

7  
TEUTATES



YEARS  
OF COOPERATION  
BETWEEN FRANCE  
AND THE UK



Ministry  
of Defence





# CON

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# 1

## The TEUTATES programme, 10 years since signing the Lancaster House Treaty

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Lancaster House Treaty sign-off by the French president Nicolas Sarkozy and the UK Prime Minister David Cameron at the London FR-UK summit on 2nd November 2010.

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# UNPRECEDENTED AND AMBITIOUS COOPERATION BETWEEN FRANCE AND THE UNITED KINGDOM

The TEUTATES Treaty between France and the United Kingdom was signed at Lancaster House, in London, on 2 November 2010, by the President of France and the UK Prime Minister. The treaty laid out the framework for cooperation between France and the United Kingdom in the field of nuclear defence. It was signed on the same day as the Treaty on general defence and security cooperation, which, while broader in scope, also implies closer ties between France and the United Kingdom. The TEUTATES programme covers the technology relating to weapons renewal programmes, with a view to maintaining the two countries' nuclear deterrent capabilities.

**This cooperation is pursued in accordance with the two nations' obligations under the Comprehensive Nuclear Test Ban Treaty (CTBT)<sup>1</sup>.** While complying with their obligations under the CTBT, the two countries have still needed to conduct experiments and, therefore, develop the radiographic and hydrodynamics facilities required to ensure the safe and reliable performance of their nuclear warheads, without the need to conduct any further nuclear tests.

As a result of a joint study, it became clear that France and the UK have very similar needs in terms of both the technology and the timelines involved, and that building and running a single facility housing all the hydrodynamics research systems required would meet the needs of both countries and also keep total expenditure down. This was the reasoning behind the decision

taken ten years ago by the French and UK governments to pool their resources and cooperate within the framework of the TEUTATES programme. **This has significantly reduced costs and enabled French and UK scientists and experts to share their knowledge and expertise** in hydrodynamics research and technology.

The TEUTATES programme thus includes the shared construction and operation of a facility for hydrodynamics and radiography research called EPURE, located in Valduc, in France, at the site owned by the Military Applications Division of the French Alternative Energies and Atomic Energy Commission (CEA/DAM). The experiments conducted at EPURE are designed to obtain physical data under laboratory conditions that is essential for validating the computer simulations used to ensure the reliability and safety of nuclear weapons. **The EPURE facility is shared by France and the United Kingdom.** However, the experimental set-ups and the results of experiments are not shared, meaning that each nation retains sovereignty over its nuclear deterrent.

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<sup>1</sup> The Comprehensive Nuclear Test Ban Treaty (CTBT) prohibits all experiment-related explosions of nuclear weapons or any other nuclear explosion.



FR-UK EPURE facility at CEA/DAM VALDUC centre (site view).

© CEA/DAM

More specifically, the hydrodynamics experiments conducted at EPURE are designed to characterise the state and the behaviour of nuclear materials, and especially of plutonium, in the most precise detail possible, under the conditions encountered during the pre-nuclear phase of weapon operation. In practice, conventional high explosives – explosives which have strong propulsive force – are used to compress the nuclear material, which then behaves like a fluid. At EPURE, this phenomenon can be studied using from one to three radiography axes to observe the evolution of the compression and the shockwaves, and the behaviour of the nuclear material. These experiments are conducted under very safe conditions, in sealed containment systems. Flash radiography images of the implosion process are obtained using extremely powerful, very high-performance X-ray machines.

**The TEUTATES programme also covers the joint construction and operation of the Technology Development Centre (TDC) at the Atomic Weapons Establishment (AWE) in Aldermaston, in the United Kingdom.** The TDC is used to develop the technological building blocks for the X-ray machines and measurement instrumentation.

Upgrading Interim Firing Point 2 (IFP2), the UK's detonics research facility at the AWE site, has also been integrated into the TEUTATES programme, as agreed by the French President and the UK's Prime Minister at the Brize Norton Summit on 31 January 2014.

Research carried out at all these shared facilities provides France and the UK with the radiographic and hydrodynamics technology needed to comply with the CTBT and ensure the safety and reliability of their nuclear warheads in a safe, secure environment, without having to conduct any nuclear tests.

By working together, we share the advantages, the costs and the risks entailed in developing such a complex programme.

**Cooperation in the area of nuclear defence ensures our two nations' capabilities in hydrodynamics research and related technologies for the long term.**

# EPURE, A THREE-DIMENSIONAL RADIOGRAPHY PLATFORM UNLIKE ANY OTHER IN THE WORLD



EPURE AIRIX x-ray machine adjustment by a couple of FR-UK operators.  
© CEA/DAM

In the ten years since the TEUTATES Treaty was signed by the French President and the UK's Prime Minister, cooperation on the shared radiography and hydrodynamics research facilities, deemed ambitious at the time, has taken shape, developed further and has become firmly planted on either side of the Channel.

Less than four years after starting work on the foundations for the facility, in November 2010, France successfully carried out the first experiment at EPURE using AIRIX, the first radiography axis, in October 2014. **Since then, the French teams have successfully carried out more than ten experiments using EPURE.**

With the buildings under the UK's responsibility commissioned in 2019, and the materials needed by the UK researchers for their first experiment delivered under the highest security conditions, the UK's first experiment at EPURE can now go ahead.

At the same time, at the TDC in the UK, work has been going on to develop the gamma cameras<sup>2</sup> for EPURE and the MERLIN<sup>3</sup> X-ray machine, which will be the second radiography axis at EPURE.

At the same time, a third radiography axis<sup>4</sup>, similar to the first, has been developed in France, at the CEA/DAM's CESTA site. The second and third axes will be installed over the next two years and brought into service by the end of 2022, so that they can then be used for experiments at EPURE from 2023.

The TEUTATES programme has also fostered a great deal of highly-rewarding scientific cooperation between France and the United

Kingdom, which will be pursued in the years to come, sustained by the enthusiasm of the French and UK teams involved. A new decade is now dawning, bringing with it new challenges that are just as ambitious as those that have been overcome in the course of these first ten years.

**Within the next few years, EPURE will become the most comprehensive X-ray facility in the world, with its three axes affording the highest possible performances. EPURE amply demonstrates the technological and scientific excellence of both France and the United Kingdom, used to underpin each nation's nuclear deterrent.**

The success of the TEUTATES programme over the last ten years reflects the high levels of mutual commitment and trust that exist between the teams from the two nations.

Now, based on such firm foundations, French-UK cooperation in relation to these radiography and hydrodynamics research facilities means that France and the United Kingdom are well-equipped, under the simulation programme, to ensure the long-term sustainability and credibility of their nuclear deterrent, in strict compliance with their international commitments.

<sup>2</sup> Measurement diagnostic devices used to record the image obtained by using the X-ray beam generated by the X-ray machine.

<sup>3</sup> IVA technology (Inductive Voltage Adder)

<sup>4</sup> LIA technology (Linear Induction Accelerator).



# 2

## The France-United Kingdom EPURE facility in Valduc, France

- 1 1<sup>st</sup> axis
- 2 2<sup>nd</sup> axis
- 3 3<sup>rd</sup> axis
- 4 Experience area
- 5 French and UK working areas



EPURE facility future three axis configuration

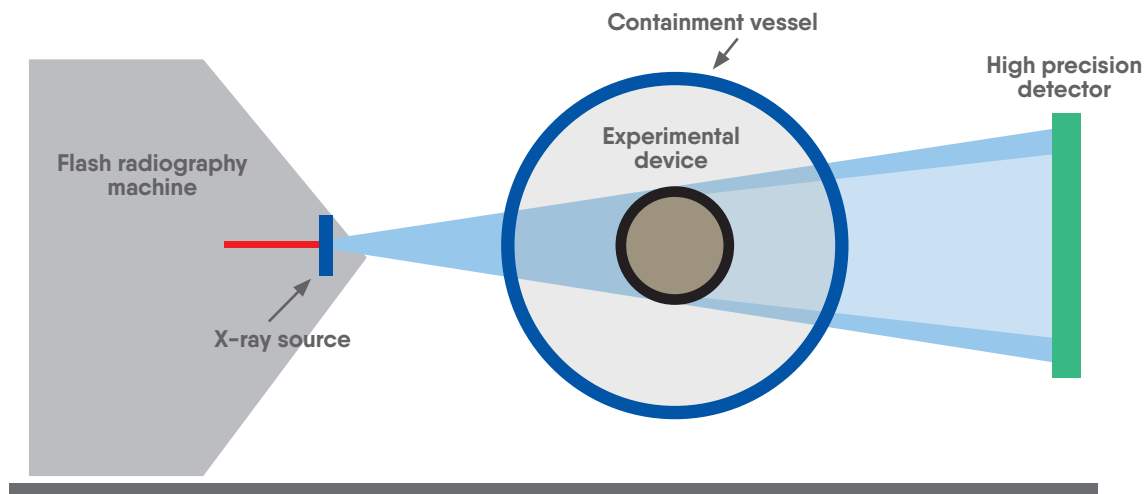


# DESCRIPTION OF THE FACILITY

A flash radiography facility for hydrodynamics research is made up of three main parts: an X-ray machine that generates an intense and very brief pulse of X-rays, a containment system to contain the materials accelerated for the purposes of an experiment, and a detection system calibrated for the high-precision recording of radiography images. The experimental device inside its containment system is placed between the X-ray source and the detector.

**EPURE, the French-UK flash radiography facility includes some areas that are shared and others that are restricted for each nation.**

To guarantee sovereignty over the experiments conducted, each nation has its own areas for preparing experiments as well as its own data recording and gathering equipment. The rest of the facility is shared and jointly operated.



Schematic of a radiographic experiment at EPURE

# THE THREE RADIOGRAPHY MACHINES



The initial set-up at EPURE, with one radiography axis, designed to conduct French experiments, has been operational since 2014. This set-up includes a French Assembly Hall<sup>5</sup>, a French explosives storage area, a firing point equipped today with a single-source x-ray machine, and a maintenance building for the X-ray machine. The results obtained since then have been used in ensuring the reliability and safety of French nuclear warheads.

**In addition, there are the areas specifically intended for use by the UK teams to conduct their experiments while preserving their sovereignty (Assembly Hall, explosives storage area and offices).**

An extension is currently being built to house the two new radiography axes, which will be connected up to the existing facility.

The AIRIX machine, which had been in use at the CEA/DAM site at Moronvilliers for thirteen years, was redeployed to EPURE in 2013. AIRIX was declared operational in July 2014, and the first hydrodynamics experiment was conducted at EPURE in October 2014.

**AIRIX is a high energy and low current (2 kA) Linear Induction Accelerator (LIA) designed to generate X-ray beams with the characteristics required for hydrodynamics experiments.**

It is made up of three sub-systems:

- the first, a 4 MeV, 2 kA beam injector, generates a 60 ns electron pulse. To do this, it creates a potential difference of 4 MV between the two electrodes into a vacuum diode. A switch then delivers the required voltage to the pulse forming lines, after which the electrons are extracted on a velvet cathode;
- the beam is accelerated through 64 induction cells that energize the electrons from 4 to 20 MeV. High-voltage generators (250 kV) are used to generate the electrical fields required to accelerate the electrons. During acceleration, the magnetic fields are used to adjust and centre the beam inside the machine;
- last, the induction coils focus the beam to a small area on the surface of the tantalum target, where the energy in the beam is converted into X-rays. The beam must be focused as precisely as possible to obtain a high-resolution X-ray image of the object under study.

<sup>5</sup> This is where the experimental device is assembled inside its containment system.



Designed to penetrate very dense, imploding materials, the AIRIX machine is able to deliver a dose of 600 rad at 1 metre for a few tens of nanoseconds. **That implies a dose that is tens of thousands of times greater than that used for a medical X-ray.**

One of the two new machines to be installed at EPURE is based on the same LIA technology as AIRIX, and has been enhanced with all the feedback from the installation and operation of AIRIX at EPURE. The only major difference between it and AIRIX is located in its terminal section, the space for focusing and converting the beam, which is fixed in place on AIRIX, but is mobile on this machine, in order to facilitate access to the equipment inside the experiment hall. The main components of this machine, the injectors, high-voltage generators and induction

cells have already been tested or are in the process of being tested at the CEA/DAM's CESTA site near Bordeaux (France).

**The last of the three X-ray machines, MERLIN, which is an Inductive Voltage Adder (IVA) machine, functions at low energy and high current (200 kA) to deliver X-rays.** This operating mode is different from the LIA machines' ones - which are high energy and low current (2 kA) machines.

The electrical power needed to operate the machine is stored in a Marx generator. It is then discharged via a series of ten pulse forming lines (PFL) in a central conductor. IVA technology is used to apply the sum of voltage output from these lines to a charge using the induction cell and to feed an electron-beam diode in

Airix flash x-ray radiographic machine installed in the EPURE facility © CEA/DAM





Third flash X-ray machine components during tests at CEA/DAM CESTA centre.  
© CEA/DAM

the downstream section of the machine and which converts the intense electrical current into X-rays. MERLIN delivers an X-ray beam comparable to that delivered by LIA machines.

Unlike the two LIA machines, which are fixed in place at EPURE, the MERLIN machine will be movable, allowing it to be moved into its operational position to perform experiments and then pushed back to provide access to carry out maintenance and adjustments between experiments. To this end, it will be assembled at EPURE on a movable steel platform (mobility system) that can be moved on a cushion of air. This system was tested and validated in 2019 in the United Kingdom. The MERLIN machine and its movable platform are currently being assembled at the EPURE facility.



MERLIN flash X-ray radiographic machine during tests in the TDC  
© Ministry of Defence

The MERLIN machine was qualified at the TDC in Aldermaston (UK) between 2015 and the beginning of 2019. Work began on dismantling it in April 2019, prior to it being transferred and re-assembled at EPURE in 2020.

**EPURE will soon be the only facility in the world with the capabilities to produce images from hydrodynamics experiments using three different radiographic sources designed for the purposes of the France and United Kingdom nuclear deterrent programmes.**

# RECORDING X-RAY IMAGES

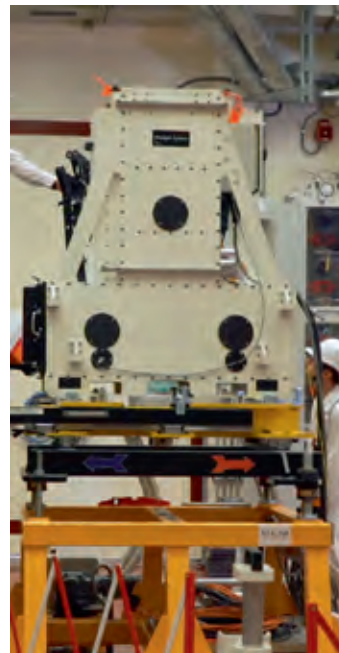
Flash X-ray radiography is used to take precision images of the material as it undergoes deformation at extreme speeds (thousands of kilometres per second) using a high-energy pulsed ('flash') X-ray beam.

**These X-ray images are recorded using detectors called gamma cameras,** which have been specially-designed for EPURE. French and UK teams have gathered their expertise to develop this technology.

For the purposes of their respective nuclear deterrent programmes, the AWE and CEA/DAM need to extract extremely precise data from these X-ray images. This entails characterising the interfaces between the materials and developing spatial mappings of material density. That means that the radiographic measurement system must be optimised to obtain high-quality radiographic images and the X-ray sources must be very precisely characterised.

The radiography line is calibrated and optimised in line with the nature of the experimental device and the aims of the experiment. Optimising the line must factor in the characteristics of the X-ray source (spectrum and dose, focal spot, emission lobe), those of the stimuable photodetectors and the gamma camera used (sensitivity, spatial and spectral response) and the geometry and characteristics of the experiment itself.

**The design of the radiography line and analysis of the images from the experiments rely on intensive use of various numerical simulation tools.**



Gamma camera to acquire  
X ray radiographics  
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# THE CONTAINMENT SYSTEM FOR THE EXPERIMENTS

**The physics experiments conducted at EPURE are designed to characterise the dynamic behaviour of materials used in the composition of the weapon, when subjected to strong compression, obtained using a conventional explosive.** Some physics experiments carried out for EPURE may use fissile material (plutonium), but in quantities that are much too small to generate any nuclear yield.. Therefore, the experimental device used should not be compared to nuclear weapons. The experiments performed in the EPURE facility therefore strictly comply with the international commitments of France and the United Kingdom in terms of the Comprehensive Nuclear Test Ban Treaty (CTBT).

In the hydrodynamics experiments conducted at the EPURE facility, conventional explosives with strong propulsive force are used to compress the material studied. **These experiments are conducted under very safe conditions, in sealed containment systems that have been certified as per nuclear safety standards.**

These containment systems are vessels designed to meet three fundamental requirements:

- 1. they must fulfil their safety function, i.e. they must withstand the blast and the impact of fragments generated as a result of the explosive, which surrounds the experimental device, without damaging containment integrity;**
- 2. they must allow the experimental measurements required to be obtained during the experiment;**
- 3. they must meet dimensional and weight requirements in line with the operational requirements of the facility.**

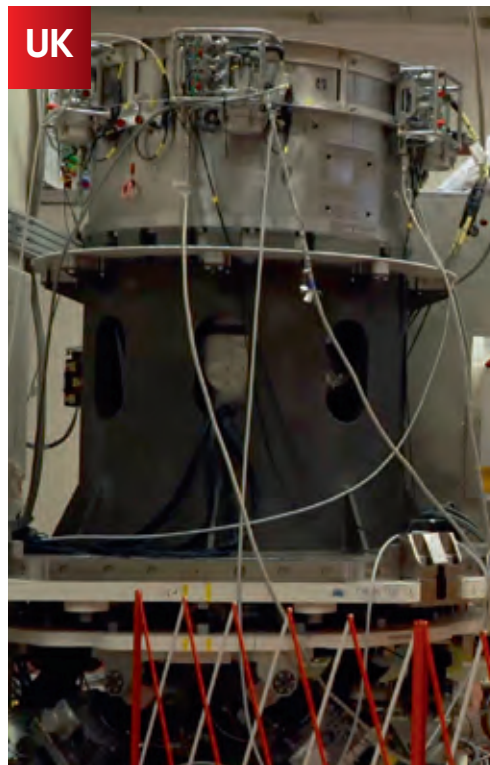
Containment vessel design is not a new field of research for either the CEA/DAM or the MOD. Nonetheless, this type of system must be constantly updated to be in accordance with the latest safety rules. France and the United Kingdom have therefore worked to achieve significant advances in vessel design compared to previous designs, to maintain their safe use at EPURE. Each of the two nations now has a qualified, operational containment system at EPURE.

**France and the United Kingdom are, for their own needs, pursuing the development of new containment systems that will enable them take full advantage of the resources available to them at EPURE once its three radiography axes are fully operational.**

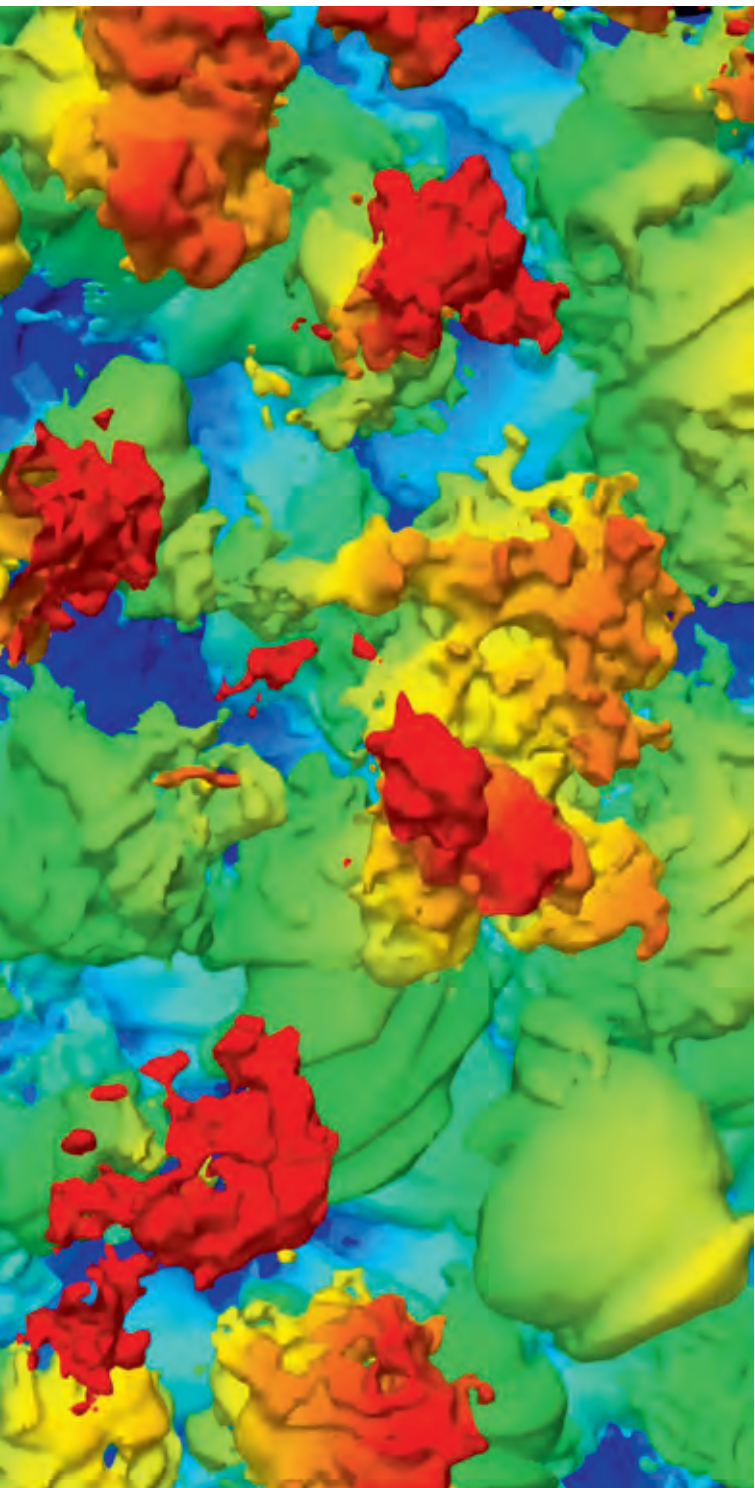
FR and UK vessels currently used in the EPURE facility to contain the hydrodynamic experiments.



© CEA/DAM



© Ministry of Defence



# 3

## Conducting experiments using EPURE

Simulations of instabilities occurring in the functioning of nuclear warheads.

© CEA/DAM



# JOINT FRANCE-UK FACILITY OPERATION



Since 2014, the EPURE facility has been organised according to an entirely two-nation system. **Thus, all the cross-cutting functions that can be shared, are managed by mixed French/UK teams.** This includes activities related to operating the Axis-1 X-ray machine, which has been in service since 2014, activities related to organising maintenance for all the shared general and special infrastructure, and management of the facility from the Work Control Centre staffed by French and UK personnel. Important messages sent using the Tannoy system from the Work Control Centre are systematically sent in both French and English to ensure that the information is received and understood.

Administrative tasks including scheduling and secretarial assistance (using a shared dedicated network), together with radiological protection, are also managed by mixed French and UK teams. Access to premises in which data that cannot be shared is used or stored, which includes areas used to assemble the experimental set-ups and for sensitive experimental data acquisition, as well as some offices, is restricted to either French or UK personnel only. These areas are marked using 'Restricted area' pictograms. The Facility Manager, acting as the French nuclear operator, may organise safety and security inspections of any part of the facility, including those areas reserved for UK personnel, submitted to UK agreement and accompanied by the UK Senior Manager (who represents the UK technical operator at the facility).

Furthermore, each nation's team carries out unshared tasks which are mainly related to the preparation of the experimental devices, their implementation in the experiment hall and the acquisition of the data produced.

Performing the experiments does imply the use of shared systems, in addition of the Axis 1 X-ray machine.

# CONDUCTING EXPERIMENTS USING ONE RADIOGRAPHY AXIS



All experiments are performed inside sealed containment vessels. The vessels are checked when they are first brought into the facility, in a shared hall designed for this purpose and in which the French and UK teams each work on their respective equipment. These vessels can then be taken into the restricted areas where the experimental devices are assembled and positioned inside the containment vessel.

**During these phases, the joint teams tasked with preparing and qualifying the beam generated by the X-ray machine, fully use this equipment** to tune the stability of the operating point chosen and characterise the X-ray source obtained. Preparing the first radiography machine at the EPURE facility for a hydrodynamics experiment is a process that takes several weeks. The required exposure time (60 billionths of a second), the precise instant of the flash (to within 3 billionths of a second), and the extremely high energy of the X-rays generated (as high as 20 MeV) are very demanding constraints that require an incredible amount of high-precision work to prepare the accelerator.

**The French and UK technicians and engineers routinely work as a single team to operate the particle accelerator.** Working as a joint team is the best way to ensure that all the challenges involved in operating such a machine and preparing experiments can be tackled together. The France-UK team boasts a vast range of cutting-edge expertise in fields as

diverse a high-energy electron pulses, accelerator physics, vacuum technology and ancillary fluids systems, alignment, I&C systems, and digitisation and synchronisation electronics.

**Joint FR-UK operational team in the EPURE facility control room.**

© CEA/DAM





## FUTURE EXPERIMENTS USING THREE RADIOGRAPHY AXES

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Once the X-ray machine is operational and the X-ray beam has been fully characterised, the experimental device inside its containment vessel can be transferred, using special equipment, from the Assembly and Integration Hall to the firing point aligned with the radiographic source. It takes several weeks to connect the containment vessel up to the firing point, align it, align the detectors with the beam and validate the entire experiment sequence, including the chronometric coordination of each diagnostics system connected to the device positioned in the containment. **Throughout this cycle, the X-ray machine is operated by the joint team, while each national team prepares and manages the experiment data.** On completing the experiment, the national team backs up the data and sends it to the manager in charge of the experiment, for processing. The containment vessel must be depressurised and then move for storage. Another cycle of experiments can then be started.

**By the end of 2022, the EPURE facility will have three radiography axes, extending the experimental resources available for the two nations** to conduct experiments involving three different angles of vision and affording various possibilities for observations over time, including, as required, either the detailed observation of a specific instant, or the observation over time of expected phenomena.

**It will be possible to take full advantage of these new resources,** taking account of effects inherent in the complexity of a multi-axis, multi-time radiography facility, effects resulting from the cross-perturbation of the X-ray scattering and electrical functioning between the three axes.

**Another of the challenges involved will be to optimise the design and scheduling of experiments and operations to prepare the 3 axes.**

