Chapter 3: Study of laser wakefield acceleration in self-modulated regime

In order to induce self-injection of electrons for their acceleration in the laser wakefield, the wakefield amplitude should reach the wave-breaking limit. This could be more efficiently achieved when the wakefield is excited resonantly i.e. when the laser pulse length \( c \tau_0 \) (where \( \tau_0 \) is the FWHM duration) is equal to half-wave period \( (\lambda_p/2) \) of the plasma wave, as described in Chapter 1. However, for laser pulse duration \( \sim 50 \text{ fs} \) or more, produced from typical 10 TW kind of laser systems like one we have used for our investigations, the resonance condition requires that the plasma density \( n_e \) to be \( < 10^{19} \text{ cm}^{-3} \) and the corresponding laser intensity required to drive the wakefield till wave-breaking takes place, is very large \( (a_0 >> 1) \). Such a high intensity is not possible to achieve using 10 TW class lasers.

As discussed in Chapter 1, relativistic self-focusing can increase the laser intensity inside the plasma, if the laser power is above the critical power for a given plasma density, i.e. \( P > P_c \) [85]. However, due to a small fraction of power (usually \( \sim 50\% \)) in the focal spot and other competing processes in the plasma, self-focusing and guiding are observed for \( P >> P_c \) in typical experimental conditions. Therefore, practically laser pulse power much larger than 10 TW is required for observing self-focusing when the plasma density is \( < 10^{19} \text{ cm}^{-3} \). However, since \( P_c \propto n_e^{-1} \), the condition \( P > P_c \) can be easily met at higher plasma densities for the moderate power lasers with \( a_0 \sim 1 \) at the focus. In addition, the laser pulse duration becomes much longer than the plasma wave length \( (i.e. c \tau_0 \gg \lambda_p) \) at higher plasma densities, which facilitates self-modulation of the laser pulse. Self-focusing and self-modulation of the laser pulse at higher plasma densities together lead to the laser wakefield acceleration in the self-modulated regime. In this regime, a single long laser pulse with duration \( c \tau \gg \lambda_p \) breaks up
into multiple short pulses through forward Raman scattering (FRS) instability [14], each of which has a width of about half the plasma wavelength ($\lambda_p/2$) and separation between the pulse-lets equal to $\lambda_p$. Coherent (in phase) addition of the wakefields of these equi-spaced laser pulses results in a very large amplitude wakefield leading to its wave break-up, due to which the electrons from the background plasma get self-injected and are accelerated to high energies. However, the electron beams produced from SM-LWFA experimental studies in the past were reported to have large divergence and nearly 100% energy spread [84].

In this chapter, an experimental study on laser wakefield acceleration in the self-modulated regime is presented [34]. The dependence of electron beam parameters viz. charge, divergence, and the electron spectrum, on the plasma density, is discussed. Although the electron energy spectrum typically showed 100% spread at lower plasma density, at a relatively high density of $\sim 8.5 \times 10^{19}$ cm$^{-3}$, a high quality electron beam was produced with a divergence $< 10$ mrad, and quasi-mono-energetic distribution with a peak energy $\sim 20$ MeV, with small energy spread ($\Delta E/E < 10 \%$). These results, along with simultaneous detection of Raman peak in the forward laser scattering measurements, are described in detail in this chapter. The results suggest strong self-modulation of the laser pulse. Forward Raman scattering (FRS) is an inherent and important physical process occurring in the self-modulated laser wakefield acceleration. Therefore, controlling the FRS and thereby the wakefields is essential for controlling the charge, energy, and quality of the electron beam, in this regime. The effect of positively/negatively chirped laser pulses on the self-modulation induced by FRS and on electron acceleration, has been investigated [102]. The observed dependence of laser self-modulation, electron beam charge and energy on the magnitude and sign of the chirp is presented. The underlying physics of high quality beam generation based on strong self-modulation and pulse shape effects is discussed.
3.1 Experimental details

A schematic of the setup used for the experiment is shown in Fig. 3.1. The Ti:sapphire laser pulses of 45 fs (FWHM) duration, with maximum 400 mJ of energy after the compressor chamber, were used for the experiment. The laser beam was focused 1 mm above and at the front edge of the gas jet nozzle orifice using an f/10 gold-coated off-axis parabolic mirror to a spot of FWHM diameter $d_0 = 18 \mu$m. The Rayleigh length of the focused laser beam was $z_R = \pi d_0^2 / (2 M^2 \lambda \ln 2) \approx 300 \mu$m and the peak intensity at the waist was $I_L = 4 P_0 \ln 2 / \pi d_0^2 \approx 1.2 \times 10^{18} \text{W/cm}^2$, considering about 50% of the total power contained in the focal spot. Helium gas was used for the experiment and gas backing pressure was varied from about 10 bar to 70 bar, to vary the neutral gas density in the range of 1-5x10$^{19}$ cm$^{-3}$. An integrating current transformer (ICT), with a 4 mm thick annular aluminium disc in front, was kept after the gas jet to measure the electron beam charge. The aluminium disc had a hole of 50 mm diameter to allow electrons emitted within a full cone angle of approximately 20$^0$ to pass through the ICT. A DRZ phosphor screen (covered with 30 µm thick aluminium foil on the front side to stop the laser light interaction with the phosphor screen) coupled with a 12-bit CCD camera (Make: SamBa) was used to detect the high energy electrons. The energy spectrum of the electrons was measured using an electron spectrograph (described in Chapter...
The slit in front of the magnet had angular dimensions 33 mrad and 60 mrad in the plane containing energy dispersion direction and perpendicular to it, respectively. The laser-plasma interaction was observed through side imaging of the linear Thomson side-scattering of the laser radiation, with 5X magnification. A narrow band-pass filter was placed in front of the side imaging 12-bit CCD camera to allow only the scattered radiation from the plasma within the wavelength range of 800±20 nm to pass through. To detect and measure the wavelength shifts in the transmitted spectrum due to forward Raman scattering, a part of the transmitted laser light from the interaction region at an angle of 6° w.r.to laser axis was attenuated, reflected using a glass wedge, collected by a lens, and focused onto the entrance slit of an optical spectrograph covering a spectral range of 550 – 1100 nm. A long pass filter (RG 850), in combination with an appropriate number of neutral density filters, was placed in front of the spectrograph to cut off the transmitted laser spectrum below 850 nm. This improved the sensitivity of detection of the less intense red-shifted signal expected due to stimulated FRS.

### 3.2 Electron beam profile measurement

After scanning the backing pressure of the gas jet and optimization of laser focus position in the gas jet, accelerated electron beam was observed for plasma electron densities above 5×10^{19} cm^{-3} in every laser shot, with energy integrated total charge in excess of 2 nC. As the ICT collected the electrons within a cone angle of 20°, therefore the total charge includes large divergence, low energy electrons also. When the density was below ~ 5×10^{19} cm^{-3}, no high energy electrons were observed, as in this case, the amplitude of the plasma wave was not high enough for self-injection of the electrons for acceleration. The images of the electron beam produced at different plasma densities are as shown in Fig. 3.2. As seen in this figure, the electron beam, in general, shows an increase in divergence with increase in
plasma density. Moreover, the images showed saturation at higher plasma density due to higher charge, as a result of which the finer features of the beam profile were lost. In order to overcome this saturation, a 5 mm thick aluminium plate was kept in front of the phosphor screen to cut off lower energy (<5 MeV) electrons reaching the phosphor screen. In this case, at a plasma density of around $8.5 \pm 0.5 \times 10^{19}$ cm$^{-3}$, a highly collimated (divergence < 10 mrad) electron beam was observed along with a background of broadly diffused electrons with larger divergence, as seen in Fig. 3.2(d). The pointing angle of the collimated beam varied from shot-to-shot within about $\pm 25$ mrad.

![Figure 3.2: Images of electron beam profiles at plasma density a) $6.5 \pm 0.5 \times 10^{19}$ cm$^{-3}$, b) $7.5 \pm 0.5 \times 10^{19}$ cm$^{-3}$, and c) $8.5 \pm 0.5 \times 10^{19}$ cm$^{-3}$ with 30 µm aluminium foil in front of phosphor screen. d) A well collimated electron beam with broad background observed at plasma density $6.5 \pm 0.5 \times 10^{19}$ cm$^{-3}$ when a 5 mm thick aluminium plate was kept in front of the phosphor screen to cut off the low energy (< 5 MeV) electrons.]

3.3 Forward Raman scattering measurements

For the plasma electron density in the range of $5 \times 10^{19} - 1 \times 10^{20}$ cm$^{-3}$, wherein the electron beams were observed, the plasma wavelength ($\lambda_p$) varies from 4.7 – 3.3 µm. This implies that the laser pulse length ($c\tau_l = 13.5$ µm) is about 3 to 4 times $\lambda_p$. Also, for the above density range, the laser power in the focal spot was much larger than the critical power $P_c$. 

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required for relativistic self-focusing (RSF). Therefore, the laser pulse can undergo strong self-modulation through forward Raman scattering instability. The occurrence of self-modulation was confirmed from the observation of the Stokes satellite in the forward Raman scattering spectrum. Fig. 3.3 shows the observed Stokes satellites due to forward Raman scattering and the variation of the Raman shift with the plasma density. The amplitude of Raman satellites increased with the plasma density, which shows that the self-modulation of the laser pulse becomes stronger at higher plasma density.

Figure 3.3: Forward Raman spectra at different plasma densities.

3.4 Laser channelling in plasma

As $P_L >> P_C$ for the experimental conditions, a single, long interaction channel / filament extending to several $z_R$ through RSF is expected. However, as seen in Fig. 3.4, a double filament-like structure was observed. Each of these filaments had diameter around 9 µm and length around 400 µm. The latter was about 1.3 times the $z_R$. The filaments appear at the beginning of the flat-topped portion of the gas jet profile as indicated in Fig. 3.4. They were observed in almost all the laser shots, within the density range of the experiment. In some shots at higher densities, multiple (scattered) filaments were observed. We did not observe any significant change in the length or the position of the filaments by varying the plasma density. However, there was shot-to-shot variation in the observed intensity and length of the filaments (from about 400 – 500 µm), which may be attributed to shot-to-shot
variations in laser-plasma interaction parameters. Next, there was increase in the Thomson scattering intensity with increase in the plasma density. This is expected as the scattering intensity is proportional to the plasma electron density. The separation between the filaments remained constant within the resolution of our measurement.

Figure 3.4: Thomson scattering side image laser channelling in plasma showing bifurcation of the laser beam into two filaments as indicated by the arrows on the right. The vertical dotted line shows the location of top of the gas jet density ramp.

3.5 Energy spectrum of accelerated electrons

The energy spectrum of the electron beam was measured at various plasma densities ranging from about $5 \times 10^{19}$ cm$^{-3}$ – $1 \times 10^{20}$ cm$^{-3}$. The representative electron energy spectra at different plasma densities are shown in Fig. 3.5. The typical spectra were continuous with energy distribution of the form $\sim \exp(-E/kT_{\text{eff}})$. The effective temperature ($T_{\text{eff}}$) of the electron beam is given by the slope of the semi-log plot of the spectra shown in the Fig. 3.5b. It can be seen that the temperature increased when the plasma density was increased from $6.5 \pm 0.5 \times 10^{19}$ cm$^{-3}$ to $8.5 \pm 0.5 \times 10^{19}$ cm$^{-3}$. Further increase in the plasma density to $9.5 \times 10^{19}$ cm$^{-3}$ reduced the temperature, which is close to the effective temperature at $7.5 \pm 0.5 \times 10^{19}$ cm$^{-3}$.

Figure 3.5: a) A typical image of continuous energy distribution of electron beam at plasma density $8.5 \pm 0.5 \times 10^{19}$ cm$^{-3}$. b) Energy spectra of the electron beam produced at different plasma densities.
At electron density around $8.5 \times 10^{19}$ cm$^{-3}$, in about 20% of the laser shots, highly collimated and mono-energetic electron beam with few tens of pico-coulombs of charge was observed during the electron energy measurements. Since the pointing variation is larger than the half width of the slit (16.6 mrad) of the magnet spectrograph, the collimated electron beam might have missed the slit in some of the shots. Images of energy dispersed electron beams with low divergence and quasi-mono-energetic feature are shown Fig. 3.6. Quasi-mono-energetic electron beams with energy in the range of 10 – 21 MeV were observed in a series of shots during the experiment. It may be noted that the quasi-mono-energetic electron beam is usually accompanied by large divergence and continuous energy background, as shown in Fig. 3.6a. Once in a while, electron beams with less low energy background were also observed. The energy spectrum of a quasi-mono-energetic electron beam with relatively less low energy background and its corresponding energy spectrum with peak at 21 MeV, are shown in Fig. 3.6 b and c. The vertical dimension of the quasi-mono-energetic electron beams
in the Fig. 3.6a and b represents the divergence of the electron beam, as the beam size in this
direction was not restricted by the slit height (60 mrad) of magnet spectrograph. The quasi-
mono-energetic electron beam had divergence angle (20) in the range of 4 – 7 mrad (less than
the slit width of 33 mrad), and energy spread (ΔE/E) of ± 4 – 8 %. The resolution (ΔE/E) of
the spectrograph at 21 MeV is about 1% and the value becomes smaller at lower energies (e.g.
0.5% at 10 MeV). Therefore, the estimated energy spread was the upper limit which arises
due to the finite size of the electron beam in the direction of energy dispersion on the DRZ-
phosphor screen. Therefore, the actual energy spread may be smaller than the above stated
value. The charge of the mono-energetic electron beam was estimated from the calibration of
ICT signal against the intensity of electron beam image, as recorded using the DRZ-phosphor
screen and the CCD camera. Although the total beam charge (energy integrated) was few nC,
the mono-energetic electron beam had a maximum charge of about 60 pC, carrying about
0.5% of the laser energy. Transverse geometric emittance (εx) of the mono-energetic beam
was as low as 0.01 π mm.mrad. This was estimated by assuming the upper limit on the
electron beam transverse size to be equal to the diameter of each filament and the measured
divergence.

3.6 Effect of chirp

In order to study the effect of the laser chirp, the laser pulse duration (and
consequently the chirp characteristics) was varied by scanning the compressor grating pair
separation from its optimal separation. For a chirped laser pulse, one can define the
instantaneous frequency ω as ω=ω0+bt, where t is the time in the pulse reference frame, b is
the chirp parameter given by b=2ln2/τ^2 [(π/τo)^2-1]1/2 where τ and τo are the FWHM duration of
the chirped and unchirped pulse, respectively. Hence, for a negative chirp (b > 0), the “blue”
frequencies are located at the front of the pulse and for a positive chirp (b < 0), the “red”
frequencies are located at the front of the pulse. Positively/negatively chirped pulses, with
duration ranging from 45 fs to ±450 fs (corresponding intensities varied from 1.2×10\(^{18}\) W/cm\(^2\)
down to 1.2×10\(^{17}\) W/cm\(^2\)), were generated by translating one of the two gratings of the pulse
compressor by 0 to ± 2 mm from their optimal separation for minimum pulse duration.
Hereafter, “plus” or “minus” signs will be used (except for 45 fs) together with the pulse
duration to indicate positively or negatively chirped laser pulses.

### 3.6.1 On electron beam charge

![Figure 3.7: Variation in the integrated electron beam charge at two different plasma densities (Solid squares: 8.5±0.5×10\(^{19}\) cm\(^{-3}\), and hollow squares : 6.5±0.5×10\(^{19}\) cm\(^{-3}\) ) with compressor grating pair separation (chirp) measured w.r.t. the “zero” setting (separation corresponding to minimum pulse duration). The total charge for “zero” setting of the compressor is 2 nC and 8 nC respectively for plasma density 6.5±0.5×10\(^{19}\) cm\(^{-3}\) and 8.5±0.5×10\(^{19}\) cm\(^{-3}\). The variation of the laser pulse width (circles) with grating separation is also shown.

The effect of chirp on self-modulation and electron acceleration for two different
plasma densities : \(n_e \approx 6.5\pm0.5 \times 10^{19} \text{ cm}^{-3}\) (Case 1) and \(n_e \approx 8.5\pm0.5 \times 10^{19} \text{ cm}^{-3}\) (Case 2) was
studied. Figure 3.7 shows the variation of normalized charge of the electrons with relative
separation of compressor gratings, for case 1 and case 2. For easy reference, the figure
also shows the variation of the laser pulse duration with the grating separation. In both the
cases, normalization of the charge was done w.r.t. the total charge observed with the
unchirped pulse (45 fs) interaction. The total charge for “compressor zero” setting was 2 nC and 8 nC for plasma density $6.5 \times 10^{19}$ cm$^{-3}$ and $8.5 \times 10^{19}$ cm$^{-3}$, respectively. An asymmetry in the electron beam charge w.r.t. the laser pulse chirp was observed for both the plasma densities. The maximum charge was observed for longer laser pulses with a small amount of positive chirp. The charge increased by nearly 100% and 25% for $n_e \approx 6.5 \pm 0.5 \times 10^{19}$ cm$^{-3}$ and $8.5 \pm 0.5 \times 10^{19}$ cm$^{-3}$ respectively, when positively chirped pulses of about +80 to +85 fs duration were used.

The minimum laser power at which electrons were observed was about 1.1 TW, corresponding to positively chirped laser pulse of +185 fs duration for $n_e \approx 6.5 \pm 0.5 \times 10^{19}$ cm$^{-3}$, and 0.45 TW corresponding to +420 fs for $8.5 \pm 0.5 \times 10^{19}$ cm$^{-3}$. This power is higher than the critical power $P_c \approx 0.43$ TW and 0.33 TW required for relativistic self-focusing at the two densities respectively. Along with the accelerated electrons, laser self-focusing channels of length 400–500 µm over this entire range were also observed in the Thomson scattering side images.

### 3.6.2 On forward Raman Scattering

Figure 3.8 shows the measured spectra of transmitted laser light w.r.t. the laser chirp / grating separation for $n_e \approx 6.5 \pm 0.5 \times 10^{19}$ cm$^{-3}$ and $8.5 \pm 0.5 \times 10^{19}$ cm$^{-3}$. The side bands at longer wavelengths due to stimulated FRS can be clearly seen. The wavelength shift of the side band with change in plasma density is consistent with FRS. The variation in the amplitude of the FRS signal with laser pulse chirp for a fixed density was consistent with the observed asymmetry in the electron beam charge with chirp. This clearly suggests that the laser pulse was undergoing strong self-modulation through stimulated FRS and resulting in excitation of large amplitude wakefields which could self-trap and accelerate background plasma electrons to high energy. The transmitted spectra also show red shifting of the laser light, which is
probably due to laser photon deceleration in the wakefield [103]. Since a high pass filter (RG-850), which strongly attenuates the spectrum below 850 nm, was used to attenuate the transmitted laser light, the blue shifted anti-Stokes satellite band due to FRS and blue shift due to photon acceleration [103] could not be seen in Fig. 3.8.

Figure 3.8: The transmitted laser spectra at two different plasma densities: a) without interaction with plasma, b) to f) with interaction at: \( n_e \approx 6.5 \pm 0.5 \times 10^{19} \text{ cm}^{-3} \), for grating separation of 0 (45 fs), -320 \( \mu \text{m} \) (70 fs), -600 \( \mu \text{m} \) (125 fs), -800 \( \mu \text{m} \) (170 fs), and +200 \( \mu \text{m} \) (52 fs) respectively, g) to i) at \( n_e \approx 8.5 \pm 0.5 \times 10^{19} \text{ cm}^{-3} \) for grating separation of 0 (45 fs), -400 \( \mu \text{m} \) (85 fs), and +200 \( \mu \text{m} \) (52 fs) respectively. No distinct Raman peak could be resolved from the transmitted spectra due to large broadening of laser spectrum (as shown in (e)) for grating separation \( > -800 \mu \text{m} \), for a density of \( 6.5 \pm 0.5 \times 10^{19} \text{ cm}^{-3} \). Similar observation was made for \( n_e \approx 6.5 \pm 0.5 \times 10^{19} \text{ cm}^{-3} \) at grating separation of \( < -400 \mu \text{m} \) (spectra not shown here). Raman peaks disappear for grating separation \( > +200 \mu \text{m} \) (-ve chirp).

### 3.6.3 On quasi-mono-energetic electron beam

The low divergence electron beam observed for the 45 fs duration laser pulse at plasma density of \( n_e \approx 8.5 \pm 0.5 \times 10^{19} \text{ cm}^{-3} \), was present even when a positive chirp was introduced up to about +250 fs, while it vanished on introducing a small amount of negative
chirp (≥ -60 fs). In the case of $n_e \approx 6.5 \pm 0.5 \times 10^{19} \text{ cm}^{-3}$, once in a while, a low divergence electron beam was observed when positive chirp around 85 fs was introduced. The energy spectrum of the electron beam was measured at a plasma density of $n_e \approx 8.5 \pm 0.5 \times 10^{19} \text{ cm}^{-3}$ for different positive chirp values leading to variation in the laser pulse duration from 45 fs to 135 fs. Typical recorded spectra are shown in Fig. 3.9. Generation of collimated, quasi-mono-energetic electron beams was observed for the above range of positive chirped laser pulse duration, with maximum electron beam energy of 28 MeV observed for a positive chirped laser pulse of 70 fs duration. The reproducibility of the quasi-mono-energetic electron beam in the present experiment at a plasma density of $\approx 8.5 \pm 0.5 \times 10^{19} \text{ cm}^{-3}$ was ~20%. No significant improvement in the reproducibility of the quasi-mono-energetic electron beam with the positive chirp was observed.

![Image](image.png)

**Figure 3.9:** Images of quasi-mono-energetic electron spectra recorded at $n_e \approx 8.5 \pm 0.5 \times 10^{19} \text{ cm}^{-3}$, for different separations of the laser pulse compressor gratings: a) 0 µm (45 fs), b) -320 µm (70 fs), and c) -640 µm (135 fs).

### 3.7 Discussion

First of all we consider laser channelling in under-dense plasma. We observed formation of two channels in our experiment, as shown in Fig. 3.4. Two channels formation
due to bifurcation of a single channel after some length of interaction has been reported by few other groups. For example, Chen et al [104] inferred that such bifurcation of laser channel can result from presence of a pre-pulse. Ionization by pre-pulse splits the laser propagation channel by creating a sharp localized region of lower index of refraction. Andreev et al [105] have observed that short pulses \( c \tau_L < \lambda_p \) can undergo filamentation instability seeded by hot spots in the laser beam. Due to non-ideal, near-field radial profile (neither Gaussian nor circular flat top) of practical high power laser beams with \( M^2 > 1 \), the far-field profile of the laser beam may consist of one principal spot with one or more hot spots in its periphery. Since the value of \( a_0 \) required for the growth of these hot spots is quite small, it is quite possible that one of the intense hot spots grows on the rising edge of the laser pulse over 100 \( \mu m \) of the gas density ramp and forms second intense filament, along with the filament caused by the principal spot, by the time the laser reaches the top of the density ramp, as shown in Fig. 3.4. More recently, simulation and experimental results of Thomas et al [106] have shown that appropriate choice of focusing optics \( (w_0 > \lambda_p) \) would lead to smooth self-guiding of laser over a dephasing length and produce mono-enenergetic electrons in bubble regime \( (c \tau_0 < \lambda_p) \). They also report that for the case \( w_0 < \lambda_p/2 \), multiple filaments of size \( \lambda_p \) are formed and interaction length becomes much shorter. This laser filamentation was found to produce electron beams with large divergence and continuous energy spectrum. However, we observe low divergence and quasi-mono-enenergetic electron beam from double filamenti ed propagation of laser at much higher plasma densities compared to Thomas et al [106].

Next, the occurrence of self-modulated wakefield excitation and the resulting electron acceleration can be understood as follows. The self-modulation process causes the laser pulse \( (c \tau_0 = 13.5 \ \mu m) \) to modulate itself into multiple pulse-lets of spatial length (FWHM) of approximately \( \lambda_p/2 \), separated by \( \lambda_p \) [33]. The fact that length of the filaments remains \( \sim 400 – 500 \ \mu m \), but did not last for whole 1.2 mm length of the gas jet, suggests occurrence of strong
modulation, within the first 100 -300 µm of the interaction of the laser pulse both in the axial and transverse directions, leading to formation of pulse-lets of FWHM length $\lambda_p/2$. Both, numerical simulations [107] and laboratory experiments [108], showed that the relativistic self-guiding is greatly weakened for pulses shorter than $\lambda_p$, even if the laser power exceeds the critical power for relativistic self-focusing. Therefore, the pulse-lets may not be self-guided beyond 500 µm. Self-guiding may further be inhibited as the self-modulation results in significant laser energy depletion leading to reduction in laser power below critical power ($P_C$) for self-focusing. The side images of the plasma showed that the interaction length did not change much with variation of the electron density. This suggests that the laser pulse may be getting considerably modulated even at lower electron density. Although the laser modulation is detrimental for achieving long interaction lengths, it drives a large amplitude relativistic plasma wave that traps the background hot electrons produced by the stimulated side Raman scattering process. The trapped electrons can be accelerated by the relativistic plasma wave, excited by FRS, up to the dephasing length, $L_{\text{deph}}$, which is in the range of 160 – 60 µm for $n_e = 5\times10^{19} - 1\times10^{20}$ cm$^{-3}$. Therefore, it appears that the acceleration length (and hence the maximum energy of accelerated electrons) was not limited by the interaction length. Over the initial portion (about 100s µm) of channel length, the laser pulse evolves through self-modulation before it could drive strong plasma wave. The plasma wave then traps a significant number (~ few nC) of background electrons and accelerate them. If the electrons exit the plasma after acceleration distance close to dephasing length, $L_{\text{deph}}$, the electrons gain maximum energy from the wakefield, as explained in Chapter 1.

An electron beam produced from self-modulated laser wakefield acceleration normally has high charge (typically few nano-coulombs), large divergence (~ 100 mrad or above), and continuous energy distribution (typically 100% energy spread) [22]. Also, at higher plasma electron densities (as in the present experiment), the relativistic electrons generated initially
from wakefield can gain further higher energy by direct laser acceleration (DLA) and have large divergence [91]. This may be the reason for the diffused background electrons seen in Fig. 3.2d. The same may also account for the observation of continuous energy spectrum as shown in Fig. 3.5 and 3.6. If the electrons are accelerated by only SM-LWFA, the maximum energy of the electrons is expected to decrease with electron density as the energy gain is inversely proportional to plasma density. This is due to the reduced dephasing length at higher densities. However, we have observed that the maximum energy of the electrons as well as the $T_{eff}$ increased as the plasma electron density increased from $6.5 \times 10^{19}$ to $8.5 \times 10^{19}$ cm$^{-3}$. This could occur if the electron acceleration took place due to cascade of SM-LWFA and DLA. As the laser modulation rate increases with increase in plasma density, trapping of electrons by the relativistic plasma wave would occur earlier for higher electron density. Subsequently, the electrons will be accelerated under the direct laser field for longer length resulting in increase in maximum energy or temperature of the accelerated electrons with increase in plasma electron density. Such an increase in maximum energy and $T_{eff}$, with electron density, has also been reported earlier [91, 109]. At electron density of around $8.5 \times 10^{19}$ cm$^{-3}$, the laser pulse may be significantly modulated over the first 200 - 300 µm of interaction length, leaving one or more pulse-lets of length $\sim \lambda_p/2$ which can drive wakefields in the “bubble” or “blow-out” regime. Simulations have shown that this regime is very well suited for producing high quality electron beams [26]. However, the location of electron injection into the bubble is sensitive to the history of pulse modulation, which significantly changes with slight variation in the initial laser and plasma parameters. In the case of electron exiting the plasma after $L_{deph}$, the electron beam exhibits continuous energy spectrum [24] as seen in Fig. 3.5. For plasma density beyond $8.5 \times 10^{19}$ cm$^{-3}$, the growth rate of modulation may become so large that the laser pulse gets self-modulated very early during the interaction. The pulse-lets drive wakefield in the bubble regime and produce accelerated electron beam. Since
the injection of electrons into bubble occurs much earlier in the interaction and the dephasing length is shorter at high plasma densities, the maximum energy of the beam is reduced and the quality becomes poor [24].

The effect of laser chirp on FRS and on electron acceleration can be understood as follows. In the standard description of FRS, the growth of laser intensity modulations is caused by local enhancement of axial energy transport (group velocity dispersion) due to plasma wave density perturbations [110]. A linear chirp will be affected by the group velocity dispersion (GVD) in the plasma, which can elongate (for negative chirp) or compress (for positive chirp) the laser pulse, leading to rapid growth, higher accelerating fields, and a more rapid onset of particle trapping. The change in group velocity ($v_g$) due to the frequency chirp in practical parameters is

$$\Delta v_g \approx -c \left( n_e/n_c \right) (\Delta \lambda/\lambda)$$

[111]. The propagation distance $L_{GVD}$ required for the laser pulse to modulate at the plasma wavelength (which will drive or suppress the FRS growth) due to a linear chirp over a plasma wavelength is

$$L_{GVD} \approx c \lambda_p/\Delta v_g.$$ 

For a plasma density $n_e \approx 6.5 \times 10^{19} \text{ cm}^{-3}$ and laser parameters $\lambda = 800 \text{ nm}$ and $\Delta \lambda/\lambda = 2.5\%$, the propagation distance for GVD to enhance or suppress the FRS growth is 4.3 mm (2.8 mm at $8.5 \times 10^{19} \text{ cm}^{-3}$), which is much greater than the growth length for the FRS instability, given by

$$k_pL_{GVD} \gg w_p/\gamma_{\text{FRS}} = [8(n_e/n_c)]^{1/2}/a_0,$$ 

where $\gamma_{\text{FRS}}$ is the growth rate of FRS. This indicates that although the chirp affects the GVD throughout the pulse, the enhanced modulation due to GVD has an insignificant effect on the FRS process.

Both, analytical and PIC simulations have shown that a few percent chirp (as in the present experiment) leads to a change in growth of FRS on the order of a few percent only [111]. However, in addition to the laser pulse duration, the variation in compressor grating separation also affects the pulse shape. Leemans and his co-workers [20, 112] have studied the effect of compressor grating separation on the laser pulse shape. They have shown that an incomplete compensation (by the pulse compressor) of the positively biased non-linear
spectral phases, which arise due to laser pulse propagation in material medium (e.g. the Ti:sapphire crystal), gives rise to pulse shape asymmetry, resulting in fast/slow rising edge when slight positive/negative chirp is introduced. This was further confirmed in a recent experiment by Hafz et al [113] using SPIDER setup. The temporal intensity profiles of such pulses can be well fitted to a skewed Gaussian of the form: 

\[ I(t) = I_0 \left\{ -\frac{t^2}{2\tau^2} \right\} \left[ 1 + \frac{s}{\sqrt{t^2 + \tau^2}} \right]^{1/2} \] 

where \( |s| < 1 \) is the skew parameter which is positive (negative) for fast (slow) rise time and \( \tau \) is the pulse duration, and \( I_0 \) is the peak intensity. The simulations in the self-modulated LWFA regime [20] indicate that a larger wakefield is excited for positive skewed laser pulses, compared to the negative skewed laser pulses. FRS is seeded by the density perturbations which contain frequency components at the plasma frequency. It was observed in the above simulations that the maximum amplitude of the seed decreases with increasing density or pulse duration. This explains less enhancement in charge (25%) at \( n_e \approx 8.5 \pm 0.5 \times 10^{19} \text{ cm}^{-3} \) compared to that (100%) in the case of smaller \( n_e \approx 6.5 \pm 0.5 \times 10^{19} \text{ cm}^{-3} \) observed in our experiment. For slow rise times in the case of negatively chirped laser pulse, the response is weaker and lower amplitude plasma waves ensue. The previous study by Leemans et al [20] in the self-modulated LWFA regime has reported enhancement of electron yield by using laser pulse of intensity > \( 10^{19} \text{ W/cm}^2 \) interacting with plasma density \( n_e \approx 3 \times 10^{19} \text{ cm}^{-3} \). They found that the effect of envelope asymmetry on enhancement of FRS and self-modulation to be more important than that of linear chirp in pulses with symmetric temporal envelopes. The asymmetric dependence of the total electron beam charge on the grating separation observed in the present experiment agrees qualitatively well with that observed by Leemans et al [20, 112], although the two experiments differ in laser intensity and plasma density. This similarity indicates qualitatively similar laser pulse shape variation with grating separation in the two experiments.