First Year Interim Report

The Motional Stark Effect Diagnostic:

Measurements on MAST-U

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Abstract

The measurement of key plasma parameters and conditions is essential for optimizing the performance of tokamak plasmas, particularly on the road to commercial fusion power plants. In particular, tokamak performance can be severely limited by impurities entering the plasma.

Contents

Chapter 1

Introduction

1.1 Fusion Energy

Light elements, such as isotopes of hydrogen, can fuse together under high temperature and pressure conditions to release energy and form heavier elements. The dominant fusion mechanism in the sun occurs on an extremely slow timescale, on the order of a million years. Two protons fuse into a deuteron and release a positron. A third proton then fuses with the deuteron to produce a light isotope of helium ^{3}He. The final step includes fusing two light helium nuclei to create ^{4}He and two protons, which further the chain reaction. A practical fusion system reliant on proton-proton fusion is unfeasible; the cross section of the reaction is, albeit acceptable on the scale of the dimensions of the sun, too small to generate enough power to sustain a fusion reactor on Earth. The cross section of the reaction characterizes the likelihood of collisions, given the energy of the reactants [1]. The fusion reaction which is most favoured for use in fusion reactors is between deuterium (D) and tritium (T),

$$\mathrm{D} + \mathrm{T} \rightarrow^{4} \mathrm{He} + \mathrm{n} + 17.6\mathrm{MeV} \tag{1.1.1}$$

The cross section σ for this reaction is small at low deuteron energies, due to electrostatic repulsion from the coulomb barrier, but quantum tunnelling allows particles at lower energies to overcome this.

Maximizing fusion energy output is not as simple as just maximizing the fusion cross section alone. The scattering cross section for Coulomb collisions is much greater than the fusion cross section. Therefore, we require a Maxwellian distribution with a width determined by the thermal velocity of the particles within the plasma to conserve their kinetic energy,

$$f_M(\mathbf{r},\mathbf{v}) = \frac{n(\mathbf{r})}{[2\pi v_{th}^2(\mathbf{r})]^{\frac{3}{2}}} \exp(\frac{-v^2}{2v_{th}^2}) \tag{1.1.2}$$

The reactivity $< \sigma v >$ is defined by taking the integral of the Maxwellian distribution over all velocity space, which is a function of the mass and temperature of the plasma particles. The confinement time of the plasma τ_E is given as the ratio of the total energy stored in the plasma U to the energy loss E_L, $\tau_E = \frac{U}{\mathrm{E_L}}$ and is also dependent on temperature. This means that if we further increase the temperature, reactivity increases hence more fusion reactions will occur but this results in poor confinement time due to increased energy loss and a decrease in fuel density. Energy is lost from the system in the form of radiation (mostly bremsstrahlung); a steady state plasma would require this loss to be balanced by heating power, which could either be externally applied or from the plasma itself [2]. In tokamaks, ^{4}He alpha particles can provide the necessary heating granted that the temperature of the plasma is high enough for significant fusion yield. This leads to the Lawson criteria, or triple product, which maximizes confinement time τ_E, the temperature of the distribution T and the particle density n,

$$nT\tau_E = \frac{12}{<\sigma V>}\frac{T^2}{E_\alpha} \tag{1.1.3}$$

which is approximately equal to 3x10 ^{21} m $^{-3}$ keVs for a tokamak reactor operating in the range of 10-20keV, confining 10^{20}m^3 for on the order of a few seconds. The Q factor is an important performance parameter to measure the efficiency of a fusion reactor, which is the ratio of the fusion power output to the external heating required,

$$Q = \frac{P_{out}}{P_{ext}} \tag{1.1.4}$$

For a reactor to break even, this requires Q=1. In the case where the triple product requirement is met, then external heating power can be turned off and fusion is sustained through internal alpha heating, corresponding to the limit Q $\rightarrow \infty$.

1.2 Tokamaks

1.2.1 Plasma Confinement

How is it possible to confine a plasma? The most successful attempts so far use magnetic fields in a device known as a tokamak; a large cylindrical solenoid shaped into a torus so to avoid ends and improve plasma confinement. The tokamak co-ordinate system (R,Z,ϕ) is shown in Fig. 1.1. The major radius R of a tokamak is defined from the toroidal axis to the center of the plasma. The minor radius r is defined as the radius from the magnetic axis. The radius of the plasma is denoted as a, from which we can define an aspect ratio R/a. The toroidal aspect ratio gives a measure of "fatness" of the torus.

Toroidal field coils are shown in Fig.1.3, which wrap around the torus and produce the toroidal magnetic field B$_\phi$. A toroidal plasma current is generated by ramping current

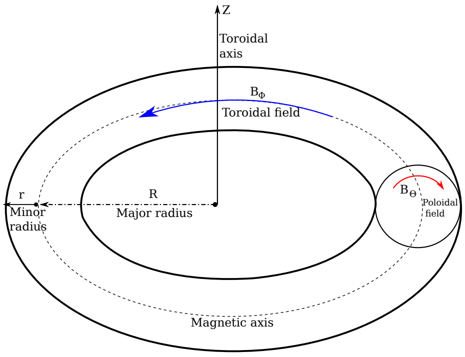
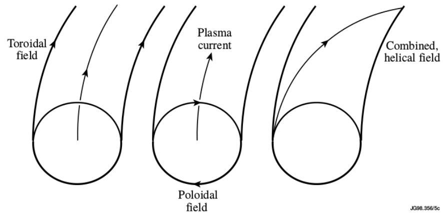


Figure 1.1: Tokamak reactor showing machine co-ordinates (R,Z,ϕ) and some defining features of a tokamak.

[fig:tokamakgeometry]



[fig:fields]

Figure 1.2: Representation of helical magnetic field structure from combining B_θ and B_ϕ.

through the central solenoid located on the toroidal axis, which is equivalent to a transformer. The change in flux induces a toroidal electric field that drives a plasma current due to opposing toroidal flow of ions and electrons. This plasma current further generates a poloidal magnetic field B_θ. Finally, further poloidal field coils are added for plasma shaping and control. B_θ and B_ϕ combine resulting in helical magnetic field lines, shown in Fig. 1.2.1 . Particles are confined along these field lines due to the Lorentz force. The magnitude of the toroidal and poloidal components of the magnetic field vary depending on position within the tokamak, however they do not overlap. This means each magnetic flux surface has a particular ratio of poloidal to toroidal field, which is known as the the safety factor q. It is possible to find the value of q as a function of major radius R, known as a q profile.

1.2.2 The Mega Amp Spherical Tokamak (MAST)

MAST is a tight aspect ratio ($R_0/a = 1.5$) spherical tokamak which can achieve plasma currents of up to 2.0 MA.

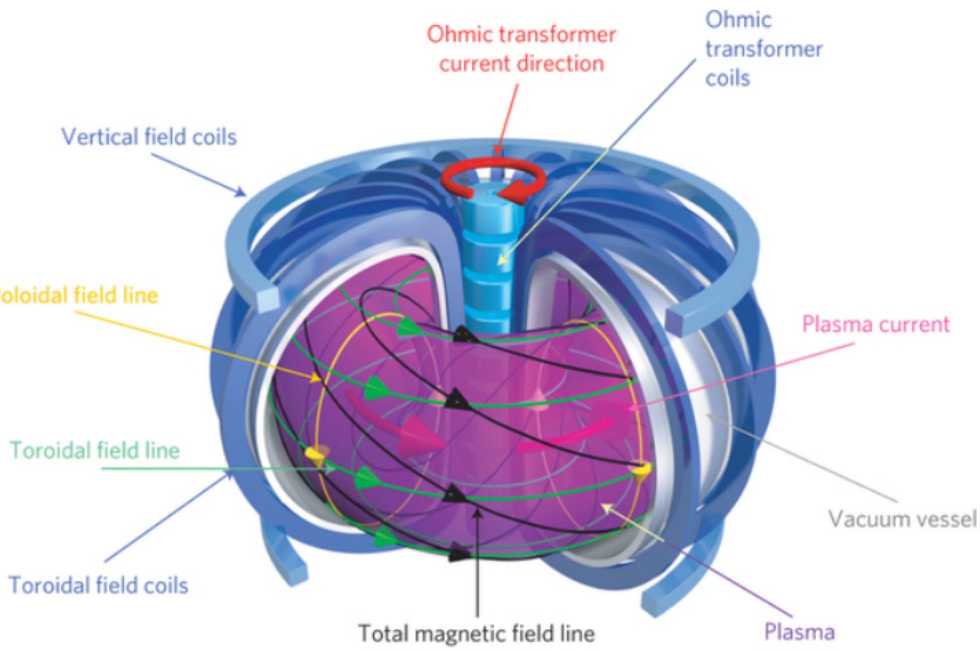


Figure 1.3: Example of a spherical tokamak with field coils and the respective magnetic fields they produce [3].

[fig:ST]

MAST Upgrade

An upgrade to MAST (MAST-U) is almost completed, with first physics set for early 2018. The upgrade features include new divertor configurations such as the Super-X which stretches out the leg to R=1.5m. Divertor geometry and exhaust physics are key research areas important to the success of ITER and fusion power plant designs. Another key mission for MAST-U is understanding plasma stability and performance limiting Edge Localised Mode (ELM). ELMs reduce the achievable pulse length, therefore they need to be mitigated. This can be achieved through accurate edge measurements of the current density j_ϕ and q profile. Instabilities within the plasma arise when q is irrational, which motivates the requirement for real time control and tailoring of q profiles. Combining measurements from diagnostics with stability analysis codes can provide greater understanding of the conditions for stability and potentially reconstruct the magnetic field within the plasma.

1.3 Plasma Diagnostics

Plasma diagnostics are vital for information on key parameters which determine

1.4 Motional Stark Effect Diagnostic on MAST-U

The Motional Stark Effect (MSE) diagnostic is a key beam spectroscopy diagnostic. Fast neutral particles from the neutral beam heating system transverse across the magnetic field. They experience a Lorentz electric field $\mathbf{E} = \mathbf{V} \times \mathbf{B}$ in their rest frame. The Stark effect causes wavelength splitting of the Balmer series, whereby the light emission is polarized with respect to the radial electric field in the plasma E_R, depending on the change in magnetic quantum number between the degenerate stark states. The MSE diagnostic measures the direction of emission linearly polarized perpendicular to the electric field which is related to the magnetic pitch angle γ_m. Therefore, this diagnostic can give insight into the current density derived from measurements of magnetic pitch angle and also the q profile across a plasma.

Chapter 2

MSE Theory

2.1 Stark Effect

2.1.1 Motional Stark Effect

Hydrogen atoms are injected into the plasma via a neutral beam heating system with a particular velocity distribution.

what is MSE/how is it different to linear stark effect parabolic co-ordinates and why we use the parabolic quantum numbers diagram of the MSE states

Chapter 3

MSE System on MAST-U

3.1 Setup

3.1.1 Filters

3.1.2 Photoelastic Modulators

Chapter 4

MSE in Context

Chapter 5

Summary

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[3] J. Ongena, et al., *Magnetic-Confinement Fusion*, Nature Physics, **12**(5), (2016), 398-410.

Appendix A

Appendix