Laser-generated toroidal helium plasmas

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Citation

Kooij, V. L. (2021, April 28). *Laser-generated toroidal helium plasmas*. *Casimir PhD Series*. Retrieved from https://hdl.handle.net/1887/3161377

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Issue date: 2021-04-28

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Introduction

In just forty minutes, the amount of energy from the sun that strikes the earth is more than the annual energy consumption of the entire world.[1] This simple observation has been the sole motivator for the nuclear fusion endeavours of mankind. But half a century of devoted research efforts have not resulted in a reliable and break-even nuclear fusion power plant.

Still, nuclear fusion offers one of the possible answers to the quest for sustainable energy, which is widely considered to be one of the greatest challenges facing humanity in the forthcoming decades. Instrumental to nuclear fusion are plasmas with temperatures of the order of 100 million degrees Celsius, to allow thermonuclear reactions to take place. To sustain these thermonuclear reactions, the Lawson criterion[2] imposes a condition on the product of the plasma density n and the energy confinement time τ, as well as on the temperature. Plasma confinement is about satisfying this criterion, and the most prominent approach in contemporary nuclear fusion research is magnetic confinement fusion.

Soviet physicists already in the 1950s conceived the tokamak. These magnetic confinement devices employ strong magnetic fields to confine the high temperature plasma into the shape of a torus, and form the leading design for an economically viable nuclear fusion reactor.

Understanding the stability of magnetically confined plasmas is of fundamental importance to successful magnetic confinement fusion, and the topology of the confining fields proves to play a pivotal role.

The connection between stability and topology has been established in 1969, when Moffatt[3] found that helicity—the quantity identified by Woltjer[4] to be conserved in a plasma with infinite conductivity—is in fact a measure of the degree of linkage and knottedness of magnetic field lines.

[1] Kopp et al. 2011; IEA 2017.

[2] F. F. Chen 1974, p. 281.

[3] Moffatt 1969.

[4] Woltjer 1958.

Kamchatnov continued from the topological nature of this invariant, to construct a magnetic field configuration consisting of closed magnetic field lines that are all linked to each other.[5] Therewith he obtained an analytical solution of the equations of magnetohydrodynamics,[6] for an ideal incompressible fluid with infinite conductivity, describing a localized topological magnetic soliton.

The topological structure found by Kamchatnov was used by Rañada,[7] and Irvine and Bouwmeester,[8] to investigate linked and knotted beams of light, continued by Kedia et al.[9] who found a set of analytical solutions to Maxwell's equations, whose electric and magnetic fields encompass all linked and knotted torus knots.[10] This work was further expanded to optical vortices,[11] and linked and knotted gravitational radiation.[12]

Recently, the connection between stability and topology has been confirmed by magnetohydrodynamics simulations, demonstrating that a magnetic field with helicity reconfigures itself into a structure of foliated toroidal surfaces.[13] These relaxed plasma configurations are not the familiar minimum energy configurations[14] found by Taylor,[15] but instead configurations where the magnetic pressure is balanced by the hydrostatic pressure.

These self-organising knotted magnetic structures are intrinsically stable and their configuration is essentially different from that of the tokamak. Namely, their hydrostatic pressure is minimal on the central circle of the foliated tori. The magnetic energy density of these knotted plasma structures is highly localised.

In the absence of electron and ion collisions, the tokamak conceived by the Soviet physicists should provide a stable plasma,[16] yet experimentally the equilibrium is unstable and will lead to chaotic plasma dynamics. Mitigating these chaotic dynamics is instrumental in contemporary magnetic confinement fusion experiments.

However, instead of mitigating chaos, the self-organising knotted magnetic structures might intrinsically provide the sought after stability. Moreover, their apparent universality suggests that these equilibria may even emerge in astrophysical environments,[17] alluding to a more fundamental importance.

Toroidal plasma structures have been observed in a vast range of experimental settings, including nanosecond discharges, laser ignition of flammable mixtures, high-power electric arcs, high-speed micro jets, and laser-induced breakdown plasmas.[18] The research presented in this dissertation started with the observation of toroidal plasma structures

[5] Kamchatnov 1982.

[6] Magnetohydrodynamics studies the behaviour of electrically conducting fluids.

[7] Rañada 1989.

[8] Irvine et al. 2008.

[9] Kedia et al. 2013.

[10] A torus knot is a knot that lies on the surface of an unknotted torus.

[11] de Klerk et al. 2017.

[12] Thompson et al. 2014.

[13] Smiet, Candelaresi et al. 2015.

[14] The force-free configuration of minimum energy subject to conservation of helicity.

[15] J. B. Taylor 1974.

[16] F. F. Chen 1974, p. 285.

[17] Smiet 2017; Smiet, de Blank et al. 2019.

[18] Stepanyan et al. 2019; Dumitrache et al. 2017; Bradley et al. 2004; Bak, Im et al. 2014; Seward 2014; Gharib et al. 2017; Nassif et al. 2000; Harilal et al. 2015; Bak, Wermer et al. 2015

that are far more symmetrical than those reported in the aforementioned studies. These plasma structures were generated using laser-induced breakdown plasmas, created in quiescent atmospheric pressure helium gas at room temperature. Their self-confined toroidal nature, and atmospheric pressure ambient conditions, provide an interesting setting for investigating the numerically predicted,[19] and intrinsically stable, self-organising knotted magnetic structures.

The long-term objective is the realisation of such self-organising knotted magnetic structures in the laboratory. This dissertation is an account of the first steps towards this goal, discussing the prime features responsible for the development of the laser-generated toroidal helium plasmas, along with their prime plasma parameters. Furthermore, the research on counteracting the transient nature of these toroidal plasmas is discussed, a property that evidently hinders the realisation of the self-organising magnetic structures.

The research starts off in chapter 2, where for the entire evolution of a toroidal plasma, tomographically reconstructed, poloidal radiant intensity profiles are presented that clearly visualise the formative fluid flow of the toroidal structure. These observations also reveal a new splitting of the toroidal plasma during the final phase of its evolution. Based on elementary thermodynamic principles, a model is developed that establishes a characteristic time scale at which structure is expected to form. This time scale is confirmed by measurements of the density of helium atoms in the centre of the toroidal plasma. By deliberately breaking the symmetry of the flow responsible for the development of the toroidal structure, the model for the formation of this structure is confirmed. The pulsating plasma observed at the beginning of the creation of a laser-induced breakdown plasma is discussed last. This repeating dynamics possibly contributes to the formation of the two-lobe structure visible in the plasma kernel.

In chapter 3, a novel interpretation of high-speed Schlieren images is presented, where a Mach reflection of shocks is visible, formed by the two-lobe plasma kernel of a laser-induced breakdown plasma. The enhanced strength of this shock is linked to the asymmetrical fluid flow necessary for the development of a toroidal plasma. The propagation of the shock is directly visualised by a novel technique, whereby a second laser-induced breakdown plasma is used as a probe. With this technique, the existence of a low density cavity, formed in the wake of the shock, is also confirmed.

Chapter 4 addresses the plasma parameters of the toroidal helium

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[19] Smiet, Candelaresi et al. 2015.

plasmas. By combining interferometric measurements using 57 GHz microwave radiation with detailed full-wave finite-element calculations, the electron number density and the electron collision rate are estimated for the entire evolution of a toroidal plasma. The microwave interferometric set-up used to measure the complex transmission coefficient is discussed in detail. Furthermore, a method is described, in which the finite-element calculations are used as a map between the measured transmission coefficient and the desired plasma parameters. In support, a number of fundamental concepts from plasma physics are reviewed.

To counteract the transient nature of the toroidal helium plasmas, a sub-microsecond rise time 1.75 kW pulsed magnetron source has been designed, for which the detailed design is presented in chapter 5. This magnetron source has been used in preliminary experiments aimed at heating the plasma by absorption of microwave radiation. During these experiments, the electrical characteristics of the magnetron source have been determined. The toroidal plasma is subjected to a high power 2.460 GHz microwave pulse, a frequency commonly used for industrial microwave sources. To apply the microwave pulse to the toroidal plasma, a 2.465 GHz iris coupled rectangular microwave cavity has been designed. The shift in frequency of 5 MHz anticipates on the detuning of the cavity due to the presence of plasma. The effect of the microwave pulse on the toroidal plasma, as well as the dark space that is observable between the microwave generated plasma and the toroidal plasma, are discussed. Finally, a poloidal excitation temperature profile of the toroidal plasma, including the additional plasma structure generated by the microwave pulse, is presented. This temperature profile has been determined by applying a standard Boltzmann analysis to two, tomographically reconstructed, poloidal radiant intensity profiles, obtained from images recorded at two different wavelengths.

Most images presented in this work have been captured through a 10 nm bandpass filter, enclosing one (or a multiplet) of the atomic helium emission lines, in order to facilitate quantitative analyses.

At the end of this dissertation, photographs have been included, to give a more vivid impression of selected experimental set-ups used for our research.

Lastly, it is noted that the electronic version of this dissertation provides hyperlinks, recognisable by their purple coloured text.