European Cryogenics Days & Cryogenic Heat and Mass Transfer Workshop 2025

Monday 27 October 2025 - Thursday 30 October 2025

University of Twente

Book of Abstracts

Contents

Poster session / 1

Towards Economic Zero Boil-Off Technology for Liquid Hydrogen Storage

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Hydrogen is increasingly recognized as a cornerstone of the transition to sustainable energy systems. Storing hydrogen in liquefied form (LH_2) is particularly advantageous due to its relatively high energy density and scalability for storage and transport. However, managing boil-off rates (BOR) during storage and transportation remains a significant challenge. Hydrogen boil-off leads to safety concerns, environmental impacts, and economic losses, highlighting the critical need for zero boil-off (ZBO) systems. Depending on the size and application, the BOR ranges from 0.05–0.2% per day for large-scale, stationary, spherical storage tanks (>500 m^3) to 0.3–1% per day for stationary cylindrical vessels (1–100 m^3), and even up to 1.5% per day for 0.1 m^3 tanks typically used in mobile applications.

Advances in passive insulation technologies, such as vacuum-insulated multi-layer insulation (MLI) and variable density MLI (VDMLI), have shown potential to reduce BOR further compared to conventional vacuum-perlite. However, passive measures alone are insufficient due to the high liquefaction energy costs (˜30% of hydrogen's energy capacity) of LH2. This underscores the need for active cooling systems to achieve ZBO in LH_2 storage and transport applications. While existing ZBO systems in aerospace demonstrate feasibility, their high energy requirements and costs limit large-scale industrial deployment.

An in-depth review of the current state of LH_2 storage technologies was conducted, focusing on BOR mitigation strategies and their limitations. A framework for the design and development of economic ZBO systems is proposed, with an emphasis on bridging the gap between laboratory-scale solutions and practical implementation. This work is part of the HyTROS program under the Dutch GroenvermogenNL initiative to advance hydrogen storage and transport technologies.

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Poster session / 2

Quantum Machine Learning for Enhancing Cryogenic Fluid Simulations through Quantum Physics-Inspired Models

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Abstract

Quantum Machine Learning (QML) is increasingly vital for modeling and optimizing cryogenic systems, particularly those involving liquid hydrogen in aviation, quantum technologies, and large-scale scientific experiments \[1,5,7]. By leveraging quantum physics-informed AI—such as Physics-Informed Neural Networks (PINNs) and Geometry-Aware Operator Transformers (GAOTs)—QML enables accurate simulation of low-temperature heat and mass transfer processes, critical for cryocooler design, storage, and transport systems \[5].

In aerospace, QML enhances predictions of thermofluidic behavior under extreme cryogenic conditions, improving safety, efficiency, and anomaly detection in hydrogen-based propulsion and storage systems \[5,8]. These models also optimize mesh generation and turbulence modeling in computational fluid dynamics (CFD), reducing computational costs while increasing predictive accuracy.

Cryogenics underpins quantum computing, where maintaining coherence in superconducting qubits requires precise thermal control. QML assists in simulating quantum dynamics and optimizing cryostat performance and error mitigation strategies \[2,6,7].

In large-scale scientific infrastructures, including high-energy physics and quantum experiments, QML accelerates materials discovery and infrastructure design by solving complex optimization problems \[1,3,4]. The intersection of QML and cryogenics is thus driving advances in simulation fidelity, thermal management, and cross-domain innovation.

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\[8] https://eng.ox.ac.uk/cryogenic-fluid-dynamics-lab/research/liquid-hydrogen-and-other-cryogenic-energy-carriers/

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Cryocooler Development for the Einstein Telescope Pathfinder

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The Einstein Telescope (ET), the next-generation underground gravitational wave observatory, demands unprecedented sensitivity to detect spacetime distortions. A critical component in achieving this sensitivity is the cryogenic cooling of its mirror systems to temperatures near 10 K. However, conventional cooling methods introduce mechanical vibrations that can compromise the interferometric measurements. To address this, a consortium comprising the University of Twente, Demcon kryoz, and Cooll has developed a zero-vibration cooling system tailored for the ET. This system leverages sorption-based cryocooling technology, originally developed for space applications, which operates without moving parts and thus eliminates vibration sources. The cooling process is achieved through thermally-driven adsorption-desorption cycles, enabling continuous operation at cryogenic temperatures without mechanical disturbance. The mirrors are cooled via thin suspension wires, ensuring thermal conduction while maintaining mechanical isolation. The innovation not only meets the stringent thermal and mechanical requirements of the ET but also sets a new benchmark for vibration-free cryogenic systems in precision instrumentation. This development is currently being validated at the ETpathfinder facility, a prototype setup designed to test key technologies for the Einstein Telescope.

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Cryogenic Composite Fuel Tanks For Space Applications

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The design and performance validation of composite overwrapped pressure vessels (COPVs), particularly Type-3 and Type-4 cryogenic tanks, are critical for space and defense applications where weight, thermal stability, and pressure resistance must be optimized. Among the most influential process parameters determining composite integrity are the resin-binder ratio, winding orientation, and curing temperature—each affecting the microstructure, interfacial adhesion, and residual stress behavior of the carbon fiber (CF)-reinforced laminate. To systematically study the complex interplay between these variables and to optimize the overwrap configuration for cryogenic performance, this study proposes a Design of Experiments (DoE) approach using the Box-Behnken design (BBD) methodology.

The Box-Behnken design is an efficient, second-order, response surface methodology that enables the investigation of multiple variables with reduced experimental runs compared to full factorial designs. In this study, BBD is employed to generate statistically robust datasets using three independent variables: (1) resin-binder ratio (wt. %), (2) winding orientation angle (±θ degrees), and (3) curing temperature (℃), with the objective of achieving optimal interlaminar shear strength (ILSS) and cryogenic tensile strength. Each experimental condition produces a specified composite thickness, similar to actual tank overwraps. The output responses include strength retention after cryogenic exposure, microcrack density, and visual delamination indices, enabling a comprehensive understanding of how manufacturing parameters influence mechanical performance.

To ensure that the mechanical behavior observed is representative of actual Type-3 and Type-4 cryogenic pressure vessels, this methodology involves winding CF over real metallic (Type-3) or polymer (Type-4) cylindrical liners, followed by controlled curing and consolidation under conditions that replicate real manufacturing setups: including fiber tension control, consolidation force, and dome transition angle geometry. Once cured, the cylindrical COPVs are axially cut into flat coupons to produce tensile specimens with real overwrap architecture. These specimens are subjected to mechanical testing in cryogenic environments using LOX (90 K), LN_2 (77 K), and LH_2 (20 K) as the temperature mediums. The resulting stress-strain behavior provides key insight into crack propagation, delamination patterns, and fiber-matrix interaction under thermal shock and contraction-induced stress fields.
The use of Box-Behnken design in this context offers several advantages. Firstly, it reduces the number of experimental iterations required to understand the main and interaction effects of critical variables, thereby saving material cost, curing time, and liquid cryogen resources. Secondly, BBD enables the generation of predictive models that can interpolate the mechanical performance at intermediate parameter values, making it possible to optimize combinations without exhaustive physical testing. Additionally, this structured statistical approach ensures repeatability and reproducibility, two critical attributes for qualification in aerospace-grade cryogenic vessels.
In a domain where each winding trial and curing cycle can be both time-intensive and cost-prohibitive, the implementation of such a DoE-driven strategy significantly accelerates the R&D cycle, guiding material scientists and process engineers to quickly converge on the most promising configurations. The microstructural analysis of cryogenically fractured specimens, coupled with stress modeling and microscopy, can validate the interfacial performance and predict long-term durability in service conditions.
As a conclusive remark, the experimental framework outlined here offers a cost-effective, scalable, and statistically rigorous pathway to determine the optimal carbon fiber overwrap conditions for cryogenic tanks. By mimicking actual tank construction, it bridges the gap between laboratory coupon testing and full-scale component qualification. This methodology empowers the industry to make data-driven decisions in selecting materials and processes that maximize performance, reliability, and safety of composite pressure vessels under cryogenic conditions. Ultimately, it aids in product translation, reducing trial-and-error costs, and enhancing the commercial readiness of indigenous Type-3 and Type-4 tank technologies for high-stakes applications in aerospace, defense, and cryogenic transport systems.

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The World's First Integrated Liquid Hydrogen Supply Chain: Innovation at Amsterdam Port

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As the demand for clean energy carriers grows, liquid hydrogen (LH_2) is gaining strategic importance—particularly in sectors such as maritime transport and port logistics, where energy density and cryogenic handling capabilities are critical. At EcoLog, we are leading the development of a large-scale LH_2 import and distribution terminal in the Port of Amsterdam, supported by advanced cryogenic storage and cargo handling systems for seagoing vessels and on shore terminals, developed by Gas and Heat.

This presentation will provide both strategic and technical insights from the Amsterdam project, covering infrastructure planning, investment strategy, and the key engineering decisions driving system scalability and safety. Topics will include LH_2 storage tank design, boil-off gas management, maritime refuelling interfaces, and integration with broader hydrogen value chains. We will also highlight the role of cross-sector partnerships, regulatory alignment, and modular infrastructure design in accelerating deployment timelines and ensuring commercial viability. Our experience offers practical lessons for stakeholders aiming to bridge the gap between demonstration projects and fully operational hydrogen infrastructure.

This session will be of particular value to cryogenics researchers, engineers, and industry leaders involved in hydrogen logistics, infrastructure development, and energy transition strategy.

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Poster session / 10

Design and Optimization of Miniature Regenerators for Pulse Tube Cryocoolers using REGEN3.3

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Co-authors: Jan G Korvink [1]; Jürgen J Brandner [1]

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Regenerators are an integral part of regenerative-type cryocoolers, such as pulse tube, Gifford-McMahon cryocoolers, etc. The main function of a regenerator is to store and release heat during the cyclic operation of cryocoolers. The performance of the regenerator directly influences the performance of the cryocooler. Therefore, regenerators should be designed and optimised carefully. The objective of the present study is to design and optimise the parameters, such as inverse mass flux, phase angle, aspect ratio of regenerator, etc. For this purpose, a well-established one-dimensional code, REGEN3.3, is used. The coefficient of performance obtained for various operational and geometrical parameters from REGEN3.3 is used for finding the optimum values. The range of parameters is carefully chosen so as to keep the values of operational parameters within practical range. Frequencies from 60 Hz to 120 Hz are used in the simulations, since the commercial compressors provide this frequency range. The targeted cold-end temperature is 80K. #635 SS-304 woven screen matrix is selected as the regenerator material. The results show that different optimum values were attained at 60 Hz, 80 Hz, 100 Hz and 120 Hz for various phase angles, and inverse mass flux. The obtained results can be helpful to the designers of cryocoolers.

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Liquid hydrogen developments at Rotterdam The Hague Airport

Author: Daan van Dijk[None]

Rotterdam The Hague Airport is at the forefront of sustainable aviation developments through its efforts in liquid hydrogen infrastructure. As part of the EU TULIPS consortium, the airport has initiated small-scale demonstrations for the storage and refueling of liquid hydrogen on the airside, supported by comprehensive safety studies and risk assessments. Next to that, the airport is involved in the EU GOLIAT consortium. In this project, the HY4 (H2FLY) aircraft will be redueled with liquid hydrogen. A temporary refueling site will be developed at the airport to support this process. In collaboration with major industry players such as Air Products, Airbus, and KLM, the airport is also contributing to the development of a national hydrogen hub aimed at decarbonizing the aviation sector

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Poster session / 18

Assessment of Open-Source simulation in cryogenic LNG re-liquefaction

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Co-authors: Gabriel Hernandez Rozo [2]; Isaias Surgek Almeida [3]; Luís Assunção [4]; Nicolas Spogis [5]

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The cryogenic re-liquefaction of Boil-Off Gas (BOG) is a critical step in LNG infrastructure, where methane vaporized due to unavoidable heat ingress must be recovered to mitigate energy losses and reduce greenhouse gas emissions. Methane's high global warming potential—over 80 times greater than that of CO_2 over a 20-year horizon—makes its release particularly concerning from both environmental and regulatory standpoints. Consequently, efficient BOG re-liquefaction systems are essential for improving the sustainability and economic performance of LNG operations. This study evaluates the applicability of DWSIM, an open-source process simulator, for modeling and optimizing cryogenic refrigeration cycles dedicated to BOG re-liquefaction. Two classical cycle configurations, Claude and Kapitza, were implemented using operational parameters extracted from the reference study by Moon et al. (2007). The Coefficient of Performance (COP) was used as the primary indicator for thermodynamic efficiency and model fidelity. Simulation results demonstrated excellent agreement with published data: the Kapitza cycle yielded a COP of 0.180, closely matching the reported value of 0.195, while the Claude cycle produced a COP of 0.170, in comparison with the literature value of 0.180. These results confirm the reliability of DWSIM in reproducing complex cryogenic processes under realistic operating conditions. Following the validation phase, a comprehensive process optimization strategy was applied. A Design of Experiments (DOE) framework based on Latin Hypercube Sampling (LHS) was employed to systematically explore the input variable space. The resulting dataset was used to train a Multi-Layer Perceptron (MLP) model capable of approximating the system's behavior across a wide range of conditions. Subsequently, a multi-objective optimization routine was performed on the trained surrogate model to identify optimal operating points that balance performance and energy consumption. This integrated methodology—combining open-source simulation, statistical design, and machine learning—provides a robust and scalable framework for process analysis and improvement in cryogenic engineering. The approach is particularly valuable for research institutions and small-to-medium enterprises (SMEs), where access to commercial simulators may be limited. Additionally, the flexibility and transparency of open-source tools like DWSIM enhance reproducibility and enable seamless integration with external analytical platforms. In summary, the study demonstrates the technical soundness of DWSIM in modeling and optimizing LNG BOG re-liquefaction cycles, highlighting its potential as a low-cost and reliable alternative for advanced cryogenic process development.
Keywords: Boil-Off Gas, LNG, Cryogenics, DWSIM, Re-liquefaction, Multi-Layer Perceptron, surrogate model

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A liquid hydrogen, fuel cell electric plane: the future of aviation

Author: Davide Mangini[1]

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AeroDelft is a student-led team working to demonstrate the potential of liquid hydrogen as a sustainable aviation fuel. To do this, the team is retrofitting a Sling-4 aircraft with a hydrogen-electric powertrain. Two hydrogen storage systems are under development: a 700-bar compressed hydrogen system, planned to fly in the 2025/26 academic year, and a cryogenic liquid hydrogen (LH_2) system, targeted for flight the year after.

This abstract focuses on the cryogenic system, which is being designed to store, condition, and deliver liquid hydrogen to a fuel cell onboard the aircraft. The system is divided into three main subsystems: storage, conditioning, and distribution.

The storage subsystem keeps hydrogen in its liquid state at around 20 K. The tank is vacuum-insulated with multilayer insulation (MLI) to reduce heat leak, which is expected to be in the range of 10–50 W, while maintaining a weight between 20 and 40 Kg. The design also ensures structural integrity under all flight conditions. Liquid-phase extraction was chosen over gas extraction, as it offers better scalability for future, higher-power systems.

The conditioning subsystem prepares the hydrogen for the fuel cell by bringing it to the right temperature and pressure. A plate heat exchanger, using the fuel cell's waste heat, is used to evaporate the LH_2 and heat the gas from 20 K up to around 323K. The heat exchanger has two stages: an evaporator to handle the latent heat of vaporization and a superheater to raise the gas temperature. The system is designed for a nominal mass flow of 3 g/s.

The distribution subsystem transports hydrogen to the fuel cell with minimal thermal losses and pressure drop. This is done using vacuum-insulated piping to avoid condensation and reduce heat ingress. Fitting the system within the tight space available in the aircraft, while keeping it efficient and reliable, has been one of the major design challenges. Integration of flow sensors, valves, and control components is especially difficult due to the lack of compact, lightweight components rated for cryogenic hydrogen.

Developing a liquid hydrogen system for an aircraft introduces several complex engineering problems, from thermal management to mechanical integration. This work presents a practical, student-built solution for small-scale aviation and aims to contribute to the growing field of hydrogen-powered flight.

This project is part of AeroDelft's ongoing efforts in hydrogen-electric propulsion and has been made possible thanks to the support of our advisors, industry partners, and partners

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Cryogenic Challenges in Infrared Astronomy: The METIS Experience

Authors: Mirka Maresca[1]; Dirk Lesman[1]

[1] *NOVA optical infrared instrumentation group at ASTRON*

The Mid-infrared ELT Imager and Spectrograph (METIS) is one of the first-generation instruments being developed for the Extremely Large Telescope (ELT). It will observe in the 3–13 μm wavelength range, which is key for studying faint thermal emission from astronomical sources like exoplanets and distant galaxies. To detect such faint signals, METIS needs a cryogenic environment that reduces thermal background and ensures reliable performance of infrared detectors, which operate most efficiently at very low temperatures, typically between 35 K and 70 K.
METIS is being developed by a consortium of international institutes, with NOVA (the Netherlands Research School for Astronomy) acting as the Principal Investigator (PI) institute. In addition to its coordinating role, NOVA is also responsible for the Core Fore Optics (CFO), which is the front-end cryogenic optical METIS subsystem. The CFO includes several optical components and mechanisms - such as filter wheels, fold mirrors, and alignment stages - which direct the beam towards either the imager or the spectrograph, and allow for various observation modes. These mechanisms operate in a cryogenic environment and must maintain high precision and reliability under low-temperature conditions.
The large cryostat that houses the cryogenic system is designed and built by ETH Zurich. It provides the required vacuum environment for the cold subsystems, contributes to the mechanical stiffness and alignment of the instrument, and supplies the necessary cooling to the optics and detectors. The cryostat is designed for partial access to the internal components, which is important for integration and maintenance.
The overall thermal design of the cryogenic system of METIS uses a staged approach. First, a liquid nitrogen (LN_2) system is used for pre-cooling during cooldown. This is followed by active cooling with several pulse tube cryocoolers (PTCs), which bring the system down to its final operating temperature and maintain it during steady-state operation. The design aims to minimize thermal loads and temperature fluctuations to ensure stable performance.
In this talk, we will focus on the cryogenic aspects of METIS. We will present the main features of the cryostat, describe the thermal design and cooling strategy, and show examples of internal mechanisms operating at cryogenic temperatures. The aim is to provide an overview of the cryogenic system and highlight some of the technical challenges involved in developing and operating a mid-infrared instrument like METIS.

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Poster session / 21

ELECTRIC DRIVEN AND LOW HEAT LOAD VALVES FOR LIQUID HELIUM APPLICATIONS

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ABSTRACT- POSTER
Electric driven and low heat load valves for liquid helium applications

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As the energy sector advances toward greener and more efficient technologies, liquid helium is playing a central role in enabling high-performance cryogenic systems. Its use is critical in superconducting applications for particle physics, fusion research, and high-tech industries such as semiconductors and quantum computing. However, the extreme sensitivity of liquid helium to heat makes low heat load valve design a fundamental requirement for system efficiency and reliability.
Even minimal heat ingress can cause significant helium evaporation, leading to increased consumption, higher refrigeration demands, and elevated operational costs. Therefore, low heat load valves are essential to:
• Minimize evaporation of valuable cryogenic fluid.
• Maintain ultra-low temperatures (around 4.2 K or -269℃) required for superconducting performance.
• Reduce refrigeration power, lowering energy consumption and environmental impact.
• Ensure system safety and stability, avoiding pressure build-up due to heat-induced boil-off.
• Enable precise flow control, critical for scientific and industrial cryogenic processes.
To meet these demands, AMPO POYAM VALVES has developed a next-generation cryogenic valve concept that combines advanced thermal design with smart electric actuation. The valve architecture includes:
• Optimized stem lengths, thin-walled components, and bellows to minimize conductive and radiative heat transfer.
• High-integrity sealing systems to reduce emissions and ensure tightness under extreme conditions.
• Optimized flow geometry for accurate and stable helium control.
• Boaflex-inset design for easier and more flexible piping integration.

• Parachute double sealing system either for gland other bellows sealed stems alternatively mountable in the same body

At the core of this innovation is AMPO's electric actuation system, based on stepper motor technology with an integrated electronic fail-safe mechanism. This solution offers:
• Precise, repeatable positioning for accurate flow regulation.
• Low energy consumption, contributing to overall system efficiency.
• Plug-and-play integration, eliminating the need for complex pneumatic infrastructure.
• Enhanced safety, with electronic fail-safe functionality ensuring secure operation in case of power loss or system failure.
According to the EnEffAH study, traditional pneumatic systems operate at only 6–15% efficiency, with significant energy losses in compression and distribution. AMPO's electric solution not only overcomes these inefficiencies but also reduces CAPEX and OPEX, while improving system compactness and maintainability.
This poster presents AMPO's comprehensive approach to cryogenic valve design for liquid helium applications, addressing the full range of thermal, mechanical, and operational challenges. The result is a high-performance, electrically actuated valve that supports the future of sustainable, high-efficiency cryogenic systems.

Keywords: Valves, Liquid Helium, Low Heat Load, Fine Flow Control, Innovative Flex Inset, fail safe electric actuation

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22

Quantum for the Curious: An academic minor to enhance quantum literacy for non-physics students

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Abstract
The quantum industry demands a diverse workforce with foundational quantum knowledge, extending beyond traditional physics specialists. To address this, the University of Twente developed Quantum for the Curious, a 15 ECTS minor introducing non-physics students to key quantum phenomena and technologies. Guided by the European Competence Framework for Quantum Technologies, the minor enhances scientific literacy and industry-relevant competencies. This talk introduces the minor, launched in 2024-2025, outlining its structure, objectives and key features. It will briefly reflect on highlights from the first year, including a lecture on cryogenics, and share initial impressions based on student feedback.

Introduction
The quantum industry requires a diverse and balanced workforce to enable its expected growth. People with a basic understanding of quantum physics principles can support the workforce, including those not directly involved in quantum technology development. [1,2] Their knowledge can aid decision-making processes, contribute to effective communication around quantum technologies, and assist in the design of related products. [3] It is a relevant educational pursuit across research and industry.

With this in mind, we developed a new minor program on quantum technology at the University of Twente, named 'Quantum for the Curious'. [4] A minor is a package of courses of usually 15 ECTS, which allows students to specialise or broaden their knowledge and competencies. The minor introduces non-physics students to key quantum physics concepts and emergent quantum technologies and applications. The minor promotes scientific literacy in quantum physics and provides essential knowledge and skills for industries increasingly using quantum technologies.

We designed the minor explicity for non-physics students, aiming to spark interest in quantum physics while exploring its emerging applications and technologies. Students are expected to master basic skills in linear algebra.

Design of the minor
We designed the minor Quantum for the Curious using the European Competence Framework for Quantum Technologies [5]. The framework defines three proficiency areas, namely (I) Quantum Concepts, (II) Quantum Technology hardware & software engineering, and (III) Quantum Technology applications & strategies. We've designed a 5 ECTS course for each proficiency area.

In the course "Quantum Concepts", the physics concepts behind quantum technology are introduced. Topics addressed are superposition, quantisation, entanglement, qubit states, operators, time-evolution and technology platforms.

The course "Quantum Technology Hardware and Software Engineering"addresses different enabling technologies, such as cryogenics, cleanroom technology, and measurement equipment. The students work on three experimental assignments: Quantum Key Distribution, Bell inequality violation, and NV-center qubits. Furthermore, the students work on two software assignments: quantum teleportation and a quantum algorithm.

The "Quantum Technology Applications and Strategies"course introduces different applications, business strategies, policies, didactics, and ethics. The students work in teams on a quantum project given by industrial or academic partners.

Oral presentation
This talk presents an overview of the minor Quantum for the Curious, which was launched in the academic year 2024-2025. I will outline the structure and objectives of the programme and highlight some distinctive features. Among these was a lecture on cryogenics, an enabling technology crucial to the functioning of many quantum systems. Drawing on student feedback and reflections, I will share some impressions on how the minor was received, and discuss ideas for further development.

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23

Cryogenic infrastructures challenges for quantum computing

Author: Simon Crispel[1]

Co-authors: Florian Martin [1]; Jean-Marc Bernhardt [1]; Loic Viguerie [1]; Mathieu Szmigiel [1]

[1] *Air Liquide Advanced Technologies*

Quantum computing has recently gained interest from industry, opening new fields of applications. Air Liquide Advanced Technologies, thanks to its experiences on low temperature systems and on Helium Refrigeration and Liquefaction systems for Physics and Industry, is actively developing solutions to address the many emerging challenges associated with Quantum Data Centers.
Recently, the challenges of scaling up various quantum computing technologies have been highlighted through the roadmaps of several major players. One key area of development is the need for increased cryogenic cooling power, which could be provided by helium refrigerators similar to those used to cool particle accelerator equipment or physics experiments.
This presentation will address the adaptation of solutions developed by Air Liquide Advanced Technologies over several years for industrial and scientific helium cryogenics applications. It will focus

on the upcoming needs of quantum computing, particularly in terms of energy efficiency, distribution, reliability, and operability leading to proposals of new cryogenic architectures.
These works are also part of collaborations that we will present with French academic partners who utilize these cryogenic technologies for their own needs and who, furthermore, possess experience and expertise in very low-temperature cryogenics.
By exploring these aspects, the presentation aims to contribute to the ongoing discourse surrounding the future of quantum computing and its integration into large-scale data centers, offering insights into the intricate challenges and innovative solutions within this burgeoning field.

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Poster session / 24

Multiphase cryogenic hydrogen fet flow: a numerical study

Author: Zhaoxin Ren[1]

[1] *Swansea University*

This research presents a numerical investigation into the multiphase behaviour of cryogenic hydrogen gas jets released into ambient air, with particular attention to the liquefaction of atmospheric water vapour induced by strong shear. The simulations are conducted using a computational fluid dynamics (CFD) solver developed within a finite volume framework, incorporating a hybrid Noble-Abel Stiffened Gas (NASG) equation of state to model multiphase thermodynamics. The study focuses on the effects of ambient humidity, which influences the amount of water vapour that condenses into liquid water, on the unsteady flow structures. Results reveal that accounting for the transient phase-change processes significantly alters vortex dynamics in the turbulent jet, thereby affecting hydrogen dispersion and multiphase mixing in the surrounding air.

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Poster session / 25

Application of neon pulsating heat pipes to cryocooler-based HTS magnets

Author: Quentin Gorit[1]

Co-authors: Andre Brem [1]; Carolin Zoller [1]; Henrique Garcia Rodriges [1]; Jaap Kosse [1]; Jacob Cornelis Maris [2]; Michal Duda [1]; Rebecca Riccioli [1]; Stephane Sanfillipo [1]; Yannik Studer [1]

[1] *Department of Accelerator Technology, Paul Scherrer Institut*

[2] *VDL ETG Technology & Development B.V.*

Cryocoolers are increasingly favored over baths or forced-flow cooling providing heat removal and thermal stability for magnets made of High Temperature Superconductor (HTS). Efficient heat transfer between magnet and cryocooler is crucial to the operation of such a system. Compared to conventional thermal buses, which are typically made of solid materials such as high-purity copper braids, the Pulsating Heat Pipe (PHP) -a passive device that operates through thermally induced two-phase flow- offers superior heat transfer performance at a reduced mass. PHPs are commonly constructed from a capillary sized tube bent in serpentine between an evaporator (in contact with the coil) and a condenser (in contact with the cryocooler). This configuration minimizes the bulk while allowing large areas of the magnet to be cooled. The tube is filled with a cryogenic fluid at saturation conditions. Heat is efficiently transferred by a combination of latent and sensible heat transfer mechanisms. In addition to being efficient, lightweight, and passive, it functions as an autonomous thermal bus and switch, capable to operate in zero-gravity, high-magnetic-field and high-radiation environments. For these reasons, the Paul Scherrer Institute (PSI), in collaboration with the VDL Enabling Technologies Group (VDL ETG), has launched a project to design, manufacture, characterize, and apply cryogenic PHPs for enhancing the cooling efficiency and reliability of cryocooler-based HTS magnets.

This contribution presents an overview of the project. The dedicated test stand, designed and commissioned at PSI, is first described. The experimental results of the manufactured and characterized PHPs using neon as working fluid are then analyzed and discussed, leading to the definition of optimal parameters and correlations to predict their performances. The numerical model, currently under development to improve performance predictions, is also presented. Finally, the first applications, to our knowledge, of neon PHPs to cool and operate insulated and non-insulated HTS coils are described, and results of experimental campaigns are presented, leading to a proof of concept.

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26

Closed-cycle mixed-refrigerant Joule-Thomson (MRJT) cryocoolers for InfraRed (IR) detectors

Author: Nir Tzabar[1]

[1] *CryoR ltd.*

Most IR detectors are currently cryocooled by Stirling type coolers, where long mission durations are required. Stirling cryocooling is a matured technology with proven capabilities by many manufacturers who suggest a wide variety of tactical coolers. System engineers learned how to integrate Stirling coolers and managing their disadvantages, mainly their size, the vibration and noise they induce, and the heat which must be removed from the warm side of the cold head and the compressor.
Closed cycle mixed-refrigerants Joule-Thomson (MRJT) cryocoolers, were first suggested in the 1970' s, and went through a long research and development process, to be suggested for tactical applications. MRJT coolers do not compete with the high efficiency of Stirling coolers (low power consumption), and the small size of the compressor; however, they benefit other major advantages.
MRJT coolers suggest the smallest cold heads, among other technologies, which allow miniaturization of the complete system. Furthermore, JT cold heads can be designed in different structures, rather than cylindrical cold fingers only, allowing new approaches for Dewar designs. The absences of moving parts at the JT cold head make it free of vibrations and noise emission. A vibration-free cold head is a well appreciated feature which already yielded the development of the Pulse-tube version of Stirling coolers, that doesn't have moving parts in the cold head, at the expense of efficiency and size. Additional advantage of MRJT coolers is the ability to locate the compressor far from the cold head (tens of meters), allowing high reliability, availability and maintainability.
The secret of MRJT is in the mixed refrigerant that holds the cooling potential, and the cold head that is designed to realize this potential. The composition of the mixed refrigerant is determined to comply with several requirements, mainly: the required cooling and ambient temperatures, and the operating pressures which are dictated by the compressor. High efficiency recuperator is essential for obtaining the desired cooling performances (temperature and power), where both high- and low-pressure streams are two-phase blends experiencing condensation and evaporation, respectively. The recuperators'effectiveness is defined by the heat transfer between the streams, while the pressure drop of the streams must also be taken into consideration. These two characteristics usually contradict each other, and a proper compromise must be accomplished. Miniature finned-tube heat exchangers are usually used in the recuperator, and the ability to make them from different raw materials and with different dimensions is crucial for obtaining efficient recuperators; and therefore, attractive JT cold heads.
At CryoR we develop state-of-the-art MRJT coolers, having the ability to design and manufacture mixed refrigerants, oil-free compressors, finned-tubes, miniature cold heads, and complete cooling systems. The ability to control every component of the cooler enables attractive integration in the system. In the current presentation we demonstrate the ability to design different MRJT coolers to comply with various system requirements.

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Poster session / **27**

Energy recovery from regassification of cryogenic liquids using isobaric expansion technology

Author: Sander Roosjen[1]

Co-authors: Alexander Kronberg [2]; Maxim Glouchenkov [2]; Sascha Kersten [1]

[1] *University of Twente*

[2] *Encontech B.V.*

The regasification of cryogenic liquids, such as liquefied natural gas (LNG), liquid hydrogen (LH_2), and industrial gases like nitrogen and oxygen, offers an unique opportunity for energy recovery during their transition from liquid to gas and subsequent gas heating to ambient temperature. Liquefaction of gases for their transport and storage occurs at extremely low temperatures and requires significant energy expenditure. However, most current regasification processes are largely passive and fail to recover any of the energy invested during liquefaction. This study presents a novel method to capture part of the lost energy by integrating Isobaric Expansion Engines (IEEs) into the regasification process
IEEs perform a simple and low-cost process. A gaseous working fluid at a low pressure is condensed when cooled by a cryogenic liquid. It is then compressed and heated by any available ambient heat, turns back into gas and produces useful work during isobaric expansion.
The system exploits the high temperature difference between the cryogenic liquid and the environment by utilizing an inert working fluid undergoing isobaric expansion, enabling energy recovery that directly offsets the energy-intensive nature of the liquefaction process. A thermodynamic evaluation of noble and inert gases; neon, argon, krypton, xenon, and nitrogen was conducted to assess their suitability as working fluids in this application. These gases exhibit properties together with acceptable safety profiles that make them ideal for energy extraction in IEEs. Heat regeneration was investigated that can increase recovery efficiency; the effect increases exponentially at larger temperature differences.
The study involved the development of a performance model comparing energy recovery efficiencies for each working fluid. The analysis demonstrated that the use of inert gases allows for the recovery of substantial portions of the original liquefaction energy when matched appropriately with the temperature profile of the regasification process. Notably, gases like argon and nitrogen offer an excellent balance between thermal performance and ease of handling. Neon, while thermodynamically attractive at ultra-low temperatures, poses practical limitations due to its narrow liquid range under moderate pressures. Xenon and krypton show a promise in higher-temperature stages of the regasification curve.
To maximize the efficiency of cold utilization, several methods can be employed, such as using an IE cycle with mixed working fluids instead of single-component ones, as mixtures can significantly enhance efficiency through improved heat regeneration. Another effective approach is the use of a cascade of several IE cycles, where multiple IEEs are arranged in series, each operating within a specific temperature range and utilizing an optimized working fluid.
The application of this technology aboard hydrogen-powered marine vessels was also explored. In such settings, recovered energy from LH_2 regasification can be reintegrated into the vessel's power management system, reducing auxiliary fuel consumption or enabling smaller hydrogen storage tanks. This is particularly important in marine transport, where space and energy density are critical.
Integrating IEEs into the cryogenic liquid handling process provides a meaningful step toward improving round-trip efficiency across the hydrogen and LNG value chains. While conventional hydrogen liquefaction processes consume around 10 –15 kWh/kg-H_2, the ability to recover energy during regasification can significantly reduce net energy costs. This aligns with global energy goals to increase the viability and sustainability of hydrogen and LNG as clean energy carriers. Furthermore, using inert, non-reactive working fluids mitigate safety risks.
The findings support the use of inert gases in both single and cascade IEE configurations, offering a technically feasible and scalable solution for energy recovery. As industries seek to decarbonize and enhance energy efficiency, the integration of IEEs presents a forward-looking strategy to reduce energy waste and improve the sustainability of cryogenic systems.

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28

Superconducting RF - some recent highlights and case studies

Author: Andrew Blackett-May[1]

[1] *UKRI-STFC Daresbury Laboratory*

Superconducting radio frequency cavities sit at the heart of modern high-energy particle accelerators. I will give a very brief overview of the current state-of-the-art, highlight some recent developments, and discuss a few current projects utilising SRF including ESS, HiLumi-LHC, and PIP-II.

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29

Cryogenics and superconductivity in high-tech industry

Authors: Aernout Kirsteman[None]; Mathijs van Gorcum[1]; Raymond Boersma[None]

[1] *VDL ETG*

Recent developments of high temperature superconductors (HTS) and cryogenic technologies make application of superconductivity in high tech industry attainable. Modern cryocoolers have enough cooling capacity for the application of ReBCO, which enables conduction-cooled vacuum systems to incorporate superconducting components. HTS tapes are available off-the-shelf from a variety of ReBCO tape manufacturers in lengths over 500m with predictable properties. The orders of magnitude increase in current density allowed by superconductivity enables several new applications, from motors and actuators to plasma containment in fusion, from MRI and NMR to high-voltage power transport.
Here we show the steps taken at VDL ETG to build knowledge and gain engineering experience with superconducting systems. We developed a conduction-cooled cryostat initially used to test different superconducting electromagnets. Based on the experience gained this culminated in a north-south magnet pair reaching 9.8T in the bore.
Building on this we are currently in the process of developing a linear actuator using a superconducting stator demonstrator. We'll discuss the lessons learned and challenges to overcome to finding superconducting applications in high-tech industry.

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30

Cryogenic Electronics for Quantum-Classical Applications

Author: Edoardo Charbon[1]

[1] *EPFL*

The core of a quantum computer or a quantum sensor is generally an array of qubits or quantum detectors and classical electronics for its control; it operates on the qubits/detectors with nanosecond latency and a very low noise. Classical electronics is generally operating at room temperature, however recently, we have proposed that it moves closer to the qubits/detectors and operates at cryogenic temperatures to improve compactness and reliability. This has introduced new constraints to the electronics, especially in terms of noise and power dissipation, due to the extremely weak signals generated by quantum devices that require highly sensitive circuits and systems, along with very precise timing capability. We advocate the use of CMOS technologies to achieve these goals, whereas the circuits will be operated at 2-10K. We believe that these, collectively known as cryo-CMOS circuits, will make future qubit arrays scalable, enabling a faster growth in qubit count. Quantum sensing based on superconducting materials, will become more reliable and robust to the conditions of operation. In the talk, the challenges of designing and operating complex circuits and systems at deep-cryogenic temperatures will be outlined, along with preliminary results achieved in the control of quantum devices by ad hoc integrated circuits that were optimized to operate at low power in these conditions. The talk will conclude with a perspective on the field and its trends.

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Poster session / 31

Coriolis flow meters offer custody transfer level of accuracy for liquid hydrogen measurement

Author: Aleksandr Druzhkov[1]

Co-authors: Maarten Brugman [1]; Yaser Alghanmi [1]

[1] *Emerson*

As with LNG in the past, LH2 has the potential to revolutionize the energy storage and transportation sectors and roll out the net zero economy on a large scale. However, to enable global hydrogen trade, a list of challenges must be solved. Apart from safety issues, measuring LH2 for custody transfer is one of the main challenges. The key complication of measuring LH2 is its ultra low temperature (around -253℃) and low density, even in its liquid state (˜70 kg/m³).
Coriolis technology has the highest potential as a reliable flow measurement technique providing direct mass measurement for liquid hydrogen (LH2). The technology complies with explosion-proof requirements and has proven reliable record performance in liquid helium applications [1].
Coriolis meters can be calibrated with water at room temperature and still be used with all fluids [2]. Modern Coriolis meters are enabled with automatic corrections for different gases and viscous fluids with extremely high (+350℃) and low (-200℃) temperatures and high pressures. One major advantage of Coriolis meter is the water transferability feature. The concept has been proven for years in multiple major industries including the oil and gas sector.
The ultra-low temperature of LH2 does not allow for the use of an embedded temperature sensor in a Coriolis meter. This is why a newly patented method of temperature correction through known density has been developed. The proven water transferability concept for Coriolis meters and the patented temperature correction method can be used to establish LH2 measurement traceability. The proposed temperature correction method based on density is practical and can be easily verified at liquefied nitrogen (LN_2) facilities.
This work explains the basic principles of Coriolis meter operation and the reason for the vacuum secondary case of the Coriolis meter, as well as the principles of the new temperature correction. The combination of the proposed technical solutions can provide an accuracy of up to ±0.35% [3]. The work demonstrates test results of the proposed methods using LN2.

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32

Facility design and manufacturing to measure the thermal flux on liquid hydrogen tank during vacuum breaks

Author: Jean-Marc Poncet[1]

Co-authors: Davide Duri [1]; Matthias Raba [1]

[1] *CEA - Grenoble*

With the development of the liquid hydrogen as an energy vector, some questions about its storage safety have to be addressed. Cryogenic tanks are thermally insulated with vacuum and possibly multi-layer insulation (MLI) blankets and the loss of vacuum (LOVA) is a classical accident to be considered. The key parameter to perform the safety device sizing is the thermal flux during this kind of LOVA events. In a cryostat without MLI, Belonogov [1] measured a heat flux close to the hydrogen critical flux at a pressure just above the atmospheric pressure (9.4 W/cm²) whereas following the standard ISO 21013-3 norm the thermal flux to be used is for the result of liquid helium tank LOVA experiments performed by KIT [2]. Without MLI the thermal flux with liquid helium is 3.8 W/cm² in contradiction with the Belonogov measurement. Bibliographic review has demonstrated that available quantitative data for hydrogen are poor, the safety design sizing is then complicated. Additionally, in the MLI-equipped case, other works [3] have shown that the values indicated in the same standard with MLI seems optimistic.
In order to have a better understanding of these issues and to obtain experimental data on a broader range of storage conditions the project ESKHYMO (Enhance Safety Knowledge for Hydrogen Measurements/Modelling in cryOgenic phase) funded by France 2030 [4], has been proposed by CEA and other academic and industrial partners to work on safety questions linked to liquid hydrogen usage. Within this project a dedicate and fully instrumented liquid hydrogen test bench for the thermal flux measurement during vacuum break has to be manufactured and tested. The test facility design carried out by the DSBT and the on-going manufacturing status is presented.
The main driver for the design is the bench flexibility to be able to test different accidental scenario typically either in subcritical discharge or supercritical one, with or without additional thermal insulation (MLI or other). Two vacuum vessels have been considered, the first one around the tank and the second above the tank for the instrumentation specifically designed by the DSBT. The vacuum is broken only around the thank and kept around the instrumentation to avoid any thermally-induced influence the response of the sensors during the test. The bottom part of the tank can be changed depending on the test to perform, and above all to adjust the thermal resistance of the tank wall when the operating safety device pressure is modified. Whenever possible, the components supplied (i.e. valves, safety devices, pumps) were chosen to comply with explosive atmosphere ATEX requirements. Special attention has been devoted to operate the installation safely. Designed to be transportable to areas compatible with the use of hydrogen the setup can be operated remotely. All the components have been supplied and the cryostat is under manufacturing for a delivery in the beginning of 2026.
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33

Cryogenics at the ESS - On the way to steady state operations

Author: Philipp Arnold[None]

The European Spallation Source (ESS) is a neutron-scattering facility being built with extensive international collaboration in Lund, Sweden. Cryogenic technology is utilized in essential parts of the project, particularly in the superconducting linear 2.0 GeV proton accelerator (linac), in the liquid hydrogen moderators and for cryogenic cooling and creation of large magnetic fields for the sample environments of the neutron instruments.
Most of the cryogenic system has been installed, commissioned and acceptance tested. However, the complex interaction of the entire system with its clients and system flaws that could not be detected earlier bring about new challenges on the way to steady state operations of the ESS facility.
This talk gives an overview of the cryogenic subsystems at ESS, explain the background of some special requirements, inform about the current status, challenges we faced in the last operation and commissioning runs and how they are addressed.

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34

A CFD comparison of interfacial phase change models for boil-off, self-pressurisation and thermal stratification in liquid hydrogen storage tanks

Author: Shawn Fernandes[1]

Co-authors: Carol Eastwick [1]; Christopher Ellis [1]; Evgenia Korsukova [1]; Stephen Ambrose [1]

[1] *University of Nottingham*

Adoption of liquid hydrogen (LH_2) as a clean, high-energy-density fuel across heavy-duty road vehicles, marine propulsion, and aerospace applications will form a critical component in the decarbonisation of the transport sector. Its ability to deliver zero-carbon energy with rapid refuelling and long-range capability makes LH_2 a cornerstone of future sustainable mobility. However, the cryogenic nature of LH_2 introduces significant engineering challenges, particularly in its storage and handling. Self-pressurisation and boil-off losses due to ambient heat ingress can compromise safety,

efficiency, and operational reliability, making accurate predictive modelling of these phenomena essential for system design and optimisation.

This study presents a comparative assessment of three widely used interfacial phase change models: the Schrage, the Modified Energy Jump (MeJ), and the Lee model. A parametric study was conducted across three coefficients for each model, with validation against five benchmark experiments from NASA's K-Site and MHTB cryogenic tank datasets. These cases focused on planar interface problems under normal gravity with thermally induced phase change. Simulations were performed using STAR-CCM+, evaluating each model's ability to predict tank pressure evolution, temperature distribution, and boil-off behaviour.

The Schrage model emerged as the most robust and accurate, demonstrating minimal sensitivity to coefficient variation and achieving a maximum mean absolute percentage error (MAPE) of 3.0% in pressurisation predictions. The MeJ model showed comparable performance when its heat transfer coefficient was carefully tuned, underscoring its empirical dependence. In contrast, the Lee model exhibited numerical instability and significant deviation in pressure predictions, with errors reaching up to 11% MAPE.

Further results of the flow field and boiloff flux distribution highlight the discrete difference between the near-wall liquid-vapour interface, showing significantly higher boiloff mass flux at the wall, while near-uniform boiloff mass flux is present away from the wall, often showing values signifying condensation. The high-fidelity results highlight a clear need for the near-wall boiloff mass flux to be considered in reduced-order models.

This work delivers practical guidance for CFD practitioners and LH_2 system designers, enabling more reliable and physically consistent modelling of LH_2 storage tanks. The findings support the deployment of hydrogen technologies in industrial applications, contributing to the broader decarbonisation of transport and energy systems.

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Poster session / 35

Cryolines and Warmlines for ITER Project

Author: Vijay GEHANI[None]

Co-author: Bhumika JOSHI

ITER (www.iter.org) is an international collaborative project to harness controlled nuclear fusion of Hydrogen isotopes to produce energy. It is an important step towards an alternative and virtually limitless source of clean energy. ITER-India (www.iter-india.org), part of the Institute for Plasma Research under the Dept. of Atomic Energy, is responsible for Indian contributions to the project. ITER employs a magnetic "cage"to contain the hot plasma. This cage makes use of superconducting magnets, which must be cooled to minus 269 deg-C, just 4 degrees above absolute zero. ITER will employ the biggest Cryoplant in the world coupled to a Nuclear Facility, and the liquid helium & nitrogen produced by this plant will be distributed to the magnets through a massive network of

"cryolines". Approximately 4 km of Cryolines, operating at temperatures ranging from minus 269 to minus 193 deg-C, and about 6 km of return lines for warm gases, have been manufactured by M/s INOXCVA (www.inoxcva.com) in India and then dispatched to the ITER Worksite in France. These Cryolines are made to stringent Nuclear standards.

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36

Main Requirements of the Divertor Tokamak Test (DTT) Cryogenic Plant

Authors: Antonio Frattolillo[None]; Antonio Froio[None]; Davide Duri[1]; Erik Gallo[None]; Fabrizio Lisanti[None]; Frederic Michel[None]; Morena Angelucci[None]; Pascal Roussel[None]; Roberto Bonifetto[None]; Roberto Zanino[2]; Silvio Migliori[None]; andrea iaboni[3]

[1] *CEA - Grenoble*

[2] *Politecnico di Torino*

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The Divertor Tokamak Test (DTT) -https://www.dtt-project.it/- is an experimental facility currently under construction in Frascati (Rome, Italy), designed to investigate the challenges of heat exhaust under operating conditions representative of commercial fusion power plants, [1]. In order to ensure its relevance to ITER and DEMO, DTT must be capable of sustaining sufficiently long plasma pulses, which necessitates the use of a superconducting magnetic system. Consequently, DTT requires a dedicated Cryogenic Plant (or CryoPlant) capable of providing thermal control to the magnets and associated systems.
The cryogenic users in DTT are grouped into three temperature levels:
• 4.6 K helium is supplied to the magnets—including 18 Toroidal Field (TF) coils, 6 Poloidal Field (PF) coils, 6 Central Solenoid (CS) modules and a HTS insert—as well as to their supporting structures, thermal anchors and feeders. Additionally, cryopanels operating at this temperature are necessary for ensuring helium and hydrogen adsorption inside the plasma chamber;
• 50 K helium is supplied to the High Temperature Superconducting (HTS) current leads;
• 80 K helium is supplied to the thermal shields and chevron baffles, which protect the magnets and the cryopanels from excessive radiative heat loads.
During DTT operations, the cryogenic users are expected to demand a total cooling capacity of approximately 10 kW of equivalent power at 4.5 K. The most demanding operational state is the Plasma Operation State (POS), where magnets are subjected to peak heat deposition due to AC Losses (hysteresis and eddy currents during plasma current ramping) and nuclear heating. The Cryogenic System shall be able to handle the variable loads, as well as the static and continuous loads coming from resistivity losses and thermal radiation of the warmer surrounding components, [2].
This poster provides an overview of the thermohydraulic heat loads, duty cycle and process requirements of the DTT Cryoplant across its various operational states.

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37

Solubility of hydrogen in liquid helium –measurement project

Author: Julian Will[None]

Co-author: Christoph Haberstroh

Hydrogen contamination in liquid helium has been recognized as a problem for several years now. A number of industrial helium extraction plants in the Mediterranean region have been pinpointed by the authors as the possible source. Hydrogen contamination has now been found in a large number of local helium liquefaction plants. These impurities were brought in with the helium deliveries and continue to accumulate. This often results in significant operational disruptions at the universities or research institutes affected: For example, this can be seen as frequent blockages in helium flow cryostats or in throttle sections of pumped systems.

The solubility of hydrogen in liquid helium is very low, and the exact value remains unknown. It is reasonable to assume that other factors also play a role.

One of the aims of the *HyLiqHe* project is to investigate the issue in more detail. The project is funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation). Appropriate measurement setups and measurements are underway. In addition to reliably quantifying hydrogen in the parts per billion (ppb) range, it is particularly challenging to distinguish between dispersion and solution within the liquid.

This contribution presents the results of a preliminary orientation experiment. The objective of this study is to obtain an approximate value for the solubility limit. A standard laboratory dewar was intentionally contaminated with a comparatively large amount of hydrogen, then sampled at various points within the helium reservoir using gas chromatography. Agglomerates of precipitated, solid hydrogen were observed at the phase boundary, alongside high levels of contamination in the low temperature gas phase. Reproducible values slightly below 100 ppb were measured in the liquid. The results are discussed; they support existing hypotheses on contamination behaviour within cryogenic facilities.

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38

Status of the cryogenic infrastructure upgrade for the High Luminosity LHC at CERN

Author: Fabio Merli[1]

Co-authors: Andrew Lees [1]; Antonio Perin [1]; Emmanuel Monneret [1]; Michele Sisti [1]; Serge Claudet [1]; Vanessa Gahier [1]

[1] *CERN*

The High Luminosity LHC project is a major upgrade of the Large Hadron Collider that will provide a fivefold increase of the instantaneous collision rate and a tenfold increase of the integrated luminosity with respect to the LHC original design values for the ATLAS and CMS experiments.
To achieve the higher luminosity, the existing focusing magnets on each side of ATLAS and CMS experiments will be replaced with newly developed superconducting magnets operating in pressurized HeII at 1.9 K and new superconducting radiofrequency cavities modules ("crab-cavities"type) will be also installed on each side. The increased collision rate and beam current will generate a significantly larger heat load at 1.9 K that the current configuration, requiring new cryogenic infrastructures at Point 1 (P1) and Point 5 (P5) of LHC.
The upgraded cryogenic configuration requires two new helium cryogenic plants & their ancillary infrastructure at both P1 and P5, each with an equivalent capacity of about 14 kW at 4.5 K, including a capacity of about 3 kW at 1.9 K. The refrigerators will include a cold box located in a surface building that will provide 4.5 K supercritical helium, and a cold compressor box, required for 1.9 K operation, located in an underground cavern. The surface cold box will be connected to the underground cold compressor box with a vertical multi-header transfer line and the cold compressor box will also be connected to new cryogenic distribution lines feeding the LHC tunnel cryogenic equipment on both sides of the interaction points. This multi-header cryogenic line will interface with the cryogenic devices of the accelerator via flexible cryogenic jumpers at dedicated modules, which will also house the process control equipment like control valves and heat exchangers.
The main tenders for the refrigerators and the cryogenic distribution systems were adjudicated to industrial contractors in 2022. To anticipate all the possible activities before the next Long Shutdown 3 of the LHC (LS3, starting mid 2026 towards the objective to resume beams operation by mid 2030), these contracts are structured in phased stages of design and installation. The initial phases are currently under execution, with several equipment under construction and installation.
This presentation reports on the progress of the HL-LHC cryogenic infrastructure design, production and installation, and presents the schedule and preparatory activities for the installation foreseen for the Long Shutdown 3.

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39

Modeling internal temperature profiles in LN2-cooled cryogenic terminals with temperature-dependent axial conduction and convection coupling

Author: Darja Gacnik[1]

Co-authors: Marcel ter Brake [2]; Marc Dhallé [2]; Katja Vozel [1]; Andrej Kitanovski [1]

[1] *University of Ljubljana*

[2] *University of Twente*

Cryogenic terminals are critical thermal interfaces in superconducting power systems, where precise temperature control has a direct impact on system stability and performance. This work presents a multiscale thermal modeling framework for LN_2-cooled conduction terminals with integrated heat exchangers (HXs), developed to support robust component design under realistic operating conditions (see Figure 1). It builds upon the modeling approach presented by *Gačnik et al.* [I] and expands it into advanced thermal simulation tools.

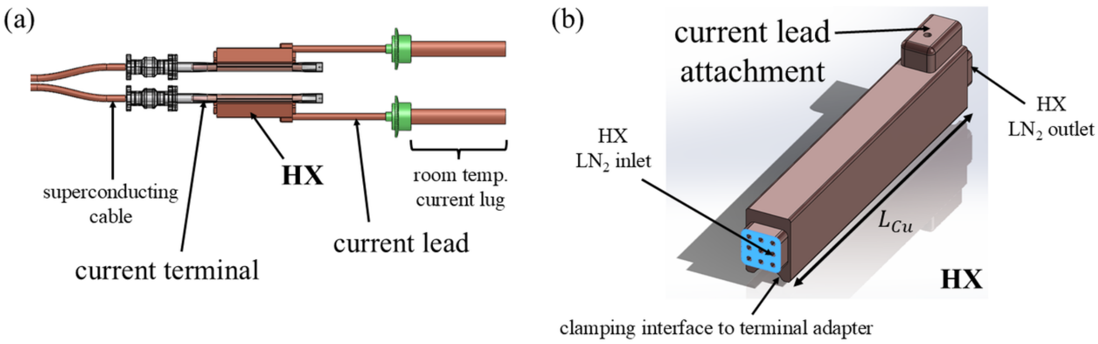

Figure 1: Figure 1: Schematic of an LN_2-cooled cryogenic terminal. (a) Cross-section showing the current lead connected to a superconducting cable, with an integrated heat exchanger (HX) for cooling. (b) 3D view of the HX geometry, highlighting the copper segment length L_Cu, clamping interface, and LN_2 inlet and outlet positions.

The analysis combines analytical modeling, CFD-informed simulations, and semi-empirical methods to resolve internal temperature profiles driven by axial heat conduction and turbulent convective cooling. Particular focus is given to the temperature-dependent thermal and electrical properties of materials, along with localized ohmic heating and its effect on axial temperature gradients. These factors significantly influence the heat transfer efficiency between the solid HX and the subcooled liquid nitrogen (LN_2).

Three analytical formulations based on analytical framework of *Chang et al.* [II], the General Model (G.M.), Averaged Model (A.M.), and Wiedemann-Franz Model (W.-F.M.), were compared to predict cold-end heat loads in copper current leads. The G.M., which accounts for temperature-dependent material properties and axial redistribution of heat, revealed that commonly used simplified models (A.M., W.-F.M.) can overestimate cold-end heat loads by more than an order of magnitude in high-current regimes. At 1300 A input current, A.M. and W.-F.M. overpredicted the cold-end heat load by factors of ˜12 and ˜16, respectively (52.5 W and 69 W vs. 4.4 W for G.M.), clearly highlighting the importance of spatially resolved conduction effects. This discrepancy may lead to design choices that appear thermally optimized but ultimately underperform due to internal heat redistribution.

CFD simulations of a representative HX geometry were conducted using COMSOL Multiphysics® to capture conjugate heat transfer and cryogenic flow behavior (Figure 2). Calibration of the turbulent Prandtl number ($Pr_T \approx 0.85$), which governs the ratio between momentum and thermal diffusivity in the turbulent flow k–ε RANS model [III], enabled accurate reproduction of local temperature profiles and revealed pronounced asymmetries in convective cooling, especially in regions with high velocity gradients and non-uniform heating. These insights supported the development of semi-empirical models capable of generalizing thermal performance across various HX geometries, offering rapid and physically consistent evaluation without relying on full resolution of high-fidelity CFD simulations. This approach also revealed a counterintuitive phenomenon: under specific conditions, the copper structure locally cools the LN_2 flow due to strong axial conduction and steep spatial temperature gradients.

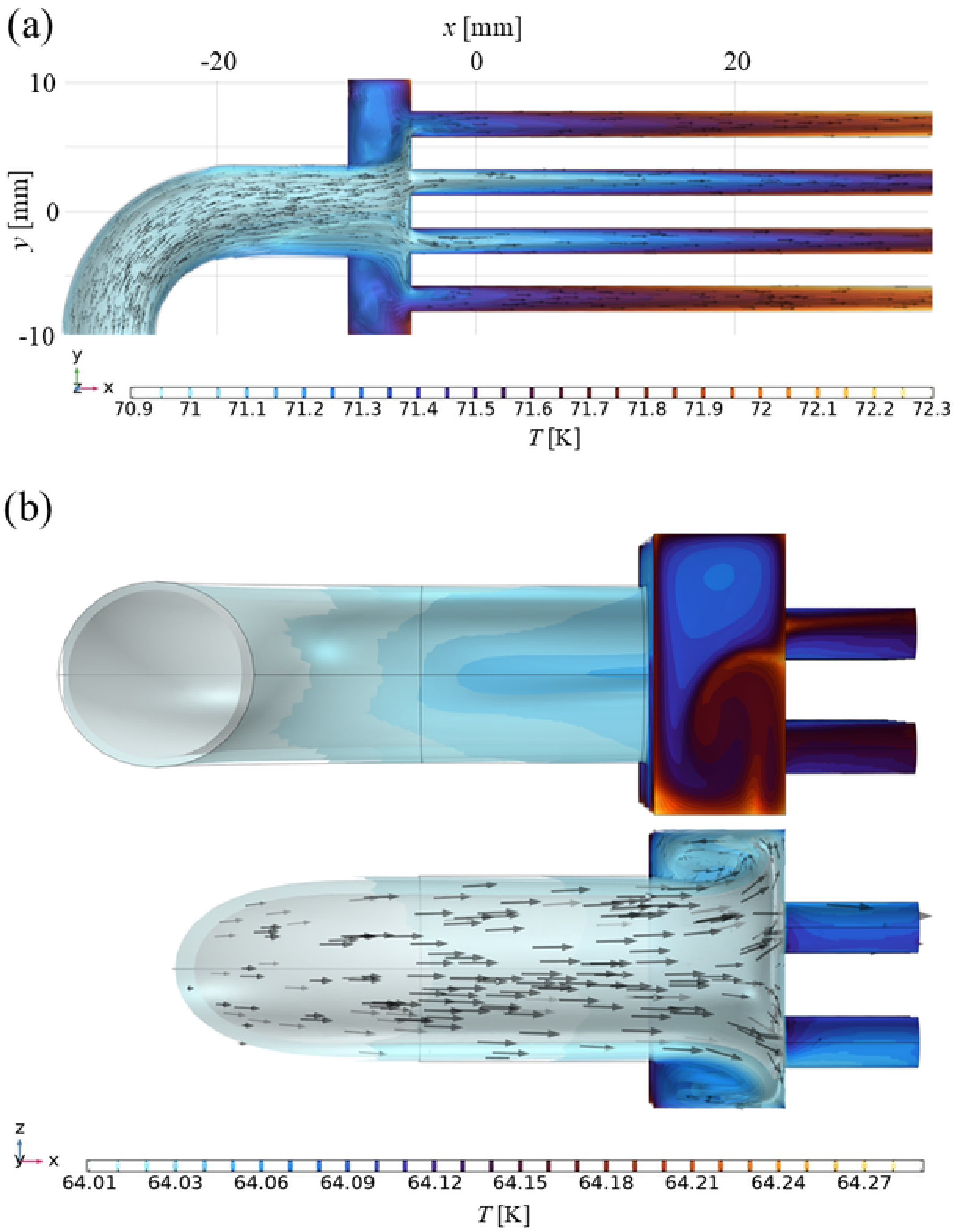

Figure 2: CFD simulation of the representative HX geometry showing cryogenic flow behavior and temperature distribution.(a) Cross-sectional temperature field and velocity vectors in the inlet manifold and parallel channels. The results show significant temperature gradients and developing flow across the HX. (b) Side view of HX wetted surface (top) and LN_2 (bottom) temperature distribution with streamlines, highlighting asymmetries in LN_2 cooling and flow recirculation zones. These spatial variations influence local heat transfer effectiveness and inform the development of semi-empirical models.

To support broader adoption and research reproducibility, the modeling framework has been implemented in TCCBuilder®, an open-source simulation platform for cryogenic thermal control circuits (TCCs) [IV]. The tool enables modular evaluation of LN_2-cooled terminals with temperature-dependent material properties and supports the integration of other key components, including thermal diodes, regulators, and switches.

This modeling framework provides a physically grounded understanding of conduction-convection interplay in cryogenic terminals and adjacent HXs, offering predictive capability for both early-stage design and system-level integration. The results emphasize the importance of accurately evaluating internal temperature profiles across all components to prevent thermal bottlenecks, ensure reliable LN_2 cooling under steady-state and transient conditions, and mitigate operational instabilities or thermal runaway in superconducting applications.

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[IV]: TCCBuilder. (2024). Thermal Control Circuit Builder: Open-source simulation tool for thermal circuit design. Retrieved August 28, 2025, from https://tccbuilder.org/.

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40

2 K Quantum cryoooler development

Authors: Daniel Willems[1]; Pieter Lerou[2]

[1] *Thales Cryogenics*

[2] *Demcon kryoz*

We present the development of a compact, rack-mountable cryocooler capable of achieving temperatures down to 2 K, designed specifically for quantum sensing environments. The system integrates pulse tube and Joule-Thomson cooling technologies to deliver high thermal stability and ultra-low vibration performance, critical for quantum applications. Engineered for maintenance-free operation, the cryocooler features a robust architecture with no moving parts in the cold head, ensuring exceptional lifetime and reliability. Its modular design supports seamless integration into laboratory and industrial setups, offering a scalable solution for next-generation quantum instrumentation.

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41

Enhancing cryogenic thermal diode performance via temperature-dependent contact resistance

Author: Katja Vozel[1]

Co-authors: Andrej Kitanovski [1]; Darja Gačnik [1]

[1] *Faculty of Mechanical Engineering, University of Ljubljana*

In macroscopic solid-state thermal diodes (MSTDs), spatial and temperature asymmetry arises from combining two materials whose thermal conductivities vary differently with temperature 1. These devices offer strong potential for passive directional heat control in cryogenic environments. However, current state-of-the-art MSTDs exhibit rectification factors (RF) that remain too low for practical implementation. The RF is defined as the ratio between forward and reverse heat flux, $\dot{q}_{\mathrm{forward}}/\dot{q}_{\mathrm{reverse}} - 1$. Examples of approaches to improving performance include introducing asymmetries via nanoscale 2 and examining the effects of thermal contact resistance (TCR) [3].

Our analysis explores a new approach to enhance MSTD performance: leveraging the temperature dependence of TCR. At cryogenic temperatures, TCR increases exponentially with decreasing temperature due to a transition from diffusive to ballistic heat transport [4]. This occurs when the mean free path of heat carriers approaches the characteristic surface roughness of the contact interface. This effect, combined with suitable material thermal conductivities, can further enhance asymmetric heat flow across the interface.

We investigate this numerically using Fourier's law and the finite volume method. The temperature dependence of the materials'thermal conductivities and the TCR are incorporated into the model. Thermal expansion is neglected. Examples of temperature-dependent TCR values at low temperatures as well as thermal conductivities are taken from the literature [5,6] and shown in Figure 1. The material pairs considered are: rhodium-iron alloy (RhFe) - sapphire (Al_2O_3), and diamond (C) - gold (Au). Rh thermal conductivity is used as a proxy for RhFe due to the missing available data.

https://www.dropbox.com/scl/fi/muaruhs25d4hvcbt4c4lm/ECD_Figure1.pdf?rlkey=sfugc325my88lxlscv5ryy12f&st=g
Figure 1. Thermal contact resistance for pairs of known materials and their thermal conductivities at low temperatures. (a) TCR value between different materials. The values of the TCR are theoretically determined values from the reference papers [5,6]. (b) Thermal conductivity of selected materials at low temperatures.

The MSTDs in this study are modeled with segments of equal length $L = 100\ \mu$m (Figure 2) and fixed terminal temperatures. Cold terminal temperature $T_{\mathrm{cold\ ter.}}$ is set for each material pair individually, between just above 0 and 20 K. The thermal bias $\Delta T = T_{\mathrm{hot\ ter.}} - T_{\mathrm{cold\ ter.}}$ ranges from 5 to 45 K. Forward and reverse biases are realized by swapping the terminal temperatures.

https://www.dropbox.com/scl/fi/q265iz3kjcy1gtzb1e8y8/ECD_Figure2.pdf?rlkey=3q1b98j4uwl1q5oo0beaxqymi&st=4
Figure 2. Representative MSTD configurations used in the analysis of the impact of temperature-dependent TCR at material interfaces on device performance.

The calculated RF values are compared with the case where the TCR is not temperature-dependent and has a constant value equal to the value above 100 K (Figure 1a). This comparison isolates the temperature dependence of the TCR to assess its influence relative to the TCR itself.

Figure 3 shows the simulation results across different temperature intervals. The results reveal a substantial increase in RF in some cases, particularly when the MSTD operates in the temperature range where the TCR function is steepest. The most significant improvement in the RF value occurs for material pair RhFe - Al_2O_3 (Figure 3a), when the RF increases from 6×10^{-3} (in the case of a

constant TCR) to 0.94 (in the case of temperature-dependent TCR) at a thermal bias of only 5 K, just above absolute zero.

Except for the RhFe - Al_2O_3 pair, literature data for TCR function near absolute zero are scarce, leaving the steepest region of the TCR function unresolved. Consequently, Figure 3b for the C - Au pair shows no improvement, or even a reduction, in RF values at the lowest temperatures. At slightly higher temperatures (10-20 K), however, the C - Au pair exhibits a moderate RF increase of up to 27 % (from 0.73 to 0.92 at $T_{\text{cold ter.}} = 16$ K and $\Delta T = 45$ K).

https://www.dropbox.com/scl/fi/dqdd4vxr0jilu2lo7d86n/ECD_Figure3.pdf?rlkey=kry3eqh5k22sdgiapd9aaqdnl&st=bnmjrslu&c
Figure 3. Influence of temperature-dependent TCR on RF for the selected MSTDs, plotted against ΔT, at different cold terminal temperatures. The filled circles represent the values of RF at constant TCR, the empty triangles the RF values at temperature-dependent TCR. (a) RhFe - Al_2O_3 pair, plotted on a logarithmic scale. (b) C - Au pair, plotted on a linear scale.

The present analysis of temperature-dependent TCR effects indicates that this factor can be exploited to improve thermal rectification in cryogenic environments. Potential applications for cryogenic MSTDs include integration into the thermal management architecture of spacecraft [7], cryogenic electronics [8], and low-temperature sensor systems [9]. In these contexts, MSTDs can suppress parasitic heat loads and protect temperature-sensitive components. This work provides a foundation for future experimental validation and targeted design optimization of MSTDs. In particular, further exploration of the interplay between thermal conductivity and (temperature-dependent) TCR, along with the effects of thermal expansion, will be important.

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42

50 mK ADR cooler for the Athena space mission: demonstration model program.

Authors: Attard[None]; Bancel[None]; Charles[None]; Durand[None]; Jean-Marc Duval[1]; Léon[None]; Marin[None]; Robert[None]; Sylvain Martin[1]

[1] *CEA Grenoble / DSBT*

Athena is a large (L-class) mission from the European Space Agency (ESA) dedicated to the study of the hot and energetic universe. One of its instruments, the X-ray Integral Field Unit (X-IFU), needs temperatures as low as 50 mK for its detectors to reach the required sensitivity. In its newly proposed design, X-IFU uses a 50 K cryostat cooled thanks to radiative cooling. Mechanical coolers provide 20 K and 5 K interface temperatures within this cryostat.
After introducing the thermal design and its constraints, this talk will focus on the multistage adiabatic demagnetization refrigerator (ADR) system planned within this cryostat and operating from a 5 K interface down to 50 mK. Magnetic coolers are indeed well adapted to space operation because of their efficient, reliable and of their independence to orientation. The proposed design is based on a succession of 5 ADR stages providing cooling interfaces at 1.8 K, 325 mK and 50 mK for the focal plan assembly (FPA) unit hosting the detector.
A demonstration model (DM) is being assembled and tested. The first purpose of this model is to validate the functional performances and correlate them with our numerical model. This will help us for the fine optimization of the sizing of the Flight Model. Secondly, the prototype will be integrated by CNES in an instrument prototype to validate the overall performance including the one of the FPA. The talk will present the DM design, as well as results on the 5 K - 1.8 K stage operation. Finally, we will describe the next steps of this long-term project.

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Poster session / 43

A submersible liquid hydrogen pump –design and initial testing

Author: Henrik-Gerd Bischoff[1]

Co-authors: Christiane Thomas [1]; Christoph Haberstroh

[1] *TU-Dresden*

As the hydrogen market expands, the need for efficient distribution of liquid hydrogen (LH_2) becomes increasingly important. The potential utilisation of liquid hydrogen in mobile applications or as an energy import vector is subject of current investigations. Reducing flash gas losses during LH_2 transfer and ensuring adequate pressurization of downstream applications, such as fuel cells and combustion engines, are challenges. Therefore, it is essential to develop pumps for liquid hydrogen and, along with this, develop test rigs in order to understand how liquid hydrogen pumps behave under various conditions. This contribution shows the current status of the development of a three-staged liquid hydrogen turbo pump with a designed of pressure head of $1\ bar$ and a flow rate of $2100\ l/hr$. It also presents a test rig for such small cryogenic pumps. The objectives are to demonstrate the pump's feasibility and to investigate the underlying thermodynamics (e.g. low-loss transfer and cavitation behaviour). The focus is on the technical implementation, particularly the mechanical design and component selection, as well as on providing insight into the initial commissioning tests.

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44

Skyfall 2: a 1.2m diameter HTS pseudo-Helmholtz magnet for liquid metal MHD studies

Author: Thomas Charignon[1]

Co-authors: Chris Acheson [1]; Francesco Volpe [1]; James Butterworth [1]; Jorge Vilhena [1]; Luca Capasso [1]; Lucas Blattner Martinho [1]; Quentin Salquebre [1]; Victor Prost [1]

[1] *Renaissance Fusion*

Renaissance Fusion is advancing the development of a stellarator-based commercial nuclear fusion reactor by combining several key enabling technologies. At the core is a novel magnet system that employs wide, laser-engraved high-temperature superconductors (HTS) to generate the complex three-dimensional stellarator magnetic fields, while simultaneously guiding a liquid metal flow along the reactor walls. This configuration provides both effective neutron shielding and efficient thermal management.

As a proof of concept, we have built a 1.2 metre diameter HTS pseudo-Helmholtz coil pair capable of producing a 1 tesla hot bore (6 tesla at the coil). This will soon be deployed in a hot liquid metal levitation test around the perimeter of a 1 metre diameter chamber. The magnets employ non-insulated, dry-wound HTS coils cooled by conduction at 20K using a custom cryogenic system.

We present the design and experimental validation of this system, with particular emphasis on the custom cryogenic system design and advanced thermal insulation strategies that limit heat transfer to the 20 K magnets located less than 40 mm from the 850 °C liquid metal chamber.

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45

Twente and Gravitational Waves: How a circle of research life closes.

Author: Marcel ter Brake[1]

[1] *University of Twente, The Netherlands*

In this presentation, I will reflect on two research lines that characterized my research career at the University of Twente; The development of SQUID-based magnetometers systems in the 80s and 90s, mostly focusing on biomagnetic applications, followed by the development of vibration-free cryocoolers.
Since the early 2000s, we have been working on small Joule-Thomson cold stages driven by sorption-based compressors initially focusing on cooling of infrared detectors in scientific space missions. Pushed by the extremely low level of vibrations and the long lifetime this technology was also investigated for terrestrial applications in large space observatories such as the European Extremely Large Telescope (ELT) in Chili in the mid 2010s, and more recently in the Einstein Telescope (ET).
In the upcoming Lunar Gravitational Wave Antenna project (LGWA) both lines, SQUID magnetometers and sorption-based vibration-free coolers may be combined, thus closing the circle of my research life.

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47

Cryogenics for Aviation: Opportunities and Challenges

Author: Arvind Gangoli Rao[1]

Co-author: Chiara Falsetti

[1] *Delft University of Technology*

Aviation is an important pillar of mobility and is essential for a globalized world. The aviation industry has recovered from the Corona crisis and, as expected, is poised to grow in the coming decades at a rate of around 4% per annum. With this compounding growth, the climate impact of aviation is expected to increase substantially. While ground transportation can electrify, at least to a large extent, this option is not realistic for aviation due to the low energy density of batteries. In this scenario, hydrogen, particularly cryogenic liquid hydrogen (LH2), offers a promising alternative to decarbonize the aviation sector, especially for the short to medium range aircraft. The paper outlines the opportunities that LH2 offers to decarbonize the aviation industry, especially in terms of climate impact, and the challenges in terms of fuel supply, fuel storage and refueling systems.
The paper describes the LH2 refueling systems for aircraft, as well as the onboard fuel supply systems required for two different propulsion concepts, namely a hydrogen-electric powertrain for a turboprop and a gas-turbine-powered SMR aircraft. The overall propulsion system for both aircraft types is discussed in detail with their impact on the LH2 fuel system design.

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Poster session / 48

Measurement of critical heat flux and heat transfer coefficient via quenching experiments in cryogenic fluids.

Author: Farheen Muhammed[1]

Co-authors: Ed Walsh [1]; Peter Ireland [1]; Ruoya Li [1]

[1] *University of Oxford*

The emergence of the liquid hydrogen (LH2) industry promises transformative potential across sectors like energy storage, propulsion, and synthetic fuels. However, the complex thermophysical behaviour of LH_2 —applicable to production, storage, transportation, distribution and end use — requires deeper understanding to enable efficient system design. Some examples include cryogenic phase change dynamics, cool-down times and multiphase heat exchanger performance. A critical aspect is pool boiling and boil off, where Critical Heat Flux (CHF) and Heat Transfer Coefficient (HTC) are highly sensitive to surface-liquid interactions, particularly influenced by surface microstructures. Accurate measurement of CHF and HTC on cryogenically relevant surfaces remains elusive.

This study introduces an Inverse Heat Transfer (IHT) model to calculate HTC and CHF from thermocouple data during quenching with a cryogenic fluid. The methodology is initially validated with a fluorocarbon using transient and steady state test conditions. The technique is then extended to liquid nitrogen and applied to surfaces with different microscale features to determine HTC and CHF. The research provides novel pool boiling measurements of HTC and CHF on cryogenic fluids using different metals and identifies the limitations of using an IHT model with cryogenic fluids.

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Poster session / 49

Development of a programmable PID thermal control system for a laboratory cryostat

Author: Sandra Pérez Barrio[1]

Co-authors: Carolina Martín [1]; Cristóbal González [1]; Miguel Fernández Sánchez [1]

[1] *INTA*

A programmable PID thermal control system, implemented using Python with a user interface, has been developed for a laboratory cryostat, enabling precise regulation of multiple temperature stages. The system allows each stage to reach commanded setpoints and maintain them for a defined dwell time or until the target temperature is achieved. Users can fully configure setpoints, PID parameters, and tolerances, providing flexible control over temperature ramps and stabilization criteria.

The control system was validated with two independent heater channels executing programmed thermal cycles. Heater currents were adjusted to achieve the desired thermal trajectories, demonstrating that the system can synchronize multiple plates at the same temperature even when individual heaters require different power levels. Combined plots of heater power and stage temperatures confirm accurate implementation of setpoints, dwell times, and configurable tolerance.

These results show that the developed PID thermal control system enables precise, flexible, and effective temperature management in a laboratory cryostat. The system provides a practical platform for experiments requiring controlled thermal cycling and demonstrates the effectiveness of independently configurable heater control for consistent thermal performance across multiple stages.

This work is supported by Grant PID2020-115325GB-C31 funded by MCIN/AEI/ 10.13039/501100011033.

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50

Improving accuracy of liquid hydrogen measurements by development of dedicated reference measurement standards

Author: Menne Schakel[None]

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[5] *GERG*

Metrology is the science of measurement for which a global measurement infrastructure exists via the Bureau International des Poids et Mesures (BIPM). The BIPM members have signed the meter convention committing themselves to the usage of the SI-units of measurement (e.g., kilogram, second, meter etc.). National Metrology Institutes (NMIs) maintain the (reference) measurement standards that act as references to the SI-units of measurement. NMIs also maintain measurement standards for derived units such as flow units (kg/s, m3/h).

Liquid hydrogen poses challenges to the accurate measurement of measurands, i.e., the quantity to be measured, in any experimental setup or process. Temperature measurement standards maintained at NMIs typically do not range further down than 77 K (or −196 ℃), which limits the possibilities for accurate liquid hydrogen temperature determination at 20 K (or -253 ℃; at atmospheric pressure). The SI-units of measurement include the mole to express the amount of hydrogen molecules in any gas mixture, however accurate determination of the ortho- and para-spin isomer composition of liquid hydrogen are hampered by the lack of methods to determine their mole fractions at a particular cryogenic temperature. Flow meters can be used to determine the quantity of hydrogen transferred in a scientific experiment or, for instance, when delivered to an airplane. However, it is well-known that the accuracy of flow meters can be affected by the extreme low temperatures of liquid hydrogen; the extent to which is strictly unknown until a reference measurement standard which realizes the flow unit on liquid hydrogen conditions is used to compare it with. Thus, dedicated (reference) measurement standards, which directly link liquid hydrogen measurements to SI-units, are needed.

In 2025, the CryoMet project started as part of the European Partnership on Metrology. It sets out to deliver (reference) measurement standards for liquid hydrogen. These measurement standards will enable the determination of the accuracy of measuring equipment, such as a thermometer, in its process conditions (i.e., as installed in its experimental or industrial configuration). The measurement standards'direct link to the SI-units in combination with their usability in process conditions enables to identify unknown measurement errors of other sensors by their comparison with the reference measurement standards. The CryoMet project consortium will develop:
(1) Reference measurement standards for liquid hydrogen temperature determination suitable for industrial applications (target uncertainty up to 0.5 ℃ (k = 2)). This includes the development of highly accurate, cost-effective laboratory temperature sensor calibration capabilities at liquid hydrogen temperatures.
(2) Novel methods for SI-traceable measurements of the ortho- and para-spin isomer composition of liquid hydrogen. These methods are based on (I) Raman spectroscopy and (II) sound-speed measurements. Anticipated measurement uncertainty is at 1.0 % (k = 2).
(3) Validation of flow unit references through a bilateral intercomparison at industrial scale (up to 600 kg/h). Anticipated, validated measurement uncertainty is estimated at 0.5 % (k = 2).

Delivery of the metrological reference measurement standards by the CryoMet consortium will have an impact across the entire liquid hydrogen measurement chain. Thermodynamic equation-of-state modelling of liquid hydrogen will be improved by the reference measurement standards for temperature and ortho- and para-spin isomer composition. Safe transport of liquid hydrogen at industrial scales requires accurate temperature and ortho- and para-spin isomer composition determination.

Cleary, progression of liquid hydrogen research and engineering towards the larger scale usage in a decarbonized energy system will be stimulated by the liquid hydrogen reference measurement standards.

Acknowledgements
This project (CryoMet, 24GRD07) has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

This project has received funding from the Ministry of Economic Affairs and Climate Policy of the Netherlands.

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51

A cryogenic cooling plant for the world's first utility-scale quantum computer

Author: Lutz Decker[1]

Co-authors: Burkhard Zinzius [1]; Hermann Stiasny [1]

[1] *Linde Kryotechnik AG*

Quantum effects have already been in use for a long time: Technologies such as X-rays, transistors, lasers, LEDs etc. are all based on the control of quantum bundles. Today, individual quanta can be manipulated in a targeted manner. Their interconnection into millions of qubits enables the construction of useful quantum computers.. Quantum computing is expected to drive advancements in healthcare, energy, material design, and encryption.
Quantum computers can be based on very different approaches –but what they all have in common is the need to minimize external influences on the state of the qubits or their downstream evaluation, for example through cold. Quantum computers based on superconducting electronic circuits or photonic integrated circuits are considered to be particularly advanced. Both systems are cooled down to deep cryogenic temperatures in several cooling stages.
Linde Kryotechnik has signed an agreement with PsiQuantum to deliver a cryogenic cooling plant for the world's first utility-scale quantum computer in Brisbane, Queensland, Australia. With a total cooling capacity of 36 kW at a temperature of 4.5 K, this system is by far the world's most powerful cooling system in the field of quantum computers and also one of the most powerful cryogenic refrigeration systems ever built. It will cool tens of thousands of PsiQuantum's new Omega photonic chips housed in cabinets that will be networked together with standard optical fiber.

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52

Cryogenic supply for FAIR- an update

Author: Holger Kollmus[1]

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One of the world's most ambitious research facilities is currently being built near Darmstadt in Germany. Cryogenics plays a central role in this project, as the two largest components of the facility, SIS100 and SuperFRS, use superconducting magnets. Since the last ECD in Darmstadt, a lot has happened on our campus and the cryogenic supply for FAIR is taking shape.
This presentation provides an update on the key components of the cryogenic system: The final preparations for commissioning the refrigeration plant CRYO2, the installation work on the campus wide distribution system and the final procurements for the local cryogenic supply.
Now since work on the technical infrastructure has been completed, we can move forward with commissioning the refrigeration plant. The presentation covers the various steps leading up to mechanical completion, the successful combination/coordination of the various partners involved in the construction, and the steps still required to reach the acceptance test for 14kW at 4.4K.
Since March 2023, the piping support infrastructure has been constructed and the manufacture and installation of the distribution system has begun. Together with the final procurements for the local cryogenic supply systems for Super-FRS and SIS100, the goal of cool FAIR machines available for the first beam experiments in 2028 can be achieved.

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53

Developments in liquid hydrogen systems for mobility

Author: Hendrie Derking[1]

Co-author: Marcel Keezer [1]

[1] *Cryoworld BV*

To reduce the environmental impact of mobility, liquid hydrogen has been identified as promising energy carrier. Many initiatives are ongoing to investigate the use of liquid hydrogen for mobility. In the Netherlands, Cryoworld plays a significant role in these projects as liquid hydrogen knowledge partner. Cryoworld is involved in developing and manufacturing fuel tanks for aircrafts and trucks, liquid hydrogen fuelling systems, vent stacks, lab-scale liquefiers and other standard products for storage and safe handling.
This presentation gives an overview of the developments in liquid hydrogen systems at Cryoworld. It will cover the development of aluminium fuel tanks for aviation and discuss the design of ground-based infrastructure. Further, the status of development of a lab-scale hydrogen liquefier will be discussed.

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54

Cryogenics for the fusion devices: An overview of heating, fueling, exhaust and fuel separation systems

Author: Chandra Prakash Dhard[1]

Co-authors: Jürgen Baldzuhn [1]; Larry Baylor [2]; Heinrich Peter Laqua [1]; Bart Lomanowski [2]; Steven Meitner [2]; Dirk Naujoks [1]; Hans Quack [3]; Naoki Tamura [1]

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The exponentially increasing power consumption of the world requires a tremendously large source of power production, nuclear fusion has the potential to meet this requirement. Among various possible nuclear fusion reactions, deuterium-tritium (D-T) reaction has emerged as the most favorable reaction. Energy production by the D-T reaction has been demonstrated in the Tokamak Fusion Test Reactor (TFTR) and Joint European Torus (JET) fusion devices based on the magnetic confinement. The scientific breakeven, i.e. produced fusion power exceeding the input power, is aimed to be demonstrated in the International Thermonuclear Experimental Reactor (ITER) and SPARC fusion devices currently in construction. The toroidal devices based on the magnetic confinement are of two types, i.e., tokamaks and stellarators, having 2D and 3D the magnetic geometries respectively. Optimized stellarator Wendelstein 7-X (W7-X) 1, in operation since 2015, has successfully completed the sixth plasma campaign, i.e. OP2.3 in 2025, preparations are being made for the next campaign.

Though the first fusion devices began operation towards the end of 1950s (e.g., T-1 tokamak), as the development progressed towards the steady state, high power operation, after about two decades

cryogenics stepped in. Towards the end of 1970s, fusion devices were in operation with the superconducting toroidal field magnets (e.g., T-7 tokamak) and the electron cyclotron resonance heating gyrotrons with superconducting solenoids (e.g., Axially Symmetric Divertor Experiment (ASDEX)). Around the same time, cryogenically frozen H/D pellets were developed to fuel the plasma 2 (e.g., ASDEX [3]). Cryogenics was also used for the large cryo-vacuum pumps, for achieving high levels of vacuum in the plasma vessel, neutral beam injection (NBI) heating boxes (e.g., JET) and exhaust improvements. Developments are currently taking place for the separation of H, D, T and He from the exhaust gas mixtures in the fuel cycle system, using cryogenic fuel separation techniques [4].

In W7-X, ECRH is the main heating system for the long plasma pulse operation, there are, eleven pieces of MW-class gyrotrons generating a microwave frequency of 140 GHz to deliver up to 8.5 MW power to the plasma. Each gyrotron is equipped with three superconducting solenoids immerged in liquid He bath, generating a magnetic field of about 5.6 T [5]. The continuous pellet fuelling system is used to inject frozen H pellets (disc of diameter/height ca. 2-3 mm) at a frequency of 10 Hz from the outboard low field side with a speed of 200-800 m/s to fuel the plasma [6]. Cooling of H is done using the closed-cycle Gifford McMahon cryo-coolers. Ten cryo-vacuum pumps are installed within the plasma vessel located behind the divertor to improve the gas exhaust, helping for a better plasma density control and reduction of gas recycling from the plasma-facing wall. The cryo pumps are cooled with supercritical helium at ca. 4 K, thermal shield is cooled with liquid nitrogen at ca. 80 K [7].

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Poster session / 55

A high-turnaround cryogenic platform for a 4 Kelvin production testing

Authors: Andre Koj[None]; Markus Nilsson[None]; Priyamvada Bhaskar[1]; Robert Rehammar[None]; Zaid Saeed[None]

[1] *Scalinq*

The rapid expansion of cryogenic technologies, such as quantum computing, necessitates robust, scalable, and high-throughput cryogenic testing infrastructure. As these systems transition from pro-

totypes to commercial products, a significant bottleneck emerges in the need for efficient, production-level testing of numerous components at low temperatures. While many cryogenic systems are designed for research and development at the milli-Kelvin scale, the development of automated, high-density testing platforms operating at 4 Kelvin is crucial. Such platforms are essential for accelerating production testing, enabling large-scale manufacturing, and reducing the overall cost of these technologies.
This work presents a custom-built testing platform using a Gifford-McMahon (GM) cooler, specifically designed to meet the demands of rapid production testing of our cryogenic products at 4 K. The system's key innovation is a high-density radio frequency (RF) and direct current (DC) wiring solution, enabling the simultaneous testing of numerous devices in a single thermal cycle. High throughput is further enhanced by a cost-effective resistive heating solution for rapid system warm-up.
The core of our platform is a custom-designed radio frequency (RF) wiring tree. To maximize signal density, a high-density epoxy-beaded sub-miniature push-on micro (SMPM) connector feedthrough, with up to 61 individual RF lines per single flange, is integrated into a custom vacuum flange. This compact arrangement is thermally and mechanically robust, ensuring vacuum integrity and a large number of mating cycles.
The signal chain utilizes semi-rigid stainless steel coaxial cables to minimize thermal load to the 4 K stage. At the 4 K plate, a custom fanout box provides a standardized SubMiniature version A (SMA) interface for connecting to devices under test. This fanout box features a standardized array of SMA connectors, providing a convenient, robust and well-established interface for connecting to the devices under test and external measurement equipment. This design allows for rapid test setup reconfiguration, which is critical for a high-throughput environment. The high-density feedthrough demonstrates excellent performance, with an insertion loss below 0.32 dB and a return loss less than 20 dB for frequencies up to 15 GHz at room temperature. We have also characterized the full RF chain at 4 K to ensure signal fidelity. This RF chain, paired with a cryogenic calibration kit can enable the precise characterization of crucial microwave properties such as S-parameters, at 4 K.
In addition to the RF capabilities, our system includes a parallel tree for DC signal delivery. These DC lines, essential for powering and controlling devices, are thermally managed through an appropriate feedthrough printed circuit board (PCB) at each temperature stage of the GM cooler. This multi-stage layout allows for efficient thermal anchoring of the DC lines at each intermediate temperature, ensuring that the final heat load to the 4 K stage is minimized. For the DC connections, we have Molex PicoBlade connectors, for a compact and reliable high-density solution. Woven loom 42 SWG manganin serves as wiring, offering low thermal load and minimal thermal coefficient of resistance. The design also allows direct solderability of manganin onto the PCB for minimal contact resistances, a crucial feature for the warm-up heaters.
This dual-purpose wiring architecture, with dedicated, optimized paths for both RF and DC signals, creates a comprehensive and efficient testing environment. In conclusion, our custom-built GM cooler system with its high-density, multi-channel wiring tree represents a step forward in cryogenic production testing at 4K. It underscores its value in bridging the gap between small-scale cryogenic research and the demands of industrial-scale manufacturing, and emphasizes cryogenic quality and performance characterization of components, particularly in the quantum computation industry.

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56

Vapor bubble growth in liquid nitrogen pool at normal gravity

Author: Alessandro Novi[1]

Co-authors: Jorge Pinho [1]; Laura Peveroni [1]

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Cryogenic propellants are increasingly considered the best candidates to fuel future space propulsion systems, as they offer the best performances. However, their effective exploitation requires reliable in-space long-term storage and the capability of performing safe and efficient fluid transfer to allow in-orbit tank refilling. Both aspects remain a formidable challenge due to the susceptibility of cryogenic liquids to phase change under even small thermal disturbances. The mitigation of undesired vapor generation is critical, since uncontrolled boiling not only leads to propellant losses but also introduces bubbles that can compromise the performance of liquid acquisition devices and disrupt propellant transfer operations in microgravity.

In current storage concepts, multilayer insulation (MLI) is applied extensively to minimize heat leaks, but structural penetrations such as tank struts remain unavoidable thermal bridges. These localized conduction paths can generate hot spots at the liquid–wall interface, initiating nucleate boiling. Bubble nucleation at such sites is a critical phenomenon: the resulting vapor bubbles grow, detach, and coalesce, influencing both local and global thermodynamic stability. Understanding the dynamics of bubble nucleation and growth under cryogenic conditions is therefore essential to anticipate and mitigate the risks of phase change during long-term storage in space.

The present work addresses this issue by investigating nucleate boiling in a controlled cryogenic environment. Experiments are conducted in a liquid nitrogen pool, chosen as a representative cryogenic fluid, where nucleation is triggered on a well-defined artificial cavity. Localized heating is provided by a Joule heater embedded at the nucleation site. The experimental setup enables direct visualization of bubble dynamics under steady thermophysical conditions. Images are acquired to capture the growth, shape evolution, and detachment of individual vapor bubbles generated at the cavity.

The analysis focuses on the equivalent bubble diameter as a function of time during the growth phase preceding detachment. By quantifying this parameter, insights are gained into the kinetics of vapor generation. The experimental results provide valuable benchmarks for validating theoretical models of nucleate boiling in cryogenic fluids, which remain scarce compared to the extensive body of knowledge available at ambient conditions.

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57

A Powerfull Cryogenic Plateform at 0.5-1.0 K for Spin-Qubits Quantum Processor Applications

Author: philippe camus[None]

Co-authors: Jeremy Vessaire [1]; Marek Zeman [1]; Thierry Trollier [2]; Tristan Meunier [3]; Victor Doebele [3]; mathieu davaine [2]

[1] *CNRS / Neel Insitute*

[2] *Absolut-System*

[3] *Quobly*

The development of Quantum Processing Units (QPUs) based on spin-qubit technology requires significant cooling power in the 0.5–1.0 K temperature range. We present the design and performance of QuCUBE, a cryogenic platform delivering 100 mW of cooling power at 500 mK through a high-flow helium-3 Joule–Thomson refrigerator pre-cooled by a 4 K pulse-tube cryocooler. QuCUBE can also operate at 1.0 K with enhanced cooling capacity (~250 mW) using helium-4.

The platform is currently employed for the development of a 100-qubit spin-based QPU by the start-up Quobly in Grenoble. We report on the achieved performance and operational insights gained from intensive system use. Owing to the high level of integration enabled by CMOS silicon technology, spin qubits promise compact device volumes even at larger scales. According to the current roadmap, a demonstration of more than 1,000 qubits is anticipated by 2030, requiring a proportional scaling of the cryogenic infrastructure.

We conclude by outlining ongoing developments at the Néel Institute and Absolut System aimed at maintaining a compact cryogenic architecture while ensuring compatibility with next-generation quantum components.

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58

Closed cycle dilution refrigerator 3He-4He for space application

Author: Jérémy VESSAIRE[1]

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The studies of the cosmic microwave background (CMB) face significant technical constraints. To obtain accurate maps, the instrument must be capable of measuring fluctuations on the order of microkelvin over long observation periods (greater than two years). The Planck mission was a success, but with performance of 0.1 μW at 100 mK, its lifetime was limited by the maximum amount

of helium that could be loaded onboard the satellite. Indeed, the ^3He dilution refrigerator in superfluid ^4He operated as an open-cycle dilution refrigerator (OCDR) venting into space. Future space missions require more cooling power, lower temperatures, and extended lifetimes. Consequently, unlike Planck, it is necessary to close the dilution cycle using a isotope separator.

On one hand, based on historical work carried out at the Néel Institute on the OCDR, we have developed a demonstrator model (TRL4) of a closed-cycle dilution refrigerator (CCDR). This setup performs 2 µW at 50 mK with the challenge that all the physical processes involved in the demonstrator are against the gravitational field (unlike conventional dilution refrigerators, which use gravity to both distill and dilute 3He). On the other hand, recently, a transfer of know-how from the CNRS/Institut Néel to the CEA/DSBT has been set up to carry out the next developments of the CCDR in order to increase its technological maturity to TRL6 (e.g., mechanical environment).

We will present the latest CCDR developments obtained at the Institut Néel and the CEA/DSBT.

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59

Numerical investigation of subcritical and supercritical spray dynamics in cryogenic refuelling processes

Author: Yuzhao Liu[1]

Co-author: Konstantina Vogiatzaki [1]

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The transition to cleaner energy carriers is essential for reducing greenhouse gas emissions. As the market share of cryogenic fuels such as liquefied natural gas (LNG) and liquid hydrogen (LH_2) increases, cryogenic fluid transportation and storage systems are becoming increasingly important. The unique thermophysical properties of cryogenic fluids pose significant challenges for the injection, storage, and transportation, requiring accurate modelling tools for cryogenic fluid management.
As an application case, subcooled liquid hydrogen (sLH_2) refuelling sprays are examined in the context of heavy-duty truck operations. Compared with gaseous hydrogen or low-pressure liquid hydrogen storage, sLH_2 offers benefits due to its high energy density, low storage pressure, and suitability for long-haul operations. In sLH_2 refuelling systems, the target tank pressure typically exceeds the critical pressure of hydrogen (Pc = 12.964 bar, Tc = 33.145 K). As a result, the injected sprays conditions range across multiple thermophysical regimes. Such transitions require the development of a unified numerical framework that can consistently capture the cryogenic spray dynamics.
A newly developed numerical solver, CoolFoam, is employed to simulate cryogenic spray behavior under varying thermodynamic conditions. The solver is developed on the OpenFOAM platform, specifically tailored for compressible, non-isothermal, multi-fluid, and cryogenic flows. The influence of tank pressure, temperature, and refuelling mass flow rate on spray development is systematically assessed. Results highlight the influences of key operational parameters in determining spray

penetration, evaporation rate, and heat transfer, which directly affect the efficiency, safety, and reliability of hydrogen refuelling for vehicle tanks.
The validated framework therefore offers a novel tool for evaluating cryogenic spray and optimizing refuelling strategies across both subcritical and supercritical regimes. These insights contribute to the development of safer and more energy-efficient cryogenic refuelling protocols, thereby supporting a wider adoption of cleaner cryogenic fuel applications.

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60

Advances and applications of superconducting nanowire single photon detectors (SNSPDs) and systems

Author: Mario Castaneda[1]

[1] *Single Quantum*

Superconducting nanowire single photon detectors (SNSPDs) deliver unmatched efficiency, timing precision and spectral range. In this talk we will give an overview of recent advances in this technology with focus on applications such as quantum communication, computing, and imaging.

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61

Quocca: A scalable quantum control and readout platform

Author: Jonas Buehler[None]

Universal quantum computing, requires a scalable system with millions of qubits. One of the current bottlenecks is a fast and high fidelity readout without limiting the scalability by area consumption, wiring, or power dissipation. We address this challenge by developing an integrated readout circuitry (IC), in a 22 nm FD-SOI technology, operating at deep cryogenic temperatures. The IC will be connected to a Single Electron Transistor (SET). The prototype is made for reading out two SETs. It implements a high speed mode, to perform a single bit readout to distinct $|0\rangle$ and $|1\rangle$ state and a high resolution mode for tuning, which amplifies the signal and passes it to the room-temperature electronics.

We characterize this IC inside a closed cycle Gifford-McMahon cryostat at a temperature of 6 K. The measurement shows a power consumption of 33.6 µW/SET for the single bit readout and 216 µW for the high-resolution mode. With a sampling time of 2×1 µs, the circuit shows low noise of 223 pA (1σ) for single bit readout, while the high-resolution mode has an input-referred noise level of 188 pA RMS (10 Hz to 1 MHz).

With its high bandwidth, low input noise and low power consumption, this IC paves the way for scalable integrated readout and is a decisive step on the way to universal quantum computing

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62

High-Capacity GM Cryocoolers and Circulating Cooling Systems

Author: Santhosh Kumar Gandla[1]

[1] *Sumitomo (SHI) Cryogenics of America Inc*

Sumitomo (SHI) cryogenics has been a pioneer and industry leader in developing cryocoolers for all major cryogenic applications including healthcare, semiconductor manufacturing, laboratory research, and quantum
computing, for customers globally. With the rising demand for 20K and high temperature superconducting (HTS) applications we have increased our efforts in the last decade to develop and offer cryogenic cooling solutions like single stage Gifford-McMahon (GM) cryocoolers and cryogenic circulating cooling systems to address the needs of our global customers.
In this talk, we will discuss the design challenges, integration concerns, test findings and application examples for the high-capacity GM cryocoolers and cryogenic circulating systems developed by Sumitomo (SHI) Cryogenics.

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63

Reflections On Dilution Refrigerators

Author: Fons de Waele[1]

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In this presentation the key contributions in the development of DRs will be discussed from the very beginning to the present status of the technique. Also the history of GM and pulse-tube coolers will get some attention since their development runs parallel to the development of DRs and presently pulse-tube coolers and DRs are combined in the so-called dry DRs.

In the end some challenges will be discussed especially with the application in quantum computers in mind.

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64

MRI at 10 mT using SQUID detection in an open environment

Author: Dimitri Labat[1]

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While low field MRI has seen recent breakthrough in several academic and commercial groups1,2, ranging between 50 and 200 mT, field cycling studies have revealed that the most interesting contrast can be obtained in the ultra-low field (ULF) regime (⊠ 10 mT)3. However, at such low fields, low signal-to-noise ratio (SNR) becomes a problem. The use of superconducting quantum interference devices (SQUID) for signal acquisition has been proposed to tackle this issue4. In this work, we present a 3D image of a human wrist and a garlic bulb, both captured using our custom system at 10

mT using a SQUID volume gradiometer and the EDITER method5 for post-processing noise cancellation, demonstrating its potential for producing high-quality images in low-field MRI applications6. The next step is a first in vivo breast image acquired by early 2026.

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66

Introduction to quantum technology

Due to recent technological advancements academic and industrial groups are now able to test and apply many of the beautiful concepts of quantum theory. I will introduce two of the key concepts underlying quantum computing and quantum communication, namely superposition and entanglement, and I will show how these are applied in the fields of quantum communication and in quantum computation.

For the field of quantum computation different, scalable approaches are pursued. Each type of quantum bit has its own energy scale and different measurement protocols lead to different requirements for the operating conditions (temperature, noise, power consumption). The state of the art of two developments will be discussed: the superconducting transmon qubit and topological Majorana qubits.

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ET cryogenic tower developments

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Gas bearing turbo compressor and expander technology for cryogenic applications

Cryogenic applications require high complexity air and gas handling. Hydrogen is liquefied for ease of storage and transportation. Once liquefied, boil-off is avoided by cooling the hydrogen (zero-boil off). For both liquification and zero-boil off the reverse Brayton cycle is the most efficient and therefore preferred technology. Driven by a turbo compressor and a turbo expander, it is referred to as a reverse turbo-Brayton cycle cryocooler. Such cryocoolers have a low specific power (lower than 100 W/W possible at 20 K cooling temperature) and therefore are more efficient and can achieve higher cooling power per cryocooler weight and size than Gifford-McMahon or Stirling type cryocoolers. Finally, for recirculation and transport of cryogenic gases, cryo fans are employed. For all these applications, a compressor, a fan and/or an expander are key components.

Gas bearing turbo compressor, fan and expander technology has significant advantages to other technology: small size and weight due to high-speed operation, maintenance free due to an oilfree bearing and no rotating sealings, high efficiency, low amount of wetted materials and therefore no outgassing or compatibility issues, and low microvibration emission due to the continuous flow operation. The gas bearing technology, which does not require sensors, allows to fully immerse the fan and expander into the cryogenic temperatures in a cold box down to 20 K and below. However, running gas bearing turbo compressors and expanders at cryogenic temperatures is a challenge.

This presentation introduces gas bearing turbo compressor, fan and expander technology feasible for cryogenic temperatures, its advantages, limitations and key characteristics. The applicability of the gas bearing turbo compressor technology to cryogenics is demonstrated with design calculations for gas bearing stability, mechanical stability and motor/generator performance. Furthermore, an experimental proof-of-concept of a gas bearing turbo machine is presented with a cryogenic cold test.

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Roadmap for Infrared detectors

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The SUPREME plasma thruster and the testing of its cryogenic infrastructure

The EU EIC project Superconductor-Based Readiness Enhanced Magnetoplasmadynamic Electric Propulsion (SUPREME) aims to increase the technological readiness of applied-field magnetoplasmadynamic thrusters (AF MPDT) by demonstrating the integration of a high-temperature superconductor coil (HTSC) together with multiple other advanced technologies for a thruster in the 5 kW power range. Next to the integral HTS technology, SUPREME implements enabling sub-technologies such as an advanced power processing unit (PPU), radiatively cooled electrodes, an advanced thermal management system (TMS) and a heaterless multi-channel hollow cathode. In addition, investigations of the propellant supply unit (PSU) prepare the total propulsion system for flight under the consideration of the propellant flexibility that AF-MPDTs possess.

As part of the project, a breadboard model of the SUPREME thruster is assembled and experimental campaigns to provide a comprehensive investigation of the thruster performance will be conducted at the Institute of Space Systems (IRS) at the University of Stuttgart. We showcase the design of the test setup and highlights the integration of the HTSC in combination with its cryogenic cooling system.

In our talk we will present the overall design and focus on the cryogenic infrastructure and expected heat loads. Since the thruster uses mass, this results effectively in a mass leak for the vacuum system, which is to be dealt with by the vacuum pumps. During operation, we find that the elevated vacuum levels will reduce the insulation capabilities of the MLI radiation shielding. The tests at University of Twente are to ensure that a sufficient cooling performance of the coil is available for long-term thruster operation, as at an elevated temperature the coil can suffer thermal runaway and quench. It should be noted that the coil will run at DC during operations and thus the loads are expected to be minimal. Our test show that the (dummy) coil remains under 50K at 15 W, showing good performance under simulated excessive heat loads, both in the lab experiments as well as the numerical validation. The experimental campaign of the cryogenic cooling system paves the way for a successful integration phase at IRS Stuttgart and serves as a steppingstone towards a next-generation plasma thruster.

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