Expression of Interest for participating in the H2020 Innovation Pilot on detector technologies at accelerators

Title: Development of ultra-fast, high performance calorimeters for next-generation experiments

Participants:

Name of the legal entity	Type (university, institute, laboratory, company)	Country
INFN Laboratori Nazionali di Frascati	Institute	Italy
INFN Sezione di Roma	Institute	Italy
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Description:

We propose to develop an ultra-fast, highly-compact electromagnetic calorimeter with excellent rate and radiation resistance for use in forward particle detection at next-generation colliders. We envision specific applications to two intensity-frontier experiments, KLEVER, proposed to measure the ultra-rare decay $K_L \rightarrow \pi^0\nu\nu$ at the CERN SPS, and PADME, an accelerator dark matter search at the Frascati Beam-Test Facility (BTF), but the instrument will have applications at new facilities such as the ILC, FCC-ee,, and muon collider.

The goal of the KLEVER project at the CERN SPS is to measure BR($K_L \rightarrow \pi^0\nu\nu$) with a precision of 20%. Since the Standard Model BR for this decay is just 3×10^{-11} and is known to an accuracy of just a few percent, its measurement is a powerful probe for new physics at mass scales higher than can be reached in collider experiments. The success of the measurement depends entirely on the hermeticity of the photon veto system in the forward region. A small-angle calorimeter (SAC) is needed to intercept photons from K_L decays that would otherwise leave the experiment through the beam pipe. The SAC sits right in the neutral beam and must support operation at > 100 MHz. To avoid being blinded by accidental coincidence, it must have time resolution < 100 ps and double-pulse resolution ~ 1 ns.

The PADME experiment is searching for dark photons created in the annihilation of a positron beam on atomic electrons in a thin target. The effect of a non-interacting dark photon can be observed in the spectrum of reconstructed missing mass, while the invariant mass can be reconstructed for dark photons that decay to e^+e^-. Like KLEVER, PADME makes use of a highly-segmented, small-angle forward calorimeter (SAC) to detect photons emitted along the beam axis. The successful PADME design uses lead fluoride crystals, for which the Cerenkov light is read out by compact PMTs. With full digitization of the signals at 2.5 GHz by a CAEN V1742 waveform digitizer, timing performance is obtained similar to that required for the KLEVER SAC, as described above.

PADME is currently taking data with the 550 MeV e^+ beam at the Frascati BTF. This beam has a maximum intensity of 2×10^{-4} e^+ per 10 ns pulse and a repetition rate of 50 Hz, defining a very small duty fraction that effectively limits PADME sensitivity to $O(10^{-4})$ in the kinetic mixing parameter that describes the coupling of the low-mass dark photon. Running with a continuous beam and/or at higher energy facilities would greatly extend the explorable space in the mass vs. coupling plane. In this case, however, the rate- and radiation-resistance characteristics of the SAC would have to be improved, as would also be the case for use in KLEVER:

1. The transmission of Cerenkov light through lead fluoride after cumulative doses of up to 10^6 Gy or neutron fluxes of up to $10^{14}/\text{cm}^2$ requires measurement. It may be possible, through requirements on purity or trace element composition, to improve the radiation resistance. Suitable annealing processes may need to be developed. If the radiation hardness is insufficient and cannot be improved, an alternative Cerenkov radiator may need to be identified.
2. PADME has observed evidence of afterglow from fluorescence in lead fluoride. If this fluorescence cannot be eliminated through careful formulation, it may be possible to separate it from the Cerenkov light by a wavelength-selective filter.
3. Relative to current SiPMs, PMTs are more radiation resistant and can provide better time resolution. However, even PMTs might require periodic replacement in an in-beam detector. In this case, use of SiPMs may be economically advantageous. This would require advances in SiPM radiation resistance and timing performance. Such advances are of significant interest to other experiments making use of Cerenkov detectors: in NA62, optimized SiPMs could represent a high-quantum-efficiency alternative to PMTs for the RICH and KTAG, and in Belle II/III, they could replace the HPDs and MCPs in the ARICH and TOP (see separate EoI).
4. The coherent interaction for high-energy photons incident on a crystal lattice of high-Z material is known to enhance the pair-production cross section. This effect has been well demonstrated in crystal metals, and in the case of the NA48 AKS detector, has even been exploited to obtain a thin photon converter with enhanced conversion efficiency. Because of the relative ease in producing high-Z optical crystals of high quality, there are good prospects for the construction of compact scintillation or Cerenkov detectors with small radiation length, but this effect has never been exploited. This would be highly advantageous for KLEVER, where the SAC must detect a few MHz of high-energy photons from K_L decays while operating inside a 500-MHz neutral hadron beam, to which it must be as insensitive as possible. The principle could also facilitate optimization of the PADME SAC for future running with 6-10 GeV beam energy at JLAB or Cornell.

The development of a flexible, fully-digitizing readout system with on-board zero-suppression and data filtering for use with such a detector is the subject of a separate EoI.

We will dedicate substantial effort to in-beam measurements of the performance of a prototype detector. As part of AIDA2020, the Frascati BTF has recently been upgraded with the installation of the new BTF-2 beamline (Task 15.4) and an upgrade to the photon tagging system (Deliverable 15.5). Our project is an ideal test case for further development of the BTF-2 photon tagging system, with an emphasis on using it to make measurements of very small (10^{-3} to 10^{-4}) detection inefficiencies. We also intend to develop sensitive photon tagging techniques for use at higher energy, e.g. at DESY, or in the CERN North Area during LHC run 3. It may also be possible to test the prototype in situ in the NA62 experiment during Run 3.

Deliverables:

1. Validation of detector components. In collaboration with industry, identification of a SiPM with excellent timing performance and good radiation resistance. Irradiation tests of SiPMs and PbF_2 crystals, including possibly tests with 14 MeV neutrons at the Frascati Neutron Generator (ENEA).
2. Beam tests of a prototype detector with single electrons and tagged photons at the Frascati BTF to measure energy and time resolution and detection efficiency, including with tagged photons.
3. Demonstration of the feasibility of constructing a Cerenkov detector with oriented crystals to profit from the enhanced conversion efficiency from coherent interactions. Test beam program at DESY and/or the CERN North Area from 2021 onwards to measure enhancement in bremsstrahlung and pair-production in Cerenkov crystals and determine crystal axes. Construction and test of a small prototype with an oriented crystal.

Budget estimate

Total number of PMs	EC contribution (in kEUR) (a)	Matching funds (in kEUR) (b)	Full costs (in kEUR) (a) + (b)
50	175	350	525

The EC contribution includes €75k for 36 months of new post-doctoral contracts and €100k for consumables and development costs.