INTEGRATION OF THE TRACK BEAM DYNAMICS MODEL TO DECREASE LINAC TUNING TIMES

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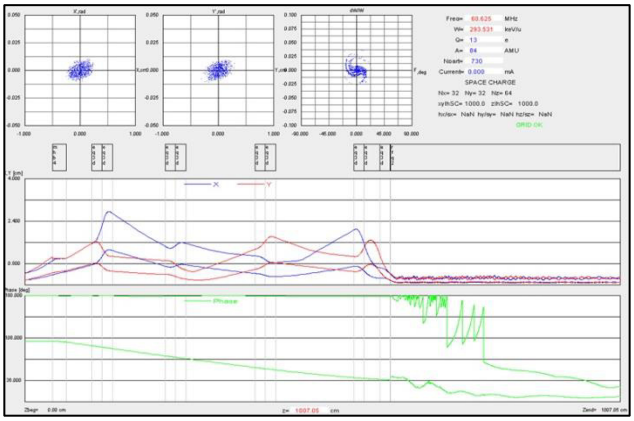
Abstract

The Accelerator R&D Group within the Argonne National Laboratory (ANL) Physics Division maintains a beam dynamics model named TRACK. This simulation code has the potential to assist operators in visualizing key performance parameters of the Argonne Tandem Linear Accelerating System (ATLAS). By having real-time access to visual and animated models of the particle beam transverse and longitudinal phase spaces, operators can more quickly iterate to a final machine tune. However, this effort requires a seamless integration into the control system, both to extract initial run-time information from the accelerator, and to present the simulation results back to the users. This paper presents efforts to pre-process, batch execute, and visualize TRACK particle beam physics simulations in real-time via the ATLAS Control System.

INTRODUCTION TO ATLAS AND TRACK

The ATLAS accelerator is located at the United States Department of Energy's Argonne National Laboratory in the suburbs of Chicago, Illinois. It is a National User Facility capable of delivering ions from hydrogen to uranium for low energy nuclear physics research in order to perform analysis of the properties of the nucleus. As a result of the wide variation of beams delivered [1], re_ tuning of the entire machine is necessary on a near weekly basis. After a series of upgrades, ATLAS will consist of two possible source lines, a common injection and beam transport line, and 8 different target areas. This wide range of possible machine configurations combined with the thousands of individual devices which support them present a very real challenge to operators to arrive at a final tune quickly.

The TRACK beam simulation program developed at ANL-PHY is available and has been validated during the design of upgrade projects at ATLAS [2]. This code can perform individual particle simulations of a beam traveling through various types of optical and RF fields in order to predict final emittance and beam shape. The resultant plots show an animation in time of beam emittance ellipses, and an overall plot of beam size vs. distance. It should be possible to link the TRACK simulation code to the real-time running parameters of ATLAS in order to give the operators a detailed overview of the tune process. This effort requires that the program be integrated into the control system in a seamless way so that non-PhD personnel can operate and understand the behavior of the machine. The TRACK program's graphical user interface (GUI) only runs in Windows (Figure 1) while the control system is primarily developed using Vista Control Systems, Inc.'s Vsystem [3].



Freq= 60.625 MHz
W= 293.531 keV/u
Q= 13 e
A= 84 AMU
Npart= 730
Current= 0.000 mA
SPACE CHARGE
Nx= 32 Ny= 32 Nz= 64
xylhSC= 1000.0 zlhSC= 1000.0
hx/sx= NaN hy/sy= NaN hz/sz= NaN
GRID OK

Zbegin= 0.00 cm z= 1007.05 cm Zend= 1007.05 cm

Figure 1: Existing TRACK GUI and Simulation.

USER INTERFACE & CONFIGURATIONS

In order to fully realize the potential of fast, real-time iterations on tuning time, the interface to TRACK must operate very similarly to the existing control system. Therefore, brand new interface windows were designed using native control system libraries (Figure 2). One important difference between the TRACK application GUI and the control system GUI is the presence of 'configuration' buttons. These are pre-selected input conditions, source/target line selections, and graph views which can be executed more quickly than re-running a full simulation for the entire machine.

Figures 3 and 4 represent a full TRACK simulation from current device settings by the operator. Note the black boxes which indicate corresponding quadrupole devices. By using the same interface as normal, operators can move sliders and immediately see the resultant simulation update.

USE CASES OF TRACK AT ATLAS

There are two main ways in which a pre-processed simulation of the beam could be useful to operators. The first is by importing the real-time settings of each device in the current beamline to give operators an overview of the performance of the machine. The second is by utilizing a database of previous runs to predict which machine configurations have been successful in the past. This second method will be useful before the start of a new experiment to predict future good tunes.

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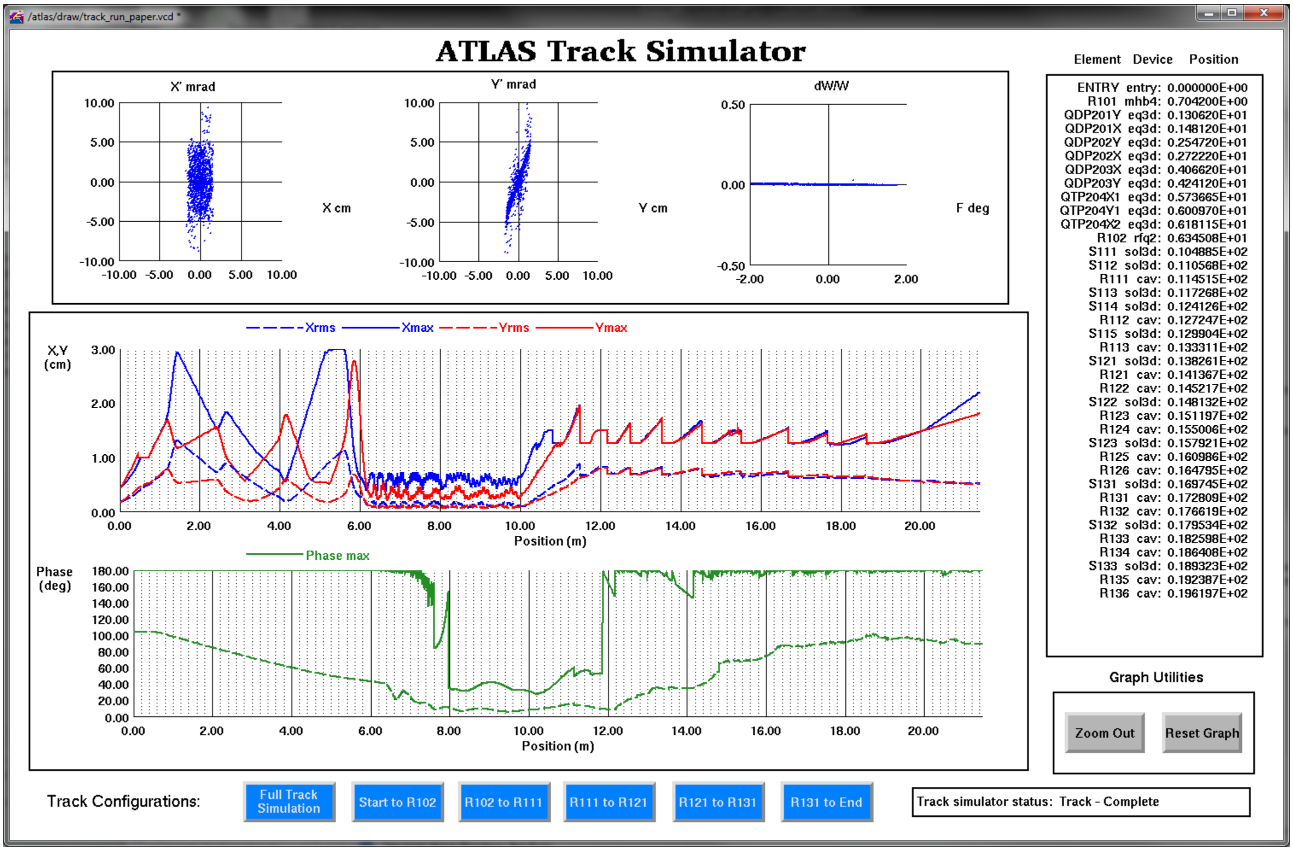
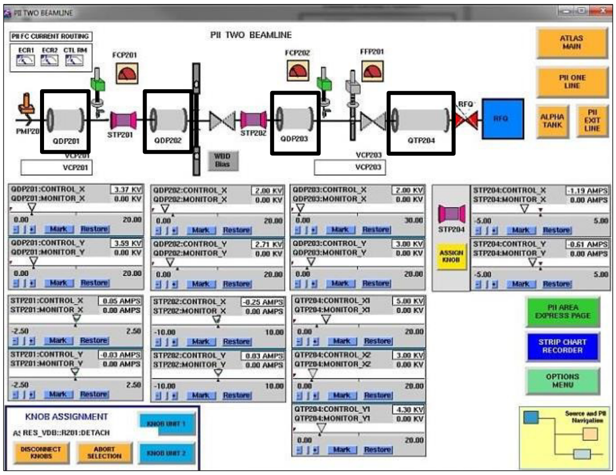


Element Device Position

```
  ENTRY  entry: 0.000000E+00
   R101  mhb4: 0.704200E+00
QDP201Y  eq3d: 0.130620E+01
QDP201X  eq3d: 0.148120E+01
QDP202Y  eq3d: 0.254720E+01
QDP202X  eq3d: 0.272220E+01
QDP203X  eq3d: 0.406620E+01
QDP203Y  eq3d: 0.424120E+01
QTP204X1 eq3d: 0.573665E+01
QTP204Y1 eq3d: 0.600970E+01
QTP204X2 eq3d: 0.618115E+01
   R102  rfq2: 0.634508E+01
   S111 sol3d: 0.104885E+02
   S112 sol3d: 0.110568E+02
   R111   cav: 0.114515E+02
   S113 sol3d: 0.117268E+02
   S114 sol3d: 0.124126E+02
   R112   cav: 0.127247E+02
   S115 sol3d: 0.129904E+02
   R113   cav: 0.133311E+02
   S121 sol3d: 0.138261E+02
   R121   cav: 0.141367E+02
   R122   cav: 0.145217E+02
   S122 sol3d: 0.148132E+02
   R123   cav: 0.151197E+02
   R124   cav: 0.155006E+02
   S123 sol3d: 0.157921E+02
   R125   cav: 0.160986E+02
   R126   cav: 0.164795E+02
   S131 sol3d: 0.169745E+02
   R131   cav: 0.172809E+02
   R132   cav: 0.176619E+02
   S132 sol3d: 0.179534E+02
   R133   cav: 0.182598E+02
   R134   cav: 0.186408E+02
   S133 sol3d: 0.189323E+02
   R135   cav: 0.192387E+02
   R136   cav: 0.196197E+02
```

Track simulator status: Track - Complete

Figure 2: Control System TRACK GUI: (top) animated emittance plots; (middle) red and blue lines show the transverse X/Y size of the beam; (bottom) maximum and mean longitudinal phase plots.



QDP201:CONTROL_X 3.37 KV
QDP201:MONITOR_X 0.00 KV
0.00 20.00

QDP201:CONTROL_Y 3.59 KV
QDP201:MONITOR_Y 0.00 KV
0.00 20.00

STP201:CONTROL_X 0.05 AMPS
STP201:MONITOR_X 0.00 AMPS
-2.50 2.50

STP201:CONTROL_Y -0.03 AMPS
STP201:MONITOR_Y 0.00 AMPS
-2.50 2.50

QDP202:CONTROL_X 2.00 KV
QDP202:MONITOR_X 0.00 KV
0.00 20.00

QDP202:CONTROL_Y 2.71 KV
QDP202:MONITOR_Y 0.00 KV
0.00 20.00

STP202:CONTROL_X -0.25 AMPS
STP202:MONITOR_X 0.00 AMPS
-10.00 10.00

STP202:CONTROL_Y 0.03 AMPS
STP202:MONITOR_Y 0.00 AMPS
-10.00 10.00

QDP203:CONTROL_X 2.00 KV
QDP203:MONITOR_X 0.00 KV
0.00 30.00

QDP203:CONTROL_Y 3.00 KV
QDP203:MONITOR_Y 0.00 KV
0.00 20.00

QTP204:CONTROL_X1 5.00 KV
QTP204:MONITOR_X1 0.00 KV
0.00 20.00

QTP204:CONTROL_X2 3.00 KV
QTP204:MONITOR_X2 0.00 KV
0.00 20.00

QTP204:CONTROL_Y1 4.30 KV
QTP204:MONITOR_Y1 0.00 KV
0.00 20.00

STP204:CONTROL_X -1.19 AMPS
STP204:MONITOR_X 0.00 AMPS
-5.00 5.00

STP204:CONTROL_Y -0.61 AMPS
STP204:MONITOR_Y 0.00 AMPS
-5.00 5.00

KNOB ASSIGNMENT
A: RES_VDB::R201:DETACH

Figure 3: Simulating four quadrupole adjustments via the standard control system interface.

Simulation of Current Real-time Settings

The first integration of a beam dynamics model into the control system provides operators with a full overview of the running experiment's beam quality. In order to simulate the current experiment, device settings are extracted from the running control system and scaled according to scaling parameters stored in the real-time database, specific to each device. These scaled values are then written, along with previously stored constants like device length and radius, to specially crafted input files.

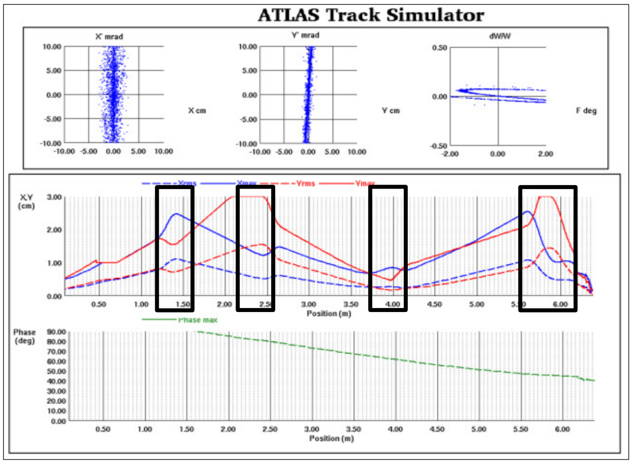


Figure 4: The four sets of brackets show the simulation results after adjusting the quadrupoles.

These input files are fed to TRACK and the resultant view of the simulation is displayed.

Simulation of Previously Archived Settings

The ATLAS Control System maintains a database of run parameters for all previous tunes [4] which runs continuously and archives relevant parameters every four hours or whenever triggered manually. This second simulation method has been implemented by utilizing a duplicate, offline version of the control system databases.

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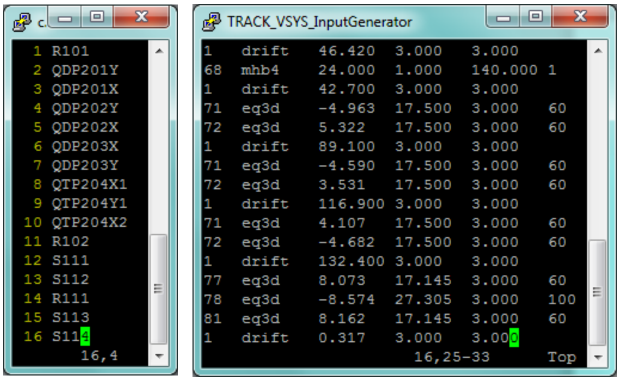
The historical run parameters are extracted from a SQL database and loaded into a staging SQL database on the real-time control system backup machine. Then the standard "Preload Machine" functionality is used to load all the previous parameters onto the backup machine real-time databases for simulation.

PROGRAM DEVELOPMENT AND FLOW

In order to extract real-time parameters, a series of new methods and programs were developed. The first program named TRACK_VSYS_InputGenerator extracts and formats an ordered device name list from an existing relational database. Depending on which source and target lines are currently selected in the control system, the program executes a series of SQL unions and sorts in order to automatically select each device which is currently in use. Next the program reads this ordered list, and for each device extracts the current set points and scales the control value to a corresponding electrical or magnetic RF field value (Figure 5). It then writes the scaled value to a specially crafted output file containing values and formats used by TRACK.



```
 1 R101
 2 QDP201Y
 3 QDP201X
 4 QDP202Y
 5 QDP202X
 6 QDP203X
 7 QDP203Y
 8 QTP204X1
 9 QTP204Y1
10 QTP204X2
11 R102
12 S111
13 S112
14 R111
15 S113
16 S114
       16,4
```

```
1    drift    46.420   3.000    3.000
68   mhb4     24.000   1.000    140.000 1
1    drift    42.700   3.000    3.000
71   eq3d     -4.963   17.500   3.000    60
72   eq3d     5.322    17.500   3.000    60
1    drift    89.100   3.000    3.000
71   eq3d     -4.590   17.500   3.000    60
72   eq3d     3.531    17.500   3.000    60
1    drift    116.900  3.000    3.000
71   eq3d     4.107    17.500   3.000    60
72   eq3d     -4.682   17.500   3.000    60
1    drift    132.400  3.000    3.000
77   eq3d     8.073    17.145   3.000    60
78   eq3d     -8.574   27.305   3.000    100
81   eq3d     8.162    17.145   3.000    60
1    drift    0.317    3.000    3.000
                         16,25-33       Top
```

Figure 5: Example of automatically generated device list (left) and associated TRACK input file containing device parameters like radius, length, and field strength (right).

The scaling factors are stored within each database and are used to scale a control system variable, e.g. '0 – 10 volts' into a representative field value, e.g. '0 - 2.6 MV/m'. These scalers are either determined from manuals or empirically using equipment like a gauss meter. These scaler values, combined with assumed initial conditions, represent critical factors which influence the accuracy of the overall simulation.

Upon completion of the TRACK simulation, the results are in the form of a large set of text files, which defines the beam state after each device. This file is then parsed by a new program called TRACK_VSYS_Graph, which reads the data and automatically uploads it into the control system for input into the new GUI system.

EFFECT OF INITIAL CONDITIONS

TRACK uses, as part of its input files, a set of parameters which define the starting normalized emittance of the beam. There are two proposed methods to determine these initial conditions, only one of which is currently in use. The R&D group has developed a PepperPot emittance measurement program [5] written in LabVIEW [6], which can take 'snapshots' of the beam projected onto a phosphorescent plate through small holes arranged in a grid layout. The program then automatically calculates the 'Twiss' parameters [7] associated with the beam. A second method is to use a beam profile monitor (BPM) and quadrupole combination. By varying the quadrupole field and monitoring the BPM, Twiss parameters can be determined [8]. One result of this work is the ability to test the level of influence beam emittance has on the tune parameters. By varying the initial conditions, it is possible to quickly determine exactly which devices are critical to achieve proper optics (Figure 6).

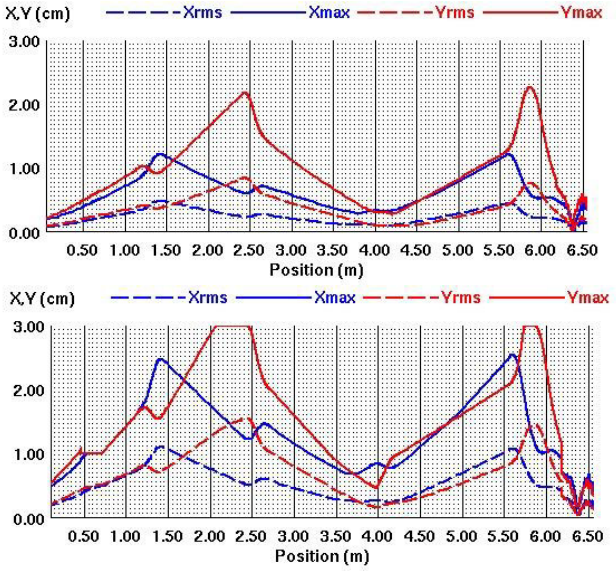


Figure 6: Effect (top to bottom) of changing only initial beam emittance parameters and keeping devices constant.

RUN TIME AND ITERATIONS

The TRACK program can be configured to perform a simulation of the entire defined beam path, or to continue from a pre-configured saved state from a previously run simulation. This 'continue' option can save a large amount of time if the user is only interested in one section of the beam path. These 'continue' options are saved as defined configurations within the buttons at the bottom of the TRACK simulation page (Figure 2). If the user pushes one of the partial beam path buttons, iterations of the tune become very rapid between changing a device set point and seeing the results on the screen.

INTERPRETATION OF RESULT PLOTS

Table 1 summarizes the execution time of the current single-threaded server setup, which is not yet optimized for a dedicated simulation machine. Note the decrease in execution time between a full simulation, and a pre-configured partial section of the beam line.

Table 1: Comparison of Full/Partial Execution Time

Program and Action	Time
Extract path info and create Device List	1.0 sec
Generate TRACK input files for devices	6.1 sec
Full Execution of injection line and linac	200 sec
Partial Execution of injection line only	11 sec
Plot & animate results on User Interface	10 sec

The graphs in Figure 7 represent one possible example of an A-B comparison example between beam shapes. In general, the top plot has more variations in beam focus and size, and also hits the beam pipe starting at the 4 meter mark. In comparison, the bottom plot has smoother trends using less focusing, and hits the pipe much less. The TRACK simulation predicts 100% transmission for the bottom plot, while the top plot loses beam at the pipe.

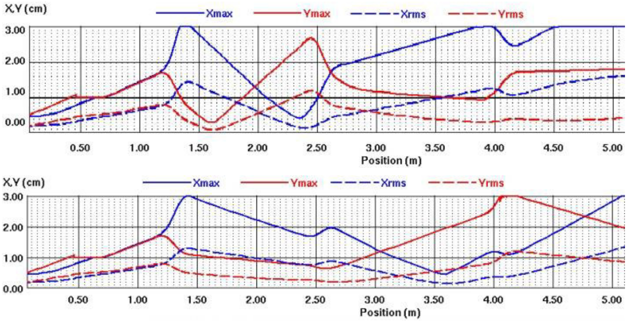


Figure 7: Comparison of good (top) & better (bottom) tunes. Note the bottom plot hits the beam pipe less.

RESULTS AND VALIDATIONS

This program is still in the early stages, and only a few beam line tunes have been simulated in advance of the actual experiment start date. The first time the plots were used, it was shown that operators had over focused the beam in several areas. By decreasing quadrupoles in key areas as suggested by the simulation, beam current immediately increased by ~5%.

Another area of validation of the TRACK simulation against machine performance is in the area of longitudinal beam size during runs with ions with relatively low mass/charge ratios. Beam transmission has historically been poor in these cases, and the simulation shows the potential for over-bunching of the beam. This is due to the configuration of the first buncher having a minimum amplitude level which is greater than the required field to bunch light ions (Figure 8).

FUTURE WORK

One of the greatest areas for improvement in iteration time is on the server which currently runs the applications. The current version runs on a standard desktop PC which is not dedicated to running simulations. A separate multi-core server with additional RAM has been ordered to speed up the simulation times.

There are several other applications going forward where this type of overall simulation can be useful. Pre-processing historical tunes would provide a catalogue of tunes which can be re-used. Operators could scroll through plots of beam sizes and determine which tunes could work for a future run. Additionally, automatic iteration of sequential simulations in order to converge on a full tune could be provided in advance of the tune day.

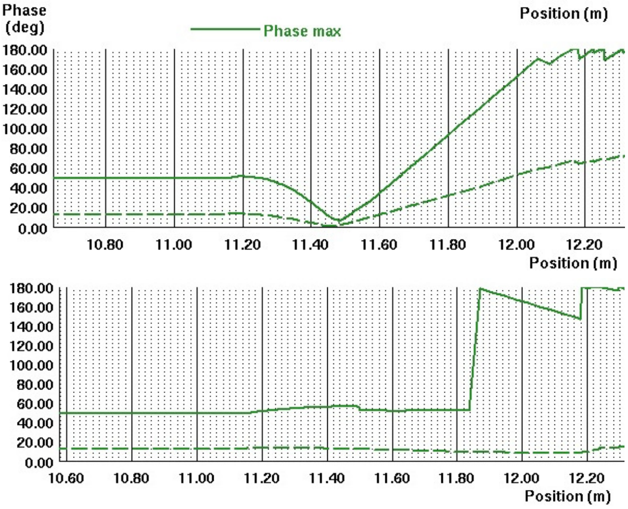


Figure 8: Top: over bunching of a 'light' beam as a result of required minimum field to run the buncher. Bottom: simulated beam at ideal 1/3 maximum amplitude.

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