ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-MOPR17

ADVANCED ACCELERATOR CONCEPTS FOR DARK SECTOR SEARCHES AND FAST MUON ACCELERATION*

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Abstract

Dielectric laser acceleration (DLA) is a promising approach to accelerate single electrons at a high repetition rate to GeV energies, for indirect dark matter searches. Relevant concepts include the integration of the dielectric structure inside the laser oscillator. To efficiently use muons for high energy physics applications, they need to be accelerated rapidly, before they decay. Plasma acceleration achieves GV/m accelerating fields and could be ideal for accelerating to muon-collider energies. Single muons could also be accelerated in DLAs for dark matter searches. They could be injected from existing low-intensity muon sources, such as the one at PSI. A workshop organized in the frame of the EU project "Innovation Fostering in Accelerator Science and Technology" (I.FAST) focused on GHz Rate & Rapid Muon Acceleration for Particle Physics to address these topics. We report highlights and future research directions.

I.FAST GR2M WORKSHOP

The topical workshop on "Gigahertz Rate and Rapid Muon Acceleration" (GR2M) was organized by I.FAST Work Package 5.2 "Pushing Accelerator Frontiers" in Bern from 10 to 13 December 2023 (Fig. 1) [1, 2]. For dark matter searches, multiple experiments are proposed. Promising emerging accelerator concepts are dielectric laser acceleration (DLA) for single electrons – perhaps muons too – and plasma wakefield acceleration (PWA) for muons and pions.

Figure 1: Participants of the I.FAST GR2M workshop.

* Work partially supported by the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No. 101004730 (I.FAST), and by the EPFLglobaLeaders fellowship programme.
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DARK MATTER

The cosmological evidence for dark matter (DM) on length scales of 1 Mpc to 14 Gpc (the size of the visible universe) is based on microwave background and Supernova data. At lesser length scales, astrophysical observations hinting at DM include the rotational velocity distributions in galaxies, gravitational lensing, and colliding galaxies. Astrophysics also offers some indications for warm DM in the 2–10 keV energy range. Particle physics addresses the question of DM by extending its Standard Model with weakly interacting DM particles. Three possible conclusions were drawn [3], ranging from optimistic to pessimistic: cold DM weakly interacting massive particles (WIMPs) exist at the 1 TeV scale; experiments will reach the "neutrino fog"; or WIMPs are not a DM candidate. An alternative class of models postulates an extended Dark Sector (DS), in which DM is not only composed of a single particle but of a set of dark particles with their own phenomenology. The particles in the DS are conjectured to feebly interact with the SM through new mediators such as the dark photon. This would allow for their production and detection in accelerator-based experiments, which can complement other endeavors, exploring the vast parameter space of potential DM candidates, particularly focusing on the region between ~MeV and few GeV (see e.g. [4] for a recent review).

A minimal set of five future DM experiments consists of [3]: (1) for electrons, the Beam-Dump eXperiment (BDX) at JLAB, which foresees sending 10^{22} e^- at 11 GeV on target [5]; (2) for protons, the SHIP experiment at CERN with an annual rate of 4×10^{19} 400-GeV p on target [6], while MicroBooNE at FNAL already took data for 7×10^{20} 8-GeV p on target [7]; (3) for photons, the proposed Gamma Factory (GF) at CERN, with an annual rate of a few 10^{23} 300-MeV γ on target [8, 9]; (4) an experiment with a high rate of single electrons, such as LDMX at SLAC [10–12] with about 4×10^{14} e^- on target in its first year; (5) the existing collider experiments with a High Level Trigger event building rate upgrade, such as ATLAS, CMS and LHCb at the LHC.

DM experiments looking for an appearance require a high flux of incoming particles. Other DM experiments search for disappearance. These mostly rely on DC-like e-beams, such as the proposed LDMX at SLAC [10–12], and would be rather insensitive to beam spot and divergence. DC-like

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muon beams could be probed with the future FNAL M3 [13] and with the existing CERN SPS NA64μ [14] experiments.

The NA64 experiment at the CERN SPS [15] is a prominent example of ongoing accelerator-based DM searches running with 100 GeV electrons [16], and recently demonstrating its potential to use positrons, exploiting the resonant annihilation channel [17]. Its complementary NA64μ mode delivered first results from a 160 GeV muon beam [18]. The proposed future LDMX experiment at SLAC [10] may set a new standard for indirect DM searches, which detect a missing energy or momentum. The indirect approach, pioneered by NA64, requires fewer particles in total than direct searches, but instead a clean, well-characterized initial state. Indirect searches can be pursued through the production of single electrons (or muons) at a high repetition rate.

Fascinatingly, advanced concepts employing DLA, in particular when integrating the accelerating structure with the laser oscillator, could achieve many orders of magnitude higher rates of single high-energy electrons entering into an NA64/LDMX-type detector [19–21]. Indirect DM searches call, e.g., for a beam with an energy of 10–20 GeV, and single electrons with a repetition rate of 100 GHz, as could be provided by advanced lasers [22] and DLA systems [19–21].

DLA BASED DM SEARCHES

DLA relies on a structure with submicron features driven by an incoming electromagnetic laser wave. See Fig. 2. Similar to a conventional microwave linac, the laser wave drives the DLA structure in resonance with the motion of the electrons, thereby accelerating the latter.

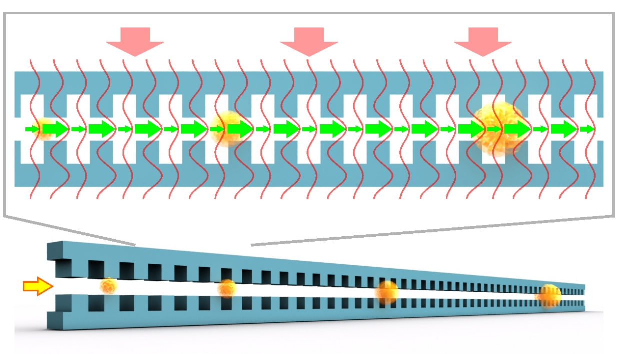

Figure 2: DLA principle: The DLA structure is illuminated by laser light from the top. Green arrows indicate the positive force of the laser's electric field that can accelerate electrons.

The DLA ingredients are: (1) e$^-$ sources that provide subnanometer emittances; (2) structures to accelerate, focus and deflect the beam, as well as structures for instrumentation and control; (3) the scalability of the concept, requiring staging of multiple structures, their synchronization, and laser power delivery. The DLA structures have evolved from bonded silica gratings (2013) over silicon pillar structures (2015) to arrive at vertically pumped systems (2021) [23].

The typical length for a 1 MeV DLA injector would be around 1 cm with an energy gradient of 500 MeV/m. The guiding concept of alternating phase focusing (APF) for a DLA requires that the laser phase in the structure be regularly flipped — through the design of the structure — so as to alternate between focusing and defocusing in each plane [24]. Figure 3 illustrates the operating parameter range for a periodic APF accelerator cell. The three-dimensional APF allows scalability to longer and multiple staged DLA structures. Phase jumps can be combined with tapering [23].

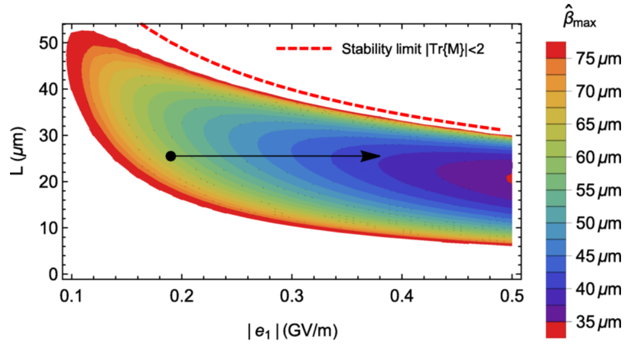

Figure 3: Contours of $\beta_{\max}$ in the $(|e_1|, L)$ plane, where L is the length of a periodic APF cell, and e_1 the accelerating electric field [24, 25]; the black arrow indicates the laser amplitude dependent tuning range, from maximal admissible beam size to the structure damage threshold [24, 26]. From Ref. [24], published under CC 4.0 license.

The physical interaction of the DLA electromagnetic field and the particle beam can be simulated by the code DLAtrack6D [27], which efficiently models the 3D APF [28], and can be used for any periodic structure [29]. This code applies one wake kick per DLA cell. However, challenges exist associated with electron tracking on a femtosecond time scale, since tiny electron bunches and huge fields can render the tracking simulations prohibitively slow. A possible solution consists in adopting a "moving window" tracker which provides (1) multiple static or frequency domain fields; (2) a clustered particle vector (direct particle-particle space-charge interaction) and (3) statistics as in a many-shot experiment. Predictions from the "FemtoTrack" code with space charge [30] were compared with beam measurements at the Stanford "glassbox" experiment [25]. DLA structures for Stanford are designed for 70 and 100 MeV/m peak gradients (35 and 50 MeV/m average), which enables sub-relativistic acceleration with high gain. Currently, at PSI, a single structure with 2 μm period is being optimised using a genetic algorithm [31]. An energy gradient of 2.14 GeV/m is assumed in the simulations. Passing through a 7 mm long structure consisting of 3500 cells, in simulations, a 1 GeV beam is accelerated by 14 MeV with a final rms relative energy spread of less than 2×10^{-5} [31]. This structure was optimized not only for low energy spread, but also for high survival rate, achieving 100% transmission after the optimisation. A single-electron source similar to those used in electron microscopes is considered, with a repetition rate of 3 GHz; the expected normalized beam emittance of 10 pm is suitable for the 400 nm aperture, even taking into account the field non-uniformity.

For future applications a key property of the DLA will be the length scalability. Two open issues in this regard are

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-MOPR17

(1) the laser synchronization over long distances, and (2) the electron confinement in tiny channels (ca. 400 nm aperture). The energy efficiency and repetition rate could be boosted by recirculating the laser pulse through the structure, that is by making the latter part of the laser oscillator [32].

A 20 m long staged dielectric structure with 1 GeV/m energy gradient could deliver single 20 GeV electrons at very high repetition rates [19–21].

μ/π PLASMA ACCELERATION

Laser- or beam-driven plasma wakefield acceleration (PWA) could be of great interest for non-ultra-relativistic and rapidly decaying particles, like muons and pions. In particular, this scheme could meet the challenging acceleration requirements for a muon collider [33–35]. Another intriguing possibility is low emittance muon sources based on plasma-wakefield accelerators [36] . Plasma acceleration could bring non-relativistic slow particles, such as muons, to relativistic velocities by slowing down the phase velocity of the plasma wake to match the speed of the particles [37, 38]. This can be achieved, for example, by using spatio-temporal laser pulses to slow down the driver [39] by varying the plasma density profile to control the velocity of the wake [37], or by a combination thereof [38]. The muons move at the plasma wave velocity if the phase locking condition [38] $d/dt\left(m_\mu c\beta(t)/\sqrt{1+\beta^2(t)}\right) = eE_0\sqrt{n}$, is met, where n denotes the electron plasma density normalized to the initial density (so that $n(0) = 1$), and E_0 the longitudinal electric field at the beginning of the acceleration process.

Detailed simulations of the beam dynamics of muons and pions in a phase-locked plasma wake have been conducted. An example is shown in Fig. 4. Even pions could be accelerated to relativistic speed at a reasonable survival rate.

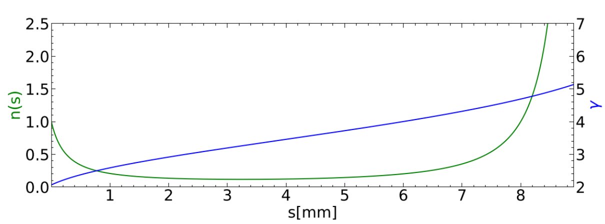

Figure 4: Simulated phase-locked plasma acceleration of muons, γ versus s (blue), over a distance of 9 mm, with subluminal driver at group velocity $0.96c$, and a tailored plasma density normalized to 10^{18} cm^{-3} (green) [38].

DISCUSSION AND ROADMAP

The workshop fostered numerous discussions and uncovered unresolved issues, such as the ultimate limits of luminosity for PeV energies [35]. Modelling the non-point-like particle luminosity is an important topic, also relevant for the GF. A related subject is the Pomeranchuk effect [40]. Muons are considered for future high-energy accelerators [33]. Both low- and high-energy muons have useful applications.

The DLA studies should be continued and, if possible, accelerated. The application of DLAs to NA64/LDMX-type of experiments is recommended. The scalability of energy from staging needs to be demonstrated and so is the integration of the accelerator structure inside the laser oscillator. Different time scales are anticipated for the proposed demonstrator experiments. Concerning DLAs, a reasonable target is a gradient of 500 MeV/m and an energy gain of 0.05 GeV on a single wafer, within 5 years, possibly at UCLA, in Erlangen, or at DESY. The demonstration of an integrated DLA laser oscillator could be foreseen at the EPFL in 5 to 7 years from now. The technology required for GHz laser cavities exists [22], but actual implementation is a challenge.

For μ acceleration studies, the dephasing issue, linked to the muons' non-ultrarelativistic energy, seems to be resolved. A demonstrator experiment for μ PWA is now called for. Questions are when and where? CERN-AWAKE [41] or PSI are candidates. Initially, within 5 years, a solid target or tape could be put into the AWAKE [41]. Later, a (pre-) cooled μ beam would allow testing the final cooling at PSI, FNAL, or CERN (i.e., injecting cold μ's into AWAKE).

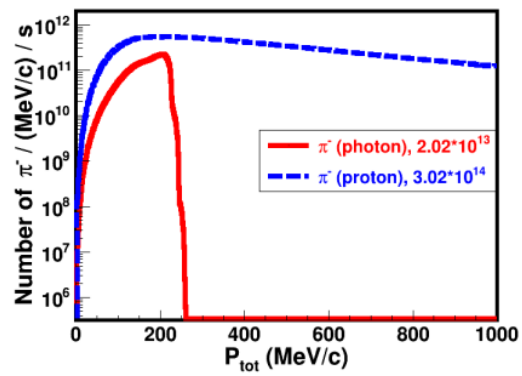

Figure 5: Comparison of differential π^- production rates for proton- and photon-driven schemes, considering either 1 MW beam of photons at 300 MeV or a 1 MW proton beam at 8 GeV hitting a 20-cm graphite target [42]. The majority of pions decay over 20 m from the production target, resulting in a high-purity muon beam. Picture from Ref. [43].

A proposal for a low-energy muon source would be timely by 2025, as input for the next European Strategy update. The GF was recognized as an intense source of polarised muons and positrons [42, 43], based on the resonant photo-excitation of Δ resonances: $\gamma + A \longrightarrow \pi + X$ followed by the $\pi \longrightarrow \mu + \nu$ decay. In order to generate muon beams of high polarisation, the pion source must produce (nearly) monochromatic pions, and the muon collection system must be sensitive to the muon emission angle. Figure 5 compares predicted pion production rates and energy spectra for a GF photon-based scheme with traditional pion production by 8 GeV protons. The Tevatron could be converted into a GF.

The GR2M workshop programme and all presentations can be found on the web at [44].

ACKNOWLEDGEMENTS

We thank T. Åkesson, M. Ferro-Luzzi, R. Jacobsson, and R. Pöttgen for helpful discussions and valuable information. C. Badiali thanks J. Vieira for constructive guidance.

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-MOPR17

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