COLUMBIA UNIVERISTY

External Kink Modes in Tokamak Plasmas

by

Patrick James Byrne

A thesis submitted in partial fulfillment for the
degree of Doctor of Philosophy

in the
Faculty Name
School of Engineering and Applied Science

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Declaration of Authorship

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Abstract

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Doctor of Philosophy

by Patrick James Byrne

The Thesis Abstract is written here (and usually kept to just this page). The page is kept centered vertically so can expand into the blank space above the title too...

Acknowledgements

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

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Abbreviations

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

Physical Constants

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

An Appendix

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