IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), January 2017.
Plenary presentation AT-3 given at 1st Asian ICMC – CSSJ 50th Anniversary Conference; Kanazawa, Japan, November 7 - 10, 2016.

1st Asian ICMC-
CSSJ 50

# Application of Superconductivity & Related Cryogenics in India : Present & Future Prospect

**T S Datta**

Inter University Accelerator Centre. New Delhi. India

**(Annotated Slide)**

IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), January 2017.
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# Japan & India ( Superconductivity & Cryogenics)

**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**

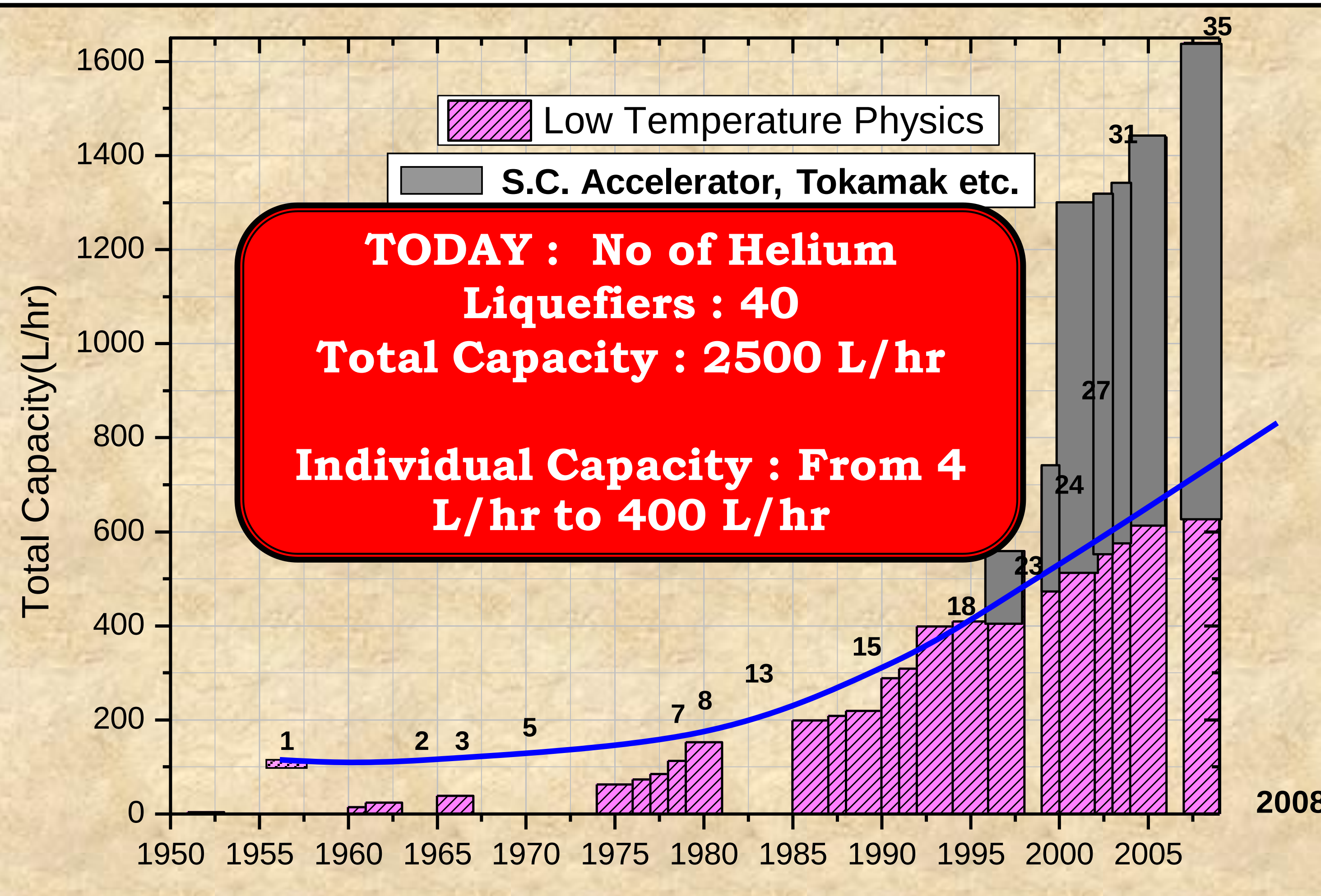
**In the Same Year ( 1952) , similar Helium Liquefier was Commissioned at National Physical Laboratory ( NPL), New Delhi, India**


**1952 was the starting period of Superconductivity Research in Japan & India**

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

(Annotated Slide)

# Journey from 4L/hr to 400 L/hr in INDIA




**90 % of The Liquefiers are from M/s Linde or M/s Air Liquide**

# Indigenous Helium Liquefier development In India

**At RRCAT, Indore**


**Claude Cycle with two Reciprocating Engine**
**Capacity : 35 Litres/hr**
**Running Since 2010 ( Started with 6 L/hr)**

**At BARC, Mumbai**

**Turbine Based / Plate fin HX**
**Capacity : 20 litres/hr**
**Commissioned in 2015**

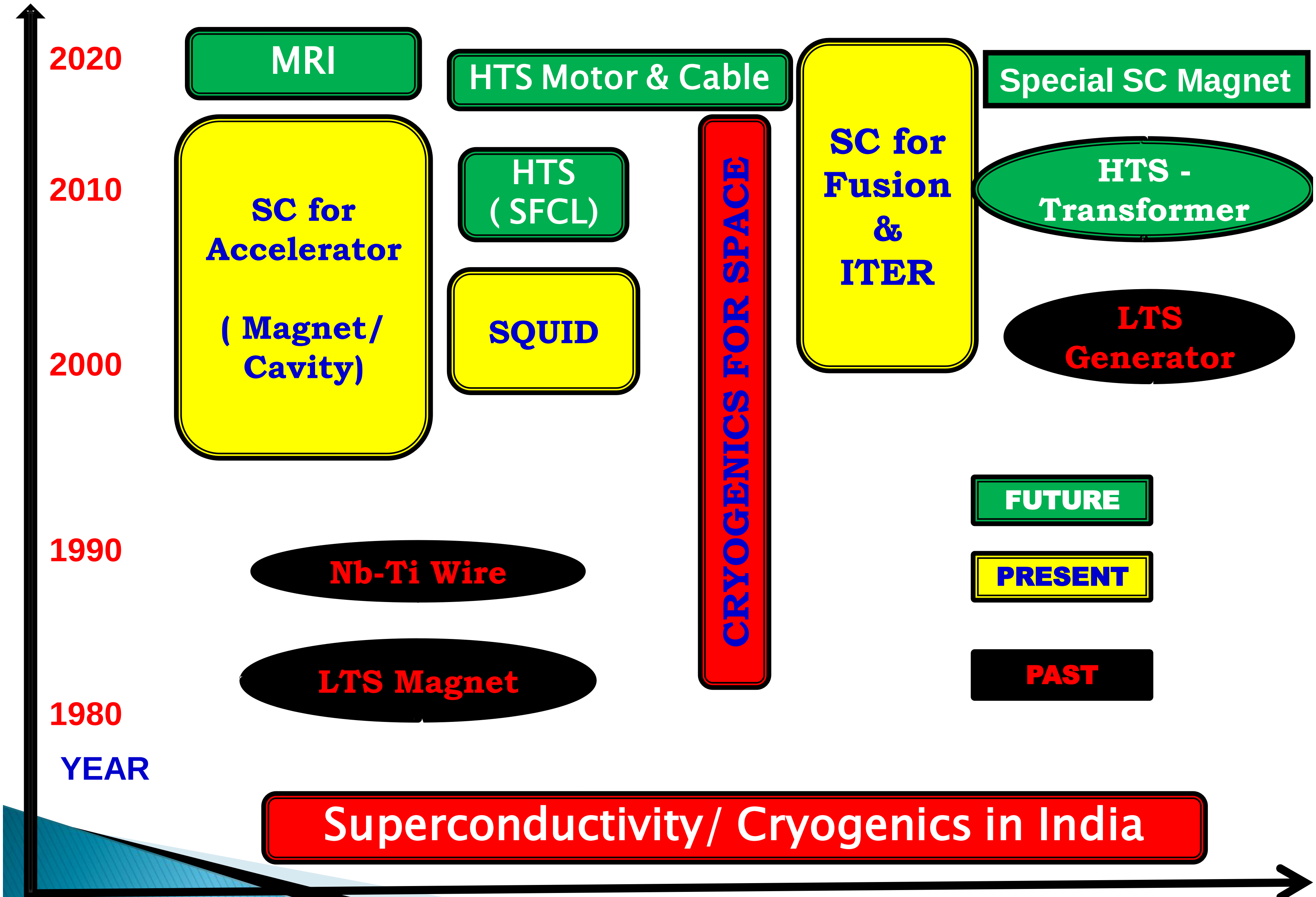
**(Annotated Slide)**

**In 60 years, there is a significant growth on Basic Research on Superconductivity ( LTSC & HTS) in Japan, India and other Asian Countries.**

**But on Applied Research & Development on Superconductivity, Japan is well ahead ( Industry support)**

**We all are waiting for Superconducting Maglev train Between Tokyo & Nagoya ( 2027)**

**Longest Network of Superconductivity & Cryogenics**


2020
2010
2000
1990
1980
YEAR
MRI
HTS Motor & Cable
SC for Fusion & ITER
Special SC Magnet
SC for Accelerator
( Magnet/ Cavity)
HTS ( SFCL)
SQUID
CRYOGENICS FOR SPACE
HTS - Transformer
LTS Generator
Nb-Ti Wire
LTS Magnet
FUTURE
PRESENT
PAST
Superconductivity/ Cryogenics in India

# BASIC RRESEARCH on Superconducting Material

1. Tata Institute Of Fundamental Research ( TIFR), Mumbai
2. UGC- DAE CSR, Indore
3. RRCAT, Indore
4. BARC, Mumbai

1. National Physical Laboratory, New Delhi
2. IIT. Kanpur

1. Indian Association for Cultivation of Research
2. S N Bose Centre. Kolkata


**50 Institutes**

- 1000 Man power
- More Than 100 PPMS, SQUID Are Procured in last 10 years

1. Indian Institute of Science ( IISc.), Bangalore
2. JNCAR, Bangalore ( Prof C N R Rao)
3. IGCAR, Kalpakkam, Chennai

(Annotated Slide)

# MAJOR PROJECTS IN THE FIELD OF SUPERCONDUCTIVITY / CRYOGENICS IN INDIA

# OUR FOUNDATION ON APPLIED SUPERCONDUCTIVITY

**Many Laboratory Scale High Field Magnet ( up to 11 Tesla) Were developed at NPL, Delhi during 1977- 1985**

**BARC , Mumbai established a facility for Multi-filamentary NbTi wire with copper and Cable during 1990 ( 1.3 mm X 500 filaments of 40 μ x 3 Km, Ic = 1300 A ( 4.97 x 2.79 mm)**

**220 KVA SC Generator with LTS Rotor at 4.2 K Developed by BHEL, Hyderabad in 1990.**

**Not Succeeded on 5 MVA Generator**

**(Annotated Slide)**

# World wide , Major Promoter on LTS Superconductivity at 4.2 K is High Energy Physics through Accelerator

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

Compact Size

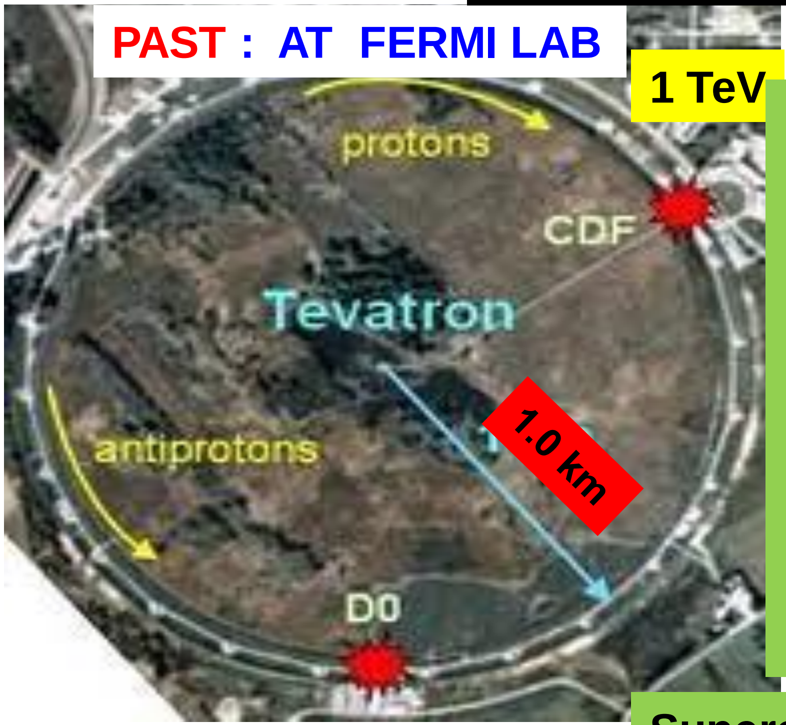
Low Power Consumption

**In India , We have Major Programmes**

# SUPERCONDUCTIVITY FOR ACCELERATOR

**PAST : AT FERMI LAB**

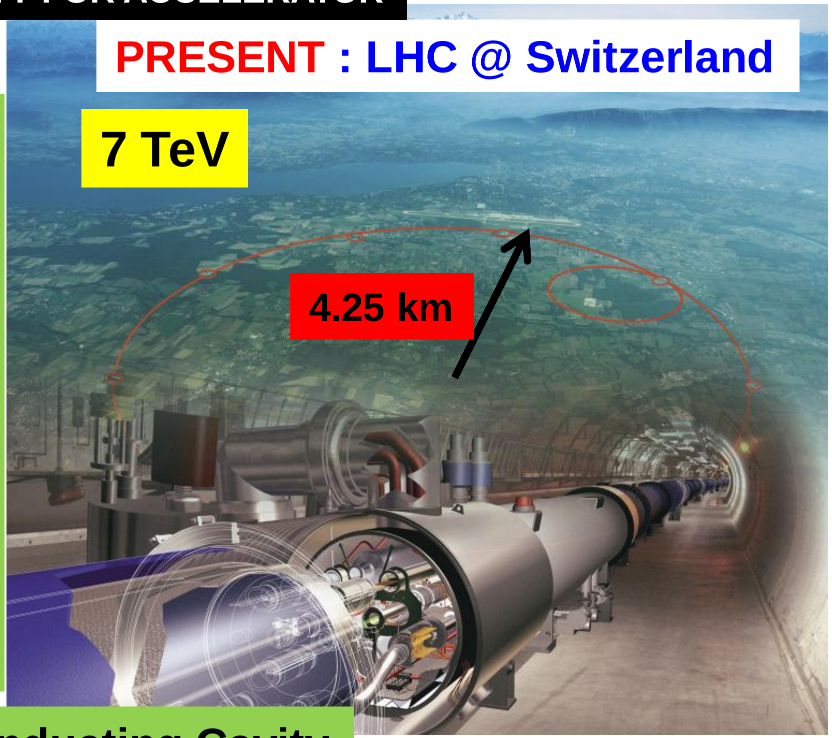
**1 TeV**



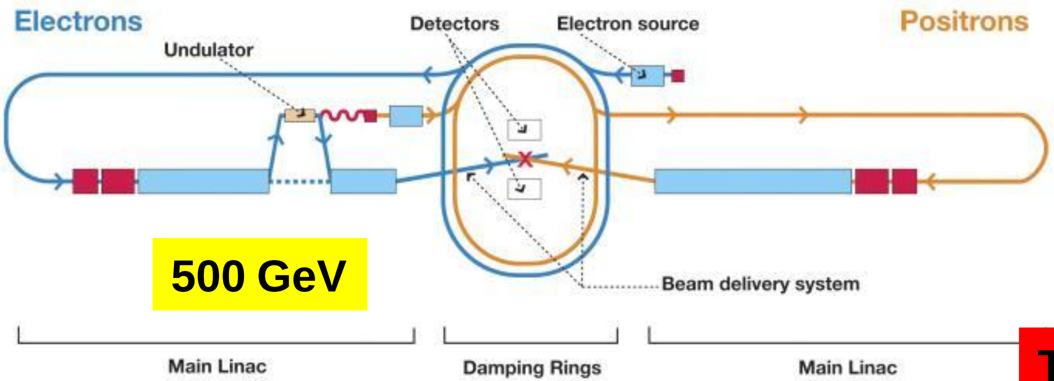

**Superconducting Magnet**

**PRESENT : LHC @ Switzerland**

**7 TeV**




**Superconducting Cavity**




**500 GeV**

**Future: ILC ( Asia/Japan)**

**Total Length : 31 km.**

(Annotated Slide)

# Cryogenics - Superconductivity - Accelerator ( Brief History)

- 1908 – Kamerlingh Onnes Liquefied Helium (4.2 K)
- 1911 – ,, Discovered Superconductivity ( Hg)

**Superconductivity is Born !!**

Heike Kamerlingh Onnes (1853-1926

- 1980 – Tevatron , First Accelerator Using SC Magnet ( 70 Yrs) !!!!
- 1986 – High Temp Superconductors ( > 77 K )
- 2005– 2013 : ECR and Spectrometer HTS Magnet with Cryocooler
- 2011 – Commissioning of LHC ( Largest Cryogenics)
- 2020 – International Linear Collider (ILC)

(Annotated Slide)

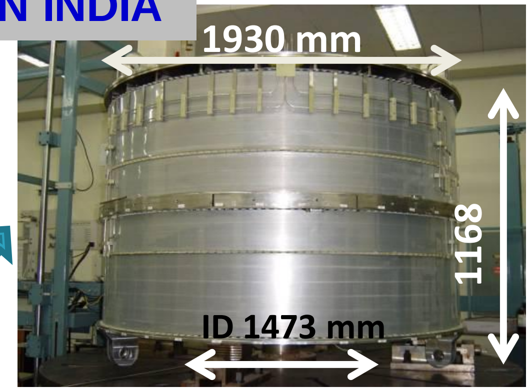
ASIA/ India

# MAJOR ACCELERATOR PROGRAMME (with cryogenics and superconductivity)

1. **Superconducting Cyclotron** : RIKEN ( JAPAN) , VECC ( INDIA), JINR ( Russia) : Nuclotron : SC Magnet
2. **Synchrotron Radiation** : SSRF ( China), NSRRC ( Taiwan), PAL (Korea) : SC Cavity
3. **Superconducting Heavy ion Booster** : JAERI ( Japan), IUAC, TIFR ( INDIA), ANU ( Australia) , : SC Cavity
4. **Proton Accelerator / ADS Programme** : J- PARC (Japan) IHEP, IMP ( China), KOMAC ( Korea), RRCAT/ BARC/VECC ( India) : Cavity
5. **Collider** : ( TRISTON, KEK-B, Super KEK B) Japan , BEPC II ( China),
6. **Other Important Programmes** : ILC- STF ( Japan), ERL ( Japan), BOOSTER for RIB at VECC ( India), FEL @ PKU ( China) : Cavity

# SUPERCONDUCTING MAGNET FOR ACCELERATOR IN INDIA

Largest & Most Complicated SC Magnet at IPR




2005

2006

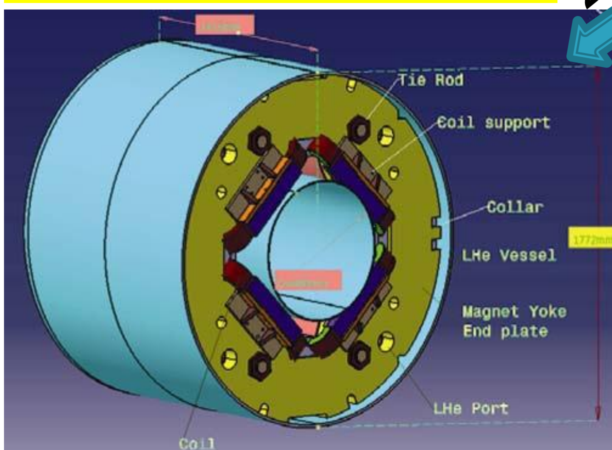
Approx. 2000 Corrector Magnets Developed at RRCAT and Supplied to CERN : Indian Industry

SC MAGNET

2014

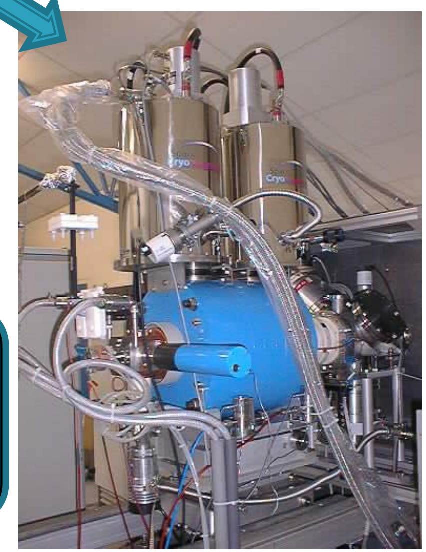
2005

Largest SC Solenoid Magnet was Developed at VECC and is operating for more than 5 Years





FIRST CRYO_FREE MAGNET(6T) DEVELOPED AT IUAC, INDIA



Large Number Super Ferric Dipole and Quadrupole Magnets For FAIR Project : Under Development at VECC. Kolkata

FIRST HTSC MAGNET at IUAC FOR ECR SOURCE JOINTLY DEVELOPED WITH PAN-TECHNIQUE,France (2006)

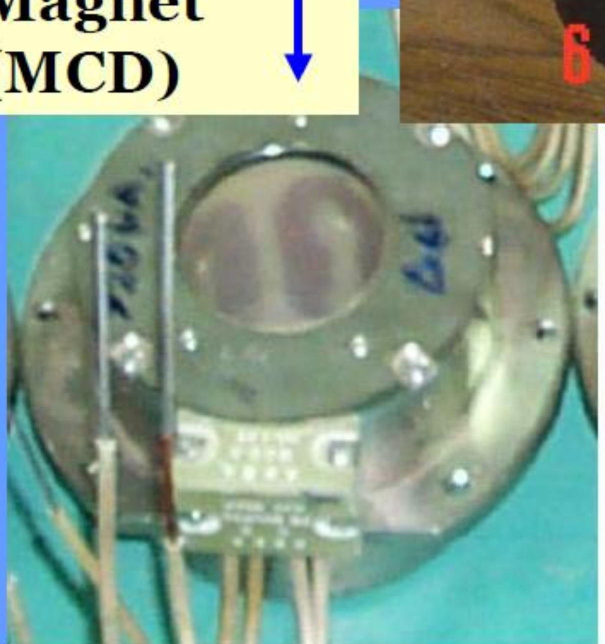
(Annotated Slide)

# APPLICATION OF SUPERCONDUCTIVITY FOR ACCELERATOR IN INDIA STARTED AT RRCAT (INDIA) FOR LHC in 1995

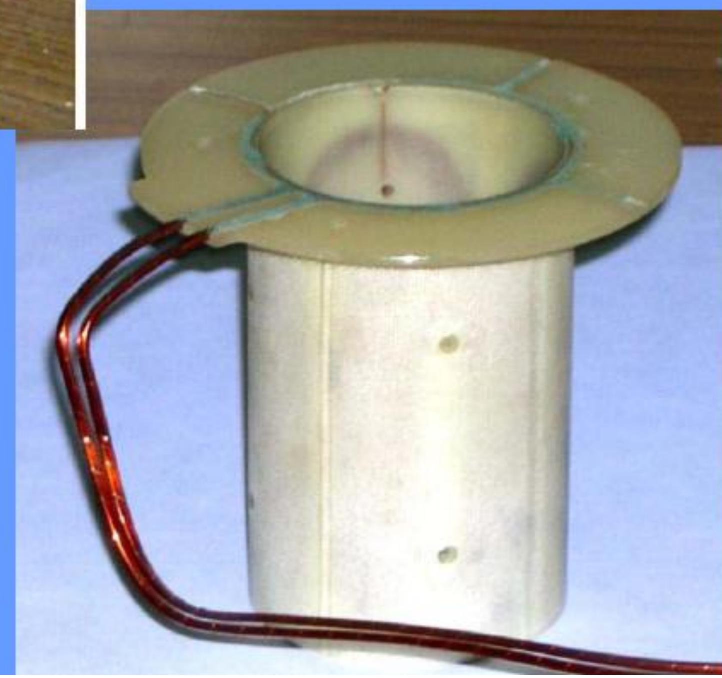

(Annotated Slide)

**Sextupole Corrector Magnet (MCS)**

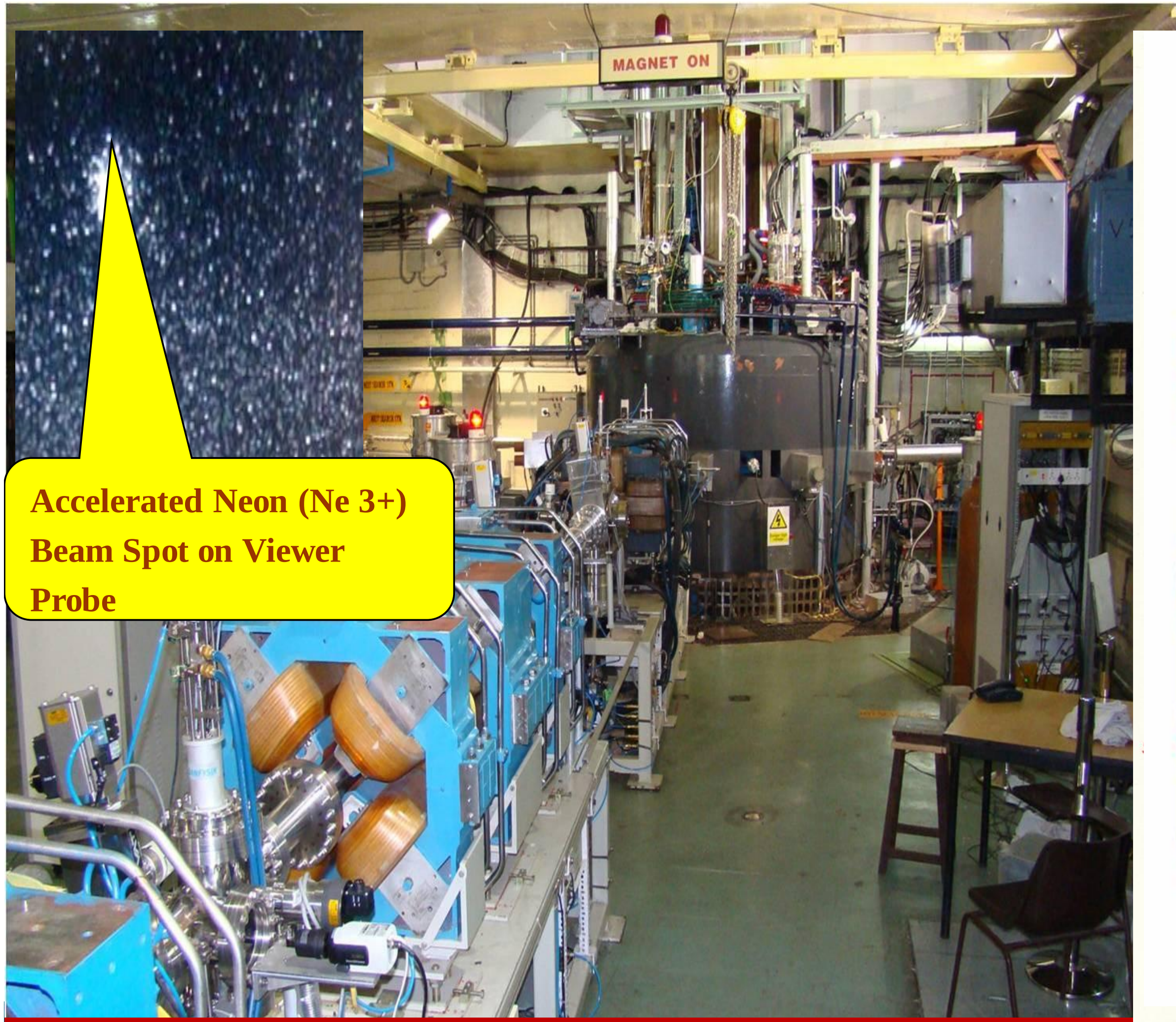

**Decapole Corrector Magnet (MCD)**



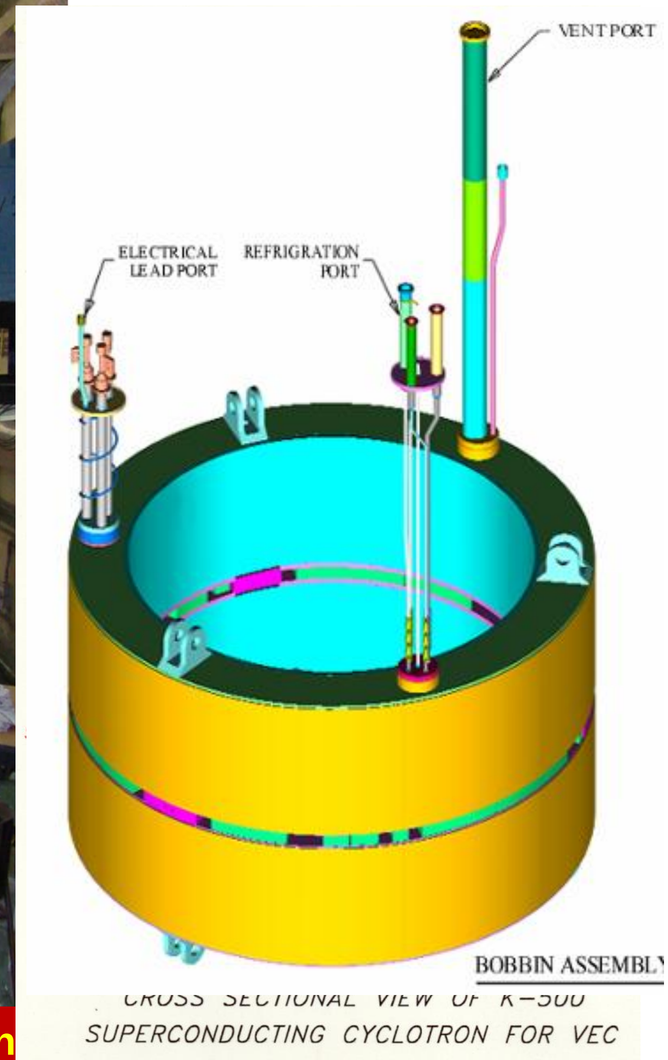
**Octupole Corrector Insert (MCO)**



# K-500 Superconducting Cyclotron at KOLKATA with its Beam Line



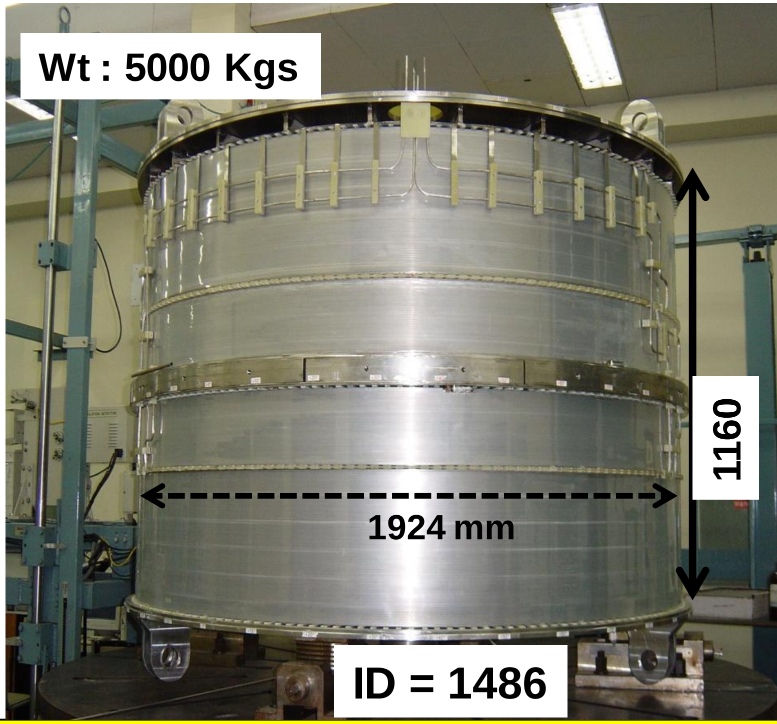

Accelerated Neon (Ne 3+) Beam Spot on Viewer Probe




**First Beam Acceleration in the Superconducting Cyclotron at VECC (August 25, 2009)**

**(Annotated Slide)**

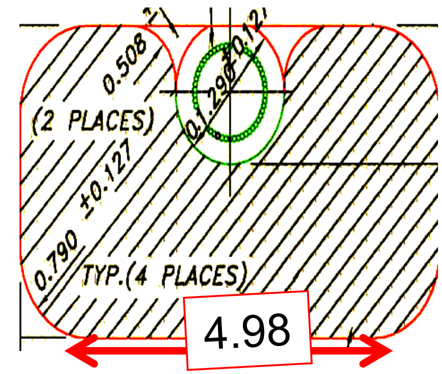
# Superconducting Magnet Coil for K-500 S.C.Cyclotron



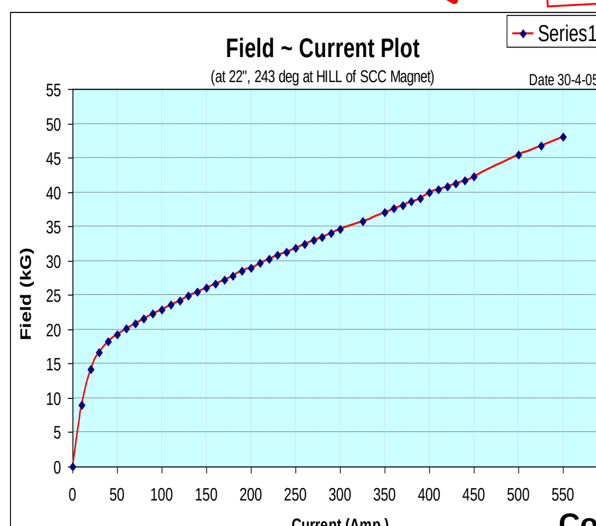

**Conductor : Nb-Ti Wire soldered in Copper Channel**

**Critical Current : 1030 A at 4.2 K and 5.5 Tesla**

**SC: Cu :: 1:20**


- **No. of Coils : 2 Alpha + 2 Beta**
- **No. of Layers : 36**
- **No. of turns/layer : 30 / 62**
- **<u>Total Length of SC Cables : 35 Km.</u>**
- **<u>Stored Energy : 22 MJ</u>**




(Annotated Slide)

Courtesy : S Saha

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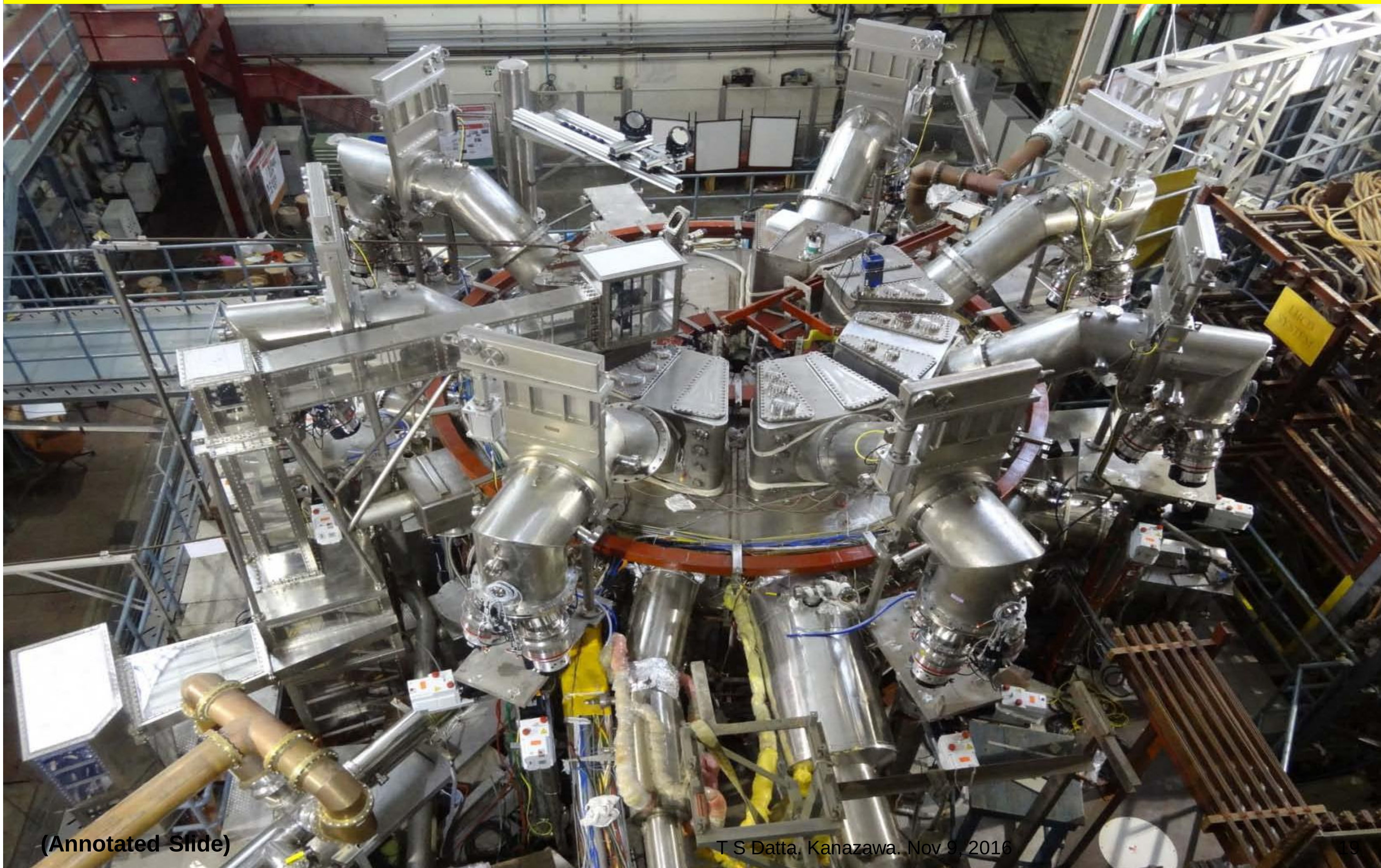
# Steady State Superconducting Tokamak (SST-1) developed at Institute for Plasma Research, Gandhinagar



(Annotated Slide)

# SST-1 MAGNET SYSTEM

## Requirements:

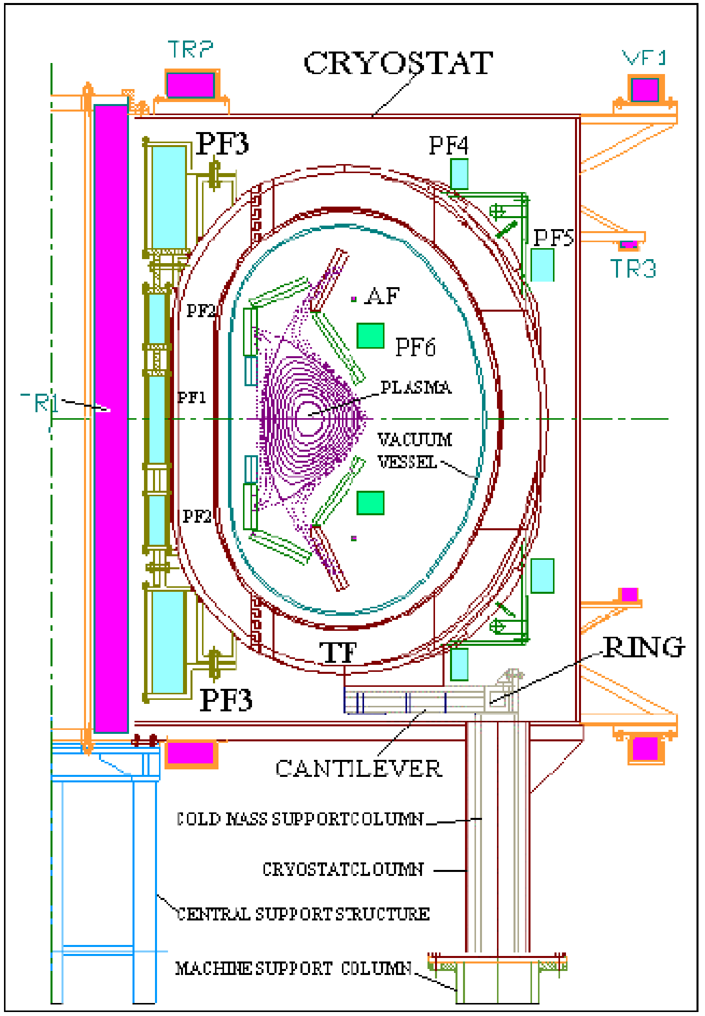
- Confinement, Shaping and Equilibrium Fields
- Ohmic Flux Storage
- Feed-Back Control

## Supercondcting Magnets:

- Toroidal Field (TF) Coils : 16 Nos.
- Poloidal Field (PF) Coils : 9 Nos.

## Copper Magnets (Water Cooled) :

- Ohmic Transformer (TR) Coils : 7 Nos.
- Poloidal Field (PF ) Coils ( in-Vessel): 2 Nos.
- Position Control Coils ( in-Vessel) : 2 Nos.




Courtesy : Prof. Y. C Saxena

(Annotated Slide)

# Conductor for SST-1 Superconducting Magnets

## Conductor Characteristics

Conductor type : CICC
Dimensions : 14.8×14.8 mm$^2$
No. of Strands : 135
Cabling Pattern : 3×3×3×5

Last stage wrapped (half overlap) with 25 μm thick SS304 tape.

**Twist Pitches:**

I stage : 40 mm;
II stage : 75 mm
III stage: 130 mm;
IV stage: 290 mm

Conduit Material : SS 304L
Conduit thickness : 1.5 mm
Void Fraction : ≥ 36 %
$I_c$ @ 5T, 4.2K : 36 kA
$I_{op}$ @ 5T, 4.5K : 10 kA

## Strand Specifications

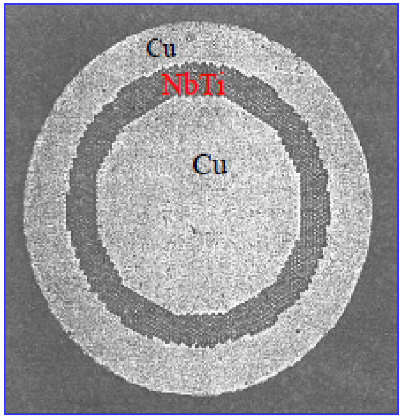
Material : NbTi in Cu
Strand Dia : 0.86 mm
Filament Dia. : 10 μm
Filaments per strand : 1272
Cu : NbTi : : 5 : 1
Cu RRR : 100
Hysterisis Losses : <100 mJ cm$^{-3}$

## Strand Characteristics:

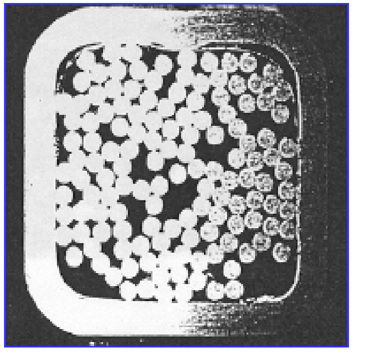
- $I_c$@4.5K; 5T : 232A
- Index ‘n’ : 45

  (0.1 μV / cm criteria)
- Hysterisis loss : 33.5 mJ cm$^{-3}$

  (±3T; 4.2K)




Strand Cross-section



CICC Cross-section

(Annotated Slide)

Courtesy : Prof. Y. C Saxena

# SUPERCONDCTING MAGNETS: TF Coils

## TF COIL Winding Pack:

D-Shaped; 6 Double Pancakes

X-section: 194x144 $mm^2$

Dimensions: 2.59 m × 1.53 m

Consolidated by VPI & encased in SS316L case

Conductor: NbTi based CICC

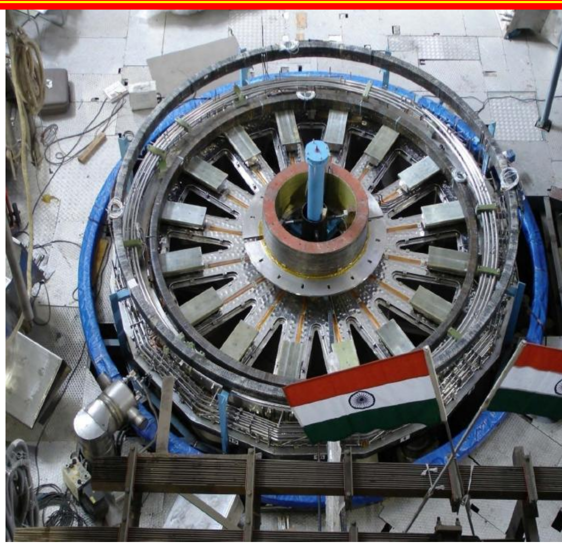
## PARAMETERS OF TF COILS:

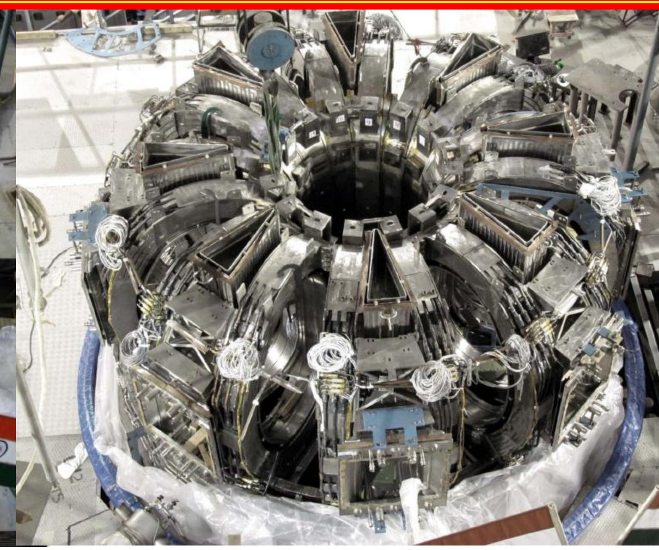
- Total No. of Coils : 16
- Turns per Coil : 108
- Current per turn (3T Field): 10 kA
- Max. Field at Conductor: 5.1 T
- Maximum Field Ripple : 0.35%
- Total Inductance : 1.12H
- Total Stored Energy: 56MJ
- Dump Time Constant: 12 s
- Peak Dump Voltage: 1.1 kV

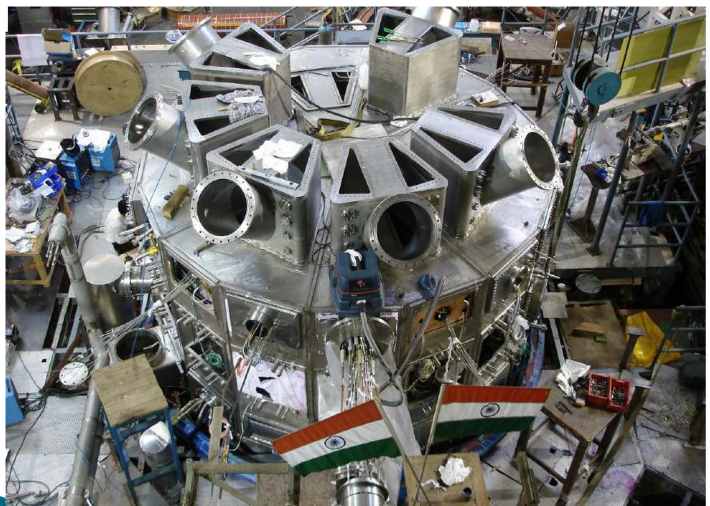
Courtesy : Prof. Y. C Saxena

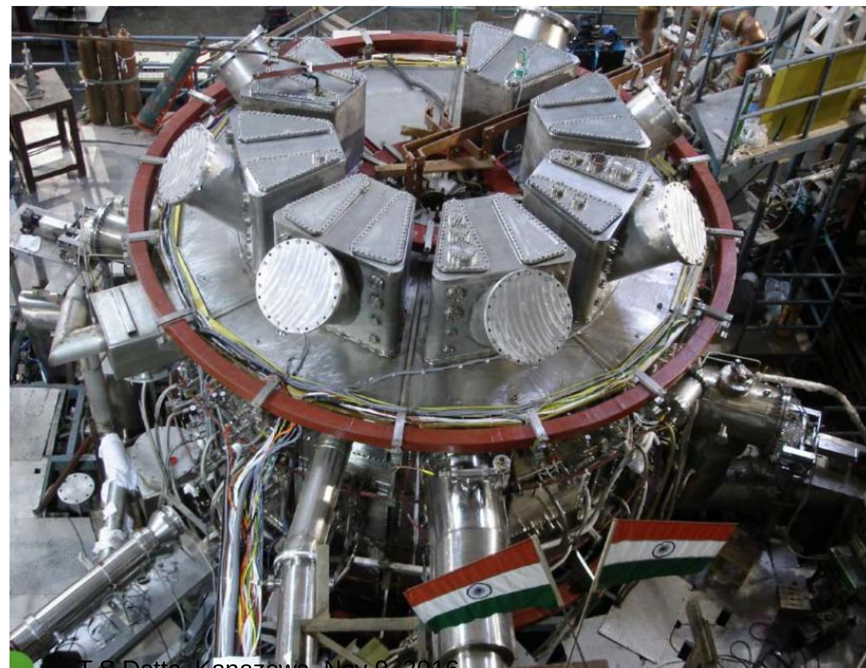
(Annotated Slide)

# DIFFERENT STAGES OF CONSTRUCTION





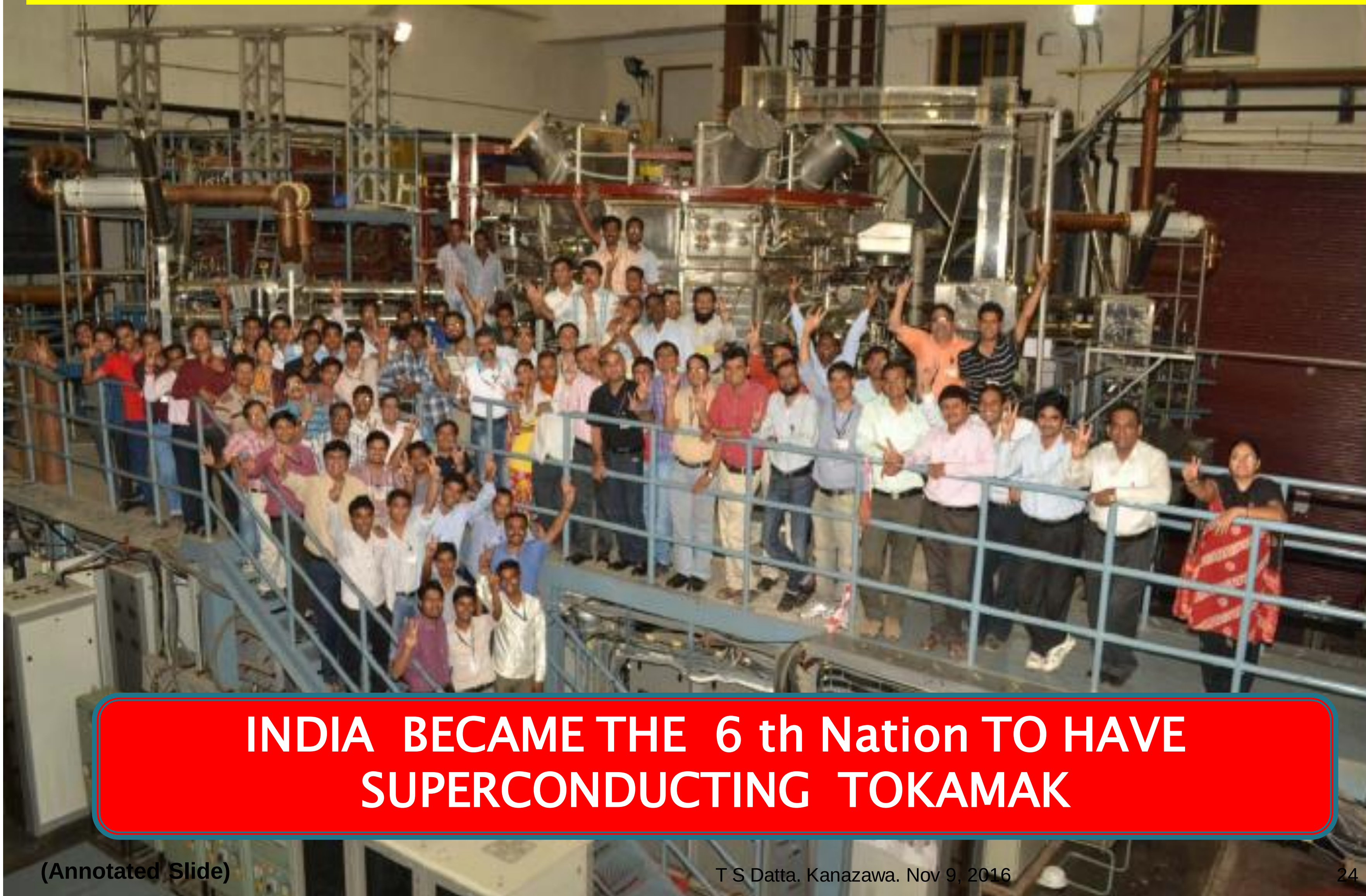




**Courtesy : Dr S Pradhan**

**(Annotated Slide)**

**SST-1 device has achieved the mission objective of obtaining a plasma current in excess of 100 KA at a central field of 1.5 T on 21st February, 2016 during the 16th experimental campaign.**



**INDIA BECAME THE 6 th Nation TO HAVE SUPERCONDUCTING TOKAMAK**

**(Annotated Slide)**

# Earlier CICC procured from Hitachi Cables. Now IPR and BARC together have developed their own Nb- Ti & Nb3Sn CICC

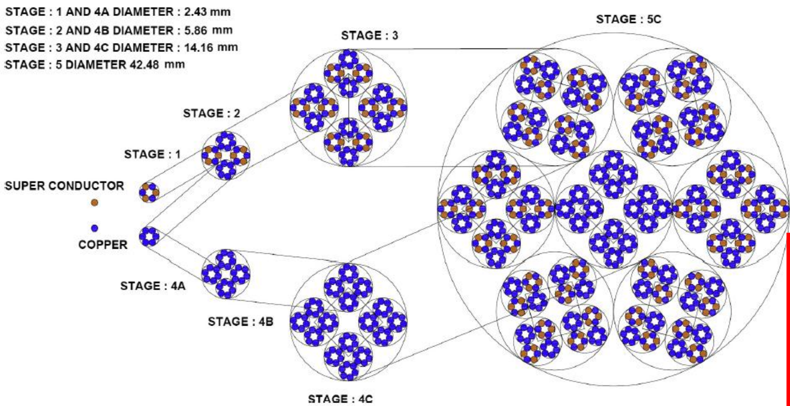


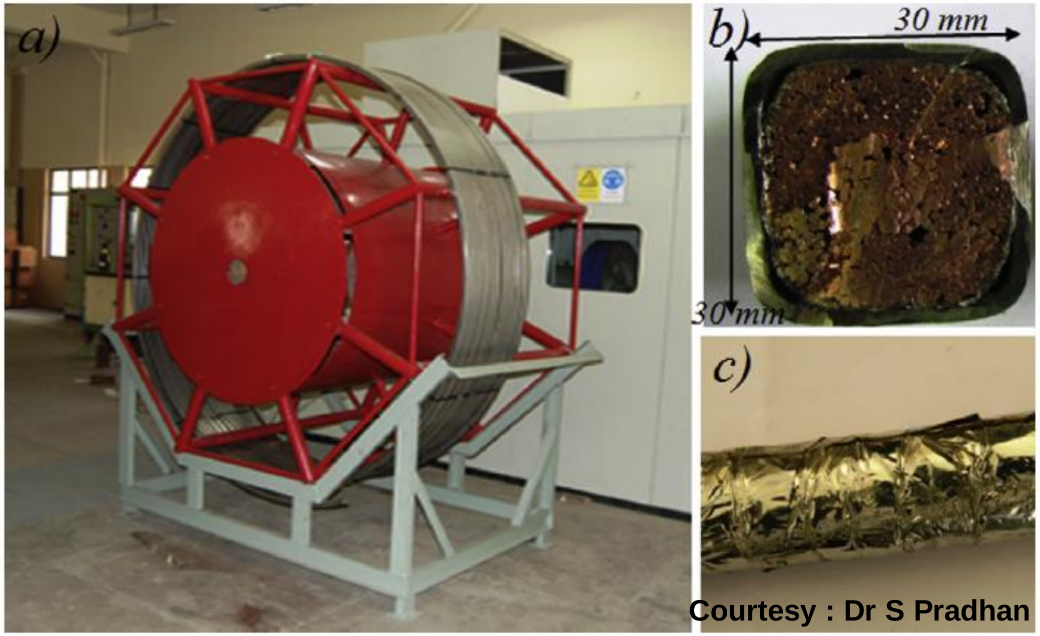

Fig. 2. Design configuration for 30 kA NbTi/Cu CICC with cabling scheme.

**Strand : NbTi from BARC, India**
**Strand : Nb3Sn from Korea**

**Manufacturing of 100 m Nb3Sn CICC capable of carrying 30 kA@12 T at 4.22 K is also completed.**

**Table 2**
Technical specification for 30 kA NbTi based CICC.

| | |
|---|---|
| *Strand* | |
| Strand type | Multifilament |
| Strand diameter | 0.81 mm |
| Number of filaments | >444 |
| Cu to NbTi ratio | 1.32:1 |
| Critical current | ~500A @ 5.5 T |
| Copper resistivity | $4.5 \times 10^{-10}\ \Omega\,m$ |
| Critical temperature | 9.2 K |
| Critical Field | 14.5 T |
| *Cable* | |
| Number of Cu strands | 528 |
| Number of NbTi strands | 144 |
| Void fraction | 46% |
| Wrapping material | SS304 |
| Theoretical outer diameter | 42.5 mm |
| Cabling configuration | $[\{(3+3)\times 2+2\times 6\}\times 4\times 6+(1\times 6)\times 4\times 4]$ |
| *Jacket* | |
| Jacket material | SS316LN |
| Outer diameter | 38.1 mm |
| Thickness | 1.5 mm |
| *CICC* | |
| Final dimensions | 30 mm × 30 mm |



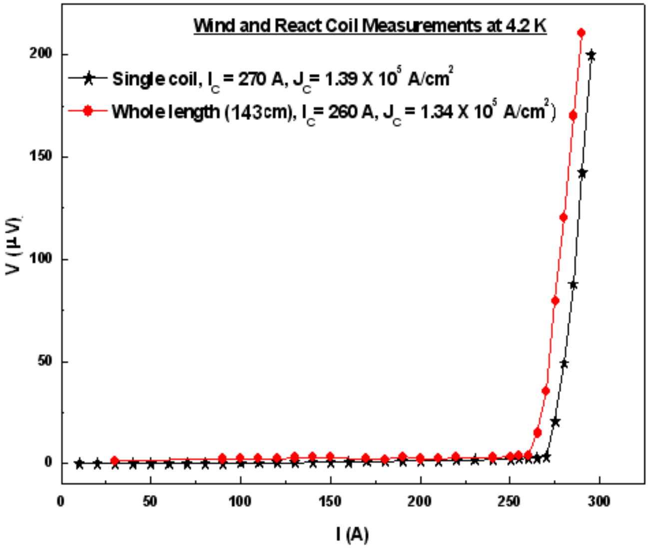

**Courtesy : Dr S Pradhan**

Fig. 10. (a) 100 m NbTi CICC spool, (b) NbTi CICC cross-section and (c) wrapped superconducting cable.

**(Annotated Slide)**

# Indigenous Development of MgB2 strand & Current Lead ( NIIST, IPR, RRCAT)

**17 Mtrs long Mono filament & 6-filament strand with 2.29 mm O.D.**




**Developed Conduction Cooled Current leads (CCCL) for National Fusion Program**

Rated **Specifications of the CCCL**

**Current at 20 K : 1000 A**
**Expected current at 5 K : : 2500 A**


**Courtesy : Dr S Pradhan**

**(Annotated Slide)**

# SUPERCONDUCTING CAVITY PROGRAMME FOR ACCELERATOR

**1990- 2000 :**

**Quarter Wave Cavity at TIFR & IUAC**

**Developed in India, $E_{acc}$ = 2.5 to 6 MV/m**
**f= 150 MHz, & 97 MHz**

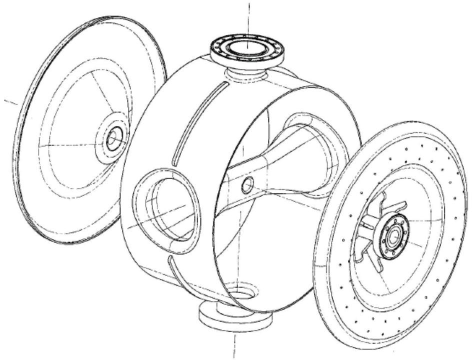
**2000- 2016 :**

**Elliptical Cavity for Proton LINAC at RRCAT, BARC, VECC (Dept of Atomic Energy)**

**( Developed In India, Surface preparation and Testing at USA : > 30 MV/m, f = 1.3 GHz )**

**Spoke Cavity and Low β cavity at IUAC For Project X at Fermi Lab and HCI at IUAC**

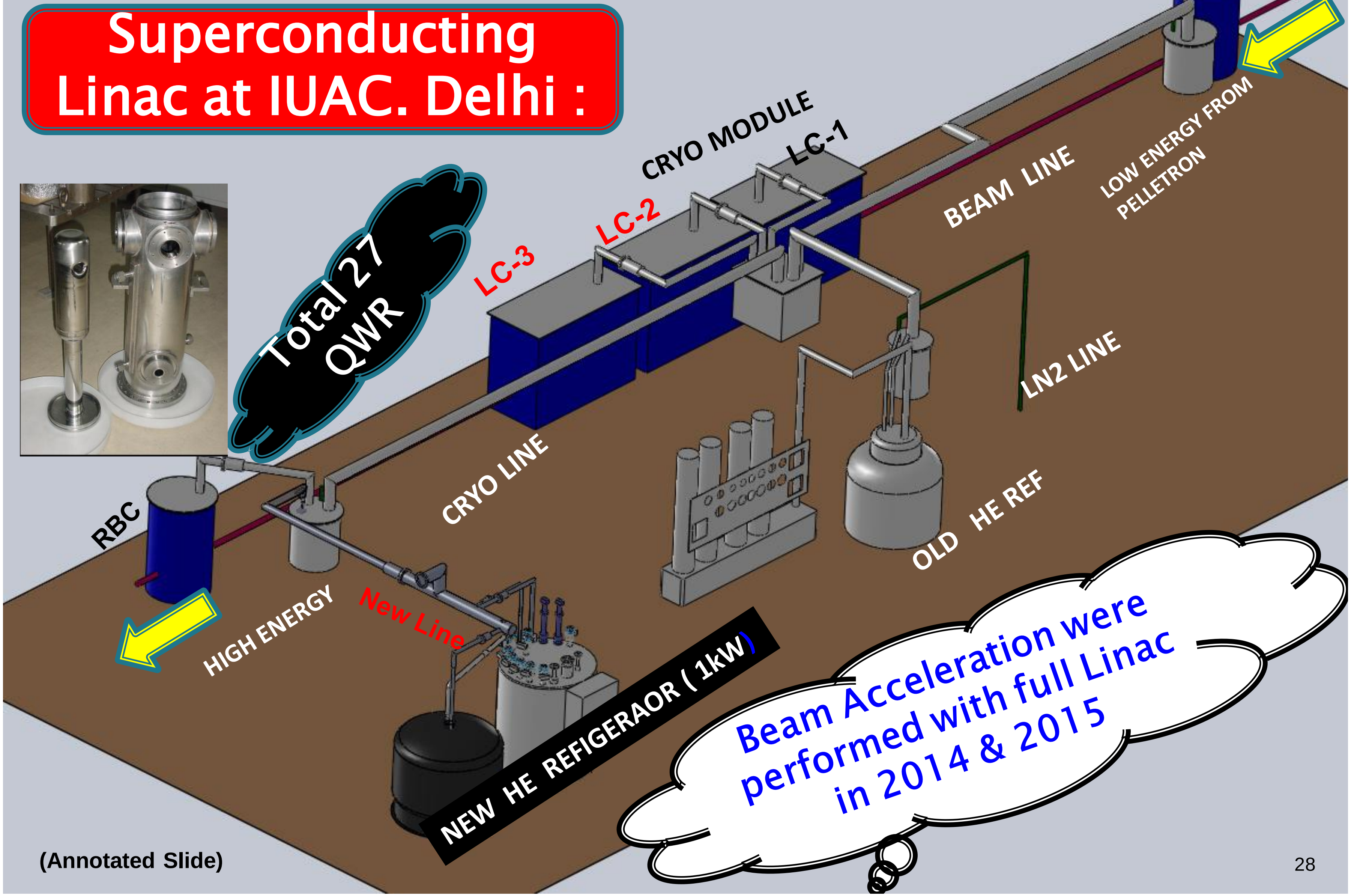
**Delivered ( 2015) to Fermi Lab and Performance Satisfactory**



**(Annotated Slide)**

**Except the Helium refrigerator, all the Components ( Cavities Cryomodule, LHe Transfer line) were developed at IUAC, Delhi**

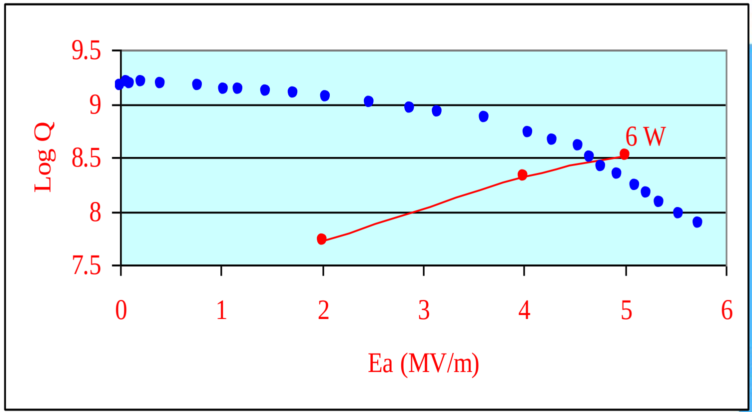
# Superconducting Linac at IUAC. Delhi :



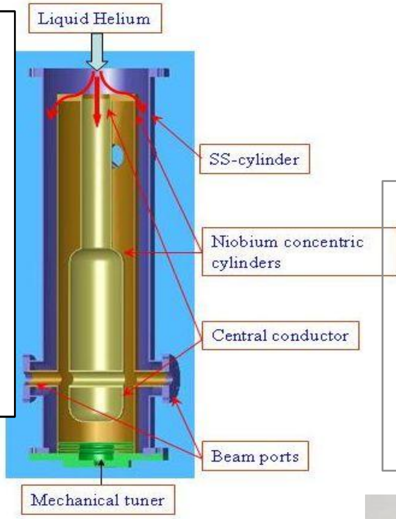

(Annotated Slide)

# 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

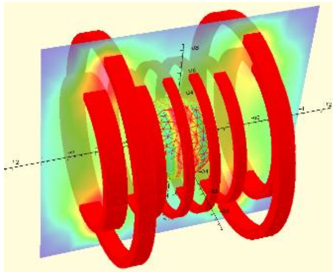


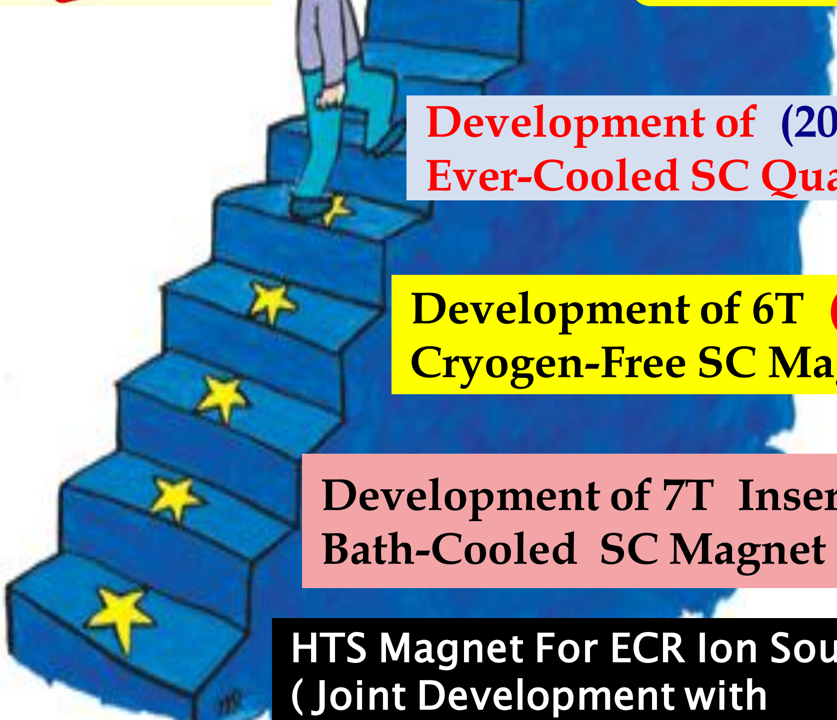

**Two Spoke Cavities developed at IUAC for PIP project ,Tested and Performance is as good as Fermi lab Spoke cavity**

Courtesy ; P N Prakash

(Annotated Slide)

# Foot Steps In Superconducting Magnet Technology at IUAC





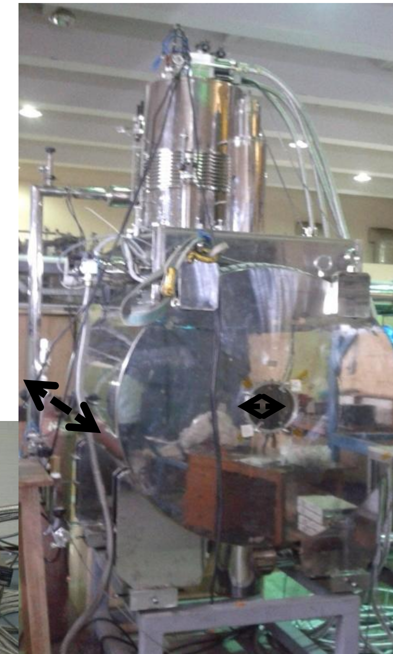
**MRI Magnet ( 1.5 T) 2018**

**Development of (2013)
Ever-Cooled SC Quadrupole**

**Development of 6T (2011)
Cryogen-Free SC Magnet**

**Development of 7T Insert
Bath-Cooled SC Magnet ( 2007)**

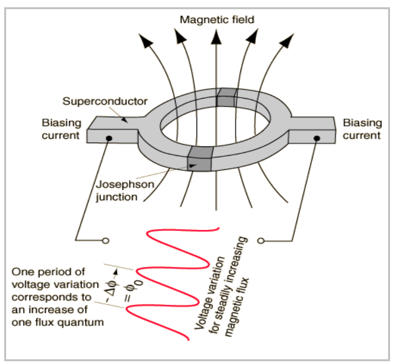
**HTS Magnet For ECR Ion Source
( Joint Development with
Pantechnique , France ( 2005)**

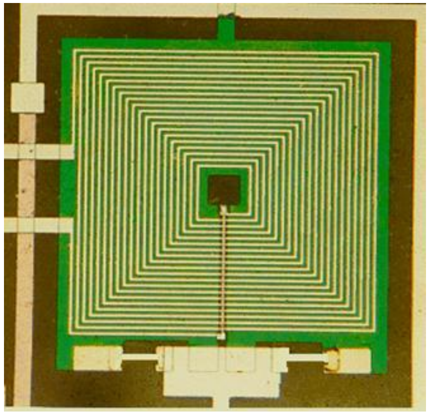


**2223 wire
cooled by 20 K
cryo-cooler**

# SQUID (Superconducting Quantum Interference Device) sensors are the most sensitive detectors of magnetic signals

**SQUID based Magnetocardiography ( MCG) and Magnetoencephalograhy ( MEG) have been successfully assembled and tested at IGCAR. Kalpakkam**

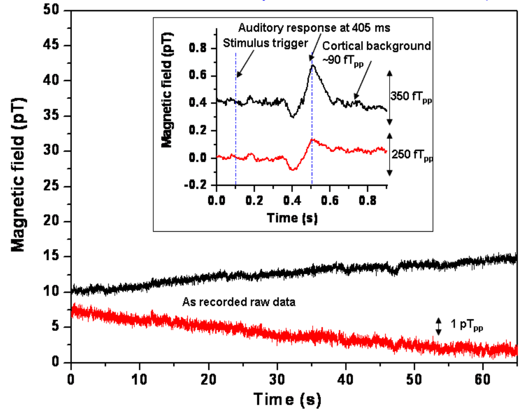


- **SQUID sensors based on Nb-AlOx-Nb Josephson junctions fabricated at IGCAR using advanced micro-fabrication techniques**
- **Active area : 100μm×100μ**
- **Josephson junction size : 5μm×μm**
- **Sensitivity : 10 femto-Tesla**

**(Annotated Slide)**

# SQUID DEVELOPMENT AT IGCAR, KALPAKKAM




**Using SQUID sensors , a 37 channel MCG ((Magneto Cardio Graphy) system has been assembled at IGCAR and used for probing cardiac disorders**

- **86 channel MEG system assembled at IGCAR to measure magnetic field produced by neuronal activity in human brain**

**(Annotated Slide)**

# Superconductivity for Power Applications in India

CPRI, Bangalore

पावरग्रिड
Power Grid Corporation of India

बी एच ई एल
BHEL

**PGCIL**- Power grid Corporation of India Limited

**CPRI**- Central Power Research Institute

**BHEL**- Bharat Heavy Electrical Limited

**CG**- Crompton Greaves

**EMCO**- EMCO Limited

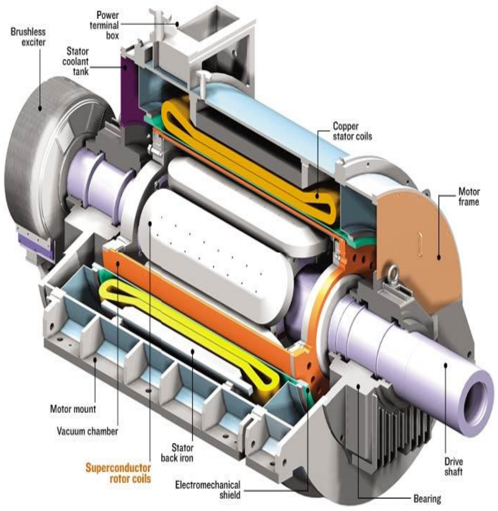
**IIT KGP**- Indian Institute of Technology, Kharagpur

Crompton Greaves

EMCO

(Annotated Slide)

# Components of Superconducting Power Grid




SMES → PGCIL

HTSC Generator → BHEL

HTSC Transmission cables → CPRI, Bruker & PGCIL

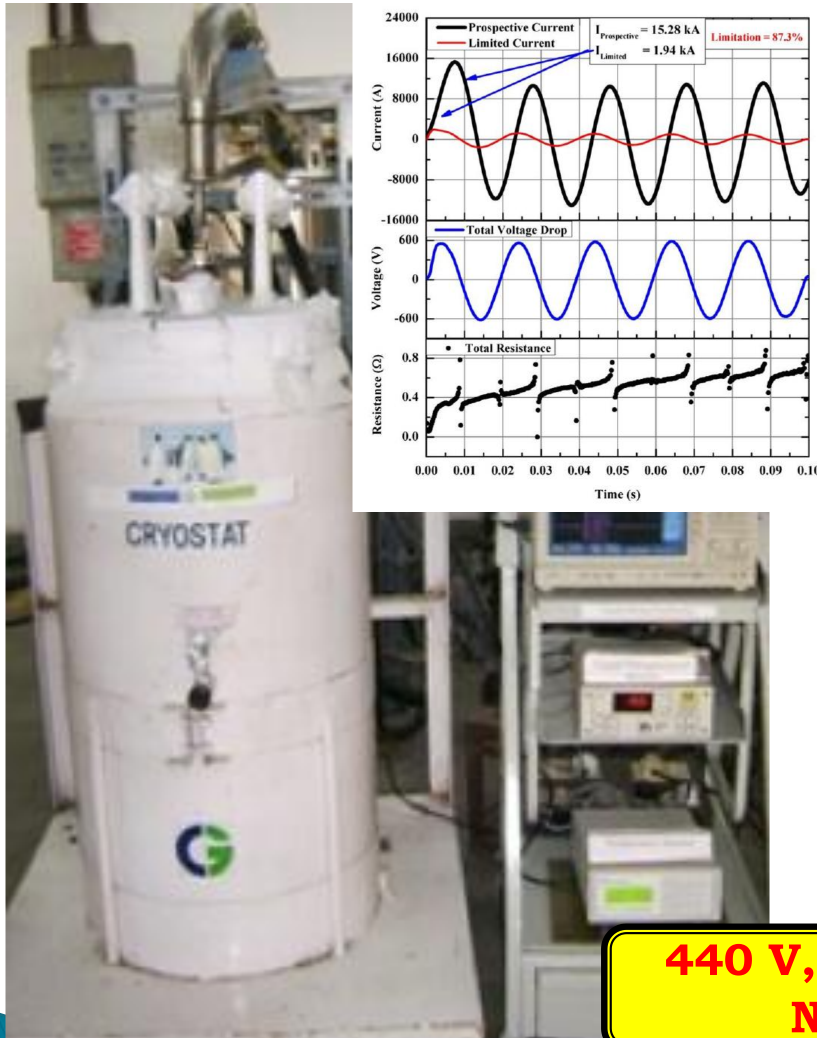
HTSC Fault Current Limiter → CG, PGCIL & Bruker

HTSC Transformers → EMCO

HTSC Motors 200kW, 250 RPM → BHEL

(Annotated Slide)

# SFCL developed by Crompton Greaves




**440 V, 800 A Single Developed**
**Next : 12 kV, 1200A**

# Superconucting Transformer by EMCO

Range : 630 KVA Three Phase
Voltage : 11KV/ 0.433 KV
Cooling : Liquid Nitrogen
Developed By : EMCO/ CPRI

# INDIAN SPACE RESEARCH ORGANISATION & CRYOGENICS

**CRYOGENICS BECOAME HOUSEHOLD NAME IN INDIA BY NEWS REPORT WHEN WE DENIED CRYOGENIC ENGINE TECHNOLOGY BY RUSSIA In 1990**

## That Motivates to develop Cryogenic Engine in India

**GSLV-D5, launched on 5 January 2014, was the first successful flight using the indigenously developed cryogenic engine, the CE 7.5 ( Thrust 75 kN)**

**Indigenous Cryogenic Upper Stage is integrated with GSLV-D5 Second Stage**


**Fuel : Liquid Hydrogen ( 20 K) & Liquid Oxygen ( 90 K)**
**Fuel Mass : 12 Tons**
**Duration : 720 Sec**
**Thrust : 75 kN**

CE-7.5

CE-20

**NEXT WITH MORE POWERFUL ENGINE CE 20 WITH THURST 200 kN , Expected Launching in Dec 2016**

**Three Stage ( Solid, Liquid & Cryogenic) Launch Vehicle with Cryo Engine**

**(Annotated Slide)**

## Fully integrated GSLV-D5 in the Vehicle Assembly Building

## GSLVD5 lift off – View

**INDIAN CRYOGENIC COMMUNITY ARE PROUD WITH ISRO ACHIEVMENT**

# Conclusion & Summary

- Over last 50 years there is a significant growth of activity in the field of Applied Superconductivity & Cryogenics in India

- Accelerator & Fusion Programme dominates along with Space Cryogenics & It will continue in Future

- Superconductivity ( HTS & Cryo Cooler) for Power Application will be the Future Thrust Area in India.

- MRI, NMR and Cryo-cooler based small Liquefier will be the major market share in India and hoping Industry based support will be available in India

# ACKNOWLEDGEMENT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- Dr V Narayanan ( LPSC, ISRO)
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- Dr K Gireesan ( IGCAR, Kalpakkam)
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- M/S Crompton Greaves, M/S EMCO, CPRI


MY ASSOCIATION WITH JAPAN
At KEK with Prof Nakai-san
With Prof Kurokawa-san
NIMS
1020
RIKEN
Kanazawa Inspiration ( Prof. Kiss)
My Teacher Prof Hosoyama
At Sumitomo
Asian Cryogenics Team
(Annotated Slide)
T S Datta. Kanazawa. Nov 9, 2016
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# Congratulation CSSJ ( 50 Years)

Indian Cryogenics Council ( ICC) will celebrate 50 years in 2024.
Need Strong Interaction & Collaboration Between CSSJ & ICC

Will Tiny Superconductor Control Power, Transport ???

Thank You

(Annotated Slide)