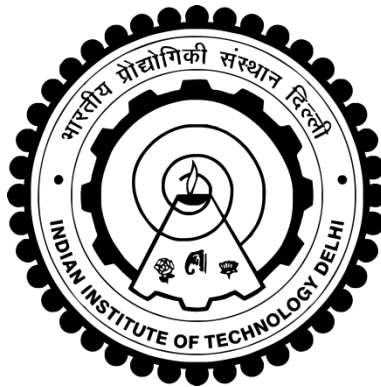


**LASER PLASMA INTERACTION AND ITS
APPLICATIONS TO PHOTODISRUPTION
AND LABORATORY PLASMA**

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**CENTRE FOR ENERGY STUDIES
INDIAN INSTITUTE OF TECHNOLOGY DELHI
OCTOBER 2018**

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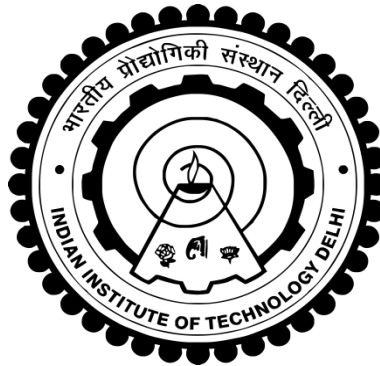
by

PRADEEP KUMAR GUPTA

Centre for Energy Studies

Submitted

In fulfilment of the requirements of the degree of Doctor of philosophy
to the



INDIAN INSTITUTE OF TECHNOLOGY DELHI

OCTOBER 2018



Dedicated to
my
Beloved Parents



Certificate

This is to certify that the thesis entitled “*Laser plasma interaction and its applications to photodisruption and laboratory plasma*” being submitted by **Pradeep Kumar Gupta** to the **Indian Institute of Technology, Delhi** is worthy of consideration for the award of the degree of ‘*Doctor of Philosophy*’ in Centre for Energy Studies, and is a record of bonafide research work carried out by him. The thesis has reached the standards fulfilling the requirement of the regulations relating to the degree. The results contained in this thesis have not been submitted in part or full to any other university or institute for the award of any degree or diploma. We approve the thesis for the award of the aforesaid degree.

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Abstract

The present thesis is an attempt mainly to understand the application of laser plasma interaction during photodisruption of crystalline lens (human eye lens) in order to cure presbyopia. This thesis also include the application of laser plasma interaction in compression of high power short laser pulse and study of turbulence in mega gauss magnetic field produced during high power ultrashort pulsed laser plasma interaction. The objectives of the present thesis have been achieved by solving the model equation through numerical simulations as well as by semi analytical technique under the paraxial ray approximation.

Presbyopia is the functional loss of the accommodative property of eye. It arises due to hardening of crystalline lens with aging. Selective photodisruption of crystalline lens increases the elasticity of lens. Photodisruption is process of minimal invasive surgery, through plasma generation via laser induced optical breakdown of medium utilizing femtosecond laser pulses, used in ophthalmology.

Focusing of laser pulse at the preferred position in a small area is the most important part during photodisruption of crystalline lens. The laser pulse dynamics decide location of focusing point and spot size of laser pulse inside the crystalline lens. Crystalline lens has parabolic graded refractive index (GRIN) structure. Along with dispersive and diffractive property of crystalline lens GRIN structure of crystalline lens also play role in determination of laser pulse dynamics during photodisruption of crystalline lens. During photodisruption dielectric constant of medium changes appreciably due to formation of electron plasma via laser induced breakdown (LIB) and an intensity dependent part of dielectric constant also arises due to high intensity of laser pulse. This intensity dependent part of dielectric constant makes the laser pulse dynamics nonlinear.

The second chapter of this thesis deals with the effect of collisional nonlinearity on the laser pulse evolution inside crystalline lens. The density gradient arises due to the nonuniform heating of plasma generated by the same laser pulse of the order of nanosecond duration or more. In chapter three, femtosecond laser pulse has been considered for the photodisruption in the crystalline lens, which has intensity high enough to generate plasma through LIB by multiphoton absorption. Generation of plasma by multiphoton absorption is a nonlinear phenomenon which changes the laser pulse dynamics. Chapter four of present thesis deals with spatiotemporal evolution of the femtosecond laser pulse during propagation of laser pulse in crystalline lens in presence of Kerr self focusing. This spatiotemporal dynamics is much more informative than only spatial dynamics because it gives the more exact estimate of the peak intensity available for plasma generation. Energy absorption from laser pulse via multiphoton absorption and plasma absorption processes play important role in spatiotemporal dynamics of the laser pulse during photodisruption of crystalline lens. Hence, a comprehensive model has been discussed in the chapter five for a focused laser pulse inside crystalline lens. This model contain the effect of transverse beam diffraction, group velocity dispersion, Kerr self-focusing, laser induced breakdown in which an electron plasma is generated, plasma absorption and multiphoton absorption.

These studies (from chapter two to five) show that self focusing of longer laser pulse happens due to collisional nonlinearity but plasma generation by the femtosecond laser pulse causes defocusing of pulse. Kerr nonlinearity of medium causes self focusing of laser pulses. This self focusing (which arises due to spatial response of nonlinearity) is not only decides the spot size at focusing point of laser pulse and location of focusing point but also plays crucial role in the breakdown of medium which is main part of the photodisruption technique. These

results also show that evolution of pulse duration (which governed by the temporal response of nonlinearity) decides the available intensity of laser pulse for photodisruption. Spatiotemporal evolution of pulse shape inside crystalline lens decides the nature of pulse beyond the focusing point. These studies also points out the relevance of the present investigations to cavitation bubble formation for restoring the elasticity of the crystalline lens. This study presents a rough estimate of plasma temperature at the focusing point during cavitation bubble generation. This type of work along with experimental predictions is very useful in understanding the process of elasticity enhancement of eye lens.

In the sixth chapter of this thesis, possibility of compression and intensity enhancement of a high power short laser pulse, utilizing relativistic nonlinearity induced by same pulse in plasma, has been discussed. It is found that pulse compression is highly sensitive to plasma frequency and initial value of electric field of pulse. Seventh chapter of this thesis deals with the turbulence in giant magnetic field reported in laboratory experiments. This study has been done by considering the relativistic nonlinearity induced during laser plasma interaction at high power. It is found that chaos in magnetic field the laser pulse play an important role in the magnetic field turbulence during the laser plasma interaction.

सार

वर्तमान थीसिस मुख्य रूप से प्रेस्बिओपिया का इलाज करने के लिए क्रिस्टलीय लेंस (मानव आंखों के लेंस) के फोटोडिसशन के दौरान लेजर प्लाज्मा इंटरैक्शन के अनुप्रयोग को समझने का प्रयास है। इस थीसिस में उच्च शक्ति शॉर्ट लेजर नाड़ी के संपीड़न और उच्च शक्ति अल्ट्राशॉर्ट स्पंदित लेजर प्लाज्मा इंटरैक्शन के दौरान उत्पादित मेगा गॉस चुंबकीय क्षेत्र में अशांति के अध्ययन में लेजर प्लाज्मा इंटरैक्शन का उपयोग भी शामिल है। वर्तमान थीसिस के उद्देश्यों को संख्यात्मक सिमुलेशन के साथ-साथ पैराएक्सियल किरण सन्निकटन के तहत अर्द्ध विश्लेषणात्मक तकनीक के माध्यम से मॉडल समीकरण को हल करके हासिल किया गया है। प्रेस्बिओपिया आंख की समायोज्य संपत्ति का कार्यात्मक नुकसान है। उम्र बढ़ने के साथ क्रिस्टलीय लेंस की सख्त होने के कारण यह उत्पन्न होता है। क्रिस्टलीय लेंस के चुनिंदा फोटोडिसशन लेंस की लोच बढ़ाता है। फोटोडिसप्शन, कम से कम आक्रामक सर्जरी की प्रक्रिया है, प्लाज्मा उत्पादन के माध्यम से लेजर प्रेरित ऑप्टिकल ब्रेकडाउन के माध्यम से महिलाओं का उपयोग करने वाले मध्यम पदार्थों का उपयोग करते हुए, नेत्र विज्ञान में प्रयोग किया जाता है।

एक छोटे से क्षेत्र में पसंदीदा स्थिति में लेजर पल्स पर ध्यान केंद्रित करना क्रिस्टलीय लेंस के फोटोडिसशन के दौरान सबसे महत्वपूर्ण हिस्सा है। लेजर पल्स गतिशीलता क्रिस्टलीय लेंस के अंदर लेजर पल्स के फोकस बिंदु और स्पॉट आकार का स्थान तय करती है। क्रिस्टलीय लेंस में पैराबॉलिक ग्रेडेड अपवर्तक सूचकांक (जीआरआईएन) संरचना है। क्रिस्टलीय लेंस की फैलाव और विवर्तनकारी संपत्ति के साथ क्रिस्टलीय लेंस की जीआरआईएन संरचना क्रिस्टलीय लेंस के फोटोडिसशन के दौरान लेजर पल्स गतिशीलता के निर्धारण में भी भूमिका निभाती है। लेजर प्रेरित ब्रेकडाउन (एलआईबी) के माध्यम से इलेक्ट्रॉन प्लाज्मा के गठन के कारण मध्यम परिवर्तनों के फोटोडिसप्शन के ढांकता हुआ निरंतर स्थिरता के दौरान और ढांकता हुआ निरंतरता का एक तीव्रता निर्भर भाग भी लेजर पल्स की उच्च तीव्रता के कारण उत्पन्न होता है। ढांकता हुआ निरंतरता की यह तीव्रता निर्भर भाग लेजर पल्स गतिशीलता nonlinear बनाता है।

इस थीसिस का दूसरा अध्याय क्रिस्टलीय लेंस के अंदर लेजर पल्स विकास पर टक्कर रहित nonlinearity के प्रभाव से संबंधित है। घनत्व ढाल नैनोसेकंद अवधि या अधिक के क्रम के समान लेजर पल्स द्वारा उत्पन्न प्लाज्मा के नॉनफॉर्मॉर्म हीटिंग के कारण उत्पन्न होता है। अध्याय तीन में, क्रिस्टलीय लेंस में फोटोडिसप्शन के लिए फिफ्टोसेकंद लेजर पल्स पर विचार किया गया है, जिसमें मल्टीफोटन अवशोषण द्वारा एलआईबी के माध्यम से प्लाज्मा उत्पन्न करने के लिए पर्याप्त तीव्रता है। मल्टीफोटन अवशोषण द्वारा प्लाज्मा की पीढ़ी एक गैरलाइन घटना है जो लेजर पल्स गतिशीलता को बदलती है। वर्तमान सिद्धांत के अध्याय चार में केर स्वयं ध्यान देने की उपस्थिति में क्रिस्टलीय लेंस में लेजर पल्स के प्रचार के दौरान फिफ्टोसेकंद लेजर पल्स के स्पैटिओटेम्पोरल विकास से संबंधित है। यह spatiotemporal गतिशीलता केवल

स्थानिक गतिशीलता की तुलना में अधिक जानकारीपूर्ण है क्योंकि यह प्लाज्मा उत्पादन के लिए उपलब्ध चरम तीव्रता का अधिक सटीक अनुमान देता है। मल्टीफोटन अवशोषण और प्लाज्मा अवशोषण प्रक्रियाओं के माध्यम से लेजर पल्स से ऊर्जा अवशोषण क्रिस्टलीय लेंस के फोटोडिसेशन के दौरान लेजर पल्स की स्पैतिओटेम्पोरल गतिशीलता में महत्वपूर्ण भूमिका निभाता है। इसलिए, क्रिस्टलीय लेंस के अंदर एक केंद्रित लेजर नाड़ी के लिए अध्याय पांच में एक व्यापक मॉडल पर चर्चा की गई है। इस मॉडल में ट्रांसवर्स बीम विवर्तन, समूह वेग फैलाव, केर स्व-फोकस करने, लेजर प्रेरित ब्रेकडाउन का प्रभाव होता है जिसमें एक इलेक्ट्रॉन प्लाज्मा उत्पन्न होता है, प्लाज्मा अवशोषण और मल्टीफोटन अवशोषण होता है।

इन अध्ययनों (अध्याय दो से पांच तक) दिखाते हैं कि लंबे लेजर नाड़ी का स्वयं ध्यान केंद्रित टकराव संबंधी गैर-रेखा के कारण होता है लेकिन फिजेट पीढ़ी फिफ्टोसेकंद लेजर पल्स द्वारा नाड़ी को रोकना पड़ता है। माध्यम के केर nonlinearity लेजर दालों का ध्यान केंद्रित करने का कारण बनता है। यह स्वयं केंद्रित (जो nonlinearity की स्थानिक प्रतिक्रिया के कारण उत्पन्न होता है) न केवल लेजर पल्स और फोकस करने के बिंदु पर ध्यान केंद्रित करने के स्थान पर स्पॉट आकार का निर्णय लेता है बल्कि माध्यम के टूटने में महत्वपूर्ण भूमिका निभाता है जो फोटोडिसप्शन तकनीक का मुख्य हिस्सा है। इन नतीजे यह भी दिखाते हैं कि नाड़ी अवधि का विकास (जो nonlinearity की अस्थायी प्रतिक्रिया द्वारा शासित) फोटोडिसेशन के लिए लेजर पल्स की उपलब्ध तीव्रता का फैसला करता है। क्रिस्टलीय लेंस के अंदर नाड़ी के आकार के स्पैतिओटेम्पोरल विकास फोकस बिंदु से परे नाड़ी की प्रकृति का फैसला करता है। इन अध्ययनों में क्रिस्टलीय लेंस की लोच को बहाल करने के लिए वर्तमान में जांच की प्रासंगिकता की प्रासंगिकता को दर्शाता है। यह अध्ययन पोकेशन बबल पीढ़ी के दौरान ध्यान केंद्रित बिंदु पर प्लाज्मा तापमान का अनुमान लगाता है। प्रयोगात्मक भविष्यवाणियों के साथ इस प्रकार का काम आंखों के लेंस की लोच में वृद्धि की प्रक्रिया को समझने में बहुत उपयोगी है।

इस थीसिस के छठे अध्याय में, प्लाज्मा में एक ही नाड़ी से प्रेरित सापेक्ष nonlinearity का उपयोग, उच्च शक्ति शॉर्ट लेजर नाड़ी के संपीड़न और तीव्रता वृद्धि की संभावना पर चर्चा की गई है। यह पाया जाता है कि नाड़ी संपीड़न प्लाज्मा आवृत्ति और इलेक्ट्रिक के प्रारंभिक मूल्य के लिए अत्यधिक संवेदनशील है

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