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EuPRAXIA, A STEP TOWARD A PLASMA-WAKEFIELD BASED ACCELERATOR WITH HIGH BEAM QUALITY*

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Abstract

The EuPRAXIA project aims at designing the world's first accelerator based on advanced plasma-wakefield techniques to deliver 5 GeV electron beams that simultaneously have high charge, low emittance and low energy spread, which are required for applications by future user communities. Meeting this challenging objective will only be possible through dedicated effort. Many injection/acceleration schemes and techniques have been explored by means of thorough simulations in more than ten European research institutes. This enables selection of the most appropriate methods for solving each particular problem. The specific challenge of generating, extracting and transporting high charge beams, while maintaining the high quality needed for user applications, are being tackled using innovative approaches. This article highlights preliminary results obtained by the EuPRAXIA collaboration, which also exhibit the required laser and plasma parameters.

INTRODUCTION

Particle acceleration using plasma wakefields have field gradients several orders of magnitude higher than conventional RF fields. This concept has been extensively studied experimentally and theoretically [1-3]. The EuPRAXIA collaboration [4] aims to advance a step further, by designing the worldwide first plasma-based accelerator as a user facility. Such an infrastructure should be able to run 24/7, with an industrial-level reliability and reproducibility, at a high repetition rate > 10 Hz. The requirements on beam parameters are quite challenging, especially for the Free Electron Laser application, as the beam should simultaneously reach high energy, while also achieving high beam charge and high beam quality (Table 1).

Table 1: Beam Parameter Requirements at the Exit of the Laser-Plasma (LP), RF Injector, and Plasma Accelerator

Parameter	LP injector	RF injector	Accel-erator
Energy (GeV)	0.150	0.28-0.5	5 (1)
Charge (pC)	30	30	30
Bunch length$_{FWHM}$ (fs)	10	10	10
RMS en.spread (%)	5	0.2	1
Slice en.spread (%)	n.a.	n.a.	0.1
RMS emittance (μm)	1	1	1
Slice emittance (μm)	n.a.	n.a.	1

In order to progress from acceleration as a physics experiment to an accelerator as a facility with unprecedented beam requirements, specific studies should be developed. This article describes the strategy and methods used in this process: broad exploration and downselection, decoupling injection and acceleration, tackling the beam quality issue, the beam charge issue, and the beam transfer issue. Finally, the required laser and plasma parameters are given.

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BROAD EXPLORATION AND DOWNSELECTION

We adopt here the design strategy combining experience from plasma accelerators with well-proven approaches in conventional accelerators: first the desired beam parameters are defined, then all the configurations capable of fulfilling them are explored through simulations, and, depending on the selected configuration, specifications for laser and plasma systems are deduced consequently.

Many different injection/acceleration schemes were initially considered, with an RF or LP injector followed or not by one or two acceleration plasma stages, in LWFA (laser driven), or PWFA (particle driven), or hybrid modes. Rapidly, studies converged on the schemes sketched in Fig. 1.

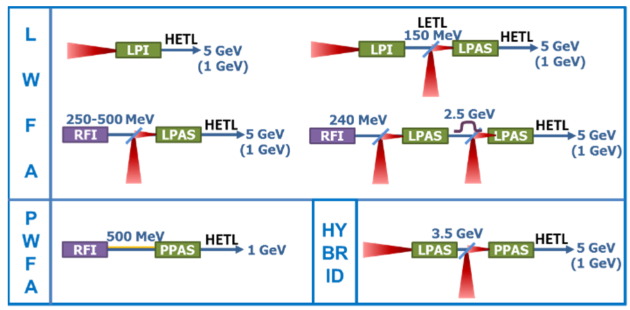

Figure 1: The studied Inject./Accelerat. schemes. LPI, RFI, LPAS, PPAS, LETL, HETL stand for, resp., Laser-Plasma / RF Injector, Laser-Plasma Acceleration / Particle-driven Plasma Acceleration Stage, Low Energy / High Energy Transfer Line. The laser beams are presented in red.

For the RF injection technique, two linacs have been designed as external injector of the LWFA mode: one accelerating to 240 MeV, based on S-band technology with an RF and magnetic bunch compressor [5], and another reaching 500 MeV by combining S-band and X-band structures [6]. The latter can also provide driver and witness beams to the PWFA mode via the Comb technique [7, 8].

Different injection techniques are also studied for the 150 MeV LP injector. The simplest is self-injection by wave breaking followed by acceleration in the nonlinear regime [9]. Two more sophisticated techniques, shock-front injection in the blowout regime [10] and ionization injection in the quasilinear regime [11, 12], produce beams closer to requirements. Only two more complex techniques of these two ones, down-ramp injection [13] and Resonant Multi-Pulse Ionization Injection (ReMPI) [14, 15] respectively, can achieve all beam requirements. See Fig. 2.

For the 5 GeV Laser Plasma Acceleration Stage (LPAS) injected either by an RF or LP injector, as described above, the quasilinear regime is explored for a single stage [16-18], while the blowout regime is assumed for a two-stage setup with a magnetic chicane in between [19]. The Particle Plasma Acceleration Stage (PPAS) is simulated in the weakly nonlinear regime up to 1 GeV for now. The PPAS of the Hybrid scheme is simulated in the blowout regime, with either the Trojan Horse [20] or the Wakefield Induced injection [21, 22] techniques. Figure 3 summarizes the

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beam parameters obtained compared to the requirements. Four configurations lead to results close to all requirements. Moreover, three configurations with an LPAS following a RF or LP injector, use similar laser and plasma parameters to obtain similar results, despite the different injector technologies, beam energies and the radically different simulations codes. This is a remarkable result: there exists a solution meeting the EuPRAXIA objectives and this solution has a highly promising robustness as regard to the large range of input parameters and assumptions.

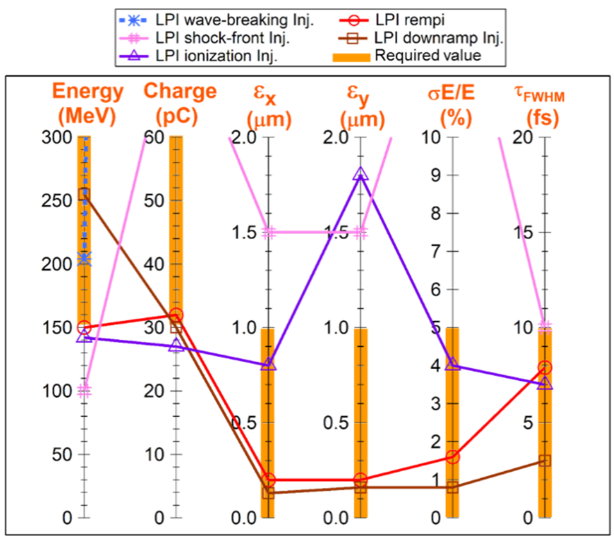

Figure 2: Results obtained for different injection / acceleration configurations at 150 MeV. See text.

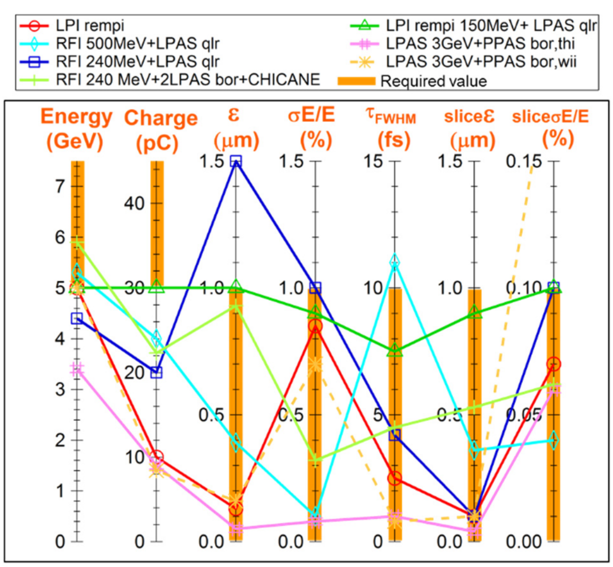

Figure 3: Results obtained for different injection/ acceleration configurations at 5 GeV. See text.

DECOUPLING INJECTION AND ACCELERATION

The above downselection procedure shows that a certain degree of sophistication of the accelerator setups is necessary. A single plasma stage combining injection and acceleration is likely not enough. At least two stages, one dedicated to injection and the other to acceleration are needed, as two independent knobs are necessary for tuning high beam charge and high beam quality.

Yet, even better beam quality is predicted in our studies when in the injector stage the processes of injection and acceleration are uncoupled. This is the case for the RF injector, where injection, acceleration and shaping of the beam are independently performed. For the LP injector, we see in Fig. 2 that a simple shock-front injection, with a steep increase then immediately decrease of the density at the plasma entrance, does not deliver the required performances. A more sophisticated density profile, where a small plateau separating the increasing and decreasing parts, combined to a tunable down ramp, allows to tune the injection duration and the acceleration process separately, and promises improved beam quality.

A similar case is observed for ionization injection. A single laser beam does not allow to obtain high beam charge and high energy at once, and furthermore lead to a much higher emittance in the laser polarization direction. In contrast, the ReMPI technique is more complex as it requires to split the laser pulse into three pulses (see Fig. 4), the first of small energy for ionizing the gas, the second containing the main part of energy itself decomposed in a series of 4 sub-pulses to excite the wakefield without ionizing the gas, and the third pulse carrying a tiny fraction of energy to symmetrize the beam in the perpendicular direction. Yet, this process generates a 30 pC, 150 MeV beam with 0.2 μm emittance and energy spread less than 2%.

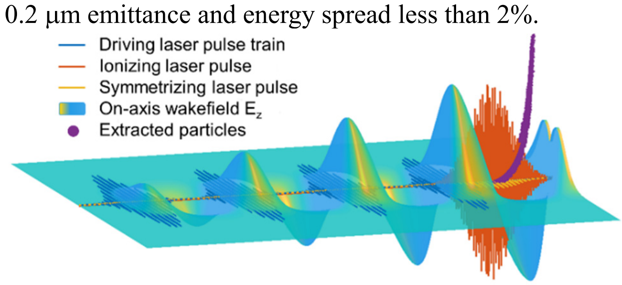

Figure 4: The ReMPI technique with a laser beam split into three beams (see text).

BEAM QUALITY AND CHARGE ISSUES

The beam quality must be assured everywhere in the chain of injection, acceleration and transportation, since the slightest degradation in a given section can be difficult to compensate for downstream. The challenge is initially minimizing then preserving as much as possible the 6D-phase space. In the LWFA case, a powerful laser beam creates the wakefield structure while external injection ensures the beam quality. The beam quality injected by a LP injector has been discussed above. The use of an RF injector would ensure a very small emittance at injection, but in our context of high charge and short bunch, additional efforts are needed to compress the bunch length when high space charge is present. In the case of Trojan Horse Injection, the reverse is achieved: a strong particle beam excites the wakefield and a weak laser beam delicately ionizes the gas to generate small emittance beams [20].

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Applications also require a small energy spread. Due to the variation of the accelerating field with the phase of the wakefield, it is well known that minimizing the bunch length reduces the energy spread. But in the case of high beam charge in the quasilinear regime, the beam-loading field is substantial, and its effect on the energy spread not only depends on the bunch length but also on the bunch radius [23]. As a consequence, for a given configuration where the beam radius is optimized, there exists a bunch length that minimizes the energy spread (Fig. 5a). In contrast, the slice energy spread depends only on the beam-loading field which is governed by the beam density and the laser strength. Optimizing jointly these two parameters allows to minimize the slice energy spread (Fig. 5b). In the blowout regime, as the beam-loading field is smaller, the additional injection of a tailored escort beam induces the appropriate beam-loading field [24]. Introducing a magnetic chicane in between two plasma stages to dechirp the energy spread is also a promising solution [19].

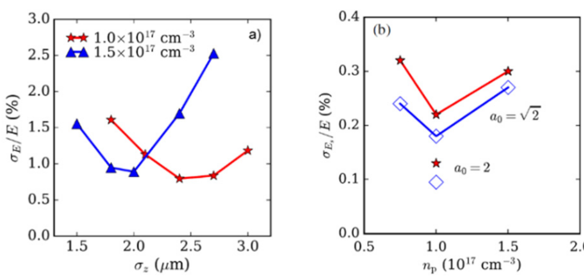

Figure 5: (a) Minimization of energy spread with the bunch length. (b) Minimization of slice energy spread with the laser strength and the plasma density.

BEAM TRANSPORT ISSUES

As for any accelerator, simulations must be carried out from start to end, including injection into and extraction from plasma stages as well as beam transport. The main concern in the latter is emittance growth by a factor of 10 or more, when the beam abruptly leaves the very strong focusing field of the plasma to enter into free space. Many theoretical studies have been undertaken on this subject [25, 26, 27]. An efficient process is still to be set to avoid emittance growth in the case of significant beam loading as with EuPRAXIA. A study is carried out, revealing all the parameters governing the phase emittance growth through a free drift, the trace emittance growth when crossing a focusing element, and pointing out these two emittances are equal at any beam waist [28]. Based on this model, the following three recommendations can be suggested for mitigating emittance growth effectively: 1) minimizing emittance and energy spread during acceleration, which should be done exclusively in the plasma acceleration part; 2) minimizing the Twiss parameter γ at the plasma exit, which should be done exclusively in the plasma down ramp, with the reservation that the latter would not itself induce significant emittance growth; 3) minimizing the total length and integrated focusing strength in the transfer line, which should be the exclusive role of the focusing elements in the transfer line. Optimizing all these aspects at each of those three components ensures a minimized emittance growth. If, however, it is not properly achieved at a given stage, it cannot be compensated elsewhere.

It is then demonstrated that transport lines composed of six quadrupoles for achieving the required beam size, divergence and emittance, associated to the plasma up and down ramps with optimized lengths (whatever the shape), allow to limit emittance growth to ~20% through injection, acceleration, extraction and transport to the user. Current efforts are focused on lengthening slightly these transport lines to introduce diagnostics, driver removals, chicanes, etc. State-of-the-art techniques, some still under development, will be used to monitor the full 6D phase space. R&D work is ongoing, in particular to improve the compactness and single shot capabilities of diagnostic systems [29].

LASER AND PLASMA REQUIREMENTS

Once the configurations giving beam parameters closest to the requirements are identified, the specifications for the laser and plasma physical parameters can be determined. For the LPI at 150 MeV, in the case of ReMPI, the required laser parameters are (λ = 800 nm): P = 125 TW, E = 5 J, strength $a_0 = 1$ (split into three beams as explained above); and for the plasma: N^{5+}, uniform density $n_0 = 5\times10^{17}$ cm^{-3}, 3.5 mm long, 1 mm down ramp and a 3 mm passive plasma lens, $n_0 = 1.4\times10^{16}$ cm^{-3}. In the case of down-ramp injection, the laser parameters are much relaxed: P = 35 TW, E = 1 J, a_0 = 1.8; but the plasma is more complex: $n_0 = 6\times10^{18}$ cm^{-3}, density increase then decrease with a plateau between, on a few 0.1 mm, 0.15 mm down ramp at the exit, and a 4 mm passive plasma lens with $n_0 = 1\times10^{16}$ cm^{-3}.

For the LPAS at 5 GeV, the required laser parameters are: P = 400 TW, E = 60 J, a_0 = 2.42; and for the plasma: radially parabolic, longitudinally uniform, 300-500 mm long, $n_0 = 1$ to 2×10^{17} cm^{-3}, entrance / exit ramps ~20 mm.

These laser specifications are under consideration for designing a viable solution based on Ti:Sa amplifiers with the most advanced kW-scale concepts, aiming at a high repetition rate up to 100 Hz, with exploration toward 1 kHz [30]. Developments of required plasmas are also underway. Plasma for the LPI have been achieved experimentally as tailored density profiles inside custom-designed gas cells [31]. Several schemes are being explored to develop stable, long plasmas for the LPAS at high repetition rate, including optically [32] or discharge [33] preformed channels.

CONCLUSION

Tremendous simulation and optimization efforts have been performed on a broad range of injection / acceleration schemes and techniques, thanks to the involvement of many EuPRAXIA member institutes. The issues of beam quality, beam charge and beam transport are being addressed using innovative approaches. Despite the challenges imposed by a highly demanding plasma-based accelerator, it is found that solutions do exist. Studies of sensitivity to errors are being finalized. Developments are on the way for laser, plasma and diagnostic systems, aiming for high reliability, reproducibility and repetition rate.

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