Layout considerations for a future electron plasma research accelerator facility EuPRAXIA

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Abstract:
The Horizon 2020 Project EuPRAXIA (“European Plasma Research Accelerator with eXcellence In Applications”) is preparing a conceptual design for a highly compact and cost-effective European facility with multi-GeV electron beams using plasma as the acceleration medium. The design includes two user areas: one for FEL science and one for High Energy Physics (HEP) detector development and other pilot applications. The accelerator facility will be based on a laser and/or a beam driven plasma acceleration approach. This contribution introduces layout considerations of the future plasma accelerator facilities in the context of EuPRAXIA. It compares conventional and novel plasma accelerator facility requirements and presents potential layouts for the future site. Together with performance analysis, cost effectiveness, and targeted user cases of the individual configurations, such layout studies will later enable a ranking of potential configurations. Based on this information the optimal combination of technologies will be defined for the 2019 conceptual design report of the EuPRAXIA facility.

1. Introduction

16 European partner laboratories and additional 22 associated partners from the EU, Israel, China, Japan, Russia and the USA [1, 2] have formed the EuPRAXIA collaboration. EuPRAXIA is structured into 14 working packages of which eight work packages (“WP”) receive direct 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 tabletop test beam for HEP and other applications (WP7). WP1 and WP8 concentrate on management and outreach to the public, respectively. 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. Partners from industry are Amplitude Technologies, Thales and Trumpf Scientific which contribute their experience towards a successful completion of the design report.

2. Plasma acceleration

Plasma acceleration has been first proposed by Veksler [2] and Tajima and Dawson [3] decades ago. Both electron beams (plasma wakefield acceleration, PWFA) or intense laser pulses (laser wakefield acceleration, LWFA) are well suited for accelerating charged particles [4] by creating longitudinal plasma waves. While many advances have been achieved over the last two decades [5-25], both within the PWFA and LWFA community, this paper concentrates on combining the advances of both within in one facility. It describes the current approach to plan a facility based on the best available technology and available simulations.
3. Layout considerations

Because 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 considered at this point of the EuPRAXIA study, the design of the facility considers all of these techniques. The final EuPRAXIA facility design will include either one or several of the proposed options depending on the available funding and the science targeted.

The first iteration of the design parameters to provide a 5 GeV beam, FEL radiation and other pilot applications such as positron production, detector tests, and compact X-ray sources, was published in October 2016 [31]. A more detailed description of all goal parameters can be found in [1, 31]. The different configurations to achieve these goals 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).

These configurations of a potential layout of the EuPRAXIA accelerator tunnel [43] are shown in Figure 1, excluding user areas. Configurations 1 to 4 are visualized with configuration 5 being able to be implemented in configuration 1 to 4. All RF and laser infrastructure is being supplied from the level above (laser paths are shown in red) and undulators are shown in the bottom right corners (yellow).

Figure 1a depicts configuration 1: LWFA with internal injection in which two plasma stages are included supplied with two laser beams (red). Figure 1b shows configuration 2: LWFA with external injection from an RF accelerator. The RF gun and S-band structures are shown in front of a dogleg which transports the electrons to the two plasma stages. In addition to the S-band structures, where acceleration is achieved with S-band sections (more than the 3 shown) and with an additional chicane, X-band structures could be used behind the S-band structure to accelerate the beam up to 540 MeV before the beam is transported to the plasma cell. Configuration 3 is shown in Figure 1c: LWFA with external injection from a laser plasma injector. The externally injected electron beam could be supplied by the laser plasma injector, which is driven by a separate laser (faint red line). And Figure 1d depicts configuration 4: beam driven plasma acceleration. Using the same infrastructure of RF gun and S-band structure, the PWFA case uses additional X-band structures to accelerate beams to ~500 MeV before using it inside a single plasma accelerator stage. The footprint of the accelerator tunnel could be up to 5 times smaller than in conventional accelerator facilities.

The two-level layout of the building is shown in Figure 2, in which the RF and laser infrastructure for RF and plasma acceleration cavities on the first floor is shown. On a third level (not shown) other infrastructure such as heating, cooling and electricity supplies could be located. EuPRAXIA is a site-independent design study and potential sites that have been discussed are: EuPRAXIA@SPARC_LAB (Frascati, Italy), SINBAD (Hamburg, Germany), CILEX (Paris, France), CLF (Didcot, UK) and ELI_beams (Prague, Czech Republic).

4. 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. Both laser and electron beams are considered as power sources for the plasma accelerator and a potential layout is presented. The final facility layout may only include one or two configurations dependent on user needs and funding available. This decision will be made in 2019.
Figure 1. The preliminary layout of the EUPRAXIA accelerator tunnel is shown. Four of the five configurations are depicted, with the configuration 5 being able to be implemented in all previous configurations.

Figure 2. The two level structure for the preliminary EuPRAXIA layout is shown: above the accelerator tunnel, with RF, plasma cavities, and undulators, the infrastructure of the RF and laser power sources is positioned. The high power laser will be available in the user areas, as indicated by the faint red line.
References
[1] P. A. Walker et al., Horizon 2020 EuPRAXIA design study, J. Phys.: Conf. Ser. 874, 012029 (2017)
[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 centimetre-scale accelerator Nat. Phys. 2(10):696–699
[12] Wang X et al. 2012 Petawatt-laser-driven wakefield acceleration of electrons to 2 GeV in 1017 cm3 plasma wave 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 2011(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

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