# FY21 Status Report for LDMX Dark Matter New Initiative

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# 1 Introduction

One of three Priority Research Directions identified in the "Dark Matter New Initiatives" (DMNI) BRN report [1] is

> **PRD 1: Create and detect dark matter particles below the proton mass and associated forces, leveraging DOE accelerators that produce beams of energetic particles**... Interactions of energetic particles recreate the conditions of dark matter production in the early universe. Small experiments using established technology can detect dark matter production with sufficient sensitivity to test compelling explanations for the origin of dark matter and explore the nature of its interactions with ordinary matter.

In discussing this Priority Research Direction, the report highlights a strong motivation for "10- to 1000-fold improvements in sensitivity over current searches" for dark matter (DM) production (Thrust 1) and discusses the unique capability of the missing-momentum technique to meet or exceed this goal over most of the MeV-GeV mass range. The report also notes a secondary emphasis on "explor[ing] the structure of the dark sector by producing and detecting unstable dark particles" (Thrust 2).

The Light Dark Matter eXperiment (LDMX) is a small experiment that realizes this missing-momentum concept. As shown in Figure 1, dark matter is produced in electron fixed-target collisions and detected through the use of tracking and calorimetry to identify events where an incoming electron lost most of its energy to DM production. Operating at high rate in a continuous-wave (CW) electron beam for only a few years, this approach can fully address Thrust 1 by achieving a 1000-fold improvement in sensitivity to dark matter production, while also broadly searching for unstable dark particles that are the objective of Thrust 2. In addition to the primary dark matter motivation, LDMX data can also provide measurements of electron-nucleon interactions at large momentum transfers that are of critical importance to interpreting the data from the flagship neutrino program at Fermilab.

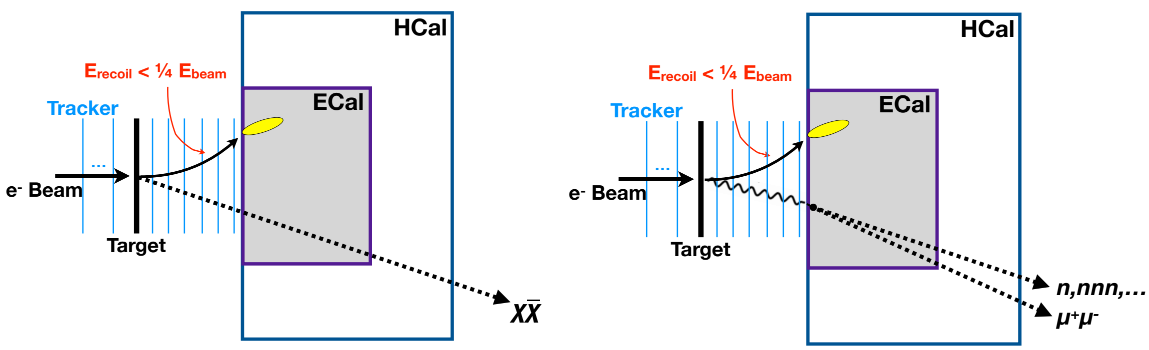



Figure 1: The conceptual layout of the LDMX apparatus demonstrating the missing-momentum technique of searching for dark matter in fixed target production (left) and key backgrounds that the detector is designed to reject (right). In signal events, an incoming beam electron loses most of its energy and experiences a hard kick in transverse momentum in the production process, producing a soft, high-angle recoil and no other detectable interaction products in strong contrast to the Standard Model scattering processes. However, in cases that are rare but relevant to a high-statistics experiment, a hard bremsstrahlung photon is produced that undergoes muon conversion or photo-nuclear reactions in the detector material that are difficult to detect. These backgrounds define the required veto performance of the detector.

While this experiment can achieve new sensitivity for sub-GeV dark matter with fewer than $10^{12}$ electrons on target (EOT) – only weeks of operation – achieving the full potential of the experiment requires event yields as high as $10^{16}$ EOT. Meanwhile, ensuring high purity for the missing momentum signature requires the ability to correctly associate all of the particles belonging to each individual event so that each incoming electron is correctly tagged to its interaction products. For large event yields, this requires a near-CW beam and granular detectors with high-rate capability and excellent time resolution. Furthermore, because the experiment is an active dump, some elements of the detector must be relatively radiation tolerant.

Most of the technologies required to meet these challenges are well established, and none of them is beyond the state of the art. High repetition rate electron beams are available within the DOE complex at both SLAC and JLab, as well as at other labs worldwide. Charged particle tracking with the granularity and rate capability required for the experiment has existed for at least 20 years, and the technologies needed for hadronic calorimetry, triggering, and data acquisition are similarly mature. Only the electromagnetic calorimeter faces rates and radiation doses that require the newest detector technologies. As a result, little fundamental development is required: the task is one of adapting technologies, designs, and hardware that already exist in a way that optimizes the performance while minimizing the technical risk, cost, and effort involved in mounting the experiment. In particular, LDMX re-purposes designs from the HPS Silicon Vertex Tracker for tracking, the CMS upgrade HGCal for the ECal, and the Mu2e Cosmic Ray veto for the HCal, and plans to use LCLS-II drive beam at SLAC in a way that is parasitic and invisible to the primary photon science program.

Commensurately, the LDMX DMNI project is a "Track 1" project, consisting of the design and prototyping required to adapt hardware and technologies developed for other experiments to the needs of LDMX and integrate them into a coherent whole, computing support for the physics studies needed to achieve a robust and efficient design, and project planning and management expertise necessary to develop a design report and project execution plan for construction and operation of the experiment. The goal of this project is to be ready to begin construction of the LDMX apparatus before the beginning of FY23 and to be ready for operations in FY25. In accordance with guidance from OHEP, we are planning towards a Preliminary Design Review mid-way through FY22, with a Final Design Review at the end of FY22 to approve project start.

At the time of this report, LDMX has not received FY21 funds. Some tasks scheduled for FY21 have been delayed as a result, while others have been completed using redirected effort and outside resources. In light of this progress, the float in the original schedule, and the continuing availability of required effort, the DMNI project can remain on track to achieve its goals on the above-stated timeline provided that FY21 funding is received soon.

# 2 Science Goals and Details

The primary goal of LDMX is a missing-momentum search for dark matter (PRD1, Thrust 1). Beyond this objective, LDMX is a multi-purpose forward experiment that can search for unstable dark-sector particles (PRD2, Thrust 2) and can make electronuclear measurements for neutrino physics. Further applications, such as searches for rare meson decays, are also being explored. This section summarizes the motivations and LDMX's expected capabilities in each of these domains.

### Dark Matter Production: (PRD 1, Thrust 1)

The exemplar of the "compelling explanations for the origin of dark matter" emphasized in the BRN report is the idea that dark matter arose as a thermal relic from the hot early Universe. This paradigm is viable over the MeV to TeV mass range, and requires a small non-gravitational interaction between dark and familiar matter. Any such interaction implies a DM production mechanism in accelerator-based experiments; in most sub-GeV realizations, electron-DM couplings are key to the thermal DM origin, and so measurements of these couplings are a priority. LDMX's missing momentum measurement directly explores this coupling.

Scalar, Majorana, or Pseudo-Dirac particle DM can be thermally produced through contact interactions with Standard Model leptons $f$ (for example, $\frac{1}{\Lambda^2}\bar{\chi}\sigma^{\mu}\chi\bar{f}\sigma_{\mu}f$ for the Majorana fermion $\chi$). All three scenarios are consistent with CMB bounds on DM annihilation [2]; the fermion models in particular are compatible with a small DM mass (i.e. technically natural) and are poorly constrained by existing terrestrial experiments. Thermal freeze-out predicts the interaction scale $\Lambda$ for a given DM mass $m_{\chi}$, or equivalently $y \approx 0.9m_{\chi}^4/\Lambda^4$ shown in Figure 2. These predicted couplings define an important sensitivity milestone [3, 4, 1]. Most of their parameter space falls within a factor of 10 to 1000 of the interaction strengths that have been explored to date by both beam-dump experiments [5, 6] and fixed-target missing-energy searches [7]. A mediator particle (for example, a dark photon $A'$) must resolve this interaction at a scale $\lesssim \Lambda$, and may be experimentally accessible.

The three panels of Figure 2 illustrates the power of LDMX to explore these scenarios, including challenging milestones such as Pseudo-Dirac dark matter [3] over a wide range of mediator masses, and thermal freeze-out with a mediator that is near-resonance [9] or below the DM pair threshold [3, 10]. Furthermore,

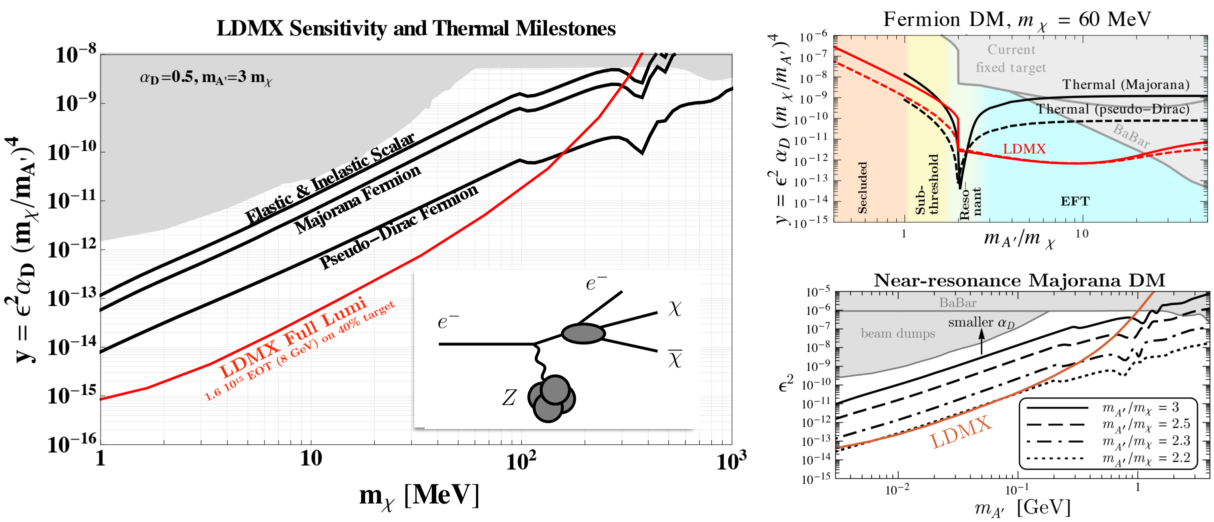



Figure 2: Left: Thermal dark matter milestones (black curves), present constraints (gray), and LDMX projected reach, in the conventions of [4]. LDMX improves over existing DM production searches by three orders of magnitude or more, which is required to robustly explore the thermal freeze-out scenarios highlighted by PRD 1. The inset shows a DM production reaction observable at LDMX; the mediator can be on- or off-shell. Right top: milestones, LDMX reach, and present constraints for a fixed DM mass of 60 MeV, as a function of the mediator-to-DM mass ratio, for Majorana (solid) and pseudo-Dirac (dashed) DM. Colored bands indicate different qualitative domains of DM annihilation, discussed in the text. Right bottom (adapted from [8]): milestones in the resonant region, plotted as in [9] for up to 10% mass tunings.

by exploring deep in the coupling parameter space LDMX probes models such as secluded annihilation [11] of light DM into scalar mediators, motivated parameter space for DM-electron couplings through other types of mediators [10], and SIMP and ELDER models [12, 13, 14] where DM interactions with ordinary matter maintain kinetic equilibrium while DM self-interactions deplete its abundance.

### Broad Dark Sector Sensitivity (PRD 1, Thrust 2)

In addition to the above-mentioned dark matter searches, LDMX makes several notable contributions to searches for unstable dark sector particles beyond DM (Thrust 2). Some of these scenarios — such as millicharged particles and $B-L$ gauge bosons decaying to neutrinos — are tested directly by LDMX's standard missing-momentum analysis. In particular, LDMX's excellent sensitivity to millicharged particle production has substantial overlap with the parameter space motivated by the EDGES anomaly [10], exceeds existing limits by up to an order of magnitude, and surpasses the sensitivity of dedicated millicharge detector proposals in the $< 100$ MeV mass range [15].

In addition, distinct analyses can search for long-lived dark sector particles decaying deep in the LDMX calorimeters [10]. Such searches are sensitive to axion-like particles and dark photons as well as large-splitting inelastic dark matter and SIMP models.

### Intensity-Frontier Synergy: Electronuclear Measurements for Neutrino Program

Beyond dark sector physics, LDMX can make powerful measurements [16] of electron-nuclear scattering, which address key systematics for DUNE and other neutrino oscillation experiments (see [17, 18]). LDMX complements other experimental efforts in this direction (mainly at JLab [19, 20, 21, 22, 23, 24]) that can be used to improve neutrino scattering models in generators such as GENIE and GiBUU. These generators have been found to differ from *inclusive* electron-scattering cross-sections by up to $\mathcal{O}(50\%)$ [18]. Compared to the experiments and proposals above, LDMX is unique for its broad (nearly 40 degree) forward coverage, low reconstruction energy threshold in various hadronic final states, and ability to detect neutrons with high efficiency. These will allow LDMX to perform *semi-exclusive* measurements of nuclear multiplicity and kinematics within its phase space in addition to electron kinematics [16]. Moreover, due to LDMX's use of a 4–8 GeV beam, LDMX data used to search for dark matter will be taken in a range of momentum and energy transfer that closely overlaps the region most relevant to DUNE [16]. For these reasons, the LDMX collaboration has a dedicated effort to include an electro-nuclear trigger for data taking and is engaged in ongoing studies with neutrino physicists to refine our understanding of LDMX capabilities in this area.

## 2.1 LDMX On the World Stage

### 2.1.1 Accelerator-Based Experiments

The expected sensitivity of LDMX, compared with other accelerator-based experiments (completed, ongoing, and proposed), is illustrated in Figure 3. At low masses, LDMX is uniquely capable of 1000-fold improvements in sensitivity, with sensitivity unrivaled by other experiments. The most relevant accelerator searches to compare with LDMX include:

- *Collider missing-mass searches (Belle-II)* are most relevant to thermal DM above $\sim 100$ MeV produced through an on-shell mediator, complementing LDMX's sensitivity to lower-mass DM and production through off-shell mediators. A Belle II 20 fb$^{-1}$ study [25] projects a factor of 10 sensitivity improvement over BABAR's [26] missing mass search, constraining $y \gtrsim 10^{-9}$. Neglecting background and systematic uncertainties, which are known to be the limiting factor, extrapolations suggest up to 10-100 further improvement might be possible with the full Belle II dataset by the end of the 2020's.
- *Beam dump based searches (e.g. CCM [27], MiniBooNE-DM[6])* are limited by signal rate – their sensitivity scales with 4 powers of the small interaction coupling, compared to only 2 powers for missing mass/energy/momentum searches. Therefore, even with substantially increased current or geometric/kinematic acceptance, state-of-the-art proposals [28, 29, 30, 31, 32, 33, 34, 4] achieve only 10-fold sensitivity increases (for clarity, only CCM is shown in Fig. 3; others are comparable). These generally test baryonic couplings, while thermal freeze-out of DM below $\sim 100$ MeV relies on electron couplings; these couplings are similar strength in the hidden-photon model assumed in the comparison.
- *Missing energy searches (NA64)* can certainly compete with DMNI projects such as LDMX and CCM. The only such experiment is CERN's NA64 [35, 7], situated in the H4 beamline [36], which delivers a secondary electron beam to the front of NA64's calorimeters. NA64's published results use a sample of $2.8 \cdot 10^{11}$ EOT with a $0.5 \pm 0.2$ event background estimate. A scheduled 2021 run hopes to accumulate $5 \cdot 10^{11}$ EOT, which would roughly triple their sensitivity when combined with past data [37] if backgrounds remain small with similar signal efficiency. That even these low integrated charges compete favorably with beam-dump experiments that integrate $10^{22}$ particles on target illustrates the power of missing energy and/or momentum as DM search tools, but fulling exploring thermal relic milestones requires higher statistics. Long-term NA64 projections reflect a goal of integrating $5 \cdot 10^{12}$ EOT before LS3 (2025), close to their setup's irreducible neutrino-background floor [38]; this projection, shown as a thin dotted line in Fig. 3(left), relies on NA64's approval for substantially longer running and 10-fold improvement in background rejection over [7]. If these goals are realized before completion of LDMX, NA64 could probe much of the scalar and Majorana benchmark models outside of the resonance region. LDMX would still explore new, well-motivated parameter space including the resonance regions of these models and the pseudo-Dirac benchmark. *Moreover, a few-week LDMX pilot run could compete with NA64's most aggressive sensitivity projections, motivating accelerated preparations.* NA64 is also scheduled to test a muon-beam configuration, which has similar sensitivity in dark-photon models but would not directly probe the electron-DM coupling relevant to thermal dark matter below O(100) MeV.

### 2.1.2 Non-Accelerator-Based Experiment

Recent advances in low-threshold direct detection in both semiconductor and noble-liquid detectors [42, 43, 44, 45] offer a complementary window on sub-GeV DM. Broad comparisons are difficult to make because accelerators probe interactions of semi-relativistic dark matter while direct detection involves scattering with

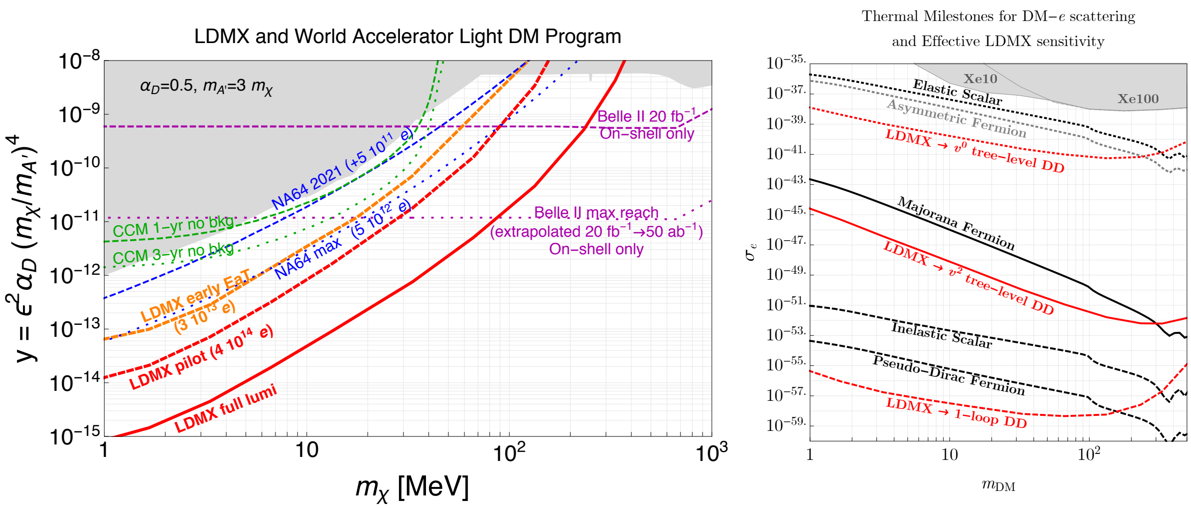



Figure 3: **Left:** The expected sensitivity of LDMX (thick red), a $4 \cdot 10^{14}$ EOT pilot run (thick dashed red), and an early running EaT analysis in $3 \cdot 10^{13}$ EOT (thick dashed orange, see Sec. 2.2) compared with current constraints (shaded) from [39, 26, 40, 7, 5], with expected near-term analyses (dashed) and long-term projections (dotted) from ongoing experiments NA64 (blue) and Belle II (magenta) and DMNI project CCM (green). NA64 projections are scaled from [7] assuming zero background and unchanged acceptance; CCM projections are scaled from [27] to 2.8 events in 1 and 3 years respectively. The Belle II dotted line neglects background systematics, which are thought to dominate at these luminosities[41]. **Right:** Milestones for thermal relic freeze-out and asymmetric fermion DM in electron-recoil direct detection, which vary over 20 orders of magnitude depending primarily on whether the structure of DM-SM interactions induces velocity-independent (dotted), $v^2$-suppressed (solid), or 1-loop (dashed) scattering. LDMX sensitivity can also be mapped onto this parameter space for each scenario.

much lower momentum transfer. *In general, thermal DM predictions for accelerators have mild dependence on DM spin because both early-universe thermal DM production and accelerator production probe similar momentum scales. By contrast, direct detection probes very different kinematics and so thermal DM predictions for scattering cross-section span 20 orders of magnitude (with only the best-case scenario appearing on the scale of most projections).* The full range of predictions is shown in Fig. 3(right), along with model-dependent mappings of LDMX's sensitivity to the direct detection parameter space. For specific benchmark models discussed in the BRN Report [1]:

- (elastic scalar dark matter benchmark) is comparably accessible to DMNI sub-GeV direct detection and LDMX, because the dark matter scattering is velocity-independent in such models.
- (Majorana fermion dark matter benchmarks) is accessible to LDMX, but direct detection cross-section is suppressed by CM-frame $v^2$ (a $10^{-6} - 10^{-10}$ cross-section suppression).
- (inelastic scalar or fermion, aka pseudo-Dirac, dark matter benchmarks) is accessible to LDMX, but the leading direct-detection reaction is a one-loop diagram rather than tree-level (suppressing the cross-section by $\sim 10^{-15} - 10^{-20}$).

Thoroughly exploring thermal freeze-out for all DM spins is important, and requires a powerful accelerator-based search such as LDMX. Indeed, fermionic models may even be theoretically favored over the scalar benchmark since they are (at the effective operator level) technically natural.

The broad complementarity between low-threhold direct detection and LDMX extends beyond the thermal freeze-out paradigm. For example, IR freeze-in through an ultra-light mediator [46, 47, 48] has couplings well below LDMX's sensitivity, but can be observable in direct detection because low-momentum scattering is enhanced. By contrast, UV-dominated freeze-in [49, 50, 8] produces observable signals at LDMX without a direct detection signal. **The overarching conclusion from these model-specific comparisons is that the physical parameter spaces for dark matter detection in accelerators and direct detection are fundamentally different and highly complementary.**

## 2.2 Background Rejection, Early Running, and Mass Reconstruction

**Performance and Design Studies** To maximize its reach associated with the PRD 1, Thrust 1 physics goal, the LDMX design is driven by the requirement to have a sensitive response to Standard Model reactions associated with a multi-GeV electron interacting and showering on normal detector materials. Figure 4 depicts the types and relative rates of such reactions, and also lists the types of detector sub-systems in our concept with an efficient response. The combined detector response forms the foundation of a background veto used to identify dark matter production events. Whereas potential weak-interaction backgrounds with a recoil track are negligible at LDMX luminosities, and beam backgrounds are rejected to a negligible level by a tagging tracker, rejection of potential photon-induced instrumental backgrounds places demands on the geometric acceptances, depth, and performance of multiple detector sub-systems. These are therefore an important design driver for the experiment. While NA64 has demonstrated background rejection at a level equivalent to $\sim 10^{-12}$ per electron on target (EOT) at LDMX, LDMX aims for $100\times$ greater rejection in a 4 GeV pilot run and 1,000-10,000-fold improvement in rejection in a full-luminosity run at 8 GeV.

With these requirements in mind, LDMX has undertaken a systematic background study [51] corresponding to a pilot-run luminosity of $2 \cdot 10^{14}$ EOT at 4 GeV. Anticipating few-body photonuclear reactions and metastable charged particles as drivers of LDMX's ultimate performance, the collaboration has closely studied the modeling of these reactions in our Geant 10.2.3 Monte Carlo (MC) and implemented bug fixes in the Bertini Cascade model (subsequently incorporated in Geant4 10.5) as well as exact tree-level matrix elements for muon conversion.

The results of this study show explicitly that pilot-run backgrounds can be robustly rejected by a combination of energy deposition and pattern recognition vetoes in each sub-detector — by design, the rejection *does not use recoil electron $p_T$*, thereby providing a comforting margin of safety. This strategy allows LDMX to use recoil $p_T$ as an unbiased additional handle for signal confirmation (an unexpected background excess would have lower recoil $p_T$ than a signal) and for mass measurement as discussed below — capabilities that missing-energy experiments like NA64 cannot match.

The study also confirms our conceptual understanding of the background: the non-Gaussian tails in ECal energy deposition are dominated by rare photon-induced reactions (as illustrated in Figure 1 (right)), with processes of particular interest highlighted in Figure 4). Most such events are still rejected simultaneously by two subsystems, providing redundancy in the veto. More specifically, multi-body photonuclear final states are generally rejectable by **both** unusual energy deposition patterns in the ECal (e.g. MIP-like tracks, isolated hits in deep layers) *and* energy deposition in the HCal. Events with two-body final states in asymmetric kinematics, where a single hadron or muon carries most of the "missing" energy lost by the electron, have been modeled with particular care because their rejection leans strongly on either the ECal or HCal performance. Single neutrons and $K_L$'s are rejected primarily by the HCal, while single muons and charged kaons are detected by their tracks in the ECal, with performance limited by rejection of early decays-in-flight with soft charged decay products.

The full LDMX run luminosity will attain 50x more statistics than were used for [51], but at 8 GeV rather than 4 GeV. However, preliminary studies of the leading photonuclear backgrounds show that the ECal veto *alone* rejects at least $10-20\times$ more background at 8 GeV than 4 GeV. HCal-only veto efficiencies also improve. This improvement is expected a priori because (a) more energetic final-state particles are easier to reject, (b) cross-sections for two-body photonuclear reactions, the most challenging to reject, fall as $1/E^3$, and (c) decay-in-flight backgrounds are further suppressed when the decaying meson is boosted. So in practice, the more difficult background situation that LDMX will encounter is actually for the planned 4 GeV pilot run.

**Opportunities for Early Running with ECal as Target (EaT)** LDMX will integrate its ultimate luminosity over a few-year period of running. However, competition from NA64 to explore the higher-coupling scalar and Majorana thermal relic models motivates an effort to attain the greatest possible sensitivity from a rapid analysis of early data. To this end, LDMX can exploit signal production in the ECal *in addition to* signal production in the target in an "ECal as Target" (EaT) analysis, increasing the effective luminosity by a factor of $\sim 5$. At high event statistics, this analysis is subject to greater backgrounds than the standard LDMX analysis, but it is a powerful tool for maximizing sensitivity in early running.

The EaT analysis uses the standard LDMX trigger but a complementary offline event selection, requiring

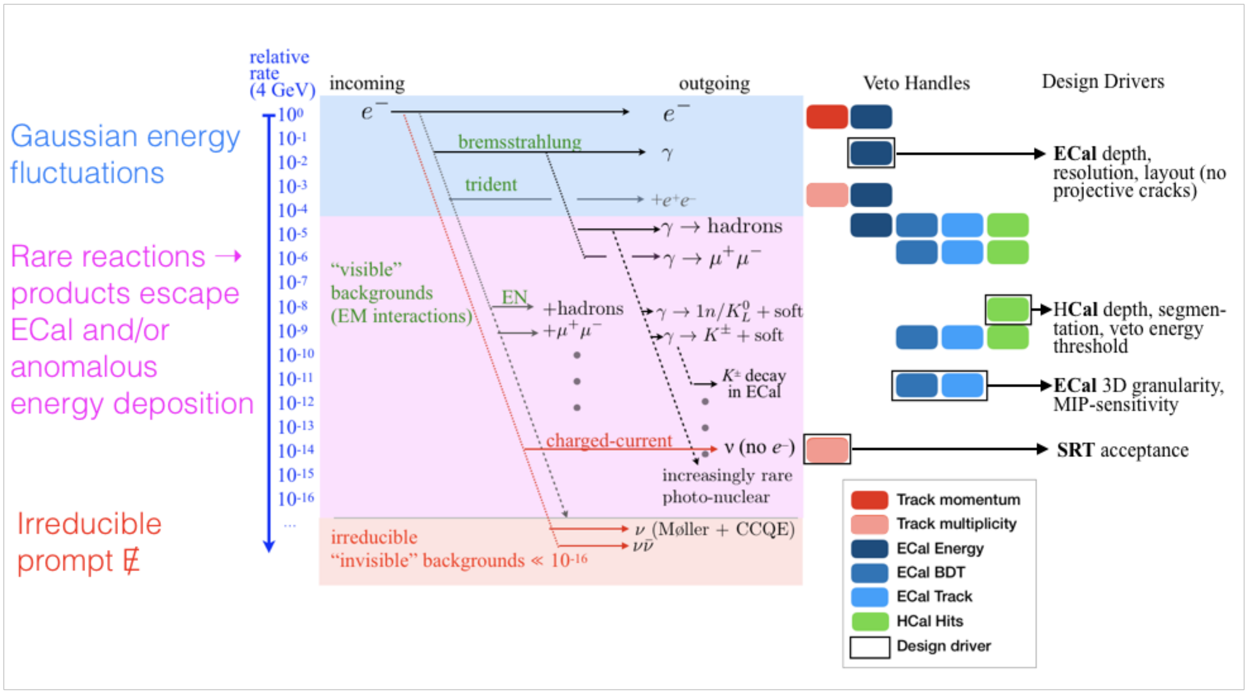



Figure 4: Standard Model reactions associated with a multi-GeV electron interacting and showering on detector materials. The LDMX design is driven by the requirement of providing a sufficiently sensitive response to these reactions to robustly veto them relative to dark matter production, in which the hard bremsstrahlung chain is replaced by dark matter that carries most of the energy of the event. Most reactions listed are redundantly vetoed by multiple detector subsystems. Reaction chains vetoed primarily by one subsystem are highlighted by black rectangles. These have been a focus of LDMX performance and design studies. Detector considerations needed to veto these reactions are highlighted to the right of the figure.

a *beam-energy* track in the recoil tracker rather than a low-energy track. A simplified EaT analysis has been developed for early running, which requires only that the ECal reconstructed energy be $< 1$ GeV and the summed HCal signal $< 10$ photoelectrons. For this very simple analysis, $\lesssim 1$ background event is expected in $3 \cdot 10^{13}$ EoT allowing a sensitivity comparable to the best-case accumulated statistics of NA64. The expected sensitivity of this analysis is shown by a dashed orange curve in Fig. 3. With modest optimizations, the EaT analysis may also enhance LDMX's sensitivity in the full $\mathcal{O}(10^{14})$ EOT pilot run.

**Mass Measurement from Transverse Momenta** The transverse momentum of the recoiling electron in high-missing-energy events is an important feature of LDMX's DM signal. As noted above, LDMX's strategy is to reject events *without* using this feature, reserving transverse momentum as a final cross-check and a measurement handle.

Figure 5 illustrates the power of this measurement assuming an on-shell $A'$ decay to dark matter, with coupling corresponding to the scalar thermal target with $m_\chi = 1/3 m_{A'}$ and $\alpha_D = 0.5$. In a $4 \cdot 10^{14}$ EOT pilot run, 7–60 signal events are expected for $A'$ masses between 3 and 300 MeV. For masses in the 10s of MeV where the signal yields are largest, the $p_T$ distribution allows an $A'$ mass estimate to within 50% or better. This performance is dramatically better than could be obtained using the recoil electron's energy distribution alone (e.g. at NA64 or in an LDMX EaT analysis).

A recent phenomenology paper [52] also suggests some discrimination (at higher statistics) between on- and off-shell mediators and by combining cross-section measurements at 4 and 8 GeV beam energies.

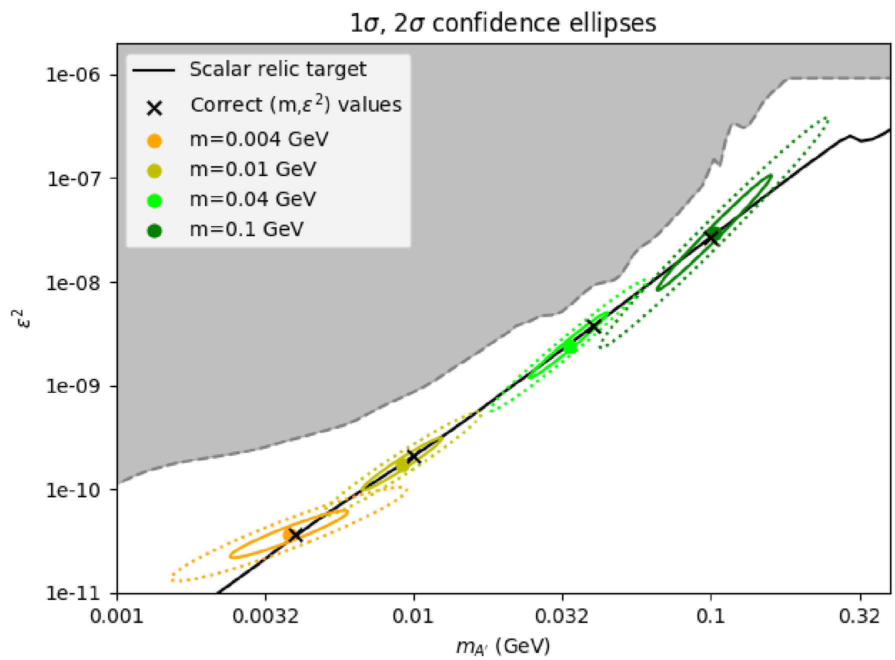



Figure 5: For several choices of $A'$ mass, and couplings corresponding to thermal freeze-out with $m_{A'} = 3m_\chi$ and $\alpha_D = 0.5$, the solid (dashed) error ellipses indicate the $1\sigma$ ($2\sigma$) resolution on reconstructed $m_{A'}$ and $\epsilon^2$ assuming an on-shell mediator decay interpretation of an LDMX signal in a $4 \cdot 10^{14}$ EOT pilot-run with no expected background. Parameters are inferred from the recoil electron $p_T$ (and, to a lesser extent, energy) distribution and observed event rate. The $\times$'s denote the correct results for each reconstruction test, and the colored dots represent the best fit.

# 3 Description of Project

## 3.1 Technical

### 3.1.1 Description of LDMX Technical Design

The missing momentum signature exploited by LDMX to search for Dark Matter has three components:

1. substantial energy loss by the incoming beam electron, leaving the recoiling electron with a small fraction (e.g. less than 30%) of its initial energy.

2. a large transverse momentum kick of the electron, which together with the degraded energy means the recoiling electron is ejected at a large angle with respect to the incoming beam.

3. the absence of any other visible final-state particles that could carry away the significant energy lost by the electron.

These three observables, and the ability to utilize them at high rates for up to $10^{16}$ incoming electrons to search for only a few signal events, define the composition and layout of the apparatus.

Taken together, the first two elements of this signature require estimation of the change in vector momentum of individual electrons across a thin ($10 - 40\%$ $X_0$) target, where multiple scattering in the target determines the useful precision. Although the beam energy is known, the beam can be contaminated with off-energy electrons or other particles, so the momentum of each incoming electron must be robustly measured. This can be accomplished with a narrow, low-mass tracker upstream of the target in a magnetic field optimized for measuring beam-energy electrons. The same technology may be used for measuring downstream recoils, but the low energy and wide angles of signal recoils demand wider acceptance in a lower magnetic field. The third element of this signature requires a highly sensitive veto for additional outgoing particles, suggesting hermetic, large-acceptance calorimetry placed directly in the beamline behind the target. Because the vast majority of outgoing particles are scattered electrons or bremsstrahlung photons, the central part of this calorimeter must be optimized for electromagnetic showers (an "ECal"). Furthermore, because the ECal signal rate is of the same order as the repetition rate of the beam, the ECal must be fast and have good spatial and temporal resolution to distinguish energy deposits from different events. Indeed, the ability to resolve the ECal responses to individual electrons sets the overall ceiling on the beam repetition rate ($\lesssim$ 40 MHz) as well as limiting each bunch to a few electrons spatially separated within the beam spot. The LESA beamline (see Sec. 3.4.1) can operate at these limits, allowing LDMX to accumulate $10^{16}$ electrons on target in a reasonable few-year running period. Meanwhile, the most pernicious potential backgrounds involve a hard bremsstrahlung that carries away most of the electron energy, followed by a highly atypical muon conversion or photo-nuclear reaction that happens to leave little energy in the ECal (see Figure 4). Identification of these events calls for a large and highly sensitive hadronic calorimeter (HCal) surrounding the ECal to veto events with any significant in-time energy deposit.

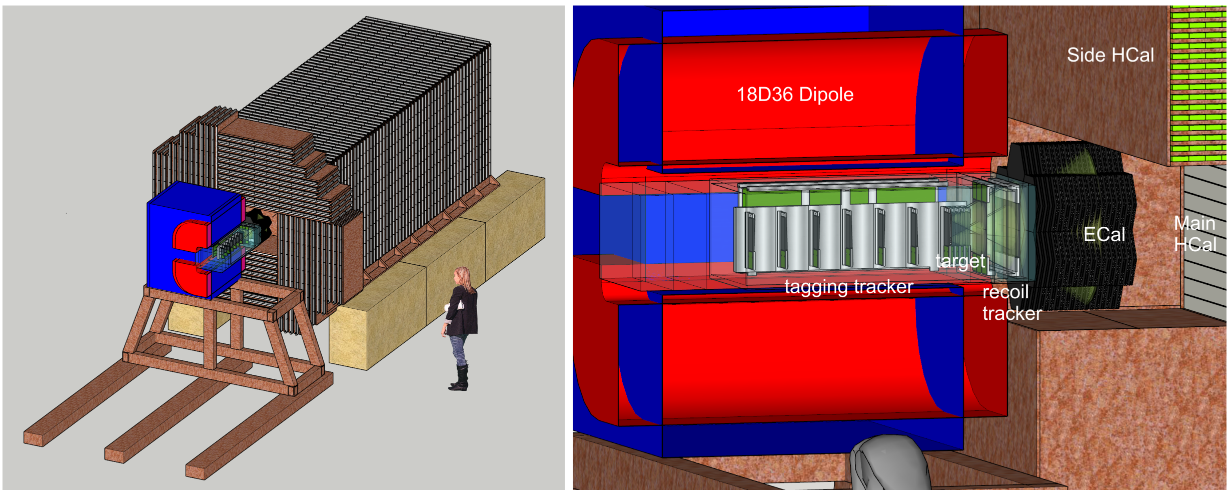



Figure 6: Left: An overview of the LDMX detector showing the full detector apparatus with a person for scale. Right: A cutaway overview of the LDMX detector showing, from left to right, the trackers and target inside the spectrometer dipole, the ECal, and the HCal.

The LDMX apparatus, a compact realization of this concept, has been presented in detail in [53] and is shown in Figure 6. Following the beam, the detector subsystems in the magnet region are a silicon tagging tracker (STT) inside a dipole magnet and a silicon recoil tracker (SRT) in the fringe field of the magnet, with a thin tungsten target interposed between them. Behind the SRT is a compact and highly segmented Si-W electromagnetic calorimeter (ECal) with excellent MIP sensitivity that is surrounded by a large scintillator-based hadronic veto system (HCal) with low energy thresholds. Two important details follow from this picture. First, because the beam passes directly through the trackers and into the ECal, these detectors must contend with high radiation doses to enable an experiment for $10^{16}$ EOT. To mitigate this issue, and also reduce the peak occupancies in these devices, a large, rectangular beamspot with area on the order of 20 $\text{cm}^2$ is used. As a result, only the ECal has challenging requirements for radiation tolerance. Second, the rates in the detector prohibit streaming readout: a fast trigger is required. Because signal events have unusually large missing energy in the ECal, and such events are very rare, the simplest strategy is to trigger on low energy in the ECal. In order to set an appropriate energy threshold for this trigger, the number of incoming electrons in each beam bunch must be known. This can be easily accomplished with an array of small scintillator bars – a Trigger Scintillator (TS) system – placed in the path of the beam to count the number of incoming electrons in each bunch.

These detector subsystems – Beamline and Magnet, Trigger Scintillator, Tracking, ECal and HCal – along with the trigger and data acquisition electronics (TDAQ) and the software and computing environment required for simulation and analysis of the data define the scope of the technical systems for the experiment that are being developed under the DMNI project in preparation for construction. The following provides an overview of the technical details of these systems.

**Beamline and Magnet Design** The baseline design for LDMX assumes operation at the proposed Linac to End Station A (LESA) facility being built at SLAC. This user facility will take drive beam for LCLS-II that would otherwise go to a beam dump and divert it to an existing test beam facility in End Station A via a new transfer line, the Sector 30 Transfer Line (S30XL), which is currently under construction as a DOE Accelerator Improvement Project (AIP). Because LCLS-II fills only 1 MHz of the 186 MHz bunches accelerated by the linac and diverts them to undulator lines for producing x-ray pulses, roughly 60% of the duty cycle of the accelerator can be made available to LESA without impacting LCLS-II operations. For LDMX, LESA will produce bunches with one or a few electrons per pulse, and use collimators and quadrupole magnets to produce the large, uniform, rectangular beamspot. This leaves LDMX responsible for a small number of additional beamline elements: a final section of large-diameter beampipe terminated with a thin vacuum window in front of the apparatus, additional vacuum pumping and monitoring for this final beamline section, and basic monitoring to measure the background and radiation environment around the periphery of the beamline where it enters the detector.

The various subsystems of the detector are built in and around the spectrometer magnet for the trackers, a standard 18D36 dipole magnet with a 14" vertical gap already in hand at SLAC. The trackers, target, and trigger scintillator systems and their front-end readout electronics are installed in a support box that is inserted into the magnet bore from the upstream side, while the ECal is mounted on a support frame attached to the back side of the magnet. The magnet is supported on rails, and can be retracted upstream from the HCal for access to the ECal and the front of the HCal.

**Tracking Design** A tracker design similar to the Silicon Vertex Tracker of the HPS experiment [54] is well suited to the precision, timing, and acceptance requirements for LDMX. Immediately upstream of the target is the 60 cm long STT inside the 1.5 T central field of the magnet, with coverage sufficient to contain the entire beamspot. Seven evenly-spaced, low-mass double-sided layers of silicon microstrips provide the precision momentum measurement for incoming particles needed to reject low-energy beam backgrounds. The 18 cm long SRT is immediately downstream of the target, with much wider coverage to capture low energy recoils at large scattering angles. To optimize tracking for low-momentum recoils (50 MeV to few GeV), the SRT is placed in the fringe field of the magnet and includes four closely spaced stereo modules identical to those in the tagging tracker directly behind the target, and two larger axial-only layers closer to the ECal face to maximize acceptance and minimize material. The sensors are $p^+$-in-$n$ type silicon with a sense (readout) pitch of 30 (60) $\mu$m, providing excellent spatial resolution at high signal-to-noise ratios with 0.3% $X_0$ per hit. The front end electronics are identical to those used in the HPS SVT, including readout with CMS APV25 ASICs in multi-peak mode, which enables $\approx 2$ ns hit time resolution.

**Trigger Scintillator Design** Arrays of scintillator bars will be used to estimate the number of beam electrons within each time sample. One array of 48 bars will be placed near the target to ensure electrons traverse the target. The segmentation of the scintillator arrays will provide the primary means of counting electrons. There will be 2 additional arrays upstream of the tagger tracker. Requiring a coincidence of hits in each array helps mitigate effects of secondaries produced in the target or the tracker material. Each scintillator bar will be read out with independent Silicon Photomultipliers (SiPMs). Each bar will be 30 mm long with a cross sectional area of 2x3 mm$^2$, which is well suited to readily available (SiPMs). Each array will be arranged in a 2x24 grid with bars stacked horizontally with two layers separated along the direction of the beam. Layers are offset by half a bar's width in the vertical direction to ensure there are no projective gaps in the detector.

The SiPM signals will be digitized by deadtimeless readout board developed for the phase 1 CMS HCal upgrades. These boards will produce low noise charge integrating amplitude measurements and pulse arrival time measurements with 0.5 ns precision. The front-end electronics will be controlled via a Zynq based interface that will manage fast signals and parameter configuration of frontend electronics and SiPM boards. Data will be continuously streamed to ATCA-based electronics over 5 Ghz fiber optics, where trigger primitives are computed and data pipelines will be managed.

In additional to plastic scintillator arrays, we are also developing a design for an active target that would make use of the Trigger Scintillator readout. The active target will be made with 10% $X_0$ thick LYSO scintillator read out by SiPMs. Such a design is expected to help identify photonuclear reaction in the target by measuring the energy loss of by-product of these reactions, and will be evaluated as an alternative to the solid Tungsten target during the DMNI phase.

**ECal Design** The need for granularity, very high efficiency, radiation hardness, and speed led to the selection of high granularity silicon technology for the LDMX ECal. To this end, we adopt designs from the CMS High Granularity Calorimeter (HGC) for the CMS phase 2 upgrade [55]. The ECal, shown in black in Figure 6, is a sampling calorimeter with $W$ absorber planes corresponding to 40 radiation lengths, interleaved with 34 Silicon layers, paired into 17 doublelayers. Motherboards carrying trigger and data signals overlay and connect the 7 modules per layer. The motherboards host data-processing and control mezzanines based on the radiation-tolerant Polarfire FPGA. Control and readout is carried on optical fibers to electronics hosted in the experiment's common ATCA DAQ crate.

The total number of modules in LDMX correspond to less than 1% of the number to be built for CMS. We will use the CMS high density (HD) HGC module design, possibly with thicker silicon to improve signal given the lower radiation environment at LDMX than CMS, (thickness optimization studies will be completed in 1–2 years prior to placing silicon orders; these scientific studies are not in the DMNI scope). The hexagonal HD sensor maximizes space available on an 8" wafer with a flat-to-flat size of ∼17 cm and is divided into 432 individual hexagonal readout pads, each with an area of 0.56 cm$^2$, fitting in a circle of radius ∼0.47 cm. The ECal and trigger of LDMX rely on the CMS HGCROC ASIC developed by the LLR Omega group.

An ECal based on silicon pad sensors is well-suited to identify photons and electrons with high efficiency and good energy resolution, as well as rejection of photonuclear backgrounds with modest or even very small energy depositions using shower shapes and particle tracking. The ECal energy resolution has a very small constant term and stochastic term of $\sim 20\%/\sqrt{E}$. The Moliére radius is ∼2.5-3.0 cm. The radius of containment of 68% of the energy in EM showers is less than 1 cm in the first 15 layers of the ECal, enabling discrimination of individual electrons and photons at small angular separations. It also provides efficient detection of charged hadrons that range out in a single silicon layer and tracks those that traverse multiple planes with excellent per-cell efficiency for minimum ionizing particles. The large ECal depth — $40X_0$ of W absorber — is driven by ensuring that late developing EM showers and photonuclear reactions still deposit sufficient energy in the ECal to be detected, down to the $10^{-16}$ level. A large depth also improves detection of muons and charged hadrons.

Each ECal doublelayer has a core cooling plane covered on both sides by $W$ plates, followed by modules and motherboards. An additional $W$ plane is added to one side of the doublelayer to provide the absorber layer between it and its nearest neighbor. The 7 modules per layer are arrayed in a flower configuration with a central module surrounded by a ring of six others. The sampling planes, (7 modules and 2 motherboards) are ∼6 mm thick, including the module baseplates made from a thin C-Fiber layer or simple printed circuit board (PCB) with integrated Cu shielding. The cooling layer have ∼4 mm O.D. thin-wall stainless steel cooling tubes embedded in, and covered by, C-Fiber sheets. The doublelayer thickness excluding $W$ is ∼2.3 cm. The depth of the entire device, including $W$ and gaps between doublelayers is ∼55 cm. The detection volume is thus about 55x 55x 55 cm$^3$, while the full system occupies a volume of 95x 65 cm$^2$ and depth of 65 cm. It is small and compact, but dense, with a mass of ∼825 kg. The support structure holds this large mass while precisely positioning doublelayers and absorber planes.

The ECal is designed to be disassembled to replace problematic components or to reconfigure plane positions should that be later deemed advantageous for rare backgrounds, systematic uncertainties, or signal sensitivity. Small transverse offsets between sensing layers will improve resolution of charged particle tracks and avoid overlap of small dead regions between modules. The designs will include manifolds for distribution of coolant and dry nitrogen. Solutions have been identified for low-voltage power using radiation-tolerant DC/DC converters and for the necessary feed-throughs and cabling harnesses.

**HCal Design** The HCal is a scintillator-based sampling calorimeter comprising a large number of nuclear interaction lengths of steel absorber. Its main function is to detect neutral hadrons - mostly neutrons produced in the target or ECal - in the energy range from hundreds of MeV to several GeV with very high efficiency. The HCal must also measure the component of electromagnetic showers escaping the ECal, and be sensitive to MIPs, such as muons. Good efficiency for lower energy neutrons requires sampling thickness of the absorber plates less than 30% of a strong interaction length ($\lambda_A$), while ensuring that high-energy forward neutrons interact in the detector to the desired level requires a total depth of approximately 15 $\lambda_A$.

The calorimeter consists of two major parts: the Main HCal located behind the ECal, as well as a smaller device surrounding the ECal, termed the Side HCal. The dimensions and segmentation are still being optimized with detailed GEANT simulations, including several key background processes and single particle response. We plan to finalize the design at the end of fall 2021. In the current version, the Main HCal contains 96 layers of 25mm absorber plates. Scintillator bars, similar to those used in the Mu2e Cosmic Ray Veto system, are deployed in an X,Y configuration. The scintillator is in the form of doped polystyrene bars 20 mm thick $\times$ 50 mm wide, co-extruded with an integrated $TiO_2$ reflector. The extrusion also includes a through hole into which a 1.8mm wavelength-shifting fiber is inserted. The scintillator response to minimum ionizing particles has been measured to be around 90 photo-electrons, providing an adequate signal for LDMX. The scintillator bars are assembled into units of four bars ("quad-counter") onto which readout electronics is mounted. The quad-counters are attached to the steel absorber plates, and fully equipped layers are grouped in 12 modules of 8 layers each, supported by an external frame. The Side HCal consists of 4 modules arranged in a pinwheel-like fashion around the ECal approximating the shape of a disk. Each module contains 24 layers of 20mm absorber with scintillator bars arranged in a X,Z or Y,Z configuration to provide 3d information.

The readout electronics is adapted from the Mu2e CRV system and the HL-LHC upgrade of the CMS end cap calorimeter. Each quad-counter fiber is read out at each bar end by a SiPM mounted on a Counter Mother Board (CMB). The latter provides bias to the SiPMs, has a temperature monitor, and flasher LEDs to calibrate each bar independently. Given the mechanical constraints, the Side HCal bars are only read out at a single end. The four SiPM signals are then transmitted to a High Granularity Calorimeter Read Out Chip (HGCROC) board via an HDMI cable. A single HGCROC Board is designed to operate and read out the signals from 16 CMBs. Four HGCROC boards are housed on a large back plane board, together with a Mezzanine card providing the DAQ logic and the initial trigger calculations. As described under HCal Development in section 3.1.2, the CMBs, HGCROC boards and backplane boards are under production for the coming test beam in the fall. Ten HGCROCv2 are at hand for this and are more than sufficient for these tests, and as mentioned under ECal Development in 3.1.2, a first Mezzanine card has already been produced.

**Trigger and Data Acquisition Design** The trigger, data acquisition, and slow control (TDAQ) system of LDMX consists of a custom electronics hardware trigger which decides which events are saved and reads out the thousands of LDMX channels to be saved for offline analysis while providing the communication mechanism to control and monitor the detector. The main technological requirements of the TDAQ system are:

- 25 kHz DAQ rate based on the tracker readout ASIC bandwidth; this in turn sets a 5 kHz trigger rate requirement (including a large safety factor)
- 10 Gb/s DAQ data rate based on modest modern technological capabilities
- 3.5 $\mu s$ latency to deliver the trigger decision to the detector front-end controllers; consequently we require $2 \mu s$ latency to formulate the trigger decision

The TDAQ system borrows from existing electronics hardware platforms in order to reduce risk and resources. The Reconfigurable Cluster Element (RCE) [56] is a data acquisition system based on the ATCA standard. It is a flexible DAQ system developed by SLAC and is already used to read out and provide slow control to the HPS SVT, upon which LDMX tracking is based. It is well-understood system also used for ATLAS CSC muon system readout since 2015, and in the development of LSST and ProtoDUNE experiments. The RCE DAQ system is a good technological match to perform the same tasks for the other LDMX subsystems: ECal, HCal, and target scintillator.

The trigger of LDMX should read out trigger primitives from the ECal, HCal, and trigger scintillator systems at full rate and reduce the event rate to 5 kHz using information from those subsystems. The primary task of the trigger system is to save events for which one of the incoming electrons lost a significant fraction of its energy. However, a wide range of secondary triggers are expected in order to collect background sideband data, calibration data, and physics data for other dark matter and nuclear measurement final states. Because the trigger system must perform a wide range of tasks under challenging latency constraints, we will use a different ATCA-based board for triggering with a more powerful processing FPGA and more optical links per FPGA in order to aggregate all detector signals in a single processing node in order to meet latency constraints. We will use the APx (Advanced Processing) board developed for the CMS L1 Trigger upgrade.

**Software and Computing Design** `ldmx-sw` is a `C++` event processing and simulation framework that implements a software bus model to facilitate communication between data processing modules. At the heart of `ldmx-sw` is the "Framework"; a library that builds the processing pipeline, manages the configuration of the modules and provides the event bus used to pass data between them. An embedded python interpreter allows for the configuration of the pipeline at runtime by using basic python commands. These features make the Framework very lightweight as only necessary modules are loaded dynamically.

Each of the modules contains sub-detector specific algorithms used to digitize and reconstruct data, apply filtering based on event conditions and implement vetoes. The simulation is also implemented as a module and wraps a custom version of the Geant4 toolkit (10.02.p03) that includes bug-fixes to the Bertini Cascade model as well as to the tree-level matrix elements for muon conversion[53]. Other enhancements to the simulation include, dedicated process and cross-section biasing, ROOT based persistence and a GDML based geometry system.

All software is open source and hosted on GitHub to facilitate collaboration. Currently, the branching flow being used is based on GitHub Flow. Features are developed on branches which are either merged into trunk or a release branch. GitHub Actions are leveraged to automate unit testing of new features before being merged into trunk. Once a release is made, the packaging of `ldmx-sw` and its dependencies into a Docker container is done automatically. This facilitates the deployment of the software stack to multiple-sites without having to recreate the dependency environment. Deployment of new releases is currently done manually but there is a plan to switch to a continuous deployment model in the near future.

The generation of MC samples has leveraged both the LDMX Distributed Computing System (LDCS)[57] and the SLAC Shared Scientific Data Facility (SDF). LDCS is a distributed computing system consisting of 4 sites: Caltech, Lund, SLAC and UCSB. All sites have access to local storage along with GridFTP storage at SLAC that is accessible by the whole collaboration. All simulation jobs were run at all sites and the resulting files were catalogued using Rucio. Once a job was completed, the resulting file is uploaded via GridFTP to SLAC which serves as the primary storage site. LDCS has been crucial in generating the large scale MC samples needed for design studies especially given LDMX's limited access to SLAC resources.

Recently, SLAC has shifted its computing strategy to delivering a common shared computing infrastructure focused on massive throughput data analytics. Under the SLAC SDF model, a group and its users are granted access to baseline computing capabilities including 100 TB (25 GB) of storage per group (user) and access to the shared CPU node partitions. Currently, LDMX is making use of the baseline capabilities to run limited simulation jobs. In order for LDMX to make use of resources beyond baseline, it will need to contribute storage and CPU nodes to SDF.

### 3.1.2 Description and Status of Technical Development Plan

The LDMX DMNI project comprises the tasks required to prepare a baseline design, along with the scope, cost, and schedule for realization of the experiment. The heart of the plan is the development of the subsystem designs discussed in the last section, and their integration into a complete apparatus, to the point where the scope, cost, and schedule can be accurately presented and reviewed. As part of this process, there are a few remaining design decisions to be made. These include whether shielding is required, whether to use a passive or active target, the silicon thickness for the ECal and absorber grading for the HCal, and the coating of the trigger scintillator bars. The development of these baseline designs is monitored by the LDMX Coordination and Project Management team described in Section 3.3.

In addition to design and technical work required to establish the design, there are physics studies required by scientific personnel to optimize the design and ensure that it robustly meets the requirements of the experiment. While the effort for this task is not supported by the DMNI project, it requires computing resources that are part of the project. Finally, in order to prepare for a review of the construction project, project management effort is required to develop the project plan, along with the cost, schedule, milestones, and risk registry, and to produce the documentation required to ensure that that project adheres to all standard policies and procedures. The following sections describe the elements of this plan, and their

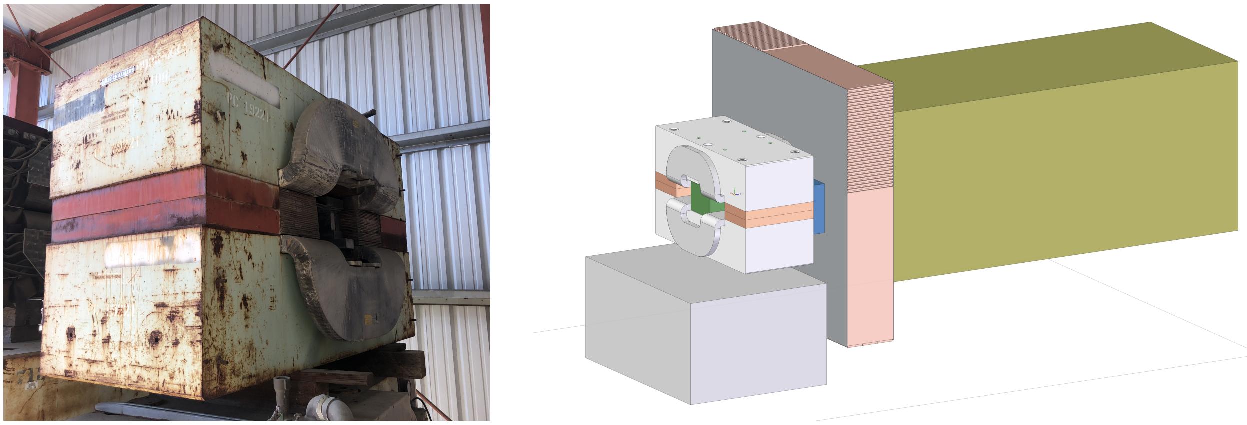


Figure 7: **Left:** The 18D36 dipole magnet that will be refurbished for the experiment. **Right:** A preliminary CAD model of the detector being used to define stay clears and develop interfaces.

current status. Substantial progress has been made in all areas since the submission of the original DMNI proposal and many specific items are detailed below.

**Beamline and Magnet Development** With most of the beamline already in place or funded as part of the LESA project, the components that LDMX is responsible for are small in scope and need no development work. These consist of a section of large diameter beampipe terminating in a thin vacuum window in front of the apparatus, additional vacuum pumping and monitoring in this region, and simple beam halo counters to monitor the extent of the beam at the front of the detector. However, since LDMX is effectively a beam dump, it is important to understand the radiation environment around the detector. With typical beam currents of 10-100 pA, it is expected that the detector will not need shielding or may easily be made sufficiently self-shielding. However, the potential for brief accidental exposure to a small number (one to a few) of much larger pulses intended for LCLS-II must be considered and could impact the detector design. For the LESA project, this issue has already been studied for beam going to the End Station A dump. The development plan includes effort by the LESA radiation physicist to extend these studies to the case where the beam terminates at the LDMX detector. This work was planned to begin with FY21 funds and can be completed on a very short timescale.

The 18D36 dipole magnet LDMX plans to use, shown in Figure 7 has been sitting in storage at SLAC for many years and requires refurbishment. Extensive test data from 1978 and experience with other magnets of the same design (e.g. used by HPS) establish the suitability of this magnet for LDMX, and a preliminary expert assessment of the magnet and the refurbishment task has been used to establish the cost and effort of this undertaking. However, further investigation of these records and the condition of the magnet will better define the scope of the magnet refurbishment project. Meanwhile, as the central element around which the various subsystems are built, the magnet forms a critical interface for all of the subsystem designs, so an accurate CAD model of the magnet is the place to begin to develop an integrated model of the apparatus. For these reasons, a key task is a more thorough investigation of the magnet and its condition, careful measurements of its dimensions and features, and the development of an integrated CAD model for the experiment with this magnet as the first element. Rough measurements of the magnet have been made, and a preliminary CAD model developed from these measurements, shown in Figure 7, has been used to begin defining interfaces to other detector systems, and in particular the concept for supporting the ECal from the back of the magnet. Work remains to create a more accurate model of the magnet, which is needed for the ECal and other subsystems to complete their designs. This work was planned to begin with FY21 funds and can be completed on a very short timescale.

Finally, there are already power supplies in End Station A that are in good working condition and are suitable for powering the magnet. However, the control systems for these supplies are need to be updated. A preliminary design is required to define the cost of this work to the construction project. Therefore, an important task is the development of a preliminary design for the magnet control system, sufficient to determine the scope of work. This work has not been planned to begin until FY22.

**Tracker Development** The strong resemblance of the LDMX trackers to the recently-built HPS SVT greatly simplifies the task of designing this system and understanding the scope, cost, and schedule for construction. In particular, the modules and front-end readout electronics need only minor layout changes to be used directly in LDMX. The main differences are in the mechanical interfaces with the magnet and the trigger scintillator, and changes to the layout of the Front End Boards (FEBs) that digitize the data and provide clocking, control, and power to the modules to adapt to a different arrangement of components inside the magnet.

Commensurately, the first task is design work to understand the integration of the tracking system – including the support and cooling systems for the modules and the FEBs – with the magnet, and the mechanical interfaces with the other subsystems, especially the Trigger Scintillator. This work was planned to begin with FY21 funds, requires eight weeks of effort, and can be completed within six months of when a CAD model of the magnet is complete (see Beamline and Magnet development plan above).

The second task is a redesign of the HPS FEB system suitable for use in LDMX. This involves design work for new FEBs, procurement of a small run of prototypes, followed by testing to verify the design. This work is not planned to begin until FY22, requires 20 weeks of effort and can be completed in approximately six months.

**Trigger Scintillator Development** The trigger scintillator (TS) development work has three main pieces: (a) designing and prototyping scintillator modules (both plastic- and LYSO-based modules); (b) designing and prototyping the front end control system; and (c) finalizing designs for the front end readout electronics. This work will enable full validation of the TS design, from active components through the readout chain.

In the first year, we planned to produce scintillating bars that could support characterization measurements, finalize designs of the mechanical housing that would support the scintillating bars and the corresponding Silicon Photomultipliers (SiPM), and complete the design of the mounting board for SiPMs. We also planned to prototype LYSO bars for active target design studies. In the second year, we planned to fabricate the SiPM mounting boards, design and fabricate the control system, and test the integration of these components with the front end electronics. In year three, we planned to finalize the firmware designs for the electronics.

We have ordered samples of both plastic and LYSO scintillating bars for characterization measurements. These samples have been tested using radioactive sources to confirm their response to minimum ionizing particles MIP and support simulation studies. These measurements suggest that $0.05X_0$ thick LYSO ( 2 mm thick plastic) bars produce roughly 290 (130) detected photoelectrons per (MIP). Fig. 8 shows measures of LYSO and plastic scintillator response to $Co^{57}$ and $Sr^{90}$ sources, respectively.

We have also studied light barriers for improving our detector response and channel isolation. Two options have been explored. One option utilizes thin sheets of Enhanced Specular Reflector (ESR) surrounding individual bars and another thin film depositions of aluminum. Aluminum depositions could simplify the assembly of scintillator modules and dramatically reduce gaps between channels. Detailed comparisons between the performances of these two approaches will be evaluated during our DMNI work.

Plastic scintillator has been purchased for producing bars. Bars were cut from sheets of scintillator and polished. We have also ordered a small batch of pre-cut and polished scintillator bars directly from the manufacturer. In both cases, we have tested tolerances and light yield performance. Light yields are comparable, but dimensional tolerances of bars produced at the manufacturer are currently better. We are continuing to refine our polishing procedures. Dimensional tolerances from the manufacturer's bars were roughly $8 - 10$ $\mu$m along the 3 mm dimension and $20 - 25$ $\mu$m along the 2 mm dimension. A tolerance of 50 $\mu$m will be sufficient for aligning SiPMs with scintillators.

A design for the scintillator mechanical housing has been produced. A prototype housing was built in PLA using a 3D printer (Fig. 9d). The prototype has been used to assemble scintillator arrays with ESR to verify the mechanical design. Interfaces between this housing and other components are still to be finalized, especially the SiPM board interface.

A design for the SiPM mounting board has been produced. As planned in FY21, a small batch of boards has been fabricated, and work is underway to partially assemble them (Fig. 9a). The electrical characteristics

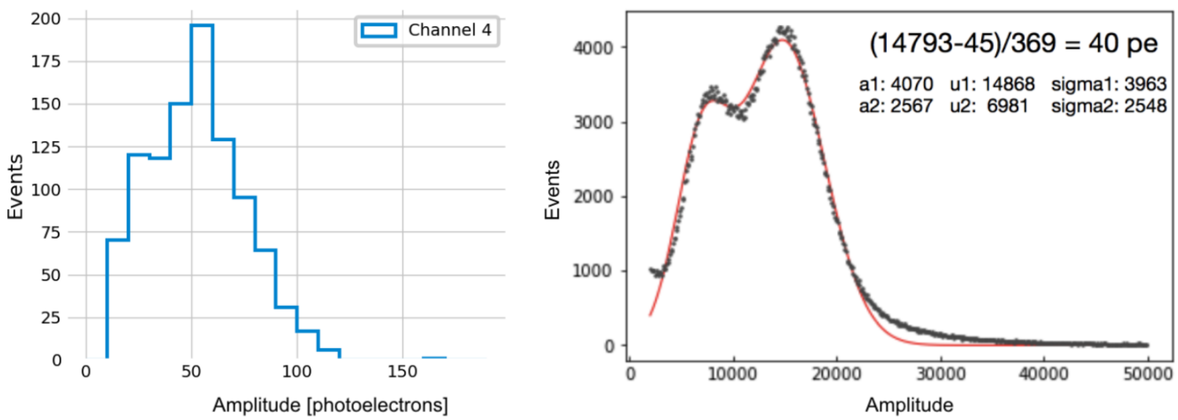



Figure 8: Left: Plastic scintillator response to a $Sr^{90}$ source. Measurements were taken with $1.3 \times 1.3$ mm$^2$ SiPM, while a $2 \times 2$ mm$^2$ SiPM will be used. Right: LYSO response to a $Co^{57}$ source. Amplitude is shown in arbitrary units. The second peak corresponds to the detection of a 122 keV photon with an observed response of 40 photoelectrons, where a MIP signal is expected to be 888 keV.

of these boards will then be studied. Prototype boards will also be used to finalize the interface of the SiPM mounting boards to the scintillator housing. FY21 funds will allow this work to be completed.

Considerable progress has also been made toward year 2 development work. We have a design for backplanes, which will provide an interface between frontend electronics and the control system (Fig. 9b), and the Zynq-based control system, known as the zCCM (Fig. 9c). These components are necessary to test the functionality of front end electronics and the data integrity of scintillator signals. FY21 funds will allow fabrication of these boards and completion of this work.

Long lead-time components have also been purchased, including a Zynq ultrascale mezzanine for the control system and SiPMs for SiPM mounting board testing. We have also acquired a front end module for integration tests.

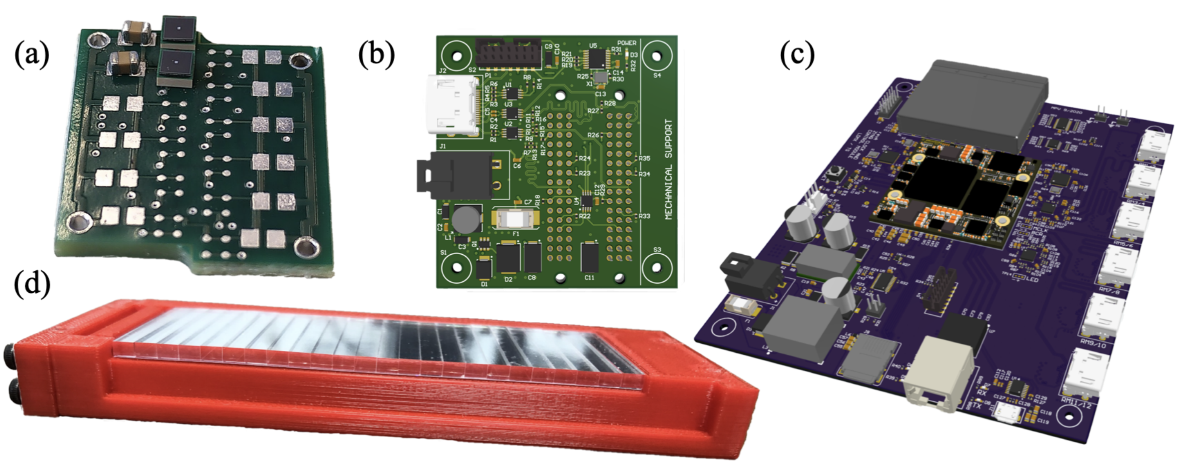



Figure 9: Trigger scintillator prototype components and designs for components. (a) shows a prototype SiPM mounting board. (b) and (c) show 3D models of the backplane and zCCM designs. (d) shows a prototype scintillator array.

Finally, considerable work has been done on developing a realistic simulation of frontend electronics, developing reconstruction algorithms, and studying the effects of pileup. Simulations of our frontend electronics now include pulse shape modeling, a model of the digitization of the integrated charge from pulses,

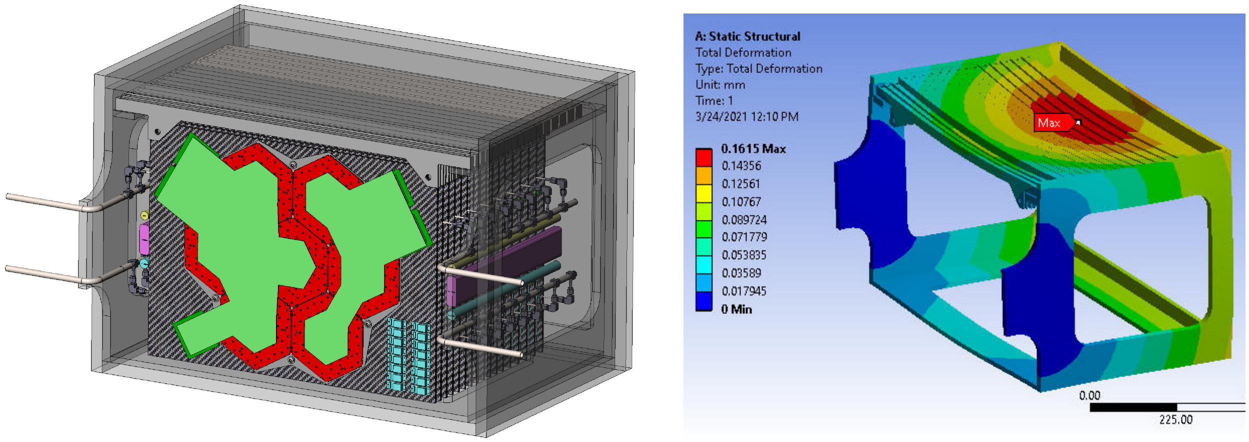



Figure 10: **Left:** The ECal detector with all 17 doublelayers and cooling is shown with one sensing plane exposed to show the 7 module flower and two motherboards hosting a total of five Polarfire mezzanines. **Right:** A Finite Element Analysis of ECal distortion and forces.

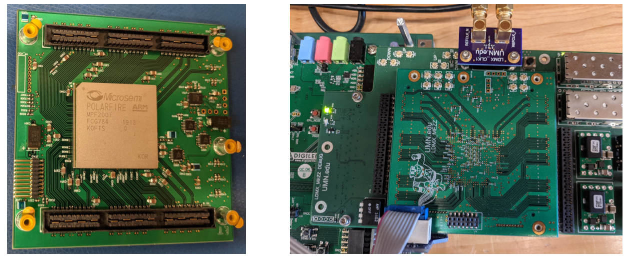
and simulation of the time-to-digital converter. The simulation also correctly models out-of-time pileup to support studies of realistic beam conditions and trigger rate calculations. We have also developed high-level object reconstruction to understand how to mitigate the effects of secondaries produced in the target or target-area detectors. These objects have been shown to improve performance in high-statistics simulated samples. We have also begun work to develop trigger simulations using a high level synthesis framework. We have also developed simulations of the active target and work is underway to study the impact an active target would have on background rejection using high-statistics simulated samples.

**Electromagnetic Calorimeter Development** Advanced designs of the LDMX support structure with integrated services and the doublelayers including Finite Element Analyses (FEA) of stresses and deflections have been completed by UCSB engineering with FY20 DMNI funding. Figure 10 shows the current system design and an example FEA. The support box is 0.75" stainless and will be supported from the LDMX Magnet at two locations (tabs appearing dark blue in the right figure). Studies for a variety of reasonable configurations find very reasonable stresses and maximum deflections ranging from 6 to 20 MPa and 0.090 to 0.162 mm, respectively. The ECal is designed to hang the doublelayers via strongbacks that will be screwed to ledges at the sides of the support box. This 'hanging file-folder' design has the advantage that the doublelayers can be removed from the top of the support box.

Next design work will focus on the cooling system with the goal of ensuring that the sensors can be maintained at temperatures as low as -30°C. Radiation damage will be significant in some regions of the ECal, but FLUKA studies indicate that the worst case will be more than two orders of magnitude below the worst case anticipated in CMS. This means that it may not be necessary to operate at -30°C but the ECal will nevertheless be capable of operating this cold should that be necessary. Power use of the sensing layers is dominated by the 6 HGCROC ASICs per module that will each use about 1W of power. With other components, and assuming a worst case dark current from radiation damage, we conservatively assume 10W/module for a total of 2.4kW. Power use by other electronics within the support structure volume will be of order 2kW and so a Julabo W56 chiller with $\sim$7 kW capacity at -30°C would be adequate for the ECal. The plan is to completely insulate the box with 1" thick PVC sheets and dry nitrogen will flow through the box, with manifolds inside the box to provide flow to individual doublelayers to keep the modules dry. Radiation damage will be mainly concentrated in a few layers in the region of shower maximum. For power supply system and cooling design, we conservatively assume that the silicon may need to be biased to 800V near end of life.

The UCSB group has already built over 100 HGC modules for the HL-LHC CMS upgrade project, including a handful of Low Density (LD) modules that make use of HGCROCv2 chips, and near-final PCB and sensor designs. At the time of this writing, the group is preparing to build the first HGCROCv2 HD modules and later this year will build LD and HD modules with the next version (v3) of the readout chip. By

Figure 11: Prototype Polarfire mezzanine for use in the ECal and HCal readout and trigger systems (left), mounted on a test system (right).



late 2021 or early 2022, a fairly large number of HD modules will have been built for use in an array of tests and we will use some in LDMX doublelayers as well. With the remaining DMNI funds for the engineering at UCSB we will build a partial or possibly even complete prototype of the support structure as well as two doublelayers. This would provide an excellent preparation for refining our designs and launching the full project at the start of FY23.

The heart of the readout and control system for the ECal and HCal is a radiation-tolerant FPGA (Polarfire) which controls and collects data from the HGCROC ASICs.The University of Minnesota group is responsible for the readout and electrical services integration for the ECal. During the last year, a first prototype mezzanine hosting the Polarfire has been designed using DMNI funds and constructed using University funds. A photo of the prototype, mounted on a test fixture, is shown in Fig. 11. Substantial firmware was developed for the DAQ and control functions during 2020 through University support of an undergraduate computer engineering student. During the coming year, the plan is the development of a motherboard which will connect the mezzanine to a CMS prototype silicon module and the demonstration of data transfer and control functions. This motherboard must also integrate with the mechanical constraints of the ECal double-layer structure. The same firmware will be used in the HCal system for the planned testbeam and further development of the HCal system.

**Hadronic Calorimeter Development** The hadronic calorimeter is modeled on the Mu2e Cosmic Ray Veto (CRV) system and the HL-LHC upgrade of the CMS end cap calorimeter, greatly simplifying the design effort and facilitating the understanding of the construction cost and schedule. Development activities are only required to adapt the fabrication procedure to the LDMX geometry, engineer the support structures, adapt the front-end and readout electronics, and construct a small scale HCal prototype.

As outlined in the previous section, scintillator bars are assembled into units of four bars (quad-counters) onto which the front-end electronics is mounted. During FY21, we have adapted the Mu2e CRV fabrication process, based on a di-counter with 2 fibers per bar, to the quad-counter geometry with a single fiber per bar. The fiber guide bar housing the fibers at each end of the scintillator has been re-designed, and a full quad-counter prototype has been produced, as shown in Fig. 12. We plan to fabricate a series of quad-counters during the summer to construct a HCal prototype and further optimize the production process. We have also started to develop the fabrication procedures to mount quad-counter onto absorber plates and assemble layers into modules. This effort will continue in FY22 after the completion of the test beam. While a conceptual design for the support structure has been formulated, a fully engineered solution need to be developed. This work will take 6 weeks of effort, planned for FY22.

The front-end electronics is adapted from the Mu2e CRV system, re-designed for the quad-counter geometry and the characteristics of the SiPM chosen for LDMX. The CMB circuitry has also been simplified as functionalities required for Mu2e were superfluous, thus reducing the cost. Several CMB prototypes have already been assembled to validate the design (see Fig. 12), and pre-production boards are currently fabricated for the HCal prototype. A QC station to test 16 CMBs simultaneously has been designed and constructed as well. The DAQ software is currently based on the Mu2e system, but it will be upgraded to use the readout electronics developed for the experiment in the future. This work has been performed in FY21, and we only anticipate minor modifications to the CMB design for FY22 (4 weeks of effort scheduled after the test beam completion).

The readout electronics is based on the High Granularity Calorimeter Read Out Chip (HGCROC), a multi purpose readout chip providing the DAQ and Triggering capabilities required by the HCal. Four HGCROC boards are housed on a large back plane board, together with one Mezzanine card. During FY21, we have completed the initial design of the HGCROC board and back plane board (Fig. 12). Part of this effort is

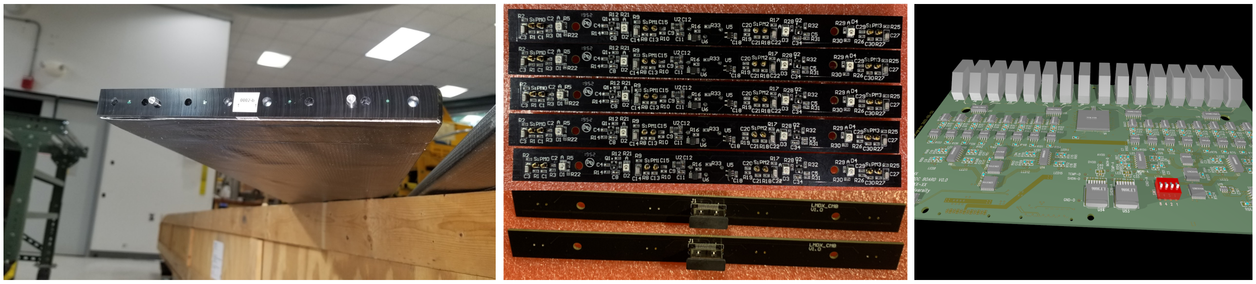


Figure 12: **Left:** A quad-counter prototype developed at the University of Virginia, **Middle:** counter motherboard prototypes developed at Caltech, and **Right:** schematic of the HGCROC board developed by the Lund University.

driven by our international collaborators (see section 3.7 for details). The mezzanine card is developed for the ECal electronics and will be readily integrated. We have started the fabrication of prototype HGCROC and back plane boards. We anticipate a round of design revision for FY22 for a duration of 20 weeks.

The HCal design effort would greatly benefit from a beam test of a small-scale prototype to validate the full hardware chain, and, more importantly, benchmark the Monte Carlo simulation against the calorimeter single particle response. The design effort relies heavily on the simulation of hadronic interactions in the few GeV region, which remains subject to large uncertainties. Moreover, the calibration of the HCal will partially rely on the simulation, since a full *in situ* calibration cannot be performed with an electron beam in the shadow of the ECal. A two week period at the CERN T9 beam line has been allocated in October 2021 to conduct this activity. To this end, we have started the construction of the test-beam prototype. The latter will contain 19 layers of 25 mm steel absorber, sufficient to fully contain electromagnetic showers and a large fraction of hadronic showers. The scintillator bars will be 2m long, the transverse size envisioned for the Main HCal, allowing us to measure the scintillator response as a function of the distance from the SiPM. The readout electronics will be based on the CMB, HGCROC and back plane board prototypes currently under fabrication. We also plan to monitor the response of the scintillator bars over a longer period of time to study aging effects. The construction of the prototype is partially funded by by our international collaborators, as detailed in section 3.7.

Complementing these activities, much effort has been devoted to develop a GEANT4 simulation of the HCal, including a realistic description of the front-end electronics and the associated reconstruction algorithms. Further developments are underway to improve the response of the scintillator, based on dedicated simulations developed for the Mu2e experiment. Additional work is planned to further optimize and validate the detector geometry, estimate the various backgrounds and assess the HCal performance (displaced vertices reconstruction efficiency, photon/neutron separation, impact of slow neutrons on the signal efficiency, ...).

**Trigger and Data Acquisition Development** The main technological goals for this proposal are system demonstrations in three primary areas:

- data readout paths for each of the detector subsystems
- trigger critical path for the primary trigger demonstrating the decision within the allotted 2 $\mu$s latency
- software and firmware interfaces for fast control trigger and clock distribution and common subsystem slow control

The activities for the work plan for TDAQ is focused towards the latter part of the development period as each of the detector subsystem development is performed. Our goal is to assemble a small slice demonstration of the TDAQ system. Early work in the development period has focused on defining the interfaces; initial work has been completed on firmware blocks for distributing the timing and trigger signals to the detector subsystems. Current efforts have been focused on defining interfaces between the subsystems and the TDAQ for both trigger and data acquisition paths. We will set up simulated data transfers between the different subsystems and the TDAQ system and measure the latency to read out each of the detectors including deriving some first reasonable estimates for the latency for the trigger algorithms themselves. To perform the tasks above, engineering resources are required both to set up communication and firmware for the DAQ system and the trigger boards. A modest amount of electronics hardware is also needed to perform these tests.

**Software and Computing Development** The software development effort has been focused on:

- optimizing the algorithms used by the simulation
- development of the reconstruction pipeline
- creation of the tools to facilitate multi-site deployment of the LDMX software stack.

Generating the samples used to perform the studies described in Section 2.2 for a (1-4) $\times 10^{14}$, 4 GeV pilot run was achieved by using a combination of bremsstrahlung pre-selection and the Geant4 occurrence biasing toolkit. Updates to these algorithms have resulted in a factor of 5 improvement in the performance of the simulation. However, even with these improvement, generating a full Phase II sample will require $\sim$ 50M CPU hours and several PBs of disk space. Ongoing work aims at boosting the performance of the algorithms further by introducing concurrency. Development of the emulation of the front end electronics for all sub-detectors has been a collaboration wide effort and significant progress has been made to put in place a baseline design. Going forward, improving the emulation, developing clustering algorithms for the ECal and HCal and tracking in all subdetectors will be the major focus of the software group. In parallel, the software group has made great strides in developing both Docker and Singularity images needed for deployment across different compute clusters which has facilitated contributions from collaborators.

As discussed in Section 3.1.1, LDMX is making use of LDCS and baseline SDF resources to generate MC samples needed for design studies. Although LDMX has been able to heavily rely on LDCS, additional cores will be needed to allow for the generation of MC and processing of raw data in a timely manner. Given the expected raw and MC data volumes described in Sec. 3.8, contributing an additional 1024 CPU cores to SDF will be needed long term. However, in the short term, buying a single 128 core node will give LDMX users enough fair share on the SDF cluster to allow for the prompt analysis of design study samples. LDMX is also actively exploring making use of the Open Science Grid for the generation of large scale MC samples.

The lack of disk space at SLAC has also made it difficult to store all samples centrally. In the short term, LDMX needs $\sim$ 200 TB of space to comfortably store design study samples. These issues will be mitigated with the purchase of disk space with FY21 funding.

**Subsystem Integration Development and Project Planning** Planning the high-level integration of the detector subsystems is a key task in developing a design that is ready for construction. This begins with the process of defining key interfaces between subsystems and developing the necessary tools to ensure their smooth integration into a coherent design with no missing pieces. This task requires the assignment of an experienced engineer as the Project Engineer. Beginning in FY21, a SLAC Lead Mechanical Engineer has taken on the role of Project Engineer for LDMX. This has led to some initial work in understanding integration between the detector subsystems, and in particular between the ECal and the Magnet as discussed above.

A critical component in preparing for construction of the experiment is the Project Management task required to develop a baseline scope, cost, and schedule that can be reviewed for funding of the construction project. The SLAC Project Engineer is also taking on the formal project management role, and together with the Technical Coordinator of the LDMX Collaboration (see Section 3.2) and the PIs, will develop the project plan. While the collaboration has produced a number of successively more complete and realistic cost estimates for past reports, the addition of this effort has enabled the collaboration to initiate a more formal project management process, including the development of a complete set of Basis of Estimate (BOE) documents for construction of the experiment, and an accompanying resource loaded schedule. The cost and schedule information presented in this report is based upon the first attempt to complete this exercise to produce an updated cost estimate and schedule for the construction project.

### 3.1.3 Use of DOE Lab Infrastructure and Capabilities

The use of DOE Laboratory infrastructure and technical capabilities is an integral and critical part of the LDMX project. First and foremost, the entire experimental concept depends upon DOE accelerators to deliver the electron beam required for the experiment, either with the LESA facility at SLAC, or by using the CEBAF at JLab. Without a CW or high-rep-rate multi-GeV electron beam, the experiment cannot be realized. Related to this are other technical capabilities at the labs that are needed to develop and mount an accelerator-based experiment: expertise in beamline components and vacuum systems, special expertise required to refurbish and characterize the dipole magnet for the experiment, and the heavy fabrication and conventional facilities that must be developed.

Another area where LDMX leverages DOE Laboratory expertise are the electronics required for the data acquisition and control systems for the experiment. The design and implementation of these systems for LDMX rely upon previous generations of specialized hardware developed at SLAC and FNAL for other experiments, and the key experts in adapting these designs to the needs of the LDMX experiment.

Finally, the extensive experience at SLAC in developing and managing projects at all scales is critical to the stewardship of the LDMX project. This includes formal project planning and coordination, project scheduling, budgeting and financial oversight and reporting, procurement, quality assurance, and management of ES&H required for a Small Project.

#### 3.1.4 Investigation of Alternatives

Previous to the start of the DMNI effort, the collaboration considered a number of alternatives in the development of the design, including the use of a crystal ECal and alternative absorber materials in the HCal. The technologies identified were determined to be the best choices for meeting the physics goals of the experiment.

Some alternatives and options in the final design are still under study. For the target, we are studying the opportunity of using an LYSO active target as discussed in Section 3.1.2. The active target could offer opportunities to further suppress nuclear interactions in the target. For the TDAQ, some alternative existing custom and commercial hardware platforms for both DAQ and trigger operations are under consideration as alternatives. Such alternatives could provide better performance or easier maintenance.

#### 3.1.5 ES&H Planning

The LDMX Project has the duty to follow the guiding principles and core functions of the Integrated Safety and Environmental Management System to conduct all work safely, effectively, and efficiently to ensure the protection of workers, the public, and the environment. The ES&H plan covers all phases of the project including design, development, fabrication, assembly, handling, transportation, storage, integration, test, and operation. Safety is optimized in the design, construction, and operation of the LDMX experiment, consistent with performance, schedule and budget. Personnel safety will include site-specific training as deemed appropriate by the project's SLAC safety representative, Norm Picker. The SLAC safety representative is working on a list of ES&H deliverables for the project which will include:

- an Integrated Safety Management Plan
- Hazard List
- Preliminary Hazard Analysis Report (later to become a HAR)
- Complete National Environmental Policy Act (NEPA) strategy, as required by DOE O 451.1B
- Prepare Environmental Compliance Strategy
- Prepare Construction Safety and Health Plan
- Prepare Radiation Protection Documentation

Hazards associated with the system are identified and evaluated at both the subsystem level and integrated experiment. The risks associated with all identified hazards are controlled to acceptable levels and documented in standard hazard assessment matrices.

#### 3.1.6 Computing and Data Management Plan

As discussed in Sec. 3.1.1, LDMX MC generation and analysis is currently leveraging LDCS and SDF. Currently only SDF baseline capabilities are being used. Once LDMX receives FY21 funding, additional storage and cpu nodes needed to accelerate work will be purchased.

The data distribution and access policy is set by the Collaboration Board on behalf of the LDMX collaboration. The policy can be revised by the Collaboration Board at any time after a review process with input from the collaboration.

**Data Description & Processing of Products** LDMX will produce data from the following sources

- Raw data from testing and calibration of detector prototypes at collaborating institutions
- Monte Carlo data generated using the Lightweight Distributed Computing Service.
- Raw and reconstructed data from the two different periods of operation described in Sec. 3.8.

As discussed in Sec.3.1.1, `ldmx-sw` will be used to build the reconstruction and analysis pipelines needed to process and persist the data. All data is persisted to a ROOT based data model. All data will be centrally stored at SLAC and be made available to all members of the LDMX collaboration.

**Plan for Serving Data to the Collaboration and Community** Before being released to the LDMX collaboration, data is tagged using the framework version used to produced it. These tagged releases will serve as the standard data sets that will be used for analysis and publication. Dissemination of the data beyond collaborators will be cost prohibitive.

**Plan for Making Data Used in Publications Available** In all cases of publications, data in the plots, charts and figures, and Digital Object Identifiers will be made available in accordance with policy at the time of publication by using mechanisms provided by the publisher, hosting by a collaborating institution, or services provide by INSPIRE. This includes publications resulting from research data from experiments, simulation, and research and development projects such as detector prototype data.

**Responsiveness to Office of Science Statement on Digital Data Management** The data management plan fully adheres to the recently implemented policy of the
DOE Office of Science: http://sciences.energy.gov/funding-opportunities/digital-data-management/.

### 3.1.7 QA Planning

The goal of the LDMX quality assurance program is to provide mechanisms for controlling activities that affect product quality, or protect the environment and health and safety of both the public and personnel involved with the project. These mechanisms are intended to establish a graded approach to quality assurance, invoked to the extent consistent with the importance of the activity. Not all items, processes, activities, and services have the same effect on health and safety, reliability, environmental protection, or program objectives. Therefore, such a graded approach acknowledges the importance in establishing the applicability of aspects of quality assurance to specific activities and to the degree to which they need to be applied. Considerations include:

- The relative importance to safety, safeguards, and security
- Compliance with SLAC and other institutional Policies and Regulations
- LDMX project mission and programmatic impact

The objective of this graded approach is to ensure that activities affecting quality are managed through adequate systems and procedures that are commensurate with the complexity and hazards of the work being performed. LDMX project management and collaboration members are responsible for identifying the activities that are subject to these requirements, and for carrying out an analysis to justify the degree of rigor to be applied.

Work planning control (WPC) is the formal process by which the project will identify and mitigate risks and hazards. This formal process occurs at the earliest stage of the project during the initial design and planning and continues through releasing and performing the actual work. Norm Picker (SLAC) has been identified as our project safety officer and will assist in WPC for the LDMX project.

## 3.2 The LDMX Collaboration

The LDMX collaboration is centered around the SLAC team which provides core leadership scientifically, technically, and managerially for the collaboration. In total, the collaboration consists of eight institutions. The collaboration formed informally through the period 2016-2018 and took formal shape through the adoption of bylaws and selection of officers including co-spokespersons in 2019. The organization chart for the collaboration is shown in Fig. 13. The CIDER committee is responsible for collaboration climate, diversity, and outreach activities.

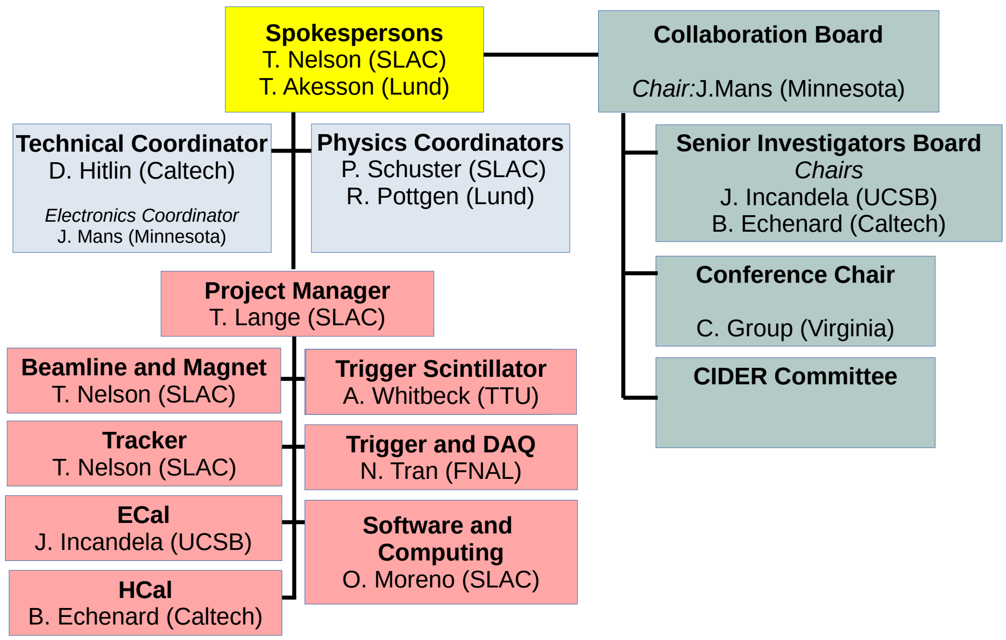



Figure 13: Organization chart of the LDMX Collaboration.

Each of the institutions in the collaboration has particular roles in the development and planned construction of the experiment and brings specific and important knowledge and capabilities to the collaboration. The list of institutions below is given in alphabetical order.

- *California Institute of Technology* (PI: B. Echenard) – The Caltech group is responsible for overall design and integration of the HCal detector. B. Echenard is the HCal coordinator and co-chair of the Senior Investigators Board. D. Hitlin serves as the Technical Coordinator for LDMX. The Caltech group also leads the exploration of the potential of a LYSO-based active target.

- *Fermilab* (PI: N. Tran) – The FNAL group is responsible for off-detector trigger electronics for the ECal and HCal systems (based on work underway for the HL-LHC CMS upgrade), as well as the motherboard for the HCal readout/trigger electronics. N. Tran is coordinator for Trigger and DAQ.

- *Lund University (Sweden)* (PI: T. Akesson) – The Lund University group is responsible for the digitizer board for the HCal, based on the HGCROC ASIC. The group is also very active in computing, including supporting the LDCS distributed computing system [57]. T. Akesson is a co-spokesperson for LDMX and R. Pottgen is a co-physics coordinator.

- *SLAC/Stanford* (PI: T. Nelson) – The SLAC group provides core management and leadership for the collaboration as well as holding responsibility for specific subsystems. The group is responsible for the preparation of the beamline, the refurbishment of the experimental magnet, the construction and integration of the tracker, and the readout of the trigger scintillator and its integration in the trigger. The group is also responsible for central DAQ, offline software, and computing activities. The tracker design builds extensively on the design from HPS, the DAQ is based on the SLAC RCE platform, and many aspects make heavy use of DOE laboratory expertise and unique capabilities. T. Nelson is a co-spokesperson and coordinator for the tracker and beamline, P. Schuster is a co-physics coordinator, and O. Moreno is the software and computing coordinator.

- *Texas Tech University* (PI: A. Whitbeck) – The TTU group is responsible for the construction of the trigger scintillator system and its integration with electronics developed for the CMS Phase 1 HCAL Upgrade. A. Whitbeck is the Trigger Scintillator coordinator.
- *University of California, Santa Barbara* (PI: J. Incandela) – The UCSB group is responsible for the overall ECal design and the construction of the ECal modules and ECal absorber/cooling/support structure. The module construction leverages expertise with the same task for the CMS HL-LHC upgrade, while the cooling and other engineering aspects leverage experience with construction of several trackers. J. Incandela is the ECal coordinator and co-chair of the Senior Investigators Board.
- *University of Minnesota* (PI: J. Mans) – The UMN group is responsible for the readout, on-detector trigger calculations, and services of the ECal detector. A common UMN-designed mezzanine is used to interface between the HGCROC ASICs and the off-detector electronics in both the ECal and HCal, leveraging experience from the CMS HL-LHC upgrade. The Minnesota group is also highly active in core offline-software tasks. J. Mans is the collaboration board chair and electronics coordinator.
- *University of Virginia* (PI: C. Group) – The UVA group is responsible for the construction and test of the scintillator units for the HCal detector, an activity which directly leverages experience from the Mu2e experiment construction. C. Group is the LDMX conference chair.

## 3.3 Organization and Management

The organization and management of the current DMNI development project and the planned construction project for LDMX are closely tied to the formal LDMX Collaboration described in Section 3.2. The organization of the technical arm of the collaboration, shown in pink in Figure 13, includes a set of Subsystem Coordinators, an Electronics Coordinator, and a Technical Coordinator. The PIs of the DMNI development project are the corresponding Subsystem Coordinators. The Electronics Coordinator is a co-PI and responsible for developing standards, interfaces, and an integration plan for electronic systems of the experiment, including the DAQ, trigger, online computing, detector monitoring, interlocks, and slow controls. The Technical Coordinator is a Senior Investigator on the DMNI project responsible for overall coordination of technical work across subsystems and developing an overall subsystem integration plan for the apparatus, including the mechanics, cooling and other environmental systems, and utilities. The Technical, Electronics, and Subsystem Coordinators all report directly to the spokespeople, one of whom is the lead PI of the DMNI project.

As discussed in Section 3.1.2, an element of the DMNI project is support for Lead Mechanical Engineer Travis Lange at SLAC, who has experience from the LSST project, to take on the role of Project Engineer. The DMNI project plan calls for 25% of an FTE for his time beginning in FY21. In the absence of FY21 funding for the project, SLAC has recently provided internal support for this effort. In this role, Lange takes on leadership of formal project management for the DMNI project and a corresponding position in the organization of the collaboration. Addition of this effort has allowed project planning to proceed to a more formal process for developing and documenting the budget and schedule for both the DMNI project and the construction project, beginning with the Basis of Estimate (BOE) documentation and Resource Loaded Schedules presented with this report. With a transition to the construction project for the experiment, this role is expected to grow from 25% to a full FTE throughout the construction and installation of the apparatus.

**Management of Budget, Schedule, and Milestones** Subsequent to the DMNI award, the project was re-baselined to the awarded amount and internal milestones were established to track progress. These milestones are presented in Section 3.5 and are tracked at bi-weekly Technical Coordination meetings organized by the Technical Coordinator, and attended by the Project Manager, the Electronics Coordinator and all of the Subsystem Coordinators. Missed milestones are promptly rescheduled so that minimal risk is introduced to achieving the project goals.

**Management of Risks** A critical management task is the development of a formal risk registry for the project to track potential cost and schedule risks to the project and develop plans to mitigate them. These risks are being tracked by the Technical Coordinator, and a formal risk registry will be developed by the Project Engineer to allow the modeling of potential outcomes. The risks currently being tracked are summarized in Table 1. The most obvious among these is the risk of delays to the completion of the LESA facility, which would require changes to the project that would result in additional costs as well as likely delays. Because the LDMX detector concept employs technologies that are in use in other HEP experiments, there are few technical risks relative to the preliminary nature of the design, and the vast majority of work required to prepare for fabrication is simply design effort to develop implementations of existing technologies required for the apparatus. However, there are a few areas where modest technical risk exists on the project. The principal risk discussed at the time of the proposal was the dependency of the project on the HGCal technology being developed for the CMS project. Although the success of this effort is not in question, the timescale to reach a final implementation may be longer than currently anticipated, which could delay construction of LDMX. However, as time has passed this risk has been greatly mitigated. Other items where some risk exists are in radiation environment for the ECal, which could exceed estimates based upon simulations, uncertainty in the HCal veto performance related to the fidelity of Monte Carlo simulation, the possibility that the planned trigger algorithm cannot be implemented within the required latency budget, and some uncertainty in the required scope of the Trigger Scintillator system. Several risks are already actively mitigated, such as design modifications to mitigate the effects of excess aging of the HCal scintillator. The Mu2e collaboration has measured a reduction of the scintillator light yield at the level of 7-8% / year, larger than initially expected. To address this issue, we have increased the fiber diameter from 1.4mm to 1.8mm, and the scintillator thickness from 15mm to 20mm, boosting the light yield by 50% compared to the original design. Similarly, the ECal design has been modified to increased cooling to reduce the risk of operational issues from ECal radiation damage. Finally, the computing resource required to study full $10^{16}$ statistics could prove more challenging than expected, which could delay completion of design studies for the experiment. All of these risks have clear mitigations, which are outlined in Table 1.

## 3.4 Dependencies on Outside Resources Planned

### 3.4.1 Linac to End Station A (LESA) Beamline

The unique capability of a missing momentum experiment hinges on a CW multi-GeV electron beam to achieve high statistics. The proposed Linac to End Station A (LESA) beamline at SLAC is well suited to deliver such a beam and will support long-term occupancy for LDMX. LESA beamline completion and commissioning is planned for FY23, LESA will leverage the LCLS-II superconducting linac and of the Sector 30 Transfer Line (S30XL) AIP, both of which are currently under construction. S30XL, an important precursor to LESA, will parasitically extract trains of "empty" (dark current) bunches from the LCLS-II linac's dump line, with a duty factor of roughly 60% (one 600 ns macro-pulse every 1.1$\mu$s). The window duration is limited by the time required to ramp LCLS-II and S30XL kickers before and after each pulse, so when LCLS-II operates at lower rate, longer macro-pulses and hence higher duty factors will be possible. LESA will build on S30XL by connecting this transfer line to the existing End Station A beamline and in FY24 a low-power gun laser will be added to seed dark current bunches within the S30XL macro-pulse at 37 to 46 MHz (the 5th or 4th subharmonic of the gun frequency). LESA will be completely parasitic to LCLS-II, and has been reviewed extensively for non-interference.

The End Station A line provides the capability to tune the beam current to a level of one electron per pulse, with a wide beam spot as required by LDMX — capabilities used extensively in the End Station Test Beam program. The LDMX experiment is the flagship LESA user, and is anticipated to receive the majority of LESA's available beam. LDMX will be installed near the down-beam end of End Station A for a multi-year term of running. Other comparably-low-current experiments are also anticipated to run at LESA for relatively short periods, such as test beam users and dedicated electronuclear scattering experiments. These will be installed up-beam of LDMX, with a stopper preventing beam from reaching the LDMX detector.

| System | Risk | Impact | Mitigation |
|---|---|---|---|
| All | Delays to LESA | Impossible to operate at SLAC on relevant timescale | Continue to track status of possible alternates to operation at SLAC |
| ECal/HCal | CMS HGCROCv3 submitted in late 2020 may need more submissions | Delay modules by up to 6 months | Advance other items to be ready to install modules later |
| ECal | Radiation higher than expected | Downtime, inability to fully-bias sensors, unstable gain, inadequate cooling | Radiation-qualify COTS components; swap modules; have excess cooling capacity |
| HCal | Simulation overestimates the HCal veto performance | High-level design risk to hadronic calorimeter | Early beam test of prototype to tune and validate simulation; use several MC generators to estimate hadronic uncertainties |
| Trigger/DAQ | Trigger system critical path does not meet latency requirements | Trigger capabilities and ability to perform data-driven backgrounds will be reduced | Add another design cycle for the data transfer between subsystem backend electronics and trigger electronics choices |
| Computing/ Simulation | Not capable of generating, reconstructing and storing $1 \times 10^{16}$ EOT equivalent of background samples in a timely manner | Delay in studying the performance and ability to reject backgrounds of the conceptual design | Acquire dedicated computing nodes, storage and optimize simulation algorithms |
| Trigger Scintillator | Fake rate from secondaries produced in target and tracker is significantly larger than expected | Trigger capabilities and ability to perform data-driven backgrounds will be reduced | Investigating the use of additional detector planes to mitigate impact of secondaries on counting beam particles |

Table 1: Summary of identified risks by system. Given the LDMX approach of adapting existing technologies, these risks are a mixture of technical risks held by the original systems and design concerns within LDMX.

The impact of such experiments on LDMX in terms of lost beam-time and radiation are minor. Access to the detector will, however, be impossible whenever another experiment is receiving beam in End Station A. LESA completion on the timescale of FY23 will allow for early commissioning of LDMX in End Station A with a low-current 4 GeV CW electron beam, and — depending on the LDMX project profile — possibly initial physics running. Beam availability will continue until the LCLS-II linac will be upgraded to 8 GeV energy as part of the LCLS-II-HE project, currently planned for the 2025-27 timeframe. Upon completion of this upgrade, LESA will deliver 8 GeV beam to LDMX.

Higher beam energies are advantageous to LDMX, as they sharply decrease the rates of challenging few-particle backgrounds and improve the detector's single-particle rejection capabilities. However, LDMX studies have shown that 4 GeV beam is sufficient for a low-background search at the pilot-run LDMX statistics of $1 - 4 \times 10^{14}$ electrons on target. Thus, LDMX can proceed with this run and achieve powerful physics sensitivity even if the LCLS-II-HE project is delayed.

Although LESA is a logical and efficient approach to achieving LDMX's beam requirements, and is on-track for completion on the same timescale as LDMX, alternatives exist and will be pursued aggressively by the LDMX collaboration if LESA is not completed. One possibility is to run at JLab's CEBAF, which has demonstrated delivery of pA-scale currents for short periods, for example for QWeak detector commissioning, and can deliver beam at energies up to 11 GeV to each of its four halls. Foreign facilities such as the proposed eSPS [58] at CERN could also be explored.

#### 3.4.2 External Resources for Detector Design / Construction

LDMX leverages a number of existing HEP technologies and facilities to develop and fabricate the detector. A complete list of facilities and equipment from the collaborating institutions is presented in Appendix A.4 and Appendix A.5 of the LDMX DMNI proposal. There we include descriptions of available laboratory space at collaborating institutions, the availability of engineering resources, and specialized facilities for detector fabrication. Examples of these dedicated facilities and equipment include clean rooms for silicon detector construction at SLAC and UCSB, machine shops and detector assembly facilities at TTU and UVA, the Fermilab scintillator fabrication facility, calorimeter testing equipment at Caltech, and electronics assembly and testing equipment at the University of Minnesota.

In addition to available laboratory and university facility and equipment, LDMX is leveraging technology currently being designed for other projects. LDMX is planning to use sensors designed for the CMS HGCal which are currently in pre-series production. The ECal readout electronics are also being developed for the CMS HGCal, in particular the HGCROC readout ASIC, which is in manufacture for the final planned prototype (V3). Finally, LDMX plans to use ATCA-based trigger cards being developed for the CMS L1 Trigger upgrade. These cards are currently in their pre-production phase and would already be usable by LDMX. Where appropriate, dependency of the LDMX project and schedule on these external designs have been discussed as risks in Section 3.3. Scientific effort for design and prototyping comes from external institution resources and includes activities such as physics simulation, performance, and sensitivity. This is described in detail in Section 3.7.

## 3.5 Budget and Schedule for DMNI Project Phase

The LDMX DMNI proposal for Track 1 submitted in May 2019 included a budget and schedule for a two-year project to complete a technical design and produce a baseline cost, scope and schedule for construction of the experiment. This budget totaled \$1.96M and is summarized in Table 2. The proposal was awarded on February 28, 2020, at the level of \$1.5M and with the planned profile of \$150K in FY20, \$675K in FY21, and \$675K in FY22. Before submitting the lab FWP for this work, the project was re-baselined to the award amount and planned profile in order to preserve the goal of preparing the project for Preliminary and Final Design Reviews in the latter half of FY22 and construction in FY23 with minimal additional risk. This budget, summarized in Table 2, is the current budget for the LDMX DMNI project presented in this report.

| **DMNI Phase Budget Summary** | | | | |
|---|---|---|---|---|
| | **Year 1** | **Year 2** | | **Total** |
| DMNI Proposed (K\$) | 890 | 1071 | | **1961** |
| | **FY20** | **FY21** | **FY22** | **Total** |
| DMNI Awarded (K\$) | 150 | 675 | 675 | **1500** |
| Funds Received (K\$) | 150 | | | **150** |

Table 2: High-level summary of the proposed budget for the LDMX DMNI project, the awarded budget and actual funding received. Initial funding was received in Q3 of FY20 and the latter two have been stretched to three years.

A schedule for the work plan, including internal milestones, was developed together with this budget, in order to track progress on the project. These milestones and their current status are shown in Figure 14. FY20 funding was made available in Q3, and work began on the project according to this work plan. FY20 funds, augmented with redirected effort and outside resources, have enabled some critical work to continue into FY21, and has furthered many of the key goals of the project, meeting a number of FY21 milestones. Some milestones have been missed due to delays in FY21 funding; these will be rescheduled when the funding plan is known. Other milestones have been rescheduled due to the COVID pandemic, most notably those related to the test beam activity at CERN. On the whole, the work plan contains a large amount of float given the pool of effort and resources available to the project via participating institutions, so the work required to prepare the project for Preliminary and Final Design Reviews in the second half of FY22 and construction in FY23 still fits comfortably provided that FY21 funding is not subject to extended delays.

While previous budget and schedule exercises have been performed using a collaborative cloud-based spreadsheet (Google Sheets), the additional Project Management effort at SLAC has enabled the collaboration to begin developing more formal means of tracking the budget and schedule for the DMNI project and to develop plans for the proposed construction of the LDMX experiment. Toward this end, we have adopted Microsoft Project in the Cloud as a collaborative tool. This choice appears to be appropriate for a project of the scale of LDMX. In conjunction with our Basis-of-Estimate (BOE) documents, which are kept in the Fermilab doc-db database, it can in principle be used to apply rule-based contingencies on an item-by-item

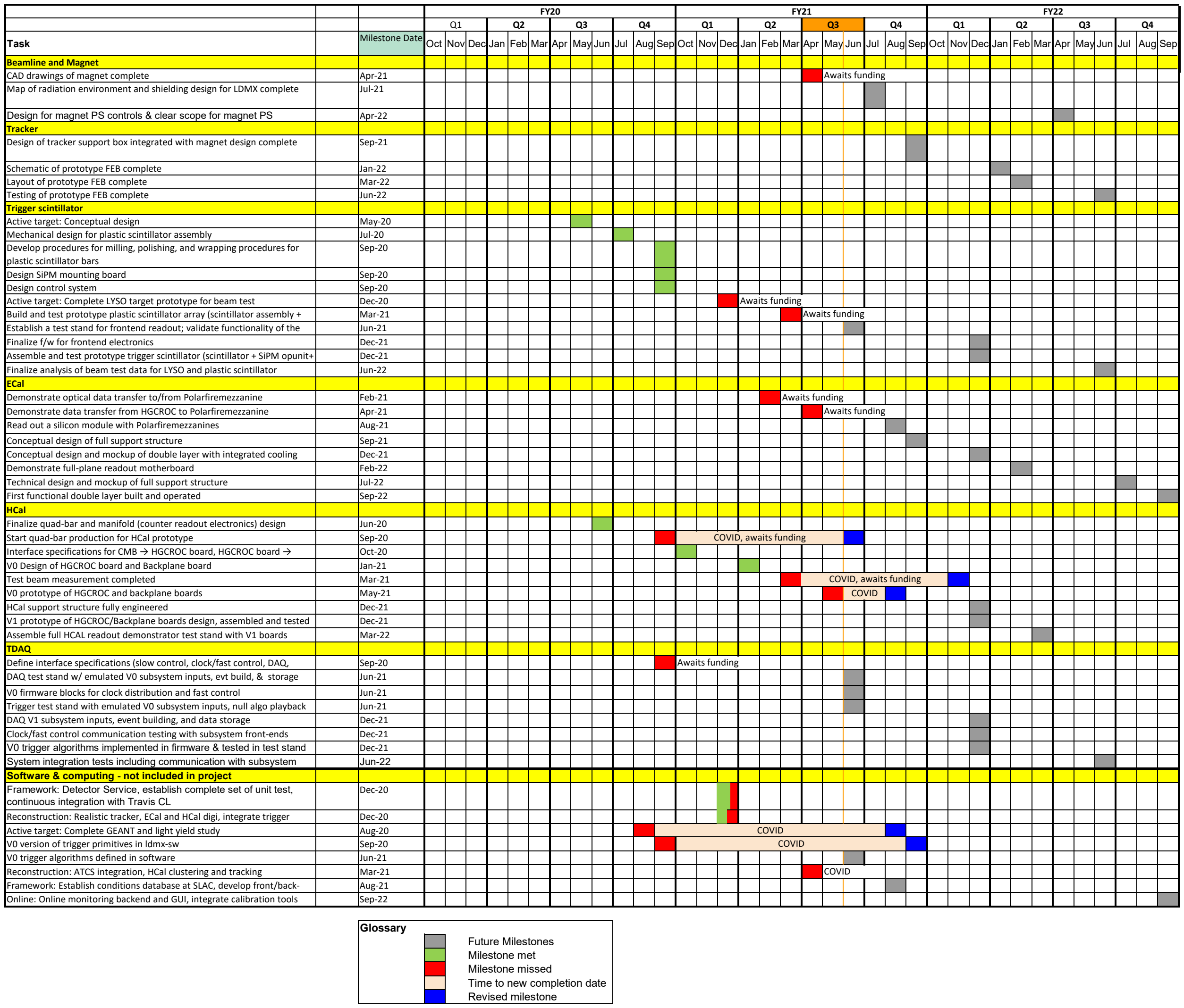



Figure 14: Milestones for the DMNI phase. We have used the color code at the bottom of the figure, together with some annotations, to compactly summarize milestones that have been met, those that have been missed due to COVID delays and the delay of FY21 funds, and those that have been replanned.

basis, can level resources and can be used to track earned value. The program is substantially less expensive than Primavera 6, requires less training, and will require a smaller group of people to administer. The WBS and resource-loaded schedule is contained in linked Project files driven from a Master file that contains common labor resources and information on indirect charges and escalation rates at each institution. The details of individual tasks are contained in Basis-of-Estimate documents in the form of Excel spreadsheets, based on a universal template used by each system. The BOEs break down the labor and M&S content of individual WBS tasks and provide engineering estimates, RFPs, invoices, *etc.* to support the estimates. A first order pass at resource-loading of the DMNI project has been made, based on the DOE-supplied plan for the fiscal years 20-22, which as of this writing, has not been fully implemented. A more realistic resource-loaded schedule can rapidly be produced when a revised funding plan is in place.

Figure 15 is a Gantt chart showing a Level 3 roll-up the DMNI resource-loaded schedule. Given the unknown funding profile, there is currently no leveling of technical resources nor management of the critical path. However, there is sufficient float in the individual system tasks that we are confident that we can produce the requisite Design Report on the original schedule.

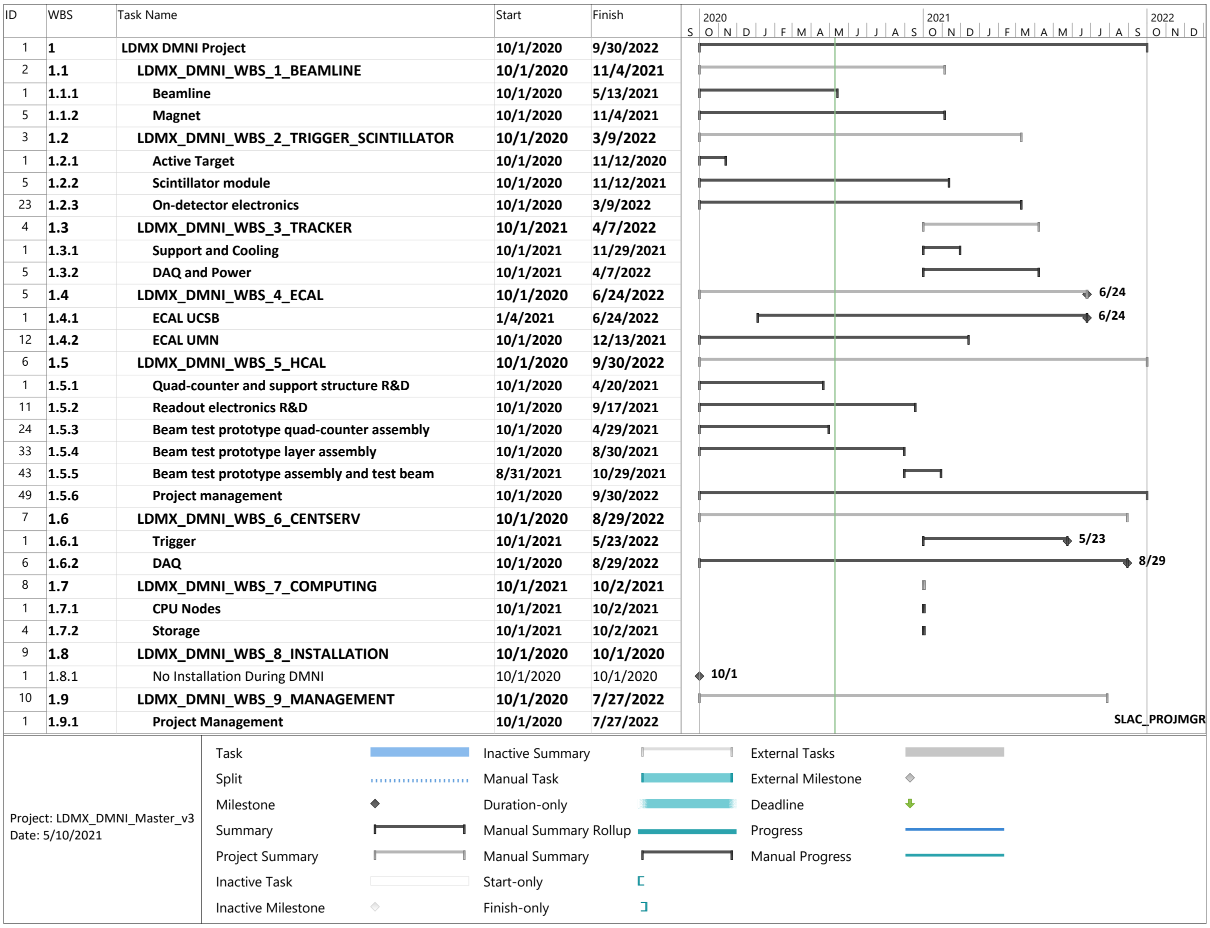



Figure 15: Summary Gantt chart at Level 3 for the DMNI phase

## 3.6 Budget and Schedule Estimate for the Small Project

The LDMX DMNI proposal included a preliminary estimate of the project cost for construction of the experiment. The budget for this estimate is shown in Table 3. This initial attempt at a complete bottom up estimate did not include a full accounting of overhead rates at some institutions or the pass-through overhead that applies for funding the project through SLAC. The computing resources required to record, process, and analyze the data were also not included. Contingency was included at the level of 25% on the detector subsystems and 50% on the Installation and Management tasks. This estimate assumed full funding of the DMNI proposal at the amount of \$1.96M. With these assumptions, the total estimated cost without (with) contingency was \$6.4M (\$8.4M).

More recently, in October 2020, in response to a request from OHEP to better understand the project scope, a more complete budget exercise was undertaken. As described in Section 3.5, this exercise used a collaborative cloud-based spreadsheet to perform a bottom up budget estimate that addressed many of the shortcomings of the estimate presented in the proposal. In particular, it included fully-loaded rates at all institutions, the overhead for funding the project through SLAC, the budget for computing resources required for the experiment, and assumed funding for the DMNI project at the awarded amount of \$1.5M. This estimate also included a first attempt to assign item-by-item risk-based contingencies, which resulted in an overall contingency rate of 34%. The estimated cost of the LDMX project resulting from this 2020 costing exercise was \$12.6M (\$16.9M) without (with) contingency.

As discussed in Section 3.5, we have recently adopted a more formal process for budgeting and scheduling of the Small Project, with the development of a formal Work Breakdown Structure (WBS), a complete set of

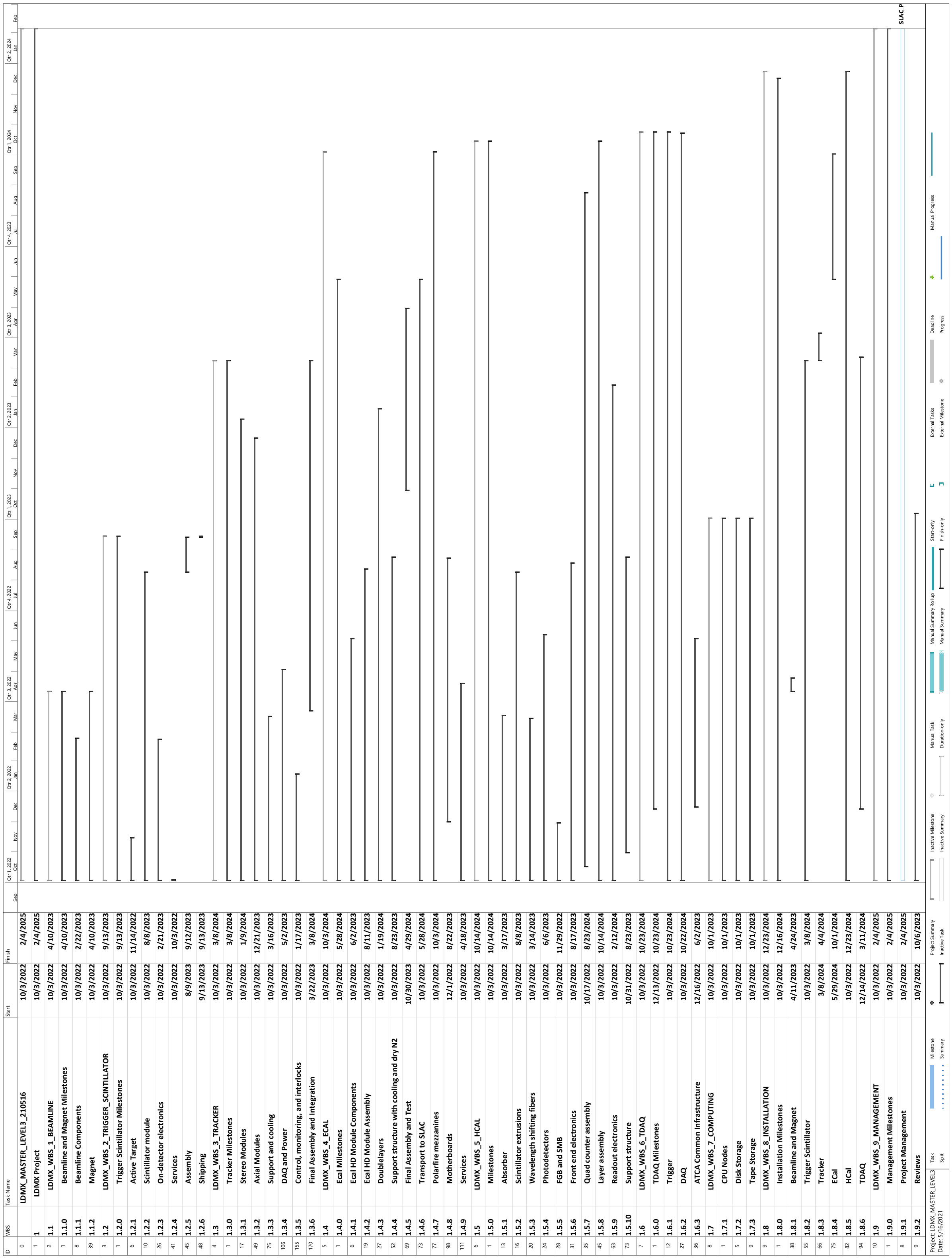



Figure 16: Summary Gantt chart at Level 3 for the LDMX Small Project. No attempt at resource-leveling has as yet been made; doing so is expected to have little effect on the completion date of the project.

| LDMX Cost Estimate from DMNI Proposal (2019) | | | | |
|---|---|---|---|---|
| **WBS** | **Item** | **M&S Total (K$)** | **Labor Total (K$)** | **Total (K$)** |
| 1 | LDMX Detector | 2,883 | 3,526 | 6,408 |
| 1.1 | Beamline | 41 | 228 | 269 |
| 1.2 | Trigger Scintillator | 43 | 108 | 150 |
| 1.3 | Tracker | 445 | 490 | 935 |
| 1.4 | ECal | 713 | 271 | 984 |
| 1.5 | HCal | 1,261 | 862 | 2,123 |
| 1.6 | Central Services (online computing+trigger+DAQ) | 252 | 220 | 473 |
| 1.7 | Installation | 22 | 142 | 164 |
| 1.8 | Management | 106 | 1,204 | 1,310 |

Table 3: The preliminary estimate of the cost of LDMX presented in the DMNI proposal, broken down by WBS, assuming funding of the DMNI project at the proposed amount of $1.96M. As described in the text, this estimate excluded a number of key items.

| Current Cost Estimate for the LDMX Project | | | | |
|---|---|---|---|---|
| **WBS** | **Item** | **M&S Total (K$)** | **Labor Total (K$)** | **Total (K$)** |
| 1 | LDMX Detector | 4,214 | 7,435 | 11,649 |
| 1.1 | Beamline | 113 | 445 | 558 |
| 1.2 | Trigger Scintillator | 103 | 109 | 212 |
| 1.3 | Tracker | 499 | 1,555 | 2,054 |
| 1.4 | ECal | 1,353 | 973 | 2,327 |
| 1.5 | HCal | 1,085 | 1,109 | 2,194 |
| 1.6 | Trigger/DAQ | 482 | 1,594 | 2,076 |
| 1.7 | Computing | 442 | 0 | 442 |
| 1.8 | Installation | 109 | 434 | 542 |
| 1.9 | Management | 28 | 1,217 | 1,246 |

Table 4: A new estimate of the cost of LDMX broken down by WBS, assuming funding of the DMNI project at the planned amount of $1.5M. Given the preliminary nature of this estimate, an overall contingency rate of 45% is currently being applied (including on international contributions) for a total estimated cost with contingency of $16.9M.

Basis of Estimate (BOE) documents for all labor and M&S, and a corresponding Resource-Loaded Schedule (RLS), which can be used to track budgets and schedules in detail. A complete set of preliminary BOEs and a RLS for the construction project have been produced, and have been used to generate a new cost estimate for the project, shown in Table 4. Fig. 16 is a Level 3 roll-up the Small Project resource-loaded schedule. This fully integrated Small Project plan will be further developed and, over time, have a full budget and schedule at an increased level of detail, including system integration, resource-leveling, and the identification of critical path items and project milestones, along with a detailed risk-based assessment of required contingency. In addition to managing and tracking the use of DOE resources and infrastructure to build the experiment, the management will also coordinate the resources contributed by international collaborators and be adapted to deal with the operations phase of the experiment.

Based upon this exercise, the total cost of the LDMX construction project is $11.65M without contingency, not including contributions through Lund University discussed in Section 3.7 valued at $547K. While the BOE documents contain full item-by-item risk-based contingencies according to established practice, these have not at this point been integrated into the RLS. Therefore, given the level of maturity of this estimate, we apply a 45% overall contingency rate, resulting in a cost estimate with contingency of $16.9M. Note that no contingency has been applied on international contributions as there is already a 30% contingency applied to those funds.

In comparison with the original DMNI cost estimate (Table 3), the current cost estimate has been updated in several areas. Across the project, appropriate overheads have been applied, including in particular the SLAC pass-through overhead mentioned above, and labor rates have been updated. Offline computing, which was not present in the original estimate, has been included, which increases the M&S cost by $442k. In the ECal system, the module-related M&S costs have been increased by 33% ($200k) relative to the large-volume CMS quotes to reflect additional fixed costs from the much-smaller LDMX production quantity. Initial engineering work on the ECal readout has also resulted in a need for a larger number of FPGA mezzanines per layer to handle the detector data volume, resulting in a cost increase of $137k. To provide risk mitigation for radiation dose to the ECal, the chiller has been upgraded, at a cost of $78k. Other services updates including the radiation-tolerant DC/DC converters, the clock fanout system, and a more-detailed costing of cabling and feedthroughs have added a total of $70k.

The largest labor cost increase comes in the area of DAQ and trigger development. The original Trigger/DAQ estimate assumed leading contributions from off-project University support; the current budget assumes on-project labor for the base cost estimate with university contributions as a possible cost reduction opportunity. Similar considerations account for cost increases in the Tracker and ECal, where more work is expected from professional staff and less from graduate students and postdoctoral researchers in firmware and DAQ in particular. The current estimate also includes $461k of final design effort in several areas which was included in the original DMNI proposal but not in the work as replanned after the award.

## 3.7 Other Contributions

LDMX is a Collaboration of eight institutions of which five are US universities, two are national laboratories, and one is a Swedish university. This section outlines other contributions than the DMNI funding used (and for Lund University also to be used) by those institutions. When the project becomes fully funded, we expect these other contributions to grow commensurately with the level of effort required to support the project.

### 3.7.1 Lund University, Sweden

Lund University[1] participates with two faculty members, one postdoctoral researcher, one engineer, graduate students and undergraduate students.

An early initial support was obtained for the DMNI-phase through the Royal Physiographic Society[2] (M&S $ 27,000) and the Crafoord Foundation[3] (M&S $ 60,000). The latter also includes some postdoctoral and travel support. These grants cover the majority of the M&S costs for the HCal prototype. Of this, roughly M&S $ 63,000 and 350 hours of engineering have been spent by the end of May this year.

The Knut & Alice Wallenberg Foundation[4] approved in October 2019 a project entitled *Light Dark Matter*, that started 1 July 2020. This project has four workpackages of which the largest is the Lund University participation in the LDMX Collaboration. It includes $ 800,000 M&S support for the HCal, $ 55,000 for LDMX datastorage at Lund University, and labor support for 1 200 hours of electronics engineering. This grant covers in addition postdoctoral and PhD-student support, and the required travel and subsistence for a proportionate presence at SLAC.

All amounts above in $ are based on the 26 April 2021 exchange rate, while the budgets are granted in SEK.

[1]https://www.lunduniversity.lu.se/
[2]https://www.fysiografen.se/en/
[3]https://www.crafoord.se/en/
[4]https://kaw.wallenberg.org/en

The faculty member participation is supported by the University research budget, the Swedish Research Council[5], and by the Knut & Alice Wallenberg Foundation.

LDMX is using the LUNARC Center for Scientific Computing[6] with 3M CPU hours allocated by Lund University and by the Swedish National Infrastructure for Computing (SNIC)[7]. For LDMX, 107 TB storage was purchased in 2018 and 125 TB dedicated to LDCS (see next paragraph) in eof 2019 for in total $ 25,000 university infrastructure funding.

The group has designed the first version of the so-called HGCROC board for the readout of the HCal. The group has also initiated and coordinated that a distributed computing system (LDCS) [57] was developed and deployed, allowing LDMX to use computing resources from several of the participating institutions, currently including at Caltech, Lund University, UCSB and SLAC.

#### 3.7.2 Caltech

Visitor J. Oyang, who is not supported by DOE, is making major contributions to the development effort on the HCal and the active target option.

#### 3.7.3 Fermilab

The PI N. Tran, along with other Fermilab scientists, was awarded a Fermilab LDRD award in 2020 for advancing accelerator-based dark matter experimental concepts. A fraction of the award, roughly $\frac{1}{4}$, was allocated to advance the LDMX detector concept and doing simulation studies to further the physics concept. The award is providing research fraction to N. Tran (0.1 FTE) and a postdoctoral fellow at 0.25 FTE time. Prior to the LDRD effort PI N. Tran worked on LDMX at the level of 0.1 FTE.

#### 3.7.4 University of Minnesota

During 2020 $ 2,500 of University funds was invested in hardware and in undergraduate engineering labor to develop firmware. In addition $ 15,000 of University funding was invested in summer research assistant support for several graduate students since 2017. In 2021, $ 6,000 in University funding was invested in hardware to maintain schedule in prototyping.

The PI J. Mans has worked 10% of his time and graduate student T. Eichlersmith 50% of his time, on LDMX. T. Eichlersmith is supported by university funds (Teaching Assistantship).

LDMX is making use of computing and data storage resources made possible by a combination of ARRA funding and university funds, supported operationally by university funds.

#### 3.7.5 University of California Santa Barbara

The UCSB work has been supported by university and donor funds as well as the synergy from DOE supported upgrade work for CMS. This has resulted in $ 50,000 per year on support for technical personnel and students since 2015[8].

LDMX is using the California Nano-Science Institute (CNSI) POD computing cluster at UCSB, supported by the university and CNSI.

Postdoctor V. Dutta is 15% on LDMX and is mainly funded by the DOE Energy Frontier, but about 10% of her salary is UCSB funds.

The graduate students A. Li and P. Masterson have been at 25% on LDMX and funded by UCSB.

Many undergraduate students have have worked for free and have made significant contributions to LDMX.

[5] https://www.vr.se/english.html

[6] https://www.lunarc.lu.se/

[7] https://www.snic.se/

[8] We acknowledgement this support from University of California Santa Barbara and The Pat and Joe Yzurdiaga Chair in Experimental Science

### 3.7.6 SLAC

The PI T. Nelson is working 25% on LDMX and the Project Scientist O. Moreno is working 75% on LDMX, funded by the DOE Intensity Frontier.

The Mechanical Engineer T. Lange is working 25% on LDMX as Project Engineer/Project Manager, funded internally at SLAC.

SLAC is using $ 115,000 of KA-25 funding towards developing generic DAQ infrastructure for LESA that will provide event building and run control for LDMX.

LDMX is utilizing computing resources funded by the DOE Intensity Frontier.

### 3.7.7 Stanford University

The PI L. Tompkins works one summer salary month from university funds for LDMX.

The group had 80% FTE of an electrical engineer from June 2020 through Feb 2021 funded by the L. Tompkins start-up funds.

L. K. Bryngemark is in the group on a Wallenberg Stanford Postdoctoral Fellowship from June 2019 to June 2021, on a grant from the Knut & Alice Wallenberg Foundation.

The group has had three short term (3 months) students funded by Stanford departmental funds.

### 3.7.8 Texas Tech University

N. Gogate, research assistant, has been supported by the PI A. Whitbeck's start-up funds.

Several students have been contributing thanks to support from the Honors College at the university.

### 3.7.9 University of Virginia

The group has two faculty members C. Group and C. Dukes each working 10% on LDMX. In addition they have a post-doc M. Solt working ∼35% and a research scientist R. Ehrlich working ∼10% on LDMX. All funded by the DOE Intensity Frontier.

## 3.8 Planning for Operations and Analysis

The LDMX experiment is planning for two different periods of operation. During a pilot run of 6 months to a year, we expect to collect $2-4\times10^{14}$ electrons on target at a beam energy of 4 GeV. Soon thereafter, LCLS-II will be upgraded to an 8 GeV drive beam (LCLS-II-HE) which mitigates key backgrounds allowing for LDMX to more easily achieve its full sensitivity. During this "Phase II" of operations, LDMX would run for 2-4 more years to achieve full sensitivity, depending upon how robust the design is to higher occupancies required to compress operations with higher beam intensities.

With the LESA facility providing beam to LDMX whenever LCLS-II is operating, the major costs to operate the experiment are electrical power, engineering and technician support, and travel costs. There are some additional small costs anticipated for consumables and the upkeep of conventional facilities in End Station A. Assuming operation of the experiment for 250 days/year, one can arrive a rough annual operating cost.

The two major consumers of electrical power are the LDMX magnet and the magnets and other components of the A-line. Smaller consumers of power are the low-conductivity water (LCW) pumps required to cool these components. The power consumption of these are well understood and the cost of electricity at SLAC is planned for years in advance, so it is not difficult to estimate these costs. The power consumption of the rest of the detector is less well known, but relatively small. The estimated electrical costs for the experiment are shown in Table 5.

Some level of engineering and technician support will be required during operations to assist with issues arising in the data acquisition and mechanical systems of the experiment. For engineering support, 4 weeks each of an electronics/DAQ engineer and a mechanical engineer are assumed during each year of operation. For technician support, 0.5 FTE of a mechanical technician and 2 weeks of an electronics technician are assumed. These costs are again summarized in Table 5

In order to control and monitor the experiment during operations, we plan to have a small control room located on the SLAC campus rather than in End Station A: we find no justification for maintaining ESA as a habitable workplace in order to operate the experiment. Furthermore, we anticipate setting up the control and monitoring to allow collaborators to take normal experimental shifts remotely. However, it will remain important to have a small number of experts at SLAC who are capable of doing hands-on work on the detector systems in an on-call capacity. Complete expert coverage for all of the detector subsystems requires a set of four experts to be available at SLAC at all times, three of whom will not be SLAC personnel. Assuming travel and per diem for two-week expert shifts, one can estimate the cost of staffing operations. These annual costs are summarized in Table 5.

| Operations item | Cost/year (K$) | Contingency/year (K$) | Total (K$) |
|---|---:|---:|---:|
| Electrical Power | 328 | 121 | 450 |
| Engineering/Technical Support | 317 | 159 | 476 |
| End Station A services and consumables | 73 | 41 | 113 |
| Travel | 326 | 163 | 490 |
| Total | 1,045 | 484 | 1,529 |

Table 5: A preliminary estimate of the annual cost of operating LDMX at SLAC.

As discussed in Sec. 3.1.2, the pilot run trigger rate is expected to be $\sim$5 kHz. Assuming a bunch structure of 37 MHz and factor of 5 safety margin in the trigger rate, LDMX is expected to collect between (1.35 - 2.7) $\times 10^{11}$ events. Assuming an event size of 3.1 kB[53], between 419 TB to 873 TB of disk space will be required to store all of the raw data. Given that the reconstruction of the data is expected to add an additional 10 kB per event, an additional 1.8 PB - 3.5 PB will be needed.

For Phase II, the trigger rate is expected to be higher given the expectation of a larger number of electrons per bunch. Assuming that the trigger rate will be limited by the tracker to 50 kHz, LDMX will collect $\sim 1.4 \times 10^{13}$ events. To store the raw data, 42 PB of disk will be needed while the reconstruction will add an additional 136 PB. It should be noted that these assume no event filtering is being applied, but this possibility will be explored.

Monte Carlo samples will be needed to compare against data and for design performance studies. In addition to a sample for the pilot run, an 8 GeV sample with background statistics equivalent to what we expect for 1 $\times 10^{16}$ electrons on target will also be needed. Table 6 shows the expected size of a full reconstructed MC data set needed for the pilot run. For Phase II, it is unrealistic to assume that we will be able to simply scale up the statistics from the pilot run study as this would lead to roughly a factor of 25 more disk space. For now, a reasonable assumption will be that the Phase II MC dataset will be reduced by a factor of 5 through filtering i.e. only keeping events that are of most interest to physics studies. As a result, storage of both the pilot and Phase II samples will require about 1 PB of space.

| **Sample** | **Total Size (TB)** |
|---|:---:|
| $1 \times 10^{14}$ ECal PN sample - unskimmed | 50 |
| $4 \times 10^{14}$ ECal PN sample - skimmed | 21 |
| $4 \times 10^{14}$ ECal PN sample multi-electron sample - skimmed | 50 |
| $4 \times 10^{14}$ ECal as a target sample | 20 |
| $4 \times 10^{14}$ Target photo/electro-nuclear sample | 10 |
| $4 \times 10^{14}$ Muon pair conversion sample | 5 |
| Inclusive + signal | 11 |
| **Total** | 167 |

Table 6: Monte Carlo samples and expected size needed for the pilot run.

# 4 Response to the Previous Review

We would like to thank the four reviewers for their careful review of our prepared materials. We found that they had a generally very good understanding and appreciation for the motivation, design and planned realization of LDMX at SLAC. In this section we focus on the very few cases where the reviewers may have benefited from some additional information and provide that here.

Reviewer 1 remarked "*I would have liked to see a bit more discussion of the beam time structure and currents needed. The proposal assumes more familiarity with the SLAC beams than I have. How would the experiment differ if run at JLab? How prone to pileup is it? How does the beam structure (super-bunches?). What is the impact on other experiments running simultaneously? Is it parasitic or dominant in the beamline?*"

LDMX is the dominant user of the beamline (LESA), but LESA is itself a parasitic co-user of the accelerator (LCLS-II linac). We are using time slices of the beam that LCLS-II is not using for the Basic Energy Science (BES) program, and extracting them downstream of the extraction points for the BES program — this setup was designed to not interfere with LCLS-II operations, and multiple S30XL/LESA reviews have affirmed the conclusion that LESA will not interfere with LCLS-II. The bunches in the LESA beamline during LDMX operation are for LDMX alone; other LESA experiments will not run simultaneously with LDMX, so there is also no impact there. For further discussion, including time structure, see Sec. 3.4.1.

The situation at JLab would be less operationally favorable for LDMX. In order to have dedicated beam at a single energy that is as high as possible, we would very likely operate in Hall D. This would mean that LDMX would have to win out against competition from nuclear physics proposals to occupy Hall D for a longer period of time than is typical for JLab experiments. At JLab, LDMX would not be at all parasitic. Technically, it appears feasible to run LDMX at JLab — JLab has demonstrated the capability to deliver low currents as required by LDMX, can deliver beam at a subharmonic of the typical 4 ns bunch spacing in order to achieve the $\geq 25$ ns bunch spacing optimal for LDMX, and could spread out a beam to the spot size required for LDMX using a series of quadrupole magnets. However, it would be quite different from standard JLab operation and would require exclusive occupancy of one of the four experimental halls.

Regarding pileup, LDMX is affected by in-time pileup, as we need to track the impact of each electron in the bunch. The detector is designed to have a fast response so that we can make use of bunches closely spaced in time (e.g. an average electron rate of between 30 and 75 MHz). For this reason we plan to start operation with an average of one electron per pulse, which means that in reality we will have more than one electron about half the time. This is really one of the prime reasons for using a highly granular electromagnetic calorimeter. With a 10% target, the case of a hard brem is rare so the multiple beam electron events that we will want to keep and analyze will contain a hard brem, recoil electron and one or more electrons that are at or close to full beam energy. The kinematics of these electrons will be well understood from the recoil tracker and electromagnetic showers in the ECal are very narrow in the earlier layers, at the level of a few millimeters. The ability to reject background without significant loss of signal efficiency will rely on this information to identify those cases where the photon trajectory is reasonably well separated from that of any electron to enable the detection of even very faint remnants of a photonuclear interaction in an isolated region of the ECal. Where the photon is projected to come relatively close to an electron, it may be necessary to reject the event out of hand and take the hit in signal acceptance. It should be mentioned that this is also something we had in mind in planning for a large beam spot to assist in the separation of electrons and subsequent brem photons. The tools needed for simulation of multi-electron events are well advanced and studies will be carried out this summer to quantify how well this situation can be handled and the impact it will have on signal efficiency.

Reviewer 1 also commented "*The budget seems well thought out - the technician and engineering resources needed may be a bit low for an experiment that needs to be so rad-hard and fault-tolerant?*". Here we would first remark that the radiation expected for the ECal, for instance, is significant but still a couple of orders of magnitude less than that of the CMS experiment and the worst of it will be concentrated in the region near shower max. This can be addressed by enhancing the cooling to those few layers or even swapping them for new ones over time. As for the more detailed issues associated with high radiation, these have been or are being studied in CMS and we will make use of CMS technology in all areas of high radiation in the ECal.

Reviewer 2 remarked "*Even though NA64 and Belle-II will set limits (or discover) DM candidates over a majority of interesting parameter space for scalars and Majorana fermions, LDMX is likely to add sensitivity* *for pseudo-Dirac fermions."* It is true that the most aggressive projections from NA64 would explore significant parameter space for the thermal scalar and Majorana fermion benchmarks. However, it is not certain when or if NA64 will reach the "max sensitivity" line in Fig. 3, in light of both competition for beam-time and background expectations for their lower-statistics analysis [7]. LDMX could well be the first to explore this interesting parameter region, especially with the timely transition to a baselined project that is the goal of the DMNI funding. Several other points are also worth emphasizing. First, many models beyond pseudo-Dirac thermal DM can lead to signals in the coupling range below NA64's "max sensitivity" projections but above that of LDMX. These include near-resonance scalar and Majorana DM (illustrated in Figure 2(right)), milli-charged DM, secluded DM, and SIMP-like DM, which may also have inelastic couplings and hence be inaccessible to direct detection [10]. Second and perhaps most importantly, the $p_T$ measurement enabled by LDMX's thin target and tracking will allow for a much more convincing discovery because it provides additional discriminating power between signal and background (as does the detailed shower shape information from LDMX's ECAL). The $p_T$ spectrum of LDMX even enables an estimate of the signal invariant mass, since higher-mass DM-pair/$A'$ production leads to larger typical recoil electron $p_T$, as shown in Figure 5.

Reviewer 2 pointed out that *"The results of LDMX will be valuable from the theoretical point of view. The experiment does not introduce new technologies and as such is unlikely to open a new chapter in DM searches."* By pursing an approach that utilizes advanced but appropriately mature detector technology, LDMX offers a low risk pathway for achieving the BRN science goals — this is by design. We would like to also make the obvious point that LDMX will open a new chapter in DM searches if it discovers a signal, and will set world-leading limits if it doesn't. As noted above, we have studied the ability of LDMX to extract information associated with a significant excess of signal events and find that it can achieve good mass and coupling resolution even in Phase I, and this becomes fairly striking in Phase II. So, should there be an observation, we believe that the technology used for LDMX would be refined in a subsequent generation to obtain significant information that would be of exceptional value to the field of DM research.

Reviewer 2 also commented that *"Even though mitigation techniques are suggested, instrumental backgrounds can ultimately limit the sensitivity of LDMX and prevent it from reaching the design goals."* We certainly agree with this statement and it is for this reason that we have taken exceptional steps to understand the nuclear models in GEANT4 and undertaken a detailed and peer-reviewed background-rejection study [51]. We have an ongoing program of producing larger MC datasets to "drill down" on the most difficult backgrounds at Monte Carlo statistics exceeding our planned running statistics, and including more detector realism. In practice, 4 GeV running will face the most challenging background rejection, but our Phase I target luminosity for 4 GeV appears to be appropriately matched to the detector capabilities as shown in [51]. Our initial results for 8 GeV running indicate that performance will improve by multiple orders of magnitude. So while the experiment is challenging, we have reason to believe that the LDMX detector will be up for this challenge.

Reviewer 3 remarked *"In fact, LDMX seems so far along that I wonder if $2M of specialized funding from this program is really needed to move the project forward to design."* We thank the reviewer for this vote of confidence and agree that the LDMX concept is quite mature. However, the stated goal for Track 1 projects is to develop a baseline design, along with the cost, scope, and schedule for the project, and DMNI funding is critically important to completing this task expeditiously. Since early data from LDMX will explore new and well-motivated DM parameter space where there is established international competition, particularly from NA64, there is a powerful incentive for timely completion of the detector in order to achieve these early goals.

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