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External Kink Modes in Shaped Tokamak Plasmas

by

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in the

Faculty Name
School of Engineering and Applied Science

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Declaration of Authorship

I, Patrick Byrne, declare that this thesis titled, 'External Kink Modes in Shaped Tokamak Plasmas' and the work presented in it are my own. I confirm that:

- This work was done wholly or mainly while in candidature for a research degree at this University.
- Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated.
- Where I have consulted the published work of others, this is always clearly attributed.
- Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.
- I have acknowledged all main sources of help.
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There is a theory which states that if ever anyone discovers exactly what the Universe is for and why it is here, it will instantly disappear and be replaced by something even more bizarre and inexplicable.

There is another theory which states that this has already happened.

Douglas Adams, *The Restaurant at the End of the Universe*

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Abstract

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This thesis represents the first study of MHD external kink modes in shaped plasmas using the high resolution High Beta Tokamak - Extended Pulse (HBT-EP) magnetic sensor set. This work required construction of a high current, low impedance poloidal field coil, as well as high-current, low-voltage capacitive power supply, and current monitoring hardware and software. This coil allows shaping of the plasma on the inboard side of the torus, above the midplane, to the point of transitioning the plasma from impingement on a material surface, to being limited by a magnetic x-point. The construction and operation of the bank is described, with a full partslist appearing in an appendix. Individual modes in plasmas are extracted from the entire signal using a technique known variously as singular value decomposition, principal component analysis, or biorthogonal decomposition. Coherent fluctuations of up to three modes is observed using the BD without the need for an a priori choice of basis set. Measurements of plasma modes are compared to the predictions of simulations involving the codes TokaMac, DCON, and VALEN. Modes with toroidal wavenumbers n=1 and n=2 are observed across both circular and shaped plasmas. As predicted by the codes we see a roughly similar poloidal mode spectrum in modes with the same toroidal number, with a pronounced change localized at the x-point. HBT-EP's active control coil set was used to excite naturally occurring modes, and the response of each type of plasma is compared. Further studies have looked into excitation of highly stable, low-n, low-m kink modes. We see a response highly localized at the x-point in shaped plasmas, which has implications for transport control in advanced fusion tokamak configurations.

Acknowledgements

The acknowledgements and the people to thank go here, don't forget to include your project advisor…

Contents

List of Figures

List of Tables

Abbreviations

LAH **L**ist **A**bbreviations **H**ere

Physical Constants

Speed of Light $\quad c \quad = \quad 2.997\ 924\ 58 \times 10^{8}\ \mathrm{ms}^{-\mathrm{S}}$ (exact)

Symbols

a	distance	m
P	power	W (Js^{-1})
ω	angular frequency	$rads^{-1}$

For/Dedicated to/To my…

Chapter 1

Introduction

The world faces a series of stark choices in the coming years. The warming of the earth continues to rise, and the rise to accelerate. As of this writing it is 68°F and it is also mid-December. Though there are a series of entrenched interests that resist acknowledging the facts as such, the use of fossil fuels forcing the change is settled science. However, human development is inextricably linked to the exploitation of energy. The environmental disruption caused by China's rapid development in the last quarter century is merely an amplified echo of that experienced by the western world during the industrial revolution. There remain billions of people on earth living in places that have yet to develop, and though raising them to the standard of life enjoyed by the first world would multiply the current consumption of fossil fuels by several times we have no moral right to deny them the lifestyle we enjoy.

Given that the use of fossil fuel is already exponentially increasing, and that they are created at a rate many orders of magnitude slower than we are exploiting them, one way or another, at some point in the future, it is guaranteed that humanity will no longer be using fossil fuels to power itself, though that replacement may be wood, peat, or dung, if a more suitable replacement is not found.

Carbon-Neutral power generation is thus a must if we are to progress as a species. The localised, seasonalised and intermittent generation from most renewables disqualifies them until and unless power storage and public grids can catch up. Hydroelectric is environmentally damaging, and as demonstrated by California's recent drought, subject to the extreme weather caused by global warming. Nuclear accidents have cost far less in terms of human morbidity than the chronic effects due to burning coal, but the poor public understanding of the physics and technology involved, and the spectacularity with which the failures occur, has made it extremely controversial.

Fusion energy is the path out of the bind we find ourselves in with a better future at the end. The fusion products do not contribute to the greenhouse effect. The generation is not dependent on seasons or weather. There is no possibility for a runaway meltdown reaction, and as a new technology with a high degree of enthusiasm among the public, it has none of the perception issues attached to fission nuclear. One component of the fuel, the hydrogen isotope deuterium, is abundant, with reserves to last several thousands of years. It is widely distributed, reducing the pressures that lead to conflict over resources. Though the containment vessel will become activated and radioactive, much like current fission reactors, the reaction products will not be nuclear waster. Further, there exist more advanced fuel mixes that are completely aneutronic, removing even that slight drawback. Harnessing fusion is not just a scientific and technical challenge, it is a moral imperative.

1.1 The D-T Fusion Reaction

Fusion occurs if two ions collide with enough energy to overcome the coulomb repulsion of their nuclei until they can come close enough for the strong force interaction to take over, merging the two nuclei. Different reactions between different reactants and occur at different temperatures, and have larger or smaller cross sections. The larger the cross section, the smaller the confinement time, or the lower the density required for a certain number of reactions to occur. Given that the ions in a plasma have a distriubtion of temperatures, the figure of merit for energy generation in a fusion plasma is the value of the so called 'triple product':

$$nT\tau_E \geq 5 * 10^{21} \frac{keV \cdot s}{m^3} \tag{1.1}$$

with n being the particle density of the plasma, τ_E being the energy confinement time, and T being the plasma temperature. The minimum value in the inequality is for the reaction between deuterium and tritium, which, as the least technically demanding fusion reaction, is the main focus of fusion research. The values of relevance to tokamak fusion are $T \simeq 10keV$, $n \simeq 10^{20}m^{-3}$, $\tau_E \simeq 5s$ This reaction creates a neutron and a helium-4, or alpha, ion:

$$D + T \rightarrow \alpha(3.5MeV) + n(14.3MeV) \tag{1.2}$$

The magnetically confined a helium 'ash' heats the plasma as it thermalizes, and the unconfined neutron carries its heat out of the plasma. The neutrons are captured in a 'blanket' that absorbs the heat and transfers it to a coolant to generate power or can be captured by a lithium coating, generating tritium, helium, and additional energy.

It is not enough, however to merely generate energy. More energy must be generated than was used to heat and confine the plasma, and the imbalance must be large enough that the excess can be sold at a low enough cost to be competitive, and at high enough volume to underwrite the operation of the plant and provide a profit for the operators. The most common measurement of tokamak efficiency is β, which is the ratio of the plasma pressure to magnetic pressure. β can be expressed with respect to either the toroidal or poloidal magnetic field, or the combination:

$$\beta_t = \frac{\langle p \rangle}{\langle B_t \rangle^2 / 2\mu_0} \tag{1.3}$$

$$\beta_p = \frac{\langle p \rangle}{\overline{B}_p^2 / 2\mu_0} \tag{1.4}$$

Where $\langle p \rangle$ is the volume averaged plasma pressure, B_t is the toroidal magnetic field, B_p is the poloidal magnetic field,Further, β_t can be normalized against the plasma current, I_p, the minor radius a,

$$\beta_N = \frac{\beta_T a B_t}{I_p} \tag{1.5}$$

1.2 plasma confinement

1.2.1 A Subsection

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1.3 Another Section

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Chapter 2

The Shaping Coil

2.1 The Coil

The shaping coil is a single continuous piece of 1/0 welding cable, run eight times toroidally between the inner ring of the toroidal field magnet cases and the vacuum vessel. This ex-vessel coil is located slightly above the midplane, mainly due to space limitations. Were complete freedom of placement to obtain, the coil would likely be placed nearer the midplane, as we have active (pre-programmed) control of the plasma's radial location, but vertical location control is only passively provided by eddies in the conducting vessel walls and shells.

2.2 The Coil

2.2.1 The Coil Holders

2.2.2 Leads & Bundle Connections

The construction of the coil out of a single conductor was accomplished through directing the conductor from one bundle to another once the number of required turns had been wound. This necessitated a poloidal run of wire to connect the two. At the end of the final bundle, the out-lead cable had to travel poloidally once again to meet the in-lead before becoming a twisted pair. These non-toroidal runs of current were canceled to the best of our ability by running the return lead back at the same location as the poloidal leads connecting each bundle. Though the thickness of the cable and the tight spaces involved precluded winding these contrary wires, they were connected with zip ties to ensure as good a canceling as possible. See Figure 1 for a schematic of the windings and location of the leads.

The twisted pair from the power supply rises from the laboratory basement, splits with one lead breaking into the lowest turn, and the other breaking out of the highest turn. The top lead is therefore unshielded for roughly 8 inches. There are two points at which the cable is bent back upon itself to begin a new bundle and reverse the direction of the current. This occurs at the same toroidal location, which is itself the same location as the leads. The current in the leads travels in the opposite direction from the current in the jumps between bundles. The lead is thus lashed to the the interbundle connections to both reduce the error fields, and prevent the jXB forces on the cables from causing damage to the coil insulation.

2.3 The Power Supply

The shaping coil is energized by a pre-programmed two-stage passive capacitive supply. A 7.5mF, 900V (max) bank provides the startup current, with a time to peak current of $800\mu s$. As this bank discharges, a high current diode passively switches a second 'crowbar' bank into the circuit. This bank has a capacitance of 0.6F, and a maximum voltage of 250V. This much larger bank is capable of providing current enough to sustain a 'flat top' current pulse of ~8kA for ~5ms. By selecting different voltages on each bank pre-discharge, a variety of different current profiles can be developed. The 'soft start' of the crowbar bank due to the used of a diode allows for a very smooth transition between the two power banks. This is compared to the current trace of the vertical field coil in Figure . The power supplies for all other equilibrium field coils are capacitive in nature, but are switched in by ignitrons, which require a voltage drop between the bank and the line into which they switch the bank. The rapid inrush current as a capacitor is switched into a line of a different voltage leads to a sharp change in the current, leading to strong eddies induced in the surrounding conducting structures. The banks are easily charged to their full voltage in less than one minute, much less time than the other equilibirum field coil banks. There are a variety of safety measures used in the bank's construction. A discussion, full partslist and circuit schematic can be found in Appendix

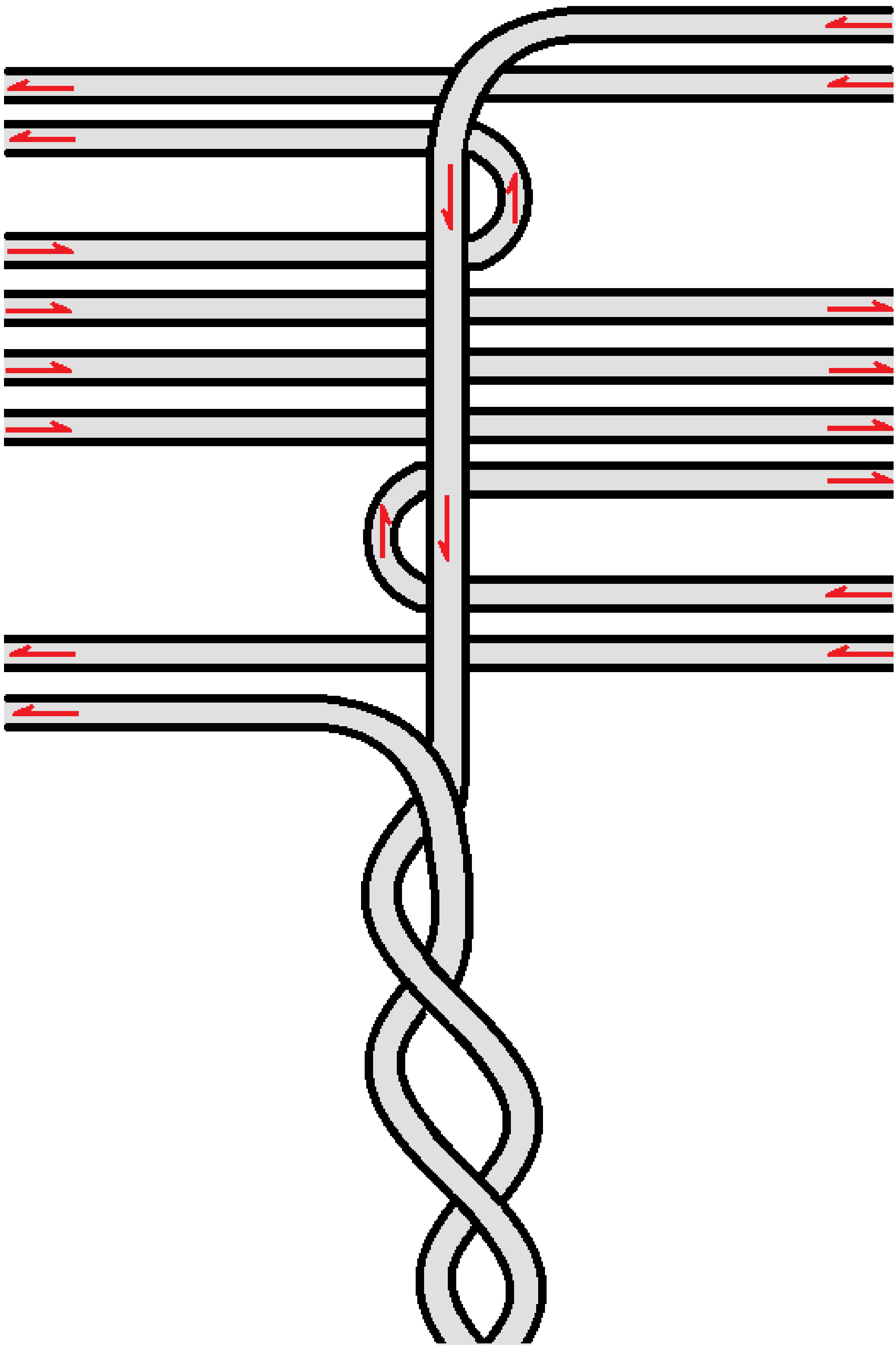

FIGURE 2.1: Rough schematic of the inter-bundle connections and coil leads, as seen by an observer between the vacuum vessel's inboard side and the coil. The toroidal direction is left/right, poloidal is up/down.

2.4 The Limiter

2.5 The Material Limiter

The poloidal array sensors are protected by $\frac{1}{16}$" stainless steel shimstock to protect against damage to the wires or ablation of the plastic forms by plasma impinging. Under normal operating conditions the last closed flux surface of the plasma is 5mm radially inward from the surface of the sensors' shielding. The plasma is in general vertically centered on the midplane, moves mostly radially, and disrupts inward, so sensors at the midplane are further protected by the inboard and outboard limiters, which establish the 5mm separation between plasma and sensors, and have much larger thermal mass than the shims that cover the sensors.

However, this is not the case for sensors higher up that are near the location of the X-point. These sensors which lack the extra protection of a limiter will see the steady state power flux increase as plasma will be preferentially exhausted along a cone expanding radially outward from the X-point. Additionally, during disruptions, there will be an upward component to the forces on the plasma. To ensure that this additional heat load does not cause harm to the sensors, a new set of limiters was machined and installed. These 'blade' limiters are attached with threaded rods to the flanges of the chamber pieces, which themselves act as limiters on the inboard side. These threaded rods were spot welded to the flanges during an up to air. These limiters extend radially inward 5mm from the inner most edge of the x-point localized PA sensors. The poloidal extent of the sensor is such that shading from the plasma is now provided from the inboard midplane to $\Theta = 90°$. The limiter is made of 3/8" 316 stainless steel

Appendix A

An Appendix

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