Investigation of GUIDEIT Ray Tracing Program

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Abstract

An investigation of the ray-tracing program GUIDEIT has been performed to gain knowledge regarding ray tracing in scintillating fibres (SciFi). GUIDEIT simulations of both single- and multi-clad fibres were developed. These simulations are of interest due to the large role of SciFi in the Barrel Calorimeter (BCAL) portion of the *GlueX* project. The simulations produced data pertaining to the Time of Flight, Number of Bounces, Exit Position and Exit Angle of photons traveling down SciFi. The data was also used to analyze Light Yield and Trapping Efficiency of SciFi.

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I. INTRODUCTION

The purpose of investigating GUIDEIT is to gain knowledge regarding ray tracing in scintillating fibres (SciFi). This knowledge is desired such that it can be incorporated into Monte Carlo simulations of the Barrel Calorimeter (BCAL) subsystem of the *GlueX* project, using the GEANT tracking package. Qualitative and quantitative analysis of photons traveling down SciFi must be performed such that these important characteristics can be included in the current energy-based simulations. The characteristics obtained from ray-tracing simulations will also play an important role in future ventures involving light collection from the BCAL.

To achieve the goals stated above the GUIDEIT software was configured to simulate photons traveling down single- and multi-clad SciFi. The remainder of this document will discuss how the GUIDEIT software operates, will touch upon previous simulations performed using GUIDEIT, and will present the progression to the new results obtained from current GUIDEIT simulations.

II. THE GUIDEIT SOFTWARE

"GUIDEIT is a ray tracing program. It is intended for modelling scintillator and light guide systems." [1] This section will be focussed on the configuration of GUIDEIT for performing simulations involving SciFi. Further details about GUIDEIT can be found in the GUIDEIT V1.1 Users Manual by Daniel A. Simon.

The basis of GUIDEIT is the configuration of surfaces, which define a geometrical shape. The fate of photons is then tracked as they travel through the user-defined shape. All of the photons travel in straight lines between surfaces and the photon reacts at each surface dependent on the properties of that surface. A complex shape can be a composition of many simple shapes; thus the primary shapes are grouped into sequences. The primary surfaces that are available in GUIDEIT are PLANEs, CIRCULARs (discs), CYLINDERs, BENTs (cylinder sections), CONEs (truncated cones), and CONSECs (conic sections of rotation). Simulations of SciFi only require two types of surfaces. CYLINDER surfaces are used to represent the axial surfaces of the core and cladding of a SciFi, and CIRCULAR surfaces are used for the end faces of the fibre.

Before configuring the surfaces for the simulation, general options must be set. Some of the options relevant to the SciFi simulations are: the random seed used for the random number generator, number of photons per source, number of sources, maximum number of bounces, number of sequences, speed of light, bulk attenuation, reflectivity, and statistical output. These options will be further discussed in the description of the simulations.

At this point the surfaces of the desired shape can be configured. As mentioned above, to model a SciFi only two types of surfaces are required. The type of the surface should be the first property defined. A surface must be defined for every orientation of a photon travelling through the shape. For example, two surfaces must be defined for the interface between the core and the cladding of a SciFi. This is because a photon can be incident upon the core cladding interface from either the core or the cladding. Furthermore, the photon reacts with that interface depending on the medium of approach, and the properties of the surface determine the details of the reaction.

The surface properties that must be defined are the *internal* and *external index of refraction* (IOR), *surface detail*, *attenuation length*, *sequence number*, *surface roughness*, *realm*, *gate type*, and *gate number*. These will be discussed in more detail below.

The internal and external IOR are defined with respect to the type of the surface, not the position of the incident photon. (The reader is directed to the GUIDEIT Users Manual's section on surface types to correctly determine what is considered internal and external for the surface of interest) The surface detail is set to NONE for simulations that deal with bare surfaces. The attenuation length property is only used when the bulk attenuation option mentioned above is turned on.

The *sequence number* plays a very important role in GUIDEIT simulations. Each surface is given a sequence number to increase the efficiency of the simulations. Following an interaction with a surface, only surfaces of the same sequence number as the current sequence status of the photon are considered as a possibility for the next surface interaction. Sequence numbers in close cooperation with the gates –that will be discussed below– largely determine the progression of the photons through the shape.

The *surface roughness* specifies the reflection coefficient of each surface, in order to model the actual roughness of non-ideal materials. Every time a photon interacts with a surface a random number is compared with the set roughness factor to determine if the photon should be terminated due to roughness. For simulations with few bounces this factor makes very little difference in the results. For simulations involving fibres or shapes that induce a high number of bounces the sensitivity to this surface roughness becomes great.

The *realm property* defines which part of the surface can be hit by a photon. The photon can be incident upon a surface from the inside or the outside. Again this is in reference to the definition of "internal" and "external" as defined by the surface type.

The final component to set for each surface is its *gate*. There are four types of gates: GATE, TOPGATE, BOTGATE, NONE. The purpose of the gates is for histogram booking and changing the sequence status of the photon. All four gates are used in SciFi simulations. When a photon passes through a GATE the associated histogram is booked and the photon is terminated. When a photon passes through a TOPGATE or BOTGATE the associated histogram is booked and then the photon is moved to the next or previous sequence respectively. If the desired sequence does not exist the photon is terminated. When a photon passes through a NONE gate no histogram is booked and the photon is terminated. Each gate in a specific sequence must have a unique gate number. This is required so that the correct values are booked in the histograms, and therefore a NONE gate does not have a gate number.

The next step is to setup the photon source for the simulation. There are two modes of operation: single source and a matrix scan source. The SciFi simulations primarily used an isotropically emitting single source. Refer to the GUIDEIT Users Manual for details regarding the configuration of a photon source.

The final step before the simulation is ready to run is the configuration of the histograms. The sequence and gate numbers are used to define where the data are obtained from when booking the histograms. Both one-dimensional and two-dimensional histograms can be created using the following factors: bounces, time, XYZ position of the photon, XYZ velocity component of the photon, angle of the photon, and XY coordinate of the starting position of the photon. GUIDEIT produces two output files, for histogram output and text output. Please refer to the GUIDEIT Users Manual for further details.

III. PREVIOUS SIMULATIONS PERFORMED USING GUIDEIT

In 2002 a paper titled "Monte Carlo Analysis of SciFi's in the HallD Barrel Calorimeter" by Keith Nakonechny included a section on Monte Carlo simulations carried out using the ray-tracing program GUIDEIT. The purpose of these simulations was to determine the light collection efficiency and photon time-of-flight to the ends of 1 mm diameter, 4.5 m long single- and multi-clad SciFi.

The cladding thicknesses were set to 3% of the fibre diameter and the IOR for the core, first and second layers of cladding were set to 1.60, 1.49, and 1.42 respectively, based on manufacturer's specifications. The source was defined to emit photons isotropically from the geometric centre of the fibre such that a first-order approximation of the light yield at the ends of the fibre could be obtained. The details of the configuration of the surfaces defining the single- and multi- clad SciFi can be viewed in Nakonechny's report.

There are a few details of the configuration used for these simulations that should be discussed. Firstly, the single-clad SciFi was represented by a combination of 5 surfaces: 3 cylinders and 2 discs, and the multi-clad SciFi was represented by a combination of 7 surfaces: 5 cylinders and 2 discs. Secondly, the internal and external indices of refraction of the two surfaces, representing a core-cladding or cladding-cladding interface, were inadvertently reversed with respect to the orientation of the realm variable. The following section describes the detrimental effects the above configuration had on the results.

In order to understand the Nakonechny results, simulations were rerun. For each of the single- and multi-clad fibre configurations 100 runs were performed, each with a different random number seed. Each run consisted of 10000 photons isotropically emitted from the geometric centre of the fibre. Results from the simulations were derived from both text output and the histogram output.

Analysis of the collected data showed that approximately 2.4% of the photons reached the end of the single-clad fibre and 2.8% of the photons reached the end of the multi-clad fibre. This roughly 20% increase in light yield from the multi-clad fibre was much less than the manufacturer's suggested 50%-70%.

The histograms produced by GUIDEIT portrayed the photon time-of-flight results for the single- and multi-clad fibres. The mean time-of-flight for 4.5 m single-clad (multi-clad) fibres was found to be 13.31 ns, and (13.26 ns).

IV. CONFIGURATION CHANGES IN RESPONSE TO PREVIOUS TESTING

After analysis of the previous simulations, it was clear that modifications were required.

Some minor adjustments were implemented first:

- The length of the fibres was changed from 4.5 m to 3.9 m, in response to the recent specifications of the fibre lengths in the BCAL.

- The fibre properties were defined in accordance with BICRON's "Single- and Multi-clad Plastic Scintillating Round Optical Fibres" specification guide. Adhering to these specifications required a change in the thickness of the outer layer of cladding in the multi-clad fibres from 3% of the fibre diameter to 1% of the fibre diameter.

Major adjustments were required in two main areas:

- The orientation of the internal and external IOR

- The relationship between surfaces and sequences.

In the Nakonechny configuration of a SciFi the IOR was defined with respect to the realm of the incident photon. For example, there are two cylinder surfaces that represent the core-cladding interface. One surface has the realm set to INSIDE and deals with photons incident from the core, and the other's realm is set to OUTSIDE and deals with photons incident from the cladding. The surface with the realm set to INSIDE would have the internal IOR set to 1.60 and the external IOR set to 1.49. The surface with the realm set to OUTSIDE would have the internal IOR set to 1.49 and the external IOR set to 1.60. This configuration is incorrect. The IOR must be defined with respect to the definition of internal and external as declared by the surface type. This means that the two surfaces that define the interface between the core and the cladding will have the same internal and external IOR values regardless of the realm setting. Without this proper configuration the SciFi simulations would be non-physical and non-logical. The photon would travel from a medium with IOR of 1.60 to a medium with IOR of 1.49 regardless of it leaving or entering the core of the SciFi. This would clearly yield incorrect results.

The second oversight of the Nakonechny simulations was that there were only gates configured for collecting data pertaining to the photons exiting the SciFi from the core. As discussed above only surfaces of the same sequence number as the current sequence status of the photon are considered as a possibility for the next surface interaction. At the ends of the fibres, Nakonechny configured a circular surface as a gate such that all of the associated histograms were booked when photons passed through that surface. Although the circular surfaces were large enough and positioned such that they would geometrically cover the entire axial cross section of the cylindrical surfaces, they were not detecting all of the photons reaching the ends of the fibre. This is because the two circular surfaces were defined as "sequence one" surfaces. Therefore, they were only available for sequence-one photons, representing only the core of the fibre. The first layer of cladding was defined as "sequence two" and the second layer of cladding was defined as "sequence three". Therefore if any of the photons were in the cladding when reaching the end of the fibre they would not be counted. Defining multiple circular surfaces at the ends of the fibres can solve this problem. A circular surface should be defined for each sequence that a photon may be in when reaching the end of the fibre. In our specific example a multi-clad fibre would require three circular surfaces at each end of the fibre, in order to book the photons exiting from the core, the first layer of cladding, and the outer layer of cladding, respectively. Since multi-clad fibres increase light yield by producing light trapping in the first layer of cladding if the gates are not configured properly the results can be very misleading.

V. NEW SIMULATIONS AND RESULTS

The changes discussed above were implemented and the capabilities of the GUIDEIT program were more deeply investigated in the new round of simulations. GUIDEIT simulations were configured for both multi-clad and single-clad fibres. Two types of sources were used in the simulations: A single point source as well as a single smeared source. The analysis of the simulations included light yield, time of flight, number of bounces, exit position, and exit angle.

A. Configuration of the Simulations

The option settings were almost the same for the single-clad and multi-clad simulations with the exception of the number of sequences, and are defined in the GUIDEIT input file. Also, variables were used instead of numerical values for the random seed number setting and the photons per source setting to facilite script and batch-mode multiple runs. The desired numerical values were substituted for the variables just prior to execution. The options were set as follows.

Options	
Random Seed	111111XXX
Photons per Source	ZZZZZ
Number of Sources	1
Maximum Bounces	100000
Number of Sequences	2 (single-clad), 3 (multi-clad)
Speed of Light	3.00E10 cm/s
Metal Crumple Angle	5.00
Metal Knock Out	4.45
Metal Index	0.44
Metal Surface	0.80
Bulk Attenuation	YES
Diag. Tracking	NO
Reflectivity	YES
Statistical Output	YES
Angular Dist.	NO

The simulations consisted of executing a sequence of 100 trials each having a different random seed value. The seed values used were the odd numbers from 1 to 199 inclusive. The majority of the simulations were run with 10,000 photons per source, and some were run with 100,000 photons per source.

The configuration of the shape representing the single-clad SciFi consisted of seven surfaces: three cylinders and four circulars (see Fig. 1).

The surfaces were configured as follows.

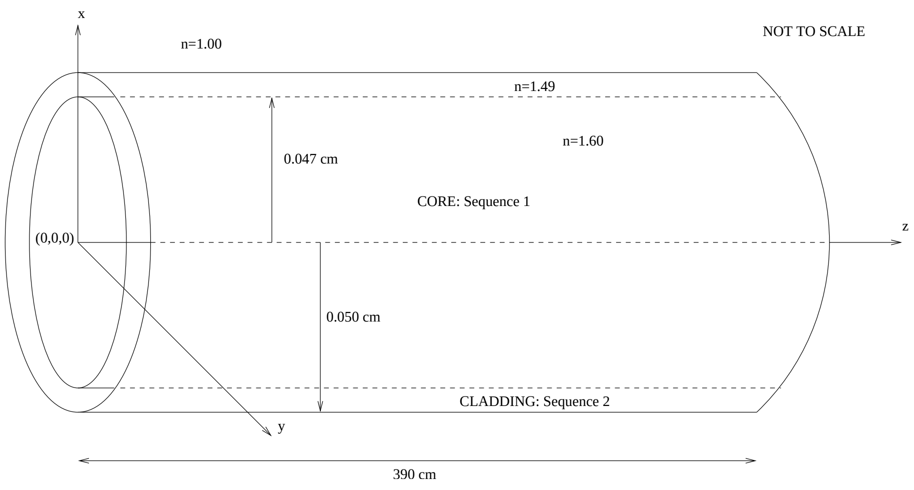

FIG. 1: Diagram of Single-Clad SciFi

Surface 1: Core-Clad

Surface Type	Cylinder
Radius	0.047 cm
Centre Coordinates	(0,0,0) cm
Vector to other end	(0,0,390) cm
Internal Index	1.60
External Index	1.49
Surface Detail	NONE
Attenuation Length	350 cm
Sequence Number	1
Surface Roughness	1.000000
Realm	INSIDE
Gate Type	TOPGATE
Gate Number	1

Surface 2: Core-Clad

Surface Type	Cylinder
Radius	0.047 cm
Centre Coordinates	(0,0,0) cm
Vector to other end	(0,0,390) cm
Internal Index	1.60
External Index	1.49
Surface Detail	NONE
Attenuation Length	1200 cm
Sequence Number	2
Surface Roughness	1.000000
Realm	OUTSIDE
Gate Type	BOTGATE
Gate Number	1

Surface 3: Clad-Air

Surface Type	Cylinder
Radius	0.050 cm
Centre Coordinates	(0,0,0) cm
Vector to other end	(0,0,390) cm
Internal Index	1.49
External Index	1.60
Surface Detail	NONE
Attenuation Length	1200 cm
Sequence Number	2
Surface Roughness	0.9990000
Realm	INSIDE
Gate Type	NONE

Surface 4: Upstream Sequence 1

Surface Type	Circular
Radius	0.050 cm
Centre Coordinates	(0,0,0) cm
Normal Unit Vector	(0,0,-1)
Internal Index	1.60
External Index	1.60
Surface Detail	NONE
Attenuation Length	350 cm
Sequence Number	1
Surface Roughness	0
Realm	INSIDE
Gate Type	GATE
Gate Number	2

Surface 5: Downstream Sequence 1

Surface Type	Circular
Radius	0.050 cm
Centre Coordinates	(0,0,390) cm
Normal Unit Vector	(0,0,1)
Internal Index	1.60
External Index	1.60
Surface Detail	NONE
Attenuation Length	350 cm
Sequence Number	1
Surface Roughness	0
Realm	INSIDE
Gate Type	GATE
Gate Number	3

Surface 6: Upstream Sequence 2

Surface Type	Circular
Radius	0.050 cm
Centre Coordinates	(0,0,0) cm
Normal Unit Vector	(0,0,-1)
Internal Index	1.60
External Index	1.60
Surface Detail	NONE
Attenuation Length	350 cm
Sequence Number	2
Surface Roughness	0
Realm	INSIDE
Gate Type	GATE
Gate Number	2

Surface 7: Downstream Sequence 2

Surface Type	Circular
Radius	0.050 cm
Centre Coordinates	(0,0,390) cm
Normal Unit Vector	(0,0,1)
Internal Index	1.60
External Index	1.60
Surface Detail	NONE
Attenuation Length	350 cm
Sequence Number	2
Surface Roughness	0
Realm	INSIDE
Gate Type	GATE
Gate Number	3

The configuration of the shape representing the multi-clad SciFi consisted of 11 surfaces: five cylinders and six circulars (see Fig. 2).

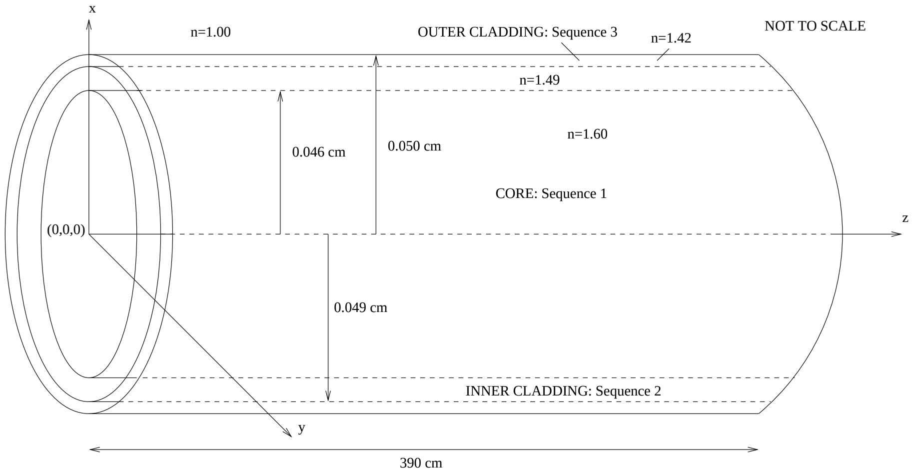

FIG. 2: Diagram of Multi-Clad SciFi

The configuration of the surfaces is similar to that shown above, and in addition there were two cylindrical surfaces that represented the outer layer of cladding. This, in turn, renders the shape a three-sequence simulation. Therefore, two additional circular surfaces are required such that the "sequence three" data can be properly accounted for. Refer to Fig. 2 for the specifications of the multi-clad SciFi.

For both the single- and multi-clad simulations the source was placed at the geometric centre of the fibre and set to emit isotropically. It was configured as follows.

Source	
Theta Min	0.0
Theta Max	180.0
Phi Min	0.0
Phi Max	360.0
Starting Position	(0,0,195) cm

Several simulation scenarios were configured with appropriate histograms for investigating the GUIDEIT application. The preliminary scenarios dealt with the exit position and angle of the photons as well as their time of flight and number of bounces. Data from these simulations provided a good basis for understanding the GUIDEIT application and ray tracing in SciFi. The results of the simulations and light yield analysis lead to further investigation of the source used in the simulations, the roughness of the fibres, the attenuation lengths of the core and the cladding materials, and the trapping efficiency of the fibres.

B. Stage 1: Preliminary Simulations

The histograms generated from the preliminary scenarios can be found in Appendix A. The exit position histograms for the multi-clad simulations clearly show that light trapping is experienced in the first layer of cladding. This result is expected, as it is the main reason for multi-clad fibres having an increased light yield over single-clad fibres. There were also some unexpected results. From the fibre-core exit position histograms one can observe that there is a higher density of light emitted from the centre of the fibres. In addition, the light yield for the single-clad fibre was greater than that of the multi-clad fibre, contrary to expectations.

C. Stage 2: Implementation of a Smeared Source

Two factors were responsible for these results: the orientation of the source and the roughness of the fibre surfaces. The effects of the source will be discussed first. As mentioned previously the source emits isotropically from the geometric centre of the fibre. It appears that the collection of light down the centre of the fibre is a result of the source being a point source at the centre of the cross section of the fibre. The collection of light emitted from the centre of the fibre was qualitatively independent of the length of the fibre or distance from the source to the end of the fibre. Moving the point source off of the central axis of the fibre produced two rings of higher density light emission. One of the rings has a radius approximately equal to the distance the source was displaced from the central axis of the fibre. The outer ring displays light collection near the core-cladding interface. The inner ring is still a strange phenomenon, but the collection of light near the core-cladding interface is an expected characteristic of light traveling down SciFi, which has been previously documented by other researchers [2].

To diminish the apparent inaccuracies of using a statically positioned isotropic source the smearing feature of GUIDEIT was tested and implemented in the fibre simulations. The idea was to make the source more realistic by smearing it across the entire cross section of the fibre as well as being isotropic. With this addition the starting point of the source is random as well as its initial direction. The result is a very uniform distribution of light at the end of the fibre with additional light collection near the core-cladding interface. The effects of this change can be viewed by observing the XY position histograms for a smeared source in Appendix B.

The resultant XY position histograms for the core of the fibres can be qualitatively understood based on geometric ray tracing theory. There are two types of rays that travel down the fibre: meridional rays and skew rays. Meridional rays are rays that pass through the axis of the optical fibre. Skew rays are rays that travel through an optical fibre without passing through its axis and their acceptance angle is larger than that of meridional rays. Also, skew rays tend to propagate near the edge of the fibre core. These skew rays are the reason for the higher density of light at the core-cladding interface [3]. As well, the Exit Theta histograms from the preliminary simulations displayed a sharp cut-off, corresponding to the maximum angle at which a photon can hit the respective surface and experience total internal reflection. On the other hand, the Exit Theta histogram for the smeared source (with skew rays) does not have this sharp cut-off. Finally, the time-of-flight and number-of-bounces histograms clearly depict the difference between skew and meridional rays.

D. Stage 3: Adjusting the Roughness Variable

Even with the new orientation of the source, the light yield of the multi-clad fibre not only did not exceed that of the single-clad fibre by the expected 60%, but in fact it was slightly less. The light yield of the fibres was determined by making a comparison between the number of photons emitted from the source and the number of photons that reached the ends of the fibre in the simulations. One million photons were emitted per simulation. For the single-clad SciFi approximately 8% of the photons reach the ends of the fibre, and for the multi-clad SciFi approximately 7%. It was discovered that the roughness variable could drastically affect the light yield in SciFi simulations. The previous results were obtained using surface roughness settings as suggested by the GUIDEIT Users Manual for simulating optical fibres. Some photons are terminated due to roughness by comparing the roughness variable with a random number upon every surface interaction. For fibre simulations this variable becomes very sensitive due to the high number of surface interactions experienced by each photon.

After testing many different configurations of the roughness variable for both single- and multi-clad SciFi simulations an orientation denoted "Inner Smooth" was used for future simulations. The Inner Smooth orientation treats all of the inner interfaces, for example core-cladding, cladding-cladding, as ideal non-rough surfaces and keeps the outer cladding-air interface with a roughness of 0.999. Therefore no photons are randomly terminated due to roughness unless they are in the outer layer of cladding. This is acceptable due to the method of manufacturing SciFi. The inner surfaces are extremely smooth while the outer surface tends to be slightly rougher. The results of these alterations to the roughness variable can be observed by viewing the respective histograms in Appendix C.

E. Stage 4: Implement Appropriate Core and Cladding Attenuation Lengths

The roughness adjustments alone, made to the fibre interfaces, were not sufficient to produce the expected 60% increase in light yield from a single- to multi-clad fibre. To address this concern the next GUIDEIT variable considered was the attenuation length. All of the simulations discussed thus far have used an attenuation length of 280 cm for all portions of the SciFi. This value was used because it was approximately the gross attenuation of the fibres previously tested in beam. BICRON has quoted the attenuation length of the core material to be 350 cm and the attenuation length of the cladding to be much longer. With this new information simulations were performed using a plethora of different cladding attenuation lengths for both single- and multi-clad fibres. Increasing the cladding attenuation length can significantly increase the light yield of a SciFi, especially for a multi-clad fibre. This is due to light trapping in the first layer of cladding in a multi-clad fibre. The light trapped in this cladding layer experiences a high number of bounces and hence a long path length. For the simulation of a 390 cm long fibre, once the cladding attenuation length became much larger than the fibre's length the resultant increases in light yield lessened. The relationship between cladding attenuation length and light yield can be viewed in Fig. 3. As a result of testing several different attenuation lengths it was discovered that an increase in light yield of 60% from a single- to multi-clad fibre could be obtained by using a cladding attenuation length of 1200 cm for a core attenuation length of 350 cm. The histograms generated from the simulations with the above attenuation length

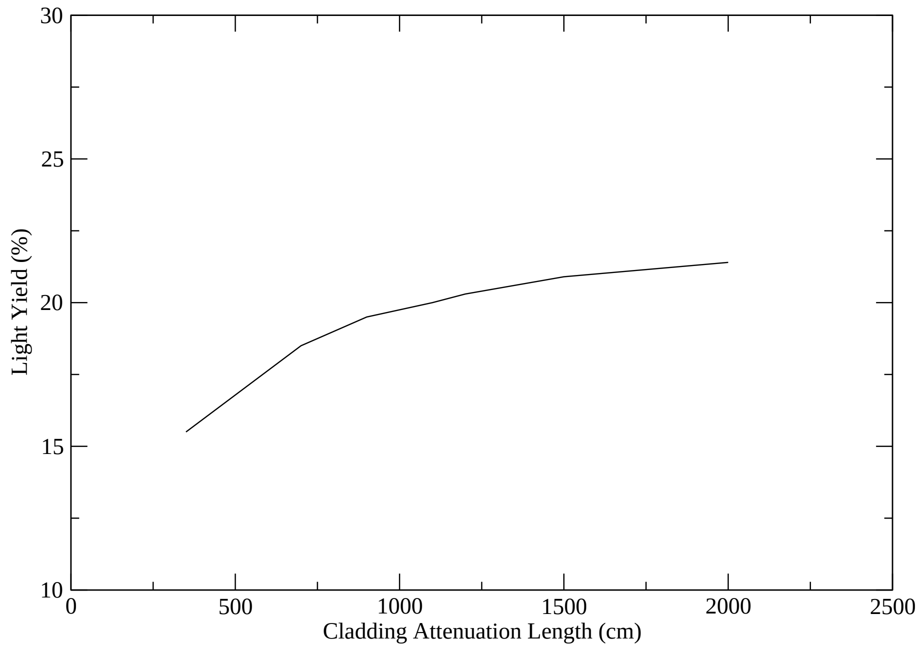

FIG. 3: Plot of Light Yield vs. Cladding Attenuation Length for a Multi-Clad Fibre

configurations can be viewed in Appendix D.

F. Gross Attenuation and Trapping Efficiency of a Multi-Clad SciFi

Once all of the adjustments discussed above were implemented, additional multi-clad simulations were performed. The purpose of these simulations was to determine the gross attenuation of a multi-clad SciFi as well as its trapping efficiency. Proper values for both of these variables are required for the GEANT simulations of the BCAL. Efforts were made to determine values for these variables by running multiple simulations with the source at different positions down the length of the fibre. For each of the source locations the simulation was run with attenuation on and attenuation off. The idea was to use the results of the simulations with attenuation turned off to determine the trapping efficiency of the fibre, and then apply that trapping efficiency to the results of the simulations with the attenuation turned on such that the gross attenuation of the fibre could be determined.

Analysis of the results showed expected trends. Unfortunately there appear to be additional parameters that must be accounted for before values can be determined for the trapping efficiency and gross attenuation length with any confidence. These investigations will be carried out in the future by the SPARRO Group.

VI. CONCLUSION

This work illustrated some of the capabilities that the GUIDEIT application has to offer with respect to SciFi simulations. The GUIDEIT application can be a very useful resource for analyzing ray tracing. This investigation shed light on the areas of time-of-flight, number-of-bounces, exit position and exit angle of photons traveling down single- and multi-clad SciFi. The information gained led to the exploration of other important areas of ray tracing in SciFi. The results showed that the photons that reach the end of the fibre include both meridional and skew rays. Also, the simulations demonstrated that the roughness of the medium interfaces and the attenuation length of the materials can drastically affect the light yield of SciFi.

It is not recommended that the current results of the GUIDEIT simulations be applied to the Monte Carlo simulations performed by GEANT at this stage. There are still other variables in the GUIDEIT simulations that should be investigated. The current roughness and attenuation length settings were determined semi-empirically based on meeting the increase in light yield specification when going from single- to multi-clad fibres. This exercise proved to be a useful learning tool for using GUIDEIT to simulate SciFi, but requires further study.

Future work should include experiments to measure the light yield of fibres that can be then simulated such that appropriate values can be confirmed for all of the variables in the simulations.

[1] Daniel A. Simon. "GUIDEIT V1.1 Users Manual". 1993.

[2] Bryan Lawrence Caron. "Simulation of the Scintillating Tile Endcap Detector of OPAL".1998.

[3] www.tpub.com/neets/tm/106-9.htm

APPENDIX A: STAGE 1: PRELIMINARY

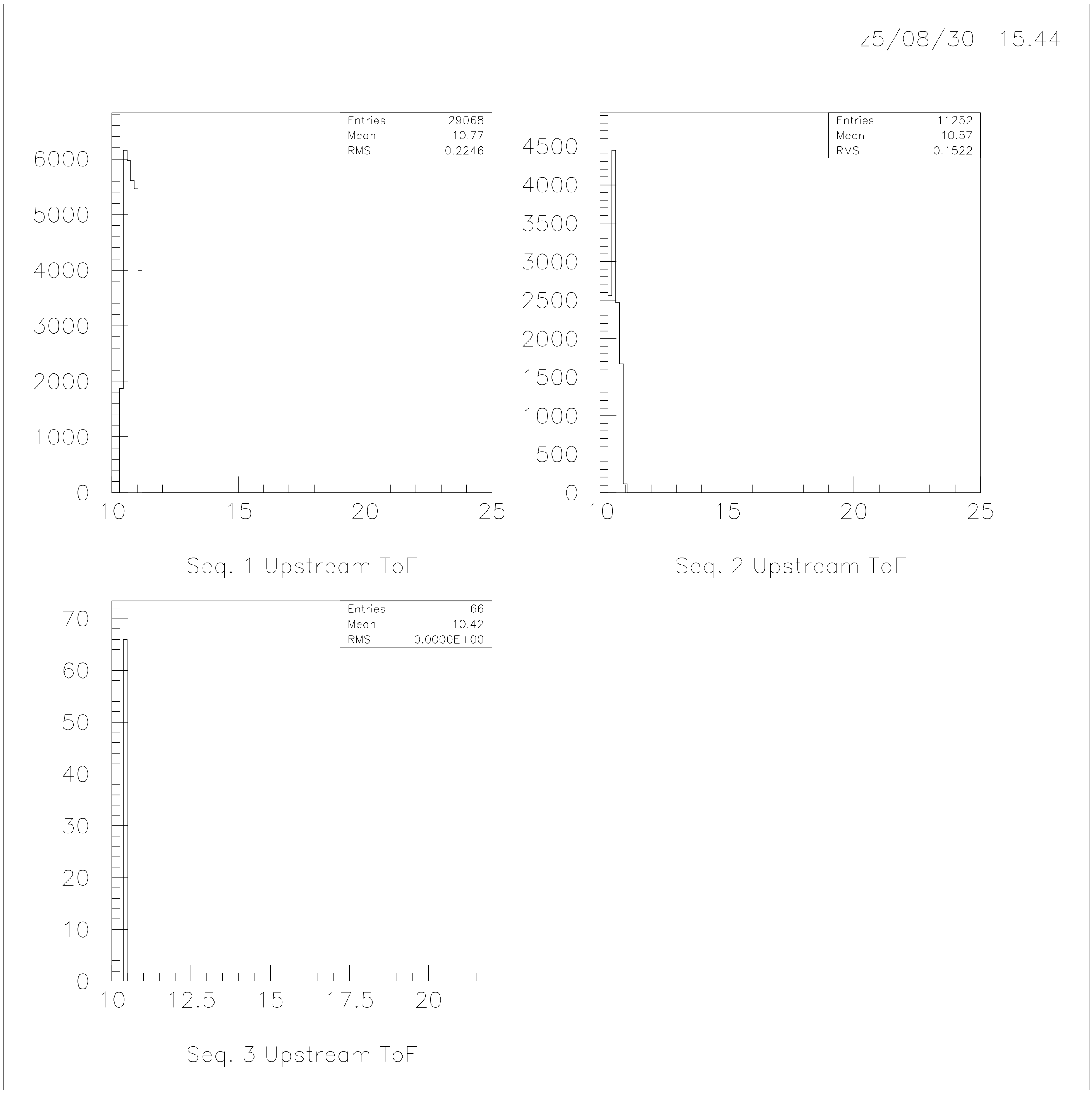

FIG. 4: Multi-Clad SciFi Time of Flight Histograms

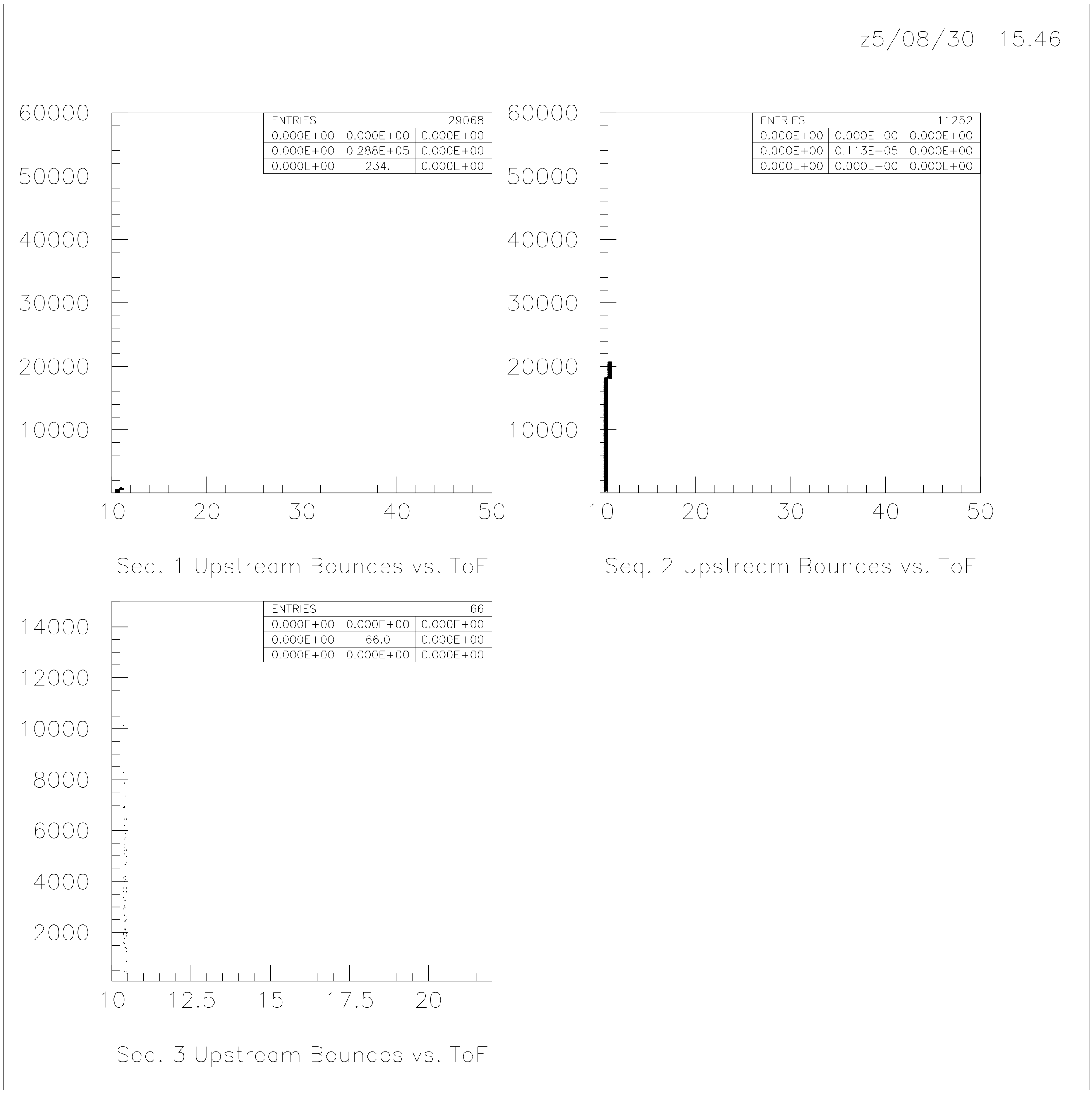

FIG. 5: Multi-Clad SciFi # of Bounces vs. Time of Flight Histograms

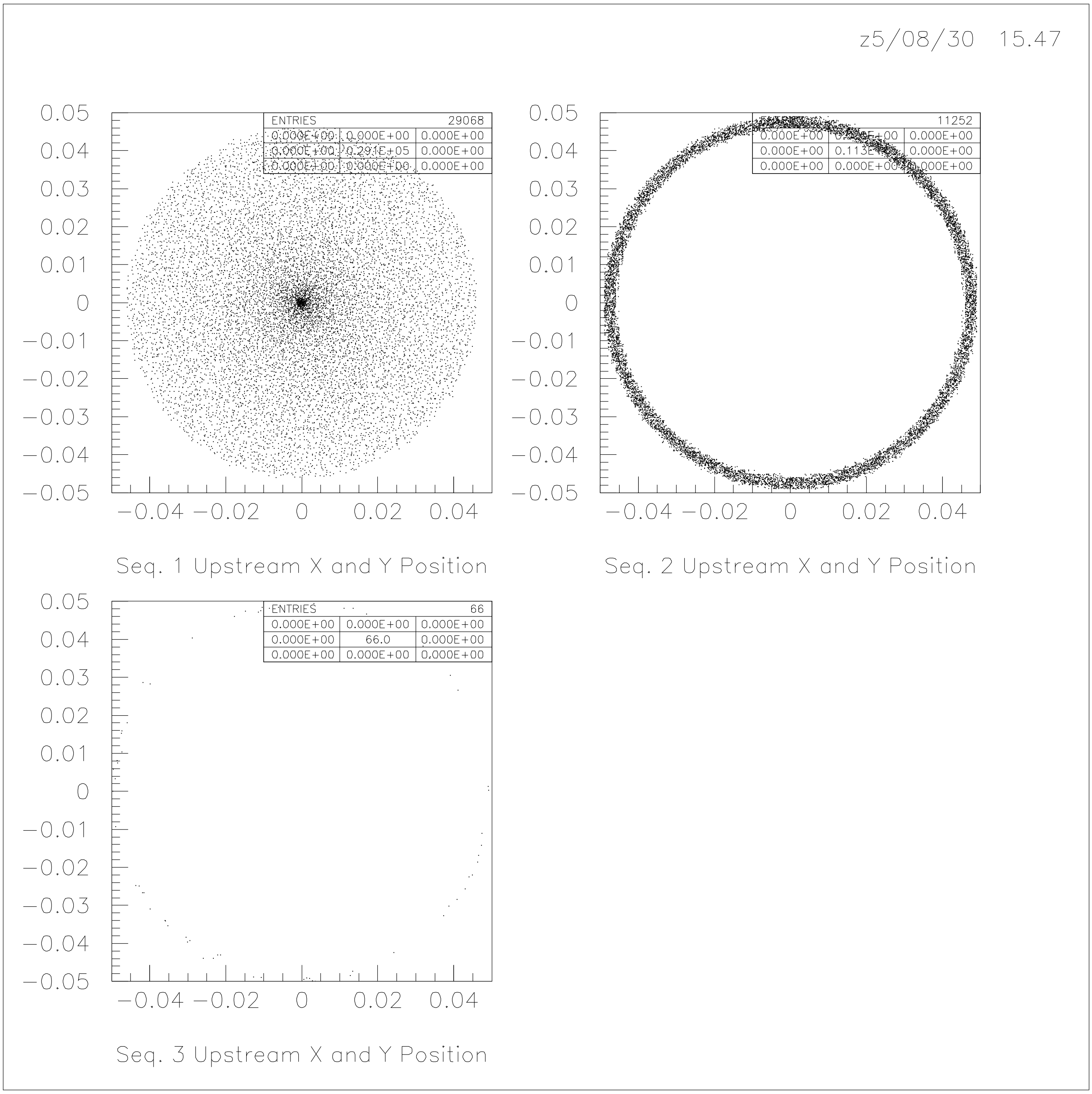

FIG. 6: Multi-Clad SciFi XY Exit Coordinate Histograms

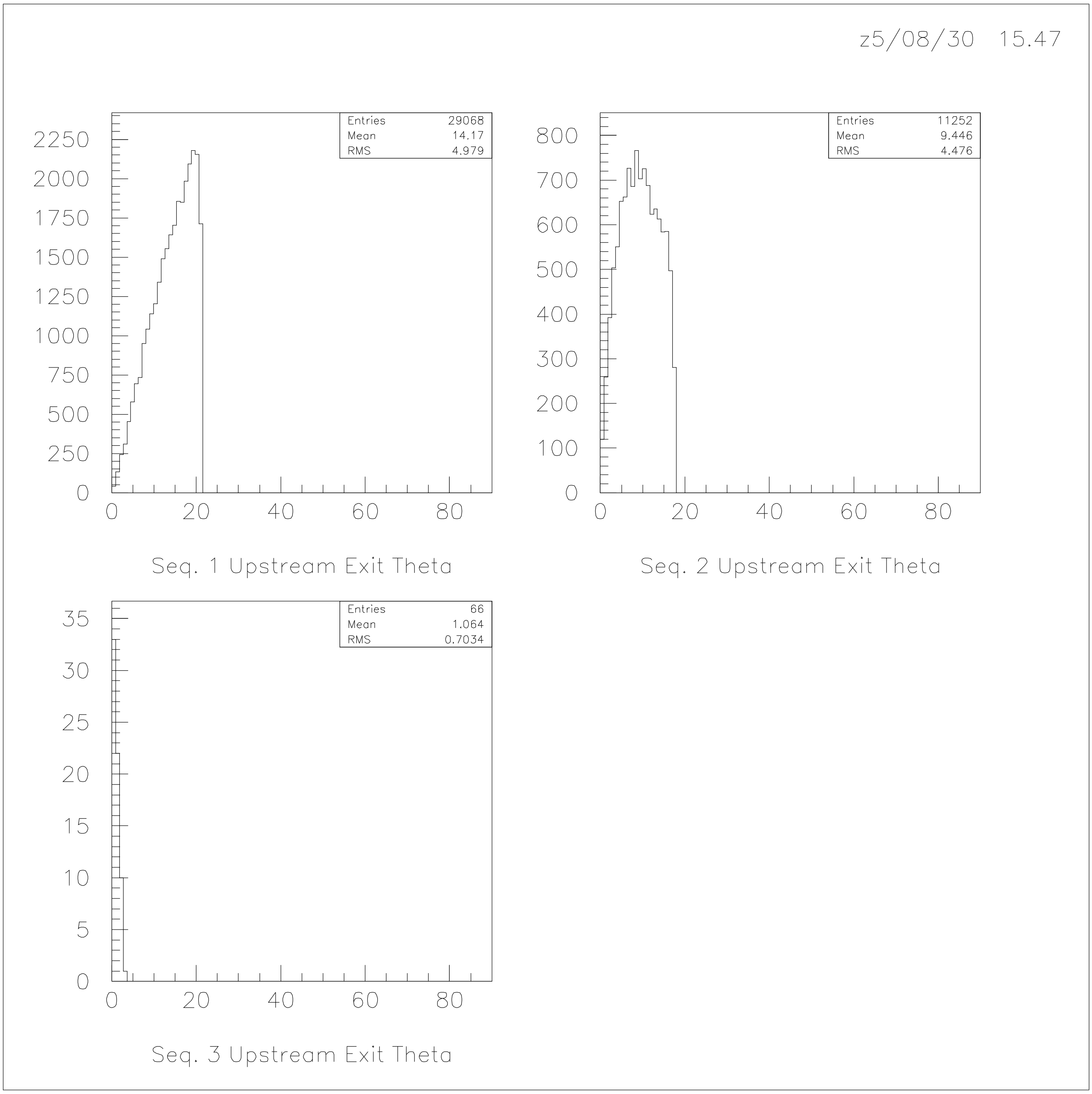

FIG. 7: Multi-Clad SciFi Exit Theta Histograms

APPENDIX B: STAGE 2: SMEARED SOURCE

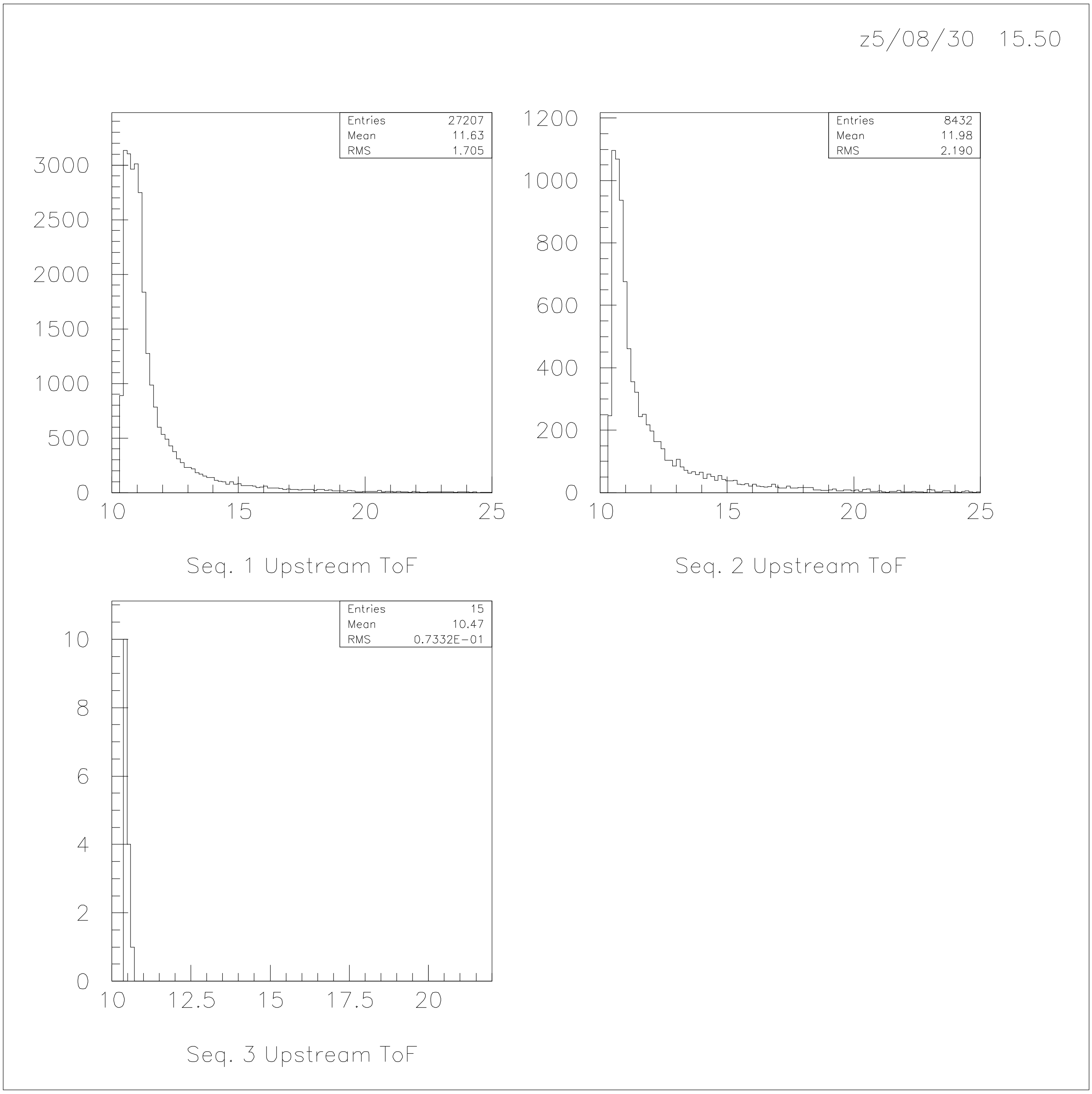

FIG. 8: Multi-Clad SciFi Time of Flight Histograms

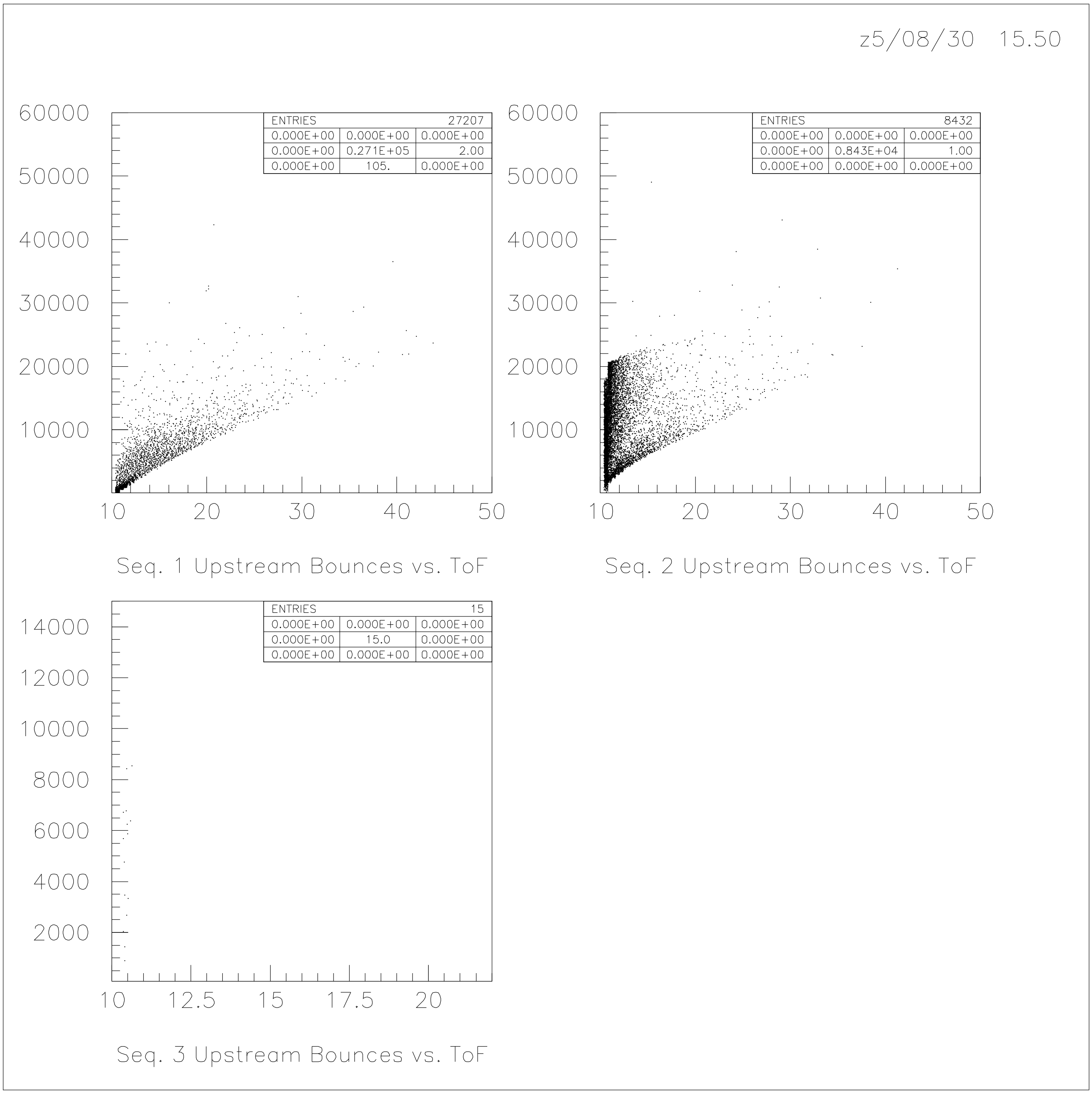

FIG. 9: Multi-Clad SciFi # of Bounces vs. Time of Flight Histograms

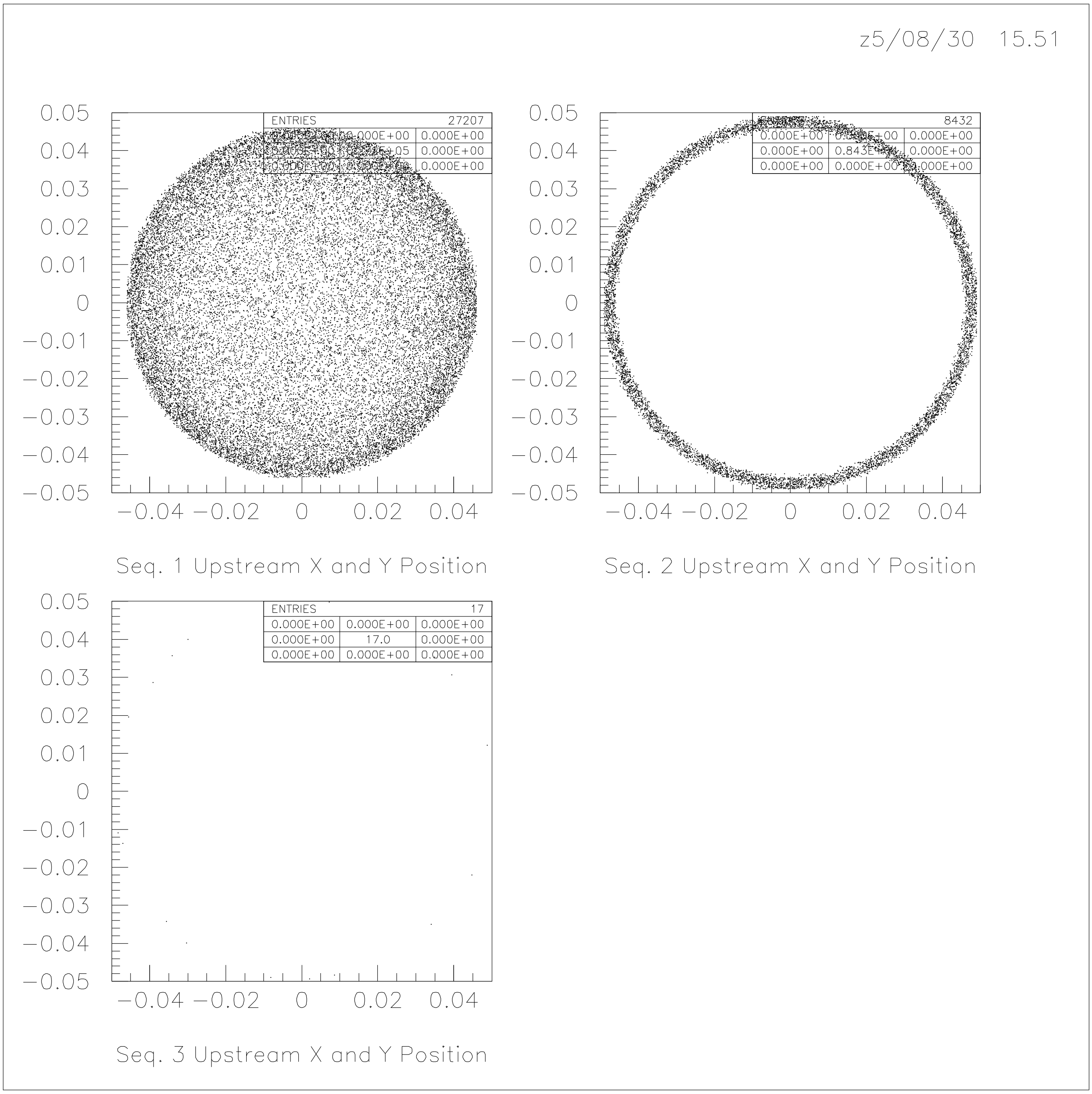

FIG. 10: Multi-Clad SciFi XY Exit Coordinate Histograms

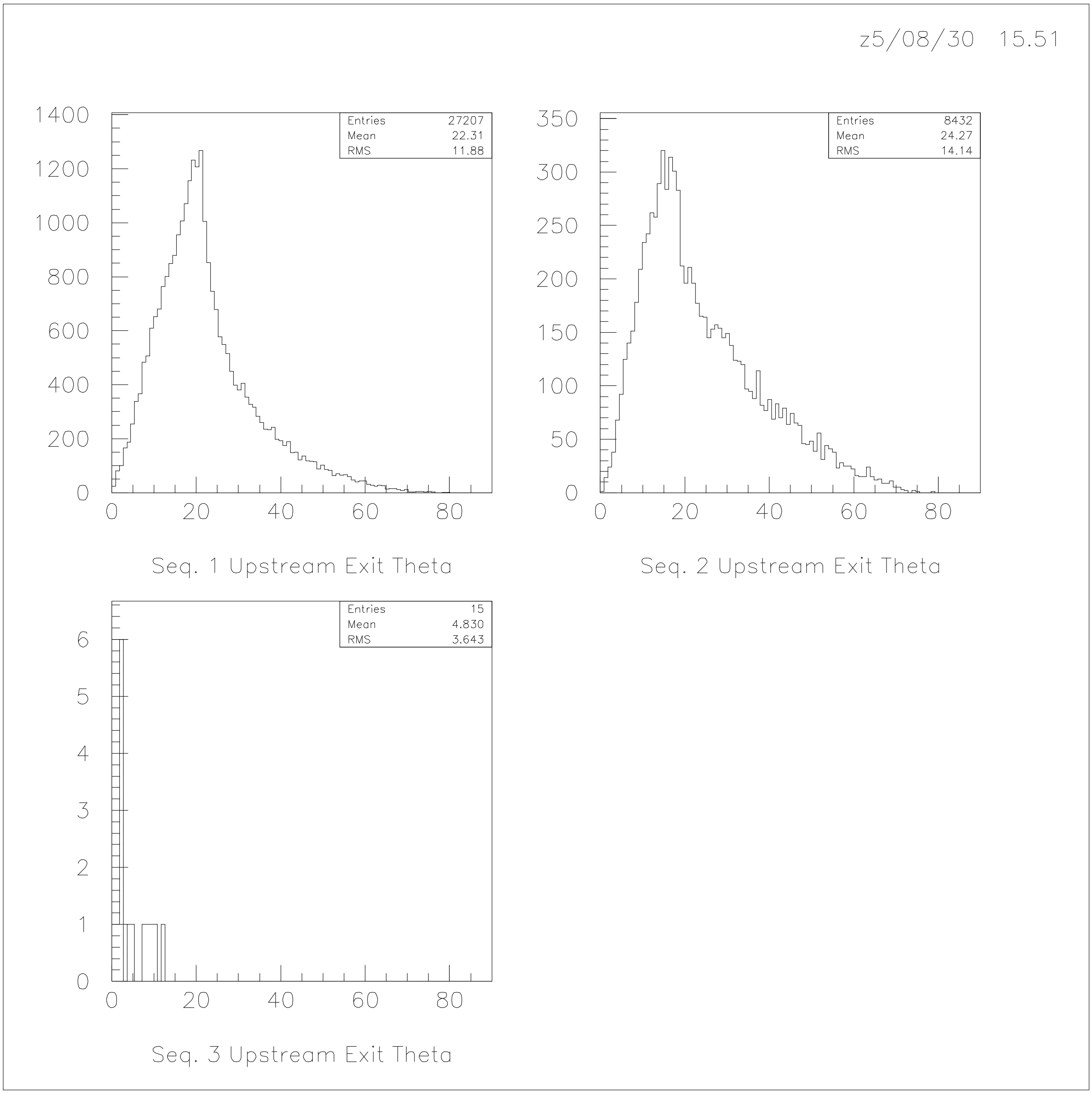

FIG. 11: Multi-Clad SciFi Exit Theta Histograms

APPENDIX C: STAGE 3: SMEARED SOURCE AND INNER SMOOTH

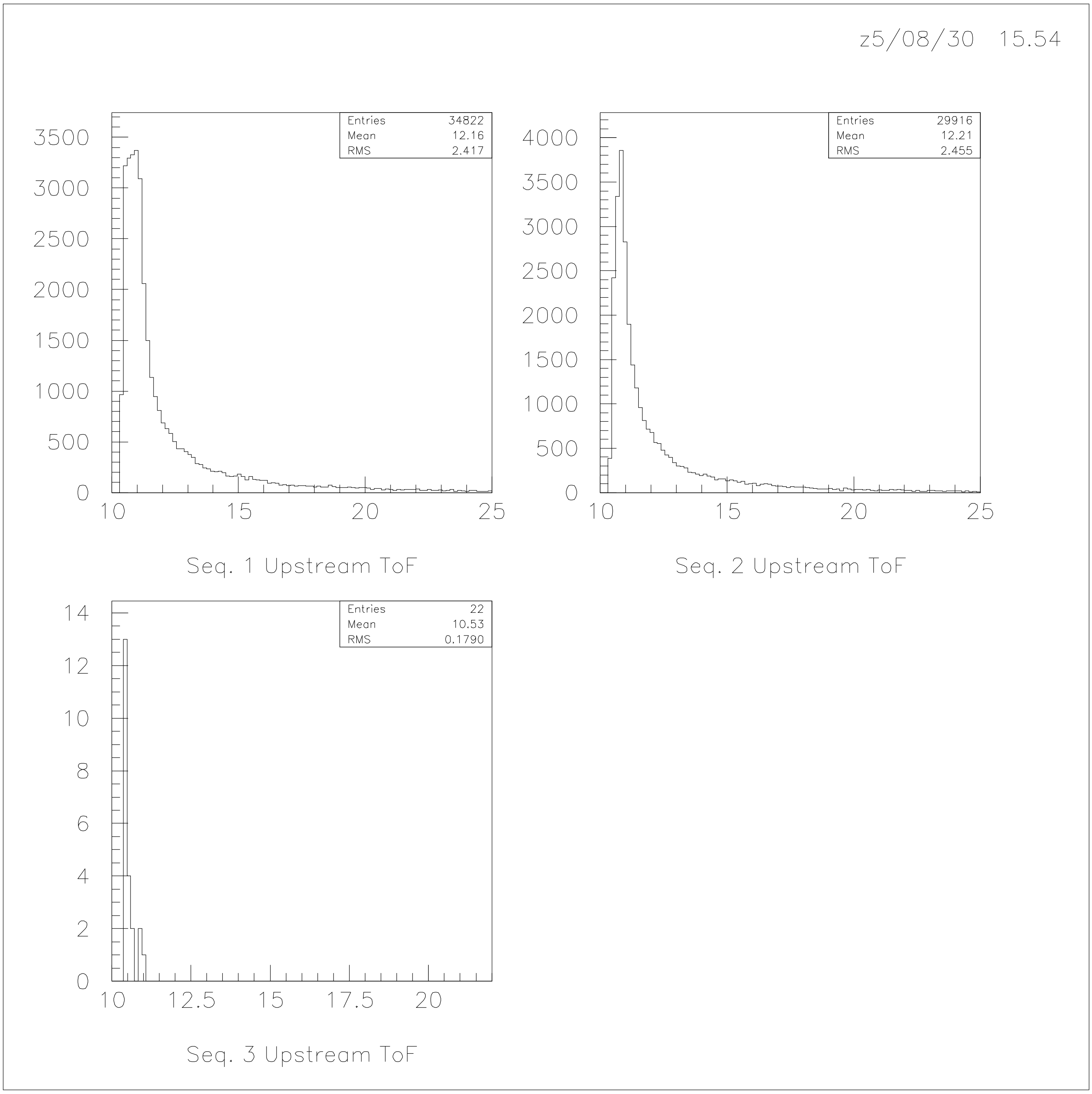

FIG. 12: Multi-Clad SciFi Time of Flight Histograms

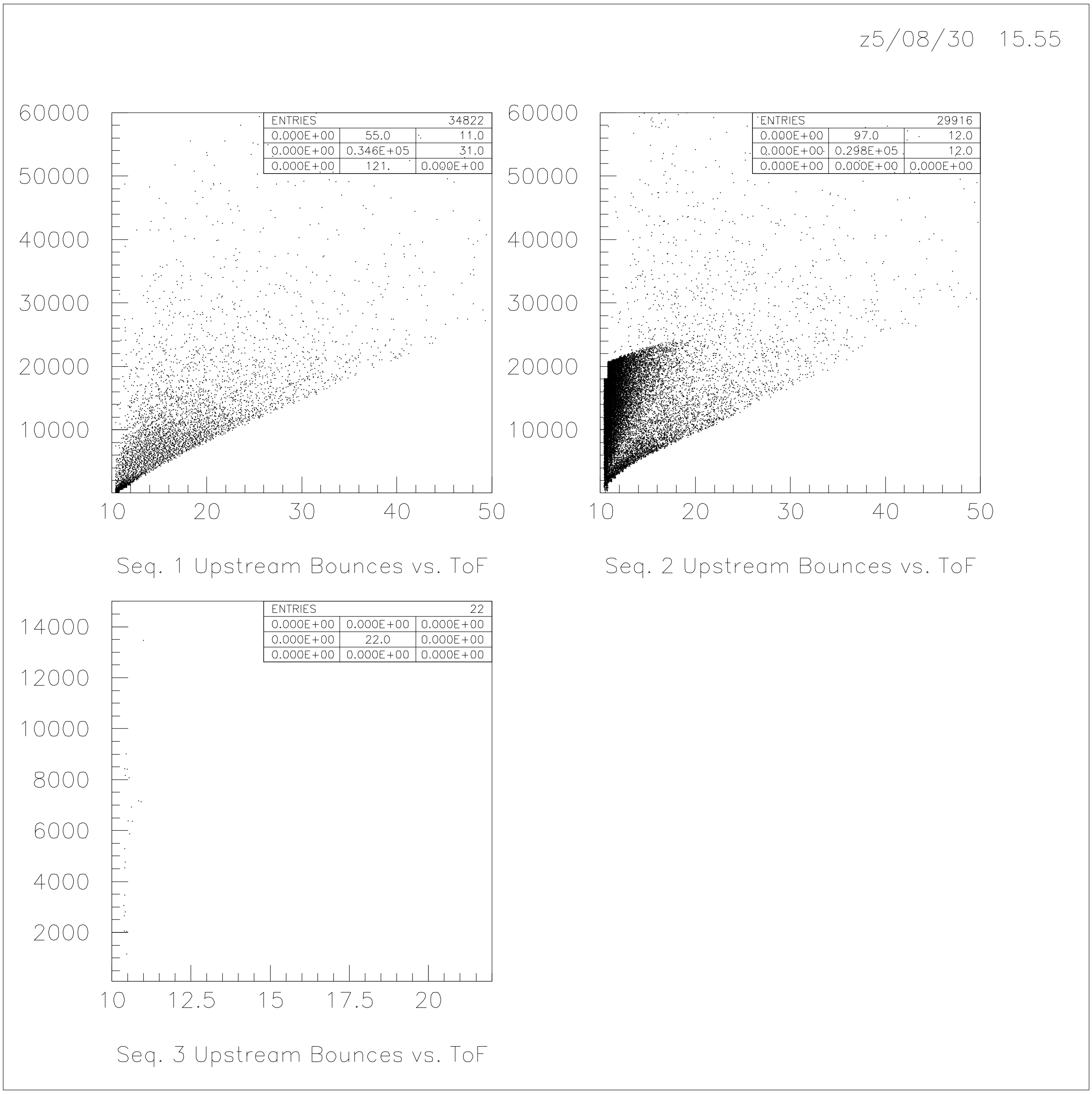

FIG. 13: Multi-Clad SciFi # of Bounces vs. Time of Flight Histograms

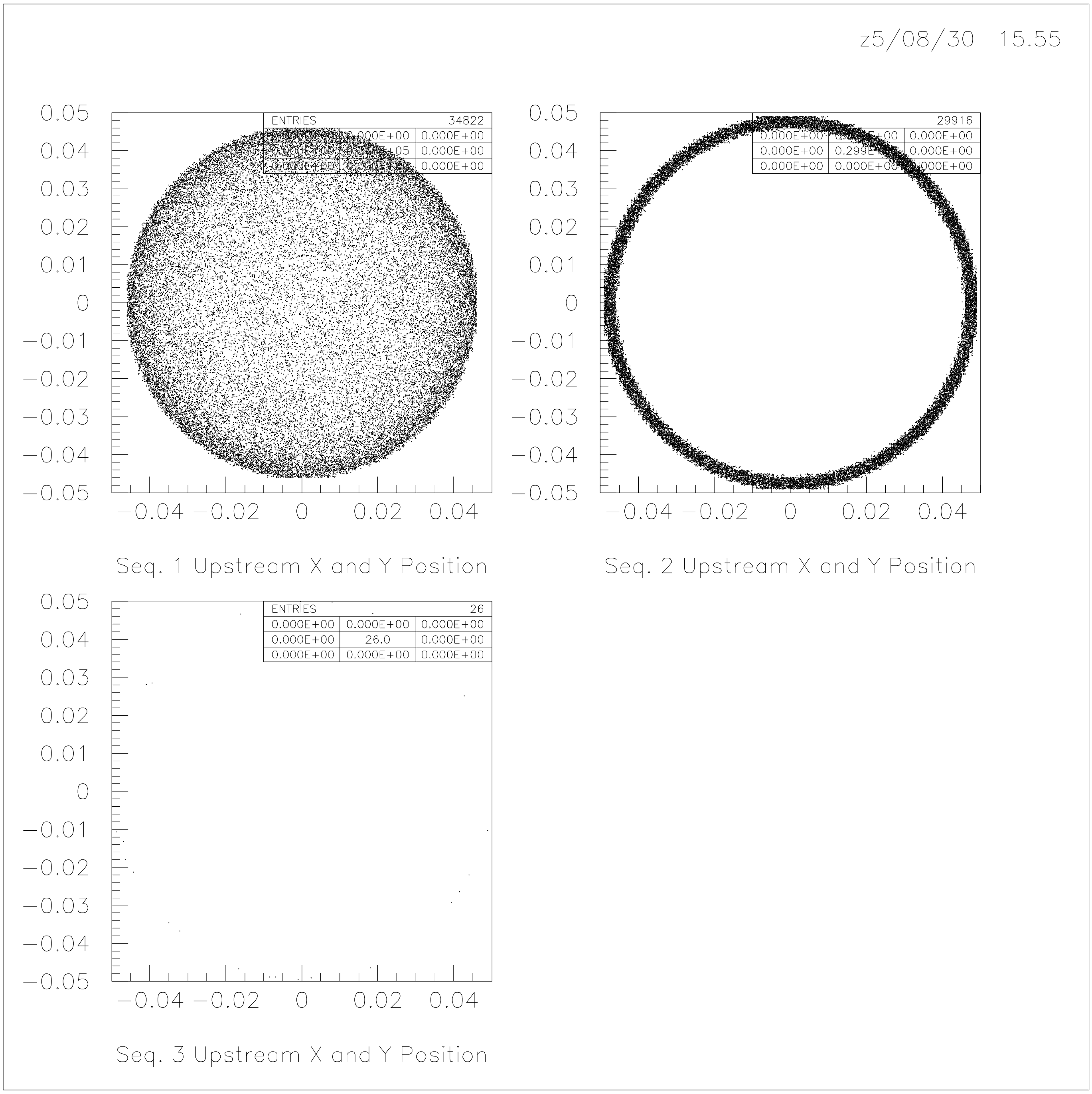

FIG. 14: Multi-Clad SciFi XY Exit Coordinate Histograms

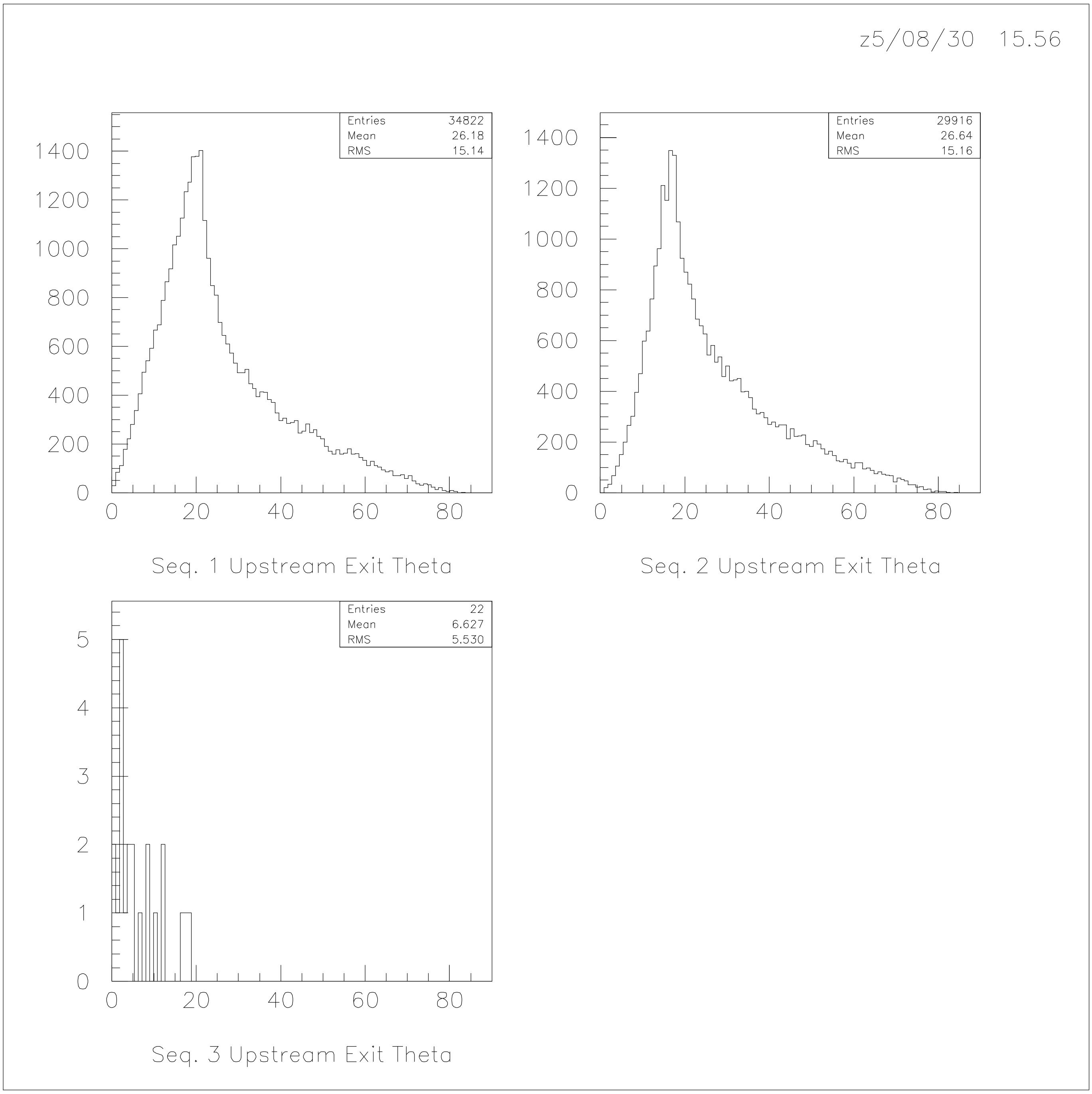

FIG. 15: Multi-Clad SciFi Exit Theta Histograms

APPENDIX D: STAGE 4: SMEARED SOURCE, INNER SMOOTH, ADJUSTED ATTENUATION LENGTHS

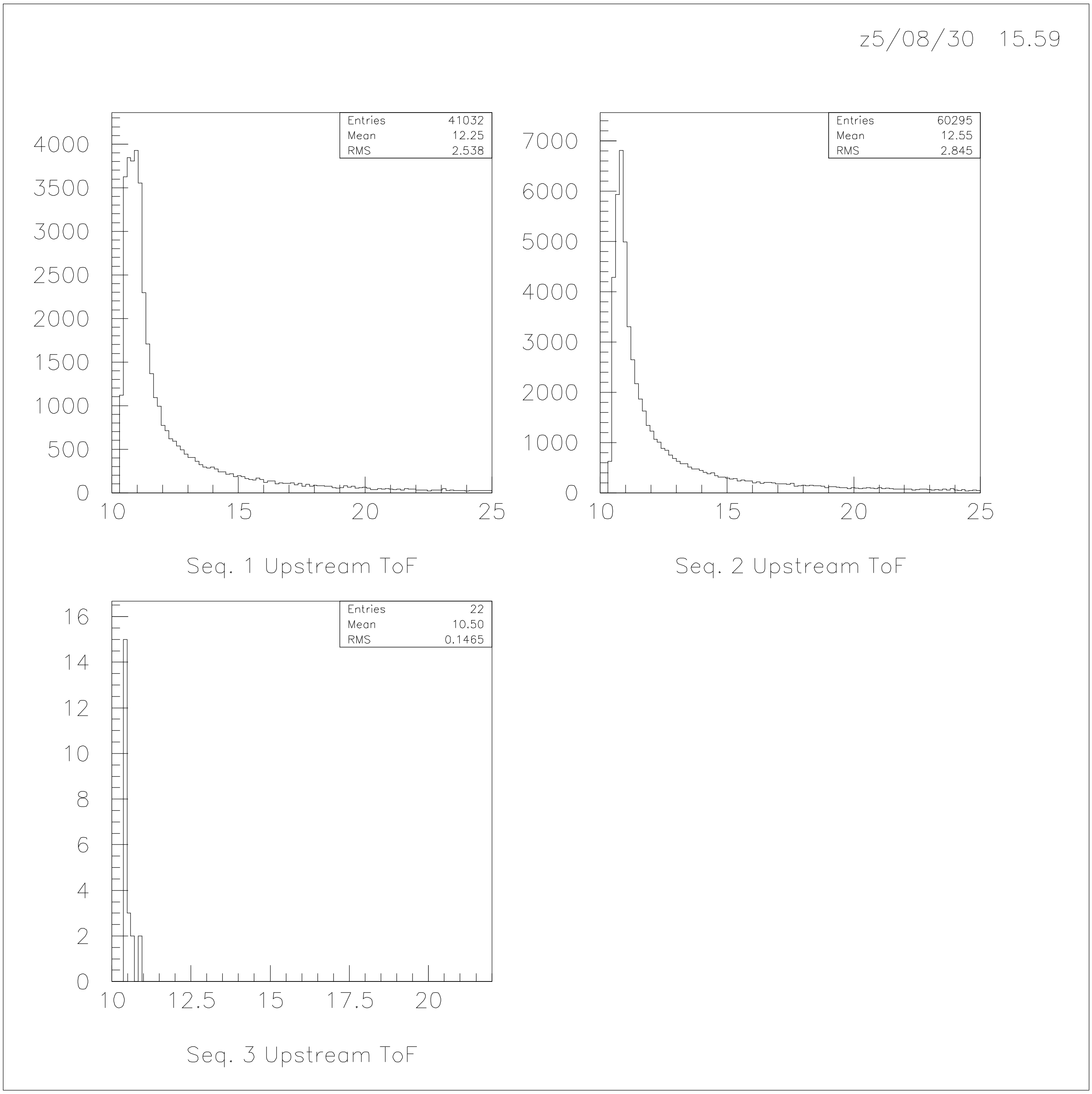

FIG. 16: Multi-Clad SciFi Time of Flight Histograms

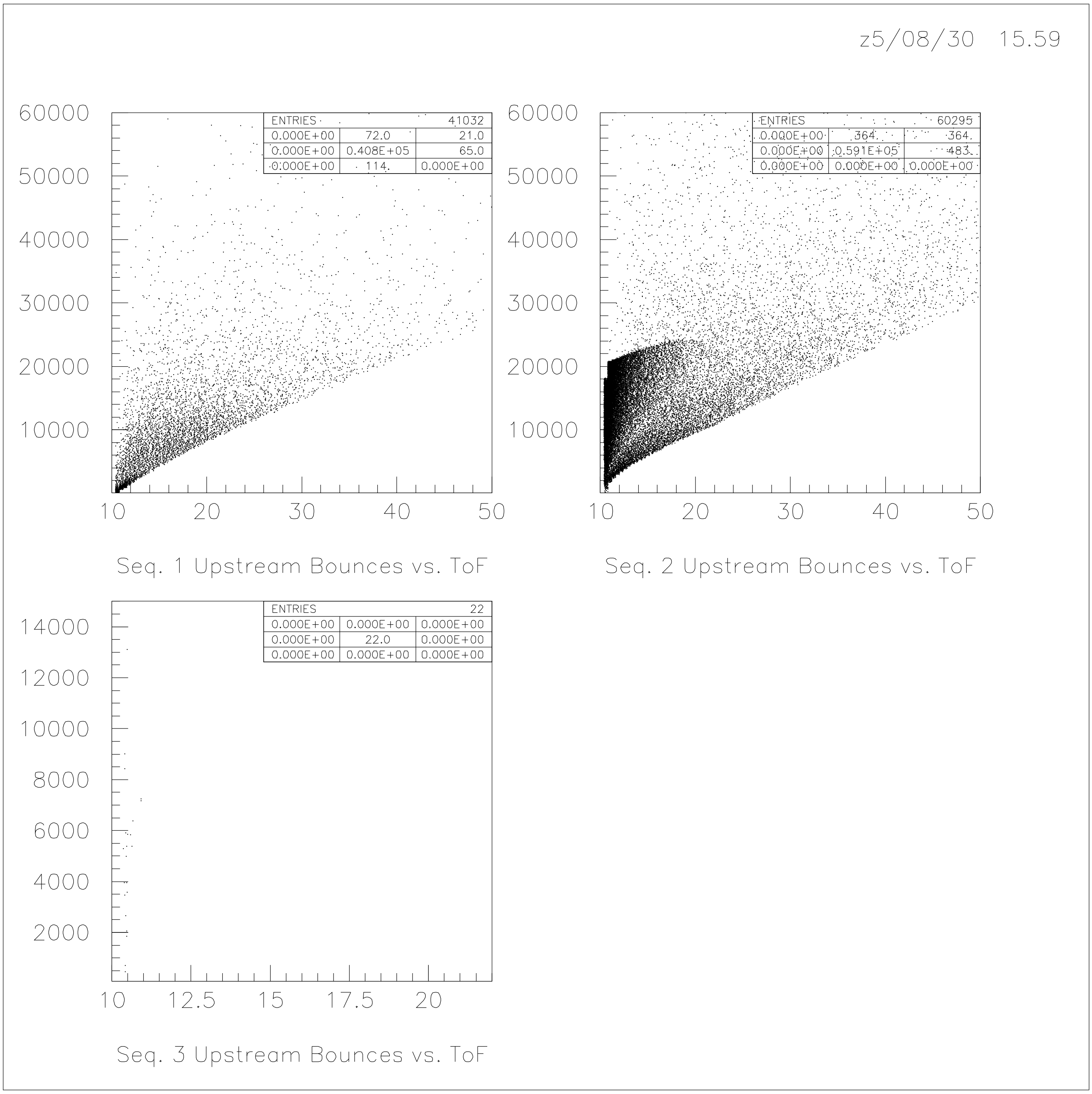

FIG. 17: Multi-Clad SciFi # of Bounces vs. Time of Flight Histograms

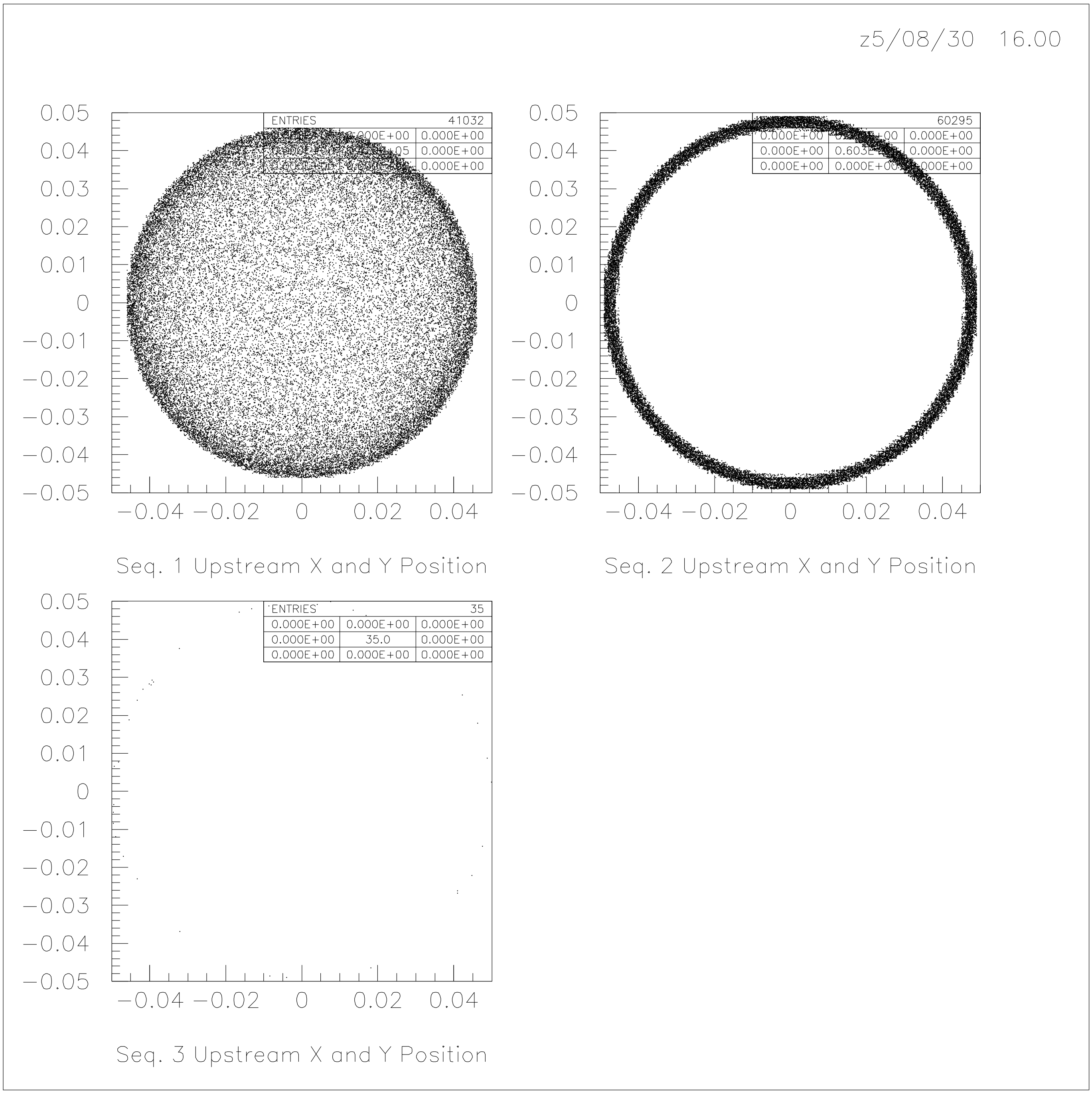

FIG. 18: Multi-Clad SciFi XY Exit Coordinate Histograms

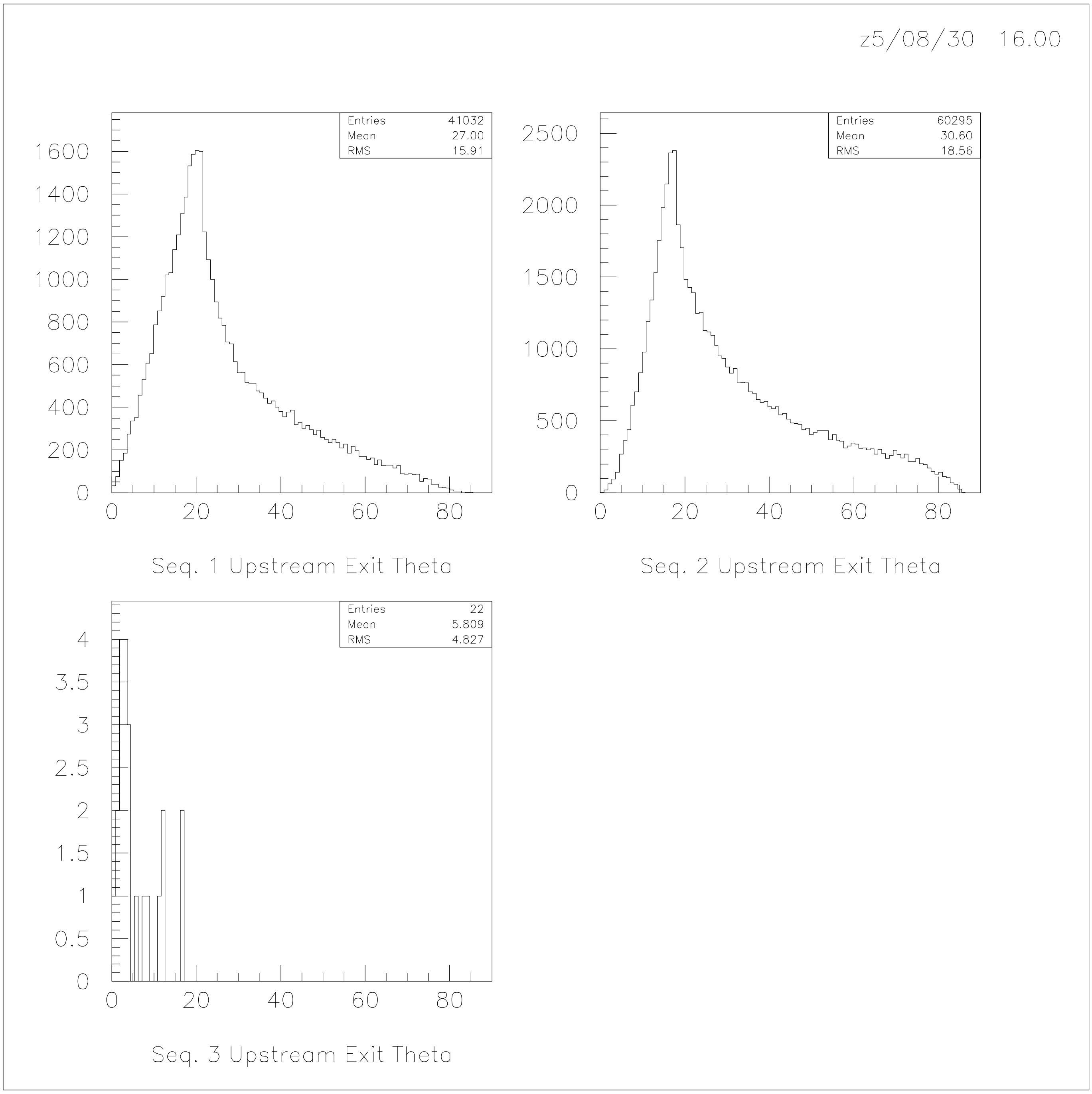

FIG. 19: Multi-Clad SciFi Exit Theta Histograms