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

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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) 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

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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.

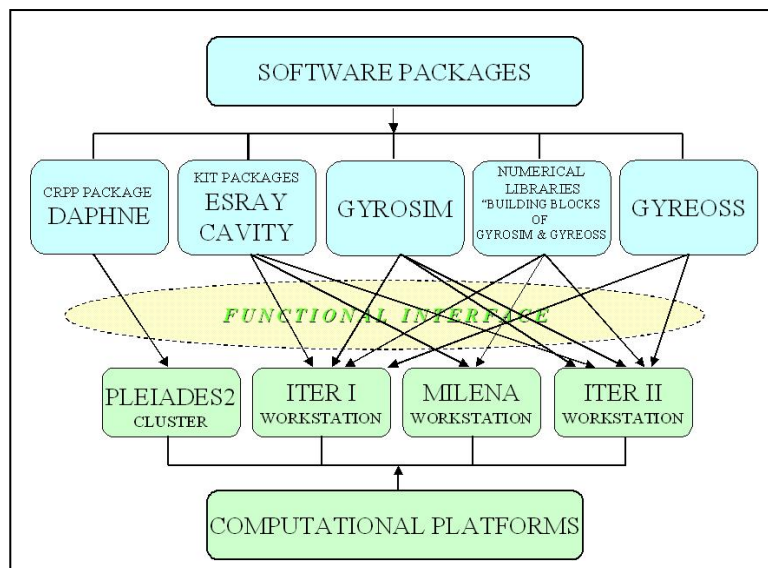


Figure 1. Structure of the software packages for simulation of gyrotrons and computational platforms on which they are operational used by the Bulgarian research team.

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

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.

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