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MODE COMPETITION EFFECTS IN FREE ELECTRON LASERS AND GYROTRONS*

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ABSTRACT

In many cases in high frequency, high power coherent radiation generators (such as free electron laser and gyrotrons) the linear gain is positive for many modes and therefore these modes will grow and compete for the beam energy. The questions related to mode competition, coherency of the radiation and maximization of the interaction efficiency are of great importance. To address these issues simple multi-mode models have been formulated. This paper is a short review of the recent results from both simulation and analyses of these models.

I. INTRODUCTION

One of the most important problems in the design of high power, high frequency coherent radiation generators such as free electron lasers and gyrotrons is insuring that the device operates in the desired mode. In many cases the linear gain is positive for many modes and therefore these modes will grow and compete for the beam energy. One is then led to ask the following questions. Is operation in a single mode possible? If so, how long will it take to reach a desired coherency? What steps must be taken to maximize the electronic efficiency of the device while ensuring single mode operation?

In our recent theoretical studies an attempt was made to address these questions regarding the stability of the single mode operation, the time scale for establishing a desired coherency and the control of the operating mode. Here we will report briefly the results of these studies and refer readers to the existing publications for the details.

II. MODEL DESCRIPTION AND STABILITY ANALYSES

The present theoretical models[1-4] are limited to the low gain regime. By this it is meant that the radiation field in the resonator can be expressed as a superposition of empty cavity modes whose amplitudes and phases change slowly in time compared with the transit time of the moving electrons with velocity v_z, through the interaction region, length L, or the time of flight of radiation through the cavity size, L_c. Thus, two distinct time scales are introduced in the model: $\tau_0 = t/(L_c/v_g)$ and $\tau_s = \left(\frac{t\omega_0}{Q}\right)$, where τ_0 is the fast time (v_g is group velocity of the radiation) and τ_s is the slow time. (Here ω_0 is the central frequency of the radiation and Q is the quality factor of the cavity).

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In the FEL case

$$\omega_n = \omega_0 + \frac{n\pi}{L_c} v_g, \tag{5}$$

where $n = 0, \pm 1, \pm 2$, labels the mode. ω_0 is the frequency of some arbitrarily chosen reference mode. In the gyrotron case

$$\omega_n = \omega_0 + \frac{2\pi}{T_R} n, \tag{6}$$

where T_R is the repetition time for the high frequency field. When many modes are present in the system each mode has its own detuning. Thus, for a given injection velocity, in the FEL case,

$$p_{inj,n} = p_{inj,0} - \epsilon\pi n, \tag{7}$$

where $p_{inj,0}$ is the detuning for the $n = 0$ mode. In the gyrotron case, the detuning

$$\delta_n = \delta_0 + \frac{2\pi}{T_0} n, \tag{8}$$

where $T_0 = T_R/T$. Thus, the parameters ϵ and T_0^{-1} measure the spectral density in FEL's and gyrotrons, respectively. To describe the gyrotron operation, an additional parameter $\mu = T\Omega_0\beta_\perp^2/2\gamma_0$ is introduced.

Finally, the last parameter is a dimensionless current, $\hat{I}$. The actual expressions for the dimensionless current for the FEL and gyrotron oscillators are quite complicated and are not presented here. One can find the appropriate formulas in Ref. 2 and Ref. 6, respectively.

In the single mode theory the number of parameters is reduced: $p_{inj,0}$ and $\hat{I}_{FEL}$, in the FEL case, and δ_0, μ and $\hat{I}_{gyr}$, in the gyrotron case, and one obtains for a given normalized current the normalized electric field strength, a_0, needed to maintain the mode in steady state. Therefore, often the normalized current is replaced by normalized electric field as a parameter.

A general feature of these devices is that for a given current modes with a range of detunings are potential stable single mode equilibria. Figure 1 shows the region of stable values of detuning p_{inj} and normalized electric field, a_0, for FEL. Also shown are the constant normalized efficiency contours and the constant dimensionless current contours. Here current, χ, is normalized to the minimum start current. As can be seen, for a given current, say $\chi = 3$ detunings p_{inj} between 2 and 5.7 are stable. The number of modes which could be stable is therefore $N \simeq 3.7/(\epsilon\pi)$.

Stability regions have been generated also for the gyrotron oscillator.[5,6] A similar conclusion, that for a given current a number of detunings are stable, is derived from that analyses. However, in the gyrotron case the picture is more the field as a function of τ_0 is practically constant and the phase is much more relaxed. Thus, the neighboring satellites do not produce strong modulation in the amplitude of the radiation, only in its phase.

IV. MODE CONTROL

Finally, recently an attempt has been made to address the third question regarding control of the operating mode.[4,6] A number of methods of mode control such as priming and mode locking suggest themselves immediately. However, we focused on the effective mode control that occurs due to the time dependence of various system parameters during the start up phase of the oscillator. If all parameters instantly achieved their final values and the noise level was low, then the mode with the largest linear gain would grow the fastest and eventually suppress its neighbors to become the single final mode.

The opposite extreme is the case in which the system parameters attain their final values on a time scale long compared with the cavity decay time. In this case the device passes through a sequence of mode "hoppings" until a final mode is reached. Mode hopping occurs when the time dependence of the system parameters carries the detuning of the dominant mode outside the range of stable operation across the stability boundary. For slow variation of parameters the hopping occurs between adjacent modes in frequency. However, in gyrotron cases we have found that the condition on the "slowness" can be severe such that hopping by more than one mode is not uncommon. Effective mode control occurs in this adiabatic case in that frequency the desired mode is one with the largest positive detuning. Thus, by programming the voltage to rise during the start up phase (which generally causes detunings to rise with time) one can insure that the final mode is within one or two modes of having the maximum stable detuning. In the case of gyrotrons for example this provides a means of accessing "hard excitation" equilibria starting from noise.

Figure 4 shows the time history of the normalized (e_n) amplitudes of a number of modes obtained from a nonlinear, numerical simulation of a gyrotron with a rising voltage pulse. The mode numbers correspond to modes whose final detunings are given by $\delta_n = 3.1 + 2\pi n/6.5$. Thus, the separation in detunings between adjacent modes is .97. Time is normalized to the cavity decay time, the rise time of the voltage was 190 cavity decay times, and the current was held constant at $\chi = 0.1$. As can be seen, the system evolves through a sequence of single mode equilibria, jumping by two modes at a time. If the voltage rise time was made still larger we anticipate that the jumping could be reduced to single mode increments allowing for accessing the hard excitation equilibrium at $\delta = 3.1$. For a voltage rise which is faster (25 cavity decay times) the system settles directly into a mode with this detuning. Whereas for still shorter rise times the final detuning is lower.

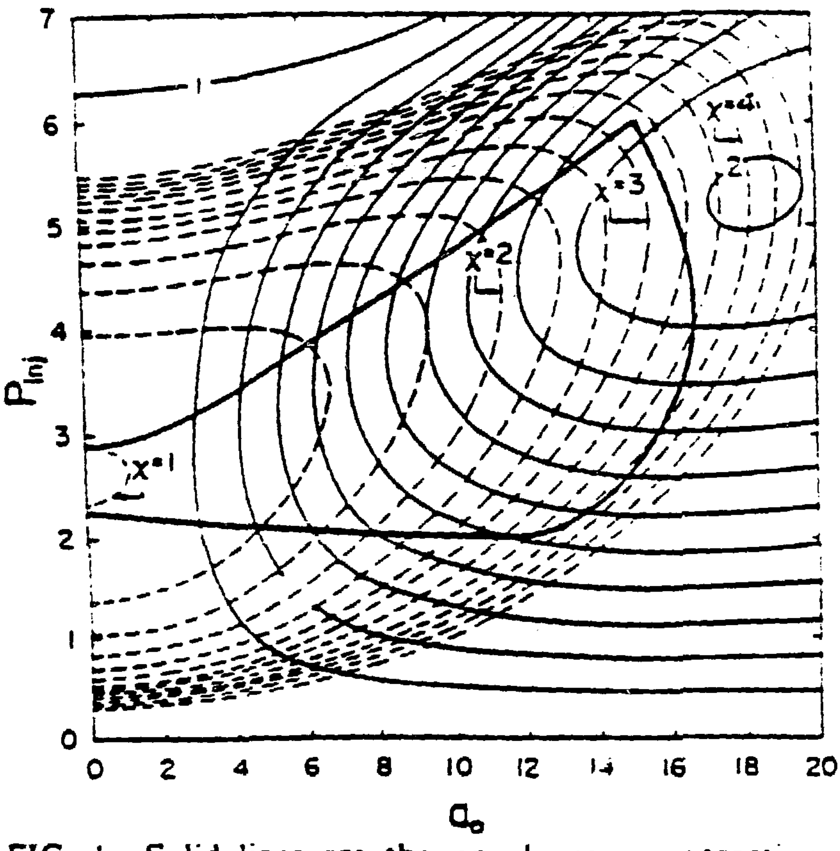

FIG. 1. Solid lines are the equal energy extraction (Δp) curves in the (p_{inj},a_0) plane. The curve labeled 1 corresponds to $\Delta p = 0$, the curve 2 corresponds to $\Delta p = 5.5$. The difference between the neighboring level curves is 0.5. The dashed lines are the level curves of $\hat{I}/v$, which is obtained from energy balance at a particular value of a_0 and p_{inj}. The numbers on the curve indicate the value of $\chi = \hat{I}/\hat{I}_{stan}$. Only inside of the triangular-shaped region is stable single-mode operation possible.

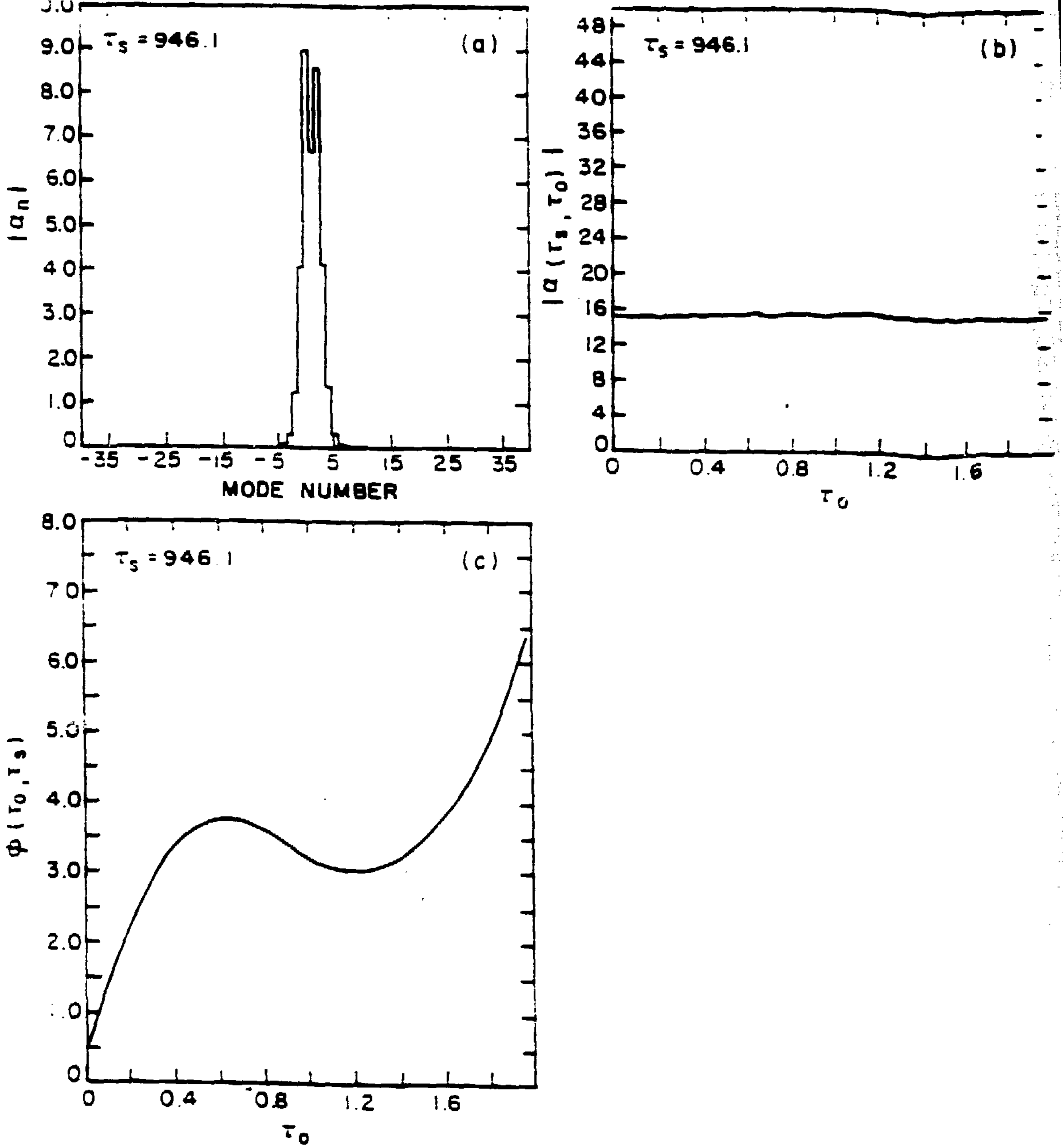

Fig. 3. The same as Fig. 2 at $\tau_s = 946.1$.