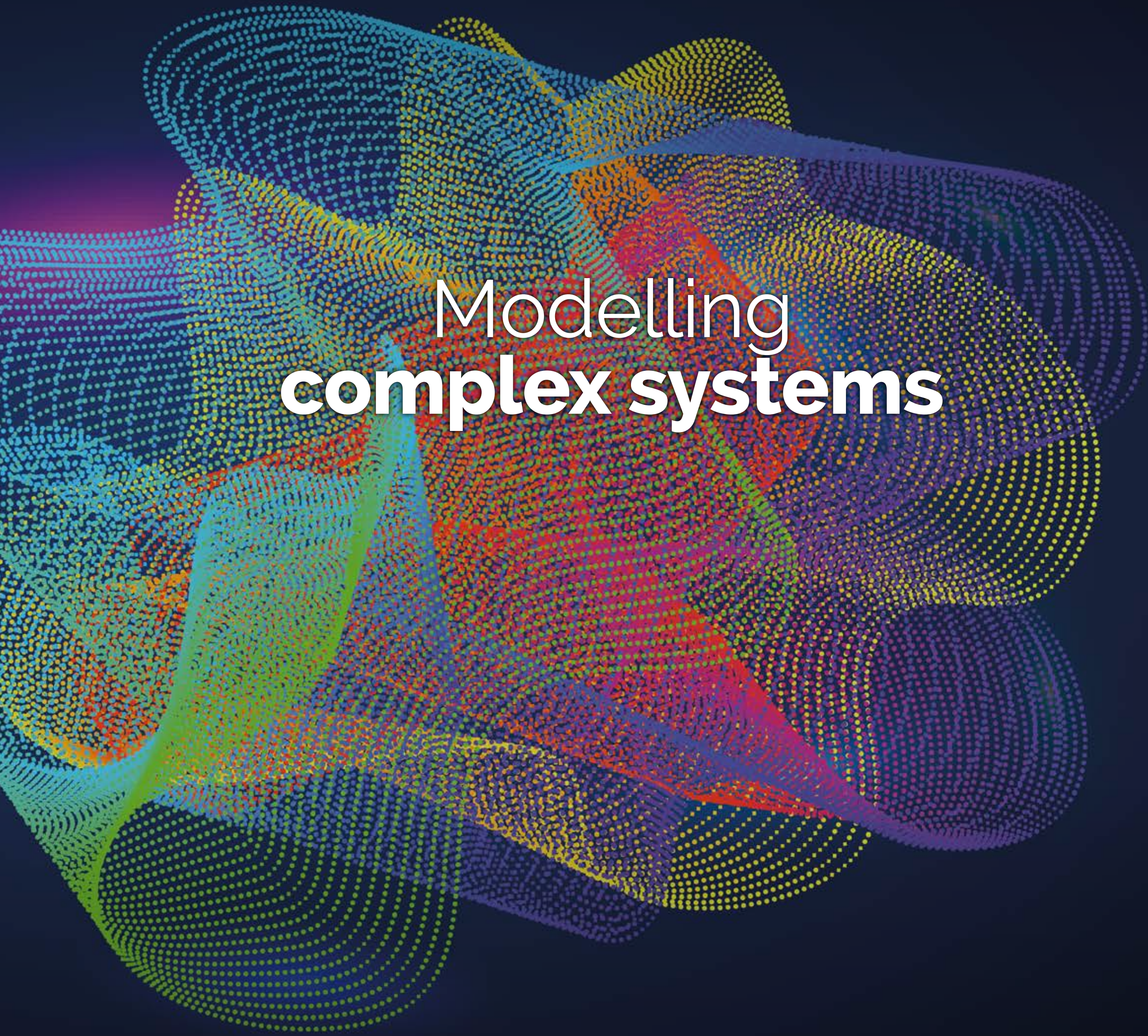
EUROPHYSICSNEWS

The magazine of the European Physical Society



Modelling complex systems

KATRIN probes neutrino mass scale

Breakthrough at the NIF

Neutrino interaction candidates at LHC

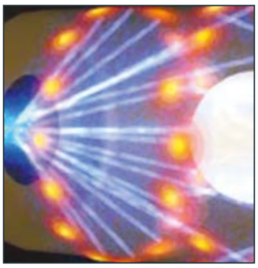
VOLUME 53 I NUMBER 1 I EUROPEAN COUNTRIES PRICE: 113€ PER YEAR (VAT NOT INCLUDED)

europhysicsnews

Cover picture: In this issue a focus on modelling complex systems introduced by the column of the Chair of the 'Statistical and Non-linear Physics' division of EPS at page 10. © iStockPhoto.

▲ PAGE 04

First neutrino interactions at LHC



▲ PAGE 18

Breakthrough at the NIF

▲ PAGE 24

KATRIN experiment

[EPS EDITORIAL]

2022 will be the International Year of Basic Sciences for Sustainable Development

This is done! After much effort and a long period of uncertainty, the International Year of Basic Sciences for Sustainable Development (IYBSSD) was proclaimed on 2 December 2021 by the United Nations (UN) General Assembly for 2022. The vote, tirelessly supported by the International Union for Pure and Applied Physics and its President, Michel Spiro, originates from the idea that all the basic scientific disciplines should mobilise in order to promote the importance of their contributions towards sustainable development goals. Initiated in 2017 and planned in 2022 - *i.e.*, in the midway of the UN's Agenda 30 and its 17 Goals "to transform our World" - this international year will show up the ways by which curiosity-driven research is vital not only to ensure no poverty and no hunger in the future, good health for all, fight climate change, preserve terrestrial and marine biodiversity, but also increase world peace and reduce inequalities. In this regard, the COVID pandemic reminds us of our dependence on basic science to ensure balanced, sustainable, and inclusive development of the planet.

The vote is the result of the mobilisation of the international scientific community driven by 28 scientific unions and research organisations. It was supported by 90 science academies, learned societies and scientific networks. The resolution, brought by Honduras in front of the UN, was co-sponsored by 36 other countries and it confirms the former declaration adapted unanimously by the UNESCO General Conference on 25 November 2019.

Of course, the European Physical Society (EPS) has strongly supported this event for the past two years and will continue to support it enthusiastically during the coming eighteen months. Our Society will visibly contribute to the events and actions related to the IYBSSD that will start at UNESCO headquarters in Paris on 30 June 2022 and will be organised around the world until 30 June 2023.

Anticipating this exceptional year, the EPS already set up two years ago the dedicated working group "Physics for Development and cooperation with Eastern States" through which several projects have been initiated or consolidated.

The first one concerns the Travel Award Fellowship Programme signed in November 2021 by the American Physical Society (APS), the International Center for Theoretical Physics (ICTP) and the EPS. This programme will help early-career researchers working in developing countries to return to their Alma Mater institution in Europe or North-America for two-month periods and thereby keep on conducting a world-class research (see the EPS News section in the former issue 52/5 of EPN).

The second initiative is the support of the EPS to Africa through, among others, our help to the 4th Physics Conference entitled "Physics for the sustainable development" that will be organised at Cape Verde in September 2022 by the Union of Physicists of Portuguese speaking countries. We shall similarly support actions of the French association "Migrations Co-Developpement Alsace" (MCDA) concerned about a better united development between North and South. ■

■ **Luc Bergé,** *EPS President*

europhysicsnews
2022 • Volume 53 • number 1

Europhysics news is the magazine of the European physics community. It is owned by the European Physical Society and produced in cooperation with EDP Sciences. The staff of EDP Sciences are involved in the production of the magazine and are not responsible for editorial content. **Most contributors to Europhysics news are volunteers and their work is greatly appreciated by the editors and the Editorial Advisory Board.**

Europhysics news is also available online at: **www.europhysicsnews.org**

Editor: Els de Wolf (NL)
Email: epn.editor@eps.org - **Twitter** @elsdewolf1

Science Editor: Ferenc Igloi (HU)
Email: igloi.ferenc@wigner.mta.hu

Executive Editor: David Lee
Email: david.lee@eps.org

Graphic designer: Xavier de Araujo
Email: xavier.dearaujo@eps.org

Director of Publication: Agnès Henri

EPS Secretariat

Address: EPS • 6 rue des Frères Lumière
68200 Mulhouse • France
Tel: +33 389 32 94 40 • **fax:** +33 389 32 94 49
www.eps.org

Secretariat is open 09.00–12.00 / 13.30–17.30 CET except weekends and French public holidays.

EDP Sciences

Managing & Publishing Director: Agnès Henri
Email: agnes.henri@edpsciences.org

Production Manager: Florence Anglezio

Advertising Manager: Bernadette Dufour
Email: bernadette.dufour@edpsciences.org

Address: EDP Sciences
17 avenue du Hoggar • BP 112 • PA de Courtabœuf
F-91944 Les Ulis Cedex A • France
Tel: +33 169 18 75 75 • **fax:** +33 169 28 84 91

www.edpsciences.org

Subscriptions

Individual Members of the European Physical Society receive Europhysics news free of charge.

Members of EPS National Member Societies receive Europhysics news through their society, except members of the Institute of Physics in the United Kingdom and the German Physical Society who have access to an e-version at www.europhysicsnews.org. The following are 2021 print version subscription prices available through EDP Sciences (Prices include postal delivery cost).

Institutions - European Union countries: 113 € (VAT not included, 20%). **Rest of the world:** 136 €

Student - European Union countries: 54.17 € (VAT not included, 20%). **Rest of the world:** 65 €

Contact: Europhysics News, EDP Sciences
17 avenue du Hoggar - Parc d'activités de Courtaboeuf
BP 112 - F-91944 Les Ulis CEDEX A, France
subscribers@edpsciences.org
or visit **www.edpsciences.org**

ISSN 0531-7479 • ISSN 1432-1092 (electronic edition)

Printer: Fabrègue • Saint-Yrieix-la-Perche, France

Legal deposit: February 2022

First neutrino interaction candidates at Large Hadron Collider

▮ **Tomoko Ariga** – Kyushu University, Nishi-ku, 819-0395 Fukuoka, Japan – DOI: https://doi.org/10.1051/epn/2022101

The FASER*ν* pilot detector observed the first neutrino interaction candidates at the Large Hadron Collider (LHC), opening a new avenue for studying neutrinos from current and future high-energy colliders.

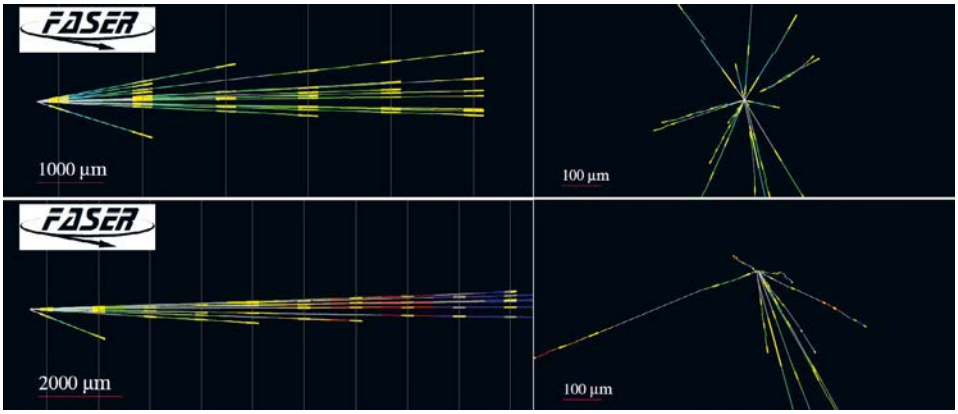
▲ FIG. 1: FASER detector installed inside tunnel shown in upper-left part of photograph.

FASER*ν*

There has been a longstanding interest in studying neutrinos produced at the Large Hadron Collider (LHC), although collider neutrinos have not been directly detected. In Run 3 of the LHC starting from 2022, proton-proton collisions at a center-of-mass energy of 13.6 TeV and with an expected integrated luminosity of 150 fb^{-1} will produce a high-intensity beam of $O(10^{12})$ neutrinos in the far-forward direction with a mean interaction energy of about ~1 TeV. In the ForwArd Search ExpeRiment (FASER) [1], a neutrino detector, called FASERν, was designed to detect these neutrinos and examine their properties [2]. In 2021, the main FASER detector was installed 480 m downstream of the ATLAS interaction point inside tunnel TI12 (Figs. 1 and 2). The FASERν detector, consisting of an emulsion/tungsten detector, a veto detector and an interface silicon detector, is being installed in front of it. Beam exposure and data collection will be conducted from 2022. FASERν is located on the beam collision axis to maximise the interaction rate of the neutrinos of all three flavors, namely ν_e, ν_μ, and ν_τ. This deployment allows FASERν to measure the charged-current interaction cross-sections in the TeV energy range, which is currently unexplored. The FASER*ν* measurements can probe the gap between accelerator measurements (E_ν<360 GeV) [3] and the IceCube data (E_ν>6.3 TeV) [4] for muon neutrinos. For electron and tau neutrinos, the existing cross-section measurements can be extended to significantly higher energy values. In addition to the charged-current interactions, neutral-current interactions can be measured. Such measurements can provide a new limit on the nonstandard interactions of neutrinos to complement existing limits [5]. Furthermore, forward hadron production, which is poorly constrained by other LHC experiments, can be investigated using FASERν. Currently, the uncertainty in forward charm production limits the clarification of the atmospheric neutrino background to astrophysical neutrino observations using neutrino telescopes. FASERν measurements of high-energy electron neutrinos, which mainly originate from charm decays, can provide the first data on high-energy and large-rapidity charm production, providing vital data in a controlled environment for astrophysical neutrino observations.

First neutrino interaction candidates

In 2018 during LHC Run 2, a pilot run was performed in the TI18 tunnel of the LHC beamline to demonstrate neutrino detection at the LHC for the first time. The data obtained from the pilot detector were used to prove the feasibility of high-energy neutrino measurements in this experimental environment. The pilot detector was incapable of identifying muons because its depth was only $0.6\lambda_{int}$, significantly shorter than the $8\lambda_{int}$ of the full FASERν detector for LHC Run 3. We searched for neutrino interactions by analysing the data corresponding to 11 kg of the target mass. We observed the first candidate events consistent with neutrino interactions, owing to neutrinos from the LHC [6]. Fig. 3 shows two candidate events. A 2.7σ excess of neutrino-like signals over the muon-induced background was measured. These results demonstrate the ability of FASERν to detect neutrinos at the LHC, thus paving the way for future collider neutrino experiments.



▲ FIG. 3: Event displays of two neutrino interaction candidate vertices [6] in y–z projection longitudinal to beam direction (left) and in view transverse to beam direction (right).

Prospects

The preparation of the FASERν detector for obtaining data in LHC Run 3 is underway. With a deeper detector and lepton identification capability, FASERν will perform better than the 2018 pilot detector. In 2022-2024, we expect to record about ~10,000 flavour-tagged charged-current neutrino interactions during LHC Run 3, along with neutral-current interactions. Furthermore, toward the high-luminosity LHC era, we are studying the possibility to conduct the more sensitive experiment (FASERν2) at a proposed facility known as the Forward Physics Facility [7]. ■

References

[1] A. Ariga *et al.* (FASER Collaboration), FASER's physics reach for long-lived particles, *Phys. Rev. D* **99**, 095011 (2019). https://journals.aps.org/prd/abstract/10.1103/PhysRevD.99.095011

[2] H. Abreu *et al.* (FASER Collaboration), Detecting and studying high-energy collider neutrinos with FASER at the LHC, *Eur. Phys. J. C* **80**, 61 (2020). https://link.springer.com/article/10.1140\%2Fepjc\%2Fs10052-020-7631-5

[3] P. A. Zyla *et al.* (Particle Data Group Collaboration), Review of particle physics, *PTEP* 2020, 083C01 (2020). https://academic.oup.com/ptep/article/2020/8/083C01/5891211

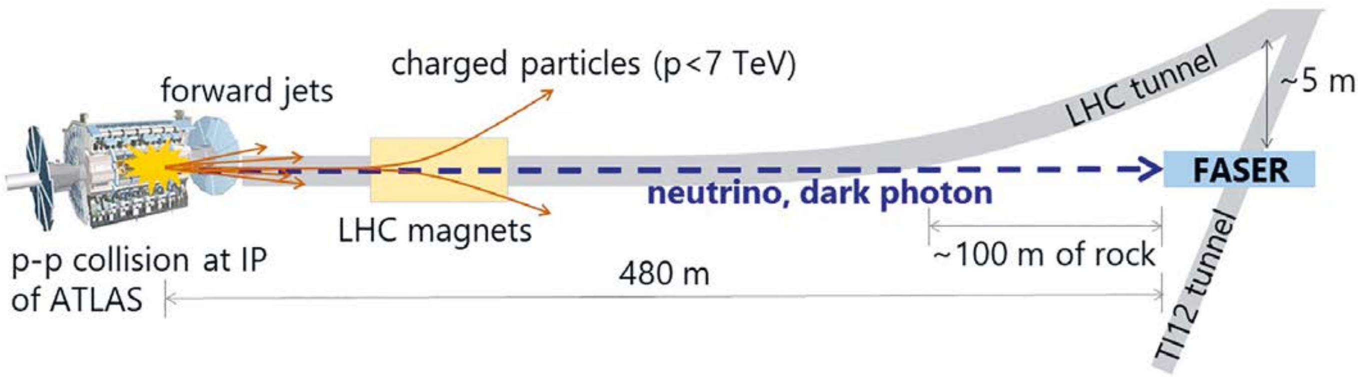
[4] M. Aartsen *et al.* (IceCube Collaboration), Measurement of the multi-TeV neutrino cross section with IceCube using Earth absorption, *Nature* **551**, 596 (2017). https://www.nature.com/articles/nature24459

[5] A. Ismail, R.M. Abraham, F. Kling, Neutral current neutrino interactions at FASERν, *Phys. Rev. D* **103**, 056014 (2021). https://journals.aps.org/prd/abstract/10.1103/PhysRevD.103.056014

[6] H. Abreu *et al.* (FASER Collaboration), First neutrino interaction candidates at the LHC, *Phys. Rev. D* **104**, L091101 (2021). https://journals.aps.org/prd/abstract/10.1103/PhysRevD.104.L091101

[7] L.A. Anchordoqui *et al.*, The Forward Physics Facility: Sites, Experiments, and Physics Potential, arXiv:2109.10905 (2021). https://arxiv.org/abs/2109.10905.

▼ FIG. 2: Location of FASER detector.



Two special issues

The mini-theme of this EPN issue is complex systems. It is also the subject of two special issues of EPJ-ST.

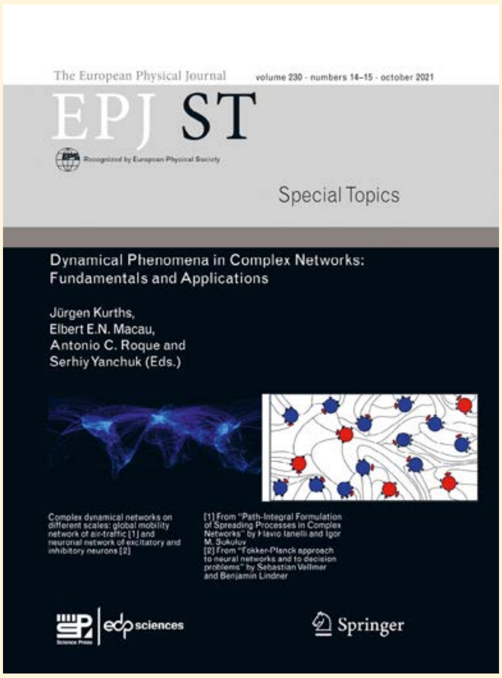
An exploration of tipping in complex systems

This special issue examines the extensive landscape of research into tipping within complex systems, and provides guidance as to where the field will likely be headed in the future.

Complex systems can be found in a diverse array of real-world scenarios, but are unified by their ability to suddenly transition between drastically different patterns of behaviour. Known as 'tipping,' this type of transformation is generally triggered by small changes in the parameters of individual systems – whose effects can rapidly cascade to alter entire networks of interacting subsystems. In this special issue, EPJST explores the nature of tipping in complex systems through 21 new articles. Together, the studies reveal recent trends and directions of research within the field, and highlight the pressing challenges it will face in the future. ■

Reference

G. Ambika and J. Kurths, Tipping in complex systems: theory, *methods and applications. Eur. Phys. J. Spec. Top.* 230, 3177–3179 (2021). https://doi.org/10.1140/epjs/s11734-021-00281-z



Examining the dynamics of complex networks

A new collection of papers focuses on the theories and methodology of dynamical networks with a focus on neuroscience and Earth sciences, and climate systems.

A special issue of EPJST, edited by Dr Jurgen Kurths, Senior Advisor at the Research Department for Complexity Science, Potsdam Institute for Climate Impact Research (PIK), and Professor and Senior Advisor at Humboldt University, Berlin, Ahmedabad, brings together a collection of papers focusing improving our understanding of the collective dynamics of complex systems. The special issue pays particular attention to the applications of this understanding in the diverse fields of neuroscience, climate modelling, and Earth science. ■

References

S. Yanchuk, A.C. Roque, E.E.N. Macau and J. Kurths "Dynamical phenomena in complex networks: fundamentals and applications". Eur. Phys. J. Spec. Top

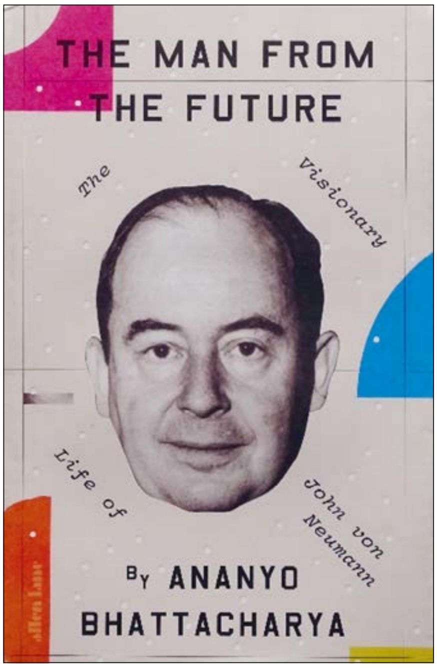
The Time-Traveler John von Neumann

According to John von Neumann, only "an intelligent exercise of day-to-day judgment" can save us and our planet.

"I am thinking about something much more important than bombs. I am thinking about computers." This was John von Neumann's (1903–1957) response in 1946 to a question about his current interest. By then he was past two major periods of his activities and others would follow during the remaining decade of his short life. His exceptional achievements, presented in Ananyo Bhattacharya's *The Man from the Future: The Visionary Life of John von Neumann*, are overwhelming.

It all began in Budapest where a number of high schools graduated great future contributors to world science such as Theodore von Kármán, Michael Polanyi, George de Hevesy, Leo Szilard, Dennis Gabor, Eugene P. Wigner, Edward Teller, and—von Neumann. He soon left Hungary, a conspicuously anti-Semitic country in post-World-War-I Europe. He embarked on a promising career in Weimar Germany only to move on even before the Nazis took it over. He was one of the first hires at the Institute for Advanced Study (IAS) in Princeton. Already as a teenager, he started publishing mathematical treatises. While in Germany, he authored the Mathematical Foundations of Quantum Mechanics. His scientific output did not suffer from the change of venue when he moved to America; on the contrary.

From 1940, he became involved in defense; steadily rising in various projects and committees. He had valuable inputs in strategic planning as well as concrete issues. He was one of the architects of the implosion ignition for the plutonium bomb and the determination of the position of exploding the atom bomb for highest efficiency. When the development of the thermonuclear bomb necessitated amounts of calculations of heretofore unseen enormity, it gave him an extra push to create the stored-program computer. An elaborate section of Bhattacharya's book discusses von Neumann's game theory and his joint book with Oskar Morgenstern, *Theory of Games and Economic Behavior*, published in 1944, amid his most intense defense-related activities.



Bhattacharya's book is not a usual day-to-day account; rather, it is more the story of von Neumann's ideas, their roots and, more importantly, their afterlives.

Quiet persuasion with reason was von Neumann's mode of operation rather than loud statements, let alone open belligerence. Yet he was a hawk (using a term that did not yet exist then) who advocated preemptive nuclear strikes on Moscow while the United States still had the atom bomb monopoly. His rational arguments made him an authority in forging post-war U.S. strategies throughout the Cold War even when he was no longer around. He supported developing the hydrogen bomb for its enormous destructive power, which was a necessity when long-range ballistic missiles did not have sufficient accuracy in reaching their target. He was very much for developing long-range missiles and producing them in a great variety. He knew that scientific and technological progress could not be stopped and was aware that all discoveries and innovations might advance human well-being as well as be utilized for military purposes. He was early in recognizing the importance of climate change, the hazards of carbon-dioxide emission, and that even changing the climate might be turned into a devastating weapon.

Von Neumann's razor-edge mind was constantly racing ahead. At one point he turned to biology. He compared the organism, a biological machine, to man-built machines, and arrived at his ultimate area of inquiry: the human brain. With his interest in replication, he embraced every area of cutting-edge science while the rest of the scientific community had still been catching up. His study, "*Can We Survive Technology?*" is a must read for everyone dealing with the future of humankind at any level, from local to global. His unfinished book, *The Computer and the Brain*, was based on his Silliman Memorial Lectures, which he could not deliver because of his devastating illness.

Bhattacharya's book is not a usual day-to-day account; rather, it is more the story of von Neumann's ideas, their roots and, more importantly, their afterlives. Those ideas have penetrated and continue to impact our every-day lives. Bhattacharya brilliantly places von Neumann's work in perspective. Even though von Neumann left behind an incomplete oeuvre, this book offers a self-consistent pattern of what he accomplished for us and for generations to come. ■

Istvan Hargittai
Budapest University of Technology and Economics
http://istvan.hargittai.com
DOI: https://doi.org/10.1051/epn/2022102

Second edition of the "Rencontres Physique Entreprise Recherche"

Daryna Pesina, Arnaud Raoux, Enrique Sánchez, Luc Bergé

The Rencontres Physique Entreprise Recherche (RPER) was born out of the observation that, despite the ongoing efforts of doctoral schools, Ph.D. candidates know little about the research performed in companies.

Conversely, the latter are not always aware of why hiring doctors can be beneficial for them. The success of the first edition organised by the French Physical Society (SFP), held in 2017 at the Mairie de Paris, confirmed once again the interest in bringing together academic and industrial research. The SFP naturally wished to repeat this event which, although delayed by the Covid crisis, was finally held "face-to-face" on September 17, 2021, at Sorbonne University. Organised in partnership with the European Physical Society (EPS) and the ESPCI Paris - PSL, the event gathered more than 400 participants, including 300 Ph.D. candidates.

Bringing together industry and academia

The SFP Youth Network and the scientific committee in charge of the day, which was chaired by Didier Roux, former Director of R&D and Innovation at Saint-Gobain, member of the French Academy of Sciences and the French Academy of Technologies, were keen to ensure that the RPER2021 programme would both respond to the questions and concerns of young participants regarding their career choices and be attractive to the participating companies. The programme, therefore, proposed to:

- involve representatives of large industries, small and medium-sized enterprises (SMEs), and start-ups through plenary **conferences or roundtables**;
- encourage exchanges with companies through a **"meeting place"** and **interactive workshops**;
- conclude with a **debate** on the employment of Ph.D. graduates in companies.

Unlike the first edition of RPER, this year's conference also hosted several events designed specifically to promote international exchanges between Ph.D. students, postdoctoral researchers and important stakeholders of the industry sector. As part of this initiative, the opening session started with the plenary talk by Gustav Kalbe, Head of Unit for "High Performance Computing and Quantum Technologies" from the European Commission. Other activities included a roundtable on Quantum Technologies, a training workshop around a quantum demonstrator, a mini-forum on entrepreneurship, and an "English Corner" as part of the "Meeting Place". Prepared by the EPS and EPS Young Minds Programme, all these events were held in English while French was the official language of the meeting.

Conferences and roundtables

The conferences and roundtables covered a wide range of topics of particular interest to physicists: energy, quantum technologies, machine learning, mobility and applications of microfluidics in industry.

Gustav Kalbe gave an overview of the EU strategy on digitalisation, emphasising the important role that quantum technologies are playing in this transformation. The presentations of Sandrine Lévêque-Fort (Abbelight) and Pascale Sennelart (Quandela) allowed the audience to discover the work and the path of two physicists who created a start-up. Jean-Philippe Bouchaud (Capital Fund Management) explained how he went from statistical physics to financial asset management. Finally, Nathalie Schmitt and Julien Dupas described the beautiful physics done within well-established companies such as Air Liquide and Nestlé in the energy and food industry.

Roundtables with more than twenty other representatives of industrial companies of all sizes completed the themes discussed during the conferences, with in particular a mini-forum on the creation of start-ups and a hands-on session around a demonstrator of a quantum computer.

The rich exchanges between the speakers and the audience throughout the conferences and roundtables gave rise to lively debates confirming the interest in the selected topics.

Meeting place

Alongside the conferences and roundtables, the "meeting place" brought together 25 stands devoted to a wide range of topics: quantum mechanics, optics, energy, mobility, fluid mechanics, *etc.* These booths provided information on opportunities in the companies represented, as well as an opportunity to discover a wide variety of careers. As most of the exhibitors were doctors in physics, they were very familiar with the questions asked by the participants, as they had been confronted themselves with the same interrogations! The enthusiastic feedback collected after the event underlined the relevance of this place of exchange and testified to the mutual pleasure shared during these meetings.

Workshops

As in the first edition of the RPER, the interactive workshops, aimed at bringing together about fifteen doctoral and post-doctoral students around a current problem encountered in the physics-based companies, were once again a great success. The topics of RPER2021 workshops were the optimisation of a medical device for liver diseases, the optimisation of telecommunications by electromagnetic waves, the use of new technologies for bio-imaging, the development of lithium batteries by means of supercapacitors, the development of sensors for the measurement of vital data during sleep and the use of innovative materials for cell therapy. The young participants appreciated the original format and more informal communication with the speakers from start-ups and SMEs on the scientific and technological issues of their company, but also on their career paths. As for the industrial managers, they were fascinated by the richness and diversity of the profiles as well as by the thoughts and technical solutions brought to the proposed topics.

Closing debate

The final debate, moderated by Yves Bréchet, Scientific Director of Saint-Gobain and member of the French Academy of Sciences, was an opportunity for four doctors in physics working in companies in various fields [Maxime Harazi (Hap2U), Thomas Houy (Télécoms ParisTech), David Louapre (Ubisoft) and Constance Moreau-Luchaire (La Maison du Whisky)] to interact with the audience on the question of "after the thesis". It emerged from the numerous discussions that the choice to go into the business world must be based on a real conviction and not be a choice by default: it is not a plan B. The creativity and ability of PhDs to grasp complex problems are two "transversal" skills developed during a thesis. They are particularly appreciated by companies and should be promoted! A Ph.D. allows you to acquire scientific skills but also to develop a state of mind, a way of asking questions and looking at the world, qualities that are at least as important.

What's next?

RPER meetings have highlighted the richness of the exchanges between the industrial world and young Ph.D. students, and the place that the latter can find in companies of all sizes. The satisfaction survey conducted after the event is very positive, even if there are still points to improve. There is clearly a real expectation for this type of event, and the EPS has decided to organise a European version at Sorbonne University next year. Mark the dates: 2-4 June 2022. That is when Paris will welcome the first edition of the EPS Forum. While the first day of the event will follow the ideas of RPER and promote young researchers to industrial partners, the second day will host a general conference in Physics with the latest achievements presented by the most renowned experts in the selected disciplines including three Nobel laureates in Physics: Barry Barish, John Michael Kosterlitz, and Serge Haroche. Please refer to https://epsforum.org/ for more information about this event. ■

Complex systems: the amazing cross-disciplinary journey of statistical physics

DOI: https://doi.org/10.1051/epn/2022103

The 2021 Nobel prize in Physics honours three outstanding scientist who, broadly speaking, have been working on complex systems: The decision of the Nobel prize committee was setting a signpost for the importance of modelling, understanding and tackling climate change (the work of Manabe and Hasselmann), and for the theoretical modelling and understanding of complex systems in general (the work of Parisi). See Europhysics News 52/5 for more detailed information on the prize winners and their work.

The current EPN issue contains two articles of K. Binder and M. Mezard related to spin glasses — one of the major cornerstones of Parisi's work in the 1980s. These systems can be regarded as physical examples of complex systems that have played an important role in the historical development of statistical physics, exhibiting typical features such as power-law decay of correlations and very long relaxation times. Glasses are in a kind of permanent nonequilibrium state. So are many complex systems, driven by external forces and influences in a heterogeneous way, which are these days investigated in a variety of sub-disciplines.

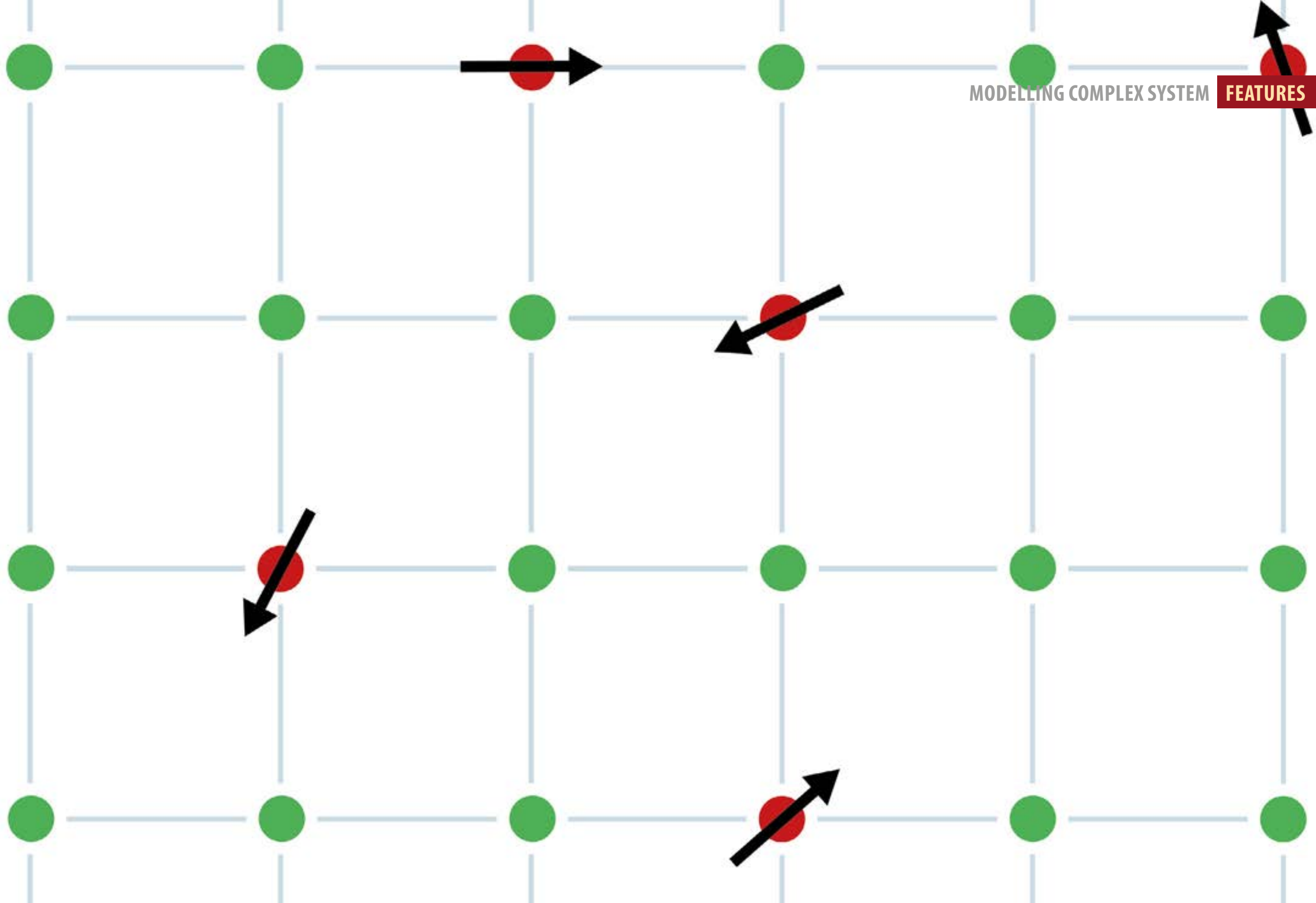
Methods used by the Nobel prize winners are highly cross-disciplinary and universally applicable and often based on stochastic modelling via stochastic differential equations. For example, the famous Parisi-Wu stochastic quantization method is just reducing path integrals (of utmost relevance in any quantum field theory) to expectation values over higher-dimensional Brownian motion trajectories in a fictitious time coordinate—thus connecting Fokker-Planck and Langevin equations used in classical nonequilibrium problems to quantum field theory. Similarly, the work of Hasselmann uses stochastic differential equations to model climate change, where the short-scale fluctuations (modelled by noise in the stochastic differential equation) corresponds to short-scale weather effects influencing the long-term climate dynamics.

The decision of the Nobel prize committee for the 2021 Physics prize, in a sense, signals what statistical physics, in its generalized sense, has evolved to in recent decades: Towards a highly cross-disciplinary science with applications not only in physics, but connecting many different areas of science, relevant for the most important topics such as climate change that need to be solved to guarantee a sustainable future.

Environmental issues such as climate tipping points, air pollution dynamics, the dynamics of sustainable power grids, or the infection dynamics of the Covid-19 pandemic, draw in crowds of the next generations of statistical physicists, for good reasons, as this research is of utmost interest to guarantee a healthy and sustainable environment for the future of mankind, and at the same time produces highly interesting theoretical research aspects. Statistical physics methods are also used to understand cities as complex systems, as well as the dynamics of living organisms (see Europhysics News 51/5) and one could continue this list of outstanding new applications. One thing is clear: The days where statistical physics was just used to describe molecules in a gas are over. Now the relevant constituents are agents, people, renewable energy sources, traffic patterns, vehicle flows, complex biomolecules, and the interactions at macroscopic level are social contacts, communications, infections, and so on. Statistical analysis of data-driven research, complex network topologies, neural networks and modern machine learning algorithms provide a powerful universal language, helping to optimize the real-world systems under consideration.

The conferences and prizes of the EPS Statistical and Nonlinear Physics Division reflect these changes. The 2021 EPS Statistical and Nonlinear Physics prize, awarded in September 2021 during the EPS conference "Statistical Physics of Complex Systems" at ICTP/SISSA in Trieste went to A.-L. Barabási (who has pioneered Complex Network Science and its cross-disciplinary applications) and A. Vulpiani (who has pioneered Nonlinear Physics, some of his work actually jointly with Parisi). For sure the journey towards outstanding cross-disciplinary applications will continue with new and unexpected scientific discoveries by the next generation of statistical physicists. ■

Christian Beck,
Chair of the Statistical and Nonlinear Physics Division



THE GLASS TRANSITION: HOW DO COMPLEX CRAGGY FREE ENERGY LANDSCAPES EMERGE?

Kurt Binder – DOI: https://doi.org/10.1051/epn/2022104
Institut für Physik, Johannes-Gutenberg-Universität Mainz, Germany

Glass as a material was already known in ancient Egypt. Now its use for windows, bottles, *etc.* is very common; thus, it may sound surprising that the glassy state of matter and the transition from an undercooled melt to this state are grand challenge problems of physics. This article describes the basic concepts; then it points out how the discovery of "spin glasses" and the theory by Giorgio Parisi has given a new boost to the interest in these problems. The status of a theory of the glass transition will be critically discussed.

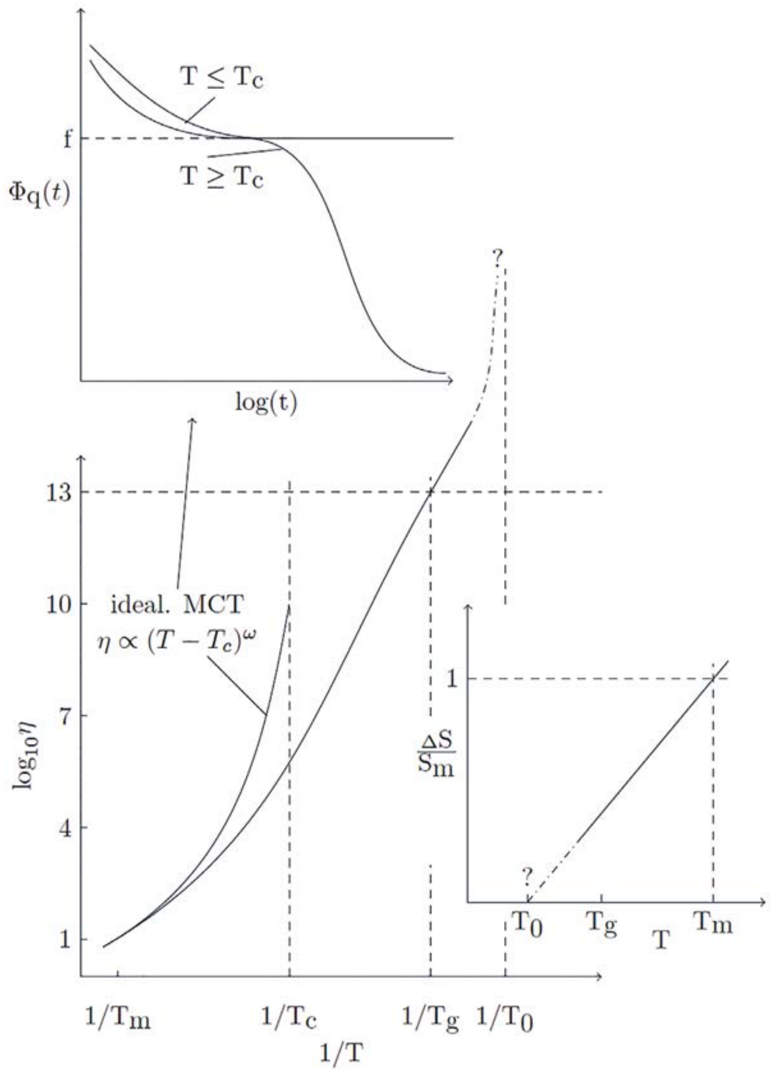
▲ A spin glass is a metal alloy where iron atoms, for example, are randomly mixed into a grid of copper atoms. Red dots: iron, green dots: copper. ©Johan Jarnestad/ The Royal Swedish Academy of Sciences

Experimental background

The state of solid materials in thermal equilibrium is crystalline. Thus, when a liquid is cooled down, crystallization occurs: Scattering experiments with X-rays or neutrons show Bragg peaks, reflecting the periodic arrangement of atoms on sites of a lattice.

However, the scattering pattern of a glass is different, it is strikingly similar to the liquid. But unlike the latter, diffusive motions and structural relaxation are "arrested" [1]. However, the mentioned techniques probe the pair correlation functions between the particles. So more subtle forms of "order" that do not show up in pair correlations are not ruled out! Also, one must understand which mechanisms slow down the particles that during the time to cool down the fluid no crystallization could occur.

In addition, all physical properties of glasses depend both on the thermodynamic state (temperature T, pressure p) that is considered, and on the "preparation history". Interestingly, NOT ONLY HUMANS AGE: GLASSES AGE AS WELL!



▲ **FIG 1: Properties of glassforming fluids. Schematic plot of the viscosity η(T) of a fluid as a function of inverse temperature 1/T. The inverse melting temperature $1/T_m$, glass transition temperature $1/T_g$ and critical temperature $1/T_c$ of MCT are indicated. The temperature T_0, where η(T) would diverge, often is associated with the temperature where the extrapolated entropy difference ΔS(T) between fluid and crystal vanishes ("Kauzmann temperature" (1)); see insert ($S_m = \Delta S(T_m)$). The idealized MCT predicts the time-dependent density correlation function $\phi_q(t \to \infty) = f$. This is not the case in reality; the further decay requires thermally activated processes, not described within idealized MCT. From Ref. (1) (Fig. 1.18).**

An important issue is the fact that not every fluid forms a glass. There are no glassy states for fluids of noble gas atoms. Also, simple metals do not freeze into glasses. Also, simple molecular fluids do not exist in glassy states.

In order that a glass forms when a fluid is cooled, there must be some energetic "frustration effect" in the local arrangement of atoms in the dense fluid. A prototype example is SiO_2. There is always a Si atom in the centre of a regular tetrahedron, with O atoms at the four corners, each O atom is shared by two neighbouring tetrahedra. These tetrahedra form perfect networks in the crystal structures, with 6-membered rings in various arrangements. In the glassy structure of SiO_2, these tetrahedra are not regular but distorted, and also 5-membered and 7-membered rings are frozen in. In the deeply cooled SiO_2 melt the covalent Si-O bonds break up and reform to allow structural relaxation. This picture is not only due to imagination, but emerges also from simulations [1], which also show that physical properties depend on the cooling rate. As a caveat, we mention that the cooling rate in simulations is orders of magnitude larger than in experiments; but when one locates a glass transition in real glasses, from a kink in the curve of volume versus temperature, there is a cooling rate dependence of the glass transition temperature T_g as well! Alternatively, a heuristic definition of T_g is that the shear viscosity has reached 10^{12} Pa.s (which corresponds to relaxation times of about one minute). Of course, this choice is arbitrary – it is broadly accepted, since larger viscosities can hardly be measured.

When one plots the logarithm of the viscosity η versus T_g/T to compare different glass formers ("Angell plot") one finds a straight line for SiO_2, i. e. an Arrhenius behaviour, $\eta \propto \exp(E_{act}/k_BT)$, where E_{act} is an activation energy and k_B Boltzmann's constant. Many other glassformers, *e.g.* molecular fluids such as glycerol, show pronounced curvature on this plot, consistent with the Vogel-Fulcher-Tammann (VFT) (1) relation,

$$\eta(T) \propto \exp[B/(T-T_0)], \qquad (1)$$

Where B is a constant and T_0, where η(T) would diverge, is about 30K below T_g.

Glassforming fluids exhibit many more interesting properties; some are shown schematically in Fig. 1, where also mode coupling theory (MCT) [2] is mentioned. Particularly interesting is the strong decrease of the entropy. When the fluid falls out of equilibrium, its entropy is frozen in, and thus the glass does not comply with the 3rd law of thermodynamics. If the entropy of small amplitude, vibration-like, motions in the fluid and crystal are similar, the extrapolation of ΔS in Fig. 1 might imply that a transition at T_0 is needed to avoid the "entropy catastrophe" (a negative entropy); but this conclusion is a speculation. The MCT predictions, are only useful for understanding the initial stages of structural relaxation of the moderately supercooled fluid. The density correlator $\phi_q(t)$ are often well described by a stretched exponential decay: $\phi_q(t) \propto \exp(-(t/\tau_q)^\beta)$ where τ_q is the structural relaxation time, and the exponent β is often close to 3/5. Another important property of glassforming fluids is their "dynamical heterogeneity" [3]: near the glass transition the Stokes-Einstein relation between selfdiffusion and viscosity and the Stokes-Einstein-Debye relation between translational and rotational diffusion of molecules fail.

Early theoretical concepts

There has never been a consensus how to understand the glass transition; very different ideas were developed, which are sketched here only very roughly.

A theory related to the decrease of entropy (Fig. 1) is the idea to introduce subsystems of dimensions ξ, in which cooperative rearrangements of the particles take place, independent of other subsystems. Each subsystem has a few energetically preferred states, and a configurational entropy of order unity. The total configurational entropy S_{conf} is proportional to the number of those regions, *i.e.* inversely proportional to their volume. Some assumptions on the kinetics of the rearrangement process yield for the relaxation time $\tau(T) \propto \exp[C/(TS_{conf})]$, where C is a constant. Assuming then that S_{conf} is proportional to $\Delta S(T) \propto T\text{-}T_0$, Eq. (1) results since $\eta(T) \propto \tau(T)$. Unfortunately, it is not clear how to define these cooperatively rearranging regions; experiments attempting to extract estimates for ξ independently were not encouraging (typically ξ = 2-3 nm), and the assumptions on the kinetics are doubtful either [1]. Simulations [1] find a gradual increase of ξ with decreasing T but cannot reach temperatures near T_g.

Contrary to emphasizing collective rearrangements, the free volume theory focuses on single particle motions. Each particle needs to find "free volume" in its neighbourhood that it can move into. Diffusion over large distances is possible if the regions identified as free volume percolate. Also, this theory can lead to Eq. (1); but the concept of free volume is somewhat vague, and the treatment requires many assumptions that cannot easily be tested.

The MCT [2] has a sound starting point in the theory of liquids. It starts out from an exact equation for the time-dependence of $\phi_q(t)$, and invokes a useful factorization of the so-called "memory functions". MCT predicts onset of slow relaxation, compatible with a stretched exponential relaxation, as seen experimentally. For $T \to T_c$ a plateau (describing the "cage effect") develops in $\phi_q(t)$. The "lifetime" of this plateau diverges as a power law in this limit (Fig. 1). While the two-step relaxation is compatible with experiments and simulations, the critical power-law is not: the predicted T_c clearly is higher than T_g. It is argued that going beyond this "idealized" version of MCT the critical divergence at T_c is rounded off: instead, a crossover to thermally activated behaviour in the region $T_g < T < T_c$ occurs [2]. However, a convincing description of this thermally activated relaxation in the framework of MCT remains to be developed.

Thus, some theories of glassy relaxation use as an input thermodynamic properties. However, there is also the view that all what matters are kinetic constraints. This view is exemplified by kinetic Ising models, without any static correlation. Constraints on the flipping rates of the Ising spins, give rise to slow relaxation resembling glassy behaviour. These models also lend support to describing the glass transition as a symmetry breaking in the space of system trajectories: rather than ensembles of states in phase space, one deals with "ensembles of histories", and dynamical transitions then can be identified. However, the precise connection between this approach and the traditional approaches remains unclear.

Spin glasses: do they provide a solution to the puzzle?

Fifty years ago, it was discovered that metals like Cu containing a few percent randomly distributed magnetic ions undergo a new type of phase transition: the magnetic susceptibility χ exhibits a cusp at a temperature T_f, but one cannot detect any ferro- or antiferromagnetic order for $T < T_f$. Dynamic spin correlations, reveal a dramatic slowing down as T approaches T_f from above: relaxation times gradually increase from picoseconds to macroscopic times! Since the sign of the interaction between the magnetic moments oscillates as function of distance, and the distances are random, for $T < T_f$ spins are frozen in random directions: hence, one has a magnetic analog of a structural glass, a SPIN GLASS!

This discovery spurred great interest: the hope was to gain insight for glass transitions in general. Soon there was consensus to simplify the model, take spins with a Gaussian distributed interaction J between any pairs of neighbours in the mean-field version; for a short-range version, the simplest model takes Ising spins on the sites of a lattice.

While these models look simple, dealing with them is still difficult; the averaging over the quenched random disorder is a real obstacle for statistical mechanics. The ingenious approach of Giorgio Parisi [4] clarified the nature of "order": there is no simple order parameter, like the magnetization for a ferromagnet, but rather an order parameter function. This function reflects the fact that for $T < T_f$ the free energy "landscape" is split into many "valleys", separated by barriers (infinitely high in the meanfield limit). The valleys correspond to the possible states of the spin glass (*i.e.*, "ergodic components").

This theory has been extremely fruitful for many other problems, in rather different fields (*e.g.* neural network models, optimization, *etc.*). It has also provided guidance to interpret numerical simulations on the $\pm$ J spin-glass, believed to correspond reasonably well to real systems.

HOWEVER, GLASSES LACK THE SPIN REVERSAL SYMMETRY OF SPIN GLASSES. Approaching T_f from above, the spin glass exhibits standard critical phenomena. So if spin-glass theory can be useful for structural glasses at all, clearly a generalization without this special symmetry is needed.

Such generalizations exist, *e.g.* the p-state Potts glass with $p > 4$: Each site can take one out of p states. The energy J between the "Potts spins" occurs if they are in the same state; else the energy is zero. Such models exhibit a 1st order transition at T_0 where glass order appears discontinuously. Interestingly, dynamic versions of this model (in the meanfield limit) experience a divergence of the relaxation time at a temperature $T_D > T_0$, and for $T < T_D$ the system is nonergodic. Denoting the probability that a state ℓ occurs by P_ℓ, we can define a configurational entropy (also called "complexity") of this nonergodic system as $I = - k_B \sum_\ell P_\ell \ln P_\ell$. For the disordered phase at $T > T_D$ there is a single "valley" in the free energy landscape; but for $T_0 < T < T_D$ then are infinitely many such "valleys" when I is extensive. No order then is possible, but I vanishes at T_0 where the glass order appears discontinuously.

To describe real systems, one would need to generalize this model with infinite range of the interactions to finite range. The many valleys at $T_0 < T < T_D$ then are separated by barriers of finite height only, so the transition at T_D is rounded, the state for $T < T_D$ can be viewed as patchwork of subregions of characteristic size ξ, each in one of the possible metastable states (different from neighbouring regions). Due to thermally activated fluctuations transitions in this "mosaic state" of subregions between different states occur. With some assumptions in this "random first order theory" one can obtain the VFT relation for the divergence of the relaxation time at T_0.

Unfortunately, this description still does not make many testable predictions, and numerical simulations [1] have not (yet?) provided clear evidence in favour or against this description, SO THE GLASS TRANSITION CONTINUES TO STAY A CHALLENGE… ■

"Numerical simulations have not (yet?) provided clear evidence in favour or against this description, so the glass transition continues to stay a challenge…"

About the Author

Kurt Binder made his Ph.D. in 1969 at the Technical University of Vienna and then moved to the Physics Department of the Technical University of Munich where he received his Habilitation in 1973. he held positions as a professor at the universities of Saarbrücken , Köln and (since 1983) Mainz, where he retired in 2012. He received many distinctions, such as the Max-Planck and Boltzmann Medals.

REFERENCES

[1] K. Binder and W. Kob, *Glassy Materials and Disordered Solids: An Introduction to Their Statistical Mechanics* (World Scientific, Singapore, 2011)

[2] W. Götze, *Complex Dynamics of Glass-Forming Liquids* (Oxford University Press, Oxford, 2009)

[3] L. Berthier, G. Biroli, J.-P. Bouchaud, L. Cipeletti and W. van Saarloos (Eds.) *Dynamical Heterogeneities in Glasses, Colloids and Granular Media* (Oxford University Press, Oxford, 2011)

[4] M. Mezard, G. Parisi, and M. A. Virasoro, *Spin Glasses Theory and Beyond* (World Scientific, Singapore, 1987)

SPIN GLASSES AND OPTIMIZATION IN COMPLEX SYSTEMS

Marc Mézard – École normale supérieure, PSL University – DOI: https://doi.org/10.1051/epn/2022105

Spin glasses are useless. Even the most imaginative physicists, submitted to grant pressure, could not find applications for these materials. Yet their study, triggered by pure intellectual interest, has created a formidable new branch of statistical physics distinguished this year by the Nobel prize attributed to Giorgio Parisi.

Several decades after being deciphered, the spin glass mystery has found applications in many other fields, from protein folding to computational neurosciences, information theory, economics theory, signal processing or machine learning.

All of these problems are described by large dimensional complex energy landscapes, in which one seeks low energy configurations. These optimization tasks are particularly challenging because of the very large dimensionality. This is precisely the "thermodynamic limit" where spin-glass based approaches bring new concepts for analyzing the landscape and its phase transitions, ideas of new algorithms and methods to analyze their performance.

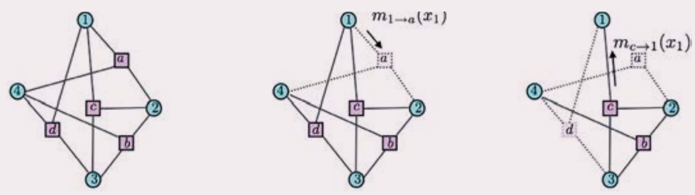
Spin glass as an archetypical optimization problem

About fifty years ago, the attention of a few physicists was drawn to the anomalous magnetic response of some special magnetic alloys like Cu-Mn, in which the magnetic moments of Mn interact by pairs through random exchange couplings which can be ferromagnetic or antiferromagnetic, depending on their distance. Specifically, two magnetic moment s_i and s_j described as Ising spins taking values ± 1, have an interaction energy $-J_{ij}\, s_i\, s_j$. If the coupling J_{ij} is positive, the low energy configurations are those with parallel spins (ferromagnetic situation), if it is negative, the energy is lower when they are antiparallel (antiferromagnetic). In a spin glass, where both types of interactions are present, finding the lowest energy configuration, the "ground state", among the 2^N configurations of N spins is very hard. It is in fact an example of a so-called NP-hard problem: there is no known algorithm that can find the ground state in a computer time growing like a power of N, all known algorithms are exponential (and all algorithms are exponential if the famous conjecture P≠NP is correct). Physically, the relaxation time of spin glasses increases very rapidly when lowering the temperature, and in the spin-glass phase one cannot reach equilibrium.

Searching the ground-state is one of the many challenges of spin glasses. One also wants to understand what are the properties of spin configurations when the system is at equilibrium at a finite temperature, what type of random order sets-up in the low temperature spin-glass phase, and what is the nature of the phase transition.

BOX 1: MESSAGE PASSING ALGORITHMS

Mean field methods go back to more than a century ago, with the work of Pierre Weiss to understand the basic mechanism of ferromagnetism. In the last two decades it has been found how to write mean field equations, called in this context belief propagation or BP equations, for a very broad class of constraint satisfaction problems. These are problems in which N variables interact by groups of K: the joint probability distribution of the N variables is expressed as a product of factors, each involving K variables. The correlation structure is best understood in terms of a factor graph (see Fig. 1). In the thermodynamic limit N→∞ at fixed K, the mean field equations can be written as messages passed between the vertices of the graph, from variable to factor and from factor to variable. Solving them iteratively provides a new class of powerful algorithms, based on.



▲ **FIG. 1:** Left: an example of a factor graph: the probability law of the four variables is written as a product of 4 factors: $P(x_1,x_2,x_3,x_4)=\Psi_a(x_1,x_2,x_4)\,\Psi_b(x_2,x_3,x_4)\,\Psi_c(x_1,x_2,x_3)\,\Psi_d(x_1,x_3,x_4)$. Middle: the message $m_{1\to a}$ is the probability of x_1 if the factor a is absent. Right: the message $m_{c\to 1}$ is the probability of x_1 if it is connected only to c. The BP equations relate these various messages, the message going out from a node being computed from the incoming message.

Disordered systems: a new chapter of statistical physics

This spin-glass mystery was solved at the beginning of the eighties [1,2]. Its solution required three major conceptual developments of statistical physics.

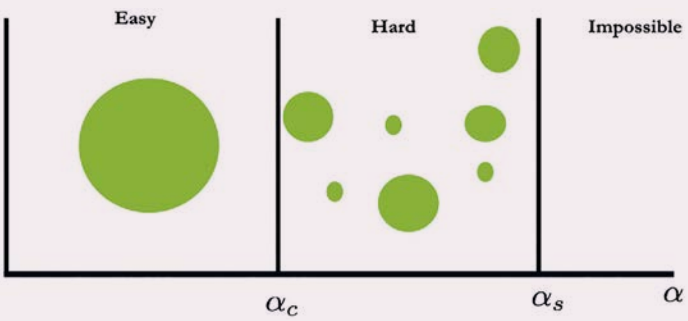
The first one is taming the disorder. In order to describe a given sample of a spin glass, one should give you the values of interaction couplings between all pairs of spins. If the interactions are short range, the number of such couplings is proportional to the number of spins, which is of the order of Avogadro's number *N*. In more general mathematical versions with long range interactions the number of couplings grows like N^2. In both cases the detailed description of a sample is impossible. Fortunately, the experimental behaviour of spin glasses, like their magnetic response to an external field, or their specific heat, does not depend on all these details: all samples of Cu-Mn with 1% of Mn atoms behave the same, provided they are well prepared. Mathematically, one introduces ensembles of spin glasses, like the one where all couplings are sampled independently from a gaussian distribution, and one proves that in the large-size limit all samples have the same thermodynamic behaviour. Yet, all samples are microscopically distinct, and have a distinct ground-state, which is NP-hard to find, which means impossible in practice even for systems of moderate sizes with a few thousands spins.

The second challenge was to identify the right order parameters for describing the spin-glass order. At low temperature each spin tends to point in a favorite direction, and the local magnetization m_i of spin i, the expectation value of s_i, is non-zero. But the magnetizations m_i are all distinct. One can thus aim at finding all the m_i. At the mean-field level one can write self-consistent equations that relate all these magnetizations, called "TAP equations" [3]. If they can be solved efficiently, this provides an algorithm.

The third main challenge is the multiplicity of states: there actually exist many ways in which the spins can freeze. A more macroscopic order parameter considers all the possible spontaneous orders of spins (all solutions of the TAP equations) and provides a statistical description of how they differ. This geometry of the space of solutions is the one that is encoded in the famous replica solution of Parisi. The precise link between this macroscopic order parameter and the microscopic magnetizations of TAP was understood through the cavity method [2] which also opened the way to rigorous mathematical proofs of the validity of the Parisi solution [4].

BOX 2: K-SATISFIABILITY

A K-SAT formula is a conjunction (an AND function) $\Phi=C_1 \wedge C_2 \wedge \ldots \wedge C_M$ of M clauses, where each clause is a disjunction (an OR) of K Boolean variables $x_1,\ldots,x_N$ or their negation. For instance, the clause $C=x_1 \vee x_2$ is TRUE unless x_1 and x_2 are FALSE. Formula Φ is satisfiable if and only if there exist an assignment of variables that satisfy all the clauses, this is then called a solution of the satisfiability problem. In random K-SAT, one wants to satisfy M= αN clauses, each involving K variables randomly chosen or their negation.



▲ **Fig.2 :** The phase diagram of random K-SAT. When the density of constraints α increases, one goes from a low-constraint "EASY" phase where the space of solutions is connected (one can move from one solution to the next by flipping one variable at a time), to an intermediate "HARD" phase where the solution space is shuttered into many pieces very far away from each other. At high constraint density, there are no solutions. α_s is the "SAT-UNSAT" phase transition, while α_c is a geometrical phase transition where efficient algorithms get stuck.

Optimizing with spin glass methods

It was soon realised that the new statistical mechanics of disordered systems developed for spin glasses might have applications in many different fields [2]. In fact, large-size systems of many "atoms" (in the Greek sense) interacting with disordered potentials are ubiquitous in science, including social sciences. In the theory of optimisation problems, phase transitions have now become an important chapter, and the theoretical methods invented in spin glass theory, mostly the replica and cavity method, provide very useful tools for their analysis.

In parallel, the development of appropriate mean-field equations for glassy systems with short-range interactions [2,5] has opened the way to powerful new types of message passing algorithms, which have become important in information theory and signal processing. They provide a fast and distributed way of estimating the marginal probability of each variable. In the general case they rely on a mean-field type of approximation that neglect some correlations, but in some well-designed problems like those appearing in information theory, they can become exact in the relevant limit of large-size systems.

The three phases of constraint satisfaction problems

One remarkable example of fruitful interactions concerns constraint satisfaction problems [5,6]. Deciding the satisfiability of a Boolean formula is a NP-hard optimization problem, actually it is at the root of the theory of NP-hardness. In random satisfiability problems, where the clauses are generated randomly, one finds a phase transition in the thermodynamic limit $N,M \to \infty$, keeping the ratio of clauses to variables, $\alpha=M/N$, fixed. Spin-glass based methods [7] allowed to precisely locate this phase transition which separates a regime of low density of constraints, $\alpha<\alpha_s$ where almost all problems have a solution from a regime $\alpha>\alpha_s$

where almost all problems have no solution. But the most surprising result obtained from the spin-glass analysis is the existence of another phase transition at a value $\alpha_c<\alpha_s$ due to a major change in the geometry of the space of solutions. In a generic random satisfiability formula with a density of constraints $\alpha<\alpha_c$ all the (exponentially many in absolute, but exponentially rare with respect to the full space) solutions build a connected cluster, and one can jump from one solution to the next by changing the assignment of one well chosen variable. Instead, in the intermediate range $\alpha_c<\alpha<\alpha_s$ the space of solution is shattered into many disconnected clusters, which are well separated from each other.

Importantly, this clustering transition of the geometry of solution space is correlated with the practical difficulty of finding fast algorithms for solving random satisfiability formulas. When $\alpha<\alpha_c$ the space of solutions is connected and there exist algorithms (for instance those based on mean-field equations) that are able to find a solution in polynomial time: the generic problem is easy. In the intermediate regime $\alpha_c<\alpha<\alpha_s$ we know that there exist solutions, but the algorithms able to find them (like the enumeration of all the 2^N possible assignments of the variables) take an exponential time: the generic problem is in-principle solvable, but it is hard from the computational point of view: in practice we have no efficient algorithms. When $\alpha>\alpha_s$ there are no solutions.

Towards a physical theory of algorithmic complexity?

This pattern with three phases, in which the solution of a constraint satisfaction problem is easy at low constraint density, then becomes algorithmically hard in an intermediate regime, and impossible in the high constraint density phase, has been found in many optimization problems. It is generally associated with a sudden shattering transition of the space of solutions. In physics language, the spin glass models which have this property are the one with a discontinuous glass transition (sometimes called "one step replica symmetry breaking" transition). The existence of well separated clusters of solutions is now seen as a possible reason from algorithmic hardness, and opens interesting routes for new approaches to algorithmic intractability [8]. In contrast to the standard classification of problems as P versus NP which is based on a worst-case analysis, this new construction will deal with "typical case" complexity, namely what happens in almost all instances generated from some given distribution.

A lesson

From the original magnetic anomaly in some "useless" alloys to its numerous applications in optimization and in so many other fields that I could not describe here, it has been a long way. This story shows once again that interesting research initially driven by pure intellectual interest can find fascinating developments in totally unexpected areas. ■

About the Author

After graduating from École normale supérieure, **Marc Mézard** became a CNRS research associate in 1981 and obtained his PhD in 1984 on spin glass theory. In 2001 he moved to Université Paris Sud as CNRS research director, and became director of the Laboratoire de physique théorique et modèles statistiques, and of the "Labex" Physics, Atoms, Light, Matter. Between 1987 and 2012 he worked as associate professor and then professor at École Polytechnique. Since 2012 he is the director of École normale supérieure in Paris. His main field of research is statistical physics of disordered systems and its use in various branches of science.

References

[1] G. Parisi, *Journal of Physics A* **13**, 1101 (1980)

[2] M. Mézard, G. Parisi and M.A. Virasoro, *Spin glass theory and beyond*, World Scientific 1987

[3] D.J.Thouless, P.W. Anderson and R.G. Palmer, *Philosophical Magazine* **35**, 593 (1977)

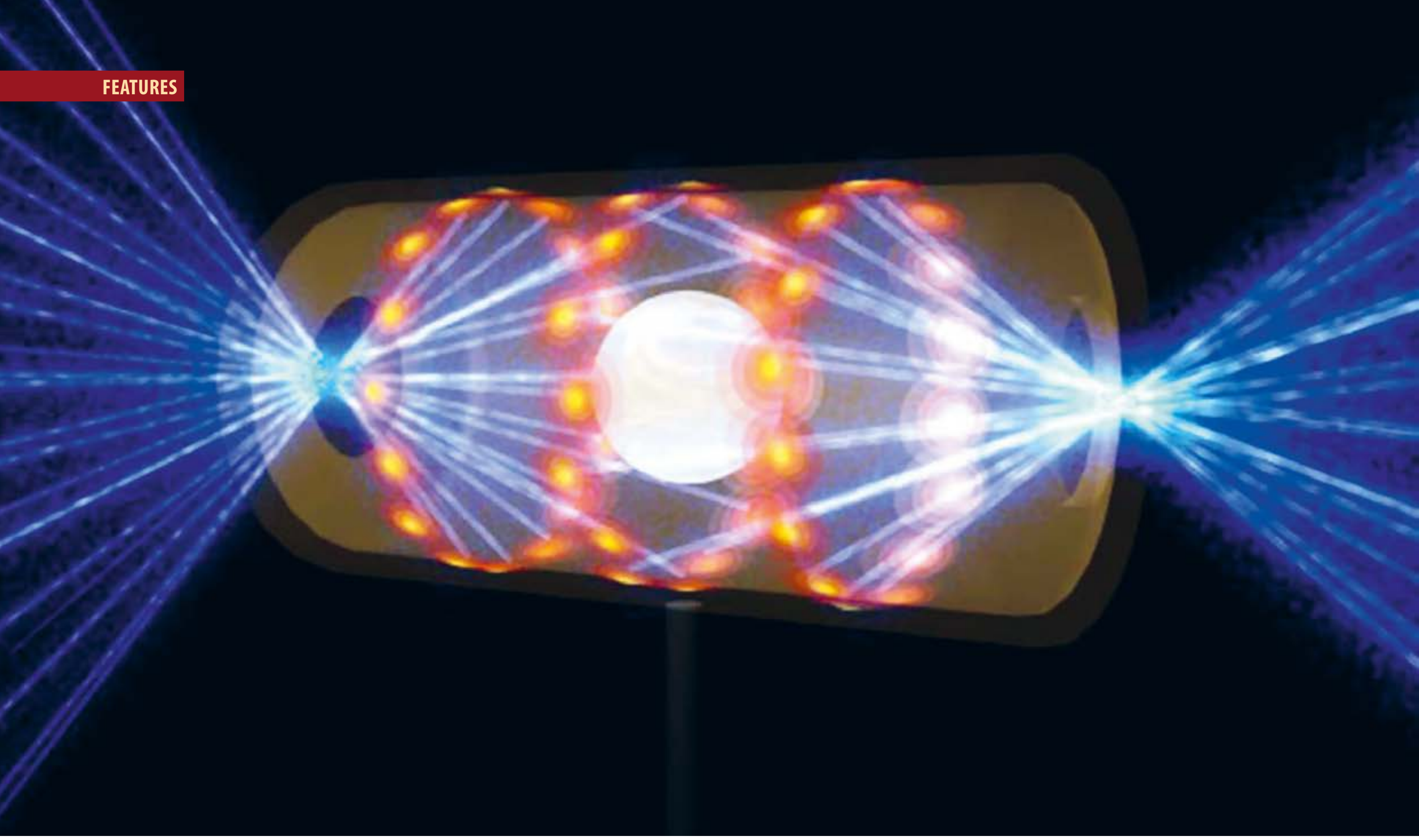
[4] D. Panchenko, *The Sherrington-Kirkpatrick Model*, Springer 2013

[5] M. Mézard and A. Montanari, *Information, physics, and computation*, Oxford University Press 2009

[6] F. Krzakala, A. Montanari, F. Ricci-Tersenghi, G. Semerjian and L. Zdeborova, *PNAS* **104**, 10318 (2007)

[7] M. Mézard, G. Parisi and R. Zecchina, *Science* **297**, 812 (2002)

[8] D. Gamarnik, PNAS 118 (41) (2021)



BREAKTHROUGH AT THE NIF
PAVES THE WAY TO INERTIAL FUSION ENERGY

S. Atzeni[1], D. Batani[2], C. N. Danson[3,4], L. A. Gizzi[5], S. Le Pape[6], J-L. Miquel[7], M. Perlado[8], R.H.H. Scott[9], M. Tatarakis[10,11], V. Tikhonchuk[2,12], and L. Volpe[13,14] – DOI: https://doi.org/10.1051/epn/2022106

[1] Dipartimento SBAI, Università di Roma "La Sapienza", 00161, Roma, Italy
[2] CELIA, Université de Bordeaux–CNRS–CEA, UMR 5107, 33405 Talence, France
[3] AWE, Aldermaston, Reading RG7 4PR, UK
[4] Centre for Intertial Fusion Studies, Blackett Laboratory, Imperial College London, London SW7 2AZ, UK
[5] Istituto Nazionale di Ottica, Consiglio Nazionale delle Ricerche, 56124 Pisa, Italy
[6] LULI - CNRS, Ecole Polytechnique, Palaiseau cedex, France
[7] CEA-DAM, DIF, F-91297 Arpajon, France and ALP, F-33114 Le Barp, France
[8] Instituto Fusión Nuclear "Guillermo Velarde" Universidad Politecnica de Madrid, 28006 Madrid, Spain
[9] Central Laser Facility, STFC Rutherford Appleton Laboratory, Harwell Oxford, Oxfordshire OX11 OQX, UK
[10] Institute of Plasma Physics and Lasers, Hellenic Mediterranean University Research Centre, 74100 Rethymno, Greece
[11] Department of Electronic Engineering, Hellenic Mediterranean University, 73133 Chania, Greece
[12] ELI-Beamlines Center, Institute of Physics, Czech Academy of Sciences, 25241 Dolni Brezany, Czech Republic
[13] Centro de Laseres Pulsados (CLPU), Parque Cientifico, E-37185 Villamayor, Salamanca, Spain
[14] Laser-Plasma Chair at the University of Salamanca, E-37185 Villamayor, Salamanca, Spain

In August 2021, at the National Ignition Facility of the Lawrence Livermore National Laboratory in the USA, a 1.35 MJ fusion yield was obtained. It is a demonstration of the validity of the Inertial Confinement Fusion approach to achieve energy-efficient thermonuclear fusion in the laboratory. It is a historical milestone that the scientific community has achieved after decades of efforts.

The concept of laser-driven inertial confinement thermonuclear fusion (ICF) for energy production was proposed in 1972 in seminal papers [1,2] that initiated a worldwide effort to demonstrate inertial fusion ignition in the laboratory. After five decades of continuous progress toward ignition, in August 2021 the National Ignition Facility (NIF) of the Lawrence Livermore National Laboratory (USA), announced a major advance[1], with 70 % of the 1.93 MJ input laser energy converted into products of the deuterium-tritium fusion reactions, namely neutrons and alpha particles. The record 1.35 MJ of output fusion energy was eight times higher than the yield obtained in previous best measurements. With this result the ignition milestone, that requires the fusion energy yield to be equal to the input laser energy, is only a small step away, proving unambiguously the validity and the feasibility of the ICF concept.

The NIF indirect drive approach and the 1.35 MJ yield experiment

The National Ignition Facility (NIF) uses the so-called *indirect drive scheme* in which the capsule containing the nuclear fuel, a mix of deuterium (D) and tritium (T), is enclosed in a gold cavity, the Hohlraum[2] (Figure 1). The inner walls of the cavity are irradiated by the 192 NIF laser beams, giving rise to intense X-ray emission that ablates of the outer surface of the capsule, accelerating the fuel inwards in a rocket-like behaviour (Figure 2).

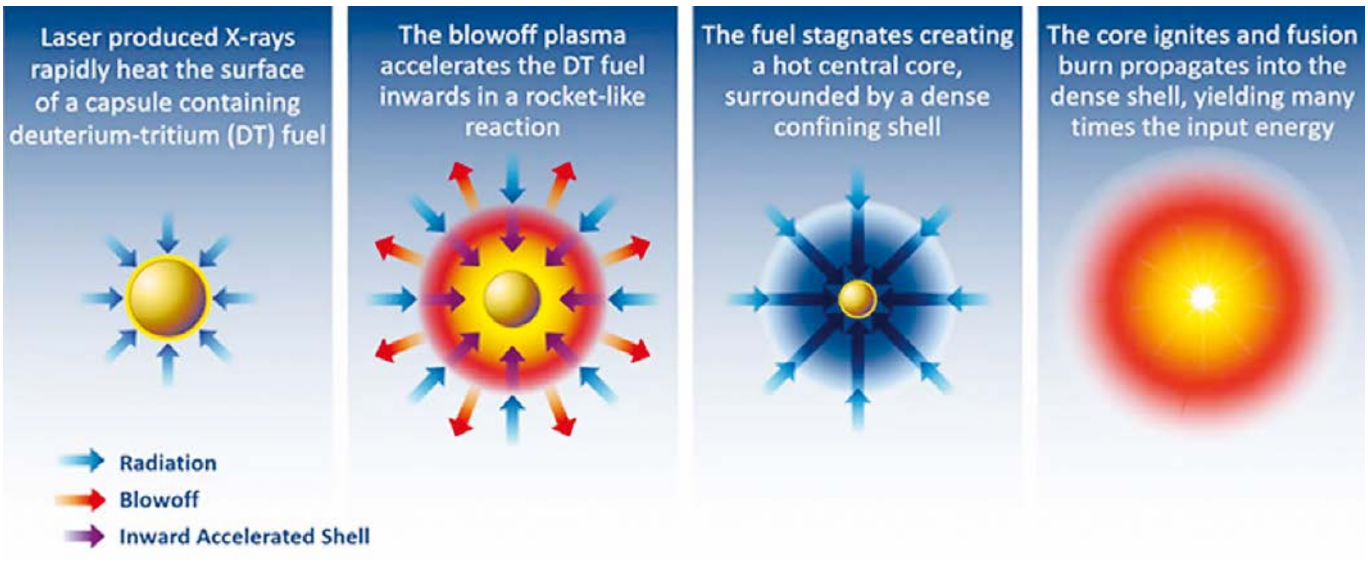
The following implosion makes the capsule shrink many times, compressing the fuel inside and increasing its density by up to about 1000 times, and heating its central part, the so-called hot-spot, to a temperature higher than 5 keV, needed to initiate copious D-T fusion reactions, each of which releases a 14.1 MeV neutron and a 3.5 MeV alpha particle. The alpha particles produced by the D-T reactions are slowed down in the compressed fuel, further heating it and compensating the losses due to radiation and heat conduction. In these conditions, a burn wave propagates out of the hot-spot into the surrounding compressed fuel and a large amount of fusion energy can then be released.

Different configurations have been designed and tested at NIF showing that a number of manufacturing issues play a crucial role in the implosion performance. Progressive control of these parameters enabled scientists to achieve successive improvements in the target design that finally led in August 2021 to an extraordinary performance in terms of neutron yield. In Figure 3 the neutron yield is shown as a function of the total hot-spot internal energy obtained from the series of implosion campaigns with different configurations. The campaigns were carried out during the past ten years. The red markers in Figure 3 indicate the major progress emerged with the High-Yield Big-Radius Implosion Design (Hybrid-E, HyE) [3]. In the figure the August 8, 2021 shot reached a total hot-spot internal energy of 65 kJ, of which 45 kJ due to self-heating from fusion reaction, yielding the production of 4.8×10^{17} neutrons and alpha particles, for a total energy of 1.35 MJ.

The high energy yield was possible thanks to the occurrence of the alpha heating mechanism. For the first time at NIF, the alpha particles generated by the fusion process were efficiently stopped in the compressed fuel, giving rise to a further heating of the

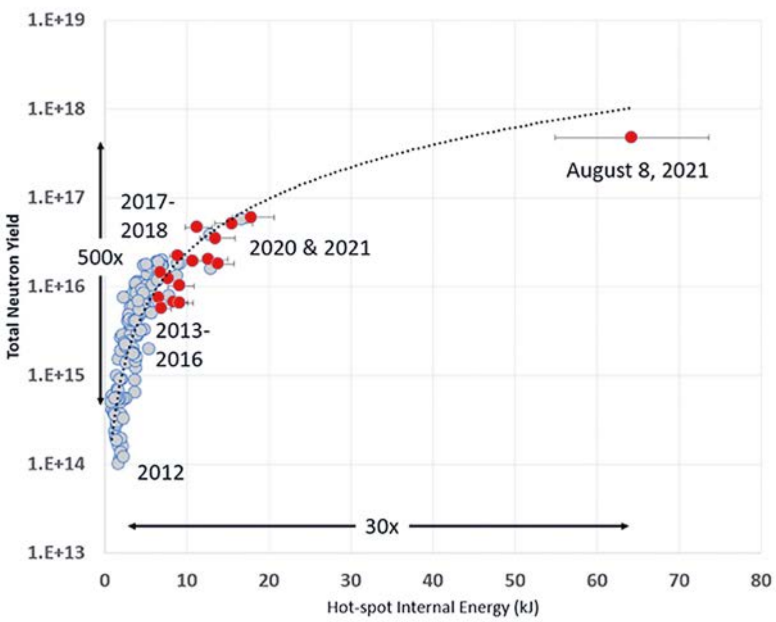
◂ **FIG. 1 - P.20:** An artist's rendering shows how the National Ignition Facility's 192 beams enter a small-size cylinder of gold and heat it from the inside to produce x-rays, which then implode the fuel capsule at its centre to create fusion. Credit: Lawrence Livermore National Laboratory

▾ **FIG. 2:** The phases of ICF including laser heating, compression, hot-spot creation and ignition.



[1] https://lasers.llnl.gov/news/hybrid-experiments-drive-nif-toward-ignition#anatomy

[2] A cavity whose walls are in radiative equilibrium with the radiant energy within the cavity.



▲ **FIG. 3:** Neutron yield as a function of the total hot-spot internal energy as obtained from recent measurements[1].

hot-spot, enabling additional fusion reactions and sustaining the propagation of thermonuclear burn out of a hot-spot that consumed approximately 2% of the compressed fuel. The small amount of burnt fuel indicates a potential of larger energy output that can be obtained, estimated to be up to 20 MJ with an overall energy gain of about 10, provided fuel confinement is appropriately increased, with a similar target design.

IMPROVING THE ENERGY YIELD

If the burn wave propagates out of the hot-spot into the surrounding compressed fuel a large amount of fusion energy can be released with the yield Y given by:

$$Y \propto \varepsilon^{23/6} \frac{v_{imp}^{23/3}}{\alpha_{if}^{12/5}} S^{14/3},$$

where ε represents the efficiency of conversion of the capsule kinetic energy into internal energy of the compressed fuel at stagnation, v_{imp} is the implosion velocity of the capsule, α_{if} is the "adiabat", a measure of the in-flight fuel entropy, and S is the spatial scale of the implosion, namely the normalised initial radius of the fuel-ablator interface. The equation clearly shows how the yield is sensitive to the implosion velocity, to the spatial scale, and to how efficiently the kinetic energy is converted into internal energy at stagnation. Based on this scaling, different configurations have been designed and tested at NIF over the past decade. Experiments have increasingly shown that a number of manufacturing issues play a crucial role in the implosion performance. Among these parameters, the roughness of the capsule surface, the thickness of the membrane holding the capsule in the Hohlraum, the diameter of the filling tube and the density of gas fill in the Hohlraum, were found to have a profound effect on the outcome of the implosion. Progressive control of these parameters enabled scientists to achieve successive improvements in the target design that finally led in August 2021 to an extraordinary performance in terms of neutron yield.

Towards high gain ICF: direct drive

The main outcome of the NIF achievement is the demonstration of the validity of the ICF approach to achieve thermonuclear fusion in the laboratory. Future experiments will tell how to improve the performance further, increase the compression of the fuel, improve implosion efficiency and increase fusion energy yield. At the same time, the results enable the community to strengthen the path towards ICF schemes with higher potential gain, tackling the major sources of loss of efficiency to overcome current limitations. The main gain limitation of the indirect drive ICF scheme used at NIF is the inefficient delivery of input energy into the capsule, that requires the prior conversion of laser energy into X-rays in the Hohlraum to smoothly drive compression of the capsule. The situation may change significantly if this intermediate step could be removed as it happens in the case of ICF with *direct drive*, in which the capsule is illuminated directly by the laser light as in the original ICF scheme [1].

Direct drive was extensively explored in the past, showing limitations due to the onset of hydrodynamic instabilities and laser-induced instabilities responsible for a high level of laser light backscattering and pre-heating of the compressed capsule due to fast electron generation.

More recently, however, advanced ignition schemes for direct drive ICF were proposed with the aim of overcoming the stringent requirements on the compression uniformity and symmetry of the original direct drive scheme to achieve central hot-spot ignition. Among these schemes the *shock-ignition* scheme [4] foresees a first phase of moderate compression followed by an ignition phase driven by a converging shock generated by a high intensity laser spike at the end of the compression phase (Figure 4). The scheme is expected to achieve high gain with moderate laser energy [4], and is being considered for Inertial Fusion Energy (IFE) research along with other advanced ignition schemes like fast ignition or magnetised linear inertial fusion.

The path to IFE: a new European Infrastructure

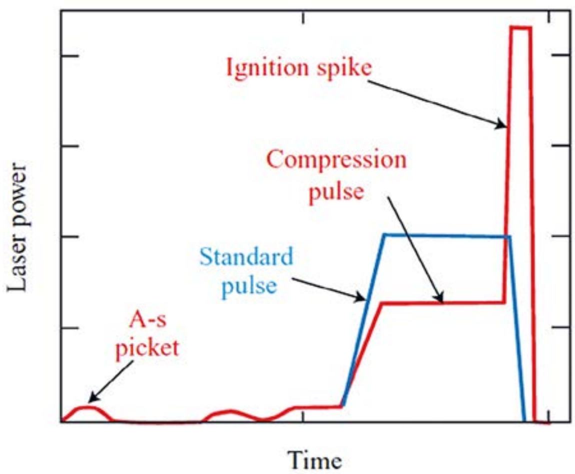
New energy sources that are both sustainable and free of CO_2 emission are required to respond to the current climate change crisis. Fusion energy is considered as the ultimate, long-term solution for energy supply and many complementary approaches are being pursued including magnetic and inertial confinement. The roadmap of magnetic fusion energy (MFE) has long been established with the International Thermonuclear Experimental Reactor (ITER) currently in construction in Cadarache (France) and other alternative smaller-scale approaches such as the stellarator

Wendelstein 7-X at the Max Planck Institute for Plasma Physics (Germany) or private endeavours like the Commonwealth Fusion Systems (USA). In contrast, an international roadmap for IFE has not yet been established, although IFE development programmes were started in several world regions, including USA, Japan and Europe.

The HiPER (High Power Laser Energy Research) infrastructure project (2006-2013) was included in the 2006 European Strategic Forum for Research Infrastructures (ESFRI) Roadmap and was aimed at exploring the science and technology of laser-driven fusion schemes, with a special focus on advanced ignition. Another equally important objective of HiPER was to build a sustainable, long-term, basic science programme in a wide range of associated fields and applications. HiPER allowed for the first time to tackle not only target ignition and burning but also reactor relevant issues like chamber design and materials under IFE conditions. The MJ scale energy yield demonstrated at NIF confirms that ICF is a viable solution for fusion energy and the scientific community is now strongly advocating [6] the establishment of a new IFE programme in Europe aimed at pursuing the original HiPER objectives and developing a roadmap to assess the feasibility of an IFE power plant based on burning of deuterium and tritium [HiPER+[3]].

An important mission of this initiative is to design and build a European intermediate-energy facility dedicated to laser fusion energy, which will scale up the many years of successful investigations carried out at several laser facilities in Europe. This scientific endeavour involves a fairly large community that is now supported for networking activities by the European research consortium EUROfusion and has fulfilled many important scientific milestones that give confidence in the • • •

▼ **FIG. 4:** Laser power temporal evolution in the two advanced ignition direct-drive ICF approaches known as shock-ignition [4].



[3] https://www.clpu.es/Laser_Fusion_HiPER

next stages to demonstrate high gain, direct drive fusion ignition. These next stages include scaled experiments at intermediate facilities, development high repetition rate laser and target technologies and materials, fusion ignition demonstration at megajoule facilities. Full-scale demonstration experiments require large laboratories of the scale of NIF or the Laser MegaJoule (LMJ) CEA, France. LMJ is currently in construction, although near completion, with ongoing precursor activity. Scaled experiments can be performed also at the Omega facility (Rochester, USA), which is the only academic installation capable of performing integrated implosion experiments; here the physics of direct-drive ICF has been investigated in depth at the energy level of 30 kJ.

A similar facility but based on the latest laser technology, possibly with a higher repetition rate, is needed by the scientific community to establish a science and technology IFE programme in Europe. High energy density science and direct-drive laser fusion could be studied there in coordination with the realization of several full-scale experiments at LMJ or NIF. This new facility will make it possible to investigate the needs and challenges of future high-repetition-rate, IFE configurations, including assessments of science-based technologies and materials for the target fabrication and reactor construction. In particular, similarly to MFE, the first wall of the vacuum chamber and blanket design for advanced reactors require dedicated experimental and modelling effort.

In this context, the recent EU large investments in the Extreme Light Infrastructure have generated a strong involvement of the EU laser industry that is now prepared to respond to the challenges that the proposed IFE infrastructure is setting. The new laser technologies developed recently, including efficient diode pumping, high repetition rate and broad-band wavelength capabilities, are becoming key building blocks in several areas of high-power laser-based technologies involving manufacturing industry, healthcare, security, as well as in other large scientific infrastructures, as demonstrated by the growing number of dedicated installations, also across EU. These technologies are crucial to future IFE power plants, and the proposed installation will set a steep change in the pace of their development and readiness, further strengthening the leading role of EU laser and high-tech industry.

IMPROVING THE CAPSULE DESIGN

A representation of the progressive improvement in performance of the sequential experimental campaigns is clearly inferred considering the *figure* of *merit* of each shot based upon the areal density, *ρR* and the temperature, *T* of the imploded hot-spot:

$$(\rho R)^3 T^3 \sim E_{HS} P_{HS}^2,$$

expressed in terms of E_{HS}, the hot-spot internal energy and P_{HS}, the hot-spot pressure [2]. It is worth mentioning here that ρRT is the analogous of the triple product $n\tau T$ used in magnetic fusion, with *n* being the ion density of the plasma. Design changes include a larger capsule, a high-density carbon ablator, a low-density gas fill, and slightly larger Hohlraum. The larger capsule considerably increases the fraction of energy coupled to the capsule and to the hot-spot. To counteract the detrimental effects expected for this change of scale on the spherical symmetry of the compression, the laser energy across the different sets of laser beams was balanced using the Cross Beam Energy Transfer (CBET) occurring in the Hohlraum due to the presence of a low-density plasma. The upgrades led to the major advance in implosion performance and neutron yield increase up to 170 kJ in 2020. A further improvement was then introduced by slightly reducing the laser entrance holes of the Hohlraum and extending the laser pulse duration by a few hundred picoseconds to sustain the implosion velocity in the late stage and increase the stagnation pressure, thus transferring more energy in the hot-spot. These further modifications, along with an improved quality of the high-density carbon capsule shell and a reduced two-micron-diameter tube to fill the capsule with fuel, were successfully implemented and led to the extraordinary result of August 2021, with the achievement of up to 11 keV burning fuel temperature and the production of 4.8×10^{17} neutrons and alpha particles, for a total energy of 1.35 MJ.

Conclusions

The achievement of megajoule energy yield at the NIF sets an historical milestone in Fusion Energy research that makes inertial fusion one of the very few viable approaches for future clean energy production. Europe has a unique opportunity to empower research in this field and the scientific community is prepared to engage in this journey.

Acknowledgements

We acknowledge the contribution of the wider scientific community engaged in ICF and related fields that has participated to the discussion and is supporting the HiPER+ initiative for the establishment of an Inertial Fusion Energy programme in Europe. This manuscript was conceived also on behalf of the above subscribing community. ■

References

[1] J. Nuckolls, *et al.*, *Nature* **239**, 139–142 (1972). https://doi.org/10.1038/239139a0

[2] N.G. Basov, O.N. Krokhin and G.V. Sklizkov, Heating of laser plasmas for thermonuclear fusion, in: *Laser Interaction and Related Plasma Phenomena* vol 2 (New York: Springer) p. 389 (1972).

[3] A.B. Zylstra et al, *Nature* **601**, 542-548 (2022) https://doi.org/10.1038/s41586-021-04281-w

[4] R. Betti, *et al.*, *Phys. Rev. Lett.* **98**, 101 (2007). https://doi.org/10.1103/PhysRevLett.98.155001

[5] S. Atzeni *et al.*, *Nucl. Fusion* **54** (2014) 054008 https://doi.org/10.1088/0029-5515/54/5/054008

[6] S. Atzeni *et al.*, *HPLSE* 9, 2e (2021) https://doi.org/10.1017/hpl.2021.41

COMPANY DIRECTORY

Highlight your expertise. Get your company listed in europhysicsnews company directory
For further information please contact bernadette.dufour@edpsciences.org

BARTINGTON INSTRUMENTS
www.bartington.com
Bartington Instruments designs and manufactures high precision fluxgate magnetometers, Helmholtz coil systems, gradiometers, magnetic susceptibility instruments and associated data processing equipment, for the precise generation and measurement of magnetic fields around physics experiments, and for calibration of magnetometers in consumer electronics.

BLUEFORS OY
Bluefors.com
Bluefors manufactures cryogenic measurement systems and has a strong focus in the field of quantum technology. Our reliable and easy-to-operate systems can be customized to meet the special requirements of each experiment allowing the customer to get in direct contact with the scientists and engineers who design their system.

EDMUND OPTICS
www.edmundoptics.com
Edmund Optics® (EO) is a leading U.S. global manufacturer and distributor of precision optics, optical assemblies and image processing components with manufacturing facilities in the U.S., Asia and Europe. EO has an extensive inventory of optical components for fast shipping and offers products, standard or customized, from small to full-production volume quantities for various industries.

INTERMODULATION PRODUCTS AB
intermodulation-products.com
We develop and sell high-speed multichannel, multifrequency lock-in amplifiers with specialized signal processing capabilities for non-linear systems. In particular we have applications for determining the tip-surface force in tapping mode AFM, and an all-in-one measurement and control instrument for quantum computing.

MB SCIENTIFIC AB
www.mbscientific.se
MB Scientific AB is a Swedish company which develops and produces state of the art instruments for the photoelectron spectroscopy experiments. Our photoelectron energy analyser MBS A-1 gives you the opportunity to do world leading research together with MBS VUV photon sources, MBS L-1 and T-1, which produce the brightest and narrowest lines existing to be used for this type of experiments.

PFEIFFER VACUUM
www.pfeiffer-vacuum.com/en/
Pfeiffer Vacuum stands for innovative and custom vacuum solutions worldwide, technological perfection, competent advice and reliable service. With the invention of the turbopump, the company paved the way for further development within the vacuum industry. Pfeiffer Vacuum offers a complete product portfolio: backing pumps, leak detectors, measurement and analysis devices, components as well as vacuum chambers and systems.

OXFORD INSTRUMENTS
nanoscience.oxinst.com
Oxford Instruments NanoScience provides market-leading cryogenic systems that enable quantum technologies, new materials and device development in the physical sciences. To learn more about Oxford Instruments NanoScience's low temperature systems for quantum computing applications, please visit our website.

THYRACONT
thyracont-vacuum.com/en
Thyracont develops vacuum gauges and supplies innovative devices for leading manufacturers of vacuum pumps and process plants. As specialists in vacuum metrology, their portfolio includes vacuum sensors, transducers, meters, switches, controllers as well as accessories and components. They likewise offer a wide range of measuring principles in various combinations. Thyracont is involved today in your technological need of tomorrow.

TOPTICA PHOTONICS
www.toptica.com
TOPTICA Photonics, founded in 1998 near Munich (Germany), develops and manufactures high-end laser systems for scientific and industrial applications. The portfolio includes diode lasers, ultrafast fiber lasers, terahertz systems and frequency combs. OEM customers, scientists, and over a dozen Nobel laureates all acknowledge the world-class exceptional specifications of TOPTICA's lasers, as well as their reliability and longevity.

The EPS is not responsible for the content of this section.

PROBING THE NEUTRINO MASS SCALE WITH THE KATRIN EXPERIMENT

Diana S. Parno[1] and Kathrin Valerius[2] – DOI: https://doi.org/10.1051/epn/2022107

[1] Carnegie Mellon University, Pittsburgh, PA 15213, USA, [2] Karlsruhe Institute of Technology, 76131 Karlsruhe, Germany

The absolute mass scale of the neutrino is one of the most fundamental open questions in contemporary particle physics, with implications from particle theory to cosmology. Through precision measurements of beta-decay kinematics, the KATRIN experiment probes the neutrino mass with unprecedented sensitivity.

▲ The interior of the KATRIN main spectrometer is lined with wire electrodes to fine-tune the retarding potential. Credit: M. Zacher/ KATRIN Collaboration.

The puzzle of neutrino mass

When Wolfgang Pauli postulated the existence of a new particle, later dubbed the "neutrino", in 1930 in order to explain nuclear beta decay spectra and save energy conservation and spin statistics, he could not anticipate its central role in the nascent field of particle physics. Indeed, estimating that the new, electrically neutral particle should carry at most 1% of the proton mass, Pauli deemed it unlikely that it should ever be experimentally detected. Now, more than 90 years later, neutrino experiments have launched an era of high rates and high statistics — yet many of the neutrino's basic characteristics remain unknown. One of these basic properties is the rest mass of neutrinos, which has eluded the grasp of experimentalists despite more than seven decades of effort.

Of course, the history of neutrino physics is built on efforts spanning decades. By the mid-1950s, in spite of Pauli's skepticism, the neutrino had been detected in an experiment using a nuclear reactor as a strong neutrino source. Over the next few decades, it was established that neutrinos come in three flavours, each associated with the charged electron, muon or tau leptons in the Standard Model of elementary particles, and neutrino measurements bolstered our understanding of the weak nuclear force that is their sole discernible means of particle interaction. Meanwhile, neutrino detectors watched deep underground for electron neutrinos from the fusion processes that fuel the sun, and they uncovered a new mystery: the detected electron-neutrino rate fell a factor of three short of theoretical models of stellar fusion. This "solar neutrino problem" persisted for three decades, until the Super-Kamiokande and SNO experiments conclusively established that neutrinos undergo flavour oscillation as they propagate between the source and the detector. The solar neutrinos were all there, as expected — but by the time they reached detectors, many of them weren't observed as electron neutrinos anymore.

After two fruitful decades of flavour-oscillation experiments, we understand each neutrino flavour state as a quantum superposition of three distinct neutrino-mass states. The neutrino is now established as a mass-carrying particle, although it is by far the most lightweight of the Standard Model fermions — Pauli's original estimate was too generous by at least seven orders of magnitude.

Tiny mass, big impact

Non-zero neutrino masses are tangible evidence pointing beyond the Standard Model, in which neutrinos are *a priori* included as massless leptons. Oscillation experiments can determine the splittings between the mass states with great precision, but they have no sensitivity to the absolute mass scale that tells us how far from zero the lightest neutrino mass lies. This mass scale has a far more fundamental role to play than just filling in a number in our textbooks.

Theorists have proposed a dazzling array of novel, possible mechanisms for generating neutrino mass. The absolute neutrino-mass scale will give critical guidance in constraining these possibilities. Massive neutrinos are a key to understanding various astrophysical processes, such as matter-enhanced oscillations across the energy spectrum of solar neutrinos arriving at Earth, or the mechanisms driving certain classes of supernova explosions. And, perhaps most profound of all, neutrinos are by far the most abundant known massive particle species in the universe: even with tiny individual masses, neutrinos have collectively played the role of "cosmic architects". In modern, precision cosmology, bounds on the neutrino-mass scale are inferred from searches for the neutrino signature, as imprinted on the formation of structures in the early universe.

The massive neutrino thus sits at the intersection of elementary particle physics, astrophysics, and cosmology, and neutrino-oscillation experiments cannot fully complete our understanding.

A kinematic trick opening direct access to neutrino masses

Two of the three principal paths towards neutrino-mass measurement, namely the interpretation of cosmological structure data and the search for hypothesized neutrinoless double beta decay, rely on intricate model assumptions. The third path is more direct, relying only on the basic kinematic principles of energy-momentum conservation and energy-mass equivalence. In a nuclear beta decay, the neutrino mass constitutes a packet of energy that cannot be carried away by the created electron. Thus, although the neutrino is experimentally undetected, we can infer the signature of its mass from the associated shape distortion at the high-energy tail of the measured electron spectrum.

This was first realised by Enrico Fermi in his 1934 seminal work on "a tentative theory of beta decay" [1]. His "Golden Rule" for the calculation of the phase space delivered all the tools necessary for experimentalists to start out on the problem. It was quickly realised that the super-allowed tritium beta decay,

$$^{3}\mathrm{H} \rightarrow {}^{3}\mathrm{He}^{+} + e^{-} + \bar{\nu}_e,$$

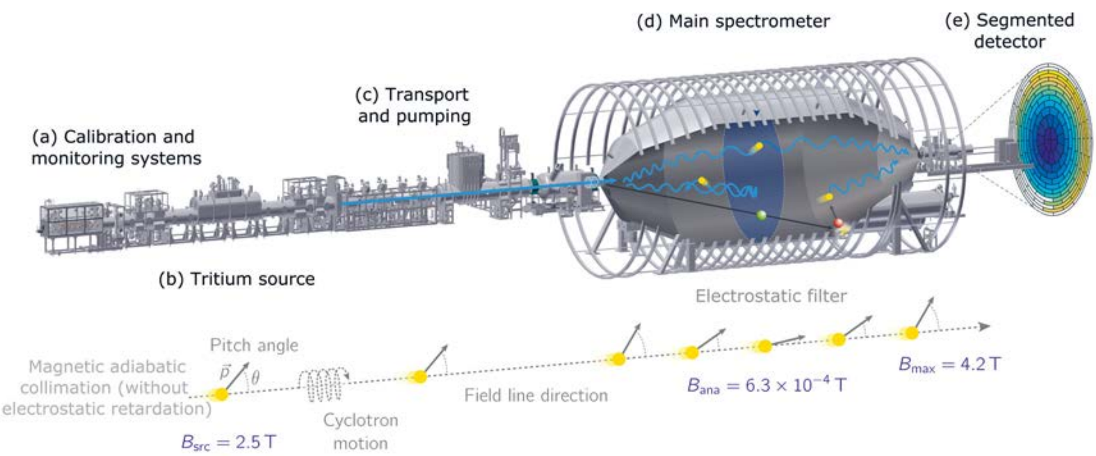
which transforms a tritium nucleus made of two neutrons and one proton into its mirror nucleus consisting of two protons and a single neutron while emitting an electron and an electron antineutrino, is ideally suited for a neutrino-mass search. This is mainly due to three favourable features:

(1) Tritium's half-life of 12.3 years is short enough to give relatively high count rates from limited amounts of the isotope, and long enough to make production, shipping and storage practical.

(2) The beta-decay endpoint of tritium is very low, at $E_0 = 18.6$ keV. This maximises the fraction of events close to the endpoint region of the beta spectrum, where the impact of the neutrino mass is most pronounced.

(3) Tritium and helium have rather simple nuclear and electronic configurations, and the T_2 molecule has only two electrons. This facilitates high-accuracy theoretical modeling of the spectrum.

In the quasi-degenerate regime in which KATRIN operates — in which the mass splittings are small compared to the absolute mass scale — the observable is an effective electron-neutrino mass square, an incoherent sum of the square of each neutrino-mass • • •



▾ **FIG. 1: Overview of the 70-m long KATRIN beamline. The key components are the calibration and monitoring systems (a) which are located at the far end of the gas-filled cryogenic tritium source (b), the transport and pumping section (c) that guides the beta electrons to the main spectrometer (d) for energy filtering. Finally, only electrons with sufficient energy are transmitted onto the segmented focal-plane detector for counting (e). For reasons of simplicity, the magnetic adiabatic collimation is illustrated neglecting the electric potentials.**

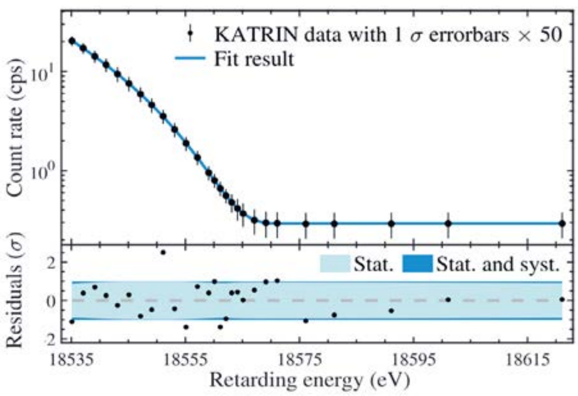
value[1] m_i weighted by its contribution $|U_{ei}|^2$ to the electron-flavour neutrino created in beta decay:

$$m^2(\nu_e) := \sum_{i=1}^{3} |U_{ei}|^2\, m_i^2.$$

Since the 1940s, experimentalists have exploited tritium beta decay for the neutrino-mass search (see [2] for a recent review). The advent of MAC-E-filter[2] technology brought a major advance in experimental accuracy, resulting in an upper bound on the electron-based neutrino mass of 2 eV/c^2 (95% C.L.) [3,4]. This held for more than a decade until the next-generation experiment, KATRIN.

A gigantic scale to weigh the lightest particles

In the Karlsruhe Tritium Neutrino experiment[3] (KATRIN), operated at the Karlsruhe Institute of Technology and hosted by the Tritium Laboratory Karlsruhe (TLK), the technology developed by the Mainz and Troitsk predecessors culminates in an ultra-luminous gaseous tritium source and a colossal main spectrometer (see opening illustration). With its diameter of 10 m and length of 24 m, the spectrometer ensures the adiabatic transport and high-resolution energy filtering of decay electrons. KATRIN pushes technological limits along its entire 70-m beamline, exemplified by the source throughput of highly purified gaseous molecular tritium at several kilograms per year, the stability of the source operational parameters at the per-mille level, successive pumping stages that reduce the tritium partial pressure by over 13 orders of magnitude without windows or barriers, the ultra-high vacuum of the main spectrometer at a residual gas pressure of 10^{-11} mbar, a monolithic silicon p-i-n diode detector with 148 pixels, and precision high voltage with part-per-million stability. Figure 1 gives an overview of the full KATRIN beamline. A comprehensive description of the set-up, commissioning and performance of the experimental apparatus is presented in [5].



▸ **FIG. 2:** Beta-decay spectrum measured in the first neutrino-mass campaign, displayed along with the fit model used to infer the neutrino mass (from [6]).

First KATRIN results, and the road ahead

After 18 years of planning, construction, and commissioning, working on the scientific and technological cutting edge in areas from tritium technology to ultra-high vacuum, the 150 scientists of the international KATRIN collaboration were finally ready to start neutrino-mass measurements in the spring of 2019. With just a four-week first science campaign and a burn-in phase limiting the source activity to a quarter of the nominal value, KATRIN collected about two million events in the region of interest extending to 40 eV below the spectral endpoint. By fitting modelled spectra to a combination of a few hundred individual up-and-down scans measuring the beta-decay spectrum, displayed in Figure 2, a new upper limit on the neutrino mass of $m(\nu_e) < 1.1$ eV/c^2 (90% C.L.) was obtained [6,7]. This first result is still strongly dominated by statistical uncertainties, but KATRIN was able to surpass the bounds obtained by its predecessors by about a factor of two. The second, longer measurement campaign has already pushed this constraint below the 1 eV/c^2 mark, setting a limit of $m(\nu_e) < 0.8$ eV/c^2 (90% C.L.) in combination with the first data set [8].

To achieve its target sensitivity of 0.2 eV/c^2 (90% C.L.), KATRIN will need to continue scanning the beta spectrum for about four more years. The overall factor of 10 improvement on the neutrino mass translates to a factor of 100 in terms of the kinematic observable, $m^2(\nu_e)$. Aside from the gain in statistics that comes with long-term operations, the collaboration is also working on improvements on key systematics through dedicated calibration measurements, and on a further reduction of the background rate.

KATRIN's unprecedented scale and precision requires exquisite care to understand and control the ways the apparatus affects the spectrum. A few examples will illustrate our detailed activities up and down the entire beamline. One calibration source, an electron gun at the far upstream end of the beamline, sends electrons with precisely controlled energies and angles all the way through to the detector — producing a uniquely precise measurement of electron scattering on tritium at low energies. Radioactive krypton gas, which emits monoenergetic electrons, can be circulated in the source alongside the tritium in order to probe the details of local space charges. A laser Raman spectroscopy system, devised to monitor the isotopic composition of the source, has introduced several novel techniques. The retarding potential is monitored with the world's highest-precision voltage dividers. The collaboration has already implemented several measures to mitigate backgrounds.

Even as KATRIN collects more data and improves systematics and performance, a future generation of neutrino-mass experiments is on the horizon. Project 8, which measures energy via the cyclotron radiation of individual beta electrons, aims to deploy an atomic tritium source to

[1] Here, we assume that neutrinos and antineutrinos share the same mass scale, as predicted by CPT symmetry in the Standard Model. We therefore use "neutrino mass" to encompass both.

[2] Magnetic Adiabatic Collimation with Electrostatic filtering – an instrument which allows sensitive electrostatic analysis of the electron energy by exploiting the magnetic bottle principle for momentum collimation.

[3] www.katrin.kit.edu

avoid spectral broadening due to molecular bonds. ECHo and HOLMES will probe the electron-capture spectrum of ^{163}Ho, complementing the tritium measurements with microcalorimetric techniques pioneered by X-ray astronomers.

Next to KATRIN's flagship neutrino-mass measurement, its treasure trove of high-precision and high-statistics tritium beta-decay spectra opens up promising additional physics sensitivity. As a first example, KATRIN was able to obtain new direct constraints on the existence of light sterile neutrinos from its first two data set [9,11] and is continuing to improve these bounds with more data. Other analyses in progress seek to constrain local over-density of cosmic relic neutrinos, Lorentz invariance violation in the neutrino sector, and exotic modifications of weak interactions. A future detector upgrade (TRISTAN) will allow a precision measurement of a wider range of the tritium spectrum, thereby enabling KATRIN to probe heavier sterile neutrinos (masses of order keV/c^2), as well [10]. With a growing data set and a wide vista of questions, KATRIN is looking ahead to some exciting answers. ■

About the Authors

Diana Parno is an assistant professor of physics at Carnegie Mellon University, in Pittsburgh, USA. In addition to her work on the neutrino mass with KATRIN, she studies coherent elastic neutrino-nucleus scattering and the molecular physics of tritium beta decay.

Kathrin Valerius is a professor of experimental astroparticle physics at KIT, in Karlsruhe, Germany. Apart from her work in neutrino physics with the KATRIN experiment, her research comprises direct Dark Matter searches with xenon-based detectors.

References

[1] E. Fermi, *Zeitschrift für Physik* **88** *(1934) 161; English translation in Am. J. Phys.* **36,** 1150 (1968)

[2] J. A. Formaggio, A. L. C. de Gouvêa, R. G. H. Robertson, *Physics Reports* **914**, 1 (2021)

[3] C. Kraus *et al.*, *Eur. Phys. J. C* **40**, 447 (2005)

[4] V. N. Aseev *et al.*, *Phys. Rev. D* **84**, 112003 (2011)

[5] M. Aker *et al.* (KATRIN Coll.), *JINST* **16,** T08015 (2021)

[6] M. Aker *et al.* (KATRIN Coll.), *Phys. Rev. Lett.* **123**, 221802 (2019)

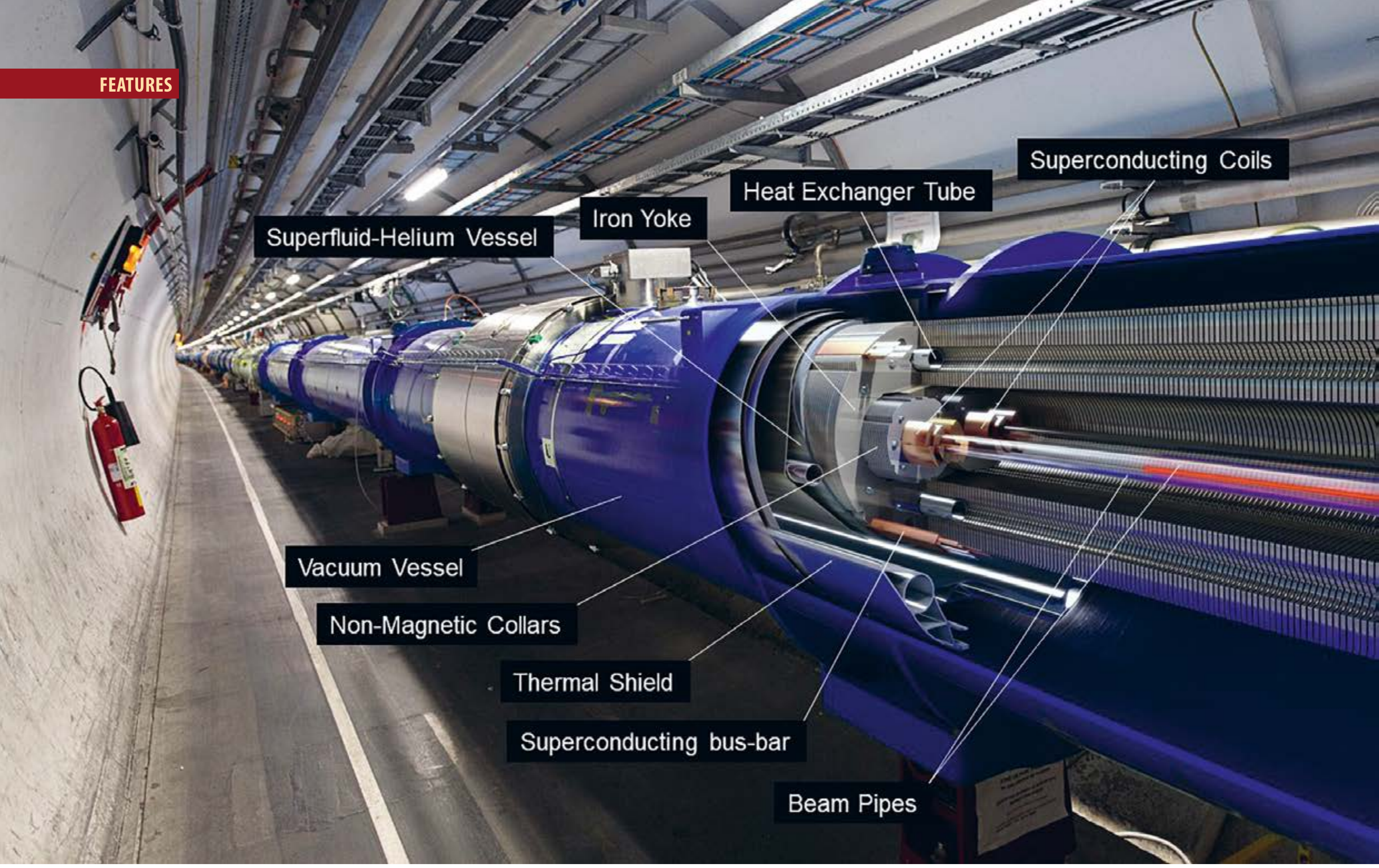
[7] M. Aker *et al.* (KATRIN Coll.), *Phys. Rev. D* **104**, 012005 (2021)

[8] M. Aker *et al.* (KATRIN Coll.), *Nature Physics* **18**, 160 (2022), https://doi.org/10.1038/s41567-021-01463-1

[9] M. Aker *et al.* (KATRIN Coll.), *Phys. Rev. Lett.* **126**, 091803 (2021)

[10] S. Mertens *et al.*, *J. Phys. G* **46**, 065203 (2019)

[11] M. Aker *et al.* (KATRIN Coll.), *Improved eV-scale Sterile-Neutrino Constraints from the Second KATRIN Measurement Campaign*, arXiv:2201.11593



QUANTUM FLUIDS AT WORK: SUPERCONDUCTIVITY AND SUPERFLUID HELIUM AT THE LARGE HADRON COLLIDER

Philippe Lebrun[1] and Laurent Tavian[2] – DOI: https://doi.org/10.1051/epn/2022108
[1]European Scientific Institute, Archamps (France) – [2]CERN, Geneva (Switzerland)

The Large Hadron Collider (LHC) at CERN makes use of superconductivity and superfluid helium cryogenics on an unprecedented scale. We review the application of these technologies to the particle collider and explain how they contribute to its unique performance.

▲ **FIG. 1:** 3-D cut of a twin-dipole cryomagnet in the LHC tunnel

The Large Hadron Collider (LHC) is a 26.7 km circumference, high-energy proton and ion collider [1] in operation at CERN to serve the world's physics community. The LHC is also the single largest application of superconductivity and helium cryogenics to date, with its 8310 superconducting magnets of all types, most of which are operated at 1.9 K in some 100 tons of superfluid helium.

High-field magnets using low-temperature superconductors

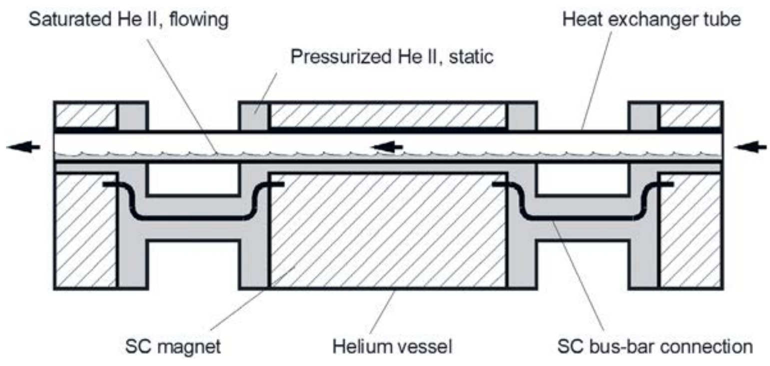
Superconductivity and helium cryogenics have become key enabling technologies for high-energy accelerators over the last decades [2]. For a given beam energy, the diameter of a circular accelerator scales inversely with the field in the bending magnets: making the latter superconducting thus renders the machine more compact, allowing substantial savings in real estate and infrastructure. Moreover, compactness also reduces the beam stored energy for a given beam intensity, an important issue in high-energy, high-luminosity machines. Finally, superconductivity is also a means of reducing power consumption and thus operating costs of accelerators through two compounding processes: by enabling to make them smaller (the compactness argument above), and by reducing power per unit length of electromagnet. The power consumption of a superconducting synchrotron is essentially that of cryogenic refrigeration, which scales with the circumference of the machine irrespective of the field in the magnets.

The main technological stake of the LHC was the development, industrialization and production of 1232 superconducting dipoles with a field of 8.3 T, 400 superconducting quadrupoles with a gradient of 223 $T.m^{-1}$, and several thousand other superconducting magnets for correcting main field errors, tuning beam parameters and bringing beams into collision at high luminosity [3]. All these magnets were manufactured by industry and reproducibly produce field of the correct strength and uniformity with a precision of up to 10^{-4}.

The main dipoles (Figure 1) feature twin apertures with equal and opposite fields in order to bend the two counter-rotating proton or ion beams along parallel paths. Two identical sets of coils are assembled in a common mechanical and magnetic structure, housed in a single cryostat. This solution is both compact in terms of transverse space occupancy and efficient, as the stray field of one aperture, channeled by the magnetic yoke, contributes to the field in the neighboring one. The coils in each aperture are wound with Rutherford-type Nb-Ti cable, in two layers with current density grading, following a "cos θ" geometry. The enormous electromagnetic forces that tend to open the structure when the magnet is powered are reacted by stiff collars of non-magnetic austenitic steel, resting on the magnetic steel yoke. The whole assembly is contained in an austenitic stainless steel pressure vessel that acts as helium enclosure.

The decrease in critical current of superconductors as the magnetic field increases restricts their use for high-field applications. This strongly limits the use of the well-known Nb-Ti alloys in normal boiling helium at 4.2 K. More advanced superconductors, such as Nb_3Sn were • • •

▸ **FIG. 2:** A 13 kA current lead using high-Tc superconductors



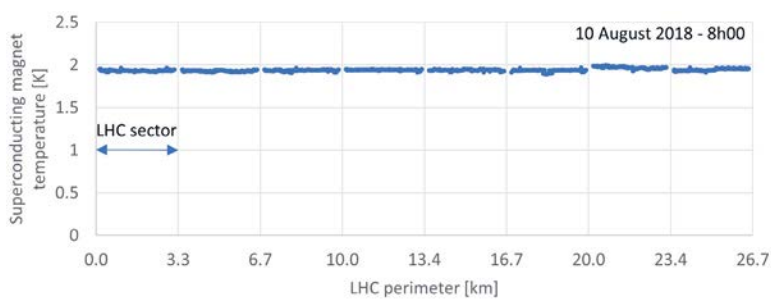
▲ **FIG. 3:** Principle of the LHC superfluid helium (He II) cooling scheme

found inadequate at the time, in view of their difficult technological implementation, limited industrial availability and high cost. CERN therefore decided to base the LHC project on Nb-Ti operated in superfluid helium at 1.9 K. At this lower temperature, the alloy exhibits sufficient current-carrying capacity to produce fields up to about 10 T, while superfluid helium maintains large enough thermal conductivity up to the lambda point. Superfluid helium, which has become a technical coolant for superconducting magnets following the pioneering work of G. Bon Mardion *et al.* [4] in Grenoble, was used for the first time in a large particle accelerator.

High-temperature superconductors for high current transport

Powering the 1720 electrical circuits of the LHC magnets requires to bring currents ranging from 60 A to 13 kA from room temperature into the cryogenic environment. This is conventionally done by "current leads", *i.e.* copper conductors cooled by escaping helium vapor that intercepts the largest fraction of the conductive and Joule heat loads before they reach the liquid helium bath. Still, the remaining heat in-leak – about 1.1 $W.kA^{-1}$ for optimized metallic current leads – would result in a prohibitively high load for the whole machine. The emergence of practical wires and ribbons made of high-Tc superconductors has made it possible to design, test and validate their use in the lower section of current leads, where they reduce significantly the residual heat load. This technique yields an overall reduction of the refrigeration load by a factor three, thus saving several MW of refrigeration compressor power at the scale of the LHC project. The 1182 high-Tc current leads equipping the high-current circuits of LHC (Figure 2) were produced by industry and are smoothly operating in the machine [5]. This represents the largest high-current application of high-Tc superconductors to-date.

▼ **FIG. 4:** Measured temperature profile around the LHC perimeter



Superfluid helium as a cooling medium

The main reason for superfluid helium cooling of the LHC magnets is the lower temperature that extends the operating range of the Nb-Ti superconductor. However, the rapid drop in specific heat of the superconducting cable at low temperature also requires taking advantage of the very peculiar transport properties of superfluid helium for thermal stabilization, heat extraction from the magnet windings and heat transport to the cold source. With its low viscosity, superfluid helium can permeate the windings and buffer thermal transients thanks to its high specific heat – 2000 times that of the conductor per unit volume. The excellent thermal conductivity of the fluid – peaking at 1000 times that of oxygen-free high-conductivity (OFHC) copper at 1.9 K for moderate heat flux – enables it to conduct heat without mass transport. In order to benefit from these unique properties, the electrical insulation of the cable must exhibit sufficient porosity and percolation, while preserving its main functions of mechanical resistance and dielectric strength. A multilayer wrapping of polyimide film with partial overlap meets these conflicting requirements.

The LHC magnets operate in static baths of pressurized superfluid helium close to atmospheric pressure. This high-conductivity mono-phase liquid is continuously cooled by heat exchange with saturated two-phase helium flowing in a 100 m-long heat exchanger tube extending over the length of the magnet string (Figure 3). The latent heat of vaporization of the flowing helium eventually absorbs the deposited heat quasi-isothermally. Other benefits of this cooling scheme are the absence of convective flow in normal operation and corresponding pumps, the limited transverse space it occupies in the magnet cross-section, the capacity to absorb magnet resistive transitions and to limit their propagation [6]. Figure 4 shows the measured temperature profile around the LHC.

In view of the low saturation pressure of helium at 1.8 K, refrigeration by vapor compression requires a pressure ratio of 80 to bring the helium back up to atmospheric pressure. To limit volume flow-rate and hence size of machinery, the large mass flow-rate in a high-power refrigerator must be processed at its highest density, *i.e.* cold. This calls for contact-less, vane-less, non-lubricated compressors of the hydrodynamic type [7]. The LHC uses eight 1.8 K refrigeration units, each with a refrigeration power of 2.4 kW, based on multistage axial-centrifugal cold compressors operating at high rotational speed on active magnetic bearings (Figure 5). This technology developed by specialized industry following

CERN's specifications was validated in the laboratory, with a measured overall coefficient of performance below 950 (ratio of electrical power to cooling power at 1.8 K).

Outlook

All the technologies developed for the LHC are used, in enhanced form, for the High-Luminosity LHC (HL-LHC) project now under construction: 1.2 km of the LHC collider will be upgraded, mainly in the regions close to the two large detectors, with the main objective to increase by a factor 10 the integrated number of collisions. New final-focus, large-aperture quadrupoles with a gradient of 948 $T.m^{-1}$ have been developed using advanced Nb_3Sn superconductors. High-energy collision debris escaping the detectors will deposit a large fraction of their energy - a factor 5 increase with respect to the LHC - in the helium enclosure of these new quadrupole magnets cooled at 1.9 K. The corresponding heat load will be extracted by two oversized heat exchanger tubes operating in parallel. Due to the high level of radiation close to the collision points, the magnet power converters and the high-Tc superconductor current leads are now located in protected areas at a distance of about 100 m from the machine tunnel. DC superconducting cables based on a novel concept using MgB_2 operated ●●●

◂ **FIG. 5:** An axial-centrifugal cold helium compressor below 20 K have been developed to transport up to 120 kA to the magnets. A novel superconducting RF system consisting of eight cavities per beam for transverse deflection (a.k.a. "crab" cavities) will compensate the geometric loss in luminosity due to the finite crossing angle and extreme focusing of the bunches in the HL-LHC.

As concerns future initiatives, the 2020 Update of the European Strategy for Particle Physics [8] has recommended as long-term priority the operation of a proton-proton collider at the highest achievable energy. Consequently, Europe together with its international partners is investigating the technical and financial feasibility of a Future Circular Collider (FCC) with a centre-of-mass energy of at least 100 TeV, located at CERN in a new 100-km circumference tunnel. This initiative will require to ramp up the R&D effort on several advanced accelerator technologies, in particular high-field superconducting magnets including high-temperature superconductors. ■

About the Authors

Philippe Lebrun. With a background in superconducting magnets and cryogenics, Philippe Lebrun led CERN's "Accelerator Technology" department during the construction of the LHC. He has received several prizes in the field of cryogenics, including the Kamerlingh Onnes Medal, the Samuel Collins Award and the Kurt Mendelssohn Award.

Laurent Tavian works in the Accelerator and Technology Sector at CERN, where he led the Cryogenics Group for 14 years. An engineer by training, he has contributed to the large superfluid helium cryogenic systems of the Tore Supra Tokamak and of the LHC.

References

[1] O. Brüning, P. Collier, Ph. Lebrun, S. Myers, R. Ostojic, J. Poole, P. Proudlock ed., *LHC design report*, CERN-2004-003 (2004)

[2] M. Wilson, Superconductivity and accelerators: the good companions, *IEEE Trans. Appl. Superconductivity* **9**, 111 (1999)

[3] L. Rossi, Experience with LHC magnets, from prototyping to large-scale industrial production, *Proc. EPAC 2004 Lucerne*, 118 (2004), JACoW web site

[4] G. Bon Mardion, G. Claudet & J. C. Vallier, *Superfluid helium bath for superconducting magnets*, *Proc. ICEC6*, IPC Science & Technology Press, Guildford (1976)

[5] A. Ballarino, High-temperature superconducting current leads for the Large Hadron Collider, *IEEE Trans. Appl. Superconductivity* **9**, 523 (1999)

[6] M. Chorowski, Ph. Lebrun, L. Serio & R. van Weelderen, Thermohydraulics of quenches and helium recovery in the LHC prototype magnet strings, *Cryogenics* **38**, 533 (1998)

[7] Ph. Lebrun & L. Tavian, *Cooling with superfluid helium*, in Proc. CAS "Superconductivity for accelerators", *CERN-2014-***005**, 453 (2014)

[8] European Strategy Group, 2020 Update of the European Strategy for Particle Physics, https://europeanstrategyupdate.web.cern.ch

Extremely Low Temperatures
using Dilution Refrigerators for Exceptional Performance and Discovery

Oxford Instruments NanoScience creates new possibilities for a variety of customer needs using its range of dilution refrigerators. From making customised systems to look at the universe, using a dilution refrigerator to cool the lensing system of a telescope, to an ultra-low temperature wet dilution refrigerator used to investigate new physics in the microkelvin regime. In this article, we look at two of the many ways Oxford Instruments NanoScience's dilution refrigerators are being used to break boundaries in physics at extremely low temperatures.

Unveiling the obscured universe

Professor Grant Wilson from the University of Massachusetts required a dilution refrigerator from Oxford Instruments NanoScience for a very special project - to unveil the very beginning of the universe. The Large Millimeter Telescope (LMT) is a 50 metre-diameter dish in Mexico enabling profound astronomical discoveries. Prof. Wilson and the team use the telescope to locate large-scale emissions of dust to trace where gas is located and where star formation is occurring in the universe - only possible at extremely low temperatures.

The LMT project team required a modular system containing Oxford Instruments NanoScience's Triton500 dilution refrigerator. It was customised to provide the team with high-thermal conductivity and high cooling power links at both the still and mixing chamber, enabling the customer to cool their large telescope lenses to temperatures that had not been achievable previously. Prof. Wilson comments, *"We have a still link at 1 Kelvin and a mixing chamber link at 0.1 Kelvin, and this is our dominant thermal impedance in the system. Having the flexibility of these braids and being able to make and break this link is essential to us. This system will open up our horizons to understand the early formation of the universe and improve our knowledge on the creation of stars."*

The LMT project is a powerful example of how low-temperature physics when combined with world-class engineering solutions at Oxford Instruments NanoScience shapes discovery beyond the realms of our planet.

▲ PhD students working on the Oxford Instruments Kelvinox400 dilution refrigerator. *Image courtesy of Royal Holloway University of London.*

Ultra-low temperatures to explore new physics

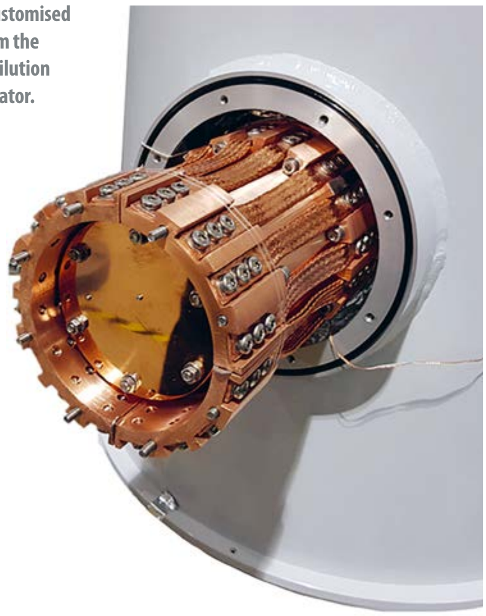
Dr. Lev Levitin from Royal Holloway, University of London uses one of the coldest dilution refrigerators in the UK to conduct research into new physics at extremely low temperatures. The London Low Temperature Laboratory has a custom-built wet dilution refrigerator, the Oxford Instruments Kevlinox400 with a home-made copper nuclear demagnetisation stage. This nuclear demagnetisation refrigerator allows the user to reach temperatures of hundreds of microkelvin. The research group is using ultra-low temperatures in order to investigate exotic fractional quantum Hall states, unconventional superconductivity and superfluidity in ^{3}He.

Dr. Levitin comments, *"Temperatures below 5 mK open a new, exciting regime to studies of low-dimensional electron systems in semiconductor heterostructures. We expect to observe new strongly-correlated electron phases, in particular exotic fractional quantum Hall states. There is both fundamental physics to be discovered and applications to be invented when you get the electrons colder than it was possible before."*

Dr. Levitin and his group cool the nuclear demagnetisation refrigerator down to 0.3 mK (300 microkelvin) in order to cool the electrons in the two-dimensional electron gas (2DEG) down to 0.9 mK. They have demonstrated the cooling of a large area two-dimensional electron system to below 1 mK, which is a significant breakthrough in quantum nanoelectronics.

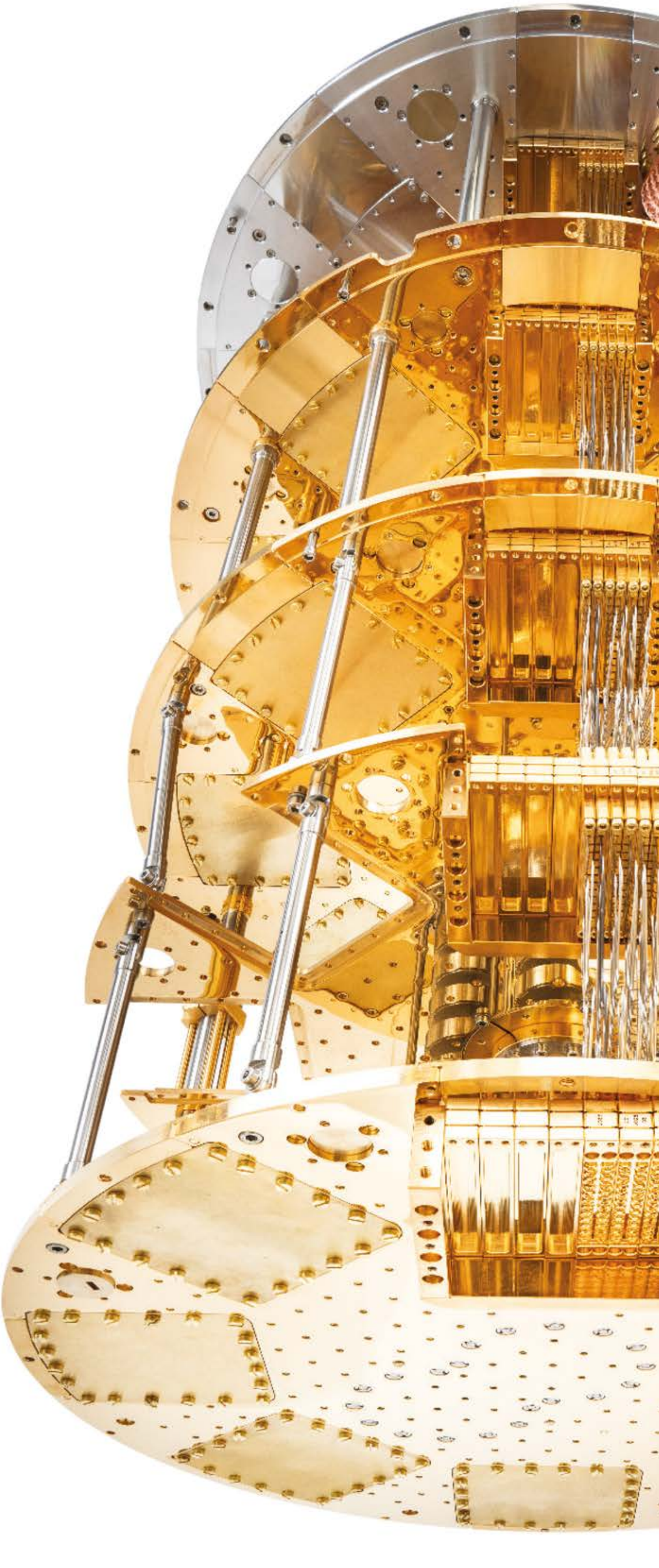
Oxford Instruments NanoScience's dilution refrigerators enable physicists to continue discovery at ultra-low temperatures. To find out more about our range of cryogenics for low-temperature experiments, visit: nanoscience.oxinst.com/cryogenics ■

▶ The customised link from the Triton dilution refrigerator.



Cool for Progress.

BLUEFORS.COM



High-density wiring

Our new high-density wiring is a modular option for the Bluefors side-loading XLDsl dilution refrigerator measurement system that enables a large scale-up of the experimental wiring, especially for high-frequency signals. It is easy to install and to maintain.

BLUE FORS