DESIGN STUDY FOR A PLASMA UNDULATOR EXPERIMENT USING CAPILLARY BASED DISCHARGE PLASMA SOURCE

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Abstract

A plasma undulator is formed when a short laser pulse is injected into plasma off-axis or at an angle that causes the centroid of this laser pulse to oscillate. Ponderomotively driven plasma wake will follow this centroid given that the product of the plasma wave number and the characteristic Rayleigh length of the laser is much larger than one. This oscillating transverse wakefield may work as an undulator forcing particles to follow sinusoidal trajectories and emit synchrotron radiation. In this paper, plans for an experiment are introduced and resulting radiation and injected beam characteristics are discussed. The aforementioned laser centroid oscillations are demonstrated using, EPOCH, a PIC code for laser-plasma interactions.

INTRODUCTION

There are various concepts to conceive a plasma undulator [1–4]. Following the one proposed by Rykovanov et al., when a laser pulse is injected into a parabolic plasma channel off-axis or at an angle with respect to the centre of the channel, the laser centroid oscillates with a period comparable to the characteristic Rayleigh length of the laser. When the laser peak power, P, is below the critical power, $P_c(GW) \cong 17(k_L/k_p)^2$, the laser centroid oscillates according to $x_c(z) = x_{ci}\cos(z/Z_R + \phi)$ where k_p and k_L are wave numbers for plasma and laser, respectively, $Z_R = \pi w_0^2/\lambda$ is the Rayleigh range of the laser, x_{ci} is the maximum value of centroid deviation and ϕ is an arbitrary phase value, w_0 is the laser spot size at focus and λ is the laser wavelength. Ponderomotively driven plasma wakefield will follow the laser centroid oscillation when $k_p Z_R >> 1$. This condition can be satisfied by adjusting the plasma density depending on spot size at the focus and wavelength of the laser.

PLANNED EXPERIMENT

The tentative layout of a planned experiment to observe this phenomenon is presented in Fig.1. The interaction of the laser pulse and plasma will be investigated to demonstrate the laser centroid oscillations. Images of the laser spot before and after the plasma may reveal an off-set in laser transverse position as an indication of theoretically predicted centroid movement. Images can be taken by using YAG:Ce or OTR screens over many shots to provide statistically significant results. Screens will be installed on push-pull motion actuators.

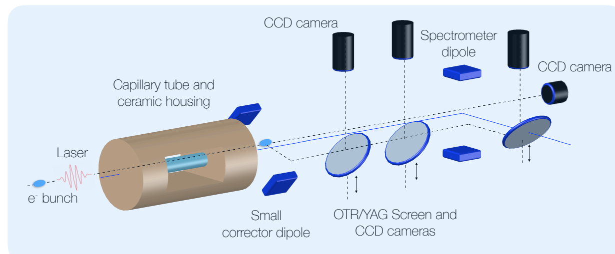

Figure 1: Tentative layout of the experiment.

Assuming that an undulator is established and a measurable amount of synchrotron radiation may be produced by an externally injected electron beam. The on-axis angular photon flux density is

$$\left.\frac{d\dot{N}}{d\omega}\right|_{\theta=0} = 1.74 \times 10^{14} N^2 E^2 I_b F_n(K) \tag{1}$$

where N is the number of undulator periods, E and I_b are the energy and current of the incoming electron beam, $F_1(K)$ is a function of K undulator strength parameter for the first harmonics as given in Eq.2.

$$F_1(K) = \frac{K^2}{(1+K^2)^2}(J_1(Y) - J_0(Y))^2, \tag{2}$$

where J_1 and J_0 are the first and second order Bessel functions of the first kind and $Y = K^2/4(1+K^2)$. In addition the strength parameter for a plasma undulator is given as

$$a_u \approx 4\pi a_0^2 C x_{ci}/\lambda \tag{3}$$

where a_0 is normalised vector potential of the laser, $C \approx 0.38$ for a linearly polarised Gaussian laser pulse and λ is laser wavelength. Consequently, for $a_0 = 0.2$ and an electron bunch of 1 nC at 250 MeV with a bunch length of 1 ps, a photon flux of $\sim 10^{18}$ (photons/sec/mrad^2/0.1%Bandwidth) can be produced over 10 periods of the plasma undulator. From the well known formula in practical units, $B_{\text{eff}}[\text{T}] = a_u/(0.934\lambda_u[\text{cm}])$, an equivalent magnetic field of 21 T can be achieved. At the considered ratio between centroid oscillation amplitude and laser spot at interaction, $x_{ci}/w_0 = 2$, radiation is emitted in a range in near ultraviolet frequencies. This radiation might be detected with a CCD camera, that is sensitive to the spectral range, directly or after a certain

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ISBN 978-3-95450-182-3

Table 1: Example Laser Specifications for the Early and Relatively Recent Experiments

Reported							Derived	
Reference	E_p (mJ)	Pulse length (fs)	w_0 (μm)	λ (nm)	I (10^{18} W/cm^2)	a_0	I (10^{18} W/cm^2)	a_0
5	400	120	5.5	800	0.26	-	0.70	0.58
6	20	100	3.6	800	0.45	-	0.98	0.68
7	40	130	6.0	800	0.20	-	0.54	0.51
8	1500	400	30/19	1057	0.40	-	0.42	0.59
9	1000	30	50	800	1	-	0.85	0.64
10	65	8.5	3	800	6	1.67	5.68	1.65

attenuation via a filter or by means of a screen depending on the intensity.

After successful incorporation (alignment and matching) of the electron beam in the system, one can test the effect of interaction on the electron beam passing through the perturbed plasma following the oscillating wake of the laser pulse. A beam area, equipped with an energy spectrometer, will enable monitoring of the energy deviations in the electron beam after it interacted with the plasma perturbed in undulator mode. This might provide an indication of longitudinal momentum loss through synchrotron radiation. Beam emittance can be measured by using a pepper-pot setup, through a quadrupole scan or by observing the change in beam size and divergence at adjacent screens (including carefully calculated divergence increase via scattering through the screens).

Laser: The key laser parameter to perturb a preformed plasma by using a short laser pulse is the normalised laser vector potential, a_0. Early and relatively recent laser-driven plasma acceleration experiments were performed for $a_0 \approx 1$ before the development of powerful petawatt lasers [5–10]. Theoretically, a plasma undulator can be achieved even for normalised vector potential values down to 0.2 [11]. The normalised vector potential in practical units as a function of laser wavelength λ, and intensity I, is,

$$a_0 \cong 8.65 \times 10^{-10} \lambda(\mu\mathrm{m}) \sqrt{I(\mathrm{W/cm^2})} \tag{4}$$

$$I(\mathrm{W/cm^2}) = \frac{2P_{\mathrm{peak}}(\mathrm{W})}{\pi r_s^2(\mathrm{cm^2})} \tag{5}$$

$$P_{\mathrm{peak}}(\mathrm{W}) = \frac{E_{\mathrm{pulse}}(\mathrm{J})}{\sigma_z(\mathrm{s})} \tag{6}$$

where P_{peak} is the peak laser power, r_s is *rms* radius of the laser spot, E_{pulse} is the laser pulse energy and σ_z is laser pulse length at FWHM. Reported laser parameters and derived values with above formulae regarding the reference experiments are presented in Table 1.

To ensure a realistic range of working points for the laser, the minimum and maximum of the laser parameters demonstrated in the above experiments were selected as reference values. The laser parameters providing an a_0 value of 1 and 0.2 were calculated of the order of these reference range as presented in Fig.2 using Eq.(4-6). This indicates an interplay

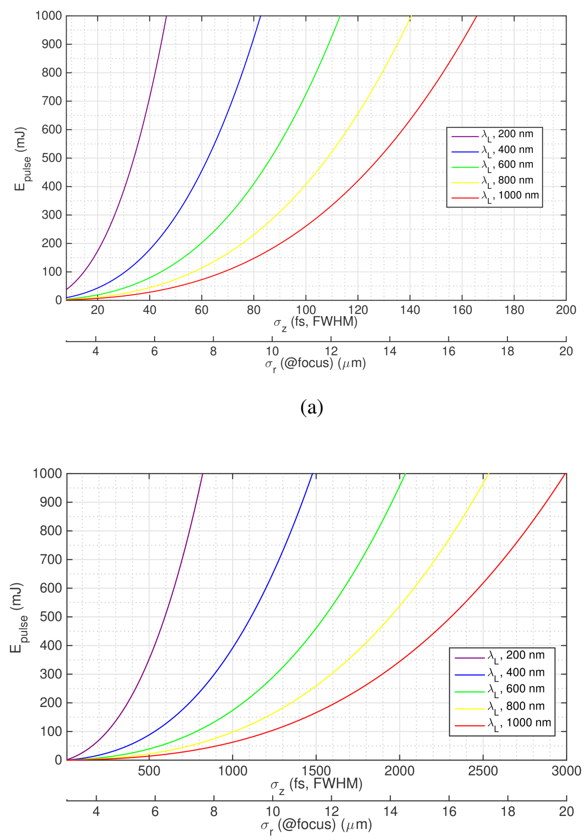


Figure 2: Laser parameters to provide an a) $a_0 = 1$ and b) $a_0 = 0.2$ for the proof of principle experiment.

between the laser pulse energy and the laser pulse volume in order to deliver a given a_0. For a given normalised vector potential and a certain laser wavelength, in case there is a limitation in available pulse energy, required intensity can be compensated by reducing the pulse volume and vice versa. Given that the assumed spot sizes are not achievable, this parameter can be relaxed by adjusting the laser pulse length.

Plasma: We plan to use a gas-filled capillary based discharge plasma source for this experiment which we are currently developing in the Cockcroft Institute, Daresbury. The setup involves 30 kV DC high voltage source, a thyratron and trigger box for discharge; half a meter vacuum chamber for

ISBN 978-3-95450-182-3

integration into an electron beamline; electrical feedthrough and glass capillary tubes in various lengths and sizes. The housings will be manufactured from Macor (Corning), a machinable ceramic. Macor has been machined into shapes more complex than those required for this design.

According to the extrapolated empirical Paschen curves given in Fig. 1, discharging a range of plasma densities between $1.5{\times}10^{13}$ to $5.3{\times}10^{16}$ cm^{-3} is achievable for a 5 cm long capillary tube when filled with Ar gas. This corresponds to a gas pressure between 0.08 to 280 mbars.

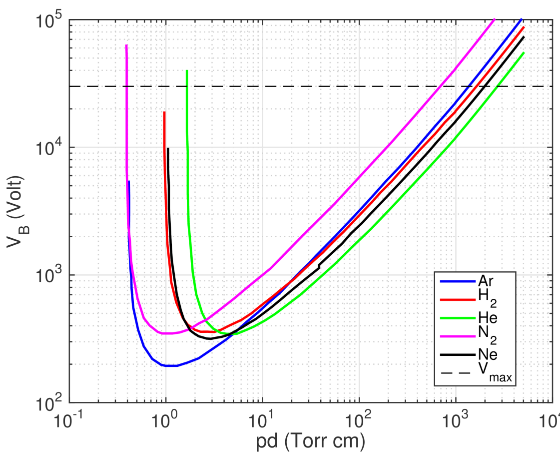
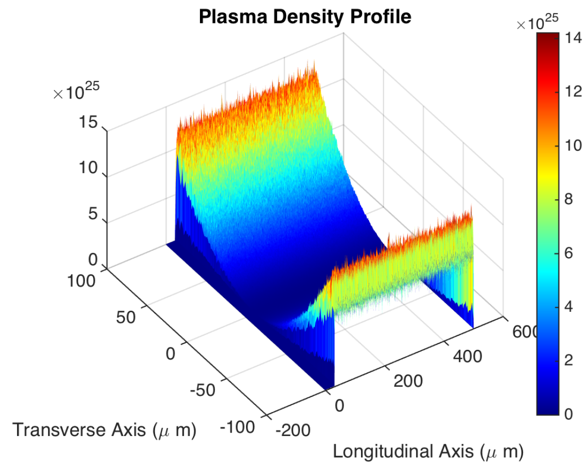


Figure 3: Empirical Paschen curves for various gases as a function of gas pressure and the distance between the discharge electrodes. Curves are extrapolated according to the maximum voltage available from the discharge source.

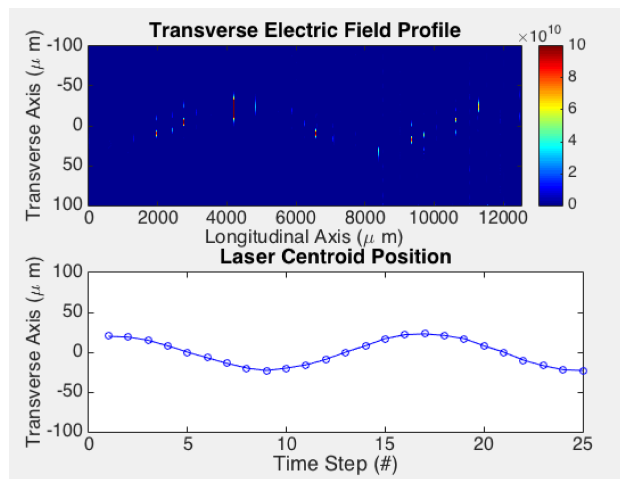
Electron Beam: A typical relativistic electron beam with well defined emittance (and perhaps divergence), energy and energy spread is appropriate for this experiment. The limitation to beam size can be defined according to the clearance provided by the plasma cell. For example, in a 1 mm diameter plasma capillary, one can fit $\pm 5\sigma$ beam spot of a 50 μm (1σ) beam radius and still allow $\pm 5\sigma$ clearance at the walls of the capillary as a precaution against position jitter of the beam and laser. The ratio between the number densities of the electron beam and the plasma electrons determines a the regime (linear or wave-breaking) where plasma wakefields occur. The bunch charge values between 100 pC to a nC can provide number densities between $10^{13} - 10^{16}$ cm^{-3} which can be matched by the plasma cell. A high repetition rate operation might be favoured as it will help with the signal-to-noise ratio for the signal integrating diagnostics.

SIMULATIONS

A plasma density profile starting with a zero density region of 30μm and followed by a parabolic plasma channel with the channel depth of $1{\times}10^{18}$ cm^{-3} was defined in EPOCH [12] (Fig. 4-a). This has been done to initiate the defined laser fields in a plasma-free region and preserve the consistency of Maxwell's equations. The laser pulse with an $a_0 = 0.2$ was sent 20μm off-axis with respect to the channel centre. This initial simulations demonstrated that laser centroid oscillates under the given conditions. Analysis and further simulations on the oscillation of the wakefields induced by the laser pulse and characterisation of the radiation emitted by a probe electron beam is ongoing.



(a)



(b)

Figure 4: a) Field profile within the plasma. b) Laser centroid position oscillating along the plasma channel with an initial off-set of 20 μm.

CONCLUSIONS

Novel technologies, with the promise of reducing the size and the cost of accelerator components, are crucial towards the realisation of next generation accelerators. Plasma undulator is one such technology which provides at least an order of magnitude larger effective field strength compared to conventional magnetic components.

REFERENCES

[1] S. G. Rykovanov, "Plasma Undulator Based on Laser Excitation of Wakefields in a Plasma Channel", Phys. Rev. Lett., vol. 114, p. 145003, 2015.

ISBN 978-3-95450-182-3

[2] I. A. Andriyash et al., "An Ultracompact X-Ray Source Based on a Laser-Plasma Undulator", Nature Comm., vol 5, p. 4736, 2014.

[3] S. Corde and K. Ta Phuoc, "Plasma Wave Undulator for Laser-Accelerated Electrons", Phys. of Plasmas, vol. 18, p. 033111, 2011.

[4] R. L. Williams et al., "Studies on Classical Radiation Emission from Plasma Wave Undulators", IEEE Trans. on Plasm. Sci., vol. 21, p. 156, 1993.

[5] J. R. Marquès et al., "Temporal and Spatial Measurements of the Electron Density Perurbation Produced in the Wake of a Short Pulse", Phys. Rev. Lett, vol. 76, p. 3566, 1996.

[6] C. W. Siders et al., "Laser Wakefield Excitation and Measurement by Femtosecond Longitudinal Interferometry", Phys. Rev. Lett, vol. 76, p. 3570, 1996.

[7] J. R. Marguès et al., "Frequency Increase and Damping of Nonlinear Electron Plasma Oscillations in Cylindrical Symmetry", vol. 78, p. 3463, 1997.

[8] F. Amiranoff et al., "Observation of Laser Wakefield Acceleration of Electrons", Phys. Rev. Lett, vol. 81, p. 995, 1998.

[9] N. H. Matlis et al., "Snapshots of Laser Wakefields", Nat. Phys., vol. 2, p. 749, 2006.

[10] A. Buck et al., "Real-Time Observation of Laser-Driven Electron Acceleration", Nat. Phys., vol. 7, p. 543, 2011.

[11] S. G. Rykonakov, Private communication.

[12] T. D. Arber et al., "Contemporary Particle-In-Cell Approach to Laser-Plasma Modeling", Plasm. Phys. Contr. Fus., vol. 57, p. 113001, 2015.

ISBN 978-3-95450-182-3