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MODELING AND SIMULATION OF GYROTRONS FOR ITER

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1. Introduction: scope and main activities of the project

As the most powerful sources of coherent radiation operating in a continuous wave (CW) mode in the sub-terahertz frequency range (i.e., with millimeter and sub-millimeter wavelengths) the gyrotrons are considered as indispensable components of the systems for electron cyclotron resonance heating (ECRH) and electron cyclotron current drive of magnetically confined plasmas in various reactors (most notably of the tokamak type) for controlled thermonuclear fusion [1, 2]. Additionally, they are used for startup (ignition), stabilization (e.g., NTM suppression and MHD control) and diagnostics of the plasma [3, 4]. It should also be noted that the gyrotrons are the only sources of RF heating, which can be both localized and steerable. The ECH system of ITER, for example, requires 24 MW installed RF power (20 MW launched in the plasma) at 170 GHz for heating and 3 MW at 127 GHz for plasma startup. According to the technical specification of the ITER project, the requirements to the gyrotrons are: (i) output power not less than 0.96 MW at the matching optic unit (MOU); (ii) output frequency of 170 ± 0.3 GHz; (iii) pulse length 3600 s; (iv) RF efficiency not less than 50 %; (v) Gaussian content of the wave beam greater than 95%; (vi) frequency of power modulation 3 – 5 kHz; (vii) reliability not less than 95 %. The state-of-the-art of the gyrotrons for fusion is summarized in [5]. Their high performance is a result of several advanced concepts incorporated in the design of the tubes, most notably: (i) internal mode converter; (ii) CVD diamond output window; (iii) efficient coupling of the gyrotron beam with the transmission line system through a MOU; (iv) depressed collector; (v) LHe and LHe-free cryomagnets, etc. Gyrotrons with an output power exceeding 1 MW (in the range 1.2 – 2 MW) represent well the current power levels achieved worldwide [5, 6]. Among them is the coaxial 170 GHz / 2 MW gyrotron developed by the EGYC (European Gyrotron Consortium, which includes CRPP, KIT, HELLAS, IFP-CNR) and is produced by Thales Electron Devices (TED). The short-pulse (in the millisecond range) pre-prototype of this tube achieved at KIT the record power of 2.2 MW at 30 % efficiency without SDC (and 45 % efficiency at 2 MW) and 96 % Gaussian mode purity [4]. However, despite these positive results, serious problems of different nature have been encountered during the recent tests (internal tube failure, operation on a wrong mode, parasitic and after-cavity oscillations, lower-than-expected efficiency, arching, to mention just a few) [7, 8]. In order to surmount these problems, it was decided in 2012 (see, for example, Ref. [9]) to switch to the development of 1 MW / 170 GHz gyrotrons with a conventional (cylindrical) cavity using the experience gained during the design and operation of other similar tubes, e.g., 1 MW / 140 GHz for the W-7X stellarator [10]. At the end of this concise introduction to the subject of our research – powerful gyrotrons for fusion – it should be mentioned that despite the remarkable achievements demonstrated recently there are many challenges and problems (physical, engineering and technological) that have to be addressed. They require further theoretical, numerical and experimental investigations. In this respect, modeling and simulation, as well as numerical experiments, are essential tools for analysis, comparison and optimization of different novel designs of the tube's main subsystems and, eventually, for computer aided design (CAD) of the entire design.

At present, the European gyrotron community uses a great number of stand-alone computer codes and several problem-oriented software packages for numerical studies and CAD of various subsystems (electron-optical system; electrodynamical system; quasi-optical system) of powerful gyrotrons (see figure 1). In them, a wide variety of physical models with different levels of adequacy (ranging from self-consistent to phenomenological, time-dependent to static, etc.) is implemented. Most of them however, are static and are formulated in a two-dimensional coordinate space (2.5D physical models) and thus do not take into account a number of factors (e.g., violation of the axial symmetry; misalignment of the coils, electrodes and so on; nonuniformity of the emission, space–charge compensation and many others). Our research team has been involved in the maintenance and further refinement (improvement, optimization, and enrichment) of the available simulation tools (physical models and computer programs), as well as in the development of novel ones. The work on this topic is being carried out in collaboration with the Institute for Pulsed Power and Microwave Technology at Karlsruhe Institute of Technology, the Association EURATOM–KIT (KIT-IHM) and the Centre de Recherches en Physique des Plasmas, École Polytechnique Fédérale de Lausanne**,** Association EURATOM–Confédération Suisse (CRPP-EPFL).

The scope of the project (Task 2.1.2) encompasses all aspects of modeling and simulation, namely: (i) theoretical work on the formulation of adequate, informative (but still numerically traceable) physical models taking into account as much as possible physical factors and phenomena; (ii) selection of appropriate numerical methods, programing libraries and environments for development of efficient algorithms describing mathematically the physical model; (iii) programming the computational modules (program implementation of the algorithms); (iv) numerical experiments for testing and benchmarking of the simulation tools, as well as for analysis of concrete designs of powerful gyrotrons.

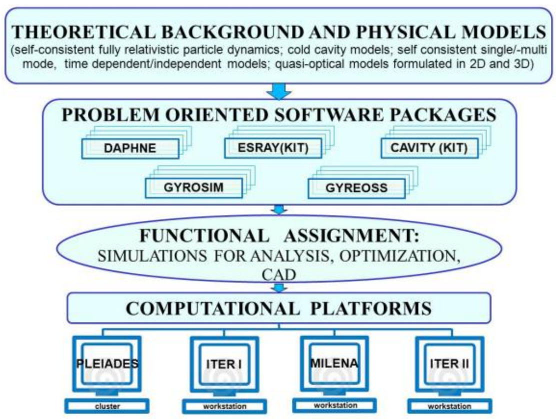

Figure 1. Structure of the simulation tools and computational infrastructure for numerical studies and CAD of gyrotrons.

The work in the above-mentioned directions follows a concept that has already been formulated in the preceding investigations [11, 12], but which has been subject to a steady and continuous development ever since [13–18]. According to this concept, the most characteristic distinguishing features of the next generation of codes are: (i) increased physical content (i.e., more physical factors and phenomena taken into account including a transition from 2D to 3D models); (ii) higher computational efficiency (economical and optimized use of computational resources, such as run time and memory); (iii) extensibility; (iv) portability to different platforms and operating systems including execution on different parallel computers.

2. Current status and functionality of the problem-oriented software packages

The hierarchy and structure of the simulation tools are presented in figure 1, together with the computational platforms on which the different packages are operational.

2.1 DAPHNE

DAPHNE package [14] (developed at CRPP-EPFL) is a programming environment for optimization of EOS of gyrotrons. It is based on an adequate self-consistent physical model (formulated in 2.5D) which consists of a field part (a boundary value problem with Dirichlet and Neumann boundary conditions for the Poisson equation that governs the electrostatic potential distribution taking into account the space charge) and a dynamical part, which contains the relativistic equation of motion of charged macro particles representing the electrons of the beam. The computational region (2D meridional cross-section of an axially symmetric EOS) is discretized using a structured mesh with rectangular cells. DAPHNE is embedded in the ASTRID problem solving environment, which includes: a data base management system for memory and data handling (MEMCOM); a 3D adaptive mesh generator; the ASTRID finite element solver, a graphic system for visualization, a command language and interfacing modules. DAPHNE is implemented as a script written in ASTRID's command language and includes the two modules CFI (for calculation of the magnetic field of the coils of the tube) and PART (for integration of the equations of particles motion) written in FORTRAN. The script invokes successively both the particle pusher (PART) and the Poisson solver in an iterative loop until the process converges to a self-consistent solution.

2.2 ESRAY (KIT)

ESRAY (KIT) [14, 17] is also a problem-oriented package for trajectory analysis (ray-tracing) of EOS based on a fully relativistic 2.5D electrostatic physical model. Its most characteristic distinguishing features are: (i) an object-oriented program implementation in C++; (ii) an advanced mesh generator which discretizes the computational domain with a great accuracy by structured boundary-fitted grids; (iii) versatile post-processing capabilities and visualization of all scalar and vector physical fields by color maps; (iv) a fast own solver for the boundary value problem by the finite difference method. The package consists of several modules: GRIDGEN (for geometry description and mesh generation), MAGGEN (for calculation of the magnetic field produced by a system of solenoids), ESRAYS (for iterative solution of the self-consistent field problem), and OVIS. The latter module serves as a GUI and postprocessor that presents and visualizes the results of the simulation.

2.3 CAVITY (KIT)

The problem-oriented software package CAVITY (KIT) consists of a hierarchy of codes that begins with simple programs (e.g., for an analysis of the mode spectrum; cold-cavity code, single-mode self-consistent code) and culminates in the most sophisticated self-consistent multimode time-dependent code SELFT. Both the structure of the package and the physical models implemented in its modules have been reviewed recently [17]. The codes are written in FORTRAN and are invoked through a GUI. The GUI itself is in fact a Tcl/Tk script for a Linux (Unix) bash shell that controls: (i) the interaction with the codes, (ii) the specification of the input data, and (iii) the visualization of the results using a set of single commands in the menu window.

2.4 GYROSIM

GYROSIM 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 [18]. Unlike the other packages described above, it is not, however, specialized to only one subsystem of the gyrotron tube. Rather, the individual components of GYROSIM are designed 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. It should be mentioned that the codes for numerical modelling of the EOS (GUN-MIG/CUSP) are based on a 2.5D physical model, which is analogous to the one implemented in DAPHNE and ESRAY, and, therefore, provides results that are consistent and in a good agreement with each other. Besides the differences in their program implementation, GUN-MIG/CUSP, however, allows magnetron injection guns (MIG) with a reversal of the magnetic field (e.g., a magnetic cusp) that form axis-encircling (aka uniaxial) beams to be simulated with an increased accuracy. Similarly, the codes of GYROSIM for simulation of the electrodynamical system cover the same functionality as the CAVITY (KIT). At the same time, there are some notable differences between them. For instance, the CAVITY (KIT) can treat both conventional and coaxial resonators but at fundamental operation, while the cavity codes belonging to GYROSIM are specialized only to cavities without an insert but can simulate operation at the second (and in the case of a large orbit gyrotron (LOG), even higher) harmonic of the cyclotron frequency. In its current form, the GYROSIM is a heterogeneous package and includes components written in different languages (Fortran 77, Fortran 90, C, C++, SciLab), 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 modify both the numerical algorithms and the physical models implemented in the programs. The latest upgrade of GYROSIM package has been carried out in parallel with the development of a novel module called GO&ART (which stands for Geometric Optics and Analytic Ray Tracing). It consists of several codes (RAYS, COMODES, and TRACE) for analysis of quasi-optical components (Vlasov and Denisov type launchers, reflectors and phase-correcting mirrors, etc.), as well as systems based on them (e.g., internal mode converters and transmission lines).

2.5 GYREOSS

Initially, GYREOSS was conceived as a package of codes for simulation of EOS using a physical model formulated in three space dimensions 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 [15]. Its initial version was implemented using the Gmsh package for meshing, pre- and post-processing and GetDP as a solver. In the recent years, however, GYREOSS has evolved as a test bench for experimenting with different numerical methods, solvers and algorithms in 3D aiming at 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 and medit (a scientific visualization software) but the compatibility with Gmsh is preserved and the latter can be used for generation and optimization of the tetrahedral mesh (alongside with the mesher embedded in FreeFEM), as well as for post-operation, post-processing and visualization of the solution. As an illustration, some meshes generated and optimized by Gmsh and used in the recent numerical experiments are shown in figure 2.

In 2012, a novel electrostatic field solver of the GYREOSS software package was developed and tested. It is parameterized in such a way as to provide convenient data structures of the electromagnetic fields at the current particle positions in both 2D and 3D. Figure 3 presents several screenshots that illustrate the visualization capabilities of GYREOSS. Figure 3a shows a map of the electrostatic potential distribution obtained in one of the test runs. The corresponding electrostatic field is shown in figure 3b.

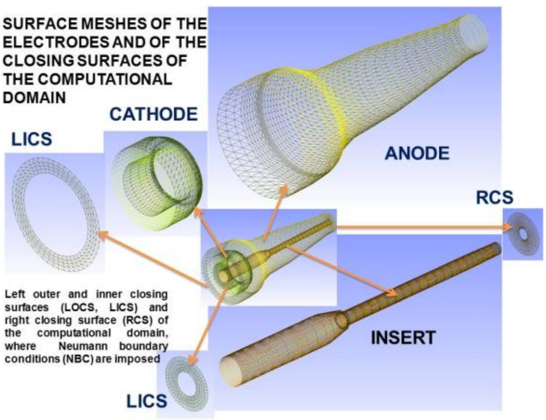

Figure 2. Surface meshes representing the electrodes of a coaxial gyrotron (2 MW/170 GHz) simulated by GYREOSS.

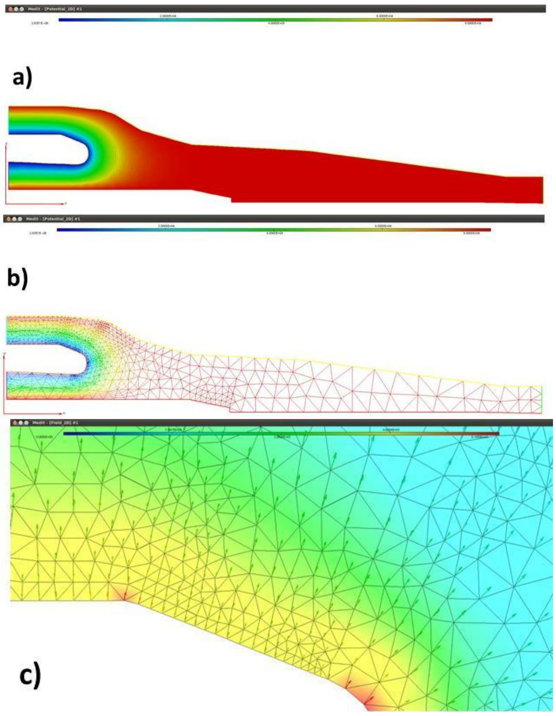

Figure 3. Electrostatic potential distribution (a); equipotential lines over the mesh (b); map and a vector representation of the electrostatic field near the emitting ring of the cathode (c), in a meridional cross-section of a coaxial magnetron injection gun (MIG) of the studied 2 MW/170 GHz gyrotron**.**

Another important task pursued during 2012 was the development of an efficient module for integration of the relativistic Newton–Lorentz equations of motion of beam electrons (usually referred to as a "particle pusher" aka "particle mover") formulated in 2D and 3D. It uses the data structure of the electromagnetic field values at the current particle positions, provided by the novel field solver described above and realized with an intended prospective parallelization of the

PIC algorithm of GYREOSS. As a preparation, different methods for particle tracing were considered and analyzed. Among them were the schemes of Boris (Tajima’s Implicit Method), Boris–Bunneman, Runge–Kutta 4th order method, Verlet’s method, and the predictor–corrector method. As many researchers did before us, and having evaluated all important factors (accuracy, stability, CPU time etc.), we finally selected the leapfrog method of the relativistic Boris–Bunneman scheme. The algorithm realized is convenient because it requires only one force evaluation per time step and needs memory for storage of only one set of coordinates and velocities for each particle. It should be noted, however, that several other advanced schemes (e.g., Lorentz invariant advance) deserve consideration and we plan to study them as well. We also intend to implement an adaptive calculation of the optimal time step (for an arbitrary gyro-frequency), which will minimize the consumed CPU time, while preserving a sufficient accuracy. The more radical optimization, however, is expected after realization of a parallel (multithreaded) implementation of the PIC algorithm of GYREOSS. As mentioned above, a preparation for such parallelization is in progress now and includes studies on MPI, multithreading and building of a computing clusters using as nodes the workstations of the available computational infrastructure at IE-BAS before going to the Pleiades cluster for full-scale simulations.

As an illustration, in figure 4 we present several trajectories traced in a coaxial magnetron injection gun (CMIG) for a 2 MW/170 GHz gyrotron calculated by GYREOSS using its novel particle mover.

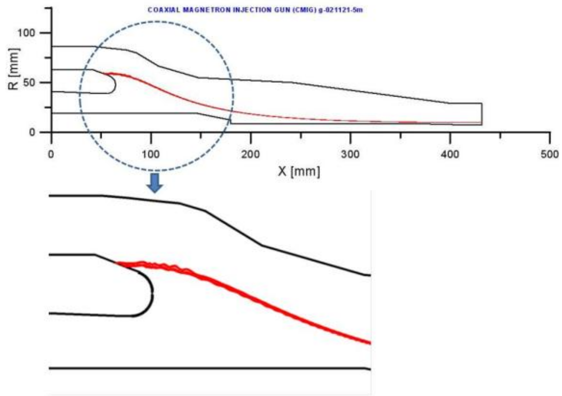

Figure 4. Geometry of the coaxial magnetron injection gun (CMIG) of a 2 MW/170 GHz gyrotron (black color) and electron rays (red color), traced by the novel relativistic particle pusher of the GYREOSS package.

3. Computational platforms used for code maintenance and development

All packages outlined above (CAVITY, ESRAY, GYROSIM, GYREOSS) are installed and are operational on the workstations of the Bulgarian research team (see figure 1), except DAPHNE, which is available to us for remote execution and maintenance on the PLEIADES2 cluster from Sofia. Since the outstanding performance of PLEIADES2 is well known, we will mention only the basic characteristics of the most powerful of our workstations. ITER I has two CPU AMD OpteronTM Dual Core 275, 2.2 GHz and RAM 4 GB DDRAM with a MB Supermicro -Dual Opteron and SVGA Nvidia GeForce 6600 TD. The workstation ITER II has 2 CPUs Intel Xeon X5680, 3.33 GHz,12 MB cache, 6 Cores; memory 4×4 GB DDR-31333. On both workstations the operating system is Ubuntu 10.04 (lucid), Kernel Linux 2.6.32-41-generic. Although some of them (e.g., DAPHNE, ESRAY-IHM, CAVITY-IHM, and various components of GYROSIM) are well validated, benchmarked and debugged, they are undergoing constant adaptation and upgrade to the ever-changing computational environments (hardware, operating systems, novel versions of the compilers and numerical libraries). Alongside with the maintenance of these codes and their usage in numerical experiments, we are working on the further development of the GYREOSS and GYROSIM packages.

4. Conclusions and outlook

The problem-oriented packages outlined in the previous section are under continuous development and improvement. Recently, they were used in a series of numerical experiments carried out to study the designs of powerful gyrotrons that are under consideration and/or development at present. The simulations conducted give a deeper physical insight into the operation of high-performance megawatt-class gyrotrons and are good benchmarks that demonstrate the improved capabilities and functionality of the upgraded codes. Moreover, these results suggest some further experiments for more detailed study of the correlation between the beam-quality parameters and efficiency, on one hand, and the particular design (configuration of the electrodes, tailoring of the magnetic field, etc.), on the other. It is expected that the novel and upgraded versions of the simulation packages will contribute to the development of the next generation of powerful gyrotrons for fusion with an improved performance.

Acknowledgements

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