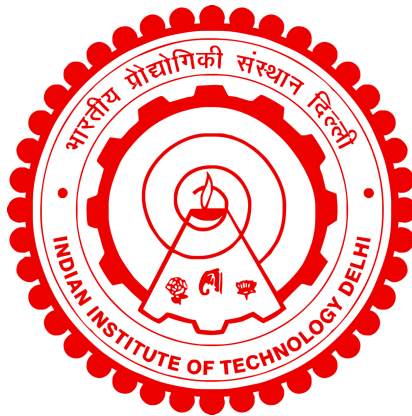


**ELECTRON AND ION SCALE MAGNETIC
TURBULENCE STUDIES RELEVANT TO
LABORATORY ASTROPHYSICS**

INDRAJ SINGH



**DEPARTMENT OF ENERGY SCIENCE AND
ENGINEERING**

**INDIAN INSTITUTE OF TECHNOLOGY
DELHI, NEW DELHI-110016, INDIA**

JULY 2023

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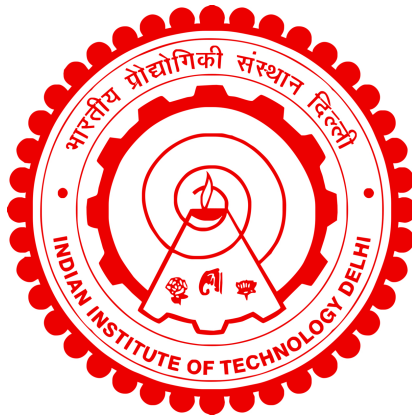
Department of Energy Science and Engineering

Submitted

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Dedicated to
my
beloved Family

Certificate

This is to certify that the thesis entitled “**Electron and ion scale magnetic turbulence studies relevant to laboratory astrophysics**”, being submitted by **Mr. Indraaj Singh** to the Indian Institute of Technology Delhi, for the award of the degree of **Doctor of Philosophy** in the Department of Energy Science and Engineering, is a record of the original bonafide research work carried out by him under my supervision and guidance.

The thesis has reached the standards fulfilling the requirements of the regulations related to the award of the degree. The results contained in this thesis have not been submitted in part or in full to any other University or Institute for the award of any degree or diploma to the best of our knowledge. I approve the thesis for the award of the aforesaid degree.

Prof. R. Uma

Department of Energy Science and
Engineering,
Indian Institute of Technology Delhi

Prof. R. P. Sharma

Department of Energy Science and
Engineering,
Indian Institute of Technology Delhi

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Abstract

Various space and astrophysical phenomena provide a unique laboratory to study magnetic field amplification, magnetic turbulence, energy cascading, and acceleration of the charged particles inside the plasma medium. The invention of the high-intensity laser-matter interaction has opened up a new field of study, where many astrophysical situations may be investigated through controlled laboratory experiments and simulations. A self-generated magnetic field is created when a solid object is irradiated with femtosecond laser pulses. Such a self-generated magnetic field is produced as a result of the interaction of the intense laser with the plasma and does not require a starting field. The emergence and development of magnetic turbulence is a pervasive and ubiquitous nonlinear process found in several laboratories and astrophysical events. In such systems, turbulence plays a crucial role in the transport of energy from large to small scales. The evolution of many astrophysical phenomena is profoundly affected by this turbulence-induced energy cascade.

Several plasma modes are supported by magnetized plasma. Depending on the plasma circumstances, the dispersive characteristics of these plasma modes are quite different from one another. In this thesis, models based on the nonlinear interaction of several plasma modes have been used to study the formation of filamentary structures, the strengthening of the magnetic field, the creation of turbulence, and the acceleration of charged particles. In this perspective, the theoretical models (Zakharov system of equations and modified nonlinear Schrödinger equation) are developed, which are solved by laboratory simulations as well as by semi-analytical models. The main goal of the proposed model, which is based on the nonlinear interaction of plasma modes, is to study the magnetic turbulence at the electron and ion scales in the magnetized plasma, as seen in laboratory and space plasmas.

The *second chapter* deals with the nonlinear interaction of the elliptically polarized electromagnetic extraordinary mode with the electrostatic upper hybrid oscillations. The laboratory simulations are employed to solve the developed coupled dynamical equations. The filamentary structures come from the results of computer simulations. Later on, the structures become chaotic, which indicates the generation of turbulence. The process by which energy is transported from one length scale to another is shown by electron-scale magnetic turbulence. A simplified model in the paraxial

approximation provides a mechanism to understand the nonlinear progression of the extraordinary mode laser beam inside the plasma medium.

The group velocity dispersion effects on the formation of the filamentary structure and electron-scale magnetic turbulence generation are described in the *third chapter* by taking the adiabatic approximation. This chapter shows how nonlinear effects like nonlinearity, diffraction, and group velocity dispersion affect the nonlinear interaction between extraordinary mode lasers and upper hybrid oscillations. The developed coupled dynamical equations were solved by numerical simulation and semi-analytical techniques. Simulation results show that there are localized structures of the solitary wave type in the space-time domain, and magnetic turbulence at the scale of the electron shows how energy is exchanged at different length scales. Semi-analytical results show the simultaneous self-compression and self-focusing of the pump x -mode laser beam inside the plasma medium.

A nonlinear wave-wave interaction among the extraordinary mode and the Trivelpiece-Gould mode propagating obliquely to the magnetic field direction is presented in the *fourth chapter*. The coupled model equations were evolved by mathematical formulation and solved by numerical simulation. The findings from the simulation show the effect of the propagation angle (θ) of the Trivelpiece-Gould mode on the filamentary structures, density harmonics, amplification of the magnetic field, and scaling of the magnetic turbulence at the electron scale. A simplified model in the paraxial approximation is also studied to see the effect of the propagation angle of the Trivelpiece-Gould mode on the localized structure formation.

The *chapter fifth* presents the nonlinear interaction of plasma waves to study the electron acceleration associated with the localized structure formation and turbulence generation. By taking the thermal effects into account, the dynamical equations of the upper hybrid wave and the extraordinary mode are developed, and computational simulations are employed to solve the formulated coupled dynamical equations. Numerical simulation results show the formation of filamentary structures, magnetic field amplification, and electron-scale turbulent spectra. The fractional diffusion technique and the Fermi acceleration model are employed to study the electron acceleration associated with the spectral index of the electron-scale turbulent spectra. A simplified model in the paraxial limit included in this study provides better insight into the nonlinear development of the x -mode laser beam inside the plasma medium.

The nonlinear coupling of the magnetosonic wave and the kinetic Alfvén wave in

the finite plasma beta region is presented in the *sixth chapter*. The semi-analytical model and laboratory simulations are used to solve the coupled model equations after they have evolved through mathematical formulation, including ponderomotive nonlinearity. The filamentary structure formation and magnetic field amplification were observed from the simulation results. The fact that the filamentary structures become chaotic at later times hints at the generation of turbulence. The time-averaged turbulent power spectra describe the transport of energy among the different length scales. The scale size of the kinetic Alfvén wave is in the range of ion gyro-radius (ρ_i), which is anticipated to contribute towards the power-law scaling of magnetic turbulence at the ion scales. The observed turbulent spectra in different wavenumber regions resemble the various astrophysical scenarios. In the paraxial limit, a semi-analytical model is used to study how the density harmonics change the nonlinear progression of the pump wave.

The *chapter seventh* presents a nonlinear coupling of plasma waves to explore how the additional density fluctuation profiles affect localized structure formation, enhancement of the magnetic field, and the scaling of turbulent spectra. The coupled dynamical equations are formulated by considering nonlinear ponderomotive force and additional density fluctuation profiles (caused by counter propagation of the ion acoustic wave). To solve the coupled model equations that evolved through mathematical formulation, the laboratory simulation and the semi-analytical approach are employed. The impact of the additional density profiles on the filamentary structure formation and amplification factor observed from simulation and semi-analytical findings. The energy cascade between distinct length scales is also affected by the additional density fluctuation profiles, which are shown by the turbulent spectra seen in simulation results. The relevance of the present studies, such as localized structure formation, enhancement of the magnetic field, and turbulent scaling at the electron and ion scales, has been shown with the various experimental observations of laser-plasma interaction replicating several astrophysical scenarios.

सार

विभिन्न अंतरिक्ष और खगोलीय घटनाएं चुंबकीय क्षेत्र प्रवर्धन, टर्बुलेन्स उत्पादन तथा चुंबकीय प्लाज्मा के अंदर ऊर्जा के प्रवाह का अध्ययन करने के लिए एक अद्वितीय प्रयोगशाला प्रदान करती हैं। उच्च तीव्रता वाले लेजर-पदार्थ इंटरैक्शन के आविष्कार ने अध्ययन का एक नया क्षेत्र खोल दिया है, जहां नियंत्रित प्रयोगशाला प्रयोगों और सिमुलेशन के माध्यम से कई खगोलभौतिकीय स्थितियों की जांच की जा सकती है। एक स्व-निर्मित चुंबकीय क्षेत्र तब बनता है जब किसी ठोस वस्तु को फेमटोसेकंड लेजर पल्स से विकिरणित किया जाता है। ऐसा स्व-निर्मित चुंबकीय क्षेत्र प्लाज्मा के साथ तीव्र लेजर की बातचीत के परिणामस्वरूप उत्पन्न होता है और इसके लिए प्रारंभिक क्षेत्र की आवश्यकता नहीं होती है। चुंबकीय टर्बुलेन्स का उद्भव और विकास एक व्यापक तथा सर्वव्यापी गैर-रैखिक प्रक्रिया है जो कई प्रयोगशालाओं और खगोलभौतिकी घटनाओं में पाई जाती है। ऐसी प्रणालियों में, बड़े पैमाने से छोटे पैमाने तक ऊर्जा के परिवहन में टर्बुलेन्स महत्वपूर्ण भूमिका निभाती है। कई खगोलीय घटनाओं का विकास इस टर्बुलेन्स-प्रेरित ऊर्जा कैसकेड से गहराई से प्रभावित होता है।

कई प्लाज्मा मोड चुंबकीय प्लाज्मा द्वारा समर्थित हैं। प्लाज्मा परिस्थितियों के आधार पर, इन प्लाज्मा मोड की फैलाव विशेषताएँ एक दूसरे से काफी भिन्न होती हैं। इस थीसिस में, फिलामेंटरी संरचनाओं के निर्माण, चुंबकीय क्षेत्र को मजबूत करने, टर्बुलेन्स के निर्माण और आवेशित कणों के त्वरण का अध्ययन करने के लिए कई प्लाज्मा मोड के नॉनलाइनियर इंटरैक्शन पर आधारित मॉडल का उपयोग किया गया है। इस परिप्रेक्ष्य में, सैद्धांतिक मॉडल (जखारोव समीकरण प्रणाली और संशोधित नॉनलाइनियर श्रोडिंगर समीकरण) विकसित किए गए हैं, जिन्हें प्रयोगशाला सिमुलेशन के साथ-साथ अर्ध-विश्लेषणात्मक मॉडल द्वारा हल किया गया है। प्रस्तावित मॉडल का मुख्य लक्ष्य, जो प्लाज्मा मोड के नॉनलाइनियर इंटरैक्शन पर आधारित है, चुंबकीय प्लाज्मा में इलेक्ट्रॉन और आयन स्केल पर चुंबकीय टर्बुलेन्स का अध्ययन करना है, जैसा कि प्रयोगशाला और अंतरिक्ष प्लाज्मा में देखा जाता है।

दूसरा अध्याय इलेक्ट्रोस्टैटिक ऊपरी संकर दोलनों (UHO) के साथ दीर्घवृत्त ध्रुवीकृत विद्युत चुम्बकीय असाधारण मोड (x -mode) की गैर-रेखीय बातचीत से संबंधित है। विकसित युग्मित गतिशील समीकरणों को हल करने के लिए प्रयोगशाला सिमुलेशन का उपयोग किया जाता है। फिलामेंटरी संरचनाएं कंप्यूटर सिमुलेशन के परिणामों से आती हैं। बाद में, संरचनाएं अव्यवस्थित हो जाती हैं, जो टर्बुलेन्स उत्पन्न होने का संकेत देती हैं। वह प्रक्रिया जिसके द्वारा ऊर्जा को एक लंबाई पैमाने से दूसरे पैमाने पर ले जाया जाता है, इलेक्ट्रॉन-स्केल चुंबकीय टर्बुलेन्स द्वारा दिखाई जाती है। पैराएक्सियल सन्निकटन में एक सरलीकृत मॉडल प्लाज्मा माध्यम के अंदर असाधारण मोड लेजर बीम की गैर-रेखीय प्रगति को समझने के लिए एक तंत्र प्रदान करता है।

फिलामेंटरी संरचना के निर्माण और इलेक्ट्रॉन-स्केल चुंबकीय टर्बुलेन्स पीढ़ी पर समूह वेग फैलाव प्रभाव (GVD) को एडियाबैटिक सन्निकटन लेकर तीसरे अध्याय में वर्णित किया गया है। यह अध्याय दिखाता है कि गैर-रैखिकता, विवर्तन और समूह वेग फैलाव जैसे गैर-रेखीय प्रभाव असाधारण मोड

लेजरों और ऊपरी संकर दोलनों के बीच गैर-रेखीय संपर्क को कैसे प्रभावित करते हैं। विकसित युग्मित गतिशील समीकरणों को संख्यात्मक सिमुलेशन और अर्ध-विश्लेषणात्मक तकनीकों द्वारा हल किया गया है। सिमुलेशन परिणाम दिखाते हैं कि अंतरिक्ष-समय डोमेन में एकान्त तरंग प्रकार की स्थानीयकृत संरचनाएं हैं, और इलेक्ट्रॉन के पैमाने पर चुंबकीय टर्बुलेन्स से पता चलता है कि विभिन्न लंबाई के पैमाने पर ऊर्जा का आदान-प्रदान कैसे होता है। अर्ध-विश्लेषणात्मक परिणाम प्लाज्मा माध्यम के अंदर पंप x -मोड लेजर बीम के एक साथ आत्म-संपीडन और आत्म-फोकसिंग को दर्शाते हैं।

असाधारण मोड (x -मोड) और चुंबकीय क्षेत्र की दिशा में तिरछे प्रसार करने वाले ट्राइवेलपीस-गोल्ड मोड (TG mode) के बीच एक नॉनलाइनियर वेव-वेव इंटरैक्शन चौथे अध्याय में प्रस्तुत किया गया है। युग्मित मॉडल समीकरण गणितीय सूत्रीकरण द्वारा विकसित किए गए और संख्यात्मक सिमुलेशन द्वारा हल किए गए। सिमुलेशन के निष्कर्ष फिलामेंटरी संरचनाओं, घनत्व हार्मोनिक्स, चुंबकीय क्षेत्र के प्रवर्धन और इलेक्ट्रॉन पैमाने पर चुंबकीय टर्बुलेन्स के स्केलिंग पर ट्राइवेलपीस-गोल्ड मोड के प्रसार कोण (θ) के प्रभाव को दर्शाते हैं। स्थानीयकृत संरचना निर्माण पर ट्राइवेलपीस-गोल्ड मोड के प्रसार कोण के प्रभाव को देखने के लिए पैराक्विसियल सन्निकटन में एक सरलीकृत मॉडल का भी अध्ययन किया गया है।

अध्याय पांचवां स्थानीय संरचना निर्माण और अशांति पीढ़ी से जुड़े इलेक्ट्रॉन त्वरण का अध्ययन करने के लिए प्लाज्मा तरंगों की गैर-रैखिक बातचीत प्रस्तुत करता है। थर्मल प्रभावों को ध्यान में रखते हुए, ऊपरी संकर तरंग (UHW) और असाधारण मोड (x -मोड) के गतिशील समीकरण विकसित किए जाते हैं, और तैयार किए गए युग्मित गतिशील समीकरणों को हल करने के लिए कम्प्यूटेशनल सिमुलेशन को नियोजित किया गया है। संख्यात्मक सिमुलेशन परिणाम फिलामेंटरी संरचनाओं, चुंबकीय क्षेत्र प्रवर्धन और इलेक्ट्रॉन-स्केल टर्बुलेन्स स्पेक्ट्रा के गठन को दर्शाते हैं। इलेक्ट्रॉन-स्केल टर्बुलेंट स्पेक्ट्रा के वर्णक्रमीय सूचकांक से जुड़े इलेक्ट्रॉन त्वरण का अध्ययन करने के लिए भिन्नात्मक प्रसार तकनीक और फर्मी त्वरण मॉडल को नियोजित किया गया है। इस अध्ययन में शामिल पैराक्विसियल सीमा में एक सरलीकृत मॉडल प्लाज्मा माध्यम के अंदर x -मोड लेजर बीम के गैर-रेखीय विकास में बेहतर अंतर्दृष्टि प्रदान करता है।

परिमित प्लाज्मा बीटा (β) क्षेत्र में मैग्नेटोसोनिक तरंग (MSW) और गतिज अल्फवेन तरंग (KAW) के अरेखीय युग्मन को छठे अध्याय में प्रस्तुत किया गया है। अर्ध-विश्लेषणात्मक मॉडल और प्रयोगशाला सिमुलेशन का उपयोग गणितीय फॉर्मूलेशन के माध्यम से विकसित होने के बाद युग्मित मॉडल समीकरणों को हल करने के लिए किया गया है, जिसमें पोंडरोमोटिव नॉनलाइनरिटी भी शामिल है। सिमुलेशन परिणामों से फिलामेंटरी संरचना निर्माण और चुंबकीय क्षेत्र प्रवर्धन देखा गया। तथ्य यह है कि बाद के समय में फिलामेंटरी संरचनाएं अव्यवस्थित हो जाती हैं, जो टर्बुलेन्स उत्पन्न होने का संकेत देती है। समय-औसत टर्बुलेंट शक्ति स्पेक्ट्रा विभिन्न लंबाई के पैमानों के बीच ऊर्जा के परिवहन का वर्णन करता है। गतिज अल्फवेन तरंग का स्केल आकार आयन जाइरो-रेडियस (ρ_i) की सीमा में है, जो आयन स्केल पर चुंबकीय अशांति के पावर-लॉ स्केलिंग में योगदान करने का अनुमान है। विभिन्न वेवनंबर क्षेत्रों में देखे गए टर्बुलेंट स्पेक्ट्रा विभिन्न खगोलभौतिकीय परिदृश्यों से मिलते जुलते हैं। पैराक्विसियल सीमा में, एक अर्ध-विश्लेषणात्मक मॉडल का उपयोग यह अध्ययन करने के लिए किया गया है कि घनत्व हार्मोनिक्स पंप तरंग की गैर-रेखीय प्रगति को कैसे बदलता है।

अध्याय सातवां यह पता लगाने के लिए प्लाज्मा तरंगों का एक गैर-रेखीय युग्मन प्रस्तुत करता है कि अतिरिक्त घनत्व उतार-चढ़ाव प्रोफाइल स्थानीय संरचना निर्माण, चुंबकीय क्षेत्र की वृद्धि और टर्बुलेंट स्पेक्ट्रा की स्केलिंग को कैसे प्रभावित करते हैं। युग्मित गतिशील समीकरण नॉनलाइनियर पॉन्डरोमोटिव बल और अतिरिक्त घनत्व उतार-चढ़ाव प्रोफाइल (आयन ध्वनिक तरंग (IAW) के काउंटर प्रसार के कारण) पर विचार करके तैयार किए गए हैं। गणितीय सूत्रीकरण के माध्यम से विकसित युग्मित मॉडल समीकरणों को हल करने के लिए प्रयोगशाला सिमुलेशन और अर्ध-विश्लेषणात्मक दृष्टिकोण को नियोजित किया गया है। सिमुलेशन और अर्ध-विश्लेषणात्मक निष्कर्षों से फिलामेंटरी संरचना निर्माण और प्रवर्धन कारक पर अतिरिक्त घनत्व प्रोफाइल का प्रभाव देखा गया। अलग-अलग लंबाई के पैमानों के बीच ऊर्जा कैसकेड अतिरिक्त घनत्व उतार-चढ़ाव प्रोफाइल से भी प्रभावित होता है, जो सिमुलेशन परिणामों में देखे गए अशांत स्पेक्ट्रा द्वारा दिखाया गया है। वर्तमान अध्ययनों की प्रासंगिकता, जैसे कि स्थानीय संरचना निर्माण, चुंबकीय क्षेत्र में वृद्धि, और इलेक्ट्रॉन और आयन स्केल पर टर्बुलेंट स्केलिंग, कई खगोलभौतिकीय परिदृश्यों की नकल करते हुए लेजर-प्लाज्मा इंटरैक्शन के विभिन्न प्रयोगात्मक अवलोकनों के साथ दिखाई गई है।

Contents

Certificate

Acknowledgements	i
------------------	---

Abstract	iii
----------	-----

Contents	x
----------	---

List of Figures	xv
-----------------	----

1 Introduction and Motivation	1
1.1 Background	1
1.2 Laser Plasma Interaction	2
1.3 Myriad Plasma Modes in Magnetized Plasma	3
1.4 Magnetic Field Amplification and Turbulence Generation	5
1.5 Presence of Magnetic Field in the Universe	7
1.5.1 Supernova remnant (SNR)	7
1.5.2 Solar wind	9
1.6 Turbulence in Magnetized Plasma and Laboratory Simulations of Astrophysical Scenarios	10
1.7 Mathematical Descriptions of Plasma	14
1.7.1 Single particle model	14
1.7.2 Magnetohydrodynamics (MHD) model	15
1.7.3 Two fluid model	17
1.7.4 Kinetic approach	18
1.8 Objective of the Thesis	19
1.9 Thesis Organisation	19
References	24

2	Nonlinear Evolution of Localized Structures and Turbulent Magnetic Field Amplification by Extraordinary Laser Beam in Laser Produced Plasmas	29
2.1	Introduction	29
2.2	Basic Model Equations:	30
2.3	Wave Dynamics for Model Equations:	31
2.3.1	Model equation for Laser:	31
2.3.2	Model equation for Upper Hybrid Oscillations:	32
2.4	Numerical Simulation:	34
2.5	Results and Discussion:	35
2.6	Simplified Model:	39
2.7	Summary and Conclusion:	41
	References	43
3	Spatiotemporal nonlinear evolution of the laser pulse and turbulence generation in laser-produced plasmas.	45
3.1	Introduction	45
3.2	Basic Equations:	46
3.3	Model Dynamical Equation:	47
3.4	Results and Discussions:	50
3.4.1	Simulation results	50
3.4.2	Semi-analytical results	52
3.5	Summary and Conclusion:	56
	References	57
4	A simulation study of electron-scale turbulence generation by non-linear wave-wave interaction in laser-produced plasma.	61
4.1	Introduction	61
4.2	Model Equations Analysis	63
4.2.1	Model Equation of Extraordinary Mode (x -mode)	63
4.2.2	Model Equation of Trivelpiece-Gould (TG) mode	65
4.3	Laboratory Simulation Details	67
4.4	Results and Discussion	68
4.4.1	Numerical Simulation Findings	68
4.4.2	Simplified model results	75
4.5	Summary and Conclusion	78
	References	79
5	A Fermi Acceleration Model to Study the Electron Acceleration in Laser-Produced Plasma with Localized Structures Formation and Turbulence Generation.	83
5.1	Introduction	83

5.2	Analysis of Model Equations	85
5.2.1	Extraordinary (x -mode) Laser analysis	85
5.2.2	Upper Hybrid (UH) Wave analysis:	86
5.3	Numerical Simulation:	87
5.4	Results and Discussions:	88
5.4.1	Simulation results	88
5.4.2	Semi-analytical results	92
5.5	Concluding Remarks:	93
	References	95
6	A nonlinear wave-based model to study the magnetic turbulence generation associated with the nonlinear evolution of Kinetic Alfvén Wave in laser-produced plasma relevant to laboratory and astrophysical plasmas.	99
6.1	Introduction:	99
6.2	Basic Model Equations:	101
6.3	Formulation of Dynamical Equations:	102
6.3.1	Dynamics of the pump wave: Kinetic Alfvén Wave	102
6.3.2	Dynamics of the low-frequency wave: Magnetosonic Wave	105
6.4	Numerical Simulation	107
6.5	Results and Discussions:	108
6.5.1	Numerical simulation results	108
6.5.2	Semi-analytical results	112
6.6	Summary and Conclusion	115
	References	117
7	Simulation to study the turbulent amplification of magnetic field relevant to laboratory and astrophysical plasmas.	121
7.1	Introduction	121
7.2	Formulation of Dynamical Equation	124
7.3	Numerical Simulation	126
7.4	Results and Discussion	127
7.4.1	Simulation results	127
7.4.2	Simplified model results	130
7.5	Summary and Conclusion	133
	References	135
8	Summary and Scope for future work	139
8.1	Summary of the thesis work	139
8.2	Future scope of work	141

List of Publications	143
-----------------------------	------------

Bio-data of the Author	147
-------------------------------	------------

List of Figures

1.1	The schematic diagram of power-spectrum depicting the process of energy cascading [38].	6
1.2	An image of the youngest radio Supernova remnant Cassiopeia A in the Milky Way galaxy. (Courtesy: https://scitechdaily.com/stepping-inside-supernova-remnant-cassiopeia-a/)	8
1.3	An picture illustrating the solar wind phenomenon. (Courtesy: https://-skyandtelescope.org/astronomy-resources/solar-wind/)	9
1.4	A schematic of the experimental setup for measuring the spatiotemporal profile of the magnetic field [9]	10
1.5	The laser-induced magnetic field profile with the spatial randomness (filamentation) [9].	11
1.6	The electron scale magnetic turbulence of the magnetic field spatial profile and inset showing the power spectrum observed from PIC simulation results [9].	12
1.7	The electron scale magnetic turbulence of the magnetic field spatial profile and inset showing the power spectrum observed from PIC simulation results [9].	13
2.1	The schematic illustration of the model depicting the Upper Hybrid Oscillations in the magnetized plasma.	35
2.2	The profile of normalized intensity of the laser beam in the z - x plane at the distinct normalized time (a) 0, (b) 15, (c) 20, and (d) 30.	36
2.3	The normalized density profile in the z - x plane for normalized time $t = 20$	36
2.4	The field localization and density cavitation profiles of x -mode laser at normalized time $t = 20$	37
2.5	The ensemble-averaged magnetic power spectrum between the normalized time 28 and 35.	37
2.6	For fixed k_x , density ($ n_k $) variation against k_z at the different normalized time (a) 10, (b) 15, (c) 20, and (d) 25.	38
2.7	The time-varying profile of $ n_k $ at $k_x = k_z = 0$	38
2.8	The normalized frequency spectrum of upper hybrid oscillations.	39

2.9	The profile of normalized intensity of the laser beam in the z - x plane (a) with no density modes and with density modes at the normalized time (b) 15, (c) 20, and (d) 25.	41
3.1	The profile of the normalized laser pulse intensity at different values of the normalized propagation distance (ζ) (a) 0, (b) 15, (c) 25, (d) 50.	51
3.2	The magnetic power spectrum (ensemble-averaged) $ B_k ^2$ versus k between the normalized propagation distance 35 and 60.	52
3.3	The profile of the normalized laser pulse intensity in the spatiotemporal domain at different propagation distances (a) $x = 0\mu m$, (b) $x = 15\mu m$, (c) $x = 20\mu m$, and (d) $x = 25\mu m$ inside the plasma for the normalized amplitude of the laser $a_0 = 0.4$	55
4.1	The geometry of the electromagnetic extraordinary mode propagating perpendicular to magnetic and electric field directions.	64
4.2	The geometry of an electrostatic Trivelpiece-Gould mode propagating obliquely at an angle (θ) with the background magnetic field direction.	66
4.3	The normalized background density profiles along with the cavities and humps at normalized time $t = 13$ for distinct propagation angle (a) $\theta = 0^\circ$, (b) $\theta = 45^\circ$, (c) $\theta = 90^\circ$ of the Trivelpiece-Gould mode from the background magnetic field.	69
4.4	The profiles of the normalized intensity (filamentary structures) of the extraordinary mode at normalized time $t = 13$ for distinct propagation angle (a) $\theta = 0^\circ$, (b) $\theta = 45^\circ$, (c) $\theta = 90^\circ$ of the Trivelpiece-Gould mode from the background magnetic field.	70
4.5	The variation of maximum intensity with time of the extraordinary pump mode for distinct propagation angle (a) $\theta = 0^\circ$, (b) $\theta = 45^\circ$, (c) $\theta = 90^\circ$ of the Trivelpiece-Gould mode from the background magnetic field.	71
4.6	The profiles of field localization of the pump wave and background density perturbations along the x -axis at normalized time $t = 13$ for distinct propagation angle (a) $\theta = 0^\circ$, (b) $\theta = 45^\circ$, (c) $\theta = 90^\circ$	72
4.7	The turbulent power spectrum (time-averaged) in the quasi-steady state for distinct propagation angle (a) $\theta = 0^\circ$, (b) $\theta = 45^\circ$, (c) $\theta = 90^\circ$ of the Trivelpiece-Gould mode from the background magnetic field.	73
4.8	The plot of density mode (harmonics) against k_z and keeping k_x fixed to zero at normalized time $t = 12$ for distinct propagation angle (a) $\theta = 0^\circ$, (b) $\theta = 45^\circ$, (c) $\theta = 90^\circ$ of the Trivelpiece-Gould mode from the background magnetic field.	74
4.9	The normalized intensity profile of the laser beam at normalized time $t = 12$ for distinct propagation angle (a) $\theta = 0^\circ$, (b) $\theta = 45^\circ$, (c) $\theta = 90^\circ$ of the Trivelpiece-Gould mode from the background magnetic field.	77

5.1	The formation of cavity and humps in the normalized density profile in the x - z plane at two normalized times (a) $t = 14$ and (b) $t = 28$.	88
5.2	The normalized intensity profile of pump x -mode laser at the normalized times (a) $t = 0$, the initial profile, and the nonlinear evolution profiles (b) $t = 14$, (c) $t = 20$, (d) $t = 28$.	89
5.3	The variation of $ E_k ^2$ with k_x (time-averaged turbulent wavenumber spectrum) among the normalized time (t) 13 to 26.	90
5.4	The formation of density harmonics (modes) against finite k_z at four different normalized times (a) $t = 10$, (b) $t = 12$, (c) $t = 14$, and (d) $t = 16$.	91
5.5	The laser beam profile in the x - z plane at (a) with no effect of density harmonics on laser beam profile and with the effect of density harmonics on laser beam profile (b) $t = 12$ (c) $t = 14$ (d) $t = 16$.	93
6.1	The profile of the normalized density at the particular normalized times (a) 22 and (b) 28 in the x - z plane.	108
6.2	The variation of the normalized intensity profile of the laser beam at the different normalized times (a) 0, (b) 8, (c) 18, (d) 22, (e) 26, and (f) 30 in the x - z plane.	109
6.3	The profiles of the localized structures of the pump wave and the density cavitation along the x -axis at the normalized times (a) 18 and (b) 26.	110
6.4	The magnetic power spectrum (ensemble-averaged) between the normalized times 24 and 38.	111
6.5	The profile of the density variation against finite k_z with k_x fixed to zero at the different normalized times (a) 4, (b) 8, (c) 12, (d) 16.	112
6.6	The normalized field intensity profile of the laser beam in the x - z plane (a) without considering the density harmonics and with considering the density harmonics at the normalized times (b) 8, (c) 12, (d) 16.	114
7.1	The profile of the normalized field intensity in the x - z plane for the different magnitudes of the background density fluctuations (a) $\eta_1 = 0$, $\eta_2 = 0$ in the absence of counter-beam propagation and (b) $\eta_1 = 0$, $\eta_2 \neq 0$, (c) $\eta_1 \neq 0$, $\eta_2 = 0$, (d) $\eta_1 \neq 0$, $\eta_2 \neq 0$ for counter-beam propagation.	127
7.2	The turbulent power spectrum of fluctuations in the magnetic field for distinct magnitudes of background density fluctuations (a) $\eta_1 \neq 0$, $\eta_2 = 0$ in the absence of counter-beam propagation and (b) $\eta_1 \neq 0$, $\eta_2 \neq 0$, (c) $\eta_1 \neq 0$, $\eta_2 = 0$, (d) $\eta_1 \neq 0$, $\eta_2 \neq 0$ for counter-beam propagation.	128

7.3	The profiles of the normalized field intensity of kinetic Alfvén wave in the x - z plane for the different magnitude of background density fluctuations (a) $\eta_1 = 0$, $\eta_2 = 0$ in the absence of counter-beam propagation, (b) $\eta_1 = 0$, $\eta_2 \neq 0$, (c) $\eta_1 \neq 0$, $\eta_2 = 0$ and (d) $\eta_1 \neq 0$, $\eta_2 \neq 0$ for counter-beam propagation.	132
-----	---	-----