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Deliverable table

Deliverable no.	4.1
Deliverable name	Simulation and proof of principle device of a detector array
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What was planned *(from Annex I:)*

D4.1: Simulation and proof of principle device of a detector array [M12]

Simulation showing number of pixels needed to achieve required specifications and a demonstration of first pixelated detector in cryostat.

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Summary

We present the basic principles of a superconducting nanowire single-photon detector (SNSPD) with special emphasis on its performance at high-count rates, i.e. when the dead time of the detector is not negligible and has to be taken into account to model the behavior of the detector. We present a simple model based on an idealized case which we use to estimate the number of elements needed to achieve the performance required for the EPIQUE project.

Introduction

The EPIQUE project represents an ambitious initiative aimed at developing and demonstrating different measurement-based photonic quantum computers in Europe, by leveraging expertise from a number of companies and research groups disseminated in various EU countries. The three different physical approaches explored in the project – a continuous variable platform and two discrete variable platforms, spatially and temporally multiplexed – show very high potential in the context of providing the foundation for a universal, scalable and fault-tolerant quantum computer, able to tackle a large set of computational problems. Furthermore, the project offers a valuable opportunity to strengthen and enhance Europe's position in this promising and high-impact field.

In order to reach the final goal, meaning to execute a set of quantum algorithms on the machines developed in the project, several challenges pertaining to the hardware components need to be addressed and solved. On one hand, this entails optimizing photonic integrated circuits components, such as modulators, switches, multiplexers etc. on different photonic platforms. On the other hand, it is also necessary to further improve high-performance quantum light sources and single photon detectors.

Single photon detectors need to be utilized in each of the three approaches explored in EPIQUE. They are responsible to perform the final qubit measurement for the discrete variable implementations, but they are also utilized in the context of feed-forward for the machine based on squeezed states of light. In order to make use of each available photon and in order to reduce losses, it is of paramount importance that the detectors exhibit very high detection efficiency. At the same time, to operate at high clock-rate speeds, the detectors should be able to maintain that same detection efficiency at high count rates, in the order of hundreds of millions of counts per second, to a billion counts per second. State of the art single photon detectors are typically able to achieve either high efficiency or high dynamic range, not simultaneously.

The demanding task of producing detectors fulfilling these requirements for EPIQUE is assigned to Single Quantum, a Dutch SME that has been developing and commercializing superconducting nanowire single photon detectors (SNSPDs) since 2012, the year of its foundation. In the first part of this report, we aim to give an introduction to the SNSPD technology, to then focus on some calculations we performed in order to establish what the design of high-efficiency, ultra-high dynamic range SNSPDs should look like.

Detecting single photons using SNSPDs

More than 20 years ago, Gregory Goltsman et al. introduced a new type of photon detector based on ultrathin superconducting material (in their case, NbN) (G. N. Goltsman, 2001). They reported that if a superconducting nanowire carrying a (bias) current happens to absorb a single photon with energy much higher than the gap of the superconductor, it will locally suppress superconductivity. This event leads to an electrical signal indicating the detection of a photon and can be further processed with electronics, for example, with a time-tagger or a counter. Moreover, for selected boundary conditions and at the correct bias current value, the detector demonstrates a single-photon detection regime scaling linearly with the input optical power, i.e. it behaves as a linear detector. This device became known in the community as superconducting nanowire single-photon detector (SNSPD) and several experiments soon demonstrated its high sensitivity from visible to infrared with low background noise. In addition to the high single-photon sensitivity, SNSPDs provide exceptional electrical properties, exhibiting a fast recovery time and a temporal resolution orders of magnitude better than alternative technologies for single-photon detectors.

Since its initial discovery, SNSPDs have been widely studied and developed by research laboratories and private companies to become the leading technology in single photon detection. The rapid expansion of quantum information applications is one of the main reasons why so much effort was dedicated to improving SNSPD performance (M. D. Eisaman, 2011).

Nowadays, SNSPDs offer outstanding performance, featuring system detection efficiencies >90%, from 400 nm to 1550 nm (F. Marsili V. B., 2013) (W. Zhang L. Y., 2017), the possibility of fabricating multi-element or SNSPD arrays and a detectable wavelength range now spanning from 5 μm (F. Marsili F. B., 2012) to the X-ray range (K. Inderbitzin, 2012). Dark count rates (the amount of noise counts per second) can be reduced to the miliHz range (C. Schuck, 2013), the dynamic range is such that detection count rates up to 1.5 GHz (W. Zhang J. H., 2019) can be achieved, yielding sub-nanosecond recovery times (A. Vetter, 2016). At the same time, and timing jitter as low as < 10 ps (Esmaeil Zadeh, et al., 2020) can be achieved. Yet, it is a paramount challenge for the community to achieve the aforementioned outstanding features *simultaneously* in one device, as we are aiming to achieve for the EPIQUE project.

Operating principles

Even though the exact microscopic detection mechanism in SNSPDs is complicated and the subject of research in the scientific community, the so-called “hot-spot” model is widely adopted to phenomenologically represent the detection process and for most cases of interest it is enough to capture the basic behavior of SNSPDs.

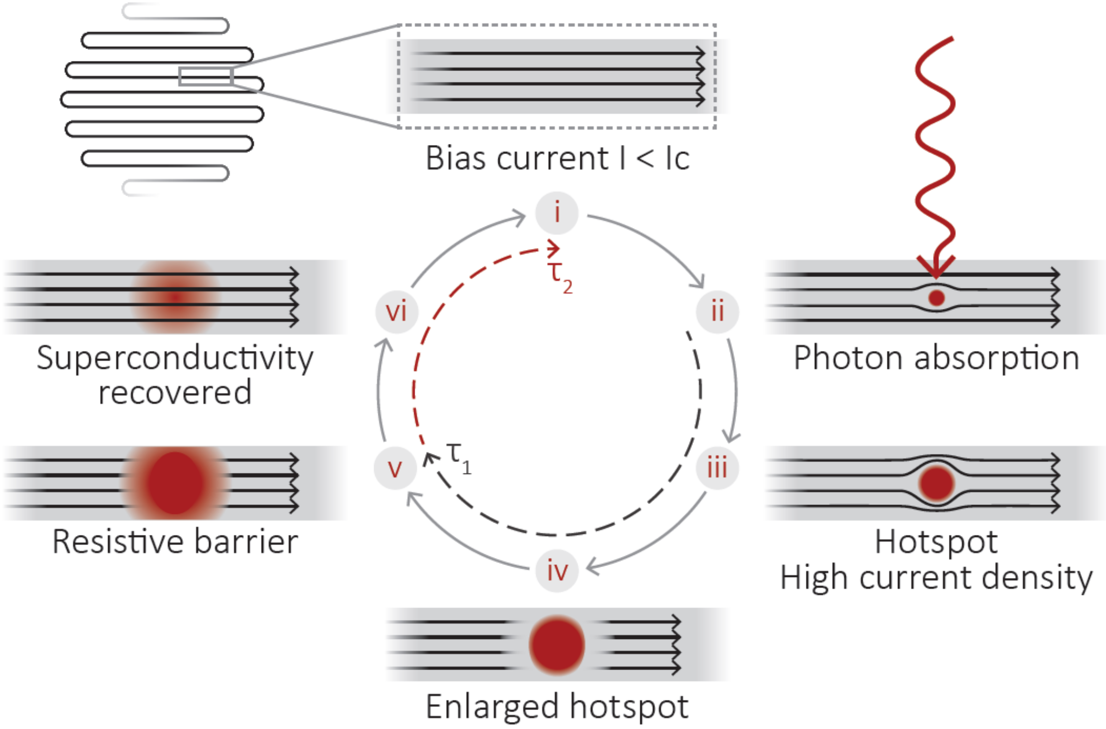

Figure 1: Hot spot model for explaining the detection mechanism of a photon of energy hv.

Figure 1 depicts the different steps of the process, as proposed firstly by Goltsman et al. (G. N. Goltsman, 2001). We start with a superconducting nanowire in the superconducting state, cooled well below its critical temperature Tc. To operate as a single photon detector, a direct bias current (arrows in Figure 1(i)) is applied just below the critical current (*Ic*), above which the superconductivity of the detector is lost. When a photon of energy *hv* is absorbed locally along the nanowire (Figure 1 (ii)), several Cooper pairs are broken which triggers the breaking of a multitude of other Cooper pairs by electron - electron inelastic scattering. This cascade effect causes superconductivity to be locally disturbed in this area, and the charge carrier density decreases. This is the so-called hot-spot. We note that the size of this area varies as a function of the photon energy. The current can still flow around the hotspot (Figure 1 (iii)) which, in turn, means that the current density in the surrounding immediately increases. When the critical current density is reached, a resistive barrier is formed across the entire width of the nanowire (Figure 1(iv)) which then quickly expands due to Joule heating caused by the current (Figure 1(v)). At his point, a section of the nanowire becomes a resistive element (with a resistance approximate value of several kΩ), which redirects the biasing current to the readout circuit. The resulting voltage pulse is fed to an amplifier whose output can be used for processing the single photon event. The detection region's cool down process is initiated by the recombination of the Cooper pairs and by coupling the energy of quasiparticle to the substrate via electron-phonon and phonon-phonon scattering (Figure 1 (vi)).

Lastly, the nanowire fully returns to the superconducting state and, after the current is flowing again, the detector is ready for another detection event.

While the superconducting film per se is sensitive to a broad spectrum, enhanced detection at specific wavelengths is achieved by depositing the SNSPD on top of an appropriately engineered optical cavity.

Electrical operation of SNSPDs

A simplified representation of a biasing/readout circuit for SNSPDs is depicted in figure 2 (a). The presented circuit allows for the creation of a biasing current and to amplify the pulse that is created when a photon is detected.

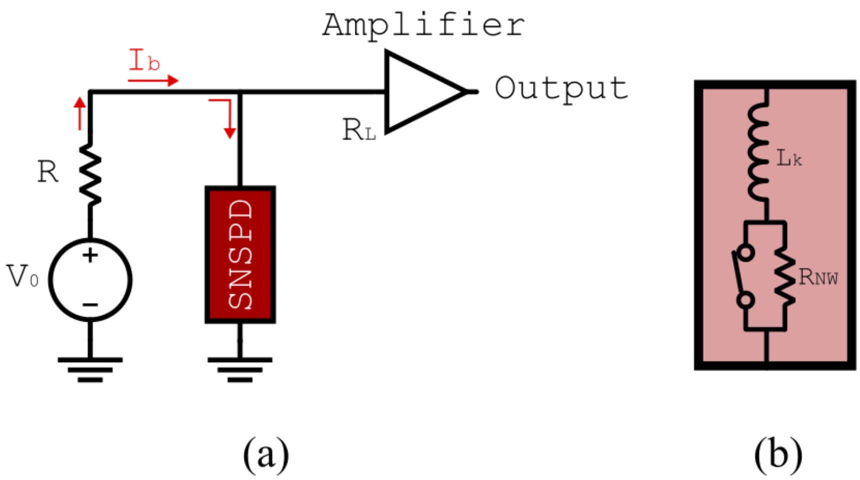

Figure 2: SNSPD electrical connection. (a) Standard circuit for biasing and amplifying the electrical pulses created when a photon is detected. The bias current I_b flows through the SNSPD to ground when the nanowire is in the superconducting state and negligible current gets to the amplifier (which has an impedance of R_L). When the nanowire is the normal state, the current flows to the amplifier instead of through the SNSPD. (b) Electrical model of an SNSPD, consisting of an inductor that represents the kinetic inductance (L_k) of the SNSPD and a switch that is closed when the nanowire is in the superconducting state and is open when it is in the normal state. In the later, the nanowire resistance (R_{NW}) plays a role. Adapted from (Gourgues, 2020)

In detail, a constant voltage source (V_0) in series with a resistor (R) provides to the superconducting detector a direct bias current (I_b) close to its critical current (I_c). Figure 2(b) depicts the electrical circuit equivalent of a SNSPD, which can be approximated by a kinetic inductance (L_k) connected in series with an electrical switch and a resistor (R_{NW}) in parallel. When the nanowire is in the superconducting state, the bias current flows without resistance as to ground. This corresponds to the model in Figure 2(b) with the switch closed. As soon the nanowire becomes resistive, its resistance jumps to a high value of several kΩ, which corresponds to an open switch in the model, with $R_{NW} \approx k\Omega$. Then the current is diverted to the amplifier, creating an output electrical pulse with a peak value on the order of $V_{peak} = I_b R_L A$, where A stands for the amplification of the amplifier. Finally, when the nanowire returns to the superconducting state, the bias current flows again through the nanowire, so it is ready for the next detection event. If the bias current is restored too quickly, the detector is unable to recover its superconducting state, and cannot therefore detect photons right away:

this phenomenon is called latching (J. K. W. Yang, 2007). In case this occurs, the bias current has to be suspended for a short time interval, allowing the superconductivity to be restored.

As mentioned before, the detection efficiency of an SNSPD depends strongly on the amount of bias current flowing in the nanowire. Therefore, the most basic characterization of an SNSPD performance consists of a curve of detection efficiency vs bias current. Figure 3 depicts such a curve for an SNSPD from SQ designed to operate at 943 nm. At very low bias currents there are almost no detection events, but their number increases in a sigmoid-like fashion, reaching a saturation plateau at the maximum efficiency level. Changing the biasing current in the saturation regime does not change the quantum efficiency, therefore the operating current of the detector is chosen in the corresponding interval. Note that at higher currents, the efficiency drops back to zero: this is the switching current, that makes the nanowire resistive even in the absence of input photons. In the example below, the plateau is reached at an outstanding detection efficiency > 96%. This is achieved in combination with an extremely low dark count rate, shown in the axis on the right, which reaches the value of 5 counts per second (cps) at around 25 μA.

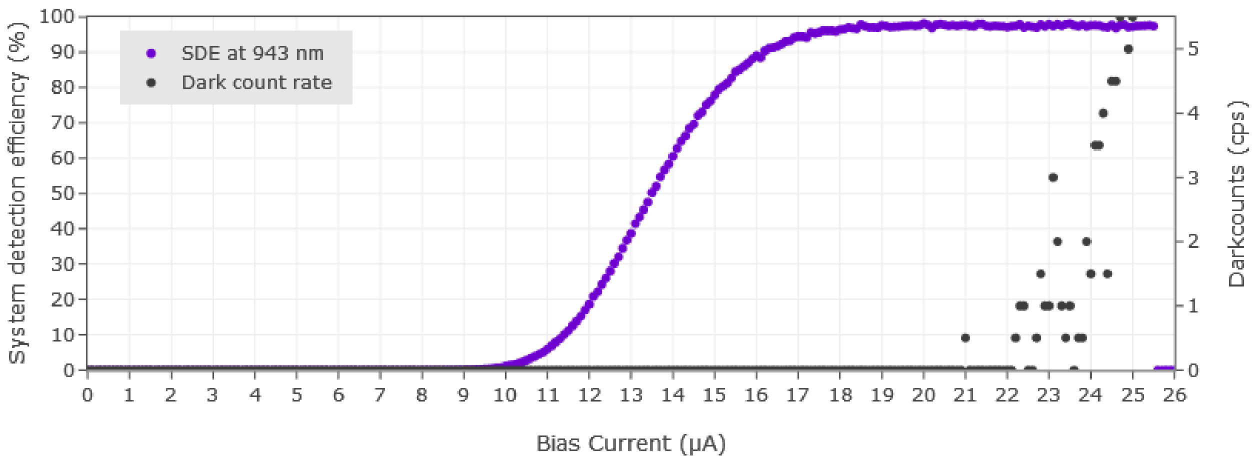

Figure 3: Quantum efficiency for an SNSPD as function of the bias current. In purple we show the measured efficiency (left axis) while in black dots we depict the dark count rate (right axis).

Using the electrical circuit from Figure 2 to drive and readout an SNSPD, we measure an output pulse that has a steep raise time and an exponentially decaying recovery, as depicted in Figure 4. The raise time is of the pulses from an SNSPD is given by

$$\tau_1 = \frac{L_k}{R_L + R_{NW}},$$

which is in the order of hundreds of picoseconds; in the specific case shown in the figure it is 273 ps. After the detection event, superconductivity is restored and then the initial bias current returns to the nanowire in an exponential manner with a time constant given by

$$\tau_{electrical} = \frac{L_k}{R_L}.$$

In the example of Figure 4, the corresponding time refers to the second part of the curve and the time $\tau_{electrical}$ is 3.9 ns. In the SNSPD community, the time τ is usually called the "electrical dead time" or simply dead time, because during this time the detector is not able to detect another photon with high quantum efficiency. Note that during this transient state the bias current is gradually increasing from a low value to the set point on the right side of the curve in Figure 3, therefore the detection efficiency is changing from zero to the maximum value in a time scale partially determined by the electrical dead time.

The presence of a dead time after a photon's detection implies an absolute maximum for the detected count rate, since the photons arriving when the detector is blind are not detected; this implies a drop in the overall measured efficiency when the detected count rate increases.

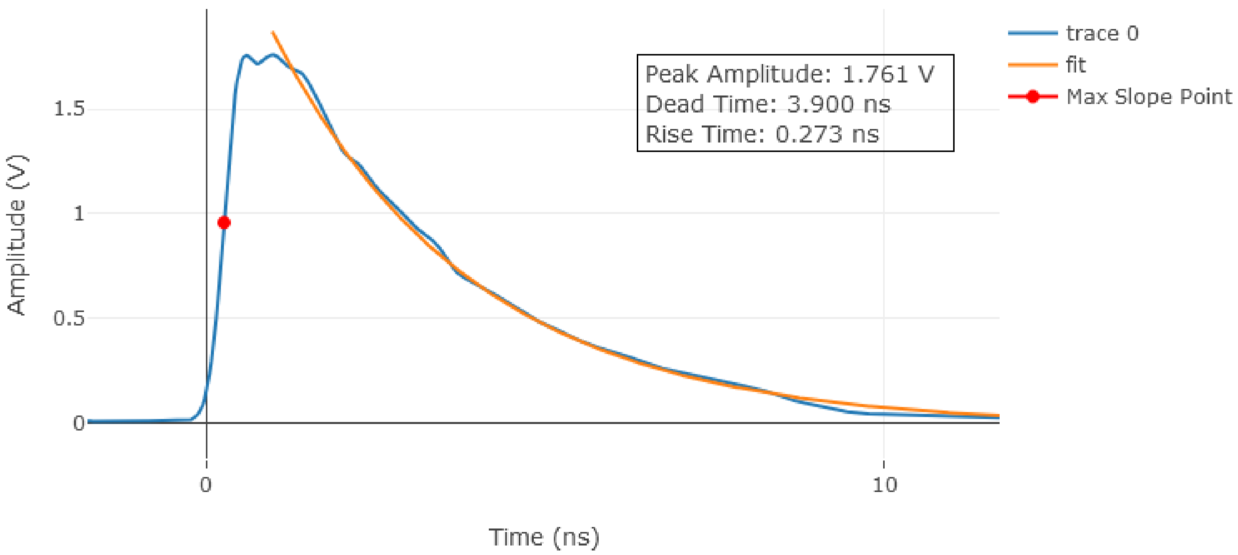

Figure 4: Electrical output pulse from an SNSPD with amplification. In blue we show the measured pulse and in orange the fitted curve, leading to a dead time of 3.9 ns. The rise time is shorter than 300 ps and the peak amplitude is higher than 1.7 V.

It is important to emphasize that the electrical dead time $\tau_{electrical}$ depends on the kinetic inductance of the SNSPD and the impedance of the readout circuit. The former depends on material properties and on the geometry of the nanowire, following the expression $L_k \propto l/A$, where l is the length of the nanowire and A is its cross section. Therefore, to reduce the dead time of an SNSPD one can decrease the length of the nanowire and increase the impedance of the readout circuit, for instance by adding a resistor in parallel.

The presence of an electrical dead time influences the probability of detecting a photon after a detection event, so the usual way to characterize this phenomenon is by making an "efficiency recovery curve". This is measured by performing a histogram with the arrival time of a photon a certain time after a detection event. Figure 5 depicts such a measurement for a fast SNSPD, showing a 50% recovery time of < 4.5 ns and a 90% recovery time < 6 ns.

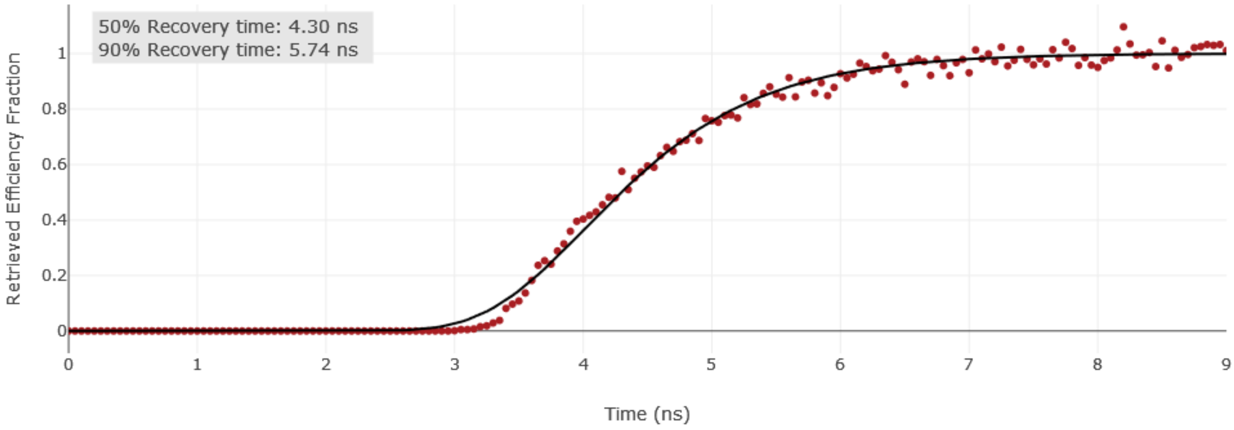

Figure 5: Efficiency recovery curve for an SNSPD. The points display the measured values and the solid line the fit to extract the recovery times depicted in the inset.

Performance indicators for an SNSPD

Now that we have presented the basics for the SNSPD operation, we briefly present the main performance indicators for an SNSPD system used as a single-photon detector.

The first one is the **system detection efficiency** of the detector η, that simply states the probability of detecting a photon after it is coupled to the detection system. We note here that the usual way to measure this value is to keep the detected count rates low, so the dead time and timing jitter are negligible.

Another performance indicator is the **dark count rate** (DCR), which measures the number of counts measured when there is no incoming photon flux onto the detector, as a function of bias current. Note that the dark count rate must be accounted for when performing measurements, especially when it comes to efficiency characterization, if it is not negligible during the integration time.

As it was anticipated in the previous section, a characterization parameter for the performance of an SNSPD is the efficiency recover time, which gives a measure of the time the detector needs to recover after the detection of a photon. Note that this is not equal to the electrical dead time, since the response is not a step function but a sigmoid-like function.

Finally, there is a characterization parameter that quantifies the timing precision that an SNSPD provides when detecting photons in the time domain, for example, by performing a time-correlated single-photon counting (TCSPC) experiment. This precision is usually referred to as the **timing jitter**, which is the spread of the time distribution of a TCSPC experiment attributed to the detector (i.e. when the jitter from all the other components of the experiment is negligible).

Measuring detection efficiency

The most straightforward way to measure an SNSPD's efficiency is to use a highly-attenuated stable continuous wave (CW) laser with power p_l as a photon source, whose output is well described by a Poisson distribution for the number of photons in a given time interval dt. The ideal inefficient detector (neglecting dead time, timing jitter and DCR) can be modeled as a Bernoulli process with success probability η and it can be shown that the composition with a Poisson-like photon source leads to a Poisson distribution for the complete process, i.e. the probability P of ***detecting*** n photons in a time interval dt when the laser output is reaching the detector is

$$P(n) = \frac{1}{n!}\Lambda^n e^{-\Lambda},$$

where $\Lambda = \eta \frac{p_l \lambda}{hc} dt$, λ is the laser wavelength, h is Plank's constant and c the speed of light in vacuum. By performing a set of measurements on the counts measured in the time interval dt, $\{n_1, n_2, \dots, n_N\}$ one can use the minimum-variance unbiased estimator for the Poisson parameter $\hat{\Lambda} = \frac{1}{N}\sum_{s=1}^{N} n_s$ to obtain the estimation of the detector efficiency:

$$\hat{\eta} = hc\ \frac{\hat{\Lambda}}{p_l}.$$

Note that the main approximation done in this analysis is that the dead time is null, and, as consequence, the detected number of photons in this idealized case scales linearly with the input number of photons. To ensure that this is a good approximation we should guarantee that the probability of missing a photon due to the dead time is negligible. This conditions translates into a maximum count rate that we can use when using the mentioned approximation. Since the number of incoming photons follows a Poisson distribution, the time between successive photons (the inter-photon time), Δt, follows an exponential distribution with a parameter $\zeta = \frac{p_l \lambda}{hc}$. From the properties of the exponential distribution we know that the mean interphoton time is given by the inverse of this parameter, which is a time scale that we can compare directly with the dead time of the SNSPD to lead to the condition: $\tau \ll \frac{hc}{p_l \lambda}$.

If the DCR is not negligible, one can simple measure it independently and subtract it from the counts measured when the laser is impinging on the detector.

Efficiency in presence of dead time

As mentioned above, the presence of a dead time can be ignored when it is negligible respect to the incoming interphoton average time, or, in other words, when the incoming photon flux into the detector is low. However, for demanding applications as in the EPIQUE project, there is a need to develop detectors that can detect photon rates on the order of GHz with high efficiency. In this regime, the interproton average time is comparable to the dead time of the SNSPD and therefore it has to be accounted for.

Several theoretical papers have been published studying the effects of dead time in the photon counting statistics and a clear model is available to describe the counting statistics of a photodetector in the presence of a dead time (Bédard, 1975). If we have a detector that provides a probability η of detecting single photons, dead time τ and an incoming photon flux Γ, the mean number of counts we expect to count in an integration time dt is given by (Bédard, 1975).

$$\hat{n} = \frac{\eta\Gamma dt}{1+\eta\Gamma\tau} + \frac{1}{2}\frac{(\eta\Gamma\tau)^2}{(1+\eta\Gamma\tau)^2} \quad (1)$$

Note that if we set null dead time in this expression we obtain the expected number of photons as $\eta\Gamma dt$ which is the linear behavior we expect for an ideal inefficient detector. If we think of the limit of high count-rate, we obtain the maximum number of photons we can detect in the integration time, dt/τ. In Figure 1 we depict the expected count rate calculated using the presented model for a detector with an efficiency of 80% and different dead times. As expected, the curves present a maximum count rate that scales with the inverse of the dead time of the detector. We note that for low input photon rates, the curve is linear, supporting then the validity of the approximation of null dead time in a range of input photon fluxes.

We note that this model is considering that the response of the detector after the detection of a photon is a step function, i.e. the probability of detecting a second photon is zero until a time τ has passed and then it becomes one. This is not the case for an SNSPD, since that response is measured to be an error-function-like curve, due to the exponential recovery of current (as shown in Figure 4) and the sigmoid-like efficiency curve (Figure 3). This means that this model accounts for the worst-case scenario situation for an SNSPD.

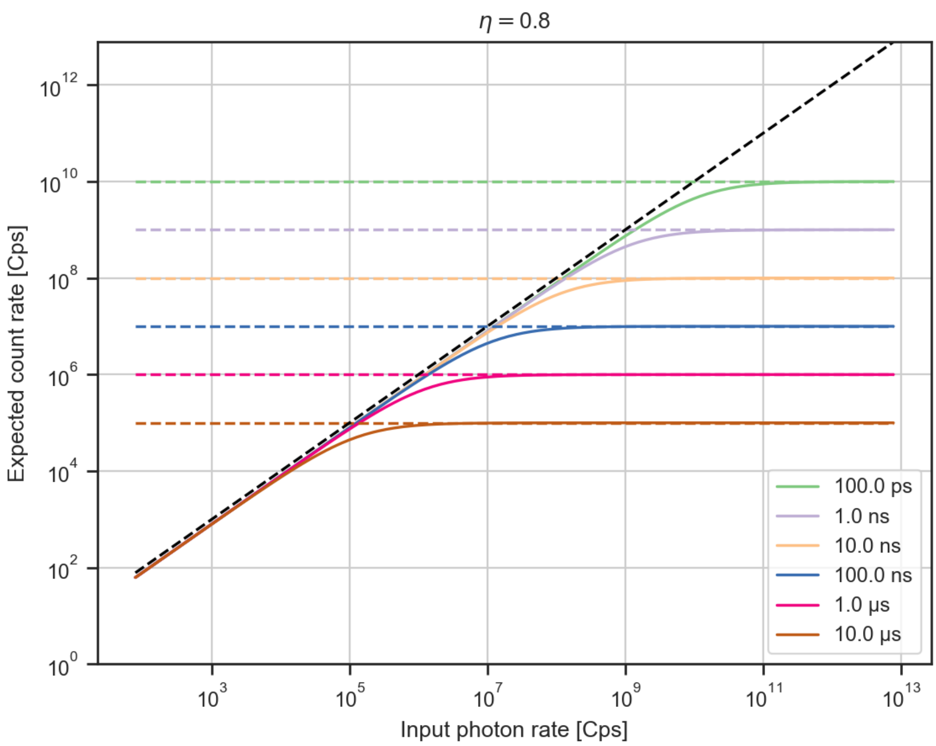

Figure 6: Expected count rate for different input photon rates for a detector with efficiency 0.8 and different deadtimes. The dashed black line denotes the ideal detector with an efficiency of 1. The color curves denote the expected count rate for each different dead time while the horizontal dashed lines denote the absolute limit for the count rate imposed by the dead time (i.e. τ^{-1}).

Results for multi-element detectors

So far we have presented the working principles of an SNSPD, its main performance indicators and a model that accounts for the behavior of a detector in the presence of dead time. We would like to use this model as a starting point for the design of a multielement SNSPD that will work in the GHz regime with high detection efficiency. In order to gain confidence in the validity of this model, we will now present experimental results from SNSPDs made at Single Quantum and fit the parameters of this model. Once we gain confidence on the validity of the model we can use its predictions for an initial design of an SNSPD that meets the high requirements expected in the EPIQUE project.

The type of multi-element detector that is designed to perform at the high-count-rate (HCR) regime is the interleaved SNSPD. Interleaved SNSPDs are detectors composed of several individually biased nanowires, whose meanders run parallel to each other in sub-diffraction distances, in such a way that optically probe the same area.

(a) (b)

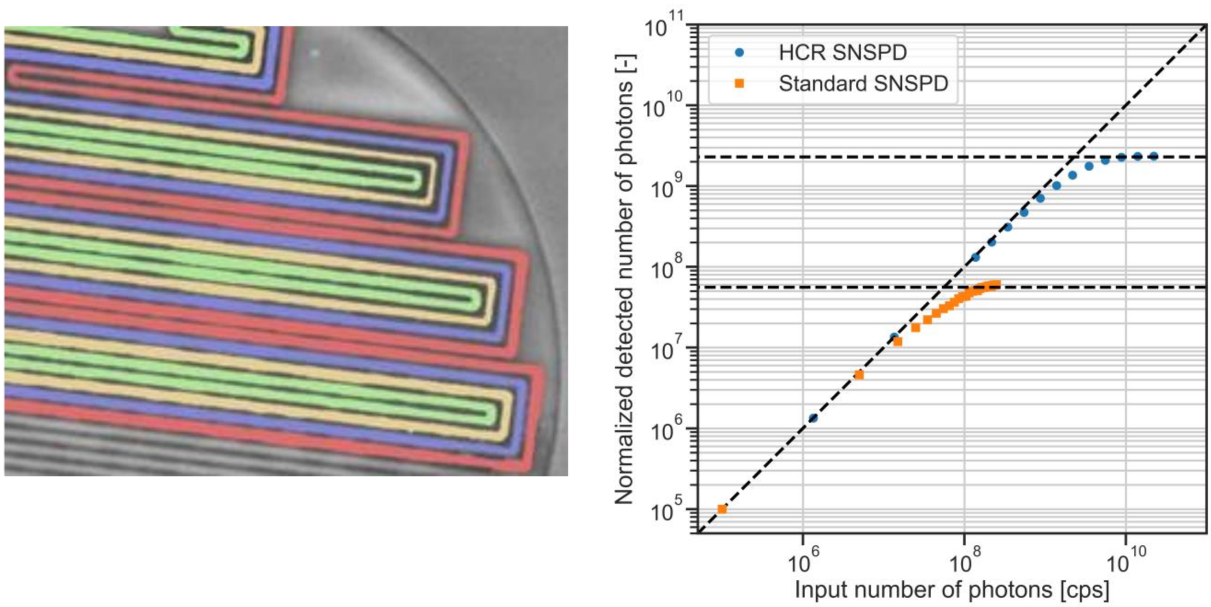

Figure 7: Interleaved SNSPD design.(a) SEM image of the detector with added color to indicate meanders of the different elements.(b) comparison of the detected number of photons for a standard SNSPD (single meander, orange squares) and an interleaved SNSPD (blue circles). The dynamic range is improved dramatically with the interleaved design.

Figure 7 (a) depicts a scanning electron microscope (SEM) image of an interleaved detector. The meanders of each element run side by side and are nested within each other, in such a way that they all have the same length and are evenly distributed through the active area, leading to the photon rate being evenly split among them. This provides a two-fold improvement: on one hand, the photon flux is divided among more elements, which increases the chances of a photon to be absorbed by an element which is not blinded by a previous detection, and on the other hand, allows each nanowire to be shorter while covering the same detection area, leading to a shorter dead time for each element. Figure 7 (b) depicts a comparison of the counts of a standard SNSPD and a 4-element interleaved

SNSPD, where it is evident the increase in the maximum count rate that the detector can handle (horizontal dashed lines), in this case more than one order of magnitude.

Model validation

In order to gain confidence in the presented model for a detector with dead time, and to test if it captures the main characteristics of an SNSPD, we take the experimental detected count rate for different input photon fluxes of various detectors previously measured at Single Quantum and fit the model of equation (1) with only the dead time as a fit parameter (the efficiency can be obtained with the low-count rate data, i.e. with the linear part of the curve). Then we can compare the dead time we get from efficiency recovery measurements.

For this procedure, we need to account for two aspects: the first one, the model is for a single element detector, so the dead time we would be extracting from the fit should be read as the effective dead time for the detector. Since the count rate is distributed equally over the different elements of the interleaved detector, given its design, we can say that the effective deadtime is four times smaller than the dead time of each element for a four element SNSPD. The second aspect is regarding the shape of the recovery curve: the model presents a step-like function for the efficiency recovery, while in reality for an SNSPD the curve is approximately a sigmoid function (see Figure 5 for an example). Therefore, the value extracted from the model can be compared with the efficiency recovery time, for example, at 50% recovery of the peak efficiency.

We depict in Figure 8 the response at high-count rates of a 4-element interleaved SNSPD, measured with a CW laser of wavelength 1542 nm. The efficiency of the detector a low-count rates is 0.75 and from the fit in the model from equation (1) to obtain an *effective* dead time $\tau_{eff} = (1.31 \pm 0.02)$ ns. Now, since we use the 4-element SNSPD as one detector, one expects that the effective dead time for the combined detector to be four times smaller than the deadtime of each individual element, since they operate as (electrically) independent detectors[1]. If we account for the fact that the time it takes for each element to reach 50% efficiency recovery is ~6 ns, $\tau_{eff} \sim \frac{6}{4} ns = 1.5$ ns, which is very close to the fitted value from the model.

[1] This statement neglect the effects of cross-talk among the different elements in the array. At the operating currents used for this measurements, the cross-talk is smaller than 0.1%.

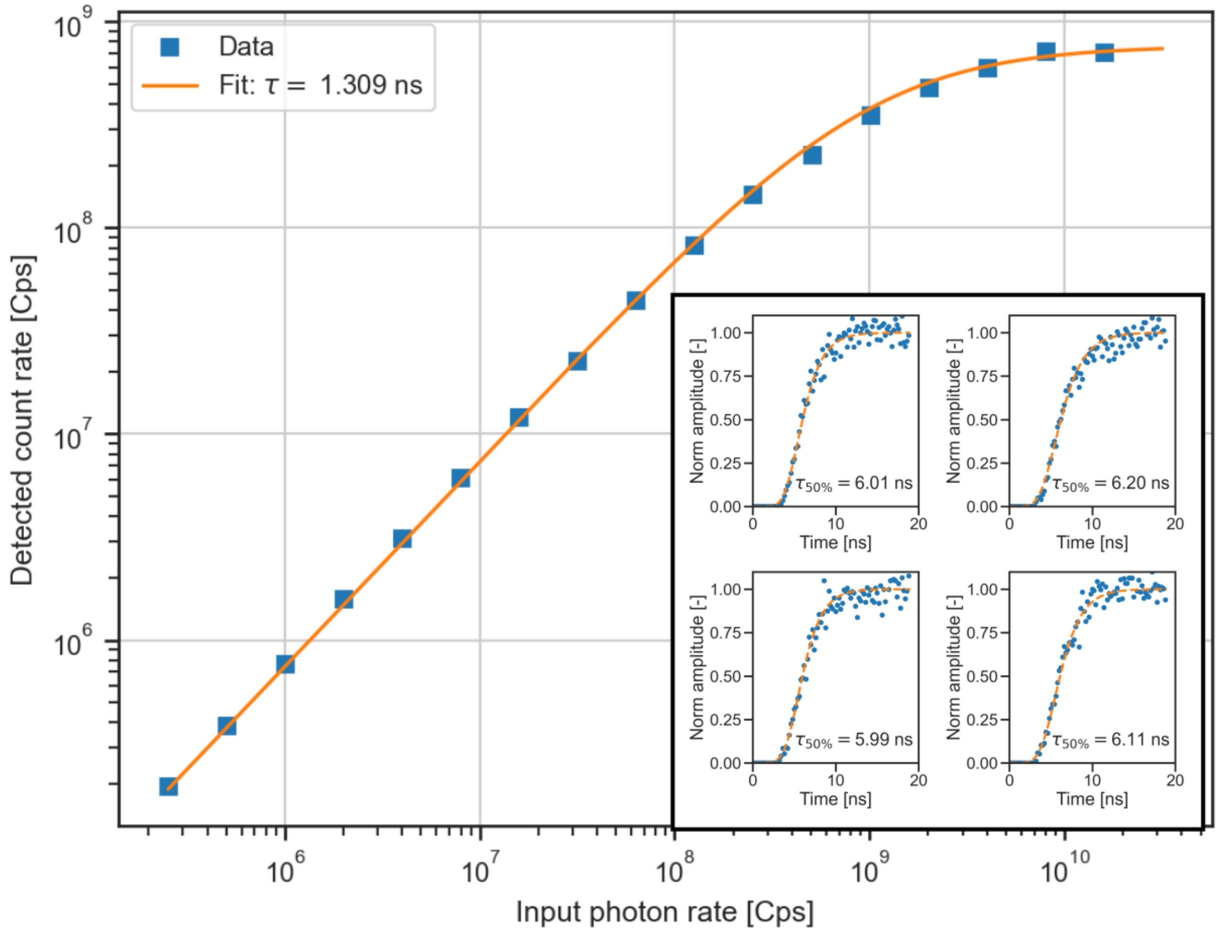

Figure 8: Detected count rate for a 4 element interleaved SNSPD for different input photon rates. The fit to the model reveals an effective dead time of 1.3 ns.The inset depicts the electrical pulse measured for each independent element of the interleaved SNSPD, resulting in an combined electrical deadtime (average) of 3.4 ns. With this dead time we estimate that the 80% peak efficiency recovery time is about 5.2 ns for each pixel.

Even though this is a simple model that does not capture all the physics behind the SNSPD detection process, by this comparison we can infer that it captures the basic limitations of a detector with a dead time working in the high-count rate regime well enough to be a valuable tool in our analysis.

Estimation of number of pixels needed

Our goal for the EPIQUE project is to produce SNSPDs that can reach 500MHz detection rates and beyond, at an efficiency higher than 90%. To achieve this, we aim to use the introduced multipixel technology with an increased number of pixels. The main question we want to answer in this section is: what is the number of pixels we need in order to achieve 500 MCPS detected count rate with 0.9 efficiency?

We assume a low-count rate efficiency of 0.95, a fixed dead time per pixel of 3, 5 and 10 ns and a variable number of pixels. Then, we can manipulate equation (1) to calculate the efficiency as a function of the input count rate and extract the input photon rate at which the efficiency reaches 0.9. The results for three different single-pixel dead times are depicted in Figure 9, where we plot the *detected* count rate at which the efficiency drops to 0.9 as function of the total number of pixels is the multi-element SNSPD. We note a linear trend, with the slope being related to the dead time of a single pixel. If we take the intermediate value of 5 ns as the benchmark, we need at least 42 elements to reach the 500MCPS detection rate. If we would like to push this to 1GCPS, then a total of at least 84 elements would be needed.

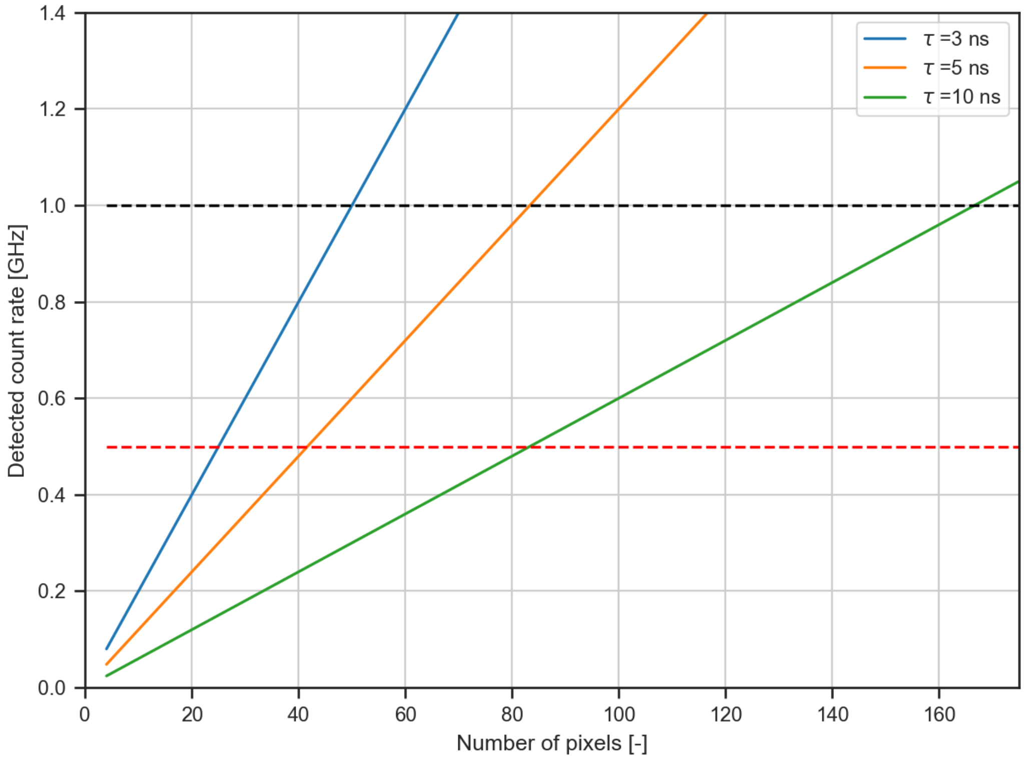

Figure 9: Detected count rate at which the efficiency drops to 0.9 for multipixel SNSPDs. We kept constant the dead time for each pixel and assumed a low-count rate efficiency of 0.95. The horizontal dashed lines depict the target count rate of 500MHz (red) and 1GHz (black). From the intersection of the horizontal lines and the different lines we can extract the needed number of pixels for the multi-element SNSPD.

Conclusions

We have presented a basic model based on the statistical properties of a detector with a dead time and used it to model the behavior of a multi-element SNSPD. Based on the good agreement between the experimental data and the model prediction, we use further this model to estimate the needed number of pixels in an SNSPD to reach an efficiency of 0.9 at a detected count rate of 500MCPS. For this high-performing detector we would need at least 42 elements, which is more than twenty times larger than the tested detectors so far. Moreover, if we aim to reach 1GCPS detected rate, the number of pixels becomes even larger, in the order of 82.

Bibliography

A. Vetter, S. F. (16). Cavity-enhanced and ultrafast superconducting single-photon detectors. *Nano Letters*, 7085-7092.

Bédard, G. (1975, July). Dead-Time Corrections to the Statistical Distribution of Photoelectrons. *Journal of the Optical Society of America*, 131–41.

C. Schuck, W. H. (2013). Waveguide integrated low noise NbTiN nanowire single photon detectors with milli-Hz dark count rate. *Scientific Reports*, 1893.

F. Marsili, F. B. (2012). Efficient single photon detection from 500 nm to 5 μm wavelength. *Nano Letters*, 4799-4804.

F. Marsili, V. B. (2013). Detecting single infrared photons with 93% system efficiency. *Nature Photonics*, 210-214.

G. N. Goltsman, O. O. (2001). Picosecond superconducting single-photon optical detector. *Applied Physics Letters*, 705-707.

Gourgues, R. (2020, Jan). Superconducting nanowire single photon detectors. *Dissertation*. Ghent University.

J. K. W. Yang, A. J. (2007). Modeling the electrical and thermal response of superconducting nanowire single-photon detectors. *IEEE Transactions on Applied Superconductivity*, 581–585.

K. Inderbitzin, A. E. (2012). An ultra-fast superconducting Nb nanowire single-photon detector for soft X-rays. *Applied Physics Letters*, 162601.

M. D. Eisaman, J. F. (2011). Invited review article: Single-photon sources and detectors. *Review of Scientific Instruments*, 071101.

Misael Caloz, B. K. (2019). Intrinsically-limited timing jitter in molybdenum silicide superconducting nanowire single-photon detectors. *J. Appl. Phys*, 164501.

W. Zhang, J. H. (2019). A 16-Pixel interleaved superconducting nanowire single-photon detector array with a maximum count rate ex-. *IEEE Transactions on Applied Superconductivity*, 1-4.

W. Zhang, L. Y. (2017). NbN superconducting nanowire single photon detector with efficiency over 90% at 1550 nm wavelength operational at compact cryocooler temperature. *Science China Physics, Mechanics & Astronomy*, 120314.