Summary of Working Group 4: Application of compact and high-gradient accelerators

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Summary of Working Group 4: Application of compact and high-gradient accelerators

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Abstract. We present here an overview of the topics presented and discussed during the Working Group 4 sessions of the European Advanced Accelerator Concepts workshop 2019 (EAAC19). The remit of Working Group 4 (WG4) is to address topics relating to all potential application areas of compact and high-gradient accelerators. This includes recent experimental results and planned demonstration experiments with relevance to radiation generation, medical, industrial, and cultural heritage sector applications, and development of advanced photon sources such as free electron lasers (FEL). Within scope of Working Group 4 is also discussions on planned facilities implementing advanced accelerator concepts that have a focus on applications, as well as beam shaping and tailoring to deliver adequate beams for applications. The topics discussed in the EAAC19 programme for Working Group 4 all fit within the following application theme areas: 1) new facilities exploiting advanced and novel accelerator concepts, 2) development of next generation photon sources, 2) imaging and spectroscopy with laser-plasma accelerator particle and photon beams, and 3) radiobiology with laser-plasma accelerator particle beams.

1. Introduction

The field of plasma-based particle acceleration is rapidly progressing to the point of translating proof-of-principle experimental demonstrations to reliable systems to be applied in industry, medicine, and applied science in general. Electron beams with durations as short as a few femtosecond are now routinely generated [1] and electron energies of the order of 8 GeV from a 20-cm long accelerator have been recently demonstrated [2]. Due to the relatively large bandwidth of these beams, different groups are studying the mechanisms leading to the injection of electrons into the accelerating structure, such as shock injection and down-ramp injection [3,4], which have been shown to produce high-quality beams with bandwidths as low as $\Delta E/E = 0.4\%$, tuneable energy in the range 200 - 600MeV and sub-mrad divergence [3]. The micron-scale source size of these beams results in ultra-low emittances [5], which are enabling studies of their injection in secondary laser-driven stages. A first proof-of-principle experiment has already demonstrated the feasibility of staging at modest energies, with a charge transfer of 3-5% [6].

Laser-driven plasma accelerators can be tuned to generate beams of electrons [1], x-rays [7] ions [8], neutrons [9] and positrons [10] with short pulse duration, high brightness, directionality, and with an energy bandwidth relevant for imaging, spectroscopy, or irradiation applications impacting on biology,
materials science, high energy density physics, cultural heritage, industry, and security. In this paper we provide a summary of the presentations and topics addressed during the EAAC19 sessions dedicated to WG4: Application of compact and high-gradient accelerators. Application theme areas covered by the speakers in WG4 session included new facilities, advanced photon sources, imaging and spectroscopy, and radiobiology. It was noted that there has been a significant uplift in activity for applications since the previous EAAC workshop, with the emergence of many proposed facilities dedicated to the endeavor of exploiting advanced and novel accelerator concepts, and plentiful experimental demonstrations of applications being realized and used routinely for impact in science and innovation.

2. New facilities exploiting advanced and novel accelerator concepts
A natural step forward for advanced and novel accelerators is to apply them for the next generation of photon sources and, more generally, of secondary sources from lasers. In WG4, several facilities have been presented and will be briefly discussed here.

2.1. EuPRAXIA: European Plasma Accelerator with eXcellence In Applications
EuPRAXIA is a Horizon2020-funded conceptual design study for a 5 GeV electron plasma accelerator with high beam quality at a high repetition rate. The first stage of the project has been recently completed with the publication of a comprehensive Conceptual Design Report [11]. At the time of EAAC 2019, the project involved 41 Universities and research institutes with collaborations from companies and industry. The target performance of EuPRAXIA is summarised in the table below:

| Parameter                  | Value                     |
|----------------------------|---------------------------|
| Energy                     | 5.9 [GeV]                 |
| Charge                     | 22 [pC]                   |
| Bunch length               | 3.5 [fs]                  |
| Energy spread              | 0.32 [%]                  |
| Transv. norm. emittance    | 0.6 – 1.6 [mm mrad]       |
| Slice energy spread        | 0.06 [%]                  |
| Slice emittance            | 0.4 – 0.7 [mm mrad]       |

Based on surveys of community needs, several pilot applications of the accelerator have been identified: a compact x-ray source based on betatron radiation [7,12], a GeV-scale positron source [13-15], free electron laser [16], an accelerator R&D test area [17-18], and a low-energy positron source for material studies [10]. During the conference, recent progress in laser-based generation of ultra-short and low-energy positrons has been reported, using the TARANIS laser at Queen’s University Belfast. The experiment, supported by matching numerical simulations indicate that small-bandwidth positron beams with a tuneable energy between 0.3 and 3 MeV and durations of the order of 10s of ps can be generated, of great interest for material science.

It is proposed to build two main plasma-based accelerators, one laser-driven and the other one beam-driven. The laser-driven site will have four different end-stations: a table-top test beam user area, an ultra-compact positron source area, and two Free Electron Laser (FEL) areas. The beam-driven site will have five different end-stations: a gamma-ray source based on Inverse Compton Scattering (ICS), a high-energy physics detector test area, a high-energy positron beam area, and two FEL areas. Subject to funding, the facility is planned to be completed within a 10 year timeframe, with first operations in 2030. The beam-driven site is planned to be built at the National Laboratories in Frascati, Italy, whereas several potential sites have been identified for the laser-drive site. During the conference, a strong proposal has been put forward by the UK and discussed, leveraging on their established reputation in laser-wakefield electron acceleration, the presence of high-intensity laser facilities both at a national and institutional level (Central Laser Facility, CLF, at Rutherford Appleton Laboratory, SCAPA at Strathclyde University, the TARANIS and TARANIS-X lasers at the Queen’s University of Belfast, and CLARA...
at Daresbury Laboratory), and the CLF’s recently funded Extreme Photonics Application Centre, EPAC, due to be online in 2024.

2.2. Sinbad: Short INnovative Bunches and Accelerators at DESY
The SINBAD facility at DESY is designed to focus on research and development on ultra-fast science and high-gradient accelerators. It is based on a more conventional S-band radiofrequency photo-injector. It aims at producing high brightness electron bunches with bunch length at fs/sub-fs level and excellent arrival time stability. The simulated working points have been presented, both at the bunch compressor exit and at the plasma entrance:

|                        | Bunch Compressor Exit | Plasma Entrance |
|------------------------|-----------------------|-----------------|
| Charge [pC]            | 0.81                  | /               |
| Duration RMS [fs]      | 0.2                   | 0.31            |
| Energy [MeV]           | 200.2                 | 200.2           |
| Energy spread [%]      | 0.12%                 | 0.16%           |
| Emittance [mm mrad]    | 0.11 x 0.10           | 0.11 x 0.12     |
| Peak Current [kA]      | 1.13                  | 0.74            |
| Brightness [Am⁻²]      | 10.74 x 10¹⁶          | 5.65 x 10¹⁶     |

One of the proposed applications for the system is to enable plasma wakefield acceleration (PWFA) with external injection, with preliminary simulations indicating the possibility of achieving 1 GeV electron beams with 0.2% energy spread and < 0.2 mm emittance. The photo-injector has been installed and the conditioning of the radio-frequency gun was reported to be ongoing.

An account of the requirements and projected performance of a PWFA-based free electron laser was also presented, with particular focus on the potential performance of the plasma photocathode technique [19-20]. Preliminary experimental results have been obtained using FACET at the Stanford Linear Accelerator Center (SLAC) and are currently being prepared for publication.

2.3. MARIX: Multi-disciplinary Advanced Research Infrastructure for the generation and application of X-rays
A design study for a facility in Milan, designed to provide high-quality x-ray beams for application, has been presented. A conceptual design report and an executive summary of the machine have been published [23,24]. Due to constraints in the infrastructural space available, of the order of 500 m, significant effort has been put in minimising the size of the FEL. The beam parameter requirements are as follows:

|                        |                        |
|------------------------|------------------------|
| Energy [GeV]           | 1.8 - 3.8              |
| Bunch charge [ps]      | 8 – 50                 |
| Bunch length [fs]      | < 20                   |
| Emittance (slice) [mm mrad] | 0.5                 |
| Bunch energy spread (slice) [%] | 0.024 – 0.045        |
| Bunch peak current [kA] | 1.6                   |
| Bunch separation [μs]  | > 1                    |
| Energy jitter shot-to-shot [%] | 0.1                 |
| Time arrival jitter [fs] | < 50                |
| Pointing jitter [μm]   | 5                      |

The system is currently designed to deliver photon beams with different characteristics depending on the specific application, which include: water window x-rays (2.77 nm), linear spectroscopy at 0.417 nm, single-shot imaging at 0.15 nm. A compact back-scattering Thomson source, BriXS, is also considered, mostly for clinical applications.
2.4. ELIMAIA: ELI Multidisciplinary Applications of laser-Ion Accelerators at ELI Beamlines

The ELIMAIA facility at ELI Beamlines [25] is a fully configured applications-focused beamline serving users accessing the beams for a wide range of applications including proton radiography, proton heating, ion beam radiobiology, ion beam nuclear reactions, radiation chemistry, mimicking space radiation, ion beam analysis, studies of ion beam stopping power, to name just a few. The facility has now been constructed and will shortly be opening for first users. The set up includes laser ion acceleration stage, ion beam collection and transport, energy selection, transport and focusing, and dosimetry and irradiation stage. The results of start-to-end simulations, carried out in collaboration with INFN-LNS, LBNL, and KIAM using 3D MHD (pre-plasma), 3D PIC (ion acceleration) and 3D GEANT4 (transport and dosimetry) codes, were presented showing expected beam energy spread and beam intensity profile at the irradiation stage of the beamline. Ion beam transport is delivered using permanent magnet quadrupoles, energy selectors, conventional elements, and a soon-to-be implemented ion buncher for generating sub-ns pulse beams. Sample irradiation is available using an in-air or in-vacuum system.

The ion beam parameters available are as follows:

| Parameter                          | Enabling/pilot exp. (2020) | Flagship exp. (2020+) |
|-----------------------------------|-----------------------------|-----------------------|
| Energy range [MeV/u]              | 3-60                        | 3-300                 |
| Ion No. / laser shot [10% bandwidth] | >10⁸                     | >10⁹                  |
| Bunch duration [ns]               | 1-10                        | 0.1-10                |
| Energy spread [%]                 | ±5                          | ±2.5                  |
| Divergence [°]                    | ±0.5                        | ±0.2                  |
| Ion Spot Size [mm]                | 0.1-10                      | 0.1-10                |
| Repetition rate [Hz]              | 0.01-1                      | 0.01-10               |

Users are expected from a diverse range of research and innovation fields, from archaeology and cultural heritage to warm dense matter physics. A focus area for the facility will be the ELIMED (ELI Medical applications) end station which will deliver prompt dose rates > 10⁹ Gy/s for radiobiological studies. The programme will attract a user community with the future goal of clinical applications, developing methodologies and delivering key demonstrations of the viability of ultra-high dose rate hadron beams, validation of laser-driven sources in view of future therapeutic use, and provision of an alternative, flexible source for radiobiological studies. R&D of high repetition rate laser targets and beam diagnostics, along with first commissioning tests with the HAPLS laser, were also presented.

3. Development of next generation photon sources

 Novel accelerator concepts are a route towards decreasing the size and therefore cost of infrastructure associated with advanced photon sources. Research and development of plasma accelerator based FEL beamlines, inverse Compton scattering sources, and sub-fs x-ray pulses were presented in WG4.

3.1. COXINEL

Test experiments towards a laser-wakefield based free electron laser are currently being designed and carried out at Coxinel. The laser-driven electron source is being provided by the Laboratoire d’Optique Appliquée (LOA), and a detailed numerical study of the required beamline to capture and manipulate the laser-driven electrons has been presented. First focussing tests have been reported [21], in agreement with numerical simulations. Electron beam transport over 9 meters has been shown, enabling beam manipulation with a broadband energy beam. This includes: a method for beam pointing alignment
compensation, fine tuning of the electron beam energy, and limited emittance growth at the undulator location. Undulator spontaneous emission has been measured after transport beam manipulation. These are all promising steps towards a plasma-based free electron laser.

3.2. FEL at BELLA
A dedicated programme for a laser-plasma based free electron laser at BELLA, hosted by the Lawrence Berkeley National Laboratory has been presented. Two phases of operation have been identified. In the first phase the laser-plasma accelerator will deliver a 100 MeV electron beam containing 25 pC of charge with an energy spread of 2.5% and a normalised emittance of 0.3 mm mrad. This will be used to drive x-ray radiation centered at 420 nm. In a second phase, the electron energy will be increased to 275 MeV, in order to reach x-ray radiation at 55 nm (23 eV photon energy). Start-to-end simulation of the accelerator, the transport line, and the undulation system have been reported to match the expected performance. The construction of the beam-line has started with several components already installed and tested (see, for instance, Ref. [22]). Plasma-based active elements are currently being implemented and tested, alongside more conventional passive beamline elements, such as a plasma lens as a compact high-resolution diagnostic.

3.3. Inverse Compton Scattering source at Tsinghua University
An x-ray source based on Inverse Compton Scattering (ICS) with photon energies ranging from 0.2 to 4.8 MeV is currently being designed at Tsinghua University. The source, called VIGAS (Very compact ICS GAMma-ray Source), exploits electrons accelerated from an s-band photo-injector providing energies up to 50MeV and 6 sections of x-band structures, which provide electron energies up to 350MeV. The electron beam is then made to interact with a 1.5 J Ti-Sapphire laser, in order to produce up to $10^9$ x-ray photons per second. The main focus of this design is on compactness, with the whole system, including the accelerator and the laser system, expected to fit within 12 meters. Even though the system is not directly based on plasma acceleration, many aspects of the development will naturally fit into plasma-based photon sources.

3.4. Radiation from dielectric laser accelerators
An alternative method for a compact radiation source that was discussed within the working group involves the use of dielectric accelerators, following the concept of “acceleration on a chip”. In a nutshell, the aim is to generate MeV-scale accelerators with a cm-scale size, with potential applications including biomedicine, radiation therapy, semiconductor industry, ultra-fast electron diffraction, and sub-fs x-ray pulses. Different configurations have been proposed based on numerical modelling and preliminary experimental results. Work presented from SLAC concluded that the use of a laser driven undulator in combination with a dielectric laser accelerator is a potential ultra-compact source of coherent attosecond undulator radiation for EUV or X-ray production.

4. Imaging and spectroscopy with laser-plasma accelerator particle and photon beams
A number of presentations were made discussing the application potential of x-rays for imaging and spectroscopy, making particular reference to the high brightness and ultra-short pulse nature of the laser-plasma concept enabling single-pulse acquisition for capturing dynamics or improving spatial resolution. Laser-driven pulses of protons and positrons were also presented for applications in sub-surface material science inspection.

4.1. Development and application of laser-plasma accelerators for X-ray radiography and spectroscopy
In the laser-wakefield acceleration (LWFA) concept, the electrons experience a longitudinal accelerating force as well as transverse restoring forces within the plasma bubble, the latter of which giving rise to ultra-short, bright pulses of synchrotron-like betatron x-ray emission with up to 10’s of keV critical energy that can be used for advanced x-ray imaging such as phase-contrast radiography.
[26]. Results were presented studying the emission of electrons and betatron x-rays as a function of gas cell length at constant gas pressure. A x-ray flux enhancement of 10 times was observed at an optimal gas cell length condition, which coincided with a drop in the critical energy of the x-ray spectrum. It was concluded that the LWFA beyond the depletion length results in a second injection of electrons which emit a large amount of photons but with lower energy. This was interpreted through the experimental electron and x-ray spectra, and PIC simulations as occurring because the second electron bunch has a larger betatron radius, resulting from a compression in the laser pulse leading to higher an.

In another presentation the laser-driven betatron emission was applied for high-resolution x-ray imaging of complex microstructures, in which micrometer scale lamellar features in lightweight Al-Si alloys were resolved [27]. Al-Si is a common material used for additive manufacturing, therefore diagnostic tools for assessing these advanced manufacturing processes is critical for quality control and performance enhancement. The x-ray images acquired from LWFA betatron emission were compared to x-ray images acquired using the Swiss Light Source (SLS) synchrotron and, while the spatial resolution of the two systems was found to be comparable (~ 1 µm), the LWFA images provided enhanced visibility of fine features. It was concluded that the 10’s fs ultra-short x-ray pulse duration of LWFA betatron was the key for optimal imaging resolution as single pulse acquisition eliminates motion blur of the sample, compared to 0.5 s exposure on SLS.

An emerging application of laser-driven betatron emission was presented in which the high brightness, ultra-short pulse exposure of the source was utilised for single-shot x-ray absorption near edge spectroscopy (XANES) with a vision for applying these beams for probing matter under extreme dynamic conditions [28]. The proof-of-principle experiment demonstrated single-shot XANES on a titanium sample, showing that the fs exposure data was capable of resolving pre-edge transitions, electron temperature/structure, and ion temperature/structure, therefore indicating its suitability for temporally resolving features and transitions within warm dense and hot dense matter. A source of noise in the data was identified as coming from the electron beam dump which could be decreased in future.

4.2. Demonstration of materials science applications with protons and positrons from laser-plasma accelerators

Proton induced x-ray emission (PIXE) is an ion beam analysis technique used to inspect the chemical composition within the surface of materials. It has an advantage over x-ray fluorescence in being able to detect low atomic number elements and with high spatial resolution. PIXE can detect down to 10 ppm and is considered a non-invasive inspection technique. It is a common ion beam analysis technique delivered with conventional accelerators, with particular impact on sub-surface materials inspection in cultural heritage. Demonstration results were presented on the first application of laser-driven proton beams for PIXE applied as a cultural heritage diagnostic, with the sample being a ceramics artefact from 1650 AD [29]. The potential for quicker scanning, over a larger area and with deeper reach, were identified as advantages of the laser-PIXE over conventional methods, due to the high brightness, large divergence, and large energy spread of the laser-driven ion beam. The design and optimisation of a laser-driven PIXE beamline for material science applications [30] was also presented using particle tracing simulations to model the transport through an energy selector and two permanent magnet quadrupoles. Future work is focused on comparing the damage induced by laser-PIXE to the conventional approaches, developing an approach for layer-by-layer analysis, and working towards applying laser-PIXE for aerosol research.

Positron annihilation lifetime spectroscopy is another materials science technique that was presented within WG4. This approach utilises the positron as a probe for identifying and quantifying sub-surface defects in the lattice structure of a material. This is conducted by analysis of the lifetime spectra of 511 keV x-rays emitted as the positrons annihilate within the sample. A laser-driven source of positrons has the potential to improve this technique by enabling deeper and/or variable depth analysis and an increase in spectral resolution, and therefore identification of smaller defects, because of the ultra-short pulse duration. The design of a laser-driven positron beamline for applications, including source generation, beam selection and transport towards a sample stage, was presented. The compact design extending less
than 1 metre incorporates a series of three permanent quadrupole magnets, followed by two dipole magnets to steer the beam towards the sample and out of line of the forward propagating MeV x-ray beam. Results of a series of simulations carried out using the FLUKA monte carlo code indicate that a positron bunch with duration less than 100 ps should be achievable at the sample plane.

5. Radiobiology with laser-plasma accelerator particle beams

Utilising ultra-short pulsed beams from laser-accelerator concepts for radiobiology is of great interest on a scientific level, because of the access to ultra-high dose rates (10⁹ Gy/s) not available by any other accelerator method, and on a technical level, because of the decrease in infrastructure needed and increased flexibility and multi-modality made available compared to conventional accelerator schemes. Presentations in WG4 focused on development of beamlines and dose measurement methodology for exploring the effect of the unique dose rate that laser-plasma accelerator concepts realise.

The ability to conduct dose controlled irradiation experiments is important for progress in the research and development of laser-driven particle beams for radiobiology. Experiments performed using the Draco laser at HZDR were presented showing the use of a tunable pulsed high-field beamline for 3D dose delivery, making use of the inherent large bandwidth of laser-driven proton beams. Two solenoids have been installed after the source generation point in order to focus protons of two different energies with 50.6 % transmission efficiency onto the sample stage in a single laser shot, thereby achieving dose homogenisation over a depth of several millimetres in a single pulse exposure. The first irradiation studies using this setup have been carried out demonstrating 0.7 Gy/pulse proton exposure onto 3D tumour spheroids (in-vitro) and zebrafish embryos (in-vivo).

Work carried out by the UK’s ASAIL collaboration on using laser-driven carbon ions, which offer high linear energy transfer (LET) in cell irradiation and therefore more complex, unrepairable damage, was presented. Radiobiology investigations using 10 MeV/u laser-driven carbon beams to irradiate Glioblastoma stem cells with 1 Gy ± 15 % in a single pulse were shown, however the study is on-going and awaiting results from conventionally sourced carbon beam irradiation for comparison. A new approach for dose measurement of high LET and low energy carbon ions was needed for this study, including the development of a new procedure for radiochromic film detector calibration since no data existed in the literature.

An interesting perspective for applying LWFA electrons for in vivo irradiation was presented by LOA, by considering that stable, high repetition rate generation of 150 MeV electrons is viable using modest laser technology and simple target engineering. However, deeper discussions on this revealed that the limiting factor will be electron beam charge reaching high enough levels (nC) in order to deliver dose irradiation conditions (few Gy/shot) needed for ultra high-dose rate radiobiology experiments.

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