After Cavity Interaction in Gyrotrons: On the Influence of Different Models for Non-uniform Magnetic Fields

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***Abstract*—To simulate after cavity interaction (ACI) in gyrotron oscillators, it is crucial to take into account the change in the static magnetic field in the uptaper section. This paper discusses different ways to extend the interaction calculations accordingly. Results in terms of calculated efficiencies after the interaction and multimode simulations are presented.**

I. Introduction And Background

After cavity interaction (ACI) in gyrotron oscillators, namely in the uptaper section, has been discussed recently as a major factor influencing the overall efficiency, both with and without depressed collector[1,2,3]. The crucial point is that in the uptaper section, at increased waveguide radius, regions exist where the decreasing magnetic field allows for undesired gyrotron interaction. This interaction reduces efficiency and increases the spread in the electron energy distribution[1,2,3], thus reducing the potential for energy recovery in the depressed collector, which again lowers the achievable efficiency.

In this paper different ways to introduce the non-uniform magnetic field into the interaction calculations are discussed: The simplest way is to consider only the corresponding change in the cyclotron frequency. With some more effort, the non-uniformity of the magnetic field can be taken into account in the equations of electron motion[4]. A complete model for weakly tapered magnetic field, finally, also requires modification of the rf field profile equations[5].

II. Comparison of simulation models

In gyrotron interaction calculations, a set of differential equations for the electron motion's momentum $\underline{p}$ and field profiles $\underline{f}$ is commonly used[4,5]. To consider a non-uniform magnetic field analytically, terms containing dB_z/dz (B_z is the z-component of the static magnetic field) must be added to the equation of motion[4,5]

$$\frac{cu_z}{\gamma}\frac{d}{dz}\left(\underline{p}\right) + j\left(\Omega_f - \Omega_0/\gamma\right)\underline{p} - \left(\frac{cu_z}{\gamma^2}\cdot\frac{1}{2B_z}\frac{dB_z}{dz}\right)\underline{p} = \underline{a} \tag{1a}$$

$$\frac{u_z}{\gamma}\frac{du_z}{dz} = -\left(\frac{u_\perp^2}{\gamma}\frac{1}{2B_z}\frac{dB_z}{dz}\right) \tag{1b}$$

and the field profiles' equation

$$\frac{\partial^2}{\partial z^2}\underline{f} + \frac{\omega^2 - \omega_\perp^2}{c^2}\underline{f} - j\frac{2\omega}{c^2}\frac{\partial}{\partial t}\underline{f} = \underline{R} \tag{2a}$$

$$\underline{R} = \mu_0 \sum_j \frac{I_{B,j}}{u_{z,j}} G_e e^{-jm\varphi_{c,j}} e^{-j(\omega-\Omega_f)t} \cdot \left(j\Omega_0 + \left(\frac{\gamma_j^2 - 1}{u_{z,j}^2}\right)\left(\frac{1}{2B_z}\frac{dB_z}{dz}\right)\right)\frac{\underline{p}_j}{\gamma_j} \tag{2b}$$

(u_z and $u_\perp$ are the parallel and perpendicular momentum, respectively; other notation is as in [5]). While the terms proportional to dB_z/dz are usually neglected, they can be taken into account in (1), (2) or both. However, the simplest model is to consider only detuning of the cyclotron frequency and changing beam radius, and keep the approximation $dB_z/dz = 0$ in the equations.

Figure 1 shows the geometry and magnetic field profile for the chosen example, which is the 140 GHz $TE_{28,8}$ gyrotron developed for the W7-X stellarator[6]. Note that in the real gyrotron a dimpled wall launcher is located in the uptaper ($z > 76$mm), so the following calculations, which don't consider the mode conversion there, are merely demonstration examples. Results for field profiles and efficiency are given in Figs. 2 and 3. Even though the efficiency curves differ slightly, it can be seen that the major effect is already described by the simplest model, while incorporating dB_z/dz in (1) or both (1) and (2) does not alter the result significantly.

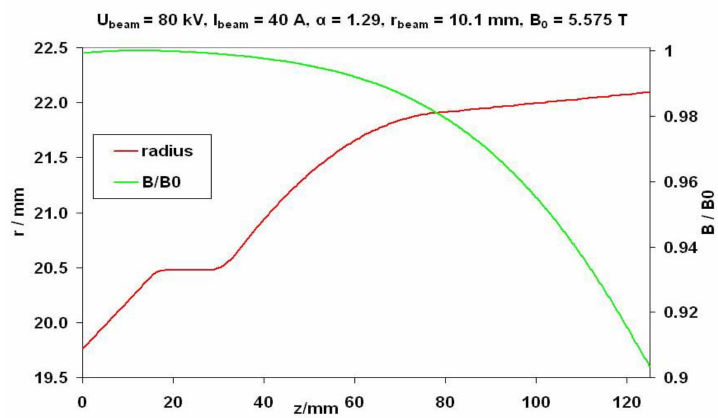

Figure 1: Cavity profile and magnetic field vs. z in the chosen example.

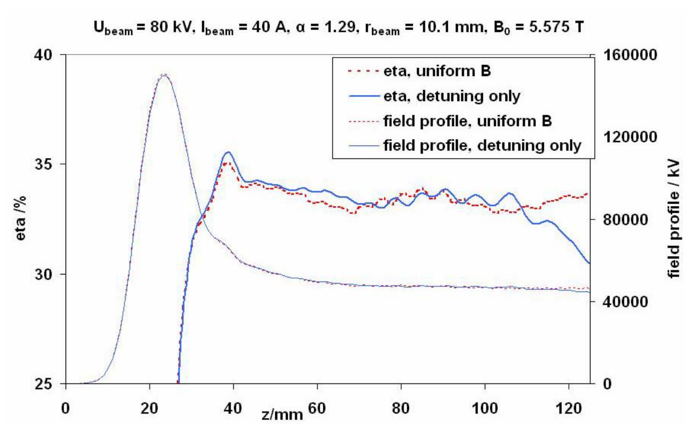

Figure 2: Efficiency and field profile vs. z for constant magnetic field (red dotted) and just taking into account the changing cyclotron frequency and beam radius (blue).

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The results concerning the energy distribution of the electrons after the interaction also vary slightly depending on the employed simulation model. Further investigations will be required to determine the influence of such small deviations e. g. on depressed collector design.

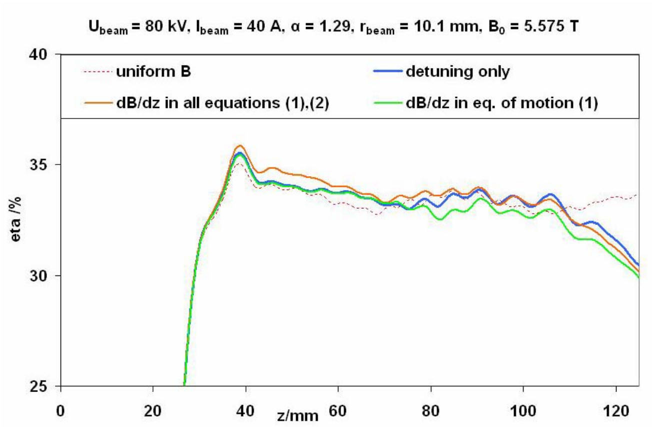

Figure 3: Efficiency vs. z for the cases of uniform B-field (red dotted), detuning only (blue), considering *dB/dz* in the equations of motion (1) (green) and the complete model, changing also the acceleration term (2b) (brown). The corresponding deviations in the field profile are insignificant.

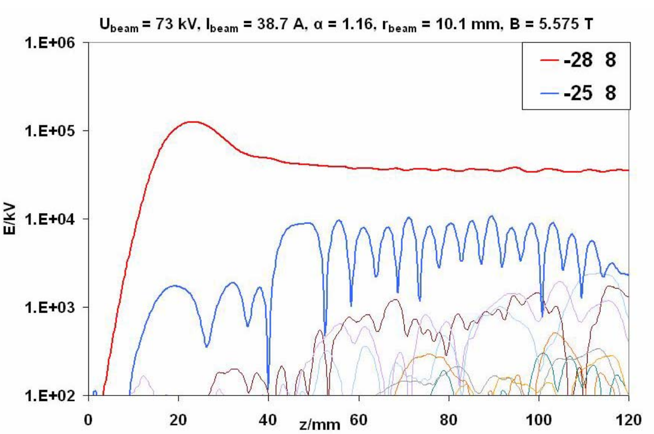

Figure 4: Field profiles in multimode calculations with constant magnetic fields. In addition to the desired $TE_{-28,8}$ mode oscillating in the cavity, an unwanted parasitic mode ($TE_{-25,8}$) is oscillating weakly in the uptaper region.

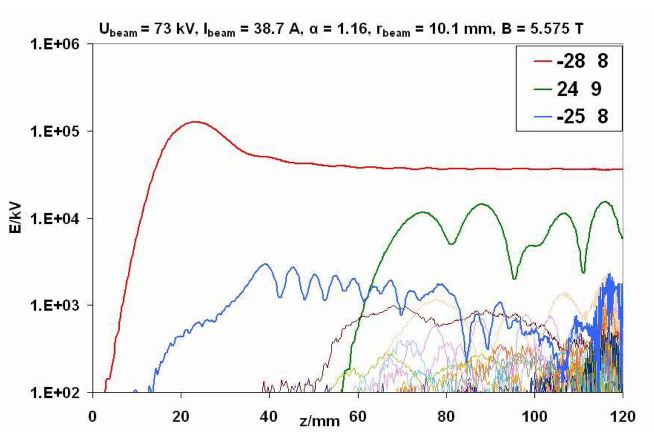

Figure 5: Field profiles in multimode calculations with non-uniform magnetic fields. Compared to Fig. 4, another mode is now oscillating in the uptaper.

III. Multi Mode Calculations

The ACI effect can, of course, also be found in multimode simulations. But the non-uniform magnetic field has the additional effect, that in some parts of the structure other modes may oscillate than in models with constant magnetic field. Figures 4 and 5 show an example: While the behavior of the operating mode is similar for both constant and non-uniform magnetic field, a different parasitic oscillation in the uptaper section appears in the second case. This variation is simply caused by the fact that the magnetic field towards the geometry output is significantly different. But the example makes clear that any attempt to simulate parasitic oscillations outside the cavity requires the consideration of the non-uniformity of the magnetic field.

IV. Conclusions

Different ways of modeling weakly tapered magnetic fields in gyrotron interaction calculations have been discussed. The examples indicate that the major effect is already described by the simplest model, taking into account the changing cyclotron frequency and beam radius without further modifications of the differential equations. Introducing a model for weakly tapered magnetic fields into the electron equations of motion or in the field profile equations does not add very much information at the price of higher calculation effort.

It is confirmed that ACI can deteriorate performance in single mode operation, as stated in [1], [2] and [3]. In addition, another significant influence can be seen in multimode calculations, when the non-uniformity of the magnetic field is large enough to change the mode competition scenario. This may be even more important than ACI, since other regions such as the beam tunnel with even stronger variation of magnetic field may be of interest in future for investigations on parasitic oscillations.

In conclusion, for reliable high power gyrotron designs it is important to consider the real geometry and magnetic field shape. The comparisons done in this paper may be viewed as a validation of calculation methods for such applications, at least for weak changes in magnetic field.

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