MCF Lab: Tokamak “flight simulator”

INTRODUCTION

The JET tokamak is currently the largest fusion device in the world and is situated in Culham Laboratory in 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.

All the simulations will be based on the configuration of the JET tokamak. METIS simulates a single tokamak ‘pulse’ in which the plasma is formed and confined for several seconds.

Initiate the METIS program from within the Virtual Desktop Service - https://workspace.york.ac.uk/RASHTML5Gateway/#/apps (you can search for the MetisPC64 app). Select JET from the list of available tokamak configurations and then load the default configuration 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-dependence of parameters that the shot length, 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, Q safety factor and beta in real-time. This is less useful for quantitative measurements.

- *'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.

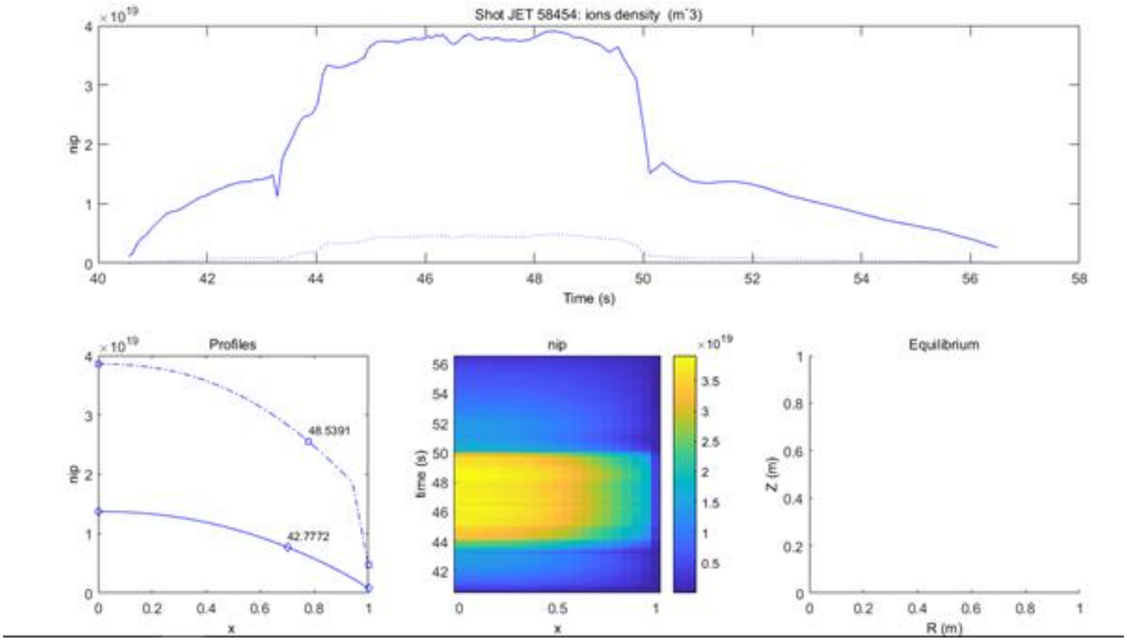

Figure 2: Time-variation and radial profiles of ion density in Data Browser (default JET)

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 '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 all data/simulations you perform with sensible and systematic filenames to make later reference easier.

Changing 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.

Power Injection and the H-Mode

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	Line averaged plasma electron density
ne0	Central plasma electron density
te0	Central electron density
pfus	Heating power due to fusion alpha particles
sext	External plasma surface area
vp	Plasma volume
W	Total plasma energy

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.

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 zero to 40 MW. A particularly interesting region of this range is below 10 MW.

Plot the ne0, te0, taue and betap parameters as a function of NBI power to see their variation. Are there any notable features in these sweeps? 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 $nT\tau_e$ triple product and compare the value obtained to the theoretical values for ignition.

Access to H-mode

The high confinement operating mode (H-mode) was discovered accidentally and involves the self-organisation of the plasma into a state with better confinement. There is a minimum input power threshold needed to access H-mode called the L-H transition threshold. This threshold depends on many parameters but in particular the plasma area, toroidal field and plasma density.

This is an important problem for magnetically confined fusion since achieving H-mode is required before significant fusion power can be produced. This power must come from external heating systems so if high power is needed then this becomes expensive. Predictions of the H-mode threshold power determine the heating power needed for ITER. These NBI systems are themselves large and complicated and the subject of continuing research. The NBI system for ITER will consist of three injectors delivering 33 MW of 1 MeV ions. Each approximately 15m long and 5m across.

Perform investigations of the effect on confinement time and the triple product, of varying the toroidal field (B0), plasma current (Ip) and average density (nbar).

Perform scans of NBI power using different values of average density or toroidal field (values larger than the default are recommended here). Comment on the power needed to enter H-mode in each case.

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

Try to understand how the threshold for H-mode varies with control parameters, running experiments as they would be done on a real experiment.

Power ramp experiments

One of the limitations of running a real experiment is that the number of JET "pulses" is very limited. On a good day JET may run 25 pulses so an experiment will usually get fewer than 10 pulses out of which to extract useful results. Here you will determine the confinement time as a function of the power input. For this study rather than running a separate simulation for each power, you will change the power to be increasing the input time. By comparing the results from this method to your earlier result, you will be able to estimate the systematic errors due in this experimental method. This is an example of the use of simulation to estimate systematic errors.

Open the 'NBI' parameter under the Waveforms ribbon as before. Now manually edit the data points by clicking on them and changing their values. Change the shape of the waveform so that the NBI heating starts at 0 MW, and increases in time. Try to cover the range from 0 to 10 MW in a small number of pulses.

There are a few other issues that you should keep in mind:

- Other quantities of interest such as the magnetic field B0, plasma current (Ip) and density (Nbar) may be changing in time. You should try to keep the power ramp in the "flat top" time range where these other parameters are approximately constant.
- There is a time delay between changing the amount of power being injected and changes in the plasma profiles.
- Many plasma properties cannot be changed independently and will respond in a nonlinear manner to changes in the control parameters.

For each pulse run the simulation then measure the confinement time at several points in time along with the NBI power at that time. Plot these values and compare them against the values you got previously.

Try varying the rate at which the power is increased, measure the confinement time, and compare the values you get for different power ramp rates. Comment on how fast the power can be varied without significantly changing the results. You can calculate a timescale for the power variation by using the following expression [hint: check the dimensions].

$$\frac{1}{\tau} = \frac{1}{P}\frac{dP}{dt} \tag{8}$$

How does this timescale relate to the confinement time, or other timescales in the system?

From these results make an estimate of the errors in the measurement of confinement time and H-mode threshold power due to the need to ramp parameters in experiments. What other effects might constrain the design of the experiment?

Extensions and further investigation

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

Machine parameter	**Limits**
NBI input power	40 MW
Plasma current (Ip)	5 MA
Toroidal magnetic field (B0)	4 Tesla

You should consider how the threshold power for access to H-mode depends on the plasma density and magnetic field and document your reasoning. A hint is that at high density the power threshold increases, but if the density is too low then the efficiency of the neutral beam injection drops (because of so-called "shinethrough")