First Electro-Optical Detection of Charged Particles

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Abstract

We have made the first observation of a charged particle beam by means of its electro-optical effect on the polarization of laser light in a birefringent crystal. The modulation of the laser light during the passage of a pulsed electron beam was observed using a fast photodiode and a digital oscilloscope. The fastest rise time measured in a single shot, 120 ps, was limited by the bandwidth of the oscilloscope and the associated electronics. This technology holds promise for detectors of greatly improved spatial and temporal resolution for single relativistic charged particles as well as particle beams.

An effort has been initiated to develop an ultra-fast charged particle detector based on the birefringence, and hence the phase difference induced between orthogonal components of polarization (ellipticity), in an optical medium by the electric field of a relativistic charged particle \cite{1}. The electro-optical effect in amorphous optical media is known as the Kerr effect \cite{2} and is quadratic in the electric field $E$. In uniaxial crystals the induced ellipticity is linear in the E-field and is known as the Pockels effect \cite{3}. The induced phase delay can then be given by $\phi = \pi (V/V_\pi)$ with $V$ the applied voltage and $V_\pi$ the voltage required for producing a phase shift between orthogonal components of polarization equal to $\pi$ radians or an ellipticity of $\pi/\sqrt{2}$ since the maximum ellipticity is induced when the polarization is at 45$^\circ$ with respect to the applied electric field direction.

The passage of a tightly bunched relativistic electron beam within several millimeters of a commercially available LiNbO$_3$ crystal \cite{4} coupled to polarization maintaining fibers of 4 microns diameter propagating polarized infrared light ($\lambda = 1.32\mu m$) was observed by the effect of a microbunched electron beam on the polarization of the light in the crystal. This was determined by means of a $\lambda/4$ plate which converted the induced ellipticity to a rotation of the initial linear polarization which had previously been nearly extinguished by the analyzer (crossed polarizer). The resulting modulation of the transmitted laser light was detected by a photodiode of 45 GHz bandwidth and pre-amplifier. The output signals were digitized in a 7 GHz sampling oscilloscope and stored in memory. The optics setup is indicated in Fig.1

A bunched charged particle beam creates an electric field, $E$, at a distance $r$ that is well approximated by Coulomb’s Law multiplied by $\gamma$, the relativistic Lorentz factor, and $N_e$ the number of particles in the beam bunch for a minimum distance $r_0 \gg$ than the dimensions of the beam bunch. The LiNbO$_3$ crystal had $V_\pi = 5$ V with an electrode separation of 15$\mu$m and a length of $l = 1.5$ cm. The integral $\int E\,dl = \int 5V/(15 \times 10^{-6} m) \,dl = 5000$ V produces $\pi/\sqrt{2}$ radians maximum ellipticity.

The integral of the electric field of the particle bunch over the crystal dimensions for a beam bunch located at the mid-plane orthogonal to the length of the crystal at a distance $r_0$ is

$$\int E\,dl = \frac{N_e\gamma q}{2\pi\epsilon_0 r_0}(1 - \sin \theta) \quad (1)$$

where $\theta$ is the angle subtended by the crystal length, $l$ and the direction to the beam center from the end of the crystal. For $r_0 = 5$ mm, $\int E\,dl =$
2.6 \times 10^{-7} \gamma N_e V which should yield an ellipticity of 
\phi = \gamma N_e \times 0.1 \text{ radian}. The signal to noise ratio for 
a measurement of this type that is photon statistics 
limited is given by

$$SNR = \phi \sqrt{\frac{PTq_p}{2h\nu}}$$

where \(P\) is the laser power, \(T\) the time resolution or 
inverse of the detection system bandwidth, \(q_p\) the 
quantum efficiency of the photodiode, and \(h\nu\) the 
laser photon energy.

A 45 MeV kinetic energy electron beam at the 
Brookhaven National Laboratory Accelerator Test 
Facility containing up to 1 nC in a diameter of 
approximately 1 mm with 10 ps duration and a 
repetition rate of 1.5 Hz was scanned across the 
crystal. Measurements were made in the single shot 
mode. The extinction was generally close to 10^{-3}.

With \(\gamma = 88\), \(P = 10\) mW, \(T = 100\) ps and 
\(q_p = 0.8\) and \(h\nu = 0.9\) eV, Eq.2 gives the required 
number of electrons in the beam for \(SNR = 1\), 
\(N_e \approx 6.8 \times 10^4\) for detection of a single beam 
bunch. However, the 7 GHz bandwidth limits 
the sensitivity to the inherently much faster signal 
by as much as factor of five implying \(\approx 3 \times 10^5\) 
singly charged particles are required for detection 
of a single ATF beam bunch. The ATF beam of 
\(N_e = 6.3 \times 10^9\) per bunch was sufficient to generate 
a detectable signal. The maximum modulation of 
the light intensity was about 9% of its DC level.

The polarization dependent signal is displayed 
in Fig. 2 (solid curve). A signal was also obtained 
when the crystal intercepted the beam (dashed 
curve) which was found to be independent of the 
analyzer and hence is polarization independent. It 
does not change sign with polarization orientation 
and it has a significantly longer decay time constant 
than the polarization dependent signal.

In order to achieve single particle detection with 
exhanced time resolution, a high power pulsed laser 
of \(10^8\) W, e.i. 10mJ for 10 ps and a transient 
digitizer of greater bandwidth, e.g. \(100\) GHz 
would require \(\gamma N_e \approx 20\) for single charged particle 
detection with a \(SNR = 1\). The use of a high 
power pulsed laser would preclude the detection of 
randomly occurring events because of the inability 
to trigger the laser. However, this would not be 
a problem at colliding beams machines where the 
beams are bunched to maximize the luminosity. 
Particles of \(\gamma Z > 20\) would be detectable at RHIC 
and the LHC.

A detector constructed of parallel rows of 
electro-optical crystals with a separation of \(100\) \(\mu\)m 
would easily provide single particle detection in 
LiNbO3 based detectors. However, the small size 
and high cost of these crystals would severely limit 
their applicability.

We have recently produced poled optical fibers [3]. 
If they or other moderately priced electro-
optical materials can yield adequate sensitivity 
for single particle detection, a new generation of 
ultrafast fine grained charged particle detectors may 
be at hand.

References

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