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DELIVERABLE REPORT

FINAL EURONNAC2 REPORT –
A EUROPEAN ROADMAP

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Abstract:

The European Network for Novel Accelerators EuroNNAc2 (WP7) is bringing together 54 institutes from Europe and the world. It promotes novel accelerator technologies that can provide orders of magnitude higher accelerating fields and thus have the potential for significantly reduced size and cost and for new applications. This report describes the present European roadmap towards a future generation of novel plasma accelerators with applications in photon science, particle physics, health and other fields, as it has been worked out over the last 4 years. Both the EuPRAXIA and AWAKE collaborations and their strategic importance are described. An outlook to plasma-enhanced or plasma-based linear colliders is given.

For more information on EuCARD-2, its partners and contributors please see http://eucard2.web.cern.ch/.

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	Name	**Partner**	**Date**
Authored by	R. Assmann	DESY	08/06/2017
Reviewed by	S. Schäfer	DESY	08/06/2017
Approved by WP coordinator	R. Assmann	DESY	08/06/2017
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1. EXECUTIVE SUMMARY

The European Network for Novel Accelerators (EuroNNAc2) has been discussing within its 54 member institutes a strategy for European R&D on advanced accelerators since 2013. This strategy is rapidly evolving and depends on technical progress, user opportunities and funding support. The present status is presented. The plans are closely discussed and to a large extent coordinated with international activities, in particular the ImPACT program in Japan and the DOE funded advanced accelerator R&D in the US.

The EuroNNAc2 strategy has been focusing first on plasma accelerators. Other methods relying on laser or THz driven dielectric accelerators are included in the discussions but are presently less advanced. These alternative methods are therefore not included into our application-oriented strategy. The EuroNNAc2 strategy involves the definition of common facilities in Europe to advance the state of development.

AWAKE at CERN is such a multi-laboratory effort to show the feasibility of proton-driven plasma acceleration. The AWAKE effort could lay the foundation of future plasma-based high energy physics colliders with good energy efficiency.

EuPRAXIA is a Horizon2020 design study, supported by 16 partners and 22 associated partners from the EuroNNAc context. It will produce a conceptual design report for the worldwide first 5 GeV plasma-based accelerator with industrial beam quality and user areas. EuPRAXIA is the required intermediate step between proof-of-principle experiments and ground-breaking, ultra-compact accelerators for science, industry, medicine or (on the long term) the energy frontier ("plasma linear collider"). The study is designing accelerator technology, laser systems and feedbacks for improving the quality of plasma-accelerated beams. Two user areas are being developed for a novel Free Electron Laser and High Energy Physics detector science. EuPRAXIA, if constructed, would be a new large research infrastructure with an estimated footprint of about 250 m. The design study is laying the foundation for a possible decision on start of construction in 2020.

The above-mentioned common experiments and facilities will help promoting and advancing the required R&D towards a possible plasma linear collider at the Higgs energy or above. It is our goal to solve the major open issues such that a plasma linear collider can be seriously considered by the mid-2030's when the LHC physics program will be completed. A first draft European roadmap towards this goal is included in this report.

Conceptual and strategic discussions are presently expanding as new experimental facilities will come online (e.g. ELI and CILEX) and as international strategy discussions are picking up momentum (e.g. driven by the ICFA panel for advanced novel accelerators ANA or in the new LEAPS initiative). EuroNNAc2 network members are involved in these activities and the network is providing input and support to national and international activities.

2. INTRODUCTION

It is well established that plasmas can be used to transform transverse fields into longitudinal fields [TAJ95]. Transverse fields in the plasma can be excited by short pulses of laser light (high transverse electrical fields, ponderomotive force) or by pulses of charged particles (space charge force). The principle of such a “plasma converter” is best understood by considering a short pulse of charged particles that is sent into a neutral plasma channel, a fully ionized gas with equal distribution of ions and free electrons. The plasma response to a short electron beam is then easily understood:

1. The electron driver pulse enters the plasma and expels the free electrons that are transversely accelerated (transverse driving force). The plasma ions move a negligible amount due to their higher mass.
2. Along the path of the e- driver pulse a positively charged ion channel is formed. Plasma electrons have been pushed out transversely by space charge.
3. Once the e- driver pulse has passed, the plasma electrons rush back in, attracted by the ion channel (transverse restoring force).
4. Due to their speed, they over-shoot the centre of the ion channel, rush back out and are attracted back by the ion channel. A space charge driven oscillation has formed.
5. Alternating regions of negative net charge and positive net charge form behind the driver beam pulse. Strong longitudinal fields are induced (``plasma wakefields").

The detailed dynamics of this process depends on the plasma density (determines plasma wavelength and accelerating gradient) and the transverse and longitudinal density of the driving beam pulse.

Electron beam-driven experiments were pioneered at SLAC and **accelerating gradients of up to 53 GV/m were reached over a length of 85 cm** [BLU07]. Alternatives for powerful drivers are short laser pulses (a 100 TW laser can have a transverse electrical field of 22 TV/m that can partially be converted into a longitudinal accelerating field). Laser-driven accelerators have generated GeV-class electron beams with **longitudinal accelerating gradients of up to 100 GeV/m** over several cm’s, achieving an rms energy spread of down to 1.5 % (see for example [LEE06]). Proton beams as drivers for plasma wakefields have only recently been investigated theoretically [CAL09] and experiments are under way at CERN [ADL11, ASS11]. The use of ultra-high gradient dielectric structures is also being studied and is making progress.

Straw man proposals for plasma-based linear collider concepts have been worked out for different driver techniques. These proposals are in a very early stage and cannot yet be used as a basis for construction projects. However, they highlight already the potential and issues of the various acceleration techniques that are presently under study. Each driver concept exhibits particular benefits. For example, laser driven linear colliders would benefit from the immense technological advances in laser science, however, would need 100’s of laser systems with still to be developed efficiency. Electron-driven plasma accelerators would rely on short electron beams that are available today with good efficiency, however, would still require 10’s to 100’s of stages. Proton beam drivers need R&D but can transfer higher energy (10-100 kJ in a proton bunch versus about 100 J in an electron beam driver and a few J in a laser driver). A single or a few accelerating p-driven stages could be sufficient for a TeV scale linear collider.

It is noted that the optimum choice or combination of advanced technologies depends on the required beam energy and beam power. For example, compact advanced accelerators for medicine and photon science require quite different drivers than particle physics colliders. Some topics are only of interest for particle physics and require specific support from High Energy Physics for further development. A good example is the topic of polarized beams in plasma, which has so far only been considered in theory [VIE11].

The strategy defined within the EuroNNAc2 network shall address the challenges that have been put forward by the communities for High Energy Physics (HEP) and Photon Science.

The European Strategy for Particle Physics in 2013 calls for a "…vigorous accelerator R&D programme, including high-field magnets and high-gradient accelerating structures...". Plasma accelerating structures, as they shall be further developed in this work, define the frontier in high gradient acceleration and therefore address this important challenge. The May 2014 Particle Physics Project Prioritization Panel (P5) report on "Building for Discovery – Strategic Plan for U.S. Particle Physics in the Global Context" identifies the "critical need for technical breakthroughs that will yield more cost-effective accelerators. For example, ultra-high gradient accelerator techniques will require the development of power sources …, and accelerating structures (plasmas, metallic, and dielectric) that can sustain high average power, have high damage threshold, and can be cascaded."

The European strategy for novel accelerators shall address the development of these ultra-high gradient accelerator structures. Finally, the 2009 report on "Next-Generation Photon Sources for Grand Challenges in Science and Energy" (p65/66) already pinpoints the user case: "The peak brilliance of this new source could be comparable with that of conventional accelerator-based FELs, while the average brilliance still needs substantial progress in pulsed-laser technologies to be considered competitive … As with many laser-based sources, the main advantage would not be the replacement of, but rather complementarity with, existing large-scale facilities to benefit a large user community."

As introduced above, proof-of-principle measurements for GeV-class plasma acceleration have been published in high-ranking journals and the physics principles are proven. The science communities have assessed plasma acceleration and have confirmed its potential, as seen in the quotes above. Issues and problems are known, are predominantly of technical nature and requirements for improvements have been listed.

The EuroNNAc2 network pursues the approach that **user beam quality for plasma accelerators** can be achieved with **adequate resources** and a **combined effort from experts** in different laboratories with a large range of expert competences. No fundamental issue that prevents these objectives is known today. It can be seen from Figure 1 that there are many institutes in Europe involved in advanced accelerator research and that there are 16 major research facilities operating or under construction in Europe. A coordinated strategy is required for creating a "combined effort" as mentioned above.

The AWAKE experiment is developing proton beams as new and hopefully highly efficient power sources for plasma accelerators. The high stored power in a single proton bunch should allow driving electrons with a single or few acceleration stages to high beam energy. This is required for a particle physics collider.

The EuPRAXIA project aims at using the available power source technology of modern lasers as of today and will not address limitations in the power source, except stability. We appreciate that laser efficiency and repetition rate are important issues for high power applications like plasma linear colliders, requiring R&D and significant improvements. There are several Horizon 2020 proposals for the Future Emerging Technology (FET) program on the subject of innovative laser power sources and higher efficiencies. As examples we mention the IZEST and XCAN activities. The EuPRAXIA partners are linked to these efforts. Low energy use cases would profit from progress in power source technology but do not require this.

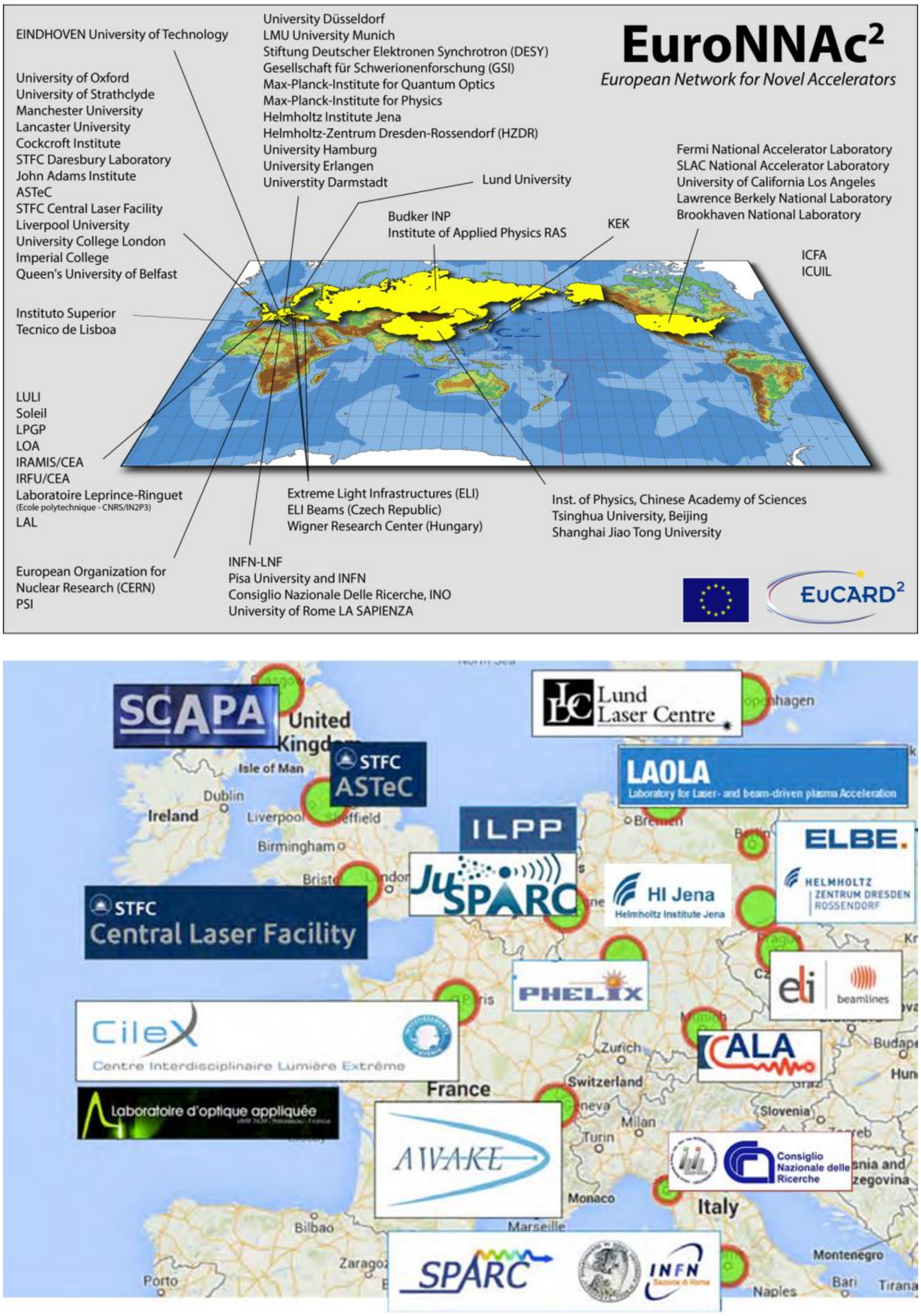

Figure 1: Top – European Network for Novel Accelerators: Membership and geographic distribution of the network. While the network is centred in Europe it is open to associated partners in Asia and the US. Bottom – Major experimental facilities for novel accelerator R&D in Europe.

3. BUILDING THE COMMUNITY

A coordinated research plan is the outcome of common discussions, meetings, brain-storming sessions and workshops. The European Network for Novel Accelerators EuroNNAc2 is organizing or co-organizing events for stimulating discussions in the accelerator and user communities. We present a selection of important EuroNNAc2-related events in the following.

3.1. 1ST AND 2ND EUROPEAN ADVANCED ACCELERATOR CONCEPTS WORKSHOP (EAAC2013 & EAAC2015) IN ELBA ITALY

A major outcome of EuroNNAc (WP7) is the founding of the European Advanced Accelerator Concepts Workshop (EAAC) and its successful organization in 2013 and 2015. It is interleaved with the long-standing Advanced Accelerator Concepts Workshop (AAC) in the US that takes place in even years. The EAAC provides for the first time a European forum for advanced accelerators. The 2nd EAAC in 2015 attracted 258 registered participants from 23 countries in 4 continents, illustrating the interest and wide support for such a European event. See Figure 2. About 16% of all participants were female scientists and about 20% were doctoral students. While we see still an imbalance in gender distribution, we remark that the innovative research on novel accelerators proves to attract more female scientists and more young researchers than usual in the quite technical accelerator field.

Concerning the scientific outcome of the EAAC we note that in 2015 in total 176 talks and 76 posters were presented. Several common experiments in European facilities were conceived at the 2013 and 2015 workshops. The proceedings of the EAAC are peer-reviewed and published in special volumes of the journal Nuclear Instruments & Methods A. From the first two EAAC workshops we published 131 papers, documenting the results and progress achieved. These publications will serve as a legacy of our work. We note that the EAAC2015 proceedings include 81 papers and were published in 2016. Within less than one year these papers were cited 83 times, illustrating the relevance and the impact of this work. The strategic approach for a European Plasma Research Accelerator with eXcellence In Applications (EuPRAXIA) was born at the EAAC.

See: https://agenda.infn.it/conferenceDisplay.py?confId=5564 and
https://agenda.infn.it/conferenceDisplay.py?confId=8146.

Figure 2: Participants at the European Advanced Accelerator Concepts Workshop (EAAC) that took place in 2015 on the Island of Elba in Italy.

3.2. THE PHYSICS AND APPLICATIONS OF HIGH BRIGHTNESS BEAMS IN HAVANA, CUBA

An ICFA and UNESCO endorsed workshop took place from March 28 to April 1, 2016 at the Hotel Nacional in Havana, Cuba. The location of the workshop indicates a continuing commitment to outreach in our field, to include a wider range of participants, including scientists from less developed countries. This workshop gathered leaders in advanced and novel acceleration techniques, experts in the intricate physics and technology of free-electron lasers, practitioners of high brightness beam physics, including those developing cutting edge concepts such as plasma-based electron beam sources and interdisciplinary researchers with direct interest in two or more of these fields. The workshop was co-organized by EuroNNAc2. Given that Cuba was hosting this workshop a particular focus was on health applications.

3.3. EUPRAXIA AND EURONNAC WORKSHOP IN PISA, ITALY

Particle accelerator experts from around the world met together with experts from the laser and novel accelerator community to discuss the design of an innovative European Plasma Accelerator in the framework of the EuPRAXIA and EuroNNAc2 projects. This science workshop took place from June 29th to July 1st at Area della Ricerca in Pisa, Italy and was hosted by Istituto Nazionale di Ottica - CNR. See https://indico.cern.ch/event/489461/.

The meeting was sponsored by INO-CNR, INFN, the European Network for Novel Accelerators (FP7/EuroNNAc2), the European Coordination of Accelerator R&D project (FP7/EuCARD2) and the Horizon2020 Design Study EuPRAXIA.

Figure 3: Participants of the EuPraxia-EuroNNAc workshop in Pisa

3.4. USER MINI WORKSHOP IN PARIS, FRANCE

The EuroNNAC and EuPRAXIA Workshop on Pilot Applications of Electron Plasma Accelerators (PAEPA) took place between 11th and 13th of October 2016 at Ecole polytechnique, Palaiseau France. 22 invited participants from four countries surveyed potential applications and corresponding requirements for EuPRAXIA electron beams. There were 22 presentations in 6 sessions. More than half of the time in each session was dedicated to discussions. The requirements in terms of beam parameters and infrastructure were defined to best possible knowledge by the participants, and were compiled and documented in a parameter table. The participants provided parameter ranges of the electron beam to be produced for the following applications:

1. Biology and medical physics
2. Test beams for high energy physics detectors
3. Experiments for dark matter searches
4. Inverse Compton scattering gamma ray sources (>1MeV)
5. Positron and muon sources
6. Neutral beam sources (e+/e– plasma)

Plasma based accelerator devices (plasma undulator for X-ray production, plasma decelerator as beam dump) were also discussed and were identified to fall within the scope of promising applications. The required characteristics of X-rays produced by betatron radiation in plasma accelerators for phase contrast imaging and for preclinical therapy were provided as well. It was seen that most applications do not put conditions on ALL beam parameters that are as stringent as those for a free-electron laser.

Several applications require not only a high-quality electron beam but in addition a synchronized laser beam in the user area, with the following characteristics in laser pulse energy and pulse duration:

High energy density physics laser needs:	>1J with ~30fs or >10J with >10ns
ICS laser needs:	1-10J with ~30fs

It has been generally agreed that we should focus on pilot applications that explicitly exploit the unique features of plasma accelerators such as the time structure and the high particle flux.

In the discussions, the question of the optimal layout of a facility has been raised. It has to be studied if driving an FEL injection beamline and providing beams to the above-mentioned applications from a single electron plasma accelerator are feasible. Even if these usages could be staged in time according to achieved beam specifications, space constraints may render this scheme difficult or impossible to implement. Providing two (or more) plasma accelerator stages pumped by the same driver is an alternative that should be considered, given that the cost for an extra plasma accelerator is expected to be low with respect to multiple drivers.

See https://indico.cern.ch/event/569936/.

Figure 4: Group photo of the PAEPA participants in front of the École polytechnique lake.

3.5. XBEAMS/EURONNAC WORKSHOP FOCUS: FUTURE FRONTIERS IN ACCELERATORS (F3IA) IN SCHARBEUTZ, GERMANY

The F^{3}iA workshop took place in Scharbeutz, at the Baltic Sea in Germany from 5-9 December 2016. The theme was "Looking beyond FCC, ILC, XFELs, ultimate storage rings, ESS, etc. - towards PeV colliders, advanced concepts, novel approaches, ultimate limits, higher intensity". The workshop gathered 24 invited participants from 16 different Institutes worldwide (Japan, USA, Italy, France, Germany and Switzerland).

The participants discussed a broad range of ideas for future accelerator developments from new acceleration schemes for compact accelerators, to very large accelerators, options for energy efficiency and recovery, concepts for keV photon beams, new accelerator components from 3D printing and the cheapness frontier for accelerators.

See https://indico.desy.de/conferenceDisplay.py?confId=15657.

Figure 5: Group photo of the F3iA workshop participants in Scharbeutz, Germany

3.6. ADVANCED AND NOVEL ACCELERATORS FOR HIGH ENERGY PHYSICS ROADMAP WORKSHOP 2017, GENEVA, SWITZERLAND

EuroNNAc participated to a strategy workshop for plasma accelerators, organized by the ICFA Panel for Advanced Novel Accelerators (ANA) and chaired by B. Cros. The EuroNNAc2 coordinator joined the organization committee and helped in organizing this workshop in his EuroNNAc2 role. The EuroNNAc2 network and its adopted strategy (as described in this report) were presented as European input to the workshop discussions.

See https://indico.cern.ch/event/569406/.

4. BUILDING THE SCIENCE AND STRATEGY ROADMAP

The EuroNNAc2 scientists have participated to various strategic discussions and have produced a number of strategy documents or project proposals during the EuCARD2 project. Major components of these considerations and documents are put together in this report, describing the 2017 status of the European strategy for novel accelerators, as it has developed and is visible today.

4.1. EURONNAC2 INPUT TO THE 2013 UPDATE OF THE EUROPEAN STRATEGY FOR PARTICLE PHYSICS

The European Network for Novel Accelerators has provided the following summary statements as input to the 2013 update of the European strategy for particle physics:

- Accelerator-based High Energy Physics will at some point become practically limited by the size and cost of the proposed e+e- colliders for the energy frontier.
- Plasma-based acceleration techniques have demonstrated accelerating gradients up to 3 orders of magnitudes beyond presently used RF technologies.
- Plasma acceleration tests have produced energy gains from above 4 GeV with lasers [LEE06, LEE14, CLA10, LU11, WAN12, MAN12] to 42 GeV with electron beam drivers [BLU07].
- Advanced e- beams reached 1% energy spread, 3% energy fluctuation, 1 mm-mrad emittance at 150 MeV [WIG10]. High quality GeV beams have been demonstrated [LEE06, LEE14].
- Plasma-based, ultra-high gradient accelerators therefore open the realistic vision of very compact accelerators for scientific, commercial and medical applications.
- The R&D now concentrates on beam quality, stability, staging and continuous operation. These are necessary steps towards various technological applications.
- Different ways to drive plasma wakefields are being investigated. Lasers, e-beam, p-beam drivers provide a varied and powerful toolbox for the accelerator builder.
- A quickly growing, inter-disciplinary community drives the research. It combines laser science, ultra-fast science, plasma science, diagnostics and beam physics.
- The progress in advanced accelerators benefits from strong synergy with general advances in technology, for example in the laser industry.
- A major milestone is an operational, 1 GeV compact accelerator (“table-top”). Challenges in repetition rate and stability must be addressed. This unit could become a stage in a high-energy accelerator.
- In the late 2020’s, ultra-high gradient plasma acceleration could be a powerful upgrade technology for a linear collider built with conventional RF technology.
- The diverse interests in the field require a presence now from particle physics, to make sure that specific research topics for colliders are addressed.
- Specific topics for plasma-based e+e- colliders include positron acceleration and technological issues of 100’s MW beam power (e.g. efficiency, cooling, polarization, …).

- An increased support from Particle Physics will foster the R&D on advanced acceleration techniques and will provide important help and guidance.
- Support should not just be of financial nature but also include technical collaboration on novel detectors, instrumentation, test beams and other areas of common interest.
- Ultra-high gradient plasma accelerators should be recognized and listed as essential inter-disciplinary R&D towards future e+e- colliders for HEP.

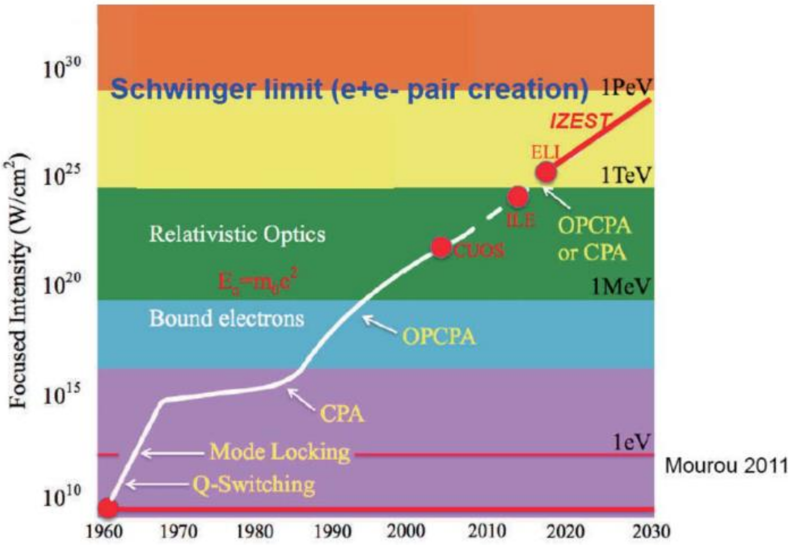

Figure 6: Updated progress in the leap of laser intensity as a function of years. From [HOM12].

4.2. VISION FOR ACCELERATORS WITH ULTRA-INTENSE LASERS

High-intensity laser fields can serve as a new tool to extend several directions of research in particle physics and cosmology in the future. Figure 6 shows the leap of laser intensity as a function of years. Several visions for high energy physics with ultra-intense lasers have recently been discussed in detail in [HOM12].

The cutting edge of the high-intensity laser is the Extreme Light Infrastructure (ELI) aiming at 10^{23-25} W/cm^2, which is approved by European Union and presently under construction. Today, a number of exawatt class facilities in Europe and in the world are already in the planning stage, like the ELI-Fourth Pillar, French LIL, and the Russian Mega Science Laser as well as Japanese Exawatt Laser. Peta-Watt lasers are being used for accelerator R&D, for example at HZDR in Germany and the BELLA facility at LBNL in the US. Several paths are discussed.

4.2.1. Use of Highest Intensity Lasers for Basic Science

The laser aspires to be the next possible paradigm in Fundamental / Particle Physics. By its coherence, monochromaticity and field magnitude, it has been the lynchpin of novel spectroscopic methods of investigation that deepened our understanding of the atomic structure. However, it was inefficient to probe the subsequent strata formed by the nucleus, the nucleon or the vacuum. Neither the laser photon energy nor its electric field has been large enough to conceive decisive experiments beyond the atomic level.

To reach the level where relevant nuclear and/or high energy physics investigations could be undertaken, large-scale laser infrastructures capable to deliver intensity in the ultra relativistic regime have been recently conceived based on the original concept introduced in 2002 [TAJ02].

1. The first embodiment is ELI. It was launched under the aegis of the European Union community and is being built in Czech Republic, Hungary and Romania. It will yield the highest peak power and laser focused intensity. With its peak power of up to 100 PW, it represents the largest planned civilian laser project in the world. This high power will be ultimately obtained by delivering few kJ in 10 fs. Focusing this power over a micrometre spot size will yield intensities in the 10^{25} W/cm^2 range, well into the ultra-relativistic regime.

   This extremely high peak intensity will correspond to the highest electric field, but also (according to the pulse intensity-duration conjecture) to the shortest pulse of high-energy particles and radiations, in the attosecond-zeptosecond regime. The particle energy, radiation and field produced with cutting-edge high intensity lasers would reach the entry point where they become relevant for Nuclear Physics, High Energy Physics or Vacuum Physics.

2. The second initiative is promulgated by the International centre on Zetta-Exawatt Science and Technology (IZEST), which was opened 2012 in France. It endeavours at the generation of exawatt-zettawatt pulses produced by the delivery of greater than 10 kJ in less than 10 fs. It relies on already built large-scale fusion lasers like the LMJ or NIF.

   To get around the grating damage threshold conundrum, a novel compression technique known as C^3 (Cascaded Compression Conversion) was conceived [MOU12]. It relies on the astute combination of the three compression techniques, CPA, OPCPA and Backward Raman Amplification (“BRA”). Based on plasma, C^3 exhibits a much superior damage threshold (10^{3-4}) than CPA or OPCPA alone. It could potentially compress more than 100 kJ to the femtosecond regime paving the way to the exawatt-zettawatt regime and laser based particle physics.

4.2.2. Laser Accelerators with kJ Lasers

When we try to reach for 100 GeV and beyond (such as TeV) the beam energies are sufficiently high for the frontier of high energy physics such as the search and study of Higgs bosons. Then it is advantageous to employ kJ lasers [NAK11]. The laser energy per stage that is required to drive a laser accelerator is inversely proportional to the plasma density to the power of 3/2. This means that we need to decrease the plasma density, while we need to increase the individual laser energy. This is an interesting route towards an eventual high energy laser accelerator. It may be called the low density paradigm of laser acceleration. In addition to the above described main advantage, low plasma density has other advantages for acceleration, such as less betatron radiation and consequential reduced beam degradation, fewer stages, smaller emittance degradation due to the jitters, etc. On the other hand, the expected elongation of the acceleration length is minor (as the optical connection between the stages are substantial and contributes to longer machine for higher densities). In order to test and promote this paradigm, we need a 1-10 kJ laser. IZEST equipped with the PEAL laser could test the described concept in this parameter regime. It is possible to test 100 GeV class experiments with or without staging.

4.2.3. High-Average Power Lasers with Improved Wall Plug Efficiency

The low-density paradigm is beneficial as described above. However, we still need on the order of 10-100 MW of electric power for lasers from the wall-plug. In order to keep this number reasonable, it is also important to have a high efficiency for these drive lasers. The ICAN (International Coherent Amplification Network) project [ICA12] aims at addressing the challenges of high average power and high efficiency laser technology that must be solved for drivers of laser accelerator based colliders. ICAN has identified fiber laser technology as the prime candidate for this driver. It has made a significant technological leap so that we can begin to see the eventual outcome of this technology product. Figure 7 shows an artist view of such a laser. The efficiency is around 30%, while average power can be on the order of 10-100 MW if we bundle up the different laser pulses coherently. In recent breakthroughs we now see that such a coherent bundling is indeed possible.

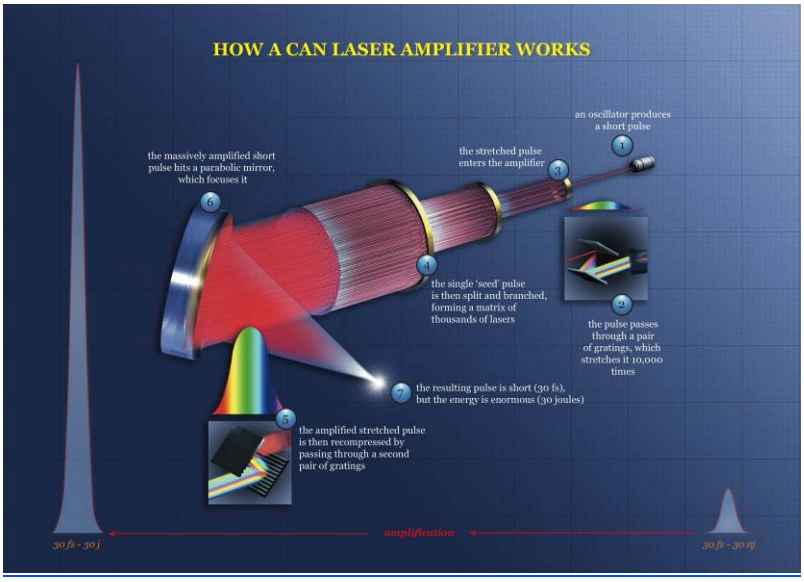

Figure 7: Principle of a CAN laser amplifier. See also text.

4.3. VISION FOR A COMPACT P-DRIVEN PLASMA ACCELERATOR: THE AWAKE PROJECT AT CERN

It has been proposed to use a high-energy proton bunch to drive a plasma wakefield for electron beam acceleration [CAL16]. The initial numerical simulations [LOT10] have shown that a 1 TeV proton bunch, with 10^{11} protons and an rms bunch length of 100 μm as driver could indeed excite a large amplitude plasma wave. Surfing the appropriate phase of the wave, the simulated electron bunch can reach energies over 600 GeV/electron in a single passage through a 450-meter plasma cell. Recent studies [KUM10, CAL11, CAL16] have shown that similar gradients can be reached with a modulated long proton bunch, opening the path for immediate experimental investigations with the existing proton bunches at CERN. The modulation of the proton density on-axis results from the modulation of the transverse profile along the bunch length. For coherent wakefield excitation, this is equivalent to having a series of ultra-short proton bunches with an effective length set by the plasma wavelength. This exciting development has led to the formation of the AWAKE Collaboration to pursue a demonstration experiment at CERN with the SPS beam. The demonstration of strong electric fields will be performed by measuring first the self-modulation of a long proton bunch and then later by the acceleration of externally injected electrons up to 1 GeV in a novel plasma cell of several meters length.

A Letter of Intent proposing an experimental study of proton-driven plasma wakefield acceleration utilizing the existing proton beam from the CERN Super Proton Synchrotron had been submitted to the CERN SPSC and received a positive review. The AWAKE Collaboration had then submitted a Conceptual Design Report and **AWAKE was then approved as an official CERN experiment.** R&D activities focused on plasma cell designs and diagnostic tools. In parallel the AWAKE facility has been constructed. First experiments with proton-induced plasma wakefields were performed at the end of 2016 by the collaboration.

The maximum wakefield amplitudes that can be achieved via the modulations of a long proton bunch were studied and parametric relations were determined [CAL11b]. In the limit of long bunches (compared to the plasma wavelength), the strength of the accelerating fields in the optimal configuration was found to be directly proportional to the transverse particle density in the drive bunch. This finding puts a premium on increasing this quantity for beams designed specifically for beam-driven wakefield acceleration via the modulation technique. The scaling laws were tested and verified in detailed simulations using parameter sets for existing or planned proton bunches at CERN; i.e., PS, SPS and LHC bunch parameters, and gradients in excess of 1 GeV/m were found (LHC case). It was found that, with excellent control of the plasma density, significant accelerating gradients could be maintained over long distances. For the LHC driver case, the protons are relativistic enough that dephasing is not a significant issue, and in this case test electrons were accelerated in simulations beyond 6 TeV. It is anticipated that the achieved energy gains could be substantially more favourable if the transverse density of protons could be improved. These exciting simulation results indicate that proton-driven PWA could indeed allow for TeV scale electron beams.

While **reaching multi-TeV electron energies looks potentially achievable with proton-driven PWA**, generating high luminosities seems impossible using existing proton drivers. A high-luminosity TeV scale proton-driven PWA will likely require a dedicated design of a rapid cycling proton accelerator. Physics topics should be investigated which would be of interest given high energies even if high luminosities are not available. The identification of such processes would open the possibility of using existing proton beams, such as that from the LHC, to investigate new physics at the mutli-TeV scale with electron beams.

Another possible use of existing proton beams for beam-driven PWA is to provide compact sources of electrons for injection into a storage ring where they can be accumulated, or in general to act as high-gradient compact accelerators. Such uses of proton drivers have not been investigated in any detail, but the existence of powerful proton beams suggests that these investigations could lead to fruitful concepts.

4.4. VISION FOR A COMPACT E-DRIVEN PLASMA ACCELERATOR WITH PILOT APPLICATIONS: THE HORIZON2020 PROJECT EUPRAXIA

The state of the art in accelerators is often summarized in the so-called Livingston curve, which shows the progress in accelerator energy versus time. Figure 8 shows an updated version of such a Livingston curve, including achievements with conventional and novel accelerators and indicating the present plans beyond today. It is seen that particle accelerators are a remarkable success story with beam energies having increased by 5 – 8 orders of magnitude since the first RF based accelerators in the 1920's. However, it is also evident that the exponential increase of beam energy with time has leveled off in conventional RF accelerators since the 1980's. Limits in conventional accelerators arise from technical limitations (e.g. breakdown effects at metallic walls of RF cavities, synchrotron power losses, maximum fields in super-conducting magnets) but also practical issues (size and cost). At the same time a new technology emerged, based on the revolutionary proposal of laser-driven plasma accelerators by Tajima and Dawson [TAJ79], and the invention of amplified chirped optical pulses (CPA) by Mourou and Strickland [MOU12].

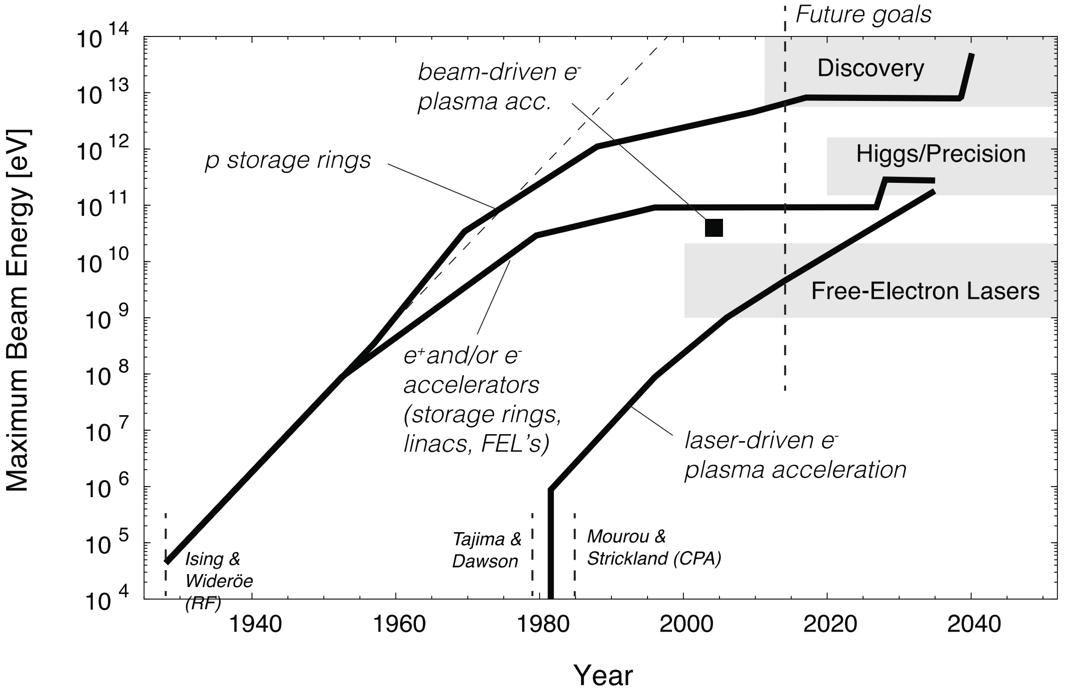

Figure 8: Livingston curve for accelerators, showing the maximum reach in beam energy versus time. Grey bands visualize accelerator applications. The left fork shows the progress in conventional accelerators from the first ideas in the 1920's. This main fork splits into two lines for electron/positron machines and for proton accelerators. A new fork of laser-driven plasma accelerators has emerged in 1980, reaching multi-GeV energies by now. Beam driven plasma acceleration results are indicated by the square point. Data beyond 2014 (vertical dashed line) indicate goals for the various technologies.

Laser plasma accelerators have seen a steep increase in energy reach since 1980 and have recently produced multi GeV electron bunches in several cm's of plasma with the record beam energy reported to be 4.25 GeV [LEE14]. Beam driven plasma experiments achieved an absolute energy gain of 42 GeV with accelerating gradients of up to 53 GV/m over a plasma length of 85 cm, however only for parts of the initially injected beam [BLU07]. The results from beam-driven plasma accelerators prove the high energy potential of the novel plasma technologies. The energies achieved in plasma accelerators have now reached the region of interest for modern free-electron lasers (FEL). The prospect of an ultra-compact, plasma-based FEL has become intriguing and world-wide research and development (R&D) is presently strongly focused on this goal.

Comparing laser-driven plasma accelerators to the state of the art in conventional accelerators we can observe the following:

1. **Plasma accelerators offer acceleration gradients that are 2 – 3 orders of magnitude higher than in conventional accelerators, therefore reducing the required acceleration length by 2 – 3 orders of magnitude**. This will allow a reduction in total accelerator size by a factor that is determined by acceleration length and the required space for lasers and transition elements.
2. Plasma accelerators successfully overcome the break-down limit that limits the accelerating gradient in metallic RF structures.
3. Plasma accelerators have so far not exhibited fundamental limitations in energy reach and are still progressing exponentially with time (see Figure 8).
4. Plasma accelerators must operate with short bunches and pulse lengths in the few femto-second and even reaching into the atto-second regime. They give access to new regimes of beam parameters. For example, plasma accelerators are natural tools for ultra-fast science and the damage-free observation of nature's fast processes. We note that the transport of short bunches is difficult but feasible.
5. Lasers required for driving plasma accelerators have become available from European industry, offering a supply chain that is not only comparable to RF industry (klystrons, modulators) but also developing in a more dynamic and innovative way.
6. **Laser-driven plasma accelerators promise a revolutionary path to more cost-effective accelerators, assuming that the reduced acceleration length can be translated into lower cost**.
7. Plasma accelerators presently offer lower beam energy than conventional accelerators. This is mainly due to the fact that cascading of plasma structures has so far not been a priority and has only recently been achieved for the first time.
8. Plasma accelerators presently offer lower beam quality than conventional accelerators. Shot-to-shot stability and optimization have only recently become a priority. The required measures tend to be expensive and work-intensive. The operation of plasma accelerators is so far limited to working hours and work days. The switching-on and switching-off generates numerous stability problems, known also in conventional accelerators.

In view of these observations the EuroNNAc2 community has proposed a Horizon2020 design study for a European Plasma Research Accelerator with eXcellence In Applications with the acronym EuPRAXIA [EUP15]. The EuPRAXIA design study has been approved and funded by the EU. It started in November 2015 with 16 partners and

22 associated partners. The study will build on the advantages of laser-driven plasma technology (topics 1 – 6), address the short-comings (topics 7 – 8) and also will include electron-driven or hybrid plasma acceleration schemes.

The situation as of today is characterized by frontier HEP colliders at a foot-print of 27 km, conventional multi-GeV FEL's at footprints of 0.5 – 1 km and proof-of-principle multi-GeV plasma accelerators at a footprint of around 30 m (including laser lab). Figures 9 and 10 show a visual summary of the present state-of-the-art, the positioning of the EuPRAXIA project and the strategic future developments and directions.

Proof-of-principle experiments for multi-GeV plasma acceleration have been successfully performed, so the idea and basic feasibility are considered proven. The EuPRAXIA design study (2015 – 2019) aims at designing the worldwide first 5 GeV plasma accelerator with usable beam quality, bringing together achievements from different experts and various fields. The successful completion of the design will provide the option of constructing such a 5 GeV European plasma accelerator in the early 2020's. This would establish for the first time operation with pilot users. **EuPRAXIA would offer a complementary beam and light source for the science communities, but also some unique ultra-fast science features. Its footprint is estimated at around 250 m, significantly more compact than existing accelerators.**

Plasma-based accelerators would become a full competitor with conventional accelerators in the late 2020's and early 2030's, based on the experience with EuPRAXIA. This is illustrated in Figures 1.5. and 1.10. At this time many of the successful optimization features of EuPRAXIA would have been reduced in size. The problem of efficient power sources will have been addressed by ongoing projects that aim at increasing drastically the efficiency of laser systems (e.g. the ICAN project described in section 4.2).

Ultra-compact accelerators ("table-top") could become a realistic possibility in the 2030's with many applications for science, industry and society. At this time a significant number of the present 30,000 accelerators in the world could be complemented by the cost-effective plasma technology.

In summary, EuPRAXIA aims at establishing a ground-breaking European design of a plasma-based accelerator with a beam quality that is compatible with user needs and even establishes new ultra-fast features. It will put plasma-based accelerators on the roadmap for future science facilities with a much-reduced footprint.

The overall concept of EuPRAXIA, as developed in the EuroNNAc2 network, is unusual and is breaking some borders in both the managerial as also the technical concept.

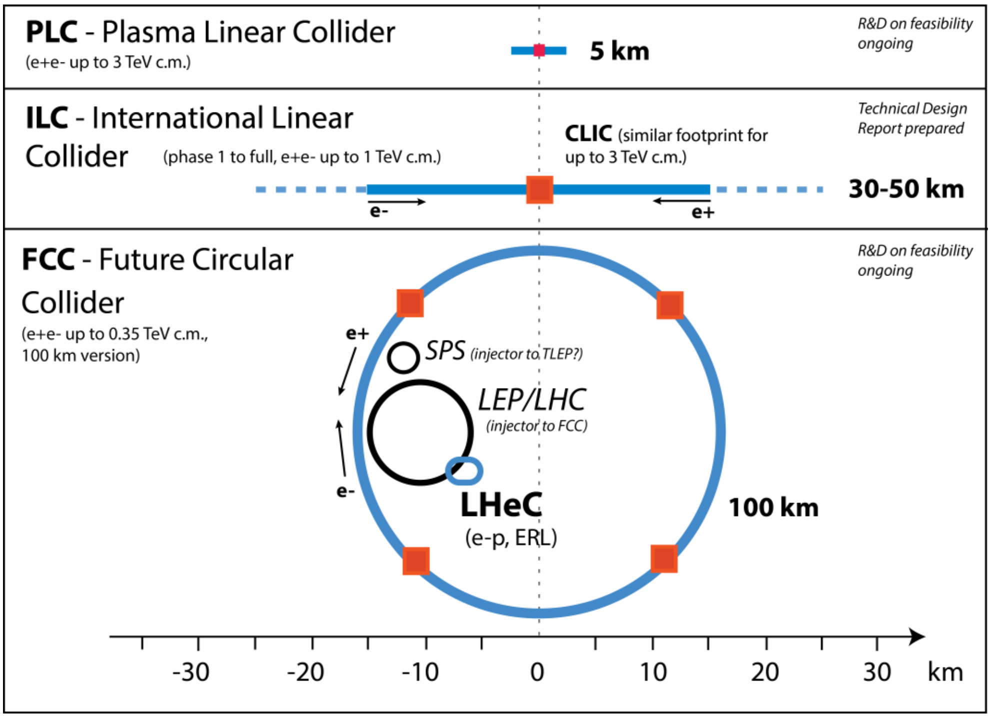

Figure 9: The footprints of various existing accelerators (solid black line for SPS, LEP/LHC) and planned projects (strong blue line for PLC, ILC, FCC, LHeC) in HEP are compared. The square (red) boxes indicate possible detectors for HEP experiments. The plasma linear collider concept aims at describing an alternative path with smaller and more cost-effective facilities. A similar reduction factor is envisaged for plasma-based FEL's.

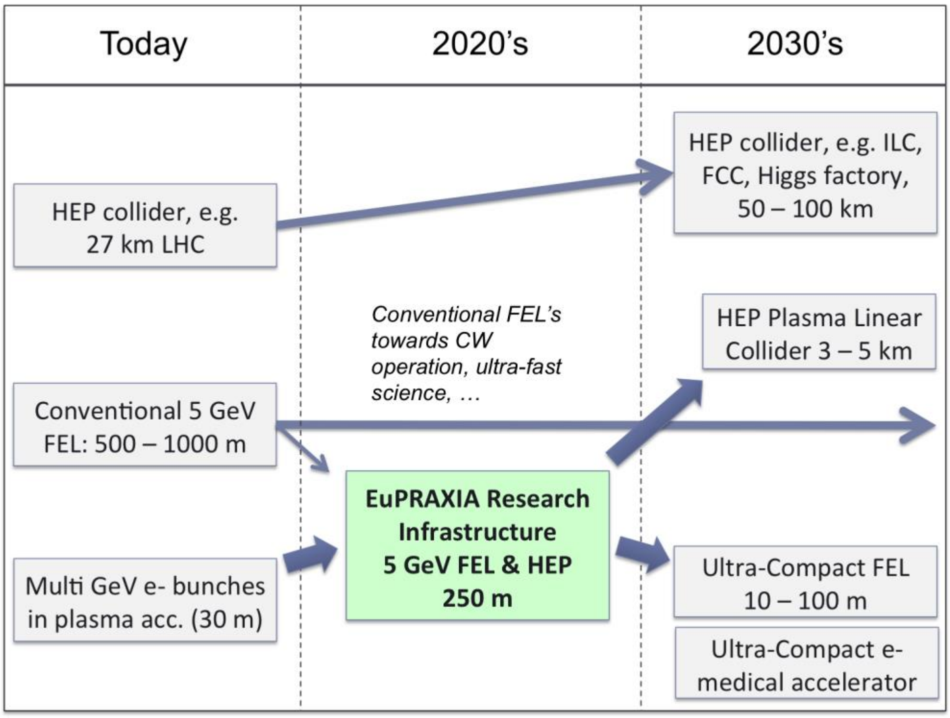

Figure 10: Strategic positioning of the EuPRAXIA project. The length scales of facilities are given including infrastructure, like the laser for plasma acceleration.

4.4.1. Managerial Concept of EuPRAXIA

The overall managerial concept assumes that plasma acceleration must move to the next stage beyond the present level of 30 – 50 M€ projects in single laboratories or countries. At the next stage (around 200 M€) there should be sufficient resources to combine expertise from many European labs and from different technical fields. It is also assumed that the next stage cannot and should not be performed at several European countries and labs in parallel. The overall managerial concept of EuPRAXIA therefore foresees a scenario where the European field comes together for common design and construction of a European plasma accelerator, which shall be installed in one central location that is identified in a common site study. Highly successful examples of this approach are large High Energy Physics detectors, big Photon Science projects but also large Telescopes. These masterpieces of modern technology are designed and constructed by wide collaborations, bringing together all required expertise, while the final device is installed and used in a central facility.

4.4.2. Technical Pillars of EuPRAXIA

The overall technical concept of the EuPRAXIA project brings together several fields of expertise that so far often are quite distinct. The concept relies on five main technical pillars:

1. Multi-GeV plasma acceleration of electron beams in laser-driven plasma structures has been achieved and reproduced. The underlying physics of plasma acceleration can be relied upon and is understood.
2. The achieved electron beam energies are in a range where many accelerators operate and are con-structed. Use cases for a linac based Free-Electron Laser (FEL) and HEP test beams are accessible for the first time.
3. Latest accelerator technology has shown the feasibility of generating and controlling small beam sizes (down to 45 nm) and short electron pulses (down to several 10 fs, less than 10 □m). At the same time, it is now possible to achieve synchronization accuracies at the 10 fs level and to keep this over 24 hours. This progress is fundamentally important for turning plasma accelerators into a realistic option for users.
4. Laser technology has reached and surpassed the 1 PW peak power level, which is required for GeV-class plasma acceleration. It is now realistic to focus technical work on improving the stability and reproducibility of laser beams and efficiency and scalability of laser installations.
5. Environmental control technology has advanced significantly, allowing, for example, temperature stabilization at sub 0.1°C, mechanical stabilization at sub-nm and various advanced correction methods.

Based on these technical pillars, bringing together different fields of expertise and knowledge, we believe that a realistic design can be established with a strong use case. Depending on the plasma density, the plasma accelerator cavity has dimensions of about 100 μm (length) times 70 μm (width), the size of a large flour mill dust particle. The importance of μm and fs engineering and control (as nowadays achieved in conventional accelerators) becomes evident. Significant synergy will be generated from the proposed combination of state-of-the-art plasma acceleration, modern lasers, latest accelerator technology, top of the line environmental control and high potential user areas. The work requires significant effort and resources for a common design. Its later implementation will require space and sufficient investment budget. The required work can only be performed with the additional resources from the EU design study EuPRAXIA, which funds the collaborative and inter-disciplinary design work.

4.4.3. Innovation Potential of EuPRAXIA

The EuPRAXIA design study prepares a 5 GeV plasma accelerator with user applications. The whole machine will be a ground-breaking innovation. It addresses the need as formulated most recently in the report of the Particle Physics Project Prioritization Panel on “Building for Discovery – Strategic Plan for U.S. Particle Physics in the Global Context”, from May 2014: “There is a critical need for technical breakthroughs that will yield more cost-effective accelerators.”

However, several other innovation potentials can be envisaged:

- Innovation can result from advances in ultra-fast electronics and control systems at the femto-s and atto-s regime, as required for EuPRAXIA. It can be envisaged that the precise timing and synchronization methods will find many applications.
- Innovation can result from the new types of plasma accelerator structures that can be cascaded, such that higher beam energy can be reached. In addition to building whole accelerators with plasma structures, one or two of these structures could be used as add-ons to existing conventional facilities, boosting the energy reach and potential for science (so-called “afterburner” concept).
- Innovation can result from new control and feedback algorithms that will be developed for lasers in the Peta-Watt class for achieving the highest possible stability and reliability. Many users and applications of lasers demand strict requirements on stability of pointing and pulsed energy. The achieved results in EuPRAXIA will be transferred to European industry.
- Innovation can result from novel, short period undulators that will be investigated for plasma accelerators. Such undulators can also find applications in conventional facilities.
- Innovation can result from the close interaction between accelerator, laser, plasma specialists and users from HEP and Photon Science. Experience shows that such a collaboration produces ideas and concepts for new experiments.

4.4.4. Impact on European industry

EuPRAXIA is presently advised by the French companies Amplitude Technologies and Thales and the Germany company TRUMPF Scientific. It is noted that European companies today set the standards for high power lasers in the Peta-Watt class. EuroNNAc2 and EuPRAXIA help the European companies in keeping this leading position and in further strengthening the European technological capacity in this domain. European industry can connect to the EuPRAXIA research infrastructure as supplier but also as user. For example it can be envisaged that industry tests and develops new laser stability measures and other technologies under the very challenging EuPRAXIA conditions and tolerances. The high demands will inspire and foster technological progress, keeping European laser industry at a leading edge.

4.4.5. New market opportunities

European industry is heavily invested in laser technology and is building the lasers for the most advanced plasma acceleration experiments. European industry is designing, building and selling accelerators for many applications, including medical, industrial and scientific purposes. European industry will therefore directly profit from the success of bringing plasma accelerators to the users and to the market. New market opportunities with high growth rates would be created. The compact size and cost-effectiveness of plasma accelerators will make accelerators space-wise feasible and/or affordable to additional users. Our dream and goal is a compact plasma FEL in the basement of every large university, a plasma accelerator for fast medical imaging in hospitals and a very compact plasma collider at a HEP lab. In many cases conventional facilities would not be replaced but complemented.

4.4.6. Knowledge transfer

EuPRAXIA would be built with parts produced by European industry, e.g. the high-power lasers and also compact magnets and undulators. Industry will then be naturally directly involved in the set up and optimization of the European plasma accelerator. Much of this work on particular components will be protected by confidentiality clauses with industry, such that the involved company will profit. General EuPRAXIA achievements, problems and solutions will be communicated to industry in workshops, schools and public events. The students and post-docs trained in EuPRAXIA will carry their knowledge to their future employers, including industry. EuPRAXIA will strengthen the competitiveness and the growth of companies.

4.5. FIRST THOUGHTS ON A ROADMAP TOWARDS HIGH-ENERGY PHYSICS PLASMA-BASED COLLIDERS

The EuroNNAc network has defined in a 2012 workshop the following six top goals for a 10 year perspective:

- Goal 1: Demonstrate working plasma-based FEL at realistic frequencies
- Goal 2: Reliable 24/7 operation of plasma-based accelerators at 1 GeV
- Goal 3: Staging
- Goal 4: High beam quality at 10 GeV from plasma accelerators
- Goal 5: GV/m positron acceleration with plasma devices while preserving emittance
- Goal 6: Demonstrate proton drivers for wake acceleration

These goals cover needs of photon science, medical applications and particle physics. If these goals can be indeed be achieved, then first operational plasma accelerators can be expected in the mid-2020's. First accelerators will operate in the GeV regime with possible applications as synchrotron radiation sources, medical beams, injection and test beams for particle physics. EuPRAXIA (described in section 4.4) is a Horizon2020 design study for such multi-GeV research infrastructure. In the second half of the 2020's, it could also be imagined to use plasma technology for boosting beam energies in conventional multi-GeV facilities.

4.5.1. R&D Topics towards an HEP Plasma-Based Collider

To achieve the top technical goals listed above, considerable work must be performed. The EuroNNAc2 network has identified the 14 most important technical R&D efforts that are presently considered in the field of advanced acceleration:

1. External optical injection
    a. Create a particle beam with laser-driven plasma source
    b. Inject into a laser-driven plasma accelerator
    c. Characterize final beam energy, quality, …
2. External RF injection
    a. Create a particle beam with an RF injector
    b. Inject into a laser-driven plasma accelerator
    c. Characterize final beam energy, quality, …
3. Laser wakefield acceleration (LWFA) with self injection
    a. Create a particle beam with laser-driven plasma source
    b. Maximize energy and/or charge
4. Multi-stage LWFA
    a. Similar to external optical injection
    b. A generic stage of laser-driven wakefield acceleration
5. Synchrotron radiation with advanced beams
    a. Transport beam from plasma injector
    b. Use to generate synchrotron radiation in classical undulators
6. Electron beam driven PWFA
    a. Use an electron beam to drive plasma wakefields
    b. Test with external injection of beam
7. Proton beam driven PWFA
    a. Use a proton beam to drive plasma wakefields
    b. Test with external injection of beam
8. Betatron radiation in plasma
    a. Off-axis oscillations of electrons within plasma wakefields
    b. Use and manipulate this process to generate synchrotron radiation
    c. Possibility for ultra-compact radiation sources (injector + transport + undulator)
9. Plasma undulator
    a. External off-axis injection into a plasma wakefield stage
    b. Any driver technology is possible
10. Stability and beam quality
    a. Measure, characterize, optimize advanced beams

   b. Any driver technology is possible

11. Polarized beams in plasmas
    a. Inject polarized beams into a plasma accelerator with any driver technology
    b. Measure depolarization
12. Positron acceleration
    a. Inject positrons into a plasma accelerator with any driver technology
    b. Measure acceleration and beam quality preservation
13. Femto-second synchronization
    a. Set up of femto-second timing and synchronization systems
    b. Cross synchronization between multiple particle and laser beam
14. Power and efficiency
    a. Technology improvement efforts to increase efficiency.
    b. Measurement of energy transfer from wall plug through laser and plasma to beam particle.
    c. Optimizing efficiency and minimizing power consumption.

These technical goals address many generic challenges for ultra-high gradient acceleration but also R&D that is specific to synchrotron radiation or particle physics applications. For example, the development of ultra-high gradient acceleration of positrons and polarized beam transport in plasmas are issues that only become relevant for e+e- colliders of particle physics. These particular topics require special support from the particle physics community to be performed in a timely matter. Figure 11 summarizes the work topics defined above and also indicates the urgency attached to the individual topics from the members of the EuroNNAc2 network.

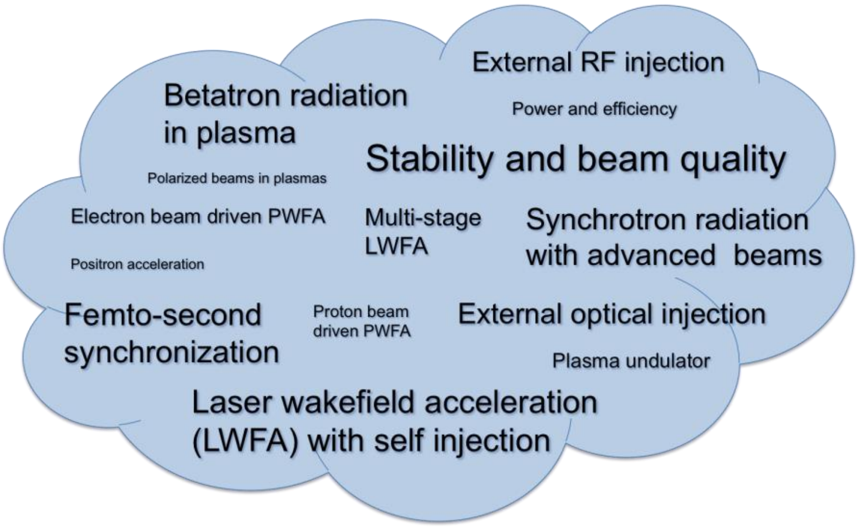

Figure 11: Graphical visualization of research topics in advanced acceleration R&D that are pursued in various facilities, as derived from Table 1. The font size reflects the priority the activity received from EuroNNAc member labs within an agreed classification scheme.

4.5.2. Plasma Technology as Upgrade Option for an HEP RF-Based Linear Collider

First, it is assumed that a linear collider based on RF technology will be constructed for the mid-2020's. Novel accelerator technology can then be used for upgrading such an RF linear collider, opening future physics reach. A possible sketch for a roadmap towards a high luminosity linear collider (conventional) with advanced features could look as follows:

- ongoing: Conceptual R&D on novel accelerators
- 2025: Conventional Linear Collider with parameters and space reservations to allow a later up-grade with ultra-high gradient acceleration techniques

  First GeV-class pilot facility of advanced, ultra-high gradient accelerators for photon science, health and other applications (e.g. EuPRAXIA research infrastructure)
- 2030: Several operational, advanced accelerator facilities, ultra-compact accelerators as "accepted" technology, focus on efficiency and higher power
- 2035: Upgrade of the existing, conventional linear collider with ultra-high gradient technology. Alternatively an independent, ultra-compact plasma linear collider can be envisaged.

Years are given as indication only, as seen from today's status. It is mentioned that an alternative approach is under study, which explores the use of laser-driven plasma accelerators for particle physics in a low luminosity paradigm. It is important to realize that an efficient upgrade approach for conventional linear colliders is only possible if its parameters are reviewed in the design phase also in respect of a future upgrade with novel technologies. For example, plasma involve short wave lengths and can therefore only be used with main linac bunches that are sufficiently short.

4.5.3. A Plasma Linear Collider for HEP

In case that a conventional linear collider or a very large hadron collider like FCC cannot be built in the foreseeable future then an alternative and cost-effective technology becomes very important and urgent. Plasma accelerators could offer a path to compact future colliders. However, all the topics listed in section 4.5.1. must be addressed. In addition the feasibility of a plasma-based user facility must have been shown for low energy applications like photon science, radiation sources or health. Only then a plasma linear collider would become a believable option for high energy physics.

Under the pre-conditions mentioned above a small sub-group[1] of the EuroNNAc2 network has drafted a possible roadmap towards a full plasma linear collider for the 2040's. This draft roadmap was presented in a 2016 workshop on the US roadmap of plasma accelerators and discussed with US colleagues. It was recently also presented as input to the "Advanced and Novel Accelerators for High Energy Physics Roadmap Workshop", organized by the ICFA Panel for Advanced Novel Accelerators (ANA) in Geneva in April 2017. The roadmap shown in Figure 12 should be taken as a first idea and attempt to do such a roadmap. It illustrates that major investments are required from the field of High Energy Physics to advance the state of development and address the required HEP specific tasks in a timely way.

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[1] Involved were the following scientists: R. Assmann, B. Cros, E. Gschwendtner, P. Muggli, A. Specka.

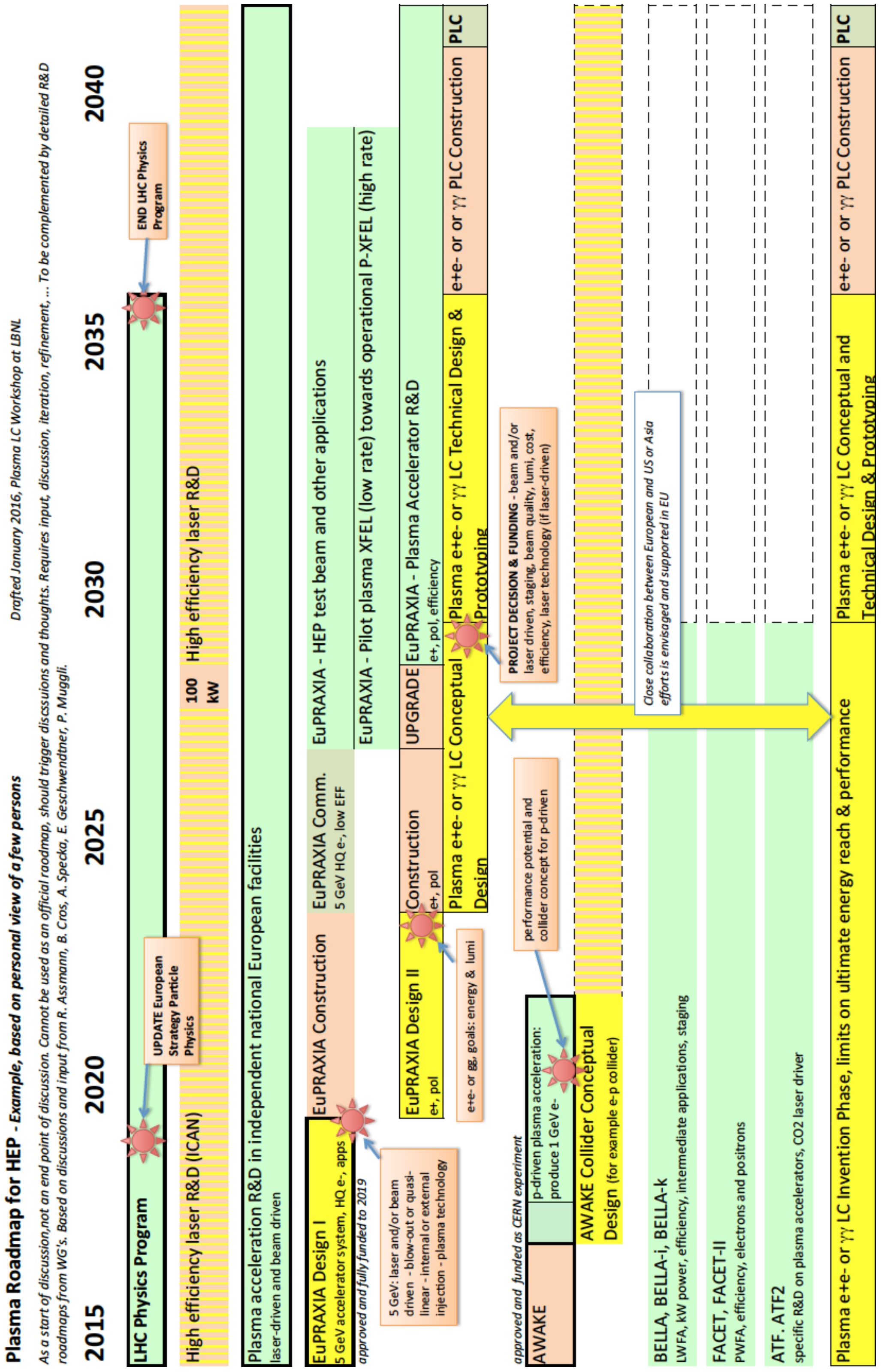

Figure 12: First attempt at a roadmap towards a plasma-based linear collider. This assumes that a conventional linear collider or a very large hadron collider like FCC cannot be built in the foreseeable future and that there is an urgent need for novel accelerator technology. Upgrade paths to an RF based linear collider are described in the text.

5. FUTURE PLANS / CONCLUSION / RELATION TO OTHER EUCARD-2 WORK

The European Network for Novel Accelerators (EuroNNAc2) has been discussing within its 54 member institutes a strategy for European R&D on advanced accelerators since 2013. This strategy is rapidly evolving and depends on technical progress, user opportunities and funding support. The present status is presented. The plans are closely discussed and to a large extent coordinated with international activities, in particular the ImPACT program in Japan and the DOE funded advanced accelerator R&D in the US.

The EuroNNAc2 strategy has been focusing first on plasma accelerators. Other methods relying on laser or THz driven dielectric accelerators are included in the discussions but are presently less advanced. These alternative methods are therefore not included into our application-oriented strategy. The EuroNNAc2 strategy involves the definition of common facilities in Europe to advance the state of development.

AWAKE at CERN is such a multi-laboratory effort to show the feasibility of proton-driven plasma acceleration. The AWAKE effort could lay the foundation of future plasma-based high energy physics colliders with good energy efficiency.

EuPRAXIA is a Horizon2020 design study, supported by 16 partners and 22 associated partners from the EuroNNAc context. It will produce a conceptual design report for the worldwide first 5 GeV plasma-based accelerator with industrial beam quality and user areas. EuPRAXIA is the required intermediate step between proof-of-principle experiments and ground-breaking, ultra-compact accelerators for science, industry, medicine or (on the long term) the energy frontier ("plasma linear collider"). The study is designing accelerator technology, laser systems and feedbacks for improving the quality of plasma-accelerated beams. Two user areas are being developed for a novel Free Electron Laser and High Energy Physics detector science. EuPRAXIA, if constructed, would be a new large research infrastructure with an estimated footprint of about 250 m. The design study is laying the foundation for a possible decision on start of construction in 2020.

The above-mentioned common experiments and facilities will help promoting and advancing the required R&D towards a possible plasma linear collider at the Higgs energy or above. It is our goal to solve the major open issues such that a plasma linear collider can be seriously considered by the mid-2030's when the LHC physics program will be completed. A first draft European roadmap towards this goal is included in this report.

Conceptual and strategic discussions are presently expanding as new experimental facilities will come online (e.g. ELI and CILEX) and as international strategy discussions are picking up momentum (e.g. driven by the ICFA panel for advanced novel accelerators ANA or in the new LEAPS initiative). EuroNNAc2 network members are involved in these activities and the network is providing input and support to national and international activities.

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