

Development of simulation tools for numerical investigation and computer-aided design (CAD) of gyrotrons

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Abstract. As the most powerful CW sources of coherent radiation in the sub-terahertz to terahertz frequency range the gyrotrons have demonstrated a remarkable potential for numerous novel and prospective applications in the fundamental physical research and the technologies. Among them are powerful gyrotrons for electron cyclotron resonance heating (ECRH) and current drive (ECCD) of magnetically confined plasma in various reactors for controlled thermonuclear fusion (e.g., tokamaks and most notably ITER), high-frequency gyrotrons for sub-terahertz spectroscopy (for example NMR-DNP, XDMR, study of the hyperfine structure of positronium, etc.), gyrotrons for thermal processing and so on. Modelling and simulation are indispensable tools for numerical studies, computer-aided design (CAD) and optimization of such sophisticated vacuum tubes (fast-wave devices) operating on a physical principle known as electron cyclotron resonance maser (ECRM) instability. During the recent years, our research team has been involved in the development of physical models and problem-oriented software packages for numerical analysis and CAD of different gyrotrons in the framework of a broad international collaboration. In this paper we present the current status of our simulation tools (GYROSIM and GYREOSS packages) and illustrate their functionality by results of numerical experiments carried out recently. Finally, we provide an outlook on the envisaged further development of the computer codes and the computational modules belonging to these packages and specialized to different subsystems of the gyrotrons.

1. Introduction

Powerful gyrotrons with megawatt output power and frequencies ranging from 77 to 170 GHz are necessary for electron cyclotron resonance heating (ECRH), electron cyclotron current drive (ECCD) [1, 2] and ECH-assisted start-up of magnetically confined plasmas in various reactors for controlled thermonuclear fusion (tokamaks and stellarators) as well as for plasma control and stabilization (e.g., NTM suppression and MHD control). The gyrotrons are used also for plasma diagnostics based on a collective Thomson scattering (CTS).

It is commonly accepted and well understood that the capabilities of the simulation tools (physical models and numerical codes) is of crucial importance for a successful computer-aided design (CAD) and optimization of high performance gyrotrons with improved operational characteristics (higher



efficiency, stability of the operation, mode purity, high-quality RF beam with a maximized Gaussian content, and so on). All this motivates the researchers involved in the development of gyrotrons for fusion to work on the improvement of the available simulation tools and on the development of novel more adequate physical models and software packages for numerical investigation and optimization of both the currently used and the future designs of these tubes. Our research team has been involved in the maintenance and further development of a great number of standalone computer programs and problem oriented software packages that are being used in the course of the CAD of gyrotrons for fusion. The work on these topics is being carried out in accordance with a recently formulated novel concept [3–6] for further improvements to the available simulation tools as well as for development of a new generation of numerical codes based on more adequate physical models, efficient numerical methods and algorithms, advanced (state-of-the-art) computational platforms. The main results obtained so far have been presented in the recent publications [7–13]. It should be noted also that in recent years the international collaboration of the Bulgarian research group has been extended to FIR FU Research Center at the University of Fukui (Japan). Although the gyrotrons that are being developed at FIR FU (except these for CTS plasma diagnostics) are dedicated to other applications, the fact that they operate on the same physical principles makes it possible to use common models and numerical codes for CAD and numerical studies of both classes of devices [13].

2. Current status of the simulation tools

GYROSIM [11] is a problem-oriented software package which includes numerical libraries and source codes of various computational modules (standalone programs, subroutines, pre-, post-processing, and visualization codes) for solving a variety of problems pertinent to the simulation and CAD of gyrotrons using a rich set of adequate physical models. Its structure is presented in Figure 1. The individual components of GYROSIM are used successively in an iterative design loop, during which numerical experiments are being performed for simulation of all main subsystems of the gyrotron tube, notably: (i) the electron-optical system (EOS), (ii) the magnetic system which includes the main magnet and an arrangement of additional coils, (iii) the electrodynamical system (resonant cavity), and (iv) the quasi-optical system for mode conversion and transmission of the radiation. The codes for numerical modelling of the EOS (GUN-MIG/CUSP) are based on a relativistic 2.5D physical model. GYROSIM includes also various cavity codes in which different physical models are implemented, e.g., time independent (static), time dependent, cold cavity, and self-consistent codes. The module GO&ART (which stands for Geometric Optics and Analytic Ray Tracing) of the GYROSIM package consists of several codes (RAYS, COMODES, and TRACE) for analysis of quasi-optical components (Vlasov and Denisov type launchers, reflectors and phase-correcting mirrors, and so on) as well as systems based on them (e.g., internal mode converters and transmission lines).

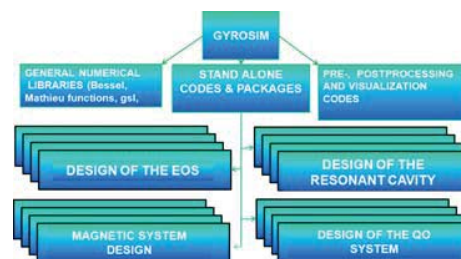


Figure 1. Structure of the package GYROSIM.

It should be mentioned that GYROSIM is a heterogeneous package since it includes components written in different languages (Fortran 77, Fortran 90, C, C++, SciLab, and so on), operational and/or portable to different computational platforms (ranging from laptops and workstations to mainframe

and supercomputers), and executable under different (genuine as well as emulated/virtualized) operating systems (e.g., Unix, Linux, Windows, Cygwin). Another characteristic feature of the package is that it is being built following a concept of extensibility which allows us to add/replace easily different computational modules and in such a way to modify accordingly both the numerical algorithms and the physical models implemented in the programs.

GYREOSS has been initially conceived as a package of codes for simulation of EOS using a physical model formulated in three space dimensions (3D) in order to take into account the departure from axial symmetry due to various misalignments (for instance of the electrodes, of the magnetic coils, etc.) and non-uniformities [8, 10, 12]. Its first version has been implemented using the *gmsh* package for meshing, pre- and post-processing and *GetDP* as a solver [14]. In the recent years, however, GYREOSS has evolved as a test bench for experimenting with different numerical methods, solvers and algorithms in 3D aiming the final goal – a parallel 3D code for numerical simulation and CAD of EOS of gyrotrons. The latest version of GYREOSS is being developed using the FreeFEM++ problem solving environment [15]. Recently, a novel field solver in both 2D and 3D has been developed. It provides the components of the electromagnetic fields at the current particle locations for the relativistic particle pusher in which the Boris–Buneman scheme is implemented. The computational modules of the GYREOSS package developed so far are presented in Figure 2. They include practically all components that are needed for PIC simulations and trajectory analysis of EOS of gyrotrons. Among them are modules for generation of the mesh, magnetic and electric field solvers, relativistic particle pusher, etc. GYREOSS_MAGFI, which calculates the magnetic field produced by an arbitrary set of solenoids, is written in C language while all other modules are programed in the language of FreeFEM++. Depending on the specified parameters (in the modules GYREOSS-parameters and GYREOSS-init_part) different simulations can be carried out (e.g., 2D or 3D simulations, loading various initial particles distributions). The modular structure of GYREOSS allows an easy modification of its components and permits to include more physics in the envisaged (planned) future versions in order to take into account those physical factors that are neglected so far (for instance the dynamics of the trapped particles, space-charge compensation and so forth).

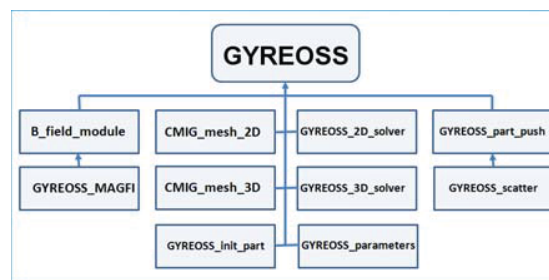


Figure 2. Computational modules of the GYREOSS package.

Some examples that characterize the visualization capabilities of the package GYREOSS are shown in figures 3 and 4, where screenshots from different stages of the numerical experiments are presented. The geometry input and generation of a tetrahedral mesh for simulations in 3D are illustrated in Figure 5, where the configuration of the EOS of a 170 GHz/2MW gyrotron with a coaxial cavity is shown.

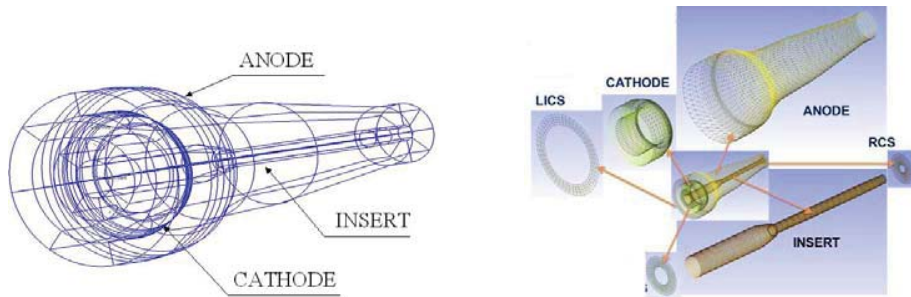


Figure 3. Geometry description (*left panel*) and boundary meshes (*right panel*) of the computational domain (including the closing surfaces on which Neumann boundary conditions are specified) used in the numerical experiments.

It should be noted that GYREOSS is able to use not only meshes generated by FreeFEM++ (which uses its own geometry description) but can import also meshes in *gms* format. While the CAD system *gms* provides means for an optimization of the mesh the FreeFEM++ package possesses powerful tools for mesh adaptation (based on a metric) with an automatic computation of the metric from a Hessian of the solution. Maps of both the potential distribution and the electric field calculated by the field solver are shown in Figure 4. The trajectories of the particles representing the electron beam in the EOS and traced using the novel relativistic particle pusher are plotted in Figure 5.

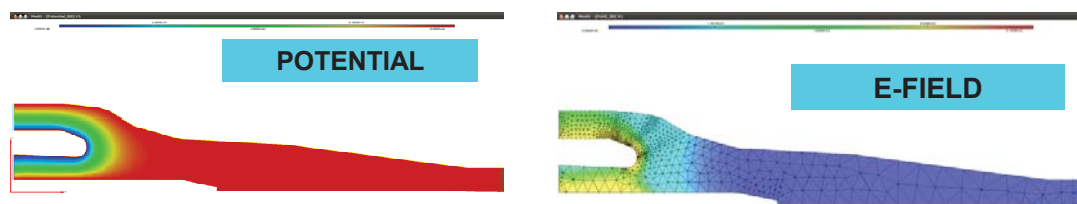


Figure 4. Maps of the potential distribution and the electrostatic field in a coaxial EOS of a 170 GHz, 2MW gyrotron.

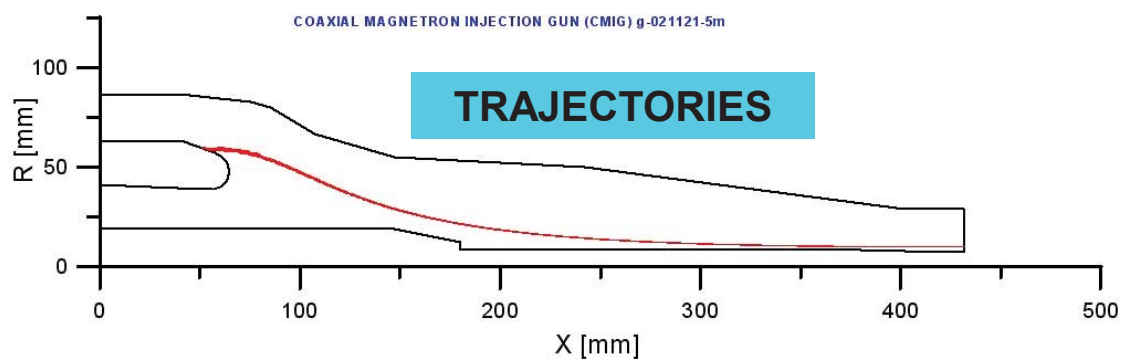


Figure 5. Electron trajectories traced by the novel relativistic particle pusher in the EOS.

An important step of any self-consistent PIC simulation is the space charge allocation (scattering) to the computational grid. Since this step of the algorithm is one of the most time-consuming its speed is of critical importance for the minimization of the required computational resources (CPU time and

memory) as well as for the optimization of the overall throughput of the code. In view of the envisaged (planned) future parallelization of the code (which is considered as an indispensable one for the 3D model) another important requirement to the algorithm is to allow an easy transition from the currently developed sequential version to a parallel one. To solve these problems an efficient algorithm has been developed. It uses a fast searching algorithm and mesh connectivity information provided by FreeFEM++ and scatters the space charge to the nodes of the grid proportionally to the barycentric coordinates of the particles in a scheme which is compatible with the charge conservation law.

3. Conclusions and outlook

The problem-oriented software packages GYROSIM and GYREOSS, whose current status and functionality have been briefly presented and illustrated in this report, are under continuous and steady development, improvement, and adaptation to the ever-changing computational infrastructure (computer platforms, operating systems and underlying numerical libraries). Although outside the scope of this short paper, several other important topics that are being pursued in parallel with the code development should be mentioned as well. Among them is an ongoing theoretical work directed towards the formulation of novel and more adequate physical models and their subsequent implementation in the computer codes using efficient numerical methods and algorithms. The aim of these studies is to take into account physical factors and phenomena that are usually neglected in the current versions but are known to be of significant importance for the practical design and operation of the gyrotrons. Such are, for example, various electron-beam instabilities; dynamics of the reflected and trapped electrons; space-charge compensation; just to name a few. The computational modules (field solvers, particle pusher, etc.) developed so far and the modular structure of the packages form an appropriate basis for adding more physics in the envisaged and planned further extensions of our simulation tools for analysis and CAD of gyrotrons.

Acknowledgements

This work was carried out in the framework of Task 2.1.2 of the scientific program of the EURATOM-INRNE Association.

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