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SPECIAL ISSUE ON NUCLEAR FUSION AND PLASMA PHYSICS

Challenges on the road towards fusion electricity

JET, The Largest Tokamak on the eve of DT Operation

The first fusion reactor: ITER

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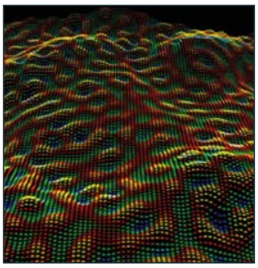
Cover picture: View into the Wendelstein 7-X stellarator during the assembly of in-vessel components which allow handling heat and particle fluxes to the wall. Source: Bernhard Ludewig.



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Physics Nobel Prizes 2016

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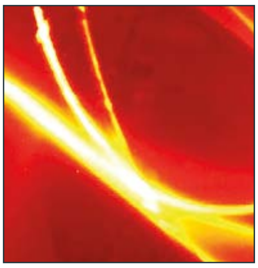
Confessions of a deuteranope



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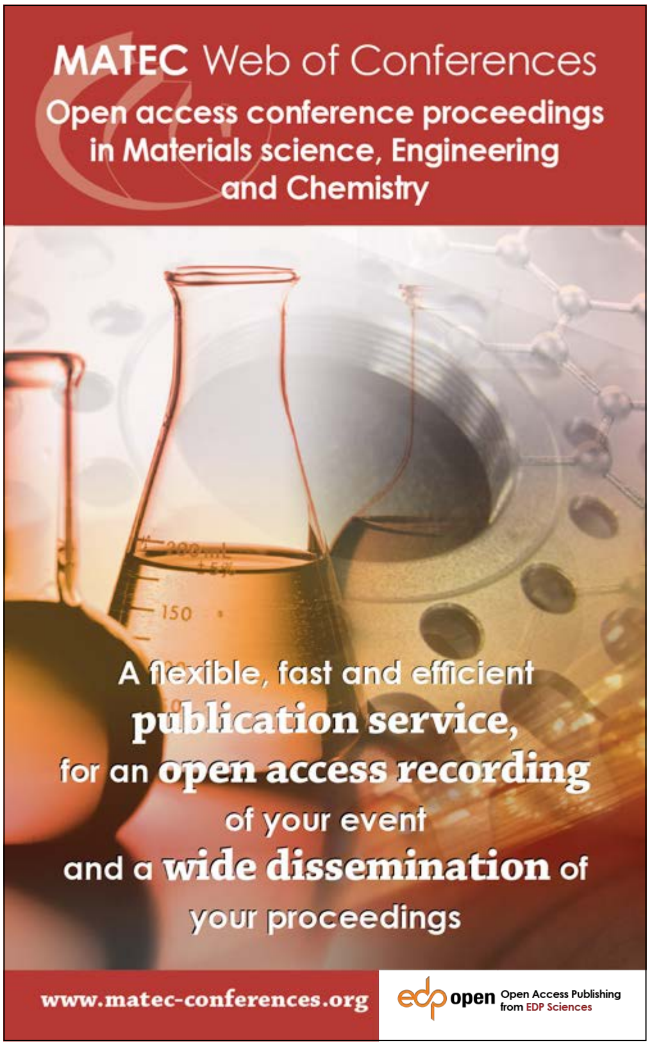
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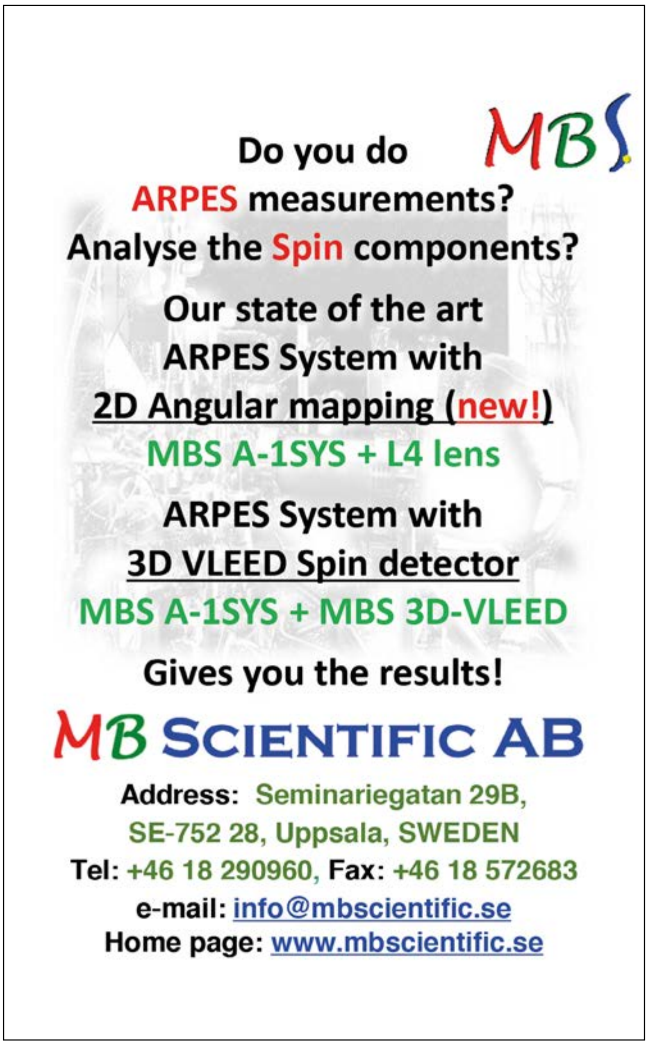
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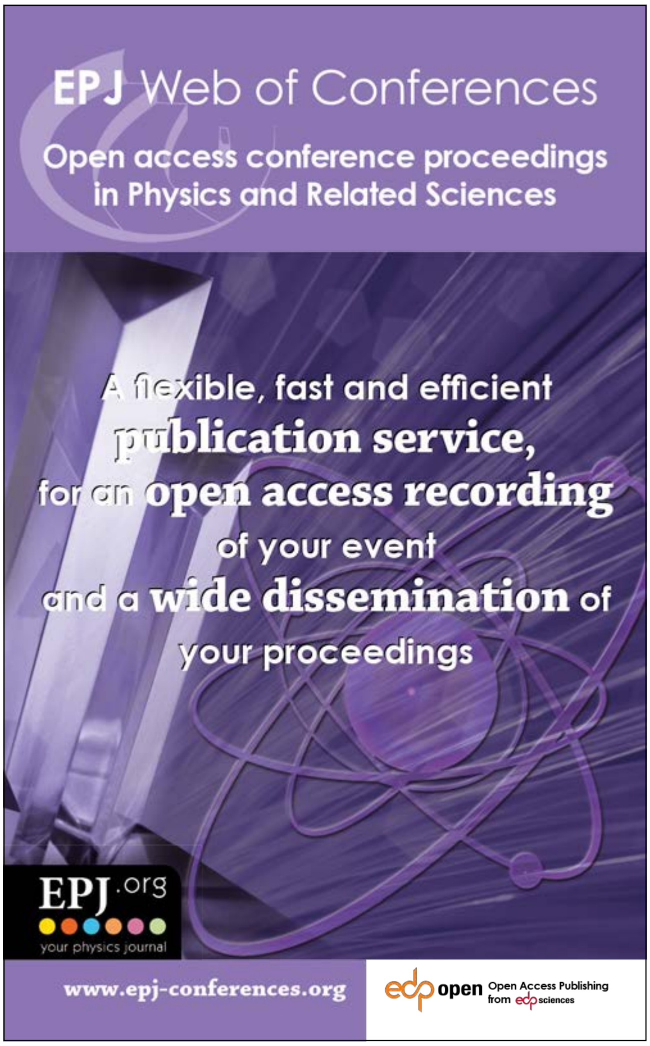
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[EDITORIAL]

Science denial

The publication of a controversial article on the 9/11 collapse of the World Trade Center buildings in our last issue of EPN has generated so much interest and so many downloads that the host server broke down for a short time. A first-time experience for our journal. Some reaction comments are published in the present issue. This shows how vivid this dramatic event remains in our collective memory but also how quickly the scientific community and the media can critically react in such a case. And this is a good thing.

This brings me to the important issue of science denial, being inspired by an article by Robert P. Crease in Physics World of last September (*Phys. World.* **29**, 9 p. 23, 2016) who proposes several ways to encourage a responsible discussion of scientific issues. He mentions that science denial is not the product of irrationality or scientific illiteracy but triggered more often by political, economic and religious interests in specific areas of science such as climate change, energy, food technology and health. Indeed, science denial is rather dangerous if it prevents constructive political decisions and corrective actions to be taken by excluding neutral scientific expertise from these decisions. But even if science deniers are spreading their own truth and can be criticized for it, they cannot be prosecuted with aggressive means as suggested by Crease. It is our role, in an objective scientific approach to challenge them with the right arguments and inform policy makers and politicians accordingly. It is the unfortunate reality that we live today in a time when scientific knowledge often faces organized and strong opposition by doubters who put the consensus of experts more openly into doubt. These controversies are usually nurtured by their own sources of information or own interpretations of research results. '*And there is so much talk about the trend (of conspiracy) these days—in books, articles, and academic conferences—that science doubt itself has become a pop-culture meme*' writes Joel Achenbach in his article '*Why do many reasonable people doubt science?*' published in the National Geographic of March 2015. '*In a sense all this is not surprising. Our lives are permeated by science and technology as never before. For many of us this new world is wondrous, comfortable, and rich in rewards—but also more complicated and sometimes unnerving. We now face risks we can't easily analyze.*' The complexity in modelling our atmosphere and predicting the global warming or the variety of scenarios for new national energy policies are the best examples where furious discussions can take place, even among reasonable scientists. I had the opportunity to experience it myself recently within our EPS Energy Group. Although such debates among scientists are part of the traditional skepticism or critical attitude in science, the image they propagate among the public can be rather negative and counterproductive. I am convinced that the right behaviour is to move forward with courageous decisions. The slightest possibility of ignoring grand challenges such as climate change might jeopardize the future of our children and grandchildren without even realizing it.

Science denial is not the product of irrationality or scientific illiteracy but triggered more often by political, economic and religious interests in specific areas of science

Interestingly, a catastrophe caused by climate change is seen as the biggest potential threat to the global economy in 2016, according to a survey of 750 experts conducted by the World Economic Forum (WEF), and published after the deal signed at the COP21 UN climate change conference in Paris.

The scientific method is a hard discipline that leads us to truths that are less than self-evident, often mind-blowing, and sometimes hard to swallow because defying common sense. We scientists should avoid the tendency to search for and see only evidence that confirms what we already believe. Luckily, peer reviewing of published scientific studies is not only the best way to check their validity but also the best way to foster progress and innovation. This holds true, even if absolute certainty does not exist as we move along the frontiers of knowledge. ■

Christophe Rossel
EPS President

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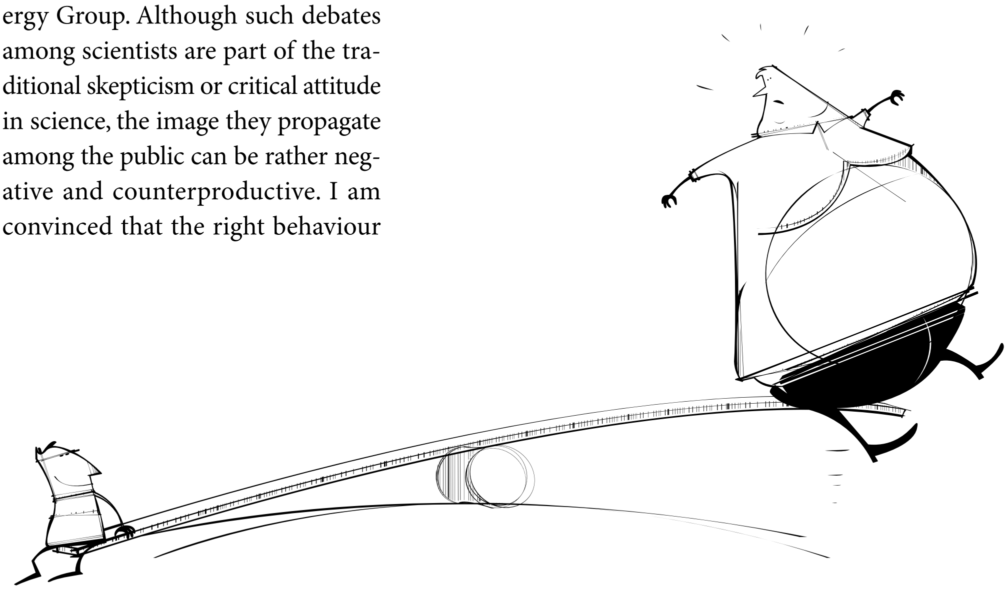

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EPS HISTORIC SITES

Former Institute of Physics, Würzburg University

Röntgenring 8, Würzburg, Germany

The European Physical Society (EPS) has distinguished the institute where in 1895 Wilhelm Conrad Röntgen discovered the radiation later named after him. The building is now the third "Historic Site" of the EPS in Germany.

London, Paris, Madrid, Rome, Berlin, Munich: Würzburg is now on a par with these European metropolises. The reasons for this lies in the history of science: Each of these cities is home to a place that has been classified as an exceptional "Historic Site" by the European Physical Society (EPS).

In Würzburg, this site is the former Institute of Physics of the University of Würzburg on Röntgenring 8. A commemorative board was installed in front of the building on Röntgenring 8. Unveiled during a ceremonial act, it documents the significance of the place.

Here Professor of Physics, Wilhelm Conrad Röntgen, discovered the famous radiation, which was later named after him, in the evening of 8 November 1895. The event was certainly a historic achievement of international importance: "X-rays have become indispensable in medicine, physics, chemistry and many other sciences," says University President Alfred Forchel. For his discovery Röntgen received the first Nobel Prize in Physics in 1901.

▾ Christophe Rossel (left), President of the European Physical Society (EPS), and University President Alfred Forchel unveiling the commemorative board. (Photo: Rudi Merkl)

According to Forchel, the weather during the ceremony, which saw around 200 invited guests gather at the historic site, was also worthy of a Nobel Prize. Forchel was pleased that the award has made "the connection of public and science" visible at such a central spot in the city.

In his opening address, however, the physicist did not only look back on Röntgen's ground-breaking discovery, he also emphasised its impact for the present: "Röntgen's discovery has led to the creation of new fields of business and activity also outside the scientific context and these are being developed further dynamically. Still today, the rays open up wholly unknown worlds for us.

Christophe Rossel, President of the EPS, said: "It is wonderful to present this award at one of the oldest universities in Europe and Germany." Rossel, too, underlined the significance of Röntgen's work for other disciplines, making the former institute building a truly historic site for all of science.

The President of Deutsche Physikalische Gesellschaft took a glimpse at the imminent next leap in knowledge "following in Röntgen's footsteps" and highlighted the great timing of the awarding. By this, Professor Rolf-Dieter Heuer was alluding to the start of the "European XFEL" at the German Electron Synchrotron (DESY) in Hamburg planned for 2017. "A top-notch research facility is being built here."

According to Professor Ralph Claessen, who followed by delivering his ceremonial address, this "X-ray laser" could allow watching chemical experiments in real-time. And he believes that this could eventually lead to more Nobel Prizes being awarded based on Röntgen's discovery - as already in around 40 cases at present.

In the first part of his address, Claessen focused on Röntgen's career. He highlighted Röntgen's persistence in pursuing a scientific career despite several setbacks and the detours he had to take to arrive there. Röntgen's actions as university dean were marked by his great commitment as was his subsequent time in Munich where he contributed among others to the founding of Deutsches Museum.

Claessen also mentioned the rapid circulation of Röntgen's work under the title "Eine neue Art von Strahlung" (On A New Kind Of Rays) which was rather atypical for the time. Only just under two weeks passed from the "key picture" of his wife Anna Bertha's hand on 22 December 1895 and the unofficial mailing of his observation to selected colleagues on New Year's Day until the first publication by newspapers in London, Vienna and New York.

Claessen closed his speech by citing examples from various fields of art, technology and research that use X-rays. Among others, X-ray spectroscopy of van Gogh paintings has allowed several works of art painted over by the artist himself to be restored – the colours included. Today it is common practice in many ports to scan arriving containers for weapons and explosives; X-ray astronomy depict supernovas, forensics determines the cause of death in deaths long past and many more.

▲ Commemorative board at the former Institute of Physics. Here Wilhelm C. Röntgen discovered the x-rays. (Photo: Marco Bosch)

Claessen finished with a statement that all attending guests could agree to: "The former Physical Institute with Röntgen's study is truly a historic site." ■

Robert Emmerich
Press and Public Relations Office
University of Würzburg

NEW EPN SCIENCE EDITOR

After having served for 8 years as EPN Science Editor, Prof. Jo Hermans of Leiden University will leave this position on January 1st 2017. Over these 8 years, Jo has performed invaluable work for the journal, finding good authors, interesting and lively features and increasing the quality of EPN's issues. Fortunately, Jo will stay on as part of the Editorial Advisory Board. We are looking forward to benefiting from his advice, and in particular his suggestions for new articles. Of course, we still expect to publish contributions from Jo in EPN, for example in the *Physics in Daily Life* section.

Thank you, Jo, for your tireless work, kindness and relentlessly positive attitude, with our gratitude and best wishes for your future activities.

The new EPN Science Editor, effective January 1st 2017, will be Prof. Ferenc Iglói of the Wigner Research Centre for Physics, Budapest. Ferenc has become familiar with the 'tricks of the EPN trade', during 2016, by serving as 'Associate Science Editor', as you will see in this EPN issue. We warmly welcome Ferenc, certain that his involvement with EPN will result in the same high quality output as for the other scientific journals he has been associated with. ■

Victor R. Velasco, EPN Editor

The EPS Edison Volta Prize 2016 awarded to Michel Orrit

The EPS, the *Fondazione Alessandro Volta* and Edison S.p.A. have awarded the 2016 EPS Edison Volta Prize for outstanding contributions to physics to Michel A.G. J. Orrit, from Leiden University, the Netherlands "for seminal contributions to optical science, to the field of single-molecule spectroscopy and imaging (first single molecule detection by fluorescence and first optical detection of magnetic resonance in single molecule) and for pioneering investigations into the photoblinking and photobleaching behaviours of individual molecules at the heart of many current optical superresolution experiments."

▲ **Left to right:** S. Zannella, M. Lucini, M. Frangi, M. Orrit, C. Rossel, V. Tartamella

Professor Orrit has made significant contributions over several decades to push back the frontiers of optical physics and spectroscopy. More than 30 years ago, he produced very early and highly insightful work on Langmuir-Blodgett films and spectral hole-burning in the 1980's.

After W. E. Moerner's efforts in 1989 at IBM San José to detect the optical absorption of a single molecule of pentacene in p-terphenyl, Prof. Orrit demonstrated one year later at the University of Bordeaux that the optical fluorescence emitted by a single molecule could be detected with greatly improved signal-to-noise ratio. This critical and ground-breaking step opened the way for many subsequent investigations of single molecules.

Throughout his career up to the present, Professor Orrit has shown an incredible ability to select and conquer some of the most interesting problems in modern molecular physics and spectroscopy. He has been Professor in Molecular Physics at Leiden University since 2001. He is heading the Molecular Nano-Optics and Spins Group at the Leiden Institute of Physics.

▼ **Left to right:** S. Zannella, M. Frangi, G. Sapede, M. Lucini, M. Orrit, C. Rossel, G. Casati

EPS Edison-Volta Prize

The EPS Edison Volta Prize promotes excellence in research and is given in recognition of outstanding research and achievements in physics. The Prize is given biennially to individuals or groups of up to three people. The laureates receive a medal, which is a faithful reproduction of the Medaglia Premio dell' Associazione per l'Incremento del Commercio in Como: a portrait of Alessandro Volta together with the saying: Alexandro Voltae Novocomensi, *i.e.* (dedicated) to Alessandro Volta from Novum Comum, which was the old name given to the city of Como by Julius Caesar.

The Prize was established in 2011 and was awarded for the first time in 2012 to R. D. Heuer, S. Bertolucci and S. Myers from CERN, Geneva and in 2014 to J.-M. Raimond from the Laboratory Kastler Brossel at the Collège de France, Paris. It was also given to three principal scientific leaders of the ESA's Max Planck Mission in 2015 in the frame of the International Year of Light 2015: N. Mandolesi, University of Ferrara, J.-L. Puget, Institut d'Astrophysique Spatiale, Université Paris Sud & CNRS, and J. Tauber, Directorate of Science and Robotic ESA (NL).

Physics Nobel Prizes 2016: Topology in condensed matter physics

This year's Nobel prize in Physics is given for the discovery of the role of topology in condensed matter. This subject has seen an explosion of interest in the last decade, but topology in condensed matter has been studied long before. The prize has been awarded to pioneering early contributions by David J. Thouless, J. Michael Kosterlitz, and F. Duncan M. Haldane.

▲ Left to right: David. J. Thouless, F. Duncan M. Haldane and J. Michael Kosterlit

An early breakthrough mentioned by the Nobel committee is the work (in the early 1970's) by Kosterlitz and Thouless on vortex excitations in planar spin systems and superfluids [1]. Such vortices are characterized by winding numbers in real space. Similar winding numbers, but playing out in momentum space, are key to the understanding of topological phases of quantum matter. The Nobel committee mentions and rewards the pioneering insight, established by Thouless and co-workers in the early 1980's, that, miraculously, momentum space winding numbers of electronic band structures translate to quantized values of observables such as the Hall conductance. These results were initially applied to quantum Hall systems, where electrons are constrained to planar geometry and subjected to a strong perpendicular magnetic field. A 1988 paper by Haldane[2] made clear that similar behaviour arises in a much more general class of systems, now known as Chern insulators. The Nobel committee also rewards Haldane's groundbreaking results on quantum spin chains, which he published in 1983[3]. In this work he recognized that chains consisting of particles with integer spin can form a topological phase of matter.

Topology in phase transitions

Kosterlitz and Thouless[1] realized the importance of topology when they studied what is called the XY model in two dimensions, a member of a family of models in d dimensions, with n component (spin)variables interacting under full rotational symmetry. The interest in these models is for the universal properties of the transition between the disordered phase at high temperatures, rotationally symmetric, and an ordered phase at low temperatures, in which the spins align along a common direction and the symmetry is broken.

Kosterlitz and Thouless discovered a new type of excitation of a topological nature, called a vortex. A vortex is a localized excitation, near which the spins on a closed path surrounding the excitation make one or more full turns when the path is followed completely. The number of turns is called the winding number. The topological nature of the excitation is reflected in the impossibility to remove the excitation by changing the spin values continuously in space.

A few years before, Mermin and Wagner had proven that in two dimensions, a continuous symmetry group like SO(2) or SO(3) cannot be broken, excluding the possibility of an ordered phase. Nevertheless Kosterlitz and Thouless were able to show the existence of a phase transition in the XY model. In the low temperature phase (without long range order) the vortices form tightly bound pairs of opposite winding number. In the high- temperature phase, vortices unbind and move freely through the system. This transition, now known as KT transition, had unexpected characteristics. The singularity in the free energy is extremely weak, while the susceptibility diverges stronger than any power law.

The use of Renormalization theory by Kosterlitz[4] gave a more complete understanding. The renormalization transformation (RT) which acts on the set of interaction parameters of the system, is equivalent with changing the spatial scale of the system. Fixed points of the RT are thus scale invariant, and correspond to continuous phase transitions. In contrast, at the KT transition the whole low-temperature phase is scale invariant, as it approaches a line of fixed points under an RT. KT transitions are found in thin superfluid films and also in equilibrium crystal shapes, at the temperature at which a facet disappears.

Topological phases of matter

Quantum Hall phases and the Haldane phase of integer-spin quantum chains are early examples of what are now called topological phases of matter. A major conceptual contribution to this field was made in a 1982 paper by Thouless, Kohmoto, Nightingale and den Nijs[5]. They used the topological notion of momentum space winding numbers, known as Chern numbers, to explain the very

precise quantization of the Hall conductance in a quantum Hall system. The same reasoning can be applied to more general systems, including the Chern-insulators that Haldane introduced in 1988. For the latter, predictions based on topology were experimentally verified in thin films of a topological insulator material (2013) and in an experiment featuring cold ^{40}K atoms in an optical lattice (2014).

A general feature of topological phases is the presence of gapless excitations at the edge of the system, or at an interface between topologically distinct phases. In the Haldane phase of integer-spin quantum chains these edge states take the form of spin-1/2 excitations located at the ends of the chain.

More recent developments

It has by now been recognized that a multitude of topological phases of matter are possible, with details depending on the dimensionality and on the presence of discrete symmetries such as particle-hole or time reversal symmetry.

During the last decade, precise theoretical predictions have been made for systems where time reversal symmetry remains unbroken and protects different types of topological phases of insulating materials. In two dimensions such a situation gives rise to what is called the quantum spin Hall effect. In three dimensions, topological insulators protected by time reversal symmetry have been predicted and observed. Their edge states are gapless surface states, with transport properties somewhat akin to those in materials such as graphene, but differing from truly two-dimensional materials in important details.

Perhaps the most spectacular of all phenomena associated to topological order in low-dimensional quantum systems is that of non-Abelian statistics of topological excitations. In their simplest guise such excitations take the form of what are called Majorana zero modes, but more general 'non-Abelian anyons' have been understood and, to some extent, classified. Perhaps the simplest systems where Majorana zero modes are expected are quantum wire systems designed to be in the universality class of the so-called 'Kitaev chain'. The excitement about these developments derives in part from the perspective of utilizing non-Abelian anyons for 'topological quantum computation' - an approach to quantum computing that uses topology to safeguard quantum bits from unwanted decoherence. The experimental situation in this fascinating domain is developing. There are indications that the quantum phase underlying the quantum Hall effect at filling factor 5/2 supports Majorana zero modes, but this remains to be confirmed experimentally. In purpose-designed quantum wire setups, signatures of Majorana zero modes have been obtained. A demonstration that such excitations indeed display non-Abelian braid statistics is eagerly awaited. ■

■ **Bernard Nienhuis**
and Kareljan Schoutens,
Delta Institute for Theoretical Physics and Institute of Physics of the University of Amsterdam

References

[1] J.M. Kosterlitz and D.J. Thouless, *J. Phys. C: (Solid State Physics)* **5**, L124 (1972), and J.M. Kosterlitz and D.J. Thouless, *J. Phys. C: (Solid State Physics)* **6**,1181 (1973).

[2] F.D.M. Haldane, *Phys. Rev. Lett.* **61**, 1988 (2015).

[3] F.D.M. Haldane, *Phys. Lett. A* **93**, 464 (1983) and F.D.M. Haldane, *Phys. Rev. Lett.* **50**, 1153 (1983).

[4] J.M. Kosterlitz, *J. Phys. C: (Solid State Physics)* **7**(6), 1046 (1974).

[5] D.J. Thouless, M. Kohmoto, M.P. Nightingale, and M. Den Nijs, *Phys. Rev. Lett.* **49**, 405 (1982).

RÜDIGER VOSS IS THE NEXT EPS PRESIDENT-ELECT

The European Physical Society [EPS] is pleased to announce that Rüdiger Voss has been elected as the next EPS President-elect. He will take up office as the President of EPS in April 2017, when the term of the current President, Christophe Rossel comes to an end.

R. Voss was elected during the Extraordinary Council meeting of the EPS held on 14 October 2016 at the EPS Secretariat in Mulhouse. It is noteworthy that Council delegates could participate either in person, or on-line through the video conferencing system. The EPS welcomed 25 delegates in person and a further 23 attended over the internet.

The Council delegates listened to three inspiring presentations from the three candidates. The EPS would like to express its heartfelt thanks to Zsolt Fülöp (HU) and Sydney Galès (FR) who also stood as candidates for President-elect. Their contributions to the EPS and their vision were impressive as well.

R. Voss has recently served as Head of International Relations at CERN. In addition to a successful scientific career at CERN, R. Voss was instrumental in setting up the SCOAP3 Open Access consortium. ■

David Lee, EPS Secretary General

Highlights from European journals

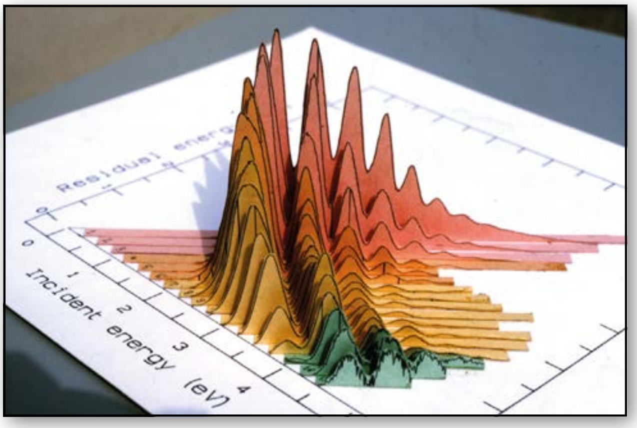
MATERIAL SCIENCE

Better material insights with gentle e-beams

Great potential for a new, more accurate, tool for using electron collisions to probe matter

There are several ways to change a molecule, chemically or physically. One way is to heat it; another is to bombard it with light particles, or photons. A lesser known method relies on electron collision, or e-beam technology, which is becoming increasingly popular in industry. In a review outlining new research avenues based on electron scattering, the authors explain the subtle intricacies of the extremely brief electron-molecule encounter, in particular with gentle, *i.e.*, very low energy electrons. In this paper, which was recently published, the authors describe how the use of very low energy electrons and a number of other performance criteria, make the approach with the so-called Fribourg instrument a more appealing candidate than previously available tools used to study electron collisions. One of the potential applications of this approach is in the quest to find a replacement for a molecule called sulfur hexafluoride (SF_6), a greenhouse gas stored in high voltage electricity distributing devices, such as switches and transformers. Electron collision could help identify a more suitable gas. ■

▾ An early 2-D EELS (Electron Energy Loss Spectra) of nitrogen.

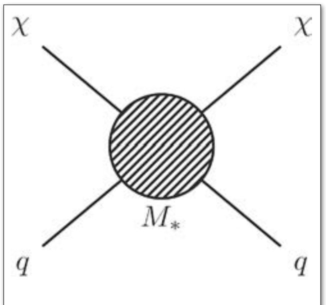


■ **M. Allan**, **K. Regeta**, **J. D. Gorfinkiel**, **Z. Mašín**, **S. Grimme** and **C. Bannwarth**,
'Recent research directions in Fribourg: nuclear dynamics in resonances revealed by 2-dimensional EEL spectra, electron collisions with ionic liquids and electronic excitation of pyrimidine', *Eur. Phys. J. D* **70**, 123 (2016)

PARTICLE PHYSICS

Better defining the signals left by as-yet-undefined dark matter at the LHC

New theoretical models that better describe the interaction between dark matter and ordinary particles advance the quest for dark matter



▴ Schematic of an Effective Field Theory interaction between dark matter and the standard model.

In the quest for dark matter, physicists rely on particle colliders such as the LHC in CERN, located near Geneva, Switzerland. The trouble is: physicists still don't know exactly what dark matter is. Indeed, they can only see its effect in the form of gravity. Until now, theoretical physicists have used models based on a simple, abstract description of the interaction between dark matter and ordinary particles, such as the Effective Field Theories (EFTs). However, until we observe dark matter, it is impossible to know whether or not these models neglect some key signals. Now, the high energy physics community has come together to develop a set of simplified models, which retain the elegance of EFT-style models yet provide a better description of the signals of dark matter, at the LHC. These developments are described in a review published by the authors. ■

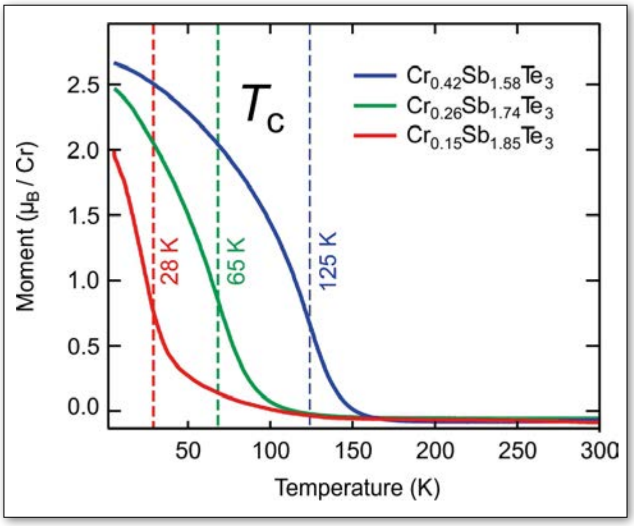
■ **A. De Simone** and **T. Jacques**,
'Simplified models vs. effective field theory approaches in dark matter searches', *Eur. Phys. J. C* **76**, 367 (2016)

CONDENSED MATTER

A New High for **Magnetically Doped Topological Insulators**

Surface phenomena in ring-shaped topological insulators are just as controllable as those in spheres made of the same material

Topological insulators (TIs) are a new phase of quantum matter whose conducting *surface* states are a result of the topology of their *bulk* band structure. Their spin-momentum locked



▲ Temperature dependence of the magnetization, M(T), of $Cr_xSb_{2-x}Te_3$ thin film samples with varying Cr concentration, x. The most highly doped and structurally uncompromised film shows a transition temperature of 125 K.

topological surface states are resilient to backscattering owing to their protection by time-reversal symmetry (TRS). These properties make them intriguing candidates for low-power devices, spintronics and quantum computation. Breaking TRS by introducing magnetic dopants, and introducing a gap in the topological surface states, unlocks exotic quantum phenomena such as the quantum anomalous Hall state. Doping TIs with magnetic impurities is an experimentally challenging process and most TI materials only exhibit magnetic ordering at low temperatures.

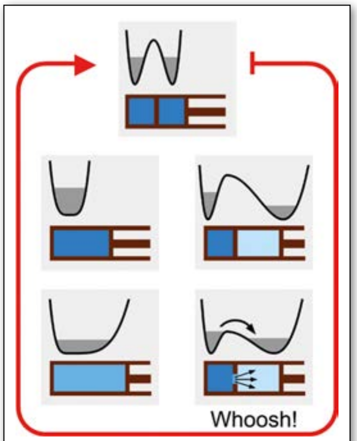
In this study, using a variety of complementary structural, electronic and magnetic characterisation techniques, we demonstrate the synthesis of magnetically doped TI thin films with high structural quality. The Cr-doped Sb_2Te_3 thin films were grown on sapphire using low-temperature molecular beam epitaxy. We show that this particular system exhibits uniform ferromagnetic ordering up to ~125 K – a step forward towards device-friendly TI materials. ■

▮ **L. J. Collins-McYntire + 13 co-authors**
'Structural, electronic, and magnetic investigation of magnetic ordering in MBE-grown $Cr_xSb_{2-x}Te_3$ thin films', *EPL* **115**, 27006 (2016)

STATISTICAL PHYSICS

Arbitrarily slow, non-quasistatic, **isothermal transformations**

Joule or free expansion of an ideal gas into a volume at lower pressure is an example of an irreversible isothermal process. This nonequilibrium example is often used in thermodynamics texts to demonstrate that an arbitrarily slow process need not be reversible. Cyclic operation of engines that involve a free expansion therefore requires work.



▲ A thermodynamically irreversible cycle for single-particle and classical engines.

Here, the authors explore experimentally the origin of thermodynamic irreversibility at the level of a single-particle "gas". A feedback trap confines a silica particle in a virtual bistable potential, creating a system analogous to two vessels connected by a valve, where the volume of one vessel is adjustable via piston. The authors operate two types of cyclic transformations; both start and end in the same equilibrium state, and both use the same basic operations—but in different order. One transformation required no work, while the other required work, no matter how slowly it was carried out.

Why the difference? As the illustration shows, the result of carrying out a protocol backwards in time may not match the initial state. This property is not possible to notice in a single repetition, unlike in a macroscopic system where free expansion is followed by a "whoosh". ■

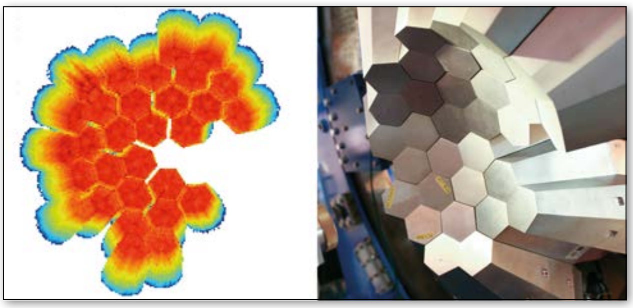
▮ **M. Gavrilov** and **J. Bechhoefer**,
'Arbitrarily slow, non-quasistatic, isothermal transformations', *EPL* **114**, 50002 (2016)

NUCLEAR PHYSICS

Germanium detectors **get position sensitive**

High purity germanium detectors have grown into very popular devices within the field of gamma ray spectroscopy. The sensitive part of these detectors consists of the largest, purest and monocrystalline semi-conductors used on earth. Ge detectors are famous for their outstanding energy resolution for electromagnetic radiation, especially in the field of nuclear

▼ Interaction positions determined by the pulse shape analysis of AGATA and the AGATA spectrometer at GANIL" (picture by P. Lecomte)



physics and astrophysics. Recently technical advances and the segmentation of the Ge crystals opened up new opportunities. In this way, the Ge detector becomes a position sensitive device and allows for the novel gamma-ray tracking technique.

New gamma ray spectrometers are currently under construction and implement the new method. The article describes all the theoretical concepts, which are needed for a precise understanding of all detector properties. Moreover, an elaborate computer code, named ADL, was developed and yielded a huge set of hundred thousands of detector pulses. These pulses are compared to measured pulses from individual gamma rays in order to extract the position where the radiation interacted with the detector material and created charges. ADL utilizes all relevant aspects of signal creation and formation with the Ge detector and the subsequent electronics. Meanwhile the code is successfully used for position sensitive spectroscopy within the AGATA project. ■

■ **B. Bruyneel**, **B. Birkenbach** and **P. Reiter**,
'Pulse shape analysis and position determination in segmented HPGe detectors: The AGATA detector library', *Eur. Phys. J. A* **52**, 70 (2016)

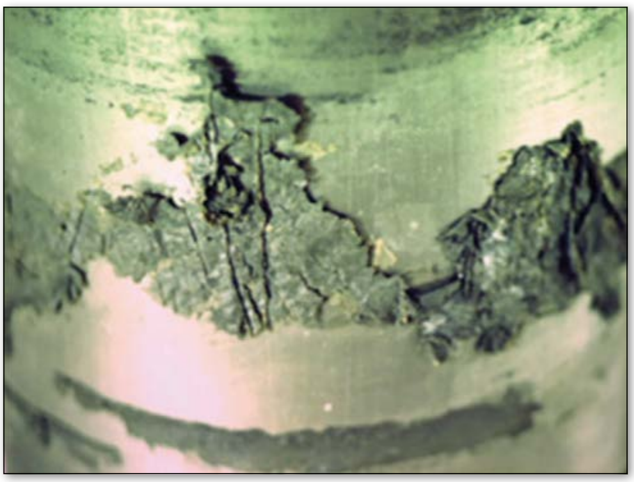
NUCLEAR PHYSICS

Improving safety of neutron sources

Testing liquid metals as target material bombarded by high-energy particles

There is a growing interest in the scientific community in a type of high-power neutron source that is created via a process referred to as spallation. This process involves accelerating high-energy protons towards a liquid metal target made of material with a heavy nucleus. The issue here is that scientists do not always understand the mechanism of residue nuclei production, which can only be identified using spectrometry methods to detect their radioactive emissions. In a new study examining the radionuclide content of lead-bismuth-eutectic (LBE) targets, the authors found that some of the radionuclides do not necessarily remain dissolved in the irradiated targets. Instead, they can be depleted in the bulk LBE material and accumulate on the target's internal surfaces. These findings have recently been published. The results improve our understanding of nuclear data related to the radionuclides stemming from high-power targets in spallation neutron sources. They contribute to improving the risk assessment of future high-power spallation neutron beam facilities — including, among others, the risk of erroneous evaluation of radiation dose rates. ■

▼ Sampling of Lead-Bismuth-eutectic material/cover gas-interface sample consisting of solid material forming a powdery crust onto the steel wall.

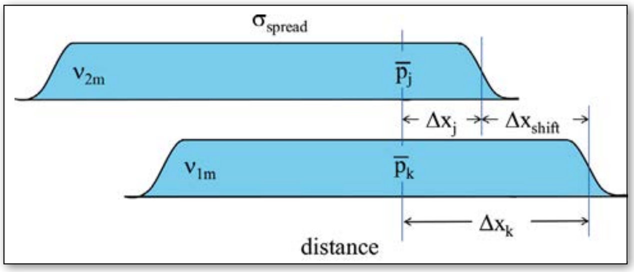


■ **B. Hammer-Rotzler**, **J. Neuhausen**, **V. Boutellier**, **M. Wohlmuther**, **L. Zanini**, **J.-C. David**, **A. Türler** and **D. Schumann**,
'Distribution and surface enrichment of radionuclides in lead-bismuth eutectic from spallation target', *Eur. Phys. J. Plus* **131**, 233 (2016)

NUCLEAR PHYSICS

Surprising neutrino decoherence inside supernovae

Theory to explain collective effects of neutrinos inside supernovae strengthened



▲ Illustration of the shift of two wave packets with large spread. Loss of coherence occurs even if the packets overlap due to the spatial energy redistribution within the whole wave packets.

Neutrinos are elementary particles known for displaying weak interactions. As a result, neutrinos passing each other in the same place hardly notice one another. Yet, neutrinos inside a supernova collectively behave differently because of their extremely high density. A new study reveals that neutrinos produced in the core of a supernova are highly localised compared to neutrinos from all other known sources. This result stems from a fresh estimate for an entity characterising these neutrinos, known as wave packets, which provide information on both their position and their momentum. These findings have just been published by the authors. The study suggests that

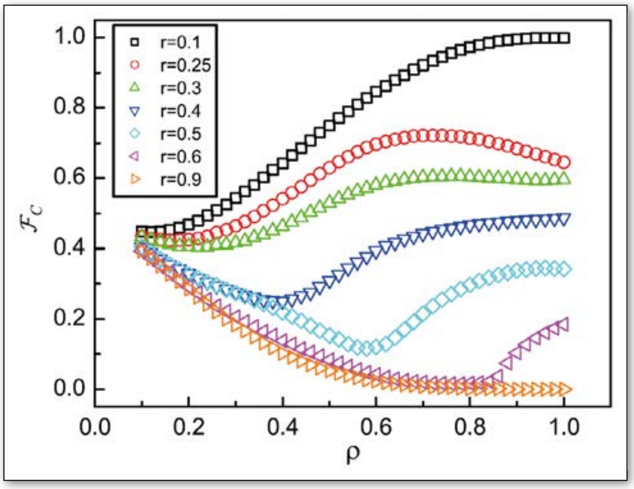
the wave packet size is irrelevant in simpler cases. This means that the standard theory for explaining neutrino behaviour, which does not rely on wavepackets, now enjoys a more sound theoretical foundation. ■

■ **J. Kersten** and **A. Yu. Smirnov**,
'Decoherence and oscillations of supernova neutrinos',
Eur. Phys. J. C **76**, 339 (2016)

COMPLEX SYSTEMS

How cooperation emerges **in competing populations**

New theoretical approach to understand the dynamics of populations reaching consensus votes or of spreading epidemics



▲ The fraction of cooperative players as a function of the site-occupancy probability ρ obtained using numerical simulations.

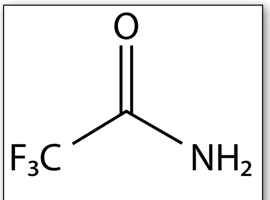
Social behaviour like reaching a consensus is a matter of cooperation. However, individuals in populations often spontaneously compete and only cooperate under certain conditions. These problems are so ubiquitous that physicists have now developed models to understand the underlying logic that drives competition. A new study published recently shows the dynamics of competing agents with an evolving tendency to collaborate that are linked through a network modelled as a disordered square lattice. These results are the work of the authors. They believe that their theoretical framework can be applied to many other problems related to understanding the dynamical processes in complex systems and networked populations, such as the voter dynamics involved in reaching a consensus and spreading dynamics in epidemic models and in social networks. ■

■ **C. Xu**, **W. Zhang**, **P. Du**, **C.W. Choi** and **P.M. Hui**,
'Understanding cooperative behaviour in structurally disordered populations', *Eur. Phys. J. B* **89**, 152 (2016)

ATOMIC AND MOLECULAR PHYSICS

Electron scavenging to mimic **radiation damage**

New study could help unveil negative effect of radiation on biological tissues due to better understanding of low energy electron-induced reactions



▲ Molecule of trifluoroacetamide (TFAA).

High energy radiation affects biological tissues, leading to short-term reactions. These generate, as a secondary product, electrons with low energy, referred to as LEEs, which are ultimately involved in radiation damage. In a new study, scientists study the effect of LEEs on a material called trifluoroacetamide (TFAA). This material was selected because it is suitable for electron scavenging using a process known as dissociative electron attachment (DEA). These findings were recently published, as part of a topical issue on Advances in Positron and Electron Scattering. Experiments confirm that DEA reactions occur due to electrons entering unoccupied molecular orbitals, at an energy level located near one electronvolt. This means that low-energy electrons can be exploited with solid materials like TFAA to trigger selective reactions, resulting in multiple bond cleavages inside the material. Ultimately, this leads to the creation of specific negative ions and stable molecules of interest. ■

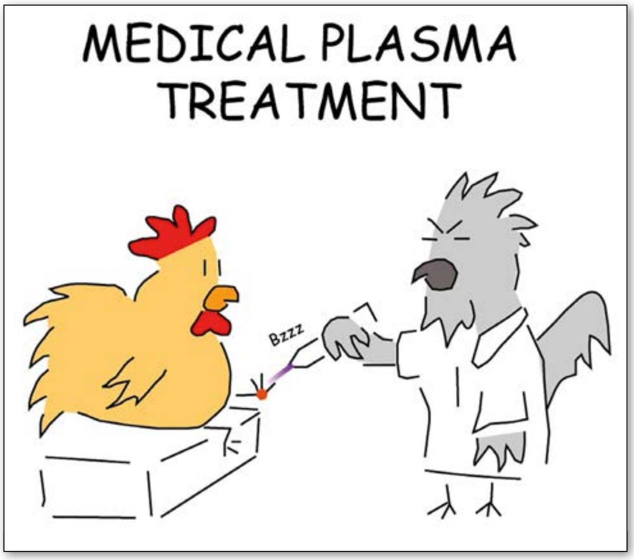
■ **J. Kopyra**, **C. König-Lehmann**, **E. Illenberger**, **J. Warneke** and **P. Swiderek**,
'Low nergy electron induced reactions in fluorinated acetamide – probing negative ions and neutral stable counterparts', *Eur. Phys. J. D* **70**, 140 (2016)

BIOPHYSICS

Metering the plasma dosage into the physiological environment

There is significant optimism that cold atmospheric (ionised gas) plasma could play a role in the treatment of life-threatening diseases, such as non-healing chronic wounds and cancers. The medical benefits from plasma are thought to arise from the reactive oxygen and nitrogen species (RONS) generated by plasma upon interaction with air and liquids. However, it is unclear what RONS are delivered by plasma into tissue fluid and tissue, and their rate of delivery. This knowledge is needed to develop safe and effective plasma therapies.

In this investigation, a simple approach was proposed to monitor the dynamic changes in the concentrations of RONS



▲ Plasma therapy.

and dissolved oxygen within tissue-like fluid and tissue during plasma treatment. A plasma "jet" device was shown to non-invasively transport RONS and oxygen deep within tissue (to millimetre depths). However, tissue fluid directly treated with the plasma jet was deoxygenated due to the gas flow purging oxygen out of the fluid.

Monitoring and controlling the plasma delivery of both RONS and oxygen into tissue fluid and tissue is necessary to avoid hypoxia in open wound treatment, to achieve targeted destruction of cancerous cells within solid tumours and to oxygenate oxygen-starved tissue to stimulate tissue regeneration. ■

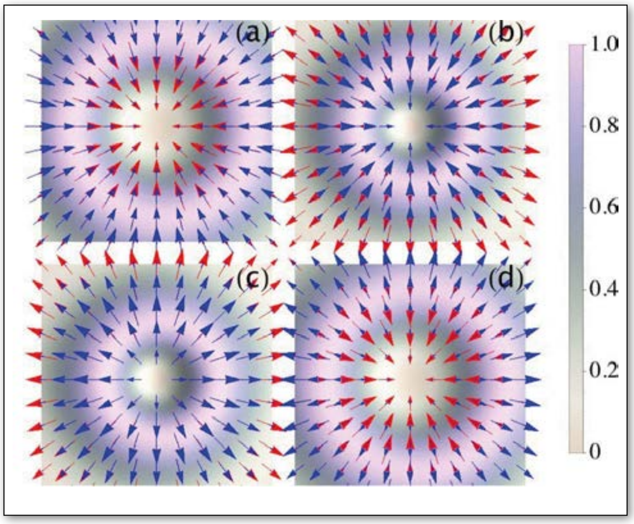
■ **J.-S. Oh**, **E. J. Szili**, **N. Gaur**, **S.-H. Hong**, **H. Furuta**, **H. Kurita**, **A. Mizuno**, **A. Hatta** and **R. D. Short**, 'How to assess the plasma delivery of RONS into tissue fluid and tissue', *J. Phys. D* **49**, 304005 (2016)

OPTICS

Polychromatic cylindrically polarized beams

Cylindrically polarized beams represent a class of solutions, where the polarization can be radially or azimuthally distributed across the intensity profile. These beams have very intriguing properties, both from a fundamental and an applied perspective. Despite their great success, they have been almost exclusively studied and realized within the monochromatic regime.

An open question is if non-monochromatic cylindrically polarized solutions of Maxwell equations exist. New research answers to this question by employing X waves with orbital angular momentum (the polychromatic counterpart of Bessel beams) as building blocks to generate optical pulses with radial and azimuthal polarization. This approach is different from the monochromatic case where Hermite-Gaussian beams are typically used. Solutions are investigated in the paraxial and the nonparaxial regime and the role of the pulse's spectrum in the polarization properties of the pulse itself is pointed out.



▲ Various polarization patterns (arrows) and intensity distributions (underlying doughnut) of a co-rotating radially polarized X-wave.

Analysis shows that the generalization of the concept of non-uniform polarization to the domain of optical pulses leads to new intriguing applications, such as spatially resolved Raman spectroscopy. Cylindrically polarized X-waves with orbital angular momentum could also open new intriguing scenarios for fundamental research and quantum optics. ■

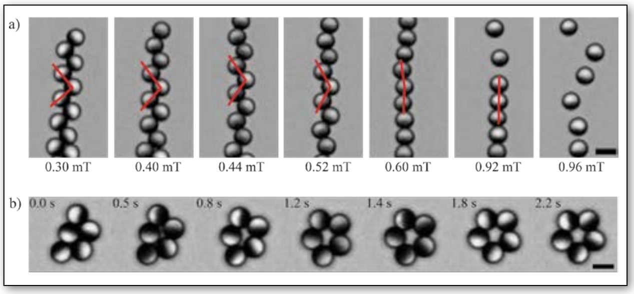
■ **M. Ornigotti**, **C. Conti** and **A. Szameit**, 'Cylindrically polarized nondiffracting optical pulses', *J. Opt.* **18**, 075605 (2016)

CONDENSED MATTER

Asymmetrical magnetic microbeads **transform into micro-robots**

Thanks to the ordering effects of two-faced magnetic beads, they can be turned into useful tools controlled by a changing external magnetic field

Janus was a Roman god with two distinct faces. Thousands of years later, he inspired material scientists working on asymmetrical microscopic spheres—with both a magnetic and a non-magnetic half—called Janus particles. Instead of behaving like normal magnetic beads, with opposite poles attracting, Janus particle assemblies look as if poles of the same type attract each other. A new study reveals that the dynamics of such assemblies can be predicted by modelling the interaction of only two particles and simply taking into account their magnetic asymmetry. These findings were recently published by



▲ Transformation of particle clusters while exposed to an oscillating external magnetic field.

the authors. It is part of a topical issue entitled "Nonequilibrium Collective Dynamics in Condensed and Biological Matter." The observed effects were exploited in a lab-on-a-chip application in which microscopic systems perform tasks in response to a changing external magnetic field, such as, for instance, to create a zipper-style micro-muscle on a chip. ■

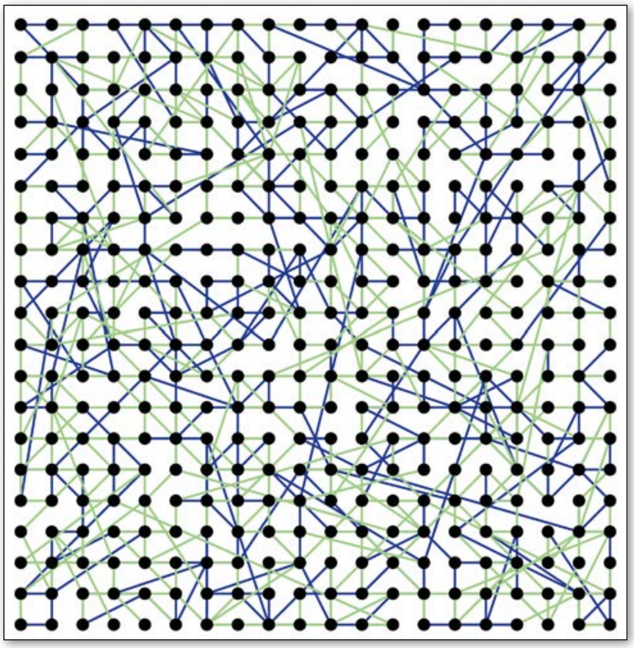
■ **G. Steinbach**, **S. Gemming** and **A. Erbe**, 'Non-equilibrium dynamics of magnetically anisotropic particles under oscillating fields', *Eur. Phys. J. E* **39**, 69 (2016)

COMPLEX SYSTEMS

The effect of spatiality on multiplex networks

When a node can only form a link to its nearest neighbour, the topology is entirely determined by the spatial locations of the nodes. But when near and far links can form, the influence of the spatial embedding of the topology is much less. In this paper, we use this to modulate the strength of spatial effects on network topology. This allows us to consider the question: Does increasing the allowed geometric length of links in a network improve its robustness? In single-layer networks, the answer is generally that it does. However, in multiplex networks, we find that increasing the link lengths actually makes the network vulnerable to more severe cascade behaviours. This is because in multiplex networks, longer links allow for a discontinuous percolation transition which is characterized by a nucleation process. Our model and results demonstrate the surprising effects of spatial embedding and provide a simple new framework for assessing spatial networks of one or more layers. ■

▼ The multiplex structure arising from beginning with nodes on a lattice and connecting them through two layers of links (gray and black) with the length of each link following an exponential distribution.

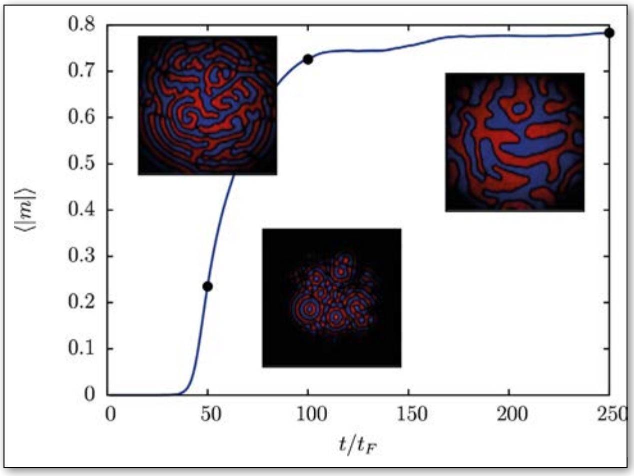


■ **M.M. Danziger**, **L.M. Shekhtman**, **Y. Berezin** and **S. Havlin**, 'The effect of spatiality on multiplex networks', *EPL* **115**, 36002 (2016)

MATERIAL SCIENCE

New method helps stabilise materials with elusive magnetism

Stabilising materials with transient magnetic characteristics makes it easier to study them



▲ Visualisation of itinerant ferromagnetic domains.

Magnetic materials displaying what is referred to as itinerant ferromagnetism are in an elusive physical state that is not yet fully understood. They behave like a magnet under very specific conditions, such as at ultracold temperatures near absolute zero. Realising the itinerant ferromagnetic state experimentally using ultracold gas is a challenging undertaking. This is because when three atoms - one with the opposite spin of the other two - come close to each other two atoms with opposite spin will form molecules and the other one carries the binding energy away; a phenomenon called rapid three-body recombination. Now, the authors, have introduced two new theoretical approaches to stabilise the ferromagnetic state in quantum gases to help

study the characteristics of itinerant ferromagnetic materials. The first approach involves imposing a moderate optical lattice. There, the three-body recombination is small enough to permit experimental detection of the phase. In a second approach, they suggest to prepare two initially separated clouds and study their time evolution. The ferromagnetic domains has longer life time because of the reduced overlap region between the two spins. These results were recently published. ■

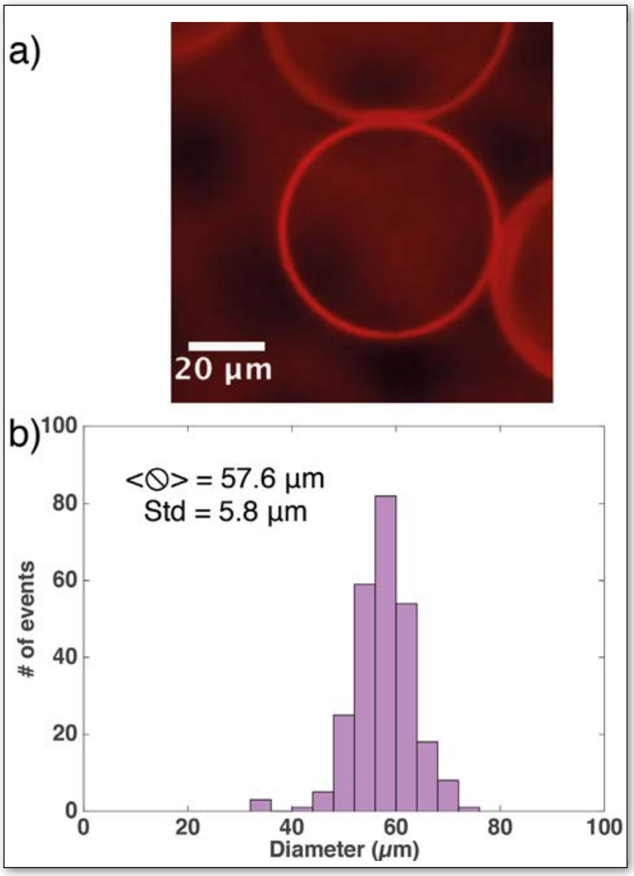
▪ **I. Zintchenko**, **L. Wang** and **M. Troyer**,
'Ferromagnetism of the repulsive atomic Fermi gas: three-body recombination and domain formation', *Eur. Phys. J. B* **89**, 180 (2016)

BIOPHYSICS

Versatile method yields synthetic biology building blocks

New high-throughput method to produce both liposomes and polymersomes on the same microfluidic chip

Synthetic biology involves creating artificial replica that mimic the building blocks of living systems. It aims at recreating biological phenomena in the laboratory following a bottom-up approach. Today scientists routinely create micro-compartments, so called vesicles, such as liposomes and polymersomes. Their membranes can host biochemical processes and are made of self-assembled lipids or a particular type of polymers, called block copolymers, respectively. In a new study, researchers have developed a high-throughput method--based on an approach known as microfluidics--for creating stable vesicles of controlled size. The method is novel in that it works for both liposomes and polymersomes, without having to change the design of the microfluidic device or the combination of liquids. The authors recently published these findings. Typical applications in synthetic biology include the encapsulation of biological agents and creation of artificial cell membranes with a specific biochemical function. They anticipate that their method might also be applicable for the controlled fabrication of hybrid vesicles used in bio-targeting and drug-delivery. ■



▲ Fluorescence microscopy image of polymersomes, taken 3 days after production.

▪ **J. Petit**, **I. Polenz**, **J.- C. Baret**, **S. Herminghaus** and **O. Bäumchen**,
'Vesicles-on-a-chip: A universal microfluidic platform for the assembly of liposomes and polymersomes', *Eur. Phys. J. E* **39**, 59 (2016)

NOMINATIONS FOR EDITOR IN CHIEF OF EPL

Nominations are now open for the Editor-in-Chief of EPL, a leading global letters journal owned and published by a consortium of 17 national physical societies in Europe. The Editor-in-Chief (EiC) needs to be a recognized authority and leading researcher in a field of physics, and have a broad knowledge and interest in physics and its frontiers. The EiC will need to demonstrate strong commitment and leadership to further develop EPL as a top-ranking journal. Experience with the editorial process for a physics journal is also desirable. The EiC is central to enhancing EPL's position as a leading global physics letters journal. The term of office of EPL Editor-in-Chief is three and a half years beginning in July 2017. A job description is available at https://www.epletters.net. Nominations must include a CV, publication list, and a brief covering letter describing the qualifications and the interest of the individual in the position of EPL Editor-in-Chief. Nominations should be sent to the EPL Editorial Office no later than 15 January 2017 (editorial.office@epletters.net). Further information can be obtained from the Editorial Office in Mulhouse. ■

by Tony Klein
School of Physics – The University of Melbourne, Australia - http://dx.doi.org/10.1051/epn/2016501

Confessions of a deuteranope

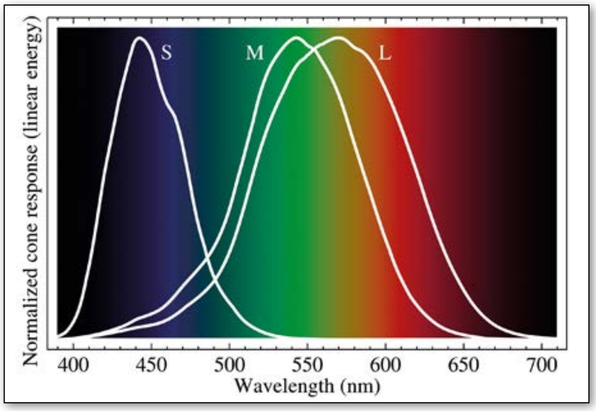
About 8% of men – but only about 0.6% of women – among us exhibit Colour Vision Deficiency (CVD), i.e., are said to be colour blind. This genetic defect, by the way, is called *"Daltonism"* in French, named after John Dalton the noted chemist, who was one of its more notorious sufferers and generators of anecdotes.

The most common form of colour blindness, called red-green colour blindness, is caused by a defect on the X chromosome, of which males have only one copy, whereas females, who have two copies may be protected by the other X chromosome if it has a non-defective gene. However one half of their male offspring will be afflicted and thus they are "carriers". In my case, I inherited my colour blindness from my maternal grandfather, and my grandson got it from me, via my daughter, who has perfect colour vision. Half my daughters and my grand-daughters, are likely to be carriers.

So, what is this defect? As is well known, there are two types of light receptor cells in the human retina: rods and cones. It is the cones that are responsible for colour vision; the more abundant rods are extremely sensitive to light but only give black-and-white information for night-vision (and information on motion and edge detection in brighter light). By the way, recent experiments have shown that one single photon is capable of triggering the receptors, provided that they have escaped capture by intervening tissue.

There are three types of cones, responsive to short, medium and long (*i.e.* S, M and L) wavelengths of visible light, but actually they have three different spectral sensitivities, as shown in Fig.1.

In a somewhat simplified explanation, if one of the M or S cones is missing (or has a much reduced abundance) in a person's retina, they will be a so-called "dichromat" or colour blind: "green-blind" or "deuteranope" (like I am) if missing the M cones; "red-blind", or "protanope" if missing L cones; "blue-blind", or "tritanope" in the rare case of missing the S cones.



▲ **FIG.1:** Spectral Sensitivities of the three types of cone cells.

What does this mean in practice? In the case of protanopes, they cannot see red traffic lights or only very dimly, and can't see red flowers very well at all. In my case, I see grass *etc.* as some shade of brown – but it's really more complicated than that. Our world is still full of colour – around 10,000 different hues, in fact, whereas people with normal colour vision can see about 1,000,000. I do, however, have trouble with red flowers having very low contrast with the surrounding green leaves in certain beautiful trees like the "flame tee" or Poinciana. Often I can't see them until up close. But I have no trouble at all with traffic lights: The "green" is really very bluish.

It's a bit like a colour printer with one of the cartridges missing, but not really: The Cyan, Yellow, Magenta system of colour printing is quite different from the Short, Medium, Long cones in the retina, but each system has in common a triple manifold of colours, *i.e.*, needing three numbers to specify a hue. I found a better set of examples in Wikipedia, while researching this column. Under "Colour Blindness" (which tells you more about the subject than you might wish to know) there are pairs of pictures that show what a normal and a red-green blind person would see. In spite of the limitations of the computer screen or

▼ **FIG. 2a:** Normal vision

▼ **FIG. 2b:** Deuteranopic vision

▼ **FIG.2c:** Tritanopic vision.

COMPANY DIRECTORY

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▲ **FIG. 3:** (a) normal and (b) deuteranope vision.

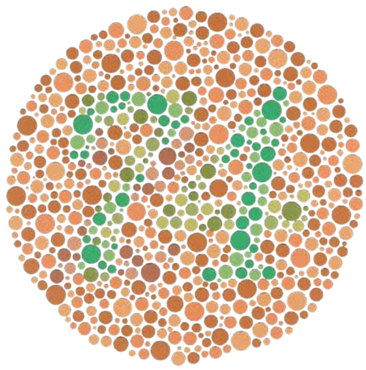
of the printed page, they look pretty good to me: I can't tell the difference! If you, the reader can't either, then you may be part of the 8% (if male) or the 0.6% (if female) – join the "club". The pictures are shown in Figs. 2a, and 2b and for the sake of completeness 2c: Tritanopic vision, the rare condition of missing the S cone.

A very interesting issue concerns colour vision in animals: It turns out that most animals (except insects) have no colour vision at all. However, birds, reptiles and amphibians (as well as some rare human females), can have four different cone types. But it turns out that most mammals are deuteranopes, *i.e.*, green blind – so people like me are by no means alone. And more recent research shows that the third type of cone has evolved rather more recently in (old-world) monkeys and presumably humans and other fruit-eaters in order to distinguish ripe fruit. This is illustrated in Fig. 3: Red and green apples as they appear to normals (a) and deuteranopes (b). Once again, I can't tell the difference!

So what sort of handicap is colour blindness and how is it diagnosed? In my case, at around the age of 3, it was found by my mother that I was using "crazy" colours in colouring books, *e.g.* ships sailing on violet seas instead of blue. She knew that her father had trouble with colours but they all thought that he had trouble naming colours because they didn't understand the concept of CVD. But to me it represented hardly any handicap in perceiving the wonderfully coloured world.

Much later, however, as a teenager, I was chucked out of flying school (much to the relief of my parents) when my CVD was properly diagnosed. This was done by the use of the most common test, the one named after its promulgator, Professor Ishihara. (Several other tests exist for other, more subtle types of CVD). The Ishihara test consists of subtly coloured dots showing numbers hidden among other coloured dots. The perceived numbers are different for normal and colour blind subjects. An example of one such test pattern is showed in Fig. 4:

Apart from being prohibited from certain occupations such as piloting or train-driving, I have hardly felt any handicap apart from a few incidents with colour-coded wires and electronic components. But otherwise it was more of a source of amusement, such as when a cousin and I (who shared a common maternal grandfather) marvelled at a rare Australian orange-bellied parrot, which turned out to have been bright green. But we had no trouble at all with other more common (Australian) coloured birds, such as rainbow lorikeets and rosellas which are, to us, bright red and what we see as nearest thing to bright green. ■

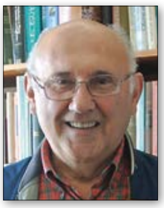


◂ **FIG. 4:** Example of an Ishihara test plate. People with normal colour vision see the number 74; I, a deuteranope, see the number 21 or 81. Protanopes see other numbers, or simply can't tell.

Acknowledgement

The author is very grateful to Dr Jessica Kvansakul, whose PhD was in the area of vision science, and whose normal colour vision allowed her to make significant improvements to the text and to the illustrations. She is the Editor of "Australian Optical Society News" where this article originally appeared.

About the author



Professor Emeritus **Tony Klein** held a Personal Chair in Physics in the University of Melbourne until his retirement in 1998. He served as President of the Australian Optical Society (1985-86); President of the Australian Institute of Physics (1990 – 91); Head of the School of Physics (1986 –95). He was elected a Fellow of the Australian Academy of Science in 1994 and was appointed a Member of the Order of Australia in 1999. He has published extensively in experimental physics, particularly about neutron optics, including focusing of neutrons with a Fresnel Zone Plate.

FOREWORD ON THE SPECIAL ISSUE ON NUCLEAR FUSION AND PLASMA PHYSICS

FROM THE EDITORS

It is with great pleasure that we present this special issue on Nuclear Fusion and Plasma Physics. The topic in this issue is both important and timely. Important because Fusion has the potential to provide mankind with a nearly unlimited source of energy. Timely, because this year has witnessed a breakthrough in this field at the Max Planck Institute for Plasma Physics in Greifswald, where the Wendelstein 7-X fusion device produced its first hydrogen plasma. We are proud and grateful that former EPS President Fritz Wagner, one of the pioneers in this field, was willing to act as a Guest Editor for this special issue. It is Fritz and his authors who should have the credit of this issue, which we hope will provide most interesting reading.

Victor R. Velasco, Jo Hermans and Ferenc Iglói

FROM THE GUEST EDITOR

The technologies which have been developed in the last centuries and which are powered by cheap energy allowed mankind to grow to more than 7 billion people on earth and produced regions with till then unknown wealth. Such an area is Europe. Our lifestyle seems to be endangered now because fossil fuels come to an end. It is not such that the wells were empty rather the atmosphere is full, full of CO_2, and the earth is at the brink of overheating. Disregarding carbon capture and sequestration mankind has three choices of a CO_2-free energy supply: fission, fusion and renewable energies.

In this special issue we present the status of fusion research and development. The principle of fusion is based on the processes in our sun and the stars which fuel the universe. Fusion research has been started after WWII and is now pursued in most industrialized countries. The original hopes have not been fulfilled to master this technology on short notice. The popular joke – when asked, the realization of fusion always takes 40 years – goes back to a roadmap which has been developed after the first energy crisis in the seventies of last century. The fusion community responded with a schedule and financial plan. The financial support collapsed as soon as the crisis was over. Probably, Lev Artsimovich, a Russian fusion pioneer, was right when he expected that fusion will be developed when mankind needs it. The time has come now and the first experimental fusion reactor, ITER, is under construction in France.

This special issue describes how fusion research in Europe has responded in its organization and in its technical and scientific objectives since the ITER decision has been taken. The tenor of the individual papers reflects these changes because much more technology, material and safety issues are addressed. The orientation of the scientific programs *e.g.* those of JET, the world-wide largest fusion device in England, is strictly oriented toward the needs of ITER. Objectives and status of ITER are presented in detail. In a separate paper the final step to a demonstration reactor, DEMO, is described discussing operational safety, waste, electricity costs and market penetration of this technology. A new device has started operation in northern Germany, Wendelstein 7-X. This device is not a tokamak like JET and ITER but a stellarator based on a completely novel concept. The ideas behind this concept and the goals of W7-X along with the arguments to pursue two representatives of toroidal magnetic confinement are presented in detail.

Fusion research with magnetic confinement is only one application of plasma physics. It is impossible to cover this large field by a special issue. Just to give the reader one example of a totally different application of plasma physics we have added a paper on the use of plasmas in medicine. We selected this paper because two of its authors received the 2016 EPS Plasma Physics Innovation Prize. ■

Fritz Wagner

CHALLENGES ON THE ROAD TOWARDS FUSION ELECTRICITY

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The ultimate aim of fusion research is to generate electricity by fusing light atoms into heavier ones, thereby converting mass into energy. The most efficient fusion reaction is based on merging the hydrogenic isotopes: Deuterium (^2D) and Tritium (^3T) into Helium (^4He) and a neutron, which releases 17.6 MeV in the form of kinetic energy of the reaction products.

The helium particle carries 20% of the reaction energy which is used for heating the plasma. The neutron with 80% of the energy is not confined by the magnetic field and will penetrate into the blanket surrounding the plasma. There it deposits its energy, leading to a temperature rise of the blanket coolant, which will drive electric turbines. In the blanket it also converts ^{6}Li into ^{3}T and ^{4}He; the ^{3}T is subsequently used as fuel.

The two main strategies to achieve fusion on Earth are based on magnetic confinement and inertial confinement. In *magnetic* confinement, a gas is heated to temperatures in the order of 1 - 1.5 × 10^8 K. At these high temperatures the gas has transformed into plasma, consisting of charged particles with sufficiently high energy to overcome the Coulomb potential and to fuse.

▾ Magnetic field lines in the Wendelstein 7-X stellarator in Greifswald, made visible by the combination of an electron gun and a fluorescent rod moved through the vacuum vessel.

Magnetic fields are used to confine the plasma and keep it away from any material surfaces. In *inertial* fusion a small pellet of solid deuterium-tritium is quickly and strongly compressed by powerful laser or particle beams, leading to sufficiently high densities and temperatures for fusion.

Magnetic Confinement Fusion

European fusion research is largely concentrated on magnetic confinement fusion, as it is the most promising concept to deliver fusion electricity. In the range of magnetic confinement devices that have been studied over the last decades, the tokamak has reached the best performance. In a tokamak, the plasma is confined by a magnetic field that is a superposition of a field generated by external magnetic coils (yielding a field in the toroidal direction) and an internal poloidal field generated by a toroidal current through the plasma which is induced by a transformer (see Figure 1).

Hitherto, the highest fusion performance (16 MW) has been achieved in the Joint European Torus, JET, world's largest tokamak (see article by L. Horton). Also the international ITER experiment (see article by D. Campbell) – a collaboration of China, Europe, India, Japan, Russia, South-Korea and the United States – is based on the tokamak concept. ITER is expected to have first plasma around the middle of the next decade and is designed to achieve fusion power generation of about 500 MW, using 50 MW of external input power. ITER will not deliver any fusion electricity and will therefore be succeeded by DEMO, the first Demonstration Fusion Power Plant (see article by D. Ward).

EUROfusion and the European Fusion Roadmap

Europe has drafted an elaborate plan to achieve the milestone of fusion electricity demonstration in DEMO by the middle of the century. In this so-called Fusion Roadmap, eight important missions have been defined, which can be grouped into:

1. Risk mitigation for ITER
2. (Pre-) Conceptual Design of DEMO
3. The stellarator as back-up strategy

Fusion research in Europe is coordinated by EUROfusion, a consortium of 29 National Fusion Laboratories from 27 countries, plus Switzerland and – from 2017 onwards - Ukraine, along with over 100 Universities, groups and industries that are acting as Linked Third Parties to the National labs (see Fig. 2).

The fusion community is confident that ITER will work and reach its full performance and all of its objectives. However, there are open research issues that, if better understood, can help ITER to optimise its research plan. It is no surprise that there are even more open issues with respect to the design of the DEMO reactor. These are largely related to the very hostile environment with strong plasma-wall interaction and high fluxes and fluences of

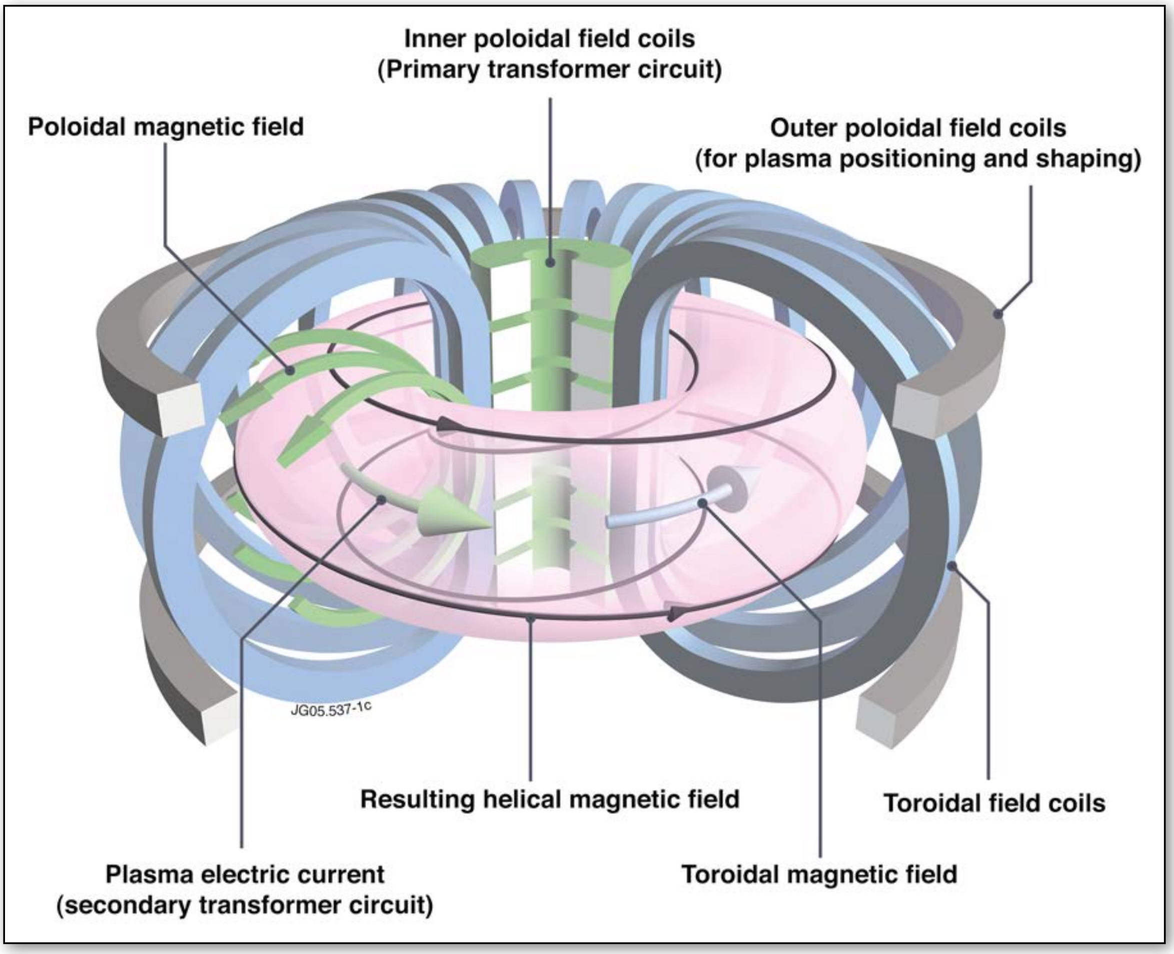
neutrons and gammas emerging from the hot plasma. In the remainder of this paper and the following ones of this special issue the reader will be guided through a few of the main physics challenges in the fusion roadmap.

The choice has been made to focus on items 1 and 3 above. Item 2 is linked to the DEMO design and preparation, and is more technology-oriented than the other two items, although it comprises challenging and interesting issues such as developing neutron-resistant materials, achieving tritium self-sufficiency, intrinsic safety, integrated DEMO design and competitive cost of electricity (see article by D. Ward).

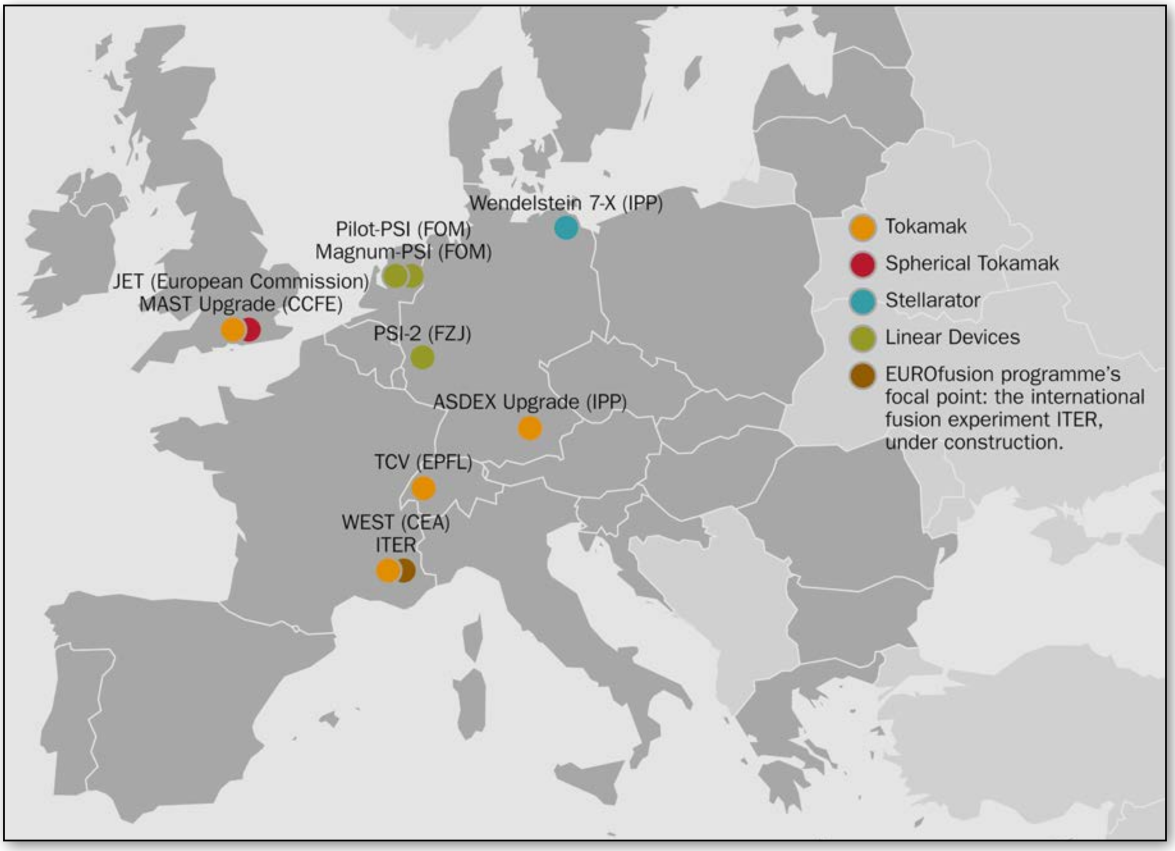
Risk mitigation for ITER (and DEMO)

The temperature of the fusion plasma in ITER (and also in DEMO) must be about 10-20 times higher than that in the core of the Sun, for colliding particles to have sufficient energy to fuse. Because there are strong temperature-, density- and current density gradients, the plasma is prone to develop microscopic instabilities (turbulence) as well as macroscopic magnetohydrodynamic instabilities, which degrade the plasma performance. The macroscopic instabilities can potentially completely destabilise a tokamak plasma which can end the plasma state. This process - called disruption - leads to strong forces onto the surrounding vacuum vessel due to induced halo currents. So plasma scenarios need to be developed in which the performance is ramped up in a controlled way and in which instabilities are actively controlled. An excellent external 'knob' to control magneto-hydrodynamic instabilities is the injection of radio waves at the place of the instability. The radio frequency waves injected are either resonant with the local electron or ion cyclotron frequency or one of its higher harmonics. This stabilisation method can act either on the electrons or on the ions in the plasma. Another possibility to act on the plasma is the injection of powerful beams of neutral particles (typical energies in ITER ~1 MeV).

ITER will bring fusion physics into a new regime: The alpha particles carry 20% of the generated fusion power, which implies that at the highest ITER performance (fusion power/input power = 10), the self-heating by the alpha particles is twice the external input power. This has a large effect on the way the plasma can be controlled. Only localized heating methods, with a high power density, like cyclotron heating can outweigh the alpha particle heating, and can therefore be used for efficient plasma control. Additionally, new effects can occur as the energetic alpha particles can interact with instabilities, which might lead to untolerable losses of fast particles. Many of these effects can be studied already in present devices by mimicking alpha particles by fast ions that are externally injected, but the ultimate understanding of alpha-particle physics needs to come from ITER.

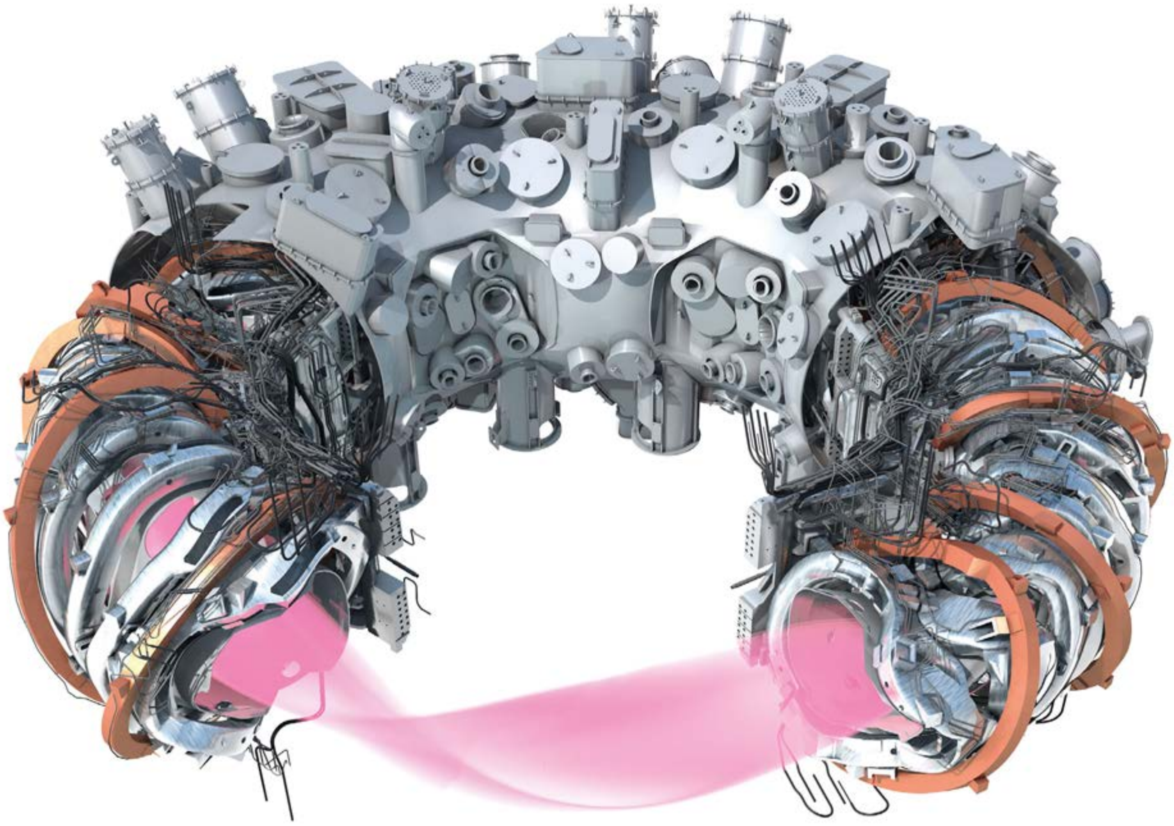


▸ **FIG. 1:** Principle of the tokamak. The hot plasma is confined by a superposition of the toroidal and the poloidal magnetic fields. The first is generated by external magnetic field coils, the second by the electrical current induced in the plasma. Due to the transformer action to induce the current in the plasma, the tokamak is a pulsed device by definition (picture EUROfusion).



◂**FIG. 2:** Dark coloured countries are involved in the EUROfusion consortium (Sweden and Finland are off the map, but are also member of EUROfusion). The bulk of the EUROfusion research is concentrated on the various devices indicated with coloured dots. A number of devices in other countries are used for specific experiments (Picture EUROfusion).

Achieving a high performance plasma is not the only challenge. By far the largest quest for the fusion researchers is to solve the heat exhaust problem. Namely, the power generated in the core of the plasma needs to be exhausted in a small part of the reaction chamber called the divertor. In ITER, the neutrons, deposit a total of 400 MW more or less uniformly into the blanket structure surrounding the vacuum chamber. But about 90% of the remaining exhaust power of about 100 MW is convected towards the divertor, leading to a steady state heat load on the divertor components in ITER with peak values of 10-20 MW/m^2. These are power densities that are close to those at the surface of the Sun! The challenge of finding a proper solution beyond ITER is largely going into two directions: development of (new) plasma-facing materials that are more robust against the plasma-wall interactions as well as developing new magnetic geometries for the divertor in which the peak heat load is distributed over a larger surface. With respect to the latter direction: options that are being studied in Europe are the snowflake divertor in the Swiss TCV tokamak, the Super-X divertor in the British MAST-Upgrade tokamak and liquid materials divertors in a number of specific experiments. *Plasma regimes of operation* (mission1) and *Heat-exhaust systems* (mission 2) in the fusion roadmap are tightly interlinked. This is illustrated by the following. Originally most tokamaks in the world utilised carbon tiles as main plasma-facing components and carbon-fibre composites (CFC) in the divertor, as this material is very strong and can withstand high temperatures up to about 1200°C. Carbon is also a relatively light atom and does not pollute the plasma too much when it enters (since the plasma is quasi-neutral, each impurity ion with charge number Z pushes out Z hydrogenic ions, leading to fuel dilution). However, carbon has two important drawbacks: 1) it forms dust, and 2) it binds with hydrogen. The effect of both is that in a machine operating with ^{3}T (like ITER) after a short time the whole tritium inventory is immobile due to retention in the carbon dust and carbon plasma-facing components. This implies opening and cleaning the machine and subsequently separating the tritium from the dust. It is for this reason that about 10-15 years ago a deliberate choice has been made in Europe to switch to full metal machines. The German ASDEX-Upgrade, has gradually changed the wall material from full carbon to full tungsten. JET has been modified in a single shutdown from a carbon machine to a device with beryllium walls and a tungsten divertor (exactly the same materials as will be employed in ITER, see the following papers). The Tore Supra superconducting tokamak in France is presently being changed into WEST, a full tungsten device able to run long plasma pulses. Tungsten has a high melting point of 3422°C, but recrystallisation becomes important above 1200°C. The result of a few years of operation of ASDEX-Upgrade with a full tungsten wall and JET with the ITER-like wall is that the hydrogen retention has been reduced by a factor of ~15, which is sufficiently good for ITER. However, it turned out to be much more challenging to achieve a high plasma performance due to influx and accumulation of tungsten in the plasma core, which – as



▸ FIG. 3: Schematic drawings of the Wendelstein 7-X stellarator, showing the complexity of the device with the magnetic field coils, cooling channels, vacuum vessel and cryostat (copyright Max-Planck-Institut für Plasmaphysik)

sketched above – leads to considerable fuel dilution. This can be avoided by using special tricks as central plasma heating (with radio frequency waves), surrounding the plasma by a seeding gas and controlling instabilities at the plasma edge to purge the tungsten out of the plasma. This shows the rather intricate interplay between reaching a high plasma performance and finding proper solutions for the plasma heat exhaust geometry and material choices.

Apart from the integrated research of plasma-wall interaction in tokamaks, new materials are constantly being developed and tested in linear plasma devices, like MAGNUM-PSI and Pilot-PSI in The Netherlands and JULE-PSI in Germany, in which the materials can be exposed to plasma fluxes and fluences that are reminiscent to those in ITER.

The stellarator as back up strategy

Undoubtedly, the tokamak has the simplest design of the relevant confinement devices. Because it also has the best performance, international research has largely concentrated on this line since the 1970's. Besides its scientific successes, the tokamak has a number of drawbacks. Firstly, it is a pulsed device due to the fact that the plasma current is induced by a transformer. Secondly, the tokamak is prone to current-driven instabilities and disruptions that necessitate active control tools for a stable operation, as outlined above.

There is a second magnetic confinement device in which the confining magnetic field is completely generated by external field coils: the stellarator. The stellarator is in principle net current free and, hence, the device is intrinsically more stable. But every advantage comes with a disadvantage: the design and construction of the stellarator is much more complex (see Fig. 3), and this is the main reason why it is generally lagging behind the tokamak.

Nevertheless, stellarator research has entered a new era: On 10 December 2015, the super-conducting Wendelstein 7-X device with its optimised magnetic configuration, located in Greifswald, Germany, and with a diameter of 16 m (see Fig. 5) has been taken into operation. Angela Merkel initiated on 3 February 2016 the first hydrogen plasma, which had already an electron temperature of 8 keV. Research in Wendelstein 7-X will show the viability of this concept and its potential for a future fusion power plant.

Concluding remarks

In this brief paper it has only been possible to describe a small fraction of the European research in nuclear fusion, and in doing that even only the tip of the iceberg could be discussed. There are still many scientific and technological challenges in fusion research, ranging from a very fundamental nature to more applied issues. More technical information is provided in the following papers of this special issue. Apart from that it is a very interesting and rewarding discipline to work in, it has the additional prospect that it is contributing towards a solution to the world energy and climate problem. ■

About the Author

Tony Donné is Programme Manager of the EUROfusion consortium, a position he has held since June 2014. He obtained his PhD degree (1985) at the Free University of Amsterdam. Most of his scientific career was devoted to research in the field of high-temperature plasma diagnostics. From 2009 – 2014 he was heading the fusion research department of the Dutch Institute for Fundamental Energy Research.

JET, THE LARGEST TOKAMAK ON THE EVE OF DT OPERATION

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[3] See the Appendix of F. Romanelli *et al.*, Proceedings of the 25th IAEA Fusion Energy Conference 2014, St. Petersburg, Russia

The Joint European Torus (JET) is the world's largest operating tokamak and the only such machine capable of operating with the fuel mixture (deuterium-tritium) foreseen for a fusion reactor. Since it came into operation in 1983, JET has explored fusion plasmas "in conditions and dimensions approaching those of a fusion reactor" [1]. JET has demonstrated world-record levels of fusion power and energy production, in conditions where the ratio of the fusion power generated to the input power to the plasma, *Q*, approaches unity.

For the last decade, the JET has been executing a Programme in Support of ITER, the next-step device presently being built in the south of France (see article by D. Campbell). The cornerstone of this programme is the test of the interaction between fusion plasmas and ITER-relevant plasma-facing components (PFCs). To date, the majority of fusion experiments have used carbon as the material in these components because of carbon's tolerance to overheating. Carbon machines can test the boundaries of plasma performance in the knowledge that overloading the PFCs will not lead to changes in the component geometry. Carbon, on the other hand, interacts chemically with the fusion fuel, leading to a large fuel retention rate in the machine. This must be avoided in a fusion reactor due to the need to breed tritium in the process and on safety grounds. Indeed, both JET and ITER have strict limits on the maximum amount of tritium that can be trapped in the PFCs.

Carrying out JET's programme has required upgrades to the facility, in particular the installation of the same combination of plasma-facing materials planned for ITER (fig.1). In order to reach the highest fusion performance, JET's heating, diagnostic, protection and control systems have also been enhanced. The programme's primary objective is presently to develop techniques in deuterium plasmas of safely delivering the increased heating power to JET whilst maximising the plasma energy confinement and thus the equivalent fusion power and whilst respecting the power and energy limits of the new metallic PFCs.

Whilst the operating parameters of JET are the closest to those foreseen for ITER, there remains a considerable extrapolation between the two devices. The JET programme thus incorporates a very strong element of theory and model validation in order to provide a sound basis for this extrapolation.

Once safe and reliable operation in deuterium has been established, the last phase of JET's present programme is to test the dependence of this operation on the mass of the fuel ions and to study and optimise deuterium-tritium plasmas with large amounts of generated fusion power. These experiments will provide a unique operational and scientific knowledge base in preparation for ITER.

In addition to the plasma physics studies, a dedicated DT technology programme is underway with projects in the areas of neutron diagnostics and radiation damage, neutronics and activation code validation, the tritium cycle, and nuclear safety.

Performance with the ITER wall material mix

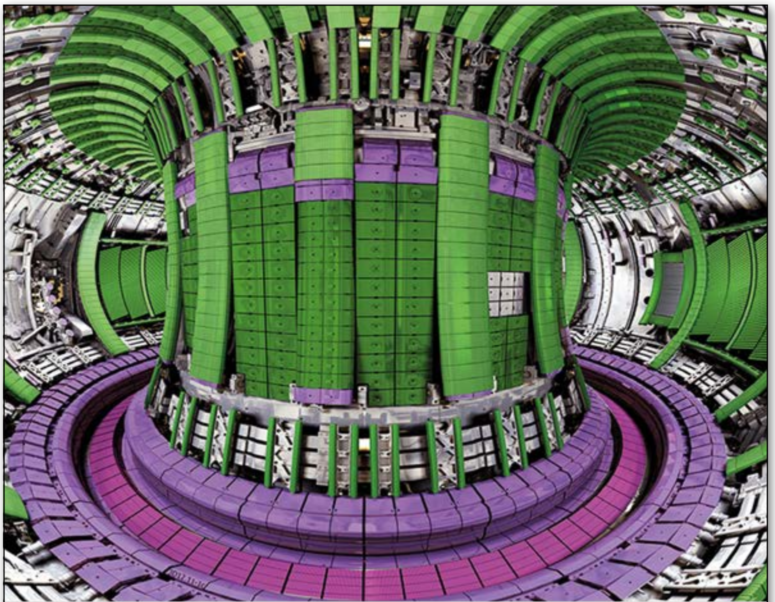
Tungsten has ideal characteristics for the divertor targets, which are subject to the highest heat and particle fluxes: it has a high threshold for sputtering by plasma particles, the highest melting point of any metal, and an acceptably low affinity for hydrogen, implying a low rate of fuel retention. While the first wall is typically subject to much lower particle fluxes than the divertor, it is exposed to higher energy particles escaping from the core plasma. Since beryllium is a low-Z material, beryllium atoms which penetrate the plasma after sputtering by these high-energy particles will contribute much less to plasma fuel dilution and plasma radiation than would tungsten. Beryllium's good thermal conductivity is also

advantageous in this application. Nevertheless, there is a residual risk of localised melting of both beryllium and tungsten under the high transient heat loads which can occur during sudden plasma events such as 'disruptions'. Adequate mitigation measures must therefore be in place to dissipate the plasma energy losses that can occur in such cases, and this is a major focus of current fusion plasma research.

The retention of hydrogen isotopes in JET has been measured both before the installation of the new wall, when JET's plasma-facing components were predominantly made of carbon, and with the new beryllium-tungsten components. The expected reduction in fuel retention of more than an order of magnitude has been confirmed, a very positive result for ITER. More importantly, the codes that describe the processes of wall erosion, material migration and re-deposition have been benchmarked on JET, also to the level of understanding the spatial pattern of these processes inside the machine. This has greatly increased confidence that the predictions of fuel retention being made for ITER are accurate.

With the change in wall material, it has been necessary to re-optimise the fusion plasmas in order to respect the tighter power and energy limits on the metallic PFCs and because of the potentially large impact of the new materials on the plasma energy confinement. A good example is the need to manage the source and transport of tungsten from the divertor to the hot fusion plasma. Accumulation of tungsten in the plasma core can lead to strong radiative losses that more than compensate for central heating and thus to hollow temperature profiles (fig.2). Control of the tungsten transport by the use of central heating can be used to avoid such accumulation and recover the high temperature conditions.

▾ **FIG. 1:** In any fusion experiment, managing the interaction between the hot plasma and the surrounding plasma-facing surfaces is crucial. The solution foreseen for ITER, a combination of beryllium in the main vacuum chamber near the hot fusion plasma and tungsten facing the lower temperature divertor plasma (at the bottom of the machine), is now being tested at JET. © CPS15.139-2C



Experiments with Tritium

Tritium affects the physics of fusion plasmas via its increased mass and, when used in combination with deuterium, via the production of high-energy alpha particles from the D-T fusion reaction. The fuel mass influences particle and energy transport due to the change in ion gyro-radius and is important also for heating schemes based on the ion cyclotron resonance (ICRH). Alpha particle production is ultimately the scheme that will be used in ITER to sustain the plasma temperature. Indeed, understanding the additional dynamics generated by such a self-sustained or burning plasmas is a key scientific objective for ITER. In JET, the power deposited in the plasma by fusion alphas will always be a small fraction of the total heating power and thus the alpha particle physics on JET focuses on single particle and threshold effects related to fast particle – wave interactions.

Integration and Performance Optimisation

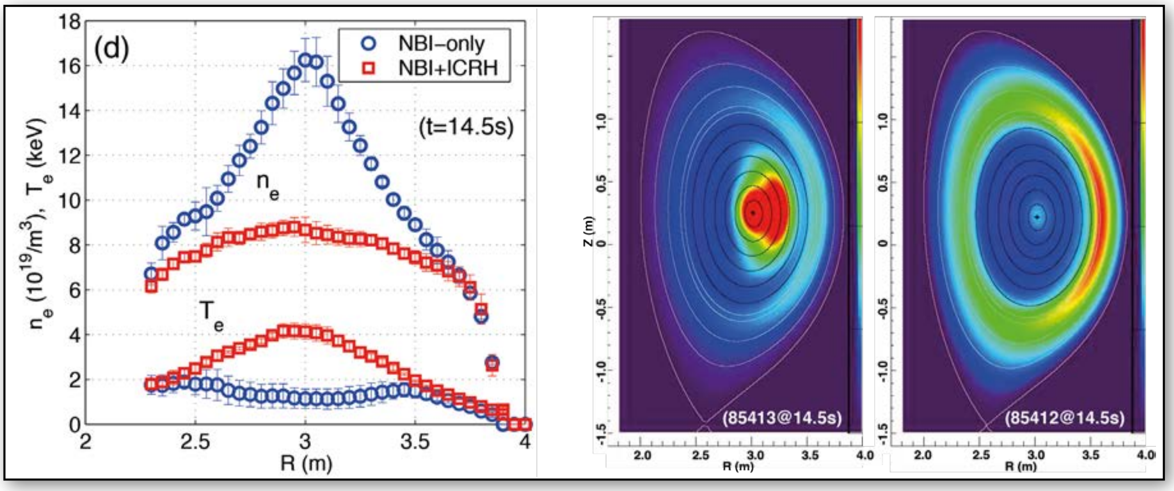
Two routes are being explored to bring JET to maximum fusion performance. The first relies on the fact that the energy confinement of the plasma increases with plasma current. By operating at the maximum possible plasma current, it was possible in the first high power DT experiment in 1997 to generate 4 MW of fusion power for the duration of the high power heating phase.

Since the experiments in 1997, it has been realised that operation at high plasma pressure can provide access to higher confinement and thus higher fusion performance for the same plasma current. This improvement with plasma pressure is then limited by the plasma stability. The second route to high fusion performance on JET relies on achieving the maximum safe plasma pressure at somewhat reduced plasma current.

Both routes to maximum fusion performance depend on applying the full available heating power and therefore on managing the exhaust of that level of power. Techniques including stability control and mitigation, seeding of extrinsic impurities to enhance edge radiation and sweeping of the areas of maximum plasma load across a wider region of the wall are being developed. The goal is to achieve fusion power well above the 4 MW reached in 1997. Obtaining standard confinement, as defined in the scaling laws used to design ITER, at JET's highest current is predicted to lead to a fusion power of about 10 MW. Matching or even bettering this target is the goal of the research into the high plasma pressure optimisation.

DT Technology Programme

The use of tritium and the production of large amounts of 14 MeV neutrons provide a unique opportunity to validate codes, assumptions, models, procedures and data currently used for ITER. An important example is the benchmarking of neutronics codes for the calculation of neutron streaming



◂ **FIG. 2:** Accumulation of tungsten in the centre of the fusion plasma can lead to large radiative losses (centre panel) central peaking of the plasma density and even inverted temperature profiles. The addition of central electron heating, in this case using ion cyclotron resonance heating (ICRH) can be used to control the tungsten transport in the plasma, avoiding the central radiation (right panel) so that the hot fusion conditions are recovered (from [2]).

through penetrations in the JET biological shield and for subsequent evaluation of the gamma dose rates in remote areas. Maps of the predicted neutron fluence generated by the planned high power DT experiment are given in fig.3. Measurements to validate these calculations are planned using a combination of activation foils and thermo-luminescent dosimeters. This validation will support the development of maintenance activities on ITER.

Conclusion

The planned extensive use of tritium in JET supports an important transition in the European fusion research programme towards the realisation of a nuclear tokamak and of fusion electricity on the grid [4]. It is an explicit strategic goal of the European fusion programme (see article by T. Donné) to train the scientists and engineers who will run ITER and JET plays a key role in achieving that goal.

The JET experiments are logically divided in two; a first Isotope Experiment in which plasma performance will be compared for all three hydrogen isotopes (protium, deuterium and tritium) and a subsequent Deuterium-Tritium Experiment in which high fusion yields will be produced and the physics associated with fusion alpha particles will be studied. On the present schedule the Isotope Experiment will take place in 2018-19 and the DT Experiment in 2019-20. Together and based on previous experimentation with JET's ITER-like Wall, these experiments allow optimisation of the ITER research plan and, in particular, for the transition from protium to deuterium to deuterium-tritium plasmas that will take place as ITER moves from commissioning to nuclear operation. ■

Acknowledgement

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About the Author

Lorne Horton is the JET Exploitation Manager, responsible for the implementation of the contract for the operation of the JET facilities on behalf of the European Commission and, in particular, for ensuring that JET operation meets the needs of the JET scientific programme defined by the EUROfusion consortium of EU fusion laboratories.

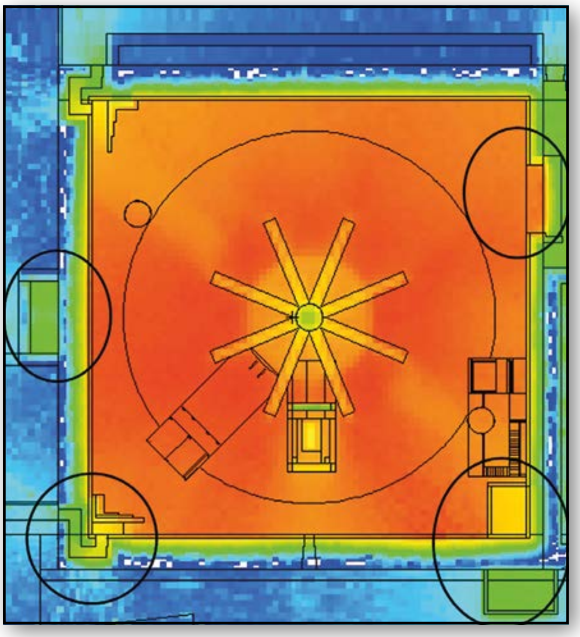
References

[1] The JET Project (Design Proposal), Report of the Commission of the European Communities, EUR 5516e, 1976.

[2] E. Lerche, M. Goniche, P. Jacquet, *et al.*, *Nucl. Fusion* **56**, 036022 (2016) (19pp).

[3] P. Batistoni, D. Campling, S. Conroy *et al.*, *Fusion Eng. Des.* **109-111**, 278 (2016) .

[4] F. Romanelli, P. Barabaschi, D. Borba, *et al.*, *A roadmap to the realisation of fusion energy*, EFDA Report, ISBN 978-3-00-040720-8 and https://www.euro-fusion.org/eurofusion/the-road-to-fusion-electricity/



◂ **FIG. 3:** Neutron fluence maps for the planned deuterium-tritium experiment, highlighting the areas in which neutron streaming through penetrations in the JET torus hall will be measured. Benchmarking these calculations with measurements will increase confidence in planning maintenance activities in ITER (from [3]).

THE FIRST FUSION REACTOR: ITER

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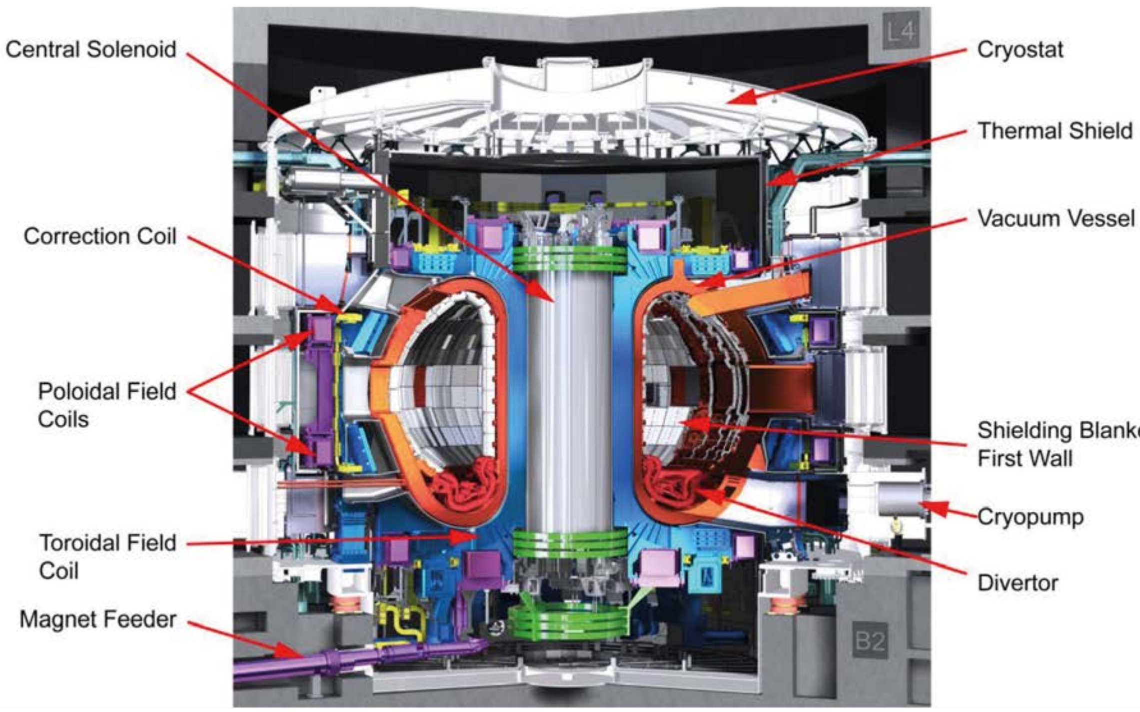
Established by the signature of the ITER Agreement in November 2006 and currently under construction at St Paul-lez-Durance in southern France, the ITER project [1,2] involves the European Union (including Switzerland), China, India, Japan, the Russian Federation, South Korea and the United States. ITER ('the way' in Latin) is a critical step in the development of fusion energy. Its role is to provide an integrated demonstration of the physics and technology required for a fusion power plant based on magnetic confinement.

In practical terms, the project's goal is to construct and operate a tokamak experiment which can confine a deuterium-tritium plasma in which the α-particle heating dominates all other forms of plasma heating. Formally, the primary mission of the ITER project is to demonstrate sustainment of a DT plasma producing ~500 MW of fusion power for durations of 300 - 500 s with a ratio of fusion output power to input heating power, Q, of at least 10. ITER is also designed to explore the physics basis for continuous operation of fusion power plants by investigating 'steady-state' plasma operation by means of non-inductive current drive for periods of up to several thousand seconds while maintaining a fusion gain, Q, of ~5. If plasma confinement characteristics are favourable, ITER would also be capable of exploring the 'controlled ignition' regime of tokamak operation (with Q ~ 30) in which power plant plasmas are expected to operate. The project's technical goals encompass significant technological demonstrations to prepare the design basis for a fusion power plant.

The unique nature of the ITER international collaboration is reflected in the scheme by which the components for the tokamak and auxiliary plant are being constructed. The ITER Organization (IO-CT) in France is responsible for design integration, procurement of components amounting to about 10% of the project's capital construction cost, management of the on-site installation of the tokamak and plant, and, ultimately,



▸ **FIG. 1:** Cutaway view of the ITER tokamak: the cryostat is about 29 m in diameter and 29 m high. © 2016, ITER Organization.

for the operation of the facility. The seven ITER partners have each established Domestic Agencies (IO-DAs) through which 90% of the facility's components are being procured 'in-kind' and supplied to the IO-CT for integration into the ITER facility.

ITER Design, Manufacturing and Construction

The engineering design for ITER has been developed around a long-pulse tokamak with an elongated plasma shape and a single-null poloidal divertor. The design has been validated by wide-ranging physics and engineering R&D: it is based on scientific understanding and extrapolations derived from extensive experimental studies in tokamaks in the international fusion research programme spanning several decades (*e.g.* [3]) and on the technical know-how flowing from the fusion technology R&D programmes in the ITER Members (*e.g.* [4]). A schematic of the ITER tokamak is shown in Fig. 1 and the principal parameters are listed in Table 1.

TABLE 1. MAIN PARAMETERS OF THE ITER TOKAMAK

Plasma current (I_p)	15 MA
Toroidal field (at R = 6.2 m)	5.3 T
Major/ minor radius (R / a)	6.2/ 2 m
Plasma elongation/ triangularity (κ / δ)	1.85/ 0.49
Installed auxiliary heating power	73 MW
Fusion power (at Q = 10)	500 MW
Pulse duration (at Q = 10)	~400 s

ITER is a superconducting device with several major magnet systems [5]: the 18 toroidal field (TF) coils and 6 central solenoid (CS) modules are fabricated from Nb_3Sn superconductor due to the high fields required, *e.g.* 13 T in the centre of the CS. The 6 poloidal field (PF) magnets use NbTi superconductor, as do the 18 correction coils (CC). The international collaboration formed around the production of superconducting magnets for the ITER tokamak has produced over 600 t of Nb_3Sn (increasing annual world production by approximately a factor of 10) and almost 250 t of NbTi superconducting strand. Over 80% of the superconductors required for the ITER magnets are now complete, and coil fabrication activities are underway in 6 of the 7 partners' factories (*e.g.*, Fig. 2(a)). Series production of the high temperature superconducting current leads will be launched during 2016. Operation of the magnet systems, which are cooled by supercritical helium, will be supported by the world's largest single-platform cryogenic plant.

Fabrication of the vacuum vessel, a double-walled stainless-steel toroidal chamber with an outside diameter of ~19.5 m and a height of ~11.5 m, is advancing, with structures being produced under the responsibility of four Domestic Agencies (*e.g.*, Fig. 2(b)). The first elements of the cryostat (~29 m diameter × ~29 m height – the largest stainless-steel high vacuum pressure vessel in existence when complete) have been delivered to the ITER site. In-vessel components such as the stainless-steel divertor cassettes (54 make up the entire divertor structure), stainless-steel shielding blanket modules (440 cover almost the entire first wall) and the associated (tungsten) divertor and (beryllium) first wall plasma facing components (PFCs) are undergoing prototyping and, in the case of the PFCs, high heat flux testing to their rated performance.

ITER will be equipped with a significant heating and current drive (H&CD) capability. This will consist initially of 33 MW of (negative ion based) neutral beam injection using 1 MeV deuterium, 20 MW of electron cyclotron resonance heating operating at 170 GHz, and 20 MW of ion cyclotron radiofrequency heating operating in the range 40-55 MHz. These systems are required for plasma initiation, heating of the plasma to temperatures at which fusion reactions can be initiated, controlling the fusion burn, provision of a substantial fraction of the non-inductive current drive for steady-state operation, control of the plasma current profile to avoid magnetohydrodynamic (MHD) instabilities and direct suppression of growing plasma instabilities. An extensive diagnostic capability consisting of about 50 large-scale systems will provide plasma measurements for control, investment protection and physics studies of burning plasmas, while a sophisticated control, data acquisition and command system will support all aspects of facility operation and protection.

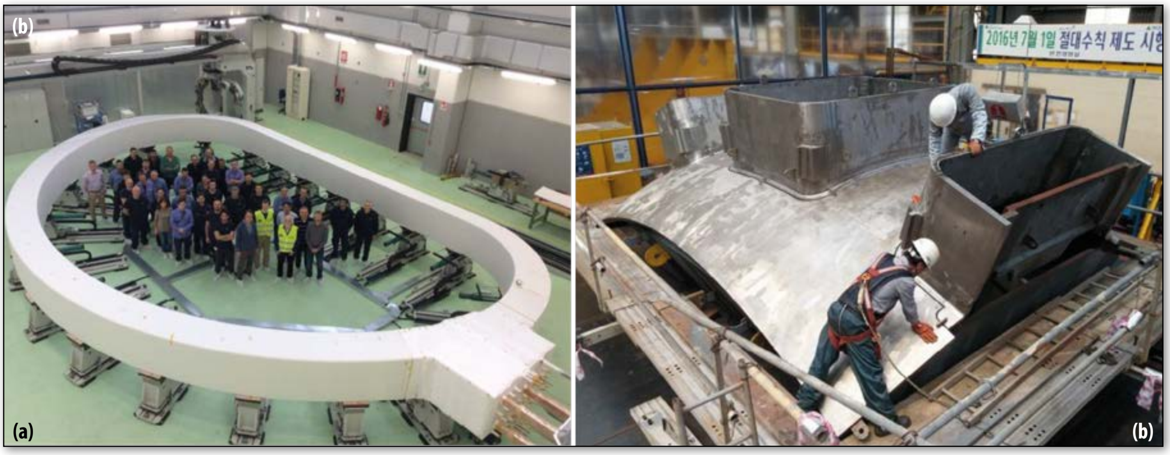
On-site construction of the ITER facility is advancing rapidly, as illustrated in Fig. 3.

Physics challenges for burning plasma studies in ITER

Successful operation of ITER will open new frontiers in fusion research involving the influence of a significant α-particle population on plasma heating, transport processes and stability. Moreover, to sustain high fusion power, it will be critical to control the exhaust of power and particles from the plasma to prevent overheating of plasma facing surfaces.

ITER operation will evolve through several stages (*e.g.* [6]): a period of hydrogen and helium operation will be used to commission all tokamak and auxiliary systems; this will be followed by a short period of deuterium operation to approach thermonuclear conditions more closely and to phase gradually into full DT operation, which will then provide access to significant levels of fusion power and α-particle heating.

Three 'design basis' scenarios have been assembled from the physics basis developed by the international fusion research community in recent decades. These reference scenarios provided a conceptual basis for the ITER design and form idealized targets for the various



▸ **FIG. 2: (a)** The first complete TF coil winding pack in the manufacturer's factory, fabricated from Nb_3Sn superconductor, with overall dimensions of 13.8 m × 8.7 m. © F4E, 2016; **(b)** An outer equatorial segment (40° toroidal, inner shell) of the ITER stainless-steel vacuum vessel with 3 port plug stubs under manufacture. © ITER Korea, 2016.

modes of plasma operation which will be explored in ITER. Their basic parameters are summarized in Table 2.

The inductive scenario is expected to provide the simplest route towards the achievement of high fusion power and to allow the first studies of substantial α-particle heating. The 'hybrid' scenario provides a relatively simple basis for technology testing under long-pulse stationary conditions.

Fully non-inductive operation is an altogether more complex plasma regime in which the total plasma current is driven by a combination of auxiliary heating systems and internal processes (bootstrap current). While the basic principles of operation in this regime have been understood for the past 20 years, and experimental demonstrations of candidate modes of operation have been made for periods of several seconds, considerable research is required, both in existing devices and, eventually, in ITER, to establish an operational mode in which all requirements of plasma confinement and stability are satisfied.

Like JET and all relevant fusion devices, ITER will also be equipped with a divertor, located in the lower region of the vacuum vessel. The material and geometry of the divertor surfaces are designed to handle high heat fluxes while allowing extraction of helium 'ash' produced by DT fusion reactions. The operational functions of the divertor are well-established in existing experiments, but the critical step that ITER will make is to integrate this power-handling strategy with a burning plasma core in such a way that the core and edge plasmas perform as intended, in benign coexistence.

Table 2. Key parameters of ITER reference scenarios

	Inductive	Hybrid	Non-inductive
Plasma current (MA)	15	13.8	9
Energy confinement time, τ_E (s)	3.4 [1]	2.7 [1]	3.1 [2]
Fusion power (MW)	500	400	360
Q	10	5.4	6
Burn duration (s)	300 – 500	>1000	~3000

[1] scaled from present experiments, [2] required to achieve $Q \geq 5$

A key aspect of this solution to the power and particle exhaust challenge is the choice of plasma facing materials. Two metals, beryllium and tungsten, have been chosen, with the former lining the first wall of the main plasma chamber and the latter covering the divertor surfaces. This material combination has been tested on JET in the frame of the ITER-like wall (see article by L. Horton).

Fusion Technology at ITER

The development and testing of key 'fusion' technologies required for construction of a fusion power plant is a principal mission goal of the ITER project. A significant element of this research is the Test Blanket Module (TBM) Programme [7], which will involve the construction and testing, by exposure to ITER plasmas, of 6 different concepts of tritium breeding module. The breeding of tritium, by reactions between neutrons emitted from the plasma and lithium contained in either ceramics or (Li-Pb) eutectics within blanket modules lining the reactor wall, is fundamental to the fuel cycle in a fusion power plant burning deuterium and tritium. While ITER can be fuelled by tritium from external sources in the fission programme, it is designed to conduct the first tests of concepts for tritium breeding which could be applied in a DEMO reactor.

The primary research goal will be to confirm the rate at which tritium can be produced: in DEMO, the 'tritium breeding ratio', defined as the ratio at which tritium is bred against the tritium burn rate, must certainly exceed unity. ITER tests will allow the first studies of the tritium production and extraction rates which can be achieved in a practical design.

Once ITER makes the transition to routine DT operation, the fusion power level, burn duration and duty cycle required will necessitate real-time reprocessing of the tokamak exhaust gas stream to provide DT fuel at an adequate rate to sustain the planned experimental programme. While a significant quantity of tritium can be stored on the ITER site, this inventory will be recycled, resulting in as much as 25 times this amount of tritium being reprocessed annually to maintain the ITER experimental programme at the required performance level. This will require a tritium

processing plant of unprecedented scale, and its operation will establish the technical basis for tritium reprocessing in fusion power plants.

The development and application of remote handling technology for ITER will also provide a substantial basis for the future application of this technology in the fusion environment. Soon after the transition to DT operation, activation of the ITER tokamak due to the interaction of 14 MeV neutrons with the reactor structure will require that all maintenance, repair and upgrade work in the tokamak core be carried out using remote handling methods.

A final significant facet of the ITER nuclear R&D programme, and a key ITER mission, will be the demonstration of the environmental and safety advantages of fusion energy. After the submission of the formal application documents and an extensive interaction between the ITER Organization and the French nuclear regulatory authorities, the French Government granted the Decree of Authorization of a nuclear facility to the ITER Organization in November 2012. ITER is now established as Basic Nuclear Installation 174 (INB-174) within the French regulatory framework.

Towards ITER Operation

Construction of the ITER facility is now moving forward rapidly and the ITER partners have recently agreed to work together towards a First Plasma date of December 2025. DT operation is expected to begin about 10 years later. The research programme under development will establish the major lines of research within the ITER experimental plan in order to optimize the fusion performance of the device and to exploit the opportunities which ITER offers for studies in burning plasma research at the reactor scale. ■

Acknowledgments

This report represents the work of the staff of the ITER Organization, the Domestic Agencies and many collaborators in the Members' fusion communities. The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.

About the Author

David Campbell spent 14 years at JET, Europe's major fusion experiment, followed by 10 years leading the EU's physics and plasma engineering R&D activities for ITER. He joined the ITER Organization in 2007 and is currently Director of the Science and Operations Department, which is responsible for developing the ITER facility's central control systems, for conducting the project's fusion physics research and for preparing the framework for ITER operations.

References

[1] ITER Technical Basis, *ITER EDA Documentation Series No. 24*, IAEA, Vienna (2002).

[2] O. Motojima, *Nucl. Fusion* **55**, 104023 (2015).

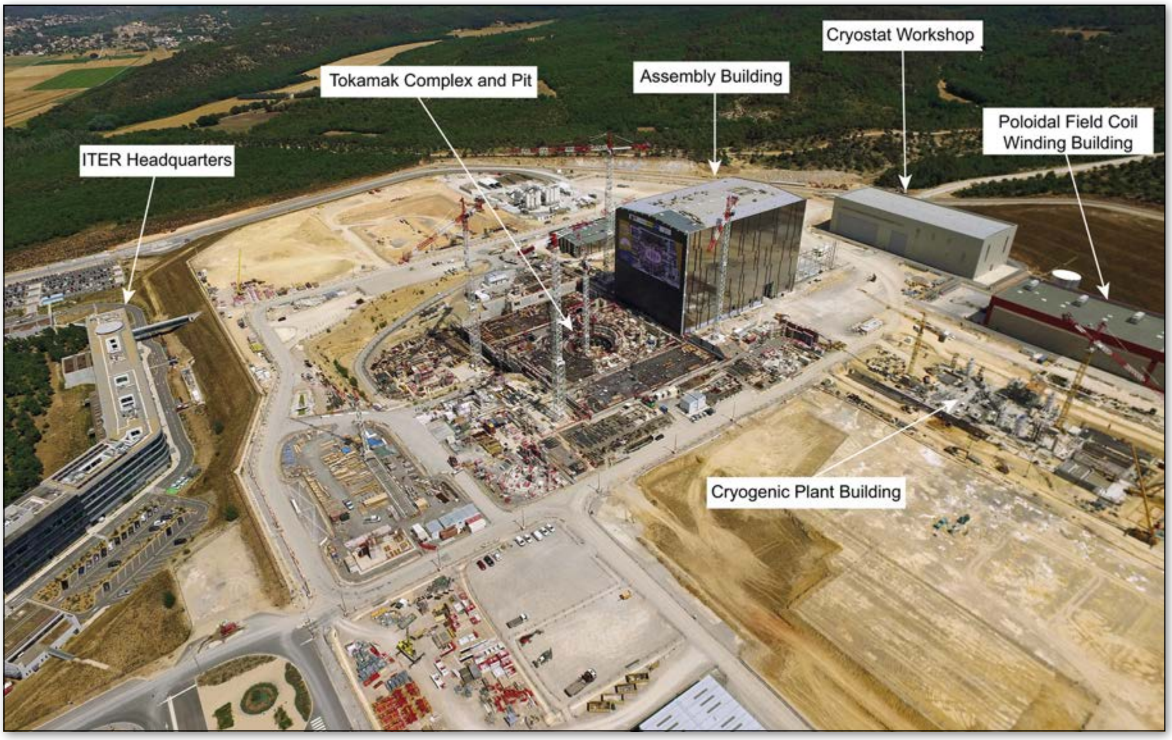
[3] Progress in the ITER Physics Basis, ITPA Topical Groups *et al.*, *Nucl. Fusion* **47**, S1 (2007).

[4] ITER Technology R&D, ITER Joint Central Team and Home Teams, *Fusion Eng. Des.* **55**, 97 (2001).

[5] N. Mitchell *et al.*, *IEEE Trans. App. Supercond.* **22(3)** (2012).

[6] D.J. Campbell *et al.*, paper ITR/P1-18, Proc. 24th IAEA Fusion Energy Conf., San Diego, (2012).

[7] L.M. Giancarli *et al.*, *Fusion Eng. Des.* **109–111**, 1491 (2016).



◂ **FIG. 3:** Aerial view of the ITER site showing the current status of facility construction. The Tokamak Pit, defined by the cylindrical bioshield (inner diameter ~30 m) visible in the centre of the Tokamak Complex, hosts the ITER tokamak shown in Fig. 1. © E. Riche / ITER Organization, July 2016.

FUSION AS A FUTURE ENERGY SOURCE

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Fusion remains the main source of energy generation in the Universe and is indirectly the origin of nearly all terrestrial energy (including fossil fuels) but it is the only fundamental energy source not used directly on Earth. Here we look at the characteristics of Earth-based fusion power, how it might contribute to future energy supply and what that tells us about the future direction of the R&D programme. The focus here is Magnetic Confinement Fusion although many of the points apply equally to inertial confinement fusion.

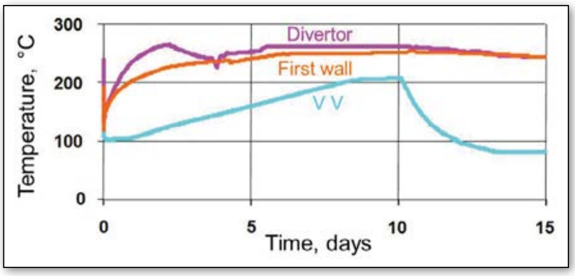
Fusion Characteristics as an Energy Source

Resources

The potential energy resource from fusion is enormous, primarily because the energy produced per unit mass of fuel is so large, and this is the principal reason why fusion R&D has been pursued. If we were able to harness energy simply from the fusion of two deuterium atoms (D-D fusion), which is possible in theory but difficult in practise, we could supply mankind's energy needs for billions of years. At present, however, we have a much less ambitious target, the fusion of deuterium with tritium (D-T fusion), which is roughly 100 times higher in cross-section. As tritium decays with a half-life of 12.3 years, it is not abundant on Earth so the plan is for a fusion power plant to be self-sufficient in tritium, using the neutrons which result from the fusion reaction to convert lithium into tritium. With present estimated fuel reserves of lithium, there is enough to provide mankind's energy needs for thousands of years, by which time we may have solved the problem of D-D fusion.

Designing a fusion plant to be self-sufficient in tritium is not a trivial problem. Although simply surrounding a fusion neutron source with natural lithium can, in theory, produce up to 70% more tritium than required, the practical reality is more difficult [1]. There needs to be a box structure to contain the lithium compound, there needs to be coolant flowing to take away the large amounts of energy deposited by the neutrons and we want to restrict the thickness of the structure to minimise the size of the containing magnets. In existing designs, changing the isotopic mix of the lithium and including a neutron multiplier such as beryllium or lead are used as tools to produce an optimised design, but this is far from complete and demonstrated. Tests of these fusion blankets are proposed for the ITER device.

One aspect of tritium supply will relate to the growth phase of fusion power. To start up a new power plant, an initial inventory of tritium is required and this will have to come either from another fusion plant or from a fission plant. Particularly in the early implementation phase, it is important to minimise the inventory of tritium needed to start up a new plant whilst ensuring sufficient tritium is available.



▸ FIG. 1: Calculated temperatures in ITER components in the event of a full loss of cooling water, taken from [6] (the curve marked VV illustrates the temperature at the Vacuum Vessel).

Waste

One of the differentiating factors of fusion when compared to fission is the waste products. Unlike fission, fusion reactions do not produce radioactive waste directly but the neutrons can cause radioactivity in the surrounding materials – hence the emphasis on developing and testing of low activation materials, those that do not generate long-lived radioactive waste [2]. The same happens in fission plants of course but there the structural activation is a very small part of the waste produced – in fusion it is the dominant part. One goal of the fusion R&D programme is to optimise the use of materials, for instance to minimise the need for repository storage, perhaps to zero, but this is not guaranteed. Optimising material properties is a key, and somewhat neglected area, and would be substantially advanced by a major materials test programme, including a source of fusion relevant, 14 MeV neutrons, such as the proposed IFMIF [3], as this is not an area of particular focus for ITER.

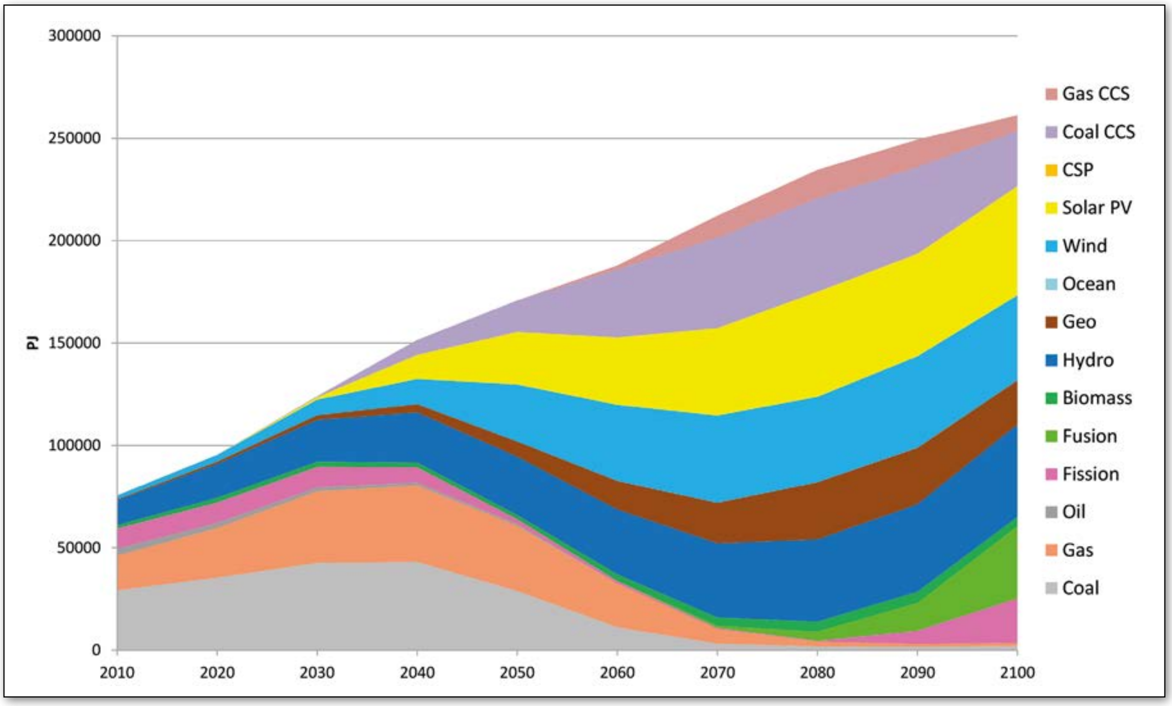


FIG. 2: Example of an exploration of how future electricity demand may be met, in a future of reduced carbon emissions. Taken from [8].

Emissions

Apart from the large potential resource the main benefit of fusion as foreseen is the lack of carbon emissions. Because it does not rely on combustion of fuels, fusion is intrinsically a low carbon energy source and the atmospheric emissions of other pollutants such as particulates, NO_x etc are also low. Evaluating the externalities of different energy sources, including fusion, leads to the conclusion that combustion-based technologies generally have the highest externalities and that the external costs of fusion are low, primarily because of low atmospheric emissions [4,5].

Safety

One aspect of fusion plant design that is considered more important than others, when optimising design, is safety. Because of the low energy available to drive an accident and the low hazard to be released in the event of an accident, fusion plants are proposed as passively safe, that is they should not cause substantial damage even if all active safety systems fail (for instance see Fig. 1). In generic studies, the objective has been to design a plant in which no design-basis accident requires the evacuation of the local population. In working with specific devices in specific locations this has to be refined to the local conditions, for instance a lot of work has been done on the safety of ITER [6]. As with tritium production, this is an active area of research for future power plants, informed by the ongoing work for the design and construction of ITER.

Costs

An area of substantial uncertainty relates to future costs of fusion power plants. Given the incomplete information for designing a power plant it is difficult to be precise about costs, although the main cost items are already known, particularly buildings, magnets and conventional equipment. In the conceptual designs that have been investigated in the past targets such as generating electricity at less than 0.1€/kWh have been used as a guide [4]. There are two particular uncertainties presently: information emerging from ITER is providing extra information on the costs of fusion, and the assumptions about plant availability in spite of needing to regularly change components in a power plant are known to be challenging. At the same time the future costs of other energy systems are also very uncertain so it is difficult to be conclusive in cost assessments – nonetheless, cost should be a strong influencing factor in design optimisation. Again, ITER is providing key information in this area.

Fusion in the Future Energy Market

In discussing fusion's role in a future energy market there are a number of key questions:

- How large will future demand for energy, particularly low carbon energy, be?
- Will fusion be available, when and at what cost relative to other low carbon sources?
- How will public acceptance of different energy technologies evolve and will that increase or reduce fusion's potential role?

The course appears to be set for emerging economies to become significant users of energy, substantially larger than present demand in developed economies; at present the pressure for this to come from low carbon sources is strong and increasing. This presents a future of dramatically increasing challenge; meeting carbon emissions targets in 2030 for instance does little to contribute to meeting targets foreseen for 2070, by which time global energy demand may have doubled again but allowable emissions fallen by another factor of 4.

The route to fusion power was originally addressed in the 1970's, at which point the work needed to achieve fusion as an energy source was mapped out and the cost of doing that work estimated. In present money that would exceed $50B [7]. JET has used about 2% of the resources that were identified as necessary at that time; ITER is likely to take us around 30-40% of the remaining way. The additional work is focussed on materials and technology testing leading to the construction of a demonstration (DEMO) device.

In costs, superconducting magnets are very expensive today but costs will fall. Fusion has strong economies of scale so larger plants are expected to be more cost competitive. The comparators for fusion may be advanced fission, solar with energy storage and coal with (improved) Carbon Capture and Storage, but such comparisons cannot be made reliably today. Given that developing a new energy source, fusion, as a low carbon energy option can be done with a tiny fraction of the resources needed to transform global energy systems to low carbon (at less than 0.1% of investment in other energy systems over the same period) it would be imprudent to stop that development on the basis of cost alone.

The influence of future public opinion is difficult to predict. In some world regions the present view of risks from radiation is very distorted when compared to other, much larger, risks to human health such as air pollution or transport accidents, and if this continues, in some world regions at least, then advanced nuclear fission plants may be disfavoured and fusion more likely to play a role. This is something that must continue to be an important consideration in the fusion R&D programme, influencing the work to optimise a fusion plant in terms of cost, safety, emissions and waste.

An evolving energy system

We have seen how the different properties of fusion make for a complex optimisation when designing a power plant and how the present programme, particularly ITER, contributes to exploring this. This same complexity extends to designing an optimised energy supply system and the role that fusion can play within it.

There is a big question around the speed with which an energy system can be changed. If a new energy technology became available in 2050, for instance, how long would it be before it could be a major player on the future energy scene [8,9]? A limit to the growth rate of a new technology may be as high as 25% per year or as low as 10% and this could have a significant impact on the introduction of fusion. Assuming that a target of 1TW installed power is needed for a significant contribution to future energy supply, then the initial scale of introduction and the growth rate determine how quickly this could be achieved. If 20 countries each introduced a 1GW plant in 2050 (and there were enough tritium to start them up) then a growth to 1TW would take between 17 and 40 years, depending on the growth rate. Although this is not a major issue today, it is an example of how consideration of the "market pull" can feedback to plant requirements, design and hence the R&D programme. Figure 2 shows an example of attempts to look at future energy scenarios, including fusion, particularly as fusion goes through a growth phase.

Impact on the R&D Programme

Producing an optimised working fusion power station is the goal of the European fusion R&D programme. Optimisation includes designing for cost, availability, safety, emissions, waste, growth rate *etc.* and is a non-trivial problem, not least because the different areas can pull in different directions and because the energy systems in which fusion will be embedded differ around the world. As the R&D moves away from physics towards technology, these new areas become increasingly important and a new skill set is required; fusion is moving out of the laboratory and the expertise contained within the R&D programme must develop accordingly. ■

About the Author

David Ward has worked in fusion since the first JET plasma and had strong involvement in the first JET deuterium-tritium experiments, in which more than 1MW of controlled fusion power was first produced on Earth, and the later experiments in which up to 16 MW of fusion power was produced. After many years of working on both theory and experiment, David took on the role of leading the JET work carried out to help in the design of the ITER. From there the transition to technical work and a management role in systems studies for power plants, in particular DEMO, was a natural step.

The work in integrated design of a conceptual power plant includes determining the expected properties of fusion as a power source with a natural link to other energy systems and the likely role of fusion in a future energy market. This has involved collaborations with other energy researchers, outside fusion and also led to David's selection as the EUROfusion Project Leader for fusion Socio-Economic studies.

References

[1] L. El Guebaly et al, *Fus. Eng. Des.* **84**, 2072 (2009).

[2] S. J. Zinkle, *Fus. Eng. Des.* **74**, 31 (2005).

[3] J. Knaster *et al.*, *Nuc. Mats. Energy*, Online May 2016.

[4] D. Maisonnier. et al, *Nuclear Fusion* **47**, 1524 (2007).

[5] D.J. Ward, *Fus. Eng. Des.* **82**, 528 (2007).

[6] N. Taylor et al, *Fus. Eng. Des.* **87**, 476 (2012).

[7] US Energy Research and Development Administration Report (1976) ERDA-76/110 (later published in Dean, *J. Fusion Energy* **17**, 263 (1998))

[8] H. Cabal *et al.*, submitted to *Energy Strategy Reviews*.

[9] K. Vaillancourt *et al.*, *Energy Policy* **36**, 2296 (2008).

A NEWCOMER: THE WENDELSTEIN 7-X STELLARATOR

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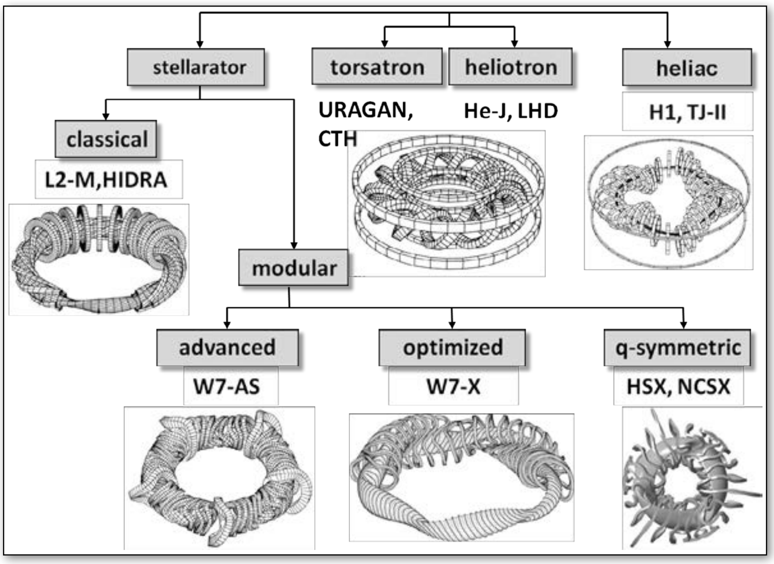
Stellarators ("star generators") belong to the earliest concepts for magnetic confinement of fusion plasmas. In May 1951, a confidential report authored by Lyman Spitzer at the Princeton Plasma Physics Laboratory (PPPL) was issued, in which he proposed the "figure eight" stellarator based on the idea to generate the required rotational transform of magnetic field lines by twisting the torus into a figure-8. The first experimental device based on this idea started operation in early 1953. In the 1950's a series of stellarator experiments were built, most of them at PPPL.

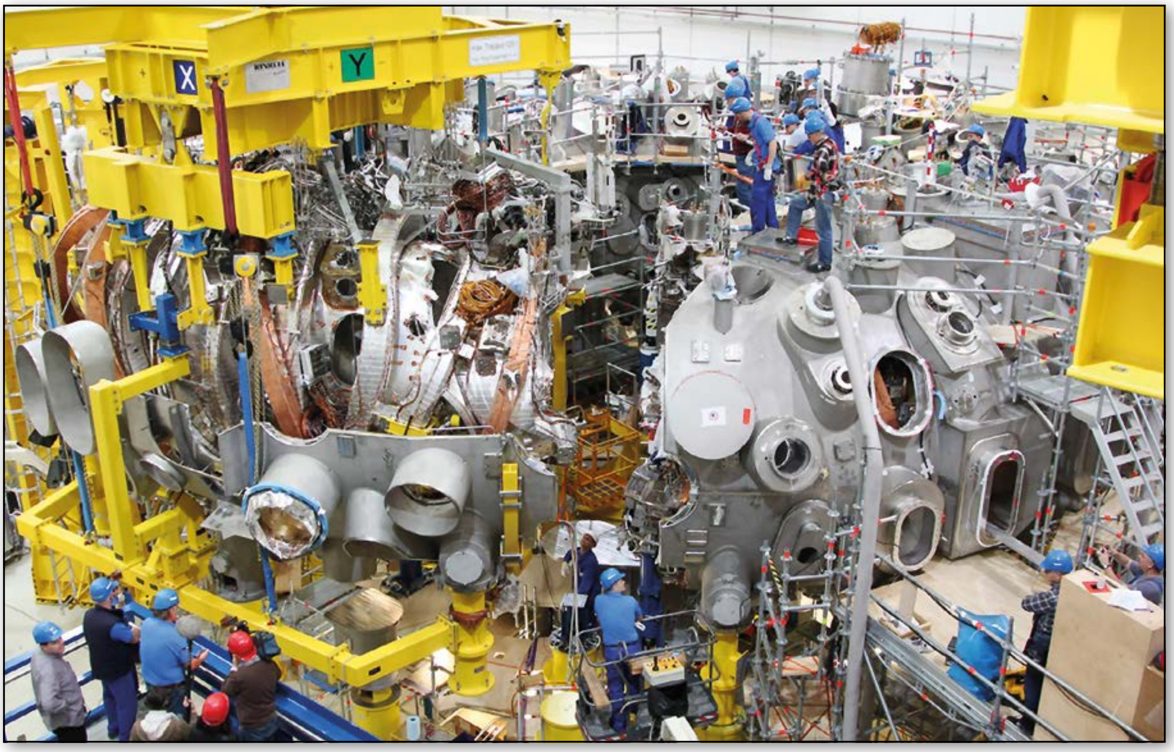
This development has led to the large "Model-C" stellarator, operated at PPPL from 1961-1969 until it was converted into the "Symmetric Tokamak" in 1970, after breakthrough results reported from Russian tokamaks in 1968. The first "Wendelstein" stellarator, the "1-A" went into operation in 1960 at the Max-Planck Institute for Physics and Astrophysics. It was followed by a series of uninterrupted developments until now, when the large, superconducting stellarator "Wendelstein 7-X" (in short W7-X) went into operation. In that sense, stellarators are not "newcomers", but the trust in the concept has undergone a number of ups and downs and W7-X intends to make a major contribution to bring stellarators to maturity.

Stellarators and optimisation

The fundamental idea of stellarators is to generate rotational transform – the twist of the magnetic field - to a major extend by external coils [1]. This is different from the tokamak concept, where the poloidal component of the magnetic field is generated by a strong current running in the plasma (see article by T. Donné). This difference has major consequences: The stellarator magnetic field is very much "frozen-in" by the external coils, whereas the tokamak field is strongly defined by the particular plasma scenario with the associated radial current distribution. Furthermore, a current-carrying plasma tends to be less stable than a current-less plasma and steady-state operation is more difficult in a tokamak because of the need for efficient non-inductive current drive. There is a lot of freedom in the choice of external coils for generating a stellarator magnetic field. Consequently, there is a whole "family" of coil configurations [2] with the main lines being (a) stellarators, (b) heliotrons/torsatrons, (c) heliacs (see Fig. 1). Indicated are also the experimental devices, smaller ones for addressing more basic plasma physics questions and bigger ones with direct relevance for reactor extrapolation. The classical stellarator combines planar coils to generate a toroidal magnetic field and sets of helical coils with counter-directed currents to create rotational transform. Torsatrons and heliotrons use helical coils with co-directed currents to produce a twisted toroidal magnetic field. A vertical magnetic field is generated as well and must be compensated with additional vertical field coils. In contrast to stellarators and heliotrons/torsatrons, the magnetic axis in a heliac follows a helical path to form a toroidal helix with twisted magnetic field lines. The vertical positions of the planar toroidal field coils follow the helical path and a central conductor further enhances the twisting of the toroidal magnetic field. Again, vertical magnetic field coils are required for compensation.

▼FIG. 1: Overview diagram of helical magnetic confinement concepts and the associated devices. The stellarator line has split up into different branches after the concept of modular coils was introduced.





▸ FIG. 2: View into the torus hall during assembly. Tools for stiffening and handling have a yellow colour. Clearly seen on the left is the (last) magnet module that is inserted into the torus.

A different approach is based on modular three-dimensionally shaped magnetic field coils. These coils allow shaping the magnetic field within a wider range, based on specific physics criteria. This iterative process is called "optimization" and the magnetic field of the modular stellarator Wendelstein 7-X was shaped to satisfy the following criteria [3]:

1. nested magnetic flux surfaces with sufficiently small magnetic islands
2. good plasma equilibrium at high average beta ≅ 4%[1]
3. good magnetohydrodynamic stability at average beta ≅ 4%
4. small neoclassical transport in the relevant collisionless regime
5. minimized bootstrap current in the relevant collisionless regime
6. improved confinement of fast particles
7. feasible modular magnetic field coils

The predecessor device of Wendelstein 7-X, the Wendelstein 7-AS, was only partially optimized and is denoted as "advanced" in comparison to classical stellarators. Wendelstein 7-AS has already shown improved plasma properties due to physics-based shaping of the magnetic field. Another sub-group are the quasisymmetric stellarators, *i.e.*, non-axisymmetric configurations in which the magnetic field strength depends only on one angular coordinate within the magnetic flux surfaces. Quasisymmetric stellarators meet optimization criteria as well but not necessarily the same as above. The three types of quasi-symmetry are: quasi-helical, quasi-poloidal, and quasi-axisymmetric. It should be emphasized that optimization of the magnetic field is a promising path to bring stellarators to maturity, *i.e.*, to allow for integrated high-performance plasma scenarios that are comparable to those of tokamaks of the same plasma volume.

The construction of Wendelstein 7-X in brief

The project Wendelstein 7-X was officially started in 1996. The initial phase of the project was dominated by design, specification and tendering of the major components of the device, *i.e.* about 60 km length of niobium-titanium superconductor, the 80 m^3 volume and 33 t heavy plasma vessel, the 525 m^3 volume and 170 t heavy outer vessel, the 254 ports, the 72 t heavy central support ring, and the manufacturing of the 20 planar and 50 non-planar superconducting coils. At the same time, the development of 10 gyrotrons with 140 GHz frequency and 1 MW output power for 30 min duration was started. The assembly of the device started in 2004 and was completed 10 years later, with more than one million assembly hours spent. The assembly work was challenging because of (a) three-dimensional geometry and high precision requirements, (b) difficult access situations especially in the cryostat and for the in-vessel components, and (c) the extremely crowded space situation in the torus hall. This leads to unusually high work density and strong sensitivity against perturbations in the work flow. Intense project management on the daily level was required, based on strict industry-proven rules and well defined processes, in particular systematic quality management, change management, and risk management.

[1] <β> is the average ratio of plasma pressure to external magnetic field pressure

The assembly can be described in 17 major assembly steps (roughly in sequence): (1) Assembly of the thermal insulation on a half-module of the plasma vessel, (2) threatening of five non-planar and two planar superconducting coils over the plasma vessel half-module, (3) bolting the coils to a segment of the central support ring, (4) welding of the additional inter-coil support elements, (5) joining two pre-assembled magnet half-modules to a module, (6) installation of the superconducting bus bars and the joints to interconnect the coils, (7) installation and welding of the helium distribution pipework, (8) assembly of the thermal insulation on the inner side of the outer vessel module, (9) insertation of the magnet module into the lower half-shell, (10) installation of the vertical supports and cryo feet, (11) welding of the outer vessel upper half-shell on the lower-half shell, (12) assembly of the thermal insulation on the ports, (13) installation of the 254 ports and their welding on the plasma vessel and the outer vessel, (14) joining the 5 modules by bolting the central ring modules, welding the vessels and connecting the pipes and bus bars, (15) assembly of the 14 current leads, (16) assembly of the in-vessel components, (17) assembly of the device periphery. Fig. 2 shows a view into the torus hall during the installation of the last of the five pre-assembled magnet modules.

The island divertor concept

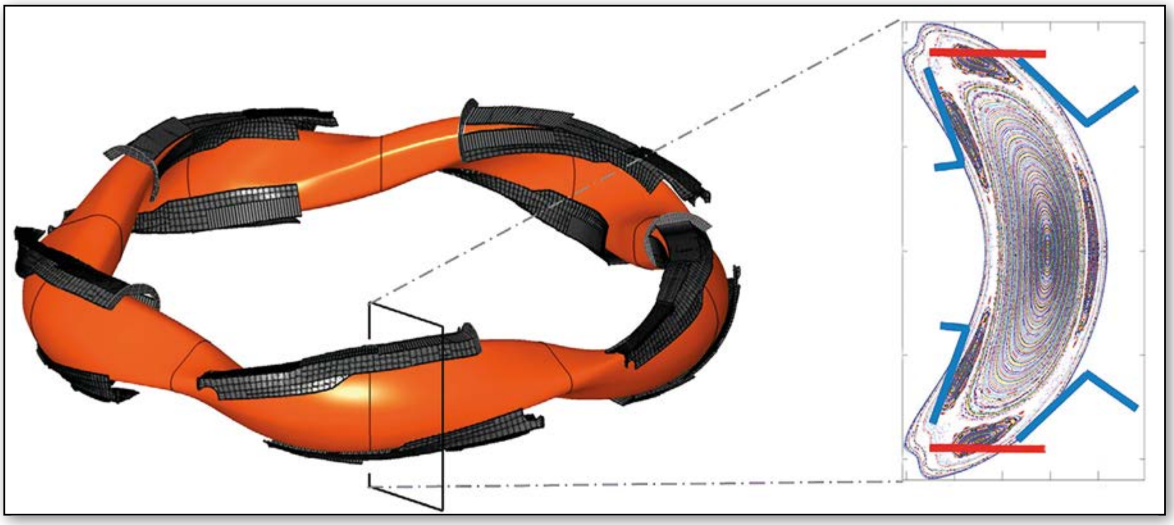
For the development of the stellarator reactor line, it is of utmost importance to qualify a viable divertor concept. Different from a tokamak, the divertor in a stellarator cannot be toroidally symmetric. One approach is a divertor with helical shape as installed in the heliotron "Large Helical Device" in Japan. For the Wendelstein 7-X optimized stellarator a different solution was found, the island divertor (Fig. 3).

The magnetic field of Wendelstein 7-X is five-fold periodic with a strong variation of the cross-section from triangular to bean-shape and exhibits natural magnetic islands at the edge where the rotational transform has a resonance[2] close to unity. On each magnetic field period, one pair of island divertor modules is installed where the cross-section of the magnetic field is predominately bean shaped. The natural magnetic islands intersect the target and partially baffle plates. In this way, a well-defined flow of particles from the plasma edge (outside the confinement volume) to the wall is ensured and the interaction between the plasma and the wall is decoupled from the core plasma region. The target plates of the island divertor have to withstand a heat flux of up to 10 MW/m^2, which is close to the technical limits, especially under steady-state conditions. Wendelstein 7-X follows a staged approach with inertially cooled limiters in the first stage of operation, an inertially cooled divertor in the second stage, and a water-cooled divertor in the third stage. In addition to the divertor and the baffles, the remaining wall surfaces are covered either with water-cooled steel panels (surface area 62 m^2) or with water-cooled graphite heat shields (surface area 47 m^2). The steady-state operation requirements of Wendelstein 7-X imply that there is no uncooled plasma facing component allowed, which means considerable efforts in design, engineering and assembly.

First results from Wendelstein 7-X operation

The assembly of Wendelstein 7-X was officially completed on 20th of May 2014. The commissioning process of the device consisted of six major steps, *i.e.*, (1) pump-down of the cryostat volume to high-vacuum conditions, (2) cool-down of the magnet system to 3.4 K, (3) test of all normal-conducting control and trim coils, (4) pump-down of the plasma vessel to ultrahigh-vacuum conditions, (5) ramp-up of the superconducting magnet system to achieve 2.5 T magnetic induction on axis, (6) preparation for plasma operation, in particular plasma vessel baking, wall conditioning, test of gas inlets and device control. After commissioning step (5), the magnetic field geometry was confirmed with an electron-beam mapping technique. Wendelstein 7-X has started operation on the 10th of December 2015 with

[2] At a resonance the twisting magnetic field line closes upon itself.



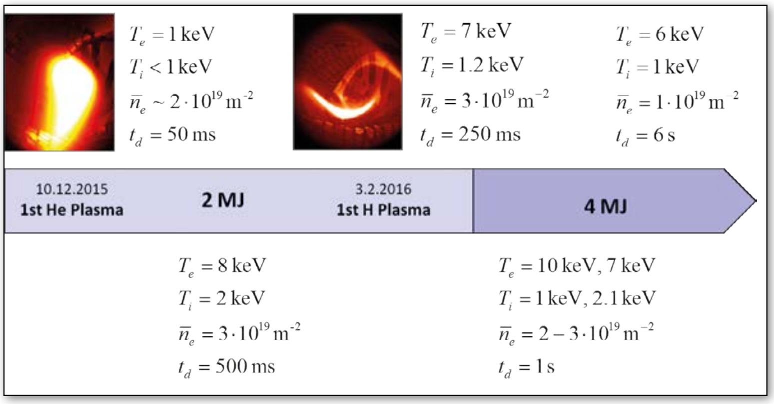
◂ **FIG. 3:** Schematic drawing of the island divertor (left diagram). Ten modules (five top and five bottom) are placed at the toroidal position with bean-shaped cross section. The target plates of the divertor, indicated by red bars, intersect the natural magnetic islands located at the edge (right diagram). The blue bars indicate the baffle plates.

helium as filling gas (Fig. 4). The maximum injected electron cyclotron resonance heating (ECRH) energy was limited to 2 MJ to protect the five inboard limiters from thermal overload. After wall conditioning with repetitive low-power ECRH pulses, the impurity level has dropped to acceptable values and the plasma parameters as well as the pulse duration have significantly improved. The maximum available ECRH power was 4.3 MW.

On the 3rd of February 2016 the operation with hydrogen as filling gas had started. The heat loads on the limiters allowed to double the maximum injected ECRH energy up to 4 MJ. This has improved the plasma performance considerably and both higher-power 1 s duration and lower-power 6 s duration discharges could be operated routinely. During the 10 weeks of operation about 1000 experiments could be conducted with the about 30 diagnostic systems in operation. The first operation stage of Wendelstein 7-X has exceeded all expectations with regard to reliability and availability of the device, plasma performance parameters, and validity of the obtained data. Already a large variety of physics programs could be conducted, including the investigation of the central electron root [6], plasma rotation, influence of external trim coils on wall loads, and first impurity transport studies. The analysis of the data is in progress and valuable experience for the next operation stage has been gained. Also the formation of the scientific and the operation team was successful, in particular the international cooperation in the framework of the EUROfusion consortium (see article by T. Donné) and a strong cooperation with U.S. American research laboratories and universities.

The path to steady-state operation of fusion relevant plasmas

Steady state operation of plasmas with fusion-relevant parameters is one of the grand challenges in fusion research. The fusion triple product $n{\cdot}T{\cdot}\tau_E$ usually deteriorates for longer plasma discharges, either due to lack of long-pulse heating and current drive performance or heat load limits of plasma facing components. The stellarator concept without net plasma current is inherently steady-state. However, a large number of measures must be taken to make a fusion device – including stellarators – steady-state capable: (a) The magnet system must be superconducting. (b) A steady-state heating system must be developed for the operation of the experimental devices. Here ECRH is a most promising path, since the gyrotron development has made enormous progress during the past 10 years. The 1 MW 140 GHz gyrotrons for Wendelstein 7-X have proven 30 min of operation without any loss of performance. Using water-cooled mirrors and diamond windows, the ECRH beam can be quasi-optically directed into the plasma. (c) All plasma-facing components must be actively (water) cooled. (d) Plasma diagnostic systems must be prepared to cope with steady-state conditions. (e) The requirements on control and data acquisition of a steady-state fusion device are much higher than for any short-pulse machine. The sheer amount of data, the necessity of highly-available systems, and continuous control of the plasma make dedicated developments indispensable. In summary, a steady-state device with fusion-relevant plasma parameters is not only a physics program (predominately aspects of plasma-wall interaction) but requires also a dedicated engineering and development program and Wendelstein 7-X will make a serious contribution.



▾ **FIG. 4:** Overview over the plasma parameters achieved during the first operation campaign of Wendelstein 7-X. The doubling of the injected ECRH energy from 2 MJ to 4 MJ has considerably improved the plasma performance.

Reactor concepts for stellarators – the way forward

Wendelstein 7-X is clearly the key device for the qualification of optimized modular stellarators as possible candidates for a fusion power plant. A burning-plasma power plant study based on stellarator optimization using non-planar coils is the HELIAS 5-B (helical-axis advanced stellarator) with the following design parameters [4]: plasma volume 1400 m^{-3}, number of non-planar coils 50, major radius 22 m, overall diameter 60 m, average magnetic induction on axis 5.9 T, magnetic energy 160 GJ. To go directly from Wendelstein 7-X to such a device would be too large a step and an intermediate device is most likely needed to study the physics of a burning stellarator plasma and to develop the related technologies, in particular blanket modules that match the stellarator geometry and the associated remote handling technologies. Prior to that step, Wendelstein 7-X has to fulfill its missions to demonstrate: (1) constructability, (2) plasma performance, (3) divertor operation, (4) steady-state operation. The forthcoming two operation phases, that extend until mid 2025, will be decisive for making major progress towards achievement of these milestones. ■

References

[1] A.H. Boozer, *Physics of Plasmas* **5(5)**, 1647 (1998)

[2] M. Wakatani, Stellarator and Heliotron Devices, Oxford University Press (1989)

[3] J. Nührenberg and R. Zille, *Phys. Lett. A* **129**, 113 (1988)

[4] F. Warmer *et al. Plasma Physics and Controlled Fusion* **58**, 074006 (2016)

LOW TEMPERATURE PLASMA APPLICATIONS IN MEDICINE

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The main field of plasma medicine is the direct application of cold atmospheric plasma (CAP) on or in the human body for therapeutic purposes. CAP is effective both to inactivate a broad spectrum of microorganisms including multiple drug resistant ones and to stimulate proliferation of mammalian cells. Clinical application has started in the field of wound healing and treatment of infective skin diseases.

Cold atmospheric plasma (CAP) sources for medical application

A well-established field of atmospheric plasma application is electro surgery where thermal plasma effects are used above all for coagulation and tissue cutting. In contrast, plasma medicine is focused actually on low temperature plasmas (< 40°C) to avoid thermal effects on living structures. Cold atmospheric plasma (CAP) sources for medical application have to meet particular requirements. Such devices have to guarantee manageable, stable, reliable, and reproducible operation at low temperature and open atmospheres. Besides a comprehensive characterization of qualitative and quantitative plasma parameters and "macroscopic" characteristics especially a meaningful knowledge of biological performance is an essential prerequisite for both effective and safe medical application.

During recent years, mainly three basic types of CAP devices were tested and partially applied for medical purposes (Fig. 1) [1,2,3].

In the volume dielectric barrier discharge (DBD) plasma is ignited in the gap between an isolated high voltage electrode and the target to be treated, *i.e.* in medical application human tissue (*e.g.* skin or wound surface) is part of the discharge electrode configuration. In the surface DBD, plasma is ignited around an individually designed electrode structure (*e.g.* circular or grid-like) which is isolated from a counter electrode. Both electrodes can serve either as high voltage or ground electrodes. For treatment of living tissue, the plasma has to be brought in close vicinity of the target to be treated. With both DBD configurations, atmospheric air is usually the working gas.

In a plasma jet device, the electrode setup for plasma generation is located usually in a capillary or tube-like arrangement in most cases inside a pen-like device. Diverse electrode configurations can be used, *e.g.* pin electrodes, ring electrodes, plate electrodes *etc.* A working gas is flowing through the tube. The plasma is ignited inside the device. The effluent is blown out along the gas flow and can be brought into direct contact with the target to be treated. Several plasma jet devices are using noble gases like helium or argon, but air or gas mixtures are also useful as working gases.

Independent on the basic principle of plasma generation, all these atmospheric pressure plasmas are small scale and filamentary and are generated inside small discharge gaps (p*d-scaling of breakdown voltage). The plasmas are non-uniform and constricted and consist of micro discharges or filaments, *i.e.* these are transient, short lived plasmas.

Biologically active plasma components and basic mechanisms of action

In general, cold atmospheric pressure plasma is a mixture of reactive components including charged species (ions and electrons), excited neutral species mainly from the working gas, reactive oxygen and nitrogen species, visible, ultraviolet (UV) and infrared (IR) radiation and other electromagnetic fields (Fig. 2). Dependent on the individual configuration of the plasma source, composition, relationship and quantity of these plasma compounds may vary significantly.

Based on a huge number of basic research using cultivated microorganisms and human cells [3], two main basic principles of biological plasma action have been identified recently:

1. Biological plasma effects are significantly caused by plasma induced changes of the liquid environment of cells.
2. Reactive oxygen and nitrogen species (ROS, RNS) generated in or transferred into liquid phases by plasma treatment play a dominating role in biological plasma activity.

According to the actual knowledge, UV part of CAP has low or no direct biological effects because typically low doses are emitted by plasma devices designated for medical use. However, its supporting role in reactive species generation by photochemical activity has to be taken into consideration.

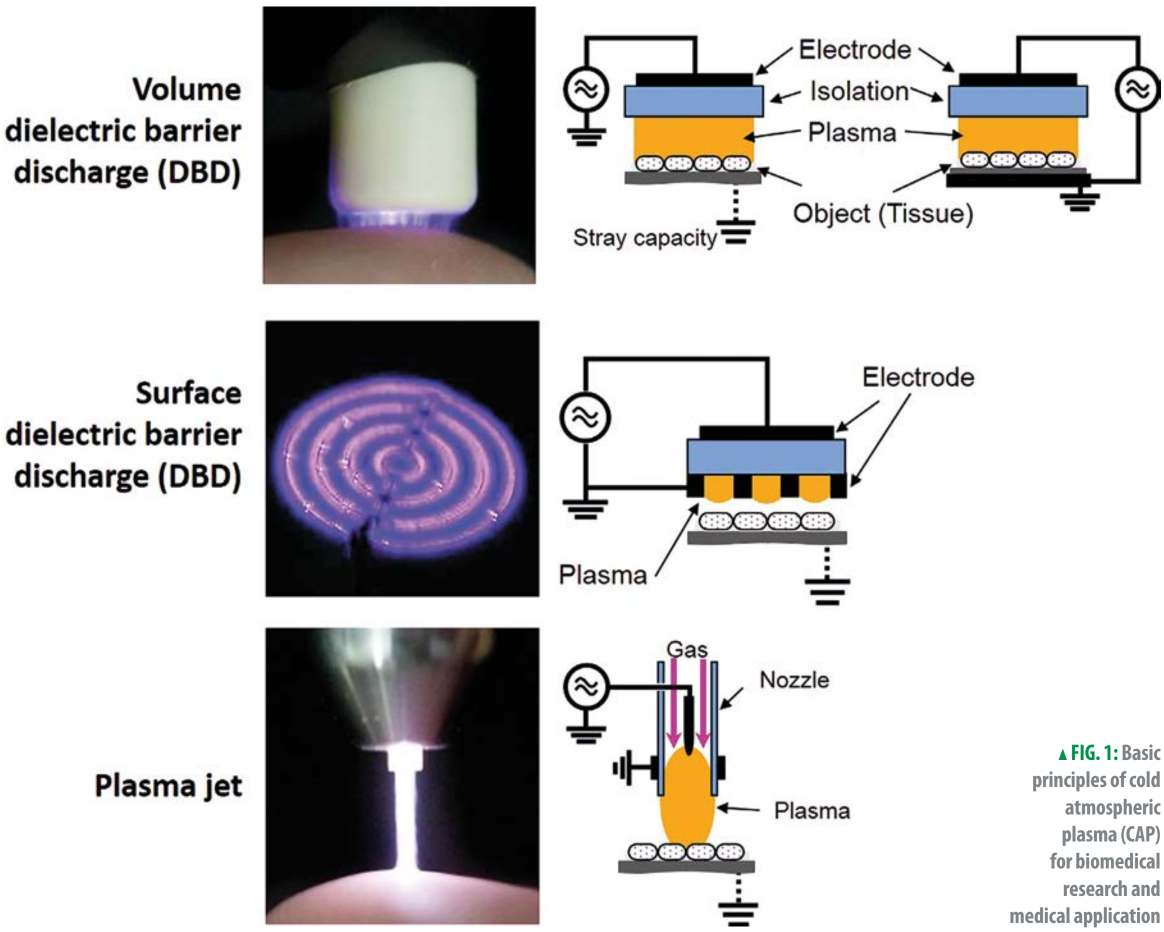
Electrical fields or current, respectively, reaching living tissue is strongly dependent on type of discharge and therefore might have varying direct biological effects. In this field, much more research is needed to finally enlighten the role of this plasma compound for its direct part in biological and medically relevant plasma action but also for its role in the generation or support of action of other plasma compounds, above all of reactive species [4].

However, the dominating role of ROS and RNS is established and demonstrated by several experimental setups independent on the specific plasma device used [5,6]. Generation of ROS and RNS is mainly referable to atmospheric oxygen and nitrogen which are part of the working gas in air-based plasma sources but is also admixed into the plasma in the case of noble gas-based plasma sources if they are working at open atmospheric conditions. According to the actual state of knowledge, differences of biological performance between plasma sources are mainly referred to quantities of ROS and RNS or its proportion of mixture in the respective plasma. However, possible role of UV radiation or electric fields has to be kept in mind.

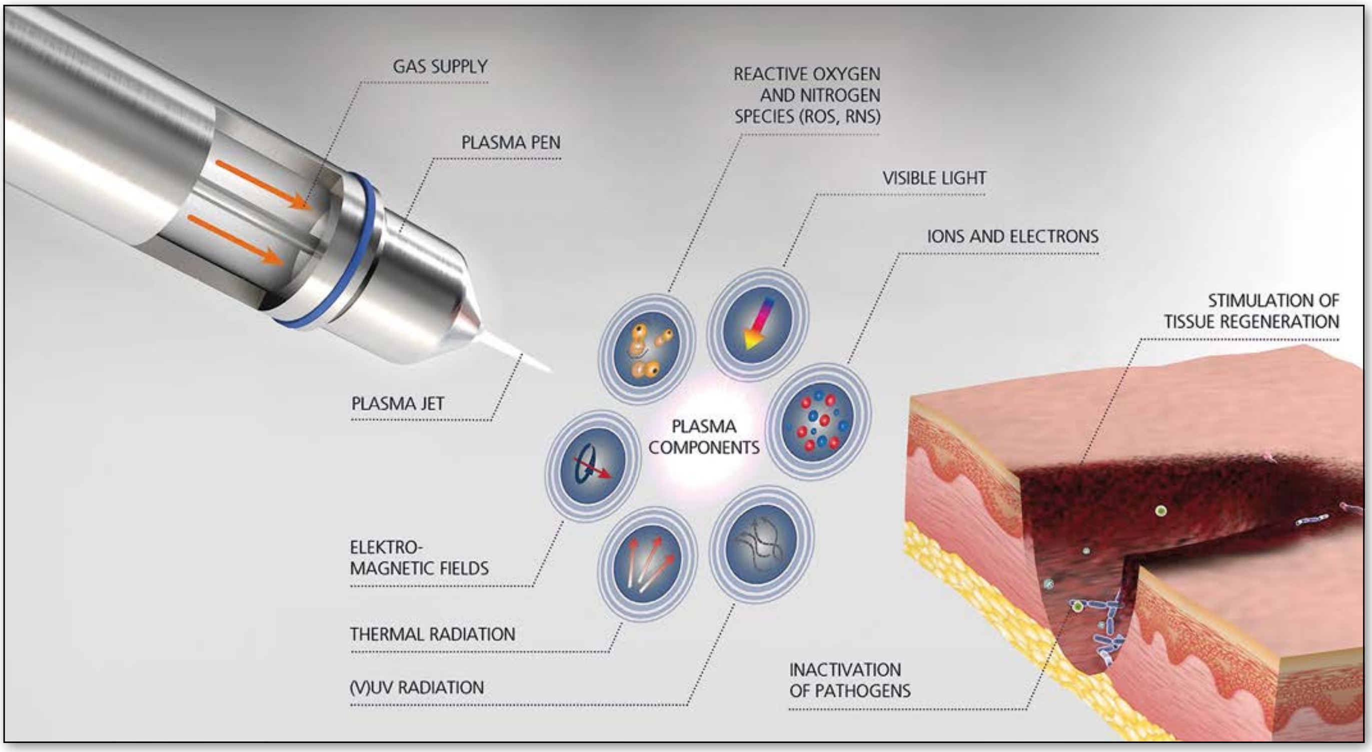
The fundamental insight of the dominating role of ROS and RNS was highly valuable because the large and well established field of redox biology now can serve as a sound scientific basis to explain biological effects of CAP. ROS and RNS regularly occur in cell biological processes (*e.g.* superoxide $O_2^{-}\bullet$, hydrogen peroxide H_2O_2, hydroxyl radical $\bullet OH$, singlet oxygen $^1O_2$, nitric oxide $\bullet NO$, nitrogen dioxide $\bullet NO_2$ und peroxynitrite $ONOO^-$). Therefore, mammalian cells have protective mechanisms to save from reactive species concentrations going beyond physiological levels. Such so-called oxidative stress might have severe consequences, *e.g.* genotoxic DNA changes. However, detailed investigations using well-established experimental procedures could demonstrate repeatedly that detrimental plasma effects on cells in general and particularly on DNA result either in cellular repair processes or in induction of programmed cell death (apoptosis) as a direct consequence. It has been demonstrated that application of cold atmospheric plasma does not cause increased risk for genotoxic effects [7,8].

Three general biological plasma effects have been described repeatedly that are most relevant for medical application [3]:

- its potential to inactivate a broad spectrum of microorganisms including multidrug resistant ones
- its potential to stimulate cell proliferation and consequently to promote tissue regeneration



▲ **FIG. 1:** Basic principles of cold atmospheric plasma (CAP) for biomedical research and medical application



▲ **FIG. 2:** With cold atmospheric plasma (CAP) a mixture of reactive components dominated by reactive oxygen and nitrogen species (ROS, RNS) is working on living tissue, *e.g.* a wound. Wound healing by plasma is a combination of inactivation of bacteria and stimulation of tissue regeneration.

- its ability to inactivate mammalian cells and especially cancer cells by initialization of the programmed cell death (apoptosis)

Medical application of CAP

Since 2013, first CAP sources got CE certification as medical devices. One of it is the argon-driven cold atmospheric plasma jet kINPen MED (neoplas tools GmbH, Greifswald, Germany), which is based on comprehensive physical, biological, pre-clinical and clinical characterization [9,10]. Two other well-investigated medical CAP devices are the jet-like microwave-driven Ar-plasma torch MicroPlasSter (ADTEC, Hunslow, UK) and the PlasmaDerm device (CINOGY GmbH Duderstadt, Germany) which is based on a volume DBD working with atmospheric air [11].

These plasma sources are certified mainly for the treatment of chronic wounds as well as pathogen-based skin diseases. The integrated concept of plasma-supported wound healing combines antimicrobial (antiseptic) plasma activity with a direct stimulation of tissue regeneration (Fig. 2). With these devices, routine application in medical practice in first clinics and doctor's offices above all in Germany has started. In the treatment of long-lasting chronic and infected wounds promising results are reported particularly in cases where conventional treatment fails. According to the feedback of the doctors that use it, a re-start or acceleration of wound healing process up to complete wound closure is reported in more than 80 % of the patients as a preliminary result. Additionally, clinical users emphasize the CAP effectivity to eradicate multiple drug resistant bacteria (*e.g.* MRSA).

A highly topical field of basic and preclinical research is CAP application in cancer therapy due to the fact that CAP can inactivate cancer cells by induction of the programmed cell death (apoptosis). Because these cells seem to be much more sensitive for CAP treatment compared to non-malignant cells it opens up new options of supportive CAP application *e.g.* in surgical or radiative cancer eradication as well as in palliative cancer therapies [12,13,14].

Possibilities of plasma application in dentistry include disinfection of tooth root canal, treatment of dental implants both for biofilm removal and improvement of bone cell adherence and therapy of intraoral infections and also wounds [15].

Besides these large fields of basic, pre-clinical and clinical research in plasma medicine, further fields of medical plasma use, such as ophthalmology, cardiology, pneumology or plastic and aesthetic surgery are investigated.

Actual challenges and further prospects

Despite the fact that first clinical application of CAP devices have already been realized, there are several needs to further improve and optimize this innovative plasma technology in medicine. There are both physical and technological but also biological and medical challenges.

Two main points have to be addressed in the next future:

- adaptation of plasma devices for specific medical applications with regard to manageability under ergonomic and application site-related aspects;
- adaptation of plasma with regard to its composition to realize specific and selective biological effects.

For application-adapted plasma devices, several physical and technical concepts are existing for flat DBD-based plasma devices and plasma jet arrangements for large-area treatment, catheter-like plasma devices for endoscopic application as well as plasma devices to reach difficult to access areas in cavities *e.g.* for dental applications [2,16,17].

For the adaptation of plasma composition to specific biological effects and subsequently to specific and selective medical applications, much more interdisciplinary research about detailed mechanisms of biological plasma effects and the specific role of the different plasma components, above all of the reactive species is needed. Furthermore, it is not known in detail how and in which extent the individual state of health of the patient influences the success of plasma therapy, which has to be taken into account to define individual treatment parameters.

Finally, perhaps the greatest challenge for the next future is to find or define a specific parameter or set of parameters for a device-independent control and monitoring of plasma treatment similar to the common "dose" in mainly irradiation-based physical therapies like laser- and radiotherapy.

"The main field of plasma medicine is the direct application of cold atmospheric plasma (CAP) on or in the human body for therapeutic purposes. CAP is effective both to inactivate a broad spectrum of microorganisms including multiple drug resistant ones and to stimulate proliferation of mammalian cells. Clinical application has started in the field of wound healing and treatment of infective skin diseases."

Unique advantages of plasma application for therapeutic purposes are:

1. Active components are generated locally and only for the required duration of the application on-site primarily by a physical process.
2. Biologically active plasma components (above all reactive oxygen and nitrogen species) are the same as occur in regular physiological and biochemical processes in the body but cannot be supported adequately by drugs.
3. Because of its localized and short-term generation by local plasma treatment these substances can be detoxified by processes of regular cell metabolism, *i.e.* there is no increased risk of plasma application.

It can be expected that plasma medicine will become an independent and successful part of modern medicine within the next years. To attain this objective, more systematic clinical trials are essential to meet the demands of evidence based medicine. ■

Acknowledgement

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References

[1] K.-D. Weltmann *et al.*, *Pure Appl. Chem.* **82**, 1223 (2010)

[2] G.Y. Park *et al.*, *Plasma Sources Sci Technol* **21**, 043001 (2012)

[3] Th. von Woedtke *et al.*, *Phys. Rep.* **530**, 291 (2013)

[4] T. Darny *et al.*, 2015 IEEE International Conference on Plasma Sciences (ICOPS); DOI: 10.1109/PLASMA.2015.7179640

[5] D.B. Graves, *J. Phys. D: Appl. Phys.* **45**, 263001 (2012)

[6] D.B. Graves, *Clin. Plasma Med.* **2**, 38 (2014)

[7] K. Wende *et al.*, *Cell Biol. Int.* **38**, 412 (2014)

[8] K. Wende *et al.*, *Mutat. Res. Genet. Toxicol. Environ. Mutagen.* **798**, 48 (2016)

[9] K.-D. Weltmann *et al.*, *Contrib. Plasma Phys.* **49**, 631 (2009)

[10] S. Bekeschus *et al.*, *Clin. Plasma Med.* **4**, 19 (2016)

[11] G. Isbary *et al.*, *Expert Rev. Med. Devices* **10**, 367 (2013)

[12] A.M. Hirst *et al.*, *Tumor Biol.* **27**, 7021 (2016)

[13] M. Keidar, *Plasma Sources Sci. Technol.* **24**, 033001 (2015)

[14] M. Schuster *et al.*, *J. Cranio Maxill. Surg.* (2016); DOI: 10.1016/j.jcms.2016.07.001

[15] S. Cha and Y.-S. Park, *Clin. Plasma Med.* **2**, 4 (2014)

[16] K.-D. Weltmann *et al.*, *Contrib. Plasma Phys.* **54**, 104 (2012)

[17] K.-D. Weltmann *et al.*, *IEEE Trans. Plasma Sci.* **40**, 2963 (2012)

Dear Editors,

I want to draw your attention on the WTC failure issue.

As Structural Engineer, specialized with Eladio Dieste in Stability of Structures, the explanation of the article on WTC is absurd. I have worked by twenty years in Intelligent Structures stability, and one structure was nominated for fib 2010 Outstanding Structure Awards.

I have studied the WTC failure by two stability investigation methods: 1) energy flow minimisation and 2) monitoring displacements *vs.* efforts convergence.

The structure of the WTC was held by the bracing of the exterior columns by the floor steel joist at each floor level. The weakest point is the union column-steel joist, and although it was fully protected with fire-resistant foam, it is a union without redundancy. Redundancy of joints is a must for live loads.

Structural stability is a subject beyond the mechanical strength; a temperature of 800 ° F (measured indirectly by the colour of steel), which does not affect the strength of steel, caused differential deflections that were enough to disconnect the junctions steel joist- pillar. The joints, which were welded for construction speed, were not redundant and failed. When the joints failed, the steel joists fell and the pillars buckled for lack of horizontal bracing.

The fire affected the floors above of the impact floor, just the failing of only two connections trigger a displacement mechanism, floor by floor, exactly as seen in the videos.

A study by two researchers at MIT, Prof. Oral Buyukozturk and Dr. Oguz Gunes, by other roads leads to the same result as listed above (see *The Collapse of Twin Towers: Causes and Effects*, Keynote Lecture, EFCA 2004 CONFERENCE, May 22-May 25, 2004 Istanbul, Turkey). Without these failings the towers would not have fallen. They recommend increasing the redundancy of connections onwards. This failure mechanism is consistent with the final NIST report 2008 in http://ws680.nist.gov/publication/get_pdf.cfm?pub_id=861610

Modern high-rise structures use other structural systems, including *e.g.* high performance concrete.

The structural engineering requires faithful adherence to the laws of physics, and good engineering judgement. People's lives depend on us. ■

José Zorrilla - Uruguay

Thoughts from a Former NIST Employee

I was a member of the NIST technical staff during the period 1997-2011. I initially joined the High Performance Systems and Services Division and later became a member of what was, at the time, the Mathematical and Computational Sciences Division of the Information Technology Laboratory. My fellow NIST employees were among the finest and most intelligent people with whom I have ever worked.

I did not contribute to the NIST WTC investigation or reports. But in August of this year, I began to read some of those reports. As I then watched several documentaries challenging the findings of the NIST investigation, I quickly became furious. First, I was furious with myself. How could I have worked at NIST all those years and not have noticed this before? Second, I was furious with NIST. The NIST I knew was intellectually open, non-defensive, and willing to consider competing explanations.

The more I investigated, the more apparent it became that NIST had reached a predetermined conclusion by ignoring, dismissing, and denying the evidence. Among the most egregious examples is the explanation for the collapse of WTC 7 as an elaborate sequence of unlikely events culminating in the almost symmetrical total collapse of a steel-frame building into its own footprint at free-fall acceleration.

I could list all the reasons why the NIST WTC reports don't add up, but others have already done so in extensive detail and there is little that I could add. What I can do, however, is share some thoughts based on common sense and experience from my fourteen years at NIST.

First, if NIST truly believes in the veracity of its WTC investigation, then it should openly share all evidence, data, models, computations, and other relevant information unless specific and compelling reasons are otherwise provided. For example, would the release of all files and calculations associated with the ANSYS collapse initiation model jeopardize public safety to an extent that outweighs the competing need for accountability?

Second, in its reports, NIST makes a great show of details leading to collapse initiation and then stops short just when it becomes interesting. The remainder of the explanation is a perfunctory statement that total collapse is inevitable and obvious. It is easy to see through this tactic as avoidance of inconvenient evidence. In response to any challenges, NIST has provided curt explanations from its Public Affairs Office. There were many contributors to the NIST WTC investigation: Why not let them openly answer questions in their own voice with the depth of knowledge and level of detail that follows from the nuts and bolts of their research?

Lastly, awareness is growing of the disconnect between the NIST WTC reports and logical reasoning. The level of interest in "15 years later" is a good example. Due to the nature of communication in today's world, that awareness may increase approximately exponentially. Why not NIST blow the whistle on itself now while there is still time?

Truth is where our healing lies. ■

Peter Michael Ketcham, USA

The Editors respond

It is the policy of EPN to publish by invitation. Prospective authors are suggested by members of our Editorial Advisory Board, who cover various disciplines and come from different countries.

This particular Feature article 'On the physics of high-rise buildings collapses', related to the attack on the WTC, followed the same route. We expected this topic to be of wide interest to our readers and thus invited the suggested authors to submit their manuscript. EPN does not have a formal review/rejection policy for invited contributions.

In the present case we realized that the final manuscript contained some speculations and had a rather controversial conclusion. Therefore a 'Note from the editors' was added, stressing that the content is the sole responsibility of the authors and does not represent an official position of EPN.

Since some controversy remains, even among more competent people in the field, we considered that the *correct scientific* way to settle this debate was to publish the manuscript and possibly trigger an open discussion leading to an undisputable truth based on solid arguments. Therefore we asked NIST, as principal investigator of the WTC collapse, to send us a reaction to the article. Their response can be found elsewhere on these pages.

It is shocking that the published article is being used to support conspiracy theories related to the attacks on the WTC buildings. The Editors of EPN do not endorse or support these views.

In future, prospective authors will be asked to provide an abstract of the proposed article, as well as an indication of other related publications to allow the editors to better assess the content of the invited articles. ■

NIST position on the WTC investigation

The NIST WTC investigation team members feel that since our study of the World Trade Center building (WTC 1, 2 and 7) collapses ended in 2008, there has been no new evidence presented that would change our findings and conclusions, and therefore, nothing new that we can contribute to the discussion.

NIST firmly stands behind its investigation results, and that the body of evidence still overwhelmingly leads to the following scenarios:

- The WTC Towers collapsed because aircraft impact damage and debris dislodged fireproofing from critical steel components, jet fuel-initiated fires burned very hot for long duration when fed by debris and office materials, and the heat eventually weakened the exposed steel until it lost integrity and led to a global failure; and
- WTC 7 collapsed because damage caused by debris from the falling WTC 1 ignited fires on multiple floors, the heat expanded and dislodged a beam connecting a key perimeter column to both a long-span central beam and a critical internal support column, and the column's failure set off a chain reaction of failures across the building's steel infrastructure.

Our comprehensive website, http://wtc.nist.gov, covers all aspects of the WTC investigation and provides three sets of "frequently asked questions" (on the overall investigation, the WTC towers and WTC 7) that address—based solely on our findings—many of the claims made by those holding alternative views as to how the three WTC buildings collapsed.

The NIST investigation into the collapses of WTC Buildings 1, 2 and 7 was the most detailed examination of structural failure ever conducted. Based on the recommendations from this investigation, two sets of major and far-reaching building and fire code changes have been adopted by the International Code Council (ICC) into the ICC's I-Codes (specifically the International Building Code, or IBC, and the International Fire Code, or IFC). The 40 code changes were adopted less than five years from the release of the final report on WTC 1 and 2, and less than two years following the release of the final report on WTC 7. This is an extraordinarily rapid pace in the code making and approval process—a solid affirmation by the ICC that the work done by the NIST WTC investigation team was of the highest quality and critical to ensuring that future buildings—especially tall structures—will be increasingly resistant to fire, more easily evacuated in emergencies, more accessible to first responders when needed, and most importantly, safer overall.

Thank you for your interest in the NIST WTC investigation. ■

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Opinion: *Die Energiewende*

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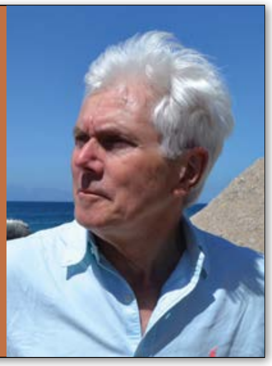

Around 2012, Germany embarked on an ambitious Renewable Energy programme aimed at phasing out fossil and nuclear power and replacing it by renewable energy, the so-called *Energiewende* or Energy Transition. Its long-term goal is to generate at least 80% of its electricity from renewables by 2050. To date the counter has hit 30% renewable electricity with about 45 GW installed wind farm capacity, a remarkable feat only surpassed by China and the USA. In solar power it ranks second to China only.

The share of renewables in Germany, now at around 30%, is an average. On a sunny and windy day, like May 8th, this may go up to 90%. On the other hand, on a calm and cloudy day like October 25th, fossil coal, lignite and gas fired power plants are scrambled to cover demand. This not only makes stability control of the electricity grid ever more challenging, it also increases carbon dioxide emissions, its reduction being one of the main objectives of the *Energiewende*. From the outset, these objectives were a clean, affordable and reliable energy supply. As it happens none of these objectives are currently met.

To bring about the *Energiewende*, the main instrument is subsidies. Investors are guaranteed a fixed high price for 20 years for their renewable electricity and this electricity has priority over other generators fed into the grid. Total cost exceeds B€ 20/yr, to be paid by customers through their electricity bill. As a consequence, electricity prices in Germany are one of the highest in Europe. A reform is now being drafted based on auctions, similar to the US. Being a step in the right direction, this is not the ideal solution either, as optimal energy use is not achieved by setting market prices on generating capacity, but requires a system approach where generation, transmission and distribution to end users are consistently managed.

A system approach not only considers the energy source but also includes energy storage. To develop energy storage, basic research needs to be stepped up. It requires a consistent long-term approach leading from basic research to pilot and demonstration. Recently, Germany did just that through the BMBF Kopernikus programme. Research Institutes and Industry collaborate in a ten year project called Power to X (P2X), aimed at converting intermittent supply of electricity into other forms of energy, like gaseous or liquid fuel or chemicals. These fuels are made from water and air (CO_2 and N_2) by splitting the molecules and recycling the CO_2 after use by recapturing it from the air. Fuels may then be stored in conventional way in large quantities for extended periods of time at high energy density to cover the mismatch between supply and demand characteristic of intermittent renewables. It couples the electricity grid to the existing gas network and to the oil infrastructure as well as powering the chemical industry.

After completion of the Kopernikus Programme, the *Energiewende* may well look different, its initial troubles likely dismissed as teething troubles. A ground swell of public opinion now steers energy policy away from fossil and nuclear power into renewables. If P2X is successful, duly integrated in 10 years' time, renewables will look cheap as prices of wind farms and solar panels continue to tumble, whilst the cost of decommissioning, waste disposal and climate change will have to be factored into the cost of nuclear and fossil power. For now, the message seems clear; do not focus on the energy source alone, take a system view and include the waste recycling, storage and public acceptance in your thinking. ■

Do not focus on the energy source alone, take a system view and include the waste recycling, storage and public acceptance in your thinking

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