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Laser measurement of the LAT detector displacement

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Abstract

The LAT (Low Angle Tagger) detector is the component of the proposed detector for measurement of the events produced in high energy $e^+ e^-$ collisions at proposed TESLA collider. In this paper we discuss the possible solutions for the positioning of the LAT electron detector by optical method. The first results of the displacement measurement using a laser beam and a charge-coupled-device sensor are described. The measurements were performed on a proof-of-principle basis with a low cost web camera and achieved the accuracy of about 1 μm.

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Introduction

In the detector for the TESLA $e^+ e^-$ linear collider [1] the very forward region is a particularly challenging area for instrumentation. The Low Angle Tagger detector (LAT) [2] is expected to give a required precision luminosity measurement and to extend calorimetric coverage of small angles of electron emission from 27.5 to 83.1 mrad. The luminosity measurement will be based on detection of Bhabha scattering. The goal is to measure the Bhabha cross section σ_B with a relative precision $\Delta\sigma_B / \sigma_B$ of about 10^{-4}. A precise measurement of the scattering polar angles requires an ultimate precision in detector mechanical construction and metrology. The crucial point is to monitor on-line the detector displacement under operation with respect to the interaction point.

Requirements

The luminosity measurement requires precise alignment of the LAT detector and precise positioning with respect to the interaction point. The beam pipe is proposed as a suitable reference because the Beam Position Monitors are mounted at fixed positions inside the vacuum pipe. This would allow calculating the actual LAT detector position with respect to the beam position and correcting for any deviation from the design position.

The Monte Carlo simulations give the required accuracy in the on-line displacement measurement. Sub-micron precision is required for the transversal (x, y) displacement and approximately of 50 μm for the axial (z, along the beam direction) one [3]. The measuring method should not interfere with mechanical support of the detector so the optical systems are preferred. The optical methods are preferred over the ones based on electric induction because of the presence of a strong magnetic field, electric noise and intensive radiation. The readout system should be gated so that the measurement is done in the time between the beam trains when the background is negligible.

Possible solutions

Several optical methods were considered for the on-line monitoring of the LAT detector displacement:

1. Laser interferometry.
   It uses a mirror fixed to the moving object as a part of the optical interferometer and measures displacement by counting the interference fringes. Simple interferometers have the accuracy of one half-wavelength of the used light (for the He-Ne laser $\lambda/2$ = 632/2 nm = 316nm). More sophisticated solutions have the accuracy of a fraction of a fringe down to $\lambda/2048$ (for the He-Ne laser 632/2048 nm = 0.30 nm). As the displacement is obtained from the number of counted fringes laser interferometers need a continuous laser beam. Any break of the beam requires a recalibration procedure since in order to measure the absolute distance the chariot with the mirror has to travel between the point of a stable reference and points of interest.
2. Laser triangulation.
   The position-sensitive detector (charge-coupled-device (CCD) or position sensitive Si diodes) records the position of the laser spot on the surface of the object. The laser beam illuminates the object at a small angle to the observation direction. The resolution depends on this angle and decreases with the measuring distance. The resolution of the distance measurement is of about 0.1 μm for the 2 mm measuring range. The linearity is 1 μm but it can be precisely calibrated.
3. Fotonic sensor.
   Fotonic probe is a fiber bundle, which contains two sets of optical fibers. Light-transmitting fibers and light-receiving fibers run together in three different configurations (random, hemispheric and concentric). The displacement measurement is based

on the interaction between the field of illumination of the transmitting fibers and the field of view of the receiving fibers. When the distance between the fiber tip and object increases the amount of light recorded by the receiving fibers is increasing too, then it saturates and eventually decreases, which limits the measuring range. Fotonic sensors have the resolution of up to 0.03 μm within the linear range limited to 140 μm. For ~2 mm linear range the resolution is about 0.25 μm. The linearity can be precisely calibrated.

4. Position sensitive photodiode offers precise X-Y measurements. As it is based on the integral effect, it is sensitive to the possible deformations of the illuminating beam spot.
5. Fine pixel CCD matrix offers X-Y measurements in a single position detector. Pixel size can be as low as 5 μm × 5 μm on the 7 mm × 7 mm matrix size. The laser beam spot can have the diameter of about 50-100 μm and does not need to be circular. A simple calculation gives the center of the ellipsoid and correction for the non-symmetric shape of the laser spot.
6. Optical grating position sensor (laser encoder) has the resolution of about 1 μm but it needs a movable chariot and continuous operation for the absolute distance measurement.

We have chosen the CCD matrix sensor to measure the transversal displacement of the LAT detector with respect to the beam pipe flange [4].

Measurement setup

The setup consisted of the movable CCD camera [5] and the illuminating laser. The simple, low cost web camera connected to the PC computer via the USB port played the role of the CCD sensor. The camera resolution was 640×480 pixels. The camera was attached to the translation table equipped with the micrometric movement control. The He-Ne laser illuminated the CCD sensor directly. The camera lens has been removed and the gray optical filter reduced the amount of light in order to prevent the sensor saturation.

Results

The CCD camera was moved across the laser beam in 50 μm steps and the pictures were taken at every step. The beam spot shape and the x, y intensity of light distributions are shown in Figs. 1 and 2.

Figure 1. Laser beam spot

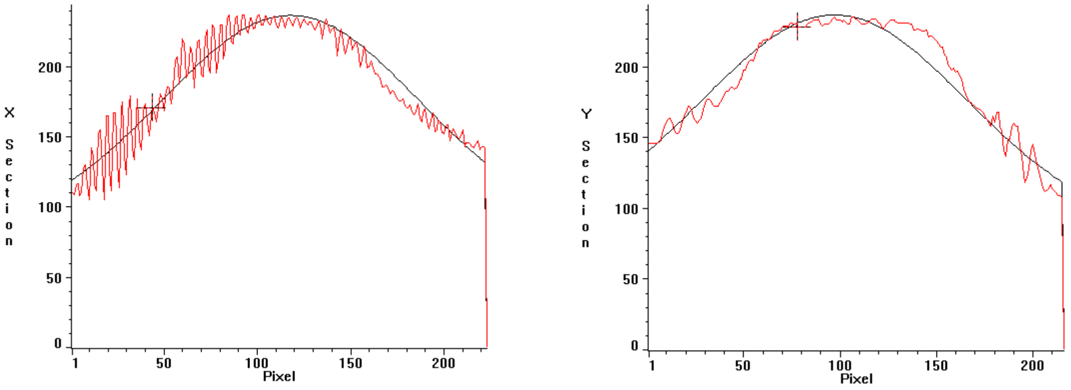

Figure 2. Light intensity distribution in x, y direction

Some saturation of the CCD sensor can still be noticed (a flat part of the light intensity distribution near the peak center and the gray optical filter of higher density should be used in the final setup. The fast interferences, which can be seen in the light distribution along the horizontal X axis (left panel of Fig. 2) and slower ones along the vertical Y axis are probably caused by the use of color camera and subsequent conversion to the gray-level picture. No such interferences are expected when a monochromatic camera is used instead. The simple 2-dimensional Gaussian fit applied to plots shown in Fig. 2 gives the center of the beam spot. The results are presented in Fig. 3.

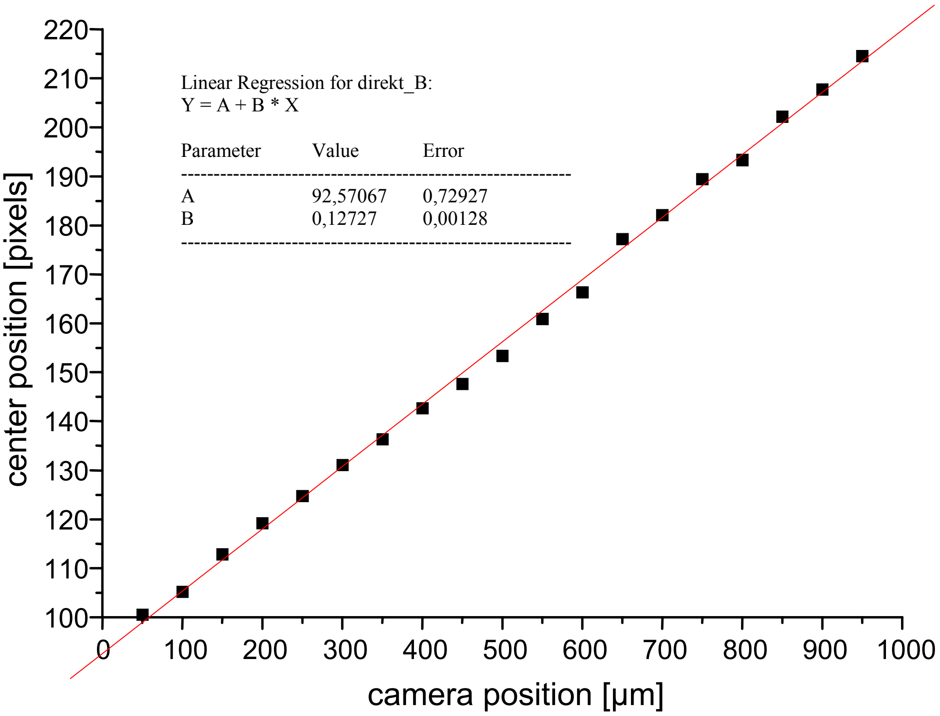

Figure 3. Calculated center of the beam spot versus camera position

The coefficient of the linear regression for the laser spot position (measured in pixel) versus the camera displacement (in µm) calculated for this set of pictures is 0.127 pixel/µm. The resolution of the displacement measurement can thus reach 1 μm if the accuracy of determination of the light spot center is better than 0.1 pixels [6].

Problems

There are several issues that should be addressed to the future experiments. The problem with the use of the color camera instead of the monochromatic one has already been mentioned. When choosing the camera, its pixel size should be considered as one of the important parameters and the smaller size should be chosen to achieve higher resolution. The CCD sensor saturation can be avoided by the use of the proper density filter.

The picture analysis algorithm is of prime importance, as it sets the limit for accuracy of the determination of the center of the laser light spot. Fortunately, efficient algorithms for this purpose are available. In the described experiment the laser beam shape has not been modified. In the final set-up the laser beam should be focused on the detector surface to achieve better resolution. The size of the laser waist should be matched to the pixel size in order to optimize the accuracy of the picture analysis algorithm. The use a semiconductor diode laser or the diode pumped solid-state laser is considered for the set-up. These lasers offer several advantages like a small size, long lifetimes, and the wavelength well matched to the detector efficiency characteristics. The angular stability of the laser beam pointing (micro pointing stability) has to be taken into account for laser types mentioned above. The micro pointing stability is lower for this type of lasers compared to the gas ones (e.g. He-Ne). It is also possible to use the laser positioned outside the valuable central area and to distribute the laser light via optical fiber. Exposure and readout synchronization in time slots between the trains of $e^+ e^-$ beams should be carefully investigated to avoid background. Radiation hardness of the CCD sensor and electronics should be studied. The CCD sensor will be placed between the rear side of a LAT calorimeter and a tungsten shield. The radiation dose in that place probably will not be so high.

The use of twin lasers in parallel configuration is considered. The detector size allows easily for that and the algorithms can cope with two laser spots. Such a configuration assures better reliability in case of a laser failure.

Conclusions

We have proved that using the above described method for measuring the detector displacement we can achieve the accuracy close to the required one. With the outlined refinements to the set-up a better picture analysis algorithm can be developed. A fine-pixel CCD sensor and careful control over the laser beam delivery path will allow the measurement of the detector displacement with higher precision.

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