

iter magazine

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#3 MAY 2014



Test convoy takes to the sea...

Editorial

A second transport convoy arrives successfully on site after testing, for the first time, the maritime leg of the ITER Itinerary. A dense web of rebar – designed to support 360,000 tons of buildings and equipment – materializes in the Tokamak Complex Seismic Pit. Conceptual designs for the machine after ITER, DEMO, progress around the world...

None of these things would be possible without the handful of physicists that, not quite a century ago, found the answer to this elementary question: "Why does our Sun shine?"

In this third edition of *ITER Mag*, we take you into the past, the present and the future.

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Test convoy takes to the sea

Back in September 2013, an 800-ton convoy had tested the physical resistance of the ITER Itinerary – a stretch of 104 kilometres of road between the Mediterranean Sea and the ITER site that has been specially modified for the transport of ITER's most exceptional components (see *ITER Mag #1, December 2013*).

Seven months later, an identical convoy was underway. This time, the goal was to test the organizational logistics behind the ITER transport operations as well as the maritime portion of the journey from the Mediterranean harbour of Fos to the northeastern shore of the inland sea

Étang de Berre – a sort of dress rehearsal in advance of the 250 or so highly exceptional loads that will travel along the ITER Itinerary for six years beginning in late 2014.

For the dozens of participants in the operation, the rendezvous point was a remote wharf at the Fos-sur-Mer industrial harbour. On Saturday 28 March the trailer and its mock load of concrete blocks (800 metric tons in all) were loaded onto a custom barge in an operation that lasted eight hours. Two days later, the barge pushed off from the quay, crossed the Fos harbour and navigated its way along a six-kilometre channel known as the Canal de Caronte that connects the Mediterranean to the Étang de Berre.

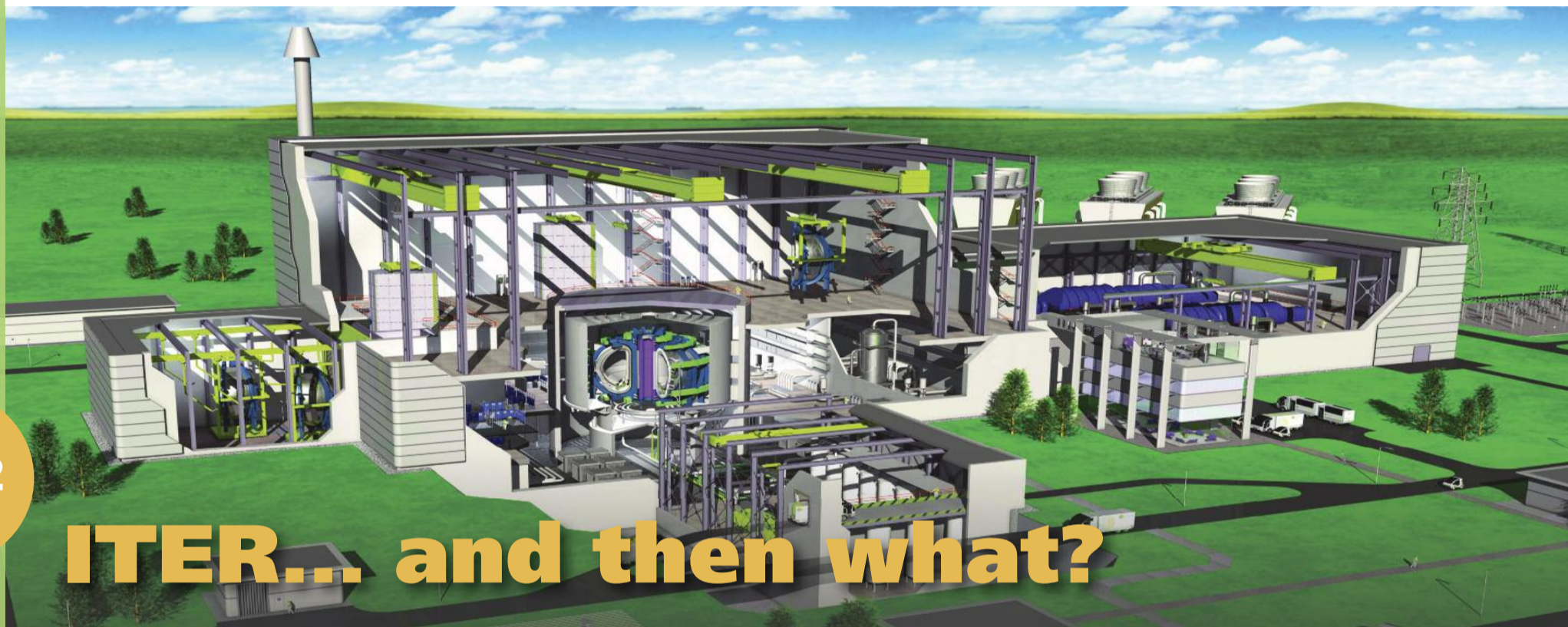
Along the banks of the Canal, which crosses the old city centre of Martigues, crowds came out to watch the unusual sight: an 80-metre barge flanked by Coast Guard patrol boats and two tugs, making its slow way

along the Canal and finally passing under a draw bridge and into the Étang.

Despite two technical incidents along the land portion of the Itinerary (related to the trailer's hydraulic system) the test convoy organizers – Agence Iter France, the logistics service provider Daher, and the French authorities – once again proved their mastery of complex technical and logistical issues.

"The incidents we suffered have helped us to identify what could, and should, be improved," stresses Bernard Bon, Daher head of convoy. "This is precisely what tests are for."

The testing phase has now come to an end and the next activity along the ITER Itinerary will be "for real": in October 2014 the first transport convoy will carry an electrical transformer from Korea (87 tons, 8.5 metres long, 4 metres wide and 5 metres high) for the supply of power to the site.



ITER... and then what?

In the world of fusion research, experimental programs aren't carried out consecutively... they overlap. Physicists were already trying to imagine ITER (under the name of INTOR) when construction of the European JET tokamak was just getting underway in the early 1980s; now, work has started around the world on the conception of the next-stage machine, DEMO, while the ITER installation is still years from finalization.

DEMO is the machine that will bring fusion energy research to the threshold of a prototype fusion reactor. After ITER – the machine that will demonstrate the technological and scientific *feasibility* of fusion energy – DEMO will open the way to its industrial and commercial exploitation.

The term DEMO describes more of a phase than a single machine. For the moment, different conceptual DEMO projects are under consideration by all ITER Members (China, the European Union, India, Japan, Korea, Russia and, to a lesser extent, the United States). It's too early to say whether DEMO will be an international collaboration, like ITER, or a series of national projects.

ITER will be the school where physicists and engineers will learn to build DEMO. In fact, it's the essence of the international collaboration that has formed behind the project: in ITER, each participating member will acquire the experience that will allow it to proceed, back home, with the next step.

Last December during the Monaco ITER International Fusion Energy Days (MIIFED 2013), the ITER Members presented their projects for DEMO. Although the timeline, the technical specifications and the level of determination varied from one Member to the next, the objective was the same for all: building the machine that will

demonstrate industrial-scale fusion electricity by 2050.

Japan, Korea, India, Europe and Russia presented a clear calendar in Monaco, stating their intention to begin building DEMO in the early 2030s in order to operate it in the 2040s.

China, after having explored physics and technological issues in a test reactor built in the 2020s (the China Fusion Engineering Test Reactor, CFETR), also plans to launch the construction of DEMO in the 2030s.

The government of the United States – for reasons related to the organization of research funding in that country – has not yet officially engaged in a DEMO project. The fusion community, for its part, considers that two intermediary machines are necessary before DEMO: a technological test facility and another facility with more scientific goals.

What might the future DEMO machine look like? The conceptual designs all sketch out a machine that is larger than ITER. The large radius ("R") of the plasma cross-section, which determines the size of the machine, ranges from 6 to 10 metres. In comparison, ITER's "R" measures 6.2 metres and that of the largest tokamak in operation, JET, measures half that.

How powerful will they be? Again, the designs vary – from 500 MW for the European DEMO to 1,500 MW for

the Japanese DEMO. (A 1,500 MW machine would be the practical equivalent of a next-generation fission reactor of the type EPR that is under construction in Flamanville, France or Olkiluoto, Finland.)

And their ambition? For some Members, DEMO will be a pre-industrial demonstration reactor; for others, it will be a quasi-prototype that requires no further experimental step before the construction of an industrial-scale fusion reactor.

In this vast panorama of possibility, one project stands out from the others: the Russian pre-DEMO project, a hybrid that would combine the principles of fission and those of fusion within the same machine.

A bit of physics is necessary to understand. Within ITER, each fusion reaction will produce one high-energy neutron. The impact of this neutron on the vessel wall will produce the heat that, in future machines, will be used for the production of energy.

Some physicists believe that the neutrons produced during fusion could be exploited in a different manner. They envisage using the energy of the neutrons for two purposes: to produce nuclear fuel for conventional fission reactors (through interaction with heavy elements like thorium or depleted uranium) and also to "break down" nuclear waste.

This is the path explored by Russian research today. As it was described in Monaco, the machine would be a hybrid reactor baptized DEMO-FNS (for Fusion Neutron Source). A small tokamak (R=1.9 m) would generate the neutrons necessary to producing fission fuel and to transmuting radioactive waste.

Although plans are on the table for the next-step device, nothing has yet been frozen. The return on experience from ITER operation will determine the final choices made for DEMO.



Four thousand tons of reinforcement will form the “skeleton” of the basemat that will support the Tokamak Complex. Steel density is at its highest in the central area (one fourth of the total rebar).

A spider web of steel

In the middle of the Tokamak Complex Seismic Pit a vast circle is now visible, part of the complex reinforcement work underway for the B2 foundation slab. Once in place, 16 levels of 40-millimetre-thick rebar will support the weight of the machine.

Four thousand tons of rebar for the Tokamak Complex basemat must be set into place precisely so that stress loads on the foundation, in normal as well as in accidental situations, are evenly distributed.

Bar after bar, level after level... the detailed plans that guide the workers' movements are the result of hundreds of hours of calculations, modelling and simulations.

The first part of the process involves defining the

buildings that the basemat will support. How big are they? How much do they weigh? And what safety functions – protection against radiation, confinement, seismic isolation – must they fulfil?

Equipment loads must then be taken into consideration as well as the forces that can result from cryostat thermal shrinkage, possible seismic events, and the normal or accidental vertical displacement of the Tokamak during operation.

In an average building, loads are measured in decanewtons; in the Tokamak Complex, meganewtons are used. These units describe the force required to give an acceleration of one metre per second to a mass of one thousand tons... every second.

Computing this impressive amount of data into models gives rebar design specialists the quantity of steel necessary to guarantee the robustness and safety of each edifice. “The code tells us how much steel by linear metre of concrete is required, but it doesn't say much about how the rebar should be arranged,” explains Laurent

Patisson, head of the Nuclear Buildings Section at ITER.

Enter the structural analysis engineers, whose job it is to interpret the raw data and translate it into detailed, three-dimensional plans, which are then refined by draftsmen. Finally, contractor consortiums create detailed execution drawings based on in-house methodology.

“In the end, we need a ‘buildable’ design,” stresses Laurent. “However dense the rebar, some access has to be preserved for the nozzle of the concrete pumps and the concrete vibrating tools.”

For the most complex area of the basemat, where orthoradial and orthogonal reinforcement meets under the future machine, a 1:1-scale mockup is being implemented to the west of the Seismic Pit to test the rebar arrangement as well as the feasibility of concrete pouring.

This long and complex procedure will be regularly controlled by the French nuclear safety authorities (ASN) in order to guarantee that even in the most improbable situations (accident, earthquake), the installation's confinement barriers will be preserved.

When fusion was almost there



A quartz tube (in reality a type of “theta-pinch” machine), a bright light and... fusion seemed close at hand.

Fifty years ago, in 1964, human beings believed in progress. Manned space capsules were routinely sent into space, a revolutionary supersonic commercial airliner was nearing the prototype stage, the computer

mouse had just been invented, and the official decision had been taken to build a cross-Channel tunnel.

Nothing epitomized this optimistic and conquering mood more than the 1964 New York World's Fair. From 22 April 1964 to 17 October 1965, the World's Fair drew over 51 million visitors – more than the entire population of France at the time.

The huge exhibition showcased and exalted the promises of mid-twentieth century technologies. In General Electric's Progressland pavilion the public pressed around a rather strange machine – a quartz tube surrounded by magnets that gave off a vivid flash and a loud report at regular intervals: the Nuclear Fusion Demonstration.

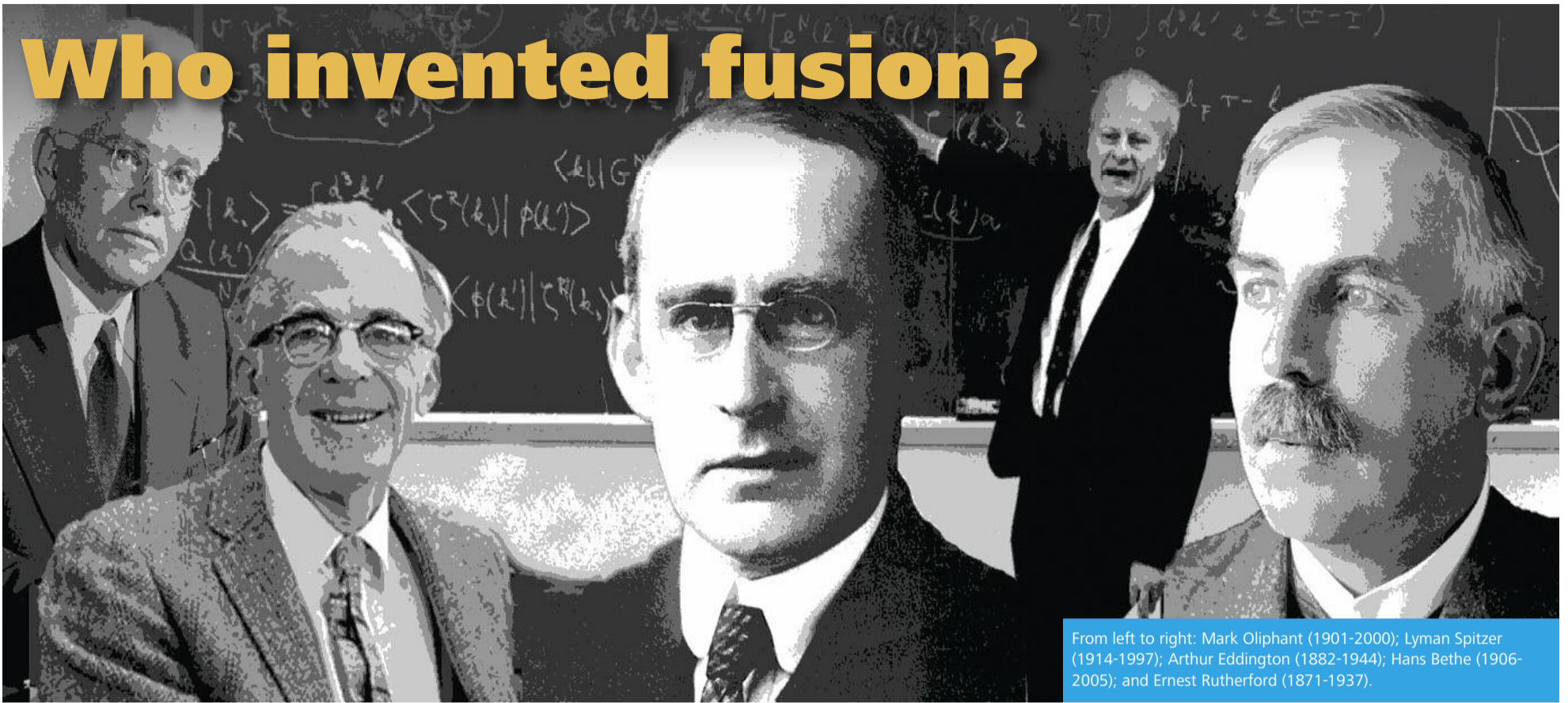
Here's how it was described in the New York World's Fair official guide: “In the first demonstration of controlled thermonuclear fusion to be witnessed by a large general audience, a magnetic field squeezes a plasma of deuterium gas for a few millionths of a second

at a temperature of 20 million degrees Fahrenheit. There is a vivid flash and a loud report as atoms collide, creating free energy (evidenced on instruments).”

The Fusion Demonstration left many visitors convinced that fusion-generated electricity was at hand, which of course did not reflect the actual state of fusion research. As General Electric reviewed its corporate involvement in fusion one year later, it concluded that “the likelihood of an economically successful fusion electricity station being developed in the foreseeable future is small.”

Fifty years have passed. Since Progressland's quartz tube and the confinement of a 20-million-degree plasma for a few millionths of a second, progress has been remarkable. Beyond ITER, beyond DEMO (see the article on page 2), the “economically successful fusion electricity station” is programmed for the middle of the century. A prospect that is hardly more distant than the “foreseeable future” of 1965.

Who invented fusion?



From left to right: Mark Oliphant (1901-2000); Lyman Spitzer (1914-1997); Arthur Eddington (1882-1944); Hans Bethe (1906-2005); and Ernest Rutherford (1871-1937).

The droves of visitors who come to see the ITER site every year often ask: "Who discovered (or invented) fusion?"

Of the many ways to answer this question the simplest and most obvious would be to say that Nature herself invented fusion. One hundred million years after the Big Bang, the first fusion reaction was produced in the ultra-dense and ultra-hot core of one of the gigantic gaseous spheres that had formed from primeval hydrogen clouds. Thus the first star was born, followed by billions of others in a process that continues to this day.

In the observable Universe, fusion is the dominant state of matter. In the solar system we inhabit, our Sun, which accounts for 99.86 percent of the total mass, is a giant ball of hydrogen sustained by the fusion reactions that have been going on for billions of years in its core.

But the shining of the Sun and the glittering of the stars were to remain an inexplicable wonder until the early years of the 20th century. In 1920, British astrophysicist Arthur Eddington (1882-1944) was the first to suggest that stars draw their apparent endless energy from the fusion of hydrogen into helium.

It took another theoretician, an expert in the relatively new science of nuclear physics, to precisely identify the processes that Eddington had postulated. The "proton-proton chain" that Hans Bethe (1906-2005) described in 1939 gave one of the keys to the mystery. Bethe's work on stellar nucleosynthesis won him the Nobel Prize in Physics in 1967.

As Eddington, Bethe and others were watching the stars (a major discovery is rarely the work of a single individual), others were exploring the intimate structure of the atom to reveal its secrets. In 1911, three years after winning the Nobel Prize in Chemistry for his work on the disintegration of the elements and the chemistry of radioactive substances, New Zealand-born physicist Ernest Rutherford (1871-1937) had elaborated the

model of the atom that bears his name. Rutherford understood what tremendous forces could be unleashed from the atom nucleus. In a famous 1934 experiment that opened the way to present-day fusion research (including ITER), he realized the fusion of deuterium (a heavy isotope of hydrogen) into helium, observing that "an enormous effect was produced."

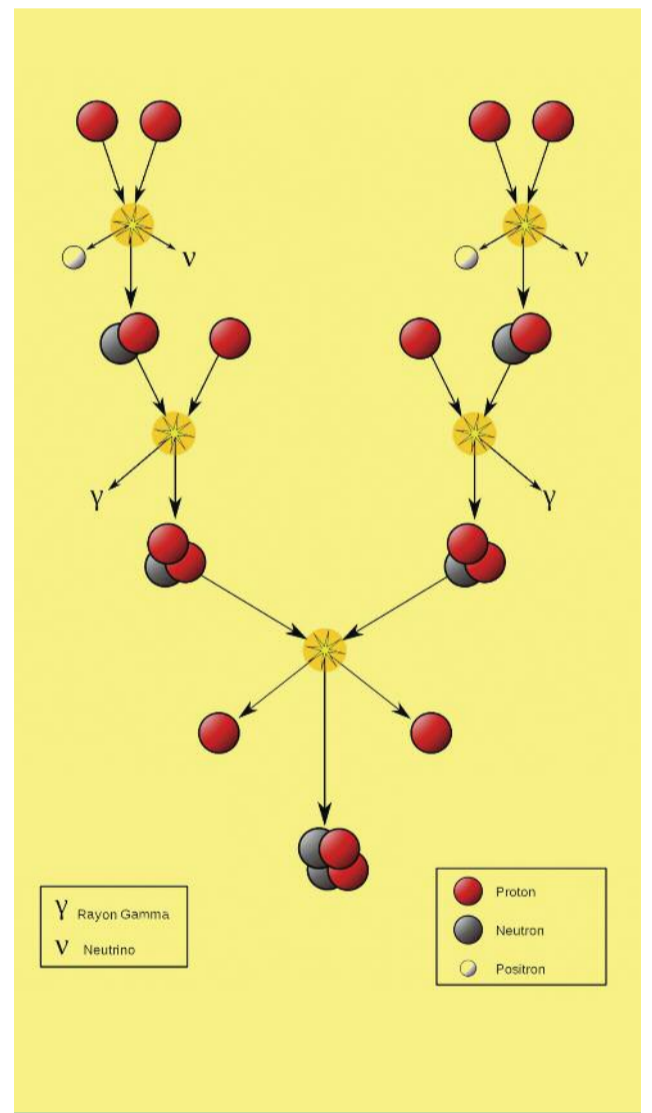
His assistant, Australian-born Mark Oliphant (1901-2000), played a key role in these early fusion experiments, discovering tritium, the second heavy isotope of hydrogen, and helium 3, the rare helium isotope that holds the promise of aneutronic fusion.

By the eve of World War II, the theoretical framework for fusion was established. Fundamental science still needed to be explored (and the exploration was to take much longer than expected) but fusion machines were already on the drawing board.

Although the first patent for a "fusion reactor" was filed in 1946 in the UK (Thomson et Blackman), it was only in 1951 that fusion research began in earnest. Following a claim by Argentina – later proven a prank – that its scientists had achieved "controlled thermonuclear fusion," the US, soon followed by Russia, the UK, France, Japan and others, scrambled to develop a device of their own.

In May 1951, a mere two months after Argentina's false claim, American astrophysicist Lyman Spitzer (1914-1997) proposed the "stellarator" concept that was to dominate fusion research throughout the 1950s and 1960s until it was dethroned by the more efficient tokamak concept born in the USSR.

The rest is history as we know it: less than one century after Eddington's theoretical breakthrough, ITER is being built to demonstrate that the power of the Sun and stars can be harnessed in a man-made machine.



The "proton-proton chain" that Hans Bethe identified in 1939 is the complex and lengthy process that enables Sun-like stars to generate energy. In a fusion reactor, the deuterium-tritium reaction is much simpler but produces the same result: light atoms (deuterium and tritium) fuse into heavier ones (helium), producing large amounts of energy in the process.

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