Laser plasma accelerators: principle, status and applications

V. Malka[1]

[1] *Laboratoire d'Optique Appliquée, ENSTA- CNRS - Ecole Polytechnique, France*
Email : victor.malka@ensta.fr

Compact accelerators based on laser plasma cavities that support hundreds of GV/m electric field deliver today electron beam with unique parameters. Quasi mono-energetic electron beams have been produced in the bubble regime by focusing intense laser beam in under-dense plasma targets. Stable and quasi mono-energetic electron beams have been demonstrated by colliding two laser pulses in under-dense plasma. This last approach is very promising because of the stability of the electron beams and the easy control of their parameters. The very high brightness and shortness (fs) make them very attractive for many applications.

1. Bubble regime

Based on 3D PIC simulations, A. Pukhov and J. Meyer-Ter-Vehn have predicted a very promising acceleration regime, called the bubble regime [1] that has been demonstrated from final quasi-monoenergetic distribution of the accelerated electrons. At lower laser intensity, such electron distributions can also be obtained in the blow-out regime [2]. In both regimes, the focused laser energy is concentrated in a very small sphere, of radius of about the plasma wavelength.

The associated very strong ponderomotive force expels radially electrons from the plasma, forming a positively charged cavity behind the laser, surrounded by a dense region of electrons. As the electrons flow along the cavity boundary and collide at the bubble base, transverse wave breaking occurs providing a well-localized region of injection in the cavity. In such scheme, the injection is well localized at the back of the cavity and all the injected electrons have similar initial properties in the phase space.

The generation of a quasi-monoenergetic electron beam is due to the fact that this injection occurs for a limited duration. After injection, the trapping stops automatically when the charge contained in the cavity compensates for the ionic charge, which screens the accelerating field of the bubble [3]. The spectral width of the electron beam is also reduced by the rotation in the phase-space.

Compared to other acceleration mechanisms, the fact that electrons are trapped behind the laser, where they no more interact with the laser field, contributes also to improve the quality of the electron beam as it demonstrated in the forced laser wakefield [4].

The scheme of principle of the bubble/blowout regime is illustrated in Fig. 1.

2. Colliding pulses Scheme

After the discovery of the bubble regime, a strong pressure from the accelerator comunity, pushes us to demonstrate a more stable scheme. In its simplest form, the colliding scheme uses two counter-propagating ultra-short pulses with the same wavelength and polarisation (see fig. 1).

The first laser pulse, the ‘pump’ pulse, creates a wakefield whereas the second laser, the ‘injection’ pulse, is only used for injecting electrons in this wakefield. The laser pulses collide in the plasma and their interference creates an electromagnetic beatwave pattern, which heats or pre-accelerates some electrons.

Those that have enough energy are trapped in the wakefield driven by the pump pulse and further accelerated to relativistic energies. This scheme that requires two laser pulses offers more flexibility: experiments have shown that the electron beam energy can be tuned continuously from 10 to 250 MeV [5].

Importantly it was shown that the colliding pulse approach allows the control of the electron beam energy, which is done simply by changing the delay between the two laser pulses. The robustness of this scheme permitted also to carry out very accurate studies of the dynamics of the electric field in presence of a high current electron beam. Indeed, in addition to the wakefield produced by the laser pulse, a high current electron beam can also drive its own wakefield. This beam loading effect was used to reduce the relative energy spread of the electron beam.

It was demonstrated that there is an optimal load which flattened the electric field, leading to the acceleration of all the electrons with the same value of the field, and producing consequently an electron beam with a very small, 1%, relative energy spread [6].

Thanks to the beam loading effect, the most energetic electrons can be slightly slowed down and accelerated to the same energy as the slowest one. In case of low charge beam, this effect does not play any role and the energy spread depends mainly on the heated volume.

For very high current, the load is too high and the most energetic electrons slow down so much that they eventually get energies smaller than the slowest electrons, increasing the relative energy spread. The existence of an optimal load was observed experimentally and supported by full 3D PIC simulations, it corresponds to a peak current in the 20-40 kA range [7].

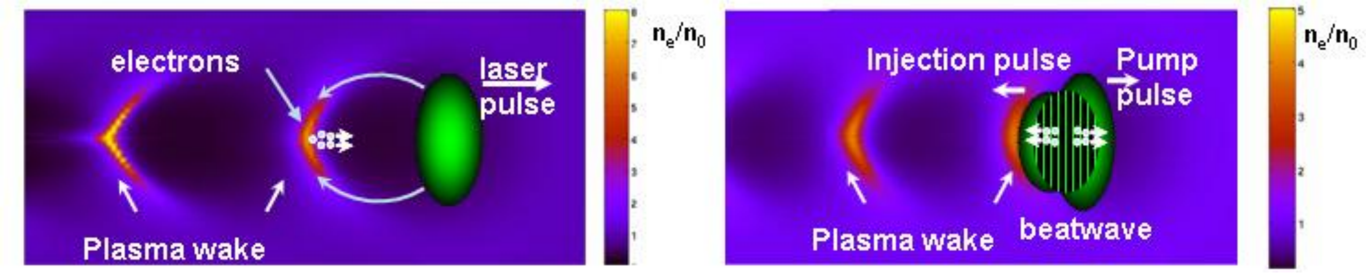

Figure 1 : On left, the bubble regime, the laser pulse that propagates from left to right, expels electrons on his path, forming a positively charged cavity. As the radially expelled electrons flow along the cavity boundary and collide at the bubble base, before being accelerated behind the laser pulse. On right, the colliding pulses injection : the two laser pulses propagate in opposite direction and collide producing a beating pattern that heat electrons that get enough longitudinal momentum to be trapped by the relativistic plasma wave driven by the pump beam

3. Conclusion

Other injection schemes [8] allow the electrons injection control by using a high Z gas and/or a high Z-low Z gas mixture, or for example by using a density gradient. Thanks to the large differences in ionization potentials between successive ionization states of the atoms, a single laser pulse can ionize the low energy level electrons in its leading edge, drive relativistic plasma waves, and inject in the wakefield the inner level electrons which are ionized when the laser intensity is close to its maximum. In the density gradient like in that in the longitudinal injection [9] the increase of the plasma wavelength facilitate the trapping and allow with one single laser beam the production of stable electron beam.

The evolution of short-pulse laser technology, a field in rapid progress, will likely contribute to the improvement of laser plasma acceleration and help to the development of societal applications [10], in material science for example for high resolution gamma radiography, in medicine for cancer treatment, in chemistry and in radiobiology.

4. References

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