The 7th Asian School on Superconductivity and Cryogenics for Accelerators

February 1–9, 2026, Korea University Sejong Campus, Sejong, Republic of Korea

Role of Cryogenics & Superconductivity for Particle Accelerator : Overview

Presented by NAKAI Hirotaka, KEK, Japan
on behalf of

T S Datta (retired from)
Indian Institute of Technology Kharagpur,
&
Inter University Accelerator Centre, India

Asian Accelerator School (AAS) at Huairou, Beijing in Dec. 1999

(Special Thrust on Cryogenics & Superconductivity)

First school (15 days) : Prof. Datta was a student

Jubilant cavity team after successful Test

Organized by KEK, JSPS & IHEP (CAS)

Many students (12 countries) from that school are contributing today on accelerator development programmes in Asia

2nd ASSCA at KEK, Japan in 2017

4th ASSCA at Korea Univ., Korea in 2023

3rd ASSCA at IHEP, China in 2018

5th ASSCA at KEK, Japan in 2024

6th ASSCA at IHEP, China in 2025

8th ASSCA?

?

7th ASSCA at Korea Univ., Korea in 2026

Realization of high power accelerator (LHC, ILC/CEPC) is possible because of superconductivity

Outline of my talk

1. Basics on cryogenics & superconductivity
2. History on accelerator with cryogenics
3. Role of superconductivity (SC) for accelerator
4. Major programs – present & future
5. Conclusion

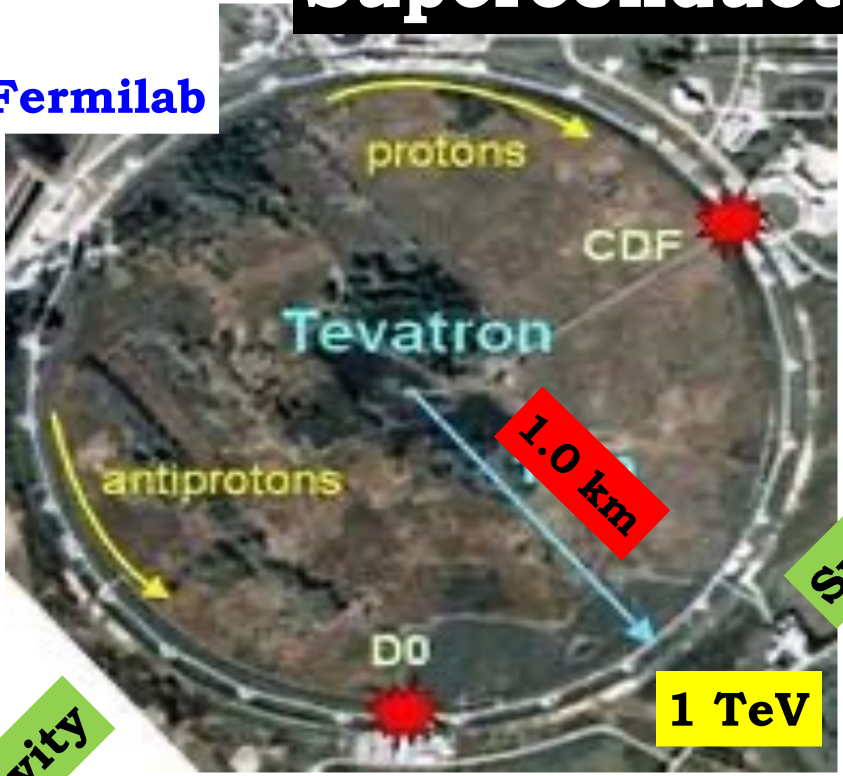
Benefits

1. Compact size
2. Low power consumption

Cryogenics → Superconductivity → Particle Accelerator

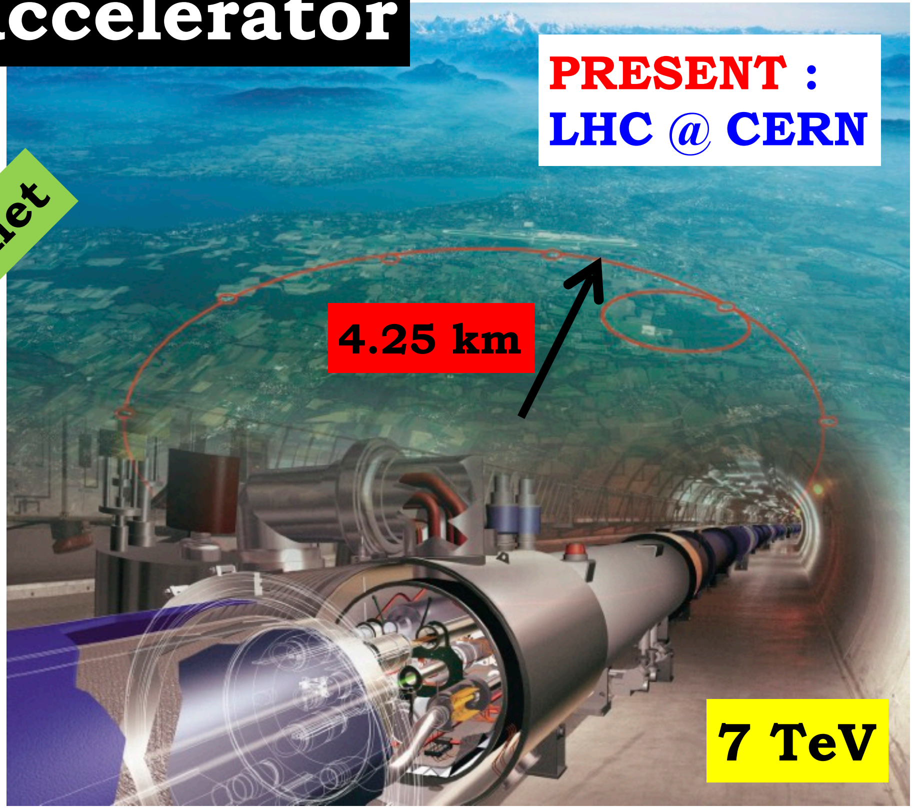
Superconductivity for accelerator

PAST : Tevatron @ Fermilab

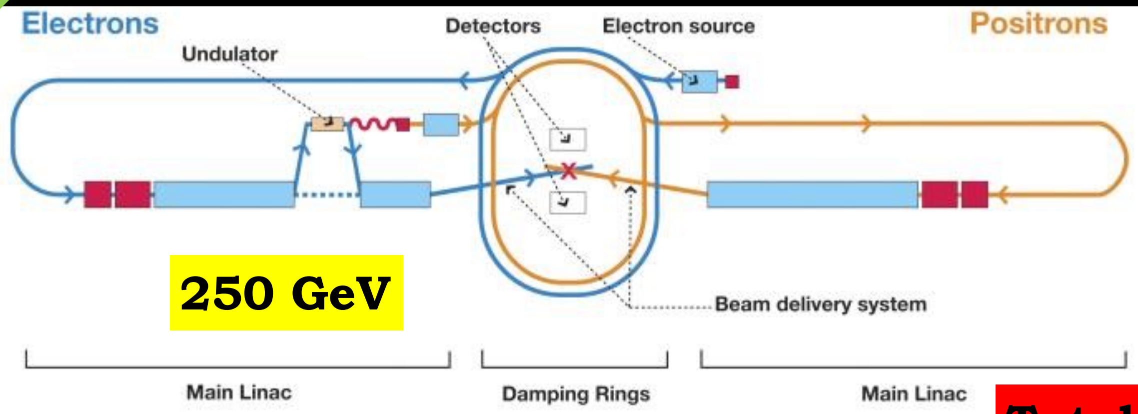


Superconducting Magnet

PRESENT : LHC @ CERN



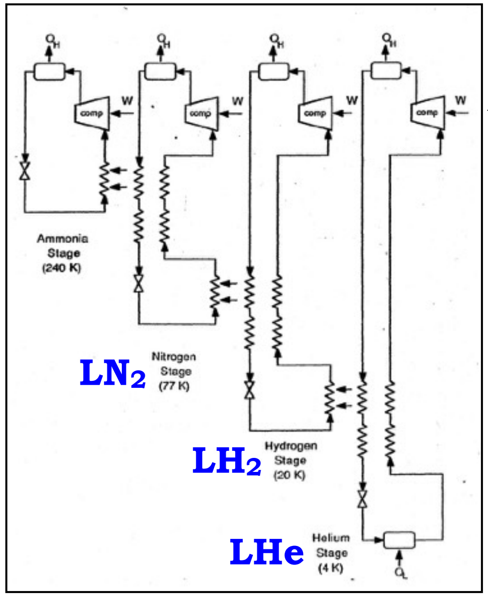
Superconducting Cavity



Future: ILC/CEPC (Asia) or VLHC @ CERN

Total Length : 31 km

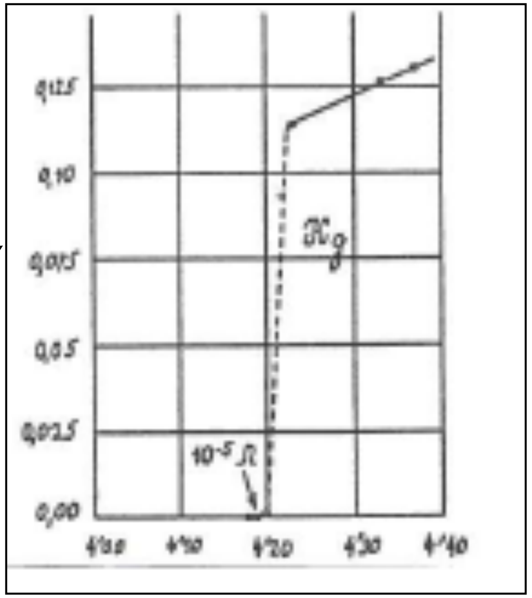
1908 : Heike Kamerlingh Onnes succeeded in liquefying helium
1911 : Discovery of superconductivity



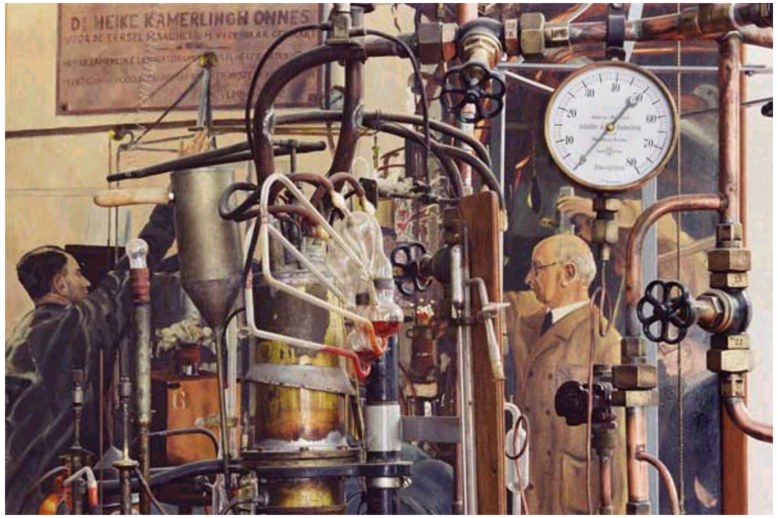
Cascade helium liquefier

(1853-1926)

Prof. discovered superconductivity with his own liquid helium 100 years back



Famous R-T plot



The physics laboratory in Leiden became the "coldest place on earth" in 1908

Cryogenics

Greek word (12th Century)

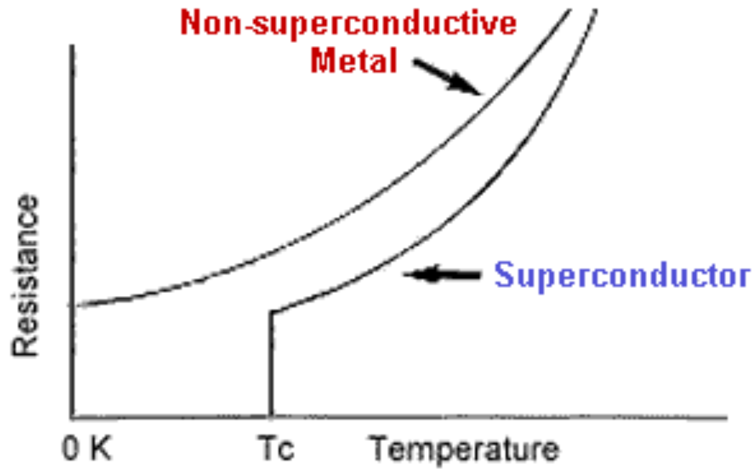
Icy, Cold → Production

Where is the boundary for cryogenic range : 120 K (-153˚C) ???

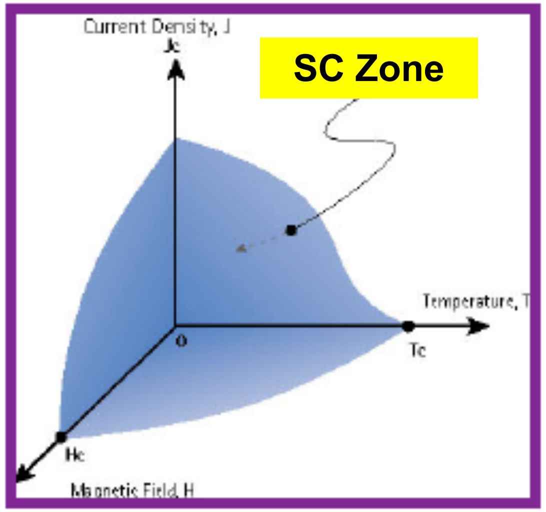
- **Superconductivity** -
  The phenomenon of losing resistivity R=0 when sufficiently cooled to a very low temperature (below a certain critical temperature).

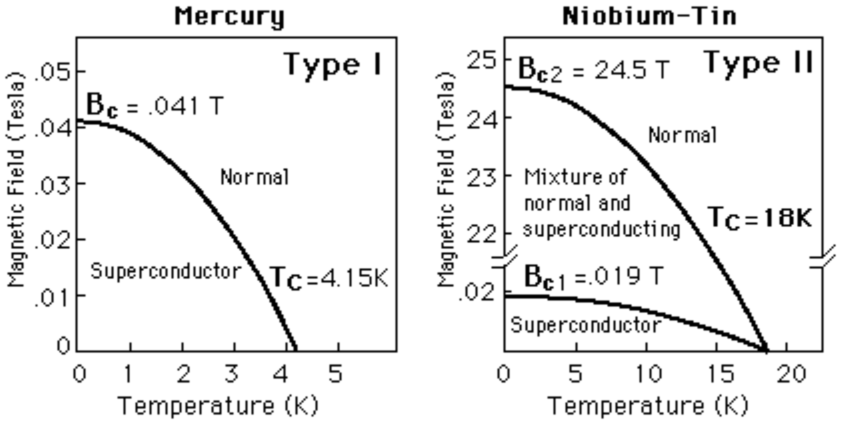
Chilled water is not enough to cool superconductor below Tc.
Hence Cryogen

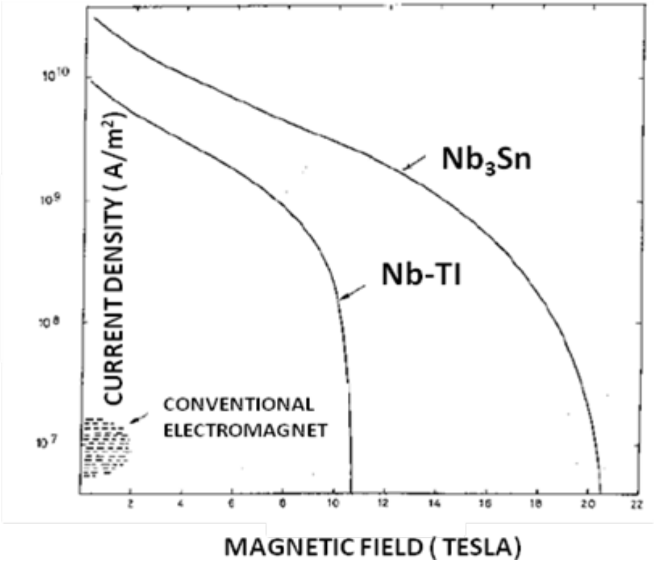
SUPERCONDUCTIVITY



Superconductivity is destroyed, if any parameter exceeds its critical value, and they are interlinked : $T > T_c$, $I > I_c$, $H > H_c$







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

A. Common Cryogen

Liquid	Boiling Point (K)
LNG	111
Liquid Oxygen	90
Liquid Argon	83
Liquid Nitrogen	77.4
Liquid Hydrogen	20
Liquid Helium	4.2
Superfluid Helium	2.17

B. Practical Superconductor

Material	T_c (K)
Hg	4.2
Pb	7.2
Nb	9.2
NbTi	10
Nb_3Sn	18
High Temp Superconductor	
MgB_2	39
YBCO	90
BSSCO	110

Blue color applicable for accelerator

Cryogenics + Superconductivity + Nuclear Science

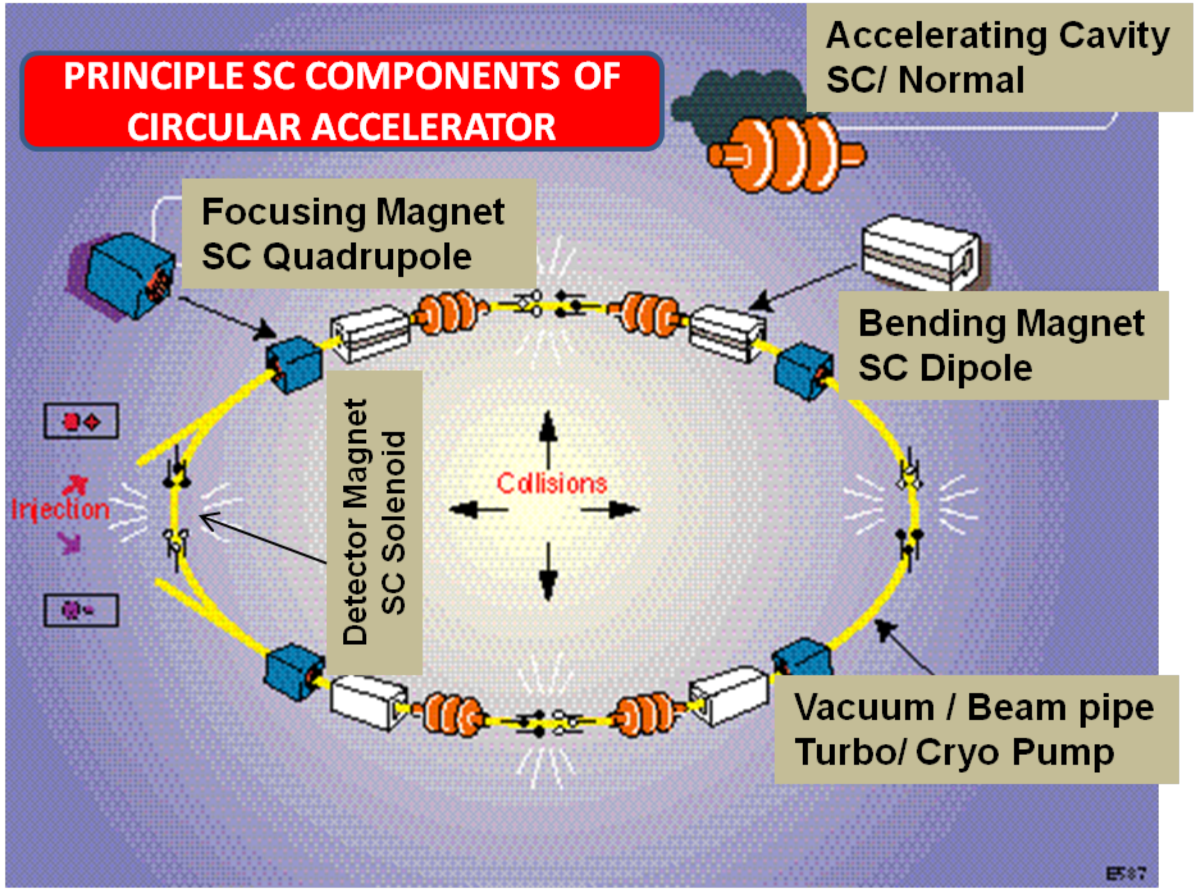
Breakthroughs :

1. ULT through nuclear adiabatic demagnetization
2. Polarized 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
7. Neutrino detector with liquid argon target

Cryogenics - Superconductivity - Accelerator (Brief History)

- 1908 - Kamerlingh Onnes liquefied helium (4.2 K)
- 1911 - Superconductivity is born!! (← rather "discovered")
- 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)
- 2010–2020 - TESLA Tech. Collaboration on cavity (achieved 35 MV/m)
- 2015–2025 - Many accelerator program with superconductivity initiated
- 2025–2030 - International Linear Collider (ILC)/CEPC/Free Electron Laser/Spallation Neutron Source/UL-LHC and many more

Main Components of a Circular Accelerator/Collider

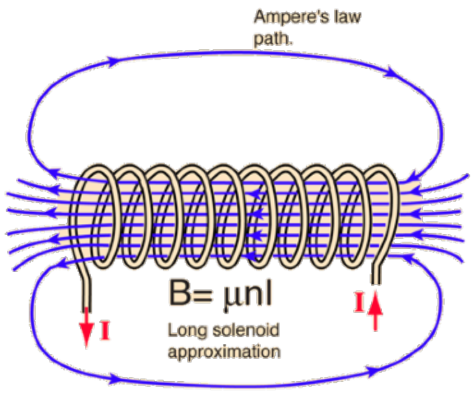


1. **Cavities : Energy**
2. **Magnets : Guides & Focuses the beam**
3. **Detector : Detects new particle**

All these main components of accelerator either can be made by normal copper conductor or by superconductor

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)



$$BL = \mu NI$$

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

$$B = \mu n I$$

High energy (E) means (high velocity (v)) needs high magnetic field (B) to bend the ion beam

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

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

Magnetic field by magnet ($\vec{B}$)

Electric field by cavity ($\vec{E}$)

B is proportional to ampere-turns (nI)

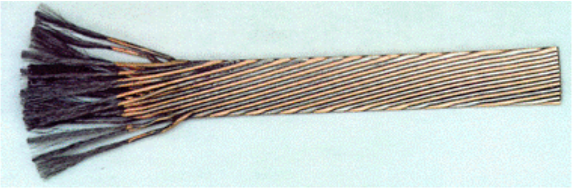
I (current) is limited in normal conductor (Cu, Al) because of Joule heating (I^2R) power loss. To compensate we can increase no of layers (size!!)

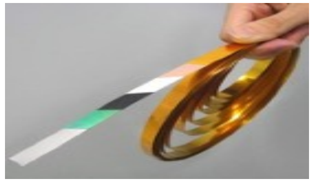
Or, we can have efficient cooling system/very high heat transfer coefficient and surface area (LN_2 Cooling ????)

(possible for high field pulsed magnet)

Superconductor (R=0) : No Joule heating (except at joint and current lead)

Practical Superconductor Today





Very good electrical conductors are not superconductor (Cu, Ag, Au)

Material	T_c (K)	H_c (T)	Application
Pb	7.2	0.08	Cavity
Nb	9.2	0.2	Cavity
NbTi	10	15	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, Not High H_c, Easy fabrication

Type 2 (Nb through MgB_2)

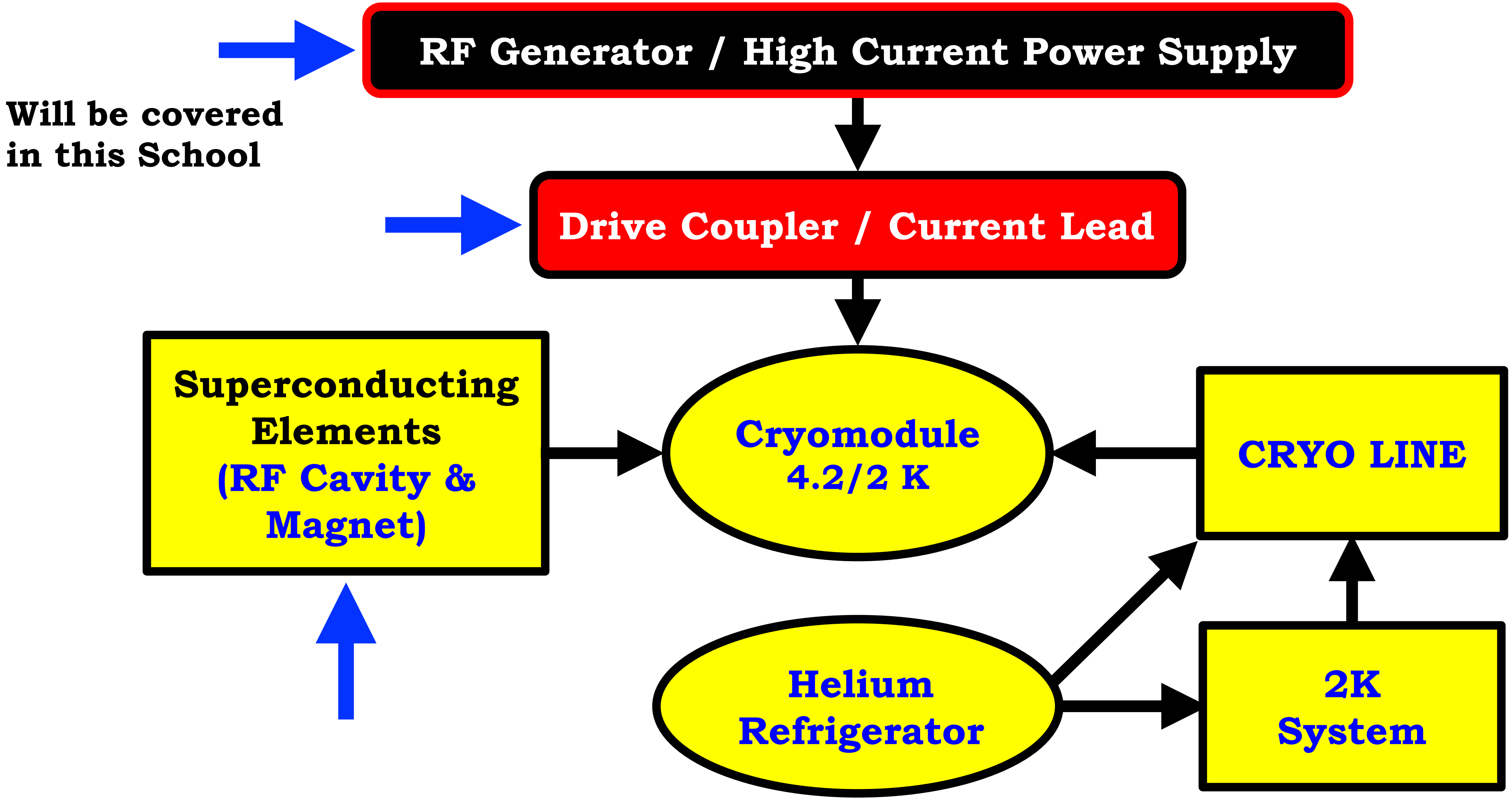
Most popular for present day accelerator (Nb, NbTi, Nb_3Sn)

High H_c, T_c Ductile

High T_c, J_c, High Cost, Brittle

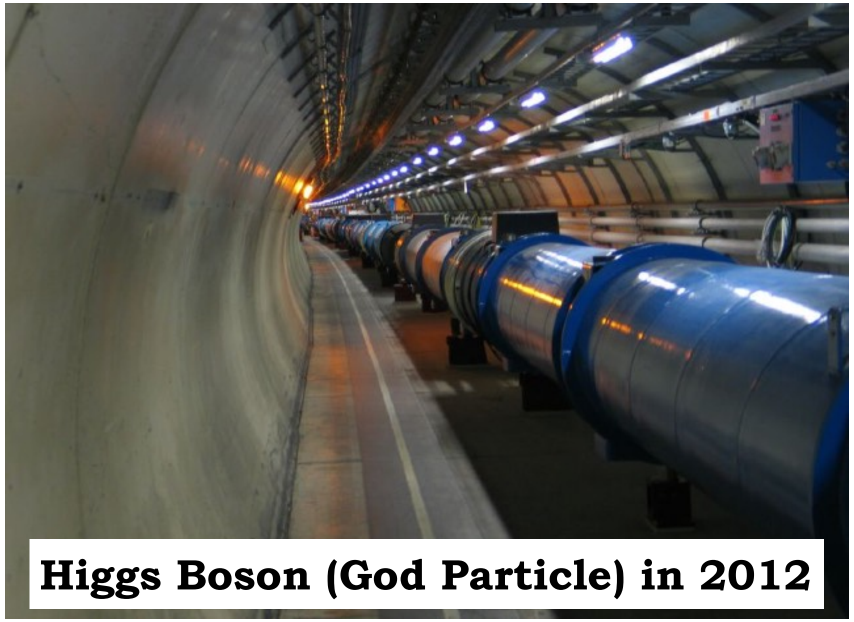
Now based on T_c, we need different cooling medium that is the criteria To distinguish LTS and HTS

Main Components for Superconducting Accelerator

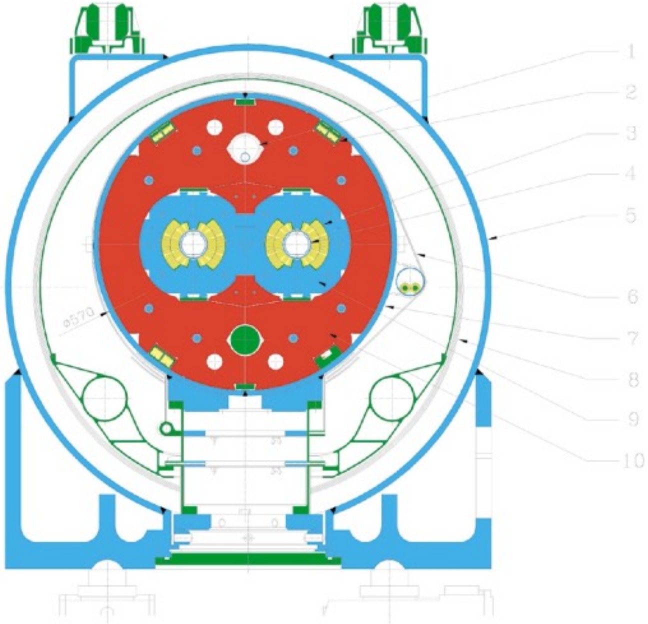


Present

Large Hadron Collider (LHC) at CERN



1. World's 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 NbTi magnets
6. Total refrigeration capacity 144 (18 x 8) kW at 4.2 K

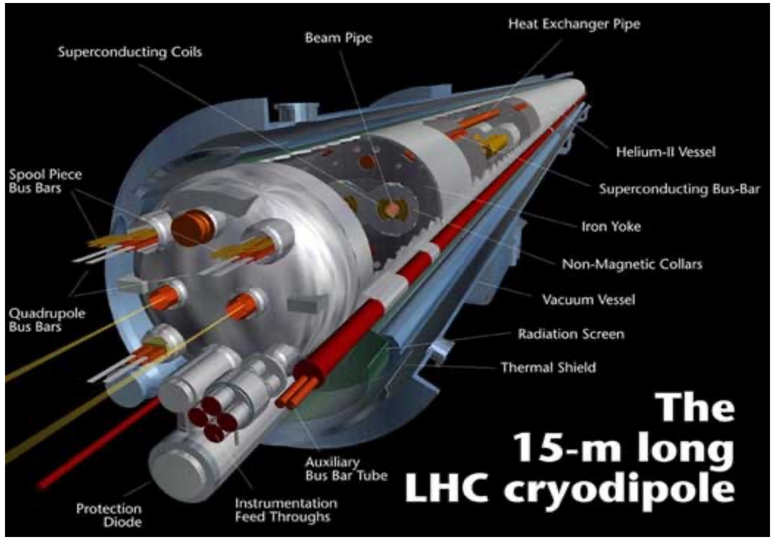


First collision at 3.5 TeV beam energy in 2010
Collision at design beam energy (7 TeV) in 2015

LHC → HL-LHC → VLHC

NbTi SC magnet generates a field 8.3 T and operates at 1.9 K

Power and Size Comparison for CERN LHC



If no superconductor

Energy : 7 TeV

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

E in GeV, B in T, R (radius) in m

Description	Superconducting Magnet	Normal Magnet
Field	8.3 T	2.1 T
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 **33 MW**	**3300 MW**

Size reduction from 108 km to 27 km

Power reduction from 3300 MW to 33 MW

Future

LHC → HL-LHC → VLHC

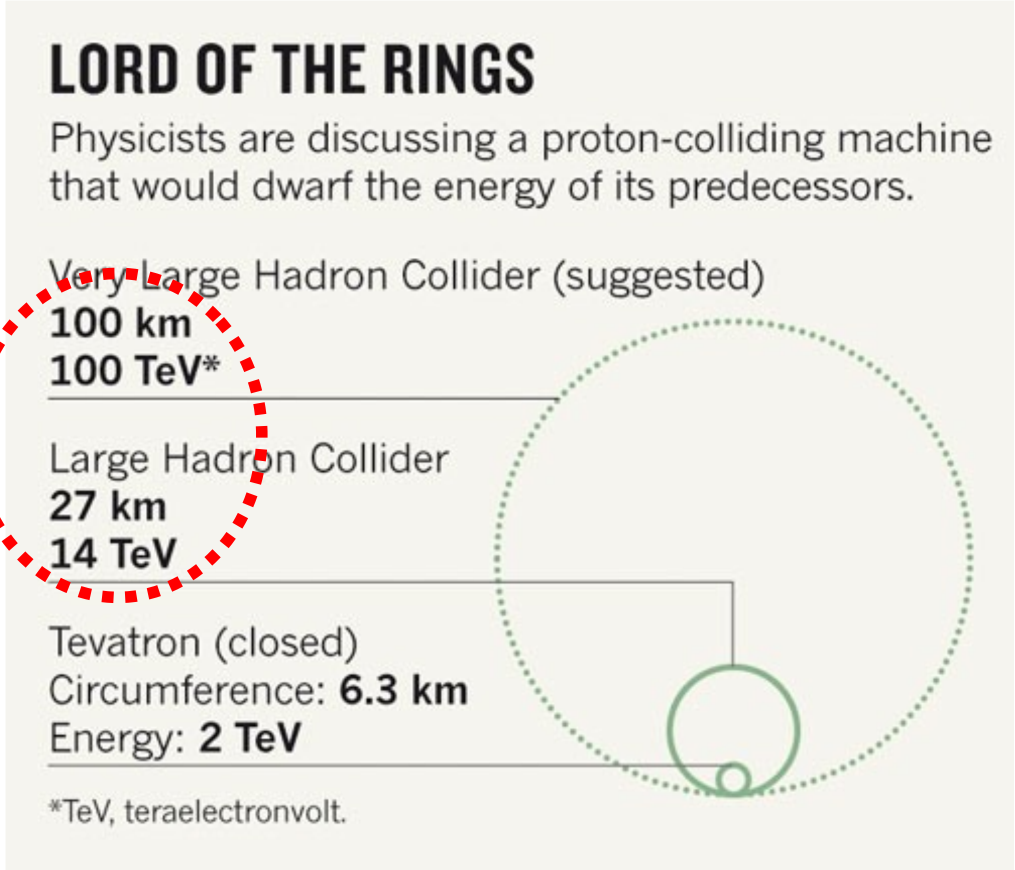
High luminosity	5 x 10^{34} $cm^{-2}s^{-1}$

24 High field Nb_3Sn quadrupole magnet (11–12 T) before and after ATLAS/CMS detector

Using of superconducting crab cavity : 16 for shaping the bunch beam

MgB_2 current lead to have higher J_c at 50 K

Total length replacement ~ 1 km



Expected to operate in 2030

16 T magnets for 100 TeV pp in 100 km

When ????????

Few Accelerators with SC Magnet

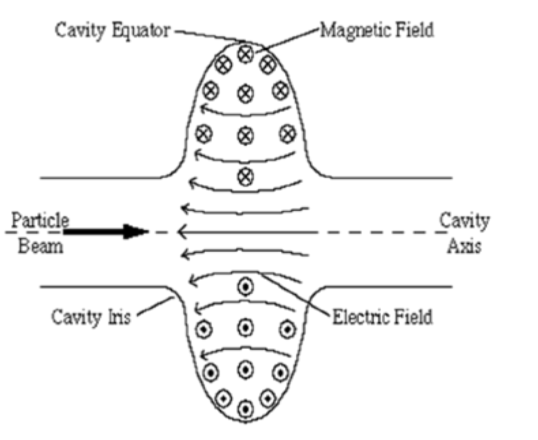
Accelerator	Energy (TeV)	Field (T)	Length (km)	Year
Tevatron (USA, P P-)	0.9	4	6.3	1984
HERA (Germany, P-e)	0.92	5.3	6.3	1989
SSC (USA P-P)	20	6.8	87	cancelled
LHC (Switzerland, P-P)	7	8.3	27	2011

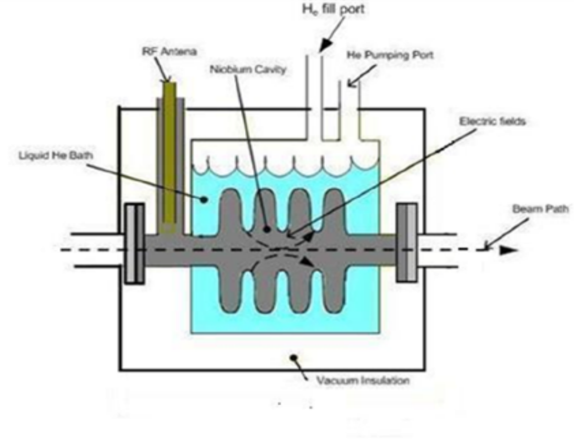
Now many are in Asian countries

Practical power comparison

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

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 (magnet), there are finite resistive power loss in RF superconductor because of surface resistance

Resonant cavities have Quality factors, Q, whose value depend on resistive losses (P_d)

High Q , Low Loss

$$P_d = \frac{\omega U_0 E_{acc}^2}{Q_0}$$

Q is inversely proportional to surface resistance

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

Surface Resistance

R_s (copper)/R_s (niobium) = 10^5

Power comparison in cavity (normal vs superconductor)

Example

Description	Normal (Cu) QWR Cavity	Superconducting (Niobium) Cavity
E_{acc} (MV/m)	1	1
G, f	17, 97 MHz	17, 97 MHz
Rs	3 mΩ	10 nΩ
Q_0= G/Rs	6.5 x 10^3	2.1 x 10^9
Power Loss	9000 W at 300 K	0.5 W at 4.2 K
Plug Power	9000 W	150–200 W

$$P_d = \frac{\omega U_0 E_{acc}^2}{Q_0}$$

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

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 Length (m)	Gradient (MV/m)
KEK	1988	508	48	4.5
DESY	1991	500	20	2
CEBAF	1996	1497	169	5
CERN	1997	352	462	6
ILC	Future	1300	22000	31.5

TESLA Technology 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 MeV/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

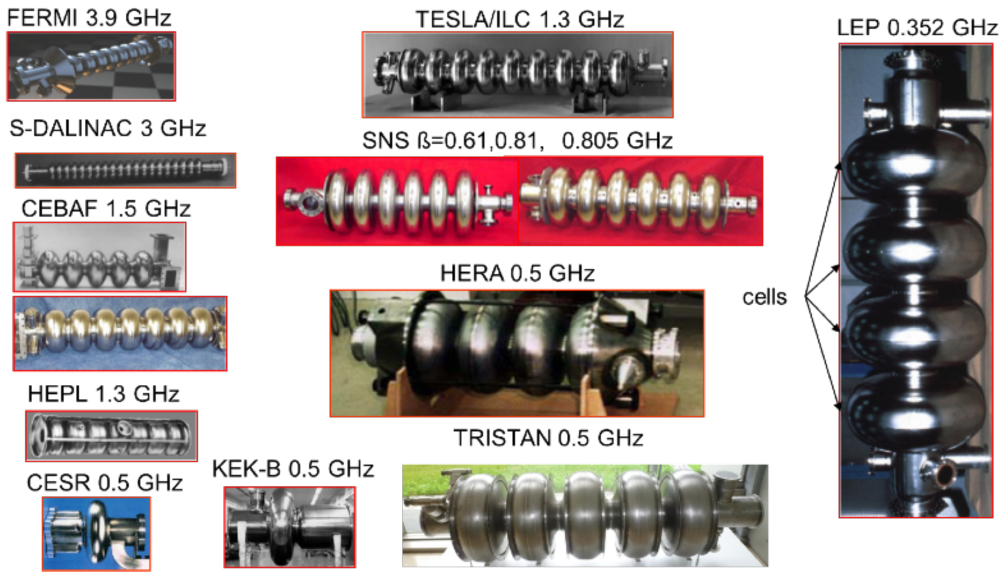
Remember $(R_s)_{sup}$ is proportional to (frequency)^2

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

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

SRF Cavity Production in Worldwide Projects

Elliptical multi-cell cavities



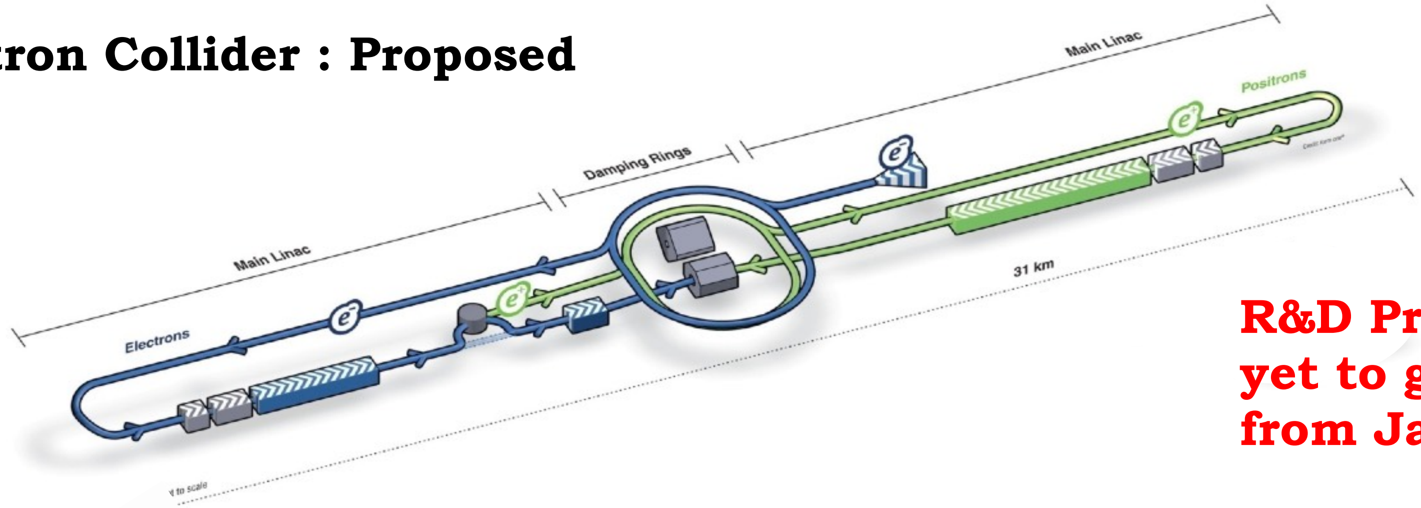
Half Wave Resonators (HWR)

Quarter Wave Resonators (QWR)

Spoke cavities

International Linear Collider (ILC)

Electron-Positron Collider : Proposed site in Japan



R&D Program are on yet to get final approval from Japanese Govt.

Max. Center-of-mass Energy	500	GeV
Peak Luminosity	~2 x 10^{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

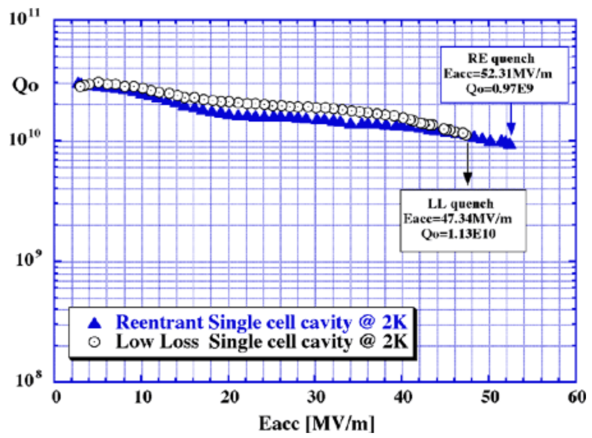
ILC Superconducting Cavity/Cryomodule

9 cell cavity, ~ 1m long

10MW
L band
klystron

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

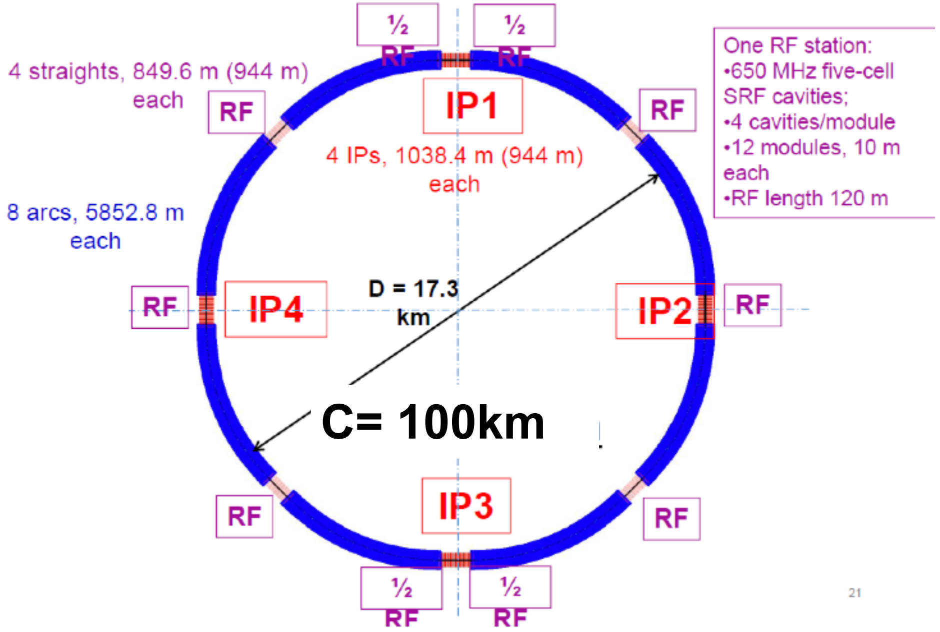
ILC needs : 16000 9-cell cavities and more than 1000 cryomodules with each length of approx. 12 m



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 Qinhuangdao, Hebei (?), China (2022–30)

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



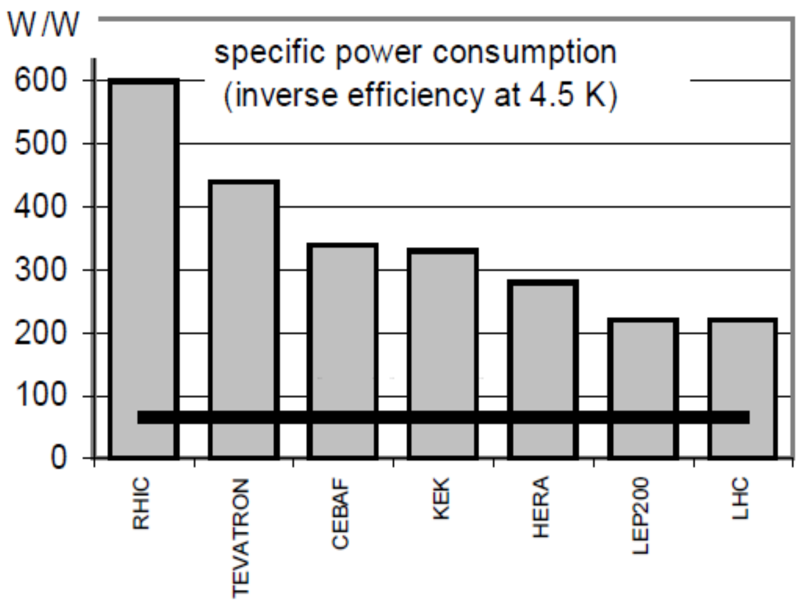
Booster ring: 256, 1.3 GHz 9-cell SC cavities
Collider ring: 480, 650 MHz 2-cell SC cavities

Note : Design under revision

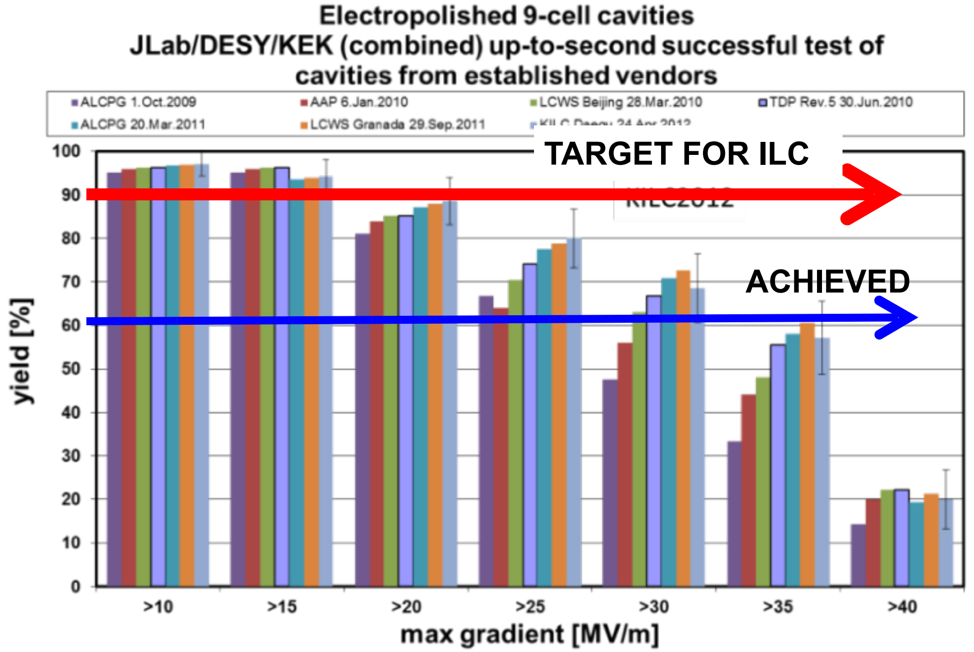
Refrigeration Capacity ~ 96 kW at 4.2 K

Estimated Project Cost ~ $6 billion

Parallel there is also improvement on efficiency of the helium refrigerator



Power consumption reduced from 600 W to 225 W to take care of 1 W loss at 4.2 K
(higher refrigeration capacity : higher Carnot efficiency %)



Not updated : % has improved for the last 5 years

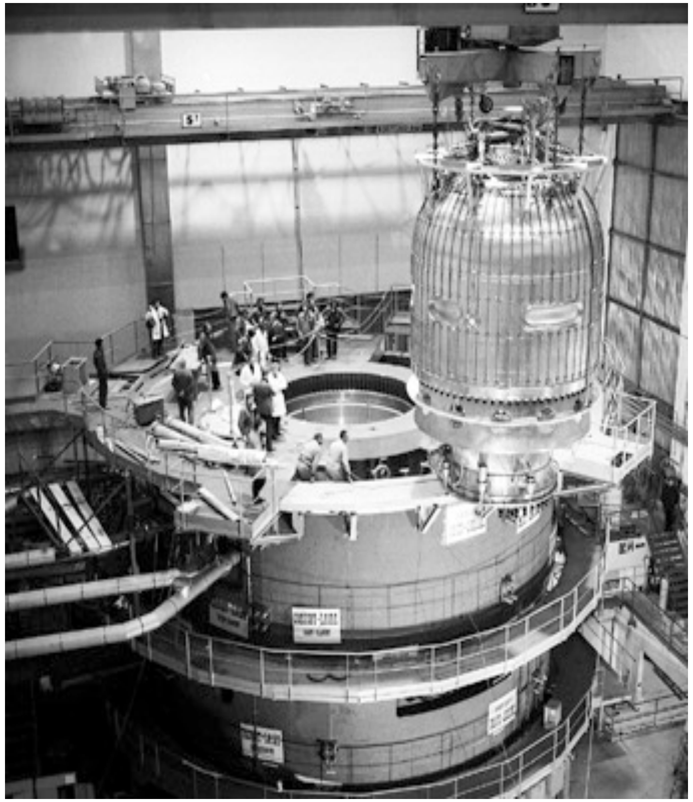
Realization of ILC/CEPC : Less power consumption by refrigerator and improvement of field gradient (> 30 MV/m) : Power and Size

Cryogenics & superconductivity for particle detector and other application

- **Bubble chamber : liquid hydrogen & SC magnet (earliest and now obsolete)**
- **Particle detector like ATLAS/CMS : Giant superconducting magnet (present) : liquid helium**
- **Neutrino detector : liquid argon (DUNE)**
- **Spallation neutron source : Supercritical subcooled liquid hydrogen (ESS)**

Bubble chamber filled with liquid hydrogen (1956–1985) (First application of cryogenics in major accelerator program)

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

Detector with superconducting magnet

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

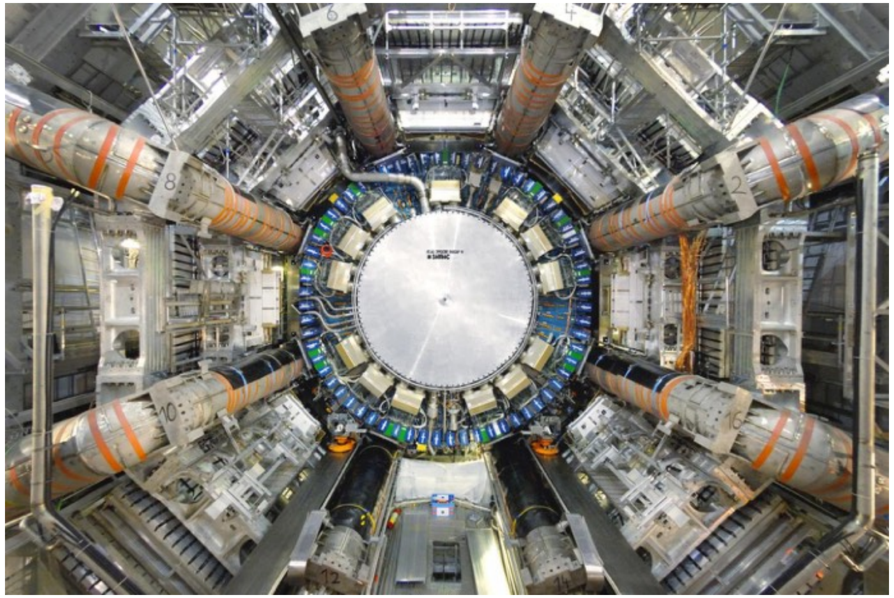
Resolution better with high field (B) and longer length (L)

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-ton detector is the largest volume particle detector ever constructed.

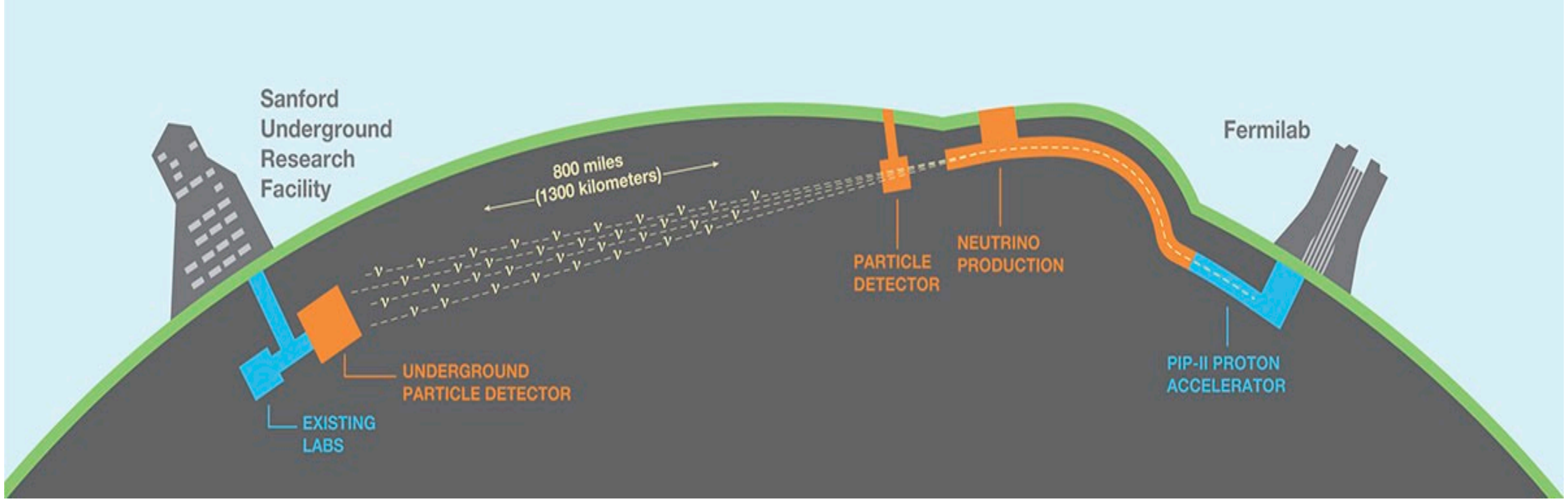
The magnet system on the ATLAS detector includes eight huge **SC magnets arranged in a torus and a central SC solenoid around the LHC beam pipe**



The Deep Underground Neutrino Experiment (DUNE) : Neutrino Detector

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

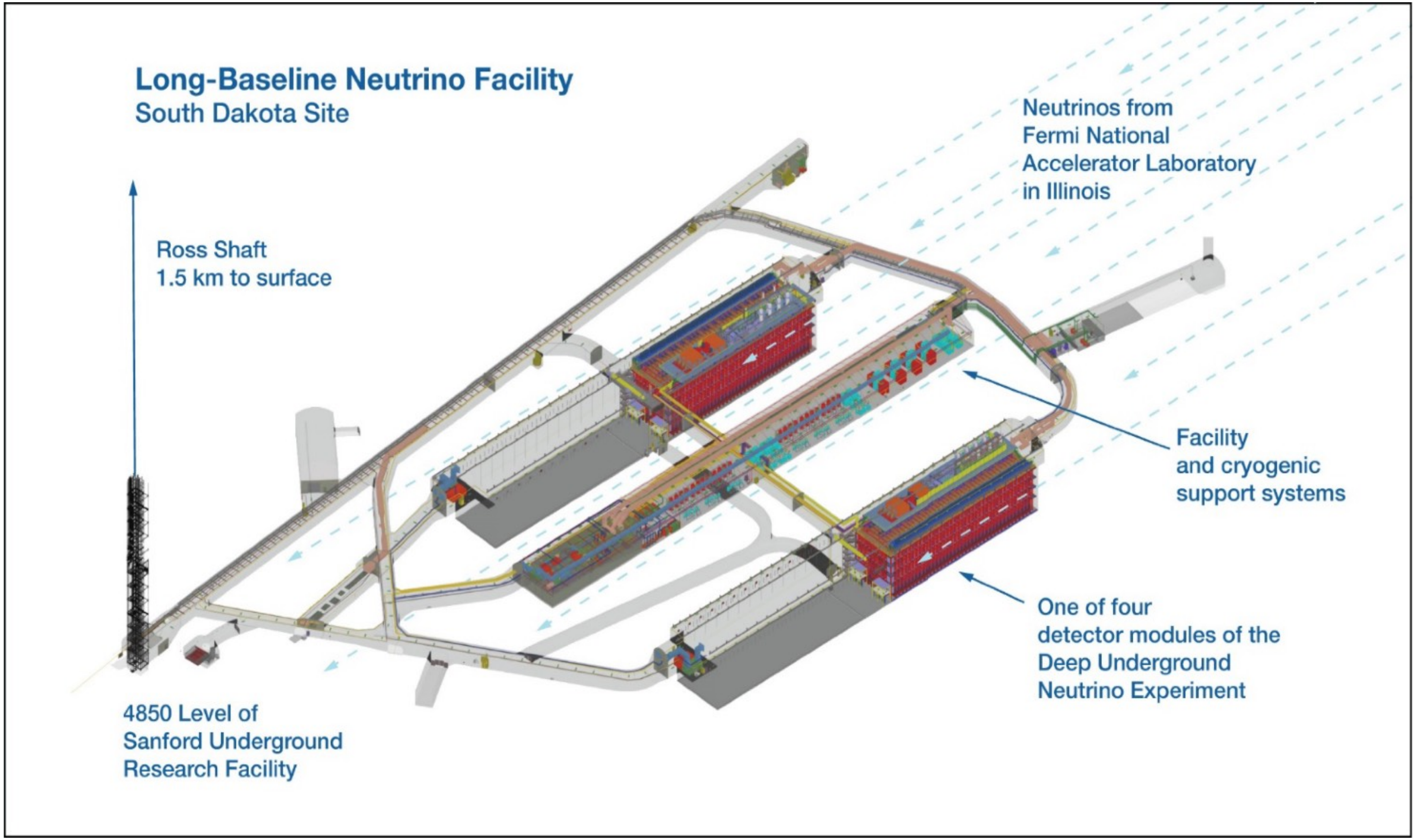
PIP-II's new linear accelerator for 100 GeV Proton will be built with the latest superconducting radio-frequency technology at Fermilab, USA.
Protons will slam into the graphite target of the Long-Baseline Neutrino Facility to produce neutrinos.



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 magnets and cavities work, if they are cooled below their critical temperatures

We need cooling medium & hence cryogenics

As on today, no superconductor with T_c at room temperature is discovered

Thank God
We did not loose our job

Transition from He I to He II (Superfluid)

78 K

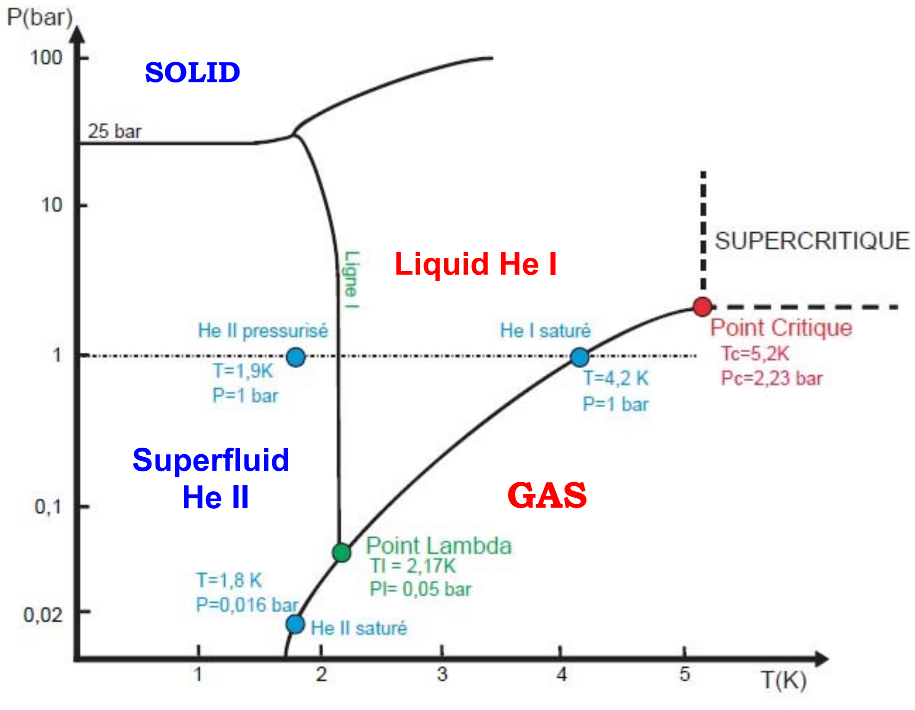
4.2 K

2 K

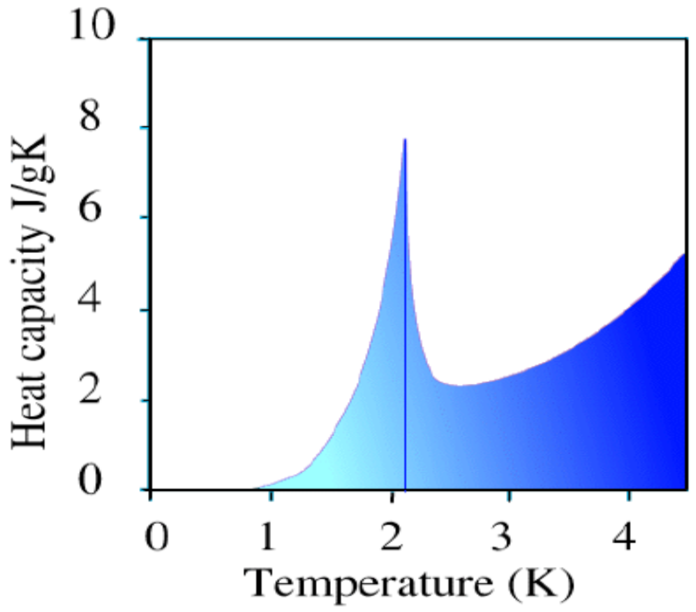
Must for present & future high power accelerator (important)

Superfluidity is the characteristic property of a fluid with zero viscosity which therefore flows without loss of kinetic energy (no pressure drop)

Transition to superfluid phase below λ-point (2.17K)



1. **Low viscosity**
2. **High conductivity**
3. **High specific Heat**

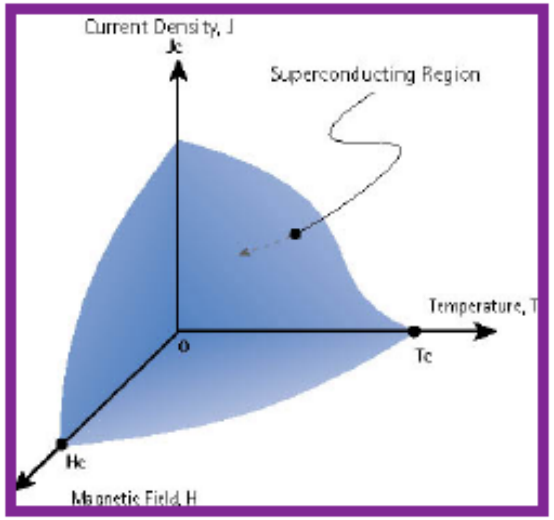


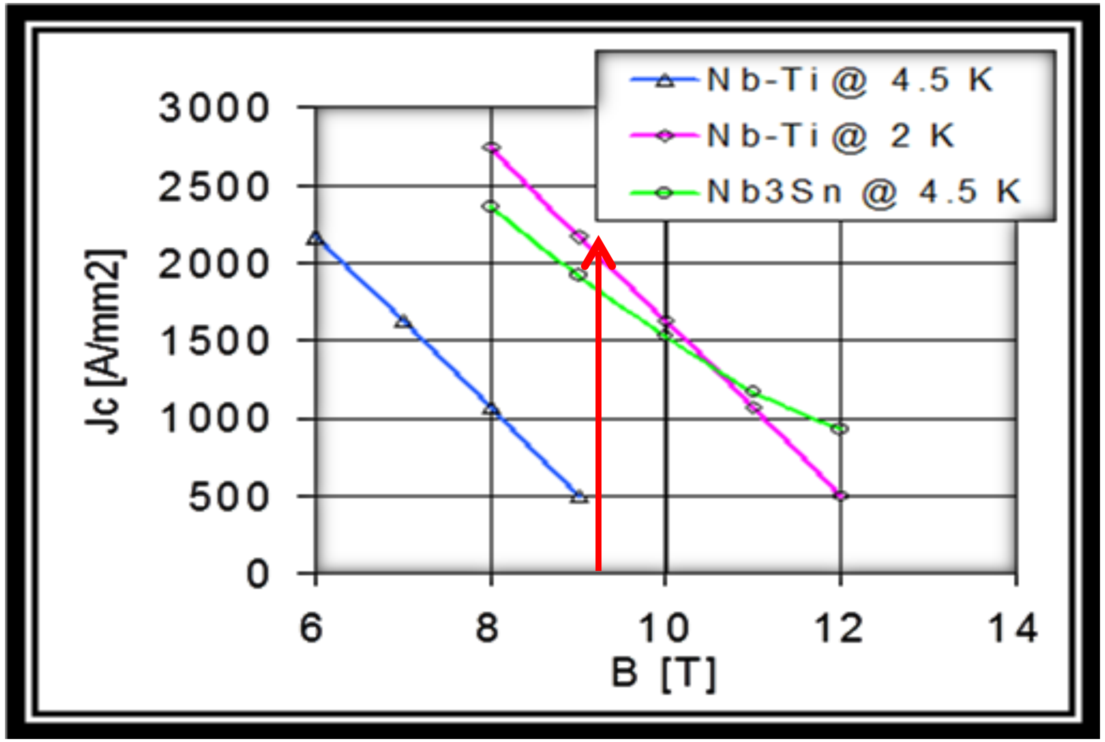
Advantages

1. **Superfluid helium can easily flow through SC strand/cable**
2. **Small temperature rise with a heat input (specific heat)**
3. **Large conductivity maintains equal temperature. SC magnet is stable**

For high field magnets like LHC at CERN

Example :





NbTi at 2 K or Nb_3Sn at 4.2 K?

It was important decision for CERN to have magnetic field of 8.3 T

Surface resistance with temperature *(T)* & RF frequency *(f)*

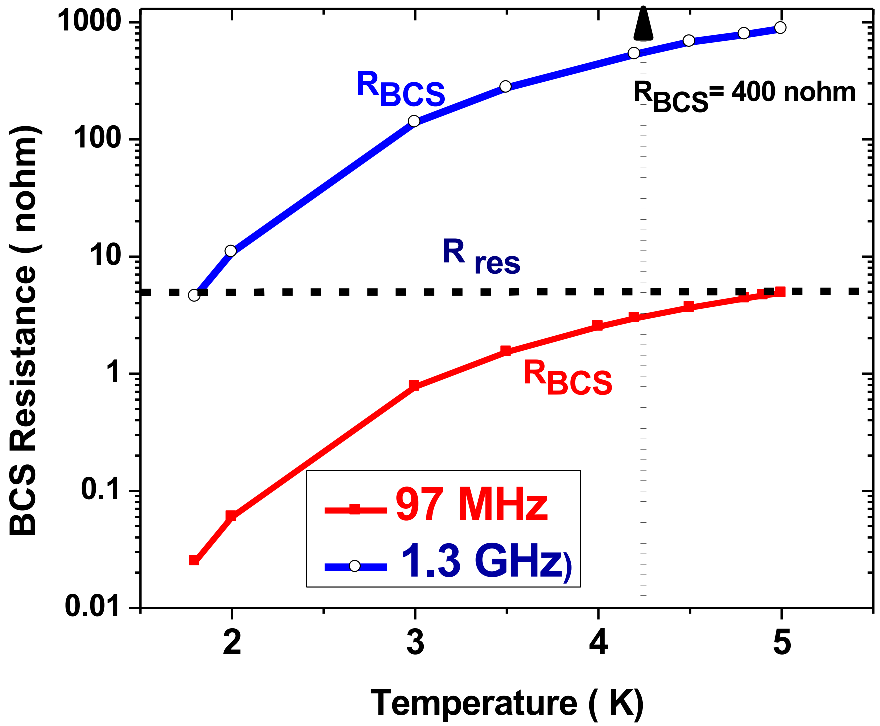
Niobium

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

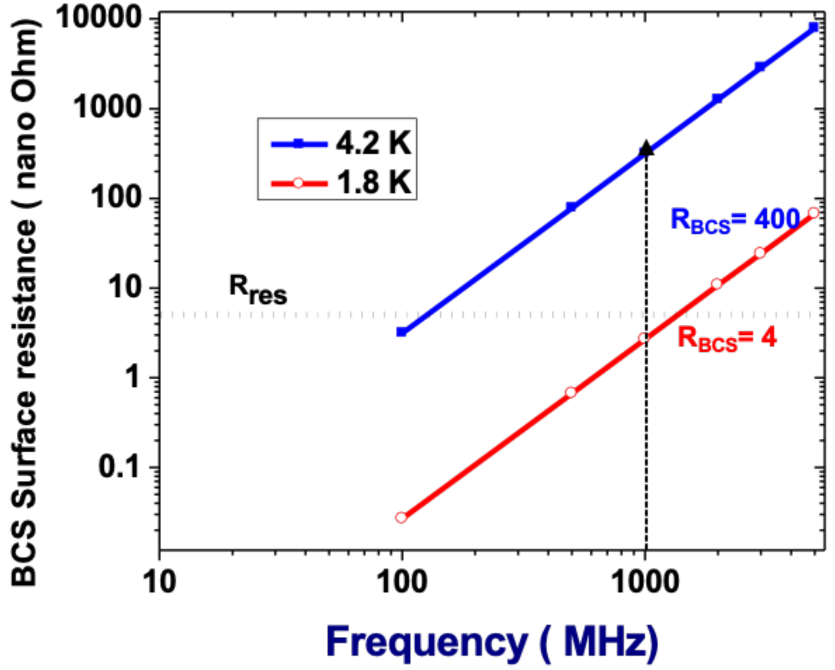
Why 2 K?

For high frequency cavity : 2 K is choice

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



Nb : T_c = 9.2 K



Major Accelerator Programs (Present & Future) with cryogenics and superconductivity

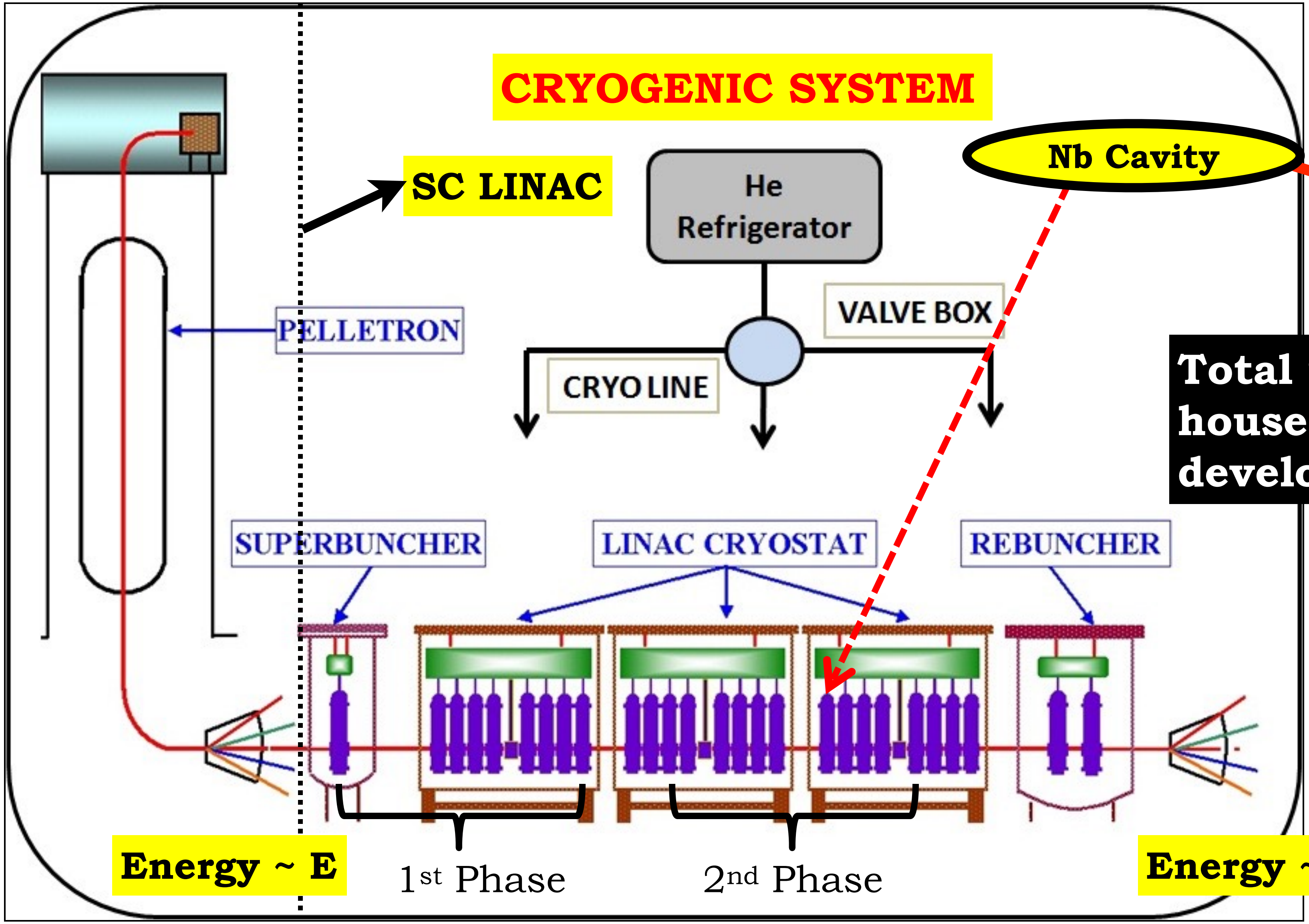
1. **China**
   i. ADS/CSNS (Cavity), ii. SHINE (Cavity), iii. CEPC (Cavity & Magnet), iv. HEPS (Cavity)
2. **Japan**
   i. SuperKEKB (Magnet & Cavity), ii. Proton Accelerator at JPARC (Magnet), iii. ILC (Cavity)
3. **Korea**
   i. RAON (Cavity & Magnet), ii. KOMAC (Cavity), iii. PLS (Cavity)
4. **India**
   i. ADS/SNS (Cavity) : RRCAT, BARC, VECC
   ii. Superconducting Linac : IUAC & TIFR
   iii. Superconducting Cyclotron : VECC, Kolkata

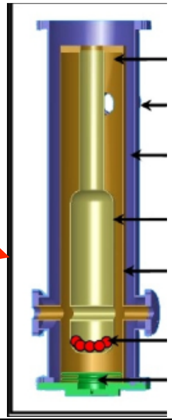
ASIA

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

Superconducting LINAC at IUAC, Delhi

where Prof. Datta worked more than 20 years

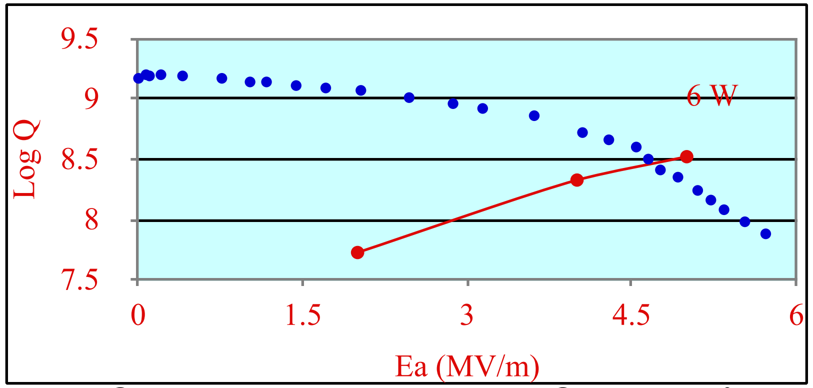




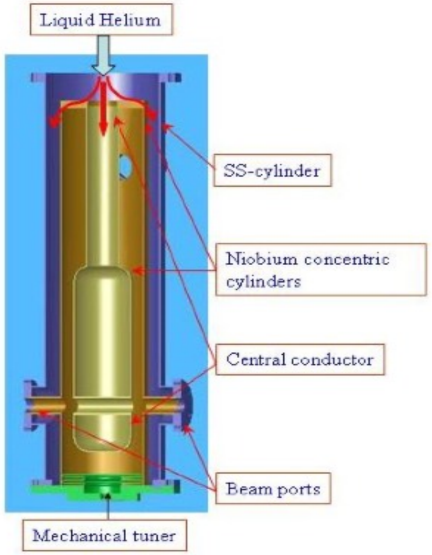
Total 27 cavities are housed in 5 indigenously developed cryomodules

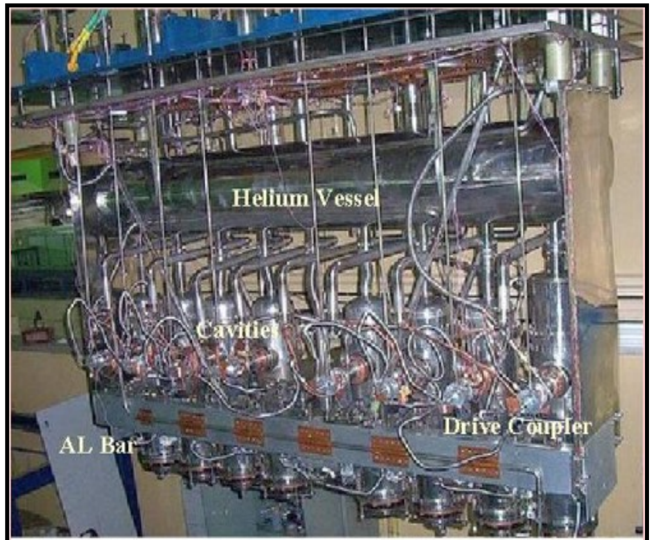
IUAC Superconducting Cavity

First lot of QWR developed at USA in collaboration with ANL. Remaining 20 cavities developed at IUAC



Performance Curve of a Cavity





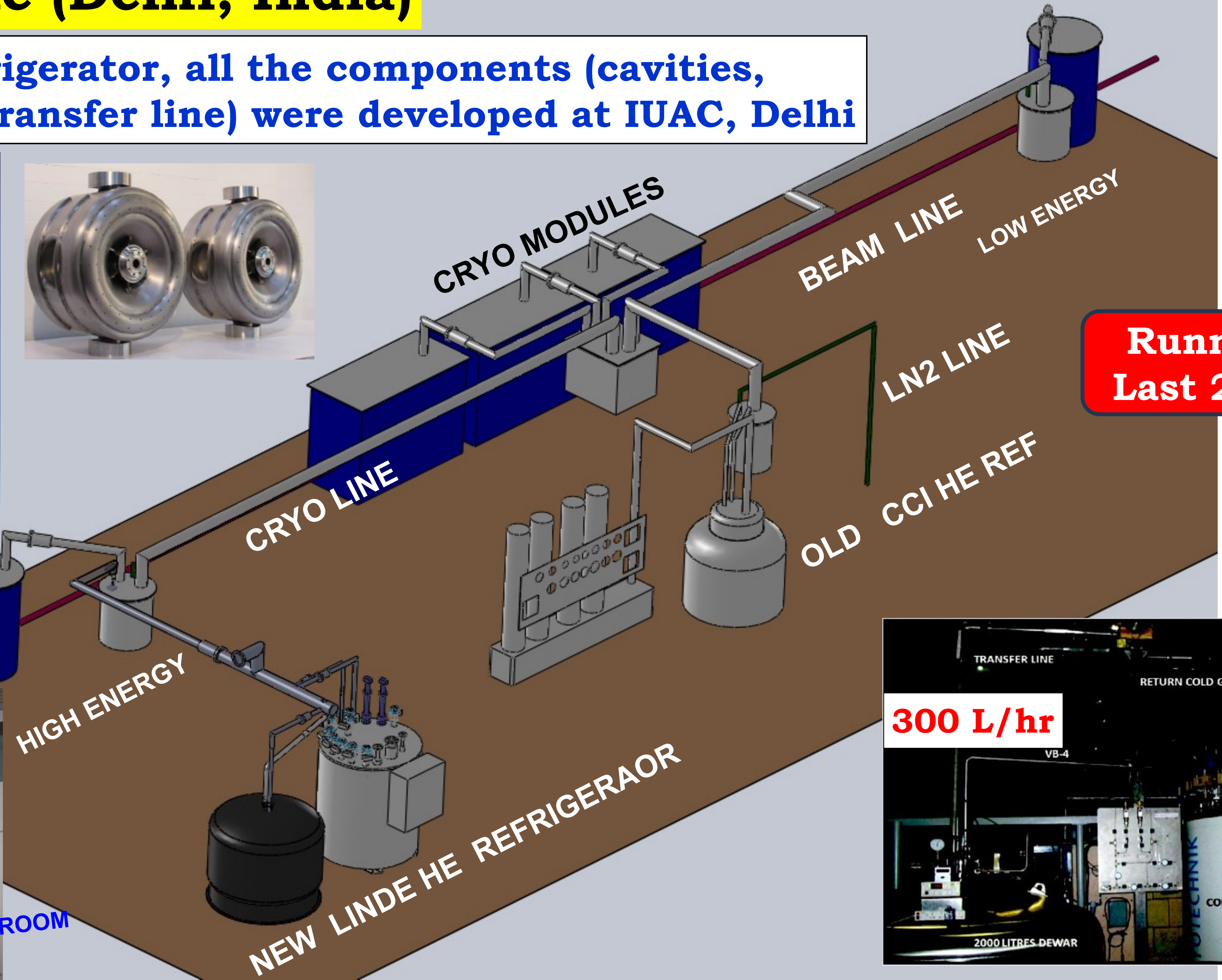
Cavities with Accessories inside Cryomodule

Two spoke cavities developed at IUAC for PIP project

IUAC SC Linac (Delhi, India)

Except helium refrigerator, all the components (cavities, cryomodule, LHe transfer line) were developed at IUAC, Delhi

SC CAVITY



Running for Last 20 years

Conclusion & Challenges

1. Superconductivity and cryogenics are essential for high power accelerator

2. Challenges
   Superconducting magnet : High field (15–20 T)
   Superconducting Cavity : Gradient 30 MV/m

3. 2 K/4 K cryomodule with low heat leak

4. Cryogenic system
   Improvement of COP (plug power vs. refrigeration load)

5. Feasibility of beam line HTS magnet (LN_2 cooled/Cryocooler)

6. Cost and restricted supply of helium gas

7. Limited man power with this specialized field (Important)

Are you ready to lead ?

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

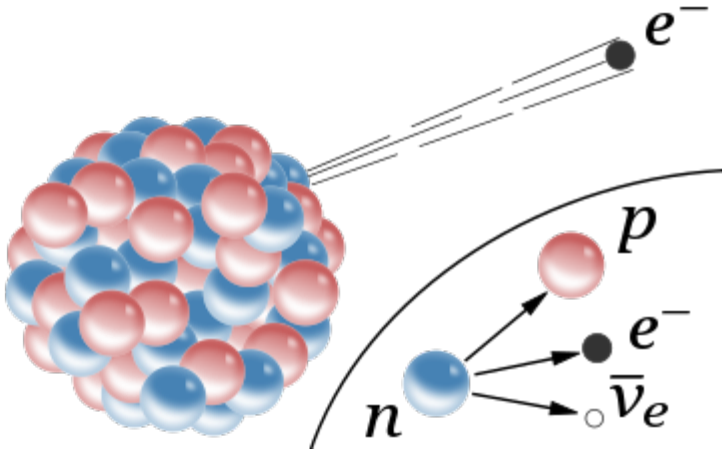
Who win? The little boy or Sumo wrestler?

Your answer?

Thanks for your kind patience
See you on Saturday morning

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

Neutrino from Nuclear Reactor and Particle Detector



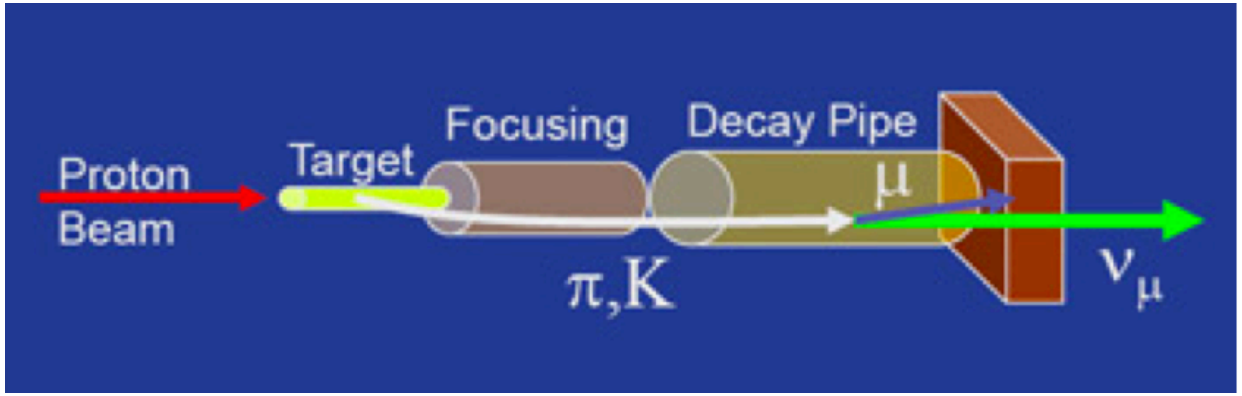
$$n \rightarrow p + e + \bar{\nu}_e$$

(udd) (udu)

Placing the detectors far underground shields them from cosmic rays and other interference at Earth's surface.

Neutrino from particle accelerator

High energy (100 GeV) proton beam exits the final accelerator of circumference 3.3 km, more than 1 MW of protons will slam into the graphite target of the long-baseline neutrino facility to produce neutrinos



The protons' interactions with the protons and neutrons in the target material produce new, short-lived particles such as pions and kaons. These particles travel a short distance (about 200 m) through a "decay pipe," decays into neutrinos that continue on in the same direction, forming a neutrino beam. Of the three known neutrino types, a beam produced in this manner contains mostly muon neutrinos.

PIP-II's new linear accelerator will be built with the latest superconducting radio-frequency technology developed at Fermilab,

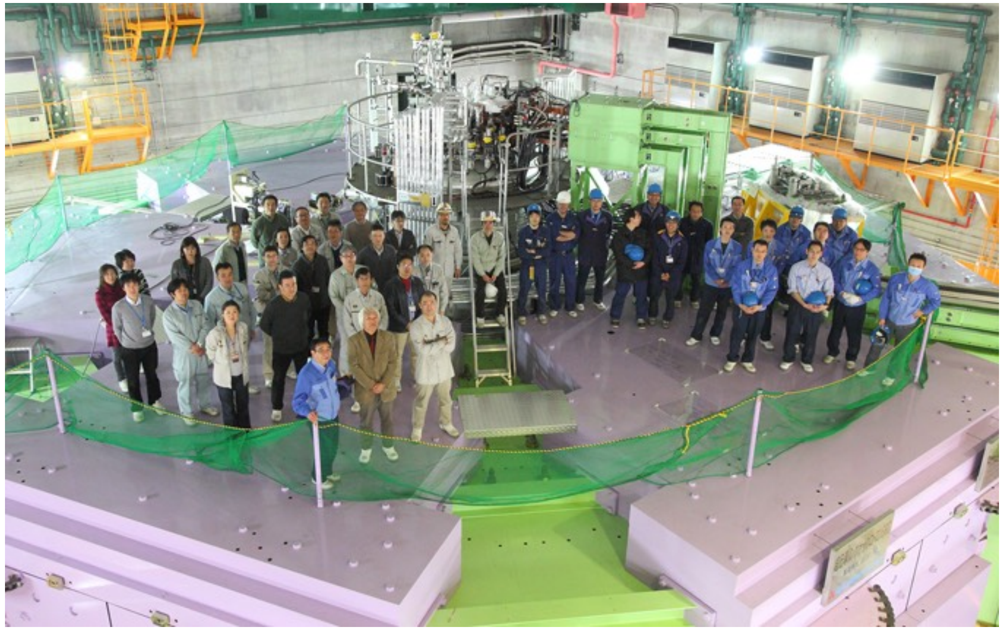
Superconducting Cyclotron

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)

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

World first superconducting cyclotron (K -500) at NSCL, MSU. USA in 1981

WORLD'S LARGEST SC CYCLOTRON IN RIKEN, JAPAN (2006–2007)



18 m dia, 9 m height, K = 2500, Weight 8000 Tons

Beam energy : 440 MeV/nucleon for Carbon

SC magnet	**: Main Coil : 6 Nos**
SC material	**: NbTi**
Type	**: Ratherford**
Max sector field : 3.8 T at 5 kA	
Operating temperature : 4.5 K	
Jacket material	**: Aluminum alloy**
Stored energy	**: 235 MJ**

By this time, you are familiar on Chinese, Japanese, Korean major particle accelerator activity with superconductivity & cryogenics

We had a nice Summary Talk on major Asian Programs : Yesterday Morning

CHINA :

1. ***SHINE***
2. ***CEPC***
3. ***CiADS/HIAF***
4. ***BEPC/ADS/HIAM***

JAPAN, KOREA & India

1. ***SuperKEKB (Japan)***
2. ***RAON (Korea)***
3. ***ILC (Japan)***
4. ***JPARC (Japan)***
5. ***SNS & Cyclotron (India)***