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MILESTONE REPORT

Beam requirements for dark-sector searches

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ABSTRACT

Particle accelerators can contribute to dark sector searches over a large energy range. Present and proposed lepton and hadron colliders can search for sterile neutrinos and feebly coupled particles, including forward detectors at the LHC and an LHC-based Gamma Factory. Also, a muon storage ring could play a role for dark neutrino searches. A different approach to the dark sector is beam dump experiments, using either proton, like SHIP, or electron beams, such as BDX and LDMX. Both indirect and direct detection is pursued. In particular, for beam dump experiments with electron beams, advanced accelerator concepts could offer an attractive path forward, such as plasma acceleration based on the AWAKE scheme for direct searches. In this paper we identify and discuss dielectric laser acceleration (DLA) as a promising candidate for indirect searches, by delivering interesting rates of individual electrons in the 5-100 GeV energy range or beyond. We present a baseline parameter set for a DLA-based dark sector searcher. Enhancements with dielectric laser deflectors and segmented detector or by making the dielectric structure be part of the laser oscillator might offer a performance well exceeding the “Extended LDMX” proposal based on LCLS-II.

For more information on IFAST, its partners and contributors please see https://ifast-project.eu/

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Executive summary

The dark sector extends over a large energy range. At high energies, particle accelerators provide essential opportunities for dark sector searches. Certain dark-sector particles can be discovered at lepton or hadron colliders, including forward-detector searches like the FASER experiment at the LHC, or the quest for right-handed heavy neutrinos at the proposed FCC-ee. Also, an LHC- or FCC-based Gamma Factory would have the potential to serve as a powerful complementary tool for dark-sector exploration thanks to its large Gamma-ray flux.

Another category of dark-sector searches is beam dump experiments either with proton beams, such as SHIP, or with electron beams, such as BDX and LDMX. Indirect and direct experiments are to be distinguished. The detector and beam requirements differ significantly. In the area of indirect beam dump experiments, advanced accelerator concepts could offer a path forward. We study beam requirements for indirect searches of dark matter and feebly coupled particles using advanced accelerator concepts, in parallel to more conventional collider experiments. Dark matter searches based on proton-driven plasma acceleration (AWAKE) are already being contemplated for direct searches. A parameter comparison reveals dielectric laser acceleration (DLA) as a rather promising candidate for delivering single-electron beams in the 5-100 GeV energy range or beyond, as required for indirect searches. We suggest a parameter set for a baseline DLA-based dark sector accelerator, and also enhanced versions thereof, including dielectric laser deflectors and segmented detectors, which might offer a performance exceeding the "Extended LDMX" proposal based on LCLS-II.

1 Introduction to the Dark Sector

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. Evidence for Dark Matter (DM) comes from astronomical observations, e.g., data about the Cosmic Microwave Background and the distribution of galaxies. The present standard model of the hidden sector does not limit the range of parameters to explore, as is illustrated in Fig. 1. Indeed, a simple model with dark matter charged under $U(1)_D$ 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.

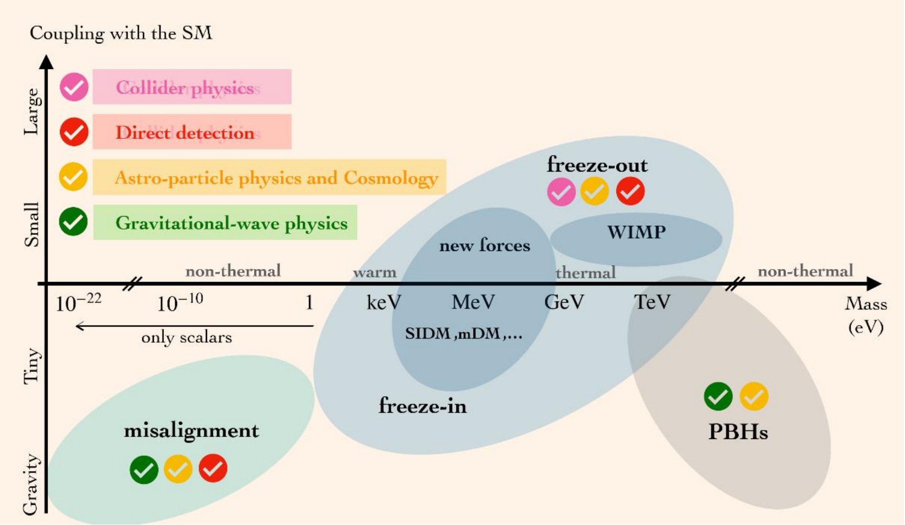


Fig. 1: Chart of mass and coupling strength of possible dark matter (Courtesy of Diego Redigolo, Alfredo Urbano. Dario Buttazzo. Paolo Panci, Emanuele Castorina, Marco Nardecchia and Roberto Franceschini; presented at eeFACT'22 [1]).

A common class of dark sector models predicts dark matter in the MeV-GeV energy range. In these, dark Matter particles χ and axion-like force carriers A' couple to ordinary electron and positrons $e^{\pm}$ and photons γ through Feynman diagrams like in Fig. 2. The coupling strength between Standard Model particles (SM) and Dark Matter is .

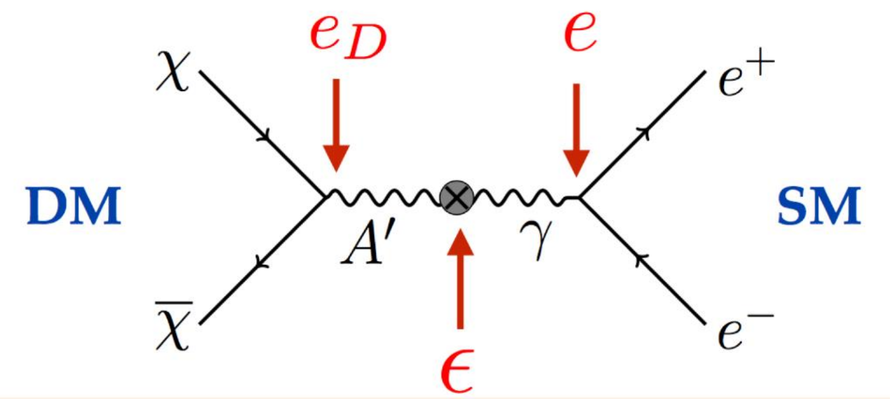


Fig. 2: Feynman diagram illustrating coupling of Standard Model particles and photons to the corresponding Dark Matter objects A' and χ, with coupling strength ϵ.

2 Collider searches

In hadron colliders, axion-like particles and neutrinos are emitted in the forward direction, as sketched in Fig. 3 for the LHC. Concerning dark-sector studies at the present LHC beam, the direction is twofold [2]: 1) searches for BSM physics and 2) neutrino measurements. The LHC Forward Physics Facility (FPF) incorporates the FASER sub-facility (Fig. 4), whose purpose is to search for light long-lived particles. This project is foreseen to be realized in the UJ12 location near ATLAS. The neutrino search at LHC can also be carried out by the FASER sub-facility. The FASER Pilot Detector, of suitcase-size, after only 4 weeks of exposure detected 6 neutrino candidates. FASER and SND@LHC will soon start to take data in LHC's forward direction. The FPF is proposed to continue this tantalizing program during the entire HL-LHC era, representing a significant extension of the LHC's physics program towards dark sectors and neutrinos. A similar program, sensitive to about ten times higher energies, can be pursued at the FCC-hh. Indeed, for any future collider, one should consider forward physics experiments (for neutrino measurements and dark matter searches) already at the design stage. In this way, the necessary caverns can be constructed together with the main tunnel, which should minimize the total cost.

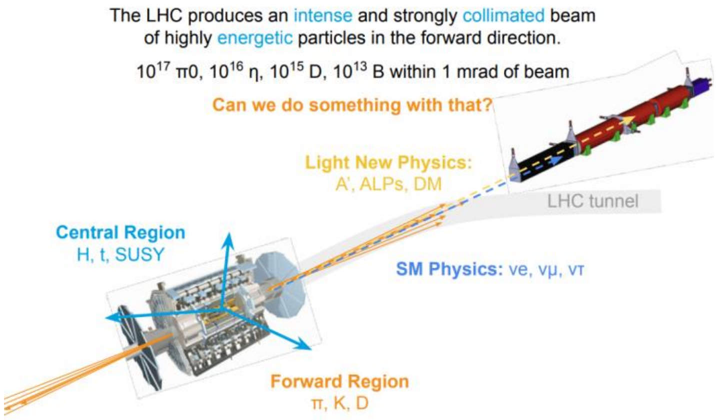


Fig. 3: Concept of distant forward detectors at the LHC sensitive to axion-like particles (ALPs) and dark matter (DM) [2].

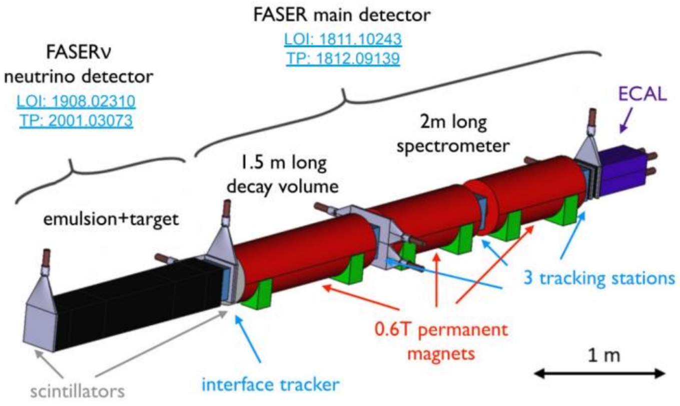


Fig. 4: Engineering design of FASER and FASER ν [2].

Lepton colliders, too, are pursuing the quest for dark matter. The present flagship collider at the luminosity frontier is SuperKEKB, where the Belle-II experiment searches for Dark Photons decaying into light Dark Matter and/or Axion-Like Particles (ALPs) with and without long-lived particles (LLPs). Belle-II also explore evidence for light scalars that couple to B-mesons. Figure 5 highlights how SuperKEKB/Belle II explores unknown territory in the $m_{A'} - \epsilon$ parameter plane, even at a still moderate integrated luminosity of ~1 ab^{-1}.

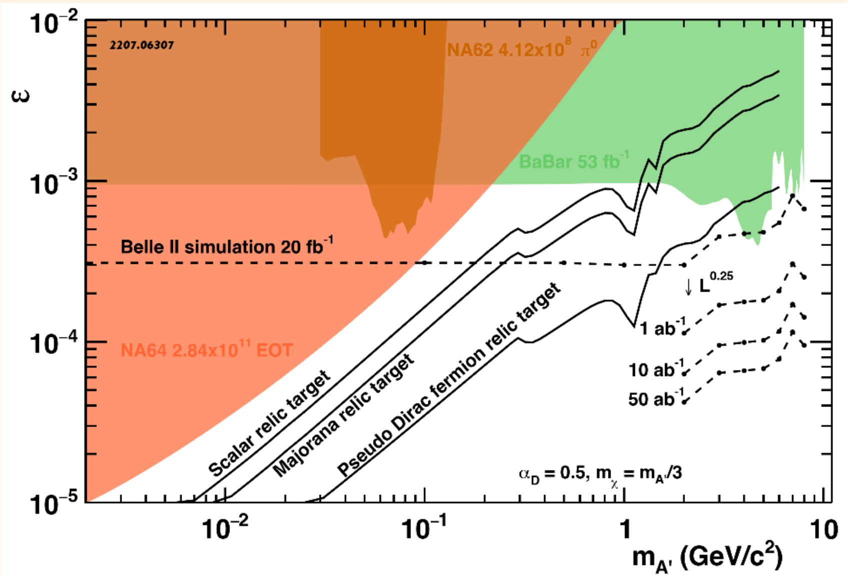
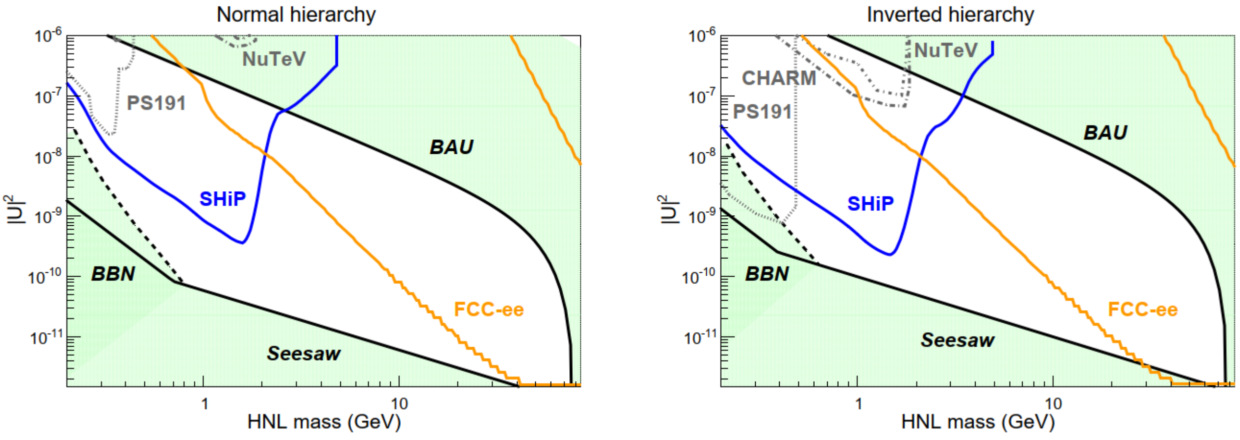


Fig. 5: Reach of Belle II dark matter search in the $m_{A'}$*-*ϵ *plane as a function of integrated luminosity, as indicated.*

A future powerful and multipurpose lepton collider is the FCC-ee [3]. Figure 6 illustrates that the FCC-ee Z pole operation (“Tera-Z factory”) will widely extend the search for heavy sterile neutrinos in the tens of GeV energy range reaching the limit expected from the sea-saw mechanism [4], nicely complementing the reach of the proposed hadron beam dump facility SHIP at GeV energies.



Decay length 0.01-500 cm, 10^{13} Z^0

Decay length 0.01-500 cm, 10^{13} Z^0

Fig. 6: Regions of sensitivity for sterile neutrinos as a function of mass and mixing to light neutrinos (normal [left] and inverted hierarchy [right]) for 10^{13} *Z decays occurring between 100 µm and 1 m from the interaction point (c) [4].*

3 Gamma Factory

The Gamma Factory based on the LHC (or FCC-hh) has a significant potential to produce, detect and investigate the properties of the keV/MeV mass-range DM particles (if they exist). Its potential to also detect DM waves of cosmic origin still remains to be demonstrated. Figure 7 sketches a possible ultimate incarnation of the LHC as a versatile Gamma factory complex supporting multiple HEP applications, with dark matter searches located on the left side.

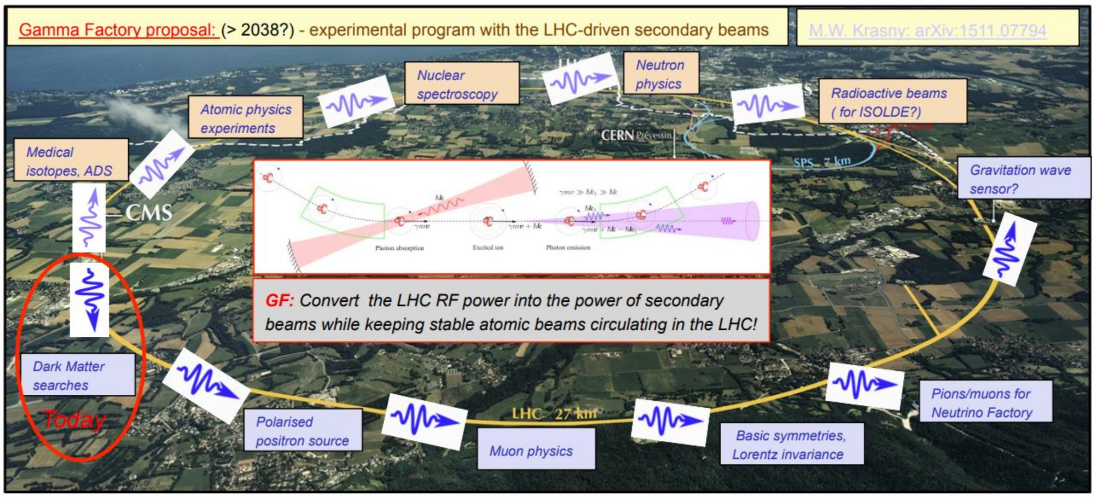


Fig. 7: Schematic transformation of the LHC into a Gamma-Factory-based driver of secondary beams [5].

The significant potential of the Gamma Factory for discovering Dark Photons and Axion-like Particles is illustrated in Figs. 8 and 9. The Gamma Factory sensitivity is limited to small masses, but it offers unique coverage for very feebly interacting dark matter particles.

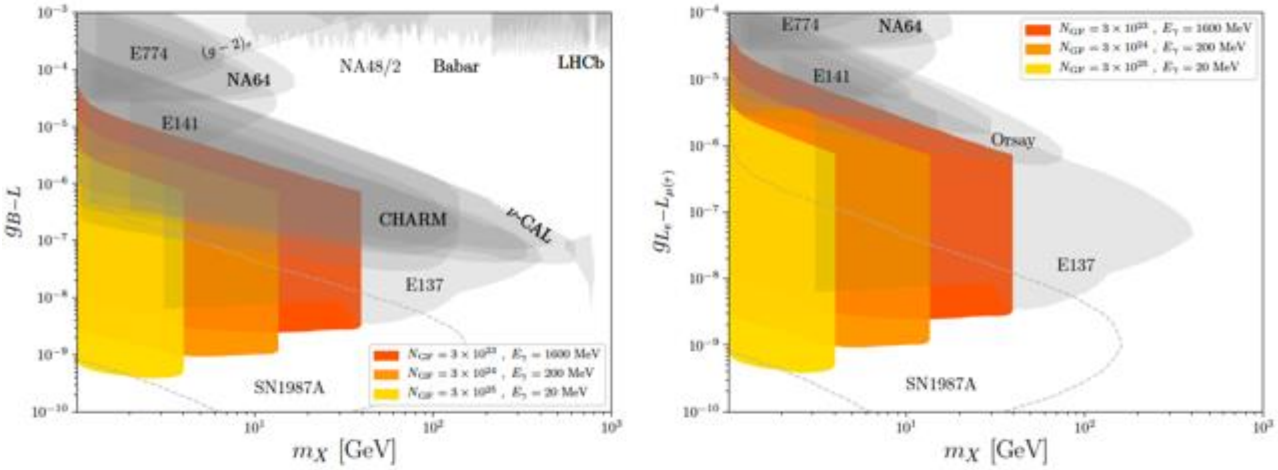


Fig. 8: Gamma Factory sensitivity for anomaly-free gauge bosons. The sensitivity reaches for B−L (left) and $L_e-L_{\mu;\tau}$ *(right) gauge bosons are shown for the three sets of GF parameters (*E_γ *;*N_{GF}*) indicated and the detector parameters* L_{decay} *=12 m and* L_{det}*= 3 m. The contours are for 3* e^+e^- *signal events and assume no background. The gray shaded regions and dashed gray line indicate existing constraints from terrestrial experiments and supernovae, respectively [6]. Here only the Compton scattering of the GF photons on the atomic shell electrons of the target nuclei is considered. Including photon conversions in the target would improve the GF search reach (to be done in the future).*

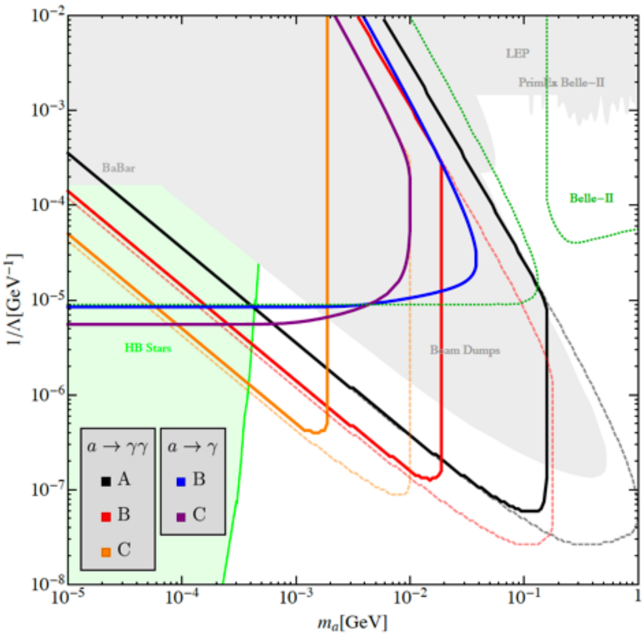


Fig. 9: Projected sensitivity of the Gamma Factory in the m_a-Λ plane in the fixed target production mode. The black, red, and orange solid curves correspond to benchmark points (A), (B), and (C), respectively, in the detection scheme first considered by R. Balkin et al. The corresponding dashed lines are the projected sensitivities in the limit of ideal angular acceptance. The blue and purple curves correspond to benchmark points (B) and (C), respectively, in another detection scheme. The grey regions are current laboratory experimental bounds from LEP, PrimEx, NA64, Belle-II, BaBar (invisible), and beam-dumps experiments. The light green and orange regions are astrophysical bounds from the stellar cooling of HB stars and the stellar evolution of white dwarfs, respectively. The dark green line is the projected sensitivity of Belle-2. For more details see [7].

4 Muon Ring

A muon ring, like the proposed nuStorm [8], would enable a search for light sterile neutrinos at ~1 GeV energies [9]. The nuStorm facility would be fed by 10^{21} protons on target (at 100 GeV), yielding ~2×10^{18} useful muon decays.

5 EDM Ring

A ring for measuring the electric dipole moment (EDM) of the proton or other charged particles allows searching for oscillating EDMs, which would be a signature of coupling from axions [10]. The frequency of longitudinal polarization oscillations, which, under certain conditions, is the difference between spin precession frequency and the revolution frequency, equals the axion-induced oscillation frequency of the EDM.

Most systematic effects limiting the sensitivity of rings searching static EDMs (typically machine operated with “frozen spin”, i.e., with the beam polarized mainly, apart a small vertical component caused by a possible EDM, in longitudinal direction all the time) are strongly suppressed for the search of oscillating EDMs. On the other hand, the resonance condition requires that the difference in the frequency of the spin and the proton match the frequency of the axions. Thus, oscillating EDMs can be identified only within a small frequency range around the frequency of the longitudinal polarization oscillations. Thus, the limitations of the sensitivity of the experiment due to statistics are enhanced by orders of magnitude unless the EDM oscillation frequency is known in advance. If the frequency of longitudinal polarization oscillations is kept constant say for one machine cycle lasting 1000 s, oscillating EDMs can be well identified within a frequency band in the order of 1 mHz.

6 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 Modell (SM) signature (i.e., by detecting scattering, decay...) and assuming DM-dark boson coupling [indirect searches]. Figure 10 illustrates the difference between direct and indirect searches. The event rate in direct searches 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.

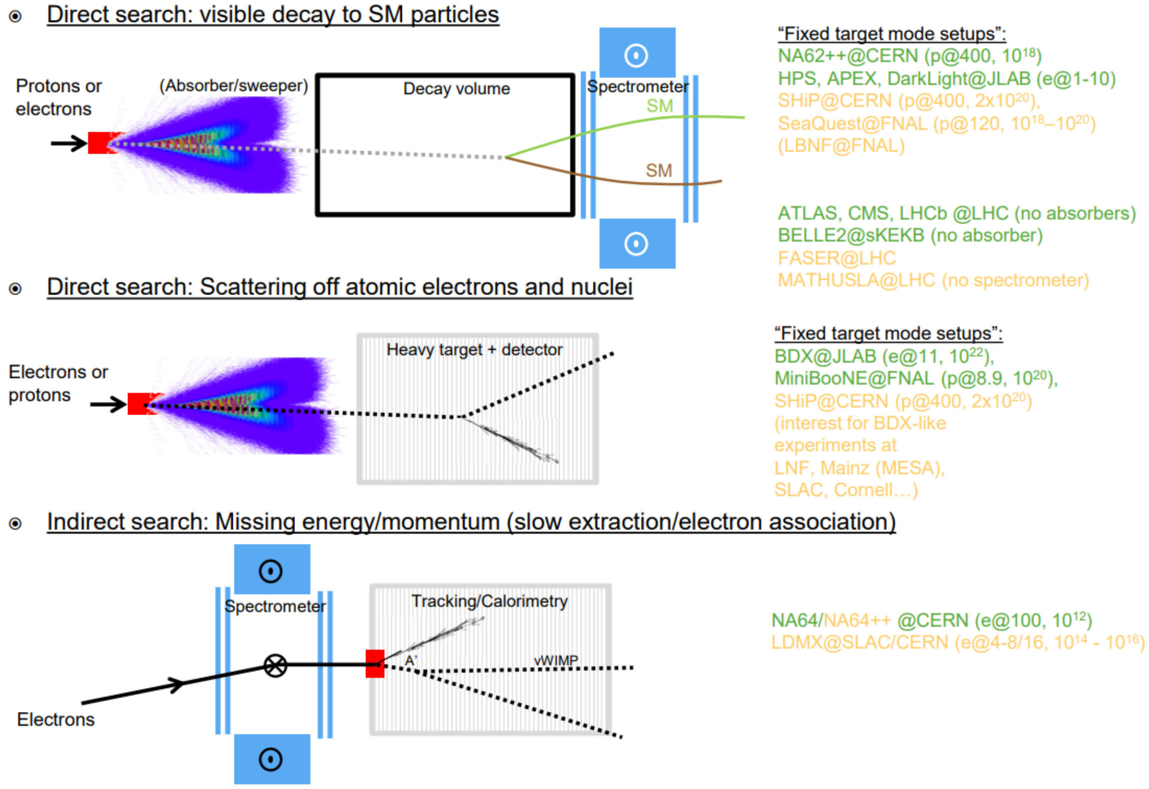


Fig. 10: Direct (top and center) and indirect searches (bottom) for Dark Matter, together with several existing and proposed experiments for each category indicated on the right [11].

A prominent proton-based beam dump experiment is SHIP [12], which is based on beam from the SPS. The SHIP experiment requires a 400 GeV proton beam from the SPS with a total of 2×10^{20}

protons on target, achievable within five years of data taking. A possible energy upgrade could be foreseen with a new superconducting SPS sc(SPS) at proton beam energies of 1 TeV or above. Such scSPS is also proposed as a possible new injector for the FCC-hh collider. Presently, in the United States, FNAL is advancing a suite of machines at the hadron intensity frontier, e.g., PIP-II, PAR, etc., that could already enable the next generation of dark-sector beam-dump experiments [130].

7 Dark Sector Searches - forecast

Direct and indirect long-lived techniques require specific detector designs and massive production of γ, g/q, b, W, Z, H. As we have seen, electron beam-dump experiments, muon colliders, and the Gamma Factory are all predicted to help unravel the mysteries of the dark sector, while, for colliders, pp and e^+e^- collisions are the preferred option. A big issue remains the sensitivity, i.e., the fact that all predictions rely on the *assumption of zero background*, which may not be easily reachable (requiring studies and detailed simulations). Figure 11 shows that, together, the beam dump facility SHIP and the lepton collider FCC-ee would cover a large portion of the DS parameter space. The remaining free space, between SHIP and FCC-ee, could be explored by forward detectors at colliders.

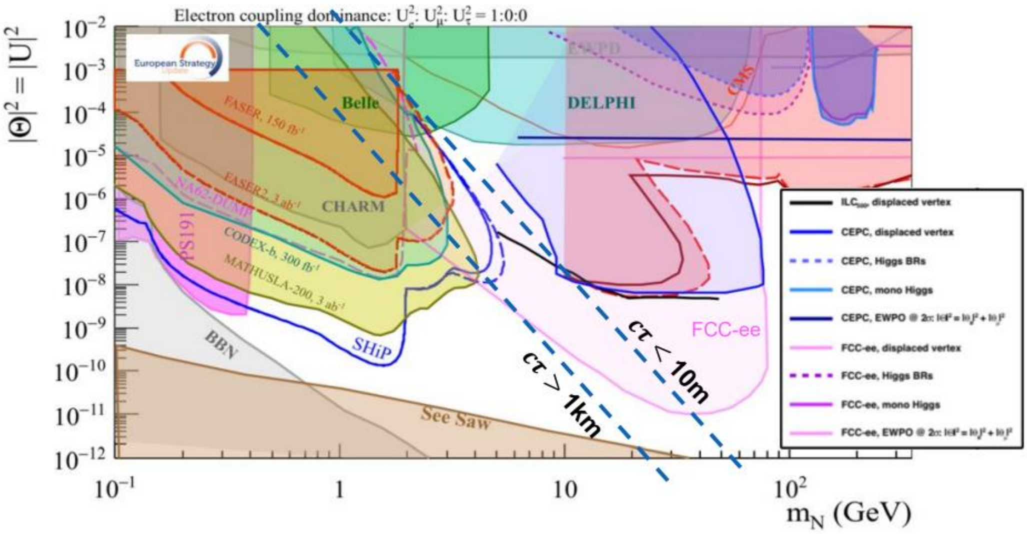


Fig. 11: Dark Sector parameter space already excluded (colored) and covered by SHIP (blue line) and FCC-ee (pink line) [11]. Specifically, the current limits and expected sensitivities of proposed accelerator-based experiments are shown for a heavy neutral lepton (HLN) with a neutrino portal as a function of the mediator's mass and the mediator-SM portal mixing matrix element $|U_\mu|^2$*, plotted against the HLN mass, assuming the latter HLN mixes only with muon flavoured neutrinos. The figure is taken from the PBC report [14].*

8 Advanced Accelerators for Dark Sector Searches

A study of possible use of advanced accelerators for dark matter searches can build upon the rich expertise with advanced accelerators that was assembled within iFAST and during previous European accelerator networking activities like ARIES and EuCARD, upon discussions of accelerator experts and particle physicists at the ARIES-iFAST joint Brainstorming and Strategy Workshop 2022, and on studies being carried out within the EPFL Global Leader programme. The present particle-physics scenarios render plasma or advanced accelerators potentially interesting tools for reaching the expected regions of discovery, as a complement to proton storage rings and e^+e^- accelerators.

8.1 PLASMA ACCELERATORS – EUPRAXIA AND AWAKE

Plasma accelerators are not easily implemented for practical high-energy applications, especially for demanding collider applications. Outstanding challenges include the issue of matching into, and out of, the plasma with rms beam sizes or order 1 µm, for beta functions of about 1 mm. Adiabatic matching [15] is one possible approach. Another challenge is the control of the offsets between the wakefield driver (laser or beam) and the accelerated electron bunch, at the 1 µm level. A third challenge is the necessity of using short bunches (few fs duration) to minimize the beam energy spread. In addition, one must achieve synchronization stability of a few fs between the injected electron bunch and the wakefield (energy stability and spread). From Simon van der Meer stems the idea to control the charge profile and use the effect of beam loading to compensate for the energy spread. The next big milestone is to develop and demonstrate the user readiness of a 5 GeV plasma-accelerated beam. EuPRAXIA project is the project presently underway to accomplish exactly this goal. As of December 2021, EuPRAXIA counts 40 member institutions and 10 observer institutions, from major European and non-European countries. Together with the Einstein Telescope, in 2021 EuPRAXIA has been one of only two new entries on the important Roadmap of the European Strategy Forum on Research Infrastructure (ESFR). Intriguingly, in the Conceptual Design for EuPRAXIA, the energy conversion efficiency from wall-plug to laser driver is 0.01%, attainable today. This still is a factor of a few 1000 lower than assumed for proposed colliders based on laser-driven plasma acceleration, hinting at a long road ahead for this type of acceleration scheme. Beam-driven plasma accelerators have much higher wall-plug-to-driver efficiencies, 58% in the case of EuPRAXIA. However, even then, the expected total energy conversion efficiency from the wall-plug to the main beam is below 3%, and hence still significantly lower than for conventional accelerators.

Nevertheless, and despite its low repetition rate, the AWAKE collaboration, which is operating a demonstrator experiment for proton-driven plasma wakefield acceleration at CERN, also envisions the use of the AWAKE scheme for conducting dark matter searches. By the conclusion of its “Run 2,” the AWAKE collaboration will have demonstrated the acceleration of electrons with stable GV/m gradients. Scalable plasma sources will have been developed that can be extendable up to even kilometers in length. The acceleration process should preserve the beam quality resulting in bunches with a transverse emittance of below 10 mm mrad. With these developments, using proton bunches from the SPS, acceleration of electrons to 10s of GeV, and even up to ~ 200 GeV, should be possible, while LHC protons with an energy of 7 TeV would enable acceleration of electrons up to about 6 TeV. A limitation of the current proton drivers is their low repetition rate and hence the luminosity of any application of the AWAKE scheme. Given this, high-energy applications are considered where new regimes are explored and where the luminosity is less critical. The first particle-physics application of AWAKE could be to generate high-energy electron beams impinging on a target in order to search for new phenomena related to dark matter [16]. The sensitivity of AWAKE-based searches to dark photons is illustrated in Fig. 12.

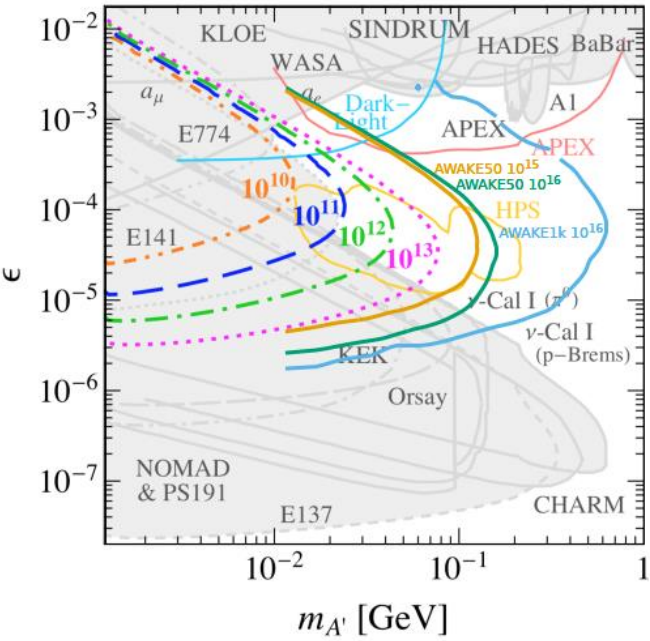


Fig. 12: Limits on dark photon production decaying to an e^+e^- pair in terms of the mixing strength, ϵ, and dark photon mass, $m_{A'}$, from previous measurements (light grey shading). The expected sensitivity for the NA64 experiment is shown for a range of electrons on target, 10^{10}–10^{13}. Expectations from other potential experiments are shown as coloured lines. Expected limits are also shown for 10^{15} (orange line) or 10^{16} (green line) electrons of 50 GeV ("AWAKE50") on target and 10^{16} (blue line) electrons of 1 TeV ("AWAKE1k") on target provided to an experiment using the future AWAKE accelerator scheme [16].

8.2 DIELECTRIC LASER ACCELERATORS

Using optical-scale lithographically fabricated particle accelerators is referred to as dielectric laser acceleration (DLA). 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 mJoule range, while repetition rates can be 10s of MHz [17].

An important point relating to dark sector searches is that laser- and beam-driven plasma accelerators are characterized by bunch charges of order 1 nC at about 15 kHz repetition rate, whereas dielectric laser accelerators have much lower charges of order 1 fC (or a few 1000 electrons per bunch) at a much higher repetition rate; see Table 1. In view of their high repetition rate and low bunch charge, the DLA-based accelerators are an appealing option for indirect DM searches, where individual incident electrons need to be precisely tracked, as sketched in Fig. 10 bottom.

Table 1: Required parameters for a linear collider with advanced high gradient acceleration [18]. Three published parameter cases are listed. This table is taken from the LDG report [19].

Parameter	**Unit**	**PWFA**	**LWFA**	**DLA**
Bunch charge	nC	1.6	0.64	4.8×10^{-6}
Number of bunches per train	-	1	1	159
Repetition rate of train	kHz	15	15	20,000
Convoluted normalized emittance ($\gamma\sqrt{\epsilon_h\epsilon_v}$)	nm-rad	592	100	0.1
Beam power at 5 GeV	kW	120	48	76
Beam power at 190 GeV	kW	4,560	1,824	2,900
Beam power at 1 TeV	kW	24,000	9,600	15,264
Relative energy spread	%		$\leq$0.35	
Polarization	%		80 (for e^-)	
Efficiency wall-plug to beam (includes drivers)	%		$\geq$10	
Luminosity regime (simple scaled calculation)	$10^{34}\text{cm}^{-2}\text{s}^{-1}$	1.1	1.0	1.9

9 Reference Experiments

A direct search is pursued by the beam-dump scattering search ϵ^4-sensitive experiment BDX (in the final configuration 10^{22} electrons on target at 11 GeV, without any time structure requirement). It will be difficult to provide so high a number of electrons in an energy-efficient way using an advanced accelerator.

Indirect experiments look more promising. A good reference point for a DLA-based dark-sector search can be the missing-momentum-technique ϵ^2-sensitive LDMX experiment (in the ultimate not-yet-approved proposal 10^{16} electrons on target at ~8 GeV energy, with a time separation between individual electrons between 20 and 25 ns, so that the electrons are easily individually distinguishable by calorimeters...

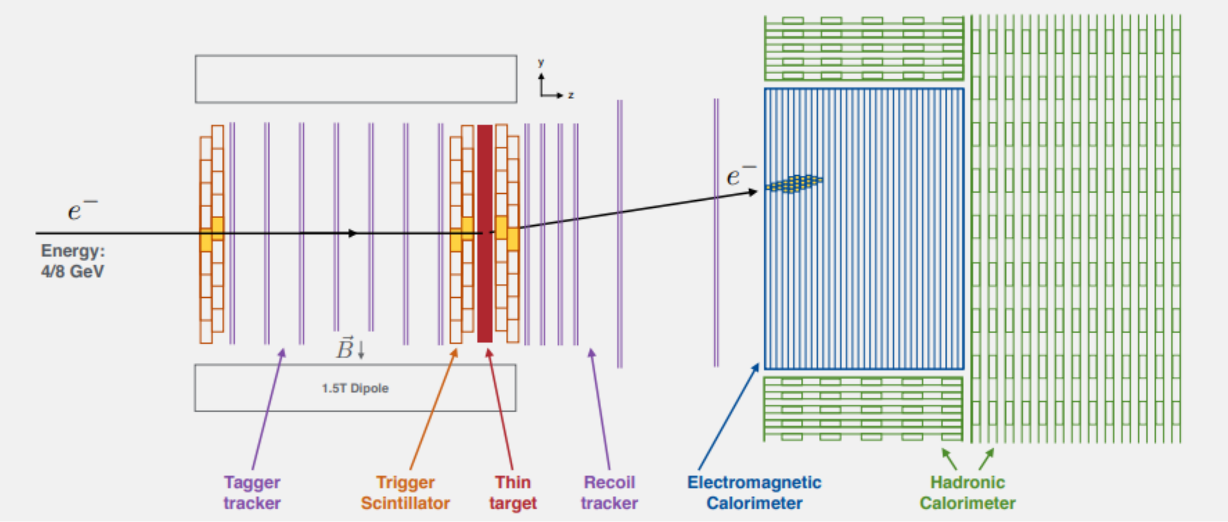


Fig. 13: Concept of LDMX experiment with detectors upstream and downstream of a thin target [20].

10 A Simple Dark Sector DLA

Figure 14 shows the scanning electron micrograph of the dual pillar accelerator structure. In Table 1, a repetition rate of 20 MHz is indicated. However, rates up to 1 GHz can be supported by a “single electron source” (similar to the source for an electron microscope) – see next section –, and by the laser system. Extrapolating from Ref. [21], and considering a final beam energy of 10 GeV, and laser pulse length of 0.1 ps, we estimate that 200 kW are required to accelerate single electrons at 60 MHz rate to this energy, at an average current of about 1 pA. With a year of 2×10^7 s, this would amount to 6×10^{14} electrons on target per year, and total energy consumption of 1 GWh per year.

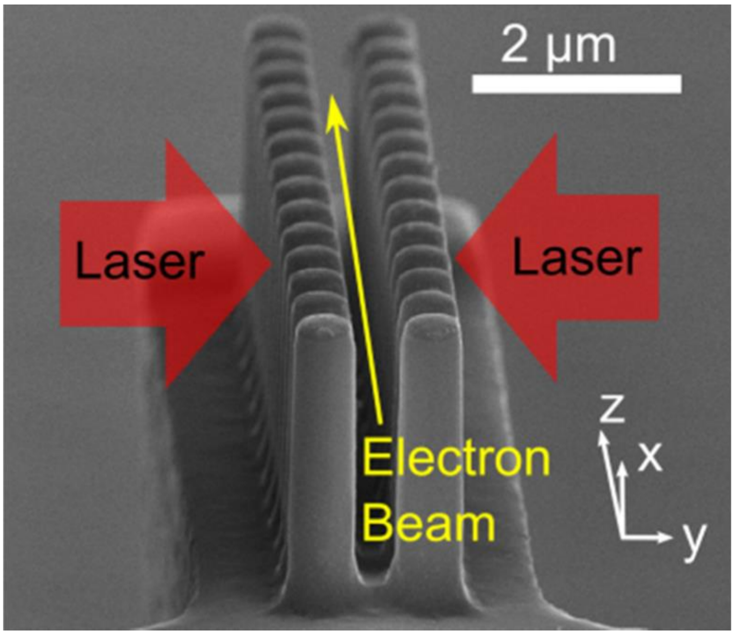


Fig. 14: Scanning electron micrograph of the dual pillar accelerator structure. The structure has 14 periods and its 15 μm long gratings are sitting on a 75 μm tall mesa [22].

11 Single Electron Source for DLA DS Searches

The generation of single electrons per pulse is essential for indirect searches of dark particles (Fig. 10 bottom). In addition, due to the small cross-section of dark matter production, a high number of electrons will be essential for a successful experiment. Therefore, a single electron source with a high repetition rate is the desired particle source for this kind of research. Recently, electron microscope experts have been working on developing such types of electron sources for time-resolved measurements.

Conventional electron microscopes provide sufficient spatial resolution for looking at atomic scales; however, ultrashort electron pulses are necessary for accessing the dynamics at the atomic levels. Therefore, a number of research groups have been working on generating electron pulses with ~1 nm beam diameter and ~100 fs time duration, which is easy to reach in a single electron regime. Among the concepts pursued, beam “blankers” (or choppers) are an interesting alternative to pulsed laser photoemission, as they allow for much higher repetition rates and reduce exposure time. Table 2 compiles some information about beam blankers reported in the literature, for use in ultrafast electron microscopes, among which the microwave cavity-based sources seem most interesting for dark sector studies. All values reported in Table 2 have been experimentally demonstrated.

The RF-cavity-based Ultrafast Transmission Electron Microscope (UTEM) produces ultrashort electron pulses by streaking the continuous beam across a small aperture (Fig. 15). In 2018, the Eindhoven University of Technology (TU/e) group successfully developed and commissioned a UTEM (Fig. 16) by equipping a commercial FEI Tecnai TF20 with a 3 GHz cavity operating in TM110 mode. The group demonstrated that a 3 GHz RF-cavity operating in TM110 mode could be used as an ultrafast beam blanker to chop the continuous electron beam of a conventional TEM into pulses with a few-100-fs duration and peak current of 814 ±2 pA [23].

Table 2: Parameters of beam blankers. H: total height of the blanker; L: active length of the single deflector plate; d: distance between deflector plates; V_{beam}: energy of electron beam; V_{def}: voltage on the deflector plates; f: frequency of blanking signal; I: average beam current after the blanker; s: temporal resolution; the brightness and energy spread depend on the used electron microscope [24].

Type	$H \times L \times d$ (mm)	V_{beam} (kV)	V_{def} (V)	f (MHz)	I (pA)	τ (ps)
Static plates	…	…	5	7	…	100
Static plates	d = 0.5	30	400	1	2	…
Static plates	…	…	…	0.04	…	…
Deflector + buncher	356.5 × 14.5 × 2	20	…	1000	10	0.2
Plug-in beam chopping system	60 × 6 (3) × 0.3 (0.2)	3	5	250	2.5	10
Elliptical plates	…	10	64	18 000	…	0.11
Horse shoe double plate	51.8 × 11.3 × 2	10	5	160	…	1600
Commercial static plates	L = 6, d = 0.3	4	10	10	0.15	90
Microwave cavity (TM_{110})	H = 17.1	30	…	3000	…	0.1
Microwave cavity (TM_{110})	H = 16.7	200	…	3000	2.7	1.1
MEMS parallel plates	5 × 0.1 × 0.001	30	10	20 000	1.3	0.4
MEMS parallel plates	L = 0.01, d = 0.001	30	10	100	0.16	0.1

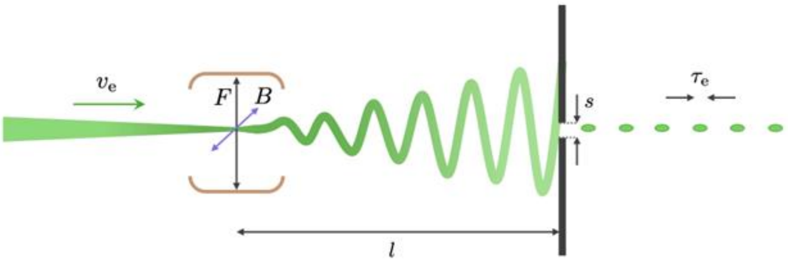


Fig. 15: Principle of beam chopping. An RF cavity periodically deflects the continuous electron beam towards an aperture. As a result, ultrashort electron pulses are created at twice the cavity's resonant frequency [25].

The challenge of using an RF-cavity-based UTEM for dark matter studies is achieving the desired electron population for each pulse. Since a thermionic electron gun emits randomly, the electrons of the continuous beam entering the RF cavity are not in phase. This means that a large portion of the electrons will not make it through the aperture. In the TU/e experiment, with a continuous beam current of only 0.1 nA, 7.5% of the pulses contained a single electron while the rest of the images contained zero electrons (private communication by Simona Borrelli). More accurate and systematic measurements are planned in the coming months. We expect that for 10 times higher average current, one can obtain a distribution with 0, 1 or 2 electrons per pulse, at a repetition rate at least in the few GHz range. Instead of a thermionic gun, a synchronized "single-photo-electron" gun using split-off photons from the first DLA laser might be more suitable for our application here.

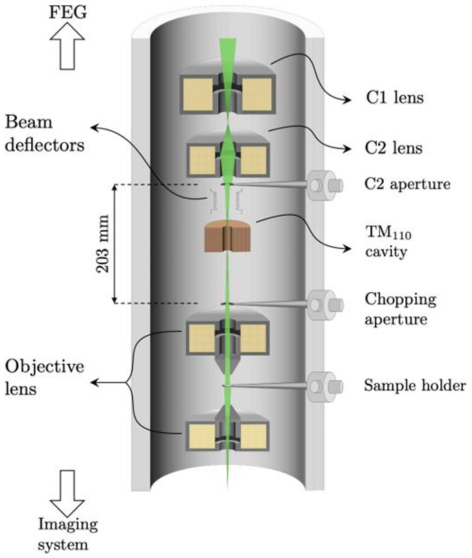


Fig. 16: Schematic of the TU/e RF-cavity-based ultrafast electron microscope. An additional 203 mm vacuum section has been added to a 200 kehV FEI Tecnai TF20 TEM below the C2-aperture. This section hosts a TM110 dual mode cavity, an additional set of beam deflectors, and an aperture holder that enables inserting different-sized chopping apertures [23].

12 Enhanced Dark Sector DLA

According to Table 1, we could enhance the rate of electrons, at about constant laser power, by a factor of 159, if we send 159 electrons per pulse (one electron per DLA "bucket"). Unfortunately, the successive electrons are only ~2 microns (about 7 fs) apart, which is much less than a possible and already ambitious 10 ps time resolution of the detectors. 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. 17. Dielectric Laser Deflectors were studied, e.g., by Kenneth J. Leedle, et al. [20] – see example deflector strengths in Fig. 18, and deflectors at terahertz frequencies have been demonstrated by Zhang et al. [26]. For 159 bunches (electrons) per pulse, we need to increase the laser pulse length to 1 ps. In this case, the average current is 150 pA. Again, considering a year of 2×10^7 s, 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 proposed LDMX experiment requires a primary electron beam with low current and high duty cycle from LCLS-II to collect 10^{14}-10^{16} electrons on target. The enhanced DLA scheme should achieve at least the same reach as for the "future" LDMX proposal shown in Fig. 19.

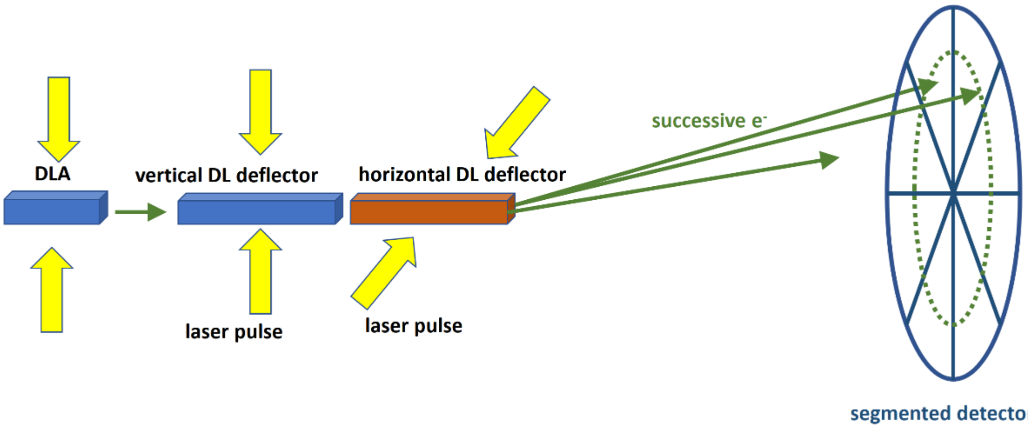


Fig. 17: After the DLA, this sketch shows a pair of orthogonal dielectric laser (DL) deflectors sending each electron in a train of ~160 onto a separate segment of the detector, thereby overcoming the time resolution limit and allowing bunch spacing of less than 10 ps within a train.

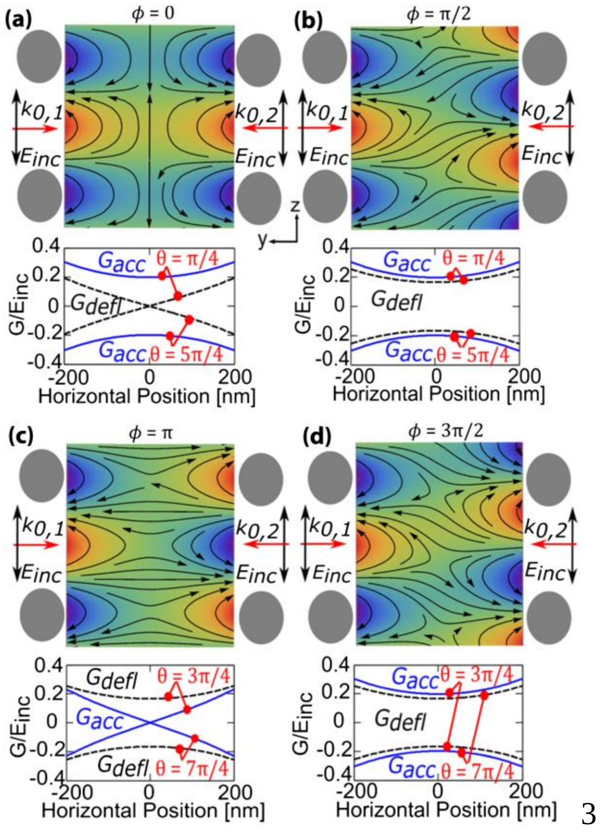


Fig. 18: Dual pillar dual-drive mode profiles with force vectors superimposed on the E_z acceleration field colour map at different relative drive phases. Insets show accelerating and deflecting gradients across the channel for illustrated optical phases θ [22].

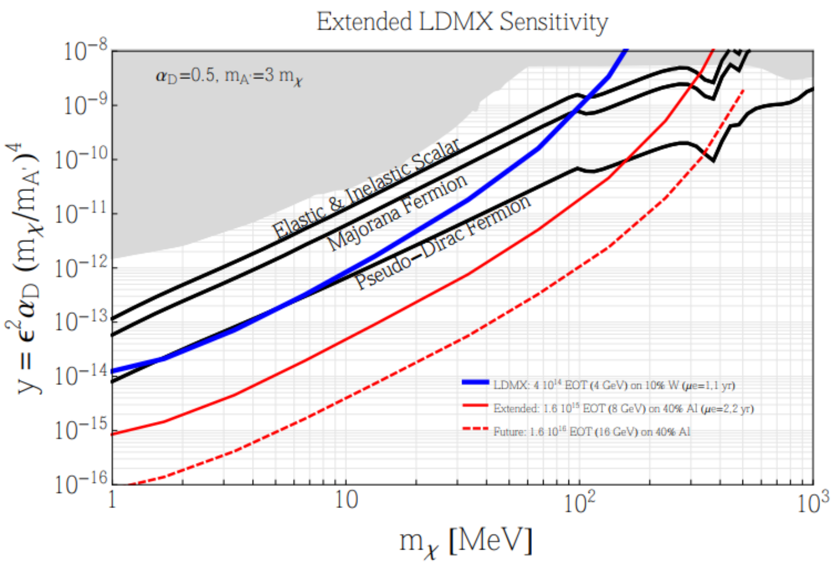


Fig. 19: The interaction strength between dark matter and Standard Model matter versus the possible mass of the dark matter particles. The black lines show the interaction strength compatible with the dark matter abundance in the universe, and for the types of dark matter particles that are not excluded from the analysis of the Cosmic Microwave Background. The grey area shows the already excluded region. The colored lines show the reach of LDMX. The plot is taken from [27].

13 Ultimate Dark Sector DLA

Another promising approach to reaching much higher electron rates is making the DLA structure part of a mm-scale laser oscillator [28] as sketched in Fig. 20.

This 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). Parameters for the three proposed DLA scenarios are compared in Table 3.

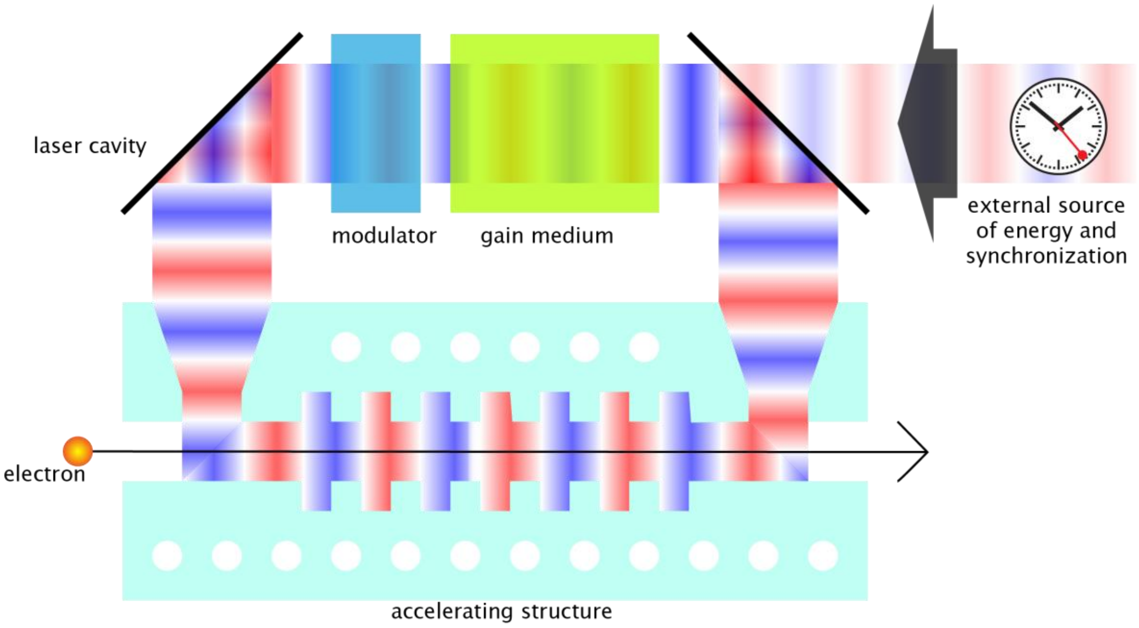


Fig. 20: Sketch of DLA structure as part of a laser oscillator. The beam moves from left to right through the structures, while the laser pulse circulates at a rate of 100 GHz (path length ~3 mm). The original version of this picture is shown in Fig. 21.

Table 3: Three options for DLA based dark sector search facilities (DSS).

	Basic DLA DSS	**Enhanced DLA DSS**	**Ultimate DLA DSS**
Beam energy [GeV]	10	10	10
Gradient [GV/m]	1	1	1
Active 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	159	1
Average current [pA]	1	150	
Time separation [ns]	17	17 between pulses (7 fs inside pulse)	0.01
Special features	-	DL deflectors & segmented detector	DLA structures part of laser oscillator
e$^-$ on target / year (2×10^7 s)	6×10^{14}	$\sim 10^{17}$	$\sim 10^{18}$
Energy consumption / year	1 GWh	10 GWh	~2 GWh

14 Future plans / Conclusion / relation to other IFAST work

SHIP and Gamma Factory offer exciting possibilities for dark sector explorations, complementing ongoing and planned searches at the LHC, Belle 2, NA64, BDX and LDMX. Muon-ring based searches might become possible in the future, should such rings be constructed.

Concerning advanced accelerators, presently efforts are underway for proton-driven plasma acceleration, offering extremely high electron energies, and for dielectric laser acceleration, enabling the delivery of single electrons at extremely high repetition rates.

The DLA related dark sector work will continue with concrete structure designs and simulations of structure wake fields and beam dynamics. Suitable μJ-GHz laser technology will need to be explored. The combined laser-structure technology and appropriate cooling will need to be further developed. 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.

A targeted iFAST meeting at CERN (Fig. 22) addressed the next steps. These include the design of a suitable DLA structure, particle tracking through this structure, and optimisation of the focusing in the transverse and longitudinal planes. In parallel, other topics should be advanced: (1) the single electron source; (2) matching the design to parameters suitable for an experiment; (3) instrumentation for the electron beam, and for the electromagnetic field; (4) manufacturing of the laser cavity and the accelerating structure; (5) transverse and longitudinal alignment; and (6) development of the couplers feeding a laser beam with transverse electromagnetic fields into, and out of, the DLA structure with a nonzero longitudinal electric field, as part of the laser oscillator.

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16 Annex: Glossary

Acronym	**Definition**
ALP	Axion-Like Particle
DLA	Dielectric Laser Accelerator
DM	Dark Matter
DSS	Dark Sector Search
LLP	Long-Lived Particle
SM	Standard Model

17 Annex: Original Figure 20

Figure 21 shows the original version of Figure 20 conceived under challenging conditions.

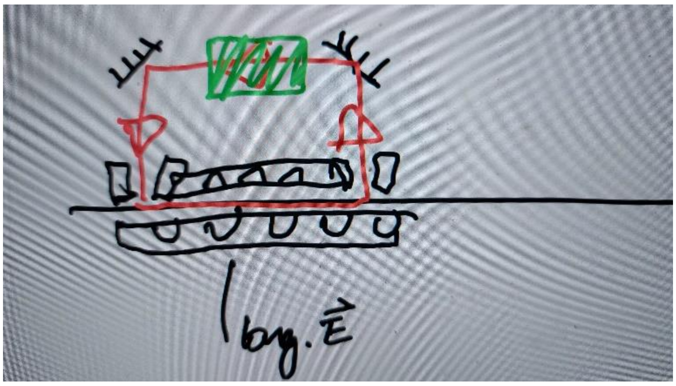

Fig. 21: Hand-drawn sketch of DLA structure as part of a laser oscillator. The beam moves from left to right through the structures, while the laser pulse circulates at a rate of 100 GHz (path length ~3 mm) [drawn by R. Ischebeck on a green field, while riding a bike to PSI].

18 Annex: Photographs from iFAST Topical Meeting

Figures 22 presents two snapshots from a, iFAST WP5.2 dark-sector accelerator meeting at CERN.

Fig. 22: Two photographs from the topical dark-sector acceleration iFAST meeting, held at CERN, on 31 October 2022.