

SHiP-LNF: 2020 Status Report

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1 Status of the SHiP project and its evolution into the SHADOWS proposal

Groups involved: INFN-Bologna, INFN-LNF, INR, MEPHY; LAL-Orsay (France) for Electronics.
Project Leaders: G. Lanfranchi (LNF-INFN) and Y. Kudenko (INR, Russia)

The SHiP Project has been not recommended by the recent European Strategy for Particle Physics (ESPP). The R&D of the Beam Dump Facility (BDF) will continue under the umbrella of the Physics Beyond Collider study group at CERN with a budget of about 1 MCHF/year for the next five years, while waiting for a final decision about the overall project by the next update of the ESPP. In the meantime the SHiP-LNF group is actively proposing another proton beam dump experiment, SHADOWS (*SHADOWS = Search for Hidden And Dark Objects With the SPS*). SHADOWS aims at searching for feebly-interacting particles at the existing P42 proton beam line in the CERN North Area. The proposal has been recently proposed (and accepted) as part of the Physics Beyond Collider activity¹ and an Expression of Interest is in preparation.

The LNF group since the beginning of the SHiP project has been involved in the design and R&D of the SHiP Muon System. The Muon System is described in Section 4.11 of the SHiP Technical Proposal¹⁾ and comprises four stations of active layers interleaved by three muon filters 6 m wide and 12 m high. The baseline technology is *scintillating tiles with direct SiPM readout*, as described in details in the 2018 and 2019 SHiP-LNF activity reports. In this document only the incremental work with respect to 2019 has been included. This technology has been proposed also for the Muon System of the SHADOWS experiment. Moreover, the R&D of the tiles has been included in the recent AIDA-Innova grant because considered of general interest also for experiments at future e^+e^- colliders (G. Lanfranchi is the PI of this R&D for AIDA-Innova at LNF).

The 2020 activity of SHiP-LNF has been focused on the R&D prototypes for the muon detector, following closely the plan outlined in 2019. The R&D comprised also a test beam performed at the Beam Test Facility (BTF) in Frascati that has been held between the 15th and the 22nd of January 2021.

2 The prototypes

Four tile prototypes have been built and characterised at test facilities in Frascati and Bologna INFN laboratories and their performance assessed first of all at a cosmic ray stand at LNF and then with a test beam at the Beam Test Facility (BTF) in January 2021. The tiles dimensions are $(150 \times 150 \times 10)$ mm³. Two (out of four) tiles are made of EJ200 cast organic scintillator from Eljen company² and the other two by organic scintillator from UNIPLAST (Vladimir, Russia).

¹See talk by G. Lanfranchi at Physics Beyond Collider Annual Workshop, <https://indico.cern.ch/event/1002356/>, March 4th, 2021.

²<https://eljentechnology.com>

Only one of the four tiles, from UNIPLAST, has undergone a process of *etching*, while the other three are painted with white reflecting paint. All the tiles are wrapped with Teflon tape.

The tiles are read out by four SiPMs Hamamatsu S13360-6050PE with $6 \times 6 \text{ mm}^2$ active area. The SiPMs with similar V_{bias} have been grouped on each tile. The SiPMs are mounted on short Kapton flex cables (invented and designed at LNF) and are placed in grooves or glued at the corners of the tile. An example of prototype with the four SiPMs connected to flex cables and placed in grooves at the tile corners is shown in Figure 1.

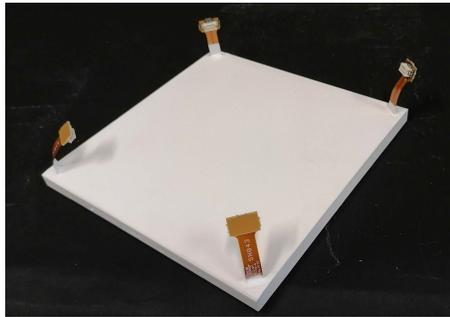


Figure 1: Tile prototype with white reflecting painting. The four SiPMs are attached to flex cables glued in grooves inside the scintillator at the tile corners.

The signals from SiPMs are read out by a custom FEE board equipped with fast pre-amplifiers and an analog sum designed, built, and characterized in Frascati. The flex cables bring the SiPM signals to the FEE mezzanine hosting the pre-amplifier stage on the motherboard. The four pre-amplified signals per tile are then sent to an analog sum stage hosted in the motherboard and then sent to an external digitizer for further processing.

The CAD version of the motherboard installed on a tile and its actual implementation (still without mezzanines) is shown in Figure 2. During the test beam campaign the four tiles were hosted into a light-tight box that acted also as a Faraday cage. The system of four-tiles + box, called *mini-module* is shown in Figure 3. The layout of the box is shown in Figure 4. The coverage of the box is provided by 0.5 mm thick copper foil, to minimize the probability of production of electromagnetic showers by the electrons during the test beam. The tiles are kept fixed to the frame by stainless steel wires connecting the two sides of the frame. A patch panel with four connectors allows the bias voltages for the SiPMs (one per tile) and the low-voltages for the FEE to be brought inside the box, and the output signals to be sent to an external digitizer. The design and realization of the light-tight box has been done at LNF.

3 Test beam setup

A test beam campaign has been performed at the Beam Test Facility (BTF) at Laboratori Nazionali di Frascati in January 2021. Electron and positron beams are created in the energy range of 25-500 MeV with an energy spread of 1% and a repetition rate varying between 10 and 40 Hz. The spot size can vary between (1-25) mm in y and (1-55) mm in x and the divergence between 1-2 mrad. Beam characteristics (spot size, divergence, momentum resolution), are strongly dependent by the multiplicity (number of particles/spill) and energy requested. For the test beam the chosen configuration was the maximum available energy and single particle bunches.

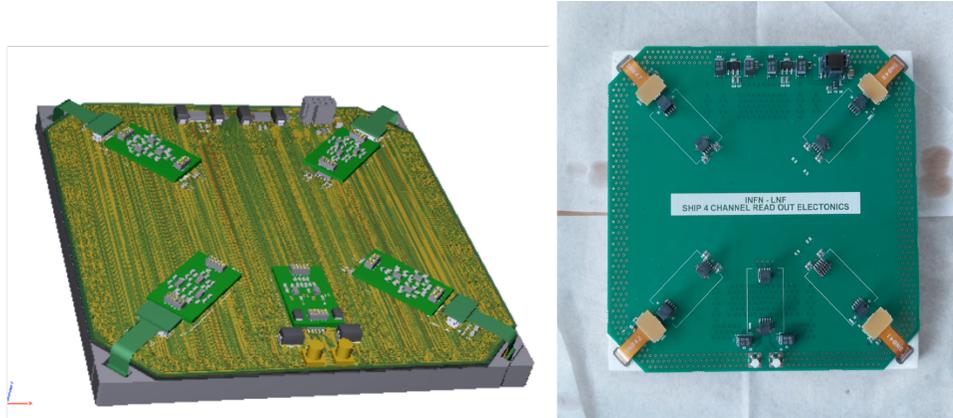


Figure 2: Left: rendering of the mother board attached to the tile. The four flex cables connecting the SiPMs to the mezzanines are visible at the corners. Right: motherboard (still without mezzanines) installed on one of the tiles.

The tiles were exposed simultaneously to the beam on a moving frame with remote control in order to study the time response and efficiency as a function of the beam impinging point. The box hosting the tiles was attached to the moving frame allowing a rigid x and y translation of the position of the tiles with respect to the beam.

The test beam setup is shown in Figure 5 (left). The trigger and time-reference was provided by a small scintillating cube of $(1 \times 1 \times 1) \text{ cm}^3$ read out by two SiPMs glued on opposite planes of the cube (see Figure 5, right). The two SiPMs signals were amplified and digitized by the same digitizer used for the tiles. The T_0 has an intrinsic time jitter of $\sigma(T_0) \sim 80 \text{ ps}$. The time reference jitter must be subtracted in quadrature to the measurement of the time resolution of the tiles.

4 Results

The analysis of the test beam data is currently ongoing. However preliminary results show that all the prototypes reach a time resolution, once subtracted the T_0 jitter, of $\sim 210 - 220 \text{ ps}$ (see Figure 6, left) independent on the released charge (Figure 6, right), and uniform over the tile area. The efficiency has been found to be better than $\varepsilon = 99.8\%$. These results confirm the choice of this technology for building large area muon detectors with high time resolution. A paper containing all the details of the results obtained at the test beam and at the cosmic rays test stand is in preparation and will be submitted to JINST.

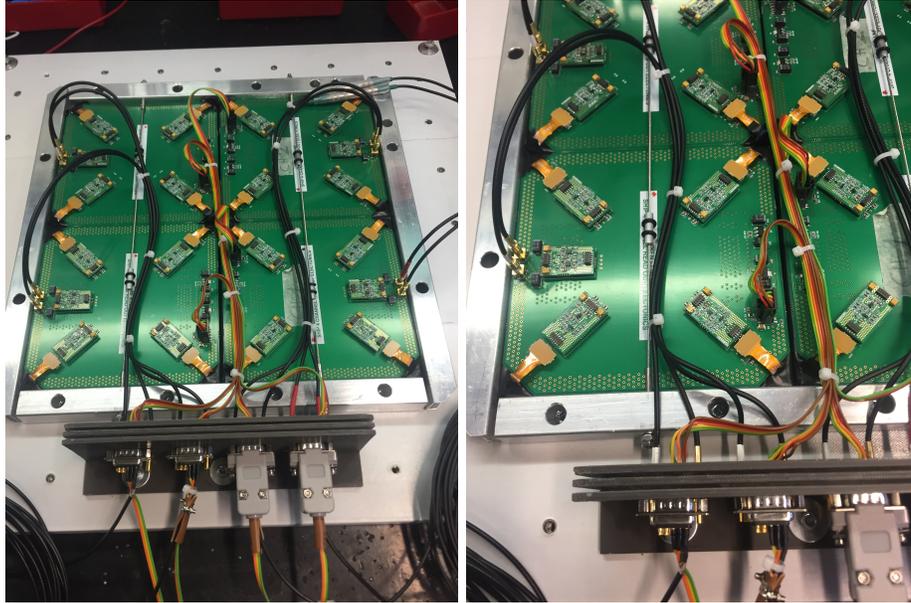


Figure 3: The minimodule: The four tiles tested at the test beam hosted in the light-tight supporting box that acts also as a Faraday cage.

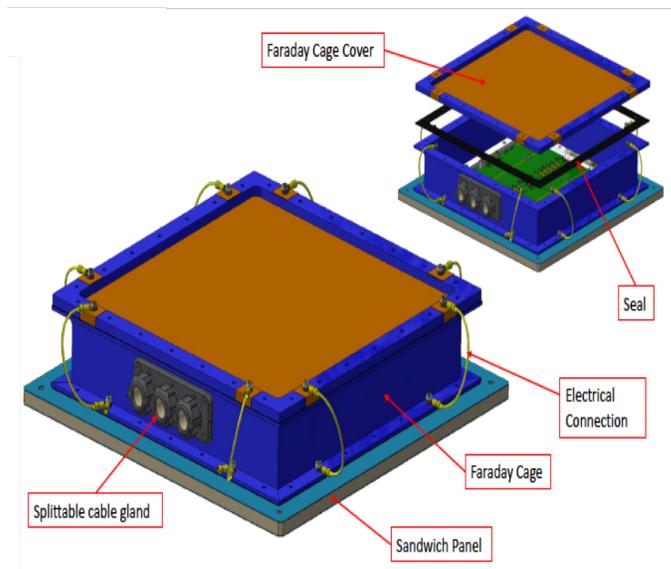


Figure 4: Layout of the light-tight supporting box hosting the four tiles tested at the test beam.

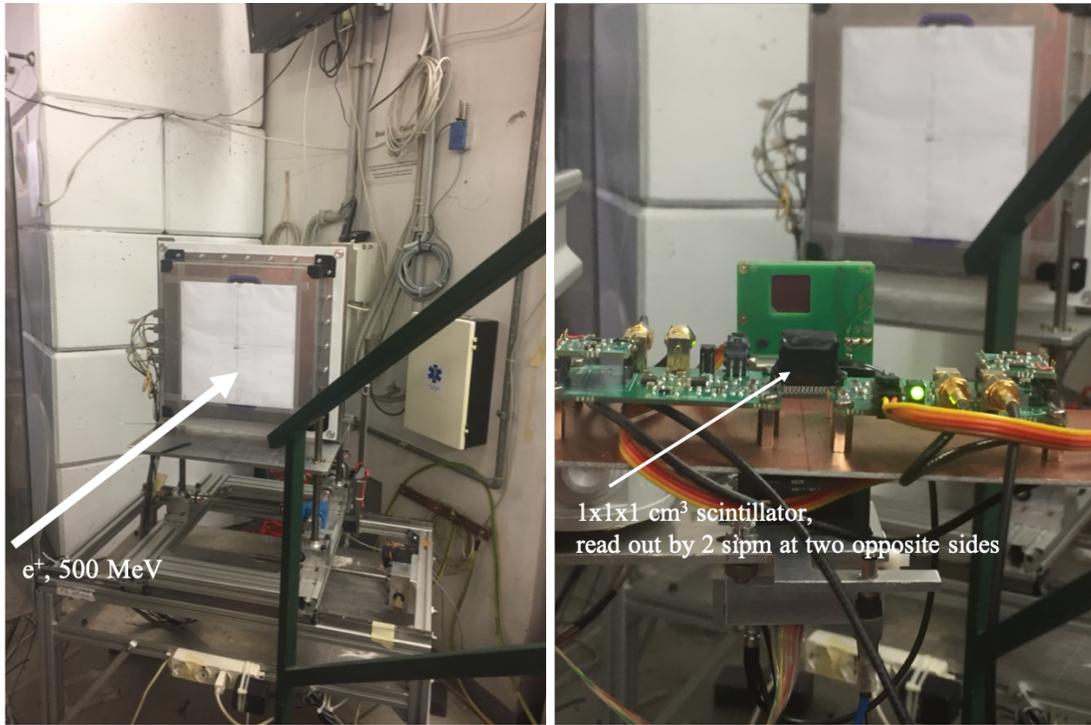


Figure 5: Left: Test beam setup with the four tiles hosted in the box and placed on the moving frame in front of the beam exit. Right: small scintillating cube of $(1 \times 1 \times 1) \text{ cm}^3$ that provided the trigger and time reference during the test beam.

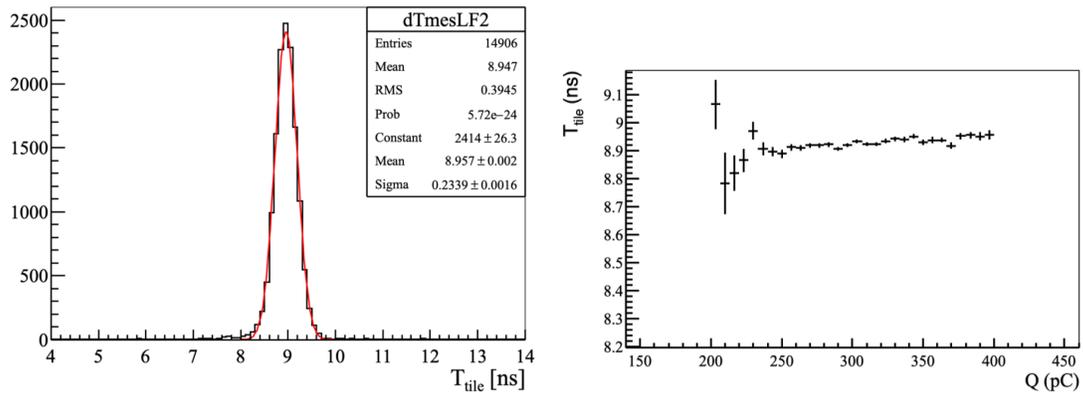


Figure 6: Left: Distribution of the arrival times of the electrons when the beam is focused at the center of the tile 1 (EJ200, SiPM in grooves). The time resolution, once subtracted the T_0 time jitter is ~ 220 ps. Right: dependence of the arrival time with the released charge.

5 SHiP-related Talks given by LNF people

- *iDMEu: Initiative for Dark Matter in Europe and beyond* , invited parallel, ICHEP 2020 conference (online), July 2020.
- *Ideas for cross-experimental collaborations to search for Dark Matter*, invited talk, DM@LHC 2020 workshop, DESY (Germany) (online), 2-5 June 2020.
- *Overview of the Physics Beyond Colliders activity and prospects; invited talk, New Opportunities at the Next Generation Neutrino Experiments 2020 Workshop*, Pittsburg (US), (online) 2-4 April 2020.
- *CERN Fixed Target Program for Dark Sector Searches and Neutrinos*, invited talk, International Conference on Neutrino and Dark Matter, Hurghada (Egypt), 10-14 January 2020.
- *Feebly Interacting Particles: experimental landscape*, invited seminar, Annual Dutch Physics meeting, Veldhoven, the Netherlands, 20-21 January, 2020.

6 SHiP-related Workshops/Conferences organized by LNF people

- *Feebly-interacting particles (FIPs) 2020*, CERN (and then online), 31st August - 4th September, <https://indico.cern.ch/event/864648/> (490 registered participants).

7 SHiP-related publications in 2020

1. SHiP collaboration, *Sensitivity of the SHiP experiment to dark photons decaying to a pair of charged particles*, arXiv:2011.05115, submitted to JHEP.
2. SHiP collaboration, *Sensitivity of the SHiP experiment to light dark matter*, arXiv:2010.11057, submitted to JHEP.
3. SHiP collaboration, *Measurement of the muon flux from 400 GeV/c protons interacting in a thick molybdenum/tungsten target*, Eur. Phys. J. C 80 (2020) 3, 284.
4. SHiP collaboration, *The magnet of the scattering and neutrino detector for the SHiP experiment at CERN*, JINST 15 (2020) 01, P01027.
5. Marco Fabbriches, Emidio Gabrielli, Gaia Lanfranchi, *The Dark Photon*, arXiv:2005.01515, Published in SpringerBriefs in Physics 2020.
6. Gaia Lanfranchi, Maxim Pospelov, Philip Schuster, *The Search for Feebly-Interacting Particles*, arXiv:2011.02157, to be published on Annual Review of Nuclear and Particle Physics.

References

1. M. Anelli *et al.* (SHiP collaboration), *Technical Proposal: A facility to Search for Hidden Particles (SHiP) at the CERN SPS*, CERN-SPSC-2015-016, SPSC-P-350, arXiv:1504.04956 [physics.ins-det].