CHANNEL FORMATION AND STIMULATED RAMAN SCATTERING DURING LASER-PLASMA INTERACTION

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by

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Dedicated to

my family and loved ones

&

those

whoever inspired and encouraged me

Certificate

This is to certify that the thesis entitled "**Channel Formation and Stimulated Raman Scattering during Laser-Plasma Interaction**" being submitted by **Mr. Manish Dwivedi** is worthy of consideration for the award of the degree of Doctor of Philosophy and is a record of the original bonafide research work carried out by him under my guidance and supervision, and that the results contained in it have not been submitted in part or full to any other university or institute for award of any degree/diploma.

I certify that he has pursued the prescribed course of research. I approve the thesis for the award of the degree of Doctor of Philosophy.

Hitendra K. Malik

Professor

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Abstract

In the present thesis, the investigation of low plasma density channel formation and stimulated Raman scattering (SRS) during laser-plasma interaction is presented. The evolution of low-density channel formed by the radial expulsion of the electrons and the ions due to the ponderomotive force of the q-Gaussian laser beam is investigated. Perturbation approximation and WKB approximation are employed to study the channel formation and propagation of the beam in the self-formed channel. Laser and plasma parameters are optimized for realizing better channelling and self-focusing of the beam. The effect of q-parameter on the channel formation and laser's spot size has been graphically presented and discussed. Also, the effects of parabolic low density plasma channel on the backward stimulated Raman scattering are investigated. Fluid model is employed to obtain the dispersion relation of the scattered laser beam. The effects of channel parameter on stimulated Raman scattering are investigated.

Stimulated Raman scattering is investigated in underdense rippled plasma with the proposal of the oblique orientation of density ripples in plasma. The presence of stationary electron density causes coupling of high phase velocity Langmuir wave to relatively low-velocity Langmuir wave generated in the process. This coupling leads to the dissipation of wave energy through the Landau damping of the latter wave, which results in the suppression of the temporal growth of SRS. It is found that even small amplitude of the ripples ($\eta < 0.03$) leads to this coupling. The growth rate of SRS is found to decrease up to a specific value with increasing ripples density amplitude η and decreasing wave number $|\vec{q}|$. The presence of rippled electron density not only leads to the dissipation of wave energy but also decreases the region of resonance where SRS takes place. Further, the SRS of circularly polarized laser in magnetized rippled density plasma is investigated. Here the growth rate of the instability is obtained using the partial fluid and kinetic models. Results show that in the sufficiently strong magnetic field, the growth rate of both RHCP (right hand circularly polarized) and LHCP (left hand circularly polarized) laser is smaller than the growth obtained in unmagnetized plasma. However, when the cyclotron frequency ω_c is smaller than the pump laser frequency ω_0, the growth rate of the LHCP laser decreases with the magnetic field, and that of the RHCP laser increases. The enhanced effect of the magnetic field is observed in the rippled density plasma. There are combined effects of the parallel magnetic field and oblique rippled density on the instability, which leads to the suppression of the instability. Detailed analysis of the magnetic field effect and parameters of ripple density on the growth rate of SRS is made numerically and graphically.

Raman backscattering of laser beam propagating in a transversely wiggler magnetized plasma is considered in the presence of density ripples. Using wave equation and nonlinear ponderomotive force and considering the coupling between the sideband wave and the upper hybrid wave, an expression of the growth rate of this instability is obtained. The calculations demonstrate that the growth rate decreases by increasing the external magnetic field since the coupling between the scattered wave and upper-hybrid wave is weak and phase matching condition is not well-satisfied for higher external magnetic field. We have observed that the instability is suppressed due to the presence of density ripples. Also, the suppression is significant for the case of small wave number density ripples as large faction of energy of the upper hybrid electrons wave transfers to the secondary hybrid electrons wave.

सार

वर्तमान थीसिस में, लेजर-प्लाज्मा इंटरैक्शन के दौरान कम प्लाज्मा घनत्व चैनल गठन और उत्तेजित रमन स्कैटरिंग (एसआरएस) की जांच प्रस्तुत की गई है। q-गॉसियन लेजर बीम के पोंडरोमोटिव बल के कारण इलेक्ट्रॉनों और आयनों के रेडियल निष्कासन द्वारा गठित कम - घनत्व - चैनल के विकास की जांच की गयी है। स्व-निर्मित चैनल में चैनल के गठन और बीम के प्रसार का अध्ययन करने के लिए गड़बड़ी सन्निकटन और WKB सन्निकटन को नियोजित किया जाता है। बीम के बेहतर चैनलिंग और आत्म-केंद्रित होने को साकार करने के लिए लेजर और प्लाज्मा मापदंडों को अनुकूलित किया गया है। चैनल के गठन और लेजर के स्पॉट आकार पर q-पैरामीटर के प्रभाव को ग्राफिक रूप से प्रस्तुत किया गया है और चर्चा की गई है। इसके अलावा, पिछड़े उत्तेजित रमन प्रकीर्णन पर परवलयिक कम घनत्व वाले प्लाज्मा चैनल के प्रभावों की जांच की गई है। बिखरे हुए लेजर बीम के फैलाव संबंध को प्राप्त करने के लिए द्रव मॉडल का उपयोग किया जाता है। उत्तेजित रमन प्रकीर्णन पर चैनल पैरामीटर के प्रभावों की जांच की गई है।

उत्तेजित रमन प्रकीर्णन की जांच प्लाज़्मा में घनत्व तरंगों के परोक्ष अभिविन्यास के प्रस्ताव के साथ कम सघन तरंगित प्लाज्मा में की गई है। स्थिर इलेक्ट्रॉन घनत्व की उपस्थिति प्रक्रिया में उत्पन्न अपेक्षाकृत कम-वेग लैंगमुइर तरंग के लिए उच्च चरण वेग लैंगमुइर तरंग के युग्मन का कारण बनती है। यह युग्मन बाद की लहर के लैंडौ डंपिंग के माध्यम से तरंग ऊर्जा के अपव्यय की ओर जाता है, जिसके परिणामस्वरूप एसआरएस के अस्थायी विकास का दमन होता है। यह पाया गया है कि तरंगों के छोटे आयाम ($\eta<0.03$) भी इस युग्मन की ओर ले जाते हैं। SRS की वृद्धि दर एक विशिष्ट मान तक घटती हुई पाई गई है जिसमें तरंग घनत्व आयाम और घटती तरंग संख्या $|q|$ है। तरंगित इलेक्ट्रॉन घनत्व की उपस्थिति न केवल तरंग ऊर्जा के अपव्यय की ओर ले जाती है बल्कि अनुनाद के क्षेत्र को भी कम कर

देती है जहां SRS होता है। इसके अलावा, चुंबकीय तरंग घनत्व प्लाज्मा में गोलाकार ध्रुवीकृत लेजर के एसआरएस की जांच की गई है। यहां आंशिक द्रव और गतिज मॉडल का उपयोग करके अस्थिरता की वृद्धि दर प्राप्त की गई है। परिणाम बताते हैं कि पर्याप्त रूप से मजबूत चुंबकीय क्षेत्र में, आरएचसीपी (दाहिने हाथ गोलाकार ध्रुवीकृत) और एलएचसीपी (बाएं हाथ गोलाकार ध्रुवीकृत) लेजर दोनों की वृद्धि दर अचुंबकीय प्लाज्मा में प्राप्त वृद्धि से कम है। हालांकि, जब साइक्लोट्रॉन आवृत्ति ω_c पंप लेजर आवृत्ति ω_0 से छोटी होती है, तो चुंबकीय क्षेत्र के साथ LHCP लेजर की वृद्धि दर घट जाती है, और RHCP लेजर की वृद्धि दर बढ़ जाती है। तरंग घनत्व वाले प्लाज्मा में चुंबकीय क्षेत्र का बढ़ा हुआ प्रभाव देखा जाता है। अस्थिरता पर समानांतर चुंबकीय क्षेत्र और तिरछी तरंग घनत्व के संयुक्त प्रभाव होते हैं, जिससे अस्थिरता का दमन होता है। एसआरएस की वृद्धि दर पर चुंबकीय क्षेत्र प्रभाव और तरंग घनत्व के मापदंडों का विस्तृत विश्लेषण संख्यात्मक और ग्राफिक रूप से किया जाता है।

एक ट्रांसवर्सली विगलर मैग्नेटाइज्ड प्लाज्मा में फैलने वाले लेजर बीम के रमन बैकस्कैटरिंग को घनत्व तरंगों की उपस्थिति में माना जाता है। वेव इक्वेशन और नॉनलाइनियर पॉन्डरोमोटिव फोर्स का उपयोग करके और साइडबैंड वेव और अपर हाइब्रिड वेव के बीच कपलिंग पर विचार करते हुए, इस अस्थिरता की वृद्धि दर की अभिव्यक्ति प्राप्त की जाती है। गणना दर्शाती है कि बाहरी चुंबकीय क्षेत्र में वृद्धि से विकास दर घट जाती है क्योंकि बिखरी हुई लहर और ऊपरी-हाइब्रिड लहर के बीच युग्मन कमजोर होता है और उच्च बाहरी चुंबकीय क्षेत्र के लिए चरण मिलान की स्थिति अच्छी तरह से संतुष्ट नहीं होती है। हमने देखा है कि घनत्व तरंगों की उपस्थिति के कारण अस्थिरता दब जाती है। इसके अलावा, छोटे तरंग संख्या घनत्व तरंगों के मामले में दमन महत्वपूर्ण है क्योंकि ऊपरी हाइब्रिड इलेक्ट्रॉनों की ऊर्जा का बड़ा गुट द्वितीयक हाइब्रिड इलेक्ट्रॉन तरंग में स्थानांतरित होता है।

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List of Symbols

a	Laser strength parameter
a	Channel width (chapter 3)
A_0	Square root of peak value of radial distribution of laser intensity
A_s	Amplitude of scattered EM wave
$\vec{B}$	Magnetic field vector of wave
B	External magnetic field
B_0	External dc magnetic field
B_h	Amplitude of wiggler magnetic field
β	Coupling factor between primary wave and secondary wave (chapter 6)
c	Speed of light in vacuum
c_s	Electron thermal speed
c_{si}	Ions thermal speed
$\chi_{\omega k}$	Electric susceptibility of primary wave
$\chi'_{\omega k}$	Electric susceptibility of secondary wave
D	Dispersion relation of scattered wave (chapter 4)
D	Dispersion matrix
δ	Normalized wave number (chapters 4,5,6)
$\frac{\delta}{T_e}$	Fraction of kinetic energy electrons gains from incident laser (chapter 1)
δ_e	Fraction of energy loss by an electron in collision with ions
E	Electric field vector of wave
e	Charge of electron
$\vec{E}_0$	Electric field vector of incident laser
$\vec{E}_s$	Electric field vector of scattered laser
ϵ_0	Electric permittivity
$\varepsilon_{\omega k}$	Effective permittivity of primary wave
$\varepsilon_{\omega k'}$	Effective permittivity of secondary wave
η	Normalized amplitude of rippled density
$f(z)$	Beam width parameter

$\vec{F}_p$	Ponderomotive force (Chapters 1 and 2)
$\vec{F}_{p\omega k}$	Ponderomotive force (Chapters 3,4 and,5)
Γ	Growth rate of scattered wave
$\boldsymbol{\gamma}$	Matrix representing the coupling of external magnetic field and incident laser
γ	Growth rate
Γ_{0BSRS}	Growth rate of backscattered stimulated Raman scattering in uniform density plasma
Γ_{SRS}	Growth rate of stimulated Raman scattering
$I(r)$	Intensity of scattered laser beam
$\vec{J}$	Current density
$\vec{J}_s^L$	Linear current density associated with scattered EM wave
$\vec{J}_s^{NL}$	Nonlinear current density associated with scattered EM wave
$\vec{J}_s$	Current density associated with scattered wave
$\vec{k}$	Wave vector of plasma frequency
$\vec{k}_0$	Wave vector of incident laser
$\vec{k}_b$	Wave vector of wiggler magnetic field
$\vec{k}_s$	Wave vector of scattered laser
λ_D	Debye length
Λ	Damping rate of secondary wave
m_e	Mass of electron
m_i	Mass of ions
μ	Electron-ion mass ratio (chapter 2)
$\boldsymbol{\mu}$	Matrix representing the beating of incident laser and scattered laser
μ_0	Magnetic permeability in vacuum
n_1	Small perturbation in electron density
n_c	Critical density
n_e	Electron perturb density
n_q^e	Ripple density
$n_{\omega k'}$	Perturbed density of secondary wave
ν_e	Electron's collisional frequency
ω	Angular frequency of plasma frequency

ω_0	Angular frequency of incident laser
ω_c	Cyclotron frequency due to dc magnetic field (chapter 5)
ω_h	Cyclotron frequency of electron due to wiggler magnetic field
ω_p	Plasma frequency
ω_{p0}	Unperturbed plasma frequency
ω_{pq}	Plasma frequency associated with density ripples
ω_s	Angular frequency of scattered laser
Φ	Electrostatic potential of plasma wave
$\Phi_{\omega k}$	Electrostatic potential of primary wave
$\phi_{\omega k}$	Amplitude of electrostatic potential of primary wave
$\Phi_{\mathrm{\omega k'}}$	Electrostatic potential of secondary wave
$\phi_{\omega k'}$	Amplitude of electrostatic potential of secondary wave
$\Phi_{p\omega k}$	Ponderomotive potential
q	q parameter of q-Gaussian laser
q	Wave number of density ripples
r	Radial coordinate
r_0	Beam width
t_0	Pulse duration
T_e	Temperature of plasma
t_e	Onset time of thermal nonlinearity
τ	Onset time of ponderomotive nonlinearity
θ	Angle between wave vector of incident laser and that of primary wave
θ_r	Angle between wave vector of incident laser and that of density ripples
$\vec{v}_0$	Quiver velocity of electron impart from incident laser
$\vec{v}_1$	Small perturbation in electron velocity
$\vec{v}_e$	Perturbed electron velocity
$\vec{v}_{\omega k}$	Phase velocity of primary wave
$\vec{v}_{\omega k'}$	Phase velocity of secondary wave
v_{th}	Thermal speed of electrons
ε	General effective permittivity of plasma

ε_0	Unperturbed effective permittivity of plasma
ε_1	Small perturbation in effective permittivity of plasma
x_0	Beam width (chapter 3)
$Z(t)$	Plasma dispersion function
ζ	Normalized distance of propagation