TWANG-PIC, a monomode gyro-averaged PIC code for gyrotron simulations

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Abstract—The new gyrotron simulation code TWANG-PIC, a Particle-In-Cell (PIC)-version of the code will be presented, which solves the slow-timescale self-consistent wave-particle interaction equations for a single transverse mode. This code represents a considerable improvement with respect to the previous trajectory-code by relaxing the approximation of a time-frozen electromagnetic (EM)-field during the electron transit across the cavity. In operating regimes dominated by self-consistent effects (gyro-backward regime) and in particular for non-stationary regimes characterized by a multifrequency spectrum, it is shown that the PIC model implemented in TWANG-PIC is in much better agreement with the experiment than the results given by TWANG.

I. INTRODUCTION

GYROTRONS are medium- to high-power microwave sources based on the Electron Cyclotron Maser (ECM) instability with frequencies in the range from several GHz to above 1 THz. They are widely used in plasma heating, but also increasingly in other applications as e.g. in spectroscopy [1]. For designing gyrotron prototypes and for a better understanding of observed phenomena, gyrotron simulations are essential and more precisely interaction codes, describing the creation of the microwave in the cavity region, are the most important tool.

In this contribution, we will report on an essential improvement of the code TWANG [2]. This code solves the slow-timescale version of the self-consistent wave-particle interaction equations for a single transverse mode and has been extended to include a one-dimensional Particle-In-Cell (PIC) approach for the description of the electron motion. In doing so, the commonly used approximation of a nearly constant field profile during the electron transit time in the cavity was relaxed. This is important especially for simulating non-stationary oscillation effects with a multifrequency or broadband spectrum. For these cases, the field profile can vary strongly within timescales, which are considerably shorter than the electron transit time, thus violating the mentioned assumption.

II. MODEL AND RESULTS

The time-dependent model of TWANG allows describing a real gyrotron cavity, which includes the axial dependence of the magnetic field and of the cavity wall radius including the first part of the uptaper region, as well as an initial distribution in electron momentum, energy or guiding center radius. The field is described by a single TE$_{m,n}$-transverse mode with a self-consistent axial profile. In order to make the outgoing wave boundary condition compatible with non-stationary oscillations, the possibility of using an integro-differential type boundary condition [3] at the cavity output is being included, which ensures zero reflection for any frequency.

With this PIC-approach, the RF-field is updated at each integration step of the electron motion instead of after every full transit of the electrons across the cavity. The field seen by the electrons (which are not on the grid points any more) is obtained using linear interpolation [6], while the source term of the wave equation is calculated on the grid points, using linear grid deposition scheme [6].

In doing so, the constraint of a constant field profile during the electron transit through the cavity is relaxed, by this extending the applicability of the model.

In order to verify the newly implemented code, the first step was to compare the results obtained with TWANG-PIC to the ones obtained with TWANG in cases, where simulations of the latter had been benchmarked. This was done by simulating the realistic case of the cavity of a gyrotron, which was designed and constructed for application in DNP-NMR (Dynamic Nuclear Polarization-enhanced Nuclear Magnetic Resonance) spectroscopy [4] and which operates at the TE$_{7,2}$ mode. It showed, that for operating points with a smaller value of magnetic field (positive detuning), corresponding to the forward-wave regime with a wave number $k_0>0$, the behavior of TWANG-PIC is very much like the behavior of TWANG. However, in the backward-regime (larger $B_0$, $k_0<0$, negative detuning), dominated by self-consistent effects, their behavior is different.

This is illustrated in Figure 1, which shows the simulated output power and frequency of the two codes for different values of the magnetic field with a beam current $I_b=20$ mA and a pitch angle $\alpha=1.9$.

For magnetic field values of $B<9.6T$, including the hard-excitation region (dash-dotted lines), the two results match very nicely. For higher magnetic fields however, in which the gyrotron is operating in the gyro-backward regime, the results obtained with TWANG differ considerably from the ones given by TWANG-PIC, if, in particular for TWANG, the arbitrary reference frequency, $\omega_0$, used in the simulation is kept constant for various $B$-fields. If however the codes are run iteratively in order to match the reference frequency to the resulting self-consistent frequency the two results again match very nicely (dashed lines). Furthermore, for regimes dominated by self-consistent effects, the self-consistent frequency and rf-power obtained with TWANG-PIC is very weakly dependent on $\omega_0$, while the one given by TWANG is strongly dependent on this parameter.
This shows that the effect of moving towards a PIC-version - and in doing so relaxing the assumption of a fixed field profile during the electron transit - is to make the code nearly independent of the choice of the reference frequency. This result is crucial for simulations of non-stationary oscillations, characterized by the excitation of side-bands, for which, since a multifrequency spectrum exists, the matching of the reference frequency to the self-consistent frequency can never be satisfied.

This was the motivation for comparing the two codes with each other and with experiment for a first test case, of which the first preliminary results are shown in Figure 2.

The simulation was performed on the case of the above-mentioned cavity, for which cases of non-stationary oscillations with nanosecond-pulses have been shown experimentally [5]. It can be seen that the TWANG-code reproduces qualitatively the behavior observed in experiment, but also that quantitatively, a significantly better agreement is obtained with TWANG-PIC.

III. SUMMARY

For relaxing an important constraint the model of the TWANG-code was modified for moving towards a PIC-approach, which was successfully implemented in the new code TWANG-PIC. This code was benchmarked against TWANG on a test case of a realistic cavity. The results of this study revealed, that, in the case of a monochromatic rf-frequency, the PIC-code is less sensitive to the choice of the reference frequency but that otherwise the results match very well. The comparison of preliminary results with experiment in the case of non-stationary oscillations, characterized by a multi-frequency spectrum, show a better agreement between TWANG-PIC and experiment.

All the steps of the model modification will be described in the presentation related to this paper, together with the results described above and a more detailed comparison for the case of non-stationary oscillations.

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