A High-Speed Gateable Image Pipeline†

A.G. Berkovski¹, G. Chiodi², J.-P. Fabre³, A. Frenkel², S.V. Golovkin⁴, Yu.I. Gubanov¹, G.N. Kislizkai¹, E.N. Kozarenko⁵, I.E. Kreslo⁵, A.E. Kushnirenko⁴, G. Martellotti², D. Mazza², A. M. Medvedkov⁴ and G. Penso²

Abstract

We present the performance of a high-speed gateable vacuum image pipeline, which permits individual images to be delayed and selected from continuous non-repetitive image stream. This novel device is composed of a vacuum tube equipped with a photocathode at one end, a phosphor screen at the other end, and a system of metal grids in between. Photoelectrons produced by the images focused on the photocathode, are guided by a uniform magnetic field, parallel to the tube axis. By changing the grid potentials, the drift time of the photoelectrons inside the tube can be varied from 0.35 to 1.5 µs. An image can then be selected by an external trigger with a time resolution in the range 4-30 ns, depending on the delay time. The selected photoelectrons are finally accelerated onto the phosphor screen, set at 10 kV, where they reproduce the desired image. With a magnetic field of 0.1 T, a spatial resolution of 33 lp/mm was obtained. The high spatial and time resolution make this device an interesting tool for high-energy physics and astrophysics experiments, and for high-speed photography.

(Submitted to Nuclear Instruments & Methods A)

† This work is part of the CERN Research and Development programme RD46.
¹ IPT, Moscow, Russia.
² Università di Roma I ‘La Sapienza’ and INFN, Rome, Italy.
³ CERN, Geneva, Switzerland.
⁴ IHEP, 142284 Protvino, Moscow region, Russia.
⁵ JINR, Dubna, Moscow region, Russia.
1 Introduction

During the last few years important progress has been achieved in developing tracking detectors based on scintillating fibres (SCIFI) and opto-electronics devices. In particular new high-resolution tracking detectors based on capillaries filled with a liquid scintillator have been developed [1]–[7] and their performance was very good.

SCIFI detectors can be used in very high intensity beams at a rate of $10^7$–$10^8$ events/s. Only a small fraction of these events are interesting for physics and should be transmitted to the subsequent optoelectronic devices and readout system. The interesting events are selected by a trigger signal which may arrive with a delay of the order of 1 $\mu$s. Therefore, light signals from the detectors must be delayed for this amount of time. For this purpose we are developing a gateable Vacuum Image Pipeline (VIP) which consists of a vacuum tube with a photocathode, a phosphor screen, and a system of metallic grids in between. Photoelectrons drift in a uniform magnetic field parallel to the axis of the tube, waiting for the trigger decision time.

The idea of taking advantage of the transit time of photoelectrons in vacuum tubes was first suggested many years ago [8]. In this approach, the main difficulty of obtaining a good time resolution is caused by the energy spread of the electrons emitted by the photocathode. So far, different VIP schemes have been considered. In the simplest type of VIP, the photoelectrons are accelerated in a gap of $\approx 0.5$ cm, between the photocathode and the first grid, and drift in a zero electric field section of $\approx 0.5$ m in length, between the first and the second grid. In this type of VIP the initial spread in energy of the photoelectrons results in a relatively large time spread of electrons at the output of the drift zone, i.e. in a non-satisfactory time resolution especially for long delay time. A time resolution of $\leq 20$ ns can be obtained only for a delay of $\leq 200$ ns.

In the second VIP scheme [9]–[12], a reflection section was introduced after the drift section. A reflecting grid, which operates at negative potential, repels the electrons back to the photocathode, so that the faster incoming electrons cover a longer distance than the slower ones. A negative voltage is applied to the first grid just before the first reflected image returns so that all the images which occur during the double transit time are captured and continue to drift with many reflections. The time dispersion of electron images is minimized after a given number of reflections which depends on the geometry of the VIP. In order to select an image from this flow, a short positive pulse is applied to the reflecting grid. This pulse allows the selected image to pass to the following image intensifying stage. This VIP scheme was proposed [12] for high-speed photography. A framing rate of $10^8$ frames/s was obtained with a spatial resolution of 10 lp/mm. However, with this VIP configuration it is not possible to work with a continuous stream of events, because the negative voltage applied to the first grid shut down the pipeline.

A third VIP scheme was envisaged [13, 14] which allows a continuous stream of images to be delayed and the desired events to be selected. In this scheme the images are focalized in time after a single reflection and then absorbed by the photocathode unless a selecting pulse is applied to the first grid of the tube. A first small prototype, with a delay time of the order of 400 ns, has been already tested by other authors [15]–[18]. In this paper we present the performance of a full-scale gateable VIP, designed to achieve a delay time of up to 1 $\mu$s without any substantial signal loss.

---

1DEP, Delft Instruments, Dwazziewegen 2, 9300 AB Roden, The Netherlands.
2Geosphaera, P.B. n. 6, Moscow, 117133, Russia.
2 VIP layout

The VIP we tested consists (Fig. 1) of a 670 mm long magnetic focusing image intensifier (II) with a photocathode and a phosphor screen at the end windows, and a system of five metallic grids (G1-G5) placed in between. The grids are made of 15 and 20 μm wires with a pitch ranging from 0.5 to 2.5 mm, in order to obtain a good electric field uniformity and tube transparency. The diameter of the glass vacuum tube is 60 mm and the useful diameter of the photocathode and of the phosphor screen is 37 mm. The inner surface of the tube is covered by a resistive coating to achieve a better electrical field distribution inside the tube. The VIP has fibre-optic input and output windows. The photocathode is a multalkali type with a maximum quantum efficiency of 12.8% at \( \lambda = 500 \) nm. The blue phosphor (KO-425, decay time \( \sim 50 \) ns) is covered with a reflecting coating to prevent the emitted light from reaching the photocathode.

![Schematic view of the VIP](image)

The VIP is placed inside a water-cooled solenoid with an inner diameter of 12 cm and a length of 120 cm, which produces a maximum magnetic field of 0.14 T, parallel to the tube axis and with a time stability of \( \sim 10^{-4} \). This magnetic field causes the photoelectrons to follow tight helical paths with their axes parallel to the tube axis, ensuring that the electrons emitted by the photocathode are focalized on the phosphor screen.

3 Operation modes

During normal operation the photocathode and the phosphor screen are set at a potential \( V_k = 0 \) and \( V_p = 10 \) kV, respectively. The first four grids are set at potentials \( (V_1-V_4) \) of a few volts, which are tuned according to the desired operating condition. The last grid G5, set at a negative potential \( (V_5) \) of some tens of volts, acts as an electric shielding to avoid influence from the high field of the amplification section on the previous section of the tube, where the field is smaller and even small disturbances may influence the quality of the VIP operation. The large field gradient near the wires of G5 may cause local distortions of the image. In order to decrease this effect, a ring has been installed in the amplification section (Fig. 1). The potential on the ring is set to \( V_r = 100-300 \) V.
The two main operating modes of the VIP are the Image Selection Mode (ISM) and the Image Elimination Mode (IEM).

In the ISM the first three grids are set at the same positive potential \(V_1 = V_2 = V_3\) so that the photoelectrons are accelerated to G1, drift between G1 and G3 at a constant velocity, and then enter the reflection section between G3 and G4, where they are repelled by the reflecting grid G4 which is set at a negative potential \(V_4\). The photoelectrons are emitted with an energy spread of a few tenths of an eV, which depends on the photocathode characteristics and the wave-length spectrum of the incident light. Photoelectrons emitted at higher energy penetrate the reflection section farther than those emitted at lower energy, thus covering a longer distance and compensating their larger velocity. After being reflected, and with an appropriate tuning of the grid potentials, electrons belonging to the same image will be focalized \cite{15} at the same time in the selection section between G1 and G2. If at that time a negative selecting pulse is applied to the selecting grid G1, the electrons present between G1 and G2 will be accelerated in the forward direction so that they can overcome the negative potential of G4 and enter the amplification section. Here they are accelerated towards the phosphor screen where they reproduce the selected image, intensified and delayed.

In the IEM the grids are set to the same potentials as in the ISM, but no selecting pulse is applied to G1, so that the photoelectrons reflected by G4 drift back to the photocathode where about 70\% of them are absorbed. The remaining 30\% are backscattered and can contribute to the noise, as will be discussed later.

In order to study the VIP characteristics, a third operating mode, which is not a normal working condition, will also be considered. In this Direct Mode (DM), all the five grids are set at the same positive potential (1–10 V) with respect to the photocathode. The VIP works as a drift tube where photoelectrons emitted by the photocathode are accelerated to G1 in the first section, travel along the tube at a constant velocity, and then enter the amplification section where they are accelerated towards the phosphor screen. In DM there is no compensation for the energy spread of the emitted photoelectrons, so the time resolution is definitely worse than in ISM.

4 Delaying characteristics

The time characteristics of the VIP have been studied with the set-up shown in Fig. 2. A fast red LED illuminates the photocathode with 2 ns FWHM light pulses. After a delay which can be varied in steps of 0.5 ns, a negative selecting pulse (\(\sim 400\) V, rise time \(\sim 4\) ns) is applied to G1 through a fast high-voltage gate generator placed close to the VIP. The electrons present between G1 and G2 at that time are thus sent to the amplification section where they are strongly accelerated towards the phosphor screen. A flexible image guide transmits the light pulses produced by the phosphor outside the magnetic field, where they are detected by a fast photomultiplier Hamamatsu R1635-02 (rise time 0.8 ns, transit time 7.8 ns). A gated analogue-to-digital converter (ADC) integrates the photomultiplier signal over 400 ns (2 \(\mu\)s in DM). A standard CAMAC acquisition system allows the pulse height distribution delivered by the ADC to be measured. The average value \(A\) of this distribution is reported in Fig. 3 as a function of the delay between the LED pulse and the selecting pulse. For this measurement the potentials of the grids G1, G2, and G3 were \(V_1 = V_2 = V_3 = +2\) V, while G4 was set at the value \(V_4 = -1.15\) V which maximizes the output signal. Three well separated peaks are present. The first peak, centred at \(T_1 \approx 20\) ns and with an amplitude \(A_1\) (measured at
Figure 2: Experimental set-up used to measure the time response of the VIP. The light pulse from the VIP phosphor is detected by a photomultiplier (PM). The analogue-to-digital converter (ADC) measures the charge delivered by the PM. A standard CAMAC acquisition system allows the average value of the output signal to be determined.

Figure 3: Delaying characteristics of the VIP in ISM. The average output signal delivered by the ADC (Fig. 2) is reported as a function of the delay between the LED pulse and the HV gate pulse. The three peaks centred at $T_1$, $T_2$, and $T_3$ correspond, respectively, to the forward-moving electrons, the reflected electrons, and the backscattered electrons. $T_2$ is the delay of the selecting pulse in normal working conditions of the VIP. $A_1$, $A_2$, and $A_3$ are the average output signals at the delays $T_1$, $T_2$, and $T_3$, respectively. The curve is drawn to guide the eye.

$T_1$ corresponds to the selection of the forward-moving image, just after being emitted by the photocathode. The second peak, centred at $T_2 \approx 1 \mu$s and with an amplitude $A_2$, corresponds to the selection of the backward-moving reflected image. This is the normal working condition of the VIP in the ISM. The transparency of the grids results in the slight attenuation ($A_2/A_1 \approx 0.9$) of the second peak with respect to the first one. Owing to the non-perfect focalization of the reflected electron bunches, this second peak is smeared compared to the first one. The third peak, at a delay of $T_3 \approx 1.04 \mu$s and with an amplitude $A_3$, corresponds to the selection of those electrons which have not been absorbed but backscattered [19] by the photocathode, so that, compared to the second peak, it appears smeared and attenuated by a factor $A_3/A_2 \approx 0.3$. If the grid potentials are not suitably modulated as described below, these backscattered
electrons continue to drift in the tube so that at a delay of $\sim 2\ \mu$s they will again be in the selection section. About 30% of them will undergo a second backscattering on the photocathode, giving rise to a back and forth electron oscillation, with a rapidly decreasing intensity.

The VIP delay, i.e. the delay $T_2$ (Fig. 3) of the selecting pulse in normal working conditions, may be varied from 1.5 to 0.35 $\mu$s by changing the common potential of G1, G2, and G3 from 1 to 20 V, as reported in Fig. 4a. For any value of $V_1 = V_2 = V_3$, the potential $V_4$ of the reflecting grid has been tuned (Fig. 4b) in order to maximize the output signal.

![Figure 4](image1)

Figure 4: a) Delay ($T_2$) of the VIP in normal working conditions as a function of the common potential of G1, G2 and G3. For each value of $V_1 = V_2 = V_3$ the potential ($V_4$) of G4 is set to the value reported in b), which maximizes the average output signal.

In Fig. 5 we report the amplitudes $A_1$ and $A_2$ as a function of the potential of G1, G2, and G3. For comparison, the average output signal in DM, obtained with an ADC gate of 2 $\mu$s, is also shown. For $V_1 = V_2 = V_3$ above $\sim 2$ V the average output signal

![Figure 5](image2)

Figure 5: Average output signal $A_1$ and $A_2$ as a function of the common potential of G1, G2, and G3. The potential $V_4$ of G4 has been set according to Fig. 4b. For comparison we report the average output signal of the VIP in DM. The curves are fitted by eye.
is practically independent of the grid voltage and, in the normal working condition (i.e. in ISM with a delay $T_2$), is about 90% of that obtainable in the other working modes. For $V_1 = V_2 = V_3$ below $\sim 2$ V, the axial length of the bunch becomes larger than the distance between G1 and G2 so that the HV gate selects only part of the reflected image.

5 Time resolution

The time resolution of the VIP is defined as the minimum time interval between images that allows the selection of one image with a negligible background from the neighbouring images. This time resolution is essentially determined by the distance ($D$) between G1 and G2, and by the axial length ($\delta$) and the velocity ($v$) of the reflected electron bunch when crossing the selection region. The axial length ($\delta$) of the electron bunch is due to the initial energy spread of the photoelectrons combined with the non-perfect focalization mechanism, and the duration of the light pulse. The time resolution is also slightly dependent on the distortion of the electric field near the wires of G1 and G2, and on the rise time and amplitude of the HV gate pulse. In our experimental conditions all these effects can be approximately taken into account by redefining $D$ as $\sim 62\%$ of the geometrical distance between G1 and G2. In a naïve model $D$, $\delta$ and $v$ are related to the FWHM ($\Gamma$) of the peak centred at $T_2$ (Fig. 3) and to the duration ($\gamma$) of its flat-top. The FWHM $\Gamma$ is equal to the drift time of the electrons between G1 and G2, and is independent of the bunch length, whilst the flat-top depends on $\delta$ and is equal to the time during which the reflected bunch travels between G2 and G1 and is completely contained in the selection section, namely: $D = \Gamma v$; $\delta = (\Gamma - \gamma)v$.

In normal working conditions the HV gate pulse is applied to G1 at the time $T_2$, i.e. when the bunch of interest is centred in the selection section. In order to have no superposition of the image relative to this bunch with the image relative to neighbouring bunches, the distance between two consecutive bunches must be greater than $(D + \delta)/2$, so that the undesired bunch is completely out of the selection section. The time resolution of the VIP is therefore: $\Delta T = (D + \delta)/(2v) = \Gamma - \gamma/2$. In Fig. 6a we report the dependence of $\Gamma$ and $\gamma$ on the common potential of G1, G2, and G3, measured with a red LED.

A small correction may be applied to this time resolution in order to take into account the finite duration of the LED light pulse. This duration gives a contribution $\delta_L$ to the bunch length $\delta$, the other contribution ($\delta_0$) being caused by the non-perfect focalization of the electrons in the selection section. Assuming that these two contributions add quadratically ($\delta^2 = \delta_0^2 + \delta_L^2$), the time resolution of the VIP, corrected for the duration of the LED pulse, is: $\Delta T_0 = (D + \delta_0)/(2v) = (\Gamma + \sqrt{(\Gamma - \gamma)^2 - \delta_0^2/v^2})/2$. In the present measurement $\delta_L/v \simeq 3$ ns. In Fig. 6b this corrected time resolution is reported as a function of the G1, G2, and G3 voltage.

The time resolution of the VIP could be improved by decreasing the distance $D$ between G1 and G2 and the bunch length $\delta$. However, the condition $D \geq \delta$ must be satisfied in order to avoid the loss of electrons belonging to the selected bunch when the HV gate pulse is applied to G1. A reduction of the bunch length $\delta$ can be envisaged in a VIP with a different grid configuration. It is of course useless to decrease $\delta_0$ much below $\delta_L$ which, in an experimental application, is determined by the duration of the light source like, for example, the decay time of a scintillator. Also a fast rise time of the HV pulse is important in order for the VIP to perform well.
Figure 6: a) FWHM ($\Gamma$) and flat-top width ($\gamma$) of the peak centered at $T_2$ (Fig. 3) as a function of the common potential of G1, G2, and G3. The potential $V_4$ of G4 has been set according to Fig. 4b. b) Time resolution of the VIP, corrected for the duration of the LED pulse.

### 6 Spatial resolution

In order to measure the spatial resolution of the VIP, the photocathode was illuminated with a standard resolution pattern comprising a set of bright and dark lines of progressively smaller spacing. When the VIP operates in DM, this pattern is continuously illuminated by the LED, so that its image formed on the phosphor screen can be easily observed with a microscope at the end of the image guide (Fig. 2). This guide$^3$, which has an active area of $16 \times 16$ mm$^2$, consists of a coherent bundle of glass fibres with a diameter of 6 $\mu$m. The distortions introduced by the image guide do not exceed one fibre diameter. They were measured with a microscope by looking directly at the resolution pattern through the guide. With this set-up we measured a spatial resolution of the VIP in DM of 30–40 lp/mm, for a magnetic field of 0.07–0.12 T, respectively. This resolution depends on the transverse momentum of the electrons emitted by the photocathode and on the magnetic field.

In order to measure the spatial resolution of the VIP in ISM, the resolution pattern must be illuminated with a pulsed LED, so that the light emitted by the phosphor is too low to be observed directly. An Electron-Bombarded-Charge-Coupled-Device (EBCCD) tube is therefore coupled to the output window of the VIP. This tube, which is magnetically focused by the same magnetic field used for the VIP, has a gain of $\sim 2000$, thus allowing the image of the pattern to be observed. The EBCCD$^5$ consists of $532 \times 290$ pixels having dimensions of $17 \times 23$ $\mu$m$^2$, and has a spatial resolution of $\sim 50$ lp/mm at $B = 0.1$ T. With this magnetic field the overall resolution of this optoelectronic chain is $\sim 27$ lp/mm so that, after subtraction of the EBCCD contribution, we obtain a spatial resolution of the VIP in ISM equal to $\sim 33$ lp/mm.

$^3$Schott Fiber Optics, Inc., Southbridge, MA01550, USA.

7
The noise of an image observed on the phosphor screen, when the VIP operates in ISM, is due to those electrons which are present in the selection section when the high voltage gate is applied, but do not belong to the desired image. This noise can be due either to forward-moving electrons which enter the selection section through G1, or to backward-moving electrons entering through G2 together with the desired image.

The first source of noise can be easily eliminated by applying, slightly before $T_2$, a positive pulse of $\sim V_1 + 10$ V to the photocathode. In this way, no electrons can enter the selection zone from the G1 side while the bunch to be selected is entering from the G2 side. This veto pulse is not applied for all the input images projected onto the photocathode, but only for the images of interest. It therefore introduces a negligible dead time.

The second source of noise is essentially caused by the electrons backscattered by the photocathode contemporaneously to the emission of the image of interest. It amounts to $\sim 30\%$ of an unselected image, if any, occurring at a time $T_1 + T_2$ before the selected image. In order to eliminate the backscattered electrons, a positive pulse of $\sim V_1 + 10$ V should be applied to the photocathode for all the unselected images, at a time slightly after $T_2$. This is only possible if the trigger logic delivers a signal for the unselected events as well. This veto pulse introduces a dead time which depends on the input image rate. If the events are not randomly distributed in time, but occur at fixed intervals (like for example in a high-energy physics experiment performed at a Collider), the VIP delay ($T_2$) can be adjusted so that the veto pulse occurs exactly between two events. In this case the backscattered electrons can be eliminated without introducing any dead time.

Because of the very high time resolution of the VIP, thermal emission from the photocathode does not contribute to the noise.

8 Image distortions

The image observed on the phosphor screen can be slightly distorted with respect to the image projected onto the photocathode. These distortions can be present if, in some region of the VIP, the electric and magnetic fields are not parallel to the tube axis. This can occur near the inner surface of the tube or near the grid wires.

In the first case, the distortion appears as a rotation of the periphery of the image around the tube axis. This distortion has been practically eliminated by depositing an appropriate resistive layer on the inner surface of the tube, and by avoiding placing the VIP near the inner surface of the solenoid where the magnetic field lines are slightly distorted.

The second type of distortion is caused by the transverse component of the electric field which is present near the grid wires. This component causes a drift of the electrons passing near a wire, in a direction parallel or antiparallel to the wire itself, depending on which side of the wire the electron is passing. Because of this effect, the image of a line perpendicular to the wires may appear as dashed and distorted. This type of distortion is only of relevance for the grid G5, where a high electric field gradient is present. If the potential of the grid G5 and of the ring R are appropriately tuned, this effect becomes negligible.
9 Conclusions

A novel optoelectronic delay line has been constructed and tested. This magnetically focused Vacuum Image Pipeline allows one image to be selected from a continuous flow, whilst waiting for a trigger decision which can arrive from 350 ns to 1.5 \( \mu \)s after the physical event. The time resolution of the VIP ranges from \( \sim 4 \) ns to \( \sim 30 \) ns, depending on the tube delay, while the spatial resolution is 30–40 lp/mm, depending on the intensity of the magnetic field. This tube can work at an event rate of \( 10^7 \)–\( 10^8 \) s\(^{-1}\), with a negligible image distortion. The VIP is therefore a very promising optoelectronic device for use in high-rate experiments.
References


