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MODELING AND SIMULATION OF GYROTRONS FOR ITER

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1. Motivation, scope and main activities of the project

High-power 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 collective Thomson scattering (CTS). Typical tubes that illustrate the state-of the-art in the development of gyrotrons for fusion are: megawatt-class CW gyrotrons with frequencies of 77 GHz for LHD, 110 GHz for JT-60SA and DIII-D, 140 GHz for W7-X, 170 GHz for ITER developed in EU, Japan, Russia, and US [3]. For example, the planned ECH and current drive (ECH&CD) system of ITER requires 24 MW installed power (20 MW delivered to the tokamak in a CW mode for 60 min) at 170 GHz and additional 3 MW at 120 GHz (~3 s) for assisting the initial breakdown. 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%. For DEMO, however, gyrotrons operating at 230–250 GHz, with step-tunability and broadband window are considered in the current design. A step-tunable 1 MW gyrotron with a frequency range 105–163 GHz has been designed and tested by IHM-KIT. For CTS on LHD a series of tubes (second harmonic 398 GHz/83 kW, and fundamental 295 GHz/0.22 MW, 77 GHz/1.9 MW) are under development. The breakthrough achievements demonstrated recently by these gyrotrons are stipulated by advanced designs concepts that are based on the use of: high performance electron-optical system (EOS); internal quasi-optical mode converter; output window of synthetic CVD-diamond; and depressed collector for energy recovery (recuperation). At the same time, despite the remarkable and promising achievements of the European 2 MW/170 GHz coaxial gyrotron, a number of problems have been encountered in an attempt to demonstrate a stable long-pulse operation in a CW mode. Due to these problems, F4E and EGYC (European GYrotron Consortium, which includes CRPP, Switzerland; KIT, Germany; HELLAS, Greece; CNR, Italy; ENEA, Italy, Thales, France) have decided to switch to a conventional cavity 1 MW CW 170 GHz $TE_{32,9}$ mode backup gyrotron replacing the EU 2 MW CW 170 GHz coaxial-cavity gyrotron. Currently, KIT is finalizing the construction and testing (due to be completed in 2014) of a novel 140 GHz, 1 MW CW gyrotron with an improved design for the W7-X stellarator in Greifswald, Germany [4]. In parallel, a feasibility study of a gyrotron operating at 240 GHz for future plasma fusion devices is underway at KIT as well. The main aim is to select an appropriate operating mode and to optimize the geometry of the cavity resonator in order to achieve an output power of about 1.5 MW [4]. Tubes that generate at even higher frequencies (up to 300 GHz) and allow frequency step-tunability are also under consideration at present [4].

According to the EFDA's Work Program 2014 (see WPHCD: H&CD Systems section of the Program) the planned activities for EC R&D include the design and start of fabrication of a pre-prototype of a step-tunable high frequency (250 GHz) gyrotron and an analysis of the integrated gyrotron parts (subsystems), while the work planned in the EC Concept Design & Analysis section of the same Program is focused on a preliminary conceptual design specifications of novel gyrotrons, HV power supplies, main transmission lines, launchers etc. The Work Plan for the Implementation of the Fusion Roadmap in 2014-2018 also includes tasks related to the development and analysis of gyrotrons for fusion. Among them are: (i) analysis of the possible designs of broadband output windows (e.g. Brewster angle windows, double-disc cavities, movable double disc arrangements etc.) and selection of appropriate technologies for their manufacturing; (ii) study, design and testing (2015-2018) of multistage depressed collectors; (iii) cold testing of various gyrotron parts (2016-2018); (iv) prequalification of gyrotron prototypes (2019).

It is now commonly accepted and well understood that the capabilities of the simulation tools (physical models and numerical codes) are 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 etc.). 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 in the framework of the collaboration between the Institute for Pulsed Power and Microwave Technology at KIT Karlsruhe (Germany), Centre de Recherches en Physique des Plasmas, École Polytechnique Fédérale de Lausanne (Switzerland), Institute of Electronics of the Bulgarian Academy of Sciences and Faculty of Physics of Sofia University (Bulgaria). The work on these topics is being carried out in accordance with a novel concept 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 [5–8]. The main results obtained so far have been published in references [9–15]. 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. Therefore, such collaboration leads to cross-fertilization of ideas and approaches and is beneficial for the development of gyrotrons for fusion research.

The scope of the work on the development of the simulation tools for numerical investigation, CAD and optimization of gyrotrons includes: (i) formulation of adequate, self-consistent and informative physical models; (ii) selection of efficient numerical methods and algorithms, programming libraries, integrated development environments (IDE), software for code optimization and debugging and their implementation and usage in the numerical codes for simulation of gyrotrons; (iii) development of pre-processing, processing (computational), and post-processing modules; (iv) maintenance, testing, benchmarking and improvements of the codes; (v) planning and conducting numerical experiments; (vi) analysis of the results and their use in the course of the computer-aided design (CAD) of optimized constructions of gyrotrons with improved performance (e.g. increased efficiency, stability of the output parameters in a CW mode of operation); (vii) integration of all available simulation tools (newly developed and various legacy codes) in problem oriented software packages. As mentioned above, the work on all these aspects of both modelling and simulation of gyrotrons follows a well-defined novel concept [5–14] that imposes the following requirements on the codes under development: (i) portable to different computational platforms and operating systems; (ii) extensible (possessing flexibility in adding new physics); (iii) efficient (using optimal numerical methods and algorithms and utilizing parallel calculations for minimization of the required computational resources); (iv) well-validated (being able to recover the results of the previously tested 2-1/2 D codes; (v) user-friendly (offering convenient pre- post-processing and visualization as well as comprehensive and detailed documentation. Since the whole set of numerical tools is heterogeneous (i.e., different codes are implemented in different algorithmic languages and compiled under different operating systems), its portability is ensured through the use of server emulation and virtualization environments (e.g. DOSBox and VirtualBox).

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

Both 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. The codes that are being maintained and developed are structured in several problem-oriented software packages (most notably CAVITY, ESRAY, GYROSIM, GYREOSS and DAPHNE) and are installed on the work-stations of the Bulgarian research team (see figure 1), except DAPHNE, which was available to us for remote execution and maintenance on the PLEIADES2 cluster from Sofia until the end of March 2013, when this cluster was de-commissioned. The most powerful of our workstations have the following characteristics. 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.

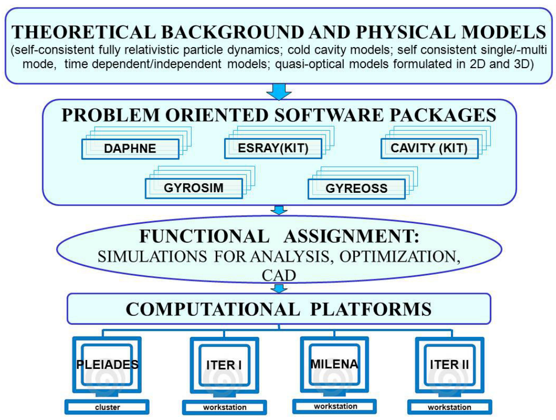

Figure 1. Structure of the simulation tools and computational infrastructure for numerical studies and CAD of gyrotrons.

The workstation ITER II has 2 CPUs Intel Xeon X5680, 3.33 GHz,12 MB cache, 6 Cores; memory 4×4 GB DDR. On both workstations the operating system is Ubuntu 10.04 (lucid), Kernel Linux 2.6.32-41-generic.

The installed packages and the underlying numerical libraries are undergoing constant adaptation and upgrade to the ever-changing computational environments (hardware, operating systems, and novel versions of the compilers). 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. Bellow we summarize briefly the current status of the main simulation tools.

The problem-oriented software package CAVITY (IHM) [11, 12] 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 multi-mode time-dependent code SELFT. 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. During 2013, the package was modified (debugging, code refinement) in order to improve its program implementation and recompiled on the workstations using the latest versions of the underlying development tools (numerical libraries and compilers).

ESRAY (IHM) [8, 11, 12] is 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) object-oriented program implementation in C++; (ii) 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) fast own solver for the boundary value problem by a finite difference method. The package consists of several modules: GRIDGEN (for geometry description and mesh generation), MAGGEN (for calculating the magnetic field of 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. Similarly to CAVITY, during 2013 this package was adapted and recompiled in order to be compatible with the recent upgrade of the software environments on the workstations where it is being maintained. The capabilities of the package have been demonstrated by numerical experiments for analysis of EOS for powerful gyrotrons [15].

GYROSIM [13] 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 2. Unlike the 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 electrodynamic 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 modeling 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, provide 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 (a.k.a. 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.

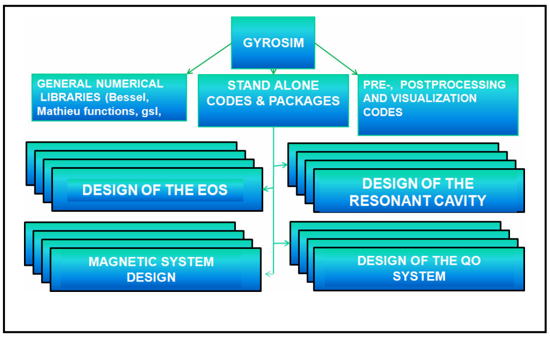

Figure 2. Structure of the package GYREOSS.

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 (i.e., cylindrical resonators) but can simulate operation at the second (and in the case of a large orbit gyrotron (LOG) even higher) harmonics 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, 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 to add/replace easily different computational modules and in such a way to modify both the numerical algorithms and the physical models implemented in the programs. The latest upgrade of the GYROSIM package was 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, and so on) as well as systems based on them (e.g., internal mode converters and transmission lines). Recently, GYROSIM was used for development of a series of high-power sub-terahertz gyrotrons for a broad spectrum of novel applications [16, 17]. The functionality of the latest version of the package was demonstrated by a series of numerical experiments presented in [15].

Initially, GYREOSS was 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 [10, 12, 14]. Its initial version was implemented using the gmsh package for meshing, pre- and post-processing and GetDP as a solver. In 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. Recently, a novel field solver in both 2D and 3D was 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. During 2013, the main focus of the work was the development of a fast charge-conserving algorithm for the space charge allocation (scattering or distribution) to the computational grid.

A characteristic distinguishing feature of GYREOSS is that it uses the advanced visualisation tools provided by gmsh and FreeFEM++. These capabilities are illustrated in the following screenshots taken during different stages of the PIC simulations. Figure 3 shows the input of the geometry description, which is used to produce the meshes used in the computations.

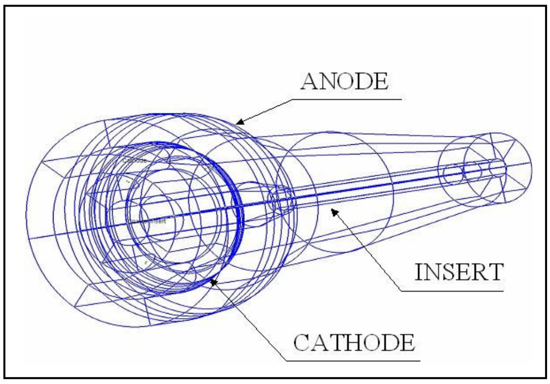

Figure 3. Description of the geometry of a coaxial gyrotron in the CAD system *gmsh.*

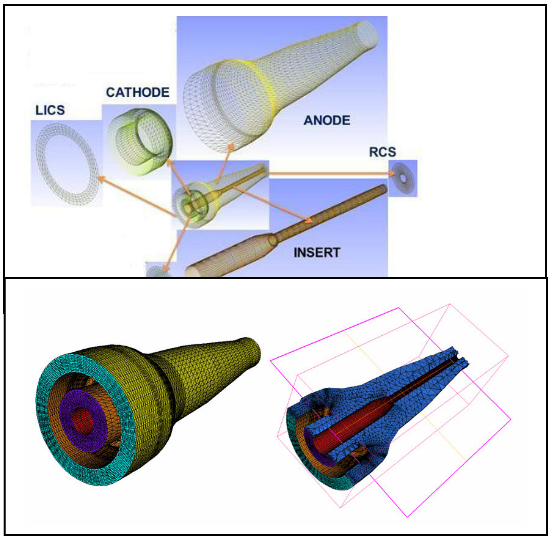

Figure 4. Meshes generated for the geometry of figure 3.

In figure 4 the upper pane represents the boundary meshes at the electrodes (on which Dirichlet boundary conditions are specified) and at the closing planes (with Neumann boundary conditions). The lower pane shows the tetrahedral mesh used in 3D simulations and its cross-section. Maps of the electrostatic potential and the electric field are plotted in figure 5 and figure 6, respectively. The electron trajectories in the studied EOS are traced by the relativistic particle pusher. Their projection in the meridional cross-section of the electron gun are plotted in figure 7.

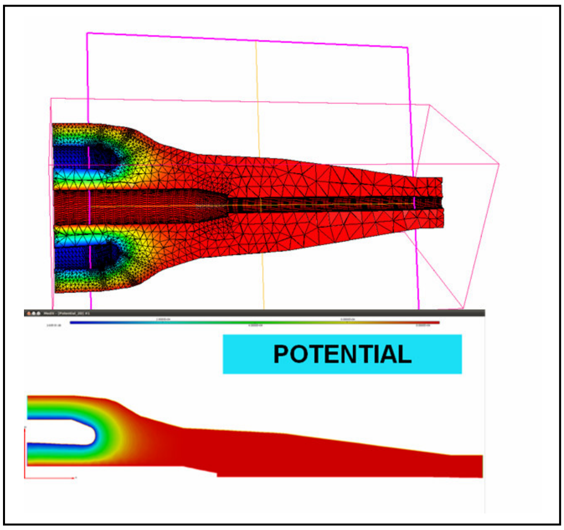

Figure 5. Maps of the potential distribution

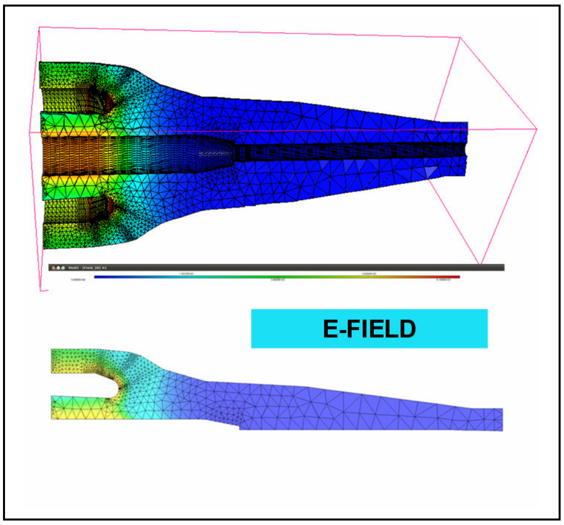

Figure 6. Maps of the electrostatic field.

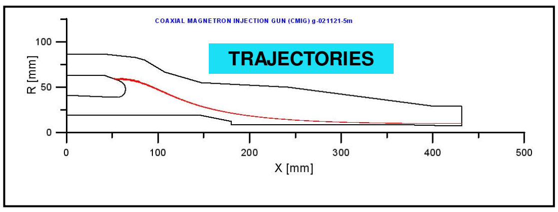

Figure 7. Trajectories of the helical electron beam in coaxial magnetron injection gun (CMIG).

3. Conclusions and outlook

The outlined problem-oriented software packages are efficient tools for numerical studies, CAD and optimization of gyrotrons for fusion. Their codes are under continuous development and improvement. Recently they have been 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 provide a deeper physical insight into the operation of high-performance gyrotrons of megawatt class and demonstrate the improved capabilities and functionality of the upgraded packages. Additionally, the 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 high-power gyrotrons for fusion with improved performance.

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