# How to bottle a star: Revolutionising fusion powerplant design with Intel technology

## Discover how the UK Atomic Energy Authority is using oneAPI and DAOS to boost supercomputing performance for fusion energy research.

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## Executive summary

With the help of cutting-edge compute technology from Intel, the UK Atomic Energy Authority (UKAEA) is working on a 'moonshot' plan that aims to make fusion a viable form of baseload power by the early 2040s.

Fusion is essentially the engine that drives the universe – the natural process that powers the heart of our Sun and the stars. Scientists have been carefully researching the science and practicality of fusion for many years, with the aim of 'bottling a star' here on Earth. Being able to do so reliably and cost-efficiently would deliver sustainable and near-limitless low carbon energy, transforming the energy sector in the net zero era.

The UKAEA's Spherical Tokamak for Energy Production (STEP) project[1] is an exciting step towards this end, a mammoth engineering challenge that is pushing the boundaries of science, technology and the engineering design process itself.

With this goal in sight, UKAEA, the Cambridge Open Zettascale Lab[2] and Intel are collaborating to accelerate and de-risk the UK's roadmap to commercial fusion power[3]. Teams across the organisations are working together to develop the next-generation engineering tools and processes necessary to design, certify, construct and regulate the world's first fusion powerplants. This involves taking existing, well-established engineering design processes into the virtual world (a world that some are now referring to as the 'Industrial Metaverse'). The aim is to 'democratise' extreme-scale simulation and AI solutions, built upon advanced solutions such as Intel® Xeon® processors, Intel® oneAPI Tools and Distributed Asynchronous Object Storage (DAOS), to engineers at the coal-face.

"Our goal is to be able to design STEP in a way where we can be more agile, so that we can adapt the design rapidly in light of new knowledge and new information as it becomes available," says Dr Rob Akers, Head of Advanced Computing, UK Atomic Energy Authority. "We want to embed robustness, flexibility and resilience into the design. This, in turn, will require unprecedented amounts of uncertainty quantification in our modelling and simulation. And that, of course, is a voracious consumer of supercomputing."

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JET began operating in 1983 and was the first device to produce controlled fusion power.

## The fusion power challenge

Fusion is routinely referred to as the ultimate power source. The process produces energy by fusing together light nuclei (such as hydrogen) at very high temperatures and pressures. This creates an incredibly hot, fluid-like state of matter called a 'plasma', which if confined well enough will release enormous quantities of low carbon energy. According to the UKAEA, the fusion process can generate "nearly four million times more energy for every kilogram of fuel than burning coal, oil or gas."

While almost any element lighter than iron will fuse in the heart of a star, creating this process on Earth is more of a challenge. The current best bet is to use a fuel mixture of deuterium and tritium – heavier versions (or 'isotopes') of the much more common hydrogen. These fuse at lower temperatures and densities than the heavier, non hydrogenic elements, but still require a plasma around ten times hotter than the core of the Sun.

"We can't in fact, replicate the exact conditions of the Sun here on Earth," says Akers. "We can't achieve the density and pressure that would be needed to replicate the Sun's fusion process, and even if we could, we would not produce enough power. So, rather than using pure hydrogen, we use deuterium and tritium. And rather than using gravity to confine our plasma (which is how the Sun works), we hold plasma away from the walls of the confining chamber (or 'tokamak') using a powerful magnetic field.

"The problem, however, is that there's so much energy inside the plasma that it drives a lot of turbulence and something that we call magnetohydrodynamic (or MHD) activity. These processes result in heat leaking out of the plasma, or, in other words, a reduction in plasma confinement. This cools the plasma down and prevents fusion from taking place, meaning we have to return more power to the plasma to keep it hot (and keep the fusion fire alight). Higher confinement ultimately means a lower cost of electricity."

Scientists at UKAEA, working closely with their European colleagues, have been addressing this problem for more than four decades. They've been working on a UK hosted machine called JET[4], a device soon to be decommissioned and replaced by a project known as ITER[5] in the South of France. Building upon the data and learning from the design, construction and operation of these existing projects is central to developing fusion as a practical energy source, and for developing the UK's own STEP prototype.

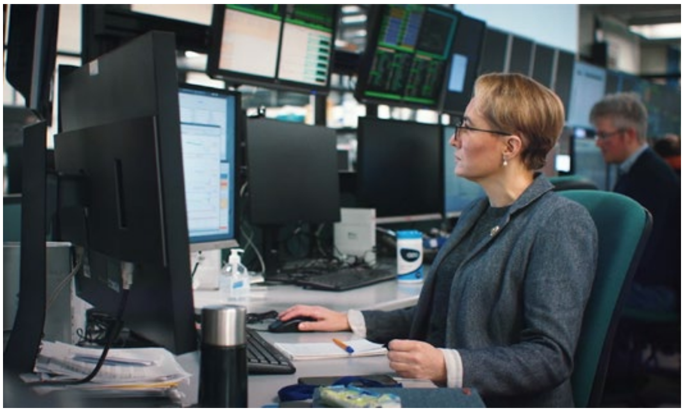
## Extreme-scale simulation

Dr Rob Akers highlights some of the practical issues involved in designing and building a working fusion powerplant: "Rather than carrying out huge amounts of expensive and time consuming 'test-based design', which is the way we've done fusion for decades (i.e. by building bigger and bigger and more complex machines as time has moved forward), we're going to take that process 'in-silico' – into the world of exascale computing, augmented with scale out artificial intelligence. The hope is to turn simulation, currently limited as an interpretive tool, into a powerful engineering tool that is actionable and can be trusted for engineering first-of-a-kind complex systems.

“Our simulations are going to rely upon some of the world's largest supercomputers and huge amounts of data science to make sense of the data we collect from machines like ITER, and also data that comes out of the simulations themselves. We’ll be very much relying upon the confluence of artificial intelligence, machine learning and high-performance computing that is now becoming a reality. It's never been done before. But I would argue strongly that the unprecedented power of these new technologies offers a unique opportunity to accelerate and de-risk the delivery of commercial fusion energy.”

Dr Paul Calleja, Director of Research Computing at the University of Cambridge, emphasises the complexity of the simulations required. “It's really multi-domain simulations [that we’re talking about here]. There are many different classes of simulation – materials, mechanics, fluid dynamics, plasma turbulence… All these phenomena individually might be what many academics focus their entire careers upon. But we’re looking at all of those things at the same time, feeding into each other in a coupled way. Ultimately, we aim to deliver a ‘digital twin’ of the world’s first fusion powerplant.”

Dr Calleja also highlights the grand challenge, multiscale nature of the physics being simulated. On the one hand, mechanical properties of the power-plant will evolve over a timescale of years, and spatial scales of metres, due to the formation of radiation induced damage or ‘microstructure’. On the other hand, the microstructural damage itself is simulated at the atomic scale. “How one deals with this multi-scale problem, coupled with the multi-domain (or ‘multi-physics’) nature of the science, is an incredibly tricky simulation challenge.”



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## The oneAPI difference

Intel is driving innovation at the bleeding edge of computing, particularly around democratising the supercomputing tools required to enhance extreme-scale simulation performance. As Dr Calleja points out, “the biggest inhibitor to simulation functionality and performance is the coding of the applications themselves.”

“We need tools that make the applications as frictionless as possible,” he explains, “especially when we enter the world of heterogeneous computing, where we start to have specialist hardware architectures for different computing functions. Most applications run on Intel x86, for example – we rely upon verified and validated models that have a heritage dating back decades, pre-dating general purpose GPU computing. Working with Intel® Xeon® Scalable Processors is nice and simple.

“But GPU computing is proving necessary to deliver scalability and energy efficiency. And if you want to use

## A short history of fusion

The Joint European Torus (JET) began construction in 1978, and began operating in 1983. It was the first device to produce controlled fusion power with deuterium and tritium and holds the world record for fusion power (1997).

Data and research from JET has been fed into the design and operational parameters for its successor, the International Thermonuclear Experimental Reactor (ITER) and the first commercial-scale fusion machine. Based in Cadarache France, ITER is a collaboration between 35 nations. ITER's First Plasma is scheduled for December 2025.

Following on from ITER, the UKAEA’s STEP (Spherical Tokamak for Energy Production) is now in the planning phase. The first phase of work aims to produce a concept design by 2024, followed by detailed engineering designs in phase 2, with construction of the prototype power plant due to begin in phase 3, targeting completion around 2040.

JET has boosted confidence in the 'tokamak' as a design for future fusion powerplants.

that to deliver codes that are sufficiently performant for engineering design, you need to rewrite all your code. And of course, I don't think it's just about GPUs and Intel® Xeon® processors. Many problems may be more effectively solved using Field Programmable Gate Arrays (FPGAs) and probably other novel architectures as they appear.

"Our solution to this code 'portability' problem is oneAPI, an open and multi-architecture programming model that frees developers to use a single code base across multiple architectures. The result is accelerated compute without vendor lock-in. Intel® oneAPI Tools and optimised AI frameworks already deliver leading performance on popular deep learning and molecular dynamics benchmarks[7]. Our challenge is to significantly broaden this application set to include engineering, fusion materials and plasma simulation."

"Without oneAPI," adds Dr Rob Akers, "we would have to take a gamble and pick what we think (or hope) might be the front runner architecture for exascale [computing]. But that might cause us to delay making a decision. We simply don't have time to sit around waiting to see what the winning architecture will be. So, being able to program for all of them is absolutely key. oneAPI is really our best shot at building agility and resiliency into the design stack we are developing for STEP."

The Cambridge Open Zettascale Lab is a oneAPI Center of Excellence, and places a focus upon porting potential exascale code such as CASTEP, FEniCS and AREPO to oneAPI. "There are around six engineers working on porting strategic code," says Dr Calleja. "By co-designing solutions with the users, they are developing a working knowledge of Intel® oneAPI Tools. The only way you can really form a working knowledge of something is to use it in anger – by getting your hands dirty. They're also tasked with disseminating that knowledge via a number of mechanisms, such as hackathons and training and outreach to the community."

## Faster I/O with DAOS

Future-proofing code with oneAPI is only one part of the exascale computing challenge. As Dr Calleja explains: "When we're talking about fusion, we're talking about some very large simulations, deployed across thousands of GPU nodes. A machine like that, running a single plasma turbulence simulation, can produce a huge amount of output in a very short time. For example, in the US, a single simulation of the XGC turbulence code, without compression, can generate a whopping 200 Petabytes of data[6].

"Dumping data for post-simulation analysis can be a rate limiting step that will slow your simulation down. So, you need a fast file system to be able to accept the simulation output. DAOS is designed to do exactly that; to accept large streaming I/O in an HDF file format from simulation to solid state storage. That's because it's designed from the ground up to be very efficient for solid state file systems."

Intel® Distributed Asynchronous Object Storage (DAOS) is the foundation of the Intel exascale storage stack. DAOS is an open-source, software-defined, scale-out object store that provides high bandwidth, low latency, and high I/O operations per second (IOPS) storage containers to HPC applications. It enables next-generation, data-centric workflows that combine simulation, data analytics, and AI.

One of the key benefits of IOPS conferred by DAOS is quite specific to fusion research. In existing research machines such as JET, plasma pulses (or 'shots') are generated several minutes apart. This creates a short window of opportunity for inter-shot calculations to be carried out, enabling the next pulse and associated measurements to be refined. However, the vast amounts of data involved, and the short window of opportunity for re-programming the feedback control system, means that not only are extremely powerful HPC processors needed, but the data pathways themselves need to be as frictionless as possible.

Dr Akers agrees, also highlighting the wider value of DAOS. “We're facing a scenario where we have not only huge amounts of experimental data to mine, but also big data from simulations. We’re working out how to combine data from both sources in an intelligent way to deliver much more actionable, predictive capability. Having platforms where streaming data to and from disk isn't a bottleneck is key to turning all that data into invaluable information and knowledge.

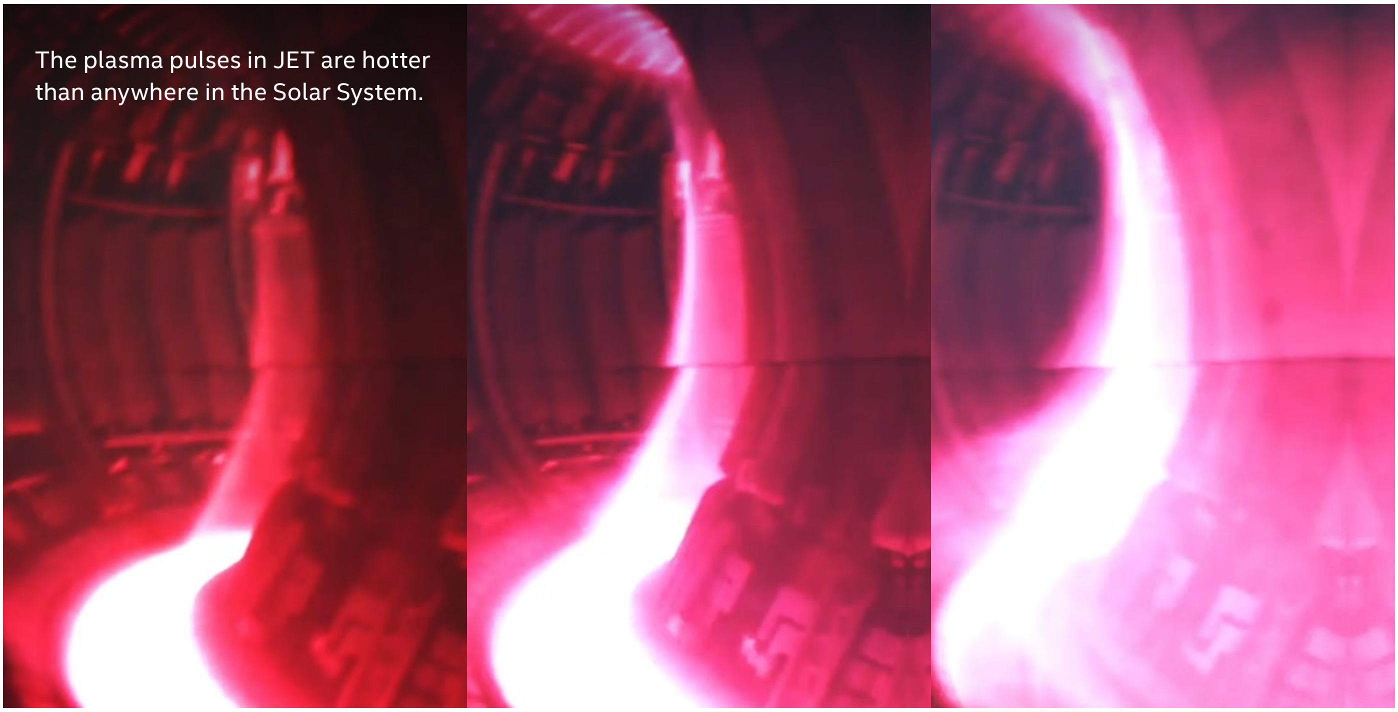
“At the moment, and even with access to these high-performance file systems, as a community we are analysing only a very small fraction of our legacy data. We can do so much better with modern technologies and the onus is now on us, as data scientists, to manage and tag that data so that it can be analysed in a few years’ time when these systems become more commonplace. There are huge opportunities, I believe, to dramatically improve that process across our science and engineering.”

## A STEP change moment

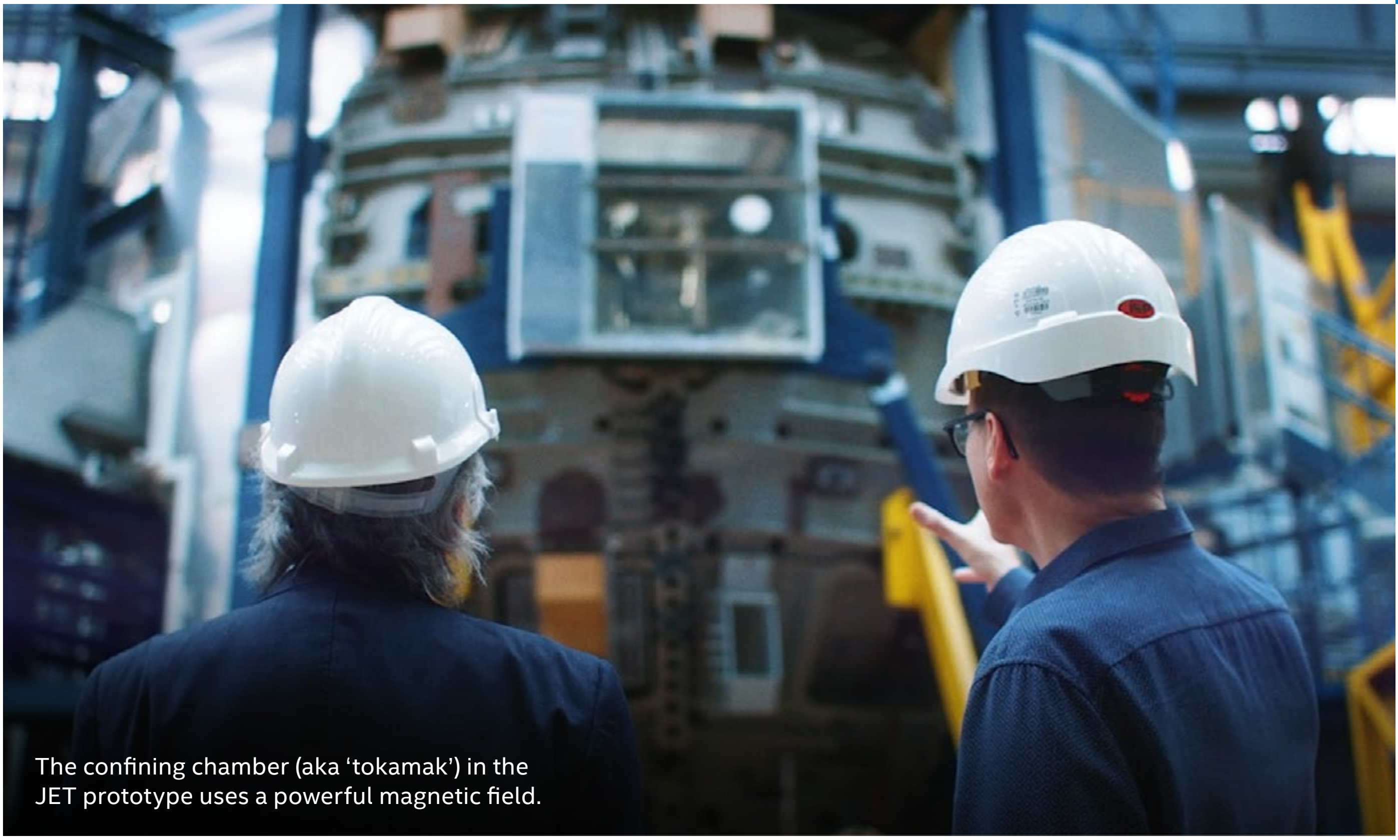
The collaboration between Intel, the Cambridge Open Zettascale Lab and UKAEA is literally aiming for the stars. “I firmly believe that the future of sustainable energy will rely upon supercomputing,” says Dr Rob Akers. “If we can efficiently bottle a star inside the chamber we call a ‘tokamak’, we will have produced a technology that we believe is going to be absolutely pivotal to creating a technologically advanced net zero world.”

### Intel® Data Center GPU Max Series

Large simulations are typically deployed across thousands of GPU nodes and the Intel® Data Center GPU Max Series can provide the raw computational power that drives them. Designed to take on the most challenging high-performance computing (HPC) and AI workloads, the Intel® Data Center GPU Max Series packs over 100 billion transistors into one GPU package and contains up to 128 Xe Cores. The entire Intel Max Series product family is unified by oneAPI for a common, open, standards-based programming model to unleash productivity and performance. Find out more.



The plasma pulses in JET are hotter than anywhere in the Solar System.



The confining chamber (aka ‘tokamak’) in the JET prototype uses a powerful magnetic field.

Intel® hardware and software, along with oneAPI and DAOS, are playing a crucial role in this endeavour, driving scientific success today, as well as shaping the HPC landscape of tomorrow. They are important parts of the jigsaw that will deliver transformation in virtual engineering, ultimately de-risking and accelerating the fusion roadmap. But the fusion use case itself is only the beginning.

“This is way bigger than fusion,” says Dr Akers. “Yes, it’s about democratising supercomputing to our engineering supply chain, but it’s also about collaborating with the engineering world at large so that other sectors benefit… It means driving a transformation towards ‘simulate first’ rather than ‘build test-rig or experiment first’. In essence, we need to reinvent the engineering design process itself. The question then is this: how can we make exascale a valuable tool for engineering design? In an ideal world, we would have had these tools more than a decade ago, when we were finalising the design of ITER. But at least we've got them for designing STEP in 2023 – and that, I think, is incredibly exciting.”

## Learn More

You may find the following resources useful:

- Intel® oneAPI Tools
- DAOS
- Cambridge Open Zettascale Lab
- Independent Review of the Future of Compute

**Solution provided by**

intel®

[1] https://step.ukaea.uk/
[2] https://www.zettascale.hpc.cam.ac.uk/
[3] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1022540/towards-fusion-energy-uk-government-fusion-strategy.pdf
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