Central Time-of-Flight Geometry for CLAS12

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Abstract

This document details the nominal geometry of the scintillation bars for the CLAS12 Central Time-of-Flight System (CTOF).

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. 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 that form a hermetic barrel. The barrel will be positioned inside of the 5 T superconducting solenoid 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 magnetic field about the PMTs needs to be reduced to a level below 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 that is 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

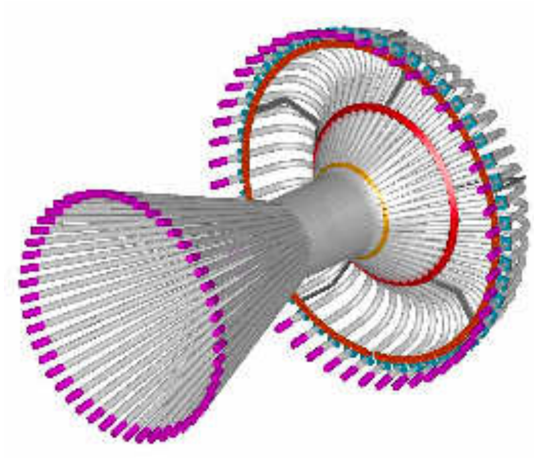

Figure 1: View of the Central Time-of-Flight system for CLAS12 showing the upstream straight light guides, the scintillation bars, and the downstream bent light guides. The PMTs are represented by the red cylinders.

luminosity of 1×10^{35} cm^{-2}s^{-1}. A summary of the CTOF technical parameters is given in Table 1.

The CTOF scintillation barrel is composed of 48 wedge-shaped counters of two slightly different designs that alternate in azimuth. A pair of neighboring CTOF counters is shown in Fig. 2. The difference between the two designs is in the pitch angle of the upstream straight light guide and the upstream end of the scintillation bars where they attach to this light guide.

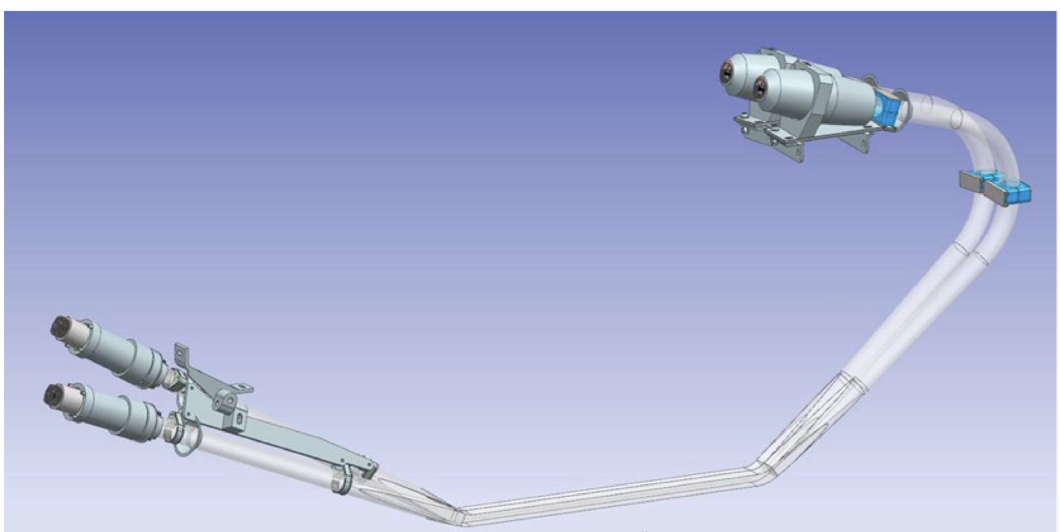

Figure 2: A pair of neighboring CTOF counters with two slightly different designs for the upstream light guide and the upstream end of the scintillation bars.

The CTOF detector will be mounted to the CLAS12 solenoid as shown in Fig. 3. The global z-axis called the beamline, lies along the symmetry axis of the CTOF barrel pointing downstream (left to right in Fig. 3). The global y-axis points upward in the drawing. The

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.

origin of the global coordinate system is set at the geometrical center of the solenoid. Here we define the downstream side of CTOF to be at positive z (on the right side of Fig. 3) and the upstream side of CTOF to be at negative z (on the left side of Fig. 3).

In this CTOF geometry document we describe in detail how to define the volumes of the scintillation bars accounting for any misalignments after installation in Hall B. This note does not include a description of the Acrylic light guides. Ultimately, a description of the light guides will have to be included in the geometry description for the CTOF, especially at the downstream end of the counters where the light guides are in the detector acceptance for angles about θ=35°.

2 Scintillation Bar Geometry

As seen in Figs. 2 and 3, the CTOF counters are complex structures. There are two groups of counters that each include 24 scintillators. Each of the two groups has a slightly different pitch angle for the scintillation bars on the upstream side. The first group, or the "low-pitch"design, has a pitch angle of 21.8°. The second group includes the scintillation bars with a pitch angle of 29.09°, referred to as the "high-pitch" design. For both the low-pitch and high-pitch designs, the scintillation bars have a pitch angle at the downstream end of 36.0°. The corresponding design drawings for the different CTOF scintillation bar designs are shown in Figs. 4 and 5.

The scintillation bar design is essentially a uniform wedge-shaped piece of BC-408 scintillator material that subtends a 7.5° azimuthal range as seen from the target. Only at the very ends of the bars do they curve upwards to join the light guides. A simplified description of the designs of the two different CTOF scintillation bar designs is as follows:

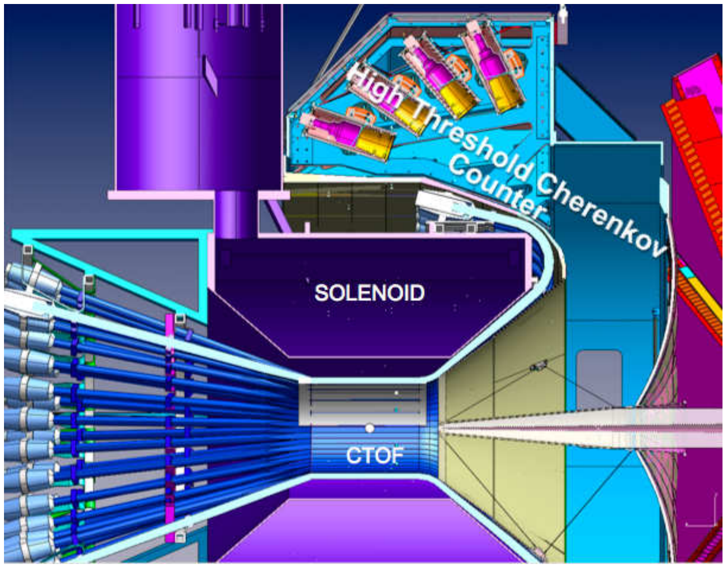

Figure 3: CTOF mounted within the CLAS12 solenoid in a cut view where the beam axis runs along the CTOF barrel symmetry axis with the beam entering from the left.

High-Pitch Design

- Upstream curved section: L_z=1.624 in, θ_{pitch}=29.09°
- Straight section: L_z=31.765 in
- Downstream curved section: L_z=2.214 in, θ_{pitch}=36.0°
- Scintillation bar: w_i=1.264 in, w_o=1.420 in, θ_{wedge}=7.5°

Low-Pitch Design

- Upstream curved section: L_z=1.151 in, θ_{pitch}=21.80°
- Straight section: L_z=31.765 in
- Downstream curved section: L_z=2.214 in, θ_{pitch}=36.0°
- Scintillation bar: w_i=1.264 in, w_o=1.420 in, θ_{wedge}=7.5°

Here L_z is the section length along the z-axis, w_i (w_o) is the width of the scintillation bar at its inside (outside) face, and θ_{wedge} is the azimuthal angle subtended by each bar as seen from the target. The complete description of the scintillation bar geometry for the CTOF is made a bit complicated by the fact that the bars are not a uniform wedge-shaped cross section from end to end. They actually have a slightly projective geometry near the ends to match the designs of the light guides. So although an approximate description of the CTOF

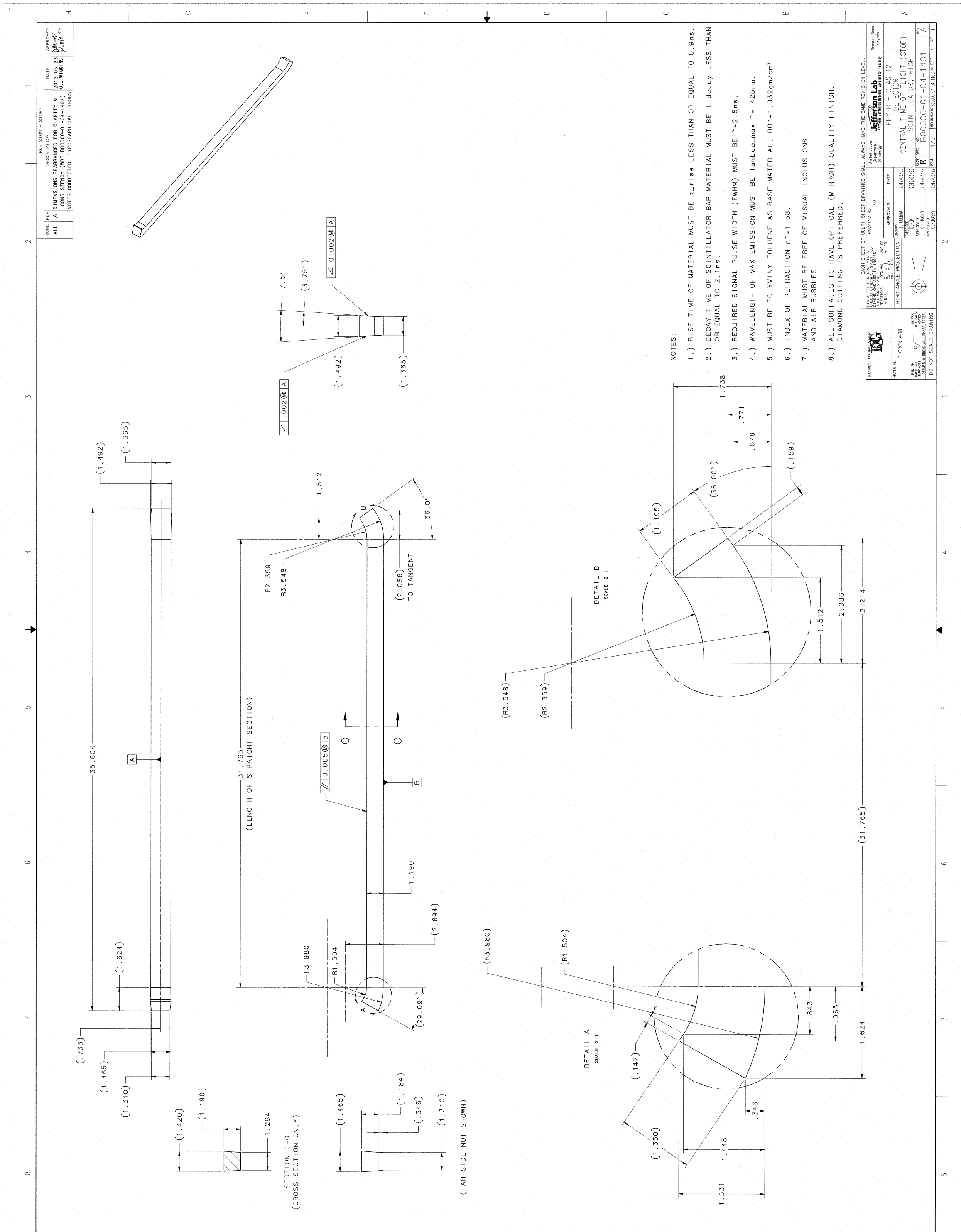

Figure 4: CTOF scintillation bar of the high-pitch design. Ref. Drawing B00000-01-04-1401.

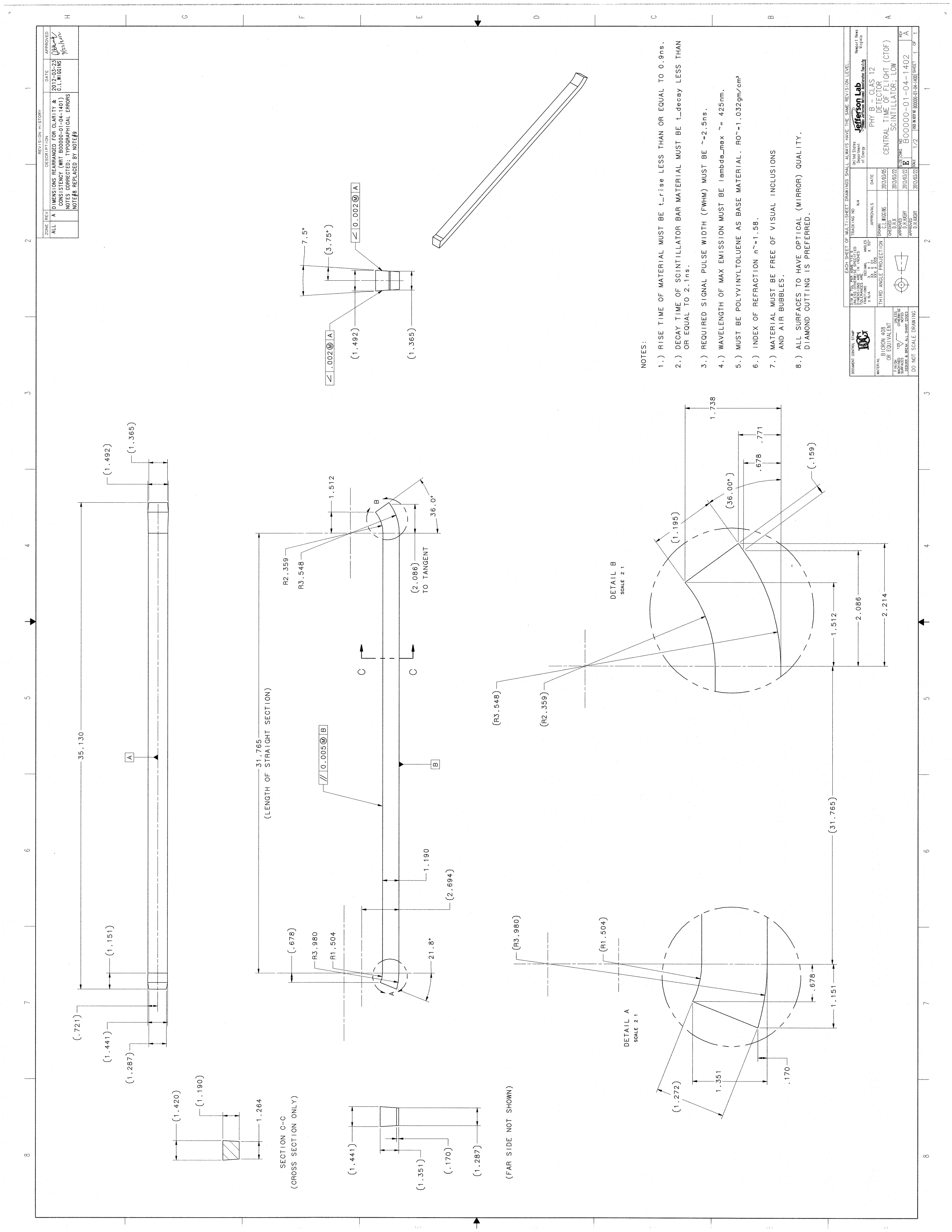

Figure 5: CTOF scintillation bar of the low-pitch design. Ref. Drawing B00000-01-04-1402.

using a uniform wedge cross section could be employed to represent the bar geometry, in this note we provide a more complete and exact description.

The approach to more accurately define the CTOF scintillation bar geometry involves segmenting each bar into its three different regions, the upstream bend section, the straight section, and the downstream bend section. Each of these different regions will then be defined in terms of the bounding shapes on each of their surfaces. These shapes are all either planes or cylinders. For the approach employed here, each scintillation bar can be defined in its entirely by eight planes and four cylinders. These twelve shapes are introduced and described in Table 2. Fig. 6 provides a pictorial definition of these shapes on a schematic scintillation bar.

#	Name	Shape Description
1	Ups Cyl1	Upstream cylinder at outer radius surface
2	Ups Cyl2	Upstream cylinder at inner radius surface
3	Dns Cyl1	Downstream cylinder at outer radius surface
4	Dns Cyl2	Downstream cylinder at inner radius surface
5	Ups Plane1	Upstream vertical plane at end of straight section
6	Ups Plane2	Upstream sloping plane
7	Dns Plane1	Downstream vertical plane at end of straight section
8	Dns Plane2	Downstream sloping plane
9	PlaneHiRad	Horizontal plane at high radius surface
10	PlaneLoRad	Horizontal plane at low radius surface
11	PlaneHiX	Side plane at positive x side
12	PlaneLoX	Side plane at negative x side

Table 2: Listing and description of the geometrical shapes required to define the geometry of the CTOF scintillation bars.

Each element listed in Table 2 is defined using two vectors. These vectors are determined in the global CLAS12 coordinate system. There is also one additional scalar value to specify the radius R_{cyl} of each of the different cylinders. The two vectors for each element are defined as: (1) vector $\vec{r}_0$ from the origin that determines a point at the axis of each cylinder or a point on each plane, and (2) a unit vector $\hat{n}$ that specifies the direction of each cylinder's axis or a normal to each plane. Fig. 7 highlights the vectors $\vec{r}_0$ and $\hat{n}$. The formulas used for the evaluation of the components of the vectors $\vec{r}_0$ and $\hat{n}$ are given in Table 3.

The values of the parameters $\vec{r}_0$ and $\hat{n}$ for each shape listed in Table 2 are derived from the reference drawings for the scintillation bars shown in Figs. 4 and 5. The base parameters from the drawings are listed in Table 4 for the high-pitch design and in Table 5 for the low-pitch design. Note that the inner radius of the CTOF barrel of 25.11 cm is not listed in the drawings shown. Also note that for the CTOF scintillation bar design the centers of the downstream cylinders happen to coincidence. This is not the case for the upstream cylinders.

The three components of each vector $\vec{r}_0$ and each vector $\hat{n}$ for the CTOF scintillation bars are listed in Table 6 for the high-pitch design and in Table 7 for the low-pitch design. Note

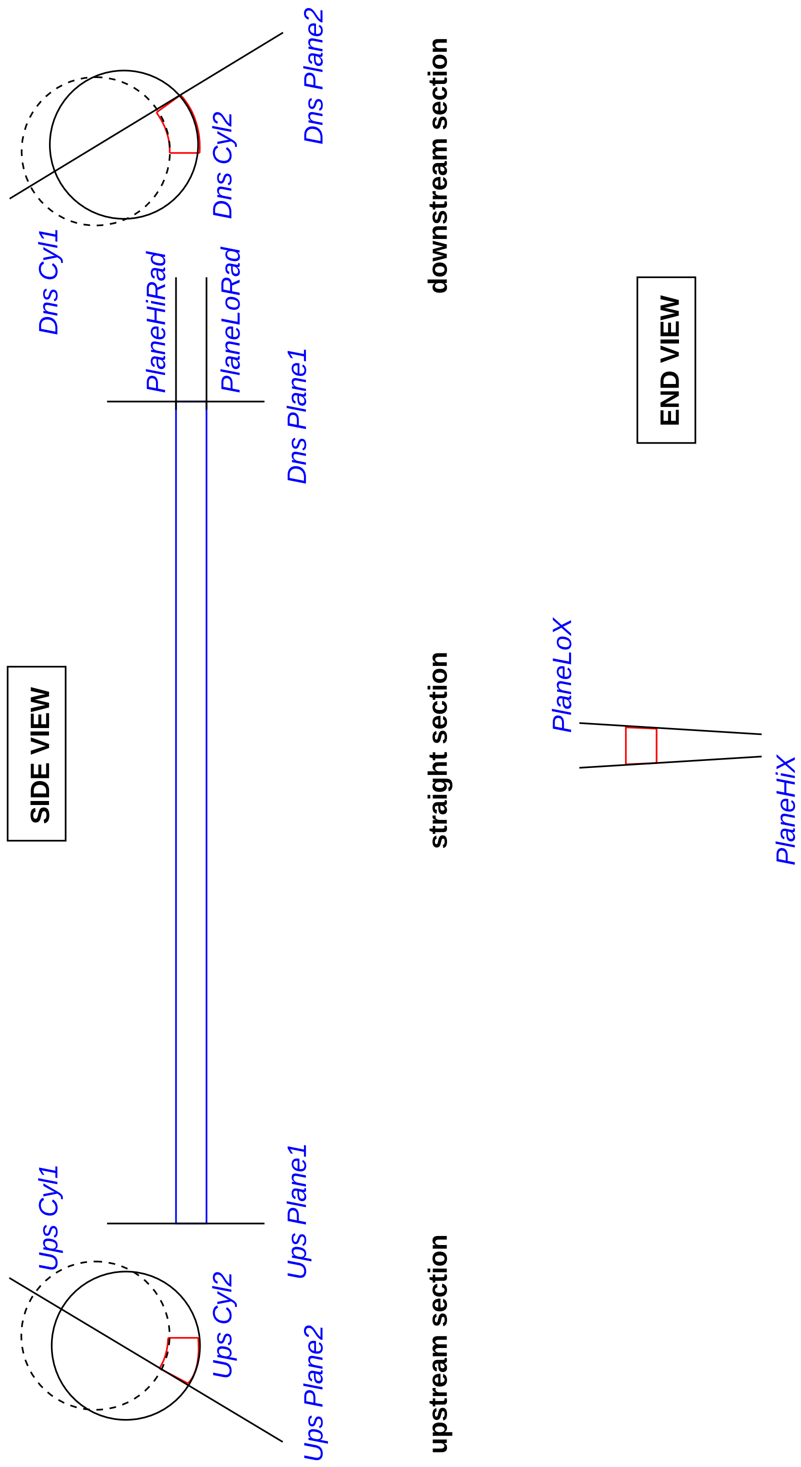

Figure 6: Schematic representation of a generic CTOF scintillation bar showing the definitions of the geometrical shapes introduced in Table 2. The “SIDE VIEW” shows the center straight section in blue and the curved end sections in red separated in z to aid in the labeling. The “END VIEW” shows the scintillation bar in red.

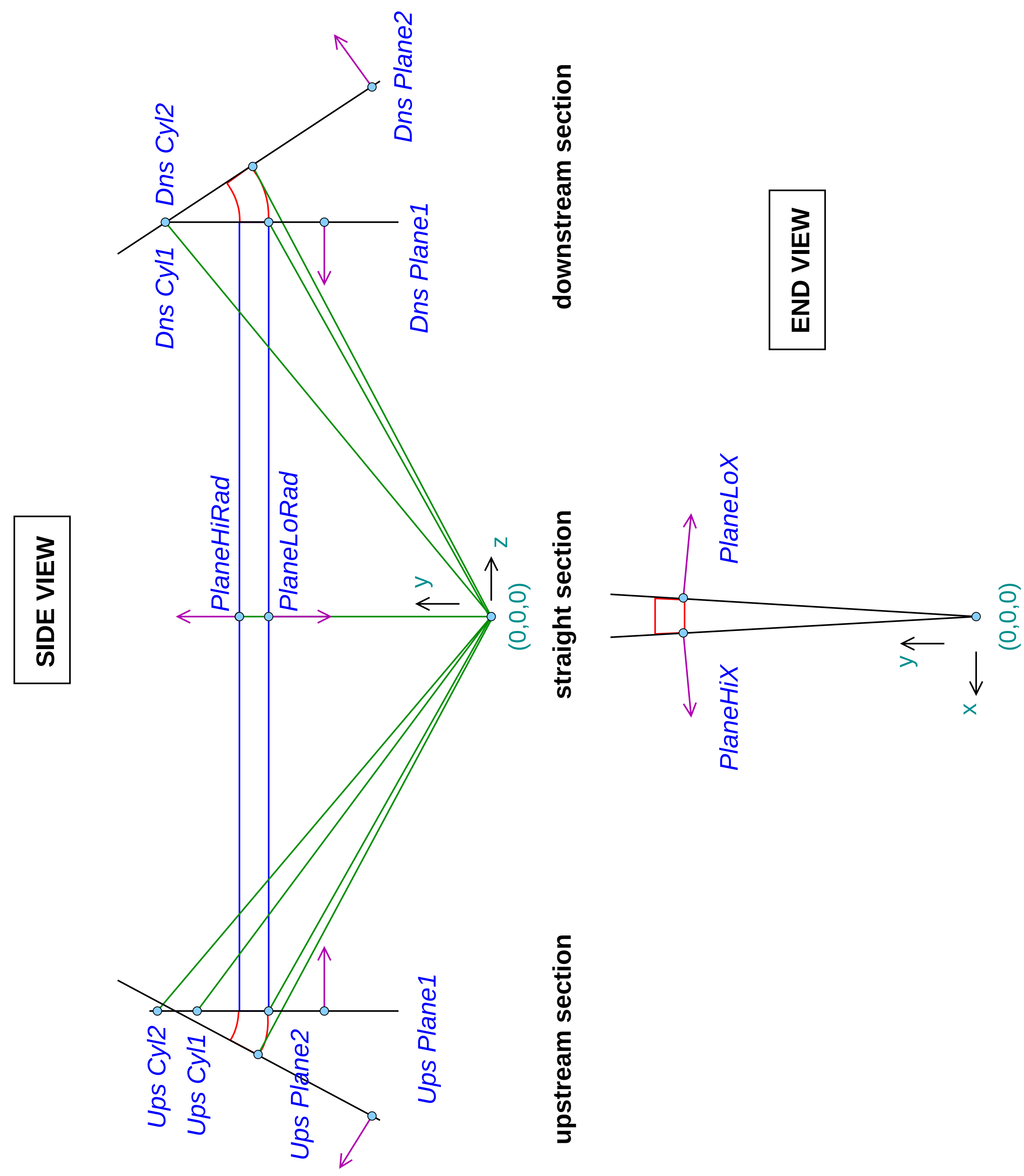

Figure 7: Schematic representation of a generic CTOF scintillation bar showing the definitions of the geometrical shapes introduced in Table 2. The "SIDE VIEW" shows the center straight section in blue and the curved end sections in red. The "END VIEW" shows the scintillation bar in red. The green lines represent the vectors $\vec{r}_0$ and the magenta lines with arrow the vectors $\hat{n}$. The definition of the CLAS12 global coordinate system is shown in each view.

		x	y	z
Ups Cyl1	$\vec{r}_0$	0.0	$R_b + \Delta t + R_{ups1}$	$-L_z/2$
	$\hat{n}$	1.0	0.0	0.0
Dns Cyl1	$\vec{r}_0$	0.0	$R_b + \Delta t + R_{dns1}$	$L_z/2$
	$\hat{n}$	1.0	0.0	0.0
Ups Cyl2	$\vec{r}_0$	0.0	$R_b + R_{ups2}$	$-L_z/2$
	$\hat{n}$	1.0	0.0	0.0
Dns Cyl2	$\vec{r}_0$	0.0	$R_b + R_{dns2}$	$L_z/2$
	$\hat{n}$	1.0	0.0	0.0
Ups Plane 1	$\vec{r}_0$	0.0	R_b	$-L_z/2$
	$\hat{n}$	0.0	0.0	1.0
Dns Plane 1	$\vec{r}_0$	0.0	R_b	$L_z/2$
	$\hat{n}$	0.0	0.0	-1.0
Ups Plane 2	$\vec{r}_0$	0.0	$R_b + r^I_{ups}$	$-(L_z/2 + z^I_{ups})$
	$\hat{n}$	0.0	$\sin\theta_{ups}$	$-\cos\theta_{ups}$
Dns Plane 2	$\vec{r}_0$	0.0	$R_b + r^I_{dns}$	$L_z/2 + z^I_{dns}$
	$\hat{n}$	0.0	$\sin\theta_{dns}$	$\cos\theta_{dns}$
PlaneHiRad	$\vec{r}_0$	0.0	$R_b + \Delta t$	0.0
	$\hat{n}$	0.0	1.0	0.0
PlaneLoRad	$\vec{r}_0$	0.0	R_b	0.0
	$\hat{n}$	0.0	-1.0	0.0
PlaneHiX	$\vec{r}_0$	$w_s/2$	R_b	0.0
	$\hat{n}$	$\cos(\theta_{div}/2)$	$-\sin(\theta_{div}/2)$	0.0
PlaneLoX	$\vec{r}_0$	$-w_s/2$	R_b	0.0
	$\hat{n}$	$-\cos(\theta_{div}/2)$	$-\sin(\theta_{div}/2)$	0.0

Table 3: Table defining the CTOF scintillation bar surface shape vectors $\vec{r}_0$ and $\hat{n}$ in terms of the design values from the drawings.

Parameter	Dimension
Barrel Inner Radius R_b	9.886 in
Trapezoid Length L_z	31.765 in
Radial Thickness Δt	1.189 in
Width Small w_s	1.264 in
Ups Cyl1 Radius R_{ups1}	1.504 in
Dns Cyl1 Radius R_{dns1}	2.359 in
Ups Cyl2 Radius R_{ups2}	3.980 in
Dns Cyl2 Radius R_{dns2}	3.548 in
Ups Plane Angle θ_{ups}	29.09°
Dns Plane Angle θ_{dns}	36.00°
Divergence Angle θ_{div}	7.50°
Ups Bend r-increment r^I_{ups}	0.346 in
Ups Bend z-increment z^I_{ups}	1.624 in
Dns Bend r-increment r^I_{dns}	0.771 in
Dns Bend z-increment z^I_{dns}	2.214 in

Table 4: Design parameters for a CTOF scintillation bar of the high-pitch design based on Ref. Drawing B00000-01-04-1402.

Parameter	Dimension
Barrel Inner Radius R_b	9.886 in
Trapezoid Length L_z	31.765 in
Radial Thickness Δt	1.189 in
Width Small w_s	1.264 in
Ups Cyl1 Radius R_{ups1}	1.504 in
Dns Cyl1 Radius R_{dns1}	2.359 in
Ups Cyl2 Radius R_{ups2}	3.980 in
Dns Cyl2 Radius R_{dns2}	3.548 in
Ups Plane Angle θ_{ups}	21.80°
Dns Plane Angle θ_{dns}	36.00°
Divergence Angle θ_{div}	7.50°
Ups Bend r-increment r^I_{ups}	0.170 in
Ups Bend z-increment z^I_{ups}	1.151 in
Dns Bend r-increment r^I_{dns}	0.771 in
Dns Bend z-increment z^I_{dns}	2.214 in

Table 5: Design parameters for a CTOF scintillation bar of the low-pitch design based on Ref. Drawing B00000-01-04-1401.

that the coordinates listed in these tables are given for counters positioned with their median plane placed at zero azimuth, which corresponds to x=0. The values given in Tables 6 and 7 use the formulae from Table 3 with the parameter values from Tables 4 and 5, respectively.

Parameter	$\vec{r}_0$ (in)			$\hat{n}$			R_{cyl} (in)
	x_0	y_0	z_0	n_x	n_y	n_z	
Ups Cyl1	0.000	12.579	-15.883	1.000	0.000	0.000	1.504
Ups Cyl2	0.000	13.886	-15.883	1.000	0.000	0.000	3.980
Ups Plane1	0.000	9.886	-15.883	0.000	0.000	1.000	–
Ups Plane2	0.000	10.232	-17.507	0.000	0.486	-0.874	
Dns Cyl1	0.000	13.434	15.883	1.000	0.000	0.000	2.359
Dns Cyl2	0.000	13.434	15.883	1.000	0.000	0.000	3.548
Dns Plane1	0.000	9.886	15.883	0.000	0.000	-1.000	–
Dns Plane2	0.000	10.657	18.097	0.000	0.588	0.809	–
PlaneHiRad	0.000	11.075	0.000	0.000	1.000	0.000	–
PlaneLoRad	0.000	9.886	0.000	0.000	-1.000	0.000	–
PlaneHiX	0.632	9.886	0.000	0.998	-0.065	0.000	–
PlaneLoX	-0.632	9.886	0.000	-0.998	-0.065	0.000	–

Table 6: Parameters of geometric primitives defined in Table 2. The parameters are listed for a scintillator of the high-pitch design with 29.09° upstream pitch and design dimensions given in drawing B00000-01-04-1402-A.

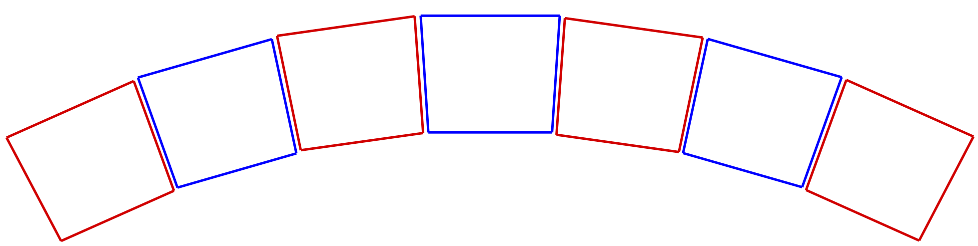

Figure 8: Cross sectional view of the upper portion of the CTOF scintillation barrel showing three scintillation bars of each design. The bars in blue are of the low-pitch design and those in red are of the high-pitch design.

Given the complete definition of the bounding surfaces for the CTOF scintillation bars, the nominal volume of the bars can be defined. Once the nominal volume for a high-pitch and a low-pitch scintillation bar has been defined, the full CTOF scintillation barrel can be defined by rotating the defined bars by their appropriate 15° increments in azimuth. Note that the counter at $x = 0$ (i.e. 12 o'clock) is a counter with the low-pitch design. Fig. 8 shows

Parameter	$\vec{r}_0$ (in)			$\hat{n}$			R_{cyl} (in)
	x_0	y_0	z_0	n_x	n_y	n_z	
Ups Cyl1	0.000	12.579	-15.883	1.000	0.000	0.000	1.504
Ups Cyl2	0.000	13.886	-15.883	1.000	0.000	0.000	3.980
Ups Plane1	0.000	9.886	-15.883	0.000	0.000	1.000	–
Ups Plane2	0.000	10.056	-17.034	0.000	0.371	-0.928	
Dns Cyl1	0.000	13.434	15.883	1.000	0.000	0.000	2.359
Dns Cyl2	0.000	13.434	15.883	1.000	0.000	0.000	3.548
Dns Plane1	0.000	9.886	15.883	0.000	0.000	-1.000	–
Dns Plane2	0.000	10.657	18.097	0.000	0.588	0.809	–
PlaneHiRad	0.000	11.075	0.000	0.000	1.000	0.000	–
PlaneLoRad	0.000	9.886	0.000	0.000	-1.000	0.000	–
PlaneHiX	0.632	9.886	0.000	0.998	-0.065	0.000	–
PlaneLoX	-0.632	9.886	0.000	-0.998	-0.065	0.000	–

Table 7: Parameters of geometric primitives defined in Table 2. The parameters are listed for a scintillator of the low-pitch design with 21.8° upstream pitch and design dimensions given in drawing B00000-01-04-1401-A.

a representation of the top portion of the CTOF scintillator barrel and the configuration of three scintillation bars of each design.

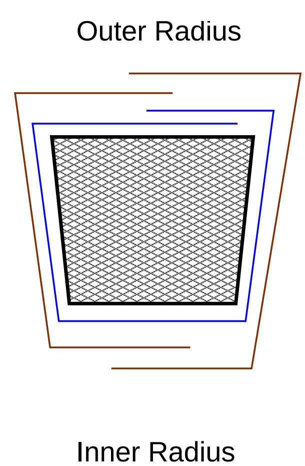

Figure 9: Cross sectional view of a CTOF scintillator (in black) and a representation of the VM2000 wrapping layer (in blue) and the Tedlar wrapping layer (in brown).

In detail, the faces of neighboring CTOF scintillation bars are co-planar. The nominal design gap from scintillation bar face to scintillation bar face is 800 μm. Each scintillation bar is nominally wrapped by two layers of VM2000 (2.6-mil-thickness) and one layer of Tedlar (2.0-mil-thickness) as shown in Fig. 9. The nominal inter-counter gap for the wrapped CTOF counters is thus 332 μm (= 800 μm - 2×50.8 μm - 4×66.0 μm - 2×50.8 μm).

2.1 Survey Plans

After installation of the CTOF counters into the CLAS12 solenoid, survey of each counter will then proceed. The survey approach for each counter will be to use the laser tracker system to site three points along the inner surface of each scintillation bar. The points selected will be at the ends of each bar just before they curve up to meet the light guides and at the center of the bar. The coordinates measured in the CLAS12 coordinate system should be accurate to 50 μm.

With the three measured points for each bar the tilt angle (or pitch angle) along the beamline can be determined as well as any radial shift. This procedure will not be sensitive to any roll angles (about the y-axis) or yaw angles (about the z-axis). Thus the software geometrical corrections to account for deviations from the ideal geometry will include only θ_{pitch} and ΔR_b for each scintillation bar.