Growth of Cryogenics and Superconductivity in India—an Overview

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WORKSHOP ON CRYOGENIC SCIENCE AND TECHNOLOGY: PRESENT AND FUTURE
I.U.A.C. NEW DELHI
APRIL 10-11, 2006
HOW DID CRYOGENICS START IN INDIA?

1952
National Physical Laboratory

- A Collin’s Type ADL 50 He Liquefier was procured
- One large size electromagnet (3.2 T) too was installed
- D. Shoenberg (Cambridge Uni.) invited to work for a year
  K.G. Ramanathan appointed Head. MSR Chari succeeded
- Fermi surface studies carried out on Bi crystals using de Haas van Affect
Indian Association for the Cultivation of Sciences

- Cascade Cooling to 2 K
- **BN Srivastava and JKN Sharma** (LO2 + LH2 + LHe – JT)
- Good enough to cool a sample for measurement (He close Loop)
- Cryostat from Oxford Instruments
- H2 Liquefier
- 1968 Installed
- A. Bose and S. Chatterjee
Low Temperature Research at TIFR

- Early Sixties TIFR got the second He-liquefier
- **Prof. Girish Chandra** provided Leadership

- Basic Research in Low Temperature Physics flourished uninterrupted

- Temperature range extended to mK using DRs/ Demagnetization

- Heavy Fermionic Systems
- High Tc Superconductors
- Boro-carbides
- CMR
- And wide range of Exotic Experiments
Large Scale Use of LHe at TIFR

- LINAC Booster for Particle Accelerator
- Pb-coated Cu Cavities
- Balloon borne IR-Astronomy Experiments
- FT-NMR

- Largest Number of Groups for Low Temperature Studies
- High LHe Consumption
Solid State Physics Laboratory, Delhi

- He-liquefaction started in mid sixties (1966)
- **Dr. A.K. Sridher** headed the Group
- **Mr. Chatwal** made a 6 T Nb3Sn magnet
- Using RCA Nb3Sn tapes
- Magneto-thermal conductivity of Ga-As studied
- LHe activities wound up around 1983

- In recent times cryo coolers (Stirling and TEP) developed and used for IR detectors
University of Delhi

- DU acquired a Russian make cascade He-liquefier in mid-sixties
- Prof. KD Chaudhury headed the LTL
- Served well for over 20 years
- Ultra sonic attenuation in Type-I SC studied
- Thermal conductivity, electron transport, Hall effect measurements
- 10-12 students took their Ph.D.s
- Low temp. activity stopped in 90s
- New He-liquefier acquired by Sophisticated Instrument Centre, but never operated

At one time Delhi had 4 He-liquefiers (NPL, DU, SSPL & INMAS)
Old Guards of Low Temperature (in 1960s)

- Prof. A. Bose, IACS
- Prof. Girish Chandra, TIFR
- Dr. K.G. Ramanathan, NPL
- Dr. M.S.R. Chari, NPL
- Prof. K.D. Chaudhury, DU
- Dr. A.K. Sridhar, SSPL
- Prof. E.S.R. Gopal, IISc & NPL
- Dr. J.K.N. Sharma, IACS & NPL
- Prof. S.K. Datta Roy, IITKh
- Dr. J.S. Dhillon, NPL
Helium Liquefaction Facilities

- IISc. Bangalore
- IACS, Kolkata
- IIT, Kanpur
- IIT, Kharagpur
- IITB, Mumbai
- IIT, Kanpur
- IITM, Chennai
- IPR,(2) Gandhinagar
- INMAS Delhi
- IGCAR Kalpakkam
- IUAC New Delhi
- BHEL Hardwar
- BARC Mumbai
- Hyd. Uni. Hyderabad
- NPL New Delhi
- RRCAT Indore
- SINP Kolkata
- TIFR(2) Mumbai
- UDCSR Indore
- INMAS Delhi
- IUAC New Delhi
<table>
<thead>
<tr>
<th>Institution</th>
<th>City</th>
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<tr>
<td>IISc</td>
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<td>ISRO</td>
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<td>RRCAT</td>
<td>Indore</td>
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<td>UDCSR</td>
<td>Indore</td>
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High Tech. Development:

- IPR  Toroidal and Poloidal SC Magnets
  Cryopanels and Transfer Lines
- VECC Superconducting Cyclotron Magnet
- NPL  11 T SC Magnets, SC Magnet system for NMR
  SC-HGMS, MF A-15  Superconductors
- IUAC SC Accelerator Cavities and LHe Transfer Lines
- TIFR SC Accelerator Cavities
- BARC Turbine based He Liquefiers
  MF Nb-Ti Wires and Cables
- BHEL SC-HGMS and SC Generator
- ISRO Cryo Engine
  Production of LO2 and LH2
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<td>IISc</td>
<td>Super insulation, LN2 Vessels, Cryo Grinding, Cryo Coolers and Many Sponsored Projects</td>
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<tr>
<td>SNBCBS</td>
<td>PPMS</td>
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<tr>
<td>NPL</td>
<td>Cryo Probes, LN2 Vessels, Super insulation, J-Tand Stirling Air Liquefiers and SC Magnets</td>
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<tr>
<td>IITB</td>
<td>Cryo Freezing and Stirling N2 Liquefier</td>
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<td>RRCAT</td>
<td>Multi Pole SC Magnets and Cryo Coolers</td>
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<td>RRLTriv.</td>
<td>Ag clad Bi-2223 tapes and SC Current Leads</td>
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Superconducting Materials

• Conventional (Metal) superconductors

  • BARC : Long lengths of MF Cu / Nb-Ti wires and Cables produced, Excellent process facilities available

  • NPL : Long lengths of A-15 superconductors (\(\text{Nb}_3\text{Sn} \& \text{V}_3\text{Ga}\)) produced on a laboratory scale by bronze route and in situ techniques, Maximum length ~ 80 meters

  • Attempts to produce Cu / Nb-Ti on commercial scale by Hindustan Cable Ltd. Failed ➤ perhaps not economically viable unless exported.
Superconducting Materials

• **High Tc (Oxide) Superconductors**

• Large No. of institutions joined the race, lot of funding by DST (under PMB), enormous data, huge army of Ph.D. students and so on

• Application programme very limited

• **RRL Trivandrum** developed Ag / Bi (2223) Tapes with a $J_c = 16,000 \text{ A} / \text{cm}^2$ (77K, 0T) and current leads up to 200 A (77K) and 400 A (64K)

• Target 1000 A current leads (BRNS Project 64 lacs) to be completed by Sept. 2007

• UDCSR to evaluate the product
Photographs of the 50 A, 100 A and 200 A current leads

TESTING AND EVALUATION OF THE LEADS (77 K)

- Self field critical current (77 K)
- Operational Stability (10 h continuous operation at full load)
- Thermal recycling stability (6 cycles, 77 K – 300 K)
- Quench Stability (10 times, 77 K – 110 K)
- Ageing test (1 Year)
Specifications of RRLAE Current Leads

- Superconductor: Bi-2223 multifilamentary tapes
- Sheath Material: Ag-2.75 Au-0.25 Cu
- Overall length: 200 mm
- Superconductor length: 100 mm
- Critical Temperature: 108 K
- Current Lead Housing: SS304
- Current Lead Encapsulation: Epoxy based composite
- Current Lead End leads: Copper

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<tr>
<th>Current Lead Model No.</th>
<th>Current Rating (A)</th>
<th>Conductive Heat Leak (W)</th>
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<tr>
<td></td>
<td>77 K</td>
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<td>RRLAE-50</td>
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<tr>
<td>RRLAE-100</td>
<td>100</td>
<td>200</td>
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<tr>
<td>RRLAE-200</td>
<td>200</td>
<td>400</td>
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Superconducting Applications

- **Magnets**
- NPL, BARC, IGCAR, RRCAT involved in the 7T Nb-Ti magnets
- RRCAT produced large No. of multi pole SC magnets for CERN
- NPL developed Nb$_3$Sn magnet technology, high homogeneity magnet for NMR application.
- NPL collaborated with BHEL to produce SC-HGMS and provided consultancy to their SC generator development
- VECC and IPR have catapulted India in to the league of developed nations by building huge SC magnets
Superconducting Magnets Developed at NPL
Superconducting Magnets Developed at NPL
Applications of Superconductivity

- **Magneto Encephalography** Programme using Nb SQUID is pursued by IGCAR Kalpakkam for Brain Research (DST)

- **Josephson Effect** being used at NPL to maintain Voltage Standard (Nb junction array producing 1 V used)

- **Quantum Hall Effect** being used at NPL to maintain Resistance Standard (requires high magnetic field and low temperature)

- **High Tc Magnet** using Bi(2223) tapes is planned at IUAC, One pair of Bi-2223 coils already in use in ECR source at the Centre
Low Temperatures and High Magnetic Field Facilities (DST)

- DST Initiative based upon Srinivasan-Chaddah Report
- Centres at IISc, UDCSR and Hyderabad University.
- Rs. 3-4 Crores given to each Centre in the Phase –I
- Liberal grants to other institutions to start low temperature research or to enhance their existing capabilities(such as IITM)
- UDCSR all set to become an important Centre in Measurement Facilities available to Uni. System
- Facilities down to 1 K and under 14 T magnetic field available now for a variety of measurements
- Hyderabad Uni. procured He liquefier and expected to start low temperature activity
- Magneto-optical experiments planned at IISc
ISRO Added a New Dimension to Cryogenic Efforts in India

- Use of Cryogens LH2 and LO2 led to high satellite launch capability
- Required for the upper stage for GSLV
- Required in lower stage too for heavy launch vehicle
- Uses high specific impulse potential of H2 and O2
- Handling of High temperature combustion and very low temperature liquids, → two diametrical opposite Situations
- Development of Cryogenic Engine → A Challenge - integration and testing is a multi stage process
- Challenge met successfully – A Pride

Liquid Propulsion System Centre (LPSC), Mahendragiri
Inter–University Accelerator Centre, New Delhi
First Time Large Scale Use of LHe through LHe Transfer Lines

8 Nb- Resonators loaded in 1st LINAC module

Buncher Cryostat integrated with LHe Cryo-Network at LINAC beam line
UDCSR (INDORE)

Low Temperature Laboratory Facilities

TCF 10 Linde 25 l / Hr

10 T SC Magnet
16 samples MR
4 samples Sp. Heat

PPMS 14T/ 0.3 K
Heat Cap. / Res.

PPMS 14 T VSM
IPR Set New Standards for Cryogenics in India-the Largest Network of LHe & LN2

Cold Box with MCD 1.3 KW @ 4.5 K
He Refrigerator (650 W + 200 l/hr)

Liquid nitrogen management system

Cold Box for Neutral Beam Injector
110 W at 3.8 K
K-500 Superconducting Cyclotron at VECC
(Heavy Ion Beam of 80 MeV / Nucleon will be available)

- Magnet Frame: 100 Tons
- Total weight of coils: 6 Tons
- Complete Cryostat: 13 Tons
- 3 m Dia. X 2.2 m height
- Maximum Operating Current: 800 Amp.
- Tested for 4.8 T at 550 Amps.

- 5.5 T Superconducting Magnet Coil

- Air Liquide Helial-50 Helium Liquefier
- 200 W refrigeration + 100 L / he. LHe
Possible Future for Cryogenics in India (say ten years)

- It is a Beginning - Long Way to go and catch up with the Developed Countries
- We must have our own He-Liquefiers say of 100 l/hr capacity (possibly BARC technology)
- A 20 T National Magnet Facility built by Indian Scientists and Engineers
- Cryofree Magnets (5-10 T) within our capability
- Cryo Coolers of 2 W cooling capacity
- Close interaction with Indian Industry will boost these efforts

- All we need is our resolve
Thank you
Liquid Helium Plant - new facility - January, 2004 at SINP

40 litres per hour with LN₂, 23 litres per hour without LN₂, Built-in purifier upto 20% contamination: Linde, Switzerland, Model: TCF 10
CRYOGENIC PLANT FOR SUPERCONDUCTING MAGNETS

1.3 kW @ 4.5 K helium refrigerator/liquefier with cold circulator (300 g/s) for forced flow cooled superconducting magnets

Cold Box with MCD 1.3 KW @ 4.5 K He Ref.

Online He Purifier (140 g/s)

He Compressor 3# 70 g/s @ 14 bar each (left) and Oil removal system (right)
Liquid helium/Super-critical helium distribution @ 4.5 K

Schematics of distribution system (left); Valve assembly chamber (right) at 4.5 K.
CRYOGENIC PLANT FOR NEUTRAL BEAM INJECTOR

110 W @ 3.8 K Helium refrigerator with vacuum screw compressor for cryo pumps

Cold box with control panel
Vacuum Screw Compressor (8g/s @0.66bar)
Valve box with 40 l Phase Separator
Sub-Atmospheric Heat Exchanger
# Warm Gas Management

## System Specifications

<table>
<thead>
<tr>
<th>System</th>
<th>Specification</th>
</tr>
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<tr>
<td>Storage systems</td>
<td>High Pressure (200 bar, 2 nos. 25 Nm³ water cap.)</td>
</tr>
<tr>
<td>Regeneration / Recovery Tanks</td>
<td>Medium Pressure (14 bar, 10 ppm purity, (3 number CS); 6 bar, 1 number SS; 68 Nm³ capacity each. SS304 piping</td>
</tr>
<tr>
<td>Interconnections</td>
<td></td>
</tr>
<tr>
<td>Recovery systems</td>
<td></td>
</tr>
<tr>
<td>Recovery compressor</td>
<td>100 Nm³/hr 1# 29 Nm³/hr 1# 3# 40 Nm³ each</td>
</tr>
<tr>
<td>Gas bag</td>
<td></td>
</tr>
<tr>
<td>Control valves</td>
<td></td>
</tr>
<tr>
<td>Automation</td>
<td>Electro-Pneumatic PLC</td>
</tr>
</tbody>
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![Diagram of Warm Gas Management System](Warm_Gas_Management_Diagram.png)

![Images of storage tanks and control valves](Images_of_Warm_Gas_Management.png)
INDIGENOUS DEVELOPMENTS

➢ CRYOGENIC TRANSFER LINES
  ➢ Liquid He
  ➢ Supercritical He
  ➢ Liquid Nitrogen

➢ TEST FACILITIES
  ➢ Large size cryostat
    (Vacuum chamber with LN₂ shield)

➢ CURRENT FEEDER SYSTEM
  ➢ Large cryostat
  ➢ Vacuum duct
  ➢ Current lead

➢ HELIUM FEEDTHRU / ELECTRICAL ISOLATOR
  ➢ 1000 numbers fabricated, tested and installed
SUPERCONDUCTING MAGNETS: TF Coils

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

TF COIL Winding Pack:
D-Shaped; 6 Double Pancakes
X-section: 194x144 mm²
Dimensions: 2.59 m × 1.53 m
Consolidated by VPI & encased in SS316L case
Conductor: NbTi based CICC
SUPERCONDUCTING MAGNETS: PF Coils

- Support single & double null equilibria
  - Triangularity (0.4-0.7),
  - Elongations (1.7-1.9), \( l_i (0.75 -1.4) \),
  - \( \beta_p (0.01-0.85) \) & slot divertor configuration
- Limiter operation during Plasma current ramp up

<table>
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<tr>
<th>Coils</th>
<th># Coils</th>
<th>Radius (m)</th>
<th>Vertical Location (m)</th>
<th>Winding Cross-section (mm²)</th>
<th># Turns</th>
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<tr>
<td>PF1</td>
<td>1</td>
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<td>PF2</td>
<td>2</td>
<td>0.45</td>
<td>±0.43</td>
<td>71x163</td>
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<td>0.50</td>
<td>±0.93</td>
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<td>PF5</td>
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<td>PF6</td>
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<td>1.35</td>
<td>±0.35</td>
<td>100x100</td>
<td>16</td>
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</table>
Conductor for SST-1 Superconducting Magnets

Conductor Characteristics

- **Conductor type**: CICC; NbTi in Cu
  
  **Cu : NbTi : : 5 : 1  Cu RRR : 100**

- **Dimensions**: 14.8×14.8 mm²
- **No. of Strands**: 135 Ø 0.86 mm
- **Filaments**: Ø 10 µm; # 1272/strand
- **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

**Parameters**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Design Values</th>
<th>Qualification Test Results</th>
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<tr>
<td></td>
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<td>Virgin Strand</td>
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<tr>
<td>I_c @ 5T; 4.2K</td>
<td>272 A</td>
<td>273 A</td>
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<tr>
<td>‘n’ @ 5T</td>
<td>≥ 25</td>
<td>46</td>
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<tr>
<td>Hysteresis Loss @±3T</td>
<td>≤ 100</td>
<td>36.5</td>
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<tr>
<td>RRR of Cu</td>
<td>~100</td>
<td>108</td>
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<tr>
<td>Filament Breakage</td>
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<tr>
<td>Cu:NbTi</td>
<td>5:1</td>
<td>4.98:1</td>
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<tr>
<th>Temperature (K)</th>
<th>I_c (A)</th>
<th>Fit, 2T</th>
<th>Fit, 3T</th>
<th>Fit, 4T</th>
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**Graphs**

- **Graph 1**: Magnetization vs. Temperature
- **Graph 2**: Temperature vs. Resistance