ENERGY ABSORPTION MECHANISMS IN LASER PLASMA INTERACTION

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INDIAN INSTITUTE OF TECHNOLOGY DELHI

JULY 2026

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ENERGY ABSORPTION MECHANISMS IN LASER PLASMA INTERACTION

by

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Department of Physics

Submitted

in the fulfillment of the requirements of the degree of Doctor of Philosophy

to the



INDIAN INSTITUTE OF TECHNOLOGY DELHI

JULY 2026

Dedicated to my parents

Certificate

This is to certify that the thesis entitled **"Energy absorption mechanisms in laser plasma interaction"**, submitted by **ROHIT JUNEJA** to the Indian Institute of Technology Delhi, for the award of the degree of **Doctor of Philosophy** in PHYSICS, is a record of the original, bona fide 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 my knowledge.

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Acknowledgements

I would like to begin by expressing my deepest and most sincere gratitude to my thesis supervisor, Prof. Amita Das. Throughout my doctoral journey, she has played the most crucial role, and I remain profoundly indebted to her for the numerous opportunities she generously provided me. I am grateful for her constant guidance, thoughtful discussions, and insightful feedback, which shaped this thesis in many important ways. What I value most is her unwavering support and belief in me, especially during challenging phases of my doctoral journey. During such times, she trusted me, gave me the freedom to explore problems at my own pace, and taught me that sincere effort and curiosity matter far more than the fear of failure. Under her supervision, I truly learned what it means to do research, how to approach a problem, think critically, and communicate ideas with clarity and rigor. Her scientific vision, disciplined approach, and commitment to research have played a decisive role in shaping me as a researcher. Working under her supervision has been a privilege, and the intellectual environment she fostered greatly strengthened my analytical abilities and scientific outlook.

I would also like to extend my sincere gratitude to the SRC members, Prof. Vikrant Saxena, Prof. V. Ravishankar, Prof. Sujin Babu, and Prof. Debaprasad Sahu, for their valuable suggestions and constructive feedback on this work.

I would like to thank my collaborators Dr. Srimanta Maity, Dr. Devshree Mandal, and Dr. Laxman Goswami for their support during the initial years of my doctoral work. I would like to extend my thanks to Trishul Dhalia, a friend and collaborator, with whom I greatly enjoyed working. I also acknowledge the many enlightening scientific discussions with Dr. Sooryansh Asthana and Dr. Rajni Bala, which were both insightful and stimulating. I would like to thank Dr. Subhasish Bag, a wonderful colleague, for his constant support. I am also thankful to all the members of the Einstein Research Scholar Room, including Mamta, Imran, Subramanya, Aman, and Yasir, for creating a supportive and welcoming research environment. I would also like to thank my friends and cousins, Piyush, Sukhvinder,

Paritosh, Harsha, Shamshe, Bhupinder, Shubham, and Sanchit, for their constant support and encouragement throughout this journey.

I express my sincere gratitude to the Council of Scientific and Industrial Research (CSIR) for financial support towards my doctoral research. I also acknowledge the Research Scholar Travel Award and Research Excellence Travel Award from IIT Delhi, along with the CSIR Foreign Travel Award and International Travel Support from ANRF, which enabled my participation in international conferences in France, Japan, Belgium, and the USA.

I would like to express my deepest gratitude to my parents, Mr. Ashok Juneja and Mrs. Jyoti Juneja, whose unwavering support, sacrifices, and constant encouragement have been the foundation of this journey. Their belief in me, patience, and understanding gave me the strength to persevere through every phase of my doctoral work. I am also deeply thankful to my brother, Mr. Ansh Juneja, for his constant support, care, and encouragement, which meant a great deal to me throughout this journey.

I may have unintentionally missed mentioning some important people in this acknowledgement due to my forgetfulness. However, my gratitude is not limited to these pages.

Rohit Juneja

Abstract

This thesis investigates the mechanisms of energy absorption in laser-plasma interactions using Particle-In-Cell (PIC) simulations performed on the OSIRIS 4.0 platform. A detailed examination of the underlying physical processes responsible for irreversible energy transfer is presented, addressing key knowledge gaps in both unmagnetized and magnetized plasma responses to intense laser fields, as outlined below.

In conventional studies, the focus has largely been on absorption mechanisms in the unmagnetized regime. Collisional and resonant processes are well-established in explaining irreversible energy transfer; however, several open questions remain for collisionless and non-resonant laser-plasma interactions. In particular, mechanisms such as vacuum heating and $\vec{J} \times \vec{B}$ heating, arising when a laser interacts with the plasma–vacuum boundary, are not yet fully understood. These processes are often attributed to the stochastic motion of particles in the combined electric field of the laser and the plasma sheath. In this work, PIC simulations are employed to explicitly study particle dynamics in the sheath region. The results clearly reveal the chaotic nature of particle trajectories, thereby identifying the intrinsic cause of irreversible energy transfer in such cases.

The study of laser-plasma interactions in the presence of an external magnetic field has only recently gained momentum. Advances in high-power, low-frequency pulsed CO_2 lasers and in generating kilotesla magnetic fields have made it possible to elicit a magnetized response from lighter electron species within the duration of a laser pulse or even a single laser period. This opens new opportunities to exploit additional plasma resonances for enhanced energy absorption. The emergence of extra pass bands, tunable via the strength and orientation of the applied magnetic field, can be harnessed for localized energy deposition. Moreover, the restricted motion of electrons in a magnetic field can enable direct ion heating by the laser. This thesis demonstrates how each of these mechanisms can be utilized for targeted energy absorption. While eliciting a magnetized response from heavier ion species in the laboratory remains impractical in the near future (requiring magnetic fields $\sim 10^3$ times stronger), such

conditions are feasible in astrophysical environments, where plasmas are often threaded by extremely intense magnetic fields.

Cyclotron and hybrid resonances are investigated in detail. A salient observation is that efficient absorption occurs when the laser frequency is slightly off-resonance, due to the competing requirements of sufficient laser penetration and proximity to resonance for optimal energy deposition. For hybrid resonances, the energy transfer is found to be necessarily mediated through electrostatic field generation, in contrast to cyclotron resonances, where no such field generation occurs. Whenever electrostatic fields mediate the transfer, particle trajectories exhibit chaotic behavior. Furthermore, the possibility of localized energy deposition is explored by suitably tailoring the spatial and temporal profiles of the applied magnetic field.

सार

यह शोध-प्रबंध OSIRIS 4.0 प्लेटफ़ॉर्म पर किए गए पार्टिकल-इन-सेल (PIC) सिमुलेशनों का उपयोग करते हुए लेज़र-प्लाज़्मा अन्योन्यक्रियाओं में ऊर्जा अवशोषण की क्रियाविधियों का अन्वेषण करता है। इसमें अप्रतिवर्ती ऊर्जा स्थानांतरण के लिए उत्तरदायी अंतर्निहित भौतिक प्रक्रियाओं का विस्तृत परीक्षण प्रस्तुत किया गया है, जो तीव्र लेज़र क्षेत्रों के प्रति अचुंबकित (unmagnetized) तथा चुंबकित (magnetized), दोनों प्रकार की प्लाज़्मा अनुक्रियाओं में विद्यमान प्रमुख ज्ञान-अंतरालों को संबोधित करता है, जैसा कि नीचे उल्लिखित है।

पारंपरिक अध्ययनों में मुख्यतः अचुंबकित व्यवस्था की अवशोषण क्रियाविधियों पर ध्यान केंद्रित रहा है। संघट्टीय (collisional) तथा अनुनादी प्रक्रियाएँ अप्रतिवर्ती ऊर्जा स्थानांतरण की व्याख्या में सुस्थापित हैं; तथापि, संघट्टहीन तथा अन-अनुनादी लेज़र-प्लाज़्मा अन्योन्यक्रियाओं के लिए अनेक प्रश्न अनुत्तरित हैं। विशेष रूप से, वैक्यूम तापन (vacuum heating) तथा $\vec{J} \times \vec{B}$ तापन जैसी क्रियाविधियाँ, जो लेज़र के प्लाज़्मा–वैक्यूम सीमा से अन्योन्यक्रिया करने पर उत्पन्न होती हैं, अभी तक पूर्णतः समझी नहीं गई हैं। इन प्रक्रियाओं को प्रायः लेज़र तथा प्लाज़्मा शीथ के संयुक्त विद्युत क्षेत्र में कणों की स्टोकैस्टिक (stochastic) गति के लिए उत्तरदायी माना जाता है। इस कार्य में, शीथ क्षेत्र में कण-गतिकी का स्पष्ट अध्ययन करने हेतु PIC सिमुलेशनों का उपयोग किया गया है। परिणाम कण-प्रक्षेप-पथों की अराजक प्रकृति को स्पष्ट रूप से प्रकट करते हैं, और इस प्रकार ऐसे मामलों में अप्रतिवर्ती ऊर्जा स्थानांतरण के आंतरिक कारण की पहचान करते हैं।

बाह्य चुंबकीय क्षेत्र की उपस्थिति में लेज़र-प्लाज़्मा अन्योन्यक्रियाओं का अध्ययन हाल ही में गति पकड़ पाया है। उच्च-शक्ति, निम्न-आवृत्ति स्पंदित CO_2 लेज़रों तथा किलोटेस्ला स्तर के चुंबकीय क्षेत्रों के उत्पादन में हुई प्रगति ने यह संभव कर दिया है कि एक लेज़र स्पंद की अवधि में, अथवा एकल लेज़र आवर्तकाल में भी, हल्के इलेक्ट्रॉनों से चुंबकित अनुक्रिया प्राप्त की जा सके। इससे संवर्धित ऊर्जा अवशोषण हेतु अतिरिक्त प्लाज़्मा अनुनादों के उपयोग की नई संभावनाएँ खुलती हैं। अनुप्रयुक्त चुंबकीय क्षेत्र की प्रबलता तथा दिशा द्वारा समायोज्य अतिरिक्त पारक-बैंडों (pass bands) का उद्भव स्थानीयकृत ऊर्जा निक्षेपण के लिए उपयोग में लाया जा सकता है। इसके अतिरिक्त, चुंबकीय क्षेत्र में इलेक्ट्रॉनों की सीमित गति लेज़र द्वारा प्रत्यक्ष आयन तापन को संभव बनाती है। यह शोध-प्रबंध दर्शाता है कि इनमें से प्रत्येक क्रियाविधि को लक्षित ऊर्जा अवशोषण हेतु किस प्रकार उपयोग में लाया जा सकता है। यद्यपि प्रयोगशाला में भारी आयनों से चुंबकित अनुक्रिया प्राप्त करना निकट भविष्य में अव्यावहारिक है (जिसके लिए लगभग 10^3 गुना अधिक प्रबल चुंबकीय क्षेत्र आवश्यक होंगे), फिर भी ऐसी परिस्थितियाँ खगोल-भौतिकीय वातावरणों में साध्य हैं, जहाँ प्लाज़्मा प्रायः अत्यंत तीव्र चुंबकीय क्षेत्रों से व्याप्त रहती है।

साइक्लोट्रॉन तथा संकर (hybrid) अनुनादों का विस्तार से अन्वेषण किया गया है। एक उल्लेखनीय प्रेक्षण यह है कि कुशल अवशोषण तब होता है जब लेज़र आवृत्ति अनुनाद से थोड़ी हटकर होती है, क्योंकि इष्टतम ऊर्जा निक्षेपण के लिए पर्याप्त लेज़र प्रवेशन तथा अनुनाद-समीपता की परस्पर विरोधी आवश्यकताएँ होती हैं। संकर अनुनादों के लिए ऊर्जा स्थानांतरण अनिवार्य रूप से स्थिरवैद्युत क्षेत्र के जनन के माध्यम से होता पाया गया, जबकि इसके विपरीत साइक्लोट्रॉन अनुनादों में ऐसा कोई क्षेत्र-जनन नहीं होता। जब भी स्थिरवैद्युत क्षेत्र स्थानांतरण में मध्यस्थता करते हैं, कण-प्रक्षेप-पथ अराजक व्यवहार प्रदर्शित करते हैं। इसके अतिरिक्त, अनुप्रयुक्त चुंबकीय क्षेत्र के स्थानिक तथा कालिक प्रोफ़ाइलों को उपयुक्त रूप से समायोजित करके स्थानीयकृत ऊर्जा निक्षेपण की संभावना का अन्वेषण किया गया है।

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Abbreviations

EM	**E**lectro**M**agnetic
CPA	**C**hirped **P**ulse **A**mplification
ICF	**I**nertial **C**onfinement **F**usion
LH	**L**ower **H**ybrid
UH	**U**pper **H**ybrid
ICR	**I**on **C**yclotron **R**esonance
ECR	**E**lectron **C**yclotron **R**esonance
RL mode	**R**ight **L**eft Circularly Polarized Mode
X-mode	**E**xtraordinary Mode
O-mode	**O**rdinary Mode
PIC	**P**article **I**n **C**ell
HHG	**H**igher **H**armonic **G**eneration
ES	**E**lectro**S**tatic
1D	**O**ne **D**imensional
2D	**T**wo **D**imensional
3D	**T**hree **D**imensional

LLE	**L**argest **L**yapunov **E**xponent
PPC	**P**article **P**er **C**ell
FFT	**F**ast **F**ourier **T**ransform