MSc Fusion Energy

MCF data analysis labs - Tokamak Flight Simulator

TOKAMAK PHYSICS

Safety Hazards and Precautions:

This experiment involves computer modelling only and hence there are no specific hazards to be addressed.

Experimental Objectives:

- To become familiar with the basis of a numerical model of a complex system.
- To map out the influence of the main control parameters on the stability of the tokamak plasma.
- To think about the optimisation process of a multi-parameter, non-linear system.

Learning Objectives:

- To become familiar with the basics of tokamak physics.
- To be aware of the assumptions and limitations that apply to computer models.
- To better understand the main trends in the historical evolution of tokamaks.

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Script last updated: 27th November 2025 by Dr Clément Moissard

1. Introduction

1.1 Background

Almost all governments are now taking measures to reduce the carbon emissions from their economy and our way of life. The unfortunate events taking place in Ukraine as you are reading this also highlighted the geopolitical implications of buying gas and oil abroad and spurred - in many countries - a desire for more energy independence. This is manifest most obviously in the UK by the proliferation of both inland and offshore wind turbines. For other countries, most notably Germany, the proliferation of solar panels is extensive with it being a requirement that at least 25% of the roof of any building under construction now consists of solar panels. Similarly, solar panel technology is now being used to provide sources of light and other low-power applications such as mobile telephones across much of the continents of Africa and India. Other countries such as France rely on nuclear power stations based on the phenomenon of nuclear fission for the vast majority of their electricity. Technologies such as wave power and tidal power are also under active development.

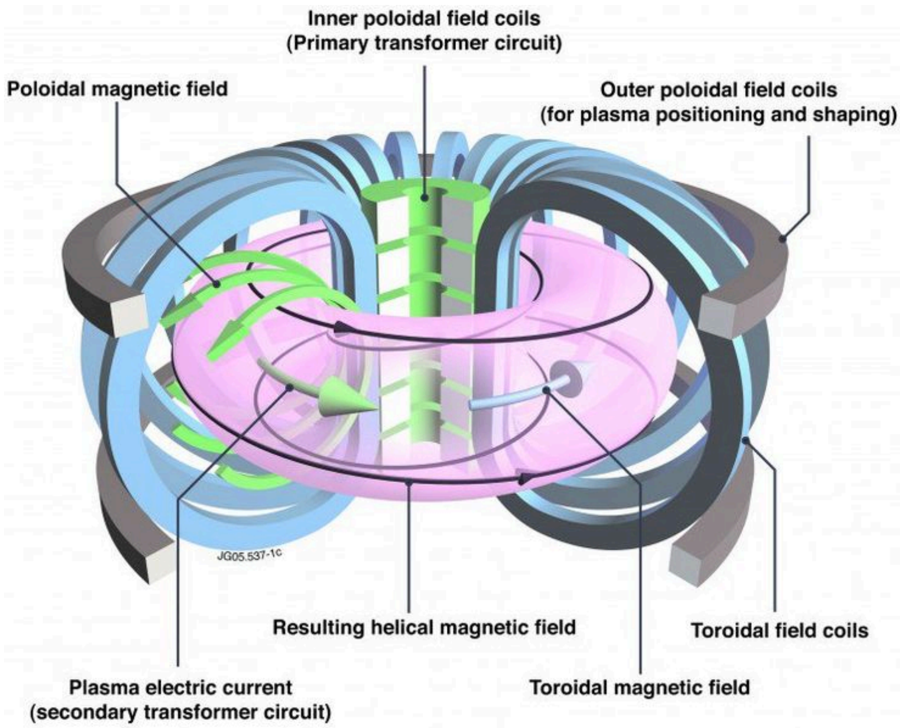

Figure 1: *Diagram of a tokamak, showing toroidal and poloidal coils, the toroidal plasma and helical magnetic field. Image courtesy of EUROfusion*

These energy sources can answer the near-term crisis of global warming and help with efforts toward not exceeding a 2^{o}C increase in the average worldwide temperature, as laid down in the Paris Climate Accord. However, in the medium to long term of this and the next century, as demand for energy seems set to continue to rise alongside electrification, a range of alternative energy sources can be considered. Among the alternatives is the concept of developing power stations based on nuclear fusion rather than nuclear fission. There are a number of advantages to using nuclear fusion energy such as the natural abundance of the fuel which is typically from isotopes of Hydrogen, *i.e.* Deuterium and Tritium, and the fact that such a system produces a very limited amount of radioactive waste which is generally only present when such a power station would need to be dismantled. The temperatures and pressures required to create nuclear fusion are extremely high, which results in the fuel necessarily being in a plasma state. The temperature of the plasma is such that it is not possible to contain it in a vessel of any known material and therefore magnetic confinement is required so the fuel does not directly come into contact with the walls. The favoured design for such a system is a toroid with sets of superconducting magnets outside. These contain the plasma according to Lorentz forces on charged particles in the presence of a magnetic field. Such machines are known as tokamaks. Figure 1 shows a schematic diagram of the overall design of a basic tokamak.

The tokamak currently holding the world record for energy production from fusion is JET – which until 2023 was in operation at Culham near Oxford in the UK. There it sits next to the UK's next-generation design for a tokamak MAST-U. For the last 20 years or so, the UK has been the focus of worldwide tokamak physics. The acronym JET stands for Joint European Torus and the facility is funded and supported by a consortium of European nations, mainly those within the EU, but also includes significant contributions and collaborations with non-European countries. In late 2021, the teams working on JET announced the impressive results of their latest Deuterium-Tritium campaign: 59MJ of thermal energy were created from fusion reactions over 5 seconds.

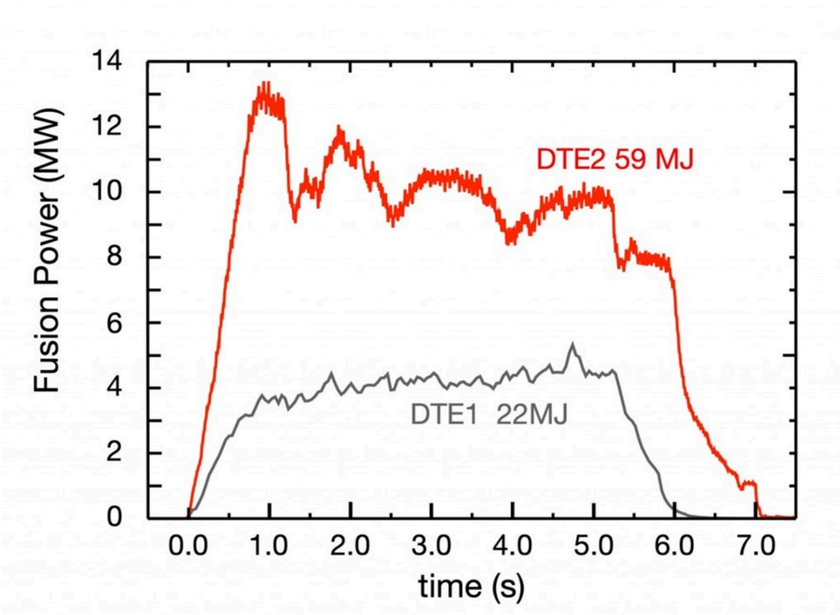

Figure 2: *The results confirm that sustained high-fusion energy production is achievable using the D-T fuel mix planned on ITER and future devices. They also show that the fusion community has the capability to model what will happen in a fusion reactor. [1]*

A worldwide international agreement to look at the development of a tokamak which would have the potential to generate a positive power output for the first time includes the original European consortium but also has significant involvement from other nations such as the United States, India, Japan, *etc.* Like CERN, the new project ITER will be in essence a United Nations project of its own kind. The School of Physics, Engineering and Technology here at the University of York is one of the leading institutions in tokamak research in the UK and possibly in any European country. The York Plasma Institute has extensive collaboration and funding from JET including a number of joint appointments and significant sponsorship for a large cohort of postgraduate students, postdocs, *etc.* It is also involved in the UK's power plant prototype tokamak design: STEP. Hence the concept of tokamak physics represents a major component of our school's activity.

In modern physics, we are confronted with trying to understand complex systems where simple, deterministic analytical models of the physical processes do not exist. In experimental physics, it is normal to apply a potential to some system and look at the resulting changes. We can then interpret the underlying processes and physics of the system. However, in many advanced systems including cosmology, plasma physics and even magnetic materials where there may be many billions of particles it is not tractable to know the form of the potential other than at an instant in time. Where such a potential is known its value will have changed in an infinitesimal period thereafter. The only way that experimental data from such systems can be interpreted is via large-scale computational models. This is particularly true in plasma physics and a significant effort in YPI is dedicated to the development and use of such models. This experiment is an exercise in which you will utilise this increasingly common technique.

1.2 Experiment Design

The experiment is designed for you to obtain and interpret numerical experiments representing the tokamak JET. The experiment will span a total of three laboratory days. First, you will become familiar with the operation of the METIS software and some basic underlying physics. The software you will use has been provided by the ITER facility which is currently being built at Cadarache in France.

The first and second parts of the experiment will be devoted to understanding the influence of important control parameters on the plasma's behaviour: How do the heating power, the magnetic field, density and current influence the stability of the plasma? In particular, you will be looking at the transition between two 'confinement modes' known as L and H modes.

In the third and last part of this experiment, you will use all your hard-earned understanding to try and optimise the yield of the fusion reactions in a *friendly* competition with your lab mates.

2. The Experiment

The JET tokamak was the largest fusion device in the world and was situated in Culham, Oxfordshire. JET holds the current record for fusion power output (16 MW), and operations on JET are a crucial preparation for ITER and future fusion power plants. In this experiment you will carry out experiments on JET using a "flight simulator" called METIS and use the resulting data to understand some of the issues and compromises which experimentalists must make when operating a tokamak.

The METIS code was developed at CEA, the French atomic energy agency, as a cut-down version of the CRONOS modelling suite. METIS and CRONOS are being used to plan fusion experiments on ITER, the next fusion device being built at Cadarache in France. METIS can quickly perform parameter scans to find promising starting points for CRONOS simulations. These simulations are becoming increasingly important to fusion research for the planning of experiments and developing an understanding of how to operate a thermonuclear "burning" reactor safely whilst operating at close to its limits.

Part 1: Introduction to METIS & influence of Pnbi

The text below is provided as a reference, but your first action should be to watch and follow this step-by-step video by Dr Ben Dudson. (Notes: Headphones are recommended - the captions were automatically generated, and while very entertaining, they may not be extremely useful).

Go the University's VDS and open METIS (in Faculty Apps).

All the simulations will be based on the configuration of the JET tokamak in Culham. METIS simulates a single tokamak 'shot' in which the plasma is heated and confined for several seconds. Initiate the METIS program (metisPC64.exe). Click 'load' and choose the following file: defaultjet.mat.

The user interface of METIS has several features. Under the Metis ribbon simulation, data/settings can be saved or loaded as .mat files. Waveforms & data edition offers the main method for adjusting parameters of the tokamak to be simulated such as plasma current (Ip) or toroidal magnetic field (B0). Parameters in the 'Metis' ribbon allow for finer adjustments, however, almost all of them will not need to be changed from the default values.
Simulations are initiated with 'Run METIS' under the Command ribbon. Run METIS using the default setup as an example. All graph windows that appear can be ignored.

For this experiment, the three methods of visualising METIS data to focus on are 'Overview', '2D equilibrium' and most importantly the 'Data Browser'. Investigate each screen to familiarise yourself with how the simulation operates.

- *'Overview'* shows the time-variation of parameters during a shot, such as power supplied to the plasma. NBI current and NBI power are of most interest here.
- *'2D time evolution'* (under 2D equi) shows a cross-sectional view of the confined plasma and the variation of parameters such as temperature, safety factor and beta over time. (Less useful for quantitative measurements but still conveys a lot!)
- *'Data browser'* is used to view parameters of interest in the plasma such as temperature or ion density quantitatively. Their variation with time can be seen, in addition to radial profiles at any chosen time. An example is given in Figure 2.

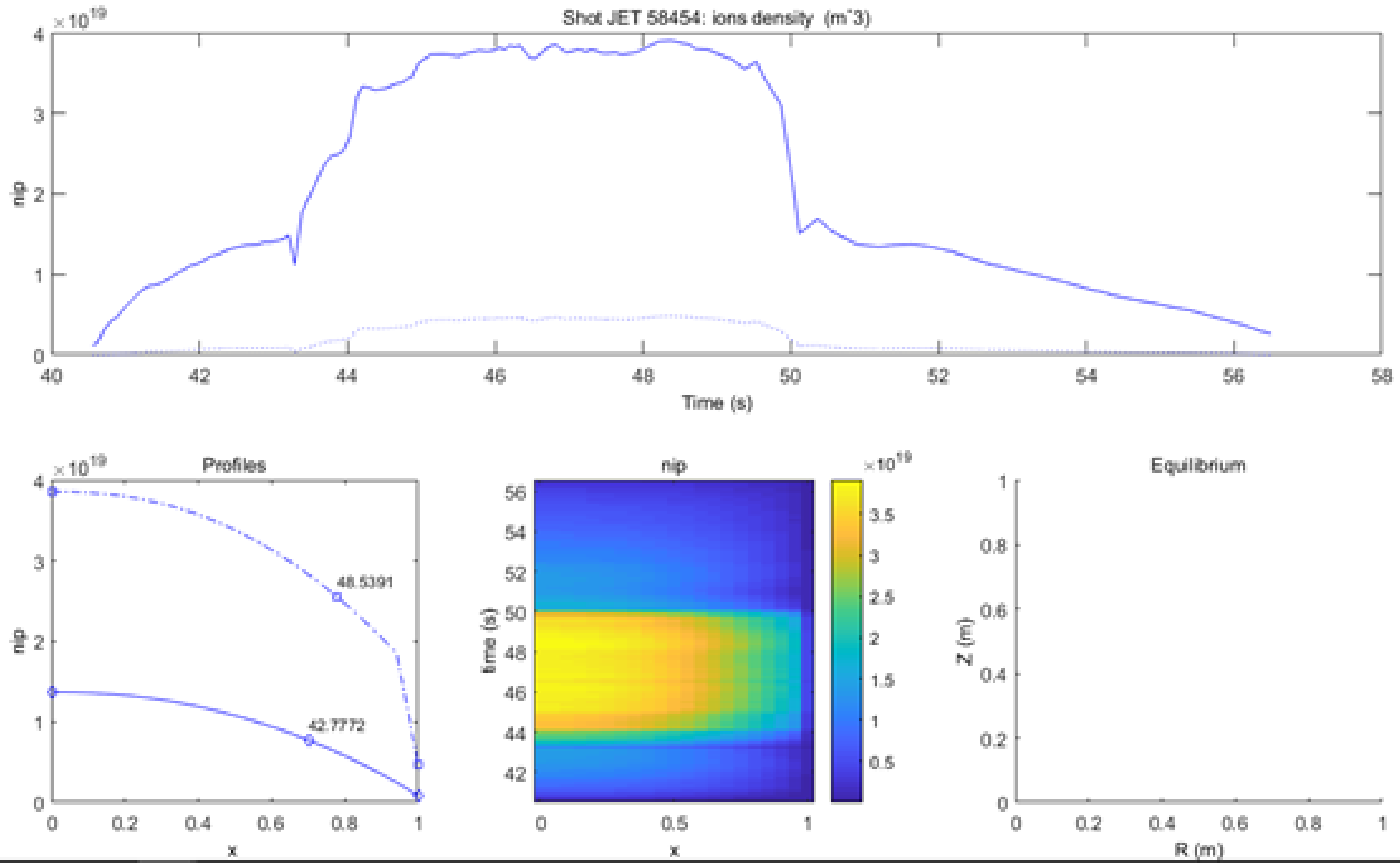

Figure 3: *Time-variation and radial profiles of ion density in Data Browser (default JET)*

Several useful features of the Data Browser are as follows:

- Parameters are chosen from alphabetical lists under ‘Metis0’ or ‘Metis Profiles’.
- Time-varying profiles generally show the parameter’s value at the centre of the plasma (x=0) unless otherwise stated in the parameter name.
- The data cursor tool is used to obtain numerical values along any profile/graph.
- Radial profiles are made by selecting the tick-box left of the *time* graph and then selecting a time on the graph using the mouse.
- Several radial profiles at different times can be plotted by selecting the tick-box left of the *profiles* graph and then selecting another radial profile to plot.
- The 2D time-radius parameter space plot allows you to observe the radial profiles of the parameter at a glance.
- Under the commands tab:
    - ‘Plot equilibrium’ plots isoflux lines of the confined plasma at a chosen time.
    - ‘Hold onto time traces/profiles’ allows you to plot two different parameters on the same axes e.g. ion density and electron density for comparison.

When measuring parameters in the Data Browser it is more representative to take an average of several times during the ‘beam on’ portion of the shot. Alternatively taking single values at a fixed time can suffice if this is difficult.

Save this default setting simulation. This will save both the data and the tokamak settings used. You are advised to **save** (not export) all data/simulations you perform with sensible and systematic filenames to make later reference easier.

You can use the following [Python Script] to extract the data from the output files from METIS.

Changing the Input Parameters

Input parameters are varied by changing their corresponding waveforms. As an example select the 'NBI' parameter under the Waveforms ribbon. Two time-varying profiles will appear each showing how the power supplied to the plasma by the NBI varies throughout the simulation. NB: *two* profiles appear for NBI simply because there are two independent power injectors in the tokamak.

The simplest way to change this waveform is to change the y-axis multiplier by a known factor e.g. 0.5x, 2x, etc. Alternatively, individual data points of the profile can have their x, y values changed manually for finer adjustment.

It is recommended that parameter adjustments are made by simply reloading and then changing the multiplier of the *default* waveform shape. The input value of this parameter can be taken as the average of points along the top of waveform i.e. for the 'on' portion of the shot. Alternatively the data browser can be used. NBI is best measured using data cursors on the 'Overview' plots.

Some parameter names of interest:

ip	Plasma current
pnbi	NBI input power
frnbi	Fraction of NBI power absorbed in the plasma
modeh	Confinement mode: 0 = L, 1 = H
betan	Normalised total plasma beta
betap	Poloidal beta
taue	Confinement time
nbar	Average fuel density
ne0	Central plasma electron density
te0	Central electron temperature
pfus	Heating power due to fusion alpha particles
sext	External plasma surface area
vp	Plasma volume
W	Total plasma energy

The experiment: Power Injection and the H-Mode

Perform several simulations sweeping a range of values for Neutral Beam Injection (NBI) power. Measure values for **number density** and **temperature** of ions and electrons in addition to energy **confinement time** and **beta** (ne0, te0, taue and betan.)

The NBI system in JET can inject approximately 25 MW of heating power and in addition there are microwave heating systems which can inject a further 5-10 MW. A reasonable range of heating power to explore is 0 to 40 MW. A particularly interesting region of this range is below 10 MW.

Plot the ne0, ni0, te0, ti0, taue and betan parameters as a function of NBI power to see their variation. Are there any notable features in these plots? Comment on the variation in confinement time with NBI power, and how this relates to the confined plasma being in H-mode. Checking the parameter 'modeh' in the data browser may be useful here. Can you suggest a reason for the behaviour of the confinement time at high power? Calculate the triple product $n\ T\ \tau_E$ (should you use ne0 and Te0 or ni0 and Ti0? why?) and compare the value obtained to the theoretical values for ignition.

Are there any additional questions you think may be interesting to answer? Why not make some up and explore?

Part 2: Influence of B_0, I_p, N_{bar}

Perform investigations of the effect on confinement time and the triple product, of varying the toroidal field (B0), plasma current (Ip) and average fuel density (nbar) within the limits specified in the table below - which correspond to the limits of JET.

Comment on how the safety factor changes with plasma current or toroidal field.

Machine parameter	**Limits**
NBI input power	40 MW
Plasma current (Ip)	5 MA
Toroidal magnetic field (B0)	4 Tesla
Density	Research the Greenwald limit!

Are there any additional questions you think may be interesting to answer? Why not make some up and explore?

Part 3: Further investigation & Maximising the Triple Product

The final part of this lab is more open-ended and is a challenge. What is the highest triple product ($n_i\ T_i\ \tau_E$) you can achieve given the following limits on the maximum plasma current, toroidal field and input power?

You should consider how the threshold power for access to H-mode depends on the plasma density and magnetic field, and document your reasoning.

Are there any additional questions you think may be interesting to answer? Why not make some up and explore?

References

[1] Image courtesy of UKAEA (https://www.iter.org/newsline/-/3722)
[2] "Tokamaks" by Wesson, chapter 6
[3] "Tokamaks" by Wesson, section 3.15, 6.18
[4] "Tokamaks" by Wesson, sections 4.12 and 4.13