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Authors
Goren, Y.
Sessler, A.M.

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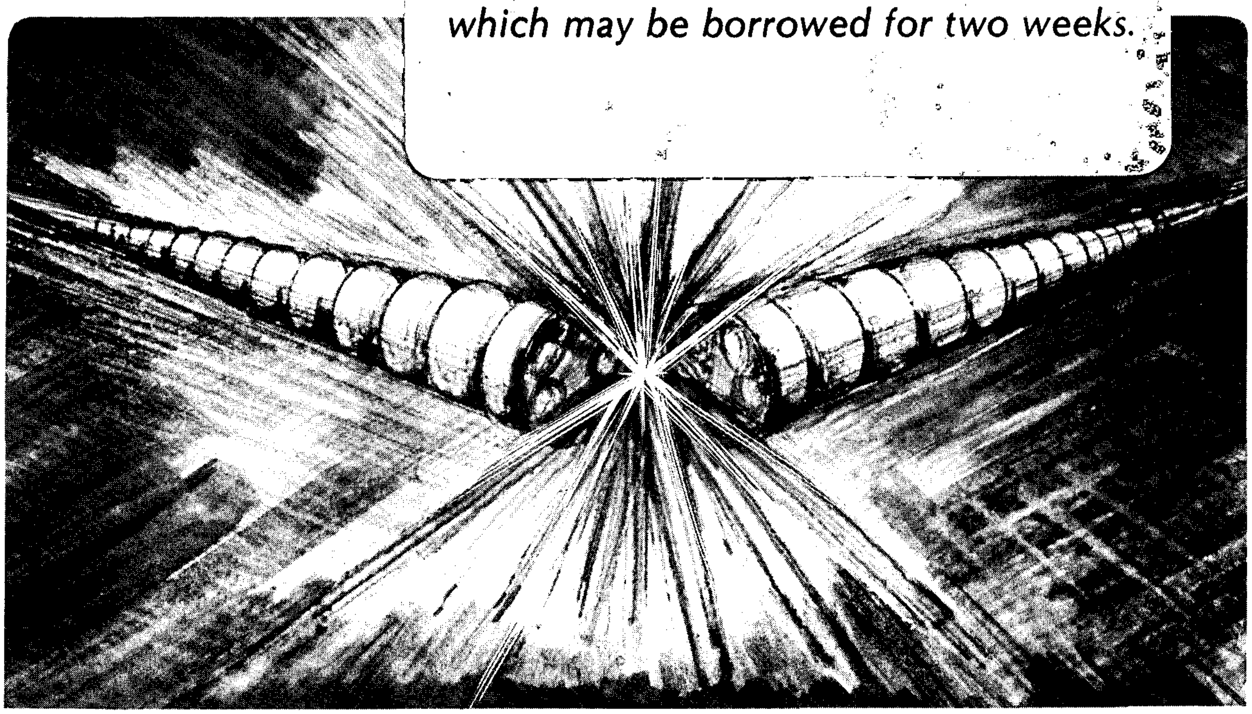

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PHASE CONTROL OF THE MICROWAVE RADIATION IN FREE ELECTRON LASER TWO-BEAM ACCELERATOR

Y. Goren and A.M. Sessler
Lawrence Berkeley Laboratory, University of California, Berkeley, CA 94720

Abstract

A phase control system for the F.E.L. portion of Two-Beam Accelerator is proposed. The control keeps the phase error within acceptable bounds. The control mechanism is analyzed, both analytically in a "resonant particle" approximation and numerically in a multi-particle simulation code. Sensitivity of phase errors to the F.E.L. parameters has been noticed.

1. INTRODUCTION

The two beam accelerator (T.B.A.) which utilizes the free electron laser (F.E.L.) has been proposed for future high gradient linear colliders.[1] To operate the T.B.A. a tight electro-magnetic phase control in its F.E.L. portion is needed.[2,3] Phase deviation results from accumulating errors in the F.E.L. section. Error sources are continuous current loss, wiggler field inaccuracy, or spatial fluctuation of the accelerating voltages across the induction units. Of particular concern is phase deviation resulting from shot-to-shot jitter in current, magnetic wigglers, and accelerating voltages. In this paper we propose a solution to the phase error caused by shot-to-shot jitter, via a "phase injection" mechanism. In this mechanism a number of correction stations will be spaced along the F.E.L. drift tube. At each station the microwave power flow will be replaced with microwave radiation of the same intensity, but with the phase expected from an ideal run (Fig. 1). In Section 2 we represent an analytical solution in the resonant particle approximation. A multi-particle numerical analysis is given in Section 3. In this section the results for phase error evolution from 1000 particles 1-D F.E.L. code will be presented and compared with the analytical results.

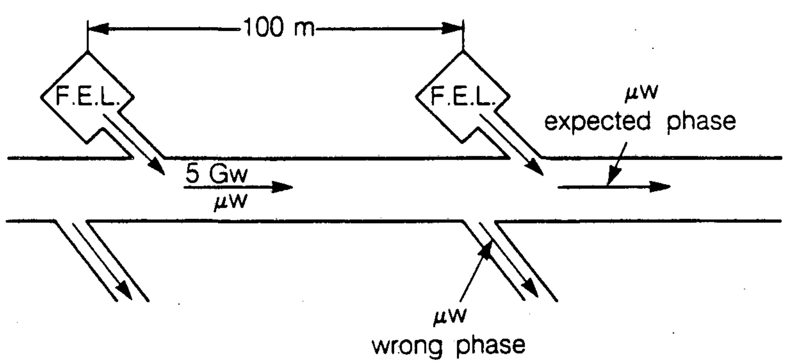

Fig. 1 Conceptual configuration of the phase injection system.

2. PHASE INJECTION IN THE RESONANT PARTICLE APPROXIMATION

To make the analysis easily understandable we shall treat the phase control mechanism only in the case of a current jitter. The same procedure applies in the other cases of fluctuations in the physical parameters. We shall use the resonant particle approximation with the standard K.M.S. notations.[4,5] The equations of motion are:

$$\frac{d\psi}{dZ} = k_w - \frac{w}{2\gamma^2 c}\left(1 + a_w^2 - 2a_w \cdot a_s \cos\psi\right) + \frac{d\phi}{dZ} \quad , \tag{1}$$

$$\frac{d\gamma}{dZ} = -w \cdot \frac{a_w \cdot a_s}{\gamma \cdot c} \sin\psi + \Delta' \quad , \tag{2}$$

$$\frac{da_s}{dZ} = \frac{1}{2} \frac{w_p^2 a_w}{w \cdot c} \frac{\sin\psi}{\gamma} - \alpha a_s \quad , \tag{3}$$

$$\frac{d\phi}{dZ} = \frac{1}{2} \frac{w_p^2 a_w}{w \cdot c\, a_s} \frac{\cos\psi}{\gamma} \quad , \tag{4}$$

where continuous acceleration, Δ', is assumed. The quantity Δ' is related to the microwave power extracted α through energy conservation:

$$\Delta' = \alpha \cdot \frac{2w^2 a_s^2}{w_p^2} \quad . \tag{5}$$

With periodic replacement of the microwave radiation with radiation of the expected phase (phase injection) Eq. (4) should be changed into:

$$\frac{d\phi}{dZ} = \frac{1}{2} \frac{w_p^2 a_w}{w\, c\, a_s} \cdot \frac{\cos\psi}{\gamma} + \sum_{M=1}^{N} (\Delta\phi_M) \cdot \delta(Z - M \cdot L) \quad , \tag{6}$$

where $\Delta\phi_M$ is the phase deviation at the M-th port and we assume in this analysis that all connected stations are equally spaced with a distance L between successive parts. The equilibrium condition (ideal run) is given by:

$$a_{s_0} = \frac{1}{2} \frac{w_p^2 a_w}{\alpha \cdot w \cdot c} \frac{\sin\psi_0}{\gamma_0} \quad , \tag{7}$$

$$\phi_0' = \frac{d\phi_0}{dZ} = \frac{1}{2} \frac{w_p^2 a_w}{w \cdot c\, a_{s_0}} \cdot \frac{\cos\psi_0}{\gamma_0} \quad ,$$

$$k_w - \frac{w}{2\gamma_0^2 c}\left(1 + a_w^2 - 2a_w \cdot a_{s_0} \cdot \cos\psi_0\right) + \frac{d\phi_0}{dZ} = 0 \quad ,$$

$$\Delta' = \frac{w \cdot a_w \cdot a_{s_0}}{c} \cdot \frac{\sin\psi_0}{\gamma_0} \quad .$$

We now study phase errors by assuming a small change from equilibrium originating from a small deviation $\zeta = -\frac{\Delta I}{I_0}$ in the injected current. Expanding all dynamical variables in ζ, we may write:

$$\psi = \psi_0 + \zeta\psi_1 + \zeta^2 \cdot \psi_2 + \dots , \tag{8}$$

$$\gamma = \gamma_0 + \zeta \cdot \gamma_1 + \zeta^2 \cdot \gamma_2 + \dots ,$$

$$a_s = a_{s_0} + \zeta \cdot a_1 + \zeta^2 \cdot a_2 + \dots ,$$

$$\phi = \phi_0 + \zeta \cdot \phi_1 + \zeta^2 \cdot \phi_2 + \dots .$$

To first order in ζ, we obtain four linear equations:

$$\frac{d\psi_1}{dZ} = -\frac{w}{2c\gamma_0^2}\left\{ -2\delta_1 \cdot U_0 + 2a_w \cdot a_{s_0} \sin\psi_0 \psi_1 - 2a_w \cdot \cos\psi_0 \cdot a_1 \right\} + \tag{9}$$

$$+ \frac{d\phi_1}{dZ} ,$$

$$\frac{d\gamma_1}{dZ} = -w \frac{a_w}{c\gamma_0}\left\{ a_1 \cdot \sin\psi_0 - \delta_1 a_{s_0} \cdot \sin\psi_0 + \psi_1 a_{s_0} \cdot \cos\psi_0 \right\} , \tag{10}$$

$$\frac{da_1}{dZ} = \frac{1}{2}\, \frac{a_w \cdot w_p^2}{w \cdot c \cdot \gamma_0}\left\{ -\sin\psi_0 - \delta_1 \sin\psi_0 + \psi_1 \cos\psi_0 \right\} - \alpha a_1 , \tag{11}$$

$$\frac{d\phi_1}{dZ} = \frac{1}{2}\, \frac{w_p^2 \cdot a_w}{w \cdot c\gamma_0 a_{s_0}}\left\{ -\cos\psi_0 - \frac{a_1}{a_{s_0}} \cos\psi_0 - \delta_1 \cos\psi_0 - \right. \tag{12}$$

$$\left. -\psi_1 \sin\psi_0 \right\} + \sum_{M=1}^{N} \Delta\phi_{M(1)} \cdot \delta(Z - M \cdot L) ,$$

where we use the notations:

$$U_0 = 1 + a_w^2 - 2a_w \cdot a_{s_0} \cdot \cos\psi_0 ,$$

$$\delta_1 = \gamma_1/\gamma_0 ,$$

and have assumed the following expansion for the phase deviation:

$$\Delta\phi_M = \zeta \cdot \Delta\phi_{M(1)} + \zeta^2\, \Delta\phi_{M(2)} + \dots . \tag{13}$$

The phase injected term in Eq. (12) acts as a periodic driving force initiating spatial oscillations of the dynamical variable. We expand the perturbated variables (Eqs. (9)-(12)) in a discrete Fourier expansion of the form:

$$\theta(Z) = \sum_{m=0}^{n-1} \theta_m \cdot \exp\left\{i\ k_m \cdot Z\right\} \quad , \tag{14}$$

where $\quad k_m = 2\pi \cdot M/L \quad ,$

$$\theta_m = \frac{1}{L} \int_0^L e^{-ik_m Z}\ \theta(Z)\ dZ \quad .$$

We obtain the four algebraic equations:

$$ik\ \psi_1 = 2\delta_1 U_0 \cdot \frac{w}{2c\gamma_0^2} - \psi_1 \frac{\Delta'}{\gamma_0} + \frac{a_1}{a_{s_0}} \cdot \frac{\Delta'}{\gamma_0} \cot\psi_0 + ik\phi_1 \quad , \tag{15}$$

$$ik \cdot \delta_1 = \frac{\Delta'}{\gamma_0} \left(- \frac{a_1}{a_{s_0}} + \delta_1 - \psi_1 \cdot \cot\psi_0 \right) \quad , \tag{16}$$

$$ik \cdot a_1 = \alpha a_{s_0} \ (-1 - \delta_1 + \psi_1 \cot\psi_0) \quad , \tag{17}$$

$$ik\phi_1 = -\phi_0' \left(1 + \frac{a_1}{a_{s_0}} + \delta_1' + \psi_1 \cot\psi_0 \right) + \frac{\Delta\phi_{(1)}}{L} \quad , \tag{18}$$

where we drop the subscript "m" in the dynamical variables and the wave number k, and we assume the same phase deviation, to first order in ζ, in each section L. The solution for the electromagnetic phase shift ϕ_1 in terms of the equilibrium parameters is given from Eqs. (15)-(18):

$$\begin{aligned} ik_m\phi_{1m} \Bigg\{ & 1 - \frac{\alpha}{q_{am}} \cdot \frac{\phi_0'}{q_{\psi m}} \cot\psi_0 \left[1 - i \frac{\Delta'}{\gamma_0 q_{\gamma m}}\right] + \frac{\phi_0'}{q_{\psi m}}\ \frac{\Delta'}{\gamma_0 q_{\gamma m}} \cot\psi_0 \Bigg[1 - \\ & i \frac{\alpha}{q_{am}} (1 - iP_m \cdot \cot\psi_0) \quad 1 - i \frac{\Delta'}{\gamma_0 q_{\gamma m}} \Bigg] - i \frac{\phi_0'}{q_{\psi m}} \tan\psi_0 \Bigg[1 - \\ & P_m \frac{\alpha}{q_{am}} \cot\psi_0 \quad 1 - i \frac{\Delta'}{\gamma_0 q_{\gamma m}} \Bigg] \Bigg\} = \\ = & - \phi_0' \left\{1 + i \frac{\alpha}{q_{am}} - \frac{\Delta'}{\gamma_0 q_{\gamma m}} \cdot \frac{\alpha}{q_{am}} \left[1 - iP_m \cot\psi_0\right] + P_m \tan\psi_0 \frac{\alpha}{q_{am}}\right\} + \\ & + \frac{\Delta\phi_{(1)}}{L} \end{aligned} \tag{19}$$

where we use the following notations:

$$iq_{\gamma m} = ik_m - \frac{\Delta'}{\gamma_0} \quad ,$$

$$iq_{\psi m} = ik_m + \frac{\Delta'}{\gamma_0} - i\,\frac{w}{c\gamma_0}\,\frac{U_0}{q_{\gamma m}} \cdot \frac{\Delta'}{\gamma_0} \cdot \cot\psi_0 \quad ,$$

$$iq_{am} = ik_m + \alpha + i\alpha a_{s_0}\,\frac{\Delta'}{\gamma_0 \cdot q_{\gamma m}}\,(1 - iP_m\cot\psi_0) + i\alpha\cot\psi_0 \cdot P_m \quad ,$$

and

$$P_m = \frac{\Delta'}{q_{\psi m}\gamma_0} \cdot \left[i\,\frac{w}{c\gamma_0}\,\frac{U_0}{q_{\gamma m}} + \cot\psi_0 \right] \quad .$$

For the zero oscillation mode, m = 0, the l.h.s. of Eq. (19) vanishes and we end up with an equation for the phase shift:

$$\Delta\phi_{(1)} = L\,\phi_0' \left\{ 1 + i\,\frac{\alpha}{q_{as}} - \frac{\Delta'}{\gamma_0 \cdot q_{\gamma_0}} \cdot \frac{\alpha}{q_{as}}\,[1 - iP_0\cot\psi_0] + \right. \tag{20}$$

$$\left. + P_0\tan\psi_0\,\frac{\alpha}{q_{a_0}} \right\} \quad .$$

In our parameter region (see Table 1) the wave numbers q_{a_0}, q_{γ_0}, q_{ψ_0} and the parameter P_0 can be approximated by:

$$q_{\gamma_0} \simeq i\,\frac{\Delta'}{\gamma_0} \quad , \quad q_{\psi_0} \simeq i\,\frac{w}{c\gamma_0}\,U_0\cot\psi_0 \quad , \tag{21}$$

$$q_{a_0} \simeq 2i\alpha \quad , \quad P_0 \simeq -i\,\tan\psi_0 \quad .$$

The average phase deviation, to first order in ζ, is given by substituting Eq. (21) in Eq. (20):

$$\Delta\overline{\zeta} = \zeta \cdot \Delta\phi_{(1)0} = \frac{1}{2}\,\zeta \cdot L\phi_0' \quad . \tag{22}$$

Hence the peak to peak phase oscillation is:

$$\Delta\phi_{pp} = 2\,\Delta\overline{\phi} = \zeta \cdot L\phi' \tag{23}$$

In the next section we present numerical results from a many particle simulation code. We shall see that analytical approximation given in Eq. (23) is in a good agreement with the numerical results.

3. MANY PARTICLE SIMULATION

In this section a many particle simulation code is used to study the behaviour of the electromagnetic phase in the phase injection scheme. Detailed description of the code is found in Ref. 6. The simulation uses discrete replenishment of the beam energy in the F.E.L. section. The code simulates the microwave propagation for different initial conditions and according to our phase injection scheme it replaces, at each correction station, the electromagnetic phase with the phase calculated from the optimum run.

In Fig. 2 we present the evolution of the phase error with distance along the F.E.L. drift tube, for the case of initial current deviation $\zeta = 0.13\%$ and without phase correction. The parameters of the run are given in Table 1. In Fig. 3 a phase injection has been applied at correct stations 60 m apart. One can see from the figure that the phase is confined in this case to $\Delta\phi_{pp} \leq 8.8°$. The analytical prediction for this set of parameters, given from Eq. (23), is $\Delta\phi_{pp} = 7.4°$. Each phase correction initiate a synchrotron oscillations, which results from the phase shift between the bunch center of gravity and the center of the potential well. The power extraction, represented by the parameter α in Eq. (3), tends to suppress these oscillations. We can see from the figure that after 3 to 4 e folds (15 to 20 m) the oscillations disappear and the phase deviation increases linearly with Z up to the next correction station.

Table 1

Parameters of the F.E.L. portion in two-beam accelerators

Average beam energy (units of mc^2)	40
Beam current	2.4 kA
Bunch length	6 m
Wiggler wavelength	27 cm
Peak wiggler field	3.2 kG
Average beam power	48 Gw
Power production	2.4 Gw/m

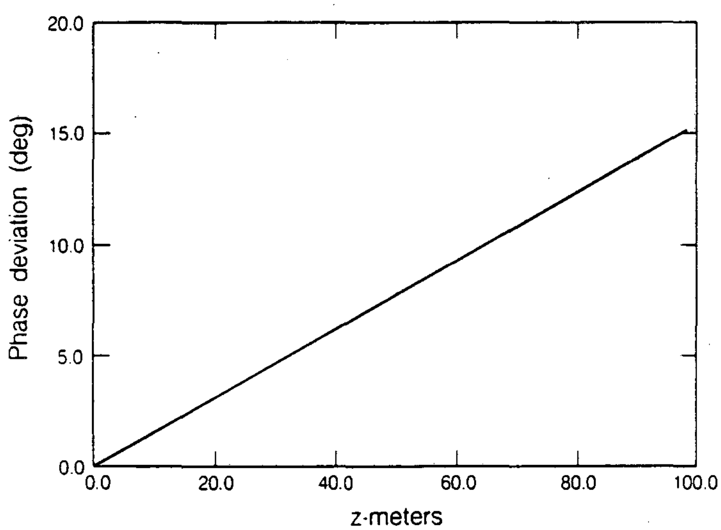

Fig. 2 Phase error vs. distance for 0.13% error in current $I_0 = 2.4$ kA.

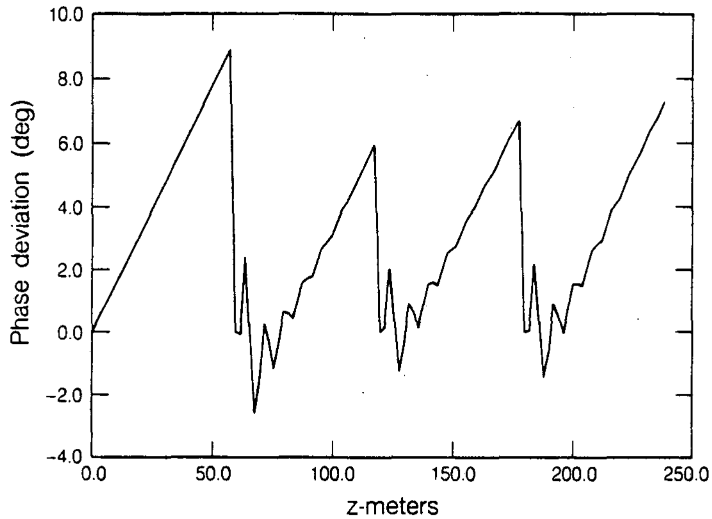

Fig. 3 Phase error vs. distance with phase injection stations 60 m apart.

To improve on this scheme we must increase the distance between correction stations without increasing the phase error. For this purpose we reduce the current flow from $I_0 = 2.4$ kA (see Table 1) to $I_0 = 2.0$ kA and the wiggler to 2.5 kG. In this mode of operation we could confine the phase error to $\Delta\phi_{pp} \lesssim 9°$ for 100 m between stations, and for the current deviation $\varsigma = 0.13\%$. Figure 4 describes the phase vs. Z for this case. Thus we see that phase error is rather sensitive to TBA parameters, and since phase control is a central issue in a TBA perhaps parameters should be chosen with careful attention to phase control.

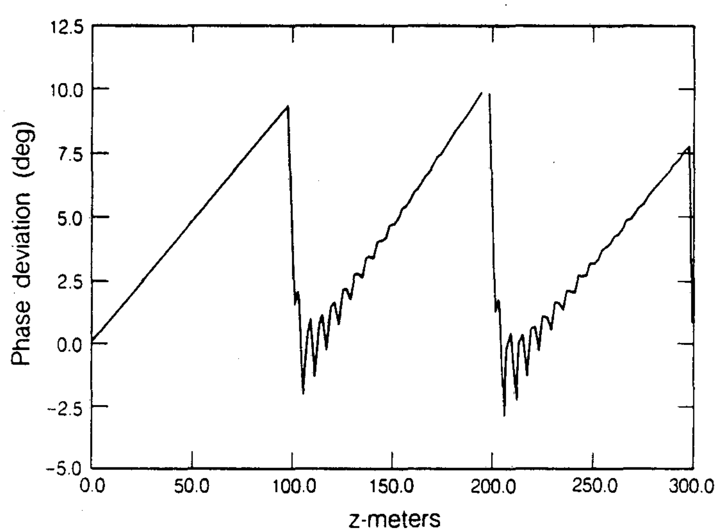

Fig. 4 Phase error vs. distance for 0.13% in current $I_0 = 2$ kA, and phase injection stations 100 m apart.

ACKNOWLEDGEMENT

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REFERENCES

1) A.M. Sessler, "The Free Electron Laser as a Power Source for a High Gradient Accelerating Structure," in Laser Acceleration of Particles, AIP Conf., Proc. No. 91, New York (1982); A.M. Sessler, IEEE Trans. on Nucl. Sci. NS-30 No. 4, 3145 (1983); A.M. Sessler, Proc. of the 12th Int. Conf. on High Energy Accelerators, Fermilab, p. 445 (1983).

2) R.W. Kuenning, "T.B.A. Phase Considerations," Lawrence Berkeley Laboratory Internal Report T.B.S. Note 12 (1984).

3) R.W. Kuenning, A.M. Sessler, and J.S. Wurtele, "Phase and Amplitude Considerations for the Two-Beam Accelerator." In Laser Acceleration of Particles II, AIP Conf. Proc., New York (1985).

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

5) R.W. Kuenning, A.M. Sessler, and E.J. Sternbach, "Radio Frequency Phase in the F.E.L. Section of a T.B.A.." In Symp. on Advance Accelerator Concept, Madison, WI, August (1986). LBL-22301

6) E.J. Sternbach and A.M. Sessler, "A Steady-State F.E.L.: Particle Dynamics in the F.E.L. Portion of a Two-Beam Accelerator." In Proc. of the 7th Int. Free-Electron Laser Conf., Tahoe City, CA. LBL-19939, September (1985).

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