DARK SECTOR SEARCHES BASED ON DIELECTRIC LASER ACCELERATION*

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Abstract

We discuss the beam requirements for indirect searches of dark matter and feebly coupled particles using advanced accelerator concepts. A parameter comparison reveals dielectric laser acceleration as a promising candidate for delivering the needed single-electron beams in the 5–100 GeV energy range or beyond. We suggest a parameter set for a baseline DLA-based dark sector accelerator. Enhancements through combining dielectric laser deflectors with a segmented detector or by making the dielectric structure be part of the laser oscillator could offer a performance significantly exceeding the "Extended LDMX" proposal based on LCLS-II.

INTRODUCTION

The Hidden Sector refers to any particles engaging in Feebly (or no) Interactions (FIPs) with the Standard Model (SM) particles. A prominent example of the Hidden Sector is Dark Matter (DM). Evidence for DM comes from astronomical observations, e.g., data about the Cosmic Microwave Background and the distribution of galaxies. The present model of the hidden sector does not limit the range of parameters to explore. Indeed, a simple model with dark matter charged under a hidden dark $U(1)_D$ symmetry yields a jungle of possibilities that depend on the tuning of the theoretical parameters. Therefore, a broad search at multiple fronts is called for, to widely cover the parameter plane. It is highly likely that advanced accelerators can help in this endeavour. A common class of dark sector models predicts DM in the MeV to GeV energy range. In these models, DM particles χ and axion-like force carriers A' couple to ordinary electrons and positrons e$^{\pm}$, and photons γ, through Feynman diagrams like the one in Fig. 1. The coupling strength between SM particles and the Dark Sector is ϵ.

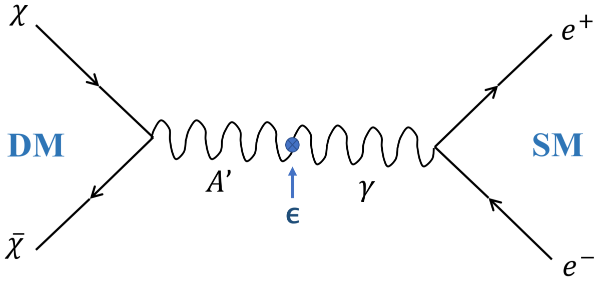

Figure 1: Feynman diagram illustrating coupling of Standard Model particles and photons to the corresponding Dark Sector objects A' and χ, with coupling strength ϵ.

BEAM DUMP EXPERIMENTS

Generic Dark Matter (DM) searches through beam dump experiments follow two main lines: 1) by detecting scattering against atomic electrons and nuclei (direct searches), or 2) through the interpretation of invisible energy accompanied by a Standard Model (SM) signature (i.e., by detecting scattering, decay...) and assuming DM-dark boson coupling (indirect searches). In direct searches the event rate is proportional to the fourth power of the coupling strength ϵ between dark matter and ordinary matter, while for indirect searches the dependence on the coupling strength ϵ is quadratic. This means that fewer beam particles are required for indirect searches, which are, however, experimentally much more challenging. An experimental set up for indirect DM searches is sketched in Fig. 2.

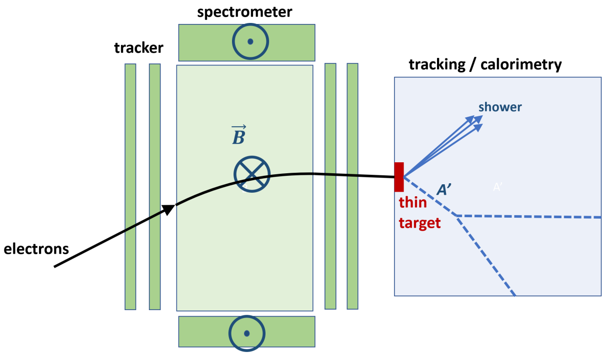

Figure 2: Concept of indirect DM search by missing momentum with spectrometer and trackers upstream and calorimeter downstream of a thin target, based on Refs. [1–3]. A' indicates a particle carrying missing energy.

Indirect ϵ^2-sensitive dark-sector searches are based on the missing-momentum-technique, such as employed for the NA64 experiment [6]. A good reference point for future facilities is the proposed Light Dark Matter eXperiment (LDMX) based on the LCLS-II linac at SLAC [3]. The 'extended'

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

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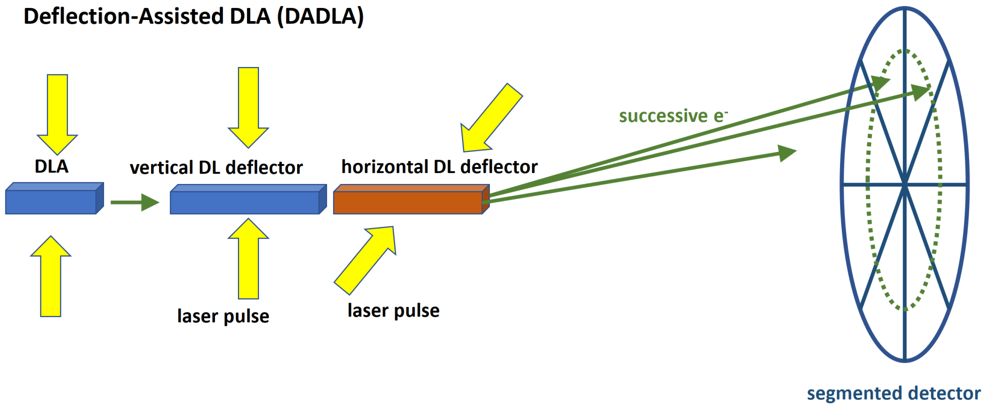

Figure 3: Sketch showing a pair of orthogonal dielectric laser deflectors installed at the exit of the DLA (DADLA setup). The deflectors are sending each electron in a train of ~160 onto a separate segment of the detector, thereby overcoming the time resolution limit and allowing bunch spacing of less than 10 ps within a train.

LDMX proposal foresees sending 1.6×10^{15} 8 GeV-electrons on target over 4 years. The electron time separation would be 20 to 25 ns, so that the electrons are easily individually distinguishable by calorimeters [3].

DIELECTRIC LASER ACCELERATORS

Dielectric laser accelerators (DLAs) are optical-scale lithographically-fabricated laser-driven particle accelerators. Typical laser pulse lengths are 0.1 to 1 ps, and the peak surface electric fields of the dielectric materials in the GV/m regime, allowing a potential length reduction of 1 or 2 orders of magnitude compared with conventional accelerators. Power sources for DLA-based accelerators are lasers, whose required pulse energies are in the mJ range, while repetition rates can be 10s of MHz [7]. An important point relating to dark sector searches is that laser- and beam-driven plasma accelerators (denoted by LWA and PWFA, respectively) feature characteristic bunch charges of order 1 nC at about 15 kHz repetition rate, whereas DLAs have much lower bunch charges of order 1 fC (or a few 1000 electrons per bunch) at a much higher repetition rate. This difference is clearly evident from Table 1, which was assembled for the European Strategy's Accelerator R&D Roadmap [5]. For all three types of accelerators, the efficiency of converting wall-plug power to beam power is forecast to exceed 10%. In view of their high repetition rate and low bunch charge, however, the DLAs are a particularly appealing option for indirect DM searches, where individual incident electron tagging and characterization is a key asset.

Table 1: Three parameter sets for a linear collider with advanced high gradient acceleration [2, 4, 5].

Parameter [unit]	PWFA	LWA	DLA
Bunch charge [nC]	1.6	0.64	5×10^{-6}
No. bunches / train	1	1	159
Train rep. rate [kHz]	15	15	20000
Norm. emit. ($\gamma\varepsilon$) [nm]	592	100	0.1
Beam power (5 GeV) [kW]	120	48	76
Relative energy spread [%]		≤ 0.35	

MINIMAL DLA (MDLA) SETUP

The individual (or event-by-event) characterization of single electrons is essential for the missing-momentum method (Fig. 2). In order to be competitive, a high number of electrons (e.g., of order 10^{15} electrons at 8 GeV on target for LDMX) must be delivered to the DM search experiment. In Table 1, a repetition rate of 20 MHz is indicated. However, higher rates of up to 1 GHz can be supported by the laser system. Also sources of single electrons at higher repetition rate are conceivable [2]; they might be similar to a pulsed transmission electron microscope [8]; also see [9].

Extrapolating from Ref. [7], and considering a laser pulse length of 0.1 ps, about 200 kW are required to accelerate single electrons to 10 GeV, at a still moderate rate of 60 MHz, or with an average current of about 10 pA. For a "year" of 2×10^{7} s, this translates to 6×10^{14} electrons on target per year, and an annual energy consumption of 1 GWh.

DEFLECTION-ASSISTED DLA (DADLA)

According to Table 1, we could enhance the rate of electrons, at about constant laser power, by a factor of 160, if we send 160 electrons per pulse (one electron per DLA "bucket"). Unfortunately, the successive electrons are only ~2 µm (about 7 fs) apart, which significantly blows the already ambitious detector time resolution of 10 ps.

A possible way out could be using two DLA deflecting structures to send each electron into a different segment of the detector, as is illustrated in Fig. 3. Dielectric laser deflectors were already studied, e.g., by Leedle et al. [10], and deflectors at terahertz frequencies have been demonstrated by Zhang et al. [11]. For 160 bunches (electrons) per pulse, we need to increase the laser pulse length to 1 ps. In this case, the average current is 1.5 nA. Again, considering a year of 2×10^{7} s with beam delivery, this now amounts to 10^{17} electrons on target per year, and to a total energy consumption of 10 GWh per year. For comparison, the Phase I of the pro-

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-MOPL068

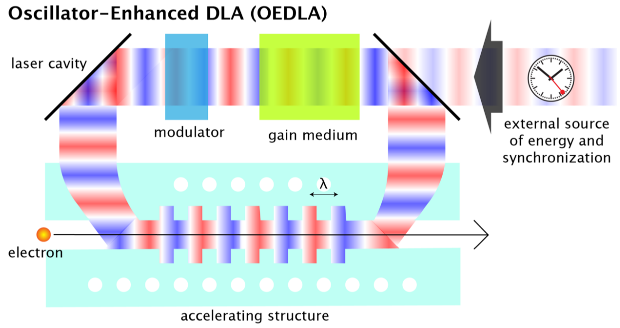

Figure 4: Sketch of a DLA structure as part of a laser oscillator (OEDLA). Electrons pass rightwards through the structure; laser pulse circulates at 100 GHz (path ~3 mm).

Table 2: Three options for DLA based dark sector searches.

DLA scheme	**MDLA**	**DADLA**	**OEDLA**
e^- energy [GeV]	10	10	10
Gradient [GV/m]	1	1	1
Act. length [m]	10	10	10
Rep. rate [GHz]	0.06	0.06	100
Pulse length [ps]	0.1	1	0.1
Single e's / pulse	1	160	1
Av. current [nA]	0.01	1.5	16
Time sep. [ns]	17	17 btw. pulses (7 fs in pulse)	0.01
Special features	—	DL defl., segm. det.	DLA in laser osc.
e^-/yr (2×10^7 s)	$6{\times}10^{14}$	$\sim 10^{17}$	$\sim 10^{18}$
Energy/yr [GWh]	1	10	~ 2

posed LDMX experiment requires a primary electron beam with low current and high duty cycle from LCLS-II to collect $4{\times}10^{14}$ electrons on target [3]. The deflection-assisted DLA (DADLA) scheme promises to achieve an about two orders of magnitude higher rate than even the extended LDMX proposal, which aims at 1.6×10^{15} electrons at 8 GeV on target during 4 years of operation [3].

OSCILLATOR-ENHANCED DLA (OEDLA)

Another promising approach to reaching much higher electron rates is making the DLA structure part of a mm-scale laser oscillator [12], as sketched in Fig. 4. Such arrangement could allow for extremely high repetition rates, at the 100 GHz level, corresponding to 10 ps time separation, which is close to the time resolution of state-of-the-art detectors. This may achieve 10^{18} electrons on target per year, with a time separation of 10 ps, for a total annual laser energy consumption of about 2 GWh (assuming per mil losses in the laser oscillator per cycle).

CONCLUSIONS AND OUTLOOK

DLAs could deliver single few-GeV electrons at extremely high repetition rates, which are ideally suited for indirect DM searches. Parameters for the three proposed DLA scenarios are compared in Table 2.

The next steps include concrete structure design and manufacturing, guided by simulations of wake fields and beam dynamics, as described in the companion paper [9]. In parallel, other topics should be advanced such as the single electron source, and instrumentation for monitoring the electron beam and the electromagnetic field. Suitable μJ-GHz laser technology will need to be explored. The OEDLA scheme requires couplers feeding the laser beam with transverse electromagnetic fields into, and out of, the DLA structure with a nonzero longitudinal electric field, and also appropriate cooling. Staging and, in particular, the precision alignment of successive DLA stages will be essential for reaching the targeted electron energies around 10 GeV or beyond.

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