

DEVELOPMENT OF THE ACCSIM TRACKING AND SIMULATION CODE

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Abstract

Accsim is a synchrotron/storage-ring tracking and simulation program that was originally written to simulate charge-exchange injection and accumulation of an intense proton beam in a KAON factory accumulator ring. It has subsequently been developed and used for other injection studies and for applications such as the optimization of collimation systems. The code performs basic six-dimensional tracking of an ensemble of particles in a magnet lattice and incorporates models for various processes such as multiturn injection, phase-space painting, RF capture, space-charge effects, interactions with stripping foils and collimators, and tabulation of particle losses and beam form factors. After a brief review of Accsim's architecture and basic design, this paper gives an update on the current status of the code and describes the more recent additions that have been made.

1 OVERVIEW

Fast tracking For Accsim's role in finding optimal injection and accumulation schemes, perhaps with many design iterations for the ring lattice and injection system, an efficient and fully symplectic particle tracking method is of paramount concern. The initial requirement was for runs with up to 10^4 particles and $2 \cdot 10^4$ turns, and subsequently the particle capacity was raised to 10^5 in order to get sufficiently good statistics in the early stages of accumulation.

The basic transport mechanism uses first-order transfer matrices, possibly spanning many magnetic elements, punctuated by kicks representing thin lenses (up to octupole order), rf cavities, space charge effects, injection foil scattering, etc. The working coordinates $(x, x', y, y', \phi, \Delta E)$ are used, where ϕ is rf phase and ΔE is the energy difference from the synchronous energy. To achieve correct longitudinal tracking, the rf phase transport incorporates the path-length terms from the matrix formalism plus an additional term to account for particle velocity.

Utilization of DIMAD At the inception it was recognized that development time could be saved by using the lattice-design program DIMAD as a pre-processor for the ring to be studied. Usually a DIMAD-format input file for the lattice would already be available (or could be converted from a MAD file), and it was a matter of running DIMAD and then cutting the relevant matrix coefficients and optical parameters from the DIMAD output and pasting them into the Accsim input file. Later, this procedure was automated via a routine in Accsim that scans the DIMAD output and extracts all the necessary quantities. Although Accsim has grown in generality and in features, this dependence on DIMAD has been retained because it brings many benefits. It allows Accsim to concentrate on tracking and simulation

and omit the considerable machinery needed for processing lattice definition files, calculating matrix terms and optical functions, fitting of element strengths, etc.

Injection foil Multiturn charge-exchange injection may lead to emittance growth due to multiple scattering during repeated traversals of the injection foil. The program provides a number of features for studying injection scenarios that reduce foil traversals by using "corner" or "postage-stamp" foils, collapsing orbit bumps, linear coupling etc. During tracking, each particle traversing the foil undergoes an energy loss sampled from a pre-calculated Landau distribution. Coulomb scattering in the foil can be simulated using an iterated single-scatter model or a faster one-shot method using a plural scattering distribution. To simulate thick foils or internal targets a Molière scattering routine is also available.

Space charge Longitudinal space charge effects are accounted for in the usual way by binning particles to obtain the line density, optionally applying smoothing, deriving the space-charge potential per turn, and applying the appropriate energy kick, pro-rated by the fraction of a turn travelled, to each particle. This procedure is performed whenever the program encounters the LSC pseudo-element. These elements are usually placed at the rf locations and can be added at intermediate locations as well if accuracy requires. A transverse space charge package was developed for Accsim by H. Schönauer. It bins particles in "amplitude space" (ε_x vs ε_y) and for each bin derives a rectangular charge density distribution based on the x - y Lissajous motion of particles averaged over all relative betatron phases. The contributions to the space-charge potential are summed and least-squares fitting of a multipole expansion yields the coefficients needed to calculate the tune shifts for individual particles. These tune shifts are (optionally) applied to each particle by rotating it in phase space. By default this is done once per turn, but recently a TSC pseudo-element has been added to enable the calculation to be done once per lattice period.

Painting A major aspect of Accsim injection studies has been phase-space painting, whereby the desired final beam distributions are arrived at via mechanisms like collapsing orbit bumps, injection steering, injection energy ramping, or even guide-field ramping. Program options are available for simulating any or all of these, using time-vs-value arrays for the parameters to be varied. Realistic orbit bumps can be set up using programmed thin dipole elements.

Built-ins Accsim provides built-in graphics, with X11 and PostScript support, for producing rapid scatterplots of phase space and real space. There are also commands for calculating RMS, 95% and 99% emittances, producing loss-mode summaries, estimating foil heating, tabulating

losses on apertures, and determining the extent and population of beam halos. For external graphics and analysis, Accsim has a plethora of diagnostic and logging options that allow virtually all of its data to be output at various intervals and ring locations as dictated by the user. On the large-scale output streams there is a binary-format option to reduce the data volume and processing time.

Development The above describes the basic machinery of Accsim. In the process of being used for many applications with differing requirements, the code has undergone a long series of ad-hoc modifications to implement an ever-growing list of features, a number of which will be reviewed in the following sections.

2 COLLIMATORS

The issue of controlling particle losses during accumulation of an intense beam prompted the development of Accsim’s COLLIMATOR elements, which simulate the interaction of protons with blocks of material of specified length, position and orientation, and can be placed in appropriate drift spaces in the ring. The collimator routine performs the necessary ray-tracing in the drift region to determine hits on the absorber blocks and does detailed tracing of proton trajectories in the blocks, with treatments of multiple scattering, energy loss, and nuclear interactions.

Tracking in the block material uses a fixed, user-settable step size, over which the energy loss (from a Landau or Gaussian distribution) and multiple scattering angle (from a Molière distribution) are calculated. For each material, a net mean free path for nuclear interactions is derived from the elastic and inelastic cross sections, and sampled interaction lengths are generated from this. Elastic scattering events result in an angular deflection sampled from a forward diffraction peak. Inelastic interactions are considered simply to be “absorption” events: the proton is removed from tracking and no attempt is made to account for secondary particles produced.

The fixed tracking step size entails a small “quantization error” in the geometry, but it has significant advantages: (1) ray-tracing is much faster because exact boundary-crossing points do not have to be calculated, (2) numerical problems at boundaries are avoided (3) it guarantees that energy loss and multiple scattering calculations always have valid step sizes. Efficiency is also gained by using small-angle approximations wherever appropriate.

In general, the intention is not to provide an exhaustive simulation (better left to codes like GEANT) but rather to provide timely estimates of collimator performance and of downstream losses due to outscattering (particles hitting shallow on an absorber block and scattering back into the vacuum chamber).

Later additions to the collimator element included: circular-contoured entrance faces (helpful in reducing outscattering), arbitrary rotation angles of the blocks around the longitudinal axis, and tracking through a uniform magnetic field in the material (a possible technique

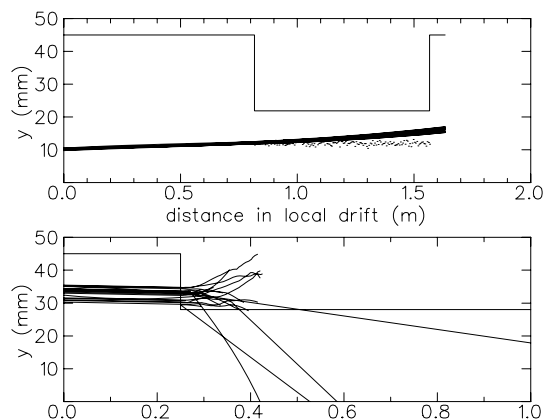


Figure 1: Proton trajectories from Accsim tracking in septum/absorber collimation system

for reducing outscattering by bending particles toward the interior of the absorber block).

3 MINI-WIRE SEPTUM

For efficient loss management in intense-beam scenarios, H. Schönauer[2] has proposed the use of a septum with very fine wires ($\sim 0.05\text{mm}$) to deflect candidate particles to higher emittances (possibly with repeated traversals of the septum) so that they can be efficiently collected by a downstream absorber. We implemented a SEPTUM element in Accsim which tracks particles through the septum field, taking into account the curvature of the fine wires due to the field, the resultant wire position errors, and multiple scattering due to collisions with the wires. Accsim runs showed that such a septum/collector system could provide cleaner loss collection than a two-stage massive collimator system.

4 ACCELERATION

The treatment of acceleration in the program is at present intended primarily to model a synchrotron’s injection and early acceleration phase, rather than to accurately follow a particle ensemble through a whole acceleration cycle. Since the transport matrix formalism represents a steady-state solution and does not admit of time-variation of fields, acceleration is simulated by updating the synchronous energy and synchronous phase on a turn-by-turn basis. To maintain synchronism and avoid artificial growth, the rf phase coordinate of each particle must also be changed by an amount equal to the increment in synchronous phase.

There are various options for specifying the guide field and rf programs including, most recently, a “machine program file” which consists of a free-format table with arbitrarily-spaced time values and parameter values chosen from the list: $(B, dB/dt), V_{rf}, \phi_s, K_d, K_q$. (The last two parameters are field strengths for optional thin dipoles and quads that can be used to produce programmed orbit bumps and programmed tunes.) By means of a variable “start time” input parameter, both the falling and rising portions of the magnet cycle can be reproduced, allowing injection to start during the falling portion if desired.

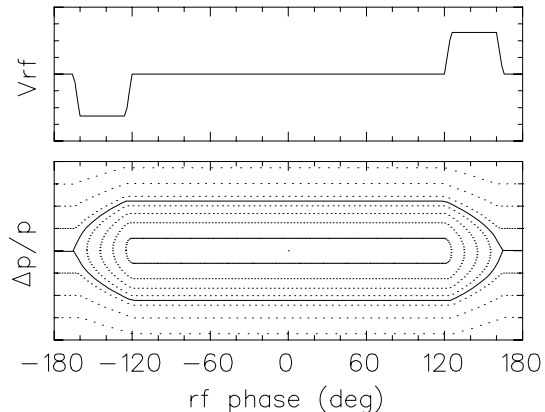


Figure 2: Barrier bucket rf waveform and longitudinal phase space trajectories

Accsim can also simulate guide-field ramping with the rf off, in which case energy and positional kicks are applied to the particles to reflect the changes in the reference energy and off-momentum orbits. This can be used to simulate H^- injection scenarios where this ramping is exploited for phase-space painting and also for carrying the injected particles on spiral trajectories away from the stripping foil.

5 BARRIER BUCKET

The use of a pulsed rf waveform, with short pulses at or near $\pm\pi$, defines a so-called barrier bucket, where particles in the bucket follow coasting trajectories except near the ends where they are bent around and reverse their direction of travel in longitudinal phase space. The resulting bunches have a line density profile that is mostly flat, and hence the longitudinal space charge forces, and the modulation of transverse space charge forces by the local charge density, are very small except near the ends of the bunch.

Features were added to Accsim in order to generate barrier-bucket rf waveforms using either trapezoidal or sinusoidal pulses, with parameters for pulse positioning, height and width, and rise and fall time.

6 MOMENTUM ANALYSIS

In the performance of phase-space rotations (for chromatic and space-charge tune shifts) and emittance calculations (for printing or transverse space-charge binning), Accsim must determine the phase-space ellipse for each particle. Formerly, this was done using the optical functions α , β , η read from DIMAD, which are valid for the linear lattice but may be inadequate if thin lenses have been added in Accsim and there is significant momentum spread. In particular, an accurate closed orbit is needed to avoid accumulation of errors during phase-space rotations.

Routines were written to perform a momentum analysis based on a nominal momentum deviation δ input by the user. A test particle is tracked through the Accsim lattice (DIMAD matrices + thin lenses) for five turns, and from the results a system of linear equations are derived that can be solved for the closed orbit, ellipse parameters, and tunes.

$\Delta p/p$	x_{co}	x'_{co}	α_x	β_x	Q_x
-0.0100	0.680	-0.144	2.191	10.452	6.749
-0.0050	0.320	-0.068	2.143	10.229	6.785
0.0000	0.000	0.000	2.103	10.043	6.821
0.0050	-0.275	0.058	2.069	9.884	6.857
0.0100	-0.502	0.106	2.041	9.758	6.893
Error in quadratic					
-0.0050	0.002	0.000	-0.001	-0.003	0.000
0.0050	-0.002	0.000	0.000	-0.001	0.000

Table 1: Example of Accsim momentum analysis for a synchrotron lattice with added thin-lens sextupoles (co = closed orbit; y results omitted for brevity)

This is done for momenta $-\delta$, 0 , $+\delta$ and for each parameter a quadratic is run through the three data points, thus giving a parameterization of the optics as a function of particle momentum. To check the goodness of fit, additional particles are run at $-\delta/2$, $+\delta/2$ and the errors with respect to the quadratics are printed.

7 MISCELLANY

There have been quite a number of other additions to the code that can only be summarized here: input linac distribution with microbunches; parameterized tails on injected distributions; rf harmonics; zoom window and coordinate readout for scatterplots; generalization from protons to arbitrary ion species (except in interactions with matter); PICKUP and DAMPER elements to model transverse damping; VCHAMBER element to simulate interactions with the vacuum chamber wall. Accsim has been ported to all the major UNIX platforms, including (soon) Intel/LINUX. Those interested in obtaining the code should connect to <http://www.triumf.ca/compserv/accsim.html>.

8 FUTURE

As part of a TRIUMF-CERN agreement, Accsim will continue to be developed in support of injection and collimation studies for LHC-era beams in the CERN PS Booster. The program is also being applied to injection simulations in various other design studies such as HIDIF, JHP, and the NSNS[3]. To support these applications, improvements in generality, features, and particularly in space-charge treatments, are being pursued.

9 REFERENCES

- [1] F.W. Jones, G.H. Mackenzie, and H. Schönauer, "ACCSIM – A Program to Simulate the Accumulation of Intense Proton Beams," *14th Int. Conf. on H. E. Accelerators*, Tsukuba, Japan, 1989, in *Particle Accelerators* **31**:199 (1990).
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- [3] A. Luccio, D. Maletic, F.W. Jones, "Proton Injection and RF Capture in the National Spallation Neutron Source," *these proceedings*.