PIZZICATO: Picosecond Scintillator Timing with Superconducting Nanowire Single-Photon Detectors

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ABSTRACT

Time-of-flight positron emission tomography (TOF-PET) visualizes molecular processes in vivo and is commonly used in the treatment of cancer. TOF-PET can be transformed into a tool for personalized medicine in a much wider range of clinical applications if we can improve the time-of-flight resolution to ~10 ps. The PIZZICATO consortium is developing a novel type of TOF-PET detector based on large-area superconducting nanowire single-photon detectors (SNSPD) optically coupled to ultrafast direct-bandgap semiconductor scintillators. Here, we present first proof-of-concept results, including the successful development of large-area SNSPDs with sub-10 ps single-photon time resolution and first measurements of scintillation signals using SNSPDs.

Keywords: medical imaging, positron emission tomography, superconducting nanowire single-photon detector, scintillator

1. INTRODUCTION

There is an urgent need in medical imaging for ultrafast radiation detectors. More accurate diagnosis and treatment of cancer, for example, has been made possible by the introduction of time-of-flight positron emission tomography (TOF-PET) scanners based on scintillation detectors with 200-300 ps time resolution [1]. TOF-PET can be transformed into a tool for personalized medicine in a much wider range of clinical applications if we can reduce the radiation dose and scan time by another order of magnitude. This can be achieved if the time resolution is improved to ~10 ps [2]. Similar requirements exist for future high-energy physics experiments, where particles will need to be detected at extreme count rates. Existing scintillation detector technology is fundamentally too slow to realize these new objectives [3].

Here, we investigate a novel type of detector that uses large-area superconducting nanowire single-photon detectors (SNSPD) to read out the ultrafast scintillation signal emitted by the direct-bandgap semiconductor PbI_2. We aim to demonstrate, for the first time, that such detectors have potential to enable ~10 ps PET.

Recent proof-of-concept experiments demonstrate efficient single-photon detection with sub-10 ps time resolution for single SNSPDs and sub-20 ps resolution for array detectors (square pixels of 25 × 25 μm^2 and circular pixels with a diameter of 50 μm) [4, 5]. The latest generation of single-pixel SNSPDs have an active area of 200 × 200 μm^2. We are optimizing the performance of these large-area devices in scope of the PIZZICATO project. Moreover, we are developing multi-pixel arrays based on large-area SNSPDs. We furthermore present first measurements in which the scintillation light from LSO:Ce^{3+} scintillators is coupled to multimode fibres and read out by large-area SNSPDs. Finally, we demonstrate intense, ultrafast donor-acceptor luminescence from PbI_2 samples at 10-30 K.

2. STATE OF THE ART

In vivo molecular imaging has emerged rapidly since the early twenty-first century [6]. PET, in particular, images radiolabeled biomarkers that decay through positron emission. This results in the back-to-back emission of pairs of annihilation quanta, which are detected in coincidence using a ring of scintillation detectors positioned around the patient.

The use of TOF improves the clinical imaging performance. This effect can be seen as an increase in effective sensitivity. Given a subject diameter $D > 0$:

$$S_{\mathrm{eff},D} \propto \eta_{\mathrm{det}}^2 \, \eta_{\mathrm{geom}} \frac{D}{\Delta t} \qquad (1)$$

with η_{det} the detection efficiency at 511 keV, η_{geom} the system angular coverage, and Δt the time resolution.

Commercial TOF-PET systems based on photomultiplier tubes (PMTs) became available in the second half of the 2000's, offering TOF resolutions of 500 - 700 ps [7-9]. The introduction of the silicon photomultiplier (SiPM) constituted the next technological breakthrough [10]. SiPM-based systems with time resolutions of 200 - 300 ps are currently available [11, 12]. In laboratory experiments, SiPMs enabled TOF resolutions of ~100 ps around 2009 already [13]. More recently, values of ~60 ps were reported [14].

Unfortunately, these achievements do not imply that 10-ps PET will come within reach soon [15]. The randomness in the scintillation photon emission makes that the lower bound on the time resolution is proportional to $\sqrt{N/\tau}$, with N the number of detected photons and τ the scintillator decay time [16]. Additional factors are the finite single-photon time resolution (SPTR) and photodetection efficiency (PDE) of the photosensor. Moreover, it follows from Eq. (1) that we must improve Δt while maintaining a high η_{det}.

Given the fundamental performance limits of lanthanide-doped scintillators [17] and the limited potential to further improve the timing properties of SiPMs [1], it appears unlikely that 10-ps PET systems can be realized through ongoing development of current TOF-PET detector technology [3].

3. BREAKTHROUGH CHARACTER OF THE PROJECT

PIZZICATO aims to develop a radically new PET detector technology utilizing superconducting nanowire single-photon detectors (SNSPDs) to read out the ultrafast donor-acceptor luminescence of certain direct-bandgap semiconductors at cryogenic temperatures.

PbI_2, for example, is a direct-bandgap semiconductor that has its main emission at ~520 nm and (at 14 K) a 6-times higher initial photon rate than the state-of-the-art PET scintillator L(Y)SO:Ce [18]. Moreover, it has a high density of 6.3 g cm^{-3} and a high effective number of ~69 (c.f. 7.1 g cm^{-3} and ~65 for L(Y)SO:Ce), so it fulfills the requirement that a high η_{det} be maintained (Eq. (1)).

SNSPDs are cryogenic single-photon sensors with unparalleled performance. They are capable of counting optical photons at very high rates, the PDE can exceed 90% [19] (cf. ~60% for SiPMs), and the SPTR is continuously being improved, with a value of 7.7 ps FWHM reported for large-area devices within the scope of this project [5] (c.f. ~50 ps FWHM for SiPMs).

Based on scintillation detector timing theory (section 2), the combination of PbI_2 and SNSPDs can be expected to enable the detection of pairs of annihilation quanta with a time resolution in the order of ~10 ps. Moreover, the high density and atomic number of PbI_2 will make it possible to develop detectors with high spatial resolution and detection efficiency. Such detectors can enable real-time, reconstruction-less imaging of molecular processes in the human body, while reducing radiation exposure and scan times by an order of magnitude.

Superconducting SNSPD-based detectors dissipate no energy. Therefore, it is foreseen that cryogenic PET scanners can be realized, similar to MRI scanners. One of the main focus points of this project is the development of photon-counting light sensors with sufficiently large active area to read out PbI_2 crystals. The proposed sensor comprises an array of SNSPDs, so as to cover a large area while maintaining the time resolution of the individual SNSPDs. Ultimately, the array format will also facilitate the decoding of the positions of interaction of the annihilation quanta in the PbI_2 crystal layer, which is a prerequisite for application in imaging devices such as PET scanners.

Thus, detectors based on large-area SNSPD arrays and direct-bandgap semiconductors may truly unleash the potential of PET as a tool for personalized medicine in a wide range of clinical applications.

4. PROJECT RESULTS

4.1 Large-area SNSPD arrays

To achieve a large active sensor area and at the same time maintain high detection efficiency and time resolution, we need to implement SNSPDs in the form of arrays. This is illustrated in Fig. 1 (a). The fill factor of SNSPD arrays (the ratio of the photo-sensitive area to the total device area) can be close to unity, because the required readout and grounding lines can be as narrow as a few hundred nm, while a regular pixel size (active area of a single SNSPD element in the array) is in the range of 20×20 μm^2. Additionally, the RF-readout and the grounding lines can be fabricated on top of one another, separated by a dielectric (for the short distances, capacitive coupling is negligible), saving further chip space that can be used to increase the active sensor area.

Within the PIZZICATO project we successfully fabricated several proof-of-concept, high-performance SNSPD arrays. A scanning electron microscope (SEM) image of such an array is shown in Fig. 1 (b). To read out these arrays, we developed a dedicated 24-channel cryogenic electronics setup, shown in Fig. 1 (c). The results of our measurements demonstrate that the detectors can achieve a PDE of ~90%, combined with 7-20 ps time resolution at visible, near-infrared, and telecom wavelengths [4, 5].

4.2 SNSPD readout of LSO:Ce crystals

As a proof-of-concept for reading out the optical signal generated by a scintillator using an SNSPD, we directly interfaced a 5 × 5 × 1 mm^3 LSO:Ce^{3+} crystal with a graded-index multimode fibre and excited the crystal using a 350 nm pulsed laser. LSO:Ce^{3+} is the state-of-

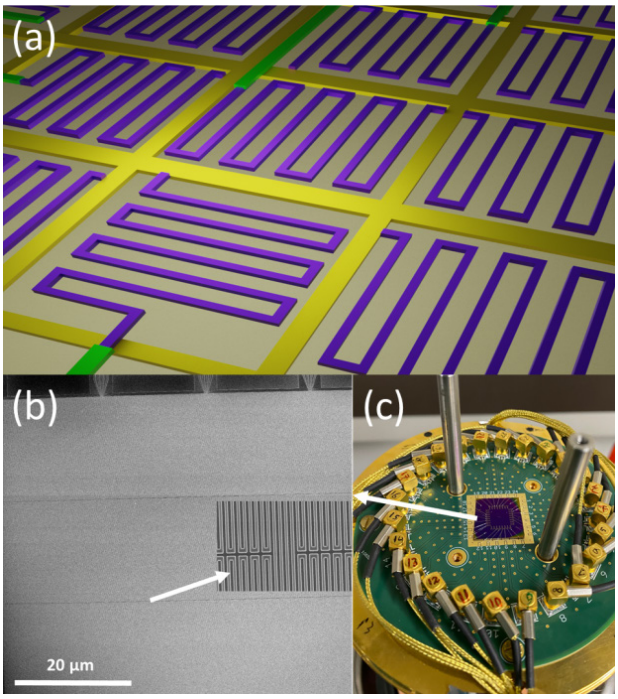

Fig. 1. (a) Schematic representation of a large-area SNSPD array: the meandering purple lines form the active detection area, while the gold and green sections represent the grounding an RF readout lines; (b) SEM image of a 16-pixel SNSPD array, with the inset showing a magnification image where 4 pixels meet; and (c) dedicated 24-channel cryo-electronic circuit developed to read out SNSPD arrays.

the-art scintillation material used in current clinical TOF-PET scanners. To perform a time-correlated single-photon counting (TCSPC) experiment, the scintillation signal was delivered to a cryogenically cooled SNSPD via the optical fibre, using a vacuum feed-through. The SNSPD output pulses were amplified using a low-noise amplifier and correlated to the excitation laser pulses using a picoquant picoharp 300. As shown in Fig. 2, the result is in good agreement with literature [20, 21].

4.3 Characterization of PbI_2 samples

To characterise the luminescence properties of our PbI_2 crystals as a function of temperature, a sample was mounted on the cold finger of a helium flow cryostat. Fig. 3 shows the emission at 10 K upon excitation with 405 nm light. The observed spectrum is in accordance with literature [18]. It is noted that the exciton emission at 497 nm is almost fully quenched in favour of the 511 nm donor-acceptor luminescence in our sample.

Similar measurements performed at different temperatures indicate that the 511 nm PbI_2 donor-acceptor emission is slightly quenched at 20 K compared to 10 K, while the intensity drops down significantly (by about 50%) at 30 K, as expected.

Fig. 2 (left) shows the decay of the PbI_2 donor-acceptor emission under excitation by an optical parametric oscillator (OPO) at 405 nm. It is to be noted that the width of the excitation pulse was about ~5 ns in this preliminary experiment. Moreover, the bin width of the waveform digitizer was 2 ns, which adds to the relatively poor time-resolving power. Taking these factors into account, the results suggest a decay time constant of the order of at most 2 ns for the 511 nm donor-acceptor emission, in accordance with literature [18]. Measurements at higher time resolution, utilizing the SNSPD-based TCSPC setup used in the LSO:Ce setup, are planned.

5. FUTURE PROJECT VISION

5.1. Technology Scaling

A number of steps must be undertaken to achieve a TRL level of 5. For example, our PbI_2 crystals are grown

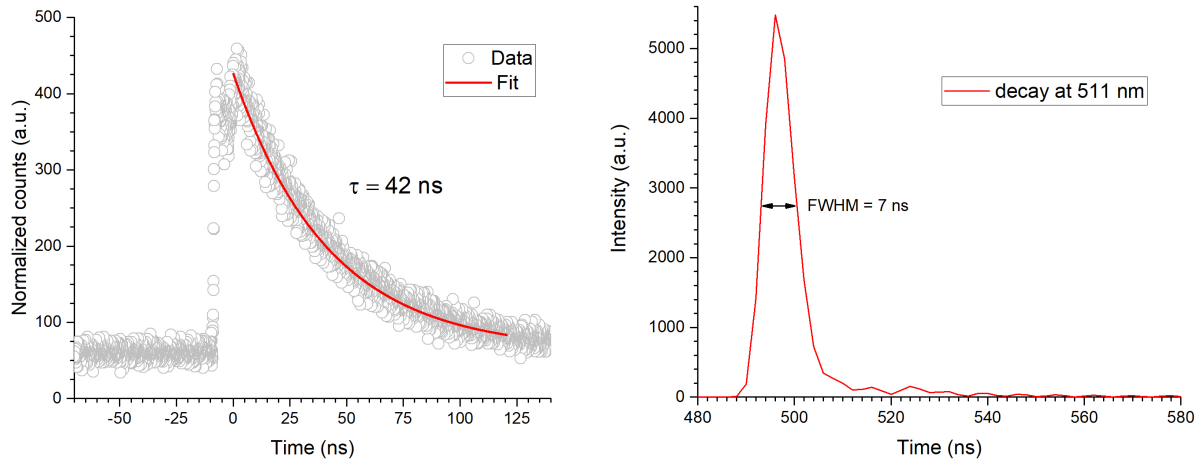

Fig. 2. Left: LSO:Ce luminescence pulse shape under 350 nm excitation, measured using a SNSPD-based time-correlated single-photon counting setup. Right: Pulse shape of PbI_2 donor-acceptor luminescence under 405 nm excitation.

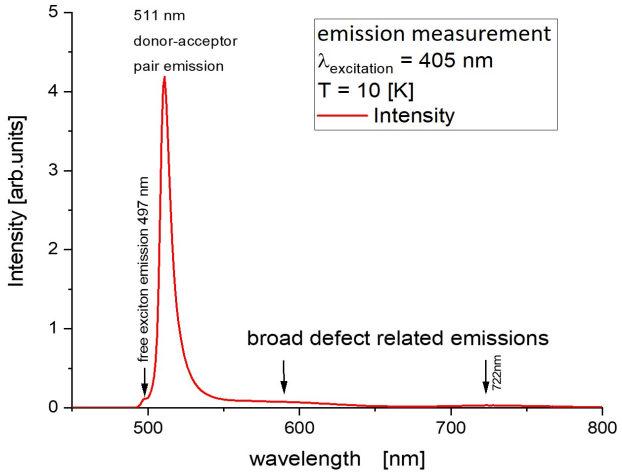

Fig. 3. PbI_2 emission spectrum under excitation with 405 nm light from a Xe lamp.

in laboratory, which is fine for material optimization and proof-of-concept demonstration. However, technology validation in a relevant environment requires scaling up of the production to a sufficiently large number of PbI_2 crystals with uniform properties.

Similar arguments apply to our SNSPD technology. Fortunately, the production is CMOS compatible. This facilitates the development of reliable SNSPD arrays of a few mm^2 ("pixels), which in turn can be assembled into pixelated imaging sensors of several cm^2, necessary to read out crystal arrays of the same dimensions. Ultimately, the development of monolithic pixelated imaging SNSPD sensors is foreseen.

The sensor-crystal adhesive should have excellent optical transparency as well as high thermal conductivity and thermal stability. Furthermore, high-speed cryogenic readout electronics (cryo-ASICs) must be produced and interfaced with large-area SNSPD arrays. Additional important tasks are the production of a suitable cryogenic platform and system integration.

Finally, performing all of the above tasks in a way that facilitates compliance with the European Medical Device Regulation (MDR) will expedite the commercialization of PIZZICATO technology in future.

5.2. Project Synergies and Outreach

An academic partner to further develop and optimize the PbI_2 properties and an industrial partner with experience in the upscaling of scintillation crystal production will be added to the project consortium. On the sensor side, we will engage with a CMOS production fab for the development of pixelated photon-counting sensors based on SNSPDs. We are currently exploring the possibilities for including a partner with expertise in cryogenic crystal-sensor coupling. Moreover, an academic and/or industrial R&D groups for the development of high-speed cryogenic readout electronics (cryo-ASICs) and a partner with experience in the development of cryogenic systems are required. Finally, we will involve an industrial partner with experience in the development, certification and marketing of medical imaging systems, to establish the right conditions for a successful transfer of PIZZICATO technology to the clinical market in future.

We are currently examining the activities and expertise of the other ATTRACT partners in the above areas. Our aim is to establish collaborations and exploit synergies within the ATTRACT consortium to the maximum extent possible and, thereby, help strengthen a potential ATTRACT Phase 2 proposal.

We furthermore aim to contribute to the ATTRACT Phase 2 proposal through the development of a plan for the exploitation, dissemination, and public awareness-raising of PIZZICATO project results. Besides project-internal outreach activities, we will actively foster joint events and other activities by the ATTRACT Phase 2 consortium as a whole.

5.3. Technology application and demonstration cases

PIZZICATO Phase 2 will demonstrate fully three-dimensional, real-time, reconstruction-less PET imaging with high spatial resolution and unprecedented sensitivity (Eq. (1)), utilizing a TOF resolution of ~10 ps. Tomographic imaging of PET performance standards and anthropomorphic phantoms will demonstrate the clinical potential of the PIZZICATO detector. This will set the stage for clinical translation, which, in turn, will unleash the true potential of PET as a tool for personalized medicine in a wide range of applications.

PIZZICATO Phase 2 will contribute importantly to the further development of the European medical imaging industry. Moreover, it addresses the societal challenge Health, Demographic Change and Wellbeing, contributing in particular to the growing role of molecular imaging in personalized medicine. As such, the project results will also help advance the mission of the EU research infrastructure EuroBioimaging.

We furthermore foresee application of PIZZICATO in other areas. Future high-energy physics experiments, such as those planned at CERN, will require technology to detect ionizing particles at extremely high count rates and time resolution. The scalability of SNSPDs facilitates translation to other areas of application.

5.4. Technology commercialization

PIZZICATO's potential to expand the PET imaging market in and beyond oncology provides a strong incentive for investors. The global molecular imaging market is projected to grow at a CAGR of 6.25% to reach €5.2 billion by 2023, driven by the aging of the population and an increasing need for early diagnosis and personalized treatment of cancer, cardiovascular and neurodegenerative diseases.

Funding of strategic collaborations or external funding is a realistic and interesting approach for a scale-

up like Single Quantum to cover the risks associated with bringing products and knowledge to market. Single Quantum itself will continue to co-fund the development of PIZZICATO technology from its revenue in the scientific quantum communication market.

The PIZZICATO partners have longstanding collaborations with major European medical imaging device manufacturers, including Philips Healthcare and Siemens Healthineers. Possibilities for collaboration are being discussed with these industrial partners.

5.5. Envisioned risks

Tab. 1. Risks and mitigation strategies

Risk	Mitigation
Production of large number of PbI_2 crystals with uniform properties delayed	Alleviate requirements on crystal production and accept some reduction in performance
Transmission of optical adhesive at cryogenic temperatures unsatisfactory	Mount crystal on SNSPD without adhesive and accept some reduction in performance
SNSPD superconducting film not uniform over centimetre scales	Optimize fabrication on thicker superconducting films, accepting minor PDE reduction. Alternatively, a few dead pixels can be accepted.
Heat load of cryogenic electronics on SNSPD arrays too high	Use flexible cryogenic PCBs with minimal heat conductance between SNSPD and readout stage, accepting a small signal distortion.

5.6. Liaison with Student Teams and Socio-Economic Study

TU Delft is well known for its student teams, which include world-famous examples such as NUNA, Delft Hyperloop and MARCH. We will foster the formation of a new student team in scope of ATTRACT. Moreover, Dr. D.R. Schaart, who is an experienced tutor and supervisor, will develop (online) materials for explaining PIZZICATO technology to MSc students.

The PIZZICATO team will contribute to the ATTRACT Socio-Economic study via interviews with its academic, SME and industrial partners.

6. ACKNOWLEDGEMENT

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