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Faktor2: A Code To Simulate Collective Effects Of Electrons And Ions

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Abstract

A new code for computing multiple effects of nonrelativistic charges is being developed. The basic method is electrostatic Particle in Cell. The underlying grid is rectangular and locally homogeneous. At regions of interest, eg. where the beam is, or near material boundaries, the mesh is refined recursively. The motion of the macroparticles is integrated with an adapted time step. Fast particles are treated with a smaller time step, and particles in regions of fine grids are also treated with a fine time step. The position of collision of particles with material boundaries are accurately resolved. Secondary particles are then created according to user specified yield functions.

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FAKTOR2: A CODE TO SIMULATE COLLECTIVE EFFECTS OF ELECTRONS AND IONS

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Abstract

A new code for computing multiple effects of nonrelativistic charges is being developed. The basic method is electrostatic Particle in Cell. The underlying grid is rectangular and locally homogeneous. At regions of interest, eg. where the beam is, or near material boundaries, the mesh is refined recursively. The motion of the macroparticles is integrated with an adapted time step. Fast particles are treated with a smaller time step, and particles in regions of fine grids are also treated with a fine time step. The position of collision of particles with material boundaries are accurately resolved. Secondary particles are then created according to user specified yield functions.

PURPOSE

Electron clouds develop in the beam pipes of accelerators eg. via ionisation of the residual gas and via secondary emission of electrons when slow electrons are accelerated by a passing beam. The newly developed programme simulates these effects. The basic method is electrostatic Particle in Cell.

The new code is meant to cover the same use as ECLOUD[2] but to be more modular and complete.

RECURSIVELY REFINED FINITE DIFFERENCE GRID

There are several reasons to use an electrostatic algorithm in a refined grid.

- Large time step: The electrostatic approximation allows to choose the time step independently of the grid spacing. We want to use quite a large time step, as we want to simulate several hundred beam passages, where each beam passage may be as long as $cT = 10\mathrm{m}$.

- Large ratio of feature sizes: To numerically resolve the motion of ions which are trapped within the potential of a beam of finite x-y size, one needs a grid spacing smaller than the smallest dimension of the beam. E.g. for CLIC, this calls for grid spacings smaller than 1μ. For taking into account the boundary effects, one has to extend the grid until the beam pipe boundary is reached. E.g. for CLIC, a diameter of about 2cm has to be covered. It is wasteful and almost impossible to cover the whole area with cells as small as needed to resolve the field within the beam.

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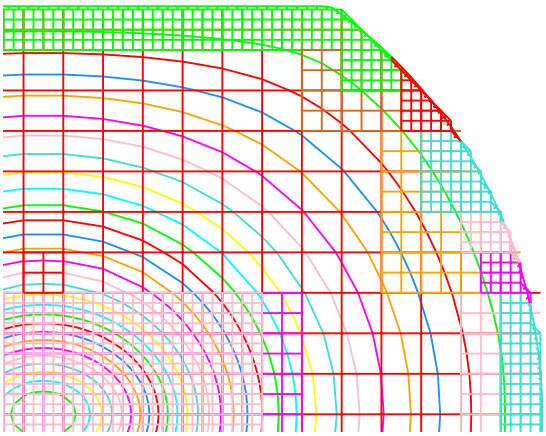

Figure 1: Subdivision of the grid near the pipe boundary and at the location of the beam. Two levels of refinement are applied. The different colours of the refined cells indicate clusters of cells which are treated as rectangular grids. The curved lines are lines of constant potential of an elliptical beam at the center.

The potential of the exciting beam and of the freely moving charges is computed on a rectangular finite difference grid, Fig. 1. The spacing is homogeneous. Each grid cell may be refined. The spacing of the grid points decreases by a factor of two per refinement level. For a more efficient handling of the grid, the refined cells are organised as clusters of cells. The electric and magnetic field of a relativistic beam is rigorously taken into account. The charge distribution of the beam may be arbitrary.

CHARGE DEPOSITION, POISSONS-EQUATION, PARTICLE PUSHING

The shape of the macroparticles is assumed to be rectangular, fig.(2). The size of the particles can be different from the grid size, and must be, as macroparticles will travel through regions with different grid spacings. Best results are obtained with a size equal to the grid size where the particle is in. The charge deposition together with the field interpolation, Fig. 2, ensures that no self field occurs when the charges have the same size as the enclosing grid.

POISSONs-equation is solved iteratively. Within an iteration, the potential within a subgrid is solved with the boundary conditions taken from the enclosing grid or from a neighbour grid, Fig. 3.

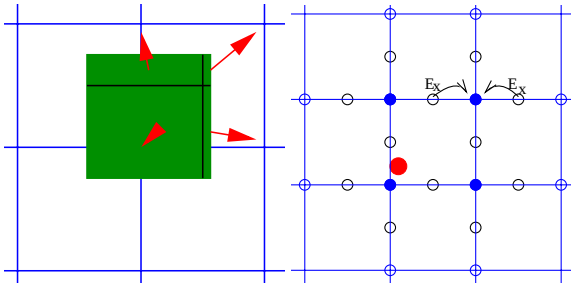

Figure 2: Left: The charge is deposited on the grid according to the area of the charges which is within the rectangular area which is nearest to a given grid point. Right: Interpolation of the field components. The electrostatic potentials at the blue circles are known from the solution of POISSONs equation. The x- and y-components of the electric field at the black circles are computed from the difference of the nearby potentials. The x- and y-components at the filled blue circles are computed as the average of the values at the nearby black circles. The field at the position of a particle, red circle, is computed by linear interpolation between the values at the four surrounding filled blue circles.

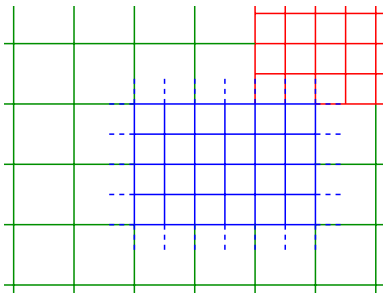

Figure 3: Grid coupling within an iteration to solve POISSONs equation: The potential values outside of the blue grid are computed by interpolating the values of the enclosing green grid and, when possible, by taking values from the red grid. After POISSONs equation for the blue grid is solved, the potential values are copied to the corresponding grid points of the green and red grid.

Particle pushing

The particles are pushed with an algorithm invented by Boris[1]. That algorithm requires the electric and magnetic field at the center of the macroparticles. Each component of the electric and magnetic fields is interpolated from the six corresponding field components nearest to the center of the macroparticle, fig. 2, right.

PARTICLES HITTING THE WALL

When particles hit the wall, ions are absorbed, and electrons have a probability to create secondary charges or to be reflected. The model of the these probabilities is as decribed in [2] [3]. It depend on the energy and the angle of the hit. The angle is modeled very accurately by encoding the actual material boundary. Arbitrary beam pipe shapes can be used, as the computational cost of detection of a particle hitting a boundary does not depend on the particular shape, fig. 4. With the chosen boundary detection, it is also easy to log the position of the deposited energy with a resolution as good as the grid spacing at the material boundary.

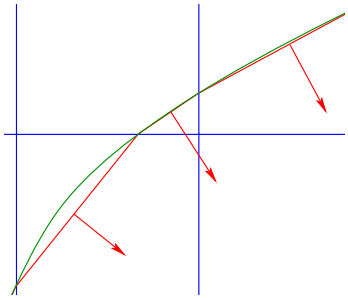

Figure 4: The material boundary, green, is encoded as a polygon, red. The encoding is created at mesh generation time. During the particle pushing, the hitting of a particle is detected by checking for a change of sign of the distance of a particle to the boundary. The angle of the hit is given via the dot product between the particles velocity and the plane normal.

EXAMPLES

Electron Clouds

We compute the buildup of electrons in a beampipe with a vertical magnetic field. As the beam is positively charged, the electrons are accelerated away from the wall. When they hit the opposite wall, secondary particles are created. The total charge is shown in Fig. 5. Snapshots of the charge density are shown in Fig. 6.

Trapped Ions

We compute the trajectories of CO ions which might be trapped within the potential of a negatively charged beam train. Trajectories and densities are shown in Figs. 7, 8, 9.

REFERENCES

[1] J. P. Boris, "Relativistic plasma simulation – Optimization of a hybrid code", in Poc. 4th Conf. Numerical Simulation of Plasmas, Washington, DC, 1970, pp. 3-67

[2] D. Schulte and F. Zimmermann, "Electron Cloud Build-Up Simulations Using ECLOUD", Proc. ECLOUD'04, Napa, CERN-2005-001 (2005) p. 143, and references therein

[3] D. Schulte et al., "Electron cloud measurements in the SPS in 2004", Proc. PAC 2005, Knoxville, p. 1371 (2005)

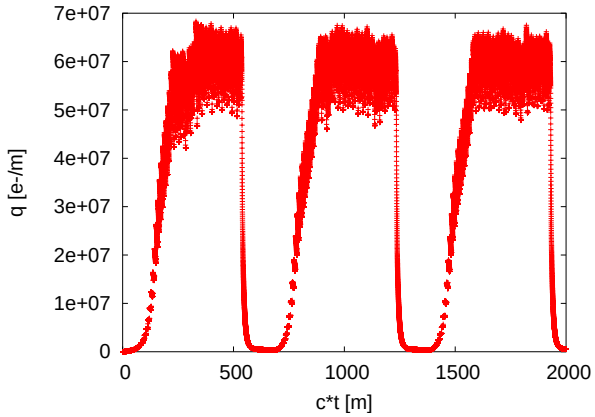

Figure 5: The total charge in a beam pipe as a function of time. Three passages of a train of 72 bunches followed by 21 emtpy bunches are simulated. The bunches have a distance of 7.48 metres and a population of 11.5×10^{10} positrons. The y-directed magnetic field has an amplitude of 0.01 Tesla, which is rather small, smaller than the typical dipole fields in LHC or SPS.

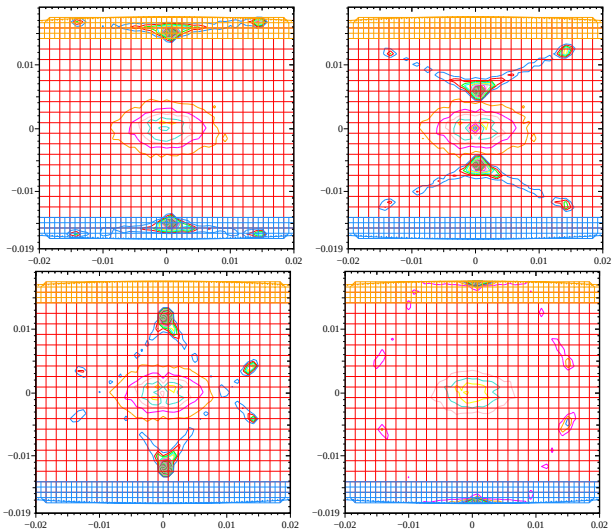

Figure 6: A zoom of the grid with charge densities at four different times, just when a beam is passing. An elliptical beampipe with x-extension of $2 \times 7.6\mathrm{cm}$ and y-extension of $2 \times 1.75\mathrm{cm}$ is modeled. The charges in the center are positively charged ions. The positive charge is much less than the negative charge and could be neglected. Above left: The electrons have just been accelerated away from the pipe boundary. Above right: The fastest electrons in the middle have almost reached the center of the beam pipe. Below left: The fast electrons have almost reached the opposite side of the beampipe, while the slower electrons have not yet reached the middle plane. Below right: Almost all electrons have reached the opposite side.

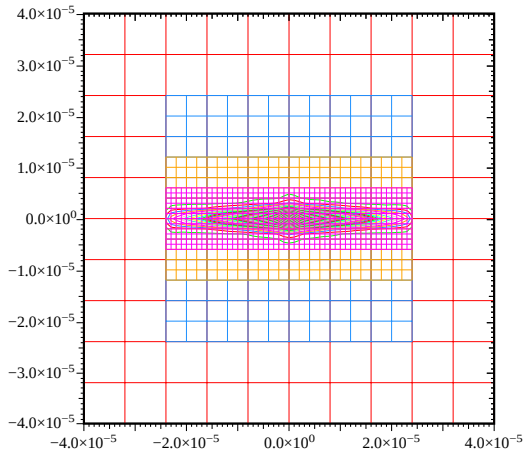

Figure 7: Density of the trapped CO-ions. The shown area is a tiny fraction of the modeled area, which is 10000 times larger. The exciting beam has $\sigma_x = 16\mu\mathrm{m}$, $\sigma_y = 1.24\mu\mathrm{m}$ and $\sigma_z = 1.55\mathrm{mm}$. The bunch population is 2.56×10^9 electrons.

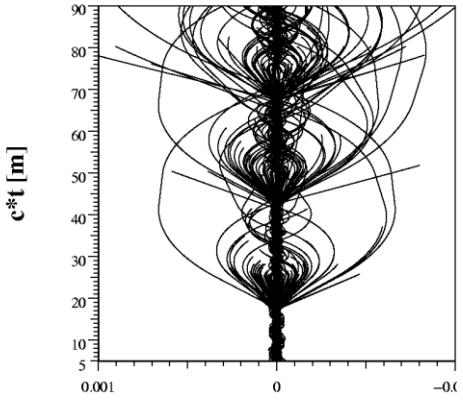

Figure 8: Trajectories of CO-ions. During the first bunch train of length $ct = 110 \times 0.16\mathrm{m}$, all freshly created CO-ions are trapped. Within the gap of length $ct = 46 \times 0.16\mathrm{m}$, most ions do not reach the beampipe wall.

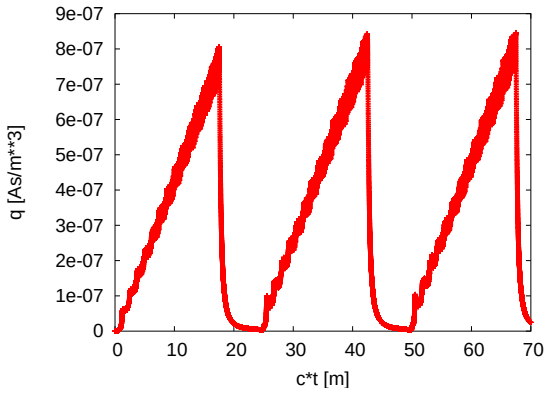

Figure 9: Density of the CO-ions on the axis as a function of time.