Role of Cryogenics & Superconductivity for Particle Accelerator : Overview

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The 4th Asian School on
Superconductivity and Cryogenics for Accelerators
Feb. 13-19, 2023, Korea University, Sejong, Korea

ASIAN ACCELERATOR SCHOOL AT BEIJING IN Dec. 1999

(Special Thrust on Cryogenics & Superconductivity)

Jubilant Cavity Team after Successful Test

Organised by KEK, JSPS , IHEP & CAS

Many Students (12 countries) from that School are contributing today on Accelerator Development programme in Asia

2nd ASSCA KEK, Japan in 2017

Present

The 4th Asian School on Superconductivity and Cryogenics for Accelerators

Feb. 13-19, 2023, Korea University, Sejong, Korea

3rd ASSCA at IHEP, Beijing in 2018

Realization of High Power Accelerator (LHC. ILC/CEPC) is possible because of Superconductivity

1. **Compact Size**
2. **Low Power Consumption**

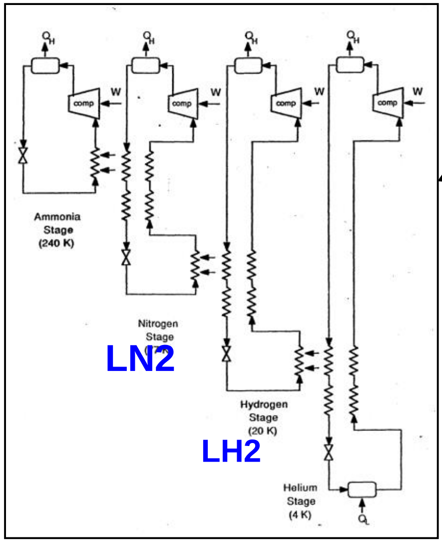
Outline of my Talk

1. **Basics on Cryogenics & Superconductivity**
2. **History on Accelerator with Cryogenics**
3. **Role of Superconductivity (SC) for Accelerator**
4. **Asian Major programme Present & Future**
5. **Conclusion**

1908 : Heike Kamerlingh Onnes Succeeded in Liquefying Helium

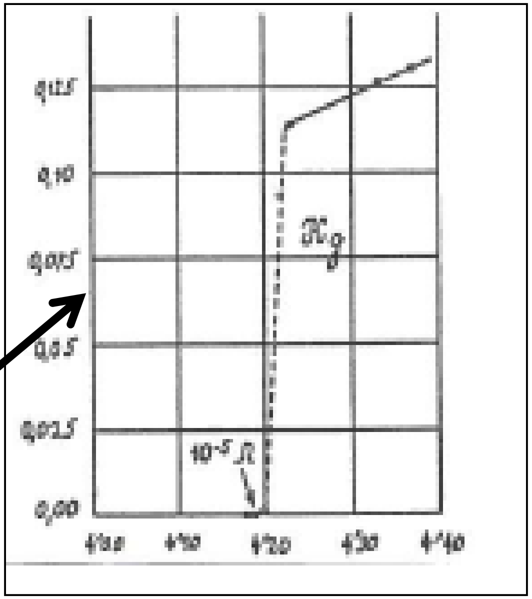
1911 : Discovery of Superconductivity

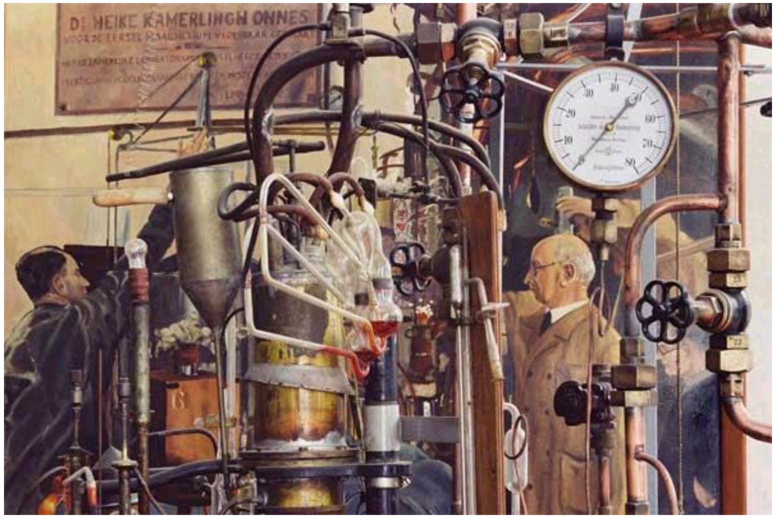
(1853-1926)



Cascade Helium Liquefier

FAMOUS R-T PLOT





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

Cryogenics

Greek Word (12 th Century)

Icy Cold — **Production**

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


GSLV D5

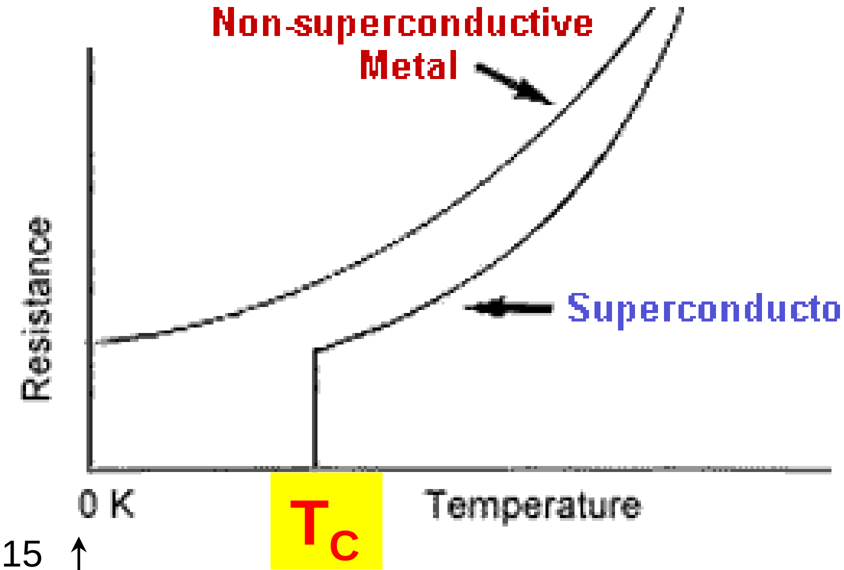
In India Cryogenics became a house hold name when Russia declined to Supply Cryogenic Engine with Technology to Indian Space Research Organisation (ISRO)

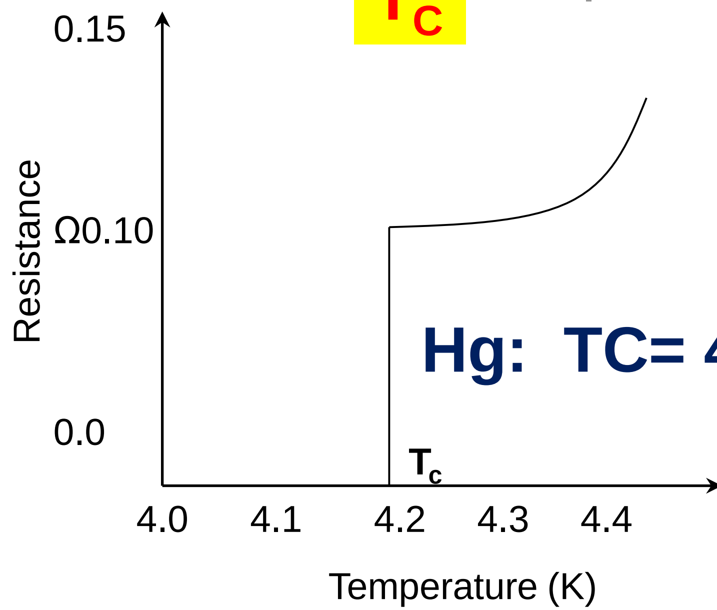
CE 7.5 Engine

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).





Chilled water is not enough to Cool below Tc .
Hence Cryogen

A. Common Cryogen

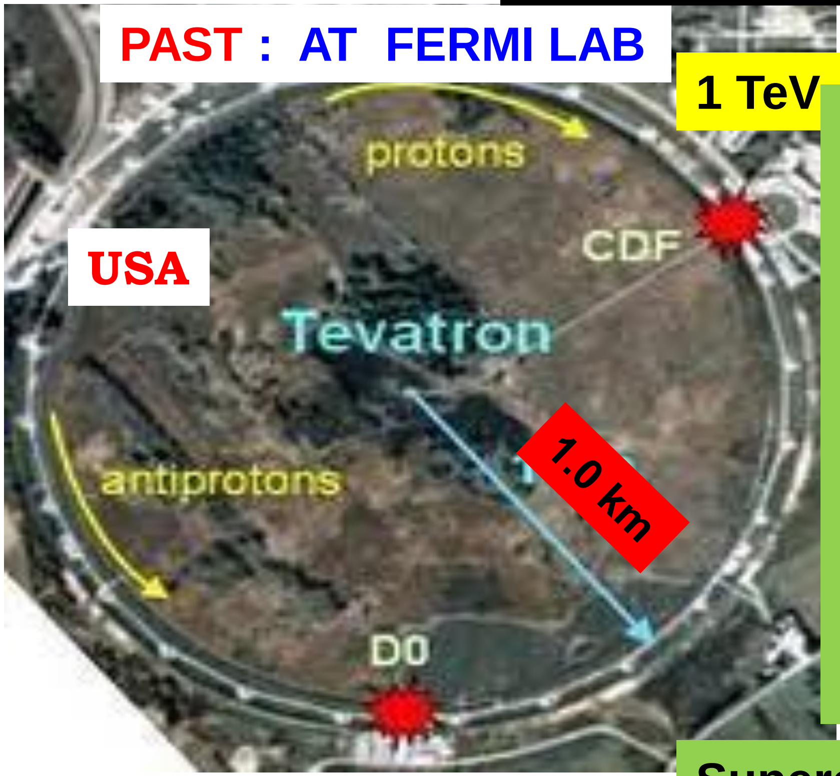
Liquid	Boiling Point
LNG	111K
Liquid Oxygen	90 K
Liquid Argon	83 K
Liquid Nitrogen	77.4 K
Liquid Hydrogen	20 K
Liquid Helium	4.2 K
Super fluid Helium	2.1 K

B. Practical Superconductor

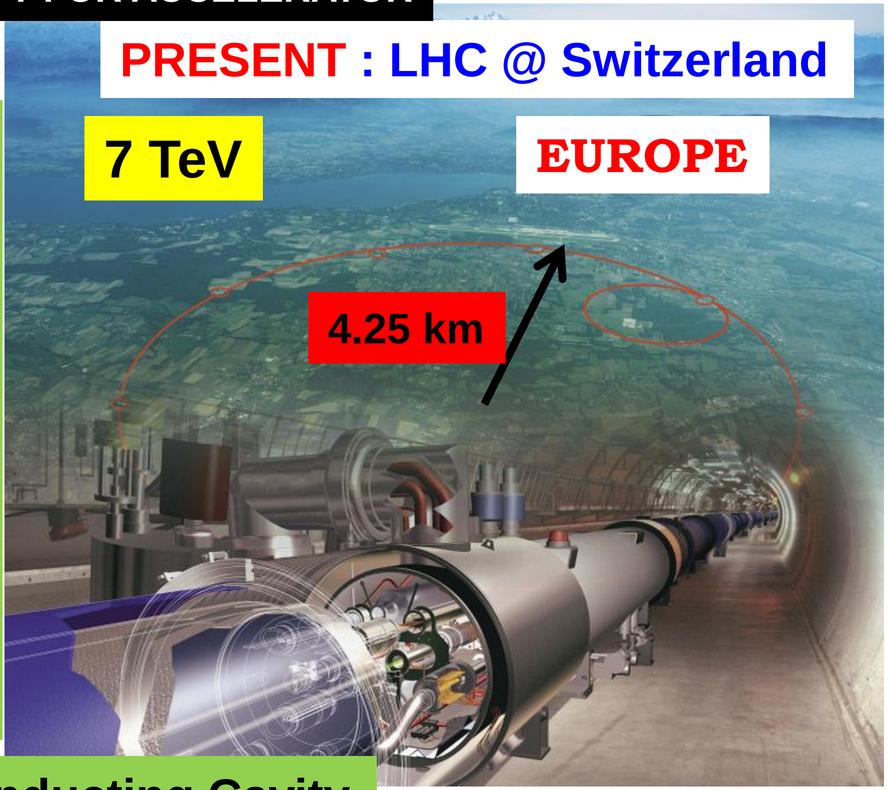
Material	T_c (K)
Hg	4.2
Pb	7.2
Nb	9.2
NbTi	10 K
Nb3Sn	18K
High Temp Superconductor	
MgB2	39K
YBCO	90
BSSCO	110 K

Blue Colour Applicable for Accelerator

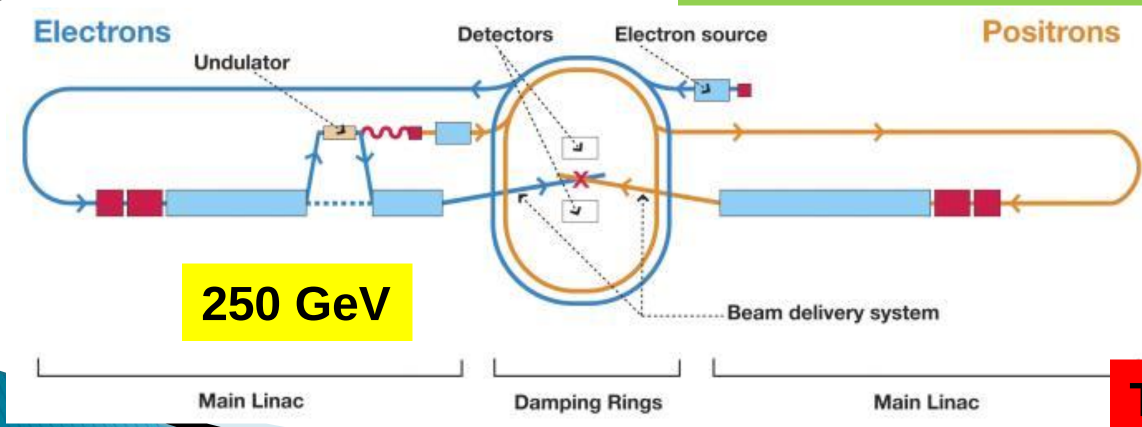
SUPERCONDUCTIVITY FOR ACCELERATOR



Superconducting Magnet



Superconducting Cavity

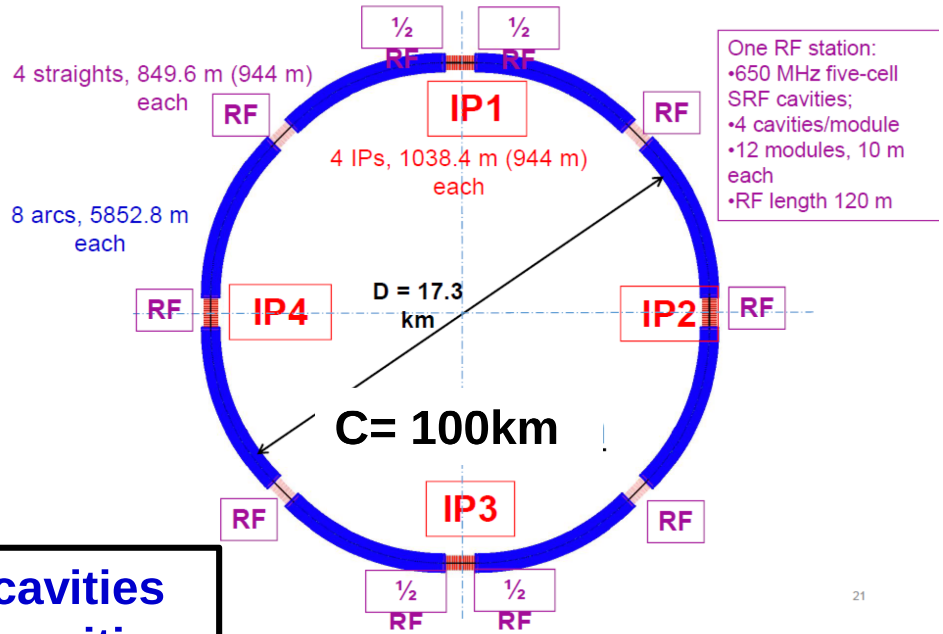


Future: ILC/ CEPC (Asia)

Total Length : 31 km.

The Circular Electron Positron Collider (CEPC) circumference of ~ 100 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

Refrigeration Capacity `96kW at 4.2 K

Estimated Project Cost ~ $6 billion

Cryogenics + Nuclear Science

Breakthroughs.

1. ULT through nuclear adiabatic demagnetisation.
2. Polarised targets for nuclear experiments. (Bubble Chamber) : Liquid Hydrogen
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
7. Neutrino Detector with Liquid Argon Target

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/Free Electron Laser / Spallation Neutron Source and many more

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

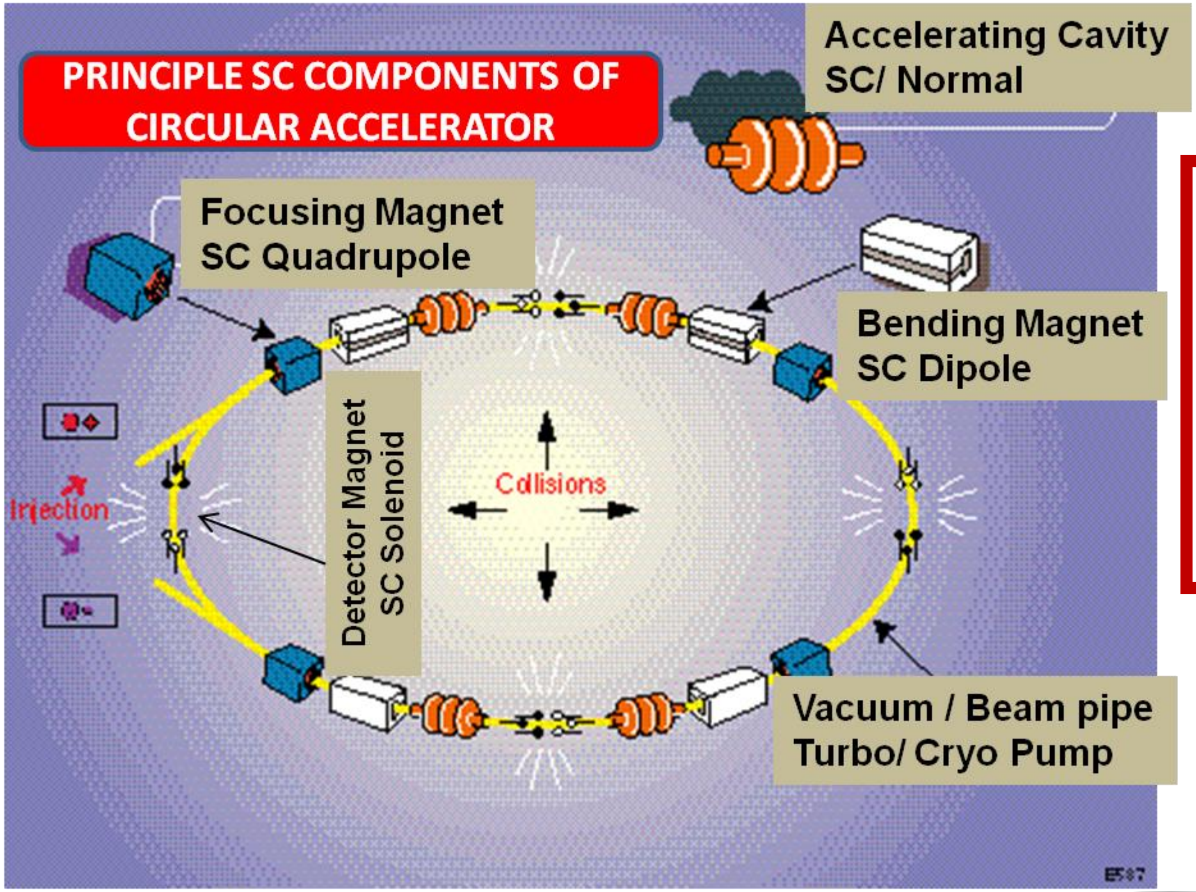
Bubble chamber : Tracks of charged particles by means of a visible string of bubbles that are left by the particles as they fly through a Liquid Hydrogen (Purest Target) at a temperature 24 to 29 K with pressure from 40 Psig to 70 Psig)

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

MAIN COMPONENTS OF A CIRCULAR ACCELERATOR

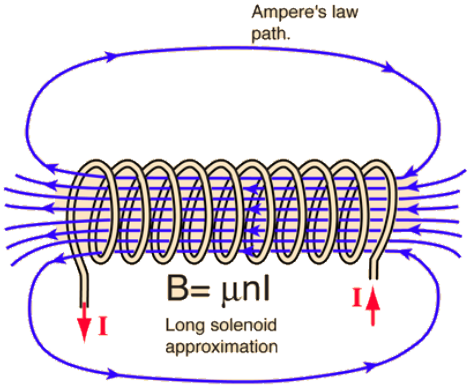


1. CAVITIES : ENERGY
2. MAGNETS : GUIDES & FOCUSS THE BEAM
3. DETECTOR : DETECTS NEW PARTICLE

Cavities are the Engine and Magnets are the Steering

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 !!)

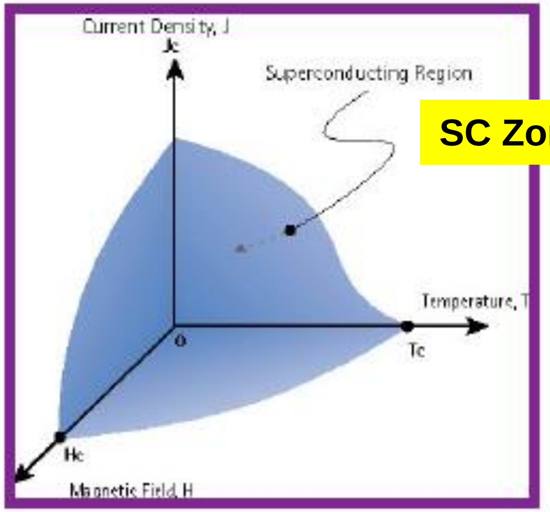
or we can have efficient cooling system/ very high heat Transfer coefficient and surface Area (LN2 Cooling ????)

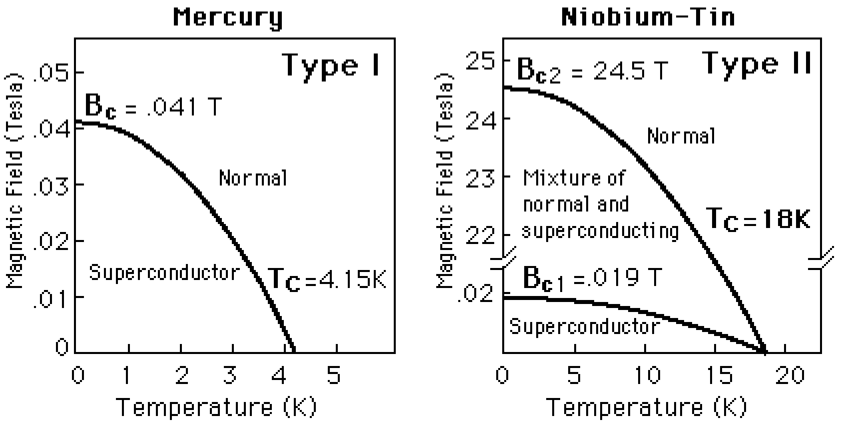
(Possible for High Field Pulsed Magnet)

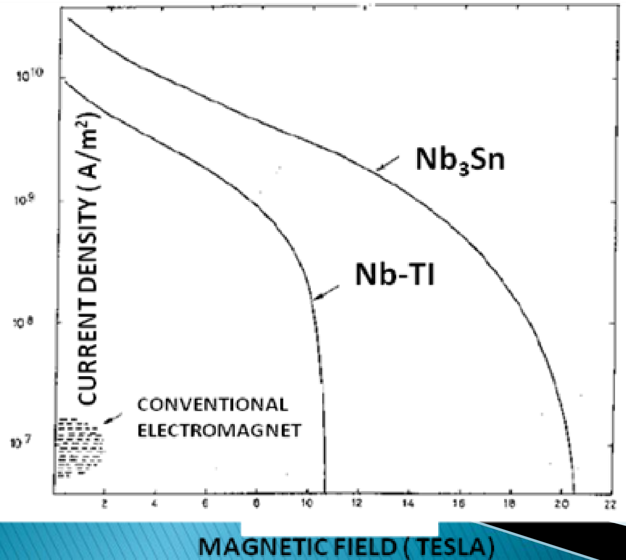
Superconductor (R=0) : No Joule Heating (Except at Joint and Current lead)

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

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



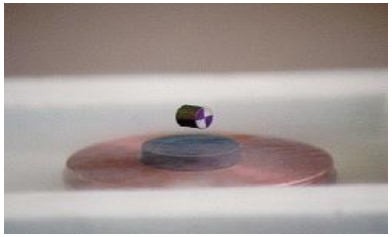


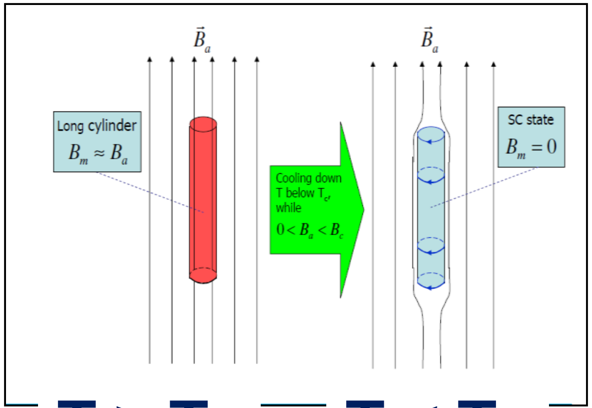


$$H_c(T) = H_c(0)\left[1 - \left(\frac{T}{T_c}\right)^2\right]$$

Another Property of Superconductor (Meissner Effect) : Perfect Diamagnetism

Expulsion of Magnetic Flux





$T > T_C$ $T < T_C$

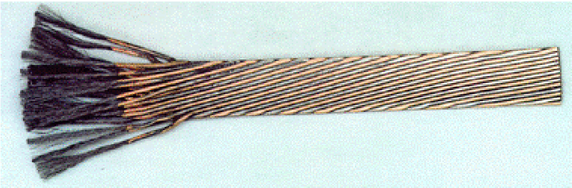
Tokyo- Nagoya : 300 Km
Travel time : 40 Minutes

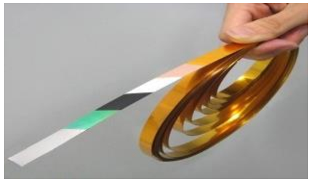
Shanghai Mag Lev Train : 434 km/hr

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

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

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

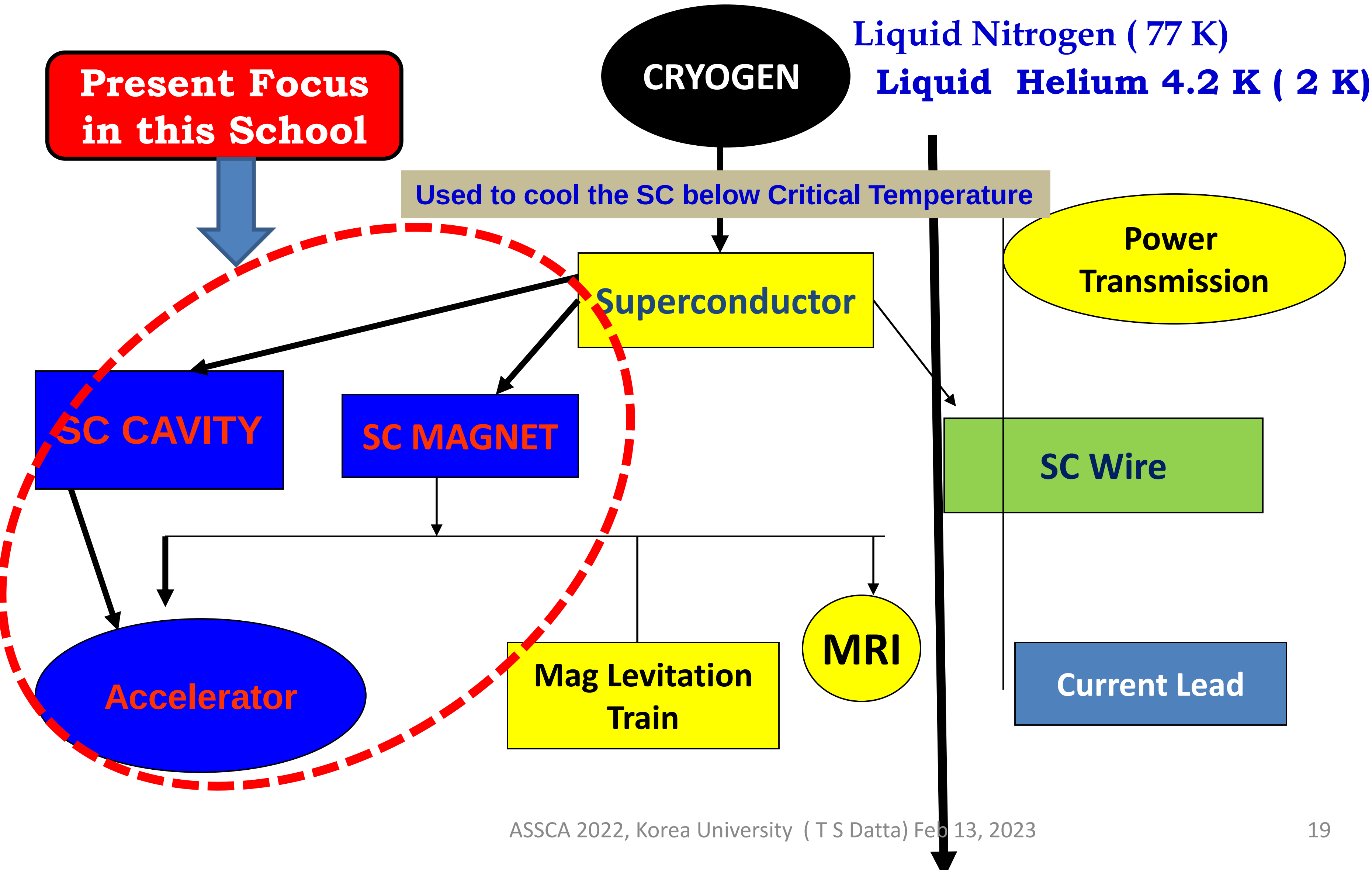
Type 2 (Nb-Ti to MgB_2)

Nb-Ti, Nb_3Sn, Nb_3Ge: High Hc, Tc Ductile

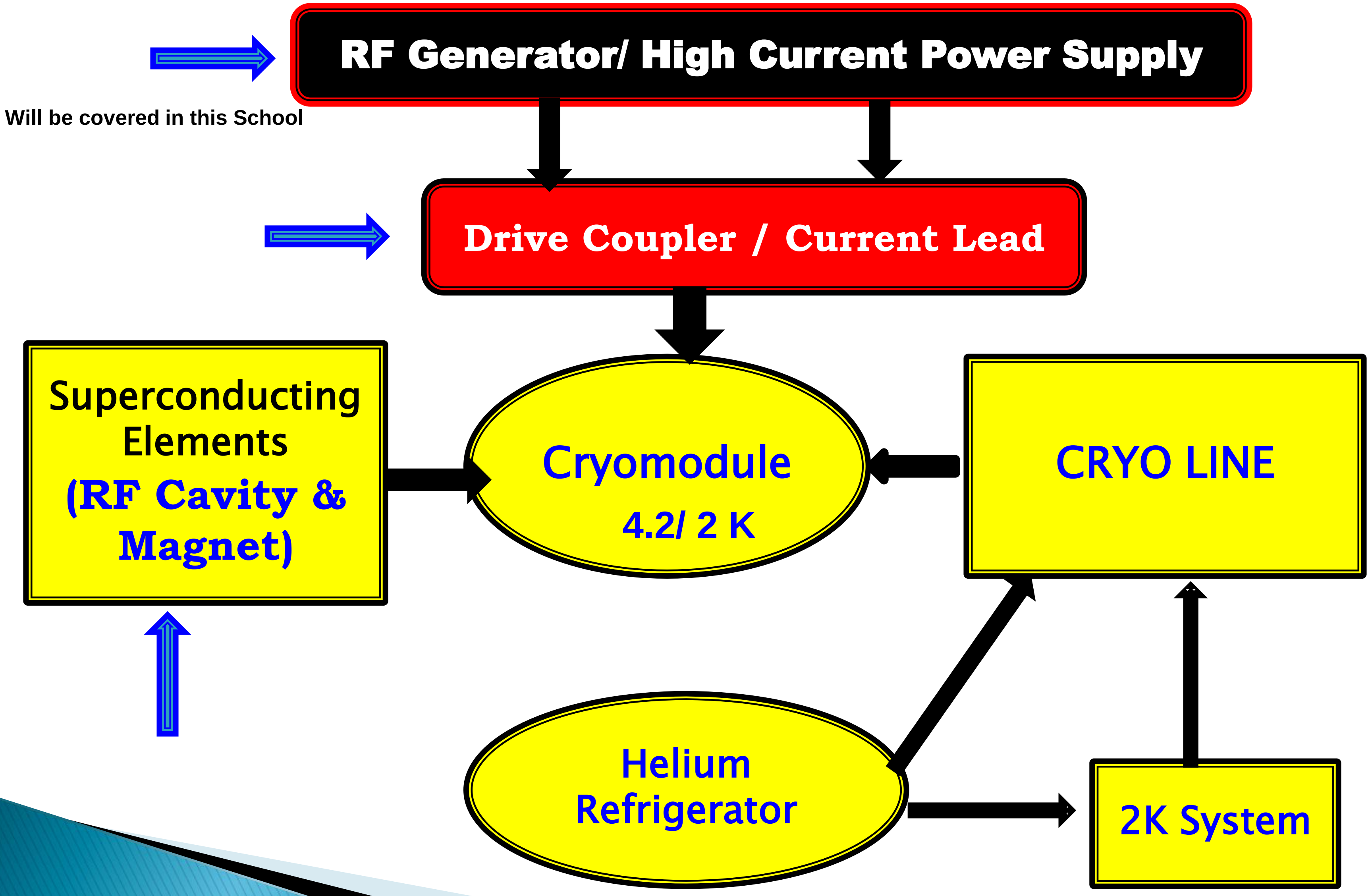
YBCO, BSSCO: High Tc, Jc, High Cost, Brittle

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

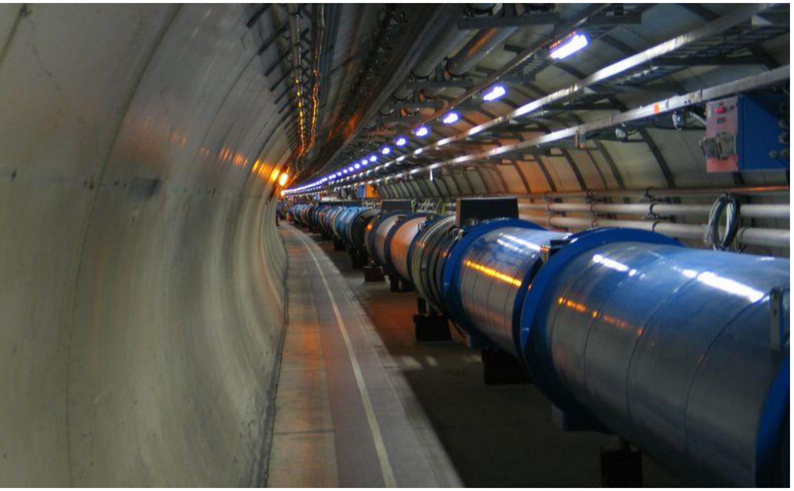
APPLICATION OF SUPERCONDUCTIVITY



Components for Superconducting Accelerator

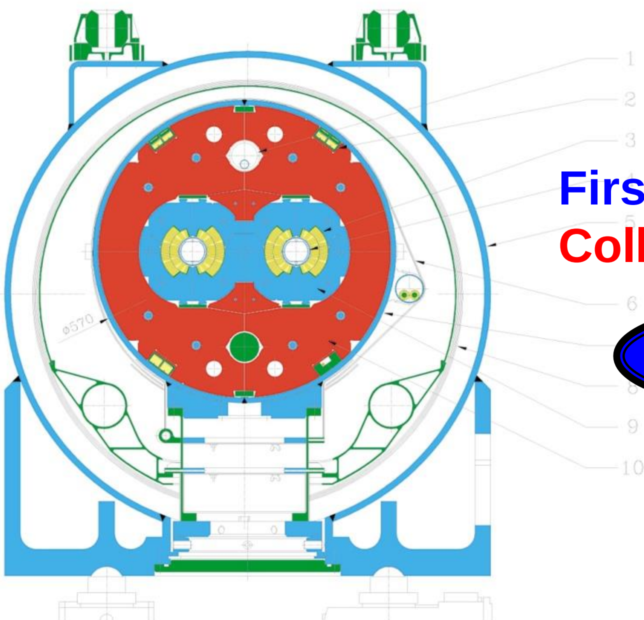


LARGE HADRON COLLIDER (LHC) AT CERN



Higgs Boson (God Particle) in 2012

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**

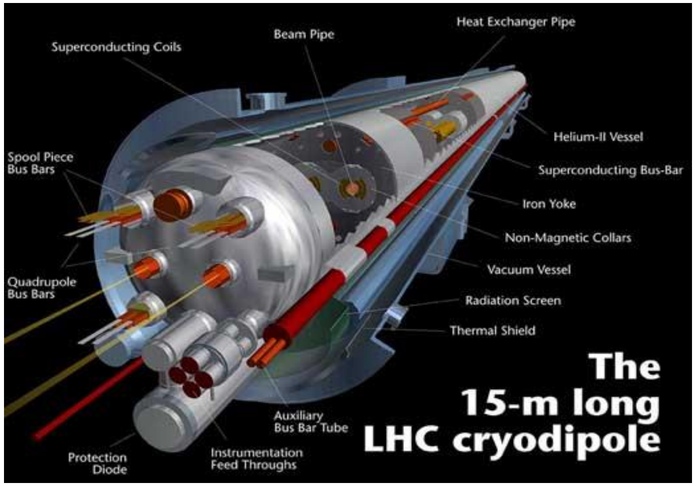
Nb- Ti SC magnet generates a field 8.3 Tesla and operates at 1.9 K

Comparison for CERN LHC

ENERGY : 7 TeV

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

E in GeV, B in Tesla, R (radius) in meter



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

Few Accelerators with SC Magnet

Accelerator	Energy (TeV)	Field (Tesla)	Length (Km.)	Year
Tevatron (USA. P P-)	0.9	4	6.3	1984
HERA (Germany, P e)	0.92	5.3	6.3	1989
SSC (USA P P)	20	6.8	87	cancel
LHC (Switzerland) P P	7	8.3	27	2011

Practical Power Comparison

SPS(CERN) : 352 MW 315 GeV : Normal
HERA(DESY) : 6MW 920 Gev : SC

Detector with Superconducting magnet

Momentum Resolution (Sagitta) ~ $$s = qBL^2 / 8p$$

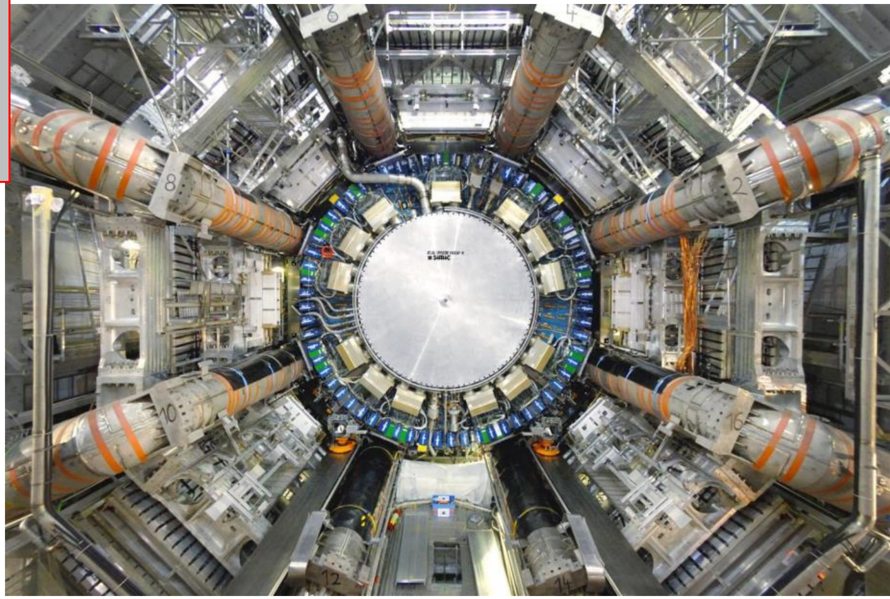
Resolution better with high field (B) and longer length (L)

Before Collision, we need strong focusing (Achieved by Quadrupole magnet High Field gradient (T/ M) h to have higher Luminosity

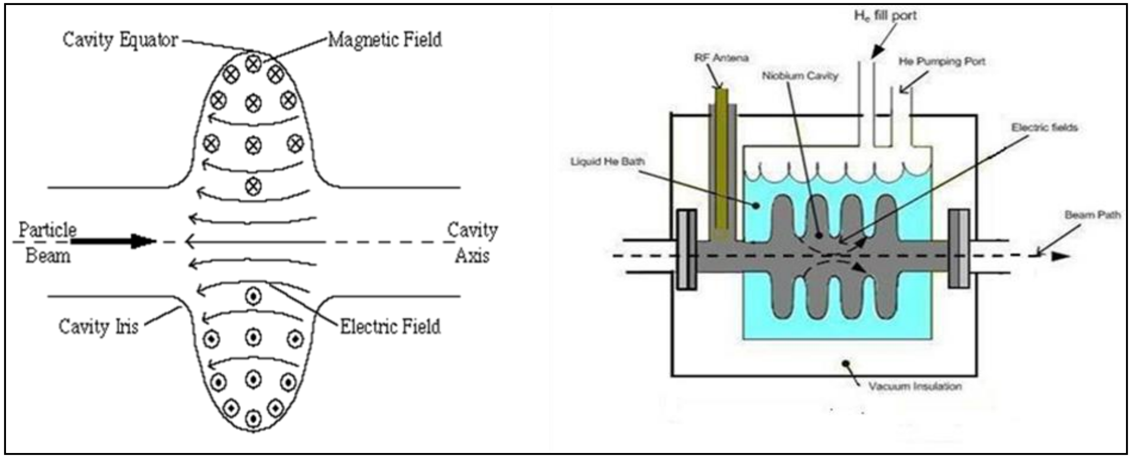
ATLAS (A Toroidal LHC ApparatuS) is Particle Detector at LHC, CERN

46 m long, 25 m high and 25 m wide, the 7000-tonne detector is the largest volume particle detector ever constructed.

The magnet system on the ATLAS detector includes eight huge **SC magnets arranged in a torus and a central SC Solenoid around the LHC beam pipe**



SUPERCONDUCTING RF CAVITY



RF POWER FEED TO THE CAVITY (LC CIRCUIT), ELECTRIC FIELD (E= 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 (Niobium) = 10^5

Surface Resistance

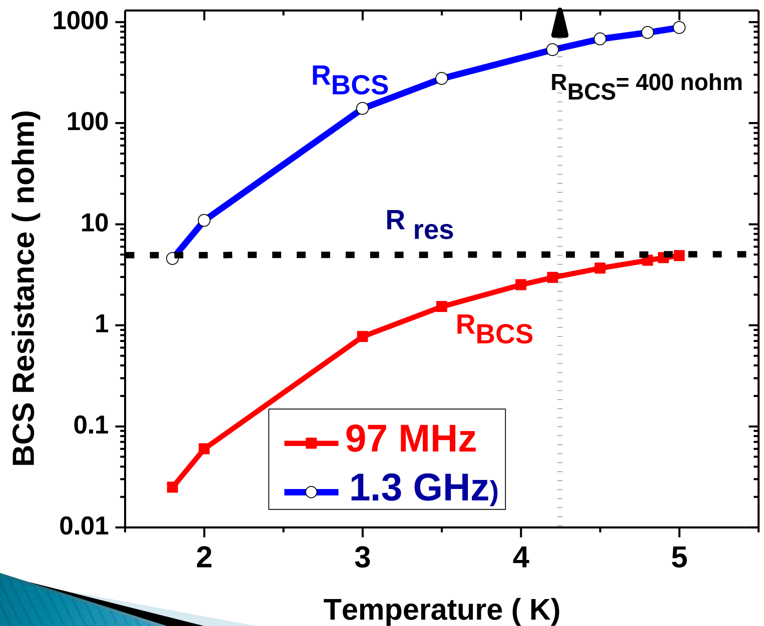
SURFACE RESISTANCE WITH TEMPERATURE (T) & RF FREQUENCY (f)

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

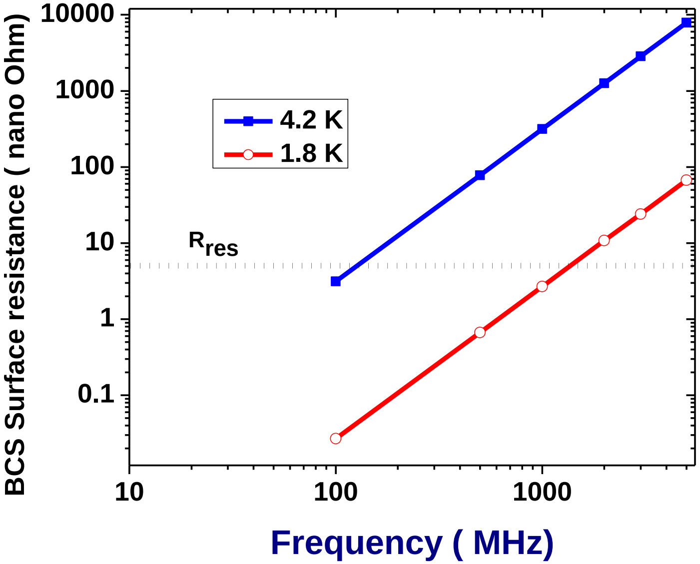
$$R_S = R_{BCS} + R_{res}$$

For High Frequency Cavity: 2 K is Choice

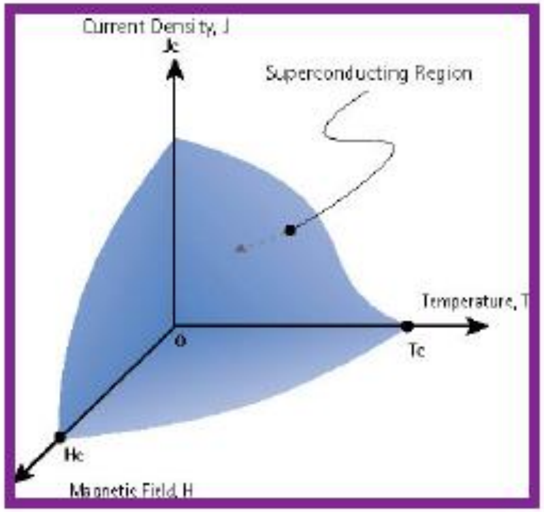
WHY 2K?

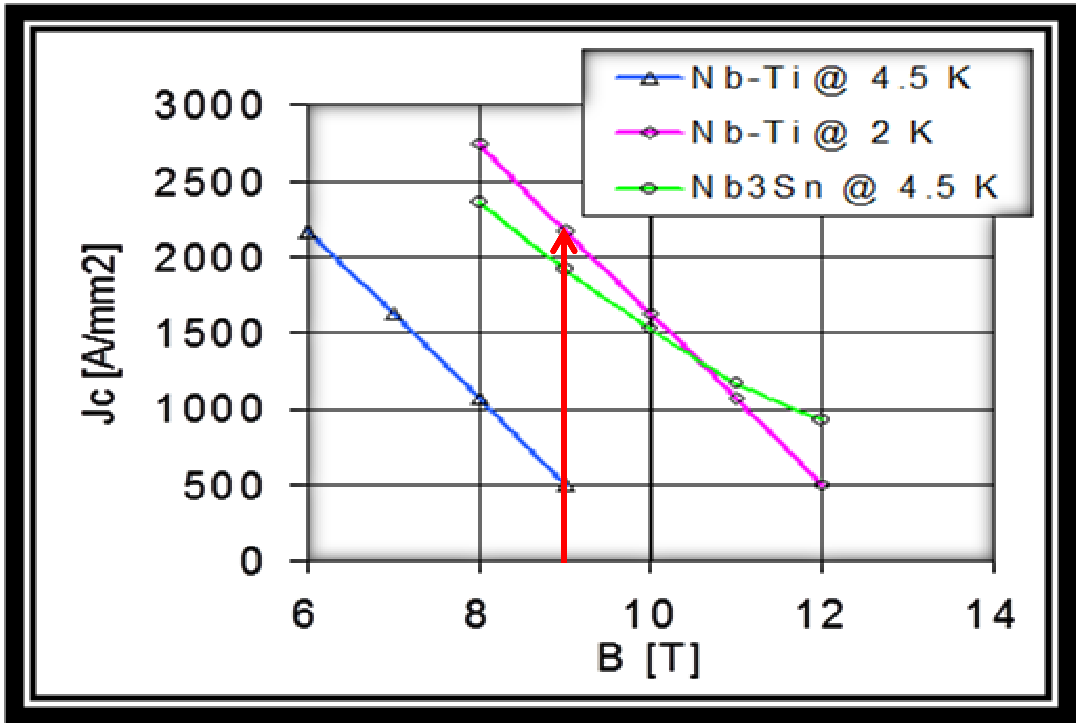


Nb : Tc= 9.2 K



FOR HIGH FIELD MAGNETS LIKE LHC AT CERN





N_bT_i at 2 K or Nb_3S_n at 4.2 K

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
Q0= G/Rs	6.5×10^{3}	2.1×10^{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
2 Standard Nuclear Power Plant : 235 MW

Accelerators with SC cavity

Lab	year	f (MHz)	Active	Gradient Length
KEK	1988	508	48m	4.5 MV/m
DESY	1991	500	20	2
CEBAF	1996	1497	169	5
CERN	1997	352	462m	6
ILC	Future	1300	22 km	31.5

TESLA COLLABORATION : Field Improved to 20 MV/m (2000 – 2008)

AND NOW : 30 – 40 MV/m

Remember : Normal Copper Cavity, We can Have,

E_{acc}= 100 MV/m

(Bunch beam rather than Continuous)

But Superconducting Cavity, Field is limited based on H_c value and It can not be more than 50 MV/m for Niobium

Very High Frequency (5 GHz) RF cavity :

Normal Copper Cavity may be better

Even at 2 K with High frequency, R_s will be high and hence higher dynamic Load at 2 K

$$R_{s\ normal} = \sqrt{\frac{\omega \mu_0}{2\sigma}}$$

Neutrino Detector & Cryogenics

Neutrinos are the most abundant matter particles in the universe, and they are all around us, but we know very little about them

Neutrinos are similar to the more familiar electron, with one crucial difference: neutrinos do not carry electric charge. Because neutrinos are electrically neutral, they are not affected by the electromagnetic forces which act on electrons.

Neutrinos able to pass through great distances in matter without being affected by it.

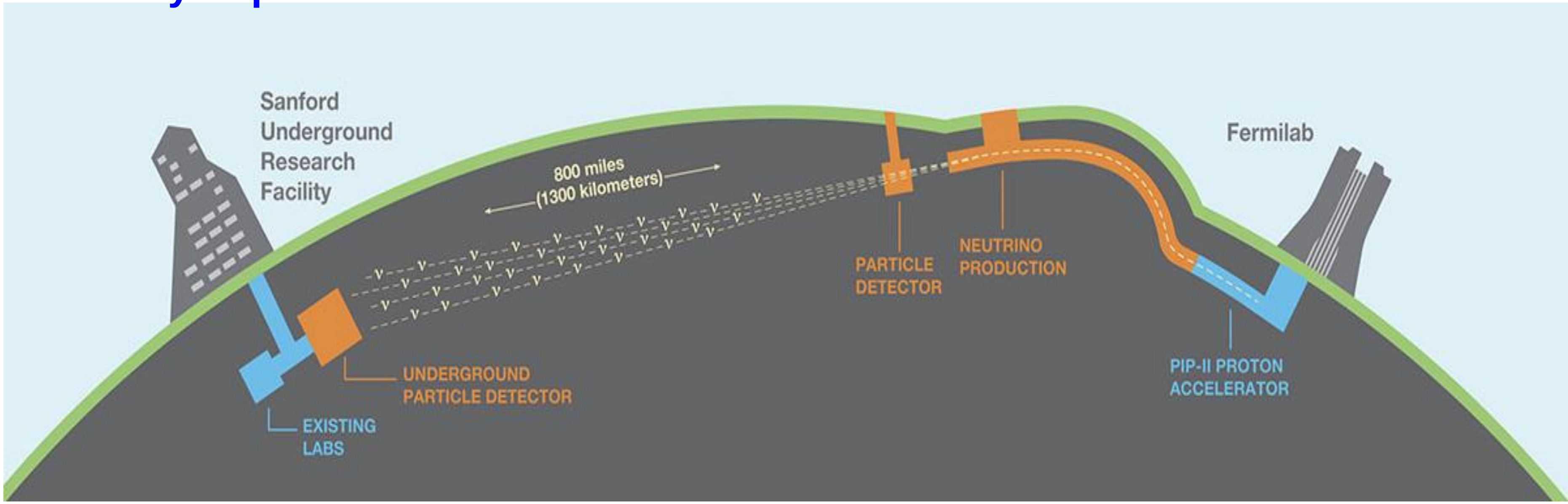
Three types of neutrinos are known;

Neutrino	ν_e	ν_μ	ν_τ
Charged Partner	electron (e)	muon (μ)	tau (τ)

The Deep Underground Neutrino Experiment (DUNE)

PIP-II's new linear accelerator for 100 GeV Proton will be built with the latest superconducting radio-frequency technology at Fermi lab, USA .

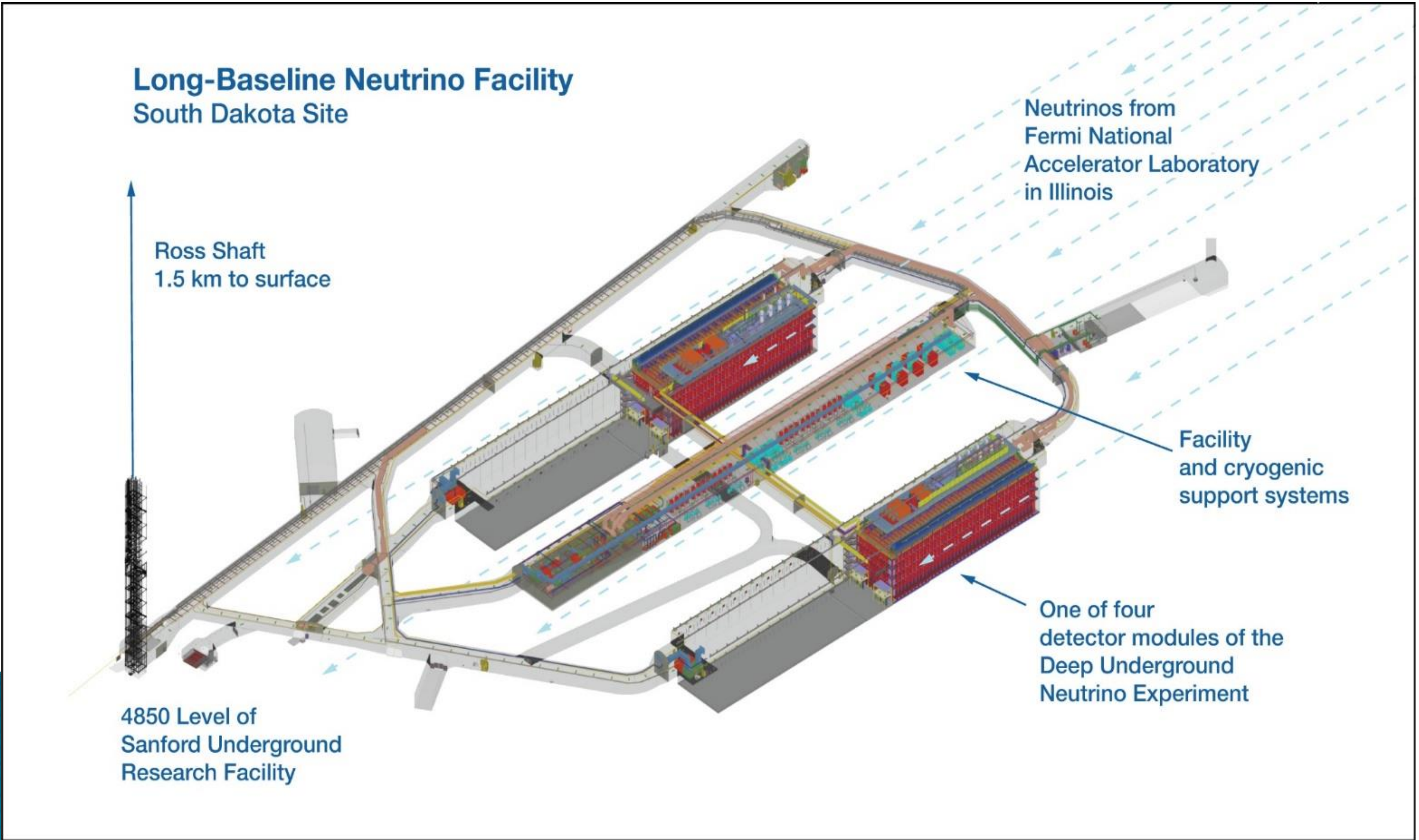
protons will slam into the graphite target of the Long-Baseline Neutrino Facility to produce neutrinos



The South Dakota Neutrino detector at Sanford will be the largest of its type ever built and will use 70,000 tons of liquid argon

The Deep Underground Neutrino Experiment (DUNE)

Each Cryostat : 18 m height , 19 m wide and 66 m long : Total four Cryostats



Why Liquid Argon ?

Argon as a noble gas, it does not react chemically.

It is its third most common component, surpassed only by nitrogen and oxygen. (Cheap)

Density is higher at Liquid Phase

Liquid argon's most important feature is that it acts as both a target and detector for neutrinos,

With 40 protons and neutrons, liquid argon is denser than water or oil, so liquid-argon detectors see more neutrino collisions per unit volume than their oil- or water-based predecessors.

All These Superconducting Magnet and Cavity works if it is cooled below its Critical Temperature

We need Cooling Medium & Hence Cryogenics

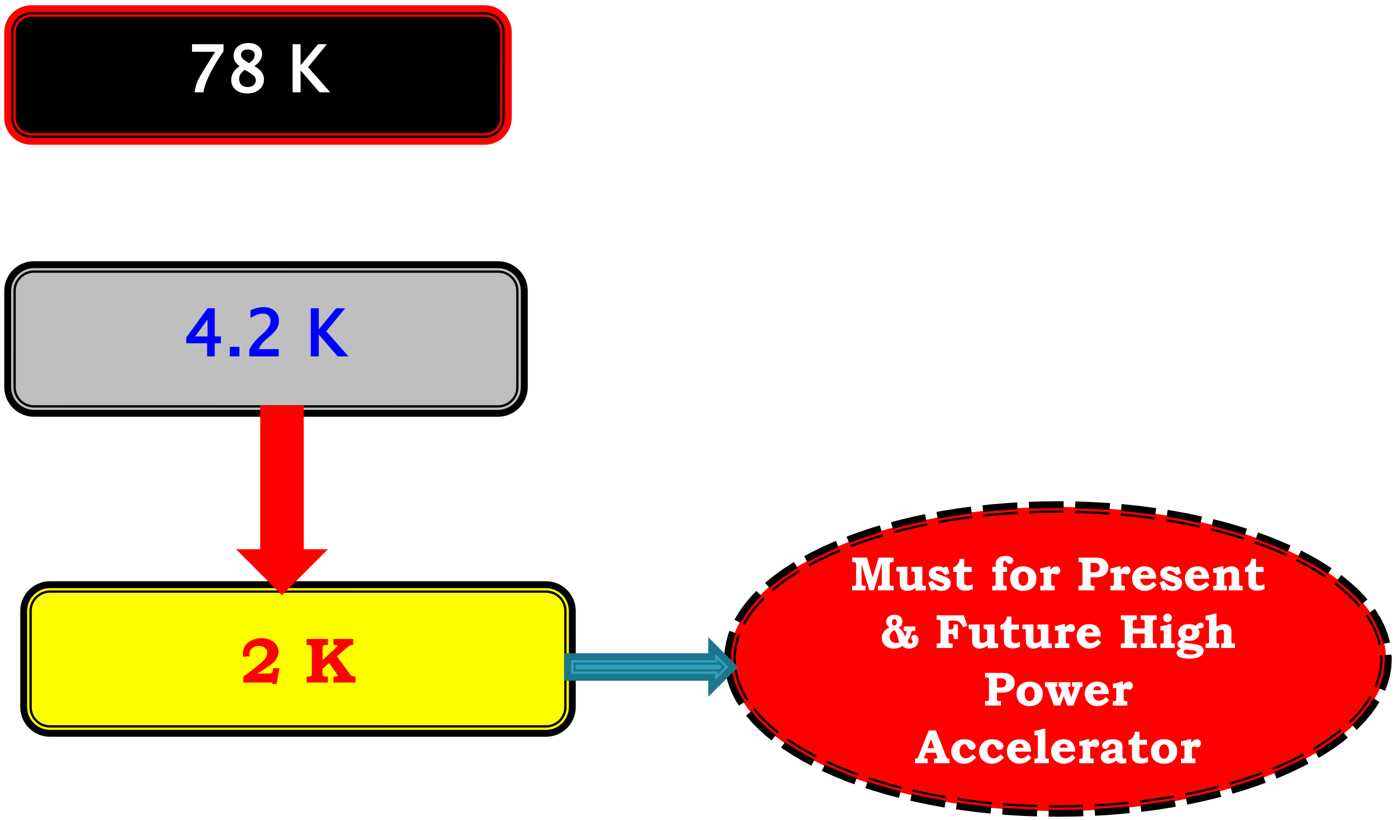
As on Today, No Superconductor with Tc at room Temperature is discovered

Thank God
We did not loose our Job

Now I will be skipping the Cryogenics (Introduction) in this lecture.

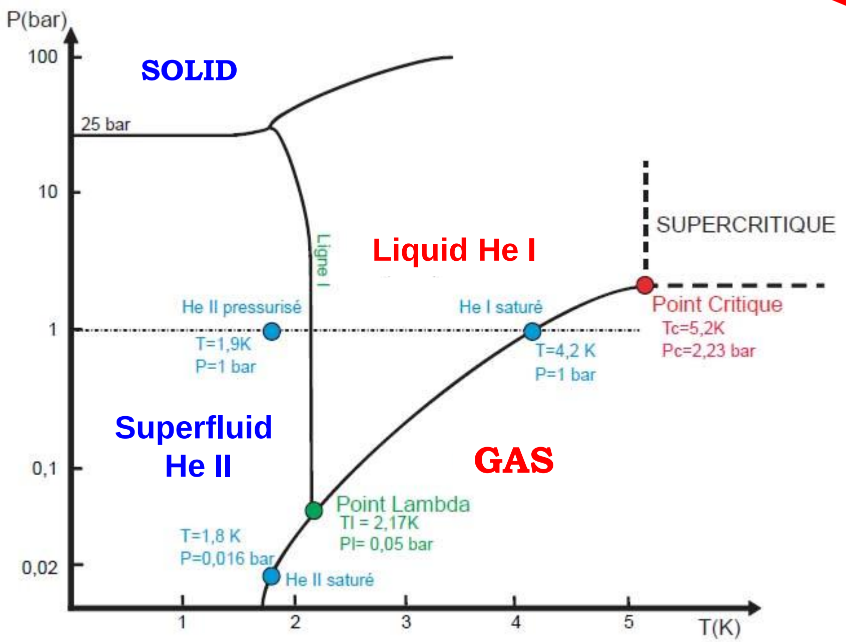
I will be talking on Cryogenics on Friday (Feb 17, 2023) Morning

Transition from He I to He II (Super fluid)

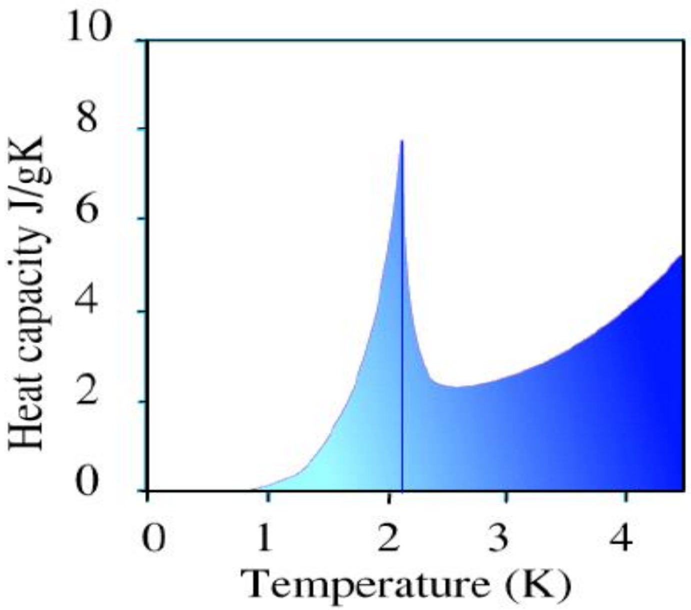


Super-fluidity is the characteristic property of a fluid with zero viscosity which therefore flows without loss of kinetic energy (no Pressure drop)

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



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



Advantages

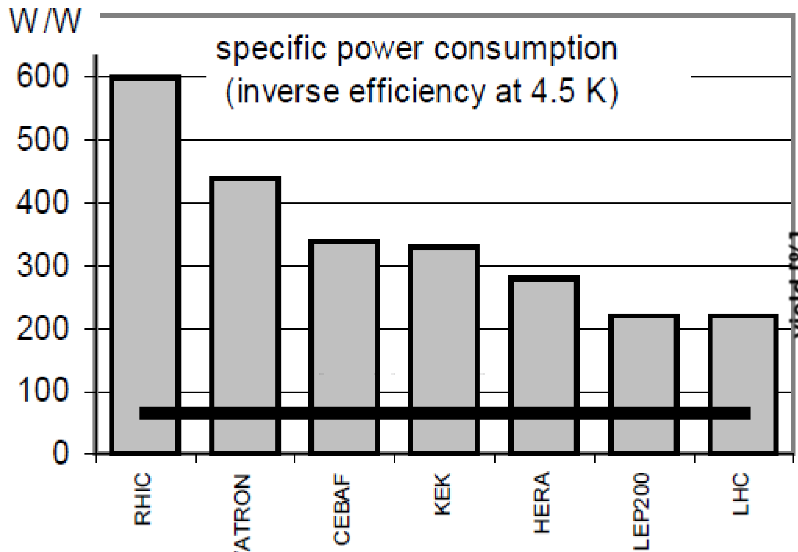
1. Super-fluid Helium can easily flow through SC strand /Cable

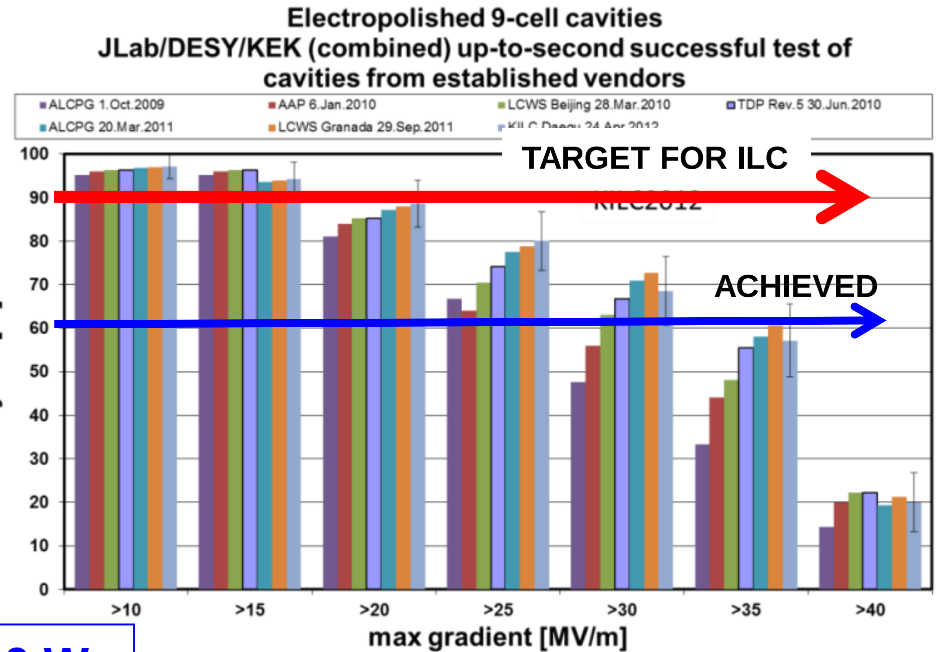
2. Small temperature rise with a heat input (specific heat)

3. Large Conductivity maintain equal temperature. SC Magnet is stable

Realization of High Power Accelerator

Parallel there is also improvement on efficiency of Helium Refrigerator





Power consumption reduced from 600 W to 225 W to take care of 1 W loss at 4.2 K (Higher Capacity : Efficiency High)

Not updated : % has improved for last 5 years

Realization of ILC/CEPC : Less Power Consumption by Refrigerator and Improvement of field gradient (> 30 MV/m) : Power and Size

MAJOR ACCELERATOR PROGRAMME
(Present & Future)
with cryogenics and superconductivity)

1. China

i. ADS / CSNS : Cavity ii. SHINE (Cavity) ii CEPC (Cavity & Magnet)

2. Japan

i. Super KeK- B : Magnet & Cavity, ii)Proton Accelerator at JPARC (Magnet) iii) ILC (Cavity)

4. Korea

i. RAON : Cavity and Magnet, KOMAC : Cavity, PLS

ASIA

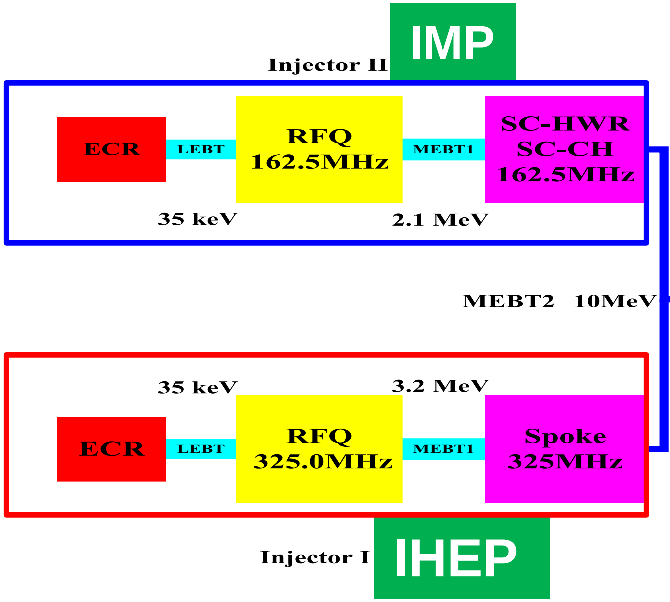
5. INDIA

i. ADS/ SNS ; Cavity (RRCAT, BARC) ii ANNURIB (VECC) : Cavity
ii. Superconducting Linac at IUAC & TIFR
iii. Superconducting Cyclotron : VECC. Kolkata

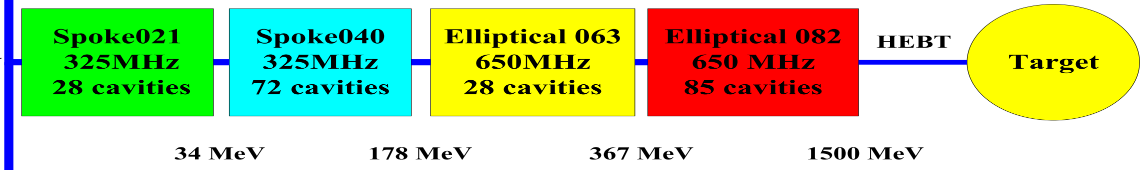
Other Major Accelerator Projects
LHC (Switzerland). ESS (Sweden), European X FEL (Germany)
FermiLab (PIP), USA, CEBAF (USA), FAIR (Germany)

CHINA

CHINA ADS PROGRAMME



Chinese ADS proton linear has two 0~10MeV injectors and one 10~1500MeV SC linac.



Present Focus

Required 2 kW @20 K By Helium Refrigerator & He- H2 Heat exchanger

Target Commissioning : 2018

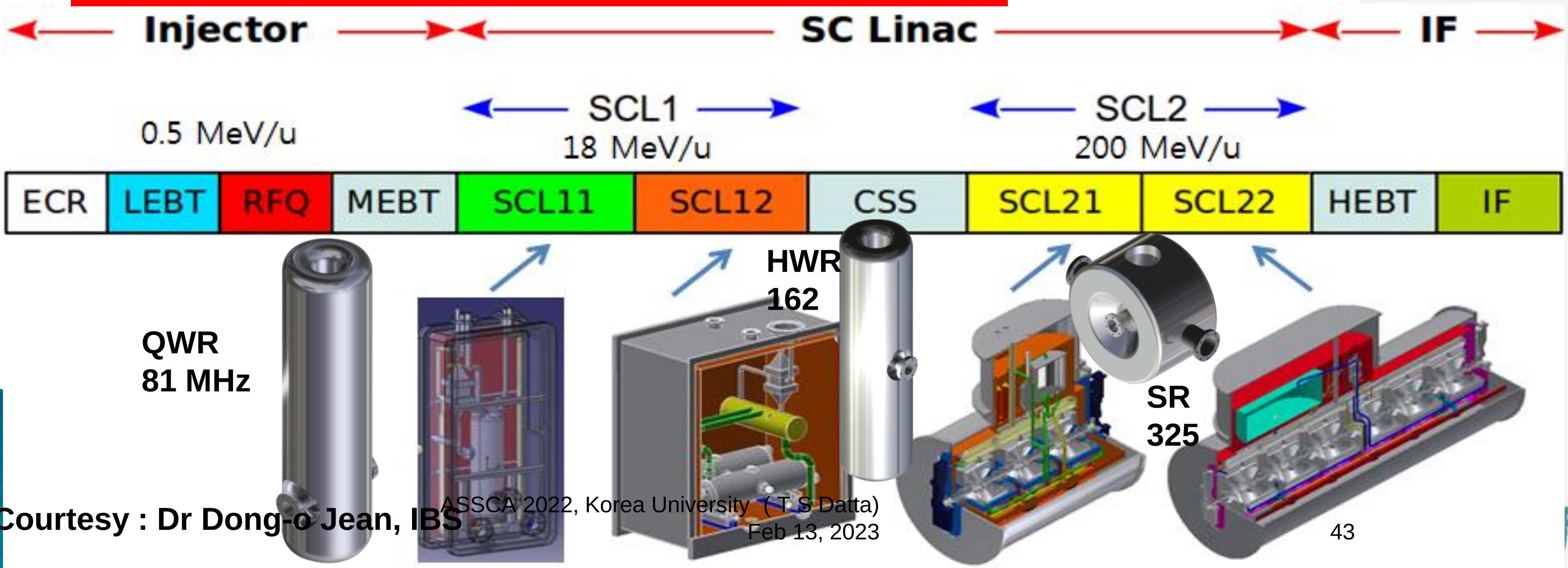
Dongguan, Guangdong

Courtesy : Prof. Shaopeng Li

RAON (Delightful) Superconducting Linac

- **RAON SCL is designed to accelerate high intensity heavy ion beams**
- **Optimized geometric beta of SC cavities (0.047, 0.12, 0.30, 0.51).**
- **Prototyping of SC cavities and cryomodules is under way at present.**

Required Refrigeration Capacity : 18 kW ; (May be the largest in Asia)



Courtesy : Dr Dong-o Jean, IBS

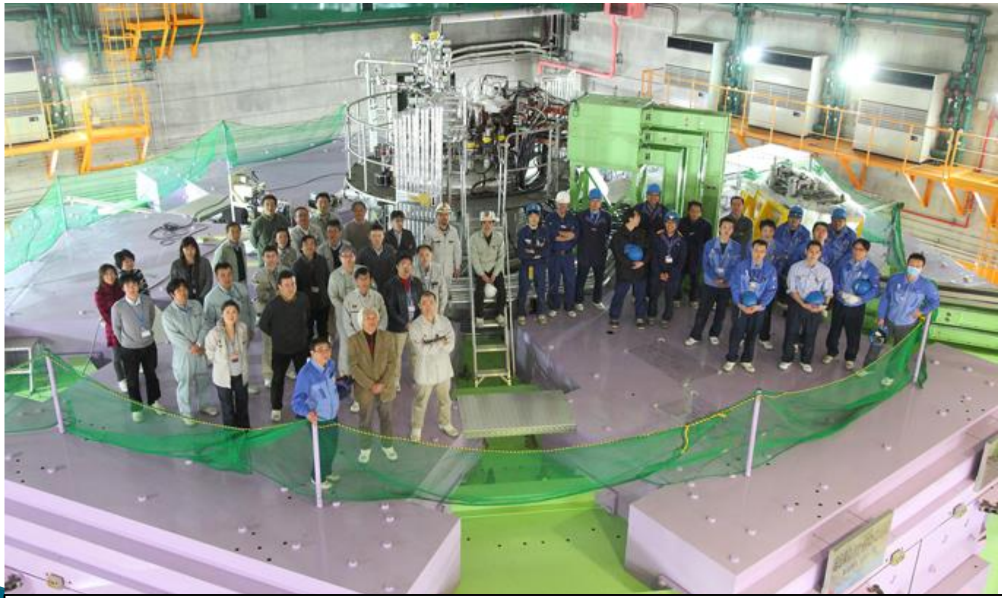
Superconducting Cyclotron

The K value of Cyclotron indirectly tells about the energy of the proton beam. Higher K value means higher Energy and that can be achieved either by increasing field (B) or by increasing diameter (2r)

$$K = \frac{e^2}{2m}(Br)^2$$

World First Superconducting Cyclotron (K -500) at NSCL, MSU. USA in 1981

WORLD'S LARGEST SC CYCLOTRON IN RIKEN. JAPAN (2006- 2007)

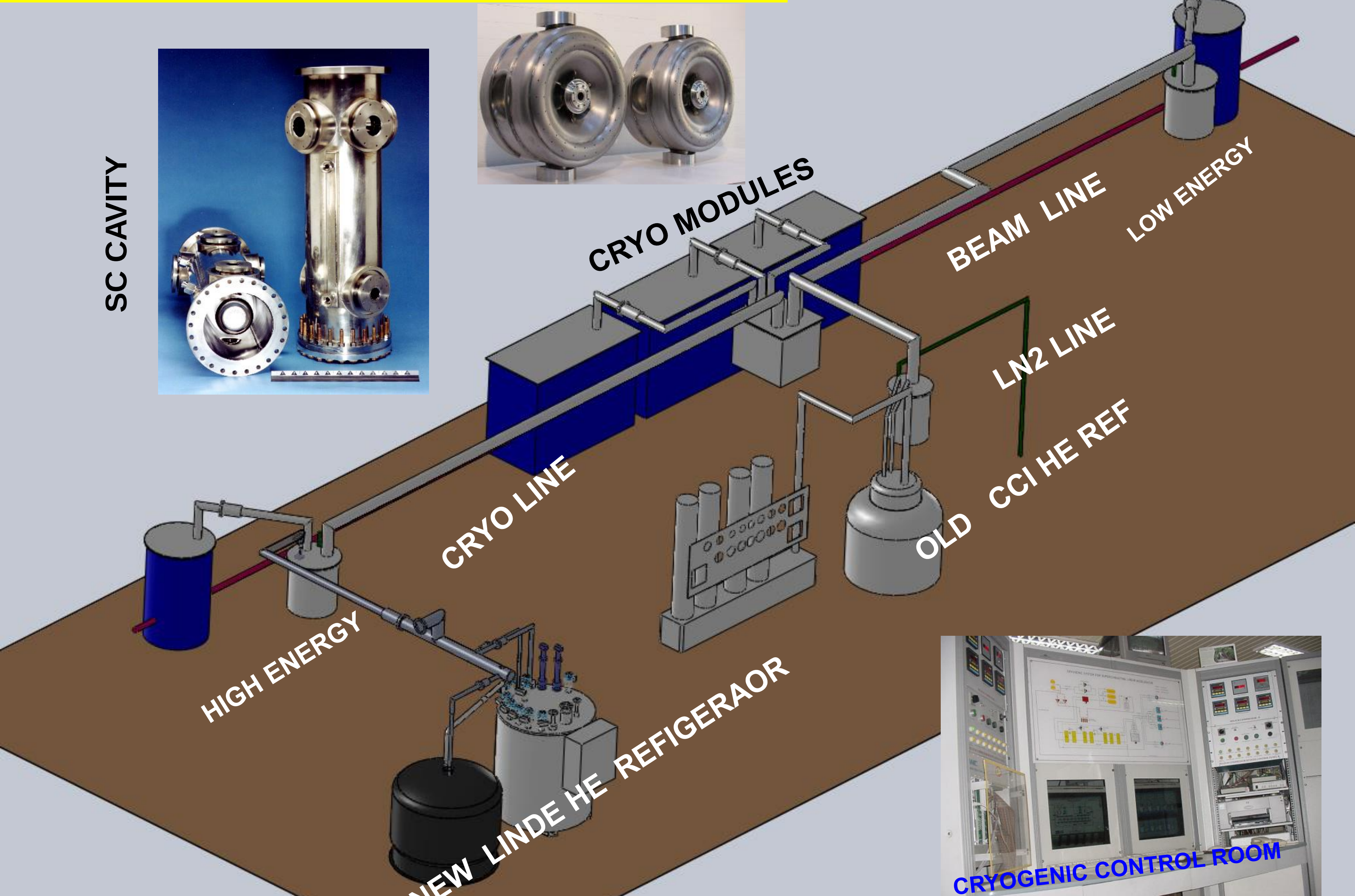


Beam energy : 440 MeV/ nucleon for Carbon

SC magnet	: Main Coil : 6 Nos
SC Material	: Nb- Ti
Type	: Ratherford
Max Sector Field : 3.8 T at 5 kA	
Operating Temperature : 4.5 K	
Jacket Material	: Aluminum alloy
Stored Energy	: 235 MJ

18 m Dia, 9 m Height, K= 2500, Weight ; 8000Tons

IUAC SC LINAC (Delhi, India)



LHC → HL-LHC → VLHC

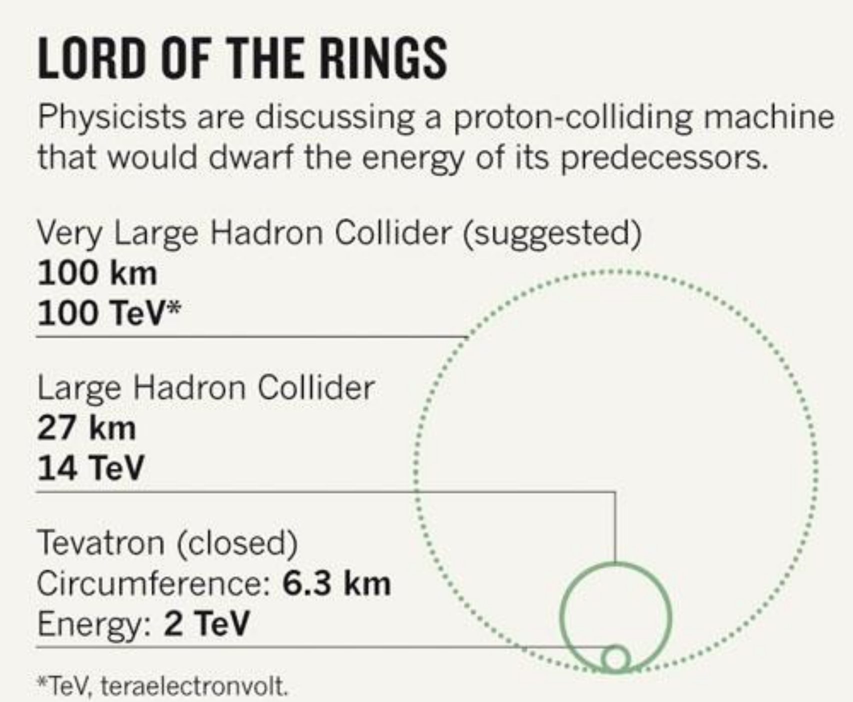
High luminosity	5 x 10^{34} $cm^{-2}s^{-1}$

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

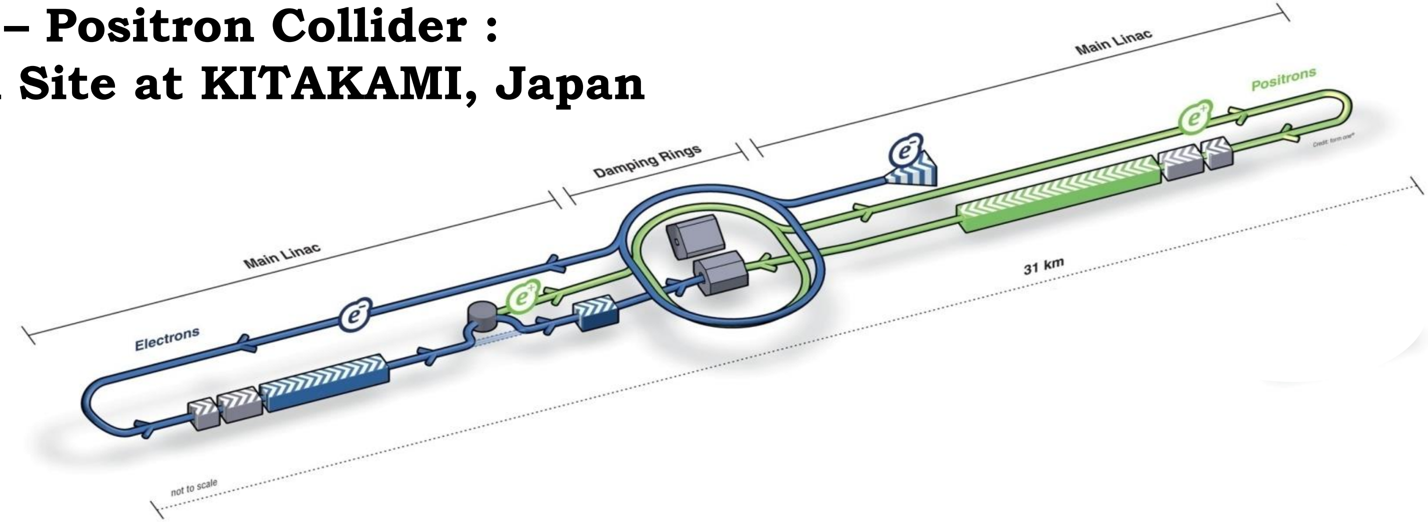


16 Tesla magnets for 100 TeV pp in 100 km

????????

INTERNATIONAL LINEAR COLLIDER (ILC)

Electron – Positron Collider :
Proposed Site at KITAKAMI, Japan



Max. Center-of-mass energy	500	GeV
Peak Luminosity	~$2x10^{34}$	$1/cm^2s$
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

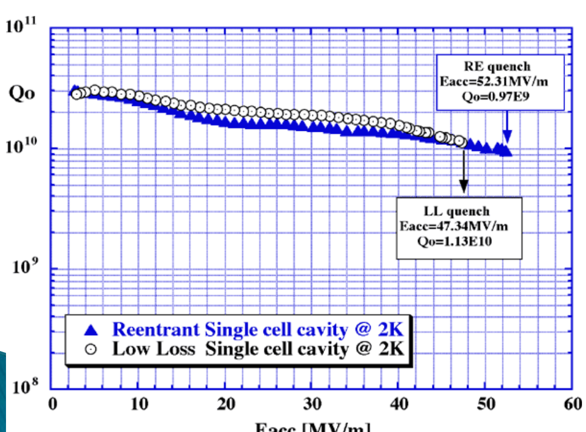
ILC Superconducting Cavity

9 cell cavity,~ 1m long

Test : > 35 MV/m, Q = 0.8 x 10^{10}, With Beam > 31.5 MV/m

10MW
L band
klystron

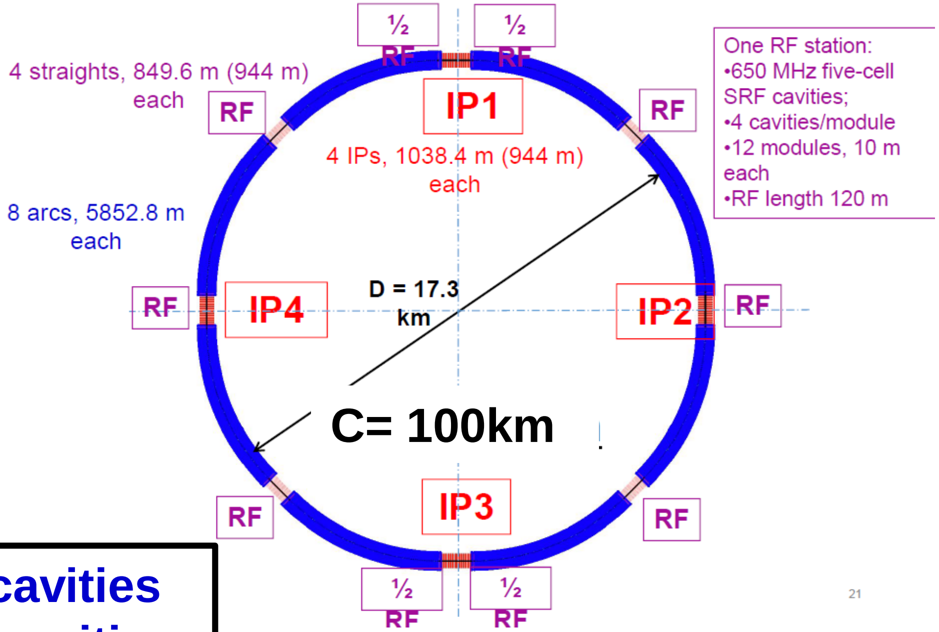
ILC needs : 16000 9- cell cavities and more than 1000 Cryomodules with each length of approx 12 m)



Total Estimated Refrigeration Capacity at 4.2 K ~ 210 kW (Remember CERN 144 kW)

The Circular Electron Positron Collider (CEPC) circumference of ~ 100 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

Refrigeration Capacity `96kW at 4.2 K

Estimated Project Cost ~ $6 billion

Technical **Challenges in this Subject**

1. **Superconducting Magnet : High Field (15 – 20 Tesla)**
2. **Superconducting Cavity : Gradient 30 MV/m :**
3. **2 K/4 K Cryomodule with low heat leak : Coupler / Current lead thermal Interception**
4. **2K System : Modification of old Refrigerator (4.5 K) with 2K system**
5. **Cryogenic System : Improvement of COP (Plug power vs. Refrigeration Load)**
6. **With advancement of 2G HTS wire , Feasibility of Beam line HTS Magnet (LN2 Cooled/ CryoCooler)**
7. **Cost and Restricted Supply of Helium Gas**
8. **Similarly gap between Niobium Supply and Demand**
9. **Limited Man Power with this specialized field**

Challenges/ Comments

1. Shortage of Helium Gas supply : Price rise (doubled from 2011)

Federal Helium Programme, USA ; Supplies Crude Helium 50 %
(They can stop any time : Earlier Deadline was Oct, 2013 Extended by Senate)
Total requirement : 200 MM3

Helium Recovery from Users has to be improved : Loss to be minimized

2 . COP (plug power for 1 W refrigeration) of Helium Refrigerator

During 1980 it was 400-500 (Tevatron) , 1998 (LHC) improved ; 225 (30 % of Carnot) : No further improvement . (Hope for ITER System) : 170 (40%)

Refrigeration capacity for ILC : 210 kW. Power Saving : 10 MW

3. Limited Niobium Supplier : Demand growth in current five years will be high

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

My Intention was only to transfer 20 % (Carnot efficiency) of my lecture to you

Thanks for your Kind Patience
See you on Friday Morning

Any doubt : Please Contact me :
tsdatta59@gmail.com