Beam Dynamic Studies with the MAFIA Module TS2

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Abstract

The MAFIA program TS2 is a $2\frac{1}{2}$-dimensional, fully relativistic particle-in-cell code. This code has been developed at DESY to study the beam dynamics of charged particles in cylindrically symmetric structures, e.g. electron guns or rf-tubes. The code and its main features will be described. Then, as an example for the wide range of applications for the program TS2, simulations of the hollow electron beam gun for the *Wake Field Transformer Experiment* at DESY will be presented.

Introduction

The program TS2 belongs to the group of fully 3-dimensional MAFIA [1] computer codes. This module is one of the latest additions to this family of well established codes solving Maxwell's equations. It is one of the new 2-dimensional codes MAFIA. TS2 solves the field equations and the equations of motion in parallel self-consistently. In TS2 space charge effects are also taken into account. The code has been developed to study the beam dynamics of charged particle pulses due to interaction with external fields in cylindrical structures. It is a useful tool for the design and the optimization of structures such as electron beam guns or high power klystrons for future accelerators as well as for the simulation of existing experimental setups like the *Wake Field Transformer Experiment*. First, we will give a description of TS2, its main features and the computational methods used in the code. Then we will report on the simulation of the hollow electron beam gun for the *Wake Field Transformer Experiment* at Desy as one application of the program. This experiment is described in detail elsewhere [2]. The laser driven hollow beam gun was developed at DESY[3]. The electrons are extracted from the cathode and accelerated by an applied pulsed high voltage between the cathode and the anode.

The MAFIA module TS2

As a part of the MAFIA family of codes, TS2 has the same structure and makes use of the features of the new release of MAFIA. One of these new features is the unified menu-controlled, user interface. All input to the program is done via commands in specific menus. As an example, in Figure 1 one of the menus is shown. Here the input parameters of the bunches, used for a specific simulation, are set. These parameters define the kind of particles, the number of bunches and the number of particles in each bunch, the time of emission, and the type of distribution for the bunches. In other menus, for example, the number and kind of external fields or the number of solenoid-coils are set.

The mesh and the material distribution, used in the calculations, are generated by the module M. Up to 64 different materials can be used in the calculations. The filling of the meshcells can be full or triangular. In TS2 it is possible to pre-load arbitrary shaped static or resonant external fields and take them as initial values of the electromagnetic field implemented on the mesh. Once they are set up, they do not need to be treated specially any longer. Thus, this makes approximations of rf cavity fields like the "port approximation" in the computer code MASK [4] unnecessary. The external fields are calculated by the other MAFIA modules, e.g. static fields by the 2-dimensional static field solver S.

At certain, user defined, time steps the calculated fields and particle properties can be printed and written to a direct access file. This file can be used by the Program P, which post-processes the solutions and displays them graphically.

The MAFIA module TS2 is a particle-in-cell code. This method of solving Maxwell's equations and the equations of motion self-consistently was first used and developed in plasma physics [5]. But it is also used in codes for the simulation of components in accelerator physics.

After the initial conditions have been defined, the following three steps are carried out for each subsequent timestep :

- 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.
- Advance particle trajectories according to the Lorentz force.

Using the finite integration theory [6], the fields and the current density are located in the mesh. The charge distribution in the bunches are described in TS2 by macro-particles which represent a rigid charge distribution in a volume corresponding to about one cell of the field mesh. In the program, any kind of charged particle can be defined. The code is not restricted to the simulation of electron bunches. Typically, one macro-particle represents about 10^8 real particles. These macro-particles are characterized by their position (r, z) and their normalized momentum $\vec{u} = (u_r, u_\varphi, u_z) = \vec{p}/mc$. The position may be anywhere inside the region covered by the mesh, the momentum is treated fully 3-dimensionally. Maxwell's equations and the equations of motion are solved by a leap-frog scheme.

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******************************************************************
*                          M A F I A                       TS2 3.C *
******************************************************************
* FLAGS: NOMENU MESSAGES PRINTSCREEN PRINTFILE NOLOGFILE NOGRAPHICS *
******************************************************************
*     TOTAL NUMBER OF PARTICLES IN ALL BUNCHES :  2500  ( MAXIMUM: 5000 ) *
* -------------------------------------------------------------- *
* BUNCH.........=     1          (1,2...,10)                          *
* PARTICLES....=   ELECTRON      (ELECTRON/POSITRON/PROTON/ANTIPROTON/ION) *
* IONMASS......=   NOT USED      (MASS OF ION IN GEV)                 *
* NUMBER.......=  2500           (NUMBER OF PARTICLES)                *
* CHARGE.......=  2.5000E-07     (CHARGE OF BUNCH)                    *
* TIMESTEP.....=     1           (TIMESTEP, AT WHICH PARTICLES ARE EMITTED) *
* -------------------------------------------------------------- *
* QUANTITY.....=   PULSE         (RADIUS/PULSE)                       *
* WIDTH........=  5.0000E-09     (RADIUS/LONGITUDINAL DURATION OF THE BUNCH) *
* DISTRIBUTION.=   GAUSSIAN      (UNIFORM/GAUSSIAN/PARABOLIC/SPECIAL) *
* KIND.........=   RANDOM        (SYSTEMATIC/RANDOM)                  *
* SHOW..........                                                      *
* RETURN........                                                      *
******************************************************************
BUNCH>
```

Figure 1: Menu of the *bunch-section* of TS2. In this section some beam parameters, e.g. charge, number of particles, and the pulse distributions, are set with their initial values

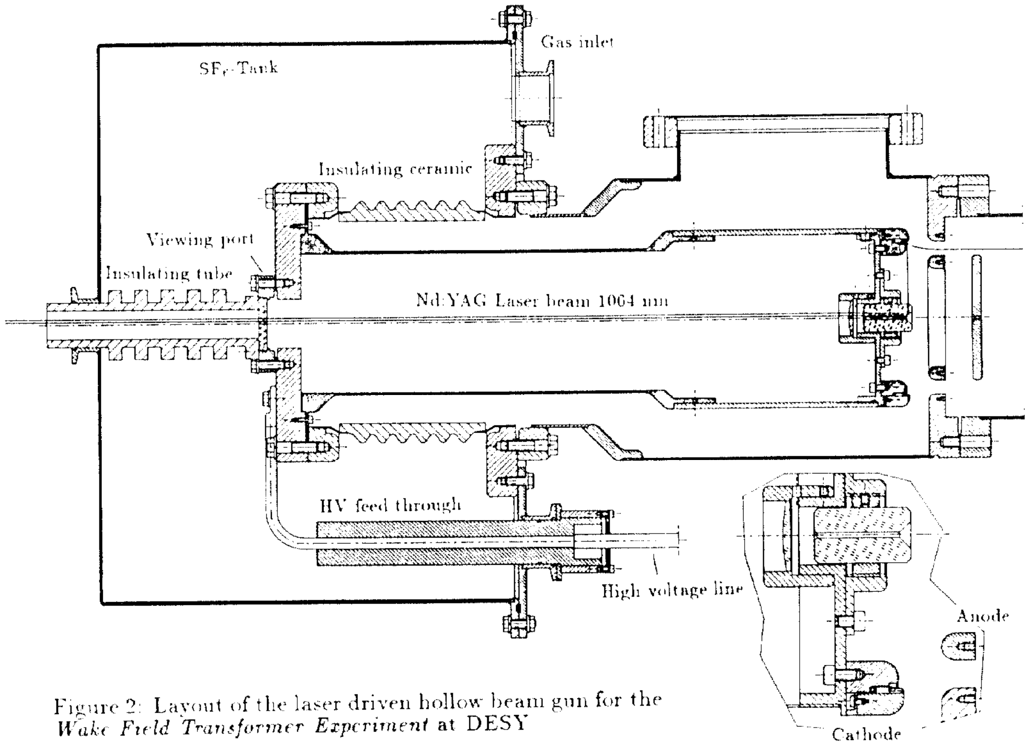

Figure 2: Layout of the laser driven hollow beam gun for the *Wake Field Transformer Experiment* at DESY

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 TS2 it is replaced by an explicit algorithm: In the first step, the momentum 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 TBCI-SF[7]. 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. Gauss' Law is used to correct the fields when charge is not conserved in the current calculation. TS2 checks the results every few time steps.

The Simulation of the Hollow Beam Gun for the Wake Field Transformer Experiment

At DESY a hollow beam gun was developed and tested. The gun is driven by a pulsed Nd:YAG laser (wavelength 1.064μm). The maximum energy of the laserpulse is 900 mJ. The ring-cathode of the electron gun has a radius of 5.5 cm. The electrons are extracted from the cathode by thermionic emission and thermionic supported photoelectric emission. Then the electrons are accelerated by an applied high voltage of up to 140 kV. The longitudinal duration of the electron bunch is 5 ns, the measured peak current is approximately 75 A. The final diameter of the hollow beam, as measured, is 10 cm and its thickness is 0.3 mm. The repetition rate for the production of electron pulses in the test gun is 20 Hz.

With the particle-in-cell code TS2 the cathode-anode-configuration of the hollow beam gun was simulated. The length of the simulated part of the gun is 7.5 cm. In Figure 2 the layout of the hollow beam gun, as it was tested at DESY is shown. In the simulation, one bunch with a parabolic shaped pulselength of 5 ns was emitted radially from the cathode. In Figure 3 the simulated cathode-anode-configuration with the electric field is shown. The cathode is on the left, the anode on the right hand side. In the calculation the bunch is emitted with an initial energy of 10 eV. After emission, the particles are accelerated by the applied field. In Figure 4 the positions of the electron bunch, represented by 3000 macroparticles, at two different timesteps, are shown.

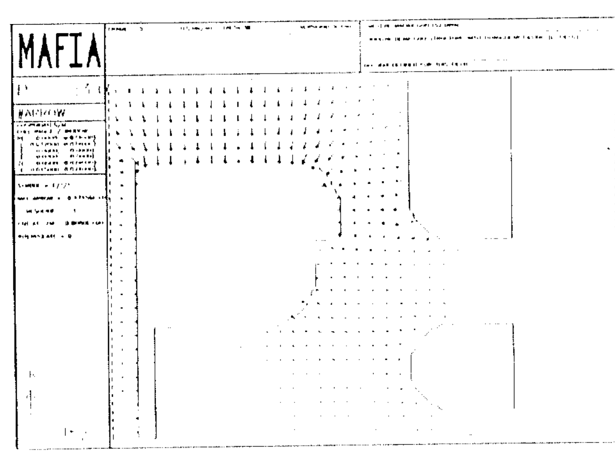

Figure 3: Simulated structure of the hollow beam gun

We varied the peak current of the electron pulse between 5 A at 20 kV and 75 A at 140 kV of the accelerating high voltage. With a simulated current monitor, 5 mm behind the anode, we observed parabolic shaped current distributions with peak values between 5 A and 75 A. The increasing kinetic energy of an electron bunch, accelerated by the field between the cathode and the anode, is shown in Figure 5.

Then we increased the charge by a factor of two. As a result of these calculations, we found that the peak current at the position of the monitor decreased. For an applied voltage of 80 kV and an initial peak current of 60 A, the peak current, seen by the simulated monitor decreased to 50 A. The same ratio of initial to final peak current was found for a voltage of 100 kV and 100 A initial peak current. For an applied voltage of 140 kV, the final peak current is reduced by nearly 30 % from 150 A to 109 A. This can be interpreted as an effect of the space-charge forces.

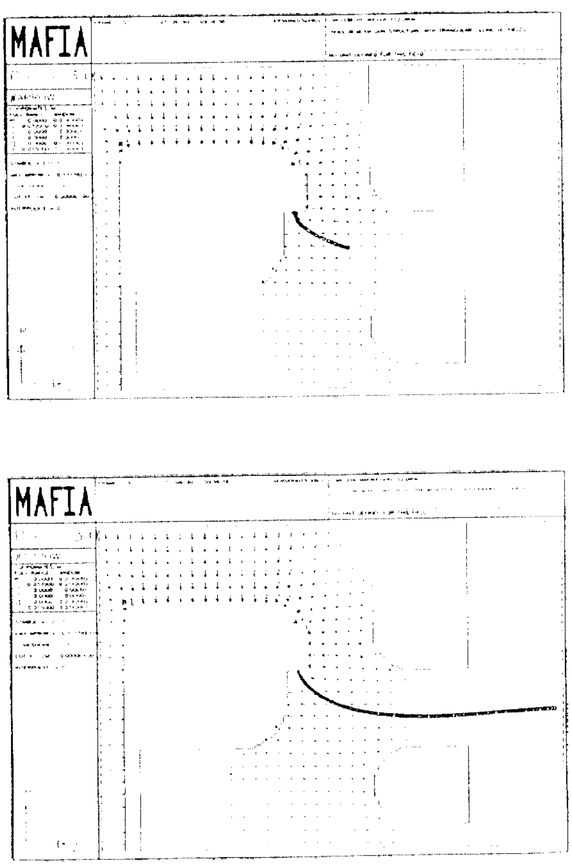

Figure 4: Position of the emitted electron bunch at two different timesteps

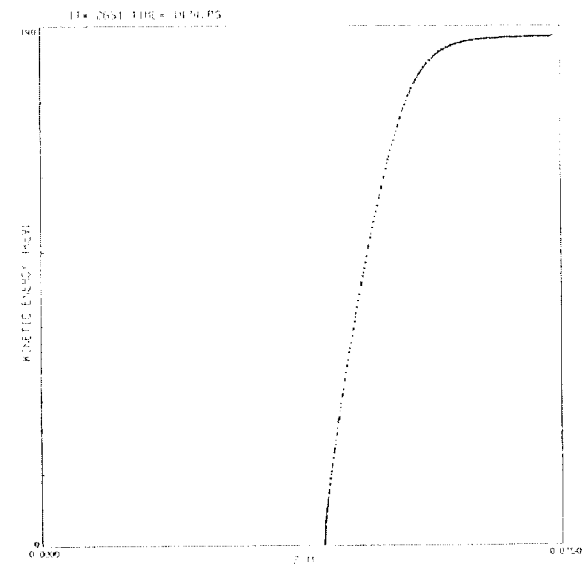

Figure 5: Kinetic energy (keV) of the elctron bunch. The applied voltage is 140 kV

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