

Fermilab Italians Summer Student 2017: Final Report

MC6 - MC7 simulation for Time-of-Flight LAPPD detectors

1 Introduction

This work has taken place at the Fermilab Test Beam Facility during the "Italians" Summer Student Program over August and September 2017.

As a graduate intern, I joined the LAPPD group at Chicago University: my work has been simulating Fermilab Test Beam Facility MC6 and MC7 experimental areas, writing a brand new simulation code. Once analyzed simulated data through PyRoot, I provided a precise study of beam properties through the experimental setup, finally coming up with indications for positioning of Time-of-Flight detectors.

2 LAPPD Project

Goal of Large Area Picosecond Photodetector (LAPPD) project, headed by University of Chicago, is manufacturing a ~ 1 ps time resolution photodetector.

Key elements of design are:

- Fast source: a psec source of many photons (e.g. Cherenkov light from a charged particle traversing radiator or the entrance window of a photodetector);
- Glass body and minimal feedthroughs;
- Micro channel plates (MCPs) made using atomic layer deposition;
- A psec-level pixel-size (10-20 μm pores in MCP);
- Transmission line anode;
- Fast and economical front-end electronics;
- Large area, flat panel photocathode.
- High gain: it has to be high enough that a single photon triggers, i.e: the first photon "in" determines the leading edge of the pulse and consequently the timing.

Applications are several, such as Time of Flight mass spectrometry, tracking, medical imaging, etc.

The reason of this work comes from the necessity of a precise knowledge of the beam where Time-of-Flight LAPPD will be tested, in order to push its properties at the best. Tests will take place in MC7 experimental area, hence MC6 and MC7 simulations become necessary.

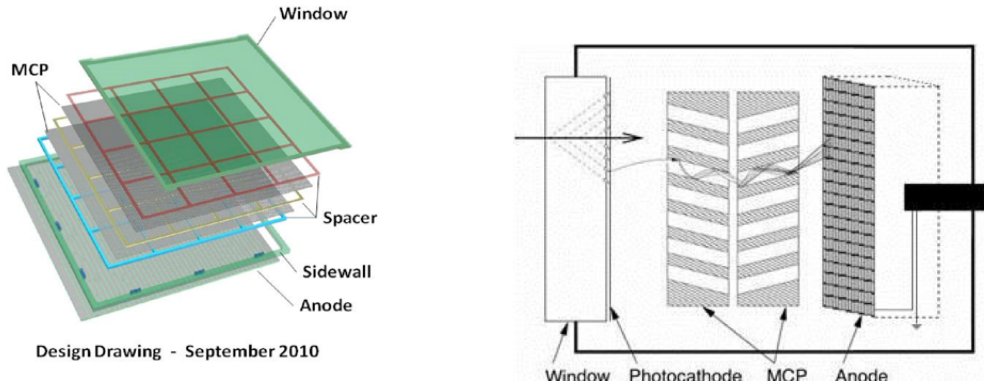


Figure 1: LAPPD layout and schematic.

3 Beam Description

Fermilab Test Beam Facility receives beam from Main Injector in 4.2-second spills, with approximately 60 seconds of repetition rate. Spills are made up of batches: 7 batches cover $11.2 \mu s$ (size of Main Injector) and every batch is composed by 84 RF buckets (size of booster). Normally, only the first batch over 7 has particles, and every bucket contains a single particle. In this way, particles in the same spill are temporally separated by 19 ns. The beam is transferred till M02 enclosure: it's then split in two beams so as to deliver particles to both MTest and Mcenter. MCenter is made up of different areas. Of our interest are MC6 (the last beam transfer line), and MC7 (the experimental area).

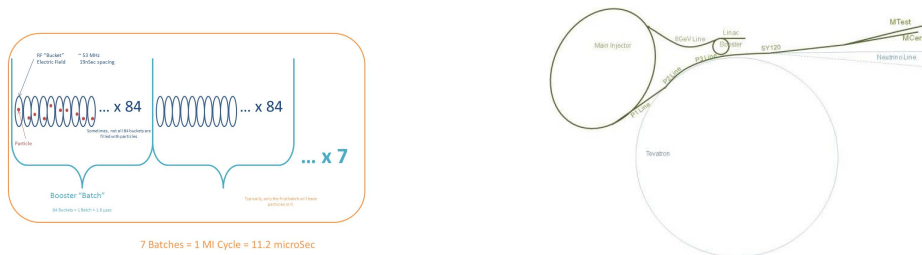


Figure 2: Beam Structure and Beam Delivery Path

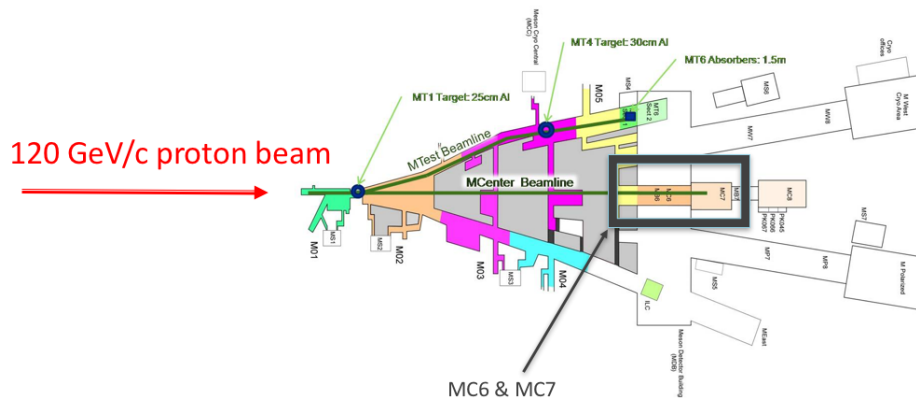


Figure 3: Test Beam Facility map

3.1 MC6

120 GeV/c proton beam reaches MC6, bent over of 1.31 degree compared to the floor, and hits a copper target (5 mm wide, 5 mm high, 200 mm long). Then, protons and interaction products are guided along the beam line. The entire length is ~ 56 m and it is composed by an ion chamber, the target, four absorbers, six quadrupoles, four dipoles, two trim magnets couples, one momentum collimator, as shown in Figure 4.

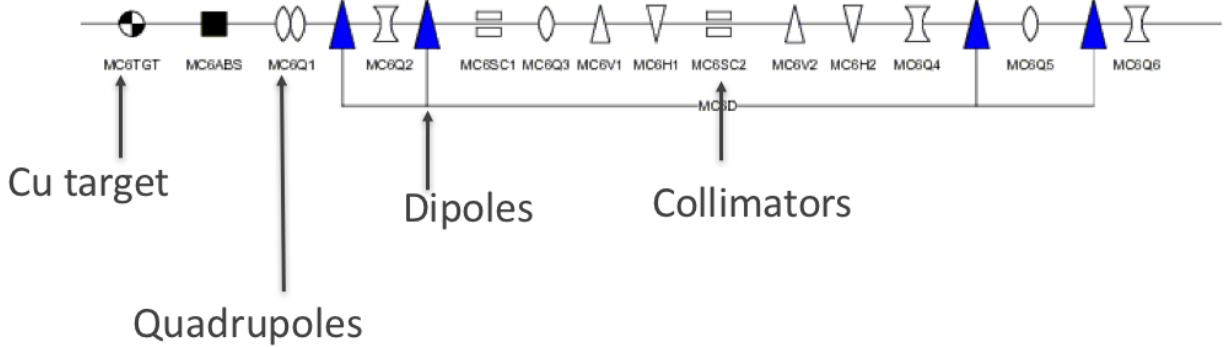


Figure 4: MC6 schematic structure

Selecting dipoles' field and quadrupoles' gradient, one can select mean momentum of particle reaching the end of the path, dumping the rest of the beam (mostly high energetic protons) on the momentum collimator. Hence, MC6 provides a low-intensity beam, of a chosen mean momentum, parallel to the floor, thanks to bending dipoles.

Four *EPB* dipoles (outlines in Figure 5) are all fed by the same power supply, indeed they provide the same field, according to the following relation:

$$MC6D = \frac{Momentum}{40} \cdot 282,7 \cdot Transfer \quad (1)$$

Where $MC6D$ is the field in dipoles (expressed in Tesla), $Momentum$ is the desired momentum (expressed in GeV/c), $Transfer$ is the value of the conversion from current delivered by the power supply to the field and its value is 0.0008886256 T/A.

Quadrupoles are fed independently; gradients (expressed in T/m) are obtained linearly scaling values provided by Main Control Room, referring to 80 GeV/c setup. There are two different kind of quadrupoles in MC6: $3Q120$ and $4Q120$ (outlines in Figure 5). They differ each other for coil aperture, transfer value, hence maximum field value.

Trim magnets are *Vernier* dipoles; smaller than others magnets, they are usually off or with a very low intense field. Combined with momentum collimator, they contribute to momentum selection precision.

Collimators are concrete blocks, divided by aluminium layers, where apertures are.

First six magnets are equipped with vacuum system, all the rest of MC6 and MC7 is located in air.

An ion chamber positioned before the target and a counter downstream the whole line provide the ratio particles downstream / particles downstream (see Figure 6).

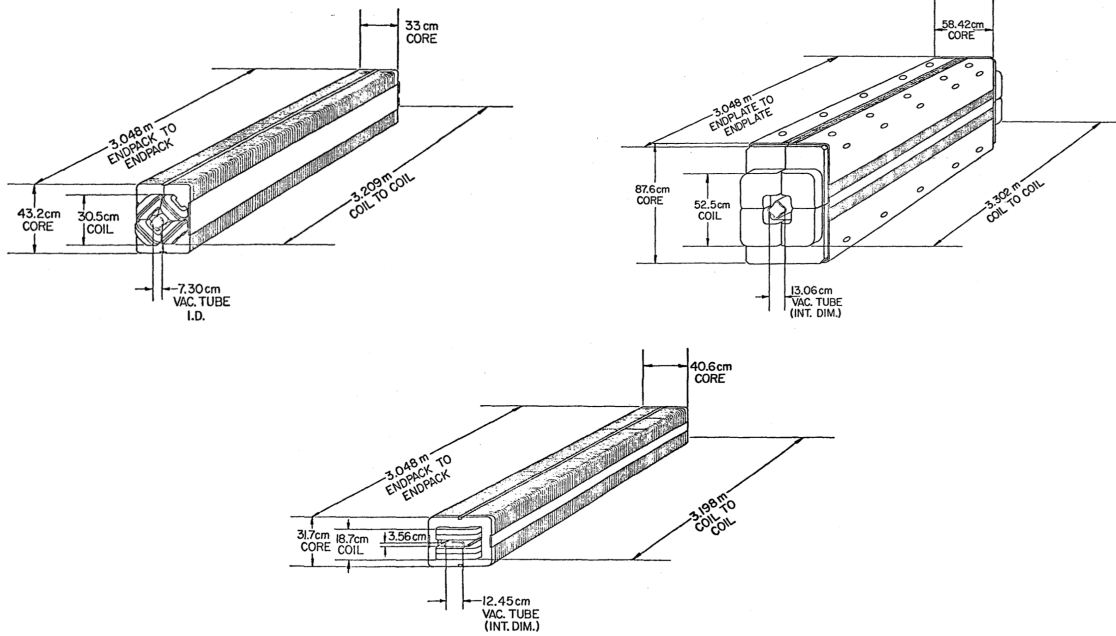


Figure 5: Clockwise from up left: $3Q$ Quadrupole, $4Q$ Quadrupole, EPB Dipole

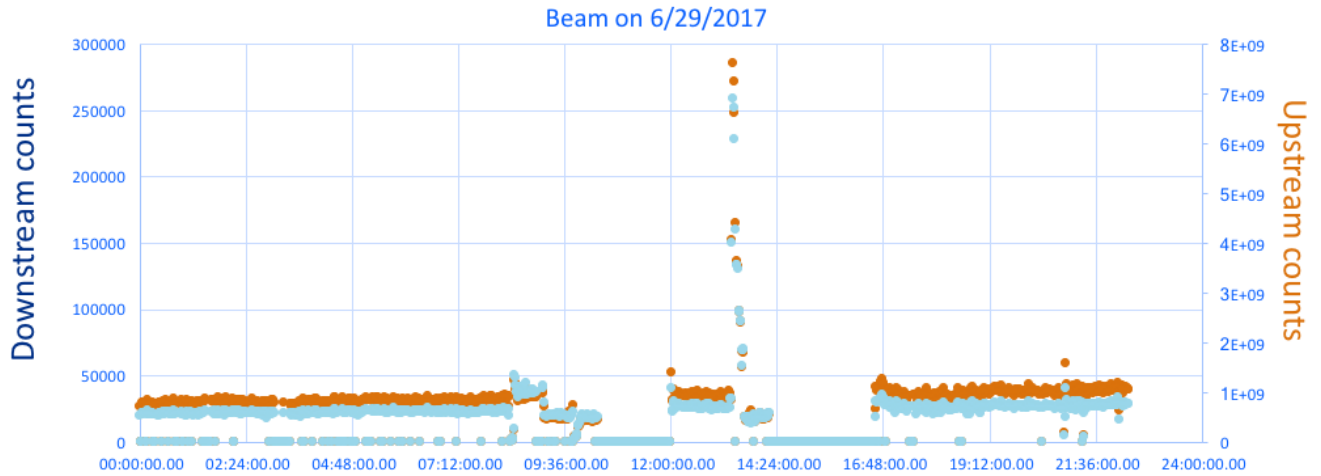


Figure 6: Counting Ratio; Average value: $\sim 0.05\%$

3.2 MC7

MC7 is divided in two experimental areas, ending with the beam dump. It is equipped with calibrated instrumentations (counters, Cherenkov detectors), patch panels and inert gas capabilities. In this case, MC7 is made up of some detectors, a copper target (approximately 6 m downstream the last MC6 quad, behind an absorber) and a collimator.

LAPPD Time of Flight setup will be straight after the collimator, in the beam direction, so as to take advantage of the shielding effect. Collimator's aperture directs the beam toward LArIAT setup, which LAPPD will work to parasitically.

The beam hitting the target has a mean momentum as selected by MC6 dipoles, and a species composition varying with energy. Ratio of species is shown in Figure 7.

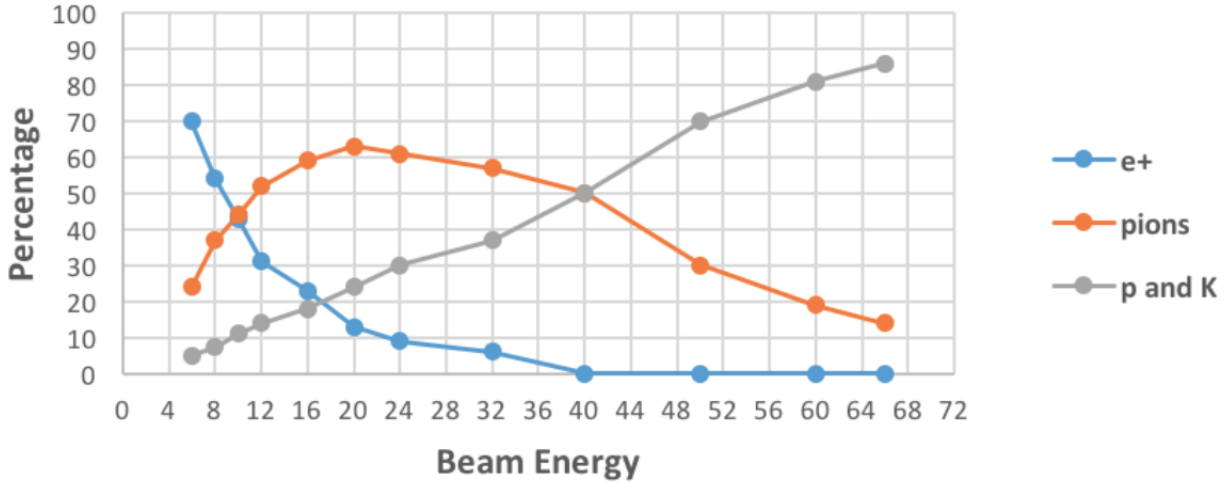


Figure 7: Particle Composition

Depending on energy, few particles overcome the collimator in beam direction; they are mostly $\mu+$. Furthermore, a large area is invested by a $\mu+$ plume coming from the primary target.

4 G4beamline code

G4beamline is a particle tracking and simulation program based on the Geant4 toolkit that is specifically designed to easily simulate beamlines and other systems. The basic structure of a G4beamline simulation is to first define beamline elements (magnets, beam pipes, etc.), including their geometry, materials, field, etc., and then to place them into the world, usually along the beam direction. The tracking of particles through the simulated system is as accurate and realistic as the Geant4 toolkit implements. The input file selects from any of the Geant4 physics lists, and can set values for the various Geant4 tracking-accuracy parameters.

4.1 What it does

MC6 - MC7 simulation code provides tracking of 120 GeV/c protons shot 200 mm before the primary target, bended of 1.31 degree compared to the ground. It runs event by event, considering a gaussian particle distribution of the beam. Simulated elements strictly comply to real ones referring to outlines, materials, field, beam environment, relative distances.

VirtualDetectors are located along the line in order to collect data about particles reaching a precise area.

G4beamline provides either visualization of simulated beamline up to ninety-nine events (see Figures 8, 9) or a ROOT file containing Ntuples referring to every *VirtualDetectors*.

The whole code has been written by the author of this report during the nine-week internship at Fermilab.

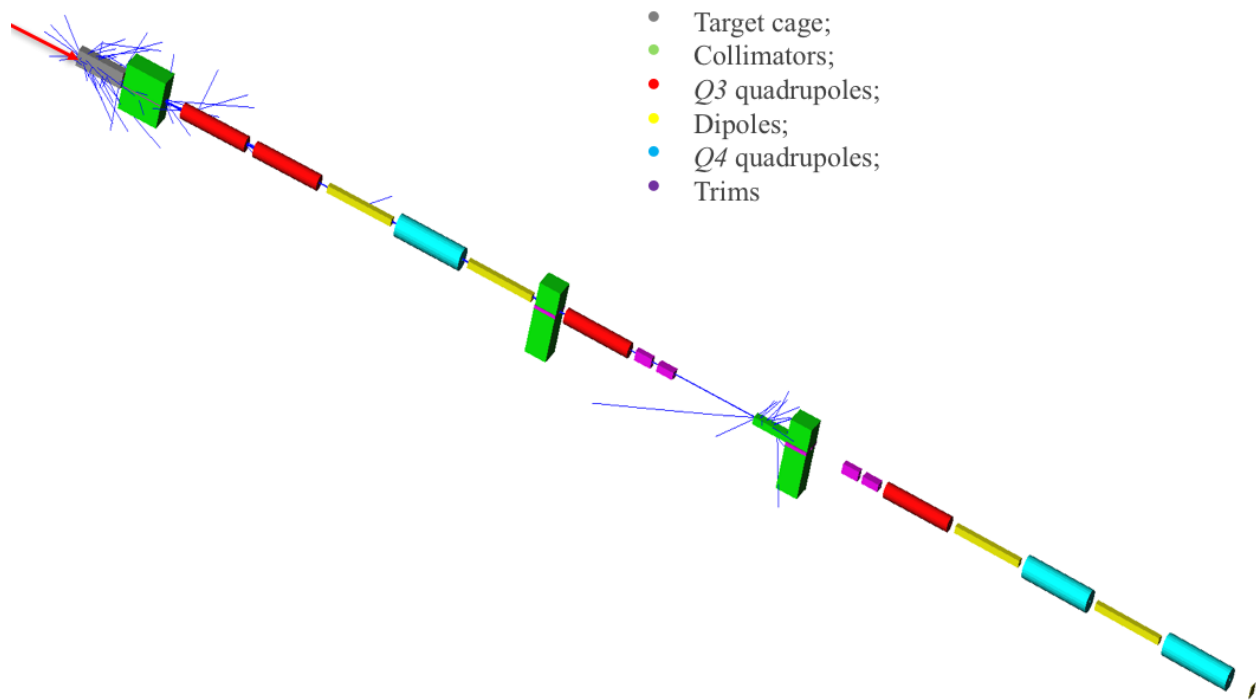


Figure 8: MC6 visualization.

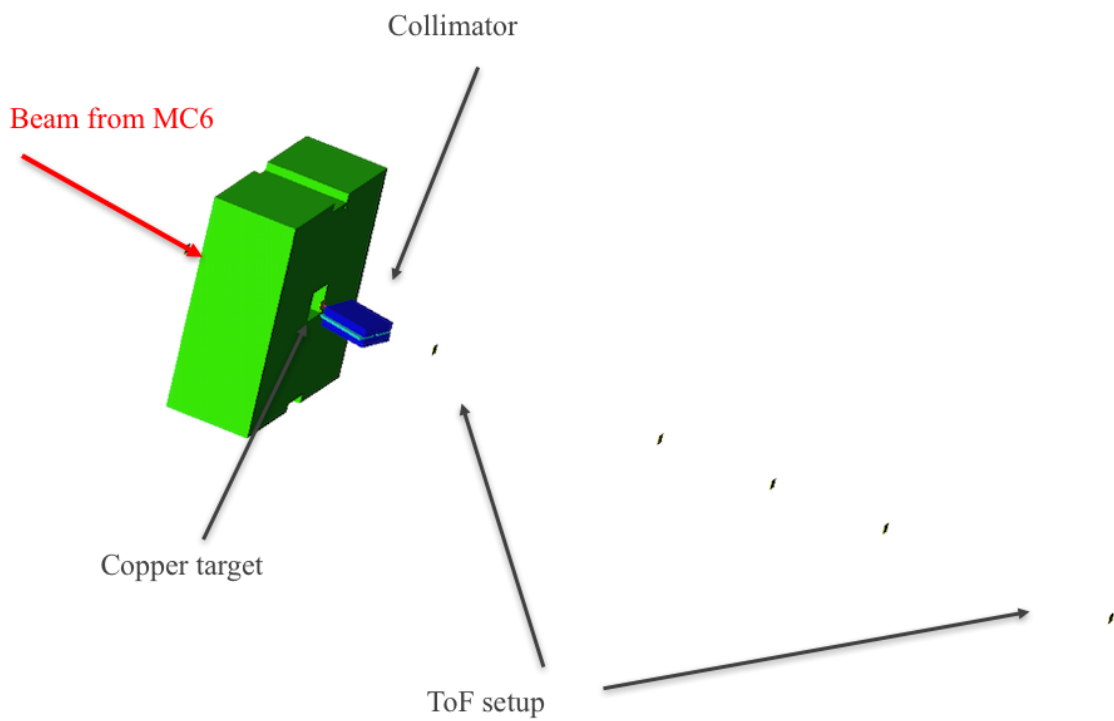


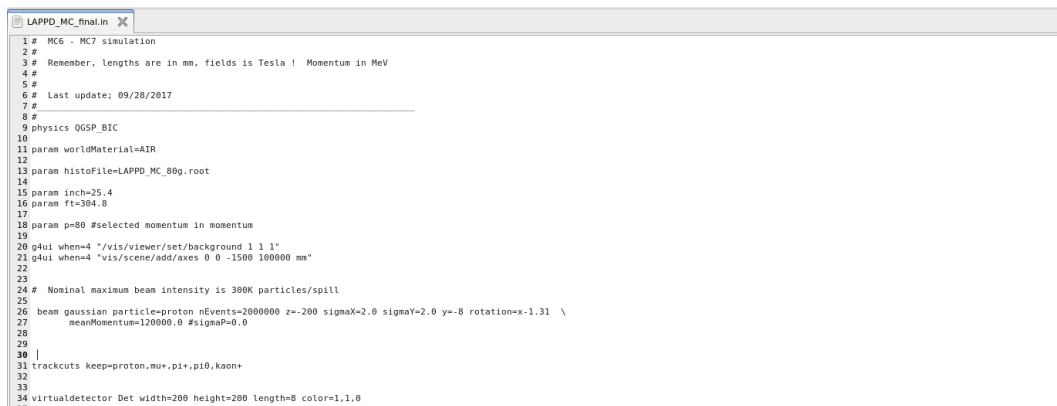
Figure 9: MC7 visualization.

4.1.1 Input

Reason of the code is being available for MCenter users, so as to be aware of beam properties before tests start.

For this reason, simulation is flexible and many parameters can be modified in the code, as well as elements' geometry and materials. Lists of command and details can be found in G4beamline help. The followings are relevant for studying beam properties in experimental areas and analyzing data (Figure 10):

- *physics* defines the properties of the "world" where simulation takes place. *QGS_PBIC* list provides useful mechanisms such as multiple scattering, Cherenkov radiation, etc.;
- *worldMaterial* sets material where the beam goes through. In MC6 and MC7 the beam runs mostly in air (*AIR* command);
- *histoFile* sets the name of the ROOT file that will be generated in the same directory where the code is;
- *p*, expressed in GeV/c, selects the desired momentum of particles reaching the end of the line: it automatically sets fields and gradients;
- *beam* defines properties of simulated beam:
 - *gaussian* sets a gaussian spatial distribution of the beam;
 - *particle* defines the kind of particle: in MC6, proton is the starting particle;
 - *nEvents* sets the number of event running in non-visualization mode;
 - *x, y, z* set the starting point of the beam;
 - *meanMomentum* sets the mean momentum of particles, expressed in MeV/c;
 - *sigmaX, sigmaY, sigmaZ* are standard deviations of spatial distributions;
 - *sigmaP*: momentum dispersion of the beam expressed in MeV/c;
 - *rotation* sets the angle of bending of the beam referring to reference trajectory.
- *trackcuts keep* sets particles that will be tracked in simulation: other particles will be killed after generation. A compromise between number of species considered and time of running must be found;



```
LAPPD_MC_final.in X
1 # MC6 - MC7 simulation
2 #
3 # Remember, lengths are in mm, fields is Tesla ! Momentum in MeV
4 #
5 #
6 # Last update: 09/28/2017
7 #
8 #
9 physics QGSP_BIC
10
11 param worldMaterial=AIR
12
13 param histoFile=LAPPD_MC_80g.root
14
15 param inch=25.4
16 param ft=304.8
17
18 param p=80 #selected momentum in momentum
19
20 g4ui when=4 "/vis/viewer/set/background 1 1 1"
21 g4ui when=4 "/vis/scene/add/axes 0 0 -1500 100000 mm"
22
23
24 # Nominal maximum beam intensity is 300K particles/spill
25
26 beam gaussian particle=proton nEvents=2000000 z=-200 sigmaX=2.0 sigmaY=2.0 y=-8 rotation=x-1.31 \
27     meanMomentum=120000.0 #sigmaP=0.0
28
29
30 |
31 trackcuts keep=proton,mu+,pi+,p10,kaon+
32
33
34 virtualdetector Det width=200 height=200 length=0 color=1,1,0
35
```

Figure 10: First line of the code, where parameters can be changed.

- *virtualdetector Det* defines detectors that will collect simulated data: one can set *width*, *height*, *length*, etc. In the code, detectors are settled using the command *place Det* in the position set by *x*, *y*, *z*; Ntuple will have the name provided with *rename* command.

4.1.2 Output

Visualization mode provides a 3D graphic view of the beam line, up to ninety-nine events. It's possible to zoom and rotate simulation. This mode is fundamental building simulation's geometry, and very useful for checking optics of most of the beam; on the other hand, rare events or low-intensity beam are difficult to be seen.

Non-visualization mode runs the number of event set by *nEvents* command. Every NTuple in the ROOT file correspond to a *VirtualDetector* and contains the following data for every particle hitting its volume:

- *Ptot*, *Px*, *Py*, *Pz*: the momentum of the track in the selected coordinates, in MeV/c;
- *x*, *y*, *z*: the position of the track, in the selected coordinates, in millimeters;
- *t*: the global time of the track, in nanoseconds;
- *PDGid*; the ID of the particle, using the assigne value from the Particle Data Group; useful values are:
 - 2212: proton;
 - 312: K+;
 - 221: $\pi+$;
 - 22: γ ;
 - 11: e-;
 - -13: $\mu+$.
- *EventID*: the event number.

4.2 Where to find it

MC6 and MC7 simulation code, and PyRoot analysis code have been written in their totality by the author of this report. They will be available from the author, Livio Verra (livio.verra@hotmail.it), at Fermilab Test Beam Facility (coordinator: Mandy Rominky, rominsky@fnal.gov), and on LAPPD project website (<https://psec.uchicago.edu>).

5 Analysis tools

5.1 HistoRoot

HistoRoot is a ROOT-based histogramming program, available from <http://historoot.muonsinc.com>, which can generate histograms in a very intuitive manner from ROOT files, via a graphical user interface (Figure 11).

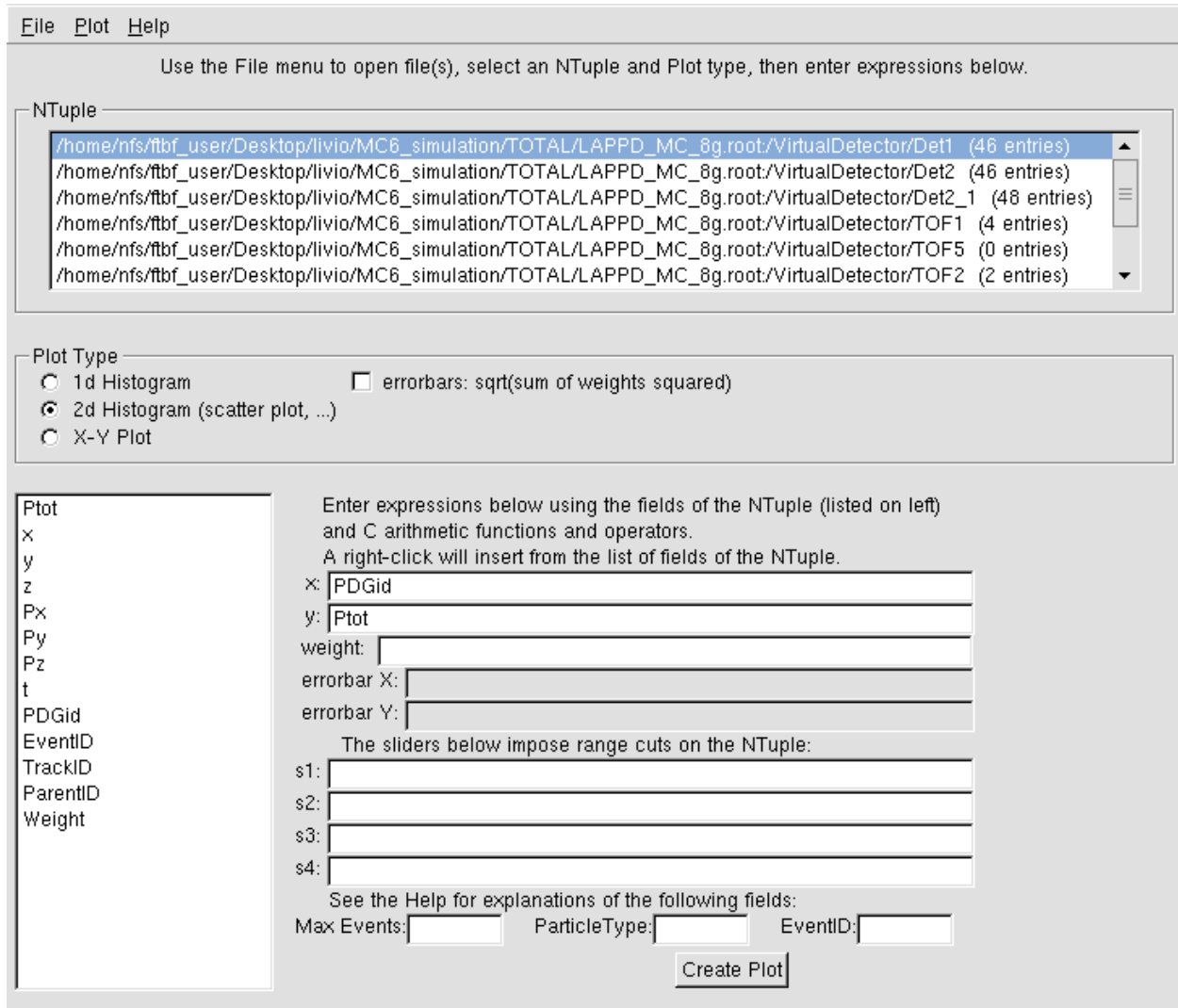


Figure 11: HistoRoot interface.

Selecting one or more NTuples, and values of interest, HistoRoot generates a plot. The tool has some limitation in use and combination of NTuple (e.g: it is not possible to calculate the time of flight of a track between two *Virtualdetector*).

5.2 PyRoot code

PyRoot analysis code has also been written during the Summer internship by the author, and it simply opens the selected ROOT file, and extracts data from desired Ntuples. Output of the code is a plot of spatial distribution of particles (divided by species) on the surface

of detector and $\beta \pm \Delta\beta$ plot for particles hitting two selected Detectors (the code considers only same-EventID particles).

Output on shell shows for every event considered:

- PDGid;
- Time of flight, expressed in seconds;
- Total momentum, expressed in MeV/c
- β value;
- $\delta\beta$ value, considering error on data dx , dy , dz (meters), dt (seconds).

```

1 #!/usr/bin/env python
2 # coding: utf-8
3
4
5 import math
6 from ROOT import TTree, TFile, TObject, TH1D, TH2D, TCanvas, TChain, TAttMarker, TMath
7 from glob import glob
8
9 fin = glob("~/home/nfs/TFDf_user/Desktop/Livio/MC_simulation/TOTAL/LAPPD_MC_64g.root")
10
11 tof1 = TChain("VirtualDetector/TOF1")
12 tof2 = TChain("VirtualDetector/TOF3")
13
14 for f in fin:
15
16 #tree = fin.Get("VirtualDetector/TOF1")
17   tof1.Add(f)
18
19 for f in fin:
20
21 #tree = fin.Get("VirtualDetector/TOF3")
22   tof2.Add(f)
23
24 entries = tof1.GetEntries()
25 entries2 = tof2.GetEntries()
26 print entries, entries2
27
28 dx = 0.0087
29 dy = dx
30 dz = dx
31 dt = 0.00000001
32
-13.0 2.50209503174e-08 7198.98108722 0.999200553415 3.33333333333e-09
-13.0 2.50231323242e-08 18122.7294255 0.999290728458 3.33333333333e-09
-13.0 2.50354309082e-08 2925.30338647 0.998656950617 3.33333333333e-09
-13.0 2.50185546875e-08 19245.5563463 0.999293449959 3.33333333333e-09

```

Figure 12: PyRoot analysis code and shell output

6 Theroretical Time of Flight study

Measuring Time of Flight of a particle between two detectors allows calculating β value and hence, knowing the energy, rest mass of the particle.

This technique is very useful for resolving different species of particles coming from the same beam, or from cosmic rays. In this kind of measurements, time and spatial resolution become critical, as they affect the error on β and, finally, on the capability of solving different particles. Ultra-fast Time-of-Flight Large Area Picosecond PhotoDetector (LAPPD) aims to reach a time resolution of 1 ps, and a $7 \mu\text{m}$ spatial resolution. This precision will allow to solve species above $\sim 2 \text{ GeV}/c$. Enhance, it would be a very useful upgrade in experiments at colliders or on cosmic rays stands.

For this reason, a study on some relevant species has been conducted during the internship, in order to start estimating Time-of-Flight distance.

Three different couples of species have been studied for the time-of-flight study because of their relevance: π^+/μ^+ , π^+/K^+ , π^-/e^- .

The first one is not a real issue in experimental physics, but it is the easiest to be verified by G4bl simulation.

In Figure 13 are shown time separation, depending on momenta, for some distances, calculated considering particles going through vacuum along a straight trajectory.

Dashed red lines on plot indicate the 1 ps time resolution threshold, under which is not possible to solve species. As one can deduce from plots, a shorter distance than 5 m would be probably not enough for solving some of considered couples (especially π^+/μ^+).

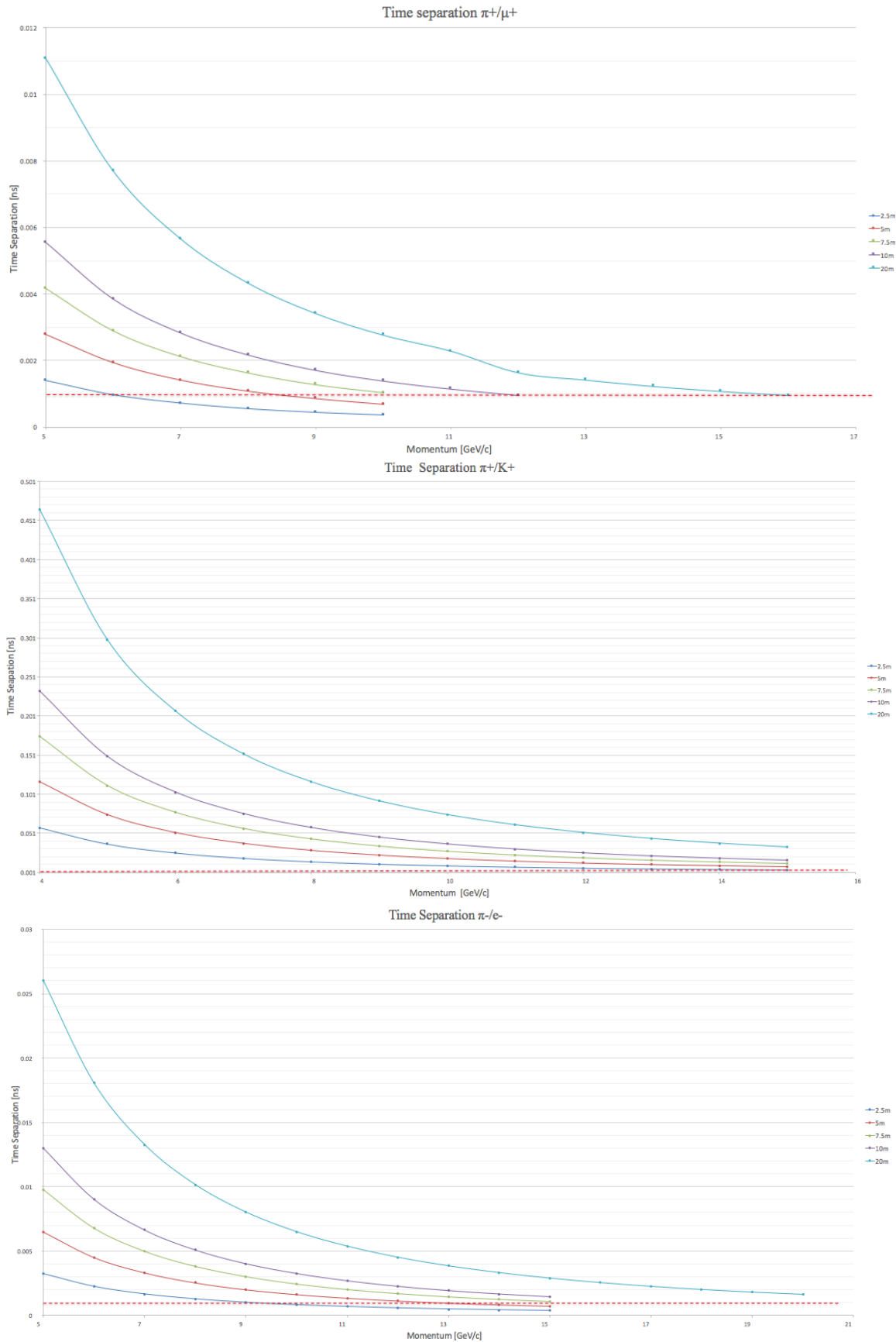


Figure 13: From the top: π^+/μ^+ , π^+/K^+ , π^-/e^- time separation plots.

7 Simulation results

Complete MC6 - MC7 simulations have been run positioning one *VirtualDetector* Det1 at the end of the last MC6 quadrupole, one before the secondary target (Det2), and six *VirtualDetectors* in MC7 for analyzing different distance combinations: the first is set right after the collimator; other five are respectively 5, 7.5, 10, 15, 20 meters apart from the first one.

Simulations have been run for different selected momentum values: 1, 8, 16, 32, 64, 80 GeV/c.

In order to have a good statistics, avoiding very long simulation running time, the following method has been adopted for obtaining results at the end of the nine-week stay at Fermilab:

- Run a 2-million event simulation;
- Analyze characteristics of species passing through Det1 and Det2: number of particles, spatial distribution, momentum distribution, etc.;
- Calculate number of events for a spill (500 millions particles at the beginning of the line);
- Run a MC7 simulation for every species, using characteristics extrapolated before;
- Analyze results for Time of Flight.

All following analysis and plots are output of author's PyRoot code.

7.1 *VirtualDetector* Det1

VirtualDetector Det1 is positioned at the end of the last MC6 quadrupole. The first check operated on every simulation refers to the ratio of particle reaching this point (cf. Section 3.1). This checking allows to consider simulations precise and reliable. As shown in Figure 14, the ratio particles over MC6 / particles hitting the primary target is reasonably close to real data ratio.

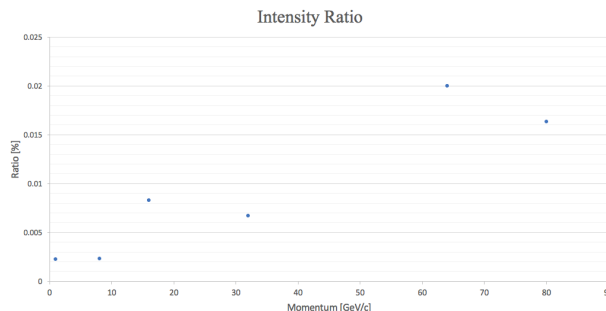


Figure 14: Intensity ratio for different selected momenta.

Then, for every simulation analysis focused on species and momenta of particle hitting the detector (whose surface is 20x20 cm²). From plots shown in Figure 15, one can extrapolate that selecting momentum implies selecting species: in fact, at high energy the prevailing species is protons, while at lower energy $\mu+$ and $\pi+$ become predominant.

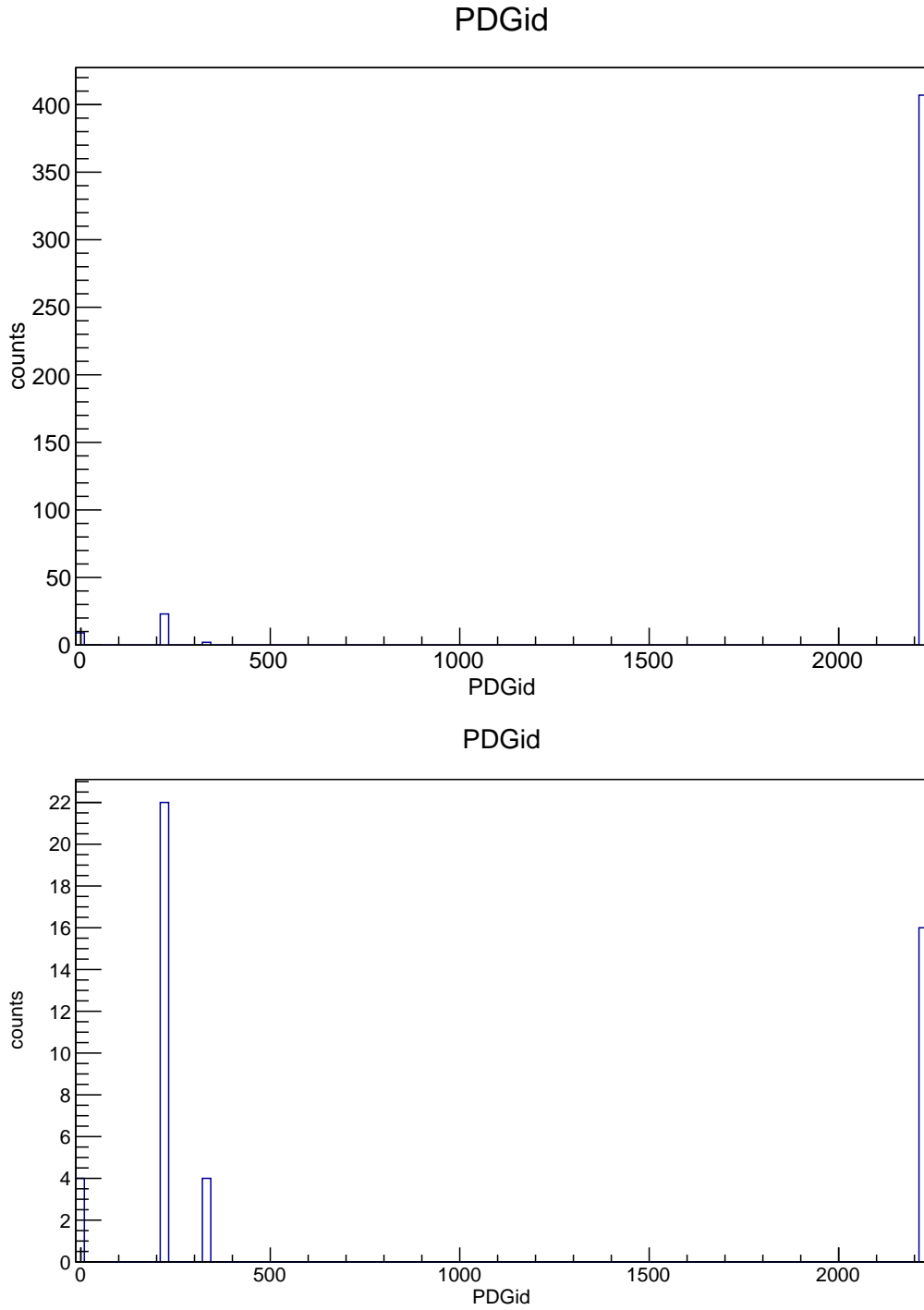


Figure 15: Top: 64 GeV/c configuration; Bottom: 8GeV/c configuration

Furthermore, plots in Figure 16 show particles' momenta, verifying the impact of changing fields in the momentum selection.

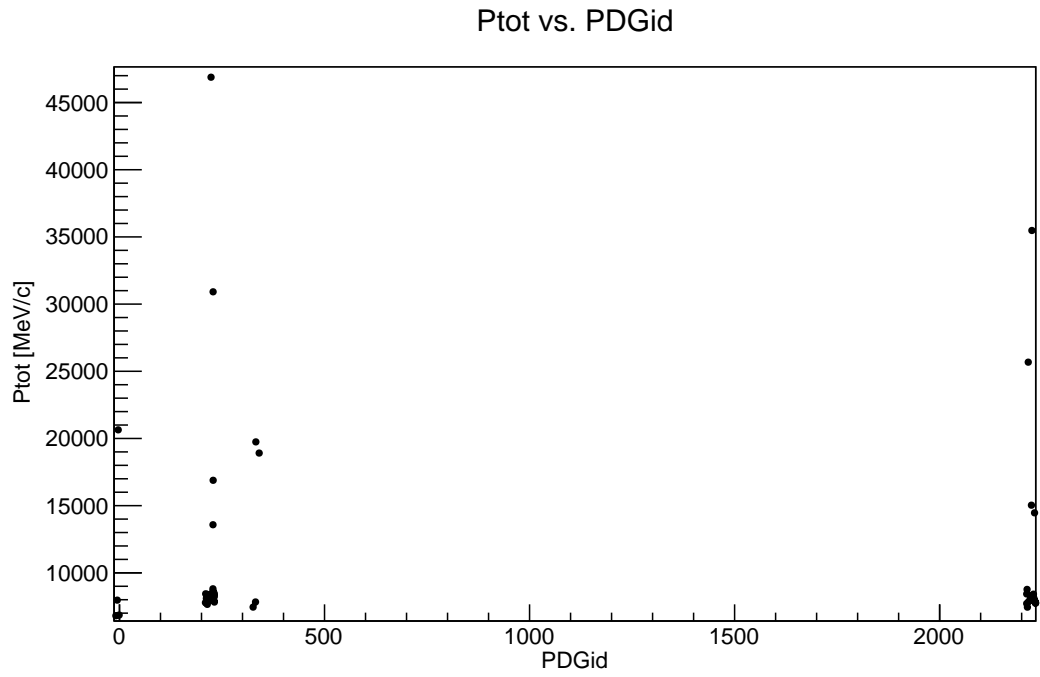
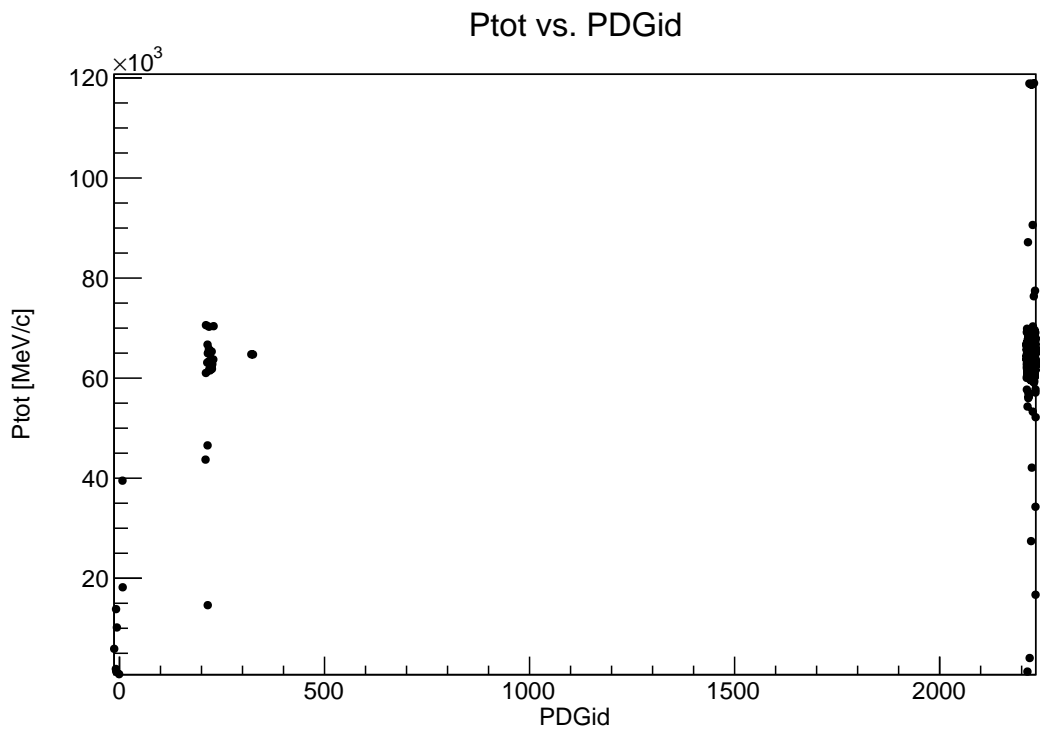


Figure 16: Top: 64 GeV/c configuration; Bottom: 8 GeV/c configuration

7.2 *VirtaulDetector* TOF1

The same kind of analysis can be conducted on the first Time of Flight detector, positioned 25 cm downstream MC7 collimator. It provides information on intensity and momentum of the beam, and on particle species overcoming the collimator.

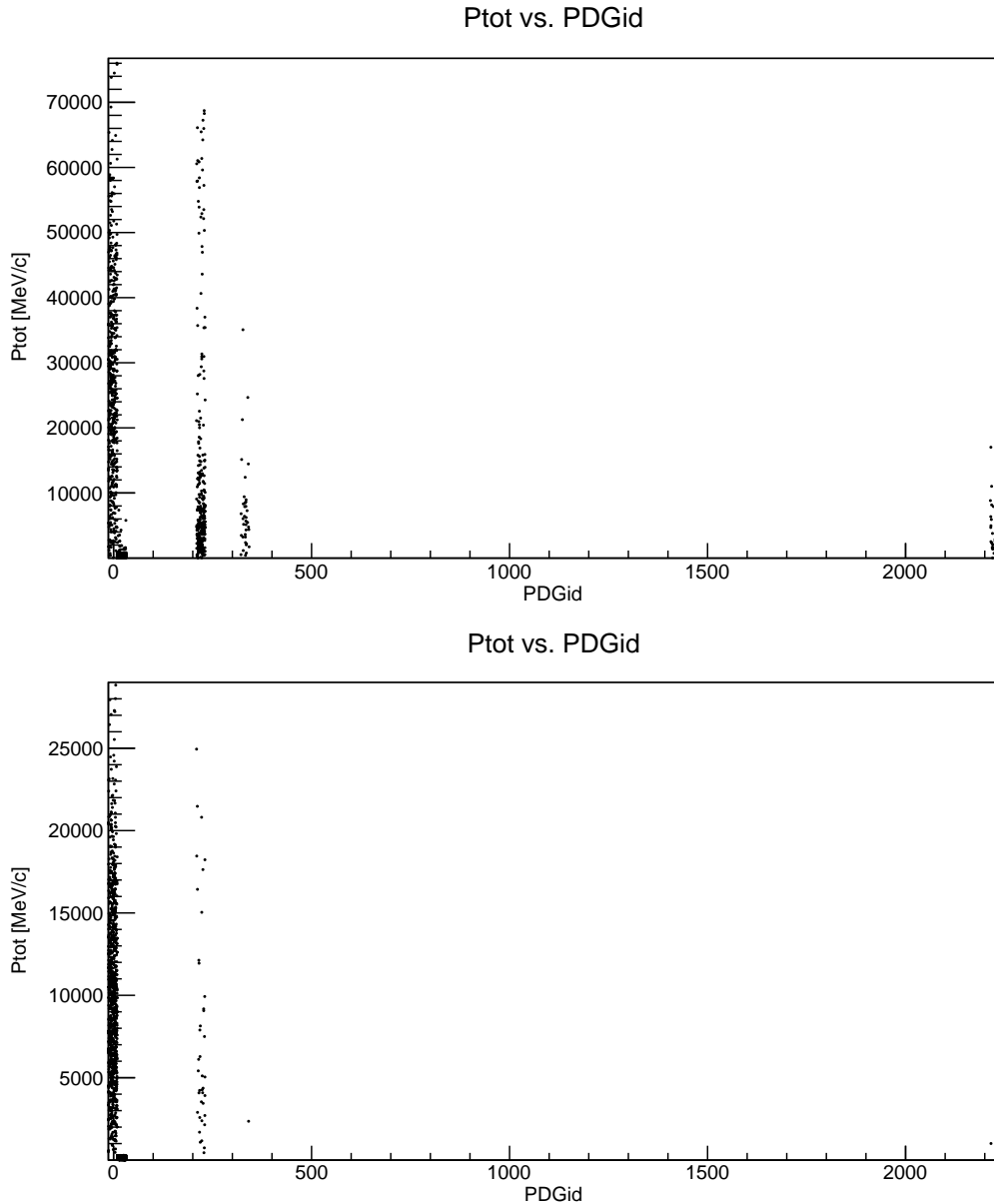


Figure 17: Top: 64 GeV/c configuration; Bottom: 8 GeV/c configuration

As shown in Figure 17, in 64 GeV/c different species overcome the collimator, while in 8 GeV/c setup, few particles but muons reach Time of Flight stand. Both configuration are useful in order to test LAPPDs: low energy beam provide a "clean" beam, giving the possibility of focusing on energy resolution; higher energies, on the other hand, supply a good environment for testing species separation.

7.3 Time of Flight *VirtualDetectors*

Simulations provide data on all particles reaching a *VirtualDetector*. Because of intrinsic divergence of the beam, and of the possible scattering (beam goes through air), intensity decrease with the distance; moreover, some particles not hitting the first Time of Flight are scattered again in the beam line, crossing one of the following detectors. For these reasons, analysis PyRoot code provide analysis on events hitting consequentially two selected Time of Flight *VirtualDetectors*.

Working with β is more appropriate, rather than time, as it takes into account distance and spatial resolution. The error $\delta\beta$ is calculated by the program, propagating error on measurements ($7 \mu\text{m}$ for x and y direction, 8 mm for longitudinal direction, 1 ps for time resolution), and it is settled round $5\text{e-}5$. β plots for different energies and distances are shown below: every bin sits in $\delta\beta$ value.

7.3.1 8 GeV/c setup

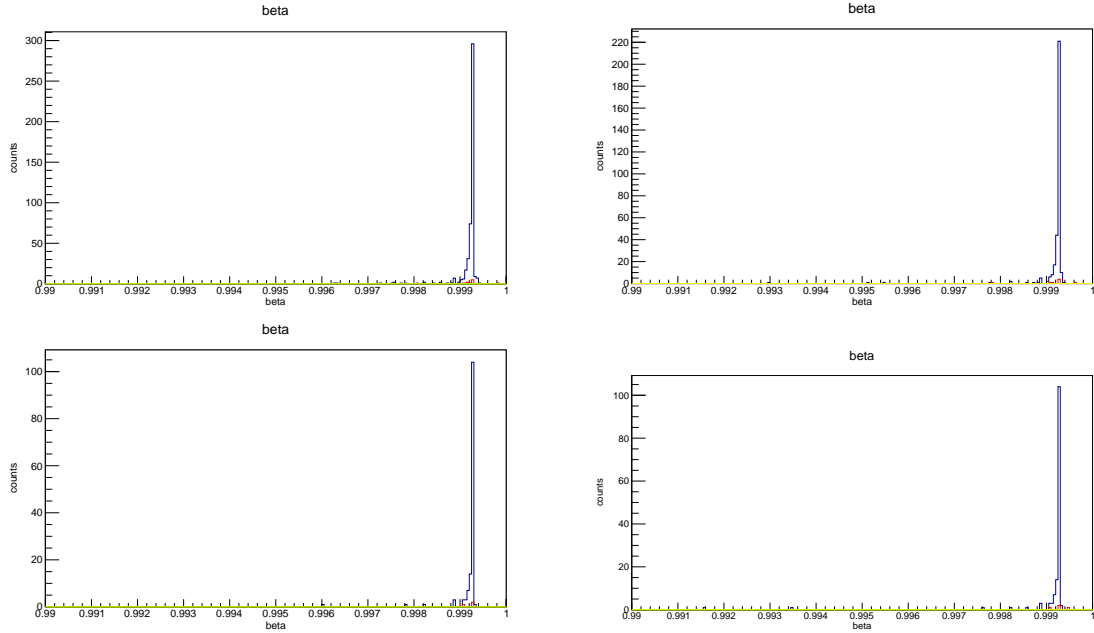


Figure 18: Counterclockwise from top left: 5 m, 7.5 m (first two detectors), 7.5 m (first and third detector), 15 m

	$\mu+$		$\pi+$		p	
	#	P_{tot} [GeV/c]	#	P_{tot} [GeV/c]	#	P_{tot} [GeV/c]
5m	479	11.9 ± 0.2	14	11 ± 1	2	$0.99\text{e-}3 \pm 0.01\text{e-}3$
7.5m(I)	326	13.0 ± 0.3	9	12 ± 2	1	$1.0\text{e-}3$
7.5m(II)	144	13.3 ± 0.4	6	10 ± 3	0	/
15m	140	13.5 ± 0.4	3	15 ± 4	0	/

Table 1

7.3.2 16 GeV/c setup

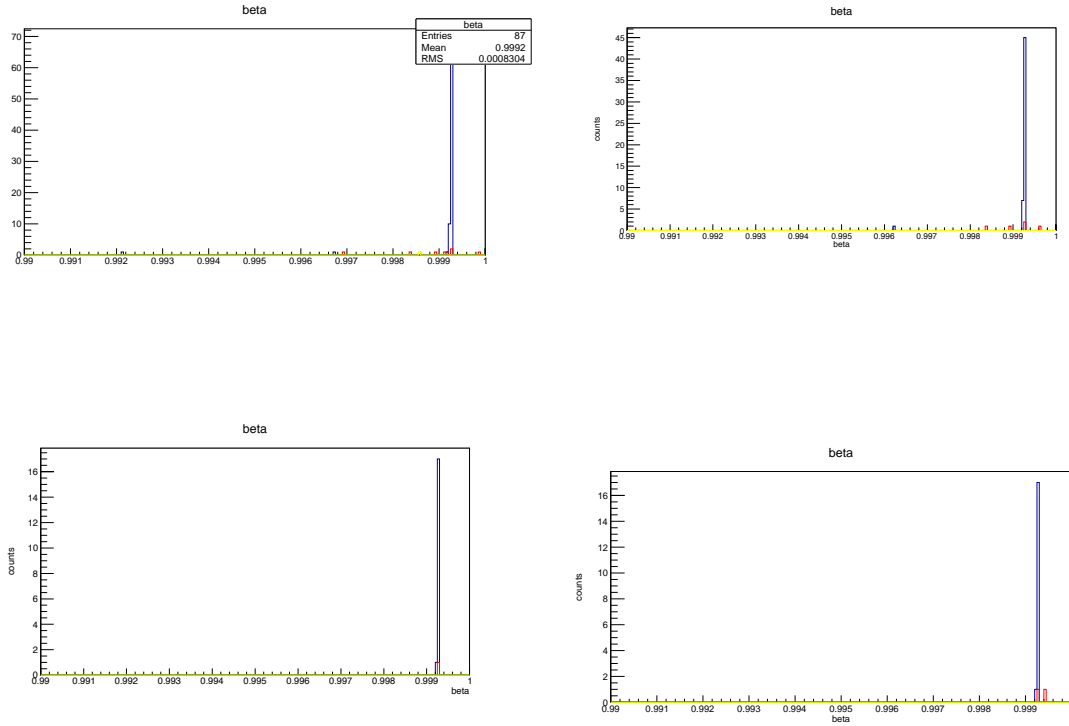


Figure 19: Counterclockwise from top left: 5 m, 7.5 m (first two detectors), 7.5 m (first and third detector), 15 m

	μ^+		π^+		p	
	#	P_{tot} [GeV/c]	#	P_{tot} [GeV/c]	#	P_{tot} [GeV/c]
5m	87	12.7 ± 0.3	10	8 ± 2	1	$0.99\text{e-}3$
7.5m(I)	55	12.9 ± 0.4	7	9 ± 3	1	$1.0\text{e-}3$
7.5m(II)	18	14.2 ± 0.6	2	10 ± 3	0	/
15m	18	14.2 ± 0.6	3	9 ± 5	0	/

Table 2

7.3.3 64 GeV/c setup

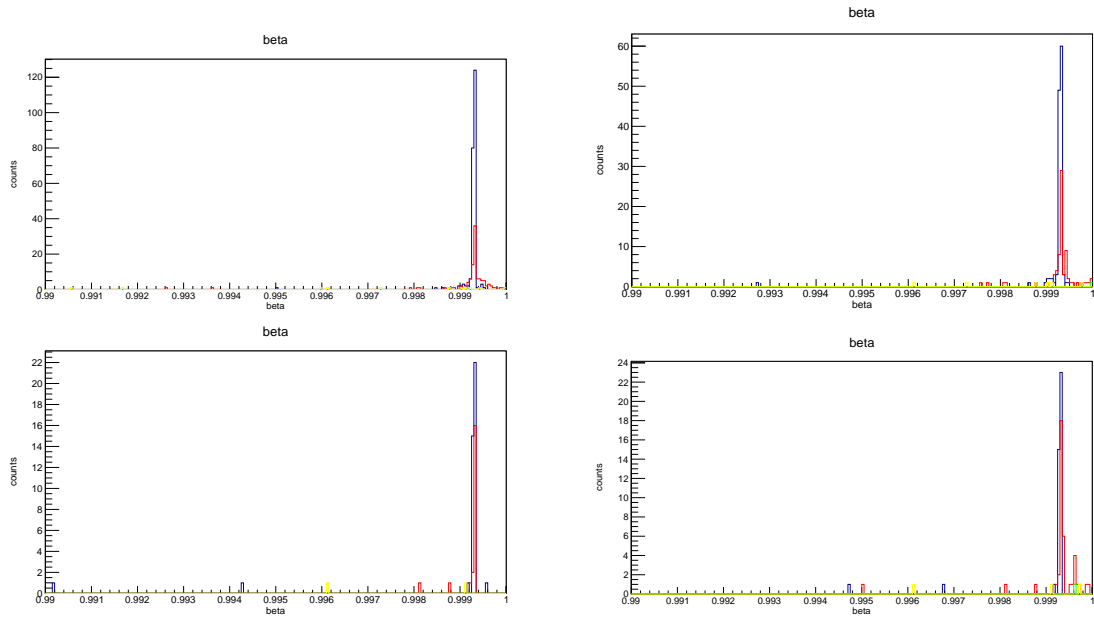


Figure 20: Counterclockwise from top left: 5 m, 7.5 m (first two detectors), 7.5 m (first and third detector), 15 m

	$\mu+$		$\pi+$		p	
	#	P_{tot} [GeV/c]	#	P_{tot} [GeV/c]	#	P_{tot} [GeV/c]
5m	239	28.2 ± 0.9	147	20 ± 2	18	$1.08\text{e-}3 \pm 0.05\text{e-}3$
7.5m(I)	128	25.7 ± 0.4	92	25 ± 2	8	$1.00\text{e-}3 \pm 0.002\text{e-}3$
7.5m(II)	42	32 ± 2	21	44 ± 5	1	$0.67\text{e-}3$
15m	42	31 ± 2	42	29.2 ± 0.3	3	$0.9\text{e-}3 \pm 0.1\text{e-}3$

Table 3

8 Conclusions

LAPPD Time-of-Flight will be tested in Fermilab Test Beam Facility MC7 experimental area, for proving time resolution properties. MCenter provides a low-intense beam, of variable momentum between 8 and 66 GeV/c. Because LAPPD setup will work parasitically to LArIAT experiment, it will be provided of a low energetic beam. Moreover, thanks to the positioning downstream the collimator, it will receive a quite "clean" muon beam.

Time-of-Flight setup will be made up of three devices; the first will be positioned as close as possible to the collimator, considering the presence of LArIAT devices. As shown in previous sections, relative distances among Time-of-Flight detectors are to be studied considering time, and hence energy, resolution.

Since the beam composition and properties, and MC7 structure, the best placement will be 7.5 m of distance between detectors. In this way, it will be possible to study results of three configurations:

1. 7.5 m (first and second detectors);
2. 15 m (second and third detectors), for a better energy resolution;
3. 7.5 m (second and third detectors): since it sits 7.5 m farther from the collimator respect to the first configuration, it will receive an even less intense beam composed by almost only muons.

Hence, the combination of these will give a complete and precise results on characteristic and capability of the device.

In order to exploiting simulation at the best, it is suggested the use of a complete high-number-of-event simulation using the *Grid computing center* or other similar clusters.

The work conducted during the Summer Student can be summarized as follows:

- Study of LAPPD device and Time-of-Flight test requirements;
- Study of Fermilab complex transfer system and MCenter structure;
- Training in order to have access to radiological restricted areas and to walk along the beam line. That allowed to have a match between simulation and real elements;
- Obtain from Fermilab Accelerator Division maps and outlines of MCenter elements, as well as fields formulas, and finally create a database with all useful information;
- Learn how to use G4beamline tool and how to build a simulation from the beginning (no previous codes were available);
- Write complete simulation code and find a way for having statistically significant data avoiding the use of the grid (no experts were available for help);
- Write a PyRoot analysis code, in order to exploit data provided by simulations;
- Analyze data and come up with some indications for the experiment.

In the end, the internship allowed me to extend and deepen my knowledge about particle accelerators, especially transfer systems. The used tools (G4beamline, ROOT) were new to me, and they will be advantageous skills in the future. Furthermore, I collaborated with different divisions at Fermilab, learning how to ask help and relate with colleagues and scientists.