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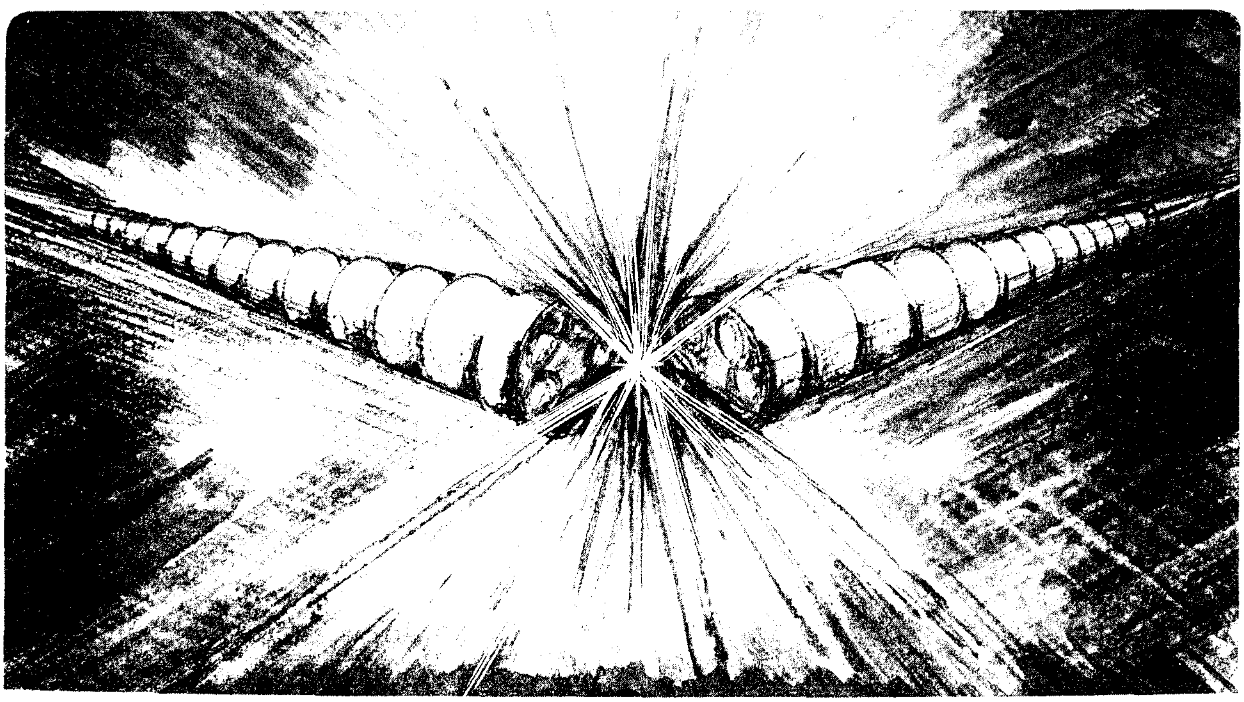

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A STUDY OF PHASE CONTROL IN THE FEL TWO-BEAM ACCELERATOR*

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Abstract A formalism is developed for the analysis of a steady-state free electron laser (FEL) and is applied to the two-beam accelerator (TBA). Conditions are derived for the design of a FEL TBA with rf output power and phase insensitive to errors in both beam current and energy. An example is presented of a suitably phase insensitive TBA design with 100 reaccelerations employing untapered FEL sections and with low power rf input to each section. The theoretical analysis is confirmed by a single particle FEL simulations.

INTRODUCTION

The free electron laser (FEL) powered two-beam accelerator[1-5] requires the propagation of a drive electron beam of kiloampere current, bunched at centimeter wavelengths, through a periodic lattice of wiggler magnets and linear induction accelerators. The drive beam amplifies microwaves in the wiggler through the FEL interaction. The high power microwaves are periodically extracted from the FEL region and fed into a high gradient structure, where they accelerate an electron or positron bunch to very high energy. In the original configuration[1], a large amplitude microwave signal propagates with the drive beam over the entire length of the accelerator. In each FEL section the microwave power was produced and extracted, by septa, in such a way that the total power remains roughly constant. This design allowed for the continuous longitudinal bunching of the electron beam through each FEL section. Studies[4,5] showed that while the longitudinal beam motion was stable, the rf phase shift produced by the FEL interaction resulted in undesirable sensitivity to shot-to-shot jitter in the accelerations from the induction units and in the beam current. In addition, the microwaves had to be transported across the induction unit gaps. Recently, a new version of the TBA has been proposed[6] to alleviate these problems.

In the new version of the FEL TBA, the rf power generated in each wiggler section is completely extracted and fed into the high gradient structure. As we will show, the full extraction of the microwave results in reduced phase sensitivity to jitter in beam current and induction unit accelerations. The new design also eliminates the need for microwave transport through the induction units.

In this paper, a formalism is developed to determine stability conditions for the rf output amplitude and phase in a steady-state FEL with small input power. This formalism can also be applied to the relativistic klystron TBA[7]. The reliable operation of a TeV electron-positron collider requires that, from shot to shot, the phase must be insensitive to fluctuations in beam current and beam energy. We take the stability conditions that the phase vary less than 10^0 for random errors and less than 5^0 for sytematic errors. This is achieved for a TBA with 100 reaccelerations and a current and injection energy error of one half percent.

STABILITY ANALYSIS

In this section we outline a simple stability condition for a periodic rf lattice driven by a single well-bunched beam, in terms of the real part of the longitudinal impedance of a single period. We neglect for now any debunching effects, using a single particle model. In this case the beam is characterized at any point by a phase, $\theta(z)$, and an energy $mc^2\gamma(z)$.

In addition, it is assumed that negligible input rf power is supplied at each period (large rf input is not necessary since the beam bunching can be maintained by the rf produced in the FEL). The dynamics in one FEL section may then be modeled with equations for the advance of beam energy, beam phase, and rf phase. The rf amplitude is determined by conservation of energy. Thus

$$\gamma_{n+1} = \gamma_n - G(\gamma_n, J_n) + \Gamma_n \ , \tag{1}$$

$$\theta_{n+1} = \theta_n - H(\gamma_n, J_n) + \Delta\theta_d \ , \tag{2}$$

$$\varphi_n = -\theta_n - F(\gamma_n, J_n) \ , \tag{3}$$

where γ_n and θ_n are the beam energy and phase at the beginning of the n^{th} FEL section, φ_n is the rf phase at the end of the n^{th} FEL section, Γ_n is the energy boost from the n^{th} reacceleration, and $\Delta\theta_d$, is the phase shift due to the drift between FEL sections, which may in principle include some dependence on particle energy. The single-period functions, F, G, and H are determined by integrating the single particle FEL equations of motion. The power extracted from the beam is then given by $P(GW) = 0.511I(kA)\gamma$. The "gain", G, is not a function of beam phase, since we are assuming no rf input to each section. (Note that G is related to the longitudinal impedance according to $mc^2G = \Re(Z_{\|})I$.) As a result, the equations above reduce to one dynamical equation for beam energy, and three dependent relations which determine beam phase, rf amplitude and rf phase, given the beam energy. Thus the stability of the "design" particle which represents the beam is determined solely by the first equation above. Under these approximations, stability hinges entirely on the evolution of beam energy through many periods, which is itself determined completely by the single-period gain as a function of beam energy, and the collection, denoted by J, of non-dynamical parameters (beam current, wiggler amplitude and wavelength, etc.).

Let (γ_0, J_0) be the design operating point where energy lost in each FEL section is exactly balanced by the boost from the linear induction accelerator (LIA) cells. Then

$$G(\gamma_0, J_0) = \Gamma_0 \ , \tag{4}$$

where Γ_0 is the design boost from the LIA.

Since large energy deviations will induce undesirable rf phase shifts, useful results can be derived by linearizing the gain equation. Let

$$\gamma_n = \gamma_0 + \delta\gamma_n \ . \tag{5}$$

Define δJ to be the error in current and $\delta\Gamma_n$ the random error in the LIA boost just after the n^{th} section. Then

$$\delta\gamma_n = \delta\overline{\gamma} + \delta\tilde{\gamma_n} \ , \tag{6}$$

where, for $n > 1$,

$$\begin{aligned} \delta\overline{\gamma} &= -\frac{\frac{\partial G}{\partial J}}{\frac{\partial G}{\partial \gamma}}\delta J \ , & (7)\\ \delta\tilde{\gamma_n} &= \kappa^{n-1}(\delta\gamma_1 - \delta\overline{\gamma}) + \delta\hat{\gamma} \ , & (8)\\ \delta\hat{\gamma} &= \sum_{j=1}^{n-1} \kappa^{j-1}\delta\Gamma_{n-j} \ , & (9)\\ \kappa &= 1 - \frac{\partial G}{\partial \gamma} \ , & (10) \end{aligned}$$

and $\delta\gamma_1$ is the error in gamma at n=1, i.e., upon injection. The term $\delta\hat{\gamma}$ is due to random LIA errors. Generally, the effect of this term should be small, scaling as $\sqrt{n}$. Thus the beam is driven, by the LIA boosts, to seek out the point on the gain curve, where the FEL takes away as much energy as the LIA replenishes. A similar, but more extensive, discussion of this feature has been given by K. Takayama[8]. The term $\delta\overline{\gamma}$ gives the shift in the equilibrium point, due to the current error. The term $\delta\tilde{\gamma_n}$ describes the oscillatory motion which occurs as the beam zeroes in on the equilibrium value, in the presence of continual random perturbations due to LIA errors. Evidently stability requires $-1 < \kappa < 1$, or $0 < \frac{\partial G}{\partial \gamma} < 2$.

PHASE SENSITIVITY

The analysis can be extended to examine phase error accumulations due to errors in injection current and energy, in a stable design. The distinction between stability and sensitivity should be noted. Stability refers to convergence of the beam energy to a bounded value. Sensitivity refers to the errors in beam phase (and, consequently, rf phase, since, with no rf input, the beam sets the clock). These errors must be kept small, despite accumulation from period to period.

Let

$$\begin{aligned} \theta_n &= \theta_0 + \delta\theta_n \ , & (11)\\ \varphi_n &= \varphi_0 + \delta\varphi_n \ , & (12)\\ \varphi_0 &= -\theta_0 - F(\gamma_0, J_0) \ , & (13) \end{aligned}$$

where (θ_0, φ_0) are the design values. Linearizing the phase advance equations yields

$$\delta\theta_{n+1} = \delta\theta_n - \frac{\partial H}{\partial\gamma}\delta\gamma_n - \frac{\partial H}{\partial J}\delta J \ , \tag{14}$$

$$\delta\varphi_{n+1} = -\delta\theta_n - \frac{\partial F}{\partial\gamma}\delta\gamma_n - \frac{\partial F}{\partial J}\delta J \ , \tag{15}$$

where the derivatives are evaluated at the point (γ_0, J_0). The behavior of $\delta\gamma_n$ has already been solved for in the previous section. It is then straightforward to solve for the beam phase,

$$\delta\theta_n = -(n-1)\delta J\left(\frac{\partial H}{\partial\gamma}\frac{\partial G}{\partial J} - \frac{\partial H}{\partial J}\frac{\partial G}{\partial\gamma}\right)\left(\frac{\partial G}{\partial\gamma}\right)^{-1} - \frac{\partial H}{\partial\gamma}\sum_{j=1}^{n-1}\delta\tilde{\gamma}_j \ , \tag{16}$$

$$\approx -(n-1)\delta J\left(\frac{\partial H}{\partial\gamma}\frac{\partial G}{\partial J} - \frac{\partial H}{\partial J}\frac{\partial G}{\partial\gamma}\right)\left(\frac{\partial G}{\partial\gamma}\right)^{-1} \tag{17}$$

$$-\frac{\frac{\partial H}{\partial\gamma}}{\frac{\partial G}{\partial\gamma}}(\delta\gamma_1 - \delta\overline{\gamma})(1-\kappa^{n-1}) + \frac{\partial H}{\partial\gamma}\sum_{j=1}^{n-1}\delta\hat{\gamma}_j \ . \tag{18}$$

From $\delta\theta_n$, the rf phase error is found to be

$$\delta\varphi_n = -\delta\theta_n - \frac{\partial F}{\partial\gamma}\delta\tilde{\gamma}_n + \delta J\left(\frac{\partial G}{\partial\gamma}\right)^{-1}\left(\frac{\partial F}{\partial\gamma}\frac{\partial G}{\partial J} - \frac{\partial F}{\partial J}\frac{\partial G}{\partial\gamma}\right) \ . \tag{19}$$

For low sensitivity to current and energy errors, the design must have

$$\left(\frac{\partial H}{\partial\gamma}\frac{\partial G}{\partial J} - \frac{\partial H}{\partial J}\frac{\partial G}{\partial\gamma}\right) << \frac{\partial G}{\partial\gamma} \ , \tag{20}$$

$$\frac{\partial H}{\partial\gamma} << \frac{\partial G}{\partial\gamma} \ , \tag{21}$$

$$\left(\frac{\partial F}{\partial\gamma}\frac{\partial G}{\partial J} - \frac{\partial F}{\partial J}\frac{\partial G}{\partial\gamma}\right) \approx \frac{\partial G}{\partial\gamma} \ . \tag{22}$$

The stability analysis derived above has been confirmed by numerical simulations in which the beam is replaced by a single design particle. The particle and field equations are the standard FEL equations appropriately modified for waveguide modes[9]. For simplicity, only the case of a superperiod consisting of an untapered wiggler section, an rf output, an LIA and a drift has been considered. The FEL equations must be supplemented by the initial conditions at the start of each FEL section of a superperiod. The particle energy and phase satisfy $\theta_{n+1}(z=0) = \theta_n(z = L_w) + \Delta\theta_d$, and $\gamma_{n+1}(z=0) = \gamma_n(z = L_w) + \Gamma_n$. An examination of the effect of rf input power showed that power levels up to 1 kW had negligible effect on the rf phase. Systematic studies of the effect of higher power levels on phase sensitivity may reveal reduced phase sensitivity.

A final constraint on the design is linear stability of the longitudinal particle motion. This stability can be studied by considering a test particle displace by a $\delta\gamma$, $\delta\theta$ from the design orbit at injection. After n periods,

$$\begin{pmatrix} \delta\gamma \\ \delta\theta \end{pmatrix}_n = \mathrm{M}^n \begin{pmatrix} \delta\gamma \\ \delta\theta \end{pmatrix}_0 \tag{23}$$

where M is the transport matrix for one period and can be calculated numerically. Since the system is Hamiltonian, $\det M = 1$ and stability against debunching requires $-2 < Tr(M) < 2$.

From the above analysis, as long as the input power is small, it is sufficient to calculate the functions F, G, and H, which depend only on the initial energy at the entrance to a FEL section and the system parameters (J).

FEL TBA DESIGN

We have made a numerical search of the parameter space in injection energy and current to locate phase insensitive designs. In fact, for an actual TBA, this might be an automated part of the control system. An example of a phase insensitive design located in this manner corresponds to the parameters of Table 1.

For this design, $\gamma_r = 25.6$ so that the beam is injected below resonance. The sensitivities to current and energy errors of 1/2% are given in Table 2 for 50 and 100 reaccelerations. The results are listed separately for the analytic expressions given in the text and for an FEL code with one design particle.

Table 1: Parameters for a TBA relatively insensitive to errors in current and energy.

Wiggler Wavelength (cm)	26.0
Wiggler Length (cm)	125
Wiggler Field Amplitude (a_w)	5.5
Waveguide Width (cm)	20.0
Waveguide Height (cm)	3.0
Beam Current (kA)	1.54
Beam Energy at Input (γ_0)	22.3
RF Power (MW/m)	384

Table 2: Phase error (in degrees) for errors in the current (I) and the energy (γ) after 50 and 100 periods of the TBA, from two different models. The first is the analysis in this paper and the second is a design particle simulation which solves the nonlinear FEL equations with reaccelerations from the LIA units.

		50	100
$\frac{\delta I}{I} = 1/2\%$	Analytic Model	4.8	9.7
	Design Particle	4.8	8.2
$\frac{\delta\gamma}{\gamma} = 1/2\%$	Analytic Model	5.0	5.0
	Design Particle	4.8	4.3

CONCLUSIONS

A formalism for the analysis of a steady state FEL has been used to derive the conditions for phase-stable operation of the FEL TBA. We have given an example of the type of sensitivity analysis which must be performed for such a device. We have presented parameters for an actual FEL TBA design, which is stable and relatively insensitive to errors in beam current and energy. Based on this preliminary survey of operating parameters, it appears that an FEL TBA will be limited to 100 periods. Fortunately, this is sufficiently long to realize the high wall-plug efficiency which originally motivated the TBA concept.

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