Recent research shows it should be possible to reach steady-state fusion production in ITER with the baseline mix of heating and current drive systems, in particular by upgrading the levels of power delivered to the plasma by neutral beam injection and electron cyclotron wave heating. 'One of the goals of ITER is to show that we can produce fusion power for an unlimited amount of time with high fusion gain (Q≥5)—so-called 'steady-state' operation,' says Alberto Loarte, Science Division Head. 'There are no physics or engineering hurdles holding us back.' But since ITER is an experimental facility, designed to facilitate a wide range of explorations, its baseline configuration is not optimized for steady-state operation. To achieve this, ITER will need to demonstrate operation with very high confinement—but not only. 'We will have to replace the inductive current provided by the central solenoid with plasma-driven current (bootstrap) and currents driven by neutral beam injection and electron cyclotron waves. And we'll have to do this for an hour at a time which, for all intents and purposes, is equivalent to steady-state operation.' Steady state can only be achieved through a delicate optimization of plasma conditions For each tokamak pulse, a plasma is created and heated. Once hot enough, the plasma produces energy through fusion reactions and the plasma current can be maintained until it consumes all the magnetic flux provided by the coil systems. Then, the plasma current decreases and the plasma cools down and terminates. H-mode (high-confinement mode) is an operational regime during which the plasma reaches a state of high energy confinement and produces fusion power with very hot plasmas and a low consumption of the magnetic flux, which is beneficial for long-pulse operation. In L-mode (low-confinement mode), by contrast, fusion power production is low, the plasma is colder and magnetic flux consumption becomes non-negligible, which shortens the length of tokamak pulses. While short-pulse operation is technically easier to achieve, it comes with disadvantages related to transient forces
and thermal cycling. The large amount of magnetic energy needed to create a plasma requires very large currents in the magnet coils for every pulse, which in turn subjects the coils to large cyclic forces and stress. As the tokamak cycles back and forth—between phases with extremely hot plasmas and high fusion power, to phases with no fusion power production—the expansion and contraction causes stresses that reduce component lifetimes. In addition, for a fusion reactor running in pulsed mode, extra measures would have to be implemented to provide the steady stream of electricity that customers need. Steady-state tokamak operation presents the advantage of having just two transient mechanical (forces) and thermal (heat-up/cool-down) events—switch-on and switch-off—over a very long period of continuous operation, however it is not an easy regime to reach. While other magnetic confinement systems such as stellarators are intrinsically steady state, reaching steady-state H-mode operation in a tokamak requires a delicate optimization of plasma conditions through operational control. 'By controlling the evolution of the plasma density and plasma current, you can establish a plasma current profile shape near what is needed to have a stable plasma in steady state, but at lower temperatures and pressures. This makes things easier,' explains Loarte. 'Then you add a lot of auxiliary heating to create the transition to H-mode, and you increase the plasma pressure to enhance the self-driven plasma current and current drive to replace the remaining inductive current. The current shape profile remains frozen due to the high temperatures, ensuring that the plasma remains stable at high pressures. That's the trick you have to pull off.' During the design phases of ITER, it was thought that a dedicated heating system, using so-called lower hybrid waves, would be required to reach steady-state operation. The project plan was to move another piece of equipment out of a port when the time came to run the steady-state experiments, in order to install the lower hybrid heating system. No one was completely comfortable with this idea. Moving systems between ports in ITER is very complex and disruptive for a number of reasons: the port plugs that house the system must be extracted and re-inserted, the pipes and transmission lines that feed the systems in the ports must be disconnected and reconnected, etc. ITER scientists were looking for a better solution. Breakthrough findings indicate ITER can reach steady state with the same heating systems that are being built now. The good news came with the recent demonstration that steady-state H-mode could be achieved at ITER without adding the lower hybrid wave heating and current drive system. 'Using integrated modelling, we set out to show that we can control core plasma stability in this scenario with the baseline heating and current drive mix at ITER,' says Alexei Polevoi, from the Plasma Modelling & Analysis Section. 'By the use of neutral beam injection and electron cyclotron wave heating and current drive, we demonstrated that it's possible to reach the target operation point, where steady state is reached, within the limits of the magnet systems that ITER has. We determined that an upgrade of the neutral beam injection system (to 49.5 MW, versus the baseline of 33 MW) and the electron cyclotron
heating system (to 30 MW, versus the baseline of 20 MW) would be required to make $Q=5$ steady-state operation, with reasonable assumptions regarding the achievable energy confinement.' This result reassured the ITER scientists, because for this upgraded power level their models require a level of confinement for $Q=5$ steady-state operation very close to what has been observed in other tokamak experiments—for example those at the DIII-D tokamak in San Diego—with density, temperature and current density shapes very similar to ITER, and a similar mix of external heating.' The researchers presented these results to the ITER Council Science and Technology Advisory Committee (STAC) in October 2018, arguing that lower hybrid wave heating would not be needed to achieve steady-state operation in ITER. The committee approved the findings. Because removing the possibility for the upgrade to lower hybrid represented an important modification to the project, the team brought this proposal before the ITER Council, where it was accepted, and then implemented the appropriate technical procedures within the project in 2019. This is good news, but more work needs to be done. 'We still need to conduct further studies on how to implement these techniques in real experiments in ITER,' says Sun Hee Kim, Scientist for Scenarios and Control. 'We need to define the experimental procedures that first get us a plasma current profile close to target, but at very low plasma pressure, and then increase the plasma pressure using heating and current drive nearly to the plasma stability limit without significantly modifying the current profile.' While mastering this delicate set of operations will be a challenge, the reward is very high plasma performance, with the sought-after steady-state operation delivering $Q=5$.

Cryostat | As clean as a freshly minted coin

Before it is encased in its protective cocoon and moved to temporary storage, the cryostat upper cylinder must be cleaned. The operation is both low-tech and essential: all the dust specks, metal particles, and traces of grease and chemicals that have accumulated during assembly and welding must be removed from both the inner and outer surfaces of the massive component. To be allowed into storage, the upper cylinder must be as clean and shiny as a freshly minted coin. The process is simple, involving just cloth, demineralized water, a standard solvent called isopropanol, and a lot of elbow grease—but the surface to be cleaned exceeds 2,500 square metres. As operations progress, a temporary plastic film is spread over the cleaned sections, prior to wrapping with much thicker cocooning material. By the end of March, the 10-metre-tall, 430-tonne component, with a diameter of 30 metres, will be completely sealed away to protect it from water, moisture and dust. Moving the upper cylinder to temporary storage on the construction platform will make room for the assembly of the top lid, whose segments are expected from Larsen & Toubro in India in July. With the assembly and welding of this final section of the cryostat (after the base, lower cylinder, and upper cylinder) a formidable industrial and technological
When Alain Bécoulet embraced plasma physics back in the mid-1980s as a student at France's prestigious École Normale Supérieure, he did it for two reasons: one was the intellectual challenge; the other was the potential 'societal impact' of this field of research. 'What I was interested in specifically was fusion and the perspective of its concrete applications.' Bécoulet, who was recently appointed Head of the ITER Engineering Domain, defines himself as a 'theoretical physicist,' but one who 'applies the theoretical approach to physical objects.' Theory in his view 'has to be put to use.' From his first student internship at the Tore Supra tokamak, located on the opposite side of the ITER/CEA-Cadarache fence, to his eight-year tenure as head of France's Institute for Magnetic Fusion Research (IRFM), theory and applications have been inseparable. 'One of the most exciting moments in a physicist's life is when theory gives you a prediction, which you can verify on a concrete object ... such as a tokamak. I've had several of these moments at JET, at DIII-D and Tore Supra.' A tokamak for Bécoulet is first and foremost a 'complete chain of functions.' When dealing with a tokamak, a physicist soon finds himself 'caught up in engineering issues and problematics.' The overhaul of Tore Supra's hybrid heating system which began in 2001 when he was head of IRFM's Heating and Confinement Division was a major challenge in this respect. 'The operation had all the dimensions one finds in ITER today: a genuine challenge in engineering and project management, the involvement of industry and strict deadlines.' In 2011, when Bécoulet took the helm of IRFM, Tore Supra had been successfully operating for almost a quarter century. At the same time, ITER was struggling in its 'take-off phase' and both machines faced an uncertain future. 'ITER success was our top priority. But by turning our platform into a test bench for some of ITER's critical path issues, we could contribute to reducing the risk and to saving time and money for the project.' WEST, which Bécoulet managed from the start, was born out of this conviction. 'WEST was not something we added to Tore Supra. It was Tore Supra becoming WEST to serve ITER.' WEST has now produced close to 3,200 plasma shots and completed Phase 1 of its operational program. In about one year, following the present shutdown phase, the machine will have acquired the capacity for long-pulse operation, and will begin producing repetitive ITER-relevant plasmas of up to 1000 seconds. Having contributed to ITER from "the other side of the fence" for three decades or more, Bécoulet will now serve it more directly. As one of the four Heads of Domains created within the new ITER organizational structure, the theoretician-turned-project manager and engineering expert will need to marshal the whole range of his experience for what he considers 'an extraordinary societal adventure.'
Image of the week | Like dancers in a vertical ballet

Of all the movements of workers and equipment in the Assembly Hall, these are the most gracious... Like ballet dancers on a vertical stage, two workers are busy dismantling the steel structure of the temporary wall (now a mere tarpaulin partition) between the Assembly Hall and the Tokamak Building. The upper part of the structure must be removed by the end of the week to allow for the passage of the overhead bridge cranes into the adjacent building. The cranes will remain in the Tokamak Building for about one month in order to undergo a series of tests designed to demonstrate the structural integrity of the load path.

Of-Interest

Young talent meets leading researchers in Thailand

ITER science and technology was one of the topics that more than 80 students from across southeast Asia explored at the sixth ASEAN School on Plasma and Nuclear Fusion and Sokendai Winter School in Thailand in late January. The school—which is organized by Sokendai University, the Thailand Institute of Nuclear Technology (TINT), and Walailak University with the support the IAEA and ITER—is part of Thailand's initiative to intensify its fusion research program and aims at promoting interaction between young talent in southeast Asian countries and leading researchers from around the world. ‘The ITER Director-General gives his full support to the school by sharing the latest developments on ITER as well as the background and rationale of its science and advanced technology,’ said Jean Jacquinot, Senior Adviser to the Director-General of the ITER Organization, and one of the lecturers at the school. Read the full story on the IAEA website.

Half time at ITER

In a rare moment off the playing field, 100 of France's top under 17 rugby players visited the ITER site last week, taking advantage of a selection camp organized locally to learn more about fusion and the ITER Project. The ITER visits team tailors its guided tours to groups of all sizes—from individuals to buses of 50 people. Since work began on the construction platform in 2007, 158,000 members of the public have passed through the gate, including 16,000 in 2019. Among the visitors last year were 7,000 French schoolchildren. See more on ITER visits here.

Video

ITER NOW 1.4: Welcome to France