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2017 J. Phys.: Conf. Ser. 874 012029

(http://iopscience.iop.org/1742-6596/874/1/012029)

8th International Particle Accelerator Conference IOP Publishing
IOP Conf. Series: Journal of Physics: Conf. Series **874** (2017) 012029 doi:10.1088/1742-6596/874/1/012029

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Abstract. The Horizon 2020 Project EuPRAXIA ("European Plasma Research Accelerator with eXcellence In Applications") is preparing a conceptual design report of a highly compact and cost-effective European facility with multi-GeV electron beams using plasma as the acceleration medium. The accelerator facility will be based on a laser and/or a beam driven plasma acceleration approach and will be used for photon science, high-energy physics (HEP) detector tests, and other applications such as compact X-ray sources for medical imaging or material processing. EuPRAXIA started in November 2015 and will deliver the design report in October 2019. EuPRAXIA aims to be included on the ESFRI roadmap in 2020.

1. Introduction

The EuPRAXIA collaboration is the first plasma accelerator collaboration on this scale bringing together 16 European partner laboratories and additional 22 associated partners from the EU, Israel, China, Japan, Russia and the USA [1]. EuPRAXIA is structured into 14 working packages each headed by two work package leaders from different institutions. Eight work packages receive EU funding and their topics include: plasma and laser simulations (WP2), plasma accelerator structures (WP3), laser design (WP4), conventional beam physics (WP5), FEL radiation (WP6), and a table-top test beam for HEP and other applications (WP7). Two further EU work packages work on the management of the collaboration (WP1) and the outreach to the public (WP8). In-kind work packages (WP9 - WP14) include additional approaches: beam driven plasma acceleration PWFA (WP9), hybrid acceleration schemes (WP14), alternative radiation generation (WP13) and alternative laser sources such as fiber lasers (WP10). WP11 and WP12 connect to prototyping on plasma-based FEL's and facility access for experiments until 2019. Industry partners Amplitude Technologies, Thales and TRUMPF Scientific take part in the scientific advisory board and contribute their experience towards a successful completion of the design report.

2. Plasma acceleration

Scientists, medical doctors and engineers have used radio-frequency (RF) based particle accelerator beams for ninety years to probe nature, to produce new particles, to generate light of exquisite quality or to irradiate tumors. The accelerators are of outstanding quality, but have grown in size and cost due to the materials used for construction, which can only sustain accelerating fields of around 100 MV/m before electrical breakdown occurs. Plasma accelerators are not subject to these electrical breakdown limits and the accelerating field reaches 100 GV/m, three orders of magnitude larger than in an RF accelerator. As a consequence, the size of plasma accelerators can potentially be quite small, reducing kilometer scale machines to the meter scale. A new generation of cost-efficient and compact accelerators could open completely new usages of particle accelerators, for example in hospitals and universities. This requires suitable stability and repetition rates.

The great potential of plasma waves for particle acceleration was first recognized by Veksler [2] and Tajima and Dawson [3]. The longitudinal plasma waves can be excited by both electron beams (plasma wakefield acceleration, PWFA) or intense laser pulses (laser wakefield acceleration, LWFA) and are well suited for accelerating charged particles to relativistic energies [4]. Electron beams that are accelerated inside a plasma accelerator structure can originate from the background plasma within the plasma accelerator structure itself ("internal injection") or from an accelerator that is situated in front of the plasma accelerator structure ("external injection"). Within the last two decades, the beam quality of LWFA accelerators has significantly improved [5-13] and the current peak energy lies at 4.2 GeV [14]. Using these beams, various types of X-ray radiation such as betatron, synchrotron, and undulator radiation down to the water-window wavelengths were produced [15-21]. While several tens of laboratories use laser systems to accelerate electrons, few laboratories have the electron beam needed for beam-driven plasma acceleration [22-28]. FACET at SLAC achieved energy doubling within a single electron beam in 2007 [24] and energy was transferred successfully from a drive beam to a witness bunch in 2014 [25].

In the EuPRAXIA study, both laser driven and beam driven approaches as well as combined plasma acceleration schemes - using LWFA-produced beams as drivers of PWFA stages [29, 30] - are taken into consideration. The final EuPRAXIA design report in 2019 will include various configurations of a possible EuPRAXIA facility. Depending on available budget and the targeted science case, one of these options, or a combination of options, might be the best choice. The design report will compare size, cost, and performance on a common basis. The first iteration of the design goals were defined in

October 2016 [31] and from these, the initial goal parameters for the 5 GeV electron beam at the entrance of the undulator are shown in Table 1. The agreed possible configurations are:

Configuration 1: LWFA with internal injection;
Configuration 2: LWFA with external injection from an RF accelerator;
Configuration 3: LWFA with external injection from a laser plasma injector;
Configuration 4: PWFA with an RF electron beam; and
Configuration 5: PWFA with LWFA produced electron beam (hybrid schemes).

In addition to the 5 GeV electron beam, the facility aims to provide a medical imaging X-ray source as well as FEL radiation ultimately concentrating in the range between 1 nm and 0.1 nm. TW laser pulses synchronized to the electron and X-ray radiation will be available in the user areas. Parameter tables for medical imaging and a table-top test beam for HEP and other applications are currently being finalized.

3. Laser and electron beam drivers

The laser used in the LWFA cases is being studied in work package 4 (WP4) with colleagues from Thales and Amplitude industry. WP4 reviewed current laser systems in 2016 [32] and proposed preliminary specifications of the EuPRAXIA laser, the so-called “100 cube” laser challenge (an energy of 100 Joule, a pulse length of 100 fs (FWHM), and a repetition rate of 100 Hz, with a contrast of 10^{10} at 10 ps). The present work towards this challenging goal disfavors a complete Ti:Sa laser system and is considering a diode-pumped solid-state laser pumping scheme. A second laser system, used for the plasma injector [33], will operate at lower energy and shorter pulse length.

Design work on the drive beam for the PWFA case is being performed in WP5. One option under discussion is that both configuration 2 (LWFA) and 4 (PWFA) use at low energy the same S-band injector and RF linac [34]. The simulated transverse phase space of a possible electron drive beam for a PWFA application is shown in Figure 1. This electron beam has an energy of 548 MeV, a peak beam current of 1 kA, transverse normalized emittances of 1 μrad m and an energy spread of below 0.07%. After acceleration through S-band and X-band structures, the beam is focused by both conventional, electro-magnets, and permanent quadrupole magnets before entering the plasma.

Table 1. Target values for the 5 GeV electron beam parameters at the entrance of the undulators [31].

Quantity	**Symbol**	**Value**
Particle type	e	Electrons
Energy	E	5 GeV
Charge	Q	30 pC
Bunch length (FWHM)	τ	10 fs
Peak current	I	3 kA
Repetition rate	f	10 Hz
Number of bunches	N	1
Total energy spread (RMS)	σ_E/E	1%
Slice energy spread (RMS)	$\sigma_{E,S}/E$	0.1%
Trans. Norm. emittance	$\varepsilon_{N,x}$, $\varepsilon_{N,y}$	1 μrad m
Alpha function	α_x, α_y	0
Beta function	β_x, β_y	5 m
Trans. beam size (RMS)	σ_x , σ_y	22 μm
Trans. divergence (RMS)	$\sigma_{x'}$, $\sigma_{y'}$	4.5 μrad

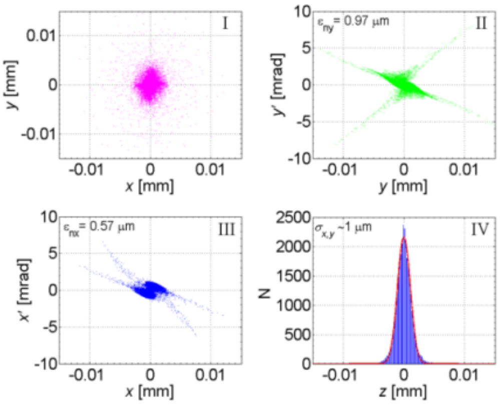

Figure 1. Preliminary simulation results for the transverse phase space of a possible PWFA drive beam (configuration 4) with an energy of 548 MeV, a peak beam current of 1 kA, transverse normalized emittances of 1 µrad m and an energy spread of below 0.07%.

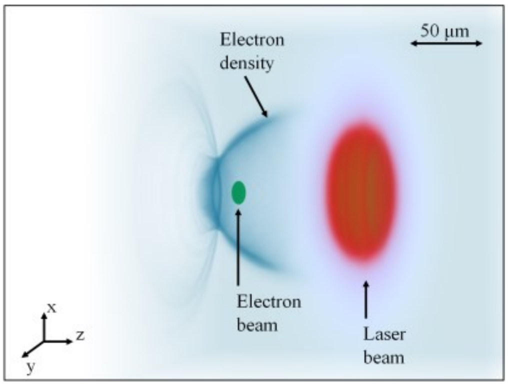

Figure 2. PIC simulation [36] of a LWFA case (configuration 2). The laser pulse (red) propagates the plasma (electron density shown in blue) from left to right and excites a wakefield, which accelerates electrons (shown in green) from 0.1 to 1 GeV in 2.5 cm.

4. Plasma accelerator structure

Components necessary for the design of the plasma accelerator structure were reviewed by WP3 in 2017 [35] in which published experimental results were examined and compared not only in terms of achieved electron properties, but also regarding their reliability, stability, or scalability to larger electron energy, or repetition rate. The proposed criteria from [35] for selecting a specific plasma accelerator structure will be used to decide which types of plasma accelerator will ultimately be incorporated into the design report.

Figure 2 shows a particle-in-cell (PIC) simulation [36, 37] performed with the OSIRIS code [38] in which a 1 PW laser traverses a plasma accelerator structure of 1.2 10^{17}cm^{-3} electron density. The externally injected electron beam (initially: energy E = 100 MeV; relative energy spread σ_E/E = 0.1%; transverse emittance $\varepsilon_{N,x}$ = 1 µrad m) exits the plasma after 2.5 cm with an energy of 1 GeV (σ_E/E = 1.5%; $\varepsilon_{N,x}$ = 1 µrad m). While emittance is well preserved, the energy spread is significantly increased due to the sizable variation of the accelerating field along the injected bunch. Beam loading techniques

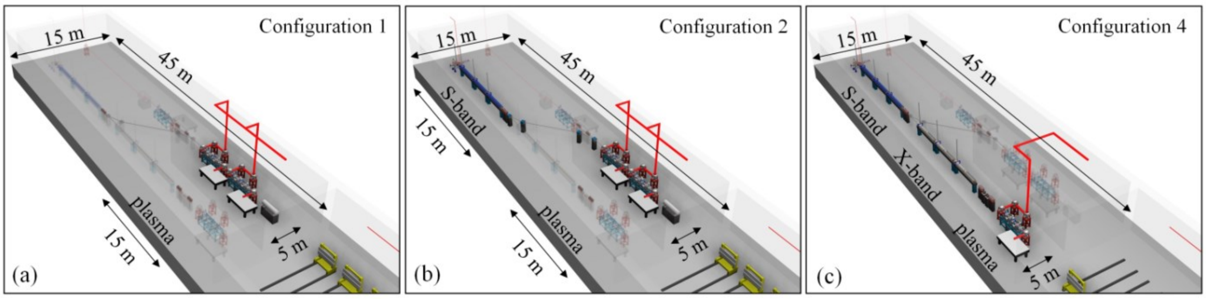

Figure 3. The preliminary layout of the EUPRAXIA accelerator tunnel is shown [43]. All RF and laser infrastructure is being supplied from the level above (not shown). Undulators (yellow) are shown in the bottom right corners. (a) Configuration 1: LWFA with internal injection. Two plasma stages are included which are supplied with two laser beams (red). (b) Configuration 2: LWFA with external injection from an RF accelerator. The RF gun and three S-band structures are shown in front of a dogleg which transports the electrons to the two plasma stages. (c) Configuration 4: PWFA. Using the same infrastructure of RF gun and S-band structure, the PWFA case uses additional X-band structures to accelerate beams to several hundred MeV before using it inside a single plasma accelerator stage.

will be used in order to compensate this gradient on the accelerating field and minimize the induced energy spread [39-42]. After completion of 1 GeV simulations with conservation of all beam qualities, simulations of the 5 GeV beam will continue.

5. Layout considerations

The preliminary layout of the EuPRAXIA accelerator tunnel [43] is shown in Figure 3, excluding user areas. Configurations 1, 2, and 4 are visualized. In the current layout, laser and RF infrastructure are situated on the level above the accelerator level floor (not shown). If individual configurations were built separately, the area for the accelerator tunnel for configuration 1, 2, 3, and 4 are 75 m^2, 175 m^2, 150 m^2, and 225 m^2, respectively and configuration 1 to 4 can incorporate configuration 5. Hence the footprint of the accelerator tunnel can be up to 5 times smaller than in conventional accelerator facilities. EuPRAXIA is a site-independent design study. Potential sites will be included in the design report and EuSPARC (Frascati, Italy), SINBAD (Hamburg, Germany), CILEX (Paris, France), CLF (Didcot, UK) and ELI (Prague, Czech Republic) have been discussed as potential sites.

6. Summary

The EuPRAXIA collaboration is preparing a conceptual design report for a multi-GeV plasma-based accelerator with outstanding beam quality. The facility design aims to include FEL radiation in the soft (to hard) X-ray range, a table-top test beam for HEP detectors and industry, and a compact X-ray source for medical imaging. Synchronized TW laser beams will be available in the user areas. Both laser and electron beams are considered as power sources for the plasma accelerator. EuPRAXIA will prepare a proposal to be included on the ESFRI roadmap in 2020 as an innovative European research infrastructure. Ultimately, EuPRAXIA will: use the world-wide leading high power lasers from European industry, drive laser innovation in the connected companies, provide for the first time usable electron beam quality from a plasma accelerator, and serve pilot users from science, engineering, medicine and industry.

References

[1] European Plasma Research Accelerator with eXcellence In Applications http://www.eupraxia-project.eu
[2] Veksler V 1956 Coherent principle of acceleration of charged particles *Proc. of the CERN Symposium on High Energy Accelerators and Pion Physics* Geneva Switzerland
[3] Tajima T and Dawson J M 1979 Laser electron-accelerator *Phys. Rev. Lett.* **43**(4):267–270
[4] Esarey E *et al.* 2009 Physics of laser-driven plasma based electron accelerators *Rev. Mod. Phys.* **81**:1229–1285
[5] Modena A *et al.* 1995 Electron acceleration from the breaking of relativistic plasma waves *Nature* **377**:606 – 608
[6] Umstadter D *et al.* 1996 Laser injection of ultrashort electron pulses into wakefield plasma waves *Phys. Rev. Lett.* **76**(12):2073–2076
[7] Malka V *et al.* 2002 Electron acceleration by a wake field forced by an intense ultrashort laser pulse *Science* **298**(5598):1596–1600
[8] Mangles S P D et al. 2004 Monoenergetic beams of relativistic electrons from intense laser plasma interactions *Nature* **431**(7008):535–538
[9] Faure J *et al.* 2004 A laser-plasma accelerator producing monoenergetic electron beams *Nature* **431**(7008):541–544
[10] Geddes C G R *et al.* 2004 High-quality electron beams from a laser wakefield accelerator using plasma-channel guiding *Nature* **431**(7008):538–541
[11] Leemans W P *et al.* 2006 GeV electron beams from a centimetrescale accelerator *Nat. Phys.* **2**(10):696–699
[12] Wang X *et al.* 2012 Petawatt-laser-driven wakefield acceleration of electrons to 2 GeV in 1017cm3 plasma *Proc. AIP* 1507(1):341–344

[13] Assmann R W *et al.* 2014 Accelerator Physics Challenges towards a Plasma Accelerator with Usable Beam Quality *Proc. of 5th International Particle Accelerator Conference* Dresden Germany

[14] Leemans W P *et al.* 2014 Multi-GeV Electron Beams from Capillary-Discharge-Guided Sub petawatt Laser Pulses in the Self-Trapping Regime *Phys. Rev. Lett.* **113** 245002

[15] Kneip S *et al.* 2009 Near-GeV acceleration of electrons by a nonlinear plasma wave driven by a self-guided laser pulse *Phys. Rev. Lett.* **103**:035002

[16] Fuchs M *et al.* 2009 Laser-driven soft-X-ray undulator source *Nature Physics* **5** 826 – 829

[17] Maier A R 2012 Stabilized Water-Window X-Ray Pulses from a Laser-Plasma Driven Undulator *PhD thesis* Ludwig-Maximilians-Universität München

[18] Lambert G *et al.* 2012 Progress on the generation of undulator radiation in the UV from a plasma-based electron beam *Proc. FEL Conf.* Nara Japan

[19] Cipiccia S *et al.* 2012 A tuneable ultra-compact high-power, ultra-short pulsed, bright gamma-ray source based on bremsstrahlung radiation from laser-plasma accelerated electrons *Journal of Applied Physics* **111**(6):063302

[20] Anania M P *et al.* 2014 An ultrashort pulse ultra-violet radiation undulator source driven by a laser plasma wakefield accelerator *Applied Physics Letters* **104** 264102

[21] Khrennikov K *et al.* 2015 Tunable all-optical quasimonochromatic Thomson X-ray source in the nonlinear regime *Phys. Rev. Lett.* **114**(19):195003

[22] Chen P 1985 Acceleration of Electrons by the Interaction of a Bunched Electron Beam with a Plasma *Phys. Rev. Lett.* **54** 693

[23] Wang S *et al.* 2001 Observation of spontaneous emitted X-ray betatron radiation in beam-plasma interactions *Proc. of 19th IEEE PAC* Chicago IL USA

[24] Blumenfeld I *et al.* 2007 Energy doubling of 42 GeV electrons in a metre-scale plasma wakefield accelerator *Nature* **445** 741

[25] Litos M *et al.* 2014 High-efficiency acceleration of an electron beam in a plasma wakefield accelerator *Nature* **515** 7525:92-5

[26] Ferrario M *et al.* 2013 SPARC_LAB present and future *Nuclear Instruments and Methods in Physics Research B* **309** 183–188

[27] Aschikhin A *et al.* 2016 The FLASHForward facility at DESY *Nucl. Instrum. Meth.* Vol. **806** 175-183

[28] Kasilnikov M *et al.* 2012 Experimentally minimized beam emittance from an L-band photoinjector *Phys. Rev. ST Accel. Beams* **15** 100701

[29] Hidding B *et al.* 2010 Monoenergetic Energy Doubling in a Hybrid Laser-Plasma Wakefield Accelerator *Phys. Rev. Lett.* **104** 195002

[30] Martinez de la Ossa A *et al.* 2013 High-Quality Electron Beams from Beam-Driven Plasma Accelerators by Wakefield-Induced Ionization Injection *Phys. Rev. Lett.* **111** 245003

[31] Walker P A *et al.* 2016 *Report defining preliminary study concept* EuPRAXIA Deliverable Report 1.2

[32] Gizzi L A *et al.* 2016 *Benchmarking of existing technology and comparison with the requirements* EuPRAXIA Deliverable Report 4.1

[33] Cros B *et al.* 2017 Electron injector for multi-stage laser-driven plasma accelerators *presented at the 8th Int. Particle Accelerator Conf.* Copenhagen Denmark WEPVA001

[34] Chiadroni E *et al.* 2016 *Preliminary RF accelerator specifications* EuPRAXIA Milestone Report 5.2

[35] Cros B *et al.* 2017 *Design for an electron injector and a laser plasma stage proposed* EuPRAXIA Milestone Report 3.1

[36] Ferran Pousa A *et al.* 2017 VisualPIC: A New Data Visualizer and Post-Processor for Particle-in-Cell Codes *presented at the 8th Int. Particle Accelerator Conf.* Copenhagen Denmark TUPIK007

[37] Mosnier A *et al.* 2017 *Report designing baseline designs* EuPRAXIA Deliverable Report 2.1

[38] Fonseca R A *et al.* 2002 *OSIRIS: A Three-Dimensional, Fully Relativistic Particle in Cell Code for Modeling Plasma Based Accelerators* Sloot P.M.A., Hoekstra A.G., Tan C.J.K., Dongarra J.J. (eds) Computational Science — ICCS 2002. ICCS 2002. Lecture Notes in Computer Science vol 2331 Springer Berlin Heidelberg
[39] Katsouleas T *et al.* 1987 Beam loading in plasma accelerators *Particle Accelerators* **22**:81–99
[40] Tzoufras M *et al.* 2008 Beam loading in the nonlinear regime of plasma-based acceleration *Phys. Rev. Lett.* **101**:145002
[41] Rechatin C *et al.* 2009 Observation of Beam Loading in a Laser-Plasma Accelerator *Phys. Rev. Lett.* **103**:194804
[42] Schroeder C B *et al.* 2013 Beam loading in a laser-plasma accelerator using a near-hollow plasma channel *Physics of Plasmas* **20** 123115
[43] Walker P A *et al.* 2017 Space considerations and possible layouts for future plasma accelerator facilities in the context of EuPRAXIA *presented at the 8th Int. Particle Accelerator Conf.* Copenhagen Denmark TUPIK012

Acknowledgments

This work was supported by the European Union‘s Horizon 2020 research and innovation programme under grant agreement No. 653782.