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UPDATE OF THE RF-TRACK PARTICLE TRACKING CODE

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Abstract

The tracking code RF-Track has been updated to include several new single-particle and collective effects: beam loading in standing and travelling wave structures, incoherent synchrotron radiation, multiple Coulomb scattering in matter, and particle lifetime. The code flexibility in handling complex simulation scenarios has also been improved. This new set of effects was focused on the simulation of high-intensity machines such as linacs for medical applications. In these machines, the beam propagation into air and water significantly impacts the beam propagation to and through the patient. Now, these effects can be included by design in the accelerator optimisation. Additionally, using these new features, RF-Track is now used to simulate the cooling channel of a future muon collider.

INTRODUCTION

RF-Track [1] is a tracking code developed at CERN over the last few years, which offers outstanding flexibility and rapid simulation speed. RF-Track is written in optimised and parallel C++ and uses the scripting languages Octave [2] and Python [3] as user interfaces.

RF-Track can simulate beams of particles with arbitrary energy, mass, and charge, even mixed, solving fully relativistic equations of motion. It can simulate the effects of space-charge forces in bunched and continuous-wave beams, beam-beam effects, short- and long-range wakefield effects, beam-loading effects and synchrotron radiation emission. It can transport particles through conventional and special elements like 1D, 2D, and 3D static or oscillating electromagnetic field maps (both standing- and travelling-wave); flux concentrators for positron sources; electron coolers, and beam-laser interaction through inverse-Compton scattering [4, 5].

Unlike conventional accelerator codes, which only advance the beam along the longitudinal axis of the accelerator, RF-Track allows particle tracking both in space and in time. This feature, normally adopted by time-dependent tracking codes such as, for instance, Geant4 [6], opens up a variety of unique simulation scenarios.

During the last year, several new capabilities were added to the code to serve different projects: beam-matter interaction, tools to perform imperfection studies, orbit correction techniques, and elements such as beam screens. Along with developing these effects, the code was generally consolidated to make it more robust and flexible. This paper gives an overview of the new features.

RF-Track is currently utilised to simulate: medical linacs for electrons or light ions, inverse-Compton scattering sources, the CLIC and FCC-ee positron sources, the electron and positron linacs of the FCC-ee injector chain, the cooling channel of a future muon collider, and several other challenging scenarios where accurate tracking with realistic effects is crucial. Several papers presented at this conference are based on results obtained with RF-Track [7–13].

NEW EFFECTS

The necessity to simulate beam propagation through air, water, and vacuum windows in medical accelerators led to adding beam-matter interaction capabilities. The simulation of electron and positron dynamics in strong magnetic fields led to the implementation of synchrotron radiation effects.

In high-intensity machines like medical linacs, inverse-Compton scattering sources, or user facilities like the CERN CLEAR test facility, high-intensity beams “load” the structures reducing the effective accelerating gradient imparted to the beam and significantly altering the beam energy profile, both in single- and multi-bunch operation modes. Accurately predicting transient and steady-state effects due to beam loading is crucial for design, optimisation, and successful operation.

Beam-matter Interaction

As described in more detail in [7], particle-matter interaction was recently introduced in RF-Track. The implementation consisted of adding three new single-particle effects: multiple Coulomb scattering (MCS), stopping power (SP), and energy straggling (ES). Since effects can be added to any element and activated independently or simultaneously, RF-Track can now perform particle tracking and beam optics calculations in matter; for instance, in air or water.

This new feature was used in the simulations of the CERN CLEAR facility [14], where the experimental beamline is in air and dosimetry measurements are performed in water [9]. Additionally, it enabled the simulation of the muon cooling channel of a future muon collider [7].

Incoherent Synchrotron Radiation

The simulation of a challenging scenario like a LEMMA scheme where 45 GeV positrons annihilate with electrons at rest to generate muon pairs [15] led to the implementation of incoherent synchrotron radiation effects.

The implementation was largely based on the model adopted by other CERN codes, like PLACET [16] and MAD-X [17]. Still, it was extended in two ways: (1) to

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work with any charged particle and (2) to consider synchrotron radiation emission due to *any* electromagnetic field, or force, acting on the particle. The emission of incoherent synchrotron radiation can now be taken into account in any element, including accelerating structures.

Self-consistent Beam-loading

A first RF-Track implementation of self-consistent beam loading (BL) effects was presented in [5]. At the time, the effect was only applied to travelling-wave (TW) structures. The capability to handle also standing-wave (SW) structures has recently been added.

The computation of BL is performed from the shunt-impedance along the structure, R, the quality factor, Q, and, in the case of TW structures, the group velocity. Whenever the accelerating field is known, for example, through a 1D, 2D, or 3D RF field map or an analytic SW or TW beamline element, the shunt impedance is computed automatically from the field. In the case of multi-bunch beams, the module can simulate both the transient regime or directly the steady state. At this conference, a detailed description of the implementation is presented in [10].

To our knowledge, the self-consistent computation of beam loading effects is a unique feature that no other tracking codes implement.

NEW BEAMLINE ELEMENTS

New elements were added to provide additional capability:

Absorber

A new element called `Absorber` was added to RF-Track to represent a block of material or target. An `Absorber` is an element where the three effects previously described, MCS, SP, and ES, are activated by default. The user can specify the material either by name or by providing the relevant parameters:

```
A = Absorber (L, material_name);
A = Absorber (L, % m
              radiation_length, % cm
              Z, A, % g/mol
              density, % g/cm3
              mean_excitation_energy); % eV

A.set_shape(rx, ry, 'elliptical');
```

Where `L` is the length of the absorber in meters. The parameter `material_name` allows the user to use predefined materials, such as: “`air`”, “`water`”, “`liquid_hydrogen`”, “`beryllium`”, “`lithium`”, or “`tungsten`”. Optionally, `Absorbers` can have an elliptical, circular, or rectangular shape, allowing for specific target simulations [7].

Space-Charge Fields

In the context of the LEMMA scheme for muon generation, the full electromagnetic interaction between bunches of different species and shapes has to be considered. This is a complex scenario where three species interact: positrons, electrons, and ions.

The interaction can be viewed as a beam-beam interaction for particles of different species (electrons and positrons) and as a space-charge interaction between particles of the same species (particularly the electrons and the ions in the plasma).

Additional difficulties arise when considering the long-range interactions between the different species and the presence of the plasma ions. This complex scenario motivated the development of a new Element, `SpaceCharge_Field`, suitable for tracking *in time*, which allowed us to perform the simulation.

This element computes the electromagnetic fields generated by an arbitrary distribution of charged particles, both inside and outside of it, and makes it available for particle tracking.

Figure 1 shows a simple test where the electric field of a uniformly distributed sphere of a charge is computed in 3D using different meshing and compared with the analytic calculation. Of course, more interesting fields are generated by arbitrary distributions.

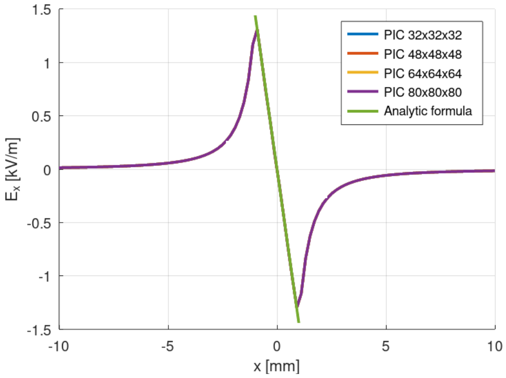

Figure 1: The electric field generated by a uniformly distributed sphere of a charge, computed in 3D using different meshing (inside and outside the sphere) and compared with the analytic calculation (inside).

Correctors and Bpms

The elements `Corrector` and `Bpm` were recently added to enable imperfection studies and the simulation of beam-based correction techniques.

NEW FEATURES

Several new features and improvements were introduced:

Integration between Volume and Lattice

RF-Track can track beams *in time*, in the tracking environment called Volume, or *in space*, in the tracking environment called Lattice. The first allows for accurate space-charge calculations and element overlap. The second corresponds to the conventional lattice description used in accelerator physics. Typically, Volume is used in field maps and injector guns where space-charge effects are important. In contrast, Lattice is used in the high-energy parts of the accelerator, where space charge can be neglected, and symplecticity is required. A smooth integration between Volume and Lattice is necessary to enable start-to-end simulations.

It is possible to join a Volume and a Lattice at arbitrary points in the 3D space, providing the (x, y, z) coordinates and the 3D orientation of the accelerator axis. An example is visible in Fig. 2. Here, particles are tracked in Volume through the 3D field map of a strongly-bent magnet. The blue line indicates the trajectory of the reference particle. When the beam intercepts one of the planes orthogonal to the reference trajectory, called “screens” (in green in the figure), its phase space is stored along with the arrival time of each particle, and tracking can be continued in a conventional Lattice. More details about this interesting study are presented at this conference in [11].

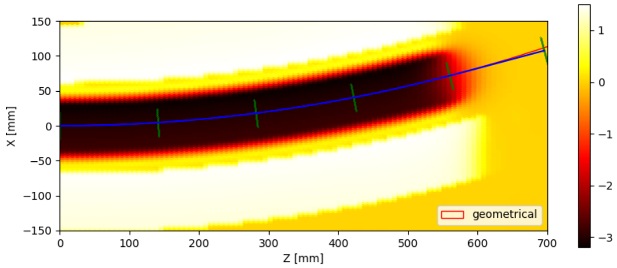

Figure 2: The 3D field map of a strongly-bent magnet. In blue is the reference trajectory. In green are the screens along it.

Photocathode Simulation

A particle generator has been introduced into RF-Track to simulate realistic distributions at photocathodes. An example of a generator setup is shown,

```
G = Bunch6d_Generator();
G.species = "electrons"; % species
G.noise_reduc = true; % noise reduction
G.q_total = 0.285; % nC bunch charge
G.phi_eff = 3.5; % eV, effective work function
G.e_photon = 4.73; % eV, photon energy
G.sig_x = 1.600; % mm, spot size rms
G.sig_t = 0.001; % ns, emission time rms
G.dist_pz = 'fd_300'; % Fermi-Dirac distribution
```

Noise-free distributions are optionally possible using quasi-random numbers, that is, low-discrepancy sequences provided by RF-Track. Quasi-random numbers have the advantage over pure- or pseudo-random numbers that they cover the domain of interest quickly and uniformly. Integrated start-to-end optimizations from photocathode to beam delivery are now possible.

Element Misalignment and Orbit Correction

The implementation of element misalignment has been completely redesigned to improve flexibility. Now, elements can be grouped, while each element can have arbitrary offsets and orientation in space, and nesting is possible. This means that individual elements can be misaligned w.r.t. a common reference, this reference misaligned w.r.t. a supporting girder, while the girder is misaligned w.r.t. the ground. Supporting routines to implement beam-based alignment quickly have been provided. Here is an example script implementing basic orbit correction:

```
% prepare for orbit correction
Res = Beamline.get_response_matrix(P0);

% perform tracking and apply orbit correction
B1_unc = Beamline.track(B0);
B1_cor = Beamline.orbit_correction(Res, B0);
```

This implementation is currently used to simulate beam-based correction in the various linacs of the FCC-ee injector complex [18].

Particles Lifetime

As RF-Track is being used for the simulations of the muon cooling channel of a future muon collider, a lifetime parameter was added to each particle. An example being:

```
% create a bunch
B0 = Bunch6d (muonmass, population, +1, ...
       [ X XP Y YP T P ]);

% set the lifetime
B0.set_lifetime (muonlifetime);
```

In this example, a bunch of muons μ^+ is created from a user-defined phase space, `[ X XP Y YP T P ]`, and the lifetime is set using a dedicated command. If not specified, the default particle lifetime is infinity.

CONCLUSIONS

In this paper, we have presented new features of the RF-Track tracking code, which opened many new simulation scenarios: from particle tracking in air and water for medical applications to the simulation of muon cooling for a future muon collider. The code’s new features also enabled fundamental beam dynamics studies, such as the representation and integration of strongly bent magnets into symplectic tracking—several papers presented at this conference report on results obtained with RF-Track.

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