Selfconsistent Simulation of High Power Tubes with TBCI-SF

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Abstract

At DESY, the computer code TBCI-SF has been developed for studies on the beam dynamics of intense electron beams in the low energy regime. This code is a $2\frac{1}{2}$-dimensional, fully relativistic particle-in-cell code. Arbitrarily shaped static or dynamic external fields can be superimposed and the code also takes the space charge effects of the electron beams into account. First the code TBCI-SF will be described. Then various applications will be presented.

Introduction

To study the dynamics of the hollow electron beam in the *Wake Field Transformer Experiment*[1,2,3], the computer code TBCI-SF[4] has been developed at DESY. The code is used to optimize the different components of the experiment and to study their influence on the electron beam due to the interaction of the external fields with the particles. The particle-in-cell code TBCI-SF is useful for the simulation of existing experimental setups as well as for planned accelerator components like sources of intense electron pulses. After a description of TBCI-SF and the computational methods used in the code, we will present the results of three different calculations to existing or planned experiments. The first application is the simulation of the bunching process of the hollow driving electron beam in the prebuncher-cavity of the *Wake Field Transformer Experiment*. A long electron bunch, produced in the electron gun passes through the prebuncher-cavity and due to the rf-field, the bunch is divided into a few subsequent smaller bunches. A second application is the simulation of the preliminary design of a planned electron source[5]. Here electrons are emitted from a photocathode located inside a superconducting cavity. The electrons are accelerated by the rf-field of the cavity to a kinetic energy of about 2 MeV. The third application of TBCI-SF is the simulation of the concept of a Lasertron[6,7]. Short electron bunches are photoemitted and accelerated by a static field between the cathode and the anode. Because of the high intensity of the bunches and the short length ($\ll 1$ ns) of the pulses, space charge effects will increase the bunchlength. After the acceleration the bunches pass through one or more output cavities which extract their rf-energy. First calculations of a Lasertron with two cavities will be presented.

TBCI-SF

The program TBCI-SF[4] is a particle-in-cell code. This method of solving Maxwell's equations and the Lorentz force equation selfconsistently has been developed in plasma physics[8] and is currently being used in accelerator physics for high current beams[9,10].
After the initial conditions have been fixed, the following three steps are carried out:

- Calculate the current density at the mesh points which corresponds to the motion of the particles.
- Advance fields in time using this current density as a driving term. (equivalent to 1 step in TBCI)
- Advance particle trajectories according to the Lorentz force.

Using the finite integration theory[11], the fields and the current density are located in the mesh. The field evaluation with time is then calculated exactly as in TBCI[12], using the current density in the mesh as a driving term for the fields. Deeper discussions of this algorithm can be found elsewhere[12,13].

The charge distribution in the bunch is described in TBCI-SF by macroparticles which represent a rigid charge distribution in a volume corresponding to about one cell of the field mesh. These macroparticles are characterized by their position (r, z) and rapidity $\vec{u} = (u_r, u_\phi, u_z) = \vec{p}/mc$. The position may be anywhere inside the region covered by the mesh, the rapidity is treated fully 3-dimensionally. The Lorentz force equation can be written as

$$\frac{d}{dt}\vec{x} = \vec{v} \tag{1}$$

$$\frac{d}{dt}\vec{u} = \frac{q}{mc}(\vec{E} + \vec{v} \times \vec{B}) \tag{2}$$

Similar to Maxwell's equations, this system is solved by a leapfrog scheme. The velocity as well as the magnetic field must be time-averaged when the velocity change is calculated. Furthermore, the second equation is implicit. In TBCI-SF it is replaced by an explicit algorithm: In the first step, the rapidity is advanced by half a time step using only the electric field. Then the rotation in the magnetic field is calculated and finally the second half step of acceleration is carried out.

In order to decrease noise amplitudes, pyramid-shaped particles are used. This allows a smooth approximation of any charge distribution at the cost of second order terms in the current density calculation. A charge-conserving scheme is used for the determination of current densities in the mesh. This is the same one used in ISIS[14] which was first described by Buneman[15]. Instead of multiplying the charge density by an average velocity, the current is calculated as a sum of charges which pass a cell wall during one time interval. The field at the particle position is calculated as a weighted mean of the fields at mesh points which are covered by the charge cloud represented by a particle.

Only two of the four Maxwell equations are needed to advance the fields in time. The others are fulfilled implicitly. One of these equations, Gauss' Law, must be used to correct the fields if the current calculation is not charge-conserving. In TBCI-SF, both are used to check the results every few time steps.
External fields created by sources other than the bunch current itself often cause problems in particle-in-cell codes. Sometimes static fields are not foreseen, and rf cavity fields can only be produced by simulating the whole filling period (which is expensive in terms of CPU-time and may be inaccurate) or by using approximations like the "port approximation" in MASK[9]. TBCI-SF allows external fields to be given as start values of the electromagnetic field implemented on the mesh. Once they are set up, they do not need to be treated specially any longer. Static fields may be precalculated by PROFI[16]. The PROFI mesh must be identical to the TBCI-SF mesh (or to a part of it) in order to avoid numerical errors due to the interpolation. Resonant fields are precalculated by URMEL[17] with the same restriction on the mesh. Both, electric and magnetic fields, are taken from URMEL results. Therefore, initial phase and amplitude of the rf field may be adjusted separately.

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The CPU time needed for the simulation is a function of the number of macroparticles used, n_M, and of the number of mesh-points, n_P:

$$t_{CPU} = (a\,\frac{n_M}{1000} + b\,\frac{n_P}{1000}) \cdot \frac{\text{number of steps}}{1000}$$

Typically n_P and n_M are of the same order of magnitude. On an IBM 3084 Q, the coefficients are $a \approx 13.5 sec$ and $b \approx 160 sec$.

The Bunching Process in the Prebuncher of the Wake Field Transformer Experiment

With the particle-in-cell code TBCI-SF, the first 1.5 m of the *Wake Field Transformer Experiment*[2,3] at DESY, with the prebuncher-cavity and the following driftspace is simulated. The dimensions of the simulated structure are the same as in the experiment. A hollow electron beam of 8 cm in diameter and parabolic density distribution along the axis of motion is generated in the electron gun. The beam is guided by a solenoid field with field strength of about 0.2 T. The pulse length of the generated beam is nearly 10 ns. The electrons then pass through the prebuncher-cavity, a single-cell cavity with frequency of ν = 500 MHz. At the end of the following driftspace, 1.5 m after the gun, a gap monitor is positioned to measure the current distribution of the compressed bunches leaving the prebuncher. In the calculations, we start with a measured value for the gun voltage of about 50 kV and increase it up to the design peak value of 150 kV. We vary the total charge of the generated hollow beam between 20 nC and 4 μC. As a third parameter we also change the cavity voltage between 60 kV and 400 kV. When the long (long compared to one rf-cycle in the cavity) hollow beam passes the cavity gap, the particles at different positions inside the bunch are accelerated or decelerated depending on the phase of the field at the time they pass through. That results in a compression of the long bunch into a few subsequent smaller bunches.

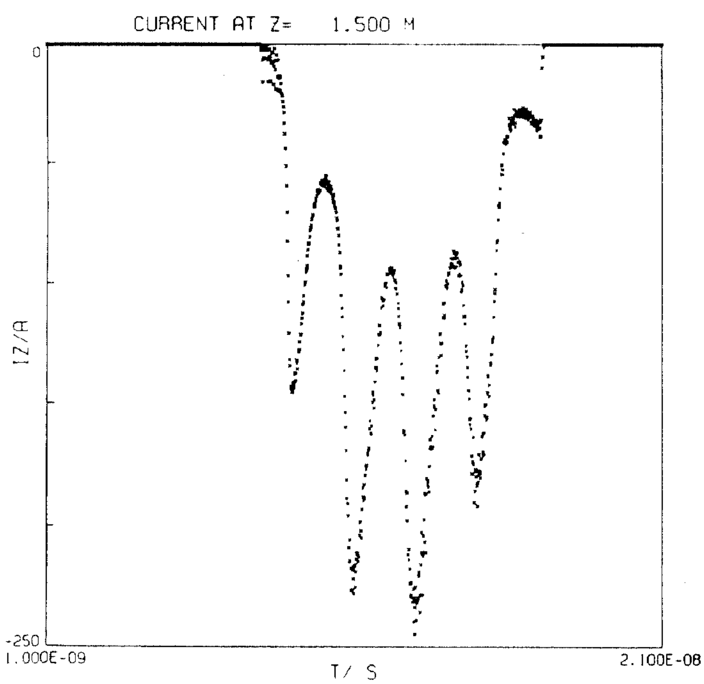

Figure 1: Current distribution of compressed bunch (total charge Q = 1 μC) at the position of the simulated monitor, 1.5 m after the electron-gun. The cavity voltage is 61 kV

As an example, Figure 1 shows the current distribution at the location of the simulated monitor. The input values are U_{Gun} = 150 kV, U_{cav} = 61 kV and a total charge of the hollow beam of Q = 1 μC. One result of the simulation is that for higher charges (beam currents), the cavity field cannot compress the long bunch. That can be interpreted as space charge effects inside the bunch resulting in a blow-up of the beam. The cavity voltage is not high enough to compensate these effects. By increasing the voltage of the cavity, the particles will be further accelerated or decelerated, strengthening bunching process and preventing the bunches from being blown-up by space charge effects. The simulation results are in agreement with this behaviour. They show that beams with higher currents can be bunched.

Simulation of a Superconducting Photoemission Source

The second application of the code TBCI-SF is the simulation of a proposed superconducting photoemission source of high brightness[5]. In Figure 2, the preliminary design of the cavity is shown. The length of the structure is 26.5 cm and the radius is 12.5 cm. A reentrant-type superconducting cavity is embedded in a vertical cryostat. Outside the cryostat are the magnets which guide the beam and the beam diagnostic systems. A pulsed Nd:YAG laser generates an electron pulse of 10 ps by photoemission from the cathode. The cathode has a diameter of 1 cm and is located inside the cavity. A parabolic current distribution of the pulse in the longitudinal direction is adopted. To get the same current density at each radius, we choose a special distribution in radial direction. We vary the mean current of the bunch between 8 A and 250 A. The rf-field inside the cavity has a frequency of about 505 MHz. The surface field strength at the cathode is 16 MV/m. To limit the needed CPU-time, the particles emitted from the cathode have an initial kinetic energy start of 0.1 keV. At t=0, the phase of the field relative to the peak value is 40°. The electrons are accelerated by the rf-field up to 1.8 MeV at the end of the cavity. Near the cathode, the bunch is radially compressed by the field, except for the highest beam current. Then for times t $\geq$ 200 ps, the radial dimensions of the bunch are greater than the initial value of 5.0 mm. The radial increase for low beam currents is about 50 % when leaving the structure. For the high current, the radial blow-up exceeds 100 %. The radial increase can be interpreted as a result of two effects. First, the radial component of the field near the beam pipe accelerates the particles in the radial direction. However, this can be reduced by decreasing the diameter of the beam pipe. Changing the pipe radius from 6 cm to 3 cm made the radial dimension of the bunch at the end of the structure approximately 1.5 % smaller. The second reason for the radial blow-up are the space charge effects, which dominate as we increase the beam current.

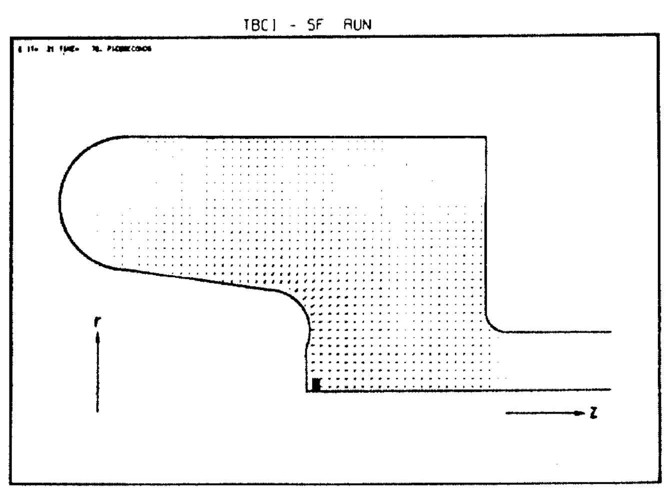

Figure 2: Preliminary design of the superconducting reentrant cavity with 3 cm beam pipe. The position of the bunch at t = 70 ps and the electric field is shown.

By changing the relative phase of the cavity-field, the radial dimensions can be further reduced. In another calculation we changed the phase at t=0 from 40° to 50° relative to the field peak value. We found a reduction of the radial dimensions of about 2 % for the highest beam current and more than 5 % for the low beam currents at the end of the structure. The longitudinal dimensions of the bunch also depend on the space charge effects. For the low currents (8 A and 16 A) the longitudinal dimension of the bunch was 2.59 mm and 2.61 mm, respectively. This was an increase of less than 2 % for the higher current compared to the low current result. For the high beam current (250 A) the bunch length at the end of the structure was 3.58 mm, an increase of nearly 40 %, compared to the low 8 A current. The initial value for the bunch length was 0.059 mm for all cases. The length of the bunches at the end of the simulated structure were 43.9, 44.2, and 60.7 times the initial values. The high value for the 250 A current is a result of the space charge forces inside the bunch.

Simulation of a Lasertron

A new concept of building a high power rf source with high efficiency is the Lasertron[7]. In the Lasertron, high current pulses are generated by a laser pulsed onto a photoemissive cathode. Unlike a conventional klystron, the electrons in the Lasertron are emitted as a bunched beam. When the short bunches leave the cathode the internal forces are higher than at any other time. This will cause a longitudinal blow-up of the bunch and this effect increases with increasing beam currents. The short electron bunches are accelerated by a constant electric field through a diode and pass through one or more output cavity gaps to improve the efficiency. In our simulation of the first design of a Lasertron which was under study at SLAC, four electron bunches of 70 ps each were emitted from the cathode[6]. The longitudinal current distribution was again parabolic, and the peak current of each bunch was 1 kA. The time between two subsequent high current bunches was 0.35 ns. The electron pulses were accelerated by a static electric field of 400 kV between the cathode and the anode. A constant magnetic field of 0.2 T guided the particles. The frequency of the two output cavities located behind the accelerating gap was 2.86 GHz. When the bunches pass through the cavity gaps at the right phase, their loss of rf-energy is (in the ideal case) so high that, at the end of the structure a dc-current reaches the collector. This can be proved by a current monitor located downstream behind the cavities. We did our simulation to demonstrate that the program TBCI-SF can reproduce values like the efficiency correctly. Comparison with results in ref.[6] showed excellent agreement. The simulated structure of the lasertron with overall length of 21 cm is shown in Figure 3.

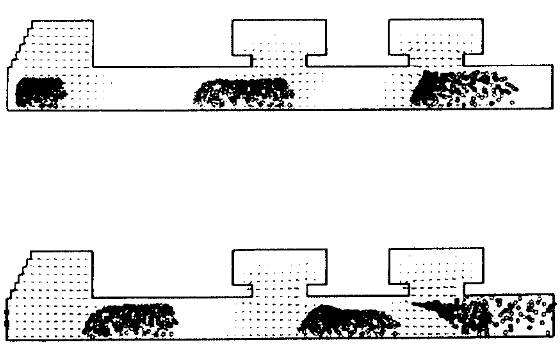

Figure 3: Structure of the SLAC Lasertron, as simulated by TBCI-SF. The position of the first three subsequent bunches is indicated for t = 0.88 ns and for t = 1.05 ns. At t = 0.88 ns (upper picture) the particles passing through the output cavity gaps are decelerated by the field. At t = 1.05 ns (lower picture) the electric field has turned, and the particles are accelerated.

Summary

The capability of calculating internal forces in an electron beam and also including external fields by which the particles are influenced, makes the particle-in-cell code TBCI-SF a useful tool for a wide range of simulations for components of high energy accelerators. The code gives reasonable results compared to other calculations, as in the case of the Lasertron simulation, and it is helpful for the design of new accelerator components.

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