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ACCELERATOR PHYSICS CHALLENGES TOWARDS A PLASMA ACCELERATOR WITH USABLE BEAM QUALITY

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Abstract

Enormous progress in compact plasma accelerators has been demonstrated over the recent years in various experiments. These experiments rely on high power pulsed lasers or short electron bunches to excite ultra-strong wakefields in plasmas. Accelerating gradients have reached several 10 GV/m up to 100 GV/m and the achieved gain in electron energy ranges from several GeV to 42 GeV for the different methods. The principle and potential of plasma accelerators have been proven and its performance is steadily improving. Particle accelerators are powerful tools that are ultimately justified by their applications in science, medicine or industry. The demonstration of useable beam quality remains to be achieved for plasma accelerators. The accelerator physics challenges to arrive at this goal are analysed and discussed.

PLASMA ACCELERATION

The concept of plasma acceleration emerged in the canonical paper by Tajima and Dawson in 1979 [1], that showed that accelerating gradients in plasmas can be 3–4 orders of magnitude higher than in conventional accelerators. The principle is illustrated in Fig. 1. The plasma response to a short laser pulse is as follows:

- The laser pulse enters the plasma and transversely accelerates plasma electrons (ponderomotive force as transverse driving force). The plasma ions move a negligible amount.
- Along the laser path a positively charged ion channel is formed.
- Once the laser pulse has passed, the plasma electrons rush back in, attracted by the ion channel (transverse restoring force).
- The electrons pass the centre of the ion channel, rush back out and are attracted back by the ion channel. A space charge driven oscillation has formed.
- Alternating regions of negative and positive net charge form behind the laser pulse. Longitudinal fields are induced ("plasma wakefields").

If a short electron bunch is placed (by means of external or self-injection) behind the laser pulse in a proper distance, then this electron beam will be accelerated with high gradient. The process is limited by (a) depletion of laser power, (b) dephasing between the relativistic electron bunch and wakefield, and (c) the Rayleigh length of the laser beam. The Rayleigh limit can be counteracted by self-guiding or external guiding of the laser in a plasma channel [2]. A similar concept has been proposed in 1985 for plasma wakefields driven by short electron bunches [3]. The Livingston curve of conventional and plasma acceleration is shown in Fig. 2.

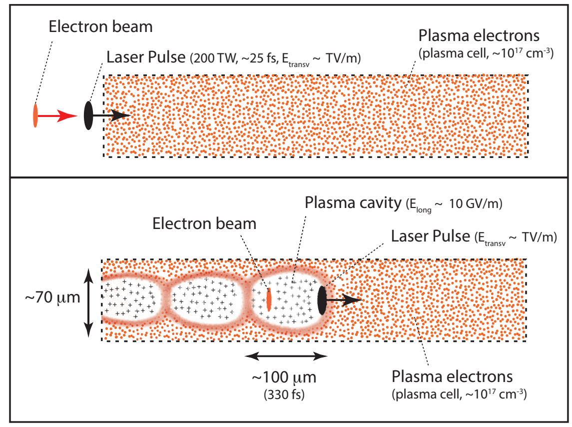

Figure 1: Illustration of laser-induced plasma wakefield acceleration with injection of an external electron beam. The red dots represent mobile plasma electrons, the black crosses the stationary ions. Ions are not shown in the regions of unperturbed plasma electrons. The listed parameters refer to an example case of a 200 TW laser exciting a wake in a plasma of 10^{17} cm^{-3} density.

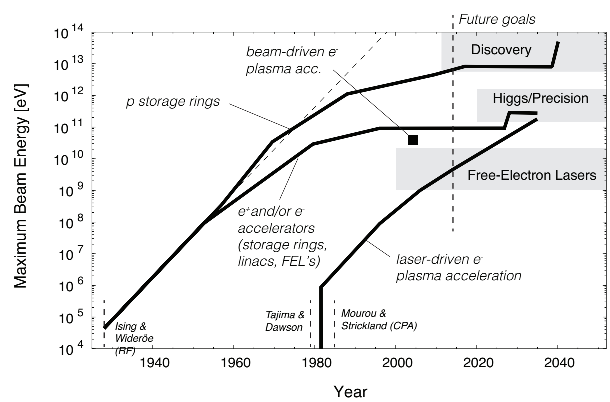

Figure 2: Livingston curve for accelerators, showing the maximum reach in beam energy for different technologies versus year. Grey bands visualize accelerator applications in science. Data beyond 2014 indicate goals for the various technologies.

Laser plasma accelerators have seen a steep increase in energy reach since the invention of compression of amplified chirped optical pulses (CPA) [4]. Laser plasma acceleration experiments have recently produced multi GeV electron bunches in several cm's of plasma [5, 6, 7] with the record beam energy reported to be 4.5 GeV. Beam driven plasma experiments achieved absolute energy gain of 42 GeV with accelerating gradients of up to 53 GV/m over a plasma length of 85 cm [8], however only for parts of the initially injected beam.

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As seen in Fig. 2, the energies achieved in plasma accelerators have reached the region of interest for modern free-electron lasers (FEL). The prospect of an ultra-compact, plasma-based FEL has become intriguing and world-wide research and development (R&D) is presently strongly focussed on this goal [9, 10, 11]. It is noted that no user facilities with GeV class, plasma generated beams could be established in the last 8 years since the GeV regime was reached the first time. The beam quality from plasma accelerators is not yet sufficient for applications with user operation.

ACCELERATOR PHYSICS CHALLENGES

In this paper we focus on challenges arising in laser-driven wakefield acceleration. Laser drivers are presently more compact than electron beam drivers. Two practical regimes can be distinguished:

- The "internal injection regime" where the electron beams are generated internally from plasma electrons that are captured, bunched, focussed and accelerated inside the plasma [12]. Many recent successes in laser driven plasma accelerators come from this technique, which is essentially a plasma-based GeV injector.
- The case of an externally injected electron bunch, as also illustrated in Fig. 1. The plasma here acts as an accelerator and focusing device. This scheme has the potential to be staged, e.g. several similar stages of the same kind can be placed in series, resulting in potentially higher beam energy.

We consider the second case as it provides a stageable technology and less complexity inside the plasma. However, while the plasma dynamics is less complicated, important requirements arise for the dynamics of the injected and extracted electron beam.

Challenge 1: Dimension, Timing, Bunch Length

The processes in a plasma accelerator are to a large extent determined by the plasma density n_0, defined as the density of plasma electrons per volume. This defines the plasma wavelength λ_p and therefore the size of the plasma accelerating structure:

$$\lambda_p \approx 1\,mm \cdot \sqrt{\frac{10^{15}\,cm^{-3}}{n_0}} \quad . \qquad (1)$$

Typical plasma densities range from 10^{14} to 10^{19} cm^{-3}. The typical plasma wavelength then ranges from 3.3 mm all the way down to 10 μm. For a plasma density of 10^{17} cm^{-3} the wavelength would be 0.1 mm. Let's assume an RF phase equivalent tolerance of 10° then the requirement on timing and synchronization is 3 μm (equivalent to 10 fs for a signal or electron traveling with light velocity). This is presently just feasible for synchronization between an RF oscillator and a laser pulse. In addition, the length of the injected bunch should be a small fraction of the plasma wavelength (1 fs for $n_0=10^{17}$ cm^{-3}).

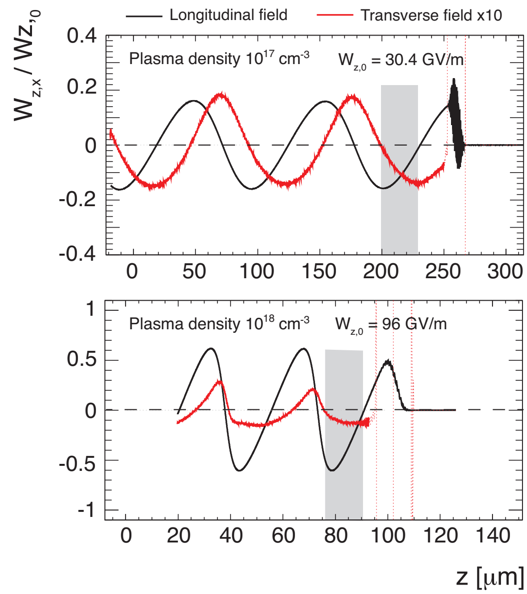

Figure 3: Longitudinal and transverse fields $W_{z,x}$ excited by a 200 TW laser in plasmas of two different densities versus the longitudinal coordinate z (OSIRIS simulation).

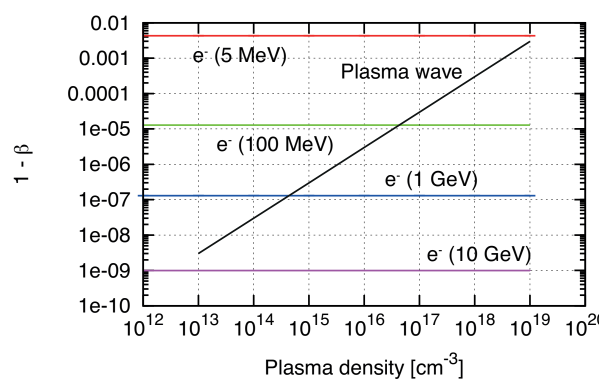

Figure 4: Difference to light velocity versus plasma density for an electron beam (5 MeV, 100 MeV, 1 GeV, 10 GeV) and for the plasma wave phase velocity.

Challenge 2: Acceleration and Phase Slippage

The fields in plasma accelerators can be accurately determined by state-of-the-art theory [13] and computer codes like OSIRIS [14]. A simulation result from the OSIRIS code for longitudinal and transverse fields is shown in Fig. 3. The fields can be estimated by simple formulae. The maximum accelerating field W_z in a plasma accelerator is given as follows:

$$W_z\ (V/m) \approx 96 \cdot \sqrt{\frac{n_0}{(cm^{-3})}} \qquad (2)$$

For a plasma density of 10^{18} cm^{-3} we estimate a gradient of 96 GV/m, three orders of magnitude above the gradients achievable in conventional accelerators.

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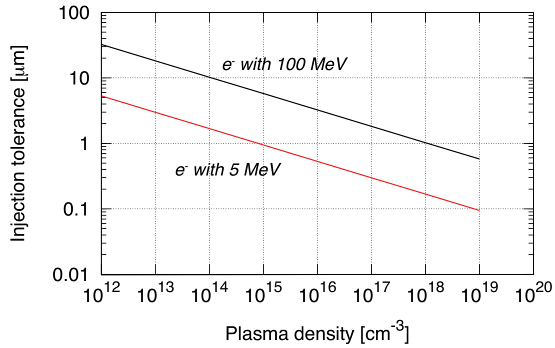

Figure 5: Transverse tolerance (offset laser – beam) for doubling the emittance of an externally injected bunch (100 MeV or 5 MeV) versus plasma density. A full dilution of the betatron oscillation is assumed.

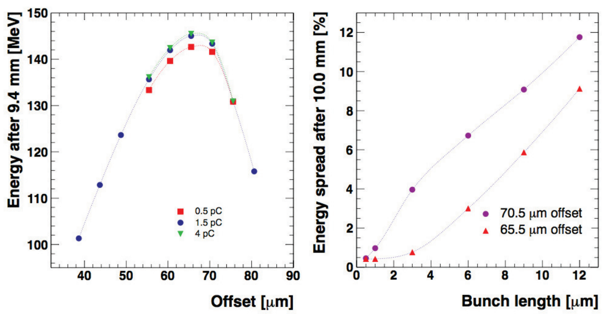

Figure 6: Simulation of externally injected electron beam into plasma of density 10^{17} cm^{-3}. Left: energy of a 100 MeV bunch after 1 cm of plasma versus injection phase offset. Right: energy spread versus injected bunch length. From [18].

The phase velocity of the laser wakefield is a well-known function of the plasma density. The energy of the injected electron beam should be matched. From Fig. 4 we can conclude the injected beam should have 100 MeV to be matched to the plasma wakefield for $n_0=10^{17}$ cm^{-3}.

Challenge 3: Transverse Focusing Fields

Strong transverse fields are generated inside plasma accelerators. The transverse focusing gradients inside the ion channel can reach several 10's of MTesla/m for a plasma density around 10^{18} cm^{-3}. Plasma accelerators must therefore operate in the regime where the beam is accelerated and the transverse fields are focusing [15]. Figure 3 illustrates the useful phase for a linear and non-linear plasma acceleration. The transverse beam dynamics of a plasma accelerator has been described in [16, 17]. It is shown there that the beta-functions (as defined in accelerator physics) that correspond to typical plasma channels range from a couple a cm's for low plasma densities (2 x 10^{14} cm^{-3}) to a few mm for high plasma densities (10^{17} cm^{-3}). Matching in and out of these plasmas becomes a major issue. Transverse injection tolerances, as shown in Fig. 5, are in the range of a few µm and below and become highly demanding.

Challenge 4: Energy Spread

The slope of the accelerating field in plasma accelerators, as shown in Fig. 3 with its useful range, tends to induce large correlated energy spread. The large energy spread couples into the transverse plane, leading to unstable beam, fluctuating emittances and changing beam divergences.

As explained in an earlier section of this paper a bunch length around 1 fs would be well adapted to plasma accelerators of intermediate plasma density. OSIRIS simulations have been performed for a plasma density of 10^{17} cm^{-3}, a plasma length of 1 cm, a 200 TW laser and an externally injected electron bunch [18]. Figure 6 shows that the acceleration seen by the electron bunch in the plasma behaves regularly and an optimal injection phase can be defined. As seen from Fig. 6, the induced energy spread can be reduced with short bunch lengths to about 0.3%. We attribute the flat behaviour of the accelerating voltage to beam loading, as explained in [19, 20]. We expect that this can be optimized further in future work.

CONCLUSION AND OUTLOOK

The case of a laser-driven plasma accelerator with externally injected electron beam has been discussed. This approach offers a reduced complexity inside the plasma, which is used for acceleration and focussing but not for beam generation and bunching. In addition, this approach allows for staging, the placement of several plasma accelerator units in series.

It has been shown that the external electron beam in the considered scenario (plasma density of 10^{17} cm^{-3}) should have beam energy of around 100 MeV. Timing and synchronization should be at the 10 fs level and the length of the injected electron bunch should be around 1 fs. Transverse injection tolerances (beam to laser) of a few µm must be achieved. Last not least, the electron beam should be matched to a beta function of a few mm at the plasma entrance and captured with similar parameters at the plasma exit.

If these conditions can be fulfilled then it is expected that a low energy spread electron bunch can be reliably accelerated and its quality preserved in a plasma accelerator. However, achieving the listed goals requires progress in conventional accelerators. The SINBAD project at DESY [21] has part of its scientific program oriented to R&D on these issues. It aims at demonstrating the required quality and accuracy in external beam generation, matching, injection and extraction.

It is noted that numerous technical issues have not been discussed here, for example efficiency, laser in- and outcoupling, vacuum issues, etc. These topics are important and must be addressed separately.

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