Simulation and Preliminary Experimental Study for Self-modulation Experiment at PITZ

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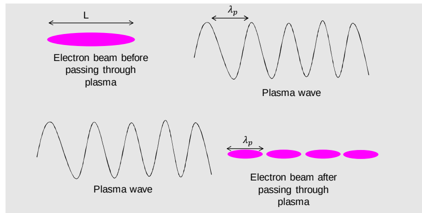
Abstract

A long, relativistic particle beam propagating in an overdense plasma is subject to the self-modulation instability. Simulations were carried out to study the self-modulation of long electron bunches in the plasma. The goal of the study is to optimize the beam and plasma parameters to get maximum beam energy modulation with minimal increase of emittance. Increase in beam energy modulation is observed with increase in plasma density and decrease in beam size. However beam emittance increases rapidly after few millimeter propagation through the plasma because of increase in divergence and compression of beam due to transverse wakefields of plasma. The possible explanation for the emittance growth is presented here.

Beam matching study is also carried out to optimize the beam parameters. The outcome shows that beam matching is unachievable with desired beam and plasma parameters for PITZ self-modulation experiment.

Calibration method of diffraction grating for spectrum analysis is presented in this poster. The calibration achieved is 0.05 nm/pixel or 11.34 nm/mm. This calibrated grating and wavelength distributed white light interference pattern later on will be used in hook's method for gas density measurement.

Self-modulation of electron beam



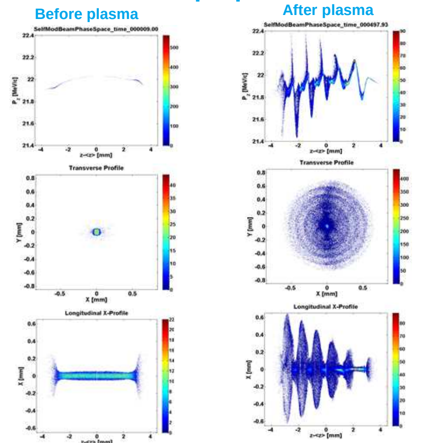
Self-modulation of the electron bunch essentially occurs due to the action of the transverse wakefields on the bunch itself.

In its simplest form of self-modulation, a long charge particle beam $(L > \lambda_p)$ when propagates through the plasma generates a wake within its body due to perturbation of plasma, which modulates the beam itself, leading to the positive feedback and unstable modulation of the whole beam along the propagation direction. This self-modulation splits the long beam into short bunches of length λ_p, which resonantly drive the plasma wake. The longitudinal electric field is given by

$$E_z = 240(MV\ m^{-1})\left(\frac{n_b}{4\times10^{10}}\right)\left(\frac{0.6}{\sigma_z(mm)}\right)^2$$

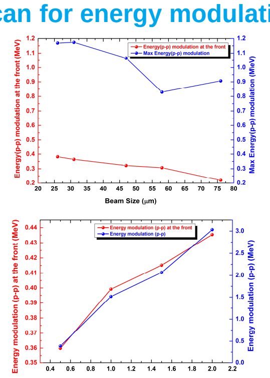
Where n_b, is beam density
σ_z is longitudinal beam size,

Beam properties



Modulation is observed more in the tail of beam.
Beam is compressed transversely due to transverse wakefield.
Different compression in x, y direction is due to asymmetrical transverse beam size.

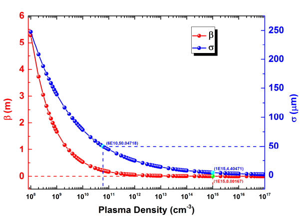
Beam size and plasma density scan for energy modulation



Smaller beam size expels plasma electron more strongly, generating strong transverse wakefields which in turn modulate beam energy strongly (upper figure).

The beam energy modulation increases with increase in plasma density, is due the fact that tansverse wakefield increases with increase in plasma density again which in turn modulate beam energy strongly (lower figure).

Beam matching for plasma



Plot for blowout regime

Beam matching for blowout regime

$$\beta_m \approx \frac{c}{\omega_\beta}, \gamma_m \approx \frac{c}{\omega_\beta}, \alpha_m = 0$$

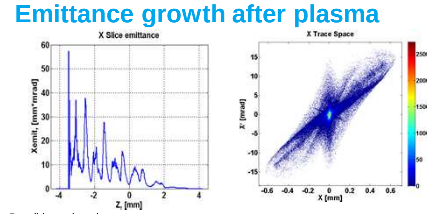
Beam matching for linear regime (e.g. Gaussian beam distribution)

$$\beta_m \approx \left(\frac{e}{2\pi}\right)^{1/4}\sqrt{\frac{\sigma_r^2\gamma}{f_0 \sin(k_p\zeta)}}$$

Where β_m, γ_m, α_m are twiss parameters, $\omega_\beta(=\omega_p/\sqrt{2\gamma})$ is betatron frequency, σ_r is beam transverse size, f_0 is n_b/n_0, k_p is plasma wave number, γ is the mean beam energy.

For beam matching for blowout regime with plasma density $10^{15}cm^{-3}$ the β_m and corresponding σ_r are quite small. This conclude that beam matching can not be achieved with desired beam and plasma parameters for PITZ self-modulation experiment.

Emittance growth after plasma



Possible explanation:
General definition of normalized emittance growth

$$\varepsilon_n^2 = \langle x^2\rangle\langle\beta^2\gamma^2x'^2\rangle - \langle x\beta\gamma x'\rangle^2 \quad (1)$$

Considering the correlation between the energy and transverse position is negligible

$$\varepsilon_n^2 = \langle\beta^2\gamma^2\rangle\langle x^2\rangle\langle x'^2\rangle - \langle\beta\gamma\rangle^2\langle xx'\rangle^2 \quad (2)$$

By the definition of relative energy spread σ_E

$$\sigma_E = \frac{\langle\beta^2\gamma^2\rangle - \langle\beta\gamma\rangle^2}{\langle\gamma\rangle^2} \quad (3)$$

Inserting eq. (3) in equation (2) gives

$$\varepsilon_n^2 = \langle\gamma^2\rangle(\sigma_E^2\sigma_x^2\sigma_{x'}^2 + \varepsilon^2) \quad (4)$$

The ratio between 1st and 2nd term of this equaiton

Before plasma	After plasma
$\frac{\sigma_E^2\sigma_x^2\sigma_{x'}^2}{\varepsilon^2} \approx 0.8$	$\frac{\sigma_E^2\sigma_x^2\sigma_{x'}^2}{\varepsilon^2} \approx 18$
For $\sigma_E = 0.1\,\%$	For $\sigma_E = 5\,\%$
$\sigma_x = 50\,\mu m$	$\sigma_x = 20\,\mu m$
$\sigma_{x'} = 1.6\,mrad$	$\sigma_{x'} = 10\,mrad$
$\varepsilon = 0.35\,mm\,mrad$	$\varepsilon = 10\,mm\,mrad$
$\gamma = 43$	$\gamma = 43$

This explains that energy spread and beam compression could be major reasons for the emittance growth.

Calibration of diffraction grating using two lasers

The calibration of diffraction grating is done by using two lasers of slightly different colors, a diffraction grating and a screen (camera). The principle is described below.

The diffraction equation is given by

$$d \sin\theta = m\lambda$$

Where d is grooves spacing in the grating,
θ is the angle of diffraction for a particular λ,
m is order of diffraction

$$\theta = sin^{-1}\left(\frac{\lambda\mu m}{1.66}\right)$$

Where $m = 1$ for first order diffraction, $d = 1.66\,\mu m$

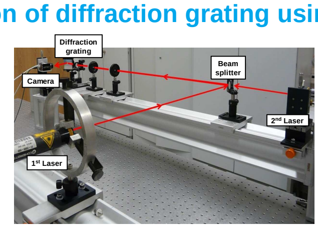
If there are two lasers of wavelength λ_1 and λ_2 the angle of diffraction will be different for both, say θ_1 and θ_2 respectivily. Let us consider the distance between grating and screen is x then the difference between first order diffraction for both wavelengths is

$$\Delta y = x(\tan\theta_1 - \tan\theta_2)$$

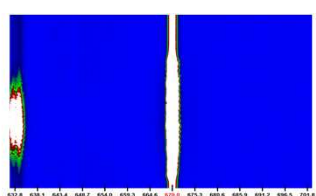
and hence

$$\Delta y = \lambda_1 - \lambda_2$$

The calibration achieved by this method is 0.05 nm/pixel or 11.34 nm/mm

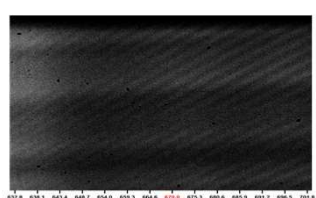


Calibration setup for diffraction grating



First order diffraction for the 670nm and 632.8nm

Diffraction pattern for the 670 nm and 632.8 nm. From right to left 0th, 1st, 2nd … order diffraction pattern. 0th order diffraction overlaps for both lasers because it is just a reflection from grating.



Wavelength distribution of white light interference

Outlook

- Further optimization by simulations will be done to achieve maximum energy modulation and minimize the emittance growth e.g. with energy chirp beam and density tapered plasma.
- Experiments are ongoing for gas density measurement.
- Different methods will be implied for gas and plasma density measurement.

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