L.1: Forward Raman Scattering technique for studying self-modulation of ultra-short intense laser pulses

Production of relativistic, mono-energetic (~20 MeV) electron beams using ultra-short (<50 fs), ultra-intense (>10^{18} W/cm^2) laser at RRCAT has been reported earlier [*RRCAT Newsletter 22(1) p.10, 2009*]. However, it is necessary to understand the various propagation instabilities, the injection mechanisms for "self-trapping" of electrons, and the electron acceleration processes. For laser pulse of length L_p ($=c\tau_L$) longer than electron plasma wavelength λ_p, the growth of electron plasma wave (EPW) can occur via self-modulation instability driven by stimulated Raman scattering process. The stimulated Raman scattering in the forward direction excites relativistic EPW and produces anti-Stokes and Stokes satellite peaks at $\omega_0 \pm \omega_p$ (where $\omega_p = (ne^2/\varepsilon_0 m_e)^{1/2}$ is the plasma frequency) on either side of laser peak at ω_0 in the scattered spectrum. The superposition of these waves *viz.* ω_0 and $\omega_0 \pm \omega_p$ results in the modulation of the laser pulse having an initial length $L_p >> \lambda_p$ into a train of pulses with $L_{pulselet} \sim \lambda_p$. This modulation results in the resonant growth of EPW and ultimately the "wave-breaking". Wave-breaking "injects" electrons with sufficient energy so that they can be "trapped" and accelerated to high energy by the EPW. In the present work, an experimental study on self-modulation of ultrashort and intense laser pulse and the growth of the plasma wave in under dense plasma was carried out from the stimulated forward Raman scattered radiation.

The experiment was performed using the table-top 10 TW titanium-sapphire laser system at Laser Plasma Division, which delivers laser pulses of 45 fs duration at peak wavelength $\lambda_0 = 790$ nm. A schematic of the experimental set-up is shown in Fig.L.1.1. The laser beam was focussed to an intensity of 1.810^{18} W/cm^2, with an *f*/10 gold-coated off-axis parabolic mirror (OAPM), at the entrance edge of a pulsed supersonic helium gas jet located in a target chamber evacuated to 10^{-5} mbar. The plasma density in the interaction

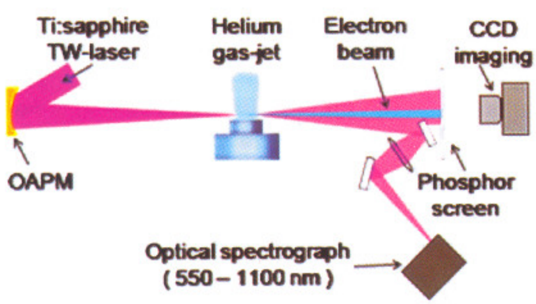

Fig.L.1.1: A schematic diagram of the experimental set-up

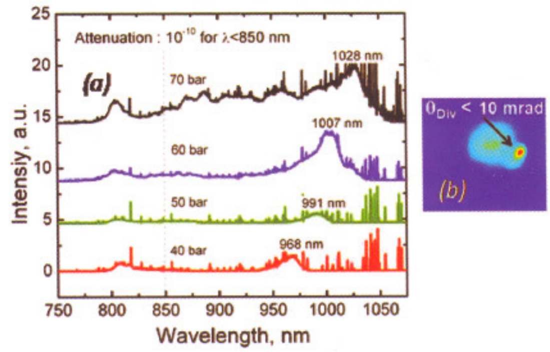

Fig.L.1.2: a) Spectrum of the scattered radiation, collected at 6° w.r.t. laser axis in the forward direction, at different backing pressures of helium gas. b) Image of the mono-energetic electron beam accelerated by the laser driven electron plasma wave

region was controlled by changing the backing pressure of the gas- jet. For the measurements of forward Raman scattering and to achieve larger signal-to-noise ratio, scattered light was collected at 6° w.r.t. the laser axis and focussed by a lens onto the entrance slit of an optical spectrometer. A phosphor screen coupled with a CCD camera was set up for detecting and imaging the accelerated electrons beam.

The satellites due to forward Raman scattering were detected for gas-jet backing pressures > 20 bar indicating to onset of self-modulation and excitation of relativistic EPW. The Stokes satellites for pressure above 40 bar are shown in Fig. L.1.2(*a*) for which accelerated electrons with a total charge >2nC were also detected. The measured of wavelength shifts of Raman satellites at various pressures were found to be consistent and they are used for *in situ* measurement of plasma density in the interaction region. The density estimated from the wavelength shifts in the forward Raman scattering agrees with that estimated from interferometry. The increase in amplitude of the scattered radiation indicates a higher growth rate of self-modulation and EPW with increase in pressure or plasma density, eventually leading to self injection of electrons by wave-breaking and electron acceleration, for gas pressure > 40 bar. At higher pressure of 65 bar or plasma density ~ 8.5x10^{19} cm^{-3}, highly collimated electron beam [see Fig. L.1.2(*b*)] with monoenergetic peak up to 21 MeV was detected [*RRCAT Newsletter 22(1) p.10, 2009*] which suggests formation of intense pulse-lets of duration ~ λ_p/c (~ *12 fs*) due to significant self-modulation of the initially 45 fs laser pulse to excite wake-field in "bubble regime". The broadening of satellites at higher plasma density also suggests less coherence of the EPW due to large number of electron injection by wave-breaking.

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