ERLS FOR PRECISION MEASUREMENTS ON EXTERNAL TARGETS

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Abstract

Recently, several energy recovering linear accelerators (ERLs) facilities have become active, and more facilities are planned. While the purpose for most of them is research in the field of accelerator physics, their unique capabilities open the pathway to a series of interesting measurements in nuclear and particle physics. This paper discusses how ERLs affect the design of such measurements, with a focus on fixed-target experiments. In particular, the advantages for searches of rare processes and precision form factor experiments will be discussed.

INTRODUCTION

Scientific progress from scattering experiments goes hand-in-hand with the increase in capabilities of available accelerator technologies. However, different technologies and experiment concepts are governed by different trade-offs. Energy recovering linear accelerators (ERLs) are the key to new experiments not feasible with classical accelerators.

LANDSCAPE FOR FIXED-TARGET EXPERIMENTS

Fixed target experiments can be divided into two groups, depending on whether the beam-target interaction happens inside the accelerator (internal target), or after the beam has been extracted from the accelerator (external target).

External target experiments, for example those at Mainz Microtron (MAMI) or Jefferson Lab., are typically limited by the maximum beam current: since the energy of the beam is lost even for those electrons that do not participate in a scattering process, the radio-frequency system has to constantly supply the full beam power plus all other losses. However, the beam quality is typically excellent, as there are no previous target-beam interactions.

External target experiments typically achieve the highest instantaneous luminosities, since the target can be made arbitrarily big, to the limit that the full beam is stopped in the target itself. This is the reason that those experiments which require the highest statistical precision often are designed in this mode, motivating the external-beam mode of the future MESA ERL for the P2 experiment [1]. However, the requirement of a thick target to achieve large luminosities is problematic for systematics (e.g., because of energy loss), and might preclude certain experiments, as some scattering products might not escape the target. An example for this is the original DarkLight design discussed in the next section. Further, this requirement rules out many measurements where the target material cannot be provided in large quantities, for example radionuclides.

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For internal targets, the classic design employs a storage ring. Here currents can be very large, in the hundreds of mA. In a storage ring, some of the stored beam current is lost over time. This is replenished either in cycles, where the stored beam is dumped and refilled, or semi-constantly in the so-called top-up mode, where new charge is added to the stored beam. In both modes, the maximum current that can be restored is limited. In turn, this, and beam blow-up from the beam-target interaction, severely limits the maximum target density. In practice, only low-pressure gas targets are feasible, and the maximum instantaneous luminosity achievable is several orders of magnitude smaller than for external target experiments. Further, the beam quality is compromised, as the phase-space of the stored beam is constantly disturbed by the beam-target interaction.

Experimental conditions at ERLs are somewhere in the middle of these extremes, combining some of the advantages of both. Beam quality is typically excellent, at currents >1 mA. At the same time, the target must be thin, however can be thicker than at a storage ring; the beam quality after passing the target must only be good enough to return the beam to the acceleration structure to recover its energy, a much easier task than keeping the beam stored in a storage ring. This leads to luminosities that can rival those chosen for many external beam experiments, while not quite reaching the highest luminosities achievable there.

This unique combination of thin targets with excellent beam quality and relatively high luminosity are prerequisite for certain measurements, or allow substantial improvements in systematics for others. In the following, I will discuss DarkLight as an example for the former, and precision form factor measurements as an example for the latter.

DARKLIGHT

The DarkLight collaboration aims to detect a force carrier in the dark sector. The existence of such a force carrier was originally proposed as a dark-sector equivalent of the standard model photon, however with mass [2, 3].

The LERF Era

The original DarkLight experiment design [4, 5] aimed to search for dark photons in the mass range up to 100 MeV, in both visible and invisible decay modes, using an electron beam on a proton target. To do so, the experiment would measure the full visible final state, i.e., an electron and proton from the scattering process, and in the case of a visible decay, another electron-positron pair. The beam energy was chosen to be below pion threshold, reducing background and possible decay channels. The dark photon would then be detected as a peak in the invariant mass spectrum of the electron-positron pair (visible decay only), and/or as a

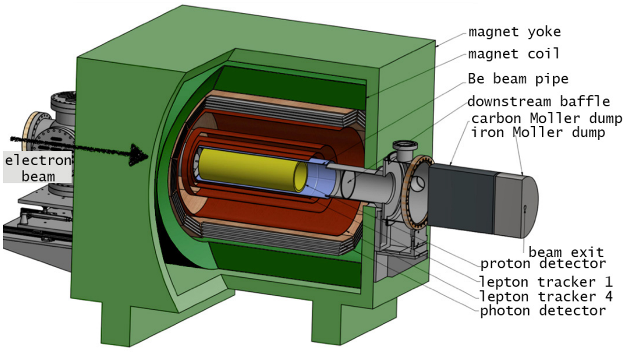

Figure 1: Experimental setup for the original DarkLight experiment. The detector is mounted inside the bore of a solenoid (green). The target region is defined by two baffles with small apertures for the beam. A proton tracker (yellow) inside the beam pipe detects the recoiling proton. Leptons exit the beam pipe made from beryllium (blue) and are detected in four layers of GEM trackers (red). A photon detector as the outer layer is used to suppress radiative backgrounds. Møller electrons are caught in the two-part Møller dump.

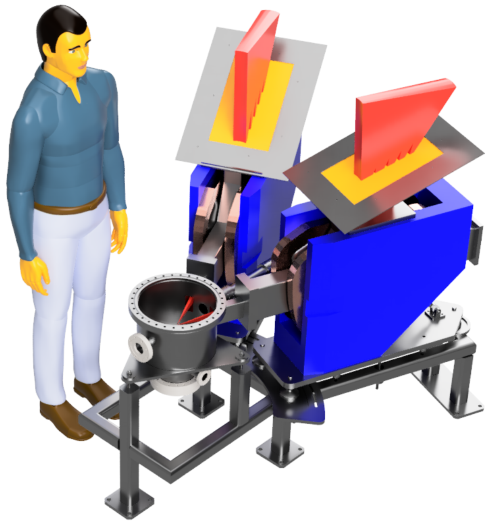

Figure 2: Conceptual design of the experiment (trigger detectors + shielding not shown). The beam is incident on a 1 μm thick tantalum foil. The red volumes represent the envelope of accepted particle tracks. Yellow is the active area of the GEMs.

peak in the missing mass spectrum reconstructed form the measured scattered electron and recoiling proton kinematics (both decay modes).

In e^--proton scattering, the dark photon would be dominantly produced similarly to initial state radiation, where the dark photon replaces the produced real photon. The cross section for this is maximal if the dark photon carries away most of the energy of the incoming beam, as this maximizes the flux for the photon exchanged between electron and proton. Vice versa, this also minimizes the proton recoil energy, making the proton hard to detect. Indeed, this precludes high-density hydrogen targets like CH_2 foils or liquid hydrogen targets, as the proton would not be able to escape the target at all, or would have significant energy loss and multiple scattering, affecting the resolution.

A thin, gaseous target is therefore required. At the same time, the rarity of the dark photon process requires high instantaneous luminosity to limit the measurement duration to manageable length. The original DarkLight design was therefore designed to run at Jefferson Lab's ERL, later named Low Energy Recirculator Facility (LERF), making use of up to 10 mA of beam current on a internal hydrogen gas target of roughly 60 cm length and few Torr pressure [6]. The experiment design is shown in Fig. 1.

It was planned to collect one inverse petabarn of luminosity. An initial test was performed in 2012 [7], which demonstrated the capability to send the beam through a 127 mm long collimator with a 2 mm opening for long periods with minimal beam loss and radiative load. This proved the feasibility of the planned experiment design. This was followed by a second test with the real target system [6] and using the solenoid. Unfortunately, the LERF was decommissioned before the full experiment could be executed.

DarkLight@ARIEL

Motivated by recent results that showed an anomaly in the decay of ${}^{8}Be$ [8], the so-called ATOMKI anomaly, which could be explained by a new, proto-phobic dark-sector force with a carrier mass around 17 MeV [9], the DarkLight collaboration pivoted to a new experiment design. Further evidence for such a carrier has been found by the same group now also for ${}^{4}He$ and ${}^{12}C$ [10–12]. Such a particle could also explain non-linearities observed in King plots of [13].

The new design will make use of the electron linac at TRIUMF's ARIEL facility and will focus on visible decays, measuring the decay electron/positron pair with two high-resolution spectrometers [14]. A conceptual drawing of the experiment is shown in Fig. 2.

The upgrade of the machine to ERL mode is a possible venue to achieve the required beam energy of 50 MeV, and will also allow a concurrent beam delivery to ARIEL and operation of the DarkLight setup, for the dark matter search or for further experiments.

PROTON FORM FACTORS

Proton form factors encode the distribution of charge and magnetization inside the proton. Precise knowledge of the form factors is therefore a keystone for our understanding of the proton and an important test for theoretical descriptions of non-perturbative QCD.

The proton form factors have been measured over many decades in better and better experiments, spanning multiple orders of magnitude in the negative four-momentum-transfer-squared (Q^2), the key scale of the reaction.

Most of the modern experiments are systematics limited. For many, a large or even dominant contribution are effects related to the target. For example, the Mainz measurement [15, 16], the by-far largest data set to date, uses a cryogenic liquid hydrogen target. This affects the measurement in three ways: First, the beam will pass the cell walls made from HAVAR alloy. This produces background, a problem especially at small Q^2, where the elastic scattering off the wall and off the hydrogen are kinematically very similar. Second, the beam will experience significant energy loss, complicating the background subtraction and widening the elastic peak reconstructed by the spectrometers. Third, the substantial target length (up to 5 cm) makes it harder to control acceptance changes when spectrometers are rotated to different scattering angles.

All of these sources can be eliminated by using a jet target. In such a target, a hypersonic jet of hydrogen is produced by a de Laval nozzle inside the target vacuum. The jet intersects the electron beam and is then recovered by a catcher, a pipe structure with special geometry than minimizes gas flow back into the target vacuum. This brings several advantages: First, the beam ideally intersects only the hydrogen beam, eliminating background. Second, the beam loses almost no energy in the target, drastically reducing peak width. Third, the interaction region is essentially point-like, reducing the effect of detector movement, and allowing for additional cuts to eliminate background.

The MAGIX collaboration at the MESA accelerator has selected such a target as the main target system for the MAGIX experimental setup and constructed a target for tests using the A1 setup at MAMI [17]. The first measurement with such a target has been performed and analyzed [18]. Results are promising and indicate the possible excellent performance at MESA. Beyond the test measurement, the usefulness for MAMI is limited—it is considerably thinner than the liquid target normally used there, and with limited beam current from MAMI, much of the kinematic phase space is not reachable in reasonable measurement time. The substantially higher current capability of MESA as an ERL are required to make optimal use of the target.

Such a target can be used with various gases. The following subsections discusses the possible impact of measurements at ERLs with focus on proton measurements.

Proton radius puzzle

The proton electric and magnetic radii are defined via the slope of the form factors at $Q^2 = 0$,

$$< r^2_{E/M} >= -6h \left. \frac{G_{E/M}(Q^2)}{G_{E/M}(0)} \right|_{Q^2=0} ,$$

and can be determined by extrapolation of fits of $G_{E/M}$ from electron scattering data. The charge radius is also accessible via spectroscopy by measurement of the Lamb shift. In 2010, with the publication of the Mainz scattering data [15] and measurements of the proton radius from muonic hydrogen spectroscopy [19], the proton radius puzzle was born: While the Mainz data is in agreement with earlier measurements from scattering and electronic hydrogen spectroscopy, the

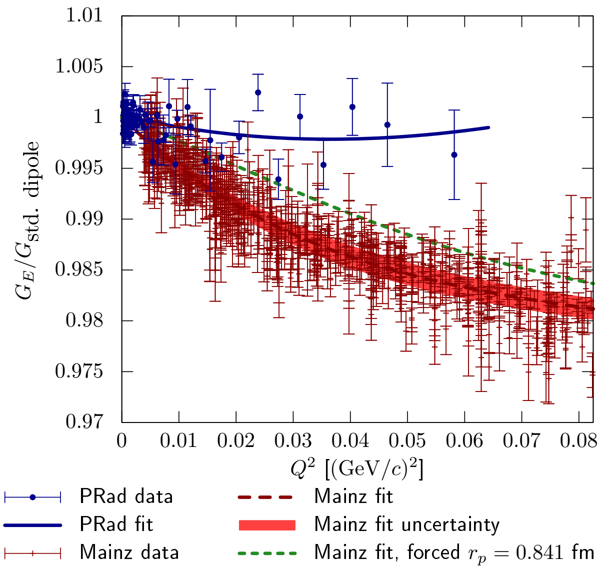

Figure 3: Comparison of PRad and Mainz results on the proton electric form factor. The form factor is expressed as a ratio to the standard dipole to compress the y-axis range and make the difference more visible.

muonic hydrogen value was about 4% smaller, with much smaller uncertainties. Depending on the averaging chosen, the discrepancy between electronic measurements and the muonic value was between 5.6 and 7σ. This discrepancy has motivated a large amount of work both on theory and experiment, and the puzzle is still not fully solved.

Form factor puzzle

Of particular interest for the discussion at hand is the result of PRad [20], a scattering experiment which produces a value smaller than, but in agreement with, the small muonic value. However the results are in strong disagreement with the Mainz data and fits to earlier data, as seen in Fig. 3. The observed differences would indicate errors of a few percent on the cross section level, much beyond the assumed systematic and statistical uncertainties.

To resolve the puzzle, it is important to understand the true shape of the form factors at these rather small Q^2. Next generation experiments at ERLs using a jet target will be an important next step in achieving better precision.

Magnetic form factor

Small Q^2 required for extraction of the charge radius can be achieved in two ways: Either by having a moderate-to-low beam energy and measuring at smallish but substantial angles (the classical method also employed by Mainz), or by measuring at angles very close to the beam, but significantly higher beam energies, like PRad.

However, the magnetic form factor cannot be measured like this. Because G_M is weighted with Q^2 in the cross section, at small Q^2, G_E dominates. To be sensitive to G_M,

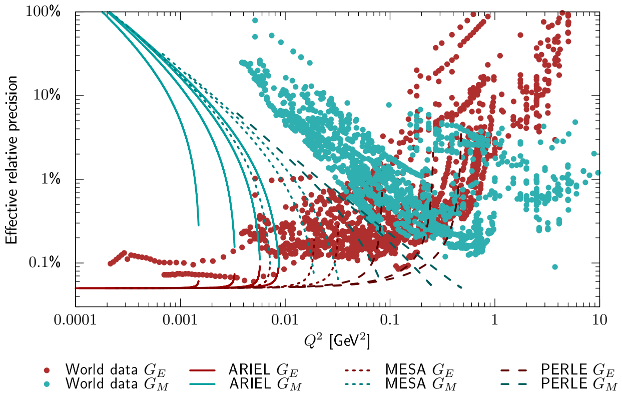

Figure 4: Effective precision of the extraction of form factors from cross section measurements, assuming perfect knowledge of the other form factor. Data points correspond to the kinematics and statistical precision of exisiting data from the compilation in [16] + the data from [20]. Red: G_E, Teal: G_M. Lines correspond to possible measurements at the energies possible at ARIEL, MESA and PERLE.

one has to measure scattering at angles close to 180°, requiring very low beam momenta to measure at Q^2 relevant for the radius extraction. Indeed, as Fig. 4 shows, the sensitivity of existing data on G_M in the relevant region below 0.1 (GeV/c)^2 is very poor, making all extractions extremely sensitive to the choice of the fit function.

Figure 4 also indicates possible sensitivities of future experiments at ERLs, for different beam energies. Assumed here are beam, detector, and target parameters similar to those of MAGIX. Most measurements along these trajectories would take a few hours at most. Only the combination of ERL current with the point-like nature of jet targets make these kind of measurements possible at a relevant statistical and systematical uncertainty level.

CONCLUSION

ERLs will open up interesting experimental design opportunities for Nuclear Physics and Particle Physics experiments, enabling completely new measurements or allowing to drastically improve existing ones. The advent of ERLs will likely rejuvenate the field for high-precision measurements at the intensity and precision frontier, far away from the energy frontier. However, for a full program, several ERL facilities with complementary energy ranges are required.

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