CERN SUMMERSCHOOL 2023

Improved Visualization of Beam Optics in EasyTracker

ATLAS Forward Proton

August 29, 2023

Submitted By:

ANDREJ SARNATSKIY

Under supervision of:

TOMAS SYKORA

ANDREA DELL'ACQUA

Contents

[1]

[1] Artist cover: https://pngtree.com/siti_11714691

1 Introduction

The LHC has been built after the decommissioning of the Large Electron Positron (LEP) collider, in order to achieve energies sufficient to produce a then hypothesized Higgs boson. It is a circular accelerator approximately 100 m under the French-Swiss border near Geneva. With an circumference of 27 km and around 10000 super conducting magnets the LHC is able to accelerate protons up to 6.8 TeV (which is around 99.999997% of the speed of light). Around one of the four interaction points (IP's) sits the ATLAS detector; a 46 m long barrel shaped collection of subdetectors with a total diameter of 25 m. It detects particles originating from the IP or their decay products. Those particles are produced by deep inelastic scattering (DIS) and most of them travel transversely to the beamline. Other protons undergo elastic - (20%) or diffractive (17% scattering whose interaction could involve hypothesized particles that have not yet been discovered.

The protons originating from the latter scatterings have a low transverse momentum and need to be detected at a very forward region. At a distance of around 200 m there are Roman Pots that bring the detectors as close as 1 mm to the beamline. Detector acceptance studies are required to investigate what magnet configuration is needed to detect as much scattered protons as possible. Moreover, given a scattering interaction, one would like to predict what pattern to expect at the detector for said magnet configuration. MAD-X is the industry standard for accelerator optics due to development of more than 20 years. However it takes time to learn and run the elaborate program.

EasyTracker is an alternative program under development. It is a lightweight program to quickly calculate and visualize particle tracks in real-time, i.e. changes made to the configuration will be implemented within seconds. The goal of this summer project is to add functionalities to EasyTracker: implementation of both arms (forward and backward), visualize using the ROOT interface, import and export data in HepMC2 and ROOT format respectively. The development aims for the program to be user friendly and aid the analysis of forward proton physics.

2 CERN

For almost fifty years the Standard Model has been the bedrock of theoretical and experimental Physics. After the discovery of the Higgs boson in 2012, no other fundamental particle has been discovered yet. All the while there are phenomena which are not (yet) described by the Standard Model: cosmological and astronomical observations of dark matter, dark energy and matter-anti-matter asymmetry, Cabibbo angle in Weak interaction, masses of fundamental particles, three generations of fermions, gravity and its unification with the strong and electroweak force. In order to probe these fundamental theories, scientist and engineers have been building bigger and more elaborate machines decade after decade. For particle physics this endeavour has resulted in a multinational collaborations called CERN. At the heart of operations is the accelerator complex, whose biggest machine is the Large Hadron Collider (LHC). There are four experiments that detect particles at the LHC: ATLAS, ALICE, CMS and LHCb. Particles accelerated in the intermediate stages are also used for experiments researching other branches of physics, e.g. neutrino- (CENF), neutron- (n_ToF), nuclear- (ISOLDE), medicinal physics (MEDICIS), antimatter (AD, ELENA) and Wake fields (AWAKE).

2.1 The LHC

The LHC accelerator is approximately one hundred meter under the French-Swiss border near Geneva. Both proton and lead[2] bunches can be accelerated to 6.8 and 5.36 TeV per nucleon respectively. [4] Protons are accelerated in stages before injected into the LHC in two beam lines. First the linear accelerator LINAC4 strips the electrons from hydrogen and accelerates the residual proton up to 160 MeV. Then via the Proton Synchrotron Booster (PSB, 2 GeV), the Proton Synchrotron (PS) accelerates and stores protons with energies up to 26 GeV. Lastly the bunches are accelerated to 450 GeV by the Super Proton Synchrotron (SPS) before being injected into the LHC in two parallel and opposite traveling beams with the use of TKickers. The 26.7 km LHC is divided in linear and bending sections. There is one linear section where the protons are accelerated by radiofrequency (RF) cavities, similar to the LINAC4. The other linear sections contains monitors and multi-pole magnets for focusing, beam stability and stochastic cooling. The bending sections contains dipole magnets that turn the beam around. There are four IP's where the two beams cross for experiments. In order to provide high luminosity for the experiments the beam is prepared and focused before the IP. Consequently the beam must be refocused after the IP for beam stability. Beam stability is of out most importance and extremely difficult, considering that on an average six hour shift of LHC the protons travel in total 6.5×10^9 km. The diameter of the vacuum tube ranges from 50 to 400 mm [16], which is a small margin across such extreme distance. In order to make such stable beam, harmonics are indispensable. For a fixed magnet configuration there exists a design orbit (nominal beam). In case a particle is exactly on this trajectory, it will never deviate from it and its beam is harmonically closed. However this is not physical. In reality the particles are bunched up in a volume, whose cross-section perpendicular to the beam axis is called the beam envelope.

2.2 Beam optics

The following section contains derived identities from a beam optics course [15]. Particle trajectories in beam optics are described by a cylindrical coordinate system (r, θ, z), where ρ and x are the design radius and the deviation from the design orbit respectively:

$$r = \rho + x \quad . \tag{1}$$

Instead of having a time dependent system, the free parameter is the arc length of the trajectory $s = vt$. If the particle's trajectory is bend by a constant

[2]Lead consists of 208 nucleons, so the total energy is 1.11 PeV per ion!

magnetic field, then by Lorentz force the equations of motion are:

$$x'' - (k - \frac{1}{\rho^2})x = \frac{1}{\rho}\frac{\Delta p}{p_0} \tag{2}$$

$$z'' + kz = 0 \tag{3}$$

Here $\frac{1}{\rho}$ is the bending strength (units rad/m), k is the focusing strength and $\frac{\Delta p}{p_0} = \xi$ is the momentum loss of the proton with respect to the nominal particle. It must be stressed that it is only valid for $x \ll \rho$ and $\frac{\Delta p}{p_0} \ll 1$. While the solution to eq. (3) is a harmonic oscillator, the solution to eq. (2) is not trivial. The general solution is of the form:

$$x(s) = C(s)x_0 + S(s)x'_0 + D(s)\xi \quad , \tag{4}$$

where $x_0 = x(s=0)$, $x'_0 = \left.\frac{\mathrm{d}x}{\mathrm{d}s}\right|_{s=0}$ and $\xi = \frac{\Delta p}{p_0}$.

$C(s)$ and $S(s)$ are two independent solutions to the homogeneous equation of eq. (2) and $D(s)$ is the normalized solution to the inhomogeneous solution. These entities are called cosinelike-, sinelike- and dispersion trajectory respectively. Using these one can calculate the future trajectory using a matrix transformation:

$$\begin{pmatrix} x \\ x' \\ \xi \end{pmatrix}_s = \begin{pmatrix} C & S & D \\ C' & S' & D' \\ 0 & 0 & 1 \end{pmatrix}_s \begin{pmatrix} x \\ x' \\ \xi \end{pmatrix}_{s_0} \quad . \tag{5}$$

Using this matrix-method, one could approximate the change of trajectory a magnet causes. For instance drift space the matrix is quite trivial:

$$M_x = M_y = \begin{pmatrix} 1 & l & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}_s \quad , \tag{6}$$

where l is the length of the drift space. The matrices that represent a quadrupole magnet that focuses vertically and refocuses horizontally is:

$$M_x = \begin{pmatrix} \cosh(\phi) & \frac{\sinh(\phi)}{\sqrt{|k|}} & 0 \\ \sqrt{|k|}\sinh(\phi) & \cosh(\phi) & 0 \\ 0 & 0 & 1 \end{pmatrix}_s \quad , \tag{7}$$

$$M_y = \begin{pmatrix} \cos(\phi) & \frac{\sin(\phi)}{\sqrt{|k|}} & 0 \\ -\sqrt{|k|}\sin(\phi) & \cos(\phi) & 0 \\ 0 & 0 & 1 \end{pmatrix}_s \quad , \tag{8}$$

where $\phi = l\sqrt{|k|}$. For reversal of polarity (focus horizontally, defocus vertically) one swaps the matrices:

$$M'_y(k) = M_x(-k) \tag{9}$$

$$M'_x(k) = M_y(-k) \quad . \tag{10}$$

Other types of magnets can be similarly represented with such matrices. For implementation of this beam optics, MAD-X uses this choice of basis: $\hat{\mathbf{x}}$ pointing outward the ring, $\hat{\mathbf{y}}$ pointing upward and $\hat{\mathbf{z}}$ pointing parallel to the ring (from top view going clockwise). The ATLAS coordinate system coincides with MAD-X for beam 1, but $\hat{\mathbf{x}}$ and $\hat{\mathbf{z}}$ are flipped for beam 2 [14]: $\hat{\mathbf{x}}$ pointing inward and $\hat{\mathbf{z}}$ pointing anti-clockwise from a top view, see fig. 1. In EasyTracker $\hat{\mathbf{s}} = -\hat{\mathbf{z}}$ and $\hat{\mathbf{s}} = \hat{\mathbf{z}}$ for beam 1 and 2 respectively. This difference is important to consider when importing TWISS files generated by MAD-X into Easytracker.

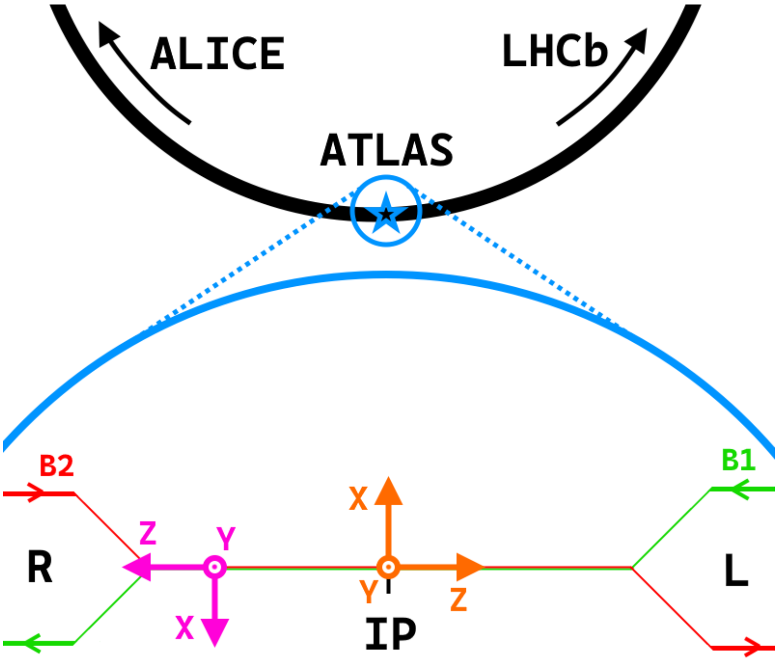

Figure 1: MAD-X, ATLAS beam 1 (magenta) and ATLAS beam 2 (orange) coordinate system for beam optics.

3 ATLAS Forward detectors

The ATLAS detector is close to be a hermetic detector (so-called 4π or barrel detector). It surrounds the beamline with subdetectors for particle measurement and identification. The Inner Detector (ID) consists of the Pixel Detector, Semi-Conductor Tracker and Transition Radiation Tracker. They track the trajectory of charged particles coming from the IP. Together with the solenoid magnet one can determine the charge of the particle. The next shell consists of electromagnetic - and hadronic calorimeters. The first is able to capture and measure the energy of electrons and photons, while the second captures hadrons. Additional (toroid) magnets are on the next shell to increase the accuracy on the momentum of the particle. Outmost shell consist of the Muon Spectrometer that collects data of muons that usually travel through the whole detector. While ATLAS has a wide coverage, the uppermost forward acceptance is $\eta < 4.9$ or $\theta > 15$ mrad. The ATLAS Forward Detectors measure particles (mostly protons) that are outside the acceptance of ATLAS.

3.1 LUCID, LHCf and ZDC

Traveling away from the IP the beam goes past the following ATLAS Forward Detectors in sequence. The LUminosity Cherenkov Integrating Detector (LUCID) detector is 17 meters away from the IP and provides additional luminosity data for the ATLAS central detector. The LHCf and the Zero Degrees Calorimeter (ZDC) collect neutral forward particles for cosmic ray studies and for centrality of the collisions, respectively, for ATLAS central and - forward detectors.

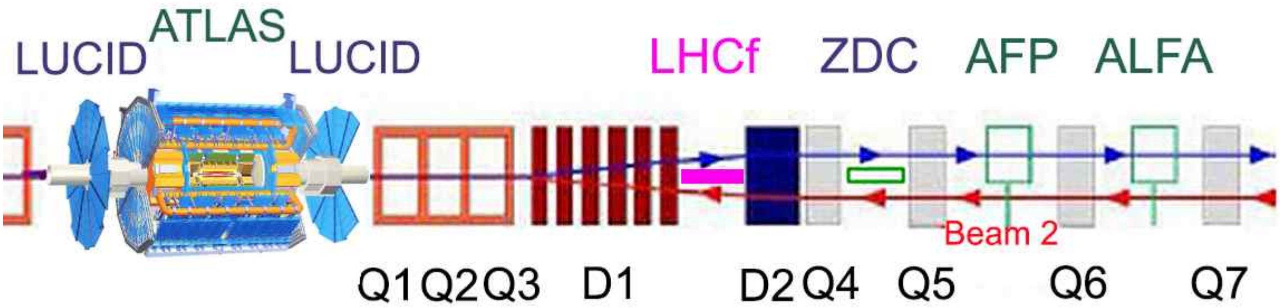

Figure 2: ATLAS Forward region [9]

3.2 AFP

The AFP is able to gather both positional and timing data from soft– and diffraction events in the high forward region. There are two roman pots located on either side of the IP (206 and 214 m). Both the near - and far detector have silicon trackers (SiT's), each consisting of four slanted silicon modules. Each module has a 16.8×20.0 mm silicon chip containing 336×80 3D pixels of size 50×250 μm^2. [8]

The far detector has in addition a time-of-flight (ToF) detector. It has 4x4 quartz bars where Cherenkov photons are induced by the passing protons. These photons are guided through the bars to the photomultiplier tube (PMT) to amplify the signal. The accuracy of the ToF is measured to be $20(26) \pm 4(5)$ ps for side A(C). The protons detected at the AFP are linked to events measured at the ATLAS central detector. [3]

3.3 ALFA

The ATLAS Forward Proton (AFP) and Absolute Luminosity For ATLAS (ALFA) detectors are placed 210 and 240 m from either side of the IP, respectively. The detectors reside in Roman Pots that can be moved as close as 2mm to the proton beam. The objective of ALFA is to measure elastically scattered protons that ATLAS cannot measure in order to measure total cross section of proton-proton interaction using Optical Theorem.

4 EasyTracker

EasyTracker is a lightweight program to simulate beam optics in real-time, meaning it would show new particle trajectories when e.g. one changes the configuration of the magnets. It was developed by Tomas Kommarek[4] and later updated by Vitaly Shinkarenko[5]. The program is written in C++17 and build by qmake in QtCreator. [5] The program is developed for both Windows - (W10) and Linux based system (Ubuntu 22.04), since Qt is a multi-platform application. The versions and kits used are tabled in table 1.

[3] Only 2500-2800 buckets of the possible 35640 are occupied, so the collision rate is in practice lower [1] [12].
[4] As part of his bachelor thesis at Palacký University Olomouc, 2013 [13].
[5] During summer programme at the Faculty of Particle & Nuclear Phys. at Charles University, Prague, 2020.

Ubuntu 22.04.3		Windows 10	
Qt	6.4.3	Qt	6.4.3
QtCreator	10.0.2	QtCreator	10.0.2
Kits			
Qt	5.15.2	Qt	5.15.2
C/C++	11.4.0	C/C++	8.1.0
CMake	3.24.2	CMake	3.24.2
Ninja	1.10.1	Ninja	–

Table 1: Program versions for used OS systems

At the beginning of this project, the program visualized the forward beam (left side, beam 2), see fig. 3. One could either add beam line elements, e.g. magnets, by hand by specifying position, length along the beam axis, bending angle, aperture size, or import the elements from a TWISS file generated by MAD-X. Then particles can be generated originating from the IP. One can specify the xy-offset of the origin of the particles, energy loss ξ, radius and angle of the beam particle in the xy-plane and the angle from the beam axis s. After generating the particles their trajectory is calculated and stored as tracks.

4.1 Changes

At the start of the project several modifications and additions to EasyTracker were set as objectives:

- Implement trajectory calculation and visualization for both sides of the IP.
- Add functionality to export particle data in ROOT format.
- Add functionality to import particle information from generators in HepMC2 format. [10]
- General modification of user interface.

Apart from changes that increase the user-friendliness, the following modifications have been implemented:

4.1.1 Removal existing 3D visualization

EasyTracker v2.0.0 provided at the start of this project caused compile errors linked to 3D packages of Qt. Several attempts have been made to install and use another version of Qt and -Creator, which might contain the requested packages. Without success, the decision has been made to comment the relevant functions out. This code will be redundant once ROOT 3D visualization is implemented.

4.1.2 HKickers, gridlines and ticks

In the original code VKickers were already implemented. In the TWISS files these magnets are labeled VKickers, however these are beam stabilizers (DC-current). The difference is that stabilizers have a constant field and kickers provide a magnetic ”kick” for a short time. These true kickers are usually labeled as TKickers and are used during injection from the SPS to the LHC. These kickers have a typical rise- and falltime in the range $50-1000$ ns. [7] The HKickers are added to the code, so that they are correctly imported from TWISS files.

4.1.3 Addition of origin z-offset

EasyTracker had the functionality to change the x- and y-coordinate of the IP , but not the z-coordinate. The width of the spread in the s- coordinate of the

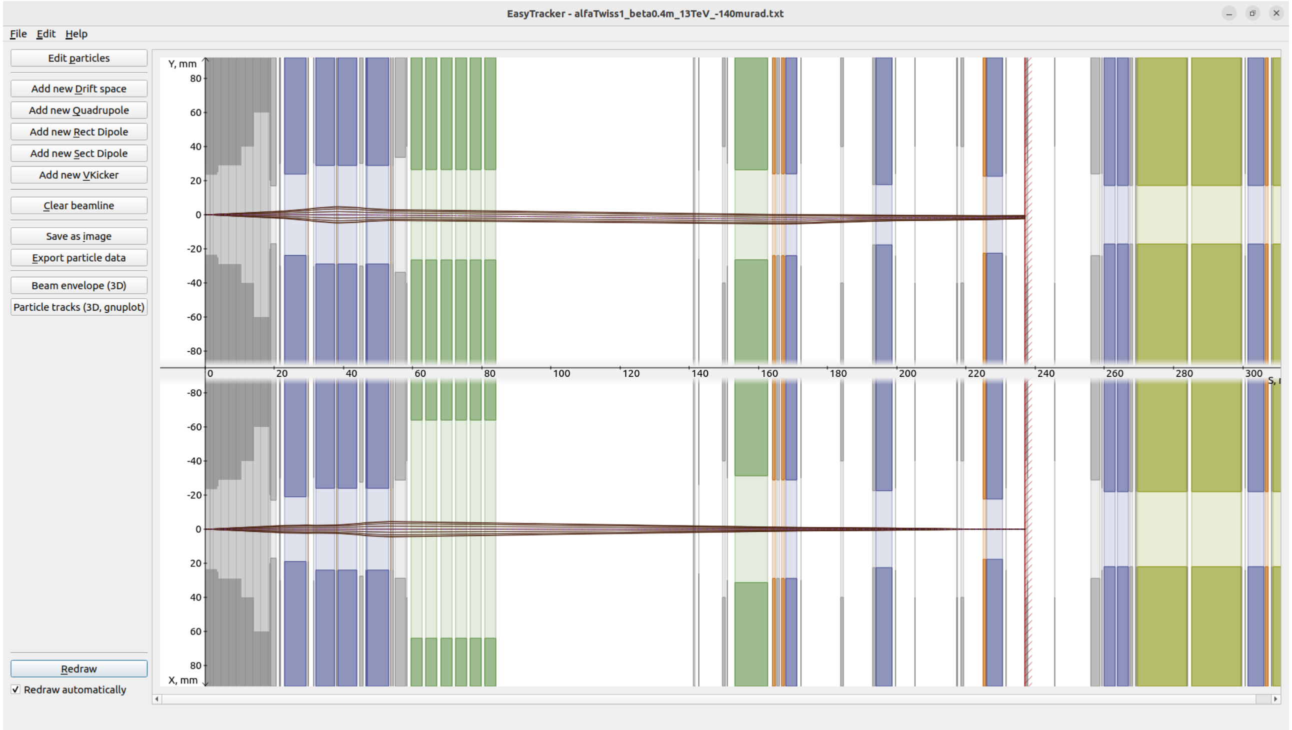

Figure 3: Original EasyTracker

reconstructed primary vertex was measured to be 100 mm in 2010 (7 TeV). [6] This can considerably change the trajectory of the particle and thus the position where it hits the detector. So the ability to specify the z-coordinate of the origin of the particle has been added. This will improve the accuracy of the simulation.

4.1.4 Visual elements

Several visual elements are added for better readability of the plots. The ticks along the axis were fixed, which was problematic when zooming in (by lowering the scale). The ability to change the ticks was added to prevent this. Along these ticks gridlines are added, which are especially favoured parallel to the (long) s-axis. This improves the readability of the plot. Lastly, the function is added to draw the projection of the detector on the xs- and ys-plane, once the dimensions of the detector is imported.

4.1.5 Backward beam

In the end the biggest and most intrusive modification has been made. If one would import particle data from a Monte Carlo generator, there will be a small asymmetry between forward - and backward beam. Also the magnets at either side can be different. In order to visualize both sides simultaneously, the backward beamline has been added. This proved to be challenging, since the whole architecture of the code was designed to calculate the particle tracks from the left (IP) to the right (terminal plane). There are two ways to realize the visualization of both beamlines. However first note that there are two layers in this program:

- Internally there is data on the position of particle trajectories and beamline elements. From the initial position of the particle calculations are made along the beamline to determine the full track. Recall that this calculation is always done from left to right.

- This data is afterwards converted to visual data. It specifies at which position (of your screen) the particle track or magnet must be drawn.

The two methods available to visualize the backward arm are thus as follows:

Either

> keep the calculation for both forward- and backward arm from left to right. Thus the s-coordinate of the particles and magnets are positive. The two beamlines are independent of each other: forward particles are influenced only by the magnets in the forward direction and vice versa. During the draw phase the s- and x-coordinate of the visuals are reflected.

Or

> reverse the calculation process for the backward particles so that their s-coordinates are (depending on offset, mostly) negative. Then these coordinates can be used by the visual functions as is.

Both introduce problems of their own. There was not sufficient time left to complete either method. The final result is shown in fig. 4. These results were also presented in an internal Forward Proton Combined Performance meeting [11].

4.2 Outlook

As all good thing must come to an end, there are tasks available for further development. Some of the following objectives were added during the project.

1. Finalize two beamlines:
   As the two beamlines are visualized, it still has bugs. As mentioned above, two methods were tried, but none of them are finalized. It is left for the next developer to choose the optimal solution.

2. Introduce solenoid magnet:
   In the ATLAS central detector there is the solenoid magnet. This magnet is part of the inner tracking and its field strength is 2 T. This can considerably affect the scattered proton tracks. This magnet should be added to the beam element list.

3. Move from qmake to CMake:
   It seemed worthwhile to develop EasyTracker in Qt ten years ago, but according to experts in the computational field at CERN it is safer for the long term to switch to CMake. This will require considerable amount of work to convert the code, because the code uses several Qt packages.

4. Import HepMC files:
   The HepMC format was studied, but there was insufficient time left to include a function to import HepMC files. The TWISS files import function can be used as a reference.

5. Export ROOT files and visualization in ROOT (3D tracks, histograms):

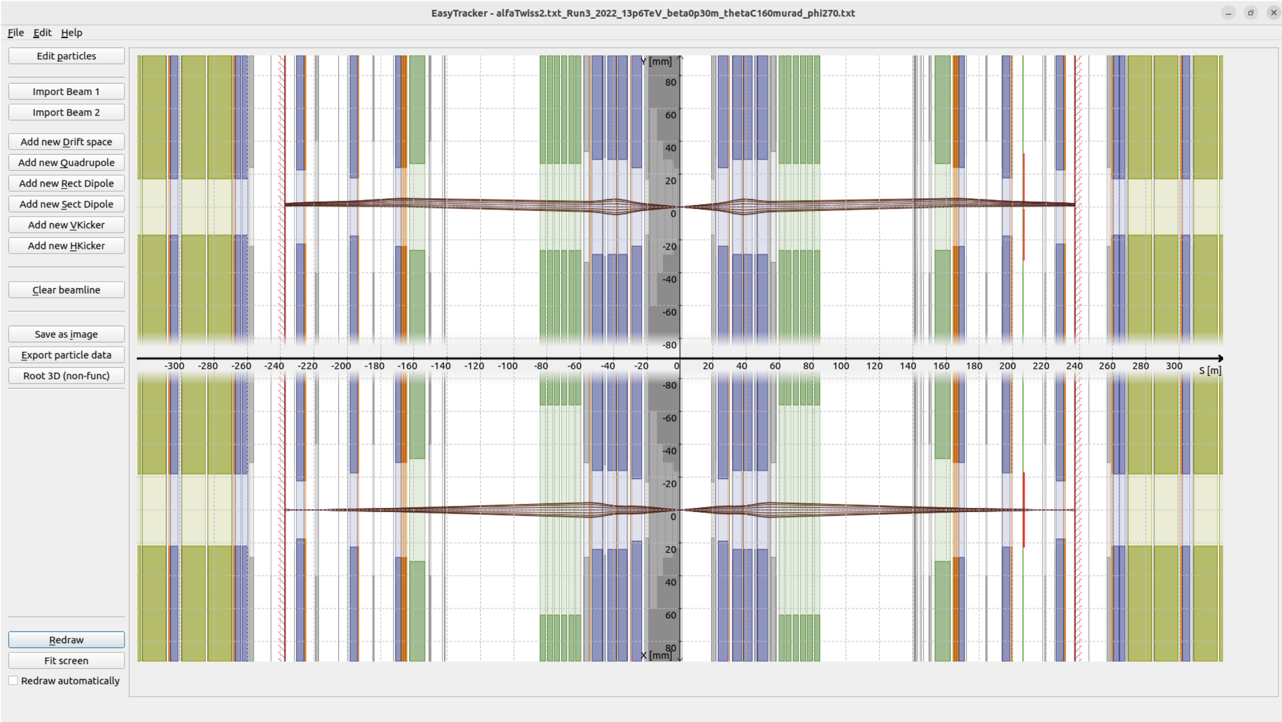

Figure 4: Modified EasyTracker

This item is related to the item concerning CMake. In the past there was an ability to combine ROOT with Qt. There is code demonstrating this. [2] [3] Several attemps have been made to marry this code with EasyTracker, without success. The advise was to compile the code with CMake and implement ROOT there.

6. Additional user-interface methods:

   Some extra functionalities would make the interface more user friendly. One of them is to be able to zoom in the plot using the mouse wheel. The other is to click-and-drag the beam elements with the mouse.

Acknowledgement

First of all, I would like to thank my daily supervisor Tomas Sykora. It was a pleasant collaboration and he always was available for questions. His knowledge and network always pointed in the right direction. Furthermore I would like to thank the following people for providing much needed answers and explanations: Andrea Dell'Acqua, Riccardo M. Bianchi, Riccardo De Maria, Fernando H. Gonzalez, Jonas Hahnfeld, Jorg Wenninger and Attila Krasznahorkay. The summerstudent program was not possible without its coordinators: Barbara Binder, Caroline Debetaz and Ana Drodevic. Much thanks to them. Then I would like to thank all the speakers for the insight in their field of expertise during the lectures. Lastly, I would like to thank CERN in general for the opportunity to come, learn

and enjoy here in Geneva; life-long memories given to students every year.

References

[1] CERN website, Buckets and Bunches https://www.lhc-closer.es/taking_a_closer_look_at_lhc/0.buckets_and_bunches.

[2] https://gitlab.cern.ch/escalade/standalone/qtcanvas.

[3] https://github.com/micahfolsom/qtcanvas.

[4] LHC proton and lead record energy, 2022. https://home.cern/news/news/experiments/first-lead-ion-collisions-lhc-record-energy.

[5] Qt creator, open-source development tools. https://www.qt.io/product/development-tools https://www.qt.io/download-open-source.

[6] Characterization of Interaction-Point Beam Parameters Using the pp Event-Vertex Distribution Reconstructed in the ATLAS Detector at the LHC. Technical report, CERN, Geneva, 2010. https://cds.cern.ch/record/1277659.

[7] Kicker systems - part 1 - introduction and hardware. 2017. https://cas.web.cern.ch/sites/default/files/lectures/erice-2017/barnesi.pdf.

[8] E; Brandt A; Bruschi M; Grinstein S; Lange J; Rijssenbeek M; Sicho P; Staszewski R; Sykora T; Trzebiński M; Chwastowski J; Korcyl K Adamczyk, L; Banaś. Technical Design Report for the ATLAS Forward Proton Detector. Technical report, CERN, ATLAS AFP, 2015. https://cds.cern.ch/record/2017378/.

[9] ATLAS Collaboration. ATLAS Forward Detectors. https://cds.cern.ch/record/2627582, 2018.

[10] Matt Dobbs and Jorgen Beck Hansen. The HepMC C++ Monte Carlo event record for High Energy Physics. Comput. Phys. Commun., 134:41–46, 2001.

[11] Matyas Draskovits and Andrej Sarnatskiy. Instantons and ALFA & AFP. 11 August 2023.

[12] Stephane Fartoukh et al. LHC Configuration and Operational Scenario for Run 3. Technical report, CERN, Geneva, 2021. https://cds.cern.ch/record/2790409.

[13] Tomáš KOMÁREK. Visualization of particle tracks in an accelerator magnetic field, 2013. https://theses.cz/id/ikzo0d/Bp_Komarek.pdf.

[14] Rafal Staszewski Tomás Sýkora Maciej Trzebinksi Peter Bussey, Ladislav Chytka. LHC and ATLAS Coordinate Conventions. internal note, 2 September 2013.

[15] P (Hamburg U.) Rossbach, J (DESY); Schmüser. Basic course on accelerator optics. CAS - CERN Accelerator School : 5th General Accelerator Physics Course, 1993. https://cds.cern.ch/record/247501.

[16] S. Karppinen J. Knaster P. Lepeule G. Schneider R. Veness. Design of beampipes for LHC experiments, 2003. https://cds.cern.ch/record/631307.