# RADIATION FROM A LASER-PLASMA ACCELERATED ELECTRON BEAM PASSING THROUGH AN UNDULATOR

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### *Abstract*

In the quest for ultra-compact sources, a test experiment is under preparation, to couple an electron beam from a laser driven plasma accelerator, stable and tunable in energy, to an undulator. The electron beam is generated in the colliding laser pulses scheme, by focusing two short and intense laser pulses in an underdense plasma plume. The electron bunch has an energy tunable in the range $100 - 300MeV$ with $1\%$ energy spread, a length $10fs$, a charge in the $10pC$ range, while its radius and divergence are respectively $1\mu m$ and $3mrad$. As a first step toward a FEL experiment, the transport and radiation through an undulator of this short and compact electron beam is studied. Numerical predictions for the spontaneous emission through an undulator in the $40-120nm$ range is presented.

## INTRODUCTION

The interaction between light pulses and rarefied matter (e.g., electrons, atoms or plasmas) may result in a net energy transfer and, as a consequence, in the amplification of an optical wave or in the acceleration of charged particles. The first process is at the base of Free-Electron Lasers (FELs), the next-generation light sources on which relies the extension of the spectral range of conventional lasers down to X-rays. Such sources have so far been implemented on conventional particle accelerators, their use ranging from fundamental research to medical and industrial applications. Much interest is also forseen in applying FEL on a plasma-based accelerator.

Over the last few years, a strong need has emerged for a source of radiation in the VUV spectral range with high brilliance, close-to-full coherence, variable polarization, bandwidth approaching the transform limit and stable temporal structure in the femtosecond time scale. The investigation realm opened by such a new source would cover all basic science fields, giving access to studies of matter in practically unexplored regimes. Nowadays, the possibility to realize a source with all the above mentioned characteristics relies on single-pass FELs. In a FEL, the light is generated when a relativistic electron beam passes through the static and periodic magnetic field produced by an undulator.

The size of conventional accelerators has to be very large both in case of linear and circular acceleration. In fact, the maximum permissible accelerating electric field must be below the material breakdown threshold, which is typically of the order of tens of MV/m. This breakdown limitation does not apply to plasmas, that are therefore regarded as the ideal medium in which charged particles can be accelerated by means of electric fields that are orders of magnitudes higher than the ones of conventional accelerators [1]. After the first pioneering experiments on plasma accelerators carried out in the early eighties, impressive progress in this field is being achieved today, following the advent of the ultra-short pulse lasers. Parallel to the experimental activity in this field, theoretical and experimental activity has been developed achieving more and more encouraging results concerning the energy and the quality of electron beam produced by laser-driven acceleration mechanisms [2, 3, 4, 5, 6, 7, 8]. Thus, developping compact sources of high-energy electrons from plasmas may be a crucial step toward a new generation of compact FELs [9, 10].

In this paper, we describe an experiment under preparation at Laboratoire d'Optique Appliquée (LOA) to make a plasma-accelerated electron beam radiate through an undulator. In a first step, we intend to characterize the spontaneous emission radiated by a plasma-based accelerated electron beam in an existing undulator. We expect that these first results provide us a better knowledge of the components of the experiment, allowing us to design further adapted equipment for being able to observe amplification of the radiation. The effect of the energy spread and the focusing configurations of the quadrupoles are investigated. Then, the spontaneous emission is characterized through simulations with the Synchrotron Radiation Workshop (SRW) [11].

## GENERAL LAYOUT

### *Plasma-acceleration Configuration*

In the laser plasma electron accelerator, the longitudinal accelerating electric field is generated by the ponderomotive force of an ultra-short and very intense laser, which pushes the plasma electrons out of the laser path and separates them from the ions. A travelling longitudinal electric field with an amplitude of several hundreds $GV/m$ is thus created in the wake of the laser beam with a phase velocity close to the speed of light, in a length given by the plasma wavelength, typically $10-30\mu m$. For being trapped and accelerated, the electrons should be injected with a sufficient initial energy.

Experimentally, at LOA, the scheme employs two counter-propagating ultra-short pulses with identical wavelength and polarisation. The so-called "pump" laser creates the wakefield in which the "injection" introduces the electrons. A preacceleration is provided via the beating between the two lasers. Such a scheme enables to tune the electron beam energy, with quasi-monoenergetic distributions. Typical characteristics of the electron beam foreseen for this experiment are listed in Tab.1.

## *Electrons Transport*

Since the electron beam is strongly divergent ($\sim 3mrad$) at the exit of the plasma source (see Fig.1), it must be focused inside the existing undulator by means of three high-gradient quadrupoles (delivering a focusing/defocusing field of up to $100T/m$ over $10cm$ each). The strengths of the quadrupoles were tuned so that the beam is focused at the center of the undulator, located at $4.5m$ from the plasma source (see Fig.2). They are located as close as possible to the plasma source. This configuration guarantees that the electron beam will stay confined inside the undulator over all the undulator length (see next paragraph for the undulator characteristics).

Simulations with TraceWin [12] and Beta [13] were cross-checked for the transport. They exhibit a large degradation in the emittance of roughly a factor 10. Degradations are mainly induced by the chromatic effects of the quadrupoles, due to the large energy spread $\sigma_\gamma/\gamma$, together with large quadrupole gradient and large $\beta$-functions. Different configurations for the quadrupoles locations have been investigated, revealing that the closer the quadrupoles to the source, together with lower energy spread, the smaller the increase in emittance is.

In parallel, the bunch length also increases from 10 to $50fs$ due to its large divergence. The different focusing configurations of the quadrupoles were chosen to yield different bunch lengths inside the undulator.

Table 1: Characteristics of the electron beam produced by the plasma-acceleration process (RMS values): $\gamma_{e-}$ is their mean energy, $\sigma_\gamma/\gamma$ their relative energy spread, $\sigma_t$ its longitudinal length (along the propagation axis), $(\sigma_{x,y}, \sigma_{x',y'}, \epsilon_{x,y})$ its horizontal/vertical (transverse) size, divergence and emittance respectively.

| $\gamma_{e-}$ $[MeV]$ | $\sigma_\gamma/\gamma$ $[\%]$ | $\sigma_t$ $[fs]$ | $\sigma_{x,y}$ $[\mu m]$ | $\sigma_{x',y'}$ $[mrad]$ | $\epsilon_{x,y}$ $[mm.mrad]$ | $q$ $[pC]$ |
|---|---|---|---|---|---|---|
| $100-300$ | $\sim 1$ | $\sim 10$ | $1\times 1$ | $3\times 3$ | 0.67 | 10 |

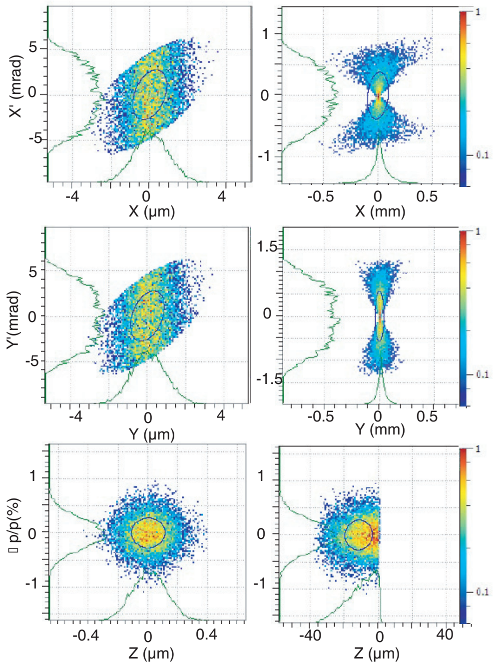

Figure 1: Electron beam phase space (respectively horizontal, vertical and longitudinal from top to bottom) at the exit of the plasma source (left) and after the transport through the quadrupoles (right), from simulations with TraceWin. Resulting emittance of $10.56mm.mrad$ horizontally and $6.86mm.mrad$ vertically at the center of the undulator. Electrons of $150MeV$ were considered.

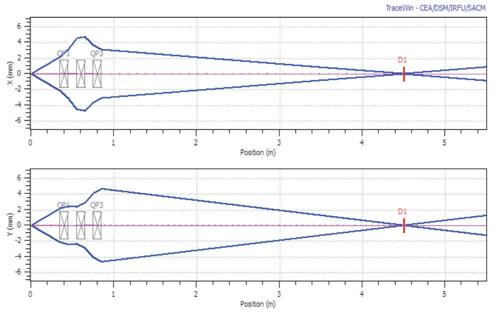

Figure 2: Electron beam horizontal (top) and vertical (down) envelops during the transport.

## *Undulator MONA*

The MONA undulator [14] is a $62cm$-long in-vacuum undulator, with 34 periods of $18mm$. It was once designed for the ELSA FEL in CEA-DAM [15], which emitted in the $18-40\mu m$ range. The minimum gap is $4mm$, for which the magnetic field is $0.6T$. For our experiment, the measurement of the undulator magnetic field was performed anew, using a standart magnetic measurement bench at SOLEIL which comports Hall probes and bodyless coil. The field first integrals of the whole device could be measured directly (as shown on Fig.3), bringing on-axis values of $-1.25Gm$ and $2.05Gm$ for the horizontal and vertical

Table 2: Characteristics of the $150MeV$ electron beam at the center of the undulator, after focusing by the three quadrupoles. Two different values of energy spread are considered. For each value, three configurations of focusing are considered, which lead to different bunch lengths.

| Case | $\sigma_z$ $[\mu m]$ | $\sigma_\gamma/\gamma$ $[\%]$ | $\epsilon_x$ $[mm.mrad]$ | $\epsilon_y$ $[mm.mrad]$ |
|---|---|---|---|---|
| 1 | 8.6 | 0.1 | 1.2 | 0.9 |
| 2 | 12.6 | 0.1 | 1.8 | 1.4 |
| 3 | 18.3 | 0.1 | 1.8 | 1.7 |
| 4 | 4.1 | 1 | 5 | 3 |
| 5 | 8.1 | 1 | 11 | 7 |
| 6 | 12.5 | 1 | 16 | 11 |

integral fields respectively, which correspond to angular deflexions of $25\mu rad$ and $41\mu rad$ in the vertical and horizontal planes respectively, for an electron beam at $150MeV$. Unfortunately, the Hall probe measurement requires a lateral access, which could not be carried out again on this device.

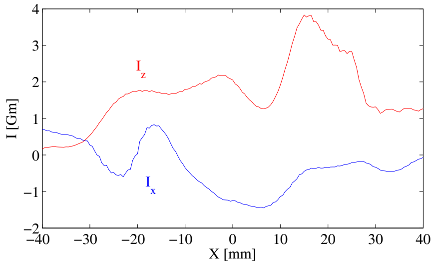

Figure 3: Field integrals of undulator MONA: $I_x$ (resp. $I_z$) stand for the integral of the horizontal (resp. vertical) magnetic field along the undulator length.

## RADIATION

Different diagnostics are being prepared such as screens for visualizing the electron beam along the transport, or a VUV monochromator which is currently available, since the undulator emission will be in the $30-150nm$ range.

Presently, the spontaneous emission of the electron beam through the MONA undulator is simulated with SRW [11] for two values of energy spread ($0.1\%$ and $1\%$). Whereas in the case of a low energy spread ($0.1\%$), the radiation of up to harmonic $5$ may be observable (see Fig.4), it may only be possible to observe the three first harmonics if the energy spread reaches $1\%$ (see Fig.5). The disappearance of this harmonic radiation (emitted on a large bandwidth) makes the energy spread a critical parameter for such an experiment. Nonetheless, in the cases of $0.1\%$ and $1\%$ energy spread, it appears that the focusing choice, and so the bunch length, has little effect on the spontaneous emission spectra. This issue is not critical here, yet it should be relevant in the case of coherent synchrotron radiation.

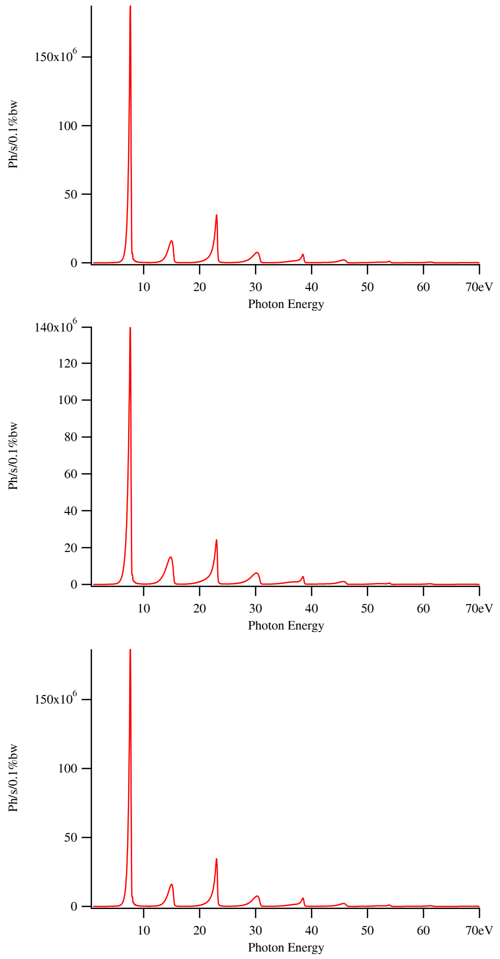

Figure 4: Spectra radiated in MONA for Cases 1 to 3 from top to bottom (see Tab.2), as simulated by SRW. The energy spread is $0.1\%$. The radiation is observed through a $10\mu m \times 100\mu m$ (hor. × vert.) pinhole placed one meter after the end of the undulator.

Finally, in order to observe if coherent amplification could be obtained from such an experiment, simulations with the GENESIS code [16] were carried. They show that the increase of radiated power is linear in the undulator (see Fig.6 for the $0.1\%$ energy spread case; the $1\%$ energy spread case yield similar results). This demonstrates that only spontaneous emission is present in such a configuration.

## CONCLUSION AND PERSPECTIVES

We presented a configuration of radiation of plasma-accelerated electron beam in a short undulator, from the source to the observation pinhole. The numerical simulations suggest that the observation of the first radiated harmonics will be possible. An extension of this work is the possibility of seeding the electron-undulator interaction, in order to reach coherent amplification in such a short undulator, which would represent one more step toward com-

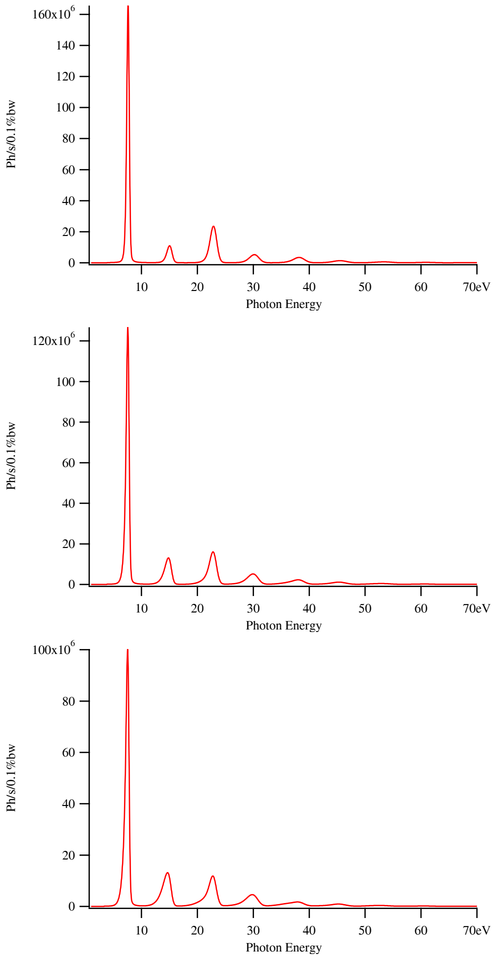

Figure 5: Spectra radiated in MONA for Cases 4 to 6 from top to bottom (see Tab.2), as simulated by SRW. The energy spread is $1\%$. The radiation is observed through a $10\mu m \times 100\mu m$ (hor. × vert.) pinhole placed one meter after the end of the undulator.

pact FELs. Another direction will consist in upgrading the components of the experiment by purchasing smaller quadrupoles or dedicated undulators for the observation of SASE.

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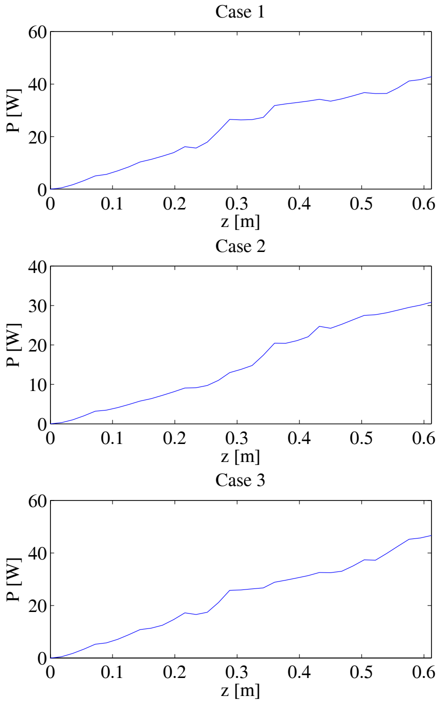

Figure 6: Power radiated along the undulator for Cases 1-3 (at $0.1\%$ energy spread).

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