INDO-US SCHOOL ON CRYOGENICS, SUPERCONDUCTIVITY, VACUUM AND LOW TEMPERATURE MEASUREMENT TECHNIQUES

NOVEMBER 19-23, 2007

at

INTER-UNIVERSITY ACCELERATOR CENTRE (IUAC)
NEW DELHI

SCHOOL BOOKLET & SOUVENIR

Organized by

Inter University Accelerator Centre (IUAC), New Delhi
&
Indian Cryogenics Council (ICC)

Supported by

INDO-US Science & Technology Forum (IUSSTF)

FOREWORD

Welcome to the “INDO-US School on Cryogenics, Superconductivity, Vacuum and Low Temperature Measurement Techniques” being organized at the Inter-University Accelerator Centre (IUAC), New Delhi, in collaboration with Indian Cryogenics Council (ICC) during November 19- 23, 2007.

High Energy Research has been the biggest promoter of superconductivity and thus of Cryogenics down to 1 K temperature. Particle accelerators capable of producing very high accelerating fields and with energies in TEV range have been made possible by the use of superconducting RF cavities wherein the energy dissipation is drastically reduced due to very low surface resistance in superconductors. Similarly, large conventional beam focusing and beam bending magnets have been replaced by more energy efficient and smaller superconducting magnets. Operation of superconducting devices, however, requires large quantities of cryogens, mostly liquid helium and liquid nitrogen. The use of cryogens calls for an efficient transfer line network, design and fabrication skill for complicated cryostats and above all an army of young talented persons especially trained in this exciting area. It need not be emphasized that high vacuum is a pre requisite and an integral part of any cryogenic activity. Hence the theme of the School.

Many accelerator upgradation programmes in India based on superconducting systems are underway. By now a pool of young scientists and engineers has been created and trained in-house by respective institutions in the country. The demand for man power trained in superconductivity and cryogenics is, however, likely to grow manifold in the coming years. It is therefore important that we keep exposing our existing staff periodically to the latest developments taking place in this field while creating curiosity in the minds of the young students opting for a career in Accelerator and Low Temperature Physics. With this dual objective in mind, we are organizing this “INDO-US School on Cryogenics, Superconductivity, Vacuum and Measurement Techniques”. We are confident that the school will enable our scientists, engineers and students to interact with the scientists & engineers from USA and other countries who are deeply involved with large scale projects on Accelerators, Colliders and Tokomak.

In USA, Europe and Japan many labs, such as Fermi Lab, Jefferson Lab, Brookhaven National Lab, CERN, and KEK have developed a high level of expertise in this emerging technology. In India, however, this technology has not matured yet and we need to train our scientists and engineers. Experts from these labs agreed enthusiastically to deliver course lectures as faculty members and share their experiences with the participants in the school. The school has been spread over 5 days covering course materials on Cryostat Test Facilities, Cryo Distribution Line, Operation of Optimal Helium Refrigeration System, Cryogenic Process Automation & Control, Superconducting Cavity & Superconducting Magnet, Cryo Pumping, and Cryogenic and Vacuum Instrumentation.

The response to the school has been overwhelming. Unfortunately we could accommodate only 90 participants due to the limitation of space at our Centre. In all, there are 15 faculty members from India and abroad who will be delivering 29 course lectures. Besides, we will have three evening lectures on the Current International Programmes by eminent Scientists.

We take this opportunity to thank all the faculty members and invitees for their participation. We place on record the fact that it would not have been possible to hold this INDO-US School but for the generous grant from INDO-US Science and Technology Forum (IUSSTF) and very much appreciate their support. We also sincerely thank Govt. funding agencies and the industry that helped us to organize this School. We welcome you all to the School. Even though our colleagues at IUAC have taken all possible measures to make the School most productive and your stay comfortable, yet some pitfalls are sometimes bound to crop up. Please bear with us. My colleagues will be there to help you out.

Once again, we welcome you all and wish you a pleasant stay.

Amit Roy
Ganapati Rao Myneni
T.S. Datta

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Willium Schneider (Jefferson Lab, USA)
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Amit Roy (IUAC, India)

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Funding from Govt. Agencies

1. Indo- US Science Technology Forum (IUSSTF, New Delhi)
2. National Fusion Programme (NFP, Gandhinagar)
3. Department of Science & Technology (DST, New Delhi)
4. Board of Research in Nuclear Science (BRNS, Mumbai)
5. Council for Scientific & Industrial Research (CSIR, New Delhi)
6. Inter-University Accelerator Centre, New Delhi

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2. M/s Linde Kryotechnique, Switzerland & M/s Linde – India
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INDO-U.S. SCIENCE AND TECHNOLOGY FORUM

Fulbright House, 12 Hailey Road, New Delhi 110 001, India

Website: www.indousstf.org

The Indo-U.S. Science and Technology Forum (IUSSTF) was established in 2000 under an agreement between the Governments of India and United States of America with a mandate to promote, catalyze and seed bilateral collaboration in science, technology, engineering and biomedical research through substantive interaction amongst government, academia and industry.

As its mandate, the IUSSTF provides an enabling platform to the scientific enterprises of the two nations by supporting an S&T program portfolio that is expected to harbor sustainable interactions with a potential to forge long term collaborations. The IUSSTF program manifests are largely catalytic in nature that helps to create awareness through exchange and dissemination of information and opportunities in promoting bilateral scientific and technological cooperation.

IUSSTF has an evolving program portfolio that is largely conceived and driven by scientific communities of both the countries through extending support for symposia, workshops, conferences on topical and thematic areas of interest; visiting professorships in academia; travel grants; training programs and advanced schools; public-private networked centres and knowledge R & D networked centres. The IUSSTF also works towards nurturing contacts between young and mid career scientists by convening stimulating flagship events like the Frontiers of Science and Frontiers of Engineering symposium through the U.S. National Academies model. At the same time it reaches out to industries by partnering with business associations to generate high quality events on technology opportunities for business development to foster elements of innovation and enterprise through networking between academia and industry.

The IUSSTF maintains a close working relationship with the federal agencies, laboratories, government institutions, and the academia in U.S. and India, cutting across all disciplines. As an autonomous, not-for-profit society, the IUSSTF has the ability, agility and flexibility to engage and involve industry, private R&D labs; and non governmental entities in its evolving activity manifold. This operational uniqueness allows the IUSSTF to receive grants and contributions from independent sources both in India and USA, besides the assured core funding from the two governments.

The IUSSTF solicits proposals for its activities thrice a year (January, May and September) and awards are made on the basis of peer reviews both in India and USA.

The IUSSTF values interactions and looks forward to work with the S&T community of both countries to implement new ideas that endeavor to promote cutting edge Indo-U.S. Science and Technology collaborations.

Programme Table

INDO-US SCHOOL ON CRYOGENICS, SUPERCONDUCTIVITY, VACCUM & LOW TEMPERATURE MEASUREMENT TECHNIQUES

PROGRAMME

NOVEMBER 18, 2007 (SUNDAY)

Registration: 17:30 - 20.00 hrs. at IUAC Lounge

NOVEMBER 19, 2007 (MONDAY)

Registration: 8:30 – 9:30 hrs. at IUAC Lounge

Inaugural Session

9:30 - 9: 40	Welcome Address	Amit Roy, Director IUAC
9:40 - 9:50	About IUSSTF	A. Mitra, Executive Director, IUSSTF
9:50 - 10:00	Inaugural Address	T. Ramasami, Secretary, DST
10:00 - 10:45	Key Note Address	Anil Kakodkar, Chairman AEC & Secretary DAE
10:45 - 11:00	Vote of thanks	T.S. Datta, IUAC, Convener

Tea: 11:00 – 11:30 hrs.

Technical Session –1; Chairman:

11:30 - 12:30	Superconducting Accelerator Components-1	Tom Peterson, Fermilab,USA
12:30 - 13:30	Helium Refrigerator-1	Rao Ganni, Jefferson Lab,USA

Lunch: 13:30 – 14:30 hrs.

Technical Session –2; Chairman:

14:30 - 15:30	Vacuum System for Accelerator -1	Christian Day, ITP, Karlsruha
15:30 - 15:45	**TEA**	
15:45 - 16:45	Basic Packaging of Cryogenics System -1	Willium Schenider, Jefferson Lab,USA
16:45 - 17:45	Helium Refrigerator -2	Rao Ganni, Jefferson Lab,USA

19:00- 20.00 hrs. : Evening Lecture
on International Linear Collider: Tom Peterson, Fermilab., USA

20:00 hrs. : Dinner
(Sponsored by M/s Pantechnik and M/s Geebee International)

NOVEMBER 20, 2007 (TUESDAY)

Technical Session –3; Chairman:

09:30- 10:30	Superconducting Cavity Fundamental -1	Amit Roy, IUAC, Delhi
10:30 - 11:00	**TEA**	
11:00 - 12:00	Superconducting Accelerator Components -2	Tom Peterson, Fermilab,USA
12:00- 13:00	Cryogenic Instrumentation -1	Ganapati Rao Myneni, Jefferson Lab,USA

Lunch: 13:00 – 14:00 hrs.

Technical Session –4; Chairman:

14:15 - 15:15	Closed Cycle Refrigerator	Subhash Jacob, IISc, Bangalore
15:15 - 15:30	**TEA**	
15:30 - 16:30	Process Control & Automation for Helium Liquefier -1	D. Arenius, Jefferson Lab,USA
16:30 - 17:30	Cryogenic Heat Exchanger	Sunil Sarangi, NIT, Rourkela

19:00- 20.00 hrs. : Popular Evening Lecture
on History of KEK on Accelerator Programme: Shin-ichi Kurokawa, KEK, Japan

NOVEMBER 21, 2007 (WEDNESDAY)

Technical Session –5; Chairman:

09:30 - 10:30	Packaging of Cryogenic System -2	Willium Schneider, Jefferson Lab.
10:30 - 11:00	**TEA**	
11:00 - 12:00	Superconducting Magnet-1	Ezio Todesco, CERN, Switzerland
12:00 - 13:00	Vacuum System for Accelerator -2	Christian Day, ITP

Lunch: 13:00 – 14:15 hrs.

Technical Session –6; Chairman:

14:15 - 15:15	Superconducting Accelerator Components -3	Tom Peterson, Fermilab
15:15 - 15:30	**TEA**	
15:30 - 16:30	Helium Refrigerator -3	Rao Ganni, Jefferson Lab
16:30 - 17:30	Special Lectures on Superconducting Cyclotron at Kolkata	Rakesh Bhandari, VECC, Kolkata

20:00 hrs. : Banquet at NII Lawns
(Sponsored by M/s Linde Kryotechnik & M/s Velan)

NOVEMBER 22, 2007 (THURSDAY)

Technical Session –7; Chairman:

09:30 - 10:30	Superconducting Magnet-2	Ezio Todesco, CERN
10:30 - 11:00	**TEA**	
11:00 – 12:00	Cryogenic Instrumentation -2	Ganapati Rao Myneni, Jefferson Lab
12:00 - 13:00	Cryo Pumping -3	Christian Day, ITP

Lunch: 13:00 – 14:15 hrs.

Technical Session –8; Chairman:

14:15 - 15:15	Helium Refrigerator-4	Rao Ganni, Jefferson Lab
15:15 - 15:30	**TEA**	
15:30 - 16:30	Superconducting Cavity and Accelerator Programme at IUAC -2	Amit Roy, IUAC
16:30 - 17:30	Process Control & Automation -2	D. Arenius, Jefferson Lab

19:00- 20:00 hrs. : Popular Evening Lecture
on ITER & ITER - INDIA: Shishir Despande, ITER- India, Gandhinagar

20:00 hrs. : Dinner
(Sponsored by M/s Inox India Ltd., Vadodara)

NOVEMBER 23, 2007 (FRIDAY)

Technical Session –9; Chairman:

09:30 - 10:30	Superconducting Magnet -3	Ezio Todesco, CERN
10:30 - 11:00	**TEA**	
11:00 - 12:00	Packaging of Cryo Modules -3	Willium Scheneider, Jefferson Lab
12:00 - 13:00	Cryogenic Instrumentation -3	Ganapatai Rao Myneni, Jefferson Lab

Lunch: 13:00 – 14:15 hrs.

Technical Session –10; Chairman:

14:15 - 15:15	Summary on Refrigerator	Arenius & Rao Ganni, Jefferson Lab
15:15 - 15:30	**TEA**	
15:30 - 17:00	Concluding Session	

19:30 hrs. : Dinner

KEY NOTE ADDRESS

OVERVIEW OF DAE ACTIVITIES ON CRYOGENICS

by
Dr. Anil Kakodkar
Chairman AEC & Secretary DAE

COURSE SUMMARY

Auxiliary Cryogenic Systems and Components

Thomas J. Peterson
Fermi National Accelerator Laboratory
Batavia, IL, U.S.A

First, we should define what we mean by "auxiliary cryogenic systems and components". I have taken this to mean special objects not covered by other speakers in this course, such as test dewars and test stands for large accelerator magnets, RF cavities, and other cryogenic components. I also take "auxiliary components" to refer to special distribution or interface devices such as large distribution "feed" boxes and transfer lines.

Part 1. (One hour) Mechanical engineering fundamentals for design of auxiliary cryogenic components and systems. Although our other presenters in this cryogenics course will also provide information about cryogenic design fundamentals, a few key points are probably worth emphasizing and repeating. Depending on to what extent such fundamental material has already been covered, we can spend more or less time on these general cryogenic engineering topics, then move on to Part 2.

Topics which are fundamental to the design of cryogenic components and systems include

- Cooling modes typically used for large cryogenic devices
- Two-phase flow of liquid and vapor helium
- Heat transfer, boiling versus convective heat transport, and superfluid heat transport
- Pressure drop in helium flow, analysis and experience
- Mechanical pipe instabilities, forces due to un-reacted pressure at bellows
- Use of multi-layer insulation and typical heat loads
- Thermal and mechanical treatment of instrumentation feed-throughs
- Insulating vacuum barriers

Part 2. (One hour) Test facilities for superconducting accelerator components. This portion of the course will focus on design, procurement, and operation of test facilities for superconducting accelerator components. These include large test dewars, magnet test stands, superconducting RF (SRF) test cryostats, and SRF cryomodule test stands. Cooling conditions may include 4.5 K saturated or subcooled liquid helium, pressurized superfluid, and/or saturated superfluid.

Procurement of these test devices typically involves at least some "in-house" (user-based) design work due to the specialized nature of these containers. The procurement may then involve a specification which details key interfaces but leaves industrially standard features up to the vendor, or the procurement may be entirely "build to print". Issues and experience with each approach will be presented, including some comments about oversight of vendor work.

Some operational results and experience for test facilities at Fermilab will be presented. Operational experience with a vertical magnet test dewar at Fermilab which is capable of subcooling a volume of about 1500 liters of helium at 1.2 bar to temperatures between 4.4 K and 1.7 K will help to illustrate some of the fundamental issues in dealing with a large volume of superfluid helium. Experience with our large LHC final-focus quadrupole magnet tests, done in 1.9 K, 1.2 bar helium, also illustrate many of the issues in test stand design, procurement, and operation.

Part 3. (One hour) Distribution components for large cryogenic systems. This portion of the class will focus on design and procurement of distribution equipment for large cryogenic systems. These include feed boxes, distribution boxes, transfer lines, etc. These devices all serve as the interface from a cryogenic plant to specialized cryogenic equipment. Such cryogenic "boxes" may include thermal transitions of various kinds, power leads for electric current which now often include high temperature superconductors, instrumentation, vacuum barriers, control valves, relief valves, etc., presenting many unique design problems. Design and procurement of these smaller components and their integration into the larger assembly will be discussed.

This lecture will include an in-depth look at design and procurement of eight large and complex distribution feed boxes (DFBX) for LHC at CERN. The step-by-step assembly process of the DFBX will be illustrated through a series of photos.

Design and Operation of Optimal Helium Refrigeration and Liquefaction Systems

Venkata Rao Ganni
TJNAF, U.S.A

This course is an attempt to provide the fundamentals for the design of an optimal helium cryogenic systems using "Simplified Concepts and Practical Viewpoints" and the operation of the existing systems at the optimal conditions.

1. Introduction: In this chapter the quality of the energy and the basic processes used for cryogenic applications are introduced. Present day cryogenic processes cycles are an extension of the base cycles presented for various cryogenic fluids with modifications to improve the five objectives for optimum cryogenic systems. The theory behind the process design, the components used and the control philosophy are described in later chapters.

2. Carnot Helium Refrigeration and Liquefaction Systems: In this chapter the Carnot work (or the minimum input work) required for refrigeration and liquefaction is explained. Also shown are the effects of non recovered expander work (generally the case for most of the helium systems) on the refrigeration and liquefaction processes. In practice all the systems are compared to the reversible (Carnot) work, which includes the expander out put work.

3. Ideal Helium Refrigeration Systems and the Carnot Step: The 'Carnot Step' is defined ***(by the author)*** as one of a given number of similar process steps that yield the minimum irreversibility. Assuming an ideal gas, the ideal refrigerator requires only a single Carnot step whereas the ideal Claude liquefier requires a number of Carnot steps, each with the same temperature ratio.

Note: ***The importance and ramifications of the Carnot step was recognized by the author in the mid-1980's***. Since then it has been taught to many colleagues and utilized in new system designs, as well as improving the operation of the existing systems.

4. The Theory behind Cycle Design: In this chapter the use of the ***Carnot step*** for cold box design is demonstrated. For a given number of expansion stages (with equally efficient expanders), these Carnot steps (the stage temperature ratios) are *theoretically* the same for both refrigerator and liquefier and result in minimizing the compressor flow and therefore, the input power. This is indirectly saying that the ideal placement of the expanders with respect to temperature for both refrigerator and liquefier is approximately (disregarding real gas effects) the same, but the flow requirement through the expanders is not the same. Due to practical limitations, the system will likely operate at different temperatures between the two modes and also away from the highest Carnot efficiency achievable if operating in an off-design mode or a different optimal condition (e.g., maximum system capacity rather than minimum input power condition).

5. System Optimization: This chapter discusses, what is an optimum system? Does it result in one, several or all of the five objectives for an optimum cryogenic system? The process optimization parameters (i.e., temperature, pressure and flow) and their trade offs on the system optimization process are discussed. The floating pressure theory and the Ganni cycle are explained.

6. Liquid Nitrogen Pre-Cooling: In this chapter the use of liquid nitrogen (LN_2) pre-cooling in helium refrigeration systems is discussed. The various benefits and drawbacks to using LN2 pre-cooling are discussed. Various configurations and their performance are presented. A discussion and simplified analyses provide a rational view to evaluate and minimize LN_2 pre-cooling consumption and capital cost while reducing the dangers of LN_2 freezing and optimizing the design.

7. Helium Refrigeration Systems for Below 4.2K Operations: The approaches presented in this chapter are those generally used for refrigeration at temperatures below the atmospheric pressure saturation temperature (4.22K). These systems inherently appear as liquefaction loads to the main (4K) refrigeration system, which is *providing the refrigeration*. The system strategy is to recover the refrigeration of the load return flow with a minimum pressure drop. As in any refrigeration system the environment is the ultimate heat rejection sink. The warm compressor's (and/or vacuum pump's) after coolers and oil coolers typically provide this heat rejection path. Four refrigeration process types and options are described. The nominal overall specific work (total input power to refrigeration power, W/W) and efficiency for these various processes are compared.

8. Typical Helium Cryogenic System and its Basic Components: The sub-system components of a typical helium cryogenic system are described in conjunction with their salient selection criteria.

9. Instrumentation and Controls: This section introduces the JLab standards for the design and selection of components for the instrumentation and control. It is not intended as a complete coverage of the instrumentation and controls issues in cryogenic systems but as a reference to areas where difficulties are anticipated based on the author’s experience. JLab solutions are provided in a few problem area instances.

10. Optimal Operation of the Existing Helium Refrigeration Systems: Generally helium refrigeration systems are designed to operate at one maximum capacity operating point. In practice, the system capacity requirement often varies depending on the load characteristics, distribution system insulating vacuum pressure, experimental setup, underperformance of the refrigerator, etc. Often, systems initially designed for different load characteristics are adapted to new loads. Operating the system at the maximum design point may not be advantageous when the full capacity is unnecessary or the required mode of operation has changed. This chapter describes how to adopt a given refrigerator to fixed or varying loads which may be different from the original refrigeration system design load and goals.

11. System Design Overview: Before beginning a new refrigeration system specification, the system ***capacity*** for the required operating modes, the recommended modes of system capacity verification and ***pressure rating*** (relief) requirements need to be analyzed. These factors strongly influence capital and operating costs.

12. Design Verification and Acceptance Testing: The need for devices necessary to quantitatively verify the system capacity is often unrecognized or underestimated. Such an oversight creates a system capacity uncertainty for the intended operational modes and can lead to misidentification of the problem(s). This consequently, results in the modification of the wrong component(s) due to a lack of understanding of which system component(s) is the under-performing.

13. Some of the Lessons Learned Over the Years: A great deal can be learned from the operation of these systems. A careful analysis of the data based on the reliable test data and operational experience is required before reaching any conclusions. ***All too often the perceptions of the system performance are considerably different from the reality of the true system performance.*** During new projects, extreme care is required in developing specifications and assuring that the scope-of-supply includes all the required items. The success of the project depends upon its organization; cost estimates based on current data, schedule planning and project execution. These in turn are dependent upon the thorough thinking through the entire project, including the consideration of the practical constraints and experienced-based risk factors and contingencies. Some of the critical areas requiring attention are listed in this chapter.

14. Some Areas of Interest for Future Development: Although some special components and processes have been developed for helium refrigeration systems, the majority of the components and processes, due to their limited market, are adopted from other thermal systems: i.e., traditional refrigeration and the chemical industry. Development areas that are useful or could be improved are listed in this chapter.

15. Conclusions: How to design a new system or to operate an existing system at optimal conditions is described in this course. *Hopefully the information presented in these notes and other information available will help you to design and operate cryogenic systems at optimal conditions and to answer the initial questions. Floating pressure-Ganni Cycles are viewed a step in that direction.* ***The central theme of these classes is to minimize the input power for all required operating conditions.*** *This will help to save our natural resources;* ***an objective that is worth pursuing****.*

Cryogenic Vacuum Pumping Systems

Christian Day
Forschungszentrum Karlsruhe GmbH, Institute for Technical Physics,
Karlsruhe, Germany

Cryopumps exploit the most elementary form of producing vacuum by lowering the temperature. Per definition, they are capture pumps which remove gas molecules by sorption or condensation/sublimation on surfaces cooled below 120 K. Often, the cooled surface is at least partly covered with a porous sorbent material. The design of a cryopump has to combine cryogenic aspects and vacuum technological considerations in a unique manner; the cryopump is by its physical principle a high-vacuum pump. Besides straightforward parameters, such as pressure and temperature, the pump performance is very much governed by the geometric design of the pump structures and the complex interaction between gas particles and cooled surface.

This course reviews the basic vacuum concepts of commercial and tailor-made cryopumping systems. The course follows a phenomenological approach in three steps. This is most of all due to the fact that no rigorous method has been developed so far to derive the integral cryovacuum pump performance directly from gas-surface interaction parameters. The final lecture will add aspects from the quality assurance and design code point of view. By that, the course looks at the modern cryopump in full detail. It will provide deep understanding of cryopumps, and illustrate benefits and limitations of such equipment.

The first lecture deals with the principle aspects of cryosystem design, with basic considerations on materials selection, fabrication techniques, identification of vacuum piping to a chamber, determining pump down time, leak rate specification, and surface preparation procedures. It will introduce the basic terms to describe a vacuum system and present the vacuum fundamentals to make the audience familiar with the central issues and challenges in designing a high vacuum system and the approaches for how to overcome them. The vacuum pump family tree (mechanical, momentum, capture) will be exemplified and the typical gas source terms inside an ultrahigh high vacuum system as well as their mitigation methods will be discussed. The gas balance equation and some solutions with examples will be presented. The basic components of a cryogenic pump are discussed.

Keywords of the first lecture are: pertinent vacuum definitions, vacuum flows and pressure regions, Knudsen number, fundamental vacuum properties (pumping speed, throughput), vacuum pump classification, a stroll through the pump types, primary pump and associated forepump combinations, vacuum system design principles, sealing issues, outgassing, conductances, essential pump-down equations, black hole pumping speed, transmission probabilities, condensation and cryosorption.

The second lecture will provide an in-depth look into available information which can be taken as a basis for the design of a cryopump. Commercial cryopumping systems are characterised, their capabilities and limitations are described. Examples are given to illustrate the stepwise approach for how to derive the detailed design of a cryosorption pumping system (system analysis and Monte Carlo simulation). It will be shown how the basic concepts relate to the practical characteristics of cryopumps, such as pumping efficiency, pumping speed and regeneration scheme.

Keywords of the second lecture are: thermal shields, pumping panels, cryosupply issues, supercritical vs. liquid cryogen, Gifford McMahon cryorefrigerators, standard cryopump characterisation (cross-over pressures, loads etc.), standard cryopump applications, Matching commercial cryopumps to applications, capture probability, sticking probability, cryopump operation scenarios, regeneration schemes, transitional flows, Monte Carlo simulation (test particle and direct), heat load calculations, thermohydraulic calculations.

An important advantage of cryopumps compared to other high vacuum pumping techniques is the versatility of the pump geometry. It can be designed tailor-made to the available space and, in this case, is often inserted into the vacuum recipient rather than flanged onto an external port.

The third lecture will exemplify this. Due to the very demanding requirements on vacuum pumping, the R&D programmes for nuclear fusion machines such as ITER have turned out to be a strong driver for designing sophisticated large-scale cryovacuum systems, operated between 4 K and 20 K. The lecture will illustrate of some state-of-the-art examples in that field. It will assess the design philosophies and some of the constructive aspects.

Keywords of the third lecture are: introduction in nuclear fusion and ITER, ITER vacuum pumping systems, cryosorption R&D results, torus exhaust cryosorption pumping system, neutral beam injector pumping system, cryostat pumping system, cryoplant and cryopump interfaces, cryogenic hydrogen safety, relevant vacuum instrumentation and control, matching tailor-made cryopumps to applications.

The fourth lecture will focus on design codes, quality assurance, procurement and project control issues, presenting many examples and pitfalls from the recent cryopump projects. It will also discuss more exotic applications of cryopumping (cold turbopumps, cold piston pumps).

Keywords of the fourth lecture are: codes and standards, Pressure vessel directive, quality assurance issues, manufacturability, welding, materials, cleaning, handling, how to work with vacuum equipment and getting discipline, testing, course wrap-up, literature recommendations.

Packaging of Cryogenic Systems

W.J. Schneider
TJNAF, U.S.A

Introduction and Overview

- Packaging Cryogenic Components
  - Superconducting Magnets
    - Characteristics
    - Accelerator Magnets
    - Detector Magnets
    - Magnet leads
    - Magnet lead Cans
  - Superconducting Cavities
    - Characteristics
    - Temperature/Frequency/Shields
    - Drift Tube Cavities
    - Elliptical Cavities
    - Couplers
    - Waveguides
  - Transfer Lines
    - Primary Lines
    - Secondary Lines

Fundamentals

- Specific Heat
- Thermal Expansion
- Modes of Heat Transfer
  - Radiation
    - Heat Shields
  - Convection
    - Gaseous Conduction
  - Conduction
    - Multilayer Insulation (MLI)

Heat Stationing
Calculations
Minimization of the overall Heat Load

Design of Cryostats

- Superconducting Magnets
  - Accelerator
  - Experimental
- Superconducting Cavities
  - Drift Tube/ Spoke

  - Elliptical
- Feed or end cans
- Transfer lines
- Types of Cryostats supports
  - Rod
  - Post
  - Fiberglass straps
  - Anchors
- Types of Cryostat Assembly
  - Axial
  - Radial
  - Bath Tub
  - Flange or welded

CEBAF Experience

- Packaging Cryomodules
  - Original Cryomodules
    - Cavity Assembly
    - Cyounit Assembly
    - Cryomodule Assembly
    - End Cans
  - SNS Cryomodules
    - Cavity Vessel String
    - Cryomodule Assembly
    - End Cans
    - Couplers
  - Upgrade Cryomodules
    - Cavity Vessel String
    - Cryomodule Assembly
    - End Cans
    - Waveguides

- FEL Mirror Cooling
  - Static Heat Loads
    - Radiation
    - Convection
    - Solid Conduction
  - Dynamic Heat Load
    - Helium Cooling
- Review
- Miscellaneous Topics
- Alignment
  - Fiducialization
- Design of Pressure Vessels
  - Pressure Vessel Code
  - Safety

International Linear Collider (ILC)

Thomas J. Peterson
Fermi National Accelerator Laboratory
Batavia, IL, U.S.A

An international design effort began in 2005 to study a Tera electron volt (TeV) scale electron-positron linear accelerator based on superconducting radio-frequency (RF) technology, called the International Linear Collider (ILC). In early 2007, the design effort culminated in a reference design for the ILC, closely based on the earlier TESLA design which was led by the German accelerator laboratory, DESY. The ILC will consist of two 250 GeV linacs, each 12 km long, which provide positron-electron collisions for high energy physics research. Superconducting niobium RF cavities operating at 2 Kelvin, cooled with superfluid helium, will accelerate the particle beams. The ILC will also include positron and electron sources, damping rings, and beam delivery systems which provide the final focus of the colliding beams within a large experimental detector. The size of the accelerator and of the cryogenic system will be comparable to those of the Large Hadron Collider (LHC), which is now being commissioned at CERN near Geneva, Switzerland. The location of the ILC is not decided, but wherever it is built, ILC will be a large international effort. This talk provides a general description of the ILC accelerator design concept with an emphasis on some of the engineering challenges involved in building such a machine.

Superconducting Cavity

Amit Roy
Inter-University Accelerator Centre, New Delhi, India

In these lectures an introduction to superconducting cavities for acceleration of both electrons and heavy ions would be given. Starting from the necessity of a cavity as the accelerating element, the advantages of superconducting cavity would be brought out. Design of such cavities and the diagnostics and measurement of cavity parameters would be described. Control of cavities would also be considered.

Vacuum and Low Temperature Measurement Techniques – Personal Perspectives

Ganapati Rao Myneni
TJNAF, U.S.A

Liquefaction of noble gases very much depended on Vacuum Techniques (Dewar) during the early development stages of Cryogenics. Advancement of the new technologies such as ITER now very much depend on Cryogenics for maintaining clean Vacuum. Sensors and detectors are the eyes and ears of all the processes involved in the scientific advances and industrial production. I am pleased to share my personal perspectives on the Low Temperature and Vacuum Measurement Techniques as reflected in the following references.

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New Frontiers of Cryocooler Technologies

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Cryocoolers have become a viable and reliable option for meeting the moderate cooling needs of many devices and systems such as detector/ sample cooling, cooling of superconducting magnets etc. They are now seen as a competing technology to liquid cryogen based cooling systems. A variety of cryocoolers such as Stirling, Gifford-McMahon (G-M), Joule-Thompson (J-T) and Pulse tube (PT) coolers are now available for specific space or ground applications. Vigorous R&D efforts are on to develop novel coolers such as solid state optical coolers based on anti-Stokes fluorescence effects.

The most remarkable cooler technology that has made rapid strides in recent times has been Pulse Tubes. They are unique compared to other active type of coolers in that they have no moving parts at the cold end, giving higher reliability, lower vibrations, lower EMI and lower cost. The Basic type Pulse tube invented by Gifford in 1964 remained as a topic of intellectual curiosity due to the rather high cold end temperature of about 120K. The first major breakthrough in Pulse tube technology came with the introduction of an orifice and reservoir by Mikulin et al. in 1984, which made the cold end temperature go down below 77K. Exciting research and development activities worldwide resulted in more versions of Pulse tube coolers such Double inlet Pulse tube coolers, G-M and Stirling type Pulse tube coolers, multistage and hybrid versions etc giving lower cold end temperature and higher wattage. 1 W at 4.2 K coolers are now available for cooling of NMR magnets, MRI applications, pre-cooling of dilution refrigerators and SQUID magnetometers. High efficiency linear motor driven pulse tube coolers have found a place for space applications due to their higher reliability compared to other types of coolers. The lowest the attainable pulse tube cold end temperature has come down to 1.78K using ^{3}He as working fluid. The success in the development of new regenerator materials having high volumetric heat capacity below 10K has contributed significantly in the development of Pulse tube coolers and G-M coolers of the class 4.2 K and below.

New frontiers of Pulse tube technology have been opened by the success of these systems for helium re-condensation/liquefaction. A 4K pulse tube system is operating for the past two years at Amundsen-Scott research station at South Pole to re-liquefy the boil off helium gas from a 4000 litre storage tank and to provide 2.7 litres /day of liquefied helium for external use. While these helium liquefiers are of low frequency G-M pulse tube coolers which have to use inefficient oil lubricated helium compressors for pressure wave generation, an attempt is on the anvil to use a hybrid of oil free linear motor compressor based high frequency pulse tube coolers and a two stage oil free linear motor compressor driven J-T system. This system is expected to give unparalleled reliability and operation at high efficiency.

Cryogenic System - Automation and Control

Dana M. Arenius
TJNAF, U.S.A

This course will outline the key fundamental control components and provide some practical incite on the design, engineering design standards, fabrication, assembly, and operation of helium plants down to 4 K and sub lambda 2 K plants.

The Course Outline includes the following elements:

Lecture One- Introduction and Overview – Provides an overview of the typical helium cryogenic plant subsystem equipment and their supportive roles. These subsystems include gaseous helium storage, helium gas purification, warm helium gas compression, oil removal, gas inventory management, refrigerator “cold box”, cold compressors, liquid storage vessels, cryogenic piping distribution, and cryostats. An emphasis is placed for developing system cost effective control design goals which that effective process cycle efficiency, stability, reliability and safety for the many modes of operation which will be encountered.

Lecture Two- Fundamentals – Looks at practical control component selection, engineering standards and specification of motor control, temperature, flow, pressure, liquid level and purity measuring components used for each of the major subsystems. Practical installation techniques for the components are presented along with considerations given to subsystem safety interlocks, maintenance requirements and failure mode analysis.

Lecture Three- Control Schemes- Provides a fundamental review of control loop mode controllers and the latest control loop scheme designs for integrated system control. Special attention is paid to the control of the refrigeration system pressure, refrigerator reciprocating /turbine expander engines and centrifugal cold compressors for sub lambda operation. Automation, operator intervention interface, data logging, alarm function, and safety shutdown functions examples are presented

Lecture Four- Review and Special Topics- An overview review of the course topics is presented and the participants are encouraged to participate in open discussion and questions concerning the course presentation and special topics/questions which come to light within the course.

Heat Exchangers

Sunil Sarangi
NIT, Rourkela, India

History of KEK on Accelerator Programme

Shin-ichi Kurokawa
KEK, Japan

Superconducting Magnets

E. Todesco
Accelerator Technology Department, CERN, Geneva

Main parameters of superconducting magnets for accelerators

1.1 Principles of a synchrotron: accelerating structure, circular parts, insertions, types of magnets and their function in the machine

1.2 Main parameters of magnets in an accelerator: relation field-energy-length, examples from several high energy physics accelerators, dependence of the size of the beam pipe on the accelerator parameters

1.3 How to produce magnetic field with windings, limits of the normal conducting technique, hints on iron dominated magnets, advantages given by superconductivity

1.4 Hints on superconductivity, brief historical overview, type I and type I superconductors, flux pinning, critical surfaces

1.5 Electromagnetic design: the case of a Nb-Ti dipole, relation field-aperture-coil width, extension to Nb_3Sn

Practical superconductors, forces and mechanical structures

2.1 Practical superconductors: multifilament wires and their physical motivations

2.2 Fabrication of multifilament wires for Nb-Ti and Nb_3Sn

2.3 Cable manufacturing and insulation

2.4 Electromagnetic forces

2.5 Mechanical structures

2.6 Magnet assembly

Stability, Quenches, Training and Protection

3.1 Stability, flux jumps and how to control instabilities

3.2 Classification of quenches, conductor limited and energy deposited quenches

3.3 Cryogenic stabilization

3.4 The training phenomena

3.5 Hints on protection

Superconducting Cyclotron at VECC, Kolkata

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Variable Energy Cyclotron Centre, Kolkata, India

The Variable Energy Cyclotron Centre at Kolkata is a premier institute working in the field of advanced accelerator technology development for basic and applied research. This Centre indigenously constructed the first large accelerator in the country - the room temperature variable energy cyclotron (VEC) with K=130. It was commissioned in 1977. Subsequently, this cyclotron was equipped with Electron Cyclotron Resonance (ECR) heavy ion sources and a variety of beams were provided to the experimentalists. About ten years ago, VECC took up a more challenging project of developing the first superconducting cyclotron (K=520) in the country. The cyclotron is now at the commissioning stage. Most of the sub-systems are installed and tested. This cyclotron will provide fully stripped ion beams with maximum energy up to ~80 MeV/nucleon and very heavy-ion beams up to ~10 MeV/nucleon. The basic design features are similar to the superconducting cyclotrons operating at Michigan State University and Texas A&M University in USA. In this presentation, primarily, a detailed account of construction, commissioning and operational experience with the 100 tonne superconducting magnet of the cyclotron as well as associated systems will be described.

The main component of the superconducting cyclotron is a pill-box type dipole magnet with a cylindrical iron structure energized by superconducting Nb-Ti coil, operating at liquid helium temperature. It produces high magnetic field to bend the charged particle beam which spirals out as energy of the beam increases. The energy is given to the beam by radiofrequency electric field produced by RF resonating cavity and electrode, conventionally called ‘Dee’. At the outermost orbit the beam is pulled out of the cyclotron with the help of electrostatic deflector and magnetic channels.

Main Magnet Iron Frame

The 80 Tonne magnet iron structure is about 2.18 m in height and 3.04 m in diameter. It has 3 spiral pole tips installed on circular plate called pole-base and an annular yoke. The iron geometry has reflection symmetry about the median plane. The composition of the magnet iron has been, largely, made from same heat of steel to ensure uniformity in chemical composition, physical homogeneity and grain size. Carbon percentage in various parts of the frame has been limited to about 0.1%

Superconducting Coil

The magnet is energized by two sets of coils made of superconducting Nb-Ti wire operating at near 4.5K temperature. Conventionally, the smaller coils are called as α-coils (nearer to median plane) and the bigger coils are called β-coils.

The coil winding was done at VECC using an automatic winding set up. Nb-Ti multifilamentary composite superconducting cable (critical current = 1030 A at 5.5 Tesla and 4.2 K), consisting of 500 filaments of 40 micron diameter embeded in copper matrix was used. The coil, wound on a SS316L bobbin, was then covered with annular outer wall and median plane inserts were welded to complete the liquid helium chamber.

Cryostat

The cryostat houses the superconducting coil in a bath of liquid helium operating at 1.2 bar absolute pressure and 4.5K temperature. The cryostat consists of two concentric annular chambers – the liquid helium chamber (bobbin) and the vacuum chamber (coil tank).

Superconducting coils wound on SS bobbin

Bobbin is an annular housing made of stainless steel (SS316L). The α and β coils are wound on its inner wall and the outer walls are welded to enclose the chamber. The liquid helium volume within the coil is about 300 litres and above the coil is about 40 litres. Seven level sensors read the helium level within and above the coils.

The bobbin is surrounded by another annular chamber called the coil tank. This chamber works as the vacuum enclosure for the bobbin. It is made of low carbon steel. A copper (CDA 110) radiation shield is placed in between the bobbin and the coil tank. It is cooled by liquid nitrogen flowing through the tubes soldered to its ends. The operating temperature of the shield is within 80-90 K. The bobbin along with the coil, weighing about 7 tonnes, is supported inside the coil tank by three horizontal and six vertical support links made of glass epoxy material (scotch ply). There are three ports at the top of the cryostat for connecting the current leads, helium lines and safety devices to the helium chamber. There are also three ports at the bottom for liquid nitrogen supply, vacuum pump connection and over-pressure safety flange connection.

Twenty radial penetrations in the median plane of cryostat to access the beam space from outside are provided. Various beam extraction and diagnostic devices like magnetic channels, deflectors, beam probe etc. pass through these penetrations to guide the beam to the desired path and finally extract from cyclotron through exit port.

Cryogenic Plant and Cryogenic Delivery system

Liquid helium and liquid nitrogen are required to be circulated for cooling the superconducting coil assembly in the cryostat and cryopanel assemblies in the cyclotron vacuum chamber. The cryogenic systems will operate in three different modes – cool down, steady state and warm up modes. During cool down the required flow rate of cold helium gas is approximately 10 gm/sec. The heat load of cryogenic systems including the transfer loss at steady state is approximately 117 Watts at 4.5 K. Specifications of the liquid helium plant are shown in the following table:

Mode of operation	*Without* *LN precooling*	*With* *LN precooling*
Refrigerator	160 Watts at 4.5 K	200 Watts at 4.5 K
liquefier	50 litres/hr	100 litres/hr
Cold helium gas supply	9.2 g/sec at 4.4K and 1.2 bar	10.9 g/sec at 4.4K and 1.2 bar

Liquid nitrogen is required for radiation shield of the cryostat and chevron baffles of the cryopumps to reduce radiation loss significantly. Liquid nitrogen requirement for these systems is about 115 litres/hr. For pre-cooling of the helium liquefier, another 100 litres/hr liquid nitrogen is required. Vacuum jacketed and liquid nitrogen shielded transfer lines suppliy the cryogens to different systems.

Commissioning of the Superconducting Magnet

Prior to cool down, moisture level in the bobbin was reduced from about 10000 ppm to below 10 ppm by repeated purging and heating cycles. Commissioning work was started by cooling down the bobbin and filling it up with liquid helium. The temperature at four different places of the coil was monitored on-line as a check to keep their maximum difference within 50K so that the thermal stress is kept under acceptable limit.

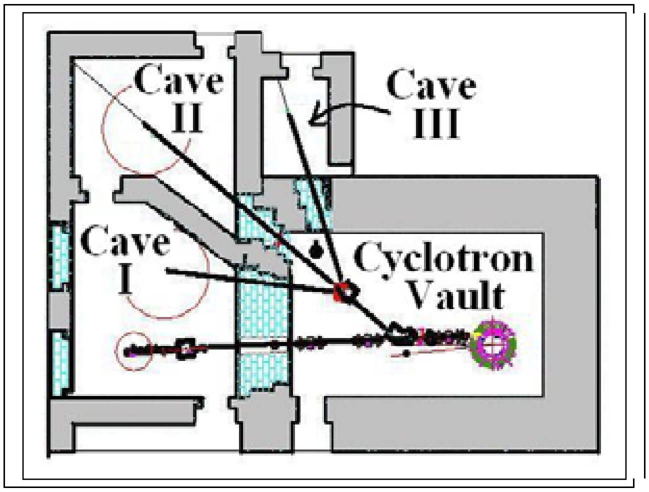
As the temperature of the bobbin reduces the forces on the support links increase. These forces were monitored continuously during the cool down process and the horizontal links were adjusted to keep the forces within 3200 Kg (~7000 lbs). When a steady state condition was achieved, the energization process was started. All the safety interlock systems were tested by forcing the coil current decay through slow and fast dump resistors. The coil was centered with respect to the magnet iron by adjusting the horizontal support links in such a way that all horizontal link forces drop down approximately by the same rate as the current increase. Several iterations were required for coil centering process and adjustment of plant parameters before reaching almost design current (~700A) in both α and β coils. Successful commissioning of the main magnet was completed in February 2006. Subsequently, elaborate magnetic field measurement were carried out and analysis of the data showed that the coil centering had been done satisfactorily.

RF system

The room-temperature RF system consists of three ½-wave resonator cavities powered by 80 kW RF amplifiers coupled by coupling capacitors. The cavities operate partially in high vacuum (~1x10^{-7} mbar) and partially in air. The operating frequencies vary from 9 to 27 MHz depending upon charge/mass and energy of the beam. The three accelerating dees are placed 120^0 apart at the cyclotron median plane and operate at 90 kV dee voltage. The space between the upper and lower liners forms the beam acceleration space where a high vacuum of the order of $1x10^{-7}$ mbar is maintained.

Injection and External Beamlines

Two ECR ion sources are being installed in the high bay of the superconducting cyclotron building to feed low energy beams in to the cyclotron. Layout of the experimentalists' beam lines is shown in the figure below. There will be two experimental caves for nuclear physics research and one for multidisciplinary research. There is also provision of future extension. Several experimental facilities, some of them utilizing cryogenic systems, are being developed for carrying out experiments in nuclear and allied sciences.



Schematic of external beam lines and caves for experiments

Present Status of ITER and Role of ITER - INDIA

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SUPPORT FROM CRYOGENIC & VACUUM INDUSTRY