Kassiopeia

A modern, extensible particle tracking package written in C++

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Overview

- Kassiopeia is a C++ framework for producing high quality particle tracking simulations
- The overall architecture is a nested set of state machines divided into run, event, track, and step levels of organization
- The global tracking scheme is factored into a small number of general, orthogonal subproblems whose solutions must implement a corresponding set of abstract interfaces
- Kassiopeia provides solutions and factorizations of each of these subproblems, shown in the adjoining boxes, affording the user a hierarchy of extension options
- Pieces of the framework can be connected together into a simulation via simple XML input files or directly in C++
- Many modern C++ techniques and high standards make the code both fast and expressive

Trajectory

How are particle states represented?
How is particle evolution computed?

- Particle states evolve according to a coupled multidimensional ordinary differential equation
- Continuous physical effects are modeled by distinct term objects in this differential equation
- The possibility to express the same physical effects using representations in several different sets of variables enables a number of novel optimizations that would otherwise be impossible
- A wide range of integrators are available, including explicit Runge-Kutta, embedded Runge-Kutta and predictor-corrector methods
- Many strategies are available to control step size used in integration and to speed interpolation
- The trajectory system uses an embedded math library utilizing expression template techniques which provides large efficiency gains over standard C routines

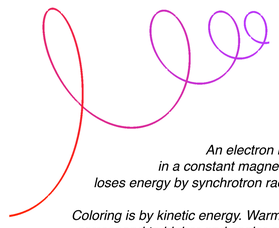
$$\frac{d\vec{r}_c}{dt} = \frac{p_\parallel}{m\gamma}\hat{B} \qquad = 0$$

$$\frac{d\phi_c}{dt} = \frac{q}{m\gamma}B \qquad = 0$$

$$\frac{dp_\perp}{dt} = \frac{p_\perp p_\parallel}{2\gamma m B_c}\vec{\nabla}B\cdot\hat{B} \qquad = 0$$

$$\frac{dp_\parallel}{dt} = -\frac{p_\perp^2}{2\gamma m B_c}\left(\vec{\nabla}B + q\vec{E}\right)\cdot\hat{B} = -\frac{\mu_0}{6\pi c}\frac{q^4}{m^3}B^2 p_\perp \gamma$$

The adiabatic representation of the propagation and synchrotron terms.



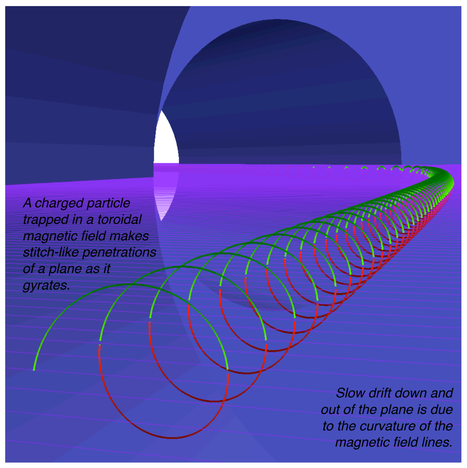
An electron moving in a constant magnetic field loses energy by synchrotron radiation.

Coloring is by kinetic energy. Warm colors correspond to higher and cooler colors to lower energies.

Navigation

Where do particles enter volumes?
Where do tracks cross boundaries?

- Accurate navigation is essential to a tracking framework where algorithm usage depends on geometrical context
- Very accurate boundary crossing and volume penetration points are necessary where physical length scales change dramatically
- Enables special behaviors as particles interact with geometric components



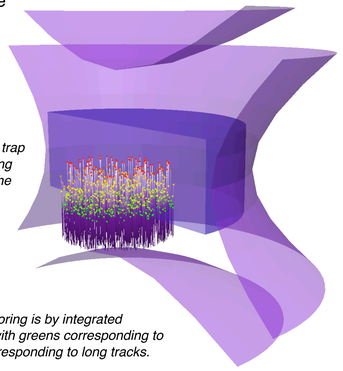
A charged particle trapped in a toroidal magnetic field makes stitch-like penetrations of a plane as it gyrates.

Slow drift down and out of the plane is due to the curvature of the magnetic field lines.

Interaction

How do particles interact with their environments?

- Particles can be subject to an arbitrary number of locally acting sudden effects such as scattering or decay
- Positions of interaction vertices are determined to high accuracy using the same equation of motion used in computing trajectories
- Modular design decouples material density calculations from cross section and final state simulation
- Interactions on interfaces are an integral part of the system with positions calculated to high precision in the navigator
- Active interactions can be swapped out according to geometric state



A set of electrons move in a penning trap with a cell containing gas positioned in the trap center where scattering occurs.

Track endpoint coloring is by integrated trajectory length, with greens corresponding to short and reds corresponding to long tracks.

Termination

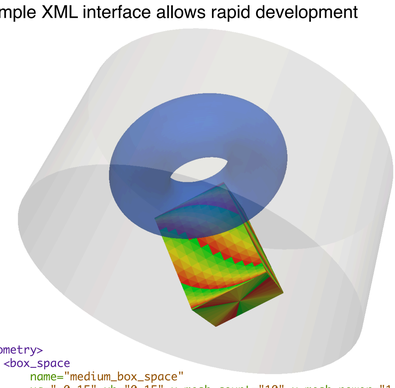
How are final track states determined?

- Terminators are extremely simple independent modules checked before each step is taken
- The track is killed if any one of the terminators signals that the track should be stopped
- Terminators can be engaged and disengaged as the particle moves through spaces and penetrates surfaces

Geometry

In what context do tracks evolve?

- New basic C++ geometry library introduced with many possible shape constructions
- Used for all simulation modules requiring geometric information
- Novel extension mechanism provides built-in discretization and randomization capabilities
- Simple XML interface allows rapid development



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...

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            <transformation d="-0.25 0.0 0.0" r_eu="20. 40. 60."/>
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...

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    />
</geometry>
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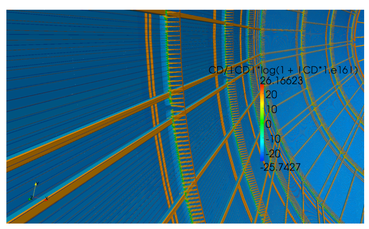
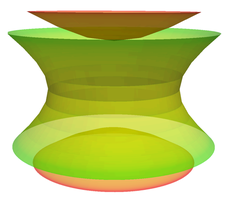
Fields

How do external electromagnetic fields affect propagation?

- KEMField library provides fast and accurate static field calculations
- Strategies used include zonal harmonics, fast multipole methods, numerical and analytic techniques
- Solvers employ finely tunable MPI and OpenCL parallelization methods
- Designed expressly for extension to time-dependent problems



Charge densities on a six million element model of the KATRIN main spectrometer. [picture courtesy T. J. Corona, author of KEMField]



Charge density simulation on a system of hyperbolic electrodes used in a penning trap.

Generation

How are initial track states created?

- Generator scheme allows for independent control over position, direction, energy and time picking policies
- Direction and position policies are further broken down by coordinate system into components
- Strategy allows a combinatorially large number of configuration structures
- High accuracy generators for radioactive decay of radon and krypton are available and tested from use in applications at KATRIN

Electrons propagate through a model of the KATRIN main spectrometer.

Coloring is by velocity component along the magnetic field.