ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-TUPA089

EARLI: DESIGN OF A LASER WAKEFIELD ACCELERATOR FOR AWAKE

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Abstract

Following the successful Run 1 experiment, the Advanced Proton Driven Plasma Wakefield Acceleration Experiment (AWAKE) Run2 experiment requires the design and implementation of a compact electron source. The "high-quality Electron Accelerator driven by a Reliable Laser wakefield for Industrial uses" (EARLI) project aims to design a stand-alone high-quality electron injector based on a laser wakefield accelerator (LWFA) as an alternative proposal to AWAKE's baseline design of an X-band electron gun. This project is currently in the design phase, including simulations and experimental tests. Exhaustive beam physics studies for conventional accelerators are applied to LWFA physics.

INTRODUCTION

Laser wakefield accelerators are a very promising concept to build compact electron sources. The transition from acceleration experiments to accelerator facilities with practical applications and users is being studied. It is thus timely to strengthen the R&D on this topic and involve industrial partners and design an electron source for specific parameters and objectives. The EARLI project is positioned at the crossroad of academic and industrial research. Its goal is to identify the most appropriate concepts and define the technical requirements necessary to enable the reliability currently missing in academic experimental demonstrations.

The EARLI project aims to design a reliable, stand-alone accelerator to be possibly used as an alternative by CERN's AWAKE collaboration. The AWAKE collaboration [1] goal is to explore the possibility of using relativistic proton bunches carrying large amounts of energy to drive wakefields in plasma. The AWAKE Run2c experiment requires the use of two plasma cells (compared to one with Run1): The proton beam driver is self-modulated at the plasma frequency in the first cell (called cell 1 in Fig. 1), then propagates in the second cell (called cell 2 in Fig. 1) where it drives a plasma cavity suitable for external electron acceleration. This requires the implementation of a compact electron source for injection into the second plasma cell. This source is required to deliver high charge, small emittance and very short electron bunches. EARLI is an alternative to AWAKE's baseline

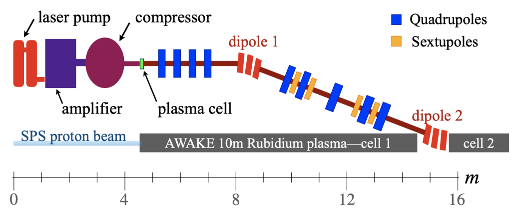

Figure 1: Schematic description of the EARLI project.

Table 1: Targeted beam requirements for AWAKE

Parameter	Value
Top-Level Requirements (TLR)	
Charge Q	$\geqslant$ 100 pC
Size $\sigma_{x,y}$	5.75 µm
Size σ_z	60 µm
Continuous operation	1-2 weeks
Operating time	5-10 years
Low-Level Requirements (LLR)	
Mean energy E_{mean}	100 to 250 MeV
Emittance $\epsilon_{\mathrm{n,rms},xy}$	$\leqslant$ 2 mm·mrad
Energy spread $\sigma_{E,\mathrm{std}}/E_{\mathrm{mean}}$	$\leqslant$ 2 %

electron source, using CERN's RF electron injector [2] composed by an S-band RF-gun, a subsequent X-band bunching and accelerating sections, and transfer lines (TLs) [3]. The CERN baseline design has been already finalized and matches the requirements for the experiment. The EARLI project will provide a comparison (including a comparison between costs, size, energy consumption, beam quality and reliability) between the RF and the LWFA-based injector. The outcome of this investigation is of general interest for the development of plasma based accelerators. In case EARLI were manufactured, AWAKE would become a full plasma accelerator with electrons created and accelerated in plasma cells only.

The EARLI project consists of three main parts (see Fig. 1): a laser system, a plasma source and a TL, used for the injection of the electron beam in the AWAKE second Rubidium plasma cell. Each part requires specific expertise, brought by different partners, that must be investigated in close collaboration with the others. The study focuses on the beam characteristics at the entrance of the AWAKE cell and the reliability and repeatability of the beam quality. The tar-

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geted beam parameters (divided into two categories based on their importance), that must be transported to the entrance of the second AWAKE plasma, are described in Table 1. The two priority parameters are high charge and small beam size. The energy spread must be kept low enough to ensure electron bunch transport. Reaching the correct charge, energy spread and emittance is very challenging. For instance, state-of-the-art beam parameters demonstrated experimentally have an energy of 250 MeV, 220 pC and 14% [4] (too large energy spread) or 282 MeV, 44 pC and 1.2% [5] (too low charge) respectively. The beam quality achieved inside the plasma has to be controlled and conserved after exiting the plasma. Note that, the planned repetition rate at 0.1 Hz is based on the proton beam repetition rate delivered at CERN SPS.

LASER-PLASMA SIMULATIONS

The heart of the LWFA is the plasma cell where laser-plasma acceleration (LPA) occurs and where the electron bunch is created and accelerated. The first goal of the EARLI design is to find configuration points providing the targeted beam parameters. This step is performed by building on published simulation results [4–6] to narrow down the initial parameter range. The mechanism of ionization injection with a hydrogen-nitrogen gas mixture is selected for its ability to provide high charge and control injection through the coupling of the laser pulse and the gas density profile.

LPA is modelled using particle-in-cell (PIC) codes. Currently, more than 5000 runs were performed using FBPIC and SMILEI with a few particles per cell. Both codes are used with a quasi-3D geometry and with azimuthal modes decomposition. FBPIC uses a boosted frame mode ($\gamma = 4.5$) and a spectral electromagnetic solver while SMILEI uses a laser envelope approximation model and an average ionization model. The use of two different codes is made by two different groups (CEA/Irfu and LPGP/CNRS) to ensure a cross-check of results and allow for comparison between both codes (see Fig. 2). In the simulation, the plasma density profile is described by two Fermi-Dirac distributions $f_\alpha(z < z_{c\alpha}) = (1 + e^{-\mu_\alpha/T_{\alpha l}})/(1 + e^{-(\mu_\alpha + z - z_{c\alpha})/T_{\alpha l}})$ and $f_\alpha(z \geq z_{c\alpha}) = (1 + e^{-\mu_\alpha/T_{\alpha r}})/(1 + e^{-(\mu_\alpha - z + z_{c\alpha})/T_{\alpha r}})$, with $\alpha = 1$ for the hydrogen-nitrogen gas mixture, $\alpha = 2$ for the pure hydrogen gas, and $z_{c\alpha}$ the gas positions. The hydrogen density is $2.089 \cdot 10^{18}$ cm^{-3} and the ratio of hydrogen in the first gas is 0.913. The simulation parameters for FBPIC (respectively for SMILEI): moving window size (r, z) 150 $\times$ 70 µm^2 with 350 $\times$ 3500 grid points (respectively 448 $\times$ 1024) and with 8 macro-electrons per cell. The differences between the results obtained with the two PIC codes in Fig. 2 are smaller than the typical differences between simulation results and the experimental measurements even at convergence (see e.g. [7]). These relatively small differences may be due to the different models to describe laser-plasma interaction and the numerical schemes used by the two codes. Similar or even smaller differences can be found in the other electron beam parameters, not reported here for brevity."

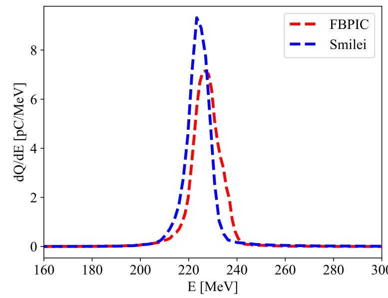

Figure 2: Cross-check between PIC codes SMILEI and FBPIC ongoing. Charge distribution for the beam of Fig. 3.

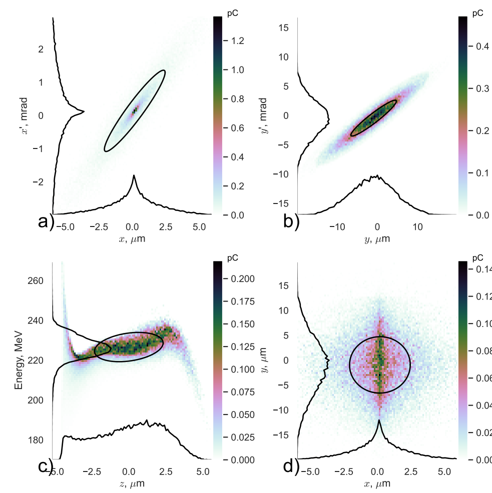

Figure 3: Electron beam obtained at the exit of the LWFA plasma cell.

A good quality bunch was obtained (see Fig. 3) at 226.6 MeV, 97.2 pC, 2.5 mm.mrad and 3.2% relative energy spread using the mentioned density profile. Simulations were performed assuming a flattened Gaussian laser beam of order 6 [8] with normalized field amplitude $a_0 = 1.36$, waist size $w_0 = 20.9$ µm, the electric field amplitude duration $\tau_0 = 25$ fs and focused at position (relative to the beginning of the plasma) $z_{foc} = 3600$ µm. The Fermi-Dirac distribution parameters for the gas 1 and 2 are $z_{c1} = 1750$ µm, $\mu_1 = 450$ µm, $T_{1l} = 90$ µm and $T_{1r} = 97$ µm, $z_{c2} = 3578$ µm, $\mu_1 = 1363$ µm, $T_{2l} = 85$ µm and $T_{2r} = 200$ µm, which gives a distribution with the nitrogen dopant concentrated in the initial density peak, as in [5]. The sensitivity of beam performances to variation of the twelve previous parameters has been analyzed. Figure 4 displays this analysis for the laser parameters. This analysis shows that a local minimum (set of optimal parameters within the considered parameter space subset) can be reached, i.e. we found the best beam possible with the two Fermi–Dirac plasma distributions around the chosen parameters. To further improve the beam characteristics by reducing the energy spread and emittance, we shall either investigate other plasma density profiles or dramatically change the considered parameter subset, aiming to find new optimal subsets.

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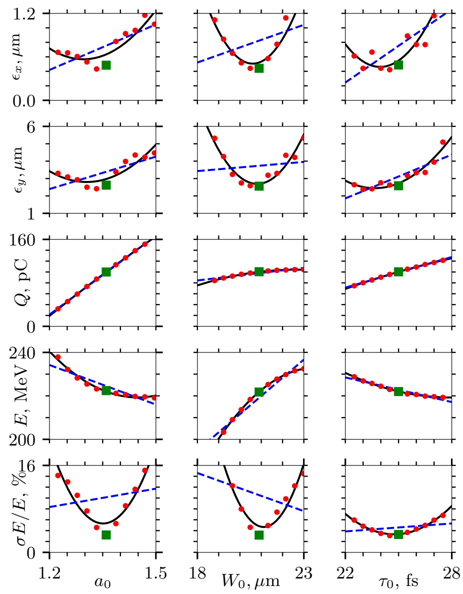

Figure 4: Beam parameter analysis from the laser inputs. Dashed blue lines are linear fits and the black curves are quadratic fits from the simulation data (red dots). Green squares correspond to the beam shown in Fig 3.

TRANSFER LINE

A compact transport and focusing line, allowing implementation of the associated diagnostics, is required to transport electrons created in the EARLI plasma cell and focus them at the entrance of the AWAKE second plasma cell. The magnetic elements must be carefully placed to control the beam. CERN's TL baseline design [3] has been completed using MADx and several optimizers. We are currently studying the TL from the EARLI plasma cell to the second AWAKE plasma chamber to accommodate the LWFA generated electron beam. Using a different code TraceWin [9] allows us to compare the results with the baseline design done in MADx. Also, a modified version for the CERN design for the transport line could be used for EARLI.

Several constraints are taken into account. The distance between the AWAKE plasma cells must be as small as possible, implying that the TL can only be ended by a dipole, with 1 m free of any magnetic component upstream. A dogleg configuration, with two dipoles, and angle $\theta = 15°$ is chosen. Output requirements are $D = D' = 0$, $\alpha_{x,y} = 0$, $\sigma_{x,y} = 5$ µm, $\sigma_z = 60$ µm and emittance growth of less than 20% from beam input. These requirements can be met by using eight to nine quadrupoles. Sextupoles, and maybe octupoles, are needed to correct strong chromatic aberrations induced by quadrupoles (focusing beam sizes from mm to µm). The beam longitudinal size (2 µm at the exit of the plasma cell) increases to 100 µm through the achromat (see bottom panel of Fig. 5). However, the first studies show that it can be reduced to 60 µm by quadrupoles in the achromat section. Those preliminary studies also show that the beam transverse size, which is 2 µm from the plasma cell exit, expands to 3-5 mm during beam transport but it can

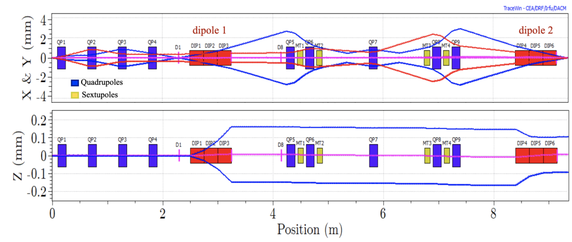

Figure 5: Beam sizes along the transfer line. Top panel: variation of the transverse rms sizes. Bottom panel: variation of the longitudinal rms size.

be reduced to 10 µm at the end of the line (see top panel of Fig. 5). One of the best configurations investigated includes four quadrupoles in the capture section upstream and five quadrupoles in the achromat (see Figs.1 and 5). Optimisations and start-to-end simulations using the beam coming from the LPA simulations are ongoing.

PLASMA CELL AND LASER SYSTEM

The design of the plasma cell aims to achieve the plasma profiles used in LPA simulations. Numerical modelling of fluid and plasma using computational fluid dynamics codes OpenFOAM and COMSOL are performed. A prototype of the plasma cell is under development. Experimental tests of this prototype are planned at existing high-intensity laser facilities.

The laser parameters and associated tolerances will be the outcome of a tradeoff discussion on technical and operational aspects between CEA/IRFU, LPGP/CNRS and THALES. Based on proven and operating technologies, the laser solution by THALES will be adapted to meet the requirements from LPA simulations. In particular, energy and beam pointing stability, symmetry of energy distribution in the focal volume, wavefront quality, pulse duration and remote control will be the considered laser design parameters to deliver the expected electron beam quality and stability.

CONCLUSIONS

This paper introduces the EARLI project, aiming at designing a high-energy electron source generated by a laser wakefield acceleration system as an alternative proposal to the RF-electron source baseline design for acceleration in AWAKE Run2c. The first simulation results are very promising for the feasibility of this project, which is an important milestone for the development of plasma accelerators. A full comparison of beam quality, reliability and footprint between EARLI and the RF-electron source baseline designs is expected.

ACKNOWLEDGEMENTS

This work was performed using HPC resources from GENCI-IDRIS (Grant 2022-A0130510062) and the Grant CCRT2023-minennda awarded by the Fundamental Research Division (DRF) of CEA.

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