Density measurements of the plasma target in laser driven plasma wakefield accelerator

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Abstract

In this report, I will introduce you one of the novel acceleration techniques – plasma wakefield acceleration, that have been demonstrated as a compact and reproducible relativistic electron source. I will also give a short introduction to the basic principles and experimental realization of the plasma density measurements utilizing a Mach-Zehnder interferometer with 25 *fs* titanium sapphire (Ti:S) laser, designed as one of the plasma target diagnostic for the plasma wakefield experiments at DESY.

Contents

Introduction

What is the plasma wakefield accelerator (PWA)?

In the past decade thanks to progress on a number of fronts in physic PWA can be presented as a new generation of advanced high-energy accelerators. The basic concept of PWA and its possibilities were originally proposed by Tajima and Dawson [1]. It describes an effective acceleration inside a static electric field of the waves in plasma formed by the electron charge distribution. Generation of the waves in plasma by the particle beam allows the production of meter-long plasmas suitable for the PWA.

A dense particle or photon bunch, propagating through a plasma target, drives the plasma wave, so-called wake. The wake consists of a high-gradient longitudinal electric field that in turn accelerates particles in the back of the plasma wave. The system effectively operates as a transformer, where energy from particles in the driver bunch is transferred to the particles that have been seed in the back, via the plasma wake [2]. Same principle is based under the laser driven plasma wakefield, but since the photon speed inside the plasma is not equal to the particle velocity, typical length of the target in a laser driven cases is limited to a few mm – few cm scale.

Comparison between plasma wakefield accelerators and conventional accelerators

Accelerators were invented in the 1930s to provide energetic particles to investigate the structure of the atomic nucleus. Since then, they have been used to investigate many aspects of particle physics. Their job is to speed up and increase the energy of a beam of particles by generating electric fields that accelerate the particles, and magnetic fields that steer and focus them.

An accelerator comes either in the form of a ring (a circular accelerator), where a beam of particles travels repeatedly round a loop, or in a straight line (a linear accelerator), where the particle beam travels from one end to the other.

The type of particle used depends on the aim of the experiment. The Large Hadron Collider (LHC) accelerates and collides protons, and also heavy lead ions. One might expect the LHC to require a large source of particles, but protons for beams in 27-kilometre ring come from a single bottle of hydrogen gas, replaced only twice per year to ensure that it is running at the correct pressure.[3] In comparison to the conventional accelerators, plasma wakefield accelerators are very compact. The plasma target could fit into humans hand, while the laser, used to excite the waves inside the plasma could fit on top of the laboratory table. Longitudinal electric fields of the plasma waves, used to accelerate the particles, could reach values ~ 100 GV/m, that is 3-4 orders of magnitude higher, than the accelerating fields in the conventional accelerators. Unfortunately due to several reasons these accelerators are strongly limited in their length. Hence, we may draw an important conclusion about advantages and disadvantages of this accelerator in comparison with traditional accelerators.

Advantages: the PWFA is simpler in operating, less in size (and therefore much cheaper) and does not require a very complex accelerating devices and ultrahigh vacuum.

Disadvantages: these accelerators are limited in length up to few cm for the laser driven experiments (according to the state-of-art lasers) or up to ~ one meter for the particle beam driven cases, that strongly limits an energy of the accelerated particles. In addition since PWA operates with highly nonlinear processes it is very difficult to control the parameters of the wake and therefore high shot-to-shot fluctuations takes place.

Possible applications

The parameter of the accelerated beam strongly depends on the plasma target which appropriates to accelerating mechanisms and on power of the laser (energy and density of the particle bunch for the beam driven cases). Despite this, a new technology will be widely used in various fields such as a contrast imaging using betatron radiation (that comes from the oscillations of the electron munch inside the plasma wake), ion acceleration and hadron therapy using solid plasma targets, soft X-ray generation by sending an electron bunches from PWA through undulators and so on.

1. Theory introduction

1.1 Theory of plasma waves

Propagating through plasma, an intense laser pulse expels the electrons transversely to the driver bunch propagation direction via the ponderomotive force. This force is proportional to the negative gradient of the laser intensity, therefore pushes electrons further from the laser axis more strongly in the regions with the higher laser intensity. Since the ions are at least two thousand times heavier than the electrons, their drift velocity is negligible in comparison to the electron velocity and in the timeframe of the laser pulse we could assume static ion field with a positive charge.

This dynamics of the charged particles behind the driver laser pulse defines the charge separation in a shape of the drop with ion core and electron surrounding. Depending on the strength of the laser it should operate in different regimes, providing different shape of the charge separation. Anyway, this charge formation results in a high focusing/defocusing transverse electric field in the middle/ends of the "drop" and in the decelerating/accelerating longitudinal electric fields in the front/back of the charge formation respectively (fig. 1). An electron bunch, seeded in the region with accelerating and focusing longitudinal and transverse field will gain energy from the plasma wave.

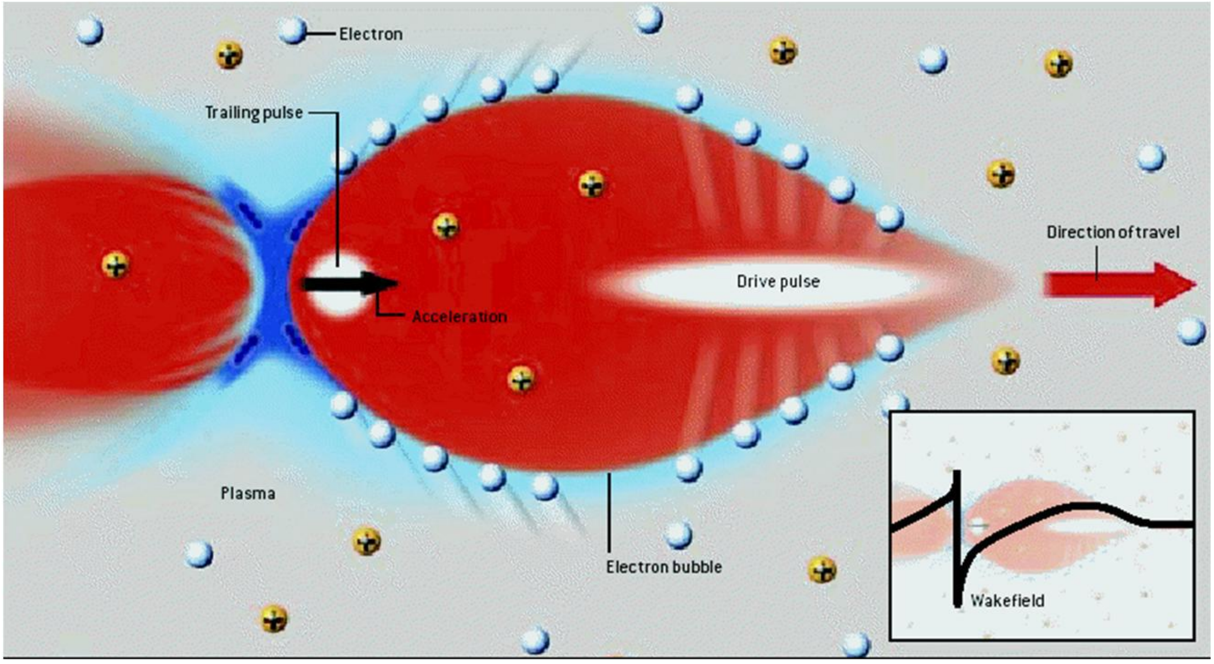

Figure 1. The scheme of the plasma wave, created by the charge distribution behind the drive pulse.

$$E_0\left[\frac{V}{cm}\right] = \frac{m_e c \omega_p}{e} \approx 0{,}96\sqrt{n_0(cm^{-3})} \qquad (1)$$

$$\omega_p = \left(\frac{e^2 n_0}{\epsilon_0 m_e}\right)^{\frac{1}{2}} \text{ is the electron plasma frequency} \qquad (2)$$

Since both the plasma wavelength and the accelerating field depends on the plasma density it is of crucial importance to control precisely the gas density inside the plasma target. For example if $n = 10^{16}\ cm^{-3}$ we obtain

$$\lambda_p = 2\pi c/\omega_p \cong 330\mu m \qquad (3)$$

Where

n is the ambient electron density,

E_0 is the amplitude of longitudinal accelerating field of plasma wave,

λ_p is the plasma wavelength,

e is the charge of an electron,

m is the mass of an electron,

ϵ_0 is the permittivity of free space. [4]

1.2. Plasma density measurements

The plasma inside the target for LPWA may be formed by ionizing a gas with a laser (multiphoton ionization, tunnel ionization or a barrier suppression) or through the capillary discharge, sent between two electrodes placed at the ends of the volume, filled with gas. The connection between laser light frequency ω and the frequency of the plasma wave ω_p is defined by the dispersion relation

$$c^2k^2 + \omega_p^2 = \omega^2 \quad (4)$$

For $\omega_p \rightarrow 0$, we obtain the usual relationship for light waves in vacuum. The phase velocity v_{ph} of the wave is given by v_{ph}= ω/k, and the refractive index N of a medium is defined by the ratio $N = c/v_{ph}$, with c being the speed of light in vacuum. Then the complex index N can be written as

$$N = (1 - \frac{\omega_p^2}{\omega^2})^{1/2} \quad (5)$$

The refractive index N in plasma is always less than 1 and for sufficiently high frequencies a real number. The phase velocity is always above the speed of light, while the group velocity $v_{gr} = \frac{d\omega}{dk}$ is always smaller than the speed of light. The refractive index decreases with increasing density and vanishes at the cutoff density n_{crit}. The phase velocity of the wave becomes infinity and the group velocity v_{gr} becomes zero. For n > n_{crit}, N is purely imaginary ($N^2 < 0$) and the electric field falls off exponentially. The displacement current due to the light wave is compensated by the electron current and the wave incident on the plasma is reflected. For $\omega \gg \omega_p$, relation (5) shows that the plasma has little influence on the propagation of the wave. At the cutoff frequency, we have.

$$\omega = (\frac{e^2 n_{crit}}{\epsilon_0 m_e})^{1/2} \tag{6}$$

and the cutoff density n_{crit} is

$$n_{crit} = \frac{4\pi^2 c^2 \epsilon_0 m_e}{\lambda^2 e^2} \tag{7}$$

The refractive index in terms of the cutoff density can be written as

$$N = (1 - \frac{n}{n_{crit}})^{1/2}$$ (8) [5]

According to this equations, it is clear, that the measurement of the plasma density turns out to be a measurement of the plasma refractive index.

1.3. Abel inversion

In general, the density along the probe ray varies, however, the line integrated density $\int n(l)dl$ is actually measured. To determine the local plasma density further information is required. Either additional measurements must be done or model assumptions must be made. Frequently, interferometric measurements at a cylindrical plasma column are carried out such that the probe ray crosses the cylindrical plasma of radius R_0 perpendicularly to the cylindrical axis. The smallest distance of the probe ray from the axis R can be measured. Several measurements with different R can be made by parallel shift of the interferometer or with several probe rays. The phase change due to the shift in position R is,

$$\varphi (R) = \frac{2\pi}{\lambda n_c} \int_R^{R_0} \frac{n(r)}{(r^2 - R^2)^{1/2}} r dr \tag{9}$$

This relation can be inverted using Abel inversion to give the plasma density,

$$n(r) = \frac{-\lambda n_c}{\pi^2} \int_r^{R_0} \frac{d\varphi(R)}{dR} \frac{dR}{(R^2 - r^2)^{1/2}} \tag{10}$$

With a sufficient number of measurements with different R the density profile can be determined. [5]

1.4. Mach Zehnder Interferometer

The method of interferometry makes use of the modulation of an electromagnetic wave due to the phase difference of two or several superimposed waves in order to measure wavelengths or characteristic properties of a medium through which the rays pass. [5] In our work was used the Mach-Zehnder interferometer to obtain the interference patterns while passing main laser beam through the target. The probe beam passing through the medium experiences phase changes that can be revealed by interferometric methods. A typical set-up for the Mach-Zehnder interferometer for plasma density measurement is given in figure 2. In the Mach-Zehnder interferometer the probe beams follow different pathways before interfering. This simplifies the interpretation of the observed fringes by passing light through the test area only once. Mach-Zender interferometers have been used extensively for measuring free electron densities of laser produced plasma by different groups. [6]

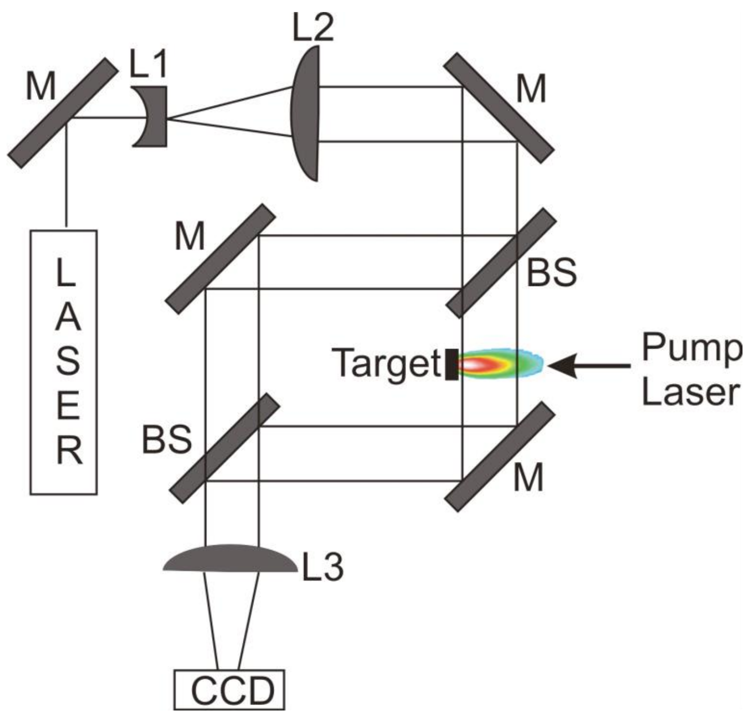

Figure 2.Mach-Zender interferometer scheme for plasma density measurement.

2. Experimental setup

2.1. Laser beam parameters

For the experiments at DESY, a powerful commercial 25 TW titanium-sapphire laser with pulse duration of 25 *fs* is used. The main parameters of the laser pulse are presented in table 1.

Parameter	Main beam	Probe beam
Energy per pulse	0.65 J	3.5 mJ
Pulse length	< 25 fs	< 25 fs (5 fs with fibre compressor)
Beam diameter	45 mm	10 mm
Rep rate	10 Hz	10 Hz
Contrast	>10^9	
Strehl ratio	0,7	

Table 1. The key parameters of the main beam and probe beam.

2.2. Experimental chamber setup

The target which is injected and accelerated electron is located in vacuum chamber volume of 0.5 (fig. 3). To protect the equipment inside the vacuum chamber I was involved in searching of rupture disk which will be set there. In current setup is using capillary filled with gas (H, He, N, Ar). High-pressure gas line for the future experiments with gas jet target was partially installed. The laser beam is focused into a gas target via off-axis parabolic mirror (OAP) onto a spot with a radius $r_{1/2}$ near 12 microns and reaches the laser intensity of a few

10^{19} W/cm^2. Transmitted laser light goes to the laser post interaction diagnostic (spectroscopy, power and pulse duration measurements) injected electron bunch goes through ICT monitor which measures the charge. Then the electron beam follows either on a scintillation screen which shows the profile of the electron beam or in the electron spectrometer consisting of a dipole magnet (0.25 T) and scintillation screens. During summer program the scintillation DRZ-High screen for the electron profile diagnostic was established and is shielded from transmitted the laser radiation. For improvement, the image quality the signal from scintillation screen is passed through the bandpath filter. (420±5 nm)

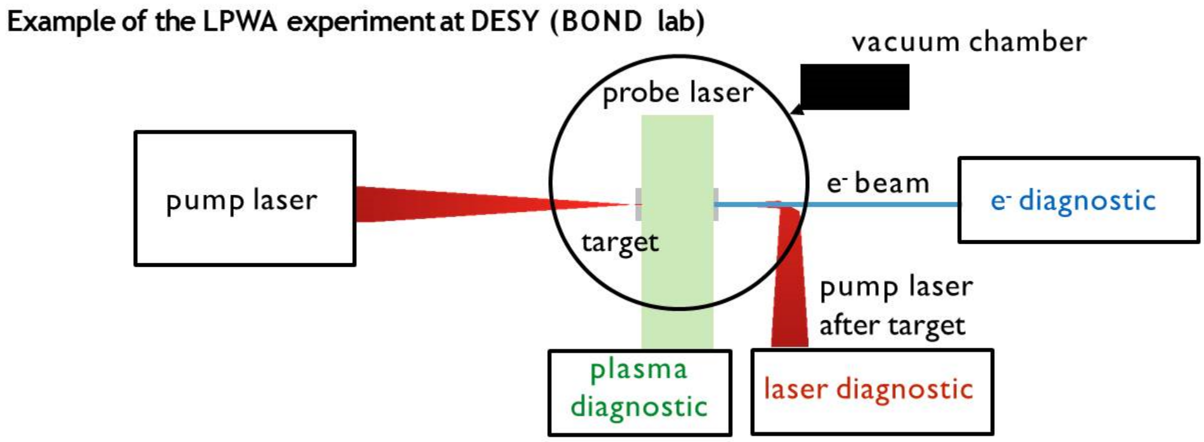

Figure 3. Scheme of laser diagnostic in experimental chamber.

Main focus of the project was alignment of a transverse probe diagnostic to measure the plasma density of the target. Laser interferometry, based on the analysis of the fringe structures originated by a probe beam crossing the plasma cloud, is a versatile tool for estimating the plume density at earlier times. It permits a very accurate determination of the electron density and is particularly used in the first instants of plume expansion. The Mach-Zehnder Interferometer uses amplitude division. The plasma formed should be placed in one of the arms of the interferometer (probe arm), while the second arm goes through the vacuum (reference arm). The plasma may consist of ions, atoms and molecules in addition to free electrons. [6]

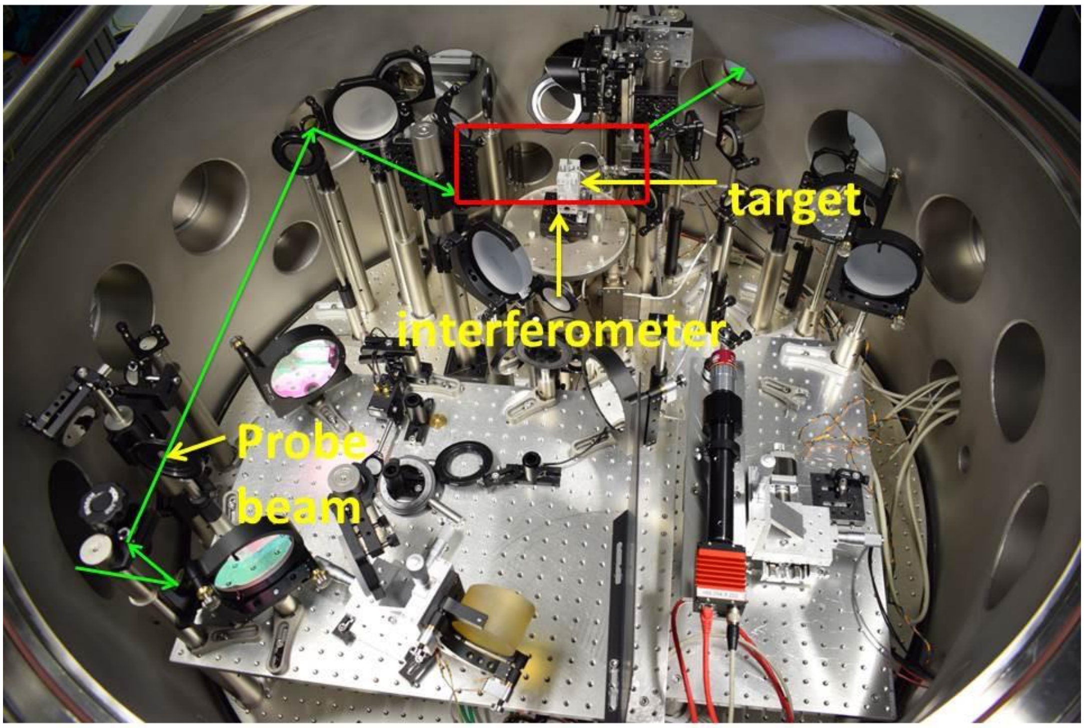

Figure 4. Photo of the experimental chamber.

2.3. Probe beam alignment

The main laser beam is split after first laser amplifier. A fraction of the main beam, that has an energy of 3.5b*J* in single pulse, goes to an air compressor where it is compressed to 25 *fs*. Afterwards the probe beam is directed to a vacuum compressor and then gets into experimental chamber where is divided into probe and reference beam (see fig. 2)

The experimental setup (see fig.5) consists of the following components: probe beam, which is very important to synchronize in space and time with the main beam to measure the density of plasma before the beginning of the recombination of free electrons and ions (~ microseconds), aperture uses for setting up correct path of the beam, mirrors and beamsplitters used for the beam direction.

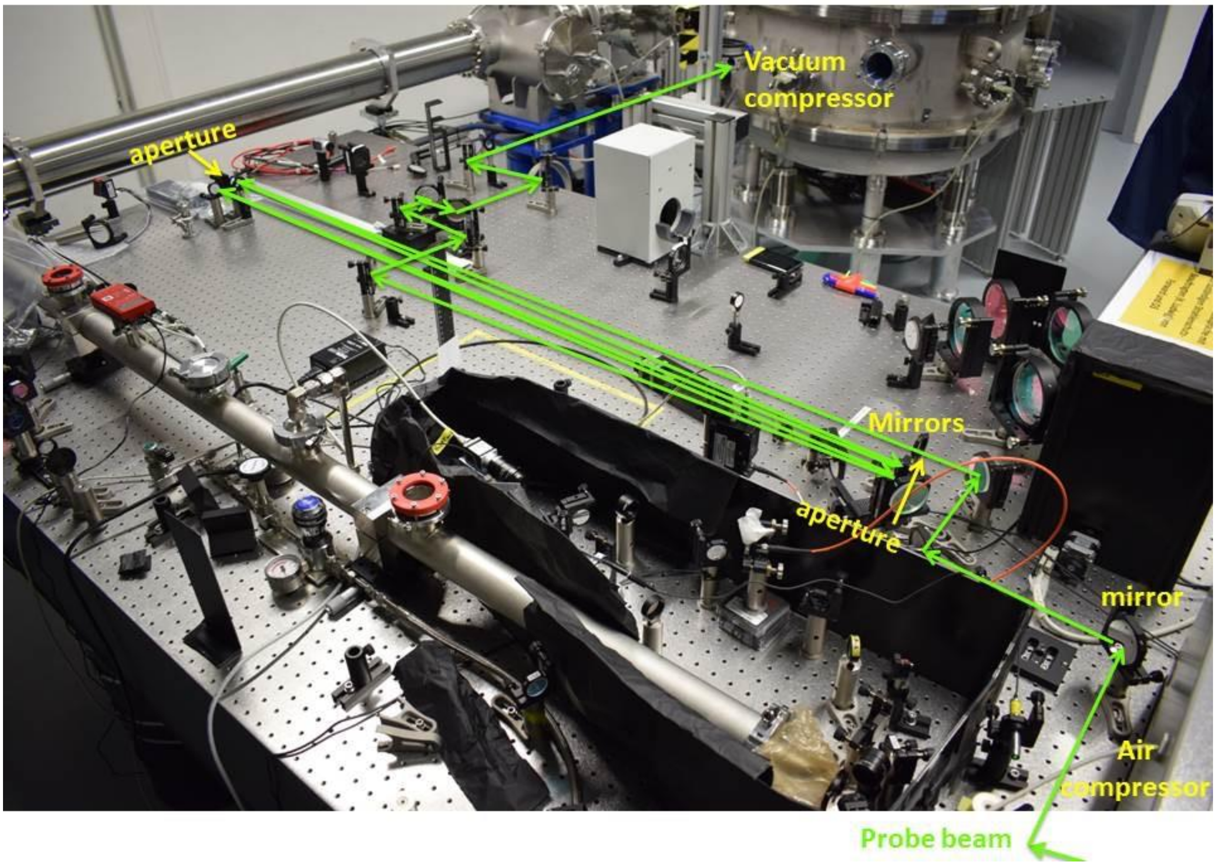

Figure 5. Probe beam alignment after air compressor.

2.4. Measurement of the signal

Throughout of the work was connected camera acA640-120gm. The camera shoots the image within the time of exposure with amplification of the signal which is given by the user directly in the program. The response time of the camera is determined by TTL signal of trigger. Communications between camera and the computer where the data is recorded carried using by DOOCS control system written in Python. Interference patterns are saved in tiff format and then analyzed using a code.

3. Data analysis

Interference patterns will be obtained using transverse probe diagnostic and will be converted into a map of the target plasma density via Abel inverse transformation. (see eq.10)

During the summer program I have started work on development of a code interferometer using MATLAB for the analysis of images obtained using the Mach-Zehnder.

Code consists of several blocks:

- reading the graphical information from the files;
- analysis interferograms of the laser beam and search of minimum intensity;
- calculating deviation of interference lines from their initial position in the field of high plasma density;
- use of Abel's inverse deviations;

After further improvement of the code it will be possible to use it for the off-line analysis and density map recovering.

Conclusion

In conclusions, plasma wakefield acceleration shows a possibility to effectively inject and accelerate electrons in a very high longitudinal electric fields, created by the charge separation. And since the amplitude of the accelerating field and the wavelength *pf* the plasma wave depends on the plasma density, it is very important to know exact value of the plasma target density.

Setting up an environment for the laser driven plasma wakefield accelerator requires a very careful alignment of the laser to the optic inside the vacuum chamber, as well as the proper alignment of the diagnostic, that could be used to measure parameters related to the electron bunch acceleration and the accelerated bunch itself.

During the summer school program, I participated to the development of the high density plasma target and it's diagnostic, utilizing use of the probe laser beam in the Mach-Zehnder transverse interferometer. I assisted during alignment of the optical light and assembling of the environment for the target and probe diagnostic. In addition I was involved in upgrading the scintillator screen for the electron bunch profile imaging and ordering of the burst disk to protect the vacuum system from potential failures of the high pressure gas target. Apart from work in the experimental area I was developing software for the analysis of the data, obtained via Mach-Zehnder interferometer.

During this time I learned a lot of information about an operation of many devices and setting up an optic equipment. I was working with a powerful (class 4) laser system in a clean laboratory and with a vacuum and high pressure equipment as well. In addition I improved knowledges of MATLAB software while developing a code to analyze obtained results from the interferometry. I got an informative overview of the plasma wakefield acceleration techniques and its applications.

References

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