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RECENT DEVELOPMENTS AND FUTURE PLANS FOR SIXTRACK

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Abstract

SixTrack is a symplectic 6D tracking code routinely used to simulate single particle trajectories in high energy circular machines like the LHC and RHIC. The paper presents recent developments and those foreseen for extending the physics models: exact Hamiltonian, different ions and charge states, RF multipoles, non-linear fringe fields, Taylor maps, e-lenses and ion scattering. New functionality like variable number of tracked particles, time dependent strengths, GPU computations with a refactoring of the core structure are also described. The developments will benefit studies of the LHC and SPS, for collimation efficiency, ion operations, failure scenarios and HL-LHC design.

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SixTrack is a symplectic 6D tracking code routinely used to simulate single particle trajectories in high energy circular machines like the LHC and RHIC. The paper presents recent developments and those foreseen for extending the physics models: exact Hamiltonian, different ions and charge states, RF multipoles, non-linear fringe fields, Taylor maps, e-lenses and ion scattering. New functionality like variable number of tracked particles, time dependent strengths, GPU computations with a refactoring of the core structure are also described. The developments will benefit studies of the LHC and SPS, for collimation efficiency, ion operations, failure scenarios and HL-LHC design.

INTRODUCTION

SixTrack is a 6D single particle symplectic tracking code [1, 2] used to compute the trajectories of individual relativistic charged particles in circular accelerators. It has been developed based on the 4D tracking code RaceTrack [3] by adding the longitudinal degree of freedom, introducing beam-beam forces and extending the pre- and post-processing capabilities. It has been developed and maintained until recently by Frank Schimdt at CERN.

SixTrack has been mainly used to help the design of the LHC [4] and it is still used for the nominal machine and its upgrades for dynamic aperture studies, tune optimization, collimation studies and failure scenarios. The code has continued its evolution towards the implementation of new beam line elements, like deflecting RF cavities [5] and [6] to support the HL-LHC studies [7].

The main value of SixTrack is the accumulated experience of a few decades of code development, experimental benchmarks and a tight integration with the LHC magnetic imperfections [8] and collimation system [9] models as well as the computing resources like CERN BATCH cluster and the collaborative computing LHC@home project [10]. SixTrack has also a well controlled floating point arithmetic and remarkable floating point reproducibility among many compilers and architectures [11].

In this paper we would like to present an overview of the recently added functionality and our plans.

EXACT HAMILTONIAN

SixTrack implements linear δ-dependent thick and thin 6D symplectic maps for the main beam line elements: drift, bending magnets, quadrupoles, solenoids and thin elements for generic thin multipoles and RF cavities. All the element maps are derived from the relativistic Hamiltonian $H = p_\sigma - p_s$ defined in terms of the conjugate coordinates pairs:

$$\left(x, p_x = \frac{m\gamma\dot{x} + qA_x}{P_0}\right) \qquad \left(y, p_y = \frac{m\gamma\dot{y} + qA_y}{P_0}\right)$$
$$\left(\sigma = s - \beta_0 ct, p_\sigma = \frac{E - E_0}{\beta_0 P_0 c}\right),$$

where x, y are the accelerator transverse coordinates, s the path length of a planar trajectory with curvature h and $p_s = m\gamma\dot{s}(1 + hx)^2/P_0 + q(1 + hx)A_s/P_0$. The map of the drift and bending magnets are derived by expanding the term:

$$\begin{aligned}\frac{p_s}{1+hx} &= \sqrt{(1+\delta)^2 - (p_x - a_x)^2 - (p_y - a_y)^2} + a_s \\ &\simeq 1 + \delta - \frac{1}{2}\frac{(p_x - a_x)^2}{1+\delta} - \frac{1}{2}\frac{(p_y - a_y)^2}{1+\delta} + a_s,\end{aligned}$$

where $a_{x,y,s} = qA_{x,y,s}/P_0$ and $\delta = P/P_0 - 1$.

The expansion is valid for many applications, which can take advantage of the simplicity of the maps (e.g. linear map for the drift). However there are cases, like the simulation of scattered particles in the collimators or failure scenarios, for which particles have large p_x, p_y or very large p_σ, implying that the neglected terms of the Taylor expansion may become relevant. To restore the accuracy it is sufficient, as long as thin maps are used, to implement the exact formulas for 1) a drift of length L [12]

$$\begin{aligned}&x' = p_x/p_z \qquad y' = p_y/p_z \\ &x \to x + x'L \qquad y \to y + y'L \\ &s \to s + L\sqrt{1 + x'^2 + y'^2} \\ &ct \to ct + L\sqrt{1 + x'^2 + y'^2}/\beta = ct + L/\beta_z \\ &\sigma \to \sigma + L\left(1 - \beta_0/\beta_z\right),\end{aligned}$$

where $p_z = \sqrt{(1+\delta)^2 - p_x^2 - p_y^2}$, and 2) the thin dipole of length L and curvature h [13]:

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$$
\begin{aligned}
&p_x \to \frac{1}{1+h^2L^2}\left[p_x - hL\left(q(1+hx)+\sqrt{p_s^2-C}\right)\right]\\
&\quad x \to x + L(1+hx)x' \qquad y \to y + L(1+hx)y'\\
&\quad \sigma \to \sigma + L - L(1+hx)\beta_0/\beta_z
\end{aligned}
$$

where $C = (hL)^2\left((hL-\delta)(2+\delta+hx)-p_y^2\right) + 2hL(1+hx)p_x$ and the x, y, σ maps depend on the new value of p_x that have to be calculated first.

In the same context it is also possible to extend the coordinates of the particles to include the rest mass, the charge state and the particle number to support the simulation of a variable number of different ion species, which is relevant for ion collimation studies (together with a new implementation of scattering routines). In addition, by using the time-of-flight instead of the path length, one can use the charge state and rest mass to account accurately for the different relativistic beta values that particles with the same beam rigidity might have at low energies.

ADDITIONAL BEAM LINE ELEMENTS

In the framework of the HL-LHC upgrade, new beam lines elements need to be included in the simulation. RF multipoles (a simplified model for generic RF fields on ultra-relativistic beam) and symplectified Taylor maps [14] have been introduced and are being used to study the impact of crab cavity field imperfections on the long term stability. Lower order multipoles are available, but higher order ones will be implemented as required.

A model of non-linear fringe fields is being formulated for an implementation in SixTrack to study the effects on large aperture quadrupoles and dipoles [15].

COLLIMATION CODE DEVELOPMENTS

Sixtrack is also used for tracking a large number of particles over few to hundred turns together with scattering routines ([9] and reference therein). It is used routinely to study particle-collimator interactions in the LHC [16]. Recent developments include new routines to handle different interaction types in bent crystals [17, 18], and an e-lens model that has been implemented as a collimator to study possible improvements of the collimation efficiency. It is also planned to add it as new element [20]. The asynchronous dump process in the LHC has been recently simulated and benchmarked with measurement on induced losses on the collimators [19]. A new element has been added to combine a Fluka simulation of detailed scattering processes in a particular region and multi turn tracking, with, in addition, a general module to simulate turn dependent kicks [21].

RUN ENVIRONMENT

Dynamic aperture studies for the LHC require the tracking over typically 10^5, 10^6, sometimes 10^7 turns of several thousands particles. The SixDesk [22] run environment prepares LHC input files to be dispatched as jobs to the LSF CERN computer cluster or the LHC@home [10] volunteering computer platform for simulations. Several thousands of CPU are normally required to complete a study within days resulting in 10^3 to 10^5 of small flat files hosted in the shared AFS file system. The present infrastructure is facing severe limitations in managing large amount of results, in particular due to the computational resources that the LHC@home platform has made available. A new infrastructure using local SQLite database and a centralized MySQL server is being put in place to speed up the post-processing and the development time. First results already show several orders of magnitude of speed improvement for cases with more than 1M initial conditions (see Fig. 1).

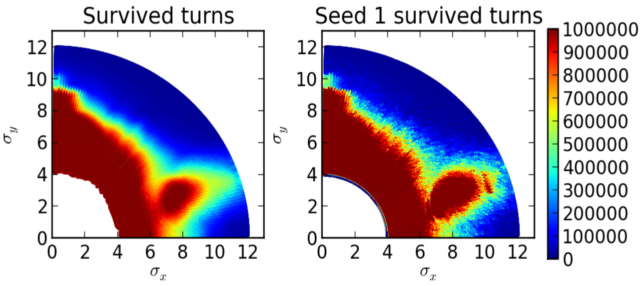

Figure 1: Survival plot in the transverse action plane for $1.2 \cdot 10^6$ particles tracked for 10^6 turns in the LHC. A smoothing over 10 amplitudes (right) or over 60 seeds (left) highlights the lifetime figures of single particles as a function of the initial transverse amplitudes.

DOCUMENTATION

A complete and updated user manual is available [1]. The physical models are described in a series of papers [23, 24, 2, 12, 13, 25], that are used as main references and describe the main tracking maps. A new physics manual [28], which aims at a self-contained exhaustive and concise description of the physics models and methods, is in preparation and available as a draft on the new SixTrack website [27]. In addition, to facilitate contributions to the code, a Wiki page [29] has been setup and enthusiastically filled in by the new developers with relevant information on the structure and naming conventions of the sources.

BUILD SYSTEM AND REFACTORING

The source code consists of 77k lines of Fortran (mainly 77) code written in 3 files organized in code fragments, that are assembled in Fortran files compiled and linked with few C/C++ libraries. The compilation of the code is non trivial as it needs to support several programming languages on many platforms and different compilers. A build system based on CMake is being investigated to provide cross-platform and daily-built executables.

The code has evolved incrementally with a large number of added features and optimizations. The internal structure is complex due to, in particular, the small number of functions, the extensive use of goto statements, redundant code blocks, and the heavy use of a limited pre-processor.

A restructuring of the code is required in order to extend the lifetime of the project and also to take advantage of the computational capabilities of the GPU that requires small kernels and tidy memory structures. However, the resources needed to carry out a complete rewrite have to take into account a restructuring of all the applications built around SixTrack (e.g. preprocessing routines for optics, collimation routines, Fluka integrations, run environments), the training of developers, benchmarking and documentation.

The level of the available resources led to the decision to follow an incremental approach starting from the documentation effort, functional to the full exploitation of the present code and for the training of new developers. Limited scope interventions will follow triggered by new applications: e.g. isolation of tracking maps when implementing exact Hamiltonian or improvements of particle data structures when introducing different ion species.

CONCLUSION

SixTrack is the workhorse of single particle tracking simulations for the LHC at CERN. It has a long history accumulating the contributions of many developers and profiting from almost two decades of studies and experimental benchmarks. The code is still used, maintained, and updated with new functionality in order to keep up with the needs of the accelerator design and performance evaluation at CERN high energy synchrotrons. A program of steady improvements and restructuring has been started to extend the lifetime of the project.

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