STATUS OF THE HORIZON 2020 EuPRAXIA CONCEPTUAL DESIGN STUDY*

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Abstract

The Horizon 2020 Project EuPRAXIA (European Plasma Research Accelerator with eXcellence In Applications) is producing a conceptual design report for a highly compact and cost-effective European facility with multi-GeV electron beams accelerated using plasmas. EuPRAXIA will be set up as a distributed Open Innovation platform with two construction sites, one with a focus on beam-driven plasma acceleration (PWFA) and another site with a focus on laser-driven plasma acceleration (LWFA). User areas at both sites will provide access to FEL pilot experiments, positron generation and acceleration, compact radiation sources, and test beams for HEP detector development. Support centres in four different countries will complement the pan-European implementation of this infrastructure.

INTRODUCTION

Since its first experimental successes more than a decade ago [1-3], plasma wakefield acceleration has in recent years drawn more and more interest in the accelerator community, as significant performance improvements and technological milestones were achieved [4-11]. Taking advantage of the extremely strong wakefields inside a plasma accelerator, these machines can accelerate electron beams created through internal injection or injected externally from another machine to hundreds of MeV up to several GeV over mm- to cm-lengths. With such a reduction in accelerating distance by up to three orders of magnitude compared to radiofrequency (RF)-based devices, plasma technology is very promising for miniaturizing accelerator-based machines, such as light sources, thus potentially

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opening up a multitude of new applications and fields of use. To advance the development of plasma accelerators towards applications and user readiness, the EuPRAXIA project [12] aims to tackle some of the field's most challenging technical and operational issues, including beam quality, machine reliability and operability as well as the currently very low repetition rate of plasma-based devices. With a team of 41 partners from 14 countries (as of November 2018 [13]), the project aims to develop a first plasma-accelerator-based user facility. It is foreseen as a distributed European demonstrator and Open Innovation platform dedicated to the research and development of accelerator concepts and applications of plasma wakefield acceleration. This paper provides a short summary of the general status of the project as well as the current considerations for the future EuPRAXIA infrastructure.

PROJECT STATUS AND SCHEDULE

As part of the conceptual design, the main technical and scientific goals for the future EuPRAXIA machine have been defined. Their status can be summarized as follows:

- ***Single- & multi-stage acceleration of electron beams to a final energy of 1-5 GeV:***

A broad range of plasma injection and acceleration mechanisms has been studied, assessed and down-selected, as described in detail in [14]. The expected final beam parameters found from start-to-end simulations of the accelerator are summarized in Table 1. As can be seen from Fig. 1 for the critical parameters of electron beam slice energy spread and emittance, the specifications fulfil the goal of high beam quality approaching typical parameters of modern, RF-based free-electron lasers (FELs). Additionally, various more practical issues have been considered for the machine design. Emphasis has been placed on topics specific to plasma acceleration, such as the synchronization between drive laser and externally injected witness beams, laser in- and outcoupling as well as electron beam dechirping. Conceptual solutions for these have been developed and will be tested and optimized in the coming technical design phase [15-18].

- ***Design of a highly compact machine layout:***

As discussed in [19], the current machine design is estimated to have a maximum length of around 175 m, including acceleration to 5 GeV and an FEL beamline. This demonstrates a reduction in size by a factor of approximately four compared to equivalent, conventional machines [20]. A focus has been put on developing transport lines and diagnostics suitable for a compact machine based on plasma technology. In both cases, a risk-mitigated strategy was chosen by combining conventional, well-tested techniques with larger footprints (such as quadrupole-based focusing and emittance scans) with novel, more compact methods better suited to plasma-accelerated beam characteristics (such as plasma lenses and single-shot betatron / transition radiation diagnostics) [21-23]. Through a step-wise replacement of the more sizable components together with other measures, a further miniaturization of the machine towards a factor of 10 and beyond throughout its lifetime is intended.

- ***Development & construction of a new generation of high-power, short-pulse laser systems:***

The current facility layout foresees three new laser systems with sub-PW to PW peak power to be developed as plasma wake drivers (see [24] for details). The design is focused on high stability and a high repetition rate of 20-100 Hz with ambitions to explore the kHz regime as a possible future development [25,26]. Such a move to higher repetition rates will not only make plasma accelerators more competitive with RF-based machines, but also allow the implementation of more complex feedback mechanisms thus improving the overall pulse-to-pulse stability.

Table 1: Expected Machine Performance Based on Start-to-End Simulations of the Conceptual Design

Parameter	**Baseline**
Energy [GeV]	1.0 – 5.5
Charge [pC]	20 – 35
Bunch length [fs]	4 – 12
Energy spread [%]	0.1 – 1.1
Slice energy spread [%]	0.02 – 0.15
Norm. transverse emittance [mm mrad]	0.35 – 1.50
Norm. slice emittance [mm mrad]	0.10 – 1.20

Specific acceleration scheme results described in [14]

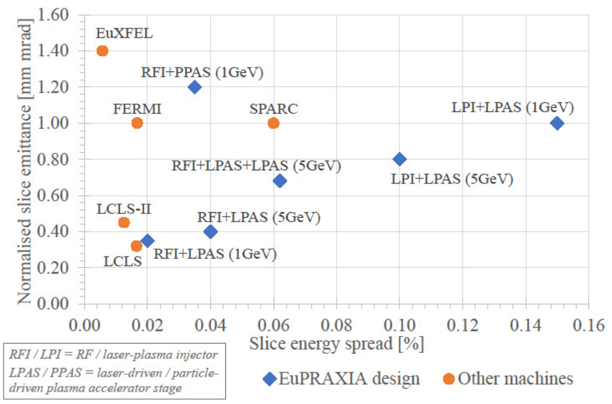

Figure 1: Comparison of electron beam parameters expected for different EuPRAXIA setups with the design and measured performance of several RF-based free-electron laser facilities [27-32].

- ***Development & construction of a new compact beam driver based on X-band RF technology:***

A design for an X-band linac with energies up to 0.5-1 GeV for EuPRAXIA's beam-driven plasma acceleration site has been devised [33]. It will provide both the drive and witness beams for the PWFA stages of the beamline using a compact, high-acceleration gradient RF setup.

- ***Design of several distributed and versatile user areas for a broad range of applications:***

The most promising exemplary applications have been identified [34] and, based on these, beamlines as well as user areas are being designed. With the concept of massive

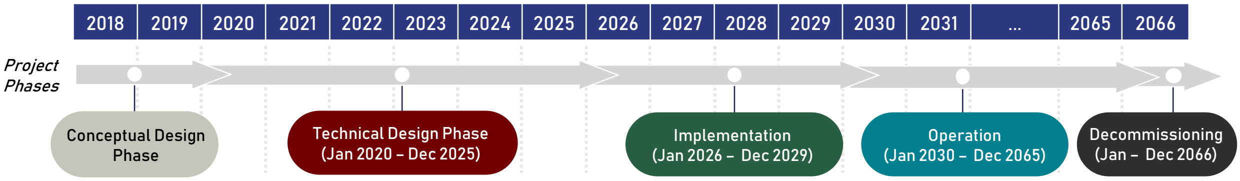

Figure 2: Preliminary EuPRAXIA schedule and project phases.

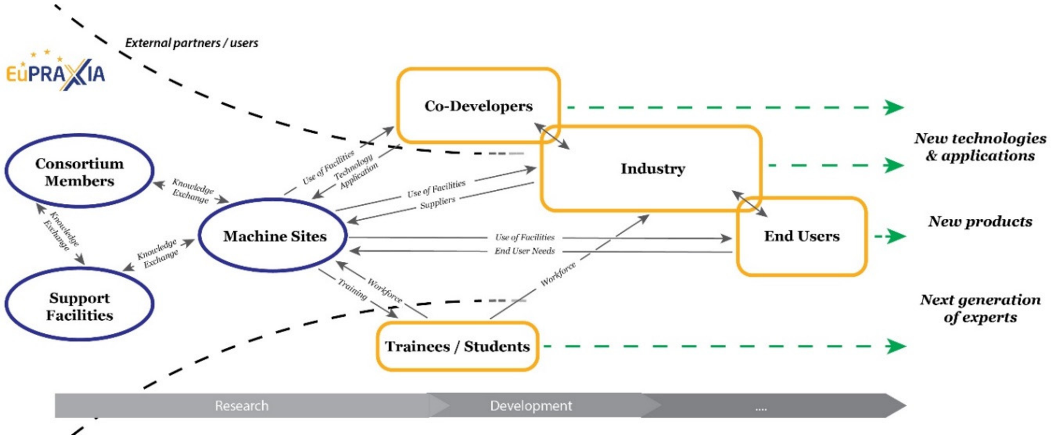

Figure 3: Overview diagram of a possible Open Innovation model for EuPRAXIA.

parallelization of user lines in mind as a key advantage of LWFA, the baseline foresees plasma FELs, high- and low-energy positron sources for high-energy physics and material science applications, compact test beams for particle physics detector design as well as X-ray & γ-ray sources for imaging and other uses. Some of the main advantages intrinsic to plasma acceleration in this context are the naturally short pulse lengths of few fs, µm-scale source sizes as well as the high synchronization level between particle and laser beams suitable for pump-probe experiments.

Following a full conceptual design based on these different aspects to be presented in October 2019, a six-year technical design phase for prototyping and R&D is foreseen, as shown in Fig. 2. An implementation of the EuPRAXIA infrastructure could then be envisaged within a 10-year time frame, subject to funding and based on a phased implementation approach.

AN OPEN INNOVATION PLATFORM

The future EuPRAXIA platform is designed as a distributed research infrastructure across six countries, with two construction sites and four support centres distributed across several European countries [19]. The facility's two construction sites are dedicated to user operation, each exhibiting 2-3 beamlines generating high-quality electron bunches and secondary photon & particle beams [18]. For the four support sites the focus lies on internal R&D. Based on existing infrastructures, they will be set up to prototype and mature the new technologies designed for EuPRAXIA. They will also act as continuous test beds for future developments and components, as the user machine sites implement upgrades throughout their operational phase. Considering both the future potential of plasma acceleration to open up new applications and markets as a complementary technology to RF machines, and the vision of EuPRAXIA as a facilitating platform in this development, a facility model based on Open Innovation is considered a very suitable strategy. Figure 3 summarizes what EuPRAXIA's Open Innovation model could effectively look like. Beyond a strong exchange of expertise within EuPRAXIA, its interactions with external partners and users – here defined as three main groups [34] – are essential. EuPRAXIA could bring together these types of users traditionally at different points along a product development chain, from students as future researchers to co-developers to beam / end users of the same technology. Thus, a unique environment could be created where knowledge, perspectives and interests can be exchanged through direct means, such as user workshops, and more indirect ones, such as the shared use of beamlines and facilities. The involvement of industry as users, co-developers and suppliers would play an essential role in this context as a more direct path for the science at EuPRAXIA to reach innovation and commercialization.

SUMMARY

In conclusion, the key technical and scientific goals of EuPRAXIA have been developed with the conceptual results showing clear R&D strategies and problem-solving approaches. The EuPRAXIA facility concept foresees a distributed infrastructure of two user machine and four support sites across Europe. It is proposed to adopt an Open Innovation framework with a conscious user definition and strong industry involvement as a most effective long-term path towards advancing plasma accelerator technology from user readiness to novel applications and markets. A more detailed and completed version of the EuPRAXIA machine and facility design will be published in October 2019 in the form of a Conceptual Design Report.

REFERENCES

[1] S. P. D. Mangles *et al.*, "Monoenergetic beams of relativistic electrons from intense laser–plasma interactions", *Nature*, vol. 431, p. 535, 2004. doi:10.1038/nature02939

ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-THPGW026

[2] C. G. R. Geddes *et al.*, “High-quality electron beams from a laser wakefield accelerator using plasma-channel guiding”, *Nature*, vol. 431, p. 538, 2004. doi:10.1038/nature02900

[3] J. Faure *et al.*, “A laser–plasma accelerator producing monoenergetic electron beams”, *Nature*, vol. 431, p. 541, 2004. doi:10.1038/nature02963

[4] A. J. Gonsalves *et al.*, "Petawatt laser guiding and electron beam acceleration to 8 GeV in a laser-heated capillary discharge waveguide, *Phy. Rev. Lett.*, vol. 122, p. 084801, 2019. doi:10.1103/PhysRevLett.122.084801

[5] I. Blumenfeld *et al.,* "Energy doubling of 42~GeV electrons in a metre-scale plasma wakefield accelerator", *Nature*, vol. 445, pp. 741 – 744, 2007. doi:10.1038/nature05538

[6] S. Steinke *et al.*, "Staging of laser-plasma accelerators", *Phys. Plasmas*, vol. 23, p. 056705, 2016. doi:10.1063/1.4948280

[7] H.-P. Schlenvoigt *et al.*, "A compact synchrotron radiation source driven by a laser-plasma wakefield accelerator", *Nature Phys.*, vol. 4, pp. 130 – 133, 2008. doi:10.1038/nphys811

[8] M. Fuchs *et al.*, "Laser-driven soft-X-ray undulator source", *Nature Phys.*, vol. 5, pp. 826 – 829, 2009. doi: 10.1038/NPHYS140

[9] M. P. Anania et al., “An ultrashort pulse ultra-violet radiation undulator source driven by a laser plasma wakefield accelerator”, Appl. Phys. Lett., vol. 104, p. 264102, 2014. doi:10.1063/1.4886997

[10] N. Delbos *et al.*, “LUX – a laser-plasma driven undulator beamline”, *Nucl. Instrum. Methods Phys. Res. A*, vol. 909, pp. 318 – 322, 2018. doi:10.1016/j.nima.2018.01.082

[11] R. Brinkmann *et al.*, "Chirp mitigation of plasma-accelerated beams by a modulated plasma density", *Phys. Rev. Lett.*, vol. 118, p. 214801, 2017. doi:10.1103/PhysRevLett.118.214801

[12] P. A. Walker et al., “Horizon 2020 EuPRAXIA design study”, *IOP Conf. Series: Journal of Physics: Conf. Series*, vol. 874, p. 012029, 2017. doi:10.1088/1742-6596/874/1/012029

[13] EuPRAXIA, www.eupraxia-project.eu/participants.html

[14] P. A. P. Nghiem *et al.*, “EuPRAXIA, a step toward a plasma-wakefield based accelerator with high quality beam”, presented at the 10th Int. Particle Accelerator Conf. (IPAC'19), Melbourne, Australia, May 2019, paper WEZZPLS2, this conference.

[15] A. Ferran Pousa, R. Assmann, R. Brinkmann, and A. Martinez de la Ossa, "External injection into a laser-driven plasma accelerator with sub-femtosecond timing jitter", *IOP Conf. Series: Journal of Physics: Conf. Series*, vol. 874, p. 012032, 2017. doi :10.1088/1742-6596/874/1/012032

[16] G.G. Manahan *et al.*, "Single-stage plasma-based correlated energy spread compensation for ultrahigh 6D brightness electron beams", *Nature Comm.*, vol. 8, p. 15705, 2017. doi: 10.1038/ncomms15705

[17] A. Ferran Pousa, A. Martinez de la Ossa, R. Brinkmann, and R. W. Assmann, "Correlated energy spread compensation in multi-stage plasma-based accelerators", 2018. arXiv:1811.07757v1 [physics.acc-ph]

[18] P. Niknejadi *et al.*, “FLASHforward Findings for the EuPRAXIA Design Study and the Next-Generation of Compact Accelerator Facilities”, presented at the 10th Int. Particle Accelerator Conf. (IPAC'19), Melbourne, Australia, May 2019, paper THPGW019, this conference.

[19] P. A. Walker *et al.*, “Layout Considerations for a European Plasma Research Accelerator Infrastructure (EuPRAXIA)”, presented at the 10th Int. Particle Accelerator Conf. (IPAC'19), Melbourne, Australia, May 2019, paper THPGW025, this conference.

[20] R. Ganter *et al.*, “Swiss FEL Conceptual Design Report”, Paul Scherrer Institut, Villigen, Switzerland, PSI Rep. No. 10-04, April 2012.

[21] R. Pompili *et al.*, "Compact and tunable focusing device for plasma wakefield acceleration", *Rev. Sci. Instrum.*, vol. 89, p. 033302, 2018. doi:10.1063/1.5006134

[22] Cianchi, A. *et al.*, "Conceptual design of electron beam diagnostics for high brightness plasma accelerator", *Nucl. Instrum. Methods Phys. Res. A*, vol. 909, pp. 350 – 354, 2018. doi:10.1016/j.nima.2018.02.095

[23] Cianchi, A. *et al.*, "Frontiers of beam diagnostics in plasma accelerators: Measuring the ultra-fast and ultra-cold", *Phys. Plasmas*, vol. 25, p. 056704, 2018. doi:10.1063/1.5017847

[24] L. A. Gizzi, L. Labate, M. Vannini, Z. Mazzotta, G. Toci, and M. Mathieu, “Lasers for Novel Accelerators”, presented at the 10th Int. Particle Accelerator Conf. (IPAC'19), Melbourne, Australia, May 2019, paper FRYPLM2, this conference.

[25] L.A. Gizzi *et al.*, "A viable laser driver for a user plasma accelerator", *Nucl. Instrum. Methods Phys. Res. A*, vol. 909, pp. 58 – 66, 2018. doi:10.1016/j.nima.2018.02.089

[26] R. Platz, B. Eppich, J. Rieprich, W. Pittroff, G. Erbert, and P. Crump, "High duty cycle, highly efficient fiber coupled 940-nm pump module for high-energy solid-state lasers", *High Power Laser Science and Engineering*, vol. 4, p. E3, 2016. doi:10.1017/hpl.2016.5

[27] A. Brachmann, "LCLS Parameters – Update December 2017", SLAC National Accelerator Laboratory, Menlo Park, USA, Dec 2017. https://portal.slac.stanford.edu/sites/lclscore_public/Accelerator_Physics_Published_Documents/LCLS-parameters-3-22-17.pdf

[28] J. Arthur *et al.*, "Linac Coherent Light Source (LCLS) Conceptual Design Report", SLAC National Accelerator Laboratory, Menlo Park, USA,Rep. SLAC-R-593, Apr 2002.

[29] M. Altarelli *et al.*, "The European X-Ray Free-Electron Laser - Technical design report", DESY, Hamburg, Germany, Rep. DESY 2006-097, Jul 2007.

[30] Elettra and FERMI lightsources, https://www.elettra.trieste.it/lightsources/fermi/fermi-machine/machineparameter.html

[31] INFN - Laboratori Nazionali di Frascati, https://www.lnf.infn.it/acceleratori/sparc/parameters.html

[32] T. Raubenheimer, "LCLS-II-HE FEL Facility Overview", presented at the Workshop on Scientific Opportunities for Ultrafast Hard X-rays at High Rep. Rate, Menlo Park, USA, Sep 2016. https://portal.slac.stanford.edu/sites/conf_public/lclsiihe2016/Documents/160926%20LCLS-II-HE%20Raubenheimer.pdf

[33] M. Ferrario *et al.*, “EUPRAXIA@SPARC_LAB design study towards a compact FEL facility at LNF”, *Nucl. Instrum. Methods Phys. Res. A*, vol. 909, pp. 134 – 138, 2018. doi:10.1016/j.nima.2018.01.094

[34] M. K. Weikum *et al.*, "EuPRAXIA - a compact, cost-efficient particle and radiation source", in Proc. CAARI'18, Grapevine, USA, Aug 2018, to be published.