OPALS: THE OXFORD PLASMA ACCELERATOR LIGHT SOURCE PROJECT

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Abstract

Recent progress in Laser Plasma Accelerators has demonstrated the possibility of generating GeV electron bunches with very interesting beam qualities. It is now conceivable that the further development of such devices could generate beams with emittance, energy spread and peak current suitable for FEL operation in the XUV range with relatively short undulator trains. In this context the OPALS project aims at the construction of a XUV radiation source, driven by a Laser Plasma Accelerator, capable of generating ultrashort fs XUV pulses. Such a source is small enough to be hosted in an academic or industrial institution and could therefore have a major impact on time-resolved science

INTRODUCTION

Laser plasma wakefield accelerators (LPWAs) have already produced intense, quasi-monochromatic electron beams with energy up to 1 GeV [1]. The encouraging improvements of the beam qualities delivered by such devices have recently stimulated the investigation of ultra compact free electron laser (FEL) sources driven by LPWAs which promise to be at the core of the next, 5^{th} generation light sources.

First experiments on the applications of these beams for the generation of synchrotron radiation have proven that ultrashort spontaneous radiation pulses can be generated in the visible range of wavelengths from a LPWA driven undulator source [2]. The next step, driving a FEL with a LPWA, is currently under investigation at several laboratories [3-5].

In this paper we describe the proposal of a prototype compact GeV electron source driving a FEL small enough to be accommodated in a University department, named OPALS (Oxford Plasma Accelerator Light Source). The LPWA is based on the capillary technology developed at Oxford [6], on a commercial pulsed laser system and on a conventional undulator. We report the initial studies on the FEL characteristics that can be obtained using realistic LPWA parameters, including seeding options and single spike operation. We show that it is conceivable to obtain a VUV FEL source within the presently achievable beam qualities and a soft X-ray source with a modest projection of the beam qualities, foreseeable in the near future. OPALS could then constitute a very high peak brightness soft X-rays facility, which could be operated flexibly to respond quickly to new ideas and opportunities. In particular it will produce soft X-ray pulses in the femtosecond regime which might have a major impact on the ultra fast time-resolved science currently performed with a variety of X-ray sources.

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OPALS LAYOUT

The basic layout of the OPALS facility consists of a 50 TW pulsed laser, a plasma channel based on capillary technology which in a first instance is 3 cm long, a short transfer line to steer and focus the electron beam to the undulator. A planar undulator based on permanent magnet technology will be used. A simplified layout is shown in Fig. 1. A set of electron beam diagnostics will be used in order to determine energy, current, emittance, energy spread and bunch length to fully characterise the performance of the LPWA.

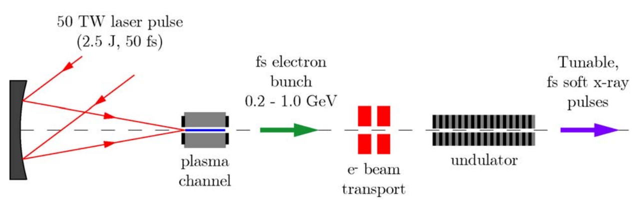

Figure 1: Simplified layout of the OPALS facility

We have investigated several regimes of operation at different wavelength assuming slightly different electron beam parameters. A conservative option will aim at FEL operation at 50 nm in the fundamental with a 400 MeV electron beam. A more aggressive option will aim at 5 nm fundamental FEL wavelength using a 1 GeV electron beam.

The 50 TW pulsed laser is commercially available from several companies. It will be capable of delivering 30-35 fs rms laser pulses at 800 nm wavelength, corresponding to an energy of 1.5-1.75 J per pulse with a repetition rate currently up to 10 Hz. The laser can be focused in the capillary down to a waist of 25 μm. Although the pulse repetition rate of the laser, and hence of the accelerator, will initially be relatively low, it is expected that the application of advances in laser technology will allow the repetition rate of the laser to be increased to the kHz range.

In the capillary, an electric pulsed discharge will form a plasma with densities 10^{18}-10^{19} cm^{-3}. A 50 TW laser pulse with a 3 cm capillary will be sufficient to generate electrons with energy up to 1 GeV.

A planar undulator with a period of 2 cm will be used to generate 50 nm with a 400 MeV electron beam (undulator parameter K = 2) and 5 nm FEL radiation with an electron energy of 1 GeV (K = 1.4). FEL simulations show that the saturation length of this device can be kept within 15 m. We assumed a segmented undulator train. The length of the undulator section should preferably be longer than the gain length and has been tentatively fixed to 1 m and will be further optimised in forthcoming studies.

BEAM DYNAMICS

Accelerating structures formed in a plasma through the interaction with an intense laser have micron level size in both the transverse and longitudinal dimension. Simulations indicate that < 10 μm rms size in each dimension can be generated without any bunch compression scheme [2].

Recent experiments have demonstrated that quasi-monoenergetic beams (~1% rms energy spread) with low transverse divergence (~1 mrad rms) can be generated[1,7-8]. Under these conditions, bunches with a charge of hundreds of pC were produced leading to a very high peak currents up to tens of kA with energies of several hundred MeV. The LPWA electron beam parameters used in the simulations are reported in Tab. 1. These are based on recent experiments and on short term projections:

Table 1: LPWA beam parameters used in the simulations

Energy	400-1000 MeV
Energy spread	0.5-1% (rms)
Bunch length	10 fs (rms)
Bunch charge	250 pC
Peak current	10-20 kA
Norm. emittance	1 μm (rms)

The LPWA beam is then steered and focussed toward the undulators train by a small transfer line containing a pair of triplets. The optics functions are matched to the undulator lattice.

Particular attention was given to the analysis of the effect of space charge forces in the highly focussed and high peak current electron beam in the transfer line from the LPWA to the undulator, in order to investigate the possibility of beam quality degradation due to space charge in the section between accelerator and undulators. Particle tracking simulations with ASTRA and CSR-track were performed to assess space charge effects on emittance, bunch length and energy spread. These simulations show that with the parameters used in Tab. 1, space charge effects appear to be rather modest both in the transverse and longitudinal plane, leading to a relatively small growth on emittance, bunch length and energy spread. Tests of free propagation in drifts sections as long as 1.5 m showed that the beam size is dominated by the natural divergence of the electron beam, the bunch length is conserved and the high peak current is maintained. Fig. 2 reports the fractional change in the normalised transverse emittance for various bunch charge and show that at 400 MeV a fractional change of about 13% in the emittance is detected only at bunch charges as large as 1 nC. At higher energies the effect of the space charge decreases rapidly: an LPWA beam of 1 GeV and the parameters of Tab.1 does not experience any significant emittance growth or bunch lengthening due to space charge.

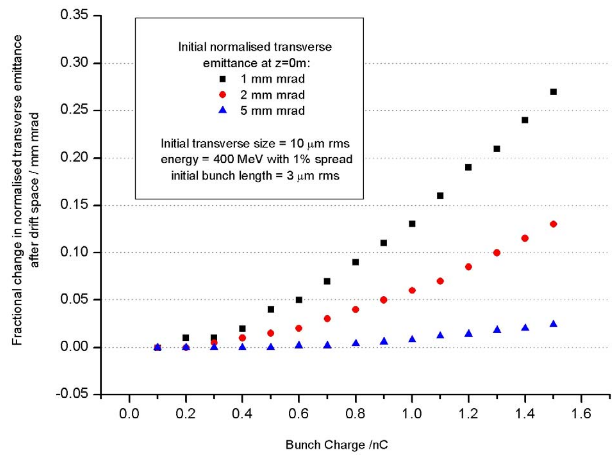

Figure 2: Fractional change in normalised emittance, after 1.5 m drift, due to space charge (CSR-track simulations).

In order to maximise the FEL efficiency, the electron beam transverse size is focussed in the undulator channel by a series of quadrupoles triplets. The waist of the electron beam is at the centre of each undulator sections as shown in Fig. 3. Shorter period implies smaller beam size.

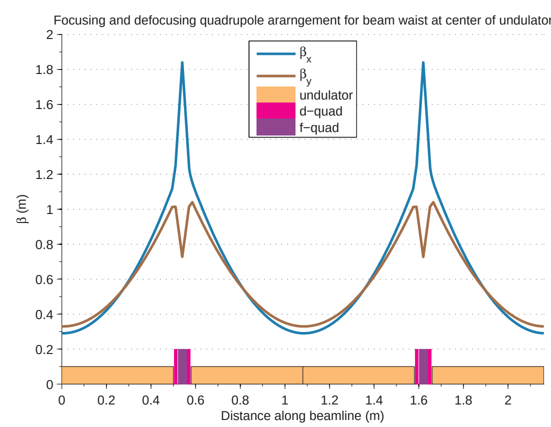

Figure 3: Optics functions along the undulator segments.

FEL DYNAMICS

The FEL interaction of the LPWA electron beam was studied with 3D time-dependent numerical simulations performed with GENESIS [9]. We studied the possibility of operating an FEL from 50 nm down to 5 nm with an undulator of 20 mm period and the beam parameter summarised in Tab. 1. The results of the FEL simulations are summarised in Tab. 2.

Table 2: Summary of FEL simulations.

Wavelength	50 nm	5 nm
Undulator period	20 mm	20 mm
Undulator K	2	1.4
Electron energy	400 MeV	1 GeV
Energy spread	1%	0.5%
Charge	250 pC	250 pC
rms bunch length	10 fs	5 fs
Norm. emittance	1 µm	1 µm
Sat. length	5.1 m	12.0 m
Pierce parameter (ρ_{3D})	$6.2 \cdot 10^{-3}$	$2.7 \cdot 10^{-3}$
Peak power	4.2 GW	300 GW
Photons per pulse	$9 \cdot 10^{12}$	$1.5 \cdot 10^{13}$
Av. Power @ 10 Hz	0.36 mW	6.0 mW

An initial study on the degradation effects of the emittance and energy spread on the FEL gain length has been performed using the Xie parameterisation for the gain length [10]. It turns out that the energy spread is the most critical parameter, as shown in the plot in Fig. 4, where the gain length for the operation at 50 nm increases steeply for energy spread values larger than 0.25%. The dependence on the emittance appears to be roughly linear in this regime of operation. At smaller wavelength the sensitivity on the energy spread is even more dramatic and the operation at 5 nm requires a relative energy spread lower than 0.5% to achieve a saturation length of about 10 m.

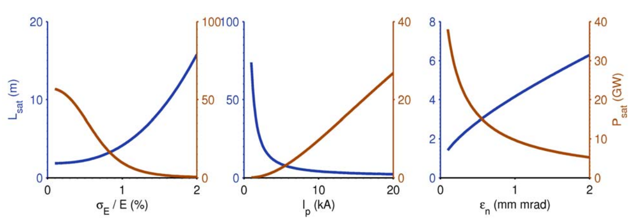

Figure 4: Dependence of the gain length (blue) and the saturation power (brown) as a function of the energy spread (left), bunch charge (middle) and emittance (right) for the FEL operation at 50 nm. The data for peak current and emittance dependence are based on 1% relative energy spread.

It should be emphasised that the electron rms bunch length σ_z of 1.7-3.3 µm (5-10 fs) assumed for the LPWA electron beam is comparable to the cooperation length of the FEL:

$$L_{coop} = \frac{\lambda_{FEL}}{4\pi\rho_{3D}}$$

which is 0.65 µm for the 50 nm FEL operation and 0.15 µm for the 5 nm FEL. Under the condition:

$$\sigma_z < 2\pi L_{coop}$$

the FEL operation occurs in a single spike regime [11] where only one FEL pulse is generated with improved temporal coherence with respect to the standard SASE operation. Our parameters are very close to satisfying the single-spike condition aforementioned. The temporal profile reported in Fig. 5 shows that at the end of the undulator the FEL output is made up of a quasi-single spike pulse of about 5 fs rms width.

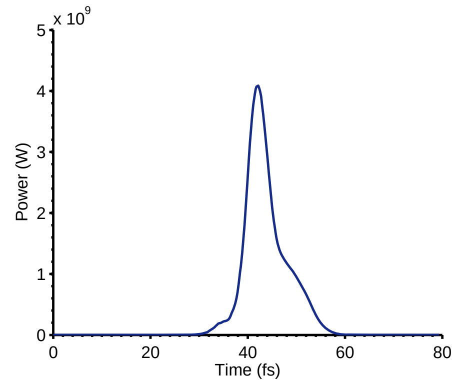

Figure 5: FEL pulse at 50 nm; no seed

In order to further improve the stability of the FEL emission and to reduce the saturation length we also considered seeded operation at 50 nm assuming a seed power in the order of tens of kW. The peak power as a function of the undulator length for the FEL operation at 50 nm with different seed level is reported in Fig. 6. Operating with a 50 kW seed reduced the gain length from 5.1 m down to 3.8 m.

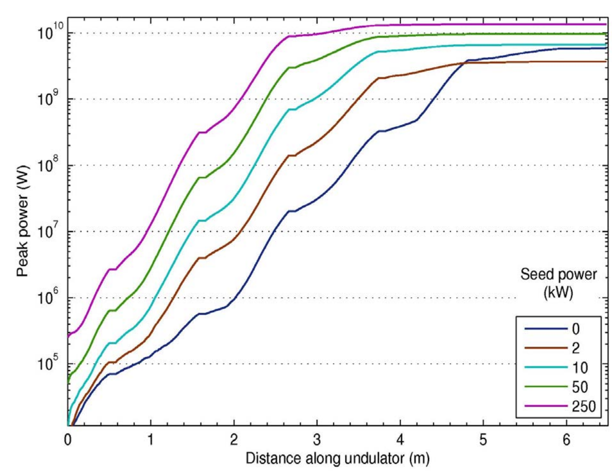

Figure 6: Power vs z for 50 nm operation and different seed level. GENESIS simulation.

Seeded operation can dramatically reduce the saturation length and further improve the temporal coherence of the output field and a higher power, true single spike operation is effectively achieved as shown in Fig. 7.

A constant seed of 50 kW at 50 nm was assumed in the FEL simulation which is possibly available from HHG sources. The implications of the pulsed structure of HHG source in the FEL interaction with an electron bunch which is close to the single spike regime are under investigation.

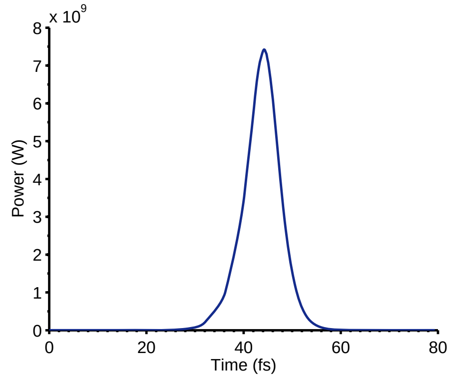

Figure 7: FEL pulse at 50 nm with a 50 kW seed.

LPWA DIAGNOSTICS

A good understanding of the electron beam properties is critical in order to achieve the required brightness and to be able to reproduce it from run to run. With this respect a significant effort has been put in the development of diagnostics for electron beams with the emittance, bunch length and stability characteristics such as those delivered by the present LPWAs.

Our group has successfully tested Optical Transition Radiation (OTR) monitors at a LPWA. OTR monitors can be used to extract the beam transverse profile, the beam energy, the beam charge and its divergence. OTR monitors have the advantage over phosphor screens or medical (lanex) screens in that they can be made out of a thin aluminium foil and thus minimize the scattering of the beam. Two retractable OTR monitors positioned before and after the spectrometer can significantly improve the resolution on the beam energy and energy spread. A spectrometer magnet will be used as an alternative measurement of the electron beam energy.

Knowledge of the electron bunch duration is crucial for establishing the peak current, and thus the FEL performance. We propose to use Smith-Purcell (SP) radiation to determine not only the duration but also the temporal profile of the fs-long electron bunches of OPALS. SP radiation is produced by the interaction of a charged particle beam and a nearby periodic metallic structure (grating) The use of SP radiation to measure the longitudinal size and profile of an electron bunch has been demonstrated over a wide range of energies [12-13] covering the energies achieved at LPWA. Although this technique has been demonstrated for picoseconds bunches its extension to the 10 fs range is foreseen at OPALS. Another potential bunch length measurement technique is coherent transition radiation: either in the terahertz spectrum from the plasma-vacuum interface [14]; or in the visible from a thin foil (as with OTR above) [15]. As with Smith-Purcell radiation, the spectral distribution of the coherent radiation can be used to non-destructively determine the bunch duration, and can also be used to deduce the longitudinal structure.

To date there is no single-shot technique for the measurement of the emittance of a beam having an energy of a few hundred MeV and above. However we have used Geant4 to simulate a modified design of “pepper-pots”. Our simulations indicate that such design could be used to measure the emittance of OPALS at 400 MeV.

CONCLUSIONS

Electron beams from laser plasma accelerators present exciting opportunities. They offer a combination of high energy with low transverse and longitudinal emittance making them suitable for driving compact free electron lasers at the XUV and soft X-ray wavelength. Significant advances in pointing stability and mean energy are still required to make radiation sources driven by these beam a viable solution. Assuming a moderate projection of the present LPWAs capabilities, we have presented the project of a possible FEL source driven by an LPWA that can deliver GWs ultrashort soft X-ray pulses achieving saturation within distances of the order of 10 m, suitable to be hosted in Universities or industrial laboratories.

Lastly, we would like to acknowledge the contribution of C. Mansell in carrying out the beam dynamics simulation with CSR-track.

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