

# STUDY OF HIGH ENERGY ELECTRON BEAM STABILITY IN LASER-DRIVEN PLASMA-BASED ACCELERATION

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## Abstract

We have studied the effect of laser focusing conditions and the pre-pulse on the generation and stability of the high energy electrons from laser-driven plasma based acceleration. The experiment was carried out using a 45 fs duration Ti:sapphire laser pulse focused to an intensity  $> 10^{18}$  W/cm<sup>2</sup> on a helium gas-jet. It was found that tighter focusing of laser beam with an f/7.5 off-axis parabolic mirror produces mono-energetic electron beam with 50 MeV energy, at a moderate laser power  $\sim 4$  TW. A strong correlation was observed between the laser pre-pulse (inherently present in the main laser) level and the electron beam stability. The study showed the importance of controlling the pre-pulse intensity for stable electron beam production.

## INTRODUCTION

The rapid progress over the past few years in the field of laser-driven plasma-based acceleration [1] following the first demonstration of mono-energetic electrons [2] shows a great promise in realizing practical table-top giga-electron-volt (GeV) level accelerator. Despite the recent proof-of-the-principle demonstration of GeV electron beam production from centimetre long laser based plasma accelerator using about 100 TW laser [3], there remains a challenge to control the shot-to-shot variations of accelerated electron beam parameters viz., energy, angular distribution (collimation), and beam pointing stability, for any practical applications of such accelerators. In the present study, we identify the effect of laser focusing conditions and the laser pre-pulse on the generation and stability of the accelerated electrons. We find that tighter focusing of laser beam produces mono-energetic electron beam with energy as high as 50 MeV, at a moderate laser power  $\sim 4$  TW. There is a strong correlation observed between the laser pre-pulse level (inherently present in the main laser) and the electron beam stability. The study indicates that it is important to control the pre-pulse intensity for stable electron beam production.

## EXPERIMENTAL SETUP

The basic experimental setup is as shown in Fig. 1. The table-top terawatt Ti:sapphire laser at Laser Plasma Division, RRCAT was used for the experiment. The laser system provides horizontally polarized, 45 fs duration pulses with pulse energy of  $\sim 300$  mJ. The central wavelength ( $\lambda_0$ ) of the laser was at 790 nm and the FWHM bandwidth ( $\Delta\lambda$ ) was 20 nm. The laser beam was

focused on a helium gas jet target using either f/10 or f/7.5 gold coated off-axis parabolic mirror (OAPM), to a spot of size of 18  $\mu\text{m}$  or 10  $\mu\text{m}$  (FWHM) with Rayleigh lengths 300  $\mu\text{m}$  and 130  $\mu\text{m}$  respectively. The intensity of the laser on target was  $> 10^{18}$  W/cm<sup>2</sup>. The contrast ratio of the pre-pulse before 8 ns was better than  $10^6$  and the contrast ratio of the pedestal due to amplified spontaneous emission (ASE) was about  $10^6$ . The length of the ASE pedestal was controlled by changing the switching time of the pulse cleaner (Pockels cell) in the regenerative amplifier. A rectangular (1.2 mm x 10 mm) slit type Laval nozzle was used to produce supersonic gas jet in pulsed mode with  $\sim 2$  ms opening duration. The laser beam was focused at a distance of 1 mm from the exit of the slit nozzle. The backing pressure of the gas jet was varied to provide helium gas density in the range of  $n_{\text{gas}} \sim 1$  to  $5 \times 10^{19}$  cm<sup>-3</sup> in the interaction region. As the helium gas gets fully ionized by the foot of the fs-laser pulse (at an intensity of  $\sim 10^{16}$  W/cm<sup>2</sup>), the electron density ( $n_e$ ), during the interaction of the main portion of the laser pulse, would be twice the initial gas density. The main diagnostics used to characterize the accelerated electron beam were: an integrating current transformer (ICT-082-070-5:1) to measure the total electron beam charge, and a phosphor screen combined with CCD imaging system for electron beam spatial profile monitoring. A single-shot electron spectrometer was set up using two circular ( $\phi 50$  mm) permanent magnets ( $B_{\text{eff}} = 0.46$  T) with pole gap of 9 mm to measure the energy of the accelerated electrons. Thomson scattering radiation at 400 nm and 800 nm was collected to record the magnified images of the laser guiding in the plasma in the direction parallel (side view) and perpendicular (top view) to the laser polarization using two 12-bit CCD cameras.

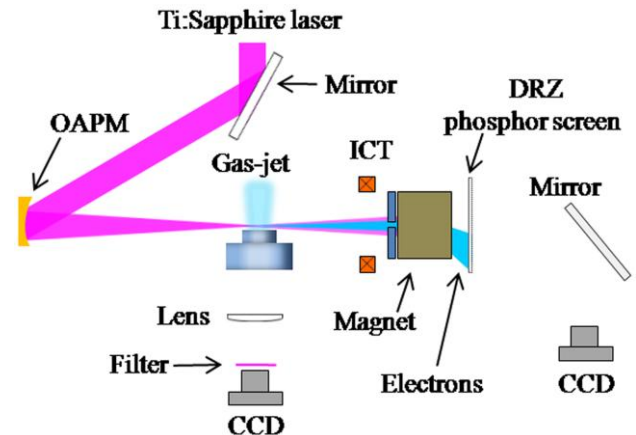


Figure 1: Schematic of the experimental setup

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## RESULTS AND DISCUSSION

Accelerated electrons were produced for gas density more than well defined threshold that depended on the f-number of the focusing optics used. The threshold gas densities for f/7.5 focusing parabola was lower due to increased intensity at the focus. The integrated charge of the electron beam in both focusing conditions was measured to be few nC. The electron beam profile was found to be sensitive to the gas density. In both cases well collimated electron beam with divergence  $< 10$  mrad was produced, but at different gas densities. A well collimated electron beam was produced at  $\sim 3 \times 10^{19} \text{ cm}^{-3}$  in the case of f/7.5 parabola while in case of f/10 parabola, it was at  $\sim 4 \times 10^{19} \text{ cm}^{-3}$ . The electron beam in the latter case consisted of background electrons with large divergence and energy  $> 1$  MeV energy, while in the former case, the collimated beam was observed to be free from background electrons. The energy measurement of the collimated beam showed mono-energetic spectrum in both the cases. The energy of the collimated electron beam in the case of the f/10 parabola was limited to only 20 MeV due to short dephasing length at higher plasma density [4]. An increase in the energy of the electron beam was observed in case of the f/7.5 parabola with the mono-energetic electron energy changing to 50 MeV, as shown in Fig.2. The charge contained in the monoenergetic peak was few tens of pC. The Thomson scattering image of the laser interaction with plasma shows oscillations in the focal spot, which is a characteristic of self-guiding. The top view image of laser guiding is as shown in Fig. 2(c). Similar images were observed even with the side view CCD camera.

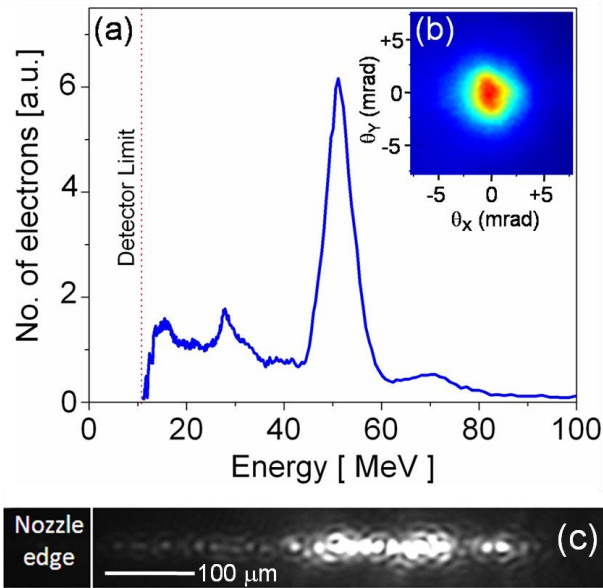


Figure 2: a) Energy spectrum of the electron beam produced at a gas density of  $3.2 \times 10^{19} \text{ cm}^{-3}$  with f/7.5 parabola, b) spatial profile of the mono-energetic electron beam, and c) Thomson scattering of laser light and guiding in plasma as seen in the top view.

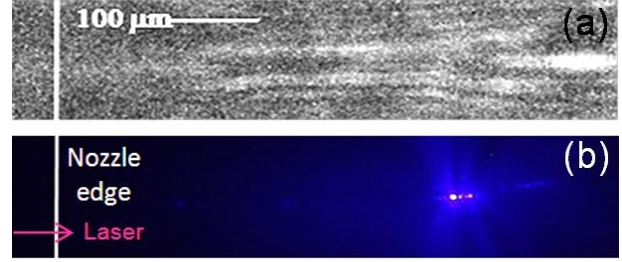


Figure 3: a) Shadowgram image of the plasma channel and b) femtosecond laser beam refraction in the plasma for pre-pulse duration of 2 ns and intensity  $\sim 10^{12} \text{ W/cm}^2$ .

To study the role of the pre-pulse, shadowgram images of the plasma were recorded using a portion of the 45 fs laser beam reaching the interaction region ahead of the main laser beam. One of the shadowgram images is shown in Fig. 3(a). It clearly shows channel formation by the ASE pre-pulse pedestal present in the main beam. This plasma channel acts like a waveguide for the high intensity main laser beam, providing much longer interaction lengths than permitted by Rayleigh length. Also, the reduced on-axis plasma density due to the channel formation increases the dephasing length and facilitates higher energy gain. The generation of high energy electrons was found to have strong correlation with the laser guiding channel. It appears that an optimum duration of the pre-pulse is required to form a plasma waveguide. Increase in the pre-pulse duration causes refraction of the main laser beam as shown in Fig 3(b) (the image was recorded by side view camera collecting non-linear Thomson scattered radiation at 400 nm), and stability of the electron beam production significantly affected. The use of laser pre-pulse provides a simple method to produce a guiding channel for the intense laser beam. However, the shot-to-shot variation in the pre-pulse intensity may change the cavity structure and electron beam parameters. If the level of pre-pulse is controlled, the method may be useful for producing very high energy and stable electron beam from longer plasma channels formed by pre-pulse pedestal.

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