MEMS-made Electron Emission Membranes (MEMBrane)

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Duration: 60 months

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<th>Proposal summary</th>
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| I propose a radically new and generic type of detector for photons, electrons and energetic charged particles: a stacked set of curved miniature dynodes in vacuum, created through MicroMechanical Electronic Systems (MEMS) fabrication techniques on top of a state-of-the-art CMOS pixel chip. This combination in itself is an extremely efficient electron detector. By capping the system with a traditional photocathode, a highly sensitive timed photon counter can be realized, outperforming all existing photon detectors. By capping it with an Electron Emission Membrane, a timed particle tracking detector is realized with a time resolution far superior to current particle detectors.  
The core innovation, i.e., the stacked curved dynodes on top of a pixel chip, will revolutionize electron detection in solid-state, atomic and molecular physics experiments. As a photon detector, it will have pico-second time resolution, much better than classical photomultipliers, at low noise. This will have impact on the field of medical imaging, optical communication, night-vision equipment and even 3D image recording by measuring the time-of flight of photons from a flashlight. As a particle detector, it will allow faster and higher-resolution measurements of the trajectories of fast charged particles, essential in modern particle physics experiments. Its time resolution is three orders of magnitude better than state-of-the-art Si planar detectors, opening new horizons for (vertex) tracking, time-of-flight spectrometers, track pattern recognition and trigger detectors.  
The realization of this detector concept requires high-risk/high-impact developments in the area of (1) fundamental understanding of electron emission, (2) the MEMS-based fabrication of novel curved transmission dynodes and (3) high-efficiency Electron Emission Membranes. To achieve these objectives, the PI will lead a concerted effort of technical physicists and theoreticians. |
B1(c) Extended Synopsis

A radical new concept in the detection of electrons, photons or high-energy charged particles.

Photon detection state-of-the-art: Since its initial development in 1934 the photomultiplier (PM) has been the fastest and most sensitive photon detector. It has, however, three major limitations: its lack of spatial resolution, its volume and mass, and its price. Due to improving the efficiency (QE) of the photocathode, by segmenting the anode, and by miniaturization, PMs continue to be popular and widely applied [1]. Photovoltaic cells developed in the 1950s ultimately resulted in photodiodes, CCDs and CMOS image sensors. As the electron/hole charge, associated with the absorption of a single photon in a depletion layer, is rather small, the detection of single photons requires electron multiplication. This is achieved in the semiconductor analog to photomultipliers: the Avalanche Photo Diode (APD), with its high reverse bias voltage over the depletion region. In the last decade, the interest in silicon photomultipliers (SiPM) has greatly increased: Single Photon Avalanche Diodes (SPADs), Geiger-Mode Avalanche Photo Diodes (GM-APDs) as well as their digital equivalents such as Digital Photon Counters (dSiPMs) and SPAD/TDC arrays, are developing rapidly [2].

Proposed breakthrough: As outlined, both the classical PM and its modern solid-state successors have distinct advantages and disadvantages. I propose a radically new and generic type of detector, combining the best of both worlds: a stacked set of curved miniature dynodes in vacuum, created through MicroMechanical Electronic Systems (MEMS) fabrication techniques on top of a state-of-the-art CMOS pixel chip. This combination in itself is an extremely efficient electron detector. By capping the system with a traditional photocathode, a highly sensitive Timed Photon Counter (TiPC or ‘Tipsy’) can be realized, outperforming all existing photodetectors. By capping it with an Electron Emission Membrane a timed energetic charged particle counter (‘Trixy’) is realized with a time resolution far superior to current particle counters. The realization of this generic detector concept requires high-risk/high-impact developments in the area of fundamental understanding of electron emission, and the MEMS-based fabrication of (curved) structures such as the transmission dynodes and CMOS pixel chips.

Impact: The proposed detector concept can be safely designated as revolutionary: Tipsy will have picosecond time resolution (1000 times better than classical PMs), very low noise, excellent spatial resolution and rate capabilities. It will have impact on the field of medical imaging (notably PET scanning), optical communication, night-vision equipment and even truly 3D image recording. The time resolution of Trixy is three orders of magnitude better than state-of-the-art Si planar detectors now widely applied in particle physics experiments, opening new horizons for (vertex) tracking, time-of-flight spectrometers, track pattern recognition and trigger detectors. The core innovation of Tipsy and Trixy (i.e the stacked curved dynodes on top of a CMOS pixel chip) will revolutionize electron detection in solid-state, atomic and molecular physics experiments.

The Timed Photon Counter ‘Tipsy’ single soft photon detector

Principles: A soft photon (0.1 µm < λ < 1 µm), entering through Tipsy's window, interacts with the photocathode. Due to the photo-effect, an electron is emitted into the evacuated space under the window. This electron is accelerated towards the first dynode, put at positive potential of ~ 150 V with respect to the photocathode. This dynode is an ultra-thin silicon-nitride layer with cone-shaped protrusions, shown in Fig 1.
These cone shapes create an electric field between the following dynode, focusing the electrons towards the top of the cones, away from the non-active support areas. The electrons arrive at the first dynode with an energy of ~150 eV. At the point of impact, secondary electrons are emitted not only from the top of the layer, but also from the bottom, due to the thickness of this transmission dynode of only 15 nm. Secondary electrons emitted from the top will fall back; those emitted from the bottom accelerate towards the next dynode. With a secondary electron yield Y and a number of sequential dynodes N, a gain G = Y^N is reached. With Y = 4 (typical for dynodes in a PM), and five dynodes, an average charge of 1 k electrons is collected onto the pixels' input pad, which is sufficient for detection [4,5,6]. With seven dynodes, a charge of 16 k electrons causes a potential change of the input pad of one volt, which can be considered as a digital signal.

**Performance:** The response time of the Tipsy detector, determined by the time it takes for the electrons to pass through the gaps between the photocathode, dynodes and pixel chip, is of the order of 50 ps. The time resolution to detect a single soft photon is mainly determined by the time the electrons take to cross the last gap between the last dynode and the pixel anode, and can be of the order of a ps. The spatial resolution of ~10 μm, in both horizontal directions is determined by the pixel pitch. The high granularity of the independent pixels allows a high multiplicity of coincident multi-photon detection while keeping the occupancy low. The maximum event rate of the device can be extremely high because of the short response time of 50 ps. Since Lorentz forces, acting on the free moving electrons are orders of magnitude smaller than the electrostatic forces, the operation of Tipsy detectors is not affected by a magnetic field, opposite to classical PMs. In addition, the repetitive focusing throughout the dynode stack positively contributes to this. In Tipsy's discrete multi-dynode system the energy of an electron-to-be-multiplied is much higher than the binding energy of electrons in the dynode material. In SiPMs, this energy is of the order of the band gap, and multiplication generates noise and bias current. Another drawback of SiPMs is the electron/hole mobility, limiting the effective speed of charge displacement, and therefore the charge signal speed.

The separation of the functionalities of photon absorption/conversion and electron multiplication of Tipsy, and the passive electron multiplication of the thin membranes makes it intrinsically superior in terms of noise, speed (time resolution, signal duration and detector response time), in photon spatial resolution, in detector occupancy, and in radiation hardness.

**The fundamental advantage of Tipsy over current photodetectors is the fact that its fast (charge) signal is generated by a small displacement of free, accelerated electrons in vacuum. The vacuum electron multiplier is free of bias current and noise. Furthermore, the fine granularity allows a good spatial resolution and a low occupancy even at high counting rates with multiple hits.**

Tipsy's efficiency to detect photons is determined by the Quantum Efficiency (QE) of the state-of-the-art photocathode (20 - 40 %) while future SiPMs may achieve even higher efficiency. In this proposal we will develop theories and practical methods (i.e. surface processing) that may result in the development of very high QE photocathodes (see Objective 2: the Electron Emission Membrane, and Objective 3: Theory).

**Applications.** Tipsy could replace any PM and SiPM: its volume is an order of magnitude smaller, and it provides more, and more precise, information. When applied as readout of scintillators, its high spatial resolution in combination with the time resolution per photon could provide 3D information of the distribution of the ionization, i.e. the conversion point of an X-ray quantum or gamma in a scintillator. The energy resolution of such a single photon counting detector would be excellent. The performance of PET and SPECT medical imaging scanners would greatly benefit from Tipsy's time and spatial resolution. The excellent energy resolution allows a good suppression of Compton events [7].

With Tipsy, high-resolution imaging will be possible with minimum light (night goggles). The measurement of the time-of-flight of reflected photons originating from a flashlight would provide true 3D images. With ps time resolution, corresponding to 0.2 mm spatial resolution in distance, this will be interesting for metrologists, and possibly consumers. The ultra-fast and potentially low-cost Tipsy sensor can also be applied in optical (fiber) communication systems and in optical (quantum) computers.

**The Trixy tracking detector for charged energetic particles**

While Tipsy is sensitive for soft photons, Trixy detects fast charged particles. Instead of a photocathode, Trixy has an Electron Emission Membrane (EEM). The unique property of this membrane is that it is highly likely to emit at least one electron after the passage of a charged particle, at the crossing point of the membrane and the particle's track. The time resolution of Trixy can be of the order of a ps, and its (track)
position resolution would be limited only by the pixel size of its CMOS readout pixel chip.

Applications. The time resolution of a Trixy detector is three orders of magnitude better than state-of-the-art Si planar detectors now widely applied in particle physics experiments [8]. This opens a new horizon for (vertex) tracking, for Time-of-Flight spectrometers, for track pattern recognition and trigger detectors.

The Trixy detector would outperform state-of-the-art semiconductor tracking detectors in terms of time resolution, rate capability, and radiation hardness.

Both the Tipsy and Trixy detectors are of great interest for bulk-volume particle physics experiments like ATLAS, CMS, Super-Kamiokande, Icarus in Gran Sasso, and several bi-phase Argon/Xenon v-less Double Beta Decay and Dark Matter experiments. The unit, formed by the dynode stack on top of the CMOS pixel chip is an electron detector that will be widely applied in solid-state, atomic and molecular physics experiments.

Objective 1: The Electron Multiplier: Transmission Dynodes [1] + 1.5 PhDs + engin. support

In a photomultiplier, electron multiplication occurs in the successive dynodes, resulting in a detectable charge pulse after the last dynode. We intend to develop, by means of Micro Electronic Mechanical Systems (MEMS) technology, a stack of miniature transmission dynodes, placed on top of a pixel chip as charge sensitive, segmented sensor. Instead of reflective dynodes, typical for photomultipliers, secondary electrons are emitted here from the bottom of the ultra-thin layers, after the impact of accelerated incoming electrons at the top [5]. The layout of such an electron multiplier is depicted in Fig 2. With state-of-the-art MEMS technology, ultra thin membranes can be made [9]. We intend to create for the first time a stack of curved thin layers forming the dynodes by the deposition of CVD silicon nitride onto a lost template: the template is removed by dry etching.

The conical shape of the protrusions has several positive aspects: a cone is more rigid, stable and stronger than a flat membrane with the same projected area. The electric field above the cone, as well as the field beneath the cone, focus the incoming, respectively the emitted electrons onto the tip of the cone, respectively the following cone (or pixel input pad). This focusing of the field above the cone array is of special interest for the first dynode: the efficiency of the Tipsy and Trixy detectors is proportional to the transmission efficiency of the photo- or EEM-emitted electrons. Electrons arriving at the not-active area between two adjacent cones will not be detected. This is not relevant for the next dynodes where a limited efficiency results in a reduction of the effective secondary electron yield (SEY), which can easily be compensated for by a higher potential difference between the dynodes, or a larger number of dynodes.

As layer material we intend to apply doped silicon nitride; crucial is the SEY as a function of the layer thickness and the energy of the incoming electrons [5,6]. Since this energy is of the same order as required in photomultipliers (~150 eV), the sequence of potentials of the dynodes is also comparable. As a result, the electric field in a gap between two dynodes is quite strong, but still orders of magnitude away from discharge risks (Fohler & Norheim limit for cold emission in vacuum [10]). A compromise must be found for the (distribution of the) electron emission work function: a low value favors the yield, but also limits the impact energy of the electrons. If sufficient yield cannot be reached, the layer could take the form of a multilayer, with better emission properties [11].

The dynode material must be slightly conductive: since more electrons leave a dynode than arrive, the vacancies must be compensated. The compensating current is largest for the last dynode. The horizontal voltage drop over a dynode due to the compensation current should not exceed ~5 V. The horizontal resistivity may be reduced by the deposition of a metal layer onto the dynode layer, in the area of the support pillars. There is a special requirement for the last dynode: the compensation of vacancies must occur within pico-seconds in order not to induce positive charge on the pixel input pad, reducing the effective (electron) charge signal. If the requirements of the first dynode, concerning focusing, can be combined with the requirements of the last dynode, concerning conductivity, then all dynodes can be identical. First prototype Tipsy detectors could be produced as soon as single dynodes can be made: a stack of these dynodes could be
placed on top of a pixel chip. In a later stage, the stack of dynodes could be made in one monolithic process. Ideally, the electron multiplier is made in a Wafer Post Processing sequence, as integrated monolithic device using the pixel chip (in wafer format) as substrate.

**Objective 2: the Electron Emission Membrane (EEM) [PI +1.5 PhD + engin. support]**
The essential property of this foil is the emission of at least one electron after the passage of a fast charged particle, close to the crossing point of the particles’ track and the foil surface. By means of photon exchange, the fast charged particle interacts with mainly the electrons in the foil. An electron with sufficient energy may cross the foil material and escape from the foil surface into the vacuum space, away from the foil. With the electron multiplier, as in Tipsy, the position of this electron, and its time of creation can be measured precisely. The emission efficiency (yield) of plain aluminium or copper foils is known to be 2 – 4 % [12]. We intend to develop a foil with electron emission yield larger than 50 percent: 1) by applying a material or coating with a low or negative work function; 2) by applying a multilayer with specific charge carriers transport properties [13]; 3) by applying a strong extracting electric field; and 4) by surface treatment: since only the skin (depth ~ 20 nm) of the surface contributes to electron emission, the yield increases when the emitting surface is increased. The ultimate yield increase by surface roughening would be reached by means of fractalising [14].

**Objective 3: theory [PI + 1 PhD + 1 Postdoc]**
For the development of EEMs, knowledge of the processes that lead to the emission of an electron from the surface into the vacuum is required. A fast charged particle passing through matter transfers energy to (bounded) electrons close to the track, resulting in a change in the distributing of their energy. This change depends on the state and energy distribution of electrons before the passage. This energy distribution propagates throughout the solid, while changing. At the surface, this energy distribution, together with the distribution of the escape potential, determines the probability to emit an electron into the vacuum. A high yield EEM may be possible using field-assisted emission multilayer technology [9]. A strong extracting field is expected to favor the electron emission yield: experiments will be supported by theory. This theoretical knowledge is required for the development of a high-yield EEM. It would also be relevant for optimizing the parameters determining the secondary electron yield of transmission dynodes: the incident electron energy, the material(s) and membrane thickness. It may also contribute to the development of new high QE photo-cathodes. This would reduce the only disadvantage of Tipsy with respect to potentially full-efficient future Si-PMs.

The Theory Objective may require ab initio and Monte Carlo simulations, and measurement of atomic emission spectra in order to obtain the binding energies of electrons in the solid.

**Parallel development: the CMOS Readout Pixel Chip**
This proposal is based on previous work by the PI in which detectors were constructed by means of MEMS technology on top of VLSI CMOS pixel chips [15]. For this, the TimePix chip has been developed [16], and its successor TimePix-3 is due to be submitted in August 2012. Although the TimePix chips are fully suitable for testing the electron multipliers proposed here, I have requested funds from the Dutch Technology Foundation STW to achieve further improvements in the CMOS pixel chip in parallel to the ERC project. Such improvements could exploit the full potential performance of our new electron multiplier:
- Anticipation of the ultra fast digital signal at the input pad: no preamps (in each pixel!) required;
- Processing of ultra-fast digital signal with ps rise time. This is an extreme situation, since the source charge signals are due to the displacement of free electrons in vacuum, and not speed limited by the electron & hole mobilities of Si-CMOS chips;
- Time registration with respect to external clock, with ps resolution, per pixel;
- Data communication interface, granularity, occupancy: an event in a Tipsy detector may include a large number of coincident soft photons, each of which timing may need to be registered and communicated.

The PIs institute Nikhef is member of the Medipix Consortium of CERN, and is actively participating in the design and development of new pixel chips.

**Methodology and team**
The objectives of this project will be addressed in parallel over the project duration of 5 years.

**Main risks.** One point of risk of the proposal is the Secondary Emission yield that can be obtained with the proposed thin transmission dynodes made of silicon nitride. The yield is expected to rise with electron energy at impact in the dynode, and thus with the potential differences over the dynodes, but the maximum
field strength between dynodes is limited to avoid breakdowns. Consequently, a higher yield should be possible with a larger distance between dynodes. This must be studied empirically: the properties of doped Si$_3$N$_4$ are not known in this respect. A sufficient yield seems possible with a larger distance between the dynodes, and sufficient gain could be reached with a larger number of dynodes. A second point of risk is the achievable yield of the Electron Emission Membrane. The only available information concerns Cu and Al foils, and Al foils with oxide surface. The yield measurement ranges between 4 and 6 percent. We intend to measure first the intrinsic electron yield of bi-alkali layers, with no surface treatment, by placing a PM without scintillator in a muon beam. Here, too, important experimental data is expected in the first half of 2012. An EEM with yield of 50% would be useful since a stack of four Trixy detectors would have a track detection efficiency of 94%. As new surface treatment technology becomes available, this yield is expected to grow in the future.

**Team and host institution.** At the core of the team are the PI, 4 PhD students and one Postdoc. One PhD and the Postdoc will focus on theory. Three PhDs will devote their time to MEMS technology and instrumentation for testing devices. They will work closely together with a PhD designing the CMOS VLSI circuitry (funded from other sources). The PI has a track record of inventing and leading the development of major detector innovations, for example for LHC experiments at CERN. For MEMS technology he will exploit existing collaborations with MESA+ (Univ. of Twente), DIMES (Delft University of Technology), IZM-Fraunhofer (Berlin) and IMEC (Louvain). The PIs institute Nikhef includes outstanding mechanical, engineering, electronics and ICT support groups.

**Budget required.** In total a budget of 2.4 MEuro is requested, mostly to fund the PI (50%), 4 PhDs (incl. fees for working in the MEMS labs), the Postdoc, and dedicated engineering support.

**Latest information.** We are currently achieving various exciting (experimental) advances relevant to this proposal. The latest progress can be found at [www.nikhef.nl/~d90/ERC](http://www.nikhef.nl/~d90/ERC) using the password tipsy.

**References**


Section 2: The Project proposal

In this proposal, I outline a radically new and generic type of detector for photons, electrons and energetic charged particles. The detector is based on the age-old design of photon detectors in which photons create electrons, which in turn are multiplied via various bulky dynode stages. We will miniaturize this design by creating a stacked set of curved miniature dynodes in vacuum through MicroMechanical Electronic Systems (MEMS) fabrication techniques on top of a state-of-the-art CMOS pixel chip. This combination in itself is an extremely efficient electron detector. By capping the system with a traditional photocathode, a highly sensitive timed photon counter (TiPC or ‘Tipsy’) can be realized, outperforming all existing photon detectors. By capping it with an Electron Emission Membrane a timed energetic charged particle counter (‘Trixy’) is realized with a time resolution far superior to current particle counters. The realization of this generic detector concept requires high-risk/high-impact developments in the area of fundamental understanding of electron emission, and the MEMS-based fabrication of (curved) structures such as the transmission dynodes and CMOS pixel chips.

a. State-of-the-art and objectives

a.1. Detecting photons

Photomultiplier tubes. The detection of (single) photons is an essential experimental tool for a wide range of research areas. Photon detection is achieved using a photomultiplier (PM) design dating back to 1934 (see frame). PMs have been improved continuously since then: the quantum efficiency (QE) of the photocathode has been improved; field-assisted photocathodes have been developed; multi-anode PM tubes to achieve some spatial resolution (1D and 2D); and finally PMs have been miniaturised by reducing their volume and mass. An example of the latter development is the μPMT of Hamamatsu, shown in Fig 2. Although no longer bulky and coarse, this new generation of the classical PM tube still has a small fiducial surface and no spatial resolution.

The classical photomultiplier (PM)
The photomultiplier (invented in 1934) is a sensitive, low-noise and fast light detector.

Fig 1. Typical photomultiplier. A soft (low-energy, i.e. infra-red, visible or ultra-violet) photon, created in, for instance, a scintillator, is converted in the photocathode into a low-energetic electron, emitted into the vacuum. This electron is accelerated towards, and focussed onto the first dynode, releasing secondary electrons. This multiplication is repeated in subsequent dynodes, resulting in a measurable electric charge at the anode.

PMs have been, and still are, used extensively in scintillating detectors in nuclear and particle physics, in astronomy, medical diagnostics, and security (imaging) devices. They have been perfected during their 70 years of existence: the quantum-efficiency of the photocathode has now reached a level of 40%, close to the theoretical maximum; electrostatic focusing by careful design of the 1st dynode have improved the single photon sensitivity and the time resolution. With new coatings the secondary electron yield of dynodes has greatly improved, reducing the required number of dynodes, and reducing their size. Nevertheless, PMs are expensive, voluminous, rather massive and they do not operate in magnetic fields. They are not photon-position sensitive, their time resolution is limited to ~ 0.5 ns, and their efficiency is determined by the quantum efficiency of the photocathode.
The MEMS made miniature μPMT, announced by Hamamatsu. It consists of a separated sensitive photo cathode area, and photoelectrons are accelerated horizontally towards the multiplier placed next to the cathode area. As a consequence, this μPMT has no spatial resolution, and only 10% of its area is sensitive. The tendency towards small gaps between adjacent dynodes, however, with a strong electric field as consequence, is obvious, and supporting the premises of this proposal. Although announced since 2010, this μPMT is not yet available [1].

From vacuum tube to semiconductor device. A major step forward in photon detection started in the 1950s, when photovoltaic cells were developed, ultimately resulted in photodiodes, CCDs and CMOS image sensors. Since the electron/hole charge, associated with the absorption of a single photon in a depletion layer, is rather small, the detection of single soft photons requires electron multiplication. This is realized in the semiconductor analogy to photomultipliers: the Avalanche Photo Diode (APD), with its high reverse bias voltage over the depletion region in which electron multiplication occurs. Although thin, flat and cheap, the quality of these devices in terms of noise and speed is limited.

Silicon PMs. Now, diode-based devices with high internal gain known as Silicon Photomultipliers (SiPMs), consisting of arrays of Geiger-Mode Avalanche Photo Diodes (GM-APDs) or Single Photon Avalanche Diodes (SPADs), as well as their digital equivalents such as Digital Photon Counters (dSiPMs) and SPAD/TDC arrays, are being developed in rapid succession. These SiPMs (see Fig 3) are considered the current state-of-the-art, yet they still suffer from various setbacks. For example, the energy of an electron-to-be-multiplied is only of the order of the band gap, and multiplication generates noise and bias current. Another limitation of SiPMs is the low electron/hole mobility, limiting the effective speed of charge displacement, and therefore the charge signal speed.

The fundamental challenge. Driven by a range of fundamental scientific challenges, for example in medical diagnostics, in high-energy and particle physics, better photon detectors are urgently needed. I propose a new and generic detector concept combining the best of the world of classical PM tubes and of the new generation of Silicon PMs. It consists of a multiple dynode assembly, fabricated on a micron scale, combined with a CMOS pixel chip with specific functionality per pixel, for spatial resolution. When combined with a photocathode, the detector functions as a highly efficient photon counter, called Tipsy (“Timed Photon Counter” of TiPC).
a.2. The Tipsy Photomultiplier

Tipsy is a detector for soft photons consisting of a pixel anode chip, covered with a stack of dynodes, as depicted in Fig 4.

![Image of Tipsy Photomultiplier]

*Fig 4. The Timed Photon Counter ‘Tipsy’. The electron-multiplication dynodes take the form of ultra-thin curved membranes.*

The monolithic assembly of the pixel chip and the stack of dynode membranes is placed in a sealed vacuum container. The entrance window has a coating acting as photocathode and is put at negative potential. Electrons released from the photocathode are accelerated, as in a PM, towards the first dynode put at positive potential with respect to the photocathode. At the point of impact, secondary electrons are emitted at both sides of the membrane. Electrons emitted at the window side of the membrane will fall back to the membrane; electrons emitted at the backside (a number of Y electrons on average) are accelerated towards the next dynode where the process repeats. With N membranes with a multiplication yield Y, the average electron avalanche counts $Y^N$ electrons, albeit that this number is subject to statistical fluctuations in the form of an exponential distribution. Each pixel in the pixel chip contains a preamplifier with its input pad facing the last dynode. The source capacitance, appearing at the pixel preamp input, can be as small as 10 fF, enabling to have a low-noise, fast and low-power preamp per pixel. With a multiplication (gain) $Y^N$ of only 1000 the charge is sufficient to cross the threshold of the circuitry in a pixel. This low source capacity is essential: only 5 membranes with a secondary electron yield of 4 (standard for dynodes in a PM) are required. With seven dynodes, a digital signal of 1 V is generated onto the input pad of the pixel circuitry, omitting preamplifier stages.

**Tipsy's performance.** Secondary electrons have a low energy of up to a few eV at their moment of creating before they are accelerated towards the next dynode. Following a straight ballistic (non-relativistic) path, they arrive at the next dynode after crossing time $t_c$:

$$t_c = D \sqrt{\frac{2m}{qV}}$$

in which $D$ is the gap size between the dynodes, $m$ the electron mass, $q$ the electron charge and $V$ the potential difference between two consecutive dynodes. With $V$ fixed at 150 V, $t_c = 0.28$ D ($t_c$ in ps, $D$ in μm). In our case, this crossing time is of the order of 5 ps.

Incoming photons are detected with a spatial resolution, in two dimensions, of order 10 μm, typically determined by the pixel pitch. With a distance between photocathode and the first dynode of ~50 μm, transverse momentum of the photo-electron has no effect on this position resolution. The response time (between the moment of the creation of the photo electron and the avalanche on the pixel input pad) equals...
the number of gap times the average crossing time (6 x 5 ps = 30 ps). The time resolution is expected to be excellent due to the small travel distances of the electrons between the last dynode and the pixel input pad (~2 ps).

The reaction time of the device is therefore 50 ps, and its time resolution could be as good as 1 ps per photon. The device should operate well in magnetic fields since the electrostatic force on the electrons is much larger than the Lorentz forces. Since the device consists of only ceramic, passively (non-semiconducting) used materials, it will be radiation hard. The CMOS pixel chip could be a limiting factor in the performance of Tipsy, and new circuitry needs to be developed.

**Tipsy's advantages with respect to SiPMs.** In Tipsy's discrete multi-dynode system the energy of an electron-to-be-multiplied is much higher than the binding energy of electrons in the dynode material. In SiPMs, this energy is of the order of the band gap, and multiplication generates therefore noise and bias current. Another limitation of SiPMs is the electron/hole mobility, limiting the effective speed of charge displacement, and therefore the charge signal speed. The separation of the functionalities of photon absorption/conversion and electron multiplication of Tipsy, and the passive electron multiplication in the thin membranes makes it intrinsically superior in terms of noise, speed (time resolution, signal duration and detector response time), in photon spatial resolution, in detector occupancy, and in radiation hardness.

The principle advantage of Tipsy over its competitors is the fact that its fast (charge) signal is caused by a small displacement of free, accelerated electrons in vacuum. The vacuum electron multiplier is free of bias current and noise. Furthermore, the fine granularity allows a good spatial resolution and a low occupancy even at high counting rates with multiple hits.

The efficiency of Tipsy is limited to the QE of up to 40% of a modern photocathode, where future SiPMs, may reach full efficiency.

**Applications.** Tipsy’s could replace any PM: it is an order of magnitude less voluminous, and it provides only more and more precise information. When applied as readout of scintillators, its high spatial resolution in combination with the time resolution per soft photon could provide info of the (3D) origin of the photon, i.e. the conversion point of a hard photon (i.e. X-ray quantum or gamma) in a scintillator. Since, in principal, individual soft photons are registered, the energy resolution of a scintillator equipped with a Tipsy detector is excellent. The performance of PET medical imaging scanners would benefit greatly from Tipsy’s time resolution and the spatial resolution, respectively. Points of positronium annihilation can be 3D reconstructed with 0.2 mm precision in the direction of annihilation, and with micron precision in two directions in the perpendicular plane. Compton events could be suppressed effectively given the good energy resolution. The low noise and the high rate capability allows short exposure times [2]. By applying Tipsy as sensor in a (consumer) camera, superb imaging would be possible with a minimum of light (night goggles). When a digital camera is equipped with Tipsy, true 3D images could be made by measuring the time-of-flight of photons from a flashlight. With 1 ps, equivalent to 0.15 mm distance resolution, it would become of metric interest. As electron detector, Tipsy’s multiplier and readout pixel chip would be a useful device in atom-, molecule- and solid state physics experiments. Tipsy would be important in space research, astronomy, in fiber optics, data communication, and possibly in future Quantum computers.

**a.3. Detecting fast charged particles**

The new detector concept I propose has implications to other experimental challenges as well. For example, it is the basic component of a revolutionary fast charged particle tracker.

**Particle detectors.** In modern particle physics experiments, the so-called ‘inner tracker’, build around the interaction point (see Fig 5), is the black sheep of the family of particle detectors. Their function is to determine the trajectory of (charged) particles, created in an event of colliding accelerated particles. Typical detector requirements are:
- good spatial resolution for accurate trajectory determination;
- good time resolution for event separation;
- low mass in order to limit multiple scattering, influencing the particles’ trajectory, and to limit the generation of background radiation;
- high processing speed in order to limit the detectors’ occupancy;
- sufficiently radiation hard: the radiation dose, close to the interaction point in modern beam collider experiments can be extremely high.

![Image of particle tracks in the Inner Tracker’s Vertex Detector of the ATLAS experiment at CERN, Geneva. By measuring track positions in several concentric detection layers, the point of origin can be obtained. Due to the magnetic field, the particles’ momentum can be calculated from the track curvature. The ATLAS experiment faces the intense radiation of the superLHC proton collider with 10 times higher luminosity. Right: the principle of the semiconductor (Silicon) tracking detector.](image)

**Fig 5.** Particle tracks in the Inner Tracker’s Vertex Detector of the ATLAS experiment at CERN, Geneva. By measuring track positions in several concentric detection layers, the point of origin can be obtained. Due to the magnetic field, the particles’ momentum can be calculated from the track curvature. The ATLAS experiment faces the intense radiation of the superLHC proton collider with 10 times higher luminosity. Right: the principle of the semiconductor (Silicon) tracking detector.

**The challenge.** State-of-the-art silicon semiconductor detectors, with their support and services (power, data transfer, cooling) included, contain a (too) large amount of material. This material causes scattering of particles, resulting in errors of the measured momentum, and it causes a background of radiation. When applied in experiments at the future superLHC collider, the radiation hardness of Silicon detectors is far from sufficient, and for experiments at the future ILC or CLIC linear colliders, their time resolution falls short by an order of magnitude. The (gaseous) Gossip detectors, developed by this PI, are an interesting alternative for semiconductor detectors, but their speed is not adequate [3]. Clearly, a new generation of detectors is urgently needed. The detector concept as proposed above has the potential to successfully address these challenges. A single change is necessary: an Electron Emission Membrane (EEM) must replace Tipsy’s photocathode layer. This is next objective of our proposal.

**a.4. The Trixy tracking detector**

The electron multiplier, formed by Tipsy’s stack of dynodes (or electron multiplication membranes), would become an instrument of importance in atomic- and molecule physics, where, in vacuum, low energetic and free electrons, protons, neutrons and ions need to be registered. The essential property of the EEM membrane is the emission of at least one electron after the passage of a fast charged particle, close to the exit crossing point of the particles’ track and the membrane surface. The emitted electron can be multiplied in the electron multiplier, with low noise, maintaining all position and time info. The resulting detector would be an ultra fast and radiation hard tracking detector with good position resolution, and superb time resolution (better than 2 ps: compare ~ 5 ns for Si). The intrinsic detector mass, consisting of some 7 membranes of less than 1 µm thickness is negligible with respect to a readout pixel chip and the mass of the detector support and services.
b. Methodology

b.1. Introduction and feasibility

The key challenge at the heart of this proposal is the fabrication of a stack of curved electron-multiplication membranes (dynodes) in vacuum using MEMS techniques. This innovation, only recently possible, is based on the PIs track record in the development of gaseous tracking detectors (see part B1a of this proposal). He has previously pioneered in the Gossip/GridPix detector, outperforming Si detectors in terms of track information (per detection layer a track segment vector is obtained instead of a space point), and radiation hardness. Two essential achievements of developing the gaseous GridPix detector are a) its sensitivity for single electrons, and b) the MEMS technology to create membranes, firmly supported by insulating spacers, onto wafers of pixel chips. In Si detectors, the charge signal is created by electron-hole generation in (depleted) Si. Typical charges are 40 k electron/holes, generated along a detector thickness (or track sample length) of 300 µm. In the gaseous GridPix detector, only ~10 electron-ion pairs are generated, on average, with strong (Landau) fluctuations, in a 1 mm thick gas layer. Each of these electrons contains position and time information of the fast charged particle passing the detector. The GridPix detector is a stepping stone proposal and illustrate the PIs track record in realizing similar innovations.

b.2. Main objectives

To realize the new detector concept, the following main objectives will be addressed: (1) fabrication of electron-multiplying membranes to form the dynodes; (2) fabrication of electron-emission membranes; and (3) theoretical advances. A fourth objective, the further development of the CMOS pixel chip, will be addressed as part of a parallel project for which funding has been requested from the Dutch Technology Foundation STW. The core innovation of the ERC proposal is independent of the CMOS developments yet they will allow further exploitation and additional impact of the MEMBrane outcomes.

Objective 1: The electron-multiplying membrane

Towards a MEMS made micro-dynode. The combination of an electron multiplier and a CMOS pixel chip has been pioneered by Vallerga, who placed, in a vacuum container, a discrete Micro Channel Plate (MCP) on top of a pixel chip: see Fig 6 [4]. The fabrication of MCP structures using wafer post processing MEMS technology, however, is notoriously (too) difficult [5]. Moreover, MCPs are known to have a poor acceptance: an incoming electron has a fair chance to end in the inter-hole area where it is lost. This reduces directly the detectors' efficiency to detect single photons. A further disadvantage of MCPs is the large amplitude fluctuations of single-electron initiated avalanches. With the construction of GridPix we gained experience with constructing a perforated membranes, supported by insulating spacers [6]. Such a grid, covered with CsI, has been demonstrated to trap photon-induced electrons, emitted from the top of the membranes, effectively into the holes, after which they were successfully multiplied by gas amplification in the gap between the grid and the anode; see Fig 7 [7].

During the development of the MEMS technology for GridPix we succeeded in creating a stack of perforated grids, as is shown in Fig 8. With this in mind, electron multiplication should be possible by placing the stack in vacuum, and apply potential differences between the membranes. The alignment of the membranes should be optimised to achieve maximum electron multiplication.
Recently, at the DIMES Institute at Delft University of Technology, ultra thin layers of Silicium Nitride (Si₃N₄) have been realised: see Fig 9. These slim membranes are excellent candidates for transmission dynodes [8]. With transmission dynodes, the electron paths are the shortest possible, favouring the multiplier's speed. The electric field between two flat transmission dynodes is homogeneous: with a given potential difference of ~ 150 V, the distance between the dynodes can be reduced, in principle, until the risk of cold emission discharges occur (Fohler & Norheim limit [9]). A distance of ~ 20 μm seems possible, and an electron crosses this gap in ~ 5 ps.

Such a fragile layer with the typical size of a pixel chip (~ 15 mm x 15 mm) requires reinforcements. Composing a dynode layer from small sections, embedded in a more rigid construction, can solve this problem. This requires focusing of the incoming electrons onto the small thin active areas, avoiding electrons to end on the thicker support areas. This can be done with the 'Colosseum' structure, where secondary electrons are focused by the electric field onto the thin area of the following dynode. We propose, however, a new way to create ultra thin, but rigid structures, in the form of an array of cones, as shown in Fig 10-right. Such a bell-shaped unit is more rigid than a flat membrane with equivalent diameter, and we expect to be able to create diameters up to 25 μm. In addition, the electric fields above and below the cones have focusing properties.

Dynode material. In 1936, Cs₃Sb was introduced as material for the photocathode as well as a high-yield material for dynodes. Ceramics like BeO have been applied, and more recently doped CVD diamond is of interest [10]. Here, a low work function seems essential, and the material should have at least some conductivity. The construction of ultra thin membranes may be a more limiting factor: 15 nm thick membranes of Si₃N₄ have been made [11]. By doping this material with Si, its conductivity can be
controlled. The secondary electron yield of a thin layer of Si$_3$N$_4$ has been measured [8], but the yield seems to depend on doping and crystal orientation. Since the mechanism of electron multiplication using backside secondary electrons is rather new, we will start our research with this material. The yield of CVD diamond can be higher, but, at present, ultra-thin layers are not possible with this material. In the future, MEMS made multilayers may be possible.

The focusing of the field above the cone array is of special interest for the first dynode: the efficiency of the Tipsy and Trixy detectors is proportional to the acceptance of the photo- or EEM-emitted electrons. Electrons arriving at the not-active area between two adjacent cones will not be detected. This is not relevant for the next dynodes where a limited efficiency results in a reduction of the effective secondary electron yield, which can easily be compensated for by a higher SEY, thus increased potential difference between the dynodes, or a larger number of dynodes. One way of focusing is depicted in Fig 11.

The last dynode. The dynode material must be slightly conductive: since more electrons leave a dynode than arrive, the vacancies must be compensated. The compensating current is largest for the last dynode. The horizontal voltage drop over a dynode due to the compensation current should not exceed ~ 5 V. The horizontal resistivity may be reduced by the deposition of a metal layer onto the dynode layer, in the area of the support pillars. There is a special requirement for the last dynode: the compensation of vacancies must occur within pico-seconds in order not to induce positive charge on the pixel input pad, reducing the effective (electron) charge signal.

Dynode R&D: MEMS technology. If the requirements of the first dynode, concerning focusing, can be combined with the requirements of the last dynode, concerning conductivity, then all dynodes can be identical. Since the first and last dynodes have additional functionality, they may differ, eventually. First prototype Tipsy detectors could be produced as soon as single dynodes can be made: a stack of these dynodes could be placed on top of a pixel chip. In a later stage, the stack of dynodes could be made in one monolithic process. Ideally, the electron multiplier is made in a Wafer Post Processing sequence, as integrated monolithic device using the pixel chip (in wafer format) as substrate. A prototype dynode is already under construction at DIMES, Delft University of Technology. A process diagram is shown in Fig 12.

This single device will be tested in a vacuum container in which free electrons are generated by shooting UV laser pulses from a N$_2$ laser onto a photocathode. By comparing charge pulses from the photocathode, the
dynode and the anode placed under the dynode, the secondary electron yield $Y$, as a function of the energy of the incident electrons, can be measured. By applying an 'inverted' bias voltage between the anode and dynode, the energy distribution of secondary electrons can be obtained. A set of operational parameters (membrane thickness, membrane material doping, incident electron energy) must be established.

**Objective 2: The Electron Emission Membrane (EEM)**

The combination of Tipsy’s electron multiplier and an Electron Emission Membrane (EEM) forms a tracking detector for fast charged particles (minimum-ionizing particles or MIPs) with excellent time resolution and radiation hardness. This is the subject of the second objective.

*State-of-the-art in electron emission.* Although electron emission due to the passage of MIPs has been studied extensively for several applications, there is no conclusive theory describing the effect [12,13]. We define the yield as the probability that at least one (low energetic) electron is emitted close to the crossing point of the track of a (minimum ionizing) charged particle and the membrane surface. In a recent study, electron emission was studied for an application as beam intensity monitor: the Secondary Emission Chamber SEC [14,15]. A test chamber was build, consisting of a stack of aluminium foils, odd and even interconnected, placed in vacuum. The current between the odd and even foils is proportional to the electron emission yield and the beam particle rate. Note that this yield differs from our definition: if in an event two electrons are emitted, this is counted as one hit, but it contributes two times more current. The yield for aluminium was found to be 4-6%, depending on the thickness of the ever-present Al$_2$O$_3$ on the surface, raising the yield. Yields up to 7% have been reported. The yield furthermore changes with irradiation dose. Since the SEC is applied as beam intensity monitor, its stability is of main concern, and therefore aluminium was chosen, and its yield stability was tested. In [15], a metal-based oxide is mentioned with a yield exceeding 30%, but without reference.

*Further improvements.* There are four ways leading to a high-yield Electron Emission Membrane: 1) apply a material with low work function; 2) field-assisted electron transport in a multilayer; 3) surface enlargement, and 4) a strong electric extracting field.

1. **Low work function material.** The emission efficiency of a flat geometry has been measured for Al and Cu [16]: values were obtained up to 7%. It was noted that aluminium with a thin layer of aluminium oxide had a higher efficiency. The efficiency of CsI was estimated to be 5% [17]. One may conclude that the material’s escape potential, or work function, is influencing the yield. For metals, the escape potential has a discrete value, but for insulators, semiconductors or high-resistivity materials the escape energy has a spectral distribution that depends on the crystal orientation [10]. Our first goal is to measure the intrinsic electron emission efficiency for a variety of materials as a function of the extracting electric field. This can be done by placing a stack of test plates in vacuum, odd-even interconnected and applied on alternating HV, measuring the current directly when irradiated by an intense beam of charged particles. **We will first measure the intrinsic (flat surface) yield of well-known low escape potential materials: a simple but interesting experiment is to put a photomultiplier, without scintillator, in a low-momentum MIP beam.** Single-electron events must be due to electrons emitted from the photocathode, which has a very low work function. Some MIPs will generate Cherenkov radiation in the glass window: the generated photons may dominate the single electron event. These Cherenkov photons would not be generated if the beam enters from the opposite side (of the electrical connection). The difference between these two yields is a measure for the rate of Cherenkov events, and the electron yield could be corrected for, although the yield could be different of an incoming MIP or exiting MIP. This experiment should be a good indication for the highest possible level of the intrinsic emission yield.

2. **Field-assisted electron transport in a multilayer.** This technology is employed for active high QE photocathodes [18], and by manufacturers of night goggles for a continuous first dynode film [19]. This method to drive electrons from bulk material towards the surface must first be studied theoretically.

![Fig 13. Surface enlargement by surface modulation.](image)
3. Surface enlargement. Essentially, only the 10 – 20 nm thick skin of the surface of the membrane contributes to emission [20]: electrons from deeper simply don’t reach the surface. By patterning the surface with a sine wave, the effective surface is enlarged. If this sinus amplitude becomes large, the non-equality of the extracting electric field becomes obvious. By modulating the strong-field area by one-third of the wave period, the field strength distribution gets narrower; see Fig 13. The ultimate surface enlargement is obtained by fractalizing. The largest period of the fractal would be set by the dimension of the detector unit, and the smallest period would be set by the available technology. There are reports about an increased electron yield after roughening [21], but also the opposite [16]. This can be explained by the self-absorption of an emitted electron in an adjacent lob. It is clear that a strong extracting field would enhance the yield. Etching poly-crystalline coagulated aluminium results in a fractal-like surface. There is a major interest in surface-enlargement technology for energy storage (electric batteries and fuel cells), and for the development of catalysis. We will explore the effects of surface processing as an essential part of our project at the MEMS labs of the University of Twente (MESA+) and Delft University of Technology (DIMES).

4. Strong electric extracting field. The electric field between the emission membrane and the first dynode has two functions: 1) it should accelerate emitted electrons towards the first dynode and 2) it should help to extract electrons from the emission membrane (lowering the effective work function). The electron energy at the first dynode should be ~150 eV; this sets the potential difference. A strong field is good for both functions. The minimum distance between the emission membrane and the first dynode is determined by the maximum field strength (determined by the ‘cold emission’ discharge limit of typical 1 kV/µm), and can be quite small: 20 - 100 µm [9]. Another way to create a strong extracting field is to shape the surface into ‘needles’ (Fig 14), where a strong field occurs at the needle tip. It should be noted that the pitch of the needles should be of the order of the thickness of the emission-active skin, otherwise a needle will be too far from the track to emit an electron. We will perform empirical research, for instance on nanotubes and “nanograss” at the DIMES facility in Delft.

Fig 14. SEM images of nanoscale needle assemblies. (left) An array of silicon whiskers formed by the so-called vapor-liquid-solid growth mechanism under gold nanoparticles. (right) Silicon ‘nanograss’ obtained by anisotropic etching.

Objective 3: Theory
To support the overall development of the detector concept, a range of theoretical exercises will need to be done in order to optimize the detector design and construction. These include ab-initio analysis and Monte Carlo simulations.

Process 1: the interaction between minimum ionizing particles (MIPs) and electrons in solid state material: the energy transfer to electrons. Although photon exchange is the basic process, the energy transmitted to an electron at distance b from the track may be calculated following the classical approach of Bethe-Bloch: \( E = \frac{2q^2}{b^2 c^2} m_0 \) where \( E \) is the energy transferred to the electron, \( q \) the unit electron charge, \( c \) the speed of the fast charged particle, and \( m_0 \) the electron rest mass. Here we are interested in the energy of the electrons (Bohr-Bethe) instead of the energy loss of the MIP (Bethe-Bloch). The process results in a distribution of transferred energy to electrons in a cylinder around the track.

Process 2: Assuming knowledge of the binding energies of electrons in the material, the new state of electrons is analysed. If an electron is in the conductive band it will propagate elsewhere and may reach the vacuum. If an electron is in the valence band but not in its lowest state, it may cause secondary radiation.

Process 3: the propagation of ‘free’ electrons in the conductive band towards the membranes’ surface (absorption, scattering, diffusion). This results in the energy distribution of electrons after arrival at the surface area of the membrane;
Process 4: for this the distribution of the escape energy (work function) must be known. This distribution, together with the energy distribution from process 3, results in the emission probability.

This theoretical knowledge is required for the development of high-efficient Electron Emission Membranes, but could also be applied for the development of high-yield transmission dynodes, and it may lead to new high-QE photocathodes.

Parallel development: The CMOS readout pixel chip

The pixel chip is an essential ingredient of the Trixy and Tipsy detectors: due to the small source capacitance of the charge signal input pad, noise can be kept low while the bandwidth can be high. An avalanche of a mere 1000 electrons is capable to drive the pixel' circuitry. Since a pixel can be considered as an individual readout unit, the granularity of the complete chip is high, and the occupancy per pixel therefore low. During the last decade, state-of-the-art pixel chips have been the basis for detectors Medipix-1 to 3, TimePix, FE-I4 and PSI-46. At present, the TimePix-3 chip is being designed by Medipix Consortium at CERN [22]; submission is expected in August 2012. The PIs institute Nikhef actively participates within this Consortium to design and development of CMOS circuitry. Although the (existing) TimePix1-3 chips are fully suitable for testing the electron multipliers proposed here, I have requested funds from the Dutch Technology Foundation STW to achieve further improvements in the CMOS pixel chip in parallel to the ERC project.

Both Trixy and Tipsy produce signals with ps rise time and arbitrarily charge amplitude. It will be a challenge to develop CMOS circuitry that can process these signals and output data with the full potential in time resolution. Vladimir Gromov (Nikhef) developed the Gromov Time-to-Digit Convertor (TDC) with a resolution of 1 ns in each individual pixel. This circuitry will be applied in the TimePix-3 chip. The time resolution of the Gromov TDC can be stretched to ~ 50 ps, but for the readout of the full potential of the Trixy and Tipsy detectors another order of magnitude is required. For this, we propose to develop a Front Propagation Priority Encoder (FPPE): a digital signal propagates with a speed of $0.8 \times c = 0.2 \text{ mm/ps}$ over a chip. By placing discriminators along a delay line, in each pixel, a spatial resolution of the typical pixel pitch ($= 55 \mu m$) could be reached. The front position could be detected by a priority encoder. We are member of the STW-SOLO Initiative group 'Single Soft Photon Detection'. Within this group, we applied funding for the development of CMOS circuitry.

b.3. Methodology and team

Team and host institution. At the core of the team are the PI, 4 PhD students and 1 Postdoc: three PhDs focusing on MEMS technology and instrumentation for testing devices, and one PhD and the Postdoc on theory. Support is provided by the experienced Nikhef crew. The MEMS PhD students will closely work together with the team addressing the parallel objective of improving the CMOS readout pixel chip. The PI has a track record of inventing and leading the development of major detector innovations, for example for LHC experiments at CERN. For MEMS technology he will exploit existing collaborations with MESA+ (Univ. of Twente), DIMES (Delft University of Technology), IZM-Fraunhofer (Berlin) and IMEC (Louvain). The PIs institute Nikhef includes outstanding mechanical, engineering, electronics and ICT support groups.

Project planning. The objectives of this project will be addressed in parallel over the project duration of 5 years. The theory PhD and Postdoc start in the first month of the project and will support the project with theoretical analysis and simulation. The three MEMS technology PhDs will develop prototype dynodes, stacks of dynodes, and Electron Emission Membranes. They will spend about half of their time in MEMS laboratories (MESA+, DIMES, IZM-Fraunhofer Berlin, IMEC). They will test their own prototypes in labs at Nikhef in an infrastructure suitable for vacuum, laser and electronic technology over a period of four years. With funding from elsewhere, a CMOS designer PhD will participate in the present international design group of the Medipix Consortium at CERN. Specialized Nikhef technicians will provide support where it is needed, or their equivalent is hired at the external MEMS labs.

Main risks. One point of risk of the proposal is the Secondary Emission Yield that can be obtained with the proposed thin transmission dynodes made of silicon nitride. The yield is expected to rise with electron energy at impact in the dynode, and thus with the potential differences over the dynodes, but the maximum field strength between dynodes is limited to avoid breakdowns. Consequently, a higher yield should be possible with a larger distance between dynodes. This must be studied empirically: the properties of doped Si$_3$N$_4$ are not known in this respect. A sufficient yield seems possible with a larger distance between the
dynodes, and sufficient gain could be reached with a larger number of dynodes. A second point of risk is the achievable yield of the Electron Emission Membrane. The only available information concerns Cu and Al foils, and Al foils with oxide surface. The yield measurement ranges between 4 and 6 percent. We intend to measure first the intrinsic electron yield of bi-alkali layers, with no surface treatment, by placing a PM without scintillator in a muon beam. Here, too, important experimental data is expected in the first half of 2012. An EEM with yield of 50% would be useful since a stack of four Trixy detectors would have a track detection efficiency of 94%. As new surface treatment technology becomes available, this yield is expected to grow in the future.

**Latest information.** We are currently achieving various exciting (experimental) advances relevant to this proposal. The latest progress can be found at [www.nikhef.nl/~d90/ERC](http://www.nikhef.nl/~d90/ERC) using the password tipsy.

### b.4. References


[5] Jurriaan Schmitz. Dutch Technology Foundation (STW) project 06630 "Plenty of room at the top"


[18] Photomultiplier Handbook, Hamamatsu


c. Resources (incl. project costs)
The budget requested mainly concerns personnel: the PI (50 %), 4 PhD students, 1 Postdoc, dedicated engineering support plus the fees for the labwork at the MEMS labs in Twente, Delft and IZM-Fraunhofer.

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<td>Does the proposed research involve research on animals?</td>
<td></td>
<td></td>
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<tr>
<td>Are those animals transgenic small laboratory animals?</td>
<td></td>
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<tr>
<td>Are those animals transgenic farm animals?</td>
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<tr>
<td>Are those animals non-human primates?</td>
<td></td>
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<tr>
<td>Are those animals cloned farm animals?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>I CONFIRM THAT NONE OF THE ABOVE ISSUES APPLY TO MY PROPOSAL</td>
<td>X</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Research Involving non-EU Countries (ICPC Countries)</th>
<th>YES</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Is the proposed research (or parts of it) going to take place in one or more of the ICPC Countries?</td>
<td></td>
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</tr>
<tr>
<td>Is any material used in the research (e.g. personal data, animal and/or human tissue samples, genetic material, live animals, etc) :</td>
<td></td>
<td></td>
</tr>
<tr>
<td>a) Collected in any of the ICPC countries?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>b) Exported to any other country (including ICPC and EU Member States)?</td>
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<tr>
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<tr>
<th>Dual Use</th>
<th>YES</th>
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<tr>
<td>Research having direct military use</td>
<td></td>
<td></td>
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<tr>
<td>Research having the potential for terrorist abuse</td>
<td></td>
<td></td>
</tr>
<tr>
<td>I CONFIRM THAT NONE OF THE ABOVE ISSUES APPLY TO MY PROPOSAL</td>
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