

# Proposed Running of the DarkLight Phase-1 Experiment

## The DarkLight Collaboration

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## 1 Introduction

The DarkLight experiment [1] was conceived and proposed at MIT-LNS to search for evidence of a dark photon in electron-proton scattering. It is motivated by theoretical consideration [2], hints from astrophysical observation [3], and the  $\approx 3\sigma$  discrepancy [4] in the measured anomalous magnetic moment of the muon with respect to the Standard Model expectation. The experiment aims to search for a bump in the reconstructed  $e^+e^-$  invariant mass while detecting the complete final-state in the process  $ep \rightarrow epe^+e^-$  at an incident energy of 100 MeV [5]. Figure 1 shows the region in mass-coupling space probed by DarkLight. While this region has been searched extensively and the  $A'$  has been excluded at  $2\sigma$ , largely via decay of the  $\pi^0$  [6], DarkLight brings a completely new technique to bear to this search with significantly increased sensitivity.

The proposal to carry out the DarkLight experiment [7] was approved by Jefferson Laboratory PAC39 in June 2012 with “A” scientific rating for 90 days assuming 10 mA of beam at 100 MeV energy. The proposed experiment is technically innovative in that it uses the energy recovery linac (ERL) beam of the Jefferson Laboratory Low Energy Recirculator Facility, a windowless hydrogen gas target of thickness  $10^{19}$  cm $^{-2}$ , and the detector must allow a search for a rare event in the presence of a very large rate of both electron-proton and electron-electron (Møller) elastic events. The proposal approval was conditional upon demonstration of the feasibility of passing the required Megawatt beam through narrow ( $\approx$ mm diameter)

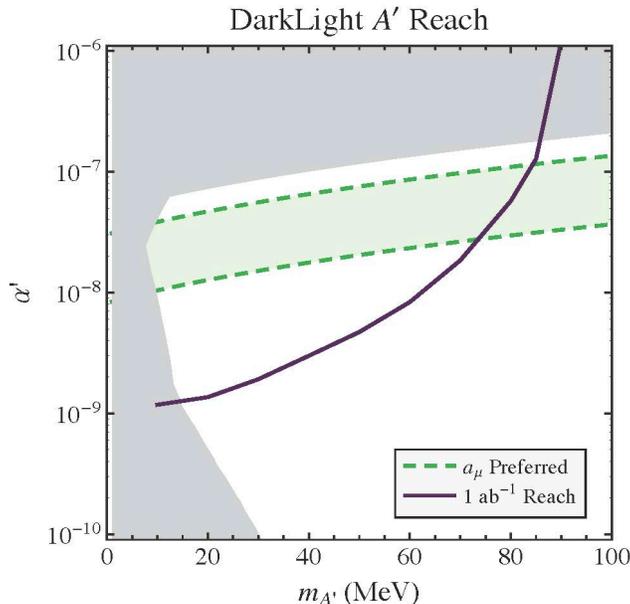


Figure 1: The  $A'$  coupling-mass space probed by the DarkLight experiment [7]. The purple line indicates the boundary of the  $5\sigma$  discovery region. The green band indicates the plausible region if the  $3\sigma$  muon ( $g-2$ ) discrepancy was due to the  $A'$ .

apertures. In July 2012, the test was successfully carried out [8, 9, 10] and the DarkLight experiment was granted full scientific approval by Jefferson Laboratory in May 2013. The DarkLight experiment layout is shown in Fig. 2.

In spring 2014, an existing solenoidal magnet that matched well the required specifications was located at Brookhaven National Laboratory. The Stony Brook group mapped the magnetic field and it was subsequently shipped to the MIT-Bates laboratory in fall 2014. In summer 2014, a phase-1 experiment received funding by the National Science Foundation (NSF) through its MRI program. The three scientific goals of the phase-1 DarkLight as proposed to the NSF are:

- **Phase-1a** Install the existing solenoidal magnet and the gas target to operate up to full thickness. In addition, detectors will be installed to measure rates and to gain valuable experience in understanding detector performance. The principal goal will be to study how the magnet and target affect the characteristics of the 100 MeV ERL beam as a function of solenoidal magnetic field strength, target thickness, and ERL beam current.
- **Phase-1b** Measure radiative Møller scattering at 100 MeV using a thin carbon foil target. This has been calculated by our collaboration [11] and its measurements requires a distinct detector configuration involving a focusing dipole magnet to detect the 1 to 5 MeV final-state electrons at angles from  $25^\circ$  to  $45^\circ$ .
- **Phase-1c** Install GEM trackers and silicon proton detectors. Measure the smooth QED background on which an  $A'$  bump would sit. Carry out a preliminary search for the  $A'$ .

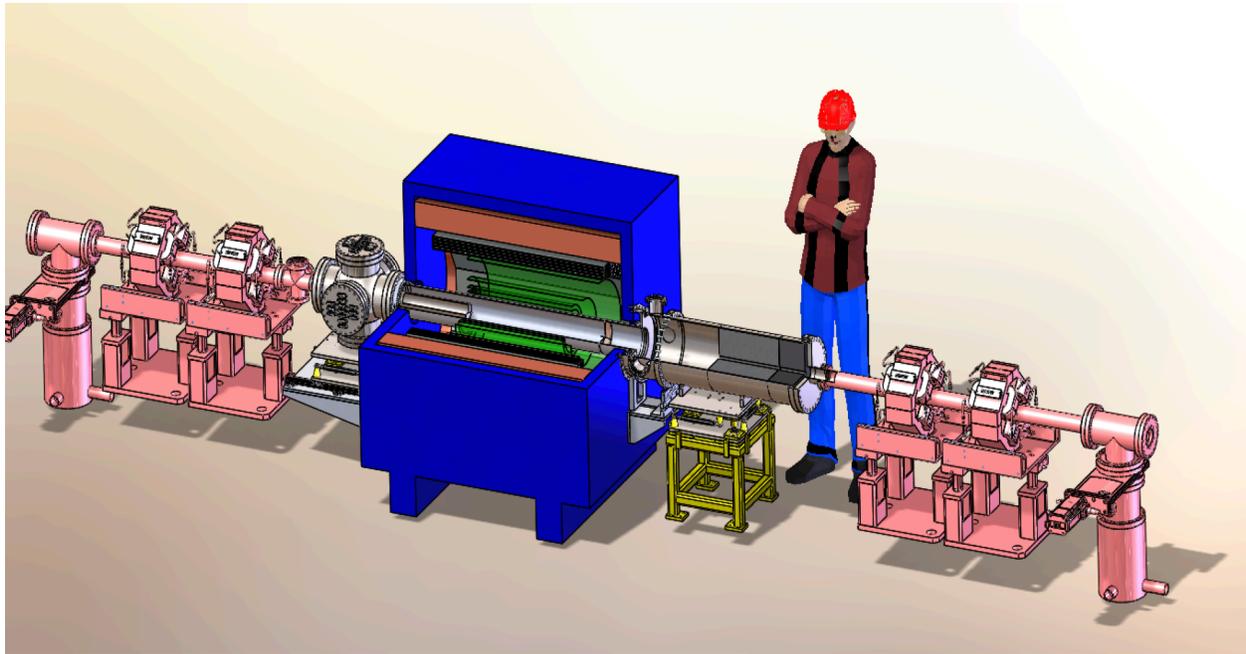


Figure 2: Schematic layout of the DarkLight experiment.

We note that there are expected to be significant differences in operation between carbon foil and gas target running with the solenoidal magnet. Without the solenoid, the H/V phase space exchange needed to control the beam breakup instability is quite different. Further, the transverse phase space match to the foil is different than that for the solenoid. It would be advantageous to schedule several weeks of beam development with the solenoidal magnet in place before operating the machine for physics. It would be desirable to work out the matching and phase space exchange, and then later migrate it to the “notionally simpler” case of the thin foil. It is necessary that the accelerator physicists have a number of weeks to set up the beam in advance of the time requested here. The availability of adequate beam diagnostics and instrumentation will be essential for progress.

## 2 Phase-1a

A central requirement of the DarkLight experiment is the high luminosity provided by the dense target we propose. Such targets have yet to be operated in ERL settings, and there is considerable interest in their performance [12, 13]. Following the beam loss tests conducted in 2012, we intend to install a windowless gas cell at LERF, and operate it at a range of areal densities to explore the system's tolerance for increased emittance caused by beam-target interactions, as well as the rate environment in the region the DarkLight detectors will occupy. This latter affords us the opportunity to position prototype Micromegas as available and scintillating fiber detectors, as available, in addition to the 10x10 cm GEM detectors that will record the bulk of our data. In addition, we intend to test commercially available, thin-foil targets of varying thicknesses.

## 3 Phase-1b

With the development of new precision physics experiments on the Intensity Frontier using lepton beams on targets containing atomic electrons, interest has been renewed in Møller and Bhabha scattering as important signal, background, and luminosity-monitoring processes. Two such experiments are DarkLight and OLYMPUS. These experiments require study of Møller scattering including radiative effects. A proper calculation of the radiative Møller process requires the combination of two calculations. This is typically performed by dividing the phase-space into two regions: soft-photon, and bremsstrahlung. In the soft-photon regime, events are typically treated with elastic kinematics with a correction factor applied to the cross-section. In the bremsstrahlung regime, a full calculation is used for the emission of a hard photon.

In regions where the kinematic Mandelstam variables  $s, t, u \sim m_e^2$ , typical soft-photon radiative corrections are insufficient due to ultra-relativistic approximations in which the electron mass is taken to be zero. Recently, these radiative corrections have been performed without any ultra-relativistic approximations, but they still have yet to be experimentally verified. A Monte Carlo event generator has been written including soft-photon radiative corrections to the Born Møller cross-section and a new, exact calculation of first-order Møller bremsstrahlung. All orders of the electron mass are kept. It is envisioned that high-precision data will be acquired in the Phase 1 DarkLight experiment in the effort to validate both the soft-photon radiative corrections and the new bremsstrahlung calculation. It is important that the data be taken where at least one of  $s, t, u \sim m_e^2$ , since this is the region in which the ultra-relativistic approximations break down. The 100 MeV JLab ERL is thus an ideal setting in which to test the Møller scattering theory.

The Møller calculation can be verified at low  $Q^2$  in DarkLight Phase 1 by precisely measuring both the angular distribution of the Møller electrons as well as the energy distribution at fixed angle. This will require an apparatus with both good angular and energy resolutions. To this end, the experiment will make use of the JLab ERL's 100 MeV electron beam incident on a thin diamond-like carbon foil. A two-armed spectrometer has been identified as an appropriate detector configuration: one as a measurement arm, and one as a fixed luminosity-normalization arm. We note that because the outgoing Møller electrons are iden-

tical, low- $Q^2$  regions can be probed at high lab-frame angles due to the ambiguity of the scattered and recoil electrons.

The electrons of interest have momenta between 1 and 5 MeV, and will be measured between the lab-frame angles of  $25^\circ$  and  $45^\circ$ . At these relatively high angles, standard (ultra-relativistic) radiative corrections lose their validity. This is therefore an attractive region in which to measure Møller scattering: only recently has a precise calculation emerged, and no data exist yet to verify it to high precision. It is envisioned that the electron momentum will be measured to  $\sim 1\%$  for momenta between 1 and 5 MeV/c. The energy distribution of the scattered electrons can be measured separately at  $25^\circ$ ,  $30^\circ$ ,  $35^\circ$ ,  $40^\circ$ ,  $45^\circ$ . An angular acceptance of approximately  $\Delta\theta \sim \Delta\phi \sim 1^\circ$  is desired. The fixed arm of the spectrometer will be used to normalize these runs relative to each other.

A thin diamond-like carbon (DLC) foil is desired as the experimental target. These are available from MicroMatter in self-supporting thicknesses of approximately  $5\ \mu\text{m}$ . This provides an electron thickness of  $\sim 3 \times 10^{20}\ \text{e}^- \text{cm}^{-2}$ . A 100 MeV, 0.01 mA electron beam will deposit approximately 0.027 Watts of power into this foil, which is manageable and will achieve a luminosity of  $\sim 2 \times 10^{34}\ \text{cm}^{-2}\text{s}^{-1}$ .

It is envisioned that the detector will consist of two spectrometer arms. One will be fixed and measure electron-carbon scattering, and the other will rotate from  $25^\circ$  to  $45^\circ$ . For a measurement of  $\leq 5$  MeV electrons, any material between the target and detector will cause undesired multiple scattering. For this reason, vacuum must be maintained from the interaction point to as close to the detector plane as possible. The solid DLC target will facilitate this. In addition, the moving spectrometer can be connected to the beamline via a bellows that enables it to be moved without breaking vacuum. Arrays of scintillating fibers are envisioned as detectors at the focal plane of the spectrometer. The run could have  $\sim 100$  settings and take place over approximately 15 days (including re-setting time).

## 4 Phase-1c

We plan to build a prototype of the DarkLight apparatus, called phase-1c, which despite reduced acceptance would allow us to verify that the lepton and proton tracking detectors perform adequately in the high luminosity, high background environment at the JLab LERF where 5 mA of 100 MeV electron beam is incident on  $10^{19}$  atoms/cm<sup>2</sup> hydrogen gas target. Scientifically, we would measure the cross section for the QED process  $ep \rightarrow epe^+e^-$  and compare with a calculation. Because of the necessity to develop the detectors and readout system, we plan to request beam time for phase-1c in summer 2017.

Fig. 3 illustrates the key components of the DarkLight phase-1c setup. The electron beam will enter from the left. The windowless hydrogen target will extend over 80 cm, bracketed at the aft/forward by flow limiters of diameter 2 mm. The section of the beam-pipe viewed by the GEMs will have a thinner wall to reduce multiple scattering of detected leptons and to improve the resolution of the reconstructed invariant mass of  $e^+e^-$  pairs. At least 2 out of 3 leptons produced in a radiative QED or  $A'$  process will be detected with two 4-GEM assemblies with limited azimuthal and longitudinal coverage. A thin silicon detector placed in the vacuum will measure the energy and position of the recoil proton allowing to further suppress background offline for a subset of the 2-lepton triggered events.

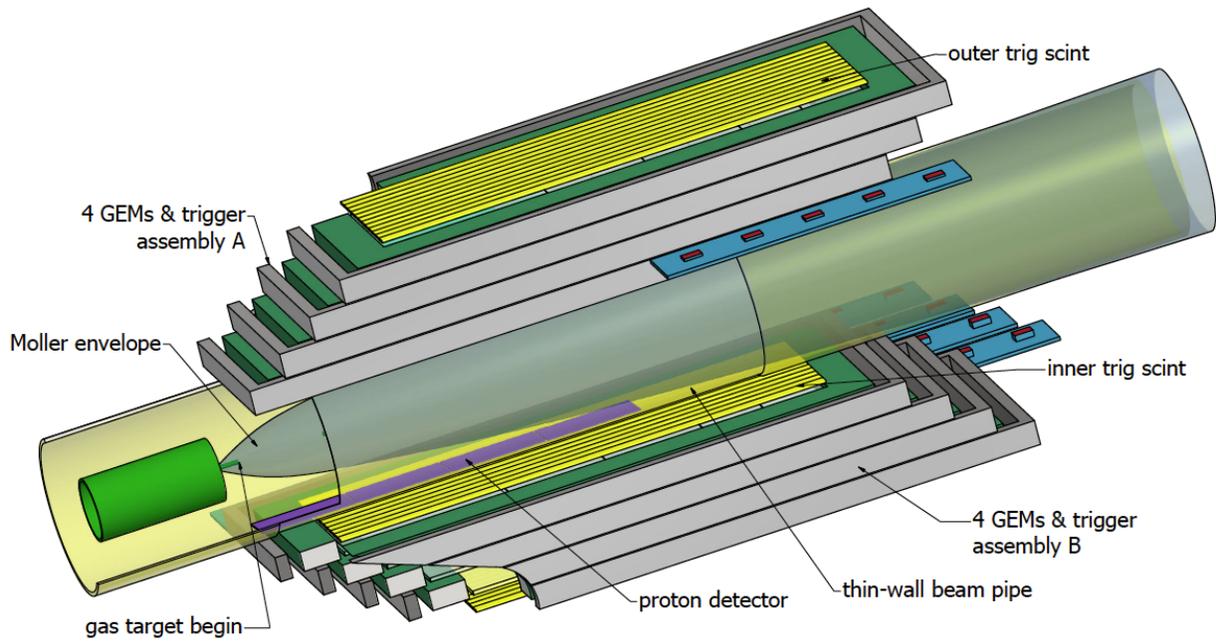


Figure 3: Key components of DarkLight phase-1c setup, the length is about 60cm.

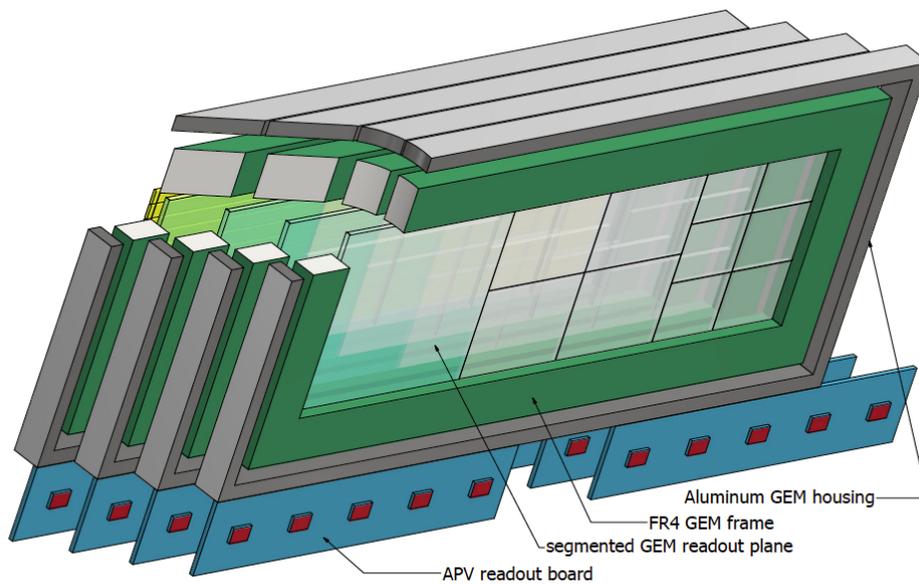


Figure 4: Lepton tracker assembly consisting of 4 GEM layers, each layer is subdivided into patches, each patch has an orthogonal strip readout.

Fig. 4 provides a more detailed view of one of the 4-GEMs tracker assembly. The active GEM area of  $12 \times 40 \text{ cm}^2$  will be subdivided into patches whose dimensions shrink at forward scattering angles. The GEM readout will consist of two layers of orthogonal strips within a patch, implemented in the strip-and-pad technology. 10 APV chips placed on 2 boards will be used to readout most of the GEM signal. The APVs will be triggered by a 4-fold coincidence provided by 4 thin-layered, segmented, fast scintillator planes. We intend to trigger APVs at 1 kHz rate and optimize the setup to suppress accidentals generated by multiple scattering of the e+p elastic and/or Møller events. Additionally, we will route about 80 channels signals from one small GEM patch into a prototype streaming readout recording data at 40 MHz. The streaming electronics is under development by the MIT group.

The DarkLight phase-1c apparatus will be contained in the 0.5 T magnetic field provided by the room temperature magnet, as shown in Fig. 5. The curvature of lepton tracks will allow us to measure lepton energy. The Møller events will be confined within the beam-pipe while inside the magnet. The carbon-iron Møller dump placed about 50 cm downstream of the magnet will absorb most of Møller electrons and reduce the amount of the back scattered background seen by GEMs and proton detector inside the magnet.

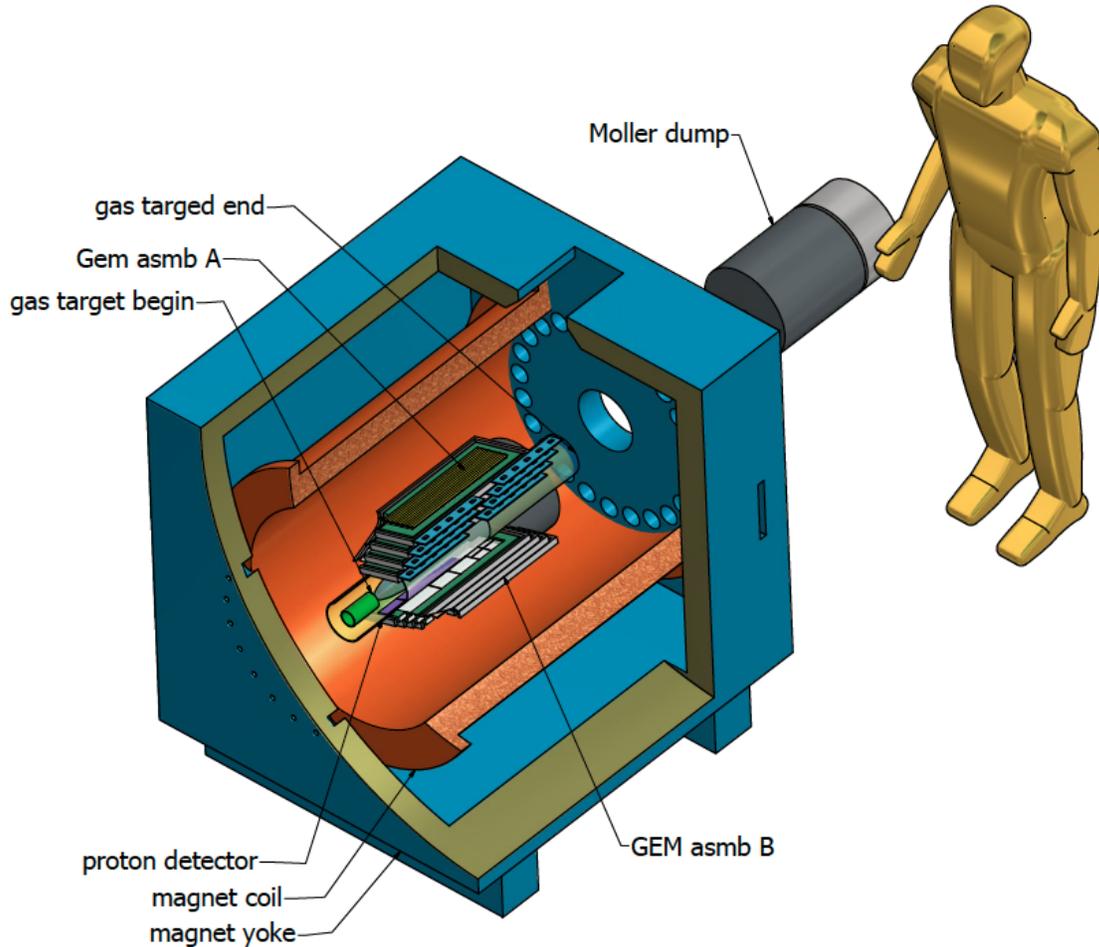


Figure 5: Side cross section of the DarkLight phase-1c experiment.

## 5 DarkLight phase-1c running

DarkLight phase-1c aims at a measurement of reconstructable  $e^+e^-$  pairs from the Standard Model QED processes in the most optimal kinematics relevant to the search for the  $A'$ . We want to validate the DarkLight detector concept and provide initial data for the reconstruction software. All DarkLight phase-1c production data would be taken with regular triggered DAQ. We are working on development of a streaming DAQ prototype that would sample concurrently a modest subset of detector channels.

## 5.1 Prerequisites

Before entering the phase-1c of DarkLight experiment we expect the following tasks to be already accomplished in phases 1a, 1b or during winter/spring of 2016:

1. DarkLight magnet can be energized stably to the full 0.5T field
2. the gas target is operational inside the energized DarkLight magnet and the LERF vacuum remains within specs
3. stable LERF beam up to 5 mA intensity passes through the gas target and the energized DarkLight magnet
4. DarkLight the data acquisition system (DAQ) is stable in the presence of the LERF beam
5. 2 sets of 4-planes GEM detectors have been constructed and commissioned with cosmic rays. The GEMs working point assures the designed resolution and efficiency. GEMs do not trip if placed in the flux of Møllers exiting the DarkLight magnet at the nominal LERF current and the nominal DL target density
6. DarkLight DAQ can read 8 GEM planes at a kHz rate with acceptably low deadtime
7. the trigger detector consisting of 4 sets of segmented scintillators have been commissioned with cosmic rays
8. the trigger detector logic is functional and compatible with the DarkLight DAQ

Additionally, we hope the following non-critical items for the phase-1c running period are also operational:

1. a proton detector that can be readout by the “regular” DAQ
2. a photon detector module can be readout by the “regular” DAQ
3. a prototype of streaming DAQ (sDAQ) that can read out a few hundred channels
4. a small patch in each of the 8 GEM planes is connected to the sDAQ
5. local storage for DarkLight raw data within the JLAB computing infrastructure, including a data path from the DAQ to the storage
6. slow control records detector run-time parameters in some database

## 6 Proposed running scenario

### 6.1 Beamtime request for 1a and 1b in 2016

Having carefully considered the available resources and engineering manpower, we propose that phases 1a and 1b take data in summer 2016 and phase 1c take data in summer 2017. Thus, in this beamtime request we focus only on the requirements for 1a and 1b. We request 40 days of beam time over about 8 weeks as outlined in Table 1. We assume two shifts per day in the request. The requested running time does not have to be continuous and could be carried out in distinct segments. The order of the Møller experiment running and solenoidal magnet running could be reversed depending upon the availability of the solenoidal magnet.

We propose that the initial commissioning and tune-up be carried out with a  $\approx 1 \mu\text{m}$  carbon foil target at low currents  $\approx 0.1 \text{ mA}$ . Targets of different thicknesses should be installed on a movable actuator to allow the determination of the maximum target thickness that is still compatible with energy recovery. Then, the Møller experiment of 1b would be installed and carried out. We estimate that we need 10 days for installation of the Møller experiment. We estimate that we will need 23 days of data taking to carry out 1b.

When 1b is completed, we would install the existing 0.5 Tesla solenoidal magnet and prototype detectors (scintillators, GEMS, *etc.*). Then the interaction of the ERL beam with the extended gas target would be studied. Charged particle rates would be measured and tracking would be carried out with the detectors.

Table 1: Proposed sequence of setup and running of the DarkLight experiment in 2016.

Task	Running time (Days)	Target	Current (mA)	Goals
1	10		No beam	Install Møller experiment
2	2	C foil	0.1	Tune up beam
3	2	C foil	0.1	Determine limits of ERL operation
4	3	C foil	0.01-0.1	Calibrations
5	23	C foil	0.01-0.1	Carry out Møller experiment
6	7		No beam	Remove Møller experiment and install solenoid and gas target
7	10	Gas target	5	Determine limits of ERL operation and measure background rates

### 6.2 Expected beam time request for DarkLight phase-1c in 2017

The following sequence of tasks would be executed in the order as specified:

1. Bring DarkLight magnet, target, and LERF into stable operation
2. Commission scintillator-based trigger with LERF beam
3. Commission GEMs

4. Take triggered QED  $e^+e^-$  production data with GEMs
5. Commission proton detector, vary LERF intensity
6. Take triggered QED  $e^+e^-p$  production data with GEMs & proton detector, vary luminosity per shift: 8 shifts
7. Commission photon detector
8. Take two types triggered QED production data :  $e^+e^-p$  and  $e^-p\gamma$  (each with 1/2 of DAQ bandwidth) with GEMs & proton detector & photon detector at highest luminosity

Assuming 2 shifts/day, we estimate we will need 10 days for commissioning of detectors and DAQ, and 21 days for data taking.

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