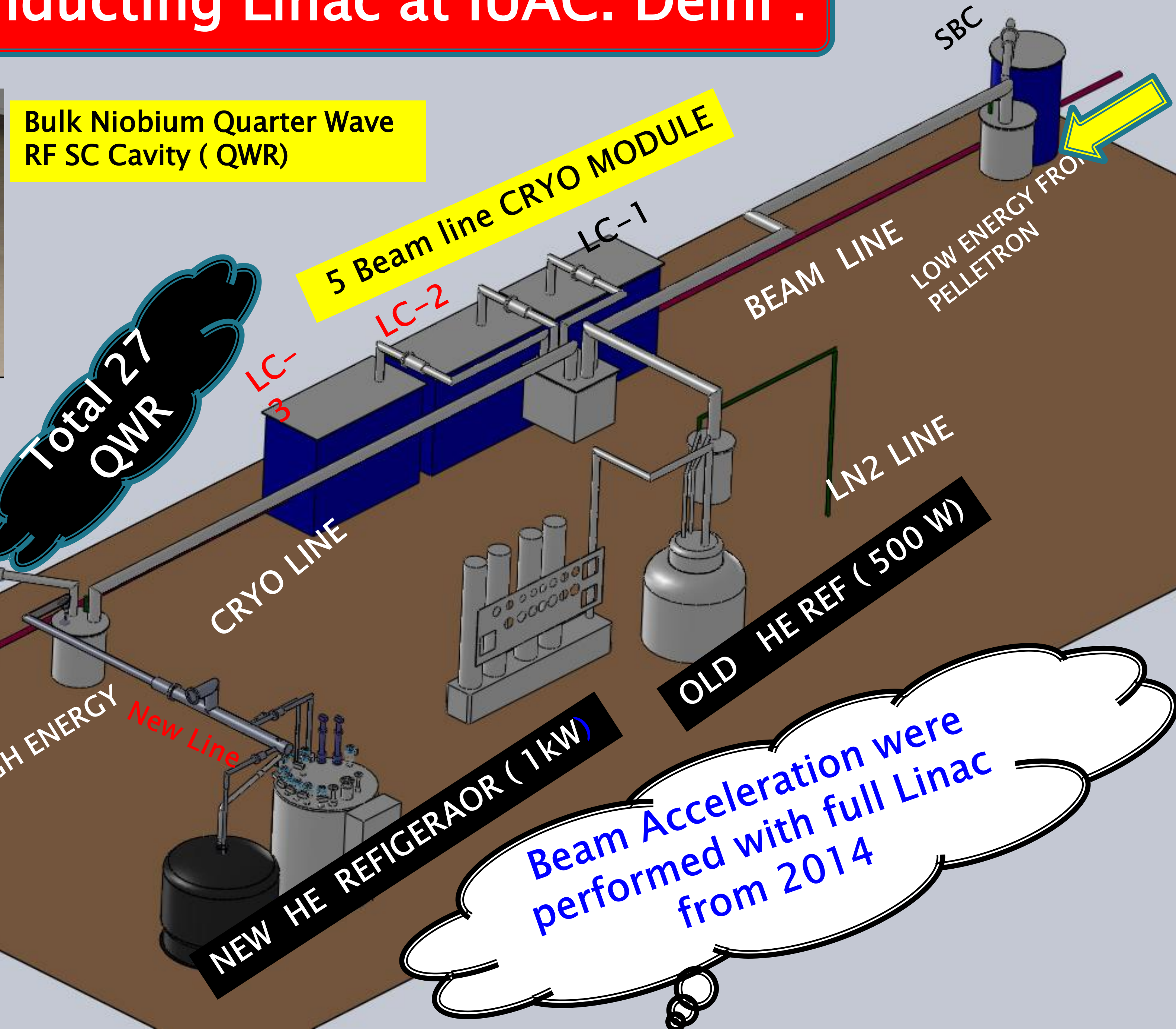
Whether we have reached peak value of 225 W ??

Efforts are on to replace the screw compressor by dry centrifugal compressors: deletion of the Oil Removal System and reduction of the electrical consumption by 12% to 20% depending on the number of compressor stages.

Isothermal efficiency of centrifugal compressors is higher than screw compressors, and this efficiency increases with the number of compressor stages.

Superconducting Linac at IUAC. Delhi :

Bulk Niobium Quarter Wave RF SC Cavity (QWR)



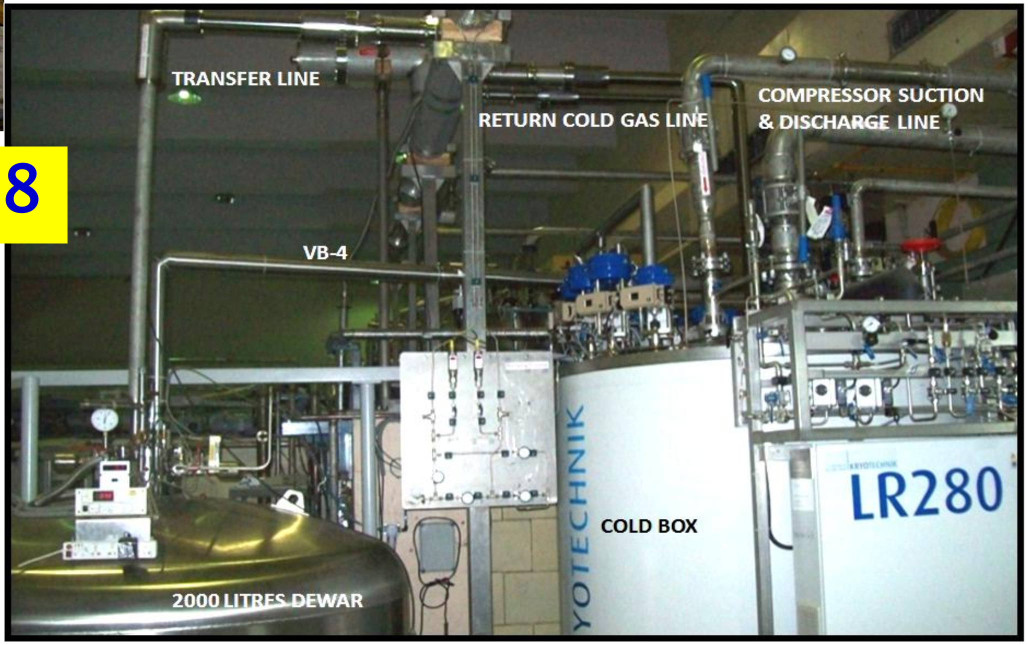
(Annotated Slide)

IUAC (Delhi) Helium Liquefier for Superconducting Acceler

1996- 2012

M/s CCI Helium Liquefier
Capacity : 500 W or 150 L/hr
Reciprocating Engine :
Parallel at 60 K and 20 K
Yield : 8 %,
Inverse COP : 500 W/W

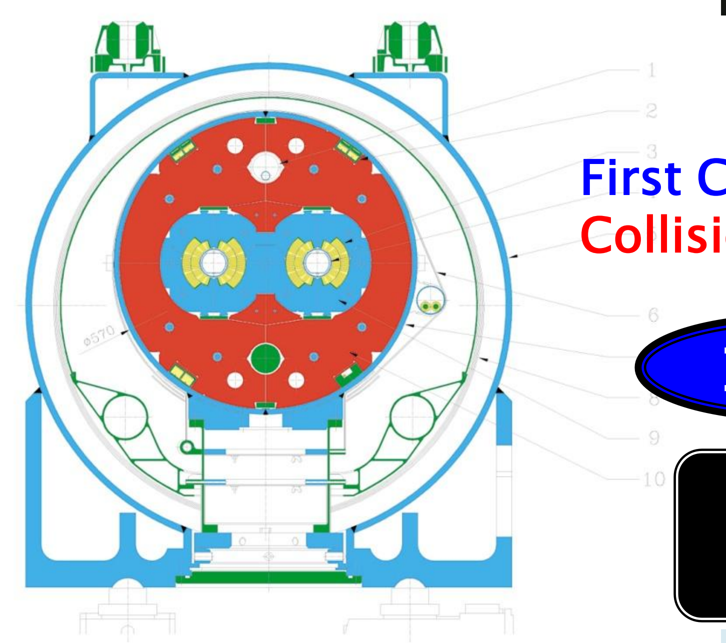
2012- 2018



M/S Linde Kryotechnik
Model : LR 280
Capacity : 900 W / 290 L/hr
Turbine in Series 60 K
Yield : 12%
Inverse COP : 300 W/ W

LARGE HADRON COLLIDER (LHC) AT CERN

1. Worlds Largest Particle Accelerator
2. 27 km Circumference at Swiss- France Border.
3. Proton – proton Collider with collision energy 14 TeV
4. **Largest Cryogenics and SC network as on Today**
5. Total 6000 Superconducting Nb–Ti Magnets (1200 Dipole + 400 Quadrupole magnet+ Rest Corrector Magnets
6. **Total Refrigeration Capacity 144 (18x8) kW at 4.2 K**



First Collision at 3.5 TeV Beam Energy in 2010

Collision at Design Beam Energy (7 TeV) in 2015

LHC → **HL-LHC** → **VLHC**

Nb- Ti SC magnet generates a field 8.3 Tesla and operates at 1.9 K

LHC → HL-LHC → VLHC

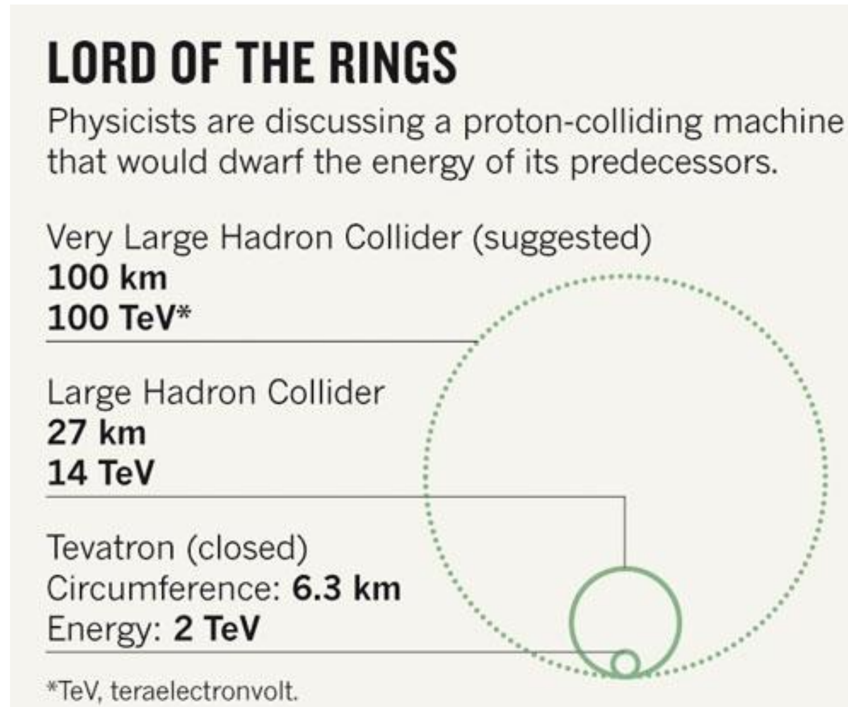
High luminosity	$5 \times 10^{34}\ cm^{-2}s^{-1}$

100 High Field Nb_3Sn Magnet (12 T) in 100 magnets before and After ATLAS/ CMS Detector

Operating Temp : 4.5 K

Using of Superconducting Crab Cavity

Total length Replacement ~ 1 km

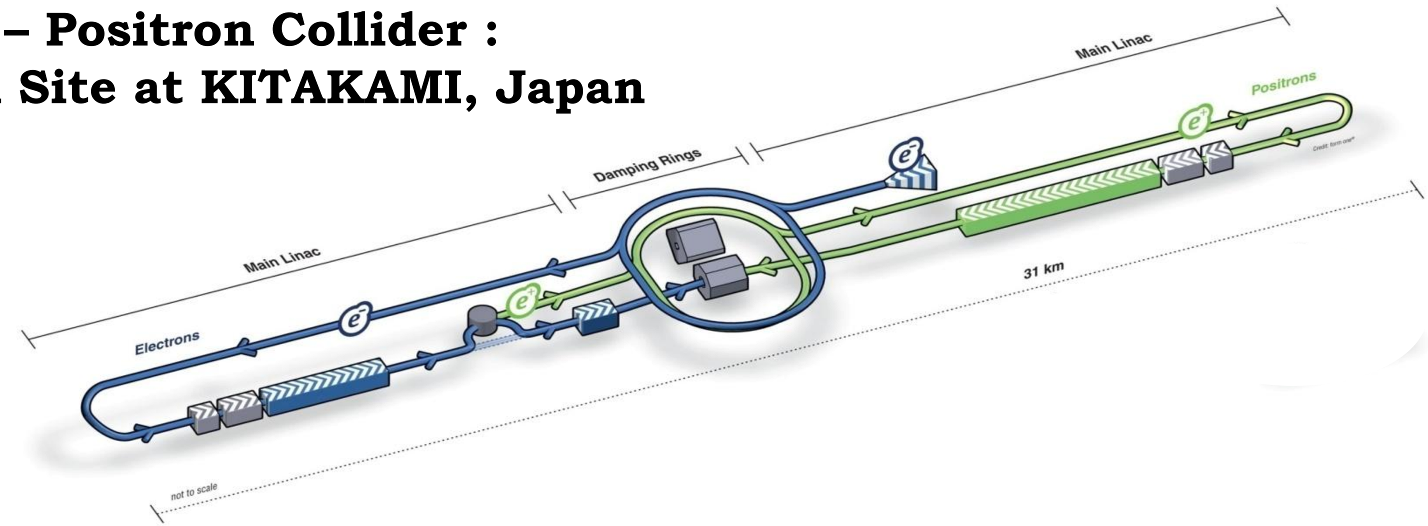


16 Tesla magnets for 100 TeV pp in 100 km

????????

INTERNATIONAL LINEAR COLLIDER (ILC)

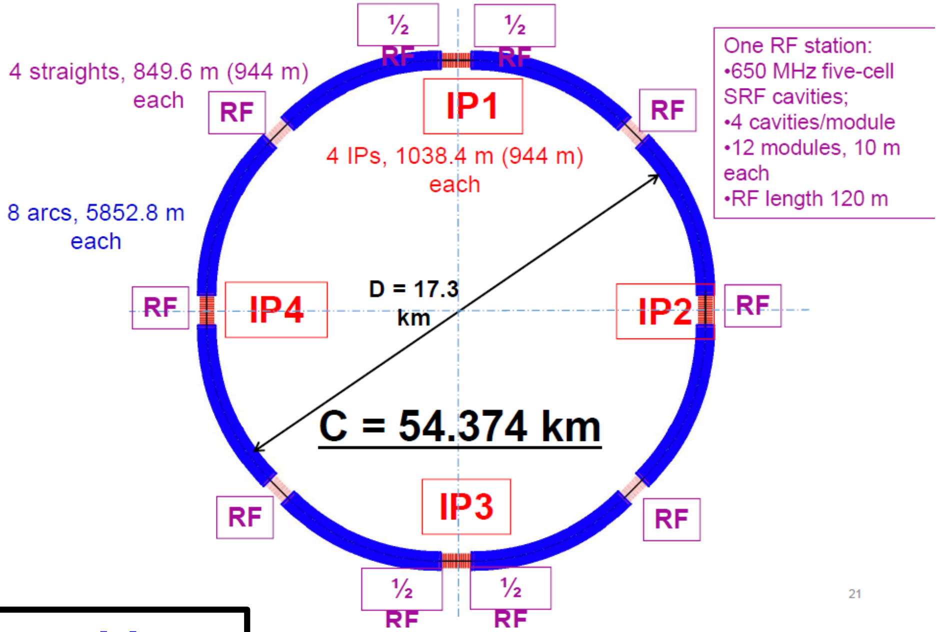
Electron – Positron Collider :
Proposed Site at KITAKAMI, Japan



Max. Center-of-mass energy	500	GeV
Peak Luminosity	$\sim 2x10^{34}$	$1/cm^2s$
Beam Current	9.0	mA
Average accelerating gradient	31.5	MV/m
Beam pulse length	0.95	ms
Total Site Length	31	km
Total AC Power Consumption	~230	MW

The Circular Electron Positron Collider (CEPC) circumference of 50 – 70 km at Quinghuada, China (2021-27)

Parameter	Design Goal
Particles	e+, e-
Center of mass energy	240 GeV
Luminosity (peak)	2*10^34/cm^2s
No. of IPs	2



Booster ring: 256, 1.3 GHz 9-cell SC cavities
Collider ring: 480, 650 MHz 2-cell SC cavities

Estimated Project Cost ~ $6 billion

International Linear Collider

We need 15000 such cavities

- 1.3 GHz 9cell ILC Cavity
- Made of Niobium
- Required Acceleration Voltage : 31.5 MV/m

Single Cryomodule
To House 9 Cavities.
Each length ~ 12 m

We need 1700 cryomodules

Required Refrigeration Capacity 210kW at 4.2 K

Acknowledgement / Reference

1. Joseph L Smith, MIT USA
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5. Ph. Lebrun, CERN
6. M/s Linde Kryotecnik, Switzerland
7. M/s Air Liquide, France

Will Superconductivity & Cryogenics Control High Energy Physics, Transport, Power and Medical in Near Future ?????

I understand how painful it is to tolerate for three hours

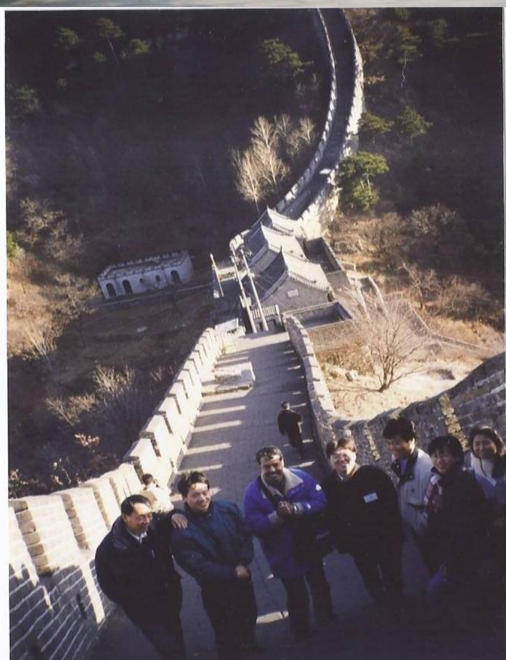
Superconductor

Thanks for your Kind Patience

No Other Option ???/

Any doubt : Please Contact me :

tsdatta59@gmail.com



Thank You China

Cryogenics Operations 2018