CRYOGENICS FOR ACCELERATOR

T.S. DATTA

Inter- University Accelerator Centre

New Delhi

1908 : Kamerlingh Onnes Succeeded in Liquefying helium

2008 : Centenary Year for Liquid helium

Heike Kamerlingh Onnes (1853-1926

Onnes's brother was able to arrange for large amounts of **monazite sand,** which contains helium, to be purchased from North Carolina. Onnes was able to extract about 300 liters of helium gas (at 1 atm) from the sand shipment.

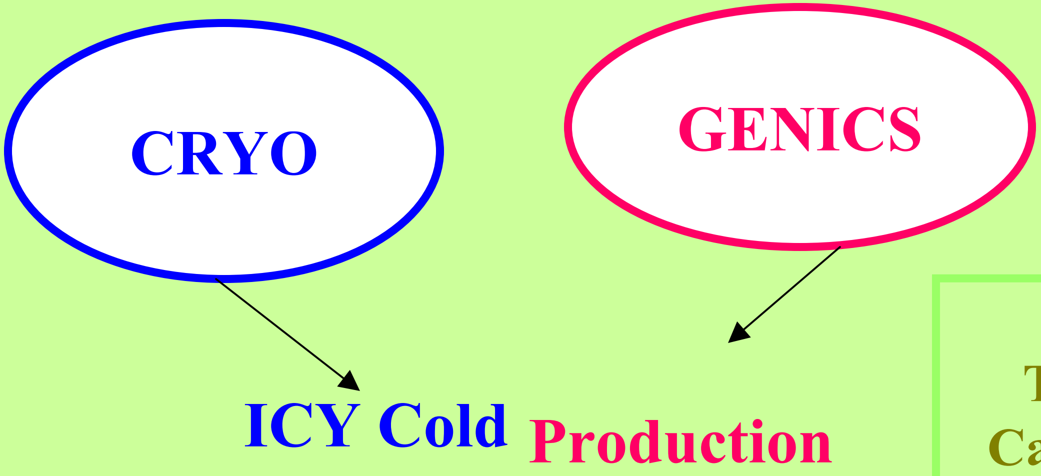
The physics laboratory in Leiden became the "coldest place on earth"

Reference

- Cryogenic System : R. Barron
- Proc. Asain Accelerator School : Prof Shin- ichi Kurokawa
- Lecture Notes : Martin Wilson, Oxford Instruments
- CERN Accelerator School : Philippe Lebrun, LHC CERN
- Lecture Notes : Guy Gistau, Air Liquide. France
- School Lecture : Ramesh Gupta, BNL, USA
- AAS : Kenji Hosoyama, KEK, Japan
- CERN Accelerator school : G. Vandoni,LHC. CERN
- Lecture Notes : Thomas Peterson, Fermi Lab
- Lecture Notes : Rao Ganni, Jefferson Lab
- Lecture Notes : Amit Roy,IUAC.Delhi
- Cryogenic Engineering : Thomas F Flynn

Cryogenic Course Material

- Introduction : What is Cryogenics and Why Cryogenics for accelerator , Present Scenario
- How to Generate low Temperature / Production of Cryogen : Thermodynamics / Refrigeration Cycle
- How to Store Cryogen : Heat transfer, Cryomodule Design, Properties of Material :
- Measurement at Low temperature :



CRYO

GENICS

ICY Cold Production

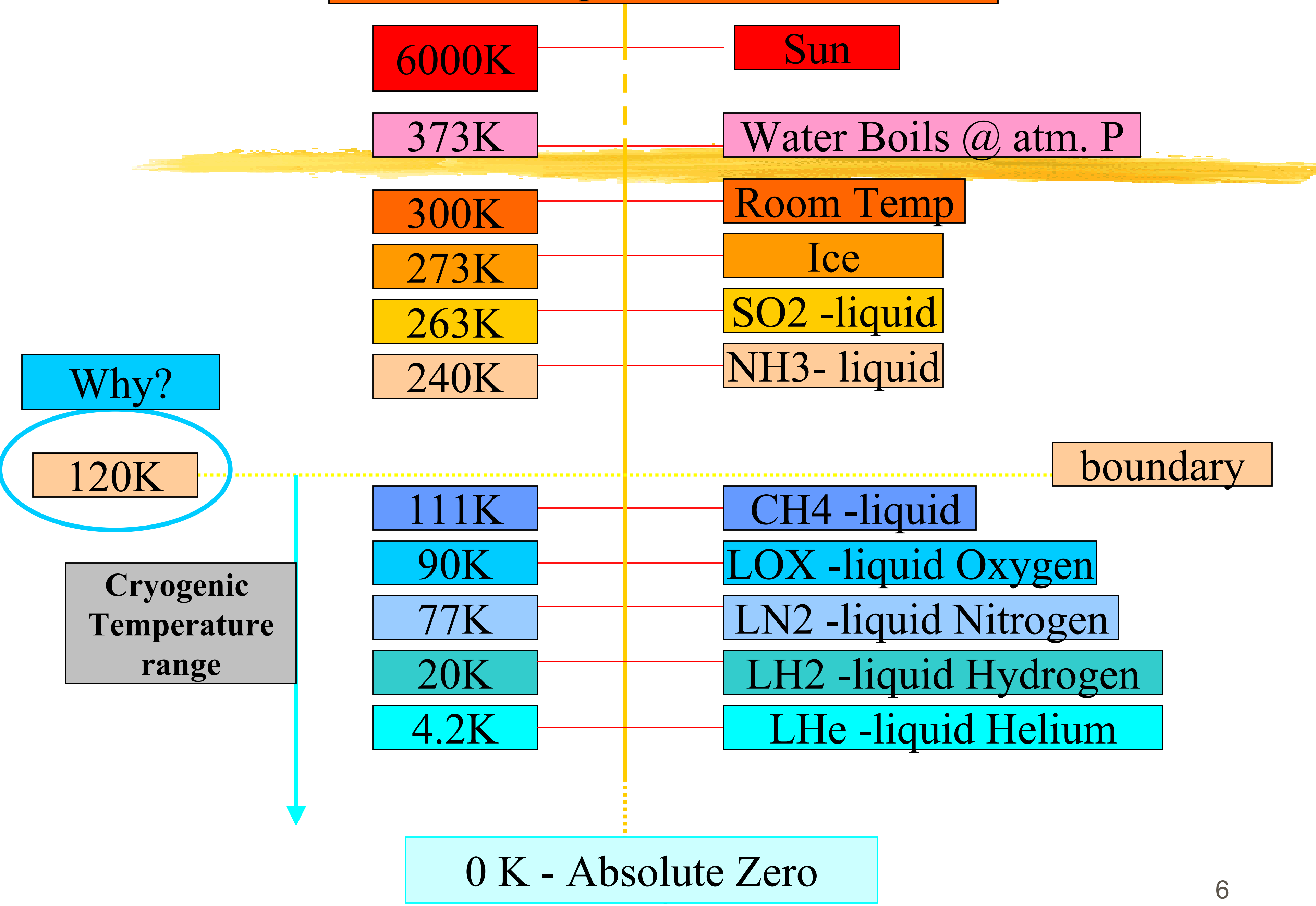
Temperature Range < 120 K

1877 : Liquefied Oxygen (90 K)

1908 : Liquid Helium (4.2K) by K. Onnes

Today
Temperature
Can be achieved
< 200 pK
by
Dilution ref.
Adiabatic demag
and
Nuclear
magnetization

Temperature Scale



6000K	Sun
373K	Water Boils @ atm. P
300K	Room Temp
273K	Ice
263K	SO2 -liquid
240K	NH3- liquid
120K	boundary
111K	CH4 -liquid
90K	LOX -liquid Oxygen
77K	LN2 -liquid Nitrogen
20K	LH2 -liquid Hydrogen
4.2K	LHe -liquid Helium

Why?

Cryogenic Temperature range

0 K - Absolute Zero

	T(boil)	T(critical)	P(critical)
SO_2	263K	432K	79 Bar
NH_3	240K	405K	115 Bar
O_2(LOX)	90K	155K	50 Bar
N_2 (LN_2)	78K	126K	34 Bar
Ne	27K	45K	27Bar
H_2 (LH_2)	20K	33K	13Bar
He(LHe)	2K	5.2K	2.2 Bar

Permanent Gases

Tc [SO_2/CO_2] > 300K (room temp)

gas

Pressure

liquid

Tc [N_2/He] < 300K (room temp)

gas

Whatever Pressure ?

No liquid

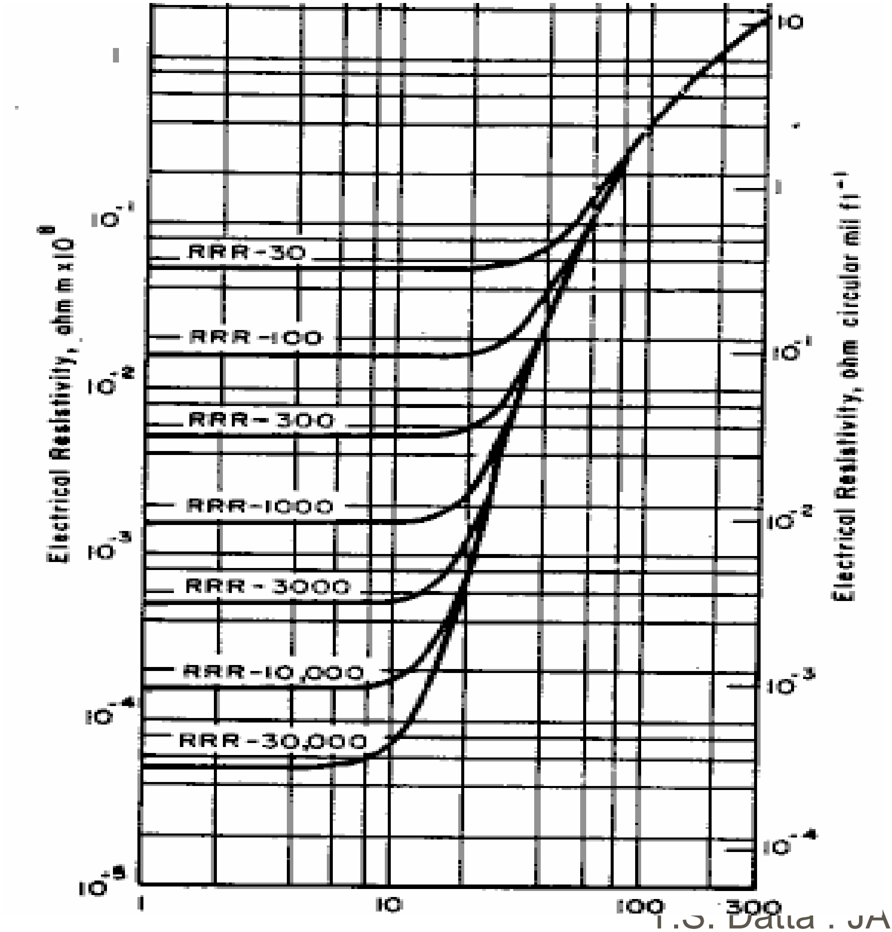
Hence they are called

Permanent Gases

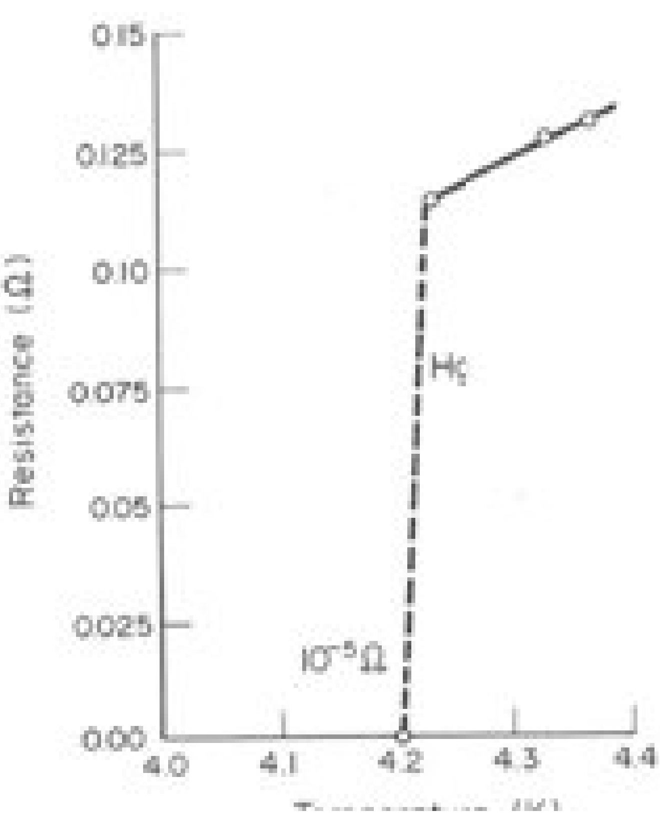
Ar, N_2, O_2, Air, Ne, H_2 and He

1911: Kamerlingh Onnes discovery of mercury superconductivity: "Perfect conductors"
1913 : Noble Prize

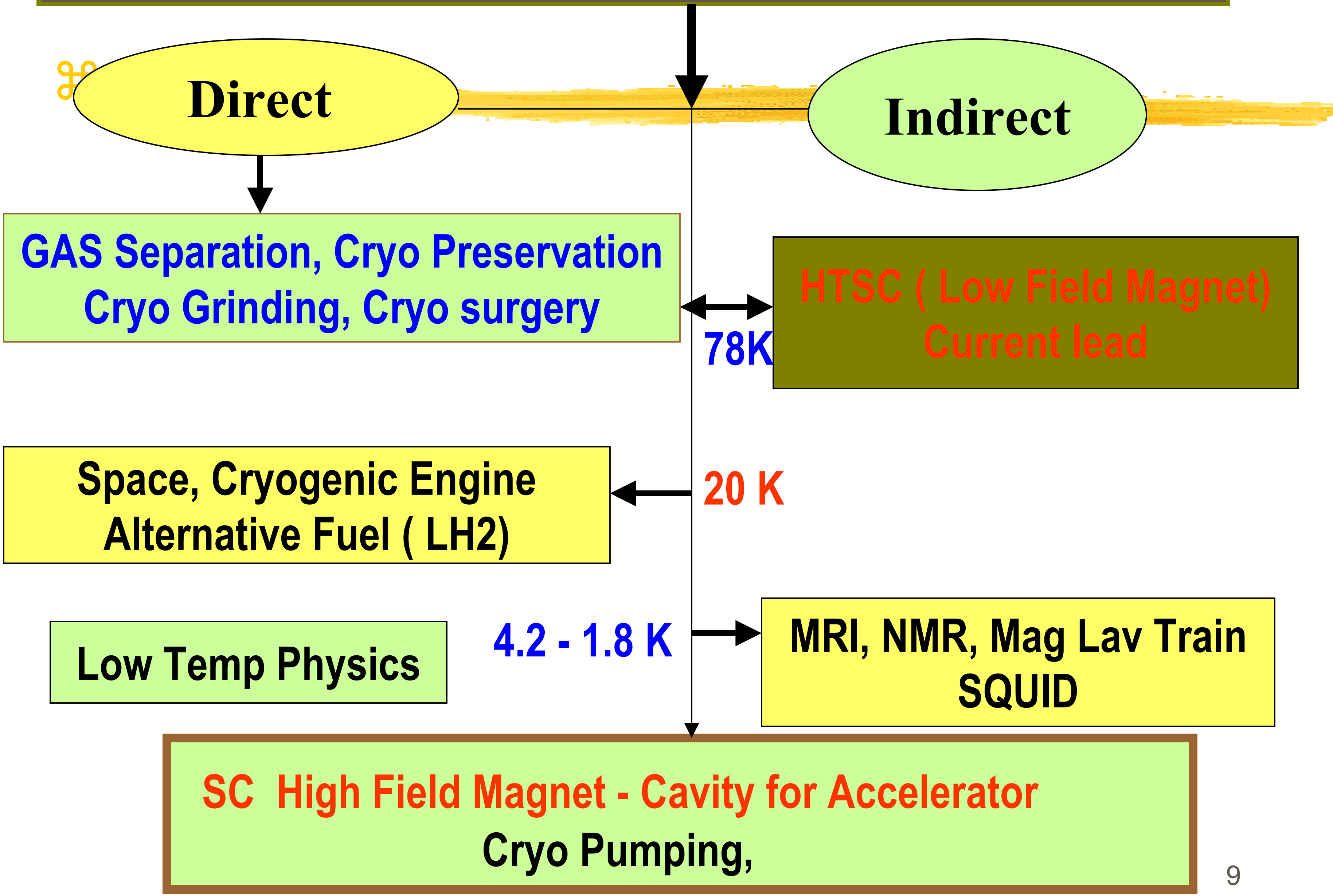
Resistivity of Cu as a function of T



Resistance of Mercury falls suddenly below at very low T First observation of "Superconductivity" by Onnes (1911)



Application of Cryogenics



Direct

Indirect

GAS Separation, Cryo Preservation
Cryo Grinding, Cryo surgery

78K

HTSC (Low Field Magnet)
Current lead

Space, Cryogenic Engine
Alternative Fuel (LH2)

20 K

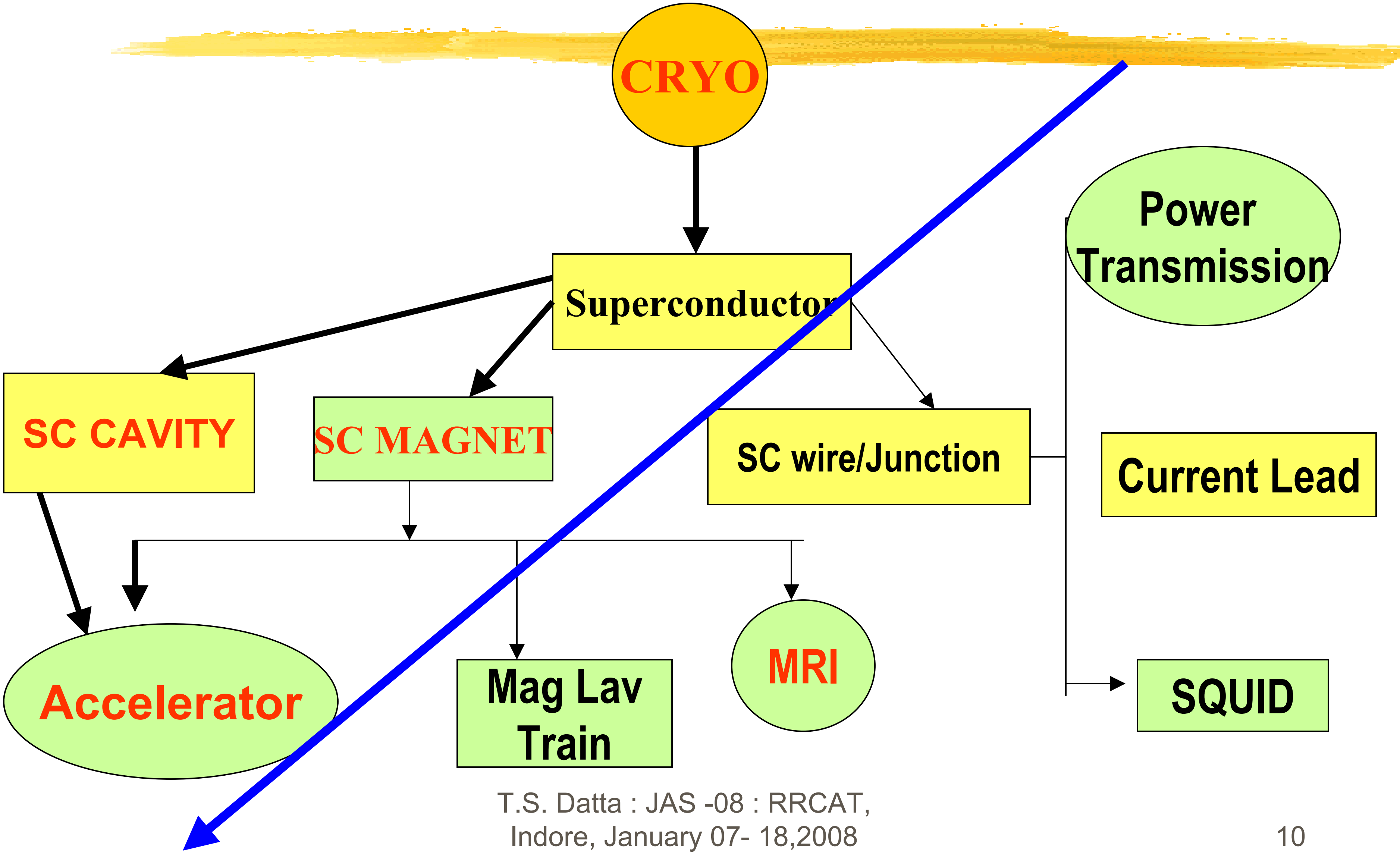
Low Temp Physics

4.2 - 1.8 K

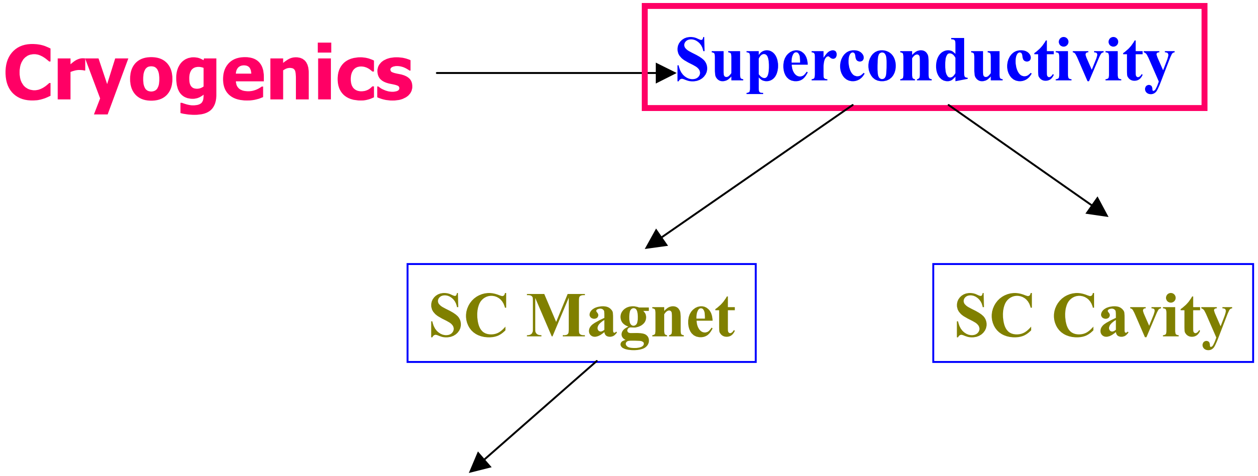
MRI, NMR, Mag Lav Train
SQUID

SC High Field Magnet - Cavity for Accelerator
Cryo Pumping,

APPLICATION OF SUPERCONDUCTIVITY



CRYOGENICS FOR ACCELERATOR



Cryogenics → Superconductivity

Superconductivity → SC Magnet

Superconductivity → SC Cavity

Magnetic Field B = C I. N

I Limited for Normal Conducter, Joule Heating, Proportional to R

High Field, Compact size

Power Required to Accelerate the beam ~ Surface resistance

Superconductor Surface resistance is low

Power factor 1000 times

Cryogenics + Nuclear Science

Breakthroughs.

Extreme low temperatures through nuclear adiabatic demagnetisation.

Polarised targets for nuclear experiments.

High field magnets for particle accelerators.

Cryogenic detectors for high precision spectroscopy.

Superconducting Cavities for Particle Accelerators.

Cryopumping for better vacuum in Beam line pipe

Cryogenics - Superconductivity - Accelerator
(Brief History)

- **1908 - Kamerling Ones Liquefied Helium** (4.2 K)
- **1911 -** Kamerling Ones Discovered Superconductivity (Hg)
- **Superconductivity is Born !!**
- **1933- Meissner Effect > Perfect Diamagnetism**
- **1957 - BCS Theory**
- **1980 -** Tevatron , First Accelerator Using SC Magnet (70 Yrs)
- **1986 - High Temp Superconductors (> 77 K)**
- **1990 -** India Embarked on SC Magnet for Accelerator
- **2001 - Low Temp SC (Mg B2) with High Tc (39 K)**

- 2007 - Commissioning of LHC (Largest Cryogenics)

Properties of Cryogenic Fluid

Fluid	He_4	H_2	Ne	N_2	O_2
B.P (K)	4.2	20	27	78	90
Tripple point (K)	2.1	14	24.6	63	54
Critical temp (K)	5.2	33	44	126	155
Critical Pressure(Bar)	2.3	13.2	27	34	50
Heat of vaporisation (J/gm)	20	400		199	200
Density (gm/ litre)	125	71	1204	808	1140
Liquid vapour Density	7.4	53	127	176	240

Temperature Below 4.2 K

- Liquid Helium (He4) : 4.2 K
- Pumping Liquid Helium : 0.8K
  Superfluid)
- Pumping Liquid He3 : 0.3K
- Dilution Refrigerator : 10 - 5 mk
- Adiabatic Demagnetisation : 1mk
- Nuclear demagnetisation : micro Kelvin
- Cascade : Nano kelvin - Pico Kelvin

As on today Minimum Temperature Achieved < 200 pK

Basic of Superconductivity

- Zero Resistance, Perfect diamagnetism below a Critical Temperature (Tc)
- **Tc** : Hg : 4.2 K, Pb : 7.2 K, Nb :9.2 K

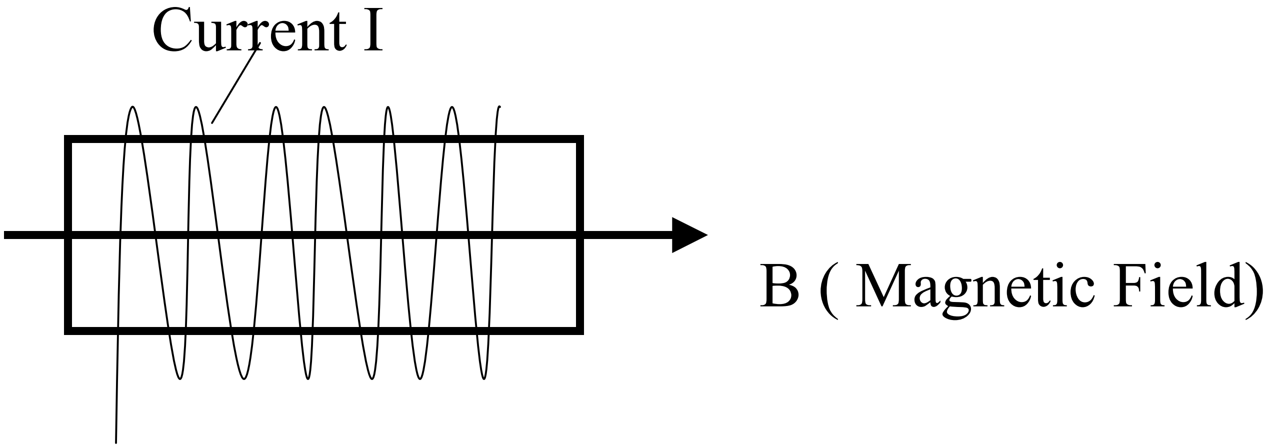
  (Used for SC Cavity) : LHe
  - **Nb - Ti : 12 K, Nb_3Sn : 18 K (high Hc2) :**

    Magnet : LHe
- **High Temperature Superconductor (Type 2)** : LN2
- Zero Joule heating loss ~ I^2 R, High Current (> 1000A can pass through < 1 mm dia wire)

That find lots of Application !!

Superconducting Magnet

$B \sim N\,I$



B is proportional to Current I and No of Turns/ Cm (N), Considering normal wire, we have limitations on increasing Current because of I^2R. Hence low Field. For superconductor, Current should be lower than Jc (1300 A/ mm2 for Nb- Ti wire at 4.2 K and 5 Tesla

Superconducting Accelerator Components

SC Cavity : Accelerating Structure ; Low power Cost (LEP, CEBAF, KEK, IUAC, ILC)

SC Dipole SC Magnet (LHC, Tevatron) : For Bending the Beam

SC Quadrupole Magnet : Better Focussing the beam because of Higher Gradient 100 T/ M against 20 T/ m

SC Solenoid Detector Magnet : Better resolution (ATLAS/LHC) $\nabla\phi \ \alpha$ BL, $\nabla p/p \ \alpha \ 1/(BL^2)$

Worlds Largest Detector of Mass 1900 Tons with a height of four Storey building is placed recently in the LHC tunnel

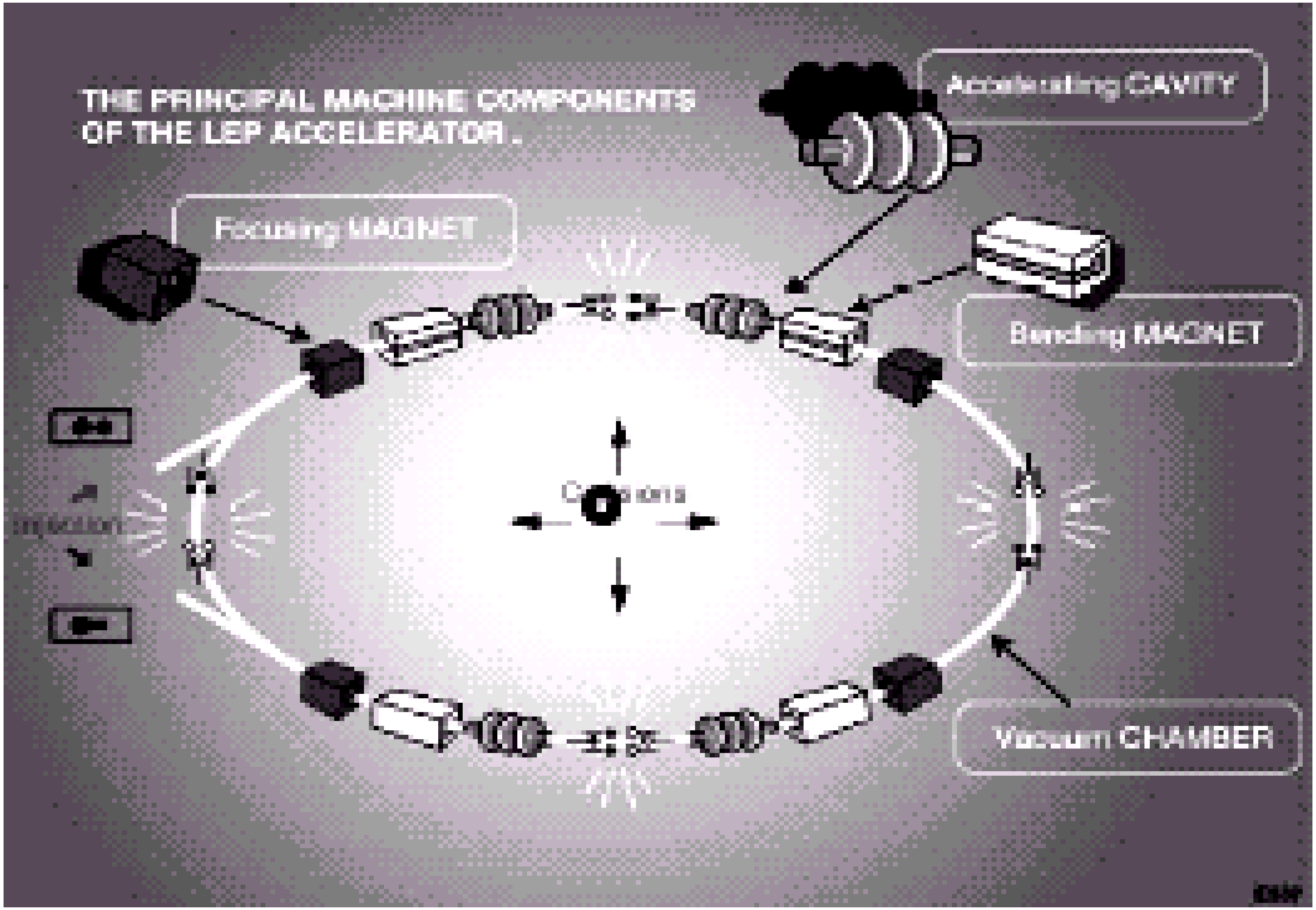


Fig. 1. Scheme of the main components of a circular accelerator. Cavities give the energy to the beam and magnetic elements take care of beam guidance and focusing.

Why High Field Magnet

Energy of Relativistic particles

E = 0.3 B dipole x R [TeV, Tesla, Kilometer)

To have higher Energy, either we have to increase diameter of the ring or to increase the magnetic Field

	Normal Magnet	SC Magnet
1.	Low Field (2 T)	High Field (10 T)
2.	Higher radius	Smaller radius
3.	Higher No of magnets	Smaller No of Magnets
4.	Higher Infrastructure cost	Lower Cost
5.	Higher Operation Cost	Lower Operation cost
6.	No Liquefier	LHe / LN2

Comparision for CERN LHC

- Energy : 7 TEV, Circumfarence : 27 Km

  Dipole Magnet Field : 8.3 Tesla

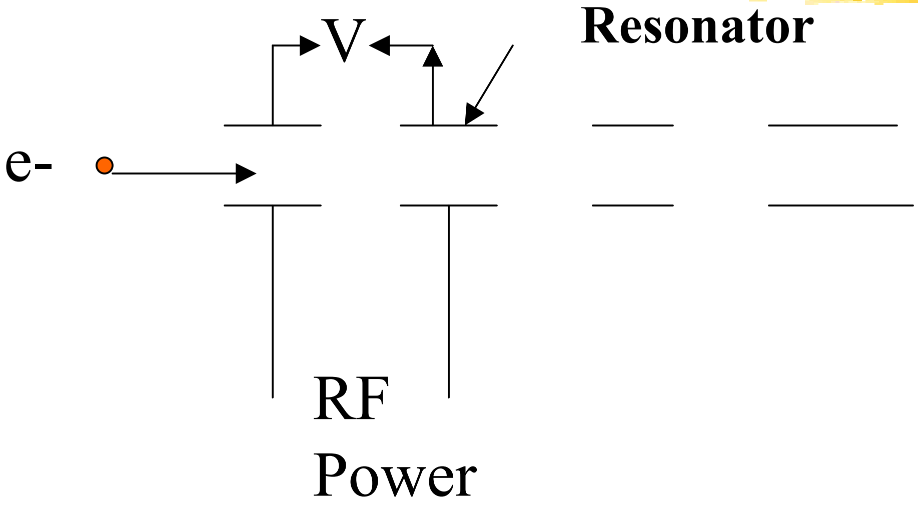
To Have the Same Energy with Normal Magnet with Field 2 Tesla,

Circumfarence would have been 27x4 = 108 Km

Required No of magnets : 1500 x4 = 6000

Refrigerator power : 144KW at 4.2 = 144x 225 KW = 33 MW at R.T

Fundamentals of Cavity



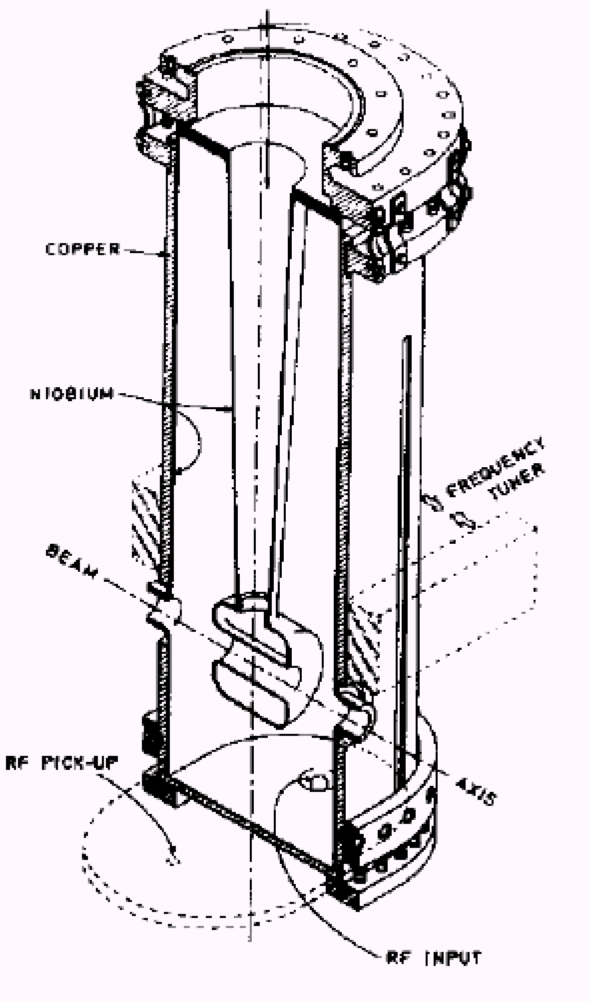
For Acceleration we need voltage gradient

Energy = Charge x Voltage

Higher Voltage is generated in a Resonator equivanent of LC circuit on resonance with RF power

RF power is converted to generate High voltage. Higher voltage , higher RF power and Power loss on Resonator. Power loss Depends on Cavity Material

Heavy Ion RF Cavity



Electron Cavity Multicell

Why Superconducting Linac?

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 resisitive losses.

High Q , Low Loss

Skin Depth ~ few μm f > 100 MHz.

Q is inversely Proportional to Surface Resistance.

For Cu at 300 K,

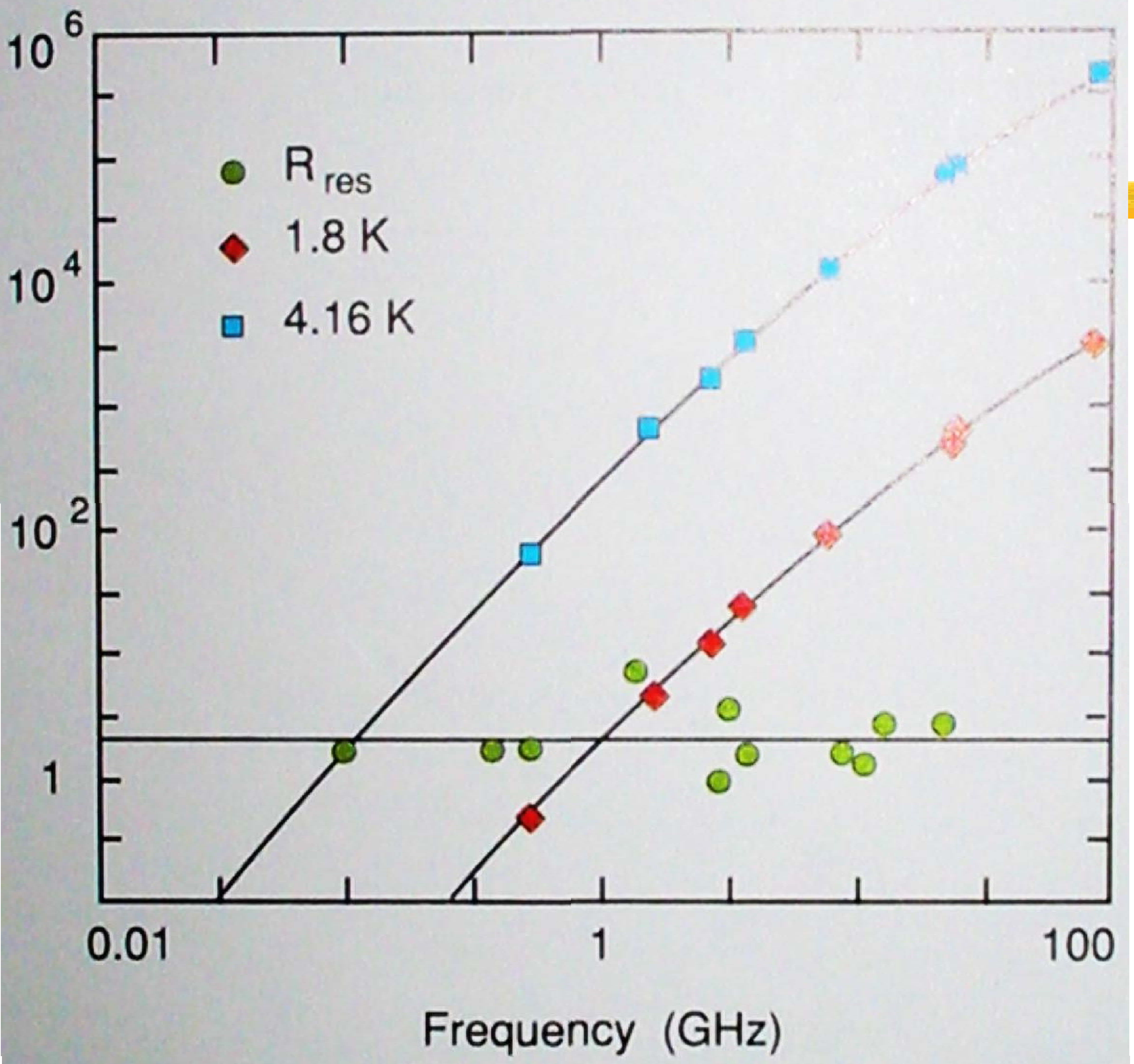
$R_S = 7.8\,[f(\mathrm{GHz})]^{1/2}\ \mathrm{m}\Omega$

For Nb at 4.2 K,

$R_S = 10^5\,[f(\mathrm{GHz})]^2 \exp[-18/T(\mathrm{K})]\ /\ T(\mathrm{K})\ \mathrm{n}\Omega$

R_S at	100 MHz	300 MHz	1GHz
Cu (300K)	0.078 mΩ	0.96 mΩ	7.8 mΩ
Nb (4.2K)	3.28 nΩ	40 nΩ	328 nΩ

For Superconducting surfaces, additional contribution from residual resistance, R_{res} .



BCS surface resistance of Nb vs frequency at 4.2 K (extrapolated to 1.8 K).

Power Comparision in Cavity

	Normal Copper Cavity	**Niobium SC Cavity**
1. Eacc =	**4 MV/ m**	**4 MV/ m**
2. Q_0 =	**10^4**	**10^9**
(Proportional to surface resistance)		
3. **Ra/Q_0**	**300 (geomery & frequency)**	**900**
4. Power	**1.7 MW**	**53 W (4.2 K)**
($P = Eacc^2/ Q_0 \times Ra/ Q_0$)		
5. Power at	**1.7MW**	**3.18 Kw**
at Room Temperature		
Considering static load of Cryostat and distribution line, power required will be double		**7 KW**

Power Ratio : 1700/ 7 = 200

Few Accelerators with SC Magnet

Accelerator	Energy	Field	Length	Year
Tevatron (USA)	0.9 Tev P P-	4 T	6.3 Km	**1987**
HERA (Germany)	0.92 P e	5.3	6.3	1989
SSC (USA)	20 P P	6.8	87	cancel
LHC (Switzerland)	7 p p	**8.3**	**27**	**2007**

Accelerators with SC cavity

Lab	year	f Mhz	Active Length	Gradient
KEK	1988	508	48m	4.5 MV/m
DESY	1991	500	20	2
CEBAF	1996	1497	169	5
CERN(LEP)	1997	352	462	6
ILC (35 Km)	Future			31 MV/m

We understand to have higher energy with low power consumption and compact size we need Superconducting Material

To Convert a normal Material to Superconductor, we have to Cool down it below Tc.

So we need cryogen like Liquid helium/ Nitrogen

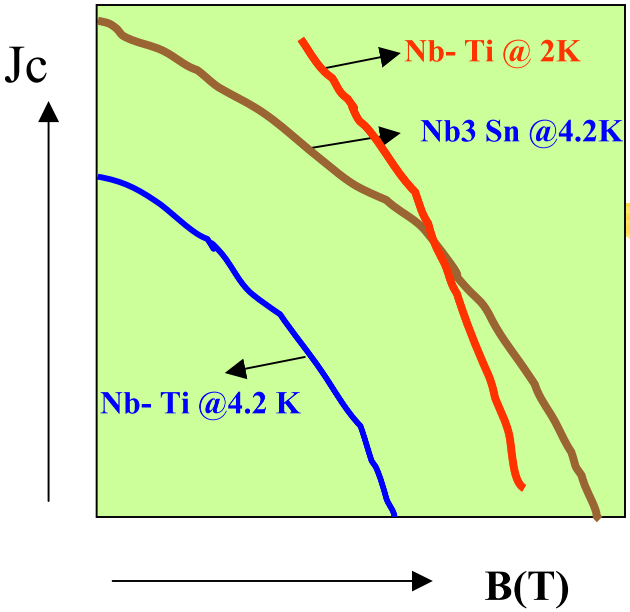
Performance/ Stability improved when operates further away fromTC

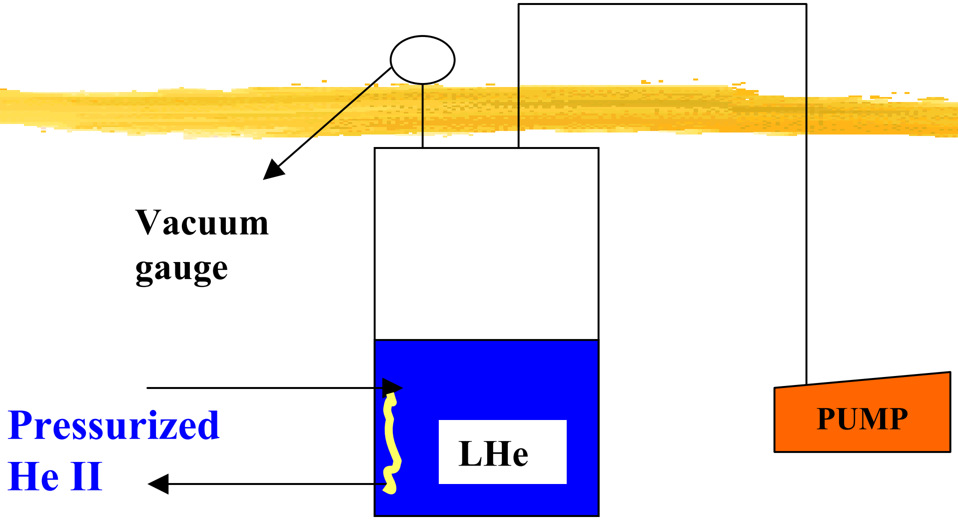
Nb - Ti : Tc = 10-12 K, Lhe : 4.2 K , Performance 4.2 << Per 2K

The need for cryogenic temperatures for cooling superconductors

Conductor	Critical temperature (K)	Typical operating temperature (K)
Nb	9.3	1.8 – 5.0
NbTi	10	1.8 – 5.0
Nb_3Sn	18	4.5 – 10
$YBa_2Cu_3O_7$ (YBCO)	92	20 – 80
$Bi_2Sr_2Ca_2Cu_3O_{10}$ (BSCCO)	108	20 – 80

LIQUID HELIUM II





By Pumping vapor over liquid Surface, Temperature can be reduced to 0.8 K

But at 50 mbar Helium I changed to Helium II (Superfluid helium)

Finds application on accelerator

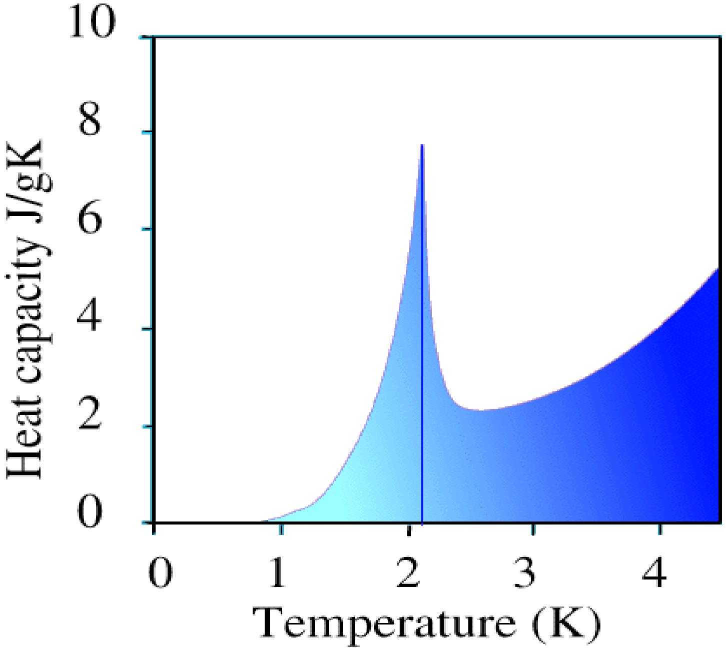
Similarly SC Cavity Surface Resistance Exponentially Decreases with the ratio of T/Tc

LIQUID HELIUM II

- **transition to a superfluid phase below the λ-point (2.17K)**

effects:

- –viscosity decreases by several orders of magnitude
- –creeps up the wall
- –heat conductivity increases by several orders of magnitude



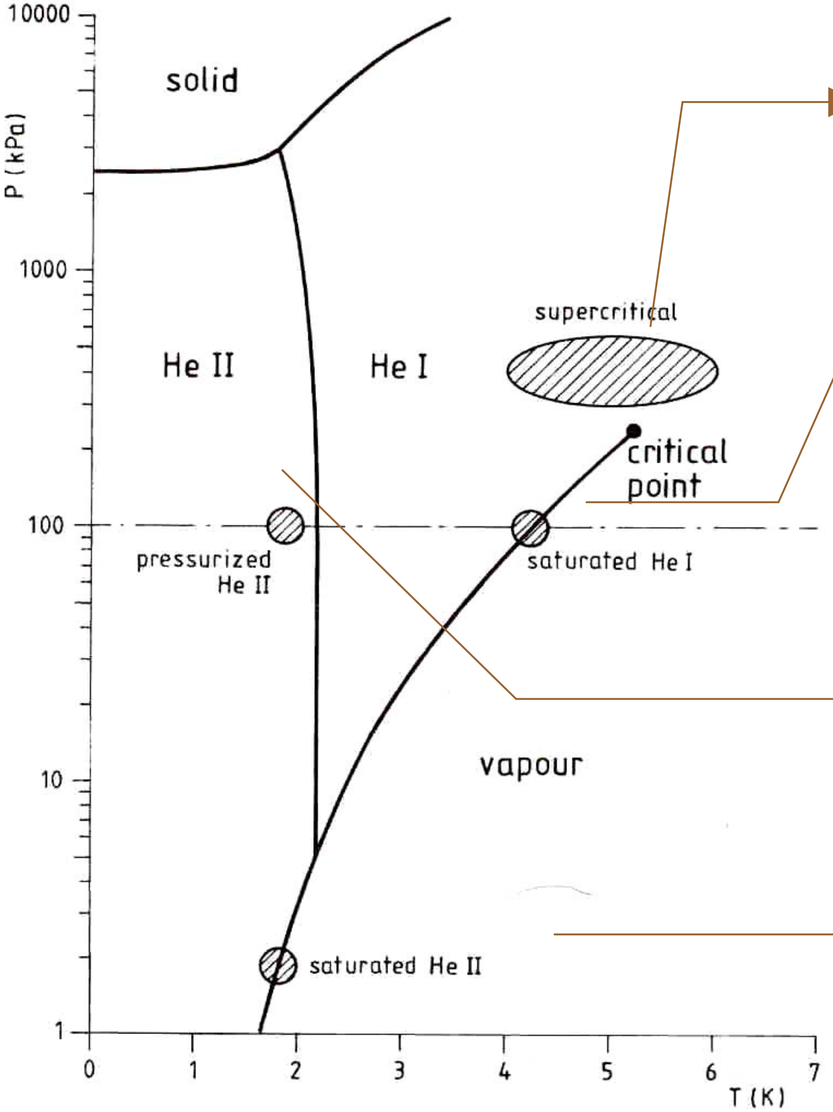
Advantage : **Superfluid Helium can easily flow through SC strand /Cable**

Small temperature rise with a heat input (specific heat)

Large Conductivity maintain equal temperature

SC Magnet is more stable

Phase diagram of helium



Mono Phase

Temperature Rise

POOL BOILING Higher Heat Trasfer

constant T,

Two phase Flow

FORCED FLOW

JT cooling, good heat transfer, small liquid inventory

flow instabilities, small (p,T) range

high HT, low T, large $C_{v,\text{Mono Phase}}$

refrigeration cost, sub-atm pipes

high HT, low T, Low Viscosity

dielectric breakdown, sub atm, large gas volume

Cooling modes in large-scale cryogenic systems recently in operation

- Pool boiling helium I (SRF for HERA, LEP, KEKB)
- Forced flow of subcooled or supercritical helium I (Tevatron, HERA, SSC)
- Stagnant, pressurized helium II (the Tore Supra tokamak in France demonstrated the technology, LHC)
- Saturated helium II (CEBAF, TTF at DESY, SNS at Oak Ridge, and foreseen for ILC)
- This list also illustrates the extent to which superconductivity and cryogenics have become standard technology for accelerators

Helium phase diagram
(S. W. VanSciver, Helium Cryogenics, p. 54)

- Critical point
  - 5.2 K, 2.245 atm
- Lambda transition at 1 atm
  - 2.172 K

- 🔴 SRF -- HERA, LEP, KEKB
- 🟢 Magnets -- HERA, Tevatron
- 🔵 Magnets -- SSC
- 🟣 Magnets -- Tore Supra, LHC
- 🟠 SRF -- CEBAF, TTF, SNS, ILC

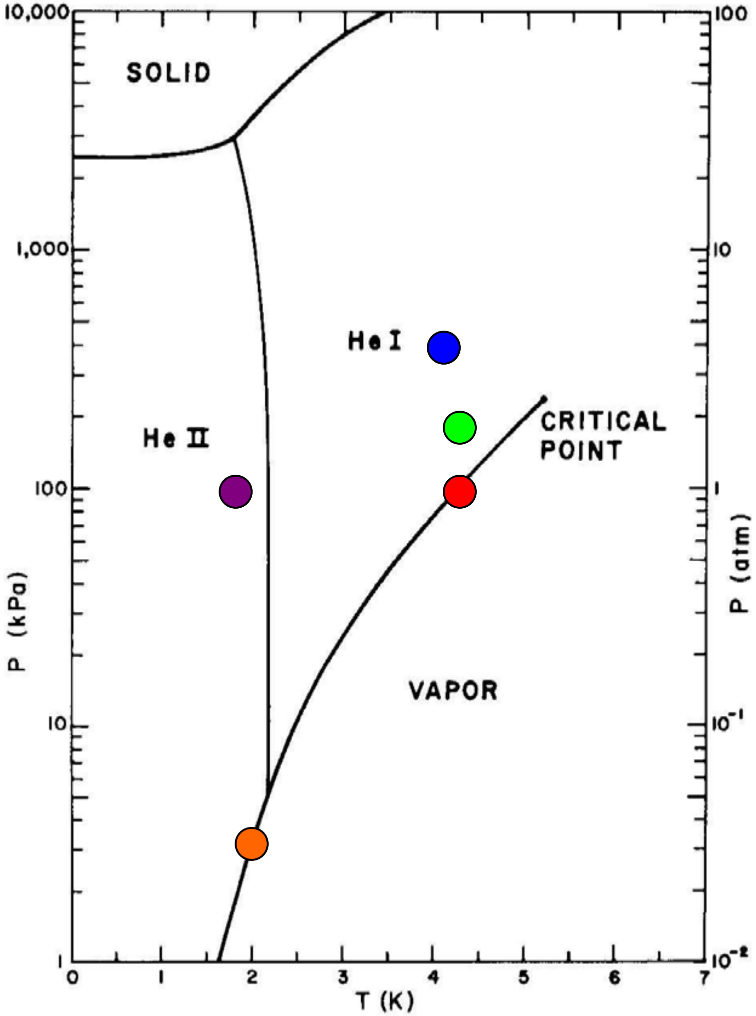


Fig. 3.1. ^{4}He phase diagram.

Thanks for your kind patience

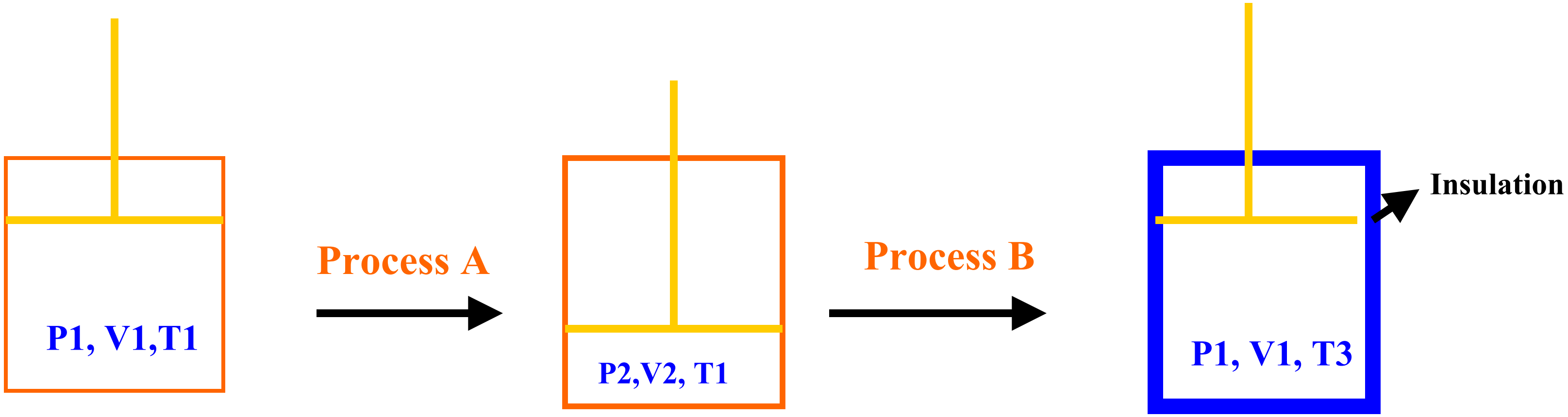
HOPE WE WILL BE MEETING TOMORROW AT THE SAME TIME

Liquefaction of gases/ Low temp Achievement

- Basic Thermodynamic Cycle
- T- S Chart
- Liquefaction cycle for N2 and He
- Components for Liquefaction
- Performance of Practical Refrigerator/ Liquefier

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. $W = m.\ T\ (R/M)\ \ln\ (P2/P1)$.

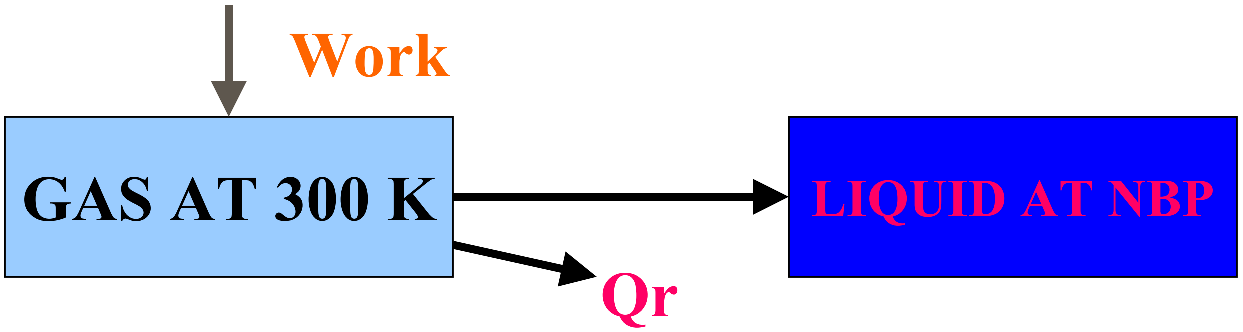
Example : 1 gm gas T= 300 K, P2/ P1 = 15

Helium : 1600 W (20 NM3), N2 = 200W (2. 8 NM3

T3 < T1 (Cooling)

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

Sensible Heat

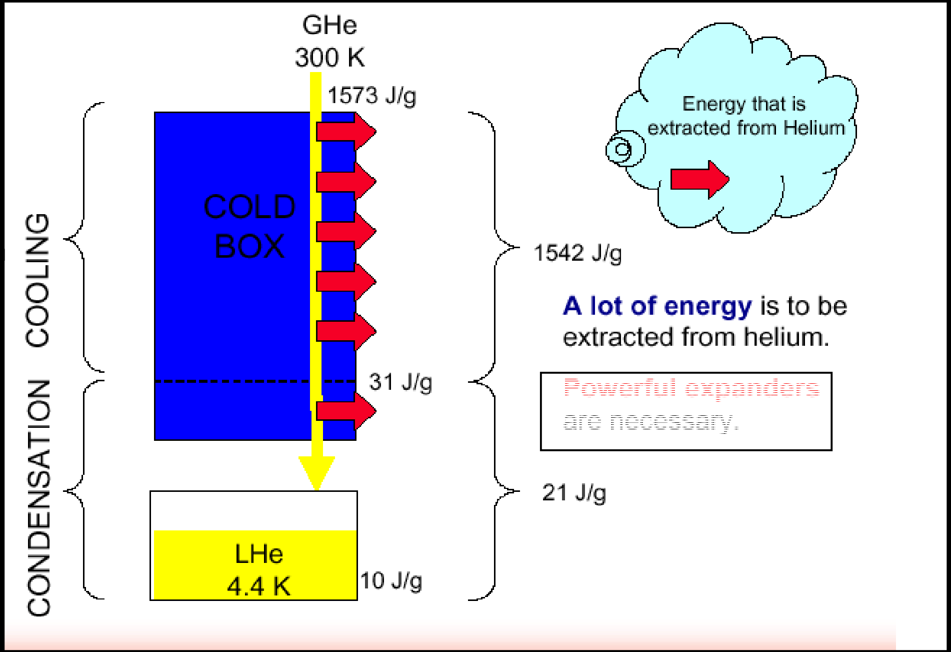
Latent Heat

To Liquefy “Permanent Gases”

Need

Cooling

Or in other way U need to extract the energy from the GAS for example HELIUM

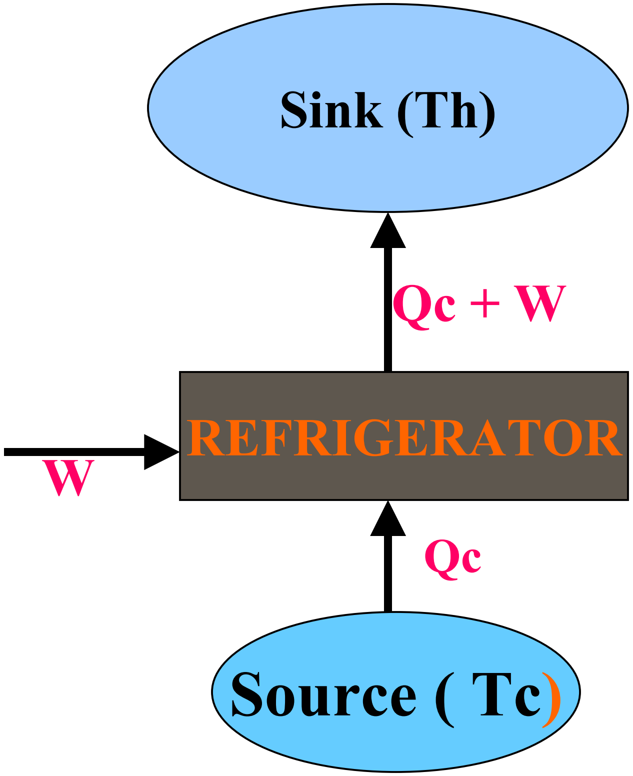


A lot of energy is to be extracted from helium.

Powerful expanders are necessary.

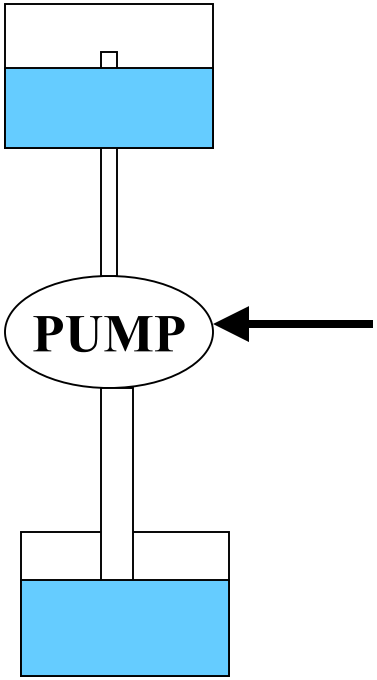
Refrigerator

To Transfer Heat from Source to Sink if source Temperature is less than Sink



Refrigerator is Analogus 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)



Power (W) required to extract 1 W refrigeration at Tc is : W = 1/ (COP)I = (Th- Tc) / Tc, Th = 300 K , Tc Vary from 200 K to .000001 K

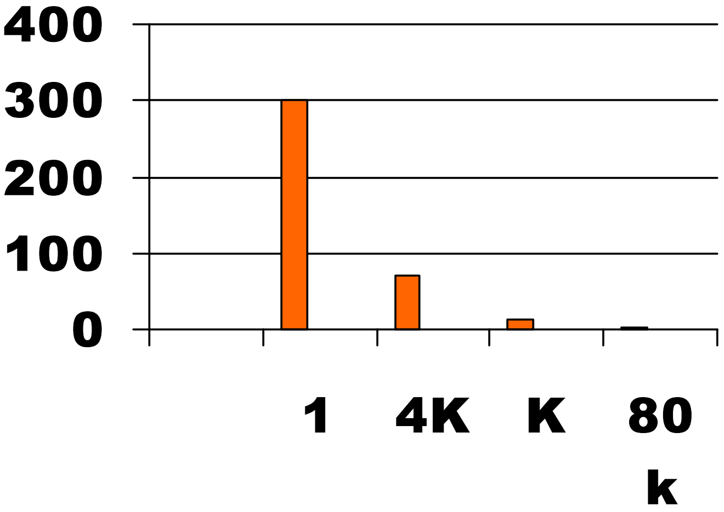
N2 , Tc = 78 K , W = 1.68 W

H2, Tc = 20 K W = 14 W

He , Tc = 4.2 K, W = 70 W

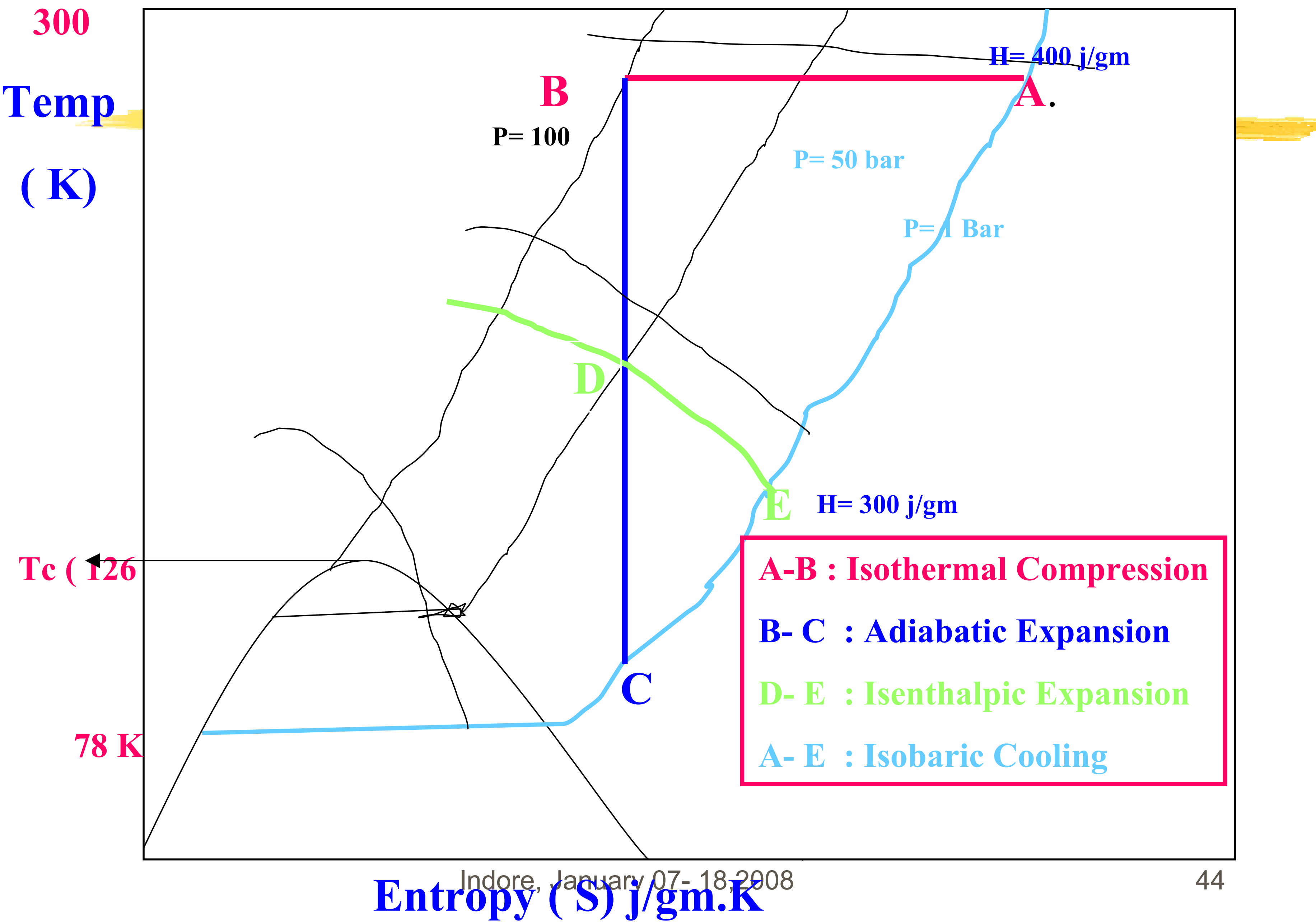
Tc = 0.1 K , W = 3000W

Tc = 0.01 W= 30000 W



These are Theoretical Power. We have to muliply first with efficiency Of the Cycle and then multiply with mechanical efficiency of all Components of refrigerator

T - S CHART FOR GAS



A-B : Isothermal Compression

B- C : Adiabatic Expansion

D- E : Isenthalpic Expansion

A- E : Isobaric Cooling

NITROGEN AND HELIUM

		Nitrogen	Helium
Normal boiling point	(K)	77.3	4.2
Density of liquid	(kg/m^3)	808	125
Density of vapour	(kg/m^3)	4.59	16.7
Normal gas density	(kg/m^3)	1.25	0.18
Heat of vaporisation	(J/g)	200	20.9
Sensible heat (sat. vapour to 300 K)	(J/g)	234	1542
Critical temperature	(K)	126	5.2
Critical pressure	(b)	34	2.2