Central Time-of-Flight Light Monitoring System

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January 5, 2015

Abstract

This document details the layout and design considerations for the CLAS12 Central Time-of-Flight Light Monitoring System, as well as the issues that we have identified.

1 CTOF Overview

The Thomas Jefferson National Accelerator Facility (JLab) is engaged in a project to double the energy of its electron accelerator from 6 to 12 GeV. This project also includes upgrades to the experimental equipment in the three experimental Halls A, B, and C, as well as the construction of a fourth experimental Hall D. The new beam facilities and the improved detection systems will be used to carry out the proposed scientific program. JLab is a nuclear physics research laboratory managed and operated by Jefferson Science Associates for the U.S. Department of Energy.

The experimental equipment in Hall B forms the large-acceptance CLAS12 spectrometer, a detector system that is based on two superconducting magnets, a solenoid about the target region and a six-fold symmetric toroid at forward angles. The detection subsystems that accompany these magnets include six sectors of drift chambers, electromagnetic calorimeters, scintillation counters, and Cherenkov detectors in the forward direction, and a vertex tracker, scintillation counters, and a neutron detector in the central region.

One of the scintillator arrays, called the Central Time-of-Flight (CTOF) system, spans laboratory angles from 35° to 125° and surrounds the experimental target at a radial distance of 25 cm. The CTOF detector consists of 48 92-cm-long scintillation bars having a trapezoidal cross section that forms a hermetic barrel. The barrel will be positioned inside of the 5 T superconducting solenoidal magnet. Each counter is read out on either end using photomultiplier tubes (PMTs) through long light guides to position the field-sensitive PMTs in reduced field regions. However, even in these positions, the PMTs will reside in inhomogeneous fringe fields from the magnet at levels as large as 1 kG. In order for the PMTs to operate properly at their design specifications for gain and timing resolution, the nominal field about the PMTs needs to be reduced to the level of 1 G. Hence the CTOF PMTs must be operated within specially designed magnetic shields.

The CTOF system shown in Fig. 1 is a major component of the CLAS12 central detector used to measure the time-of-flight of charged particles emerging from interactions in the target. The requirements for the CTOF include excellent timing resolution for particle identification and good segmentation to minimize counting rates. The system specifications call for an average time resolution for each counter along its full length of σ_{TOF}=60 ps. The system must also be capable of operating in a high-rate environment at the nominal CLAS12 luminosity of 1×10^{35} cm^{-2}s^{-1}. A summary of the CTOF technical parameters is given in Table 1.

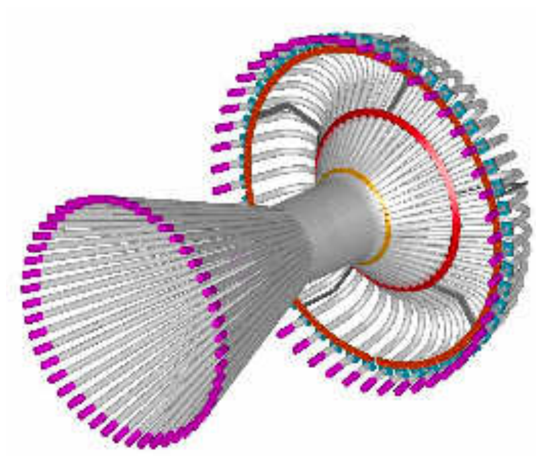

Figure 1: View of the Central Time-of-Flight system for CLAS12.

Parameter	Design Value
Counters	48 BC-408 counters forming a hermetic barrel; double-sided readout
Angular Coverage	θ: (35°,125°), ϕ: (-180°,180°)
Counter Dimensions	Trapezoidal cross section $\sim 3 \times 3 \times 92$ cm^3
PMTs	Hamamatsu R2083 (H2431-MOD assembly)
Light Guides - Upstream	O.D.=2″, 1-m-long, focusing design, straight
Light Guides - Downstream	O.D.=2″, 1.6-m-long, focusing design, bent 135°
Magnetic Shields	3-layer cylinder: Co-netic, Hiperm-48, Steel-1008; compensation coils around inner Co-netic layer
Design Resolution	60 ps
π/K separation	3.3σ up to 0.64 GeV
K/p separation	3.3σ up to 1.0 GeV
π/p separation	3.3σ up to 1.25 GeV

Table 1: CTOF technical design parameters.

2 CTOF Light Monitoring System

The average timing resolution for the CTOF counters along their full length that is required by the design specifications for the system is 60 ps. Given the location of the CTOF system in the CLAS12 central detector located only 25 cm from the beam-target interaction region, this will be a challenge to achieve and maintain. In order to be able to track the response of each PMT and each counter very closely with time, a Light Monitoring System (LMS) will be included as part of the CTOF system. The LMS will pulse light into each PMT at a rate of ∼1 Hz. These monitoring events will be part of the CLAS12 trigger configuration and will allow for detailed tracking with respect to time of the PMT gains and the individual counter timing response. These data will allow for more precise offline timing calibrations to be completed for each CTOF counter.

2.1 LMS Components

The components of the CTOF LMS include:

- The light source and driver;
- The focusing light guide;
- The fibers and alignment harness;
- The fiber coupler.

A block diagram of the CTOF LMS is shown schematically in Fig. 2. Each of the different components of the system is described below.

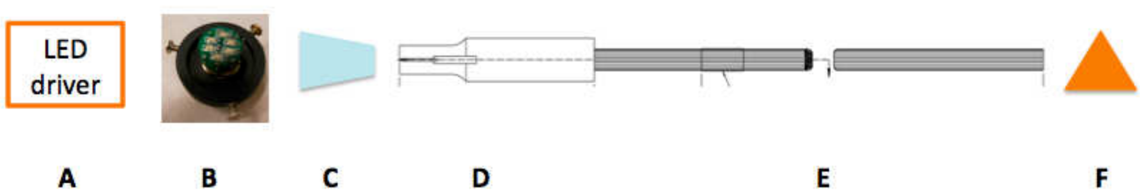

Figure 2: Block diagram of the CTOF Light Monitoring System identifying each of the system components. A. LED driver, B. LED source, C. Focusing light guide, D. Fiber harness, E. Fiber bundle, F. Fiber coupler to light guide.

1). The *light source* has been designed by the JLab Detector Group. As seen in Fig. 3, the light source consists of 6 LEDs fitted with a focusing lens that contains the light within a $\pm 10^{\circ}$ angular spread. The *driver* associated with the light source is currently being designed at JLab. In bench testing with a prototype driver, the light source has been shown to deliver 1×10^{7} photons/pulse. If this system directed all photons in each pulse to the fibers coupled to the CTOF PMTs, this would result in 1×10^{6} photons at each PMT photocathode.

However, the light losses in the coupling from the LED source to the fibers must be considered, as well as the light losses in the fibers, attenuation length effects, and the PMT photocathode quantum efficiency. Additionally, there will be a variation of the photon acceptance across the fibers.

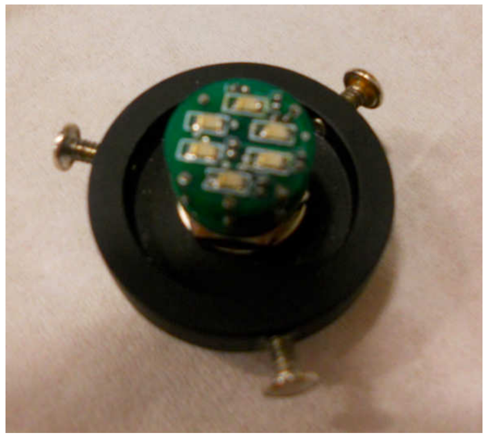

Figure 3: Photograph of the light-emitting diode (LED) light source for the CTOF LMS. The circuit board includes 6 LEDs each fitted with a focusing lens to collimate the produced light within an angular spread of $\pm 10°$.

2). The *focusing light guide* for the CTOF LMS has not yet been designed. Whether this component is a piece of shaped Acrylic or a lens is still to be determined. However, this component will attach to the light source at one end and the fibers at the other end.

One typical coupling scheme between the light source and the fibers is an integrating sphere as shown in Fig. 4. The light source shown in Fig. 3 could couple to the input port of the sphere and the bundled and collimated fibers, as shown in Fig. 5, could attach to the output port of the sphere. In fact, this approach is being employed by the High Threshold Cherenkov Counter (HTCC) for CLAS12. For the CTOF we have initially ruled out such an approach due to worries about loss of photon statistics at this juncture. Instead, we are considering a coupling between light source and fibers via a focusing light guide to direct as large a fraction of the produced light directly to the fibers. However, our goal is still to attempt to ensure as much as possible that the acceptance of light for each fiber is reasonably uniform across all fibers.

Note: The LMS does not strictly require "identical" numbers of photons per pulse at each PMT photocathode. The goal is mainly to ensure the photon statistics are sufficiently large to ensure that the gain and time resolution measurements are not statistics limited.

3). The choice of *fibers* for the CTOF system comes down to glass or plastic. The initial choice made was glass with the belief that for a given fiber length, the transmission of light through the glass would be better than for the plastic. The nominal design choice for the CTOF fibers was bare 300 μm glass fibers with a circular cross section (see Fig. 6). The plan was to cut the fibers to length, polish their ends, coat them with black paint, and bundle

Figure 4: Photograph of an integrating sphere. The LED source in Fig. 3 attaches directly to the open port. The other two ports are used for fiber attachment and for monitoring.

Figure 5: Photograph of a fiber bundle with individual jackets. The individual fibers are attached to a fiber harness to align the fibers. The fibers are polished at each end.

them together. The nominal choice for fiber length was 4.8 m. Fig. 7 shows the fibers for the CTOF LMS laid out in their production area.

Figure 6: Photograph of the bare 300 μm circular glass fibers employed for the CTOF LMS.

Figure 7: Photograph of the 4.8-m-long fibers laid out on the work preparation table.

A number of issues have come up in the preparation of the fibers. The first was associated with breakage at the ends of the fibers during the polishing step. Our process resulted in a ~30% breakage rate. The fibers could be recovered by cutting the last ~5 mm off the fiber and then repolishing. The second issue involves coating the bare fibers. The nominal plan was to spray paint the fibers before bundling them. While this step has not been carried out as of yet, thin coats of paint will likely develop scratches and openings, resulting in reduced transmission. Furthermore, it might be that using clad fibers will result in better transmittance than unclad fibers coated with paint.

A backup plan that is now being pursued is to move to a plastic fiber system produced by an outside manufacturer. This route was employed for the HTCC. They procured a fiber bundle of the desired length, polished to specifications, covered in plastic jackets, with custom bundling at the ends to mate with their light source and the PMTs. The HTCC system is shown in Figs. 3, 4, and 5.

4). The design of a single CTOF counter is shown in Fig. 8. The upstream light guide is straight and the downstream light guide is curved by 135° to enable it to fit around the downstream end of the solenoid magnet as shown in Fig. 9. The nominal plan is to attach both fibers to a fixture referred to as the *coupler* at the downstream end of each counter. This fixture is shown schematically in Fig. 8, and will have two channels that will each accept one fiber. One fiber will be directed toward the nearly PMT and the other fiber will be directed along the axis of the light guide toward the far (upstream) PMT. The end of each fiber will be glued into a small collar that will lock into the fiber coupler to provide a light-tight attachment.

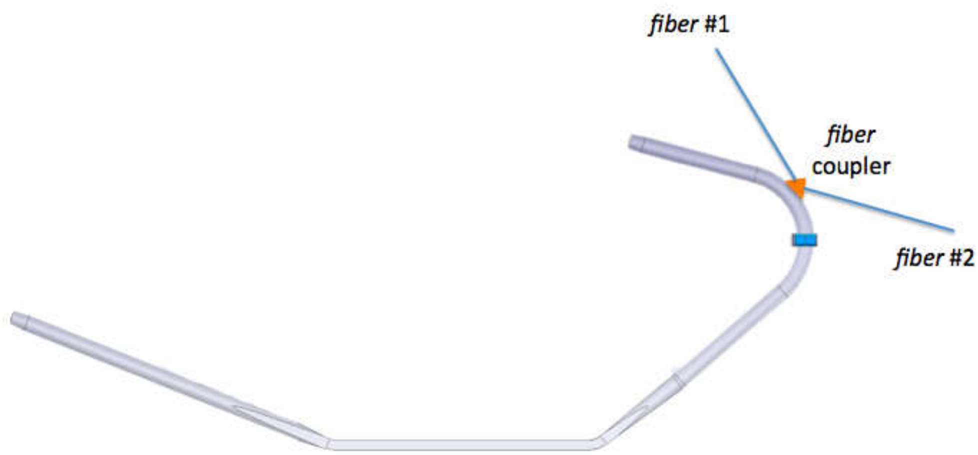

Figure 8: Schematic of a single CTOF scintillation counter. The fiber coupler (orange triangle) will be attached to the downstream end of the counter on the light guide. This coupler will accept two fibers, one will point into the downstream PMT, and the other will point along the light guide axis to send light to the upstream PMT.

3 Photoelectron Statistics

The estimate of the photoelectron statistics per pulse of the LED source is estimated as:

$$N_{pe} = \frac{N_{LED} \cdot \varepsilon_{FLG} \cdot \tau_{fiber} \cdot QE \cdot \tau_{scint}}{N_{fibers}}. \tag{1}$$

Here,

- N_{pe} = Number of primary photoelectrons produced by the flash at the photocathode of the PMT. For this application we want $N_{pe} = 1000$ photons/fiber/pulse;

Figure 9: Cut schematic view of the CTOF system installed in the CLAS12 solenoid magnet and the CTOF positioning in relation to the HTCC detector.

- N_{LED} = Number of photons per flash produced by the light source, assumed to be 1×10^7;
- ε_{FLG} = Transmission efficiency of the focusing light guide, assumed to be 50%;
- τ_{fiber} = Transmission efficiency for the fibers, assumed to be 90%;
- QE = Quantum efficiency of the PMT photocathode at the wavelength of the light source, assumed to be 20% at 400 nm wavelength;
- τ_λ = Photon transmission after attenuation length losses from end of fiber to the PMT photocathode;
- N_{fibers} = Number of fibers in the LMS bundle, 96 fibers.

For our design we have the following expectations:

$$N_{pe} = \frac{1 \times 10^7 \text{ photons/pulse} \cdot 50\% \cdot 90\% \cdot 20\% \cdot \tau_{scint}}{100 \text{ fibers}} \tag{2}$$
$$= 9 \times 10^3 \text{ photons/fiber/pulse} \cdot \tau_{scint} \tag{3}$$

To estimate the attenuation length losses of light in the system, we assume the attenuation length of the Acrylic light guides is 2.5 m and the counter-specific attenuation length for the 92-cm-long BC-408 scintillator is 0.2 m. The relevant dimensions are:

- Downstream light guide = 1.6 m
- Scintillator 92 cm

- Upstream light guide = 1.0 m

The transmittance is computed using:

$$\tau_\lambda = e^{-x/\lambda}, \tag{4}$$

where the distance from the fiber to the downstream PMT photocathode is assumed to be 0.30 m and the relevant distance from the fiber to the upstream light guide is assumed to be 3.2 m. With these numbers, we compute $\tau_\lambda^{downstream}$= 89% ($= e^{-0.3/2.5}$) and $\tau_\lambda^{upstream}$ = 25% ($= e^{-1.3/2.5} e^{-0.92/2.0} e^{-1.0/2.5}$). With these numbers we compute for our photoelectron statistics per pulse:

- N_{pe} (upstream) = 2,250 photons/pulse (per fiber)
- N_{pe} (downstream) = 8,010 photons/pulse (per fiber)

4 Design Issues

The main design issues with the CTOF LMS involve the choice of fibers and their preparation. As stated above, the initial plan was to employ bulk glass fibers, cut to length, polished at both ends, then painted and bundled. However, after an extensive effort to polish the fibers, we have experienced significant breakage, chipping, and flaking of the end of the fibers given our configuration for polishing. The job has proven to be labor intensive as well. We are not fully certain of how well the paint that we will apply will hold up with time and if we should employ clad and jacketed fibers instead.

Because of these issues we are now beginning to investigate the purchase of a commercial fiber bundle system that will be "plug and play". Namely, out of the box it will be ready to couple to our light source on one end and to the CTOF counters on the other. A similar system was purchased from LEONI Fiber Optics, Inc. (http://www.leonifo.com).

The following list summaries our open design issues with the CTOF LMS:

- Use of focusing light guide instead of an integrating sphere;
- Plastic vs. glass fibers;
- Clad vs. unclad fibers;
- Painted vs. jacketed fibers;
- Both fibers mounted at the downstream end of the counters vs. positioning fibers separately near each PMT.

5 Summary and Conclusions

In order to track the performance of the CLAS12 CTOF detector performance with time and to allow for optimal time response calibrations, the detector will be equipped with a Light Monitoring System. This system is being designed to inject light into the PMTs at a rate of $\sim$1 Hz in a dedicated data stream. The events will allow for reconstruction of the resolution vs. time and for tracking the PMT gain vs. time.

The present design involves an LED light source that will be coupled to the counters through 300 μm glass fibers. To date, the preparation of the fibers, including polishing and coating have proven data intensive. We are considering moving to a commercially prepared fiber optic system that will arrive ready for immediate integration into the CTOF system.