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LIKE INSERTING
A SHIP INTO A BOTTLE

IN THIS ISSUE

EDITORIAL

In the realm of fusion, one of the most frequently heard words is “plasma.” But do we really understand what a plasma is? On page 2 of this issue of *ITER Mag* we hope to give you a better understanding of this strange but ever-so-prevalent state of matter.

And since it’s July, and the heat is upon us, let’s travel to Finland. As the country was coming out of its subarctic winter earlier this year an important demonstration was taking place for ITER – something akin to inserting a model ship into a bottle (page 3)…

Four months after Bernard Bigot from France became the new Director-General of the ITER Organization, *ITER Mag* is celebrating an anniversary. Ten years ago, on 28 June 2005, the ITER Members unanimously chose southern France as the site for the world’s largest and most ambitious experiment in fusion.

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PLASMA: A STRANGE STATE OF MATTER

The visible Universe is nearly entirely made up of plasma. Because very hot plasmas create the conditions where atoms can fuse, for more than 50 years physicists have worked to understand this "fourth state of matter" in order to control – and exploit – its potential.

The least well-known state of matter is, paradoxically, also the most prevalent: 99.99% of the visible Universe, including stars and intergalactic matter, is in a state of plasma. Even within our solar system, home to four solid planets (including ours, covered in water) and four gaseous giants, plasma accounts for nearly all matter. Our Sun alone – an enormous sphere of burning plasma – concentrates 99.85% of our solar system's mass.

Whereas in a solid, a liquid or a gas the nuclei of atoms and electrons are closely associated, in a plasma (the fourth state of matter) electrons get stripped from their atoms under the effect of temperature. This "dissociation" creates an ionized gas with radically different properties.

Last century, as the first attempts were made to reproduce the physical reactions taking place in the Sun and stars and to capture – if possible – the prodigious energy released, two plasma properties turned out to be of particular importance: electrical conductivity and sensitivity to magnetic field. Unlike a gas, a plasma is an excellent electrical conductor – one that can be confined and shaped by magnetic field.

In the early 1950s, astrophysicist Lyman Spitzer (1914-1997) was the first to understand the potential of these unique characteristics. By heating hydrogen plasma to very high temperatures and confining it within a magnetic field, the conditions for fusion – the nuclear energy that inundates the Universe with light and energy – could be created. He built his innovative fusion device at Princeton University (USA) in 1951 and called it a "stellarator," in reference to the machine's cosmic inspiration.

With that watershed event, many were convinced that the mastery of fusion was only a few steps away. But scientists hadn't discovered yet how difficult fusion plasmas would be to tame. Stochastic, unstable, fickle and unpredictable … a plasma's energy or confinement dissipates in a fraction of an instant.

As it became clear how little was really known about this strange state of matter, a new field of scientific exploration – plasma physics – was born. Three generations of plasma physicists have worked at understanding the dynamics of plasmas, unravelling their secrets and bringing order to what is by nature chaotic.

In parallel to this fundamental research, scientists in the United States, France, Great Britain, the Soviet Union, Germany, and Japan were creating new kinds of "fusion machines" (magnetic mirror, theta-pinch, field-reversed configuration…). Although their performance turned out to be disappointing, the potential of fusion seemed too great to give up trying.

In the early 1960s, a remarkable new type of machine made its entry onto the scene. Conceived by Soviet researchers, the "tokamak" (for "toroidal chamber with magnetic coils") produced unheard-of experimental results. At the Kurchatov Institute in Moscow, researchers were able to bring plasma temperatures on the T-3 tokamak near 10 million °C and – what was even more significant for a plasma physicist – surpass 10 milliseconds of energy confinement time, fully ten times what had been achieved in any other device.

The machines that followed – hundreds of tokamaks built the world over with steadily increasing performance – would fulfil the early promise of the T-3 machine. Tokamaks today routinely produce plasmas in the hundreds of millions of degrees and in ITER, the largest tokamak ever built, energy confinement time will be on the order of several seconds … enough for fusion reactions to be initiated and for them to liberate their formidable quantities of energy.

Plasmas, for their part, continue to preserve a part of their mystery. But physicists have learned to cope. In contemporary tokamaks, plasmas are "dompted" by sophisticated magnetic systems and scientists now know how to anticipate, channel and mitigate their sudden changes of humour.

More than 60 years have passed since Spitzer's brilliant intuition. In ITER, for the first time, humanity will command the fire of the stars.

A new Director-General for a new phase

After Ambassador Kaname Ikeda (2006-2010) and the physicist Osamu Motojima (2010-2015), both Japanese, the third Director-General in ITER Organization history took up his post on 5 March 2015.

Bernard Bigot, from France, was appointed by the ITER Council at a critical time for the project, as the focus of activity is transitioning from design completion to full construction.

"EUR 7 billion are now engaged in ITER construction and manufacturing. As we prepare to assemble the ITER machine and its more than one million parts, it is my responsibility to implement the changes necessary to create the conditions for the effective and integrated management of the ITER Project."

Director-General Bigot has introduced a new organization for the project's Central Team (based at ITER Headquarters in France) and a more integrated way of working with the ITER Domestic Agencies. "In order to improve the management of critical issues that are affecting the project schedule, we must work together as a single entity in order to find solutions to the schedule delays that exist. We must establish a definitive, robust baseline for the cost, schedule and scope of the ITER Project that is fully agreed upon by all partners."

An experienced senior manager of large programs and projects, Bernard Bigot has held positions in research, higher education and government. Prior to his appointment at ITER he completed two terms (2009-2012 and 2012-2015) as Chairman and CEO of the French Alternative Energies and Atomic Energy Commission, CEA. And as High Representative for the implementation of ITER in France since 2008, he has had the responsibility of coordinating the realization of ITER and ensuring the representation of France to the ITER Members and the ITER Organization.

"The whole world needs innovative technologies to assure its long-term sustainable supply of energy. Magnetic confinement fusion is one of the most promising options. I am deeply honoured for the possibility of contributing to the large, international and ambitious research program that is ITER, which has innovation as its aim."

For Bernard Bigot, who took up his functions on 5 March 2015, all project actors must work together as a single entity.

LIKE INSERTING A SHIP INTO A BOTTLE

In the vast hall of the VTT Technical Research Centre of Finland, a 10-ton divertor cassette mockup has just been successfully inserted into a replica of the ITER vacuum vessel . . . just as delicately as a model ship gets inserted inside a bottle.

In Tampere, Finland – a small town two hours north of Helsinki – an important demonstration took place for ITER this past winter.

They came from Barcelona, where the European Domestic Agency[1] for ITER is located, and from ITER Headquarters in southern France. A dozen specialists had made the trip to witness the culmination of twenty years of effort, ingenuity and technological innovation: the insertion of a ten-ton component into a replica of an ITER vacuum vessel section.

In watching the proceedings, it's easy to think of the mariners of old who managed to insert a model ship, with fully deployed sails, into a bottle – another operation requiring careful planning, dexterity and millimetric precision within severe space constraints. But whereas the mariners didn't think of removing their models once they were in place, the 10-ton ITER component will have to be replaced at least once over the project's lifetime. After demonstrating insertion, it will be necessary to demonstrate removal.

The huge piece of equipment on the test stand is one of the 54 cassettes that make up the ITER divertor – a nine-metre ring situated at the bottom of the vacuum vessel and directly exposed to some of the highest heat fluxes of the machine.

During tokamak assembly, the nine sectors of the vacuum vessel will be installed and welded together *before* the installation of the divertor cassettes can begin. That leaves only three relatively narrow (and blind) passageways into the vacuum vessel for divertor installation.

The operation underway in the vast hall of the VTT Technical Research Centre of Finland is the last in a series of demonstrations that were initiated four years ago. "The last and the most delicate," emphasizes Mario Merola, ITER Internal Components Division head. "We are simulating the installation of one of the three central cassettes that will close the circular arrangement of the divertor assembly."

A 20-metre-long cassette multifunction mover, equipped with rails and hydraulic motors, progressively transports the mockup divertor cassette to its final dockings inside of a 1:1 scale section of the ITER vacuum vessel. The last metres are hidden from the operators' eyes, just like they will be during ITER assembly when the divertor cassettes are transported through the lower ports into position. Between the 10-ton component and the narrow passageway, there are only a few millimetres of space.

In the control room, VTT senior researcher Hannu Saarinen sits, eyes riveted to an array of screens. To his left, a large virtual image shows the progression of the cassette inside the port; on smaller screens, below, numbers and figures scroll endlessly. Without a way to fit a camera into the tunnel, all information is based on sensors and virtual reality – without it, operators would be blind. Thanks to this real-time information, Hannu knows at each instant what forces are at play on the structure and what tiny distortions are caused by the movement. "More than 80 percent of the operation is pre-programmed; we use the joystick only for small adjustments."

Hannu, his joystick and his screens are sitting only a few metres from activity on the mockup. But they could just as well be separated by millions of kilometres of space or thousands of leagues of ocean depth. "This has been one of the biggest challenges of the operation: working with pure models without any visual connexion," says VTT Executive Vice-President Jouko Suokas. "But it has been an excellent platform to increase our competency in virtual reality and control software. This expertise is now being transferred to industry, which was one of the key reasons for our involvement in this project."

In the "laboratory conditions" provided by the test bed in Tampere, the operation was a model of perfection. Years before the 54 divertor cassettes will be inserted into the ITER vacuum vessel, work is beginning now so that – in the industrial environment of ITER assembly – the same level of perfection is achieved.

"What [has been demonstrated] here today," says Carlo Damiani, the European Domestic Agency's Project Manager for remote handling systems, "is the beginning of a brand-new technology chapter written thanks to ITER. We need to design and manufacture remote handling systems that are resistant, agile and precise. It's an opportunity for industry, SMEs and laboratories to think out of the box, innovate in engineering, and shape the future fusion reactors."

Beyond ITER or fusion, the potential applications for this type of robotic system are huge. Just like with other high-tech systems – superconductivity, cryogenics, materials – the high demands of ITER are bringing known technologies to the limits of their feasibility.

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[1] *Europe's contribution to ITER remote handling systems is in the range of EUR 250 million. EUR 40 million of this has gone to the development of divertor cassette insertion and removal technologies.*

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28 JUNE 2005: A HOME AT LAST

Ten years ago, on 28 June 2005, a home was found for ITER. In Moscow, where ministerial-level representatives of the ITER Members had convened, a consensus had at last been reached: the International Thermonuclear Experimental Reactor planned by China, the European Union, Japan, Korea, Russia and the United States (India would join six months later) would be located in Cadarache, a locality in the village of Saint-Paul-lez-Durance, some 75 kilometres north of Marseille, France.

Cadarache was already a familiar name for the fusion community worldwide. Home to one of the French Atomic Energy Commission's (CEA) largest research centres, it hosts a magnetic fusion department and Tore Supra, the world's first superconducting tokamak. Built in the late 1980s, Tore Supra still holds the world record for plasma duration, with a 2003 shot that lasted six minutes and thirty seconds – an eternity in the world of plasmas.

In the last round of a two-year negotiation, this site proposed by the European Union was unanimously chosen for the world's largest fusion facility. A little less than twenty years after the design activities for the project had been launched, the Moscow decision marked the end of a long, difficult and sometimes painful process.

It all began in the spring of 2001 when the ITER Final Design Report – the detailed blueprint of the installation – was being finalized for submission to the ITER Council.

A group of Canadian industrialists and academics who were interested in being part of the project made a first proposal in April 2001 for a site in Clarington, Ontario, home to the Darlington nuclear power plant. "For the first time since the project's inception in 1985, the name 'ITER' was associated with a precise location," remembers Jean Jacquinot, one of the experts who participated in the negotiations. "The Canadian proposal lent credibility to the project."

The Canadian proposal acted as trigger and an accelerator. Experts in Cadarache had undertaken "site studies" as early as the mid-1990s. In 2003, after reactivating and updating these studies, they formed the basis of a formal proposal – first from France to Europe, and then from Europe to the ITER Members.

Two days after the historic decision, on 30 June, French President Jacques Chirac was in Cadarache. No one had "won," no one had "lost." The ITER Members had demonstrated their capacity to overcome difficult odds and to imagine a solution that was acceptable to all.

Noriaki Nakayama, the Japanese Minister of Science and Technology, and Janez Potočnik, the European Commissioner for Science. Nearly two years of negotiations were necessary to decide which of the sites proposed by Europe or Japan would host the ITER Project.

The year before, Spain had proposed a site at Vandellòs, on the Mediterranean shore south of Tarragona (also the location of a nuclear power plant), and Japan had proposed Rokkasho-Mura, where a uranium enrichment plant, a nuclear waste storage installation and a used-fuel reprocessing plant cohabit on a 14-kilometre-long peninsula.

A site in Canada, two in Europe, one in Japan – that made three sites too many. In Europe, the issue was solved on 26 November 2003 when the twenty-five Research ministers of the member states voted unanimously for Cadarache. As compensation, Spain would host the soon-to-be-established European Domestic Agency, responsible for the European in-kind contributions to the project. As for the Canadian consortium, it decided to withdraw from ITER negotiations the following month due to lack of government-level support.

The year 2003 was drawing to an end and the ITER Members still had a decision to make. Four days before Christmas, their ministerial representatives met in Reston, Virginia, a suburb of the US federal capital. The meeting was heralded as decisive; expectant TV crews camped outside the gates of the site in France, media representatives were in constant contact by telephone with the different delegations. But the Reston negotiations ended in gridlock.

An optimistic joint communique, however, proclaimed: "The six Parties have reached a strong consensus on a number of points. We have two excellent sites for ITER, so excellent in fact that we need further evaluation before making our decisions based on consensus."

Reaching consensus would require another 18 months. In order to break the gridlock, a "Broader Approach" program was devised that included the construction of a materials research installation for fusion, "a satellite machine" for ITER, a computing centre for fusion science and a centre for remote experimentation – something for which Europe had always advocated. The Broader Approach installations would offer scientific and economic "compensation" to the party that would not host the machine.

Additional meetings were organized in Vienna in February 2004 and again in June, politicians on both sides entered the game, and partisan newspaper columns were published ... some fair, some less so. On both sides, the spring of 2005 was rife with sibylline declarations, allusions, hints...

On 28 June the long-awaited decision was at last made official in a joint public announcement by Janez Potočnik, the European Commissioner for Science, and Noriaki Nakayama, the Japanese Minister of Science and Technology. "I wish to say that today Japan is both sad and happy," said Nakayama. "However, this project is so important that we have decided to overcome our grief and change it into joy."

Two days later, French President Jacques Chirac was in Cadarache to celebrate the momentous event. No one had "won," no one had "lost." The ITER Members had demonstrated their capacity to overcome difficult odds and to imagine a solution that was acceptable to all.

And so, ten years ago, the ITER Members laid the foundation for the kind of spirit that continues to carry forward a truly unique collaboration for science.

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