Journal of Physics: Conference Series

Simulation tools for computer-aided design and numerical investigations of high-power gyrotrons

To cite this article: M Damyanova *et al* 2012 *J. Phys.: Conf. Ser.* **356** 012044

Simulation tools for computer-aided design and numerical investigations of high-power gyrotrons

M Damyanova[1,4], E Balabanova[1], S Kern[2], S Illy[2], S Sabchevski[1], M Thumm[2], E Vasileva[1] and I Zhelyazkov[3]

[1] Emil Djakov Institute of Electronics, Bulgarian Academy of Sciences, Association EURATOM-INRNE, 72, Tsarigradsko Chaussee, 1784 Sofia, Bulgaria
[2] Karlsruhe Institute of Technology, Association EURATOM-KIT, Institute for Pulsed Power and Microwave Technology, Hermann-von-Helmholtz-Platz 1, D-76344 Eggenstein-Leopoldshafen, Karlsruhe, Germany
[3] Faculty of Physics, St. Kliment Ohridski University of Sofia, Association EURATOM-INRNE, 5, James Bourchier blvd., 1164 Sofia, Bulgaria

E-mail: milena@ie.bas.bg

Abstract. Modelling and simulation are essential tools for computer-aided design (CAD), analysis and optimization of high-power gyrotrons used as radiation sources for electron cyclotron resonance heating (ECRH) and current drive (ECCD) of magnetically confined plasmas in the thermonuclear reactor ITER. In this communication, we present the current status of our simulation tools and discuss their further development.

1. Introduction

Gyrotrons are among the most powerful sources of coherent microwaves in the millimeter wavelength region operating in a continuous wave (CW) mode and find diverse use ranging from fundamental research to industrial applications [1]. A typical example is fusion research, where gyrotrons are used as high-power sources of radiation for the start-up (ignition) of magnetically confined plasmas in various reactors for controlled thermonuclear fusion, for electron cyclotron resonance heating (ECRH), electron cyclotron current drive (ECCD)p as well as for stabilization and diagnostics of plasmas. In recent years, the gyrotrons for fusion developed in Europe, Japan, Russia and USA (generating at frequencies between 140 and 170 GHz) have reached the megawatt level of output power. Following this progress, the European Gyrotron Consortium (EGYC) consisting of several research institutions lead by the KIT-IHM, Germany and CRPP-EPFL, Switzerland, is currently developing a coaxial gyrotron with an output power of 2 MW and higher, delivered through a synthetic diamond output window. Despite this progress, however, there still remain certain serious problems and challenges to be addressed. Some of them (e.g., the parasitic oscillations in the beam tunnel; stray magnetic fields; Penning discharges in the technical part of the gun) have already been addressed and partially resolved. At the same time, other problems (for instance, various sources of beam instabilities, non-uniformity of the emission from the cathode [2, 3], trapped particles, space charge compensation, etc.) still pose serious theoretical and technical problems. Some of them are due

[4] To whom any correspondence should be addressed.

to physical factors and phenomena that are three-dimensional and non-stationary (3D) by nature [2, 3]. Therefore, they cannot be adequately described using the currently available physical models and computer codes, which are predominantly two-dimensional (2D) and quasi-static. All this underlines the importance of both improving the available simulation tools as well as developing novel, more efficient, models and programs that can be used for the analysis, computer aided design (CAD) and optimization of high-power gyrotrons with improved performance. A concept for the further development of these simulation tools is formulated in [4]. The first steps towards its realization are presented in [2, 3, 5–7]. In this paper, we review the current status of the simulation tools used and illustrate the functionality of their latest versions.

2. Current status and functionality of the simulation tools for analysis and CAD of gyrotrons

The structure of the simulation software used for analysis, optimization and CAD of gyrotrons is illustrated in figure 1, together with some of the computational platforms onto which different packages are operational. Although some of them (e.g., ***DAPHNE***, ***ESRAY*** [8], ***CAVITY-IHM*** [9], and various components of ***GYROSIM*** [10]) 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 use in numerical experiments, we are working on the further development of the ***GYROSIM*** [10] and ***GYREOSS*** packages.

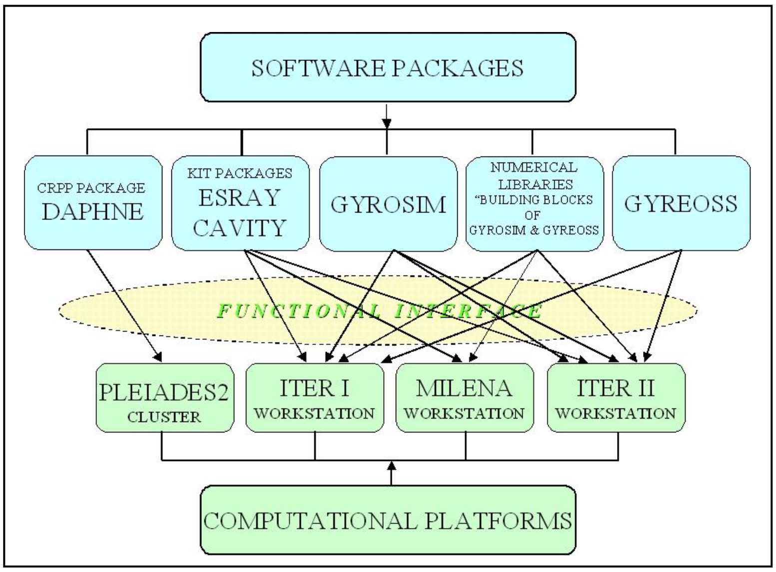
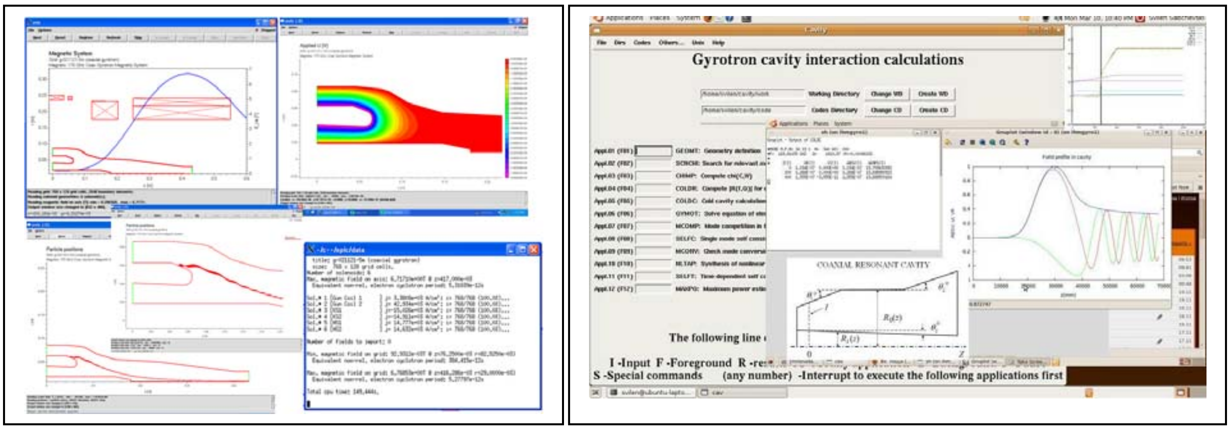


Figure 1. Structure of the software packages for simulation of gyrotrons and computational platforms on which they are operational used by the Bulgarian research team.

DAPHNE and ESRAY are ray-tracing and PIC (Particle in Cell) codes for trajectory analysis of the electron-optical system (EOS) of the tube. The same functionality has GUN-MIG/CUSP of the GYROSIM package. All they are based on adequate fully-relativistic self-consistent 2.5D physical models, but differ in the algorithms and methods employed for the solution of the field problem (boundary value problem for the electrostatic potential), the integration of the equations of motion (particle pushing), as well as in the program implementation. The most advanced amongst them is ESRAY. Advantageous and distinguishing features of this package are: (i) the use of a boundary fitted mesh to discretize the computational region with great precision; (ii) object-oriented program implementation and efficient numerical algorithms that speed-up the computation; (iii) advanced postprocessor for visualization of the results of numerical experiments. The latter is illustrated by a collage of screenshots in figure 2(a).



a) b)

Figure 2. Illustrations of the visualization capabilities of the IHM-KIT packages: a) ESRAY; b) CAVITY.

Both packages, CAVITY (IHN-KIT) and GYROSIM [10], contain a hierarchy of computer codes ranging from simple cold-cavity codes for preliminary analysis to more sophisticated time-dependent and multimode codes. In its current version, the GYROSIM package is specialized only to regular (cylindrical) cavities, while CAVITY (IHM-KIT) can also simulate coaxial gyrotron resonators. The most advanced component of CAVITY is the SELFT code, in which a self-consistent, time dependent, multimode physical model is realized [9]. Different components can be invoked through a GUI (front-end), the navigation screen of which is shown in figure 2(b), together with some illustrative visualization windows.

The main goal of the GYREOSS (which stands for GYRotron EOS Simulation) is the realization of a physical model which is able to take into account the physical factors that are three dimensional in nature. Since the simulation in 3D requires enormous computational resources (as a rule available only on parallel systems, e.g., clusters, grids, clouds etc.) its development involves utilization of advanced programming techniques, numerical libraries and integrated development environments (IDE). Currently, the work on GYREOSS is focused on the development of an efficient 3D field solver based on the finite element method (FEM) on a tetrahedral mesh. The first version (prototype) of GYREOSS was built around the GetDP solver and some of the essential, pre- and post-processing modules were integrated using gmsh. After studying, benchmarking and comparing different numerical libraries, FreeFEM++ has been selected as an appropriate building block to replace GetDP. It will be used for the realization of a novel more efficient solver as well as for programming of some of the other components of the PIC code. In the novel solver, the boundary value problem for the Poisson equation is solved in a mixed finite element formulation. A significant advantage of such an approach is the possibility to approximate the electric field with accuracy higher than when applying the conventional formulation and calculating it through numerical differentiation of the potential. This is especially important for the PIC algorithm since it is the electric field rather than its potential that is required for the calculation of the Lorentz force in view of tracing particle motion. A screenshot of the GUI of GYREOSS is shown in figure 3.

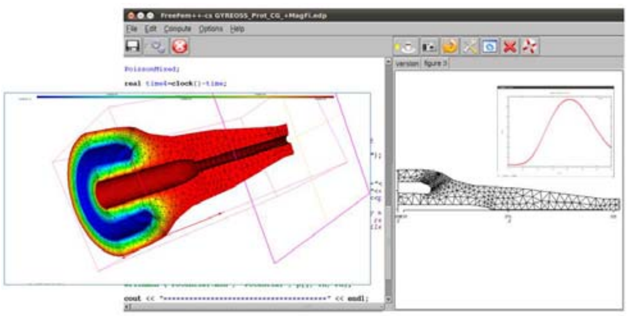


Figure 3. Illustrative screenshots of the GYREOSS code.

Conclusions

The codes outlined above have been used in a series of numerical experiments carried out to study the designs of high-power gyrotrons that are under consideration and/or development at present. The simulations performed provide a deeper physical insight into the operation of high-performance gyrotrons of the megawatt class and demonstrate the improved capabilities and functionality of the upgraded codes. Moreover, these results suggest some further experiments for more detailed studies of the correlation between the beam-quality parameters and the efficiency, on the one hand, and the particular design (configuration of the electrodes and the magnetic field, etc.), on the other. It is expected that the upgraded versions of the simulation packages will contribute to the development of the next generation of improved-performance high-power gyrotrons for fusion.

Acknowledgements

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

References

[1] Thumm M 2011 State-of-the-art of high power gyro-devices and free electron masers (Update 2010) *KIT Sci. Reports* **7575** (KIT Scientific Publishing 2010) 1–131

[2] Sabchevski S, Illy S, Piosczyk B, Borie E and Zhelyazkov I 2008 Towards the formulation of a realistic 3D model for simulation of magnetron injection guns for gyrotrons (a preliminary study) *Wissenschaftliche Berichte FZKA* **7409** 1–34

[3] Malygin A, Pagonakis I, Illy S, Avramides K, Piosczyk B, Kern S and Thumm M 2011 Three-dimensional numerical studies of non-uniform emission in magnetron injection guns *Proc. 8th Int. Workshop Strong Microwaves and Terahertz Waves: Sources and Applications* (Nizhny Novgorod Russia July 9–162011) 99–100

[4] Sabchevski S, Zhelyazkov I, Thumm M, Piosczyk B, Tran T M, Hogge J-Ph and Pagonakis J Gr 2007 Recent evolution of the simulation tools for computer aided design of electron-optical systems for powerful gyrotrons *Computer Model. Engin. & Sci.* **20** 203–220

[5] Sabchevski S and Zhelyazkov I 2007 Modelling and simulation of new generation powerful gyrotrons for the fusion research *J. Phys.: Conf. Series* **63** 012003

[6] Damyanova M, Sabchevski S and Zhelyazkov I 2010 Pre- and post-processing of data for simulation of gyrotrons by the GYREOSS software package *J. Phys.: Conf. Series* **207** 012032

[7] Damyanova M, Kern S, Illy S, Thumm M, Sabchevski S, Zhelyazkov I and Vasileva E 2010 Modelling and simulation of gyrotrons for ITER *Proc. 4th Int. Workshop & Summer School Plasma Phys.* (Kiten Bulgaria July 5–10 2010)

[8] Illy S 1997 Untersuchungen von strahlinstabilitaten in der kompressionzone von gyrotron-oszillatoren mit Hilfe der kinetischen theorie und zeitabhangiger particle-in-cell-simulationen *Wissenschaftliche Berichte FZKA* **6037** 1–145

[9] Kern S 1996 Numerische simulation der gyrotron-wechselwirkung in koaxialen resonatoren, *Wissenschaftliche Berichte FZKA* **5837** 1–245

[10] Sabchevski S, Idehara T, Saito T, Ogawa I, Mitsudo S and Tatematsu Y 2010 Physical models and computer codes of the GYROSIM (GYROtron SIMulation) software package *FIR Center Report FIR FU-99* (http://fir.u-fukui.ac.jp/FIR_FU99S.pdf)