Acknowledgements

Photographs courtesy of EFDA-JET and CCFE

JET and MAST information courtesy of CCFE

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Feedback

Any feedback or comments on the format or content of this workbook is appreciated. Please forward any comments to :

Jo Silva
Education Outreach Manager
CCFE
Culham Science Centre
ABINGDON
Oxfordshire
OX14 3DB

Telephone 01235 466538
E-mail joana.silva@ccfe.ac.uk

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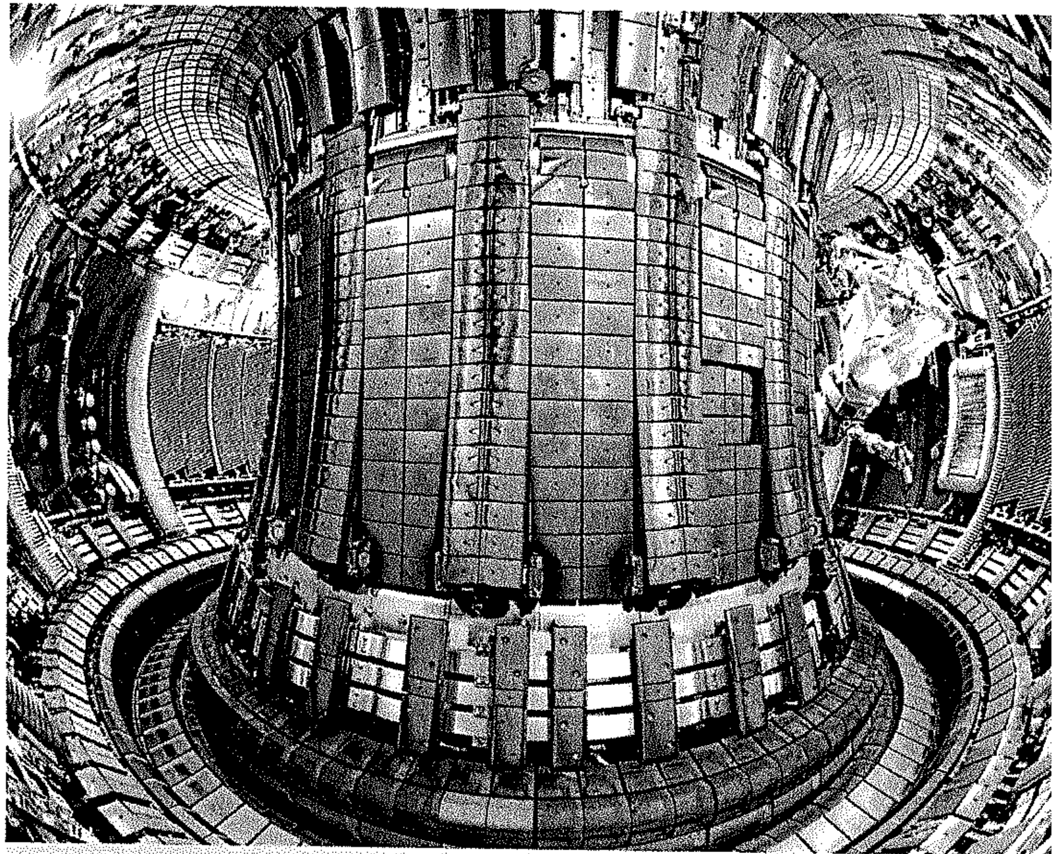
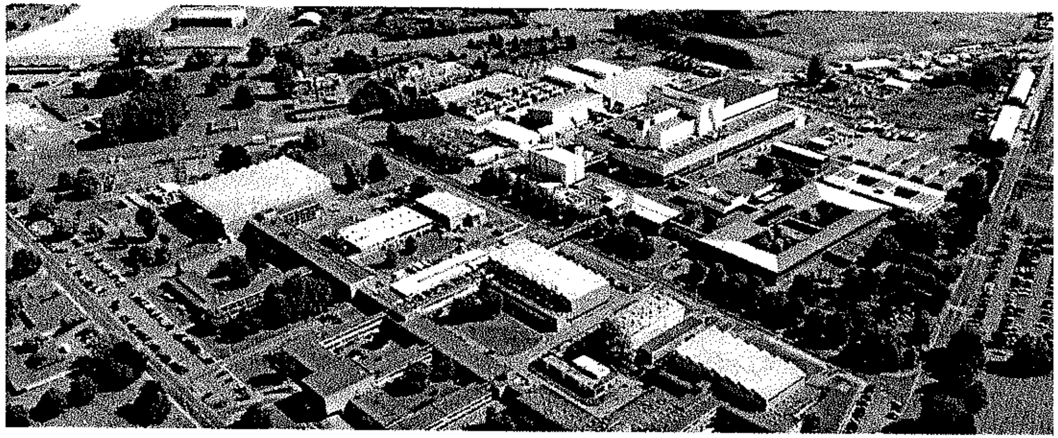
CCFE
CULHAM CENTRE FOR FUSION ENERGY

A-Level Physics Visit to Culham Science Centre



CCFE is the fusion research arm of the United Kingdom Atomic Energy Authority

Contents



An aerial view of Culham Science Centre

Message from Culham Centre For Fusion Energy

Welcome to Culham Science Centre – the UK's fusion research laboratory. We always encourage schools and colleges to visit the facilities here at Culham and learn more about a new energy source that should be playing a prominent role in the commercial energy market within your lifetime.

As the research scientists and engineers of the future, we hope to demonstrate to you – in an informal but informative way – that fusion research is leading edge and challenging. It is vitally important for our future to ensure a steady flow of quality graduates and post graduates – maybe one day one of you will be working at Culham!

I hope you enjoy your visit and – with the aid of this Work Book – take an interest in fusion research and physics and science in general.

Professor Steve Cowley
CEO, Culham Centre for Fusion Energy

Safety during your Visit

We hope you will enjoy and learn from your visit to Culham – but you are asked to follow these safety guidelines.

- If you have a pacemaker or other medical implants, you are asked to inform your teacher before the visit, who will inform CCFE

- You will be accompanied throughout all of your tour. Please do as your guide requests at all times. You may be asked to wear a safety helmet during your visit.

- In exceptional circumstances, visitors may need to co-operate with the Culham Site Emergency Plan. There will be announcements from the Public Address system on site – instructing your immediate course of action – normally taking shelter in the nearest building. Please follow the instructions from your guide as promptly as possible. If you are in the process of leaving site, you should continue to do so.

- In the event of fire or bomb alert (continuous sounder or voice alarm messages), please follow your guide to the nearest fire assembly point – normally in the Car Parks.

- Smoking is prohibited in all Culham buildings

Guidance Instructions

Who is this Work Book aimed at?

- This Work Book is aimed at GCE AS/A2 Students of Physics. Some of the information may not be in the syllabus of AS students, or common to every exam board, although all the content should be of interest to anyone wishing to further their understanding of physical processes at a research level.
- This Work Book adds to and complements a trip to Culham, putting fusion research into perspective for an A-level audience. However, a fulfilling visit to Culham is still possible if the pre- or post-visit work is only partially completed

How much time will be needed to cover all the work?

- In addition to a morning or afternoon visit to Culham, the class should need about 2 ½ hours of class time and a homework to complete all the suggested work in this Work Book.

What does this Work Book contain?

- The Work Book is split into five sections:

1. A brief introduction to fusion and the work being done by CCFE.
2. Pre-visit work. With use of the Fusion CD-ROM, this work is intended to familiarise students with all aspects of the work carried out at Culham and the reasons behind it. It will result in the students giving presentations about different areas of the fusion process.
3. Visit work. This section describes what will be seen on the visit with a few key things to think about during the time at Culham.
4. Post-visit homework. This section involves a series of exam type questions involving facts, figures and formulae related to the visit to be completed by the students.
5. Review of visit and work done. This section will review the initial presentations given by the students to consider any possible improvements.

Which parts of the syllabus are involved in the Work Book?

- Fusion research touches on many areas of basic physics:
- Definition of Power
- Resistance and Resistivity
- Transformers
- Magnetic Field Patterns
- Forces on moving charges
- Circular orbits of charged particles in magnetic field
- Uses of electromagnetic waves and the wave equation

- Superposition and interference of waves
- An application of image formation
- The relationship between the properties of a material and its application
- Cause of radioactivity, half lives and hazards
- Isotopes
- The processes of nuclear fission and fusion, and an appreciation that this involves a release of energy $\Delta E = \Delta mc^2$
- An appreciation that, for protons to fuse, Coulomb forces of repulsion must be overcome
- Use the concepts of kinetic energy and of electric potential energy, applied to charged particles, to explain why high temperatures are required for fusion
- What is meant by a plasma
- Describe how gravitational fields, inertial confinement and magnetic fields may be used to confine a plasma
- Appreciate that practical fusion reactors are under development and show an awareness of the considerable difficulties involved.
- Recall that the deuterium-tritium (D-T) reaction may be the most likely way of achieving fusion on a practical scale.
- Outline the principles of operation of a prototype (JET) fusion reactor.
- Describe how energy may be extracted from a nuclear fusion reactor.
- Describe the possible advantages of nuclear fusion as an energy source

What are the learning outcomes of this Work Book?

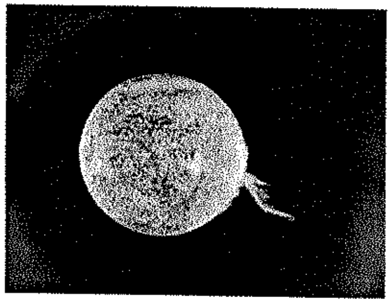
- The implications for the future of the present energy consumption and production methods.
- An understanding of fusion on an industrial scale.
- The relevance of scientific research and the impact it will have on the lives of future generations.
- The timescale over which new technologies progress.

Glossary of Terms

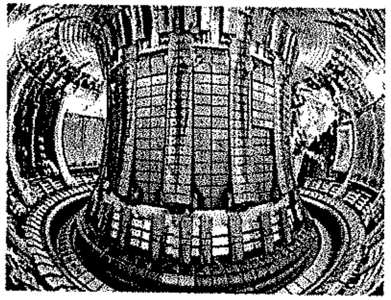
Plasma	When the temperature of a gas is raised above 10,000°C, virtually all the atoms become ionized, the electrons separating from their nuclei. The result is a complex mix of electrons and ions with the sum of all charges being close to zero. The ionized gas remains neutral throughout, and this constitutes a fourth state of matter called plasma, with a wide variety of unique features.
Fusion	The joining of light atomic nuclei to form heavier nuclei, with the release of energy. In order to fuse, nuclei need sufficient energy, hence the need for a plasma.
Tokamak	The most successful device yet found for confinement of plasma. The word is a Russian acronym for 'toroidal chamber with magnetic field coils'.
Magnetic Confinement	At the required temperature for fusion, the particles would escape in microseconds. However the charged particles in a plasma are affected by magnetic forces, and can be made to follow magnetic field lines.
JET	The Joint European Torus is the world's largest fusion research facility run as a collaboration between all European fusion organisations and with the participation of scientists from around the world.
MAST	Mega Ampere Spherical Tokamak. MAST is built to test the potential of developing spherical tokamaks for fusion power. Spherical tokamaks have potential advantages over the conventional design in terms of efficiency.

Introduction to Fusion

Q: *What does this:*



have in common with this



A: FUSION

Fusion is the process that produces energy in the sun and the stars. The temperature at the centre of the sun is 15 million °C. Our sunlight is energy produced by nuclei fusing in this incredibly hot gas.

To make fusion energy work here on Earth we have to create our own version of the sun and keep it at an even more incredible 100 million °C. At this temperature we have a plasma. In the plasma, nuclei are moving fast enough to fuse together, and we hope to capture the energy released to produce electricity.

Why do we need fusion energy?

The world we live in needs more and more energy (think of how many gadgets you have at home that need electricity to work). As the world population increases and developing countries want the same standard of living, two to three times more energy will be needed in 50 years time.

Where do we get our energy from today?

Primarily from fossil fuels (coal, oil and gas). This gives us two big problems:

1. Fossil fuels will run out. Oil prices are expected to rise dramatically in the next 5 to 15 years as it becomes more difficult to extract from the ground.

2. Fossil fuels give out harmful gases (such a CO_2) that pollute the atmosphere and contribute to the "greenhouse effect". Each year 20 000 000 000 tonnes of CO_2 are produced. We don't know enough to predict exactly what effects this will have on the world's climate, but governments are worried enough about it to try to cut down these "greenhouse gases".

In other words if we don't stop using up the world's natural energy sources we are making matters even worse for future generations – fossil fuels are "going up in smoke" forever.

What other sources of energy can we use?

Here are the options:

Renewables: Hydro, solar, tidal, biomass and wind power : water, sun and wind won't run out and don't produce harmful gases but tend to produce small amounts of energy per generator and needs energy storage facilities to provide energy non-stop.

Nuclear power: fission doesn't produce harmful gases; can supply energy non-stop but sometimes has problems with plastic confidence due to safety concerns and storage and treatment of long term radioactive waste.

Nuclear fusion: (that's where the fusion programme at Culham moves into the picture!). Fusion energy offers several attractive features:

- No harmful gases
- No long-term waste
- Fuel is cheap and easily available - 1000MW of electricity can be produced for one year using one pick-up truck loaded with fusion fuel (compared with 11 super tankers of oil, 27,000 train wagons of coal, or 100-200 square kms of solar panels).
- Safe (a nuclear fission-type meltdown can't happen).

Fusion power is still at the research stage, but with the correct investment could demonstrate electricity production in about 25-30 years from now.

The UK centre for fusion research is here in Oxfordshire. The world's leading fusion experiment JET is housed in the large white building you can see at Culham Science Centre near Abingdon. JET is the test bed for European fusion research and is visited regularly by scientists from all over Europe.

JET is operated by CCFE and its programme is co-ordinated by the European Fusion Development Agreement (EFDA). The UK's own smaller experiment MAST is also at Culham. If you want to know more about fusion research throughout the world, look at these web sites:

www.fusion.org.uk
www.jet-efda.org
www.efda.org
www.iter.org

Pre-visit work

This section provides suggested work to be completed before the Culham visit, to become familiar with the concepts, processes and reasoning behind the research being undertaken at Culham.

What to do

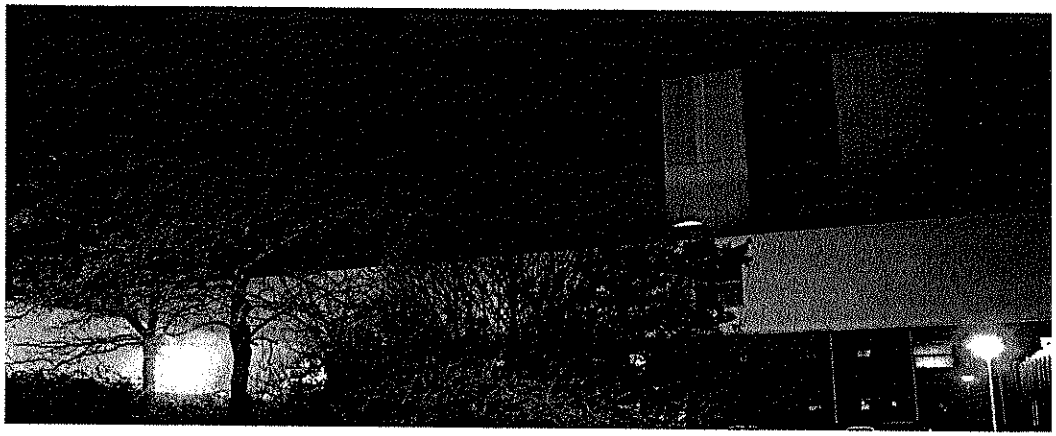
- You will be put into one of five groups by your teacher.
- Each group will be provided with a fusion CD-ROM and allocated one of five subject areas.
- Your task is to prepare a presentation to give to the rest of the class with handouts about the specific area of fusion you have been asked to focus on.
- Your presentation can be done as a Power Point presentation, a web page, or using a flip chart or OHTs, and should be at least 5 minutes long.
- In the following five pages you will find one page for your group containing questions and hints about what should be covered in your presentation.
- Use the web pages mentioned earlier in the workbook for images and extra information.
- Bear in mind anything you feel you need to know more about that can be asked about during the visit, or anything missing from the presentations.
- Your teacher will let you know how much time you have to finish this task.
- Load up the CD-ROM, find the relevant page in this book and section of the CD-ROM, and off

Fossil fuels like coal are not sustainable

GROUP ONE

CD-ROM Section:
Energy Powers our world

- What do we need energy for?
- What is the difference in energy consumption between 'Technological' man and 'Industrial' man?
- What is the average increase in energy consumption per year?
- How much of the world's energy use relies on coal, oil and gas?
- What problems do burning fossil fuels create?
- Where are most of the world oil reserves? Why do you think this is particularly relevant?
- When, if current usage continues, will each fossil fuel run out?
- What, at present, is the world's largest renewable resource?
- What are the fusion fuels?
- When could large-scale electrical production from fusion start?

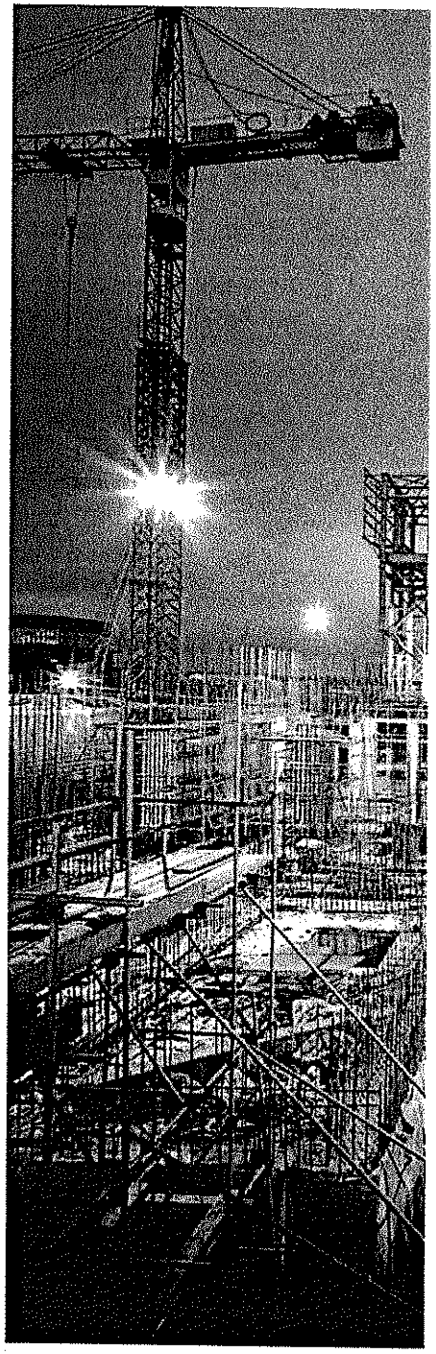


The building that houses the JET Tokamak

GROUP TWO

CD-ROM Section:
Principles of fusion energy

- Remind the class of the structure of an atom.
- What happens in the fusion process?
- Where is the energy released from?
- In what other ways do we rely on fusion reactions?
- How is fission different to fusion? In what way is fusion safer?
- Why can nuclei not usually fuse? How do extremely high temperatures solve this problem?
- What is the temperature in a fusion reactor, and how fast do hydrogen nuclei move at this temperature?
- What is a plasma? Where are they found in every day life?
- Why do plasmas need to be contained, and how is this done?
- Why are ringed shaped vessels used?
- Why is hydrogen fusion impractical? What are the reactants and products of the fusion reaction used at Culham?
- What are deuterium and tritium? Where can we find deuterium for fusion?
- If the deuterium contained in one litre of water is 'fused' with tritium, the energy released is equivalent to burning how much oil or coal?
- What is the reaction that produces tritium? Where can we find lithium?

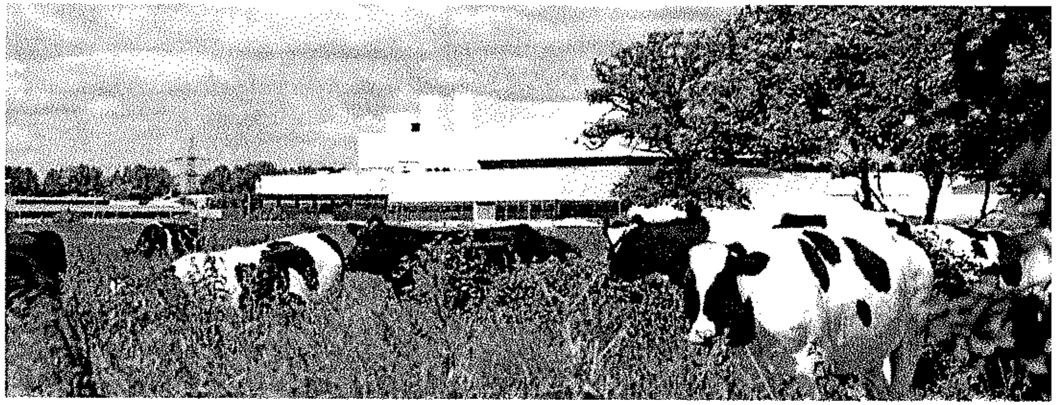


Construction of the building

GROUP THREE

CD-ROM Section:
Safety and the environment

- What are the fuels for fusion, and where can we find them?
- How much of these do you need for a developed country's citizens lifetime energy needs? Fact: At present, one citizen uses the equivalent of 6 tonnes of coal each year.
- Is there a safety risk with tritium? Explain.
- How is tritium used in other ways?
- Is the actual fusion reaction safe? This question covers 3 or 4 pages of the CD-ROM.
- How does the amount of waste from fusion compare to other types of power plant?
- What other problem is associated with waste from fusion power plants? How is this rectified? Do you feel this is OK?
- Which areas and countries are working together on fusion, and why do you think they work together rather than in competition?
- How much will fusion power cost?



The JET Building

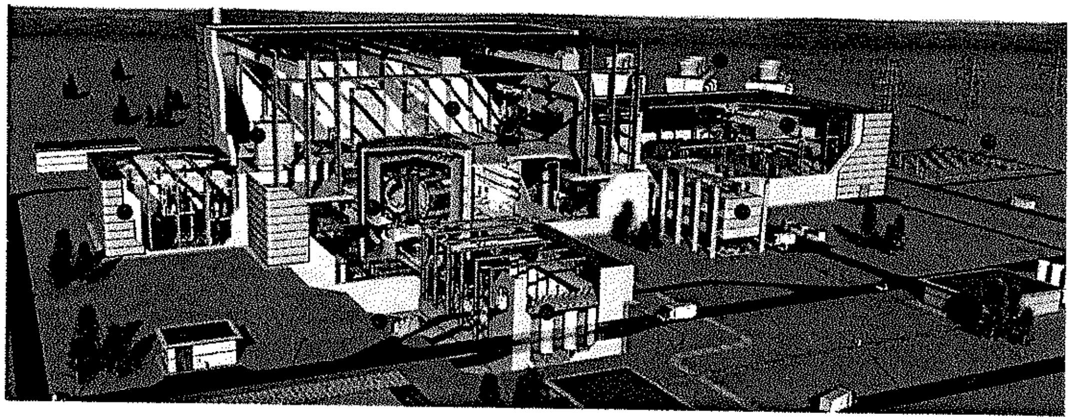
GROUP FOUR

CD-ROM Section:
Principles of fusion energy

- Sum up the history of fusion research, include:

    1. Which countries are presently involved in the ITER project?
    2. What will be the energy gain for ITER?

- What does a fusion power plant need to work? What are all its different components needed for?
- What is the plasma current? What is it needed for?
- What is the toroidal field? What is it needed for?
- How is the plasma heated?
- Which countries are involved in the next generation fusion project, ITER? Why do you think work on fusion is an international project?
- Where is the biggest fusion experiment in the world? What has it achieved so far?

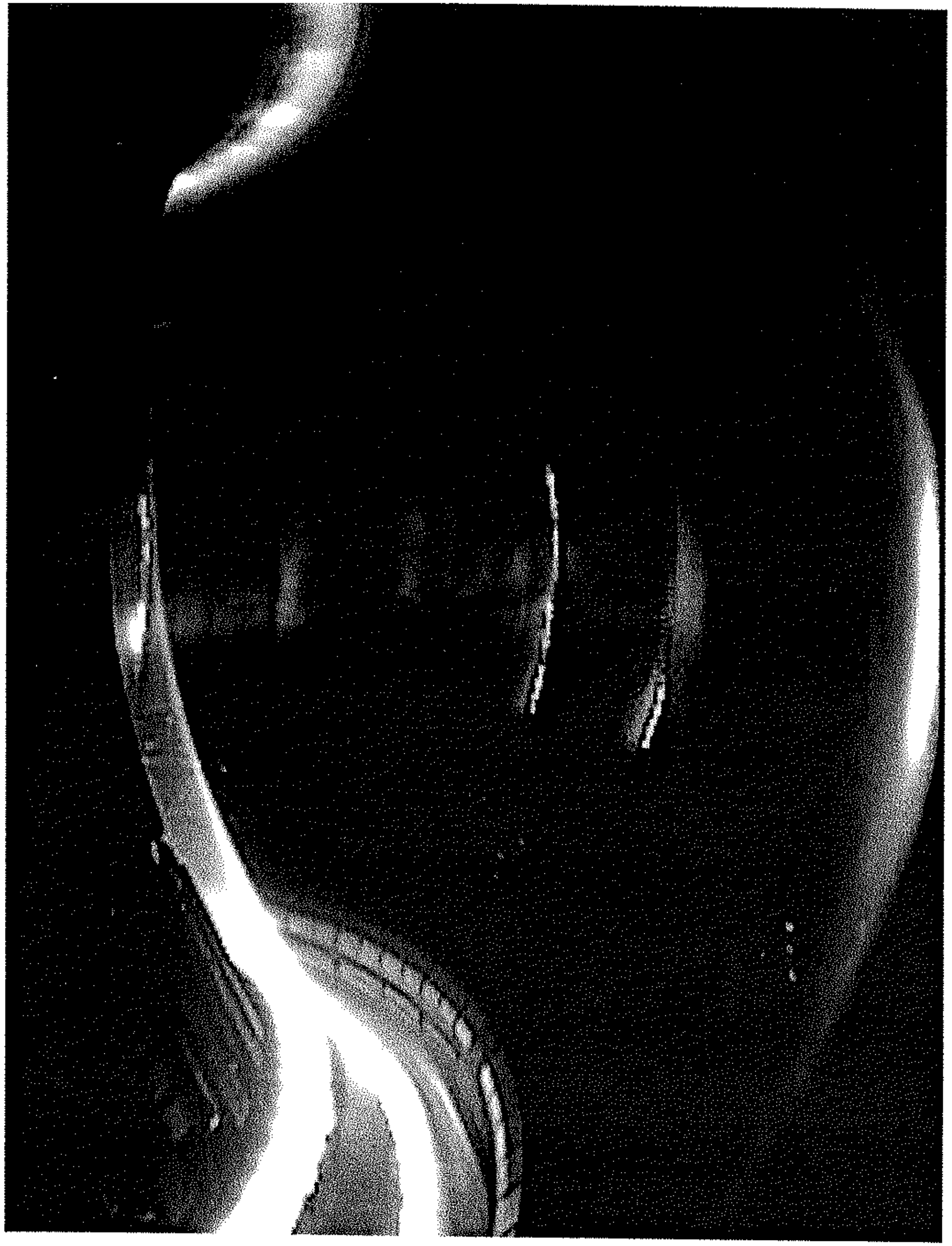


Fusion Power Plant

GROUP FIVE

CD-ROM Section:
The future of fusion research

- What does ITER mean?
- Who does it involve? What is its goal?
- How much will it cost?
- How much bigger is it than JET?
- What will be the energy gain?
- What is an extra important scientific objective of ITER?
- What sorts of technologies are involved, and what other technologies have advanced from the research?
- What are the steps in the planned life of ITER so far?
- Why do advanced materials have to be developed?
- What does IFMIF stand for?
- What is the next step after ITER, and what is the estimated timescale for the first electrical power production?
- What is DEMO short for and what will it be? How long is it suggested we will have to wait before fusion power?
- What is the predicted typical size of fusion power stations?



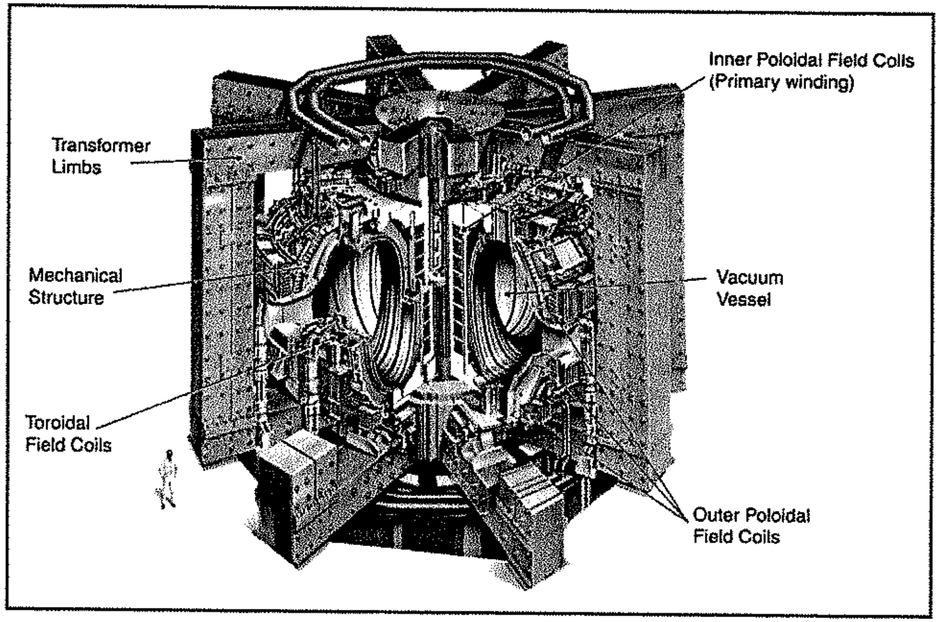
A JET Plasma

The Visit

This section provides information about the main sections of the visit, JET and MAST. It includes diagrams and descriptions of the physics involved in using the machines. You will find it useful to read this before you do your tour of Culham Science centre.

JET

The Joint European Torus was devised to make it possible to carry out tests under plasma conditions that approach those of a commercial fusion power station. Knowledge gained from this experiment will provide valuable input for the design and construction of 'next generation' devices such as ITER.



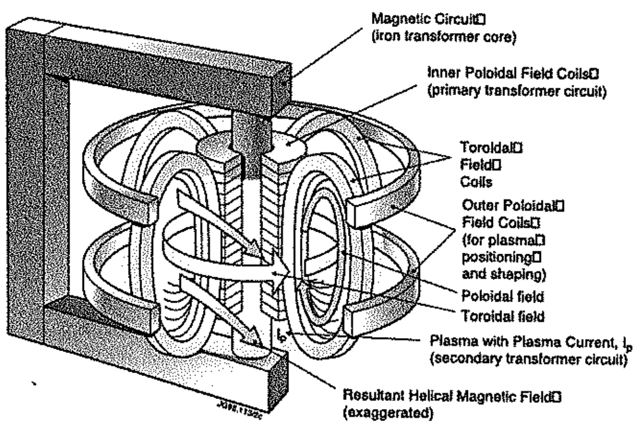
A Cutaway diagram of JET

Different magnetic fields are needed for the JET experiments. These are needed to control and confine the plasma, as well as to induce a current in the plasma, which will cause it to heat due to its own resistance.

- The toroidal component (the circular component through the Tokamak) of the magnetic field on JET is generated by 32 large D-shaped copper coils – this field (up to 4T) is the main confinement field for the plasma particles.

- The primary winding of the transformer is used to induce the plasma current (up to 5MA) and is situated at the centre of the machine. The plasma current is created by the plasma acting as a single secondary coil of a transformer, coupling with this primary winding.

- During operation large forces are produced due to interactions between the currents and magnetic fields. These forces are constrained



by the mechanical structure which encloses the central components of the machine.

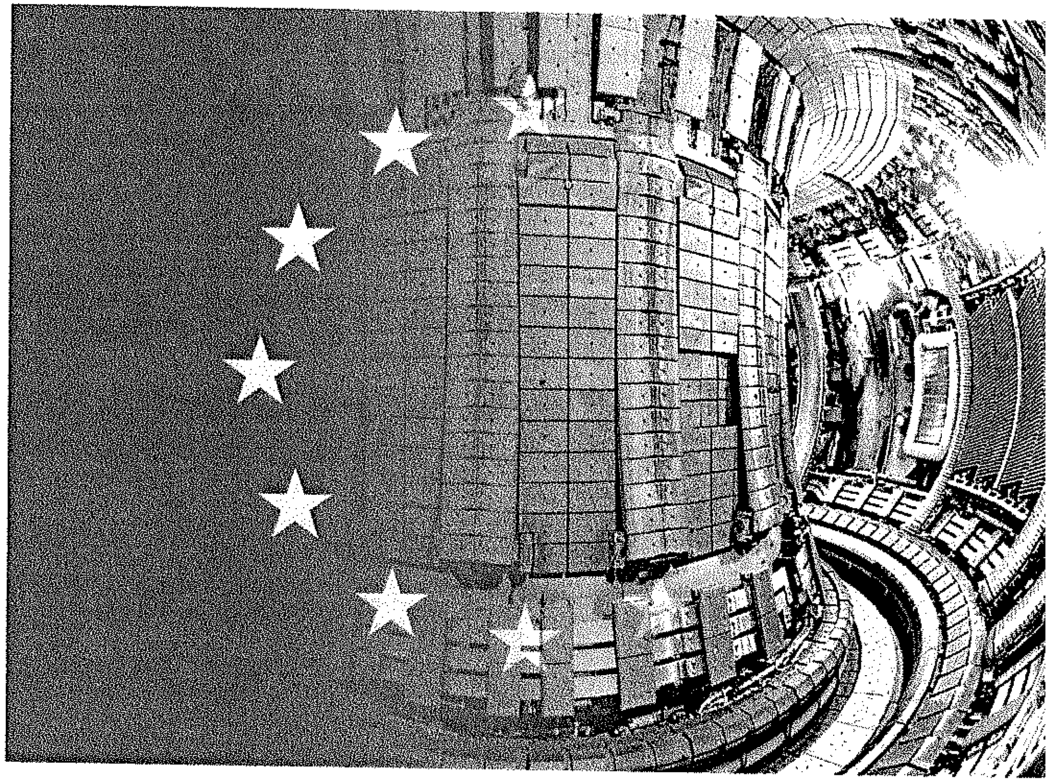
- Plasma pulses (or shots) can be produced at a maximum rate of about one every twenty minutes, and each one can last for typically 30 seconds.

- The plasma is enclosed within the doughnut shaped vacuum vessel which has a major radius of 2.96m and a D-shaped cross section of 4.2m by 2.5m.

- The amount of gas introduced into the vessel for an experimental pulse amounts to less than one tenth of a gram.

The JET Tour

The JET tour usually begins in the entrance hall and continues through two control rooms to the assembly hall.



Entrance Hall

You will see a selection of flags, a model of JET in the entrance hall & a large photo of the vessel interior.

Things to think about...

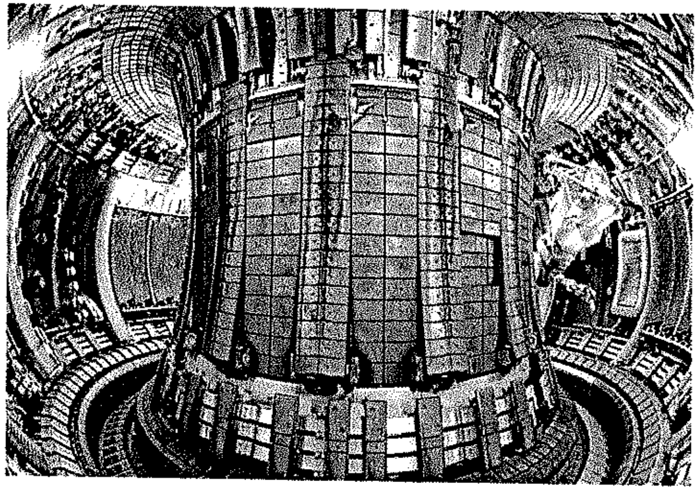
- What do the flags represent?
- Which is the flag of the home country of your guide?
- Why are there holes in the cross section of the copper coil you can see?
- How are the exhaust gases (notably helium when fusion has occurred) extracted from the plasma in JET?

JET Control Room

The JET control room is the nerve centre of the JET project.

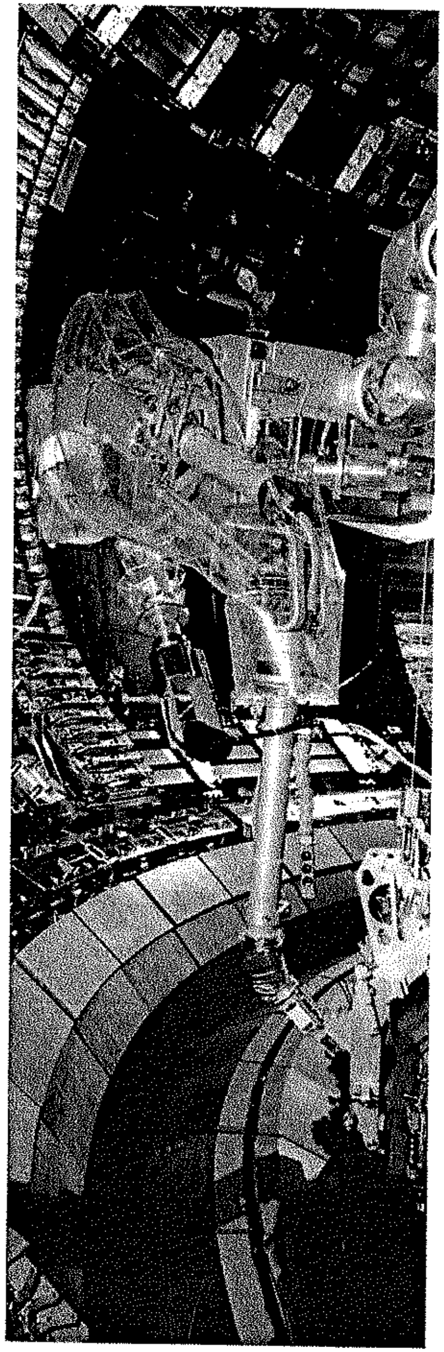
Things to think about...

- Roughly how many desktop computers are in the room?
- How much information comes into the room each time the tokamak runs?
- Which personnel are present when JET is running?
- What qualifications are needed to get a job working in this area?



Inside the Tokamak

The JET control room



The Remote Handling Manipulator on the end of the boom.

The Remote Handling Control Room

This area controls very advanced remote handling devices used to do scheduled maintenance work inside the tokamak.

Things to think about...

- Why are remote handling techniques used in the tokamak rather than people?
- How do the controllers see what the remote handling manipulator is doing? Are all of these real images? Why is false imaging used in this area?
- How are the remote handling manipulators controlled? Which sensors are used for this? What is special about what the controller feels as the screws tighten?

The Assembly Hall

This area is where all the components made for JET were originally are brought and made ready for use in the tokamak. Now, it is a massive test area. You will notice a beryllium handling facility, a mock up of the tokamak for trial purposes, and an area for the remote handlers to practise their work.

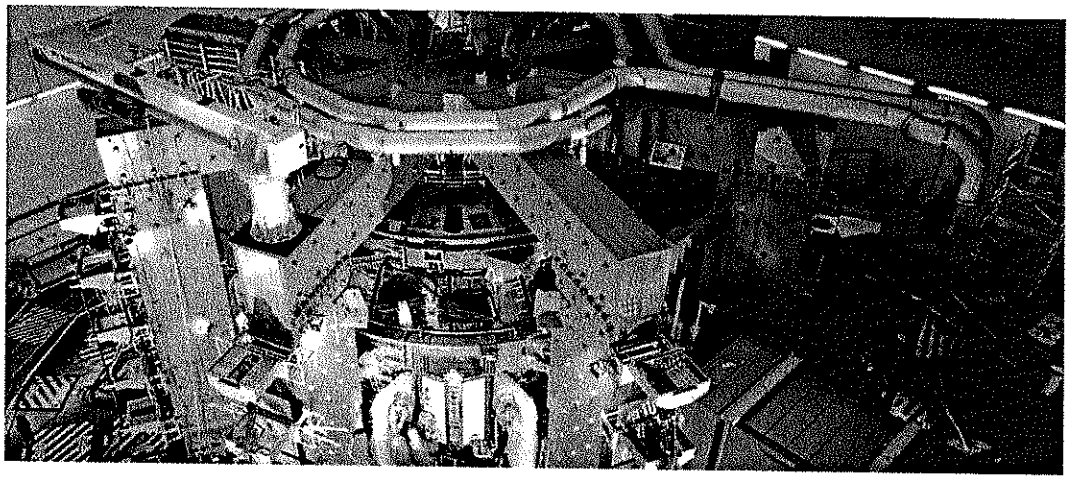
Things to think about...

- Why is beryllium used in the tokamak?
- Why does it have to be handled so carefully?
- What material is used for the inside walls of the tokamak?
- Why is this material suitable for this job?
- Why do you not want the plasma hitting the wall of the tokamak?

You may get a glimpse of JET through some very big doors if it is not in use.

Things to think about...

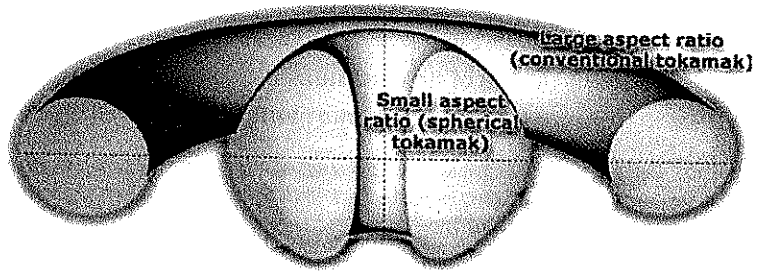
- Roughly how high is the entire JET structure?
- Why is it kept behind air locked doors when it is in use?
- How is the density of the plasma inside JET measured?



The JET machine

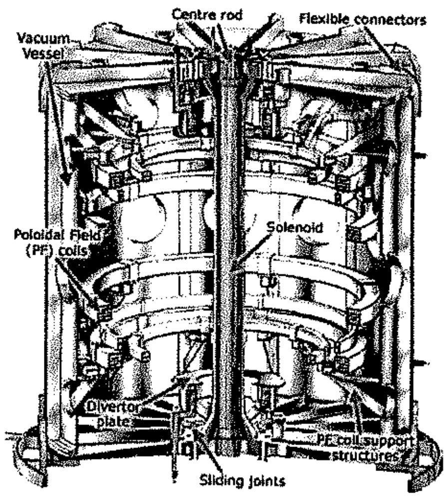
MAST

MAST stands for Mega Ampere Spherical Tokamak. In a conventional tokamak, the plasma is held in the shape of a doughnut, but in a 'spherical' tokamak the plasma shape is almost spherical.



One of the advantages of a spherical tokamak is that because it does not need to be as large as a conventional machine for the same fusion performance, it will cost less to build.
Another advantage is improved plasma efficiency. The toroidal magnetic field needed to keep the plasma stable can be a factor of 10 times less in a spherical tokamak than in a conventional tokamak carrying the same plasma current.

Although potentially attractive, there may be disadvantages of spherical tokamak designs. Notably, the narrow centre column, will need to be replaced every few years in a spherical tokamak power plant due to neutron damage.



Below is a list of some of the engineering features used in MAST's design...

Centre rod	Contains portions of all 12 toroidal field coils and a 300 turn transformer coil - used as the primary that induces the plasma current.
Vacuum vessel	Made of stainless steel. Diameter = 4m, height = 4.4m.
Poloidal field (PF Coils	Five pairs of coils used to shape and control the plasma - installed inside the vacuum vessel. Coils wound from water-cooled copper.

The MAST Tour

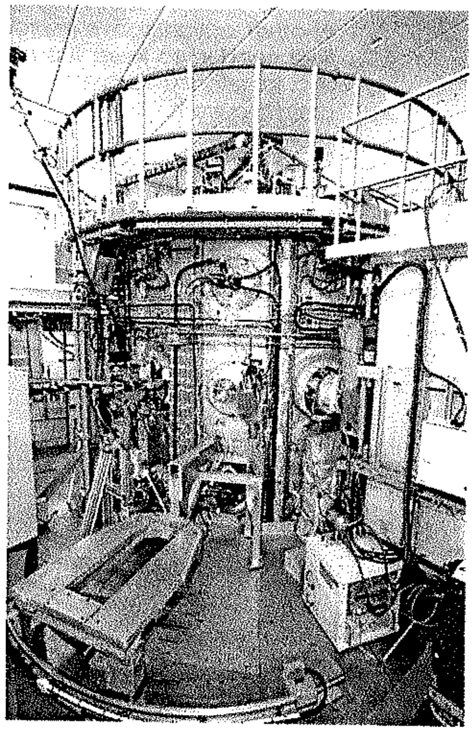
During your tour of MAST you will see a model of MAST, the control room, some of the engineering equipment used on MAST, and on non-operational days the machine itself.

MAST Model

One of the first things you see will be a model of MAST.

Things to think about...

- How does the shape of the MAST plasma compare to JET?
- Why does this shape lead to a decreased current needed for the toroidal magnetic field?
- Which material is used to cover the inner surfaces (centre column and divertor) of MAST and why?
- How is the plasma in MAST heated? Can you see where any of these



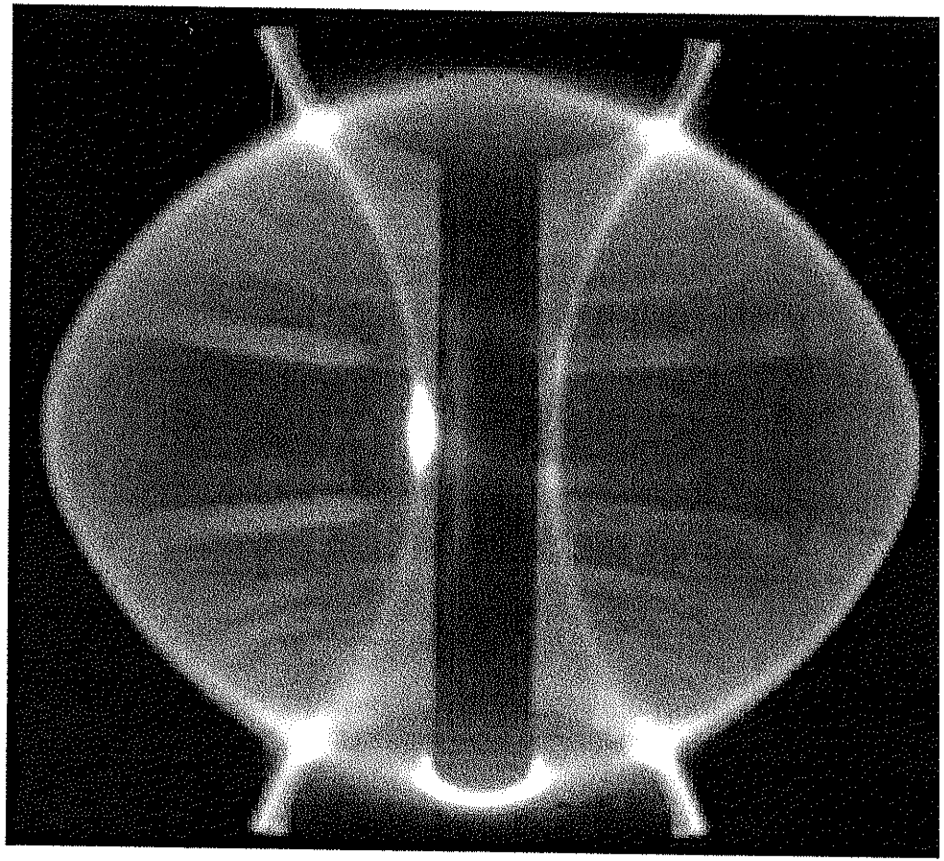
MAST machine area

The MAST Control Room

The MAST control room is the nerve centre of the MAST experiment.

Things to think about...

- Roughly how many desktop computers are present in the control room?
- Who is present during the running of the machine?
- What qualifications are needed for a job in this area?
- How often is an experiment run?
- What sorts of things are displayed on the different monitors?



A Plasma in MAST

Post - Visit Work

This section provides a chance to think back to the relevant physics seen during the tour, and answer questions, some exam style, related to the Culham visit.

Questions...

Q1: Many imaging techniques are employed on experiments at Culham.

a. Which did you come across on your tour?

b. How does each have an advantage over a person looking with their own eyes at what is happening?

Q2: Microwaves are used as one technique for heating the plasma. Some of these microwaves have a frequency of ~50MHz.

a. What does this mean?

b. What would be the wavelength of this microwave?

c. What other methods are there for the heating of the plasma?

Q3: List some of the range of sensors used in the remote handling procedures.

a. Explain how one of these works.

Q4: List some of the specialist materials used in Culham.

a. Explain how these materials are suited to their applications.

Q5: Tritium has a half-life of 12.3 years.

a. What does this mean?

b. If you have a 0.1g sample of tritium, roughly how much will be left after 100 years?

Q6: JET has produced 16MW of fusion power. This equates to a Q (fusion power out/power used to directly heat the plasma) of 0.65.

a. How much power was used to directly heat the plasma?

b. ITER is predicted to have a fusion power output of 500MW. What does this mean?

c. Q for ITER will be ~10. How much power will be used to heat the plasma in ITER?

Q7: Additional input electrical power for JET is also required for energising the magnetic field coils (in ITER this will be minimised as all the coils are superçonducting). The current drawn from the grid at 33kV is typically 7kA.

a. How much power is being drawn in a typical loading case?

Q8: The density of the plasma is found by measuring the phase shift of infared electromagnetic waves, one of which has traveled through the plasma, and one of which has traveled the same distance through air.

a. The CO_2 laser used on MAST to produce the electromagnetic wave has a wavelength of 10.6μm. What is its frequency?.

b. On MAST, one of the rays goes through 6m of plasma. When recombined with the unaffected ray, it is 3 cycles behind. How far in micrometers behind the unaffected ray is the ray which travelled through the plasma?

c. How long was the ray in the plasma delayed - to get this phase shift (i.e. how long does it take light to travel this far)?

d. How long do electromagnetic waves take to travel 6m?

e. How long did the electromagnetic wave take to travel 6m in plasma?

f. What is the speed of this wave in plasma?

g. What is the refractive index of this plasma? (n = speed in vacuum/ speed in plasma)?

Q9: In the tokamaks, the charged particles gyrate around the magnetic field lines. The magnetic field is created by the currents fed through the magnetic field coils.

The force causing the charged particles to move is equal to the product of the magnetic field strength, the charge on the particle and the velocity of the particle ($F=BQv$). This force causes the charged particles to move in a circular motion, so the force can be written as a centripetal force, equal to the product of the mass and the velocity squared, divided by the radius of the circle ($F=mv^2/r$).

a. Rearrange these formulae to produce a formula for r in terms of B, Q, m and v.

b. The charge on an electron is $1.6x10^{-19}$C, and its mass is $9.1x10^{-31}$ kg. If they are moving at $2x10^7$ms-1, what must be their radius of gyration – assuming a typical magnetic field in JET of 3T?

c. The mass of deuterium is $3.3x10^{-27}$ kg, and it moves at $1x10^6$ ms^{-1}. What is its radius of gyration in the field?

Q10: This question is about the energy produced when the D-T fusion reaction occurs. You will need to use the equation $\Delta E=\Delta mc^2$ (c, speed of light is 3×10^8 m/s).

The symbol equation for D-T fusion is:

$$D + T \rightarrow He + n$$

Particle	Mass ($x10^{-27}$ kg)
D	3.342
T	5.005
He	6.642
n	1.674

a. By working out the mass difference before and after the reaction, calculate how many joules of energy are produced per fusion reaction.

b. Show that for each kg of fusion fuel you get about $3.3x10^{14}$J. (compare this to 30MJ released upon burning a kg of fossil fuel).

Q11: This question is about the resistivity and resistance of the plasma. The resistance of a material is equal to the product of its resistivity and its length divided by its area.

$$R=\rho l/A$$

For a plasma, the resistivity changes as in the following formula, where k is a constant and T is the temperature:

$$\rho=k/T^{1.5}$$

a. What happens to the resistance of the plasma as its temperature increases?

b. At the temperatures used in the tokamaks, the resistivity of the plasma is typically 10^{-8} m. What is the resistance of a circular plasma if it has a diameter of 2.5m and a length of 20m?

c. If the current in the plasma is 5MA, what must the applied voltage be?

d. What is the heating power in the plasma with these parameters?

Follow-up Work

This section gives you a chance to revisit and evaluate your initial fusion presentations. You will discuss all of the initial presentations in your groups (1-5) following some guiding questions, then as a class brainstorm all your ideas for discussion. Your teacher will tell you how much time you have for this.

In your groups, ask yourselves the following questions. Have an answer prepared for each for discussion with the rest of the class.

- Did all the pre-visit presentations fully represent what you saw at Culham?
- What else would need to be added?
- What do you need to do more research on and why?
- What fundamental physical theories and principles did you observe in your visit? How do they interlink?
- What career paths did you observe whilst on your visit?
- Why is a degree in Physics necessary to many jobs?