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Wireless power transmission for HEP

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Modern high-energy physics (HEP) experiments demand increasingly complex and densely instrumented detectors, often comprising millions of readout channels operating under challenging spatial and environmental constraints. The need for low-mass, high-performance systems has motivated the exploration of wireless technologies capable of replacing or supplementing conventional cabling for both data and power transmission. Reducing the material budget associated with cables not only improves detector performance—by minimizing multiple scattering and secondary interactions—but also simplifies integration and maintenance in confined detector environments. Within this context, the WADAPT (Wireless Allowing Data and Power Transmission) consortium was established to investigate and develop innovative wireless solutions tailored to HEP applications. The collaboration brings together several research groups working on complementary aspects of wireless communication and power transfer, aiming to provide scalable, radiation-tolerant, and low-noise systems suitable for future collider detectors.
In particular, recent efforts have focused on laser-based power transmission, both with and without optical fibers, as a means to deliver stable and efficient energy to front-end electronics and silicon-based sensors. These studies demonstrate the potential to achieve reliable wireless operation with minimal electronic noise, marking a significant step toward realizing fully wireless detector modules.

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1. Introduction

Electronics are a key component in modern particle detectors, along with their powering system. While active materials generate measurable signals for experiments, any materials that can interact with particles but do not generate measurable signals in the particle trajectory (such as cables and mechanical support structures) will degrade the detector's performance. Therefore, material budget is one important measure to modern particle detectors, especially to the vertex and tracking detectors where at minimum one-nanometer precision is required. As the granularity required by future collider experiments continues to increase, new power solutions urgently need revolutionary changes to tackle the challenges.

Therefore, new link technology R&D (fibre, wireless, wireline) to cope with the increasing data density in experiments is urgent in the upcoming years, in order to meet other detector technology development in the period of 2030-2050, as stated in the ECFA roadmap [2]. Accordingly, 8 institutes (Upssala University, Radboud University & Nikhef, Scuola Superiore S. Anna di Pisa, INFN Pisa, CEA-Leti, CNRS/LPSC, Tel Aviv University and Gangneung-Wonju university) have formed the Wireless Allowing Data and Power Transmission (WADAPT) consortium, with an aim of developing wireless data and power transmission solutions for particle detectors. WADAPT is embedded in the ECFA DRD7 collaboration [3],

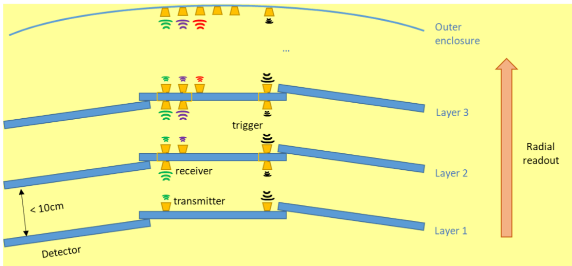


Figure 1: Wireless signal/power transmission design concept proposed by the WAPAT consortium.

The WADAPT consortium has proposed a wireless signal/power transmission design concept, see Figure 1. Such radial readout scheme with direct communication between layers aims to resolve the following issues from an conventional link system: (1) minimize material budget of cables and connectors, thus reducing unwanted impacts from multiple coulomb scatterings and nuclear interactions; (2) reduce massive services (dead-zone areas) in region between Barrel and Disks; (3) simplify detector installation and operation with new link feature such as simplified flexible transceiver placement; (4) axial readout induces important latencies. Moreover, such new scheme brings new possibilities in DAQ, such as inter-layer intelligence enabled by point-to-multi-point links, and fast triggering enabled by the data-follows-event topology.

Table 1 lists the specifications of the available wireless power transmission technologies, among which only microwaves and lasers meet the particle physics experimental conditions, i.e. high power, long distance and high frequency. Power transmission via lasers shares a strong synergy with material physics research on solar cells, which strives on improving the power conversion efficiency to be compatible with the conventional power supply system - one latest research on photovoltaic (PV) cells reached an unprecedented high conversion efficiency at 68.9% with a GaAs-

	Electromagnetic induction	Magnetic resonance	Electric coupling	Microwaves	Lasers
Power level	W-kW	W~ 10^2kW	W~kW	W~GW	W~MW
Efficiency	80-90%	80-90%	60-90%	15-30%	10-25%
Distance	mm-cm	cm-m	mm-cm	m-10^2km	m-10^3km
Frequency	85kHz	kHz-MHz	kHz-MHz	1-50GHz	10^{14}Hz

Table 1: Typical specification ranges of various available wireless power transmission technologies.

Based photonic system [4]. This paper presents the latest development within WADAPT on PV cell based power transmission solutions, with and without fiber.

2. Power over fiber

The development on power-over-fibre (PoF) is led by the Nijmegen team, aiming to demonstrate the feasibility of PoF technology in powering a particle detector. The final goal is to reach a proof-of-concept PoF based power system design to power a high precision tracker for future collider experiments. The detector example used in the demonstrator presented here is the newly developed Low Gain Avalanche Diode (LGAD) sensor for the ATLAS HGTD detector [5], thus the design goal of this PoF demonstrator is set accordingly: low voltage ripple and noise at 1A in 0-20 MHz range is below 5 mV peak-to-peak (p-p) per ASIC at 1.2 V, and the stability and noise at dynamic loads for high voltage (at an order of 100 V) to bias the LGAD sensors requires to ensure the designed pico-second timing performance. The LGAD test sample used in this study sits on a readout board for power and signal readout, will be referred as detector example in the following. This detector example requires power as below: 1) -90 V bias voltage for the senor; 2) +2.25 V at about 16 mA (about 38 mW) for the readout board (including a pre-amplifier); 3) a second-stage amplifier of 12 V at about 20 mA resulting in about 600 mW.

2.1 Preliminary demonstrator development

The PoF demonstrator setup has experienced several upgrades. The very first setup bases on the MIH PoF platform from MH GoPower, a manufacturer of 9xx nm based PoF components. This Arduino-based platform includes one power interface module (PIM) that provides laser power output up to 2.5 W to one sensor interface module (SIM) which outputs DC power up to 250 mW, which is not enough to provide the power needed for the second-stage amplifier of the detector example. The power performance of this off-shelf platform was checked in the lab, showing a 500 mV ripple with every 20 ms an 1.5 V noise peak - this sets a baseline to improve the demonstrator setup towards the need of the detector example.

The development of the preliminary PoF demonstrator presented in this paper experienced the following three phases. First, a 100 µF capacitor and a voltage regulator LTM8074 were added to the SIM 5V output, see Figure 2 (left), that reduces the ripple to 4-5 mV (see Figure 3) meeting the goal. Second, a boost converter LT8365 was added to provide a 90 V bias voltage and a 2.25 V power to the readout board. Last, an in-house power board was made hosting one MIH PV Cell YCH-L250 to replace the SIM board, see the board in Figure 2. YCH-L250 PVC is optimized most efficiently with wavelengths in the range of 915 nm to 980 nm with a fiber numerical aperture (NA)

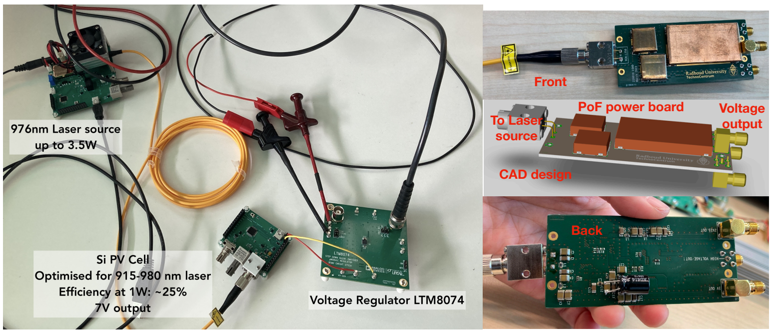


Figure 2: The PoF demonstrator: a first stage modification of the MH GoPower PoF platform with a 100 µF capacitor and a voltage regulator LTM8074 (left) and the PoF power board to host one MIH PV Cell (right).

ranging from 0.22 to 0.27. The maximum power output is 10W and its best efficiency is 25% at 1W. Ripples were measured at all the three power lines showing a p-p ripple within 10 mV. The power board includes an DC-DC converter and is encased in a heat sink fo an optimal efficiency.

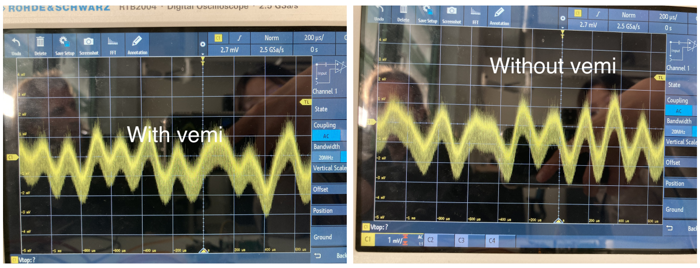


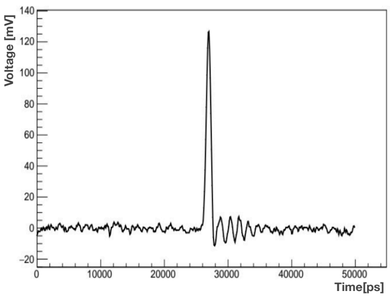
Figure 3: The measured ripple at the 5V output on the PoF demonstrator setup with the EMI filter on the LTM8074 a) on b) off, demonstrating the noise after the regulator applied is EMI-independent.

2.2 Power an LGAD

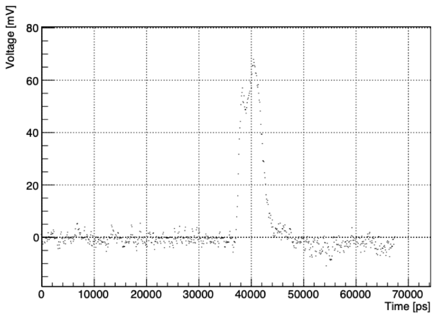
The very first functionality performance of this developed PoF demonstrator is validated by comparing the signal performance of the LGAD detector example powered by PoF and by the conventional power supply. Data was taken by an high sampling rate oscilloscope in the lab with a Sr^{90} source, in both power schemes. The signal was comparable except for the feature at the falling tail of the signal, where the PoF powered signal has a $\sim$ 10-20 mV p-p ripple sits on its falling tail, see Figure 4a. The can be a residual pattern from the laser driver on the PIM board, which is under study with a new laser driver board designed and produced in-house. Besides, the PoF results is comparable with test beam data with a conventional power supply (Figure 4b).

2.3 Next steps

An in-house laser driver board has been designed and made in 2025, in order to verify the source of the slow but high ripple pattern measured from the original MIH PoF platform, and its residual in the Pof demonstrator described here. In the meantime, material scientist specialised in PVC from Radboud joined the project and a new group III-V PVC based PoF demonstrator hosting three different PVC candidates (GaAs and InGaP) is under designed.



(a)



(b)

Figure 4: Signal response to Sr^{90} of an HGTD LGAD test setup: a) in the lab powered by the power-over-fibre setup; b) at a test beam powered by conventional power supplies.

3. Power without fiber

3.1 Setup and goals

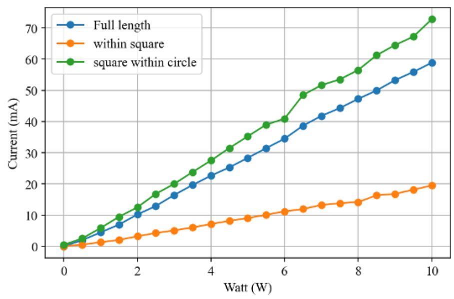
The main goal was to polarized a silicon photomultiplier with a voltage of few tens of volts. The "voltage production" setup consists of a 10 watt infra-red laser (980 nm) and a 10×10 mm^2 silicon-based photovoltaic cell (PVC). The laser is transmitted with an optic fiber so a collimator is necessary to have a laser beam with a diameter around 15 mm^2. The PVC is working as a current generator, with a DC voltage ~ 32V (after irradiation of few tens of milli-watt). A important heat sink has been installed on the PVC to dissipate the heat during the study.

3.2 Distance laser - PVC

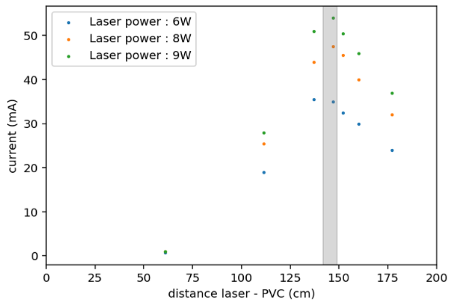
The beam size exhibits a dependence on the propagation distance as a result of the collimator-induced divergence. To investigate this effect, several beam configurations were examined, ranging from a beam fully confined within the cell volume to one exceeding the PVC dimensions. Figure 5a illustrates the measured current on the PVC as a function of the incident laser power for three representative beam size configurations. Figure 5b shows the PVC current as a function of the laser–PVC distance for three different laser power levels. The optimal configuration is achieved when the laser beam slightly overfills the PVC, with a beam radius approximately equal to the diagonal of the PVC cell. This configuration ensures uniform illumination of the target volume while maximizing the measured current, balancing the effects of beam divergence and intensity distribution across the PVC surface.

3.3 PVC efficiency and temperature dependence

Figure 6a presents, after the optimization of the distance laser-PVC, the PVC efficiency as a function of the laser power. The efficiency is around 19% for laser power above 4W.
An important parameter is the temperature of the PVC. As shown on figure 6b, the temperature (in degrees Celsius) measured on the heat sink increase with time to reach a plateau which depends on the laser power. For a 7W laser intensity, the temperature is a bit lower than 40 degrees and extrapolating the plateau curves, the temperature at 9W will be around 50 degrees, which can be a problem that must be addressed.

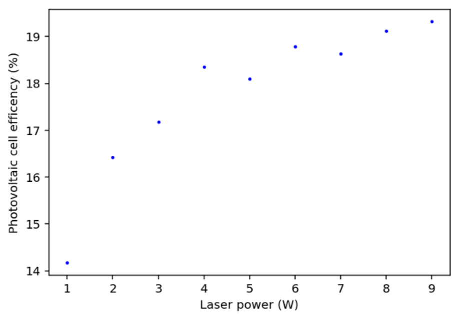


(a) Laser beam size

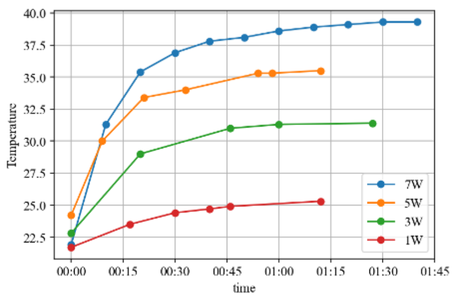


(b) Distance laser-PVC

Figure 5: a) Current measured on the PVC as a function of the laser power for three configurations: in orange, the beam is inside the PVC, in blue, the beam diameter is far larger than the PVC and in green, the beam just overfill the PVC. b) Current produced by the PVC as a distance between the laser and the PVC



(a) PVC efficency



(b) Temperature dependence

Figure 6: a) PVC efficiency as a function of the laser power. b) Temperature measured on the PVC heat sink as a function of the exposure time to laser beam.

3.4 Connection to SiPM

The PVC was connected to an electronic circuit consisting of two primary components: a voltage stabilizer, which maintains a constant output voltage, and a CAEN A7585 commercial voltage regulator, specifically designed for SiPM biasing. This regulator provides an output voltage ranging from 20V to 85V. An Onsemi MicroJ 30035 SiPM was connected to the circuit and biased at 29V, with its output signal routed to an oscilloscope. To assess the noise level, a light signal from an ultra-fast LED driver (CAEN SP5601) was injected to generate single-photon events. Figure 7 shows the resulting spectrum. The peak widths are dominated by electronic noise, which remains relatively low, indicating that the wireless power transmission does not introduce any significant additional noise. An alternative setup was implemented using two SiPMs, each coupled to a separate optical fiber, to study the system's response and verify signal uniformity. As illustrated in Figure 8a, both fibers are positioned on the same scintillator to ensure that identical scintillation light reaches each detector. Figure 8b presents a typical pulse recorded with an oscilloscope. This configuration allows comparison of the signals from both SiPMs, enabling the assessment of timing synchronization, signal amplitude consistency, and the feasibility of using multiple SiPMs

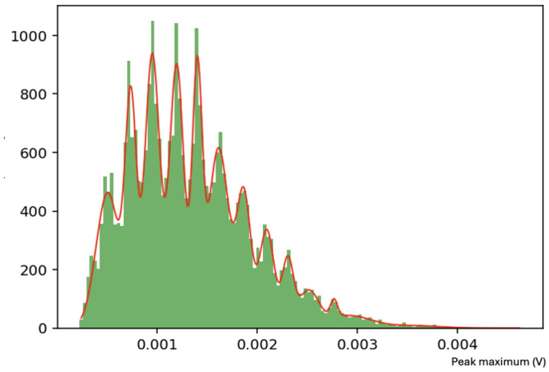
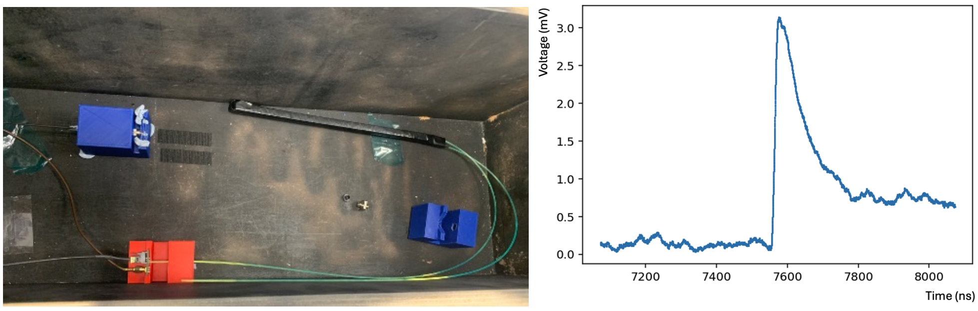


Figure 7: In green, the histogram of the SiPM signal (maximum of each pulse). In red, the single photoelectron peaks are fitted with a sum of Gaussian distributions

simultaneously for improved muon detection efficiency. The baseline measured prior to the pulse



(a) Optic fiber set up

(b) muon signal

Figure 8: a) Two fibers where glued on a scintillator. Each fiber is read by a SiPM connected to the wireless power supply circuit. b) Typical oscilloscope pulse from a cosmic muon.

confirms that the system exhibits low electronic noise. The study is ongoing to investigate the feasibility of connecting two SiPMs while maintaining equivalent efficiency in muon detection.

4. Conclusion

The WADAPT consortium is currently pursuing the development of advanced wireless technologies for both data and power transmission, with applications across high-energy physics detectors, particularly within tracking systems. Two independent research groups have initiated experimental studies on laser-based power transmission, investigating both free-space and fiber-coupled configurations. Preliminary results demonstrate the feasibility of powering silicon detectors while preserving low electronic noise levels. The ongoing research activities include the design and characterization of dedicated PVC modules, the fabrication of integrated PCBs, and the preparation of fully wireless test-beam campaigns. Further studies are planned to explore layer-to-layer power transfer mechanisms and to extend the investigation toward microwave-based transmission techniques, thereby broadening the range of potential wireless power solutions for detector applications.
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