Optical signal coupling in microchannel plate detectors with a subnanosecond performance

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For an application in high-performance mass spectrometry we adapted our recent design of a fast microchannel plate detector such that the signal output when registering a single particle is realized via optical impulses which are then forwarded to the data acquisition system. The charge impulse collected at the anode of the detector is converted to a light impulse using a vertical cavity surface emitting laser diode. Such an assembly has the advantage that the electrical circuitry at the anode is very small and thus high signal quality is achieved even in the gigahertz frequency range. Furthermore, such a detector can easily be operated at high electric potentials without the need for capacitive signal coupling. [DOI: 10.1063/1.1382640]

I. INTRODUCTION

For high-resolution time-of-flight measurements fast signal detectors are needed with temporal widths of the signal impulse of less than 1 ns when registering a single particle or photon. Typically, microchannel plate (MCP) detectors are used for that purpose. To obtain such fast signal impulses impedance matching of the geometrical extended anode to the signal transmission line is mandatory. The earliest realization of a detector with an impedance matched anode is the conical anode design.[1] A more sophisticated version of that concept is the ''Apollonius'' detector.[2,3] Most recently, we introduced a strip line design for the anode[4] that will be used in the RTOF sensor of the ROSINA instrument on the ROSETTA mission to comet Wirtanen of the European Space Agency (ESA).[5]

With shorter signal impulses, i.e., with higher frequency bandwidth of the signal, one has to pay increasing attention to parasitic capacitances and inductances in the detector and in the high voltage supply of the microchannel plates. Although the whole path from the anode to the signal cable is theoretically perfectly impedance matched, the parasitic circuit elements still cause deviations from this impedance match which results in some signal ringing, signal distortion, and even impulse broadening. Impedance discontinuities (e.g., connectors, vacuum feedthroughs) along the signal transmission line from the detector to the data acquisition electronics will cause further degrading of the signal. Therefore, we wanted to have the electrical circuitry of the signal part to be very small. Moreover, we wanted to electrically isolate the detector from the environment. Being electrically isolated has the additional advantage that no additional measures have to be taken when the detector floats at high voltages, which is often desired in mass spectrometry.

Typically, signal transmission for an electrically isolated detector is accomplished by using a high-voltage coupling capacitor in the signal line.[3,4] A different concept for signal transmission for an electrically isolated detector is to use optical transmission. One realization of this idea is to accelerate the electrons exiting from the MCP into a scintillator and register the emitted photons with a photomultiplier via a light guide.[6] Since the time resolution of the used data acquisition electronics was 10 ns nothing is known about the ultimate timing performance, but the use of photomultipliers alone makes it very unlikely that pulse widths of nanoseconds or less could be achieved. In this article we shall introduce a concept for optical signal transmission: the charge impulse collected on the anode is converted to a light impulse using a fast laser diode integrated into the anode circuitry. The optical signal is then transmitted to the data acquisition via an optical fiber.

The technology we used is adapted from the state-of-the-art high speed optical fiber data transmission lines. We decided for laser diodes to achieve the fast signal speeds we need in our applications. The vertical cavity surface emitting laser (VCSEL) diodes feature easy operation and reasonable low power requirements. These two points are very important to us because the detectors are primarily designed for use in space. In this article we report on the realization of such a detector and present the first results.

II. THEORY

When using the current impulse released from a MCP stack one has to make sure that the current amplitude is large enough to overcome the threshold of photon production of the laser diode (i.e., lasing operation).

The charge released by the MCP stack is given by the modal gain, G, of the assembly. Thus, the output charge is $Q_{\text{out}}=Gq_0$ for a single incoming particle, with q_0 the elementary charge. The temporal shape of the charge impulse arriving at t_0 can be described reasonably well by

$$I(t)=\frac{Q_{\text{out}}}{\sigma\sqrt{2\pi}}\exp\left(-\frac{1}{2}\frac{(t-t_0)^2}{\sigma^2}\right) \quad (1)$$

with the temporal width of the impulse $\Delta t=2\sigma\sqrt{2\ln 2}\approx 2.35\sigma$ full width at half maximum (FWHM). In our earlier

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work we reported that these detectors have typical impulse widths of $\Delta t = 500$ ps FWHM. Thus, the maximum output current is

$$I_{\max} = \frac{Q_{\text{out}}}{\sigma\sqrt{2\pi}} = \frac{Gq_0}{\sigma\sqrt{2\pi}}. \tag{2}$$

Laser diodes have a threshold forward current that has to be exceeded for lasing operation (i.e., photon emission). This threshold is around $I_{\text{thr}} \approx 4$ mA for the VCSEL laser diode we used.[7] To assure reliable operation we assume that a current impulse of $I_{\max} > 2I_{\text{thr}} \approx 10$ mA is sufficient. Note that such a current impulse gives an amplitude of 0.5 V for the voltage impulse on a 50 Ω resistor. From the desired forward current through the laser diode we can calculate the necessary modal gain of the MCP stack by

$$G = \frac{I_{\max}}{q_0}\sqrt{2\pi}\sigma \approx \frac{I_{\max}}{q_0}\Delta t. \tag{3}$$

The result is that a modal gain of $G \approx 3 \times 10^7$ is necessary. To obtain such a high gain we need to use a stack of three MCPs. The power of the photon impulse resulting from the current impulse is approximately given by

$$P(I) \approx \eta(I - I_{\text{thr}}) \tag{4}$$

with the slope efficiency η, which is 0.3 mW/mA for the laser diode we used.[7] Note that the threshold current and the slope efficiency are temperature dependent. For the earlier example we get $P_{\max} = 1.8$ mW. Since our signal transmission only extends over relatively short distances (of the order of meters) loss of photon power can be neglected. At the data acquisition electronics we have to convert the photon impulse back to an electric signal. This is done by a fast optical converter (model AD-200, Newport). The electrical impulse is then $U_{\max} = AP_{\max}$ with A the conversion gain of the used converter. At the wavelength of our VCSEL diode of 850 nm the conversion gain $A = 180$ V/W. Thus, we obtain a voltage impulse at the input of the electrical signal acquisition of $U_{\max} \approx 0.3$ V not considering any transmission losses. Such a signal can be detected without problems by state-of-the-art electronics.

III. DETECTOR

The design and the electrical performance of the detector used in this study have been presented in detail before.[4,8] In Fig. 1 we show an impulse recorded with an analog 1 GHz analog oscilloscope (Tektronix, model 7104, 7A29 plug-in, 1 GHz bandwidth). The detector was setup with a stack of two MCPs in matched pair configuration (Photonis, model G6-25-SE/ST/6/A). The front MCP was biased to −2700V and the anode to 0 V. This way, the signal coupling condenser, which is part of the original design, could be omitted. Note that the exit side of the MCP stack is biased to approximately −600 V by a Zener diode to accelerate the released electrons toward the anode. Since the whole circuitry along which this fast signal propagates (from anode to signal acquisition electronics there are typically distances of meters) has discontinuities in the impedance matching an overshoot and some ringing after main impulse result.[4] The signal height of the main peak of $U_{\max} = -48$ mV corresponds to a current of $I_{\max} = -0.96$ mA, which is too low to trigger the laser diode.

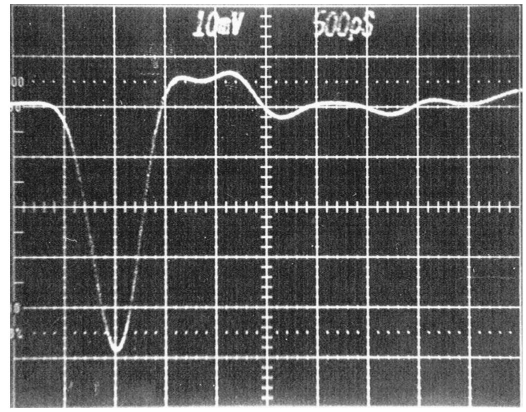

FIG. 1. Electrical performance of the original MCP detector with a matched pair of channel plates (Photonics, model G6-25-SE/ST/6/A) and without a spacer ring between the two plates. The measurement was made using a 1 GHz analog oscilloscope with the horizontal scale being 500 ps/div and the vertical scale being 10 mV/div. The front MCP voltage was $U_{\text{MCP}} = -2700$ V and the anode was at ground potential.

Therefore, some adaptations to the detector were needed for the present experiments and the modified electric circuit is shown in Fig. 2. First, instead of a matched pair of channelplates we used a stack of three plates for reasons discussed earlier, which each had a plate resistance of 200 MΩ (Galileo, model 1396-1815). Second, the signal coupling condenser on the anode was removed from the anode to be able to apply a direct current (dc) bias to the laser diode. The anode signal was directly coupled into a 50 Ω coaxial cable and connected to a 50 Ω vacuum feedthrough. The output signal could then be analyzed either electronically (oscilloscope, pulse-height distribution analysis) or coupled into a high speed fiber optic laser (VCSEL) diode to ground (model HFE4080-322/XBA, Honeywell). Without the signal coupling condenser it is not possible to float the anode voltage and we have to assure a near ground potential on the anode. However, once the laser diode is integrated in the detector and directly attached to the anode, the signal is then guided

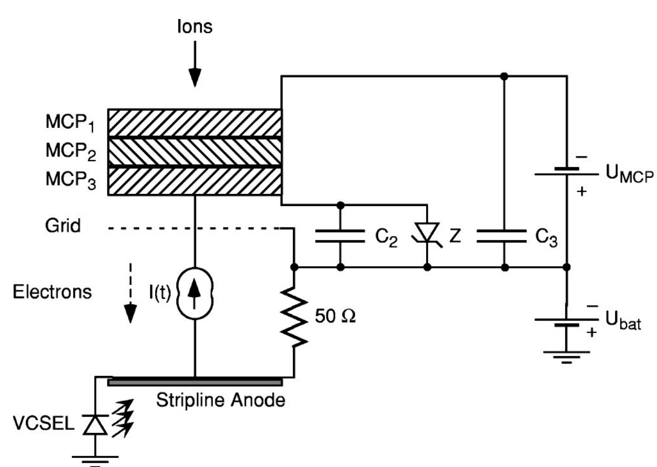

FIG. 2. Schematics of the detector electronics accommodating the laser diode. Details of the circuits have been given before (see Ref. 4).

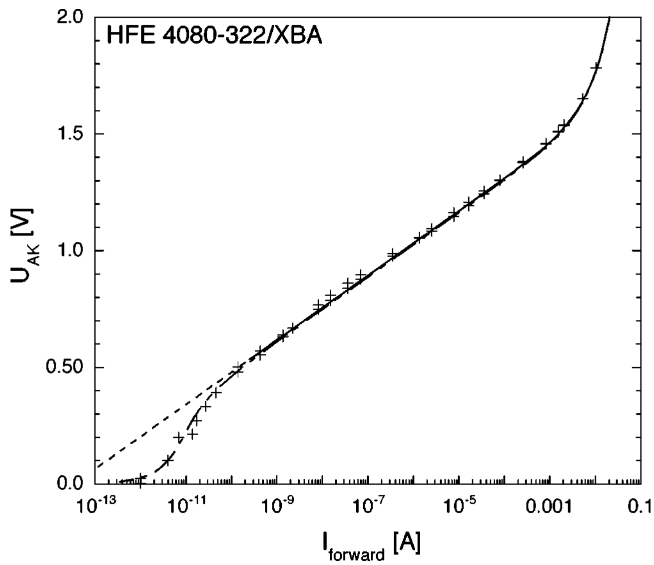

FIG. 3. Symbols give the measured voltage–current relationship of the used VCSEL (model HFE4080-322/XBA, Honeywell). The current was measured with an electrometer (Keithley, model 6517A). The solid line is a fit with the usual exponential relationship and a series resistor [Eqs. (5) and (6)], and the dashed line is the extension to lower currents where the model does not fit the measured data. The dash-pointed line gives a fit with an additional parallel resistor.

via an optical fiber vacuum feedthrough, which imposes no limitation on the detector potential or the anode potential.

Since the laser diode has a threshold for photon emission a dc bias current may be useful to overcome this threshold and optimize the performance for signal transmission. For that purpose we measured the voltage–current relationship of the laser diode for a large current range. The result is shown in Fig. 3 and it can be seen that the forward current is a strong function of the applied voltage. The voltage–current relationship of the laser diode can be described by the usual exponential relationship plus a series resistor

$$U_{\mathrm{AK}}(I_F)=U_T\ln\left(\frac{I_F}{I_S}+1\right)+I_F R_S \tag{5}$$

with U_{AK} the anode–cathode voltage applied on the leads of the diode for an applied forward current I_F. From the fit to the measured data of the VCSEL diode we obtained a saturation current of $I_S=9.3\times10^{-14}$ A, a thermal voltage of $U_T=0.060$ V, and $R_S=17.6\ \Omega$. Unlike for other diodes, the series resistance R_S is not negligible for this type of laser diodes. The simple model given by Eq. (5) fits the measured data very well (solid line in Fig. 3). Only for low forward currents the model deviates from the measurements (dashed line in Fig. 3). This deviation can be explained by an additional parallel resistor between the leads of the laser diode, which can be either of intrinsic or of extrinsic nature. Equation (5) is then modified to

$$U_{\mathrm{AK}}=(I_F+I_S)R_P-\frac{U_T}{1+R_S/R_P}\times\mathrm{Product}\ \ln\left[\frac{I_S(R_S+R_P)}{U_T}e^{[I_F R_P+I_S(R_S+R_P)]/U_T}\right]. \tag{6}$$

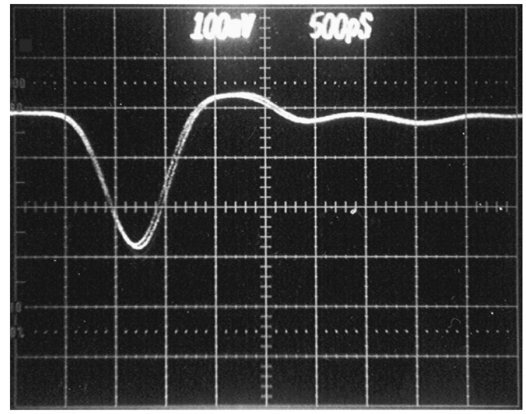

FIG. 4. Electric impulse at the anode recorded with a 1 GHz analog oscilloscope at 50 Ω input resistance with the horizontal scale being 500 ps/div and the vertical scale being 100 mV/div. The detector configuration is: three micro-channel plates, no spacer rings, $U_{\mathrm{MCP}}=-3800$ V, $U_{\mathrm{bat}}=0$ V.

The fit to the data (dash-pointed line in Fig. 3) yields a value for the parallel resistor of $R_P=2.61\times10^{10}\ \Omega$. With the extended model we find a lower value for $I_S=3.8\times10^{-14}$ A; otherwise R_P is of no concern for this application.

The pulse height of MCP pulses varies from impulse to impulse. Typically the width of the pulse height distribution ranges between 80% and 120% of the nominal gain. Thus, a considerable amount of impulses may fall below the photon production threshold of the laser diode. By floating the anode and thus the laser diode with a small voltage U_{bat} of up to 1.5 V we can change the effective threshold for impulses to be transmitted (lasing starts around 1.6 V). Depending on the bias voltage a bias current will flow through the laser diode (see Fig. 3). If this current is kept low it can be supplied by a small battery integrated in the detector assembly without the need for an external power supply.

IV. MEASUREMENTS

A. Single impulses

The gain of the original detector clearly was too low for the intended application (see Fig. 1) and we had to improve on that. Even with a stack of three microchannel plates sufficient gain was only found at high MCP voltages. For $U_{\mathrm{MCP}}=-3800$ V the output impulses we obtained were around 300 mV as shown in Fig. 4 (with occasional impulses up 500 mV), which is at the lower limit to trigger the laser diode.

We could significantly increase the modal gain with the usage of two spacer rings (45 μm Cu–Be annular rings) between the three MCPs. This gain increase is because the electrons exiting from a channel plate will disperse laterally and the electron cloud will distribute over more channels in the next plate than without such a spacer ring. Thus, self-limiting of a microchannel becomes less likely.[9] Self-limiting occurs when the number of electrons extracted from the MCP wall causes significant positive charging of the walls resulting in a relatively small amplification even when a high MCP bias voltage is applied to the plates. With three MCPs and spacer rings in between signal heights of typically to 1 V could be achieved at a considerably lower overall voltage of

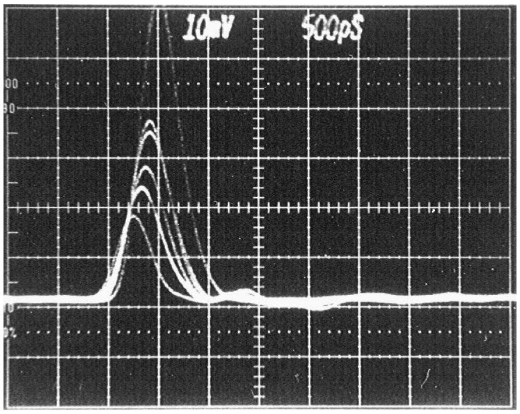

FIG. 5. Optical impulse after the optical converter (Newport, model AD-200) recorded with a 1 GHz analog oscilloscope with the horizontal scale being 500 ps/div and the vertical scale being 10 mV/div. The detector configuration is: three MCPs, no spacer rings, $U_{MCP} = -3800$ V, $U_{bat} = 1.5$ V.

$U_{MCP} = -2900$ V compared with the previous runs. Such a low voltage leaves ample reserve for voltage increase to compensate aging effects of the plates. These high voltage peaks were even high enough to trigger the VCSEL diodes without any dc bias current.

Having sufficiently large impulses from the detector, with or without spacer rings, we can investigate the optical signal transmission. We connected the VCSEL diode (model HFE4080-322/XBA, Honeywell) to the output from the anode, where a variable bias U_{bat} between 0 and 1.5 V was applied. The photon signal was routed to the optical converter using a 50 μm optical fiber with ST connectors at each end (model 2xST-50-125 5m-mg-4313-02, Honeywell). The optical converter (model AD-200, Newport, bandwidth 2.5 GHz) is directly attached to the oscilloscope and converts the optical signal back into an electrical signal. Typical output impulses for this signal are shown in Fig. 5. Note that the wave form of the signal using the optical transmission is different from the wave form of the original electrical signal (see Fig. 1), in particular the overshoot and the ringing are much smaller. The overshoot and the ringing from original electrical signal are suppressed since these amplitudes are too small to trigger the VCSEL diode. Further, note that the anode circuitry was designed to completely absorb an electrical wave going into the detector,[4] thus the impedance mismatch of the laser diode to the 50 Ω anode circuit will not cause ringing. The little ringing seen after the optical transmission is only due to the nonperfect wave form of the optical converter.[10] In a more detailed analysis of the performance we find that for an electrical impulse at the anode of $U_{max} = -0.55$ V on average we obtain $U_{out} = 0.17$ V on average after the optical transmission. According to the estimates given in Sec. II we should obtain an output impulse amplitude of $U_{out} = 0.37$ V. The difference can be attributed to a large part of the impedance mismatch between the VCSEL diode and the anode, and the remaining difference is caused by insertion and transmission losses. The VCSEL diode has a dynamical impedance of about 25 Ω whereas the anode stripline is built for 50 Ω.[4]

B. Pulse height distributions

Next to the temporal response of the detector we are of course interested in the pulse height distribution (PHD) of the signal. For this measurement we directed a 20 keV N^+ ion beam onto the detector. We analyzed both the electrical signal directly from the anode and the converted optical signal from the optical converter. To measure the PHD we amplified the signal and shaped it with a timing filter amplifier (Ortec, model 454). The timing filter amplifier converts a signal impulse to a broad impulse of ~10 ns width, broad enough for the multichannel analyzer (MCA), with an amplitude proportional to the total charge of the signal impulse. For the measurement with the optical fiber, the timing filter amplifier was also used to invert the polarity of the electronic signal provided by the optical converter. The amplification was selected to use the full scale of the MCA. The threshold of the MCA was -15 mV for all measurements. The gate was selected as small as possible to integrate only the charges belonging to the impulse. This setting was, however, not critical, since the raw signal was of good quality (see Figs. 4 and 5). The PHD measured with the MCA was recorded with a digital oscilloscope.

The measured PHDs for the electrical signal and for the optical signal at several bias voltages U_{bat} are shown in Fig. 6 for a setup using three MCPs, the spacer rings, and a MCP voltage of $U_{MCP} = -2900$ V. The top panel in Fig. 6 gives the PHD of the electrical signal on the anode. The width of the PHD is 10.7 pC FWHM corresponding to 192% FWHM, which is rather wide and results from the use of three MCPs. The PHD is reproduced very well by a Gaussian function with its maximum at 5.58 pC, which gives a gain of $G = 3.48 \times 10^7$. The lower three panels in Fig. 6 show the optical signal for $U_{bat} = 1.5$, 0.8, and 0 V, respectively. One can clearly see that the input signal to the laser diode has to exceed a certain threshold value to be transmitted via the optical link. This threshold can be adjusted by the bias voltage U_{bat}. Note that the horizontal axes of the lower panels in Fig. 6 are shifted to indicate which part of the original electrical signal is transmitted via the optical link. From the measurement of the optical signal at $U_{bat} = 1.5$ V one can deduce a width of 5.23 pC FWHM, which is narrower than the width of the PHD of the electrical signal because of the threshold operation of the laser diode. For the same reason the peak of the PHD of the optical signal is located at a lower value of 1.05 pC. For the lower bias voltages $U_{bat} = 0.8$ and 0 V we only get a part of the falling slope of the distribution. This can be improved by increasing the MCP voltage since a larger part of the PHD of the electrical signal will exceed the threshold of the laser diode. For example, with $U_{MCP} = -3000$ V we doubled the MCP gain and obtained a peaked PHD already for a bias voltage of $U_{bat} = 0.8$ V.

V. DISCUSSION

With this work we demonstrated that optical transmission of a fast signal registered with a MCP detector can be realized in a fairly simple fashion. Originally, we only aimed at single particle detection. However, the PHDs indicate that multiple ion detection, e.g., operation of the detector in ana-

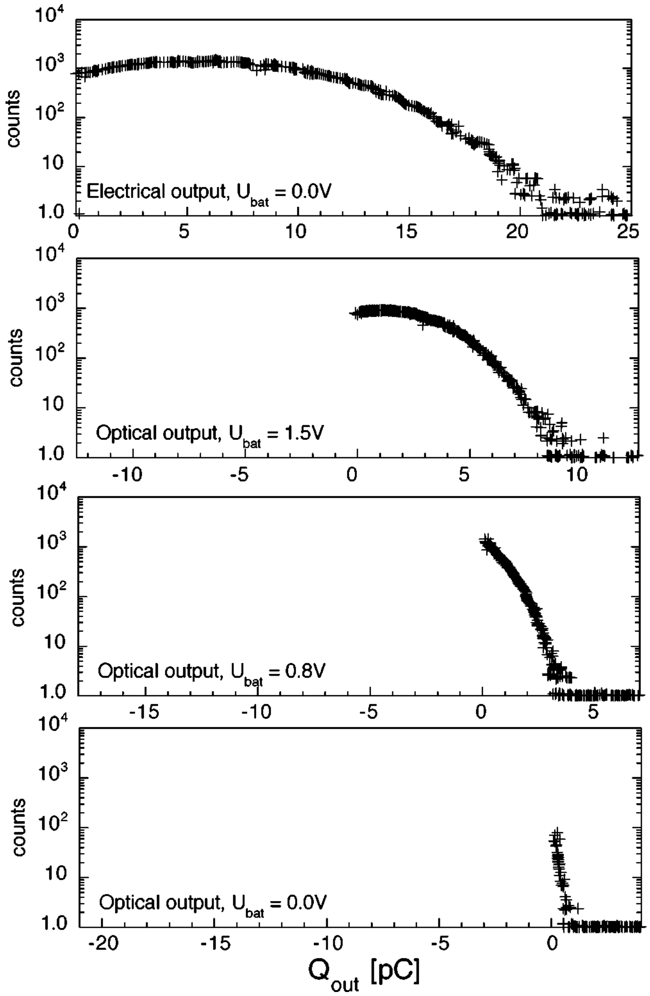

FIG. 6. PHD for the electrical and optical signal output. The detector configuration is: three MCPs (Galilleo), 45 μm spacer rings, $U_{MCP} = -2900$ V. Top panel shows the electrical signal on the anode, the lower three panels show the optical signal for $U_{bat} = 1.5$, 0.8, and 0 V, respectively. The vertical axes are not to scale. Note that the horizontal axes are shifted to indicate which part of the original electrical signal is transmitted via the optical link.

log mode, should be possible by optimizing the VCSEL bias voltage and the MCP voltage. So far our design of the detector is not fully optimized for the operation with laser diodes. In addition to finding optimal operation settings, we still have to design an anode which is matched to the dynamical impedance of VCSEL diode of 25 Ω.

The bias voltage for the laser diode can be supplied by a battery accommodated in the detector structure. Thus, we would indeed have a small circuit and no external electrical connections would be necessary. (Only the high voltage for the MCPs is supplied externally. However, the charge for the fast impulses is provided locally by the capacitors C_2 and C_3, which also establish the return path for the signal propagation.) Using a battery means that the bias current drawn by the laser diode may not be too high, otherwise the battery life time will be very limited. From size and weight considerations one can estimate that a battery charge of 500 mA h can be accommodated in the detector. At a voltage bias of 0.8 V the forward current is 2×10^{-8} A (see Fig. 3) and the battery charge would last for about 3000 years, e.g., we are only limited by the self-discharge of the battery which is about 10 years. However, at a voltage bias of 1.2 V the battery charge would only last for 2.9 years, which is somewhat short compared to the durations such a device would have to work in a space application. At a voltage bias of 1.5 V the charge would last only for 14 h, which is much too short for useful operation even in the laboratory.

The threshold behavior of the laser diode causes a substantial background suppression since the MCP noise has an exponential falloff with increasing pulse height. Thus, such a detector with the described optical link can be made virtually free of background arising from the MCPs themselves.

The temporal widths of the electrical impulses increase when going from amplification by two MCPs to three MCPs, and also when adding the spacer rings. The original detector has a measured pulse width of $\Delta t = 550$ ps (see Fig. 1), with three plates but without the spacer rings the pulse width is $\Delta t = 700$ ps (see Fig. 4), and with three plates and two spacer rings the pulse width is $\Delta t = 1100$ ps. All these pulse widths measured with a 1 GHz analog oscilloscope. This increase in pulse width is solely caused by the electron amplification and propagation in the MCPs and cannot be improved by a better anode design. Fortunately, because of the threshold behavior of the laser diode, the original signal width is restored after the optical link (see Fig. 5).

We anticipate that we will be able to make at least the optical part faster once VCSEL diodes operating in the infrared (IR) wavelength range become available. Recall that a measured rise time of 380 ps with a 1 GHz analog oscilloscope corresponds to a "true" rise time of ≈150 ps[3,4] which corresponds to a signal bandwidth of 2.2 GHz. The present VCSEL diodes operating at 850 nm have a bandwidth of 6 GHz but the optical converter for this wavelength has only a bandwidth of 2.5 GHz. Therefore, an acceleration of the optical part, in particular using the faster optical converters in the IR range may help to push rises time below 150 ps.

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[1] J. L. Wiza, Nucl. Instrum. Methods **162**, 587 (1979).
[2] P. Wurz and L. Gubler, Rev. Sci. Instrum. **65**, 871 (1994).
[3] P. Wurz and L. Gubler, Rev. Sci. Instrum. **67**, 1790 (1996).
[4] R. Schletti, P. Wurz, S. Scherer, and O. H. W. Siegmund, Rev. Sci. Instrum. **72**, 1634 (2001).
[5] H. Balsiger *et al.*, ESA **SP-1165** (2001) (in press).
[6] P. Steffens, E. Niehuis, T. Firese, D. Greifendorf, and A. Benninghoven, J. Vac. Sci. Technol. A **3**, 1322 (1985).
[7] Honeywell, Fibre Optic Products, Catalog **27** (1998).
[8] O. H. W. Siegmund, K. Kramer, P. Wurz, R. Schletti, and H. Cottard, Proc. SPIE **4140**, 229 (2001).
[9] O. H. W. Siegmund, K. Coburn, and R. F. Malina, IEEE Trans. Nucl. Sci. **NS-32**, 443 (1985).
[10] Newport Corporation, Photonics, Catalog (1999/2000).