Relativistic Effects in

Short Pulse Laser Plasma Interaction

by

Ajit Upadhyay

Submitted

In fulfillment of the requirements of the degree of

DOCTOR OF PHILOSOPHY

to the

Department of Physics

INDIAN INSTITUTE OF TECHNOLOGY, DELHI

MAY, 2002

TO MY SISTER

CERTIFICATE

This is to certify that the thesis titled "RELATIVISTIC EFFECTS IN SHORT PULSE LASER PLASMA INTERACTION" being submitted by AJIT UPADHYAY is worthy of consideration for the award of the degree of DOCTOR OF PHILOSOPHY and is a record of 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 aforesaid degree.

V.K. Tripathi

May 2002.

Prof. V. K. Tripathi
Department of Physics
I.I.T., Delhi.

ACKNOWEDGEMENT

I take this opportunity to express deep sense of gratitude and profound indebtedness towards Prof. V.K. Tripathi for his invaluable guidance, constant support and encouragement. His deep knowledge in the subject and his humanitarian approach has always been a constant source of inspiration to me. It gives me immense pleasure to express my gratitude to Prof. H.C. Pant, CAT, Indore for his support and encouragement. It gives me immense pleasure to thank Dr. D.D.Bhawalkar, Director, CAT for encouraging collaboration with other institutes, which has resulted in this work. SCC, CAT deserves special thanks for allowing me to continue with my Ph.D.

My sincere thanks are due to Dr. A.K.Sharma and Dr. R.N.Agrawal for their support and encouragement throughout my research work. Thanks are also due to my friends Naveen and Rakesh for helping me at various stages of this work. Pooja, Devki, Somnath, Manoj, Deepanjan and Amrendra deserve a mention for their support at campus life.

This acknowledgement would remain incomplete without expressing my sincere feelings towards my sister Dolly for her unconditional love, support and understanding. I wish to express my sincere feelings to the lady, who changed my life forever, for love and encouragement towards completing my research work. Atulji, Anjana bhabhi, Tanu Yashu, Poonam, Suresh and Anushree deserve hearty thanks for their love and support without which the life would have been a bit difficult. Thanks are also due to Jai, Sunil, Anand, Sujit and Avnish for their love and support. The encouragement and blessings to achieve success in my endeavors from my parents and brother can not be gratified in words, they have always been with me.

And lastly, I thank all those who have helped me directly or indirectly in my research work.

May 2002. *Ajit Upadhyay*

Abstract

In the present thesis some of the relativistic effects in short-pulse laser plasma interaction have been studied.

The temporal evolution of an intense short pulse laser in under-dense plasma is analyzed. The effect of relativistic mass non-linearity on the group velocity of the laser pulse is to modify its temporal pulse shape. The distortion in pulse shape is estimated for a uniform intensity laser pulse as well as for a Gaussian intensity laser pulse.

The asymmetric self-focusing of an intense short laser pulse in a plasma has been analyzed. The laser pulse undergoes self-pulse distortion due to combined effect of non-linearity induced self-focusing and dispersion. The non-linearity arises due to relativistic mass variation. The low intensity front of the pulse converges only mildly while higher intensity portion self-focuses strongly. However, at the intensity maxima the self-focusing effect is masked by the saturation effect of non-linear refractive index. We have used source dependent expansion method to solve the paraxial wave equation with non-linear source term, retaining cross space-time derivatives of laser amplitude, thereby allowing for self-distortion of pulse.

The effect of hot electrons on the stimulated Compton scattering (SCS) of a laser in a self-sustained plasma channel is studied. The presence of drifting energetic electrons in laser produced plasma enhances the growth rate of SCS by causing stronger Landau damping of the Langmuir wave produced in the Compton process. It also weakens the guiding process as these electrons quickly

pass through the length of the channel before they could be driven out of the channel by the ponderomotive force. Thus a self-guided laser could have a large spot size at a given power. The growth rate of SCS is derived for two species plasma, non-local effects have also been included.

The second harmonic generation in a plasma channel is studied. An intense laser beam, guided through a low-density plasma channel, produces second harmonic due to ponderomotive non-linearity. The second harmonic leaks out in the high-density outer region, propagating at low angle hollow cone with respect to filament axis. The second harmonic power and its variation with channel density is estimated.

We have studied the effect of relativistic drift and thermal spread in the velocity of electron beam on the Weibel instability in the presence of a large amplitude plasma wave. The presence of a large amplitude plasma wave has a strong influence over the growth rate of Weibel instability. The enhancement in growth rate is stronger at shorter wavelengths. The growth rate of Weibel instability is obtained for electrons having high drift velocity and large thermal spread.

CONTENTS

List of Figures

1. INTRODUCTION 1
    - 1.1 Fast Ignitor Fusion
    - 1.2 Short Pulse High Intensity Laser Plasma Interaction
        - 1.2.1 Underdense Plasma
        - 1.2.2 Overdense Plasma
    - 1.3 Discussion
2. LASER PULSE FRONT SHARPENING IN A PLASMA 25
    - 2.1 Pulse Front Sharpening in 1D
    - 2.2 2D Effects
    - 2.3 Discussion
3. ASYMMETRIC SELF-FOCUSING OF A LASER PULSE IN A PLASMA 35
    - 3.1 Wave Equation
    - 3.2 Quadratic Non-Linearity
    - 3.3 Saturation Non-Linearity
    - 3.4 Discussion
4. STIMULATED COMPTON SCATTERING BY HOT ELECTRONS IN A LASER PRODUCED PLASMA 44
    - 4.1 Self-Guided Laser
    - 4.2 Local Instability Analysis
    - 4.3 Compton Scattering with Both Sidebands
    - 4.4 Non-Local Effects
        - 4.4.1 SCS by Bulk Plasma Electrons
        - 4.4.2 SCS by Hot Electrons
    - 4.5 Discussion
5. SECOND HARMONIC GENERATION IN A PLASMA CHANNEL 68
    - 5.1 Second Harmonic Non-Linear Current Density
    - 5.2 Second Harmonic Power
    - 5.3 Discussion
6. WEIBEL INSTABILITY OF RELATIVISTIC ELECTRON FLOWS 80
    - 6.1 Weibel Instability
    - 6.2 Effect of Large Amplitude Langmuir Wave
    - 6.3 Discussion
7. CONCLUSION 91

References 95

Appendix 103

Bio-data of the author. 106

List of Figures

- Fig (1.1) Regions of plasma corona where various plasma processes take place.
- Fig (1.2) A schematic representation of fast ignitor concept.
- Fig (1.3) Target gain versus laser driver energy. Isobaric central spark indirect drive (including the NIF point design) and direct drive are shown for comparison with fast ignition gain for fuel densities 150, 200, 300 g/cc. Labels indicate fast ignitor laser pulse energy and intensity x $(\text{wavelength})^2$.
- Fig (1.4) Different fast ignitor target concepts for direct as well indirect drive compression and fast ignition.
- Fig (1.5) Physics of laser interaction with (a) Solids and (b) Gases.
- Fig (2.1) Temporal behavior of pulse as it propagates (i.e. z/t_0c increases) 1D case.
- Fig (2.2) Temporal behavior of pulse as it propagates (i.e. z/t_0c increases) 2D case.
- Fig (3.1) Temporal behaviour of pulse in case of quadratic non-linearity as it propagates (i.e. z/Rd increases).
- Fig (3.2) Temporal behaviour of pulse in case of saturation non-linearity as it propagates (i.e. z/Rd increases) for $\omega_p/\omega=0.1$.
- Fig (3.3) Temporal behaviour of pulse in case of saturation non-linearity as it propagates (i.e. z/Rd increases) for $\omega_p/\omega=0.3$.
- Fig (4.1) Growth rate of stimulated forward Compton scattering as a function of frequency of space charge mode.
- Fig (4.2) Growth rate of stimulated Compton backscattering as a function of frequency of space charge mode.

- Fig (4.3) Growth rate on hot electrons vs. space charge mode wave number (for both sidebands), without non-local effects.
- Fig (4.4) Ratio of field amplitude of lower sideband to upper sideband versus space charge mode wave number, without non-local effects.
- Fig (4.5) Growth rate on bulk plasma electrons versus space charge mode frequency, with non- local effects.
- Fig (4.6) Growth rate on hot electrons versus space charge mode frequency (upper side band), with non-local effects.
- Fig (4.7) Growth rate on bulk plasma electrons versus r0c/ωp, with non-local effects.
- Fig (5.1a) Second harmonic conversion efficiency ($\sim P_2/P_1$) versus density of plasma channel (ω_{p1}/ω_0) for channel radius a = 4.8 μm.
- Fig (5.1b) Second harmonic conversion efficiency ($\sim P_2/P_1$) versus density of plasma channel (ω_{p1}/ω_0) for channel radius a = 9.6 μm.
- Fig (5.2) Angle of second harmonic emission (θ) versus density of plasma channel (ω_{p1}/ω_0).
- Fig (6.1) Normalized growth rate (Γ/ω_p) versus normalized propagation constant of Langmuir wave (kc/ω_p).
- Fig (6.2) Normalized growth rate (Γ/ω_p) versus normalized thermal spread (p_{th}/p_0).
- Fig (6.3) Normalized growth rate (Γ/ω_p) versus relativistic gamma factor (γ_{0b}) of electron beam.