Lawrence Berkeley Laboratory

UNIVERSITY OF CALIFORNIA

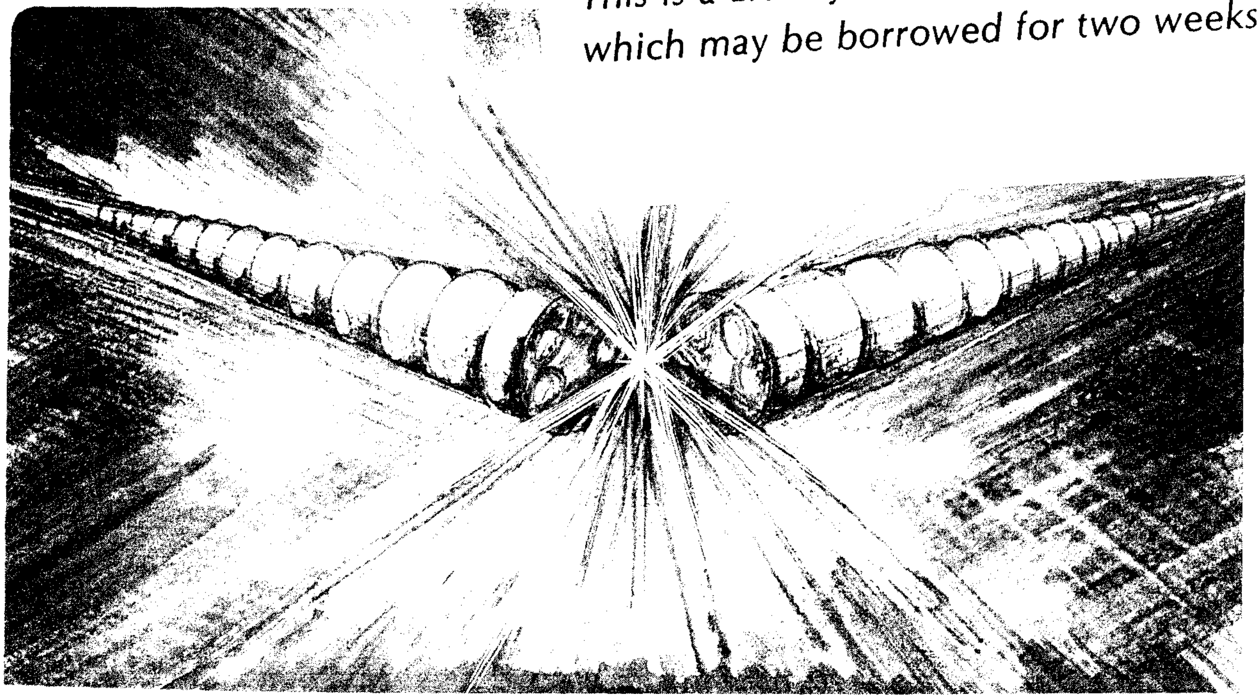
Accelerator & Fusion Research Division

Presented at the 2nd Workshop on Laser
Accelerator Particle 1985, Malibu, CA,
January 7-18, 1985

PHASE AND AMPLITUDE CONSIDERATIONS FOR THE TWO-BEAM ACCELERATOR

R.W. Kuenning, A.M. Sessler, and J.S. Wurtele

February 1985



Prepared for the U.S. Department of Energy under Contract DE-AC03-76SF00098

LBL-19064

PHASE AND AMPLITUDE CONSIDERATIONS FOR THE TWO-BEAM ACCELERATOR*

R. W. Kuenning and A. M. Sessler

Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720

and

J. S. Wurtele+

Plasma Fusion Center
Massachusetts Institute of Technology
Cambridge, MA 02139

February 1985

---

* This work was supported by the Division of High Energy Physics, Office of Energy Research, U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

+ Supported by the Office of Naval Research

LBL-19064

PHASE AND AMPLITUDE CONSIDERATIONS FOR THE TWO-BEAM ACCELERATOR*

R. W. Kuenning and A. M. Sessler
Lawrence Berkeley Laboratory, University of California
Berkeley, CA 94720

J. S. Wurtele+
Plasma Fusion Center, Massachusetts Institute of Technology,
Cambridge, MA 02139

ABSTRACT

Phase and amplitude considerations are made for a Two-Beam Accelerator and analytic formulas are obtained expressing the phase and amplitude errors in terms of magnetic wiggler errors, beam energy errors, beam current errors, and microwave field amplitude errors. The necessity of phase and amplitude control is shown and schemes are proposed which can accomplish this control.

I. THE TWO-BEAM ACCELERATOR

The Two-Beam Accelerator (TBA) was first proposed some years ago.[1] Further descriptions of this device have already been given[2,3] and a rather comprehensive description can be found in this very volume.[4]

We have, for the considerations of this paper, taken the parameters given in Ref. 4. Note, that these are somewhat revised over that given in the earlier papers. The major differences are the following. Firstly, we have gone to a top energy of 1 TeV, rather than 300 GeV, because physics interest has moved to the higher energy and, consistent with this increase in energy, we have increased the luminosity to 10^{33} cm^{-2} sec^{-1}. We have, in addition, adopted a gradient of 500 MeV/m, rather than 250 MeV/m, because recent theoretical analysis and experiments suggest that this larger value can be achieved.

As a consequence of these changes, and taking a final focus beam size of 0.1 μm, we have the parameters listed in Table I. Note that we have kept the radiation wavelength at 1 cm. We considered raising this to 2 cm, so as to ease the manufacturing problems associated with making a small structure, and believing that we could obtain the high gradient of 500 MeV/m even at this lower frequency, but the increased power demand on the FEL seemed excessive to us: The required power went from 2.2 GW/m to almost 4(2.2)GW/m.

*This work was supported by the Division of High Energy Physics, Office of Energy Research, U. S. Department of Energy under Contract No. DE-AC03-76SF00098.

+Supported by the Office of Naval Research

Table I Parameters for a Two-Beam Accelerator

Low-Energy Beam	Energy/Rest Energy (γ)	40
	Beam Current (I)	2.2 kA
	Bunch Length (ℓ)	19 m
	Number of FEL Sections	2 x 5
	Power Requirement	2.2 GW/m
Wiggler	Wavelength (λ_w)	20 cm
	Average Wiggler Peak Field (B_w)	5.8 kG
High-Energy Beam	Repetition Rate (f)	6.5 kHz
	Final Energy (E_f)	1 TeV
	Gradient	500 MeV/m
	Length of Accelerator ($2xL_A$)	2 x 5 km
	Luminosity ($\mathscr{L}$)	$10^{33}\text{cm}^{-2}\text{sec}^{-1}$
	Single Beam Power (P)	7.7 MW

II. PHASE AND AMPLITUDE ERRORS

We start with the FEL equations:

$$\frac{d\gamma_i}{dz} = -\frac{\omega}{c} a_w a_s \frac{\sin\psi_i}{\gamma_i} \quad , \tag{1}$$

$$\frac{d\psi_i}{dz} = k_w - \frac{\omega}{2c\gamma_i^2}(1 + a_w^2 - 2a_w a_s \cos\psi_i) + \frac{d\phi}{dz} \quad , \tag{2}$$

$$\frac{da_s}{dz} = \frac{\omega_p^2 a_w}{2\omega c} \left\langle \frac{\sin\psi_i}{\gamma_i} \right\rangle \quad , \tag{3}$$

$$\frac{d\phi}{dz} = \frac{\omega_p^2 a_w}{2\omega c a_s} \left\langle \frac{\cos\psi_i}{\gamma_i} \right\rangle \quad , \tag{4}$$

where we have used standard notation.[5] For a TBA, in the simplest model, we model the beam by one macro particle and modify these equations by adding to Eq. (1) the term

$$+ 2\alpha \frac{\omega^2}{\omega_p^2} a_s^2 \quad , \tag{5}$$

and to Eq. (3) the term

$$- \alpha a_s \quad . \tag{6}$$

In this model, α represents the continuous energy taken from the low energy beam to the high energy beam, while the induction units are modeled with a continuous source which puts this very same energy back into the low energy beam. The discrete nature of the energy extraction and the induction units are, of course, not included in this model.

From Eqs. (3) and (4) we can compute the error in the amplitude and phase of the signal wave:

$$\left(\frac{\Delta a_s}{a_s}\right) = k_1 L \left(\frac{\Delta a_w}{a_w} + \frac{\Delta \omega_p^2}{\omega_p^2} - \frac{\Delta \gamma}{\gamma}\right) (\sin \psi) \quad , \tag{7}$$

$$\Delta \phi = k_1 L \left(\frac{\Delta a_w}{a_w} + \frac{\Delta \omega_p^2}{\omega_p^2} - \frac{\Delta \gamma}{\gamma} - \frac{\Delta a_s}{a_s}\right) (\cos \psi) \quad , \tag{8}$$

where

$$k_1 = \frac{\omega_p^2 a_w}{2\omega c a_s \gamma} \quad . \tag{9}$$

In these equations [Eqs. (7), (8), (9)], all of the quantities such as a_w, a_s, ψ, γ, ω_p^2, ω are evaluated for the macro particle (equilibrium particle); the quantity L is the length one is considering. The fractional deviations in a_w, ω_p^2, γ, and a_s are explicitly indicated.

Numerical evaluation of the phase and amplitude deviations which one can expect in a TBA can now be done using the parameters of Section I. One has $a_s = 0.19$, $a_w = 7.7$, $\omega = 1.9\times10^{11}\text{sec}^{-1}$, $\omega_p = 1.7\times10^{10}\text{sec}^{-1}$ and hence $k_1 = 2.6$ rad/m. Taking $\psi = 0.09$ and $L = 100$ meters we see that a 0.1% relative error in any of the quantities leads to $|\Delta\phi| \simeq 0.25$ radians and $(|\Delta a_s| / a_s) \simeq 2.3\%$. Thus, without some sort of control on the phase and amplitude of the signal wave we cannot have an L of 5 km.

The four differential equations were approximated by difference equations and solved numerically. The results were $\Delta\phi = 2.6$ radians and $(|\Delta a_s| / a_s) = 0.4\%$ which only agrees to an order-of-magnitude with that given by the analytic formulas [Eqs. (7), (8), (9)].

In these estimates of the effect of errors, Eqs. (7), (8), (9), we have not considered the differential coupling between the variables a_s, ϕ, ψ, and γ as described by Eqs. (1) - (4). Of course any deviation will "propagate" through these variables, and a proper treatment of errors must involve solution of the coupled differential equations. We leave such study to the future, believing that our first estimates are adequate for this note.

III. FEEDBACK CONTROL

Proper operation of a TBA will require a master oscillator (a "clock") to which phase and amplitude is compared. This signal wave is sent down the accelerator in a third waveguide.

One possibility for control of phase and amplitude is simply not to control them, but put great effort on reducing the errors Δa_w, $\Delta\omega_p^2$, $\Delta\gamma$, and Δa_s. The Eqs. (7) and (8) can be employed to deduce the length L, once one knows the acceptable values of $\Delta\phi$ and $\Delta a_s/a_s$. The last are set by the acceptable variation in the energy of the high energy beam and, typically, are a few percent. (Since beamstrahlung will introduce an energy spread of this magnitude.) Probably, and this depends on how successful one is in practice in controlling Δa_w etc., L is of the order of 100 meters. Thus the TBA has become a multi-beam accelerator with the low energy beam going through an FEL which then powers (about) 100 meters of the high gradient structure. This is a significant modification of the TBA idea, but may be a quite acceptable concept.

A second possibility (suggested by Donald Prosnitz) is to remove all of the signal wave after a distance L (where the errors in a_s and ϕ have grown to a large value), but not to remove the low energy electron beam. Then one starts the FEL again, with the proper phase as given by the clock. The electromagnetic wave can be removed, while not removing the electron beam, by means of a thin reflecting foil. In this approach one has 2 x 5 low energy beam FELs as contrasted with the first possibility where one has 2 x 50 FEL power sources.

A third possiblity is the use of "feed back" (in this case "feed forward") to control phase and amplitude. The energy of the low energy beam is a quantity that can be readily controlled in order to dynamically correct phase errors. This could be done by small added induction accelerator units, driven by hard tubes. The hard tube driver chain could be similar to a pulser designed for the ASTRON accelerator cathode to give a 20 kV, 1000 A pulse, with a nominal 5 ns rise time.[6]

Closed loop regulation during the pulse would require gain-bandwidths larger than the state-of-the-art permits. Therefore, open-loop correction is required. Since the rf energy travels, according to waveguide propagation theory, at 0.985c and the low energy beam travels at about 0.95c, the correction of LEB energy cannot affect the portion of the rf energy on which the phase was measured. Furthermore, phase error is a cumulative effect, occurring over axial distance. It is not feasible to measure phase at one location, and apply the correction many meters downstream where an electrical signal could catch up with the same portion of the rf on which the measurements were made, since more phase errors have accumulated during the transit. Thus the correction will always be late, by the delay time in the amplifier system plus connecting cables.

We propose a feed-forward system. Obviously, the phase error accumulation during the amplifier and cable delay time must be less than the allowable error, which implies that if we have correction units every 100 meters, the error change in 10 ns must be less than 0.1% for $\Delta\phi = 0.25$ rad and $\Delta a_s/a_s = 2.3\%$. The LEB captured current and the voltage of the induction accelerator modules must not vary at a faster rate than 1.5% over the 150 ns pulse. This is reasonable to achieve but will require some extra effort in flattening the pulses. Phase measurement, within a few nanoseconds, is a subject that requires further study, and which we leave for the future.

REFERENCES

1. A. M. Sessler, "The Free Electron Laser as a Power Source for a High Gradient Structure," in Laser Acceleration of Particles, P. J. Channell, ed., AIP Conf. Proc. No. 91, New York, p. 163 (1982).

2. D. Prosnitz, IEEE Trans. on Nuclear Science NS-30, 2754 (1983).

3. D. B. Hopkins, A. M. Sessler and J. S. Wurtele, "The Two-Beam Accelerator," Nuclear Instr. & Methods in Physics Research, (to be published, 1985).

4. J. S. Wurtele, "Progress on Acceleration by the Transfer of Energy Between Two Beams" in Laser Acceleration of Particles II, AIP Conf. Proc., New York (1985).

5. N. M. Kroll, P. L. Morton and M. W. Rosenbluth, IEEE Journal of Quantum Electronics, QE-17, 1436 (1981).

6. R. W. Kuenning and S. D. Winter, "Pulser for Accelerator Cathode," Lawrence Radiation Laboratory Report UCID-15156, April 25, 1967 (unpublished).