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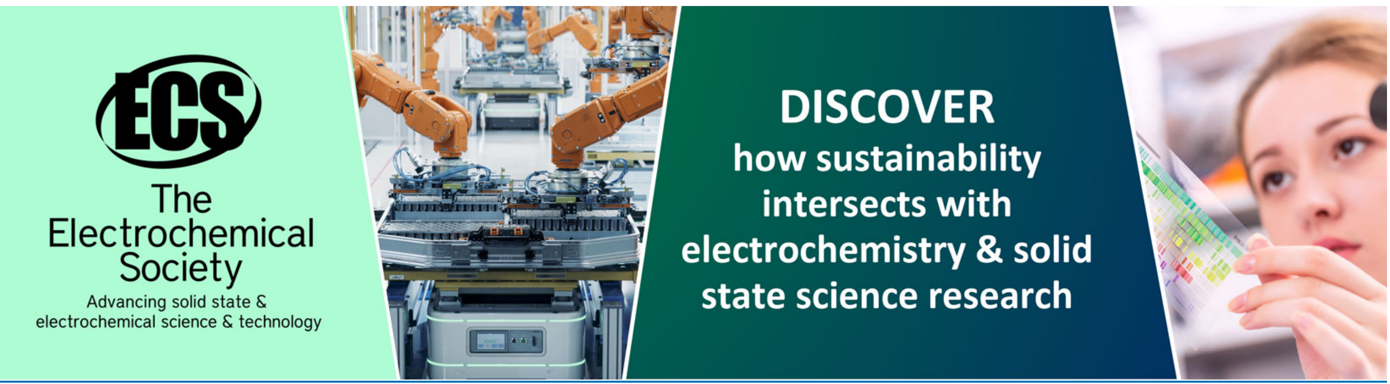

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# A start to end simulation of the laser plasma wakefield acceleration experiment at ESCULAP

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**Abstract.** We present a start to end (s2e) simulation of the Laser-plasma Wakefield Accelerator (LPWA) foreseen as the ESCULAP project. We use a photo injector to produce a 5 MeV 10 pC electron bunch with a duration of $\sim$ 1 ps RMS, it is boosted to 10 MeV by a S-band cavity and then compressed to 74 fs RMS (30 fs FWHM) by a magnetic compression chicane (dogleg). After the dogleg, a quadrupole doublet and a triplet are utilized to match the Twiss parameters before injecting into the subsequent plasma wakefield. A 40 TW laser is used to excite plasma wakefield in the 10 cm plasma cell. An optimized configuration has been determined yielding at the plasma exit an electron beam at 180 MeV with energy spread of $\sim$ 4.2%, an angular divergence of 0.6 mrad and a duration of 4 fs.

## 1. Introduction

The ESCULAP [1] project aims to combine the RF photo injector PHIL[2] and the 40 TW Laser LASERIX[3] to perform researches on external injection wakefield acceleration. A preliminary configuration optimized through a start to end simulation is presented in this paper, optimization procedure having addressed more specifically the longitudinal compression of the electron bunch before the plasma, and the interaction between the electron bunch and the plasma wave. The main objective of this optimization is to get an electron beam with an energy gain larger than 100 MeV together with low dispersion in position and momentum.

In order to get an optimized coupling between the electron bunch and the plasma wave, the initial transverse and longitudinal sizes of the bunch have to be much smaller than the plasma wave ones. For a given laser intensity, the accelerating field in the plasma increases, whereas the duration of the plasma wave period decreases, with the plasma density. In our conditions, a good compromise is reached at densities around few $10^{17}/\mathrm{cm}^3$, at which the plasma period is of few hundreds of fs. At the exit of PHIL the electron bunch has a duration of $\sim$1 ps, therefore a compression factor larger than ten is required. This can be done through ballistic bunching and magnetic compression as discussed in the next section.

In the considered density regime, non-linear effects are limited, so that the laser intensity inside the plasma is similar to the one in vacuum. An important consequence is that the transverse size of the plasma wave is given by the laser one. The accelerating field increases with the laser intensity, which is inversely proportional to its waist. Again a compromise has to be found for the laser focusing configuration to get a plasma wave having the largest transverse size together with a high accelerating field. Taking into account the properties of the LASERIX laser and the density range, it is found that a waist at the focal plane of around 50 m can yield an energy gain of 100 MeV/cm close to the focal plane, with an efficient acceleration length given by the Rayleigh length, in the range of cm. Therefore, in the present study we fix the laser focusing system to get a Rayleigh length of one cm. Having fixed the laser focusing configuration and the target density, there are still three parameters to be optimized: the target length, the laser focal plane position and the delay between the laser and the electron beam.

Considering the target length, previous calculations [?] have shown that one should use a target length much larger than the Rayleigh one. Starting the electron-plasma interaction well before the focal length allows to get a large waist in order to trap the largest percentage of electrons and also to focalize and compress further the electron bunch before the main acceleration process. In addition, to continue the interaction process after the focal plane region allows to refocus the electron bunch.Thus in the presented configuration, we use a target with a fixed length of 10 cm, which is $\sim 10$ times the Rayleigh length. In order to get a realistic results, the longitudinal density profile has been determined through hydrodynamic calculations. In the second section, we present our simulation results on the e-beam properties at several densities and for the optimal values of the laser focal plane position and of the delay between the laser and the electron beam.

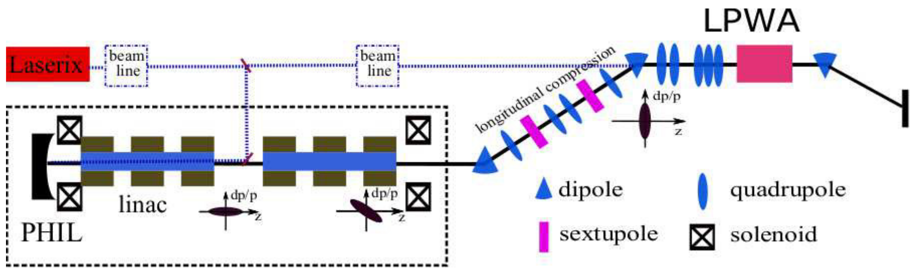


**Figure 1.** Schematic of ESCULAP.

## 2. Bunch compression and matching before the plasma cell

The electron bunch at the exit of PHIL has an energy of $\sim$5 MeV, with a duration of $\sim$1 ps, and there will be a S-band booster which will accelerate the bunch to $\sim$10 MeV. In such scheme, magnetic chicane as well as ballistic bunching can be used to compress the bunch.

In ballistic bunching, the RF curvature which introduces higher order correlation in the phase space, is the key point that limits the shortest bunch length achievable. In general, a higher harmonic RF cavity working at the decelerating phase is used to linearize the phase space, but a separate and costly RF system is required. The 'stretched mode' ballistic bunching is studied in ref [5, 6], where a S-band gun and a S-band RF booster are used to linearize the phase space, so that RF curvature can be compensated up to the 3rd order with the booster working at decelerating phase. Using this technic, in our case, an electron bunch of 10 pC can be compressed to $\sim$60 fs RMS after a drift space.

However, with ballistic bunching there is no increase in the average energy. In our case, the coupling between the electrons and the plasma wave is favoured by higher energies, that is why the RF booster is set to an accelerating phase, whereas an additional compression is introduced through a dogleg chicane, as shown in Figure 1. In this scheme, four quadrupoles are used to match the $R_{16}$ and $R_{26}$ to zero, which denote the emittance growth, and a pair of sextupoles are used to compensate the second order terms $T_{566}, T_{166}, T_{266}$, beam dynamics is studied using Impact-T [7].

Using this scheme, the electron bunch can be compressed to 30 fs FWHM, with a peak current of ∼200 A. The dogleg chicane design studies are presented in more details in [8]. The obtained bunch length versus RF phase jitter is shown in Figure 2. The phase where the minimum RMS value is achieved is referred to as 0°, the minimum FWHM value is achieved at 1.5°. After compression, the distribution of the electron bunch has a sharp peak and a long tail. Considering that the RF-laser phase stability in PHIL is better than ±1°, the reference phase is set to 1°, the obtained optimal distribution is shown in Figure 3.

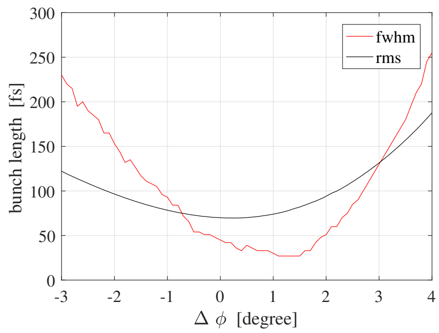


**Figure 2.** Bunch length versus phase jitter.

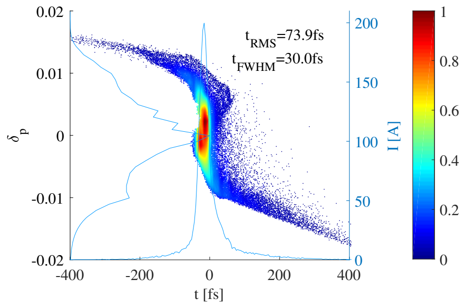


**Figure 3.** A 10 MeV 10 pC electron bunch compressed with the dogleg chicane.

After the dogleg a quadrupole doublet and a triplet are used to match the Twiss parameters to the plasma, the obtained values are $\alpha_x = \alpha_y = 0$, $\beta_x = \beta_y = 0.01$, this work is detailed in [8].

## 3. Acceleration in the plasma cell

The longitudinal gas density profile in the plasma cell has been determined with hydrodynamic calculations within the Laminar flow model. The obtained on-axis density profile is shown in Figure 4, with $n_0$ being the nominal plasma density. The laser properties of the LASERIX system can be found in [3], the wavelength is $\lambda = 0.8$ µm, the maximum energy is 2 J with a FWHM duration of 45 fs, the laser profile is assumed to have a Gaussian distribution in both longitudinal and transverse dimensions, leading to a maximum power of 41 TW. In our configuration, the focal length is set to 4.95 m, so that the laser waist at focal plane is 50.5 µm, with a Rayleigh length of one cm. The generated plasma wakefield was calculated by the code WAKE-EP, while the beam-electrons dynamics are studied by the code WakeTraj, details can be found in [4].

In the plasma wave, the phase difference between the longitudinal and the transverse electric field is $\pi/2$, thus there is a phase region of the wakefield of width $\pi/4$ for which a relativistic

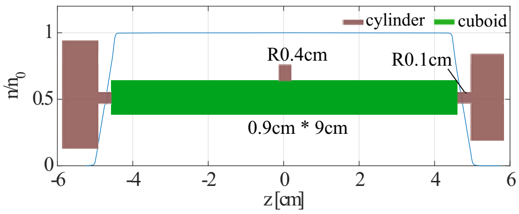


**Figure 4.** Schematic of the plasma cell and the on-axis density profile along the cell.

electron will experience simultaneous axial accelerating and radial focusing forces. To get efficient acceleration, it is of vital important to take into account the phase evolution between the plasma wave and the electron bunch.

In standard schemes of Laser Wake Field Acceleration (LWFA), the electrons are injected at energies $> 100$ MeV, at which the electron velocities are higher than the laser group velocity in the plasma. Here we consider much lower initial velocities. The Lorentz factor of the 10 MeV electron bunch is $\gamma_e \approx 19.6$, while that of the plasma wave is $\gamma_g = 93$, at $n_0 = 2 \times 10^{17}/\text{cm}^3$. Considering that the relative velocity between the electrons and the plasma wave is given by $1/2\gamma_g^2 - 1/2\gamma_e^2$, the dephasing length is much shorter than in standard situations. In our conditions, the initial dephasing length at E $=$ 10 MeV, is close to the Rayleigh length. It means that the focusing domain, between the entrance of the plasma and the laser focal plane can be used to optimize the evolution of the phase space distribution of the electron beam. This phenomena has been tracked by the WakeTraj numerical code for various laser focal plane positions and electron injection phase, at plasma densities of $n_0$ of $1.5, 2.0, 2.5 \times 10^{17}/\text{cm}^3$. An optimal case at a density of $2 \times 10^{17}/\text{cm}^3$ is reported in Figure 5, at the plasma exit. We can observe in this figure that during the focusing phase, the main part of the electrons have slipped up to the back of the first plasma bucket, where the accelerating field is maximum and its derivative is minimum, yielding to a high average energy with a minimum energy spread. We notice also that a small part of the electrons have been trapped in the second plasma bucket. In our case, the main bunch contains more than 95% of the accelerated electrons.

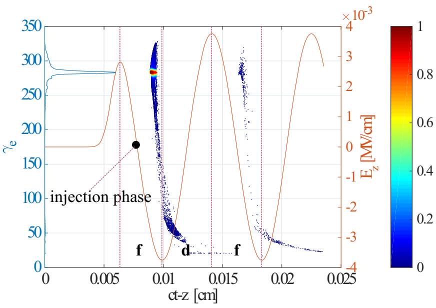


**Figure 5.** The electron distribution at the plasma ($2 \times 10^{17}/\text{cm}^3$) exit. The longitudinal electric field is from 0.6cm of plasma exit, is only used to show the optimal injection phase (near the solid circle) and phase slip process.

Main characteristics of the results obtained in the optimal configuration for a bunch charge of 10 pC and for different plasma densities are summarized in Table 1. We can observe in this table the general trend of an increase in energy with a plasma density, compensated by a reduction of the trapped electron percentage, which is still above 68%.

It is shown in Figure 6 the evolution of the average energy of the electron beam during propagation, for a plasma density of $2 \times 10^{17}/\text{cm}^3$ and a laser focal plane at 4.5 cm after the plasma entrance. It is clearly seen that the main acceleration process occurs at the focal position

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**Table 1.** Optimal results at various plasma densities.

| $\rho$ [/cm$^3$] | $\langle\gamma\rangle >$ | Q [pC] | $\sigma_\delta$ | $\epsilon_{nx}$ [µm] | $\epsilon_{ny}$ [µm] |
|---|---|---|---|---|---|
| $1.5\times10^{17}$ | 197.76 | 8.01 | 5.62% | 1.64 | 3.01 |
| $2.0\times10^{17}$ | 269.67 | 7.89 | 4.58% | 1.82 | 3.16 |
| $2.5\times10^{17}$ | 355.17 | 6.88 | 4.18% | 2.10 | 3.39 |

+/- the Rayleigh length. Before these positions, the acceleration is small, but large enough to lead to a longitudinal compression. At larger positions, the transverse field remains active to reduce the electron beam divergence.

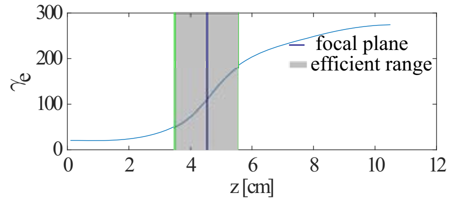


**Figure 6.** Energy gain along the plasma cell with a density $2\times10^{17}/\text{cm}^3$, the efficient acceleration range is within one Rayleigh length of the laser focal plane.

The energy distribution of the electrons at spectrometer position is shown in Figure 7. At the exit of the plasma cell, the electron bunch has an angular divergence of ∼0.6 mrad, with a duration of ∼4 fs. Note also that, as seen from Table 1, the increase of the emittance during the acceleration process is limited, the emittance at plasma entrance being $\epsilon_{x0} = 1.7\,\mu\text{m}$, $\epsilon_{y0} = 1.9\,\mu\text{m}$.

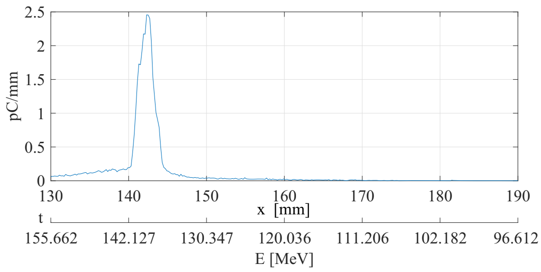


**Figure 7.** Particle distribution after spectrometer.

## 4. Conclusion

External injection of an electron beam in a plasma wave has been numerically studied within the ESCULAP project by a start to end numerical simulation. We show that the electron bunch can be compressed with a magnetic chicane up to 30 fs, in order to be efficiently coupled to a plasma wave generated by the high intensity laser LASERIX in a gas cell. By optimizing the laser-target configuration, we show that the ESCULAP setup will be able to generate an electron beam at energies close to 200 MeV with a dispersion in energy less than 5 % and a small angular divergence. Higher energies will be accessible through guiding of the laser beam. This will be the subject of future investigation.

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