ISBN: 978-3-95450-261-5 ISSN: 2673-7000 doi: 10.18429/JACoW-NAPAC2025-MOP079

PROPOSAL TO STREAK OPTICAL PULSES USING A SOLID STATE OPTICAL DEFLECTOR*

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Abstract

Streak cameras are flexible cameras used to measure the temporal profile of optical pulses. Streak cameras have been employed to measure the longitudinal beam profile on accelerators around the world. In the present work, we highlight a potential alternative to a new streak camera. We consider particularly linear (Pockels) and quadratic (Kerr) electro-optical nonlinearity solid-state streaking systems. Of the possible solid state systems, we motivate the potential advantages of a potassium tantalum niobate ($KTa_{1-x}Nb_xO_3$) crystal as a photon beam deflector to measure the longitudinal profiles of electron beams in accelerators.

INTRODUCTION

We are interested in investigating alternatives to streak cameras for the measurement of electron beams in accelerators. Essentially, we were initially interested in the possibility of applying the rising or falling edge of a fast (~ns) voltage pulse to an electro-optical component such as a Pockels cell. This is illustrated schematically in Fig. 1. The falling edge would have the same effect: the important feature is that the gradient $\mathrm{d}V/\mathrm{d}t$ is fast enough to streak bunches shorter than the time duration of the rising edge.

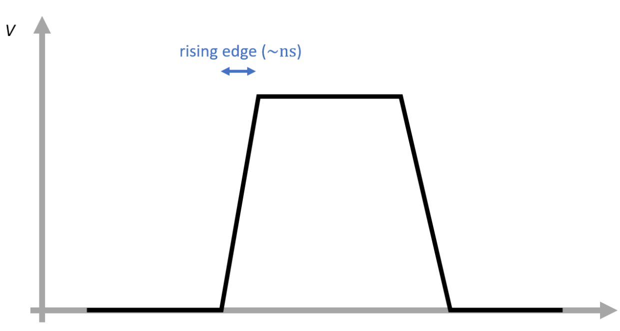

Figure 1: Schematic illustration of the rising edge of a fast (~ns) rising edge of a voltage pulse to streak a photon beam.

In the present work, we evaluate potential alternatives to a streak camera for the measurement of electron beam bunch length in particle accelerators. We consider particularly rotating mirror (mechanical) streaking systems, as well as linear (Pockels) and quadratic (Kerr) electro-optical nonlinearity solid-state streaking systems.

EXISTING OPTICAL PULSE STREAKING TECHNIQUES

Rotating Mirror

Rotating mirrors have been employed to measure the temporal distribution of electron beams in storage rings [1]. It appears that rotating mirrors were the first (mechanical) streak cameras [2]. Rotating mirrors typically operate at a frequency rate of hundreds to thousands of rotations per second. Commercial rotating mirror streak cameras are available, with a mirror rotation speed 7500 revolutions per second and corresponding temporal resolution 0.65 ns pix^{-1} [3]. These sweep rates are similar to the slow time axis on a streak camera, but not comparable to the fast time axis.

Electro-Optical Streak Camera

Streak cameras were used to measure picosecond laser pulses in the early 1970s [4, 5], and were subsequently applied to measure the length of electron bunches in particle accelerators [6]. Streak cameras have since been used to measure short electron bunch lengths at many laboratories [7–10].

Streak cameras are still used to measure the shortest optical pulses [11], and especially on times scales <1 ps. However the technology of streak cameras is focussing on the ultrafast, ultrashort pulse community and diverging from the needs of some particle accelerators: electron bunches in rings are not getting shorter. A streak camera can measure the temporal profile of electron bunches in a ring, but the temporal resolution is unnecessary.

POTENTIAL NEW APPROACHES

We review several approaches for measuring short pulses in accelerators. We especially consider a few solid-state options for streaking optical beams.

Digital Deflection Using the Linear Electro-Optic (Pockels) Effect

Pockels cells are fast polarisation-switching units in regenerative amplifier lasers. Multiple variants on this idea were proposed and tested in the 1960s for computing using optical pulses [12], and also in the 1990s for solid state streak cameras [13].

We had initially considered essentially something similar to the apparatus of Ref. [14] (Fig. 1 therein). A KDP Pockels cell is followed by a Wollaston prism. This apparatus is also similar to that of Ref. [12]. Essentially, we consider an active

* Work was supported by the U.S. DOE Office of Science-Basic Energy Sciences, under Contract No. DEAC02-06CH11357.
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ISBN: 978-3-95450-261-5 ISSN: 2673-7000 doi: 10.18429/JACoW-NAPAC2025-MOP079

component of a Potassium Dideuterium Phosphate (KD*P) crystal driven by a rising electric field pulse, followed by a passive Wollaston prism (which splits a photon beam into ordinary and extraordinary rays based on the orthogonal polarisation vectors).

What we were hoping to achieve was an analogue streaking (in angle) of an input polarised photon beam into the Pockels cell. However in this initial consideration we overlooked essentially how the Wollaston prism worked to produce a digital rather than analogue deflection.

Essentially, a Wollaston prism creates an ordinary and extraordinary rays for rays with orthogonal polarisations. It is a digital deflection (one or the other). Hence, a ray with linear polarisation components in both the horizontal and vertical plane would not receive a deflection between these two rays, but would itself be split into two (ordinary and extraordinary) rays.

Analogue Deflection Using the Linear Electro-Optic (Pockels) Effect

We consider still electro-optical deflection using a linear electro-optic effect. Essentially, the linear electro-optic effect is a linear change in the refractive index of the material with applied voltage. A fast-rising voltage pulse is applied to the active cell. Essentially, these are electro-optical deflector Q-switches [15, 16].

Devices using this effect have been demonstrated for fast-streaking of photon beams using $LiNbO_3$ prisms [17–19], or alternatively KD*P [15, 16]. An electro-optical deflector employing $LiNbO_3$ prisms is available as a commercial product [20, 21]. Other groups have also demonstrated streaking using a $LiNbO_3$ deflector [13, 22].

In addition to driving linear electro-optical effects using a single fast rising edge, a radiofrequency drive was also considered. Devices fabricated from $LiTaO_3$ were driven by 16.25 GHz radiofrequency waves to deflect optical beams [23, 24]. Using a similar technology for a different application, a radiofrequency-driven electro-optical deflector was proposed for use as an analog to digital convertor [25].

Quadratic Electro-Optic (Kerr) Effect

Compared to the linear (Pockels) effect, the quadratic (Kerr) effect yields a change in the refractive index that is proportional to the square of the applied incident electric field [26]. This is typically a weak effect, except for select materials with a large nonlinear coefficient such as $KTa_{1-x}Nb_xO_3$ (KTN).

Use of KTN crystals as a beam deflector is not a particularly new idea, dating back to the 1960's [27, 28]. An interesting KTN deflector is commercially available [29–31]. However with sweep rates on the order of 100 kHz [30], it is not fast enough to streak ultrafast pulses in such a way as to measure the pulse duration of electron beams in accelerators.

A recent KTN beam deflector development is charge injection [32–34]. The critical benefit that sets the work of Refs. [32–34] apart from previous work on KTN deflectors is the decision to actively control the temperature of the deflector device. By operating the device at 31 °C rather than 26 °C (close to room temperature), the KTN deflector is switched by an external voltage without passing through a phase transition [33]. This speeds up the response time of the device (the sweep rate) from hundreds of nanoseconds to a few nanoseconds. This is illustrated in Fig. 2 [33].

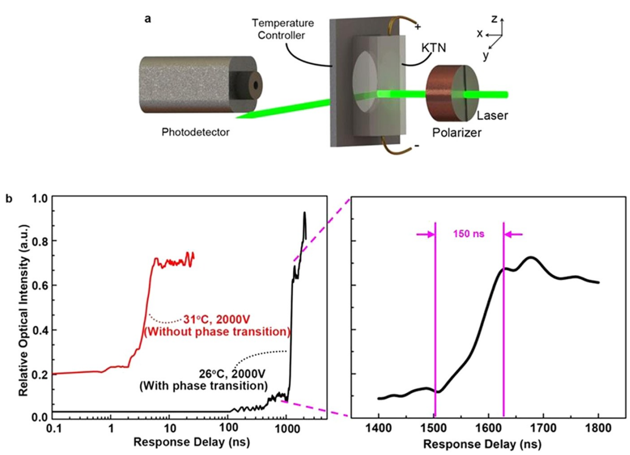

Figure 2: Controlling the operating temperature of the KTN deflector reduces the response delay of the KTN crystal by approximately two orders of magnitude to approximately a few nanoseconds: a timescale interesting for bunch length measurement. (a) Experimental apparatus of Ref. [33]. (b) Response delay with and without phase transition, results of experiment in Ref. [33]. Reproduced under CC-BY 4.0 license from Ref. [33].

This technique has been demonstrated for the purpose of multiplexing multiple laser beams together into a single beam [34]. However it appears that this could be usefully employed to measure the pulse duration of short optical pulses. A proposed benefit is that this does not rely on the input pulse being a high-intensity laser beam.

DISCUSSION

Our preferred solution is the (charge-injected) KTN deflector of Ref. [33]. This looks to match the needed streak rate for beams in a particle accelerator. Our proposed geometry for streaking photon beams from an accelerator is illustrated in Fig. 3.

We calculate the anticipated streaking performance of such a device. As an example, we use the parameters of Ref. [33] for a KTN crystal operated in the paraelectric phase. In the paraelectric phase (operational temperature of crystal at 31 °C is above the phase transition point), the deflection angle θ_p is given approximately by Ref. [33] (Eq. 15 therein):

$$\theta_p = -n^3 g_{11} \rho L \varepsilon_0 \varepsilon_r \frac{V}{d}, \tag{1}$$

where n is the refractive index of the KTN crystal, g_{11} is the quadratic electro-optic coefficient, ρ is the injected charge density, L is the length of the crystal in the beam direction,

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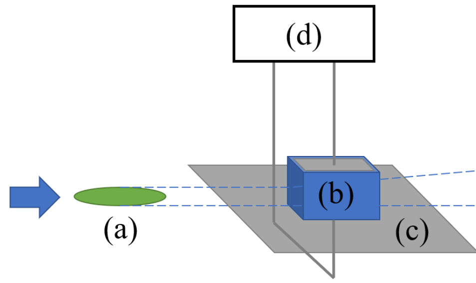

Figure 3: Proposed KTN streaking deflector geometry. (a) Pulsed photon beam (the beam direction is from left to right). (b) KTN crystal. (c) Temperature-controlled stage. (d) High-voltage pulser. (e) Imaging camera.

the permittivity of free space $\varepsilon_0 = 8.85 \times 10^{-12}\,\mathrm{F\,m^{-1}}$, the relative permittivity ε_r, V is the applied potential difference and d is the crystal thickness between the two electrodes. Substituting values of these parameters in Table 1 gives a deflection angle of $\theta_p = -6.0\,\mathrm{mrad}$.

Table 1: Calculation Parameters

Parameter	Value
n	2.314
g_{11}	$0.136\,\mathrm{m^4\,C^{-2}}$
ρ	$90\,\mathrm{C\,m^{-3}}$
L	2 mm
ε_r	7800
V	2000 V
d	7 mm

We consider applying a voltage pulse (time-varying voltage) to the crystal. Hence,

$$\frac{\mathrm{d}\theta_p}{\mathrm{d}t} = -n^3 g_{11}\rho L\varepsilon_0\varepsilon_r\frac{1}{d}\frac{\mathrm{d}V}{\mathrm{d}t}. \tag{2}$$

Several options for voltage pulsers with voltage rise and fall times on the order of 2-3 ns are available [35]. For a pulse reaching a maximum voltage of 2 kV, this corresponds to a voltage rise rate $\mathrm{d}V/\mathrm{d}t \approx 3.8 \times 10^{11}\,\mathrm{V\,s^{-1}}$.

For electron bunch durations of the Advanced Photon Source Upgrade (APS-U) storage ring on the order of δ_t = 100 ps [36], we calculate an approximate angular deflection along the pulse duration of:

$$\begin{aligned}\mathrm{d}\theta_p &\approx -n^3 g_{11}\rho L\varepsilon_0\varepsilon_r\frac{1}{d}\frac{\mathrm{d}V}{\mathrm{d}t}\delta t\\ &= -110\,\mathrm{\mu rad}.\end{aligned}$$

With the pixel pitch of modern complementary metal-oxide semiconductor (CMOS) cameras being typically 3–5 µm, a camera positioned 1 m downstream of the KTN crystal can be expected to resolve the temporal profile of bunches in the APS-U storage ring. One can position the camera at a further distance to resolve smaller angles (corresponding to shorter bunch lengths).

SUMMARY

In the present work, we evaluated several potential alternatives to a streak camera for the measurement of electron beam bunch length in particle accelerators. We consider particularly rotating mirror (mechanical) streaking systems, as well as linear (Pockels) and quadratic (Kerr) electro-optical nonlinearity solid-state streaking systems. In terms of the pursuit of new beam diagnostics techniques, of the solid state systems we prefer the $\mathrm{KTa_{1-x}Nb_xO_3}$ (KTN) beam deflector.

ACKNOWLEDGEMENTS

The submitted manuscript has been created by UChicago Argonne, LLC, Operator of Argonne National Laboratory ("Argonne"). Argonne, a U.S. Department of Energy Office of Science Laboratory, is operated under Contract No. DE-AC02-06CH11357. The U.S. Government retains for itself, and others acting on its behalf, a paid-up nonexclusive, irrevocable worldwide license in said article to reproduce, prepare derivative works, distribute copies to the public, and perform publicly and display publicly, by or on behalf of the Government. The Department of Energy will provide public access to these results of federally sponsored research in accordance with the DOE Public Access Plan. `http://energy.gov/downloads/doe-public-access-plan`

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