# Simulation of Oscillations in High Power Klystrons

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*Abstract*

Spurious oscillations can seriously limit a klystron's performance from reaching its design specifications. These are modes with frequencies different from the drive frequency, and have been found to be localized in various regions of the tube. If left unsuppressed, such oscillations can be driven to large amplitudes by the beam. As a result, the main output signal may suffer from amplitude and phase instabilities which lead to pulse shortening or reduction in power generation efficiency, as observed during the testing of the first 150MW S-band klystron, which was designed and built at SLAC as a part of an international collaboration with DESY. We present efficient methods to identify suspicious modes and then test their possibility of oscillation. In difference to [3], where each beam-loaded quality-factor $Q_{bl}$ was calculated by time-consuming PIC-simulations, now only tracking-simulations with much reduced cpu-time and less sensitivity against noise are applied. This enables the determination of $Q_{bl}$ for larger resonant structures and weaker coupled modes. Results are presented for a typical cavity and the gun-region of the klystron mentioned above.

## 1 INTRODUCTION

The development of rf-components for particle accelerators is closely related to many effects, which have to be studied carefully. One of these interesting questions is the ability of interaction between cavity modes and the charged particles. While designing the cavity shape, its frequency and the properties of the dc particle beam, one has to take care of the danger of spurious oscillation: the normal operation can be disturbed by unwanted modes, which gain energy from the dc-beam. Therefore efficient simulation tools are very helpful, which find those suspicious modes before constructing the cavity. In this paper we present such a method, which is based on the perturbation theory. As a result of these simulations, the beam loaded quality factor $Q_{bl}$ can be calculated for small mode amplitudes. This value of $Q_{bl}$ is not only needed for the study of spurious modes but is also very useful for the design of high power klystrons [1] [2].

Before a statement can be made on the danger of a spurious oscillation during operation of the klystron, one has to compare $Q_{bl}$ with other quality-factors as the cold $Q$ and the external $Q$ ($Q_0$ and $Q_{ext}$), as written in [3].

## 2 DETERMINATION OF SUSPICIOUS MODES

Before a spurious oscillation can be investigated, a mode has to be identified, that is suspicious for being driven by the electron beam. In general, such a mode is a trapped mode with only local field-components.

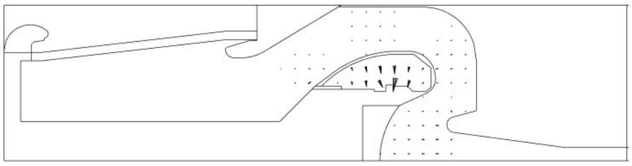

Figure 1: Trapped Mode in a hidden cavity in a electron-gun ($f = 1.365 GHz$)

Locally trapped modes can easily be calculated using an eigenmode-solver like MAFIA-E, as boundary conditions for the calculation can be chosen, which don't influence the mode. If the frequency of a spurious oscillation is known, one has to determine the eigenmode spectrum of the concerned geometry and can then select a matching mode by the frequency.

## 3 DETERMINATION OF BEAM-LOADED Q

Once a suspicious mode is found as described in the previous section, the well-known formula for the determination of any quality factor is applied to the power transfer between mode and beam to get $Q_{bl}$:

$$Q_{bl} = \frac{2\pi\ f\ \ W_{mode}}{P}. \tag{1}$$

where $f$ is the frequency of the mode, $W_{mode}$ is the time-averaged stored energy in the mode and $P$ is the power transferred from the mode to the dc-beam. Thus $P$ and also $Q_{bl}$ become negative, if the mode gains energy from the beam. The stored energy $W_{mode}$ can be calculated straight forward from the harmonic mode field $E_{mode}$ and $B_{mode}$. Therefore the main work has to be accomplished on the determination of the power $P$. The following steps have to be taken to evaluate that power-transfer: In addition to the mode fields eventually needed static fields are calculated like the electric accelerating field $E_{gun}$ inside a gun and the magnetic solenoid field $B_{sol}$ for beam-focusing. Then a separate PIC-simulation with space charge is performed

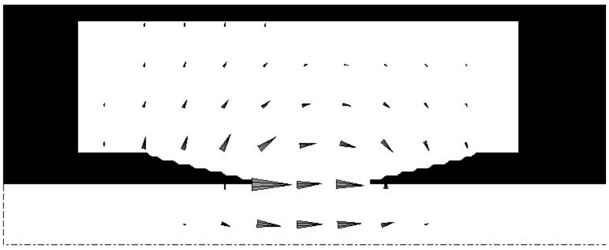

Figure 2: Fundamental Mode of the cavity ($f = 2.747GHz$).

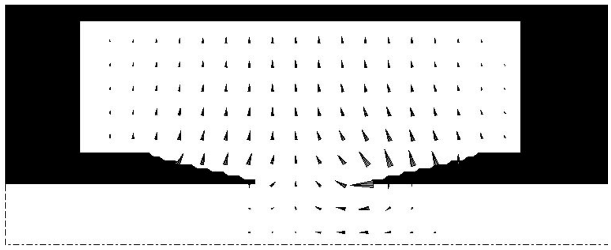

Figure 3: Higher Mode of the cavity ($f = 3.752GHz$).

| $V_{ac}/V_{dc}$ [%] | $W_{beam,ac}/J$ | $Q_{bl}$ |
|---|---|---|
| 0 | 3.7124E-03 | — |
| 3 | 3.7127E-03 | 67.23 |
| 5 | 3.7130E-03 | 81.94 |
| 7 | 3.7135E-03 | 87.17 |
| 10 | 3.7146E-03 | 86.89 |
| 15 | 3.7173E-03 | 87.38 |
| 20 | 3.7210E-03 | 87.19 |

Table 1: Results for the fundamental mode, illustrated in figure 2 ($f = 2.747GHz$).

| $V_{ac}/V_{dc}$ [%] | $W_{beam,ac}/J$ | $Q_{bl}$ |
|---|---|---|
| 0 | 2.718519E-03 | — |
| 3 | 2.718442E-03 | -2654.38 |
| 5 | 2.718438E-03 | -6991.90 |
| 7 | 2.718376E-03 | -7805.30 |
| 10 | 2.718136E-03 | -5927.36 |
| 15 | 2.717799E-03 | -7080.06 |
| 20 | 2.717386E-03 | -7998.95 |

Table 2: Beam-Loaded $Q_{bl}$ for the first higher cavity-mode, shown in figure 3 ($f = 3.752GHz$).

to get the electric and magnetic space charge fields $E_{beam}$ and $B_{beam}$. Critical points inside that PIC-simulation are the smooth excitation of the dc-current and the physical realization of the boundaries. More details concerning these features are described in [2].

Now all needed electric and magnetic fields are known and the tracking-simulation can be started. For the length of one rf-period of the studied mode particles are initialized and tracked through the structure under the influence of the total time-independent fields ($E_{gun} + E_{beam}$, $B_{sol} + B_{beam}$) and a certain amount $x$ of the harmonic mode field ($E_{mode}$, $B_{mode}$). The amplitude $x$ of the mode varies from zero up to an upper limit, which is determined by the validity of perturbation theory. This theory is only valid under the assumption of identical particle tracks for different mode amplitudes. This can be checked during the simulation by comparing the tracks of some selected particles.

At the end of each tracking-run the energies of all particles are summed up. Thus one gets the dependence of the beam energy against the mode amplitude. The total energy of the particles without preloaded mode ($W_{beam,dc}$ for $x = 0$) serves as reference value for all other energies. Thus the power $P$ can be expressed in the following way:

$$P = (W_{beam,ac} - W_{beam,dc}) * f \qquad (2)$$

where $W_{beam,ac}$ is the summed particle energy at the end of the structure with preloaded mode ($x > 0$). Finally the desired formula for $Q_{bl}$ simplifies to

$$Q_{bl} = \frac{2\pi \;\; W_{mode}}{W_{beam,ac} - W_{beam,dc}}. \qquad (3)$$

## 4 EXAMPLES

### 4.1 Cavity

In the first example a simple cavity is analyzed, which is used as buncher-cavity inside a klystron. For the two lowest modes, shown in figures 2 and 3, the interaction with a 116 kV, 88 Ampere dc-current was studied.

The mode-amplitudes are chosen in a way, that the maximum voltage $V_{ac}$, seen by the particles, amounts a few percent of the dc-voltage $V_{dc} = 116kV$.

$$V_{ac} = \int_{z_{min}}^{z_{max}} |Ez_{Mode}| dz \qquad (4)$$

The assumption of the perturbation theory is further confirmed by comparing single particle tracks, as illustrated for the gun in figure 6.

The calculation of the beam-loaded Q-value has been checked using a different method, evaluating the induced current in every time-step and afterwards fourier-transforming the power-signal. This method, which is described in detail in [2], yields $Q_{bl} = 88.7$.

### 4.2 Electron-Gun

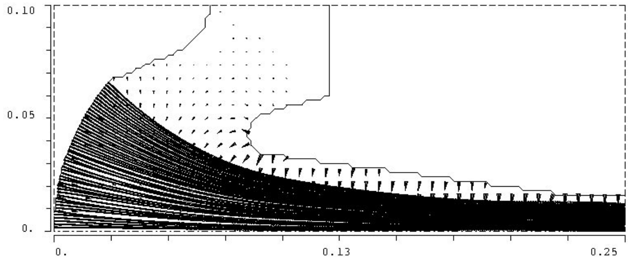


Figure 4: The 700A dc-electron beam with time-independent electric field $E_{beam}$.

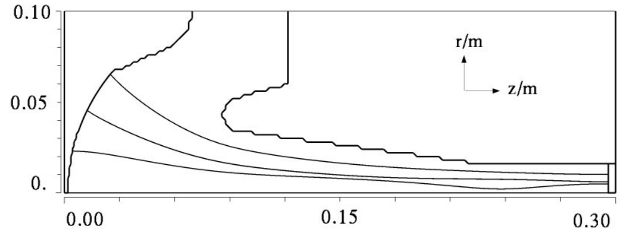


Figure 5: Three tracks of particles, for which the validity of perturbation theory is checked.

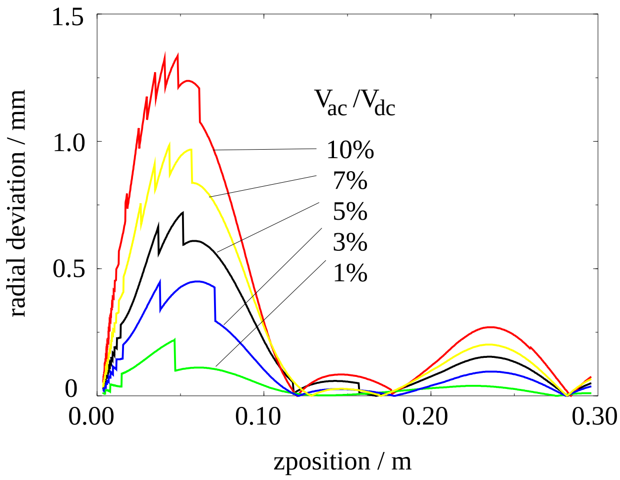


Figure 6: The radial deviation of the middle track from the dc-case for different amplitudes of studied mode.

During the cold test of the electron gun of the mentioned DESY-klystron [1], a strong radiation was detected at a frequency of 1.365 GHz. An eigenmode examination showed a mode in a hidden cavity in the gun-region at this frequency (fig. 1). Time consuming PIC-simulations including the full space-charge of the beam and the interaction of beam and electromagnetic fields could show a negative beam-loading of this mode (see [3] and [4]). The new method presented here helps reducing the costs of the simulation. Once having calculated the dc-space charge field (fig. 4), the final analysis to determine the Q-value for different mode-amplitudes takes only a few minutes of cpu-time. A radial deviation of the track up to 1 mm can be tolerated, compared to the beam radius of 50 mm in that region. The calulated value of $Q_{bl}$ of roughly -100 causes a total negative Q-value of the mode, because the external and the wall losses are much smaller than the energy gain by the beam.

| $V_{ac}/V_{dc}$ [%] | $W_{beam,ac}/J$ | $Q_{bl}$ |
|---|---|---|
| 0 | 2.46887459E-01 | — |
| 1 | 2.46827915E-01 | -55.8 |
| 3 | 2.46639366E-01 | -120.6 |
| 5 | 2.45874396E-01 | -82.0 |
| 7 | 2.45092002E-01 | -90.7 |
| 10 | 2.44274908E-01 | -127.3 |

Table 3: Beam-Loaded $Q_{bl}$ for the trapped mode in the klystron gun, shown in figure 1 ($f = 1.365GHz$).

## 5 SUMMARY

An efficient simulation method to determine dc-beam loaded Q-values of rotational symmetric resonant eigenmodes was presented. The method is derived from perturbation theory and is well suited for the study of spurious modes. The time-consuming and sometimes noisy PIC-simulation has to be applied only once to get the time independent space charge fields. Afterwards fast tracking simulations determine $Q_{bl}$ of different modes.

The method was applied to the interaction of a dc-electron beam with modes inside a gun and a cavity of a high-power klystron.

The main advantage of the presented method is the short cpu-time of only a few minutes and the insensibility against unphysical noise, produced by the macro-particles. Hence, also for larger resonant shapes the determination of $Q_{bl}$ becomes possible, even if the mode is only weakly coupled to the beam.

## 6 REFERENCES


[1] D. Sprehn, R.M. Philips, and G. Caryotakis, *The Design and Performance of 150-MW S-Band Klystrons*, SLAC PUB 6677, Stanford Linear Accelerator Center, Sep. 1994.

[2] U. Becker, M. Dohlus, T. Weiland, *Three Dimensional Klystron Simulation*, Particle Accelerators, vol.51, 1995.

[3] U. Becker, M. Dohlus, K. Ko, B. Krietenstein, T. Lee, T. Weiland, *Spurious Oscillations in High Power Klystrons*, Particle Accelerator Conference, Dallas, 1995.

[4] B. Krietenstein, *Simulation of Oscillations in High Voltage Klystrons with MAFIA*, Institut für Hochfrequenztechnik, Technische Hochschule Darmstadt, Juli 1994.

[5] Garland M. Branch, *Electron Beam Coupling in Interaction Gaps of Cylindrical Symmetry*, IRE Transactions on Electron Devices, May 1961.