ANNEX 16

Recent improvements of the self-consistent interaction code in the code-package EURIDICE*

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INTRODUCTION

For the moment, there are three codes in the European Union that are capable of fast, self-consistent simulations of the interaction of the electron beam with a set of TE modes in the gyrotron cavity. These codes are: SELFT, developed at Karlsruhe Institute of Technology (KIT, Campus North; former FZK) [1], COAXIAL, existing at University of Latvia [2], and the self-consistent interaction routine of the code-package EURIDICE for gyrotron design and simulation, developed at NTUA [3]. Interaction simulations are one of the basic tools for designing gyrotrons and supporting gyrotron experiments, and these codes are widely used for such purposes. At the same time, however, they are under continuous improvement regarding both the modelling of the interaction and the calculation speed. This improvement is necessary because the correct simulation of the beam-wave interaction in a very dense spectrum of resonant competing modes is a challenging task and, furthermore, will be even more challenging in the next generation of more powerful gyrotrons. (The dense spectrum is a consequence of the use of high-order operating modes to achieve high power.) However, as expected, there is a strong trade-off between implementing more realistic interaction models for a better description of the physics and, at the same time, retaining the capability of fast simulations which is a necessary feature for design, extended parameter studies and support to the experiments. In this report, we present the latest improvements regarding modelling and calculation speed in EURIDICE.

IMPROVEMENTS IN MODELLING

It has been recently observed that the simulations from SELFT come closer to experimental results, if the influence of the RF space charge is taken into account [4]. This influence has been neglected in the past on the grounds that it is not significant if the plasma frequency is small enough compared to the electron cyclotron frequency. However, it seems that as the output power of gyrotrons is increasing and the current of the electron beam becomes larger, this issue needs to be revisited. For that reason, the self-consistent interaction code in EURIDICE was extended to incorporate this effect. A verification of the extension by comparison to SELFT and to experimental results was performed. Single-mode simulations with and without RF space charge showed a difference of 5% in the output power, with the results coming closer to the experiment when the effect was present. Comparisons with the corresponding results from SELFT revealed a 2% difference in power, which is satisfactory, considering the different numerical schemes and approximations used by the two codes to calculate this effect. A special and lengthy effort was given to keep EURIDICE a parallel code after the inclusion of the RF space charge influence, because the latter couples the electrons making the parallelisation of the algorithm not straightforward anymore.

The self-consistent interaction code in EURIDICE has also been extended in order to take into account the variation of the axial electron velocity v_z along the interaction region. In principle, this brings the simulation closer to the physics, but it is done at the expense of calculation speed. For this reason the axial variation of v_z is neglected in SELFT and COAXIAL to speed-up calculations. In the course of the implementation of varying v_z in EURIDICE, special care was taken in order for this feature to be offered as an option in the code and not to slow down the code when it is not in use. A series of comparisons of the results of EURIDICE with those of SELFT for cases relevant to the coaxial gyrotron experiment at KIT were performed with the objectives (1) to assess the effect of the use of varying parallel electron velocity on simulation results and (2) to check the influence of using varying v_z on energy conservation. (We note that the degree of conservation of the total energy during a simulation gives information on how close to the physics is the simulation.) Regarding (1), it was found by multi-mode simulations that with varying parallel velocity the excitation of the operating $TE_{34,19}$ mode became more robust with respect to the choice of the numerical parameters. In addition, the efficiency at the operating point was 5-8% lower compared to the case of constant parallel velocity. These results indicate that the use of varying v_z has a significant influence and this has to be kept in mind. The problem is that, when using

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varying v_z, the interaction code in EURIDICE becomes slower as the number of the included modes increases. For the cases of interest it became 2-3 times slower. As far as (2) is concerned, the multi-mode simulations were unfortunately too noisy to provide any conclusions. For this reason, we performed single-mode simulations at the operating point to minimise the noise. In contrast to what was initially expected, it was concluded that, in the single-mode, steady-state case, the energy conservation in EURIDICE is not improved by using varying v_z; it remains at the same level as with constant v_z. Then, an investigation was initiated on whether the use of varying parallel velocity improves the energy conservation during start-up, where the variation of the stored energy of the mode is significant. This investigation, involving single-mode, start-up simulations, is in progress.

IMPROVEMENTS IN CALCULATION SPEED

In the course of the comparisons between the interaction routines in EURIDICE and the code SELFT, it was initially observed that EURIDICE was in many cases much slower than SELFT, even when the same simplifying assumptions were used in both codes. A comprehensive investigation of the reasons of this difference was undertaken, as calculation speed is a prerequisite for efficient parametric studies and design, especially in relation to long multi-mode simulations for present and future high-power gyrotrons with a very dense mode spectrum. It is essential to facilitate the fast comparison of the results of EURIDICE and SELFT, because any operating scenario becomes more reliable when confirmed by two independent codes.

A direct comparison of the calculation speed of SELFT and the self-consistent code of the package EURIDICE at the KIT/IHM computing facilities using the same compiler showed that EURIDICE can be up to 8-10 times slower than SELFT, depending on the distribution of the initial parameters of the electrons. With a given total number of electrons, the speed of the two codes becomes comparable when the number of the initial azimuthal phases becomes larger and SELFT becomes faster as this number becomes smaller. An investigation of the structure of the codes identified the following reasons that possibly make SELFT significantly faster: (i) use of real rather than complex numbers in the innermost loop of the calculation of the electron motion, (ii) vectorisation of this loop, and (iii) use of smaller array dimensions. The feasibility of incorporating the above features in EURIDICE was investigated, taking into account that EURIDICE’s extra options (i.e energy and guiding-centre spread, totally random initial values, interaction at higher cyclotron harmonics, varying parallel velocity, parallelisation), should be maintained.

First, the features (i)-(ii) were incorporated in EURIDICE. Unfortunately, feature (i) did not have any positive effect; neither did feature (ii). In order to explain this behaviour and, at the same time, assess the significance of the innermost loop vectorisation in SELFT, the vectorisation was artificially removed from SELFT. This resulted in a 30% slowing down of SELFT, proving that loop vectorisation is not the main cause for the difference in the calculation speed between SELFT and EURIDICE. However, the fact that vectorisation did not bring any improvement in EURIDICE was not understood and is an issue for further investigation. The incorporated features (i)-(ii) were then removed from EURIDICE, because they just complicated the code structure without any gain. Next, we concentrated on feature (iii). After some effort, a way to reduce the dimensions of the arrays was finally found by splitting the universal index of the electrons into two indices; one for the initial electron phase and one for the rest initial values. At the same time the case without guiding-centre spread was treated separately, since it makes possible to use throughout the code two-dimensional arrays instead of three-dimensional. The above modifications led to an improvement of the calculation speed in EURIDICE by more than a factor of two, resulting in EURIDICE being now less than 4 times slower than SELFT. The reason that SELFT still remains quite faster is not yet completely understood. It is believed that the more complicated code structure of EURIDICE, necessary to support the extra options, is responsible for the slowing down of the code and it does not seem possible to be modified further for the moment. The problem will be revisited again in the future if new ideas on the code structure emerge. However, the achieved upgrading of EURIDICE is already very significant and, given the fact that EURIDICE is a parallel code, the two codes can now be comparably fast if EURIDICE runs on 4 processors.

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