Title

A NEW VERSION OF A FREE ELECTRON LASER TWO BEAM ACCELERATOR

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Publication Date

2008-09-17

LBL-25937 c.2

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To be presented at the Tenth International Conference on the Application of Accelerators in Research and Industry, Denton, TX, November 7–9, 1988

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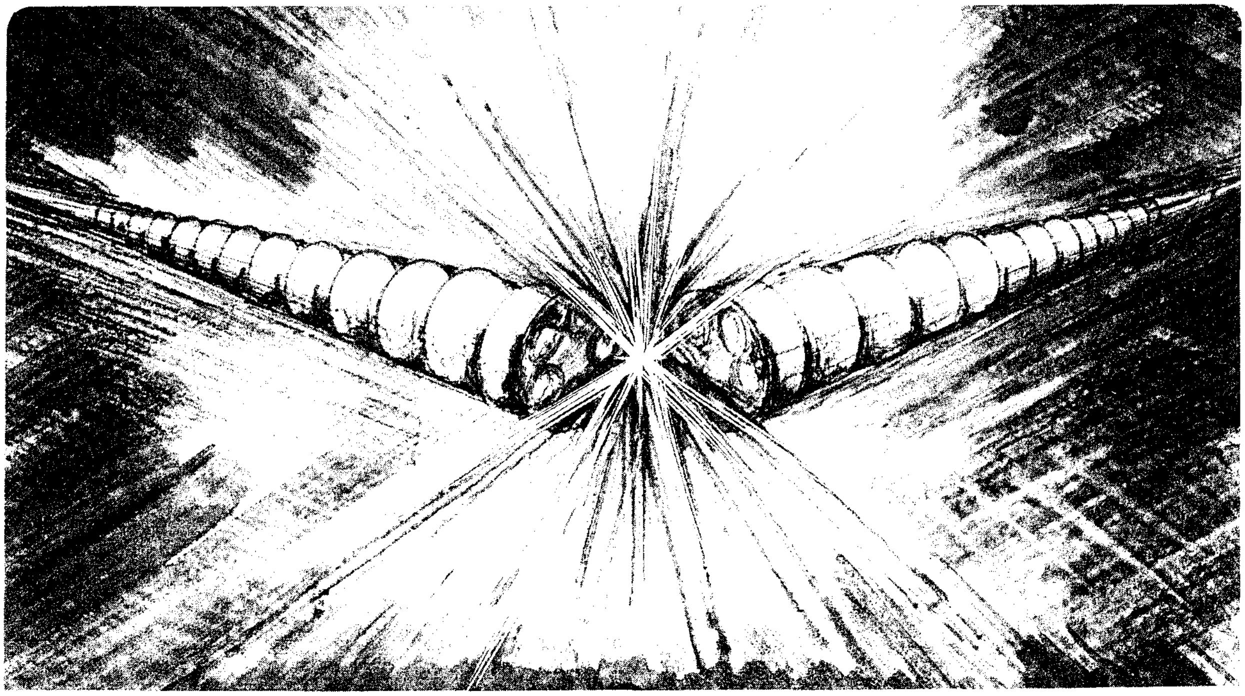

Prepared for the U.S. Department of Energy under Contract Number DE-AC03-76SF00098.

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Abstract

A new version of a Two-Beam Accelerator is proposed in which in each period of the drive structure a very small input microwave signal is amplified to a large power level and then completely removed and transferred to the accelerating structure. In this manner a number of difficulties with the original version are eliminated or greatly relieved; namely, rf phase and amplitude sensitivity, growth of sidebands, and rf manipulation (removal of the microwaves from the drive structure, and transmission of microwave power through the accelerating cavities).

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I. Introduction

As originally conceived the Two-Beam Accelerator (TBA) has the configuration shown in Fig. 1.[1] One version (TBA/FEL) as shown in Fig. 2, employes a free electron laser (FEL) as the microwave amplifier; while a second version (TBA/RK) employes transfer cavities -- a relativistic klystron (RK) as the microwave amplifier. In both cases the drive beam is powered by induction units. Although the people at CERN are pursuing the concept of replenishing the drive beam energy with superconducting cavities, we shall only concern ourselves, here, with the pulsed power method.

Quite a number of papers have been written on the TBA[2,3,4,5] concept. A number of problem areas in the TBA/FEL have been disclosed and subsequently studied. The TBA/RK has a configuration, and basic operating features, which eliminate or greatly reduce these problems. Consequently, the TBA/RK has looked more attractive than the TBA/FEL and as a result has received considerable experimental work during the last year.[6]

It is the point of this paper to suggest a new version of the TBA/FEL which appears to either eliminate or greatly relieve the problem areas intrinsic in the original version of the TBA/FEL. As a result, we now have two versions of the TBA which appear to be equally viable. Choice between them must await further work which will presumably, disclose a physics advantage, an ease of operation advantage, or an economic advantage to one version or the other. We want to emphasize, however, that at this time one can not make a rational choice between the TBA/RK and the (new) TBA/FEL.

The problem areas with the original version of the TBA/FEL have been described in the papers already cited (Ref. 1,2,3). They include the generation of sideband frequencies, the manipulation of rf (both the extraction of the rf from the drive beam waveguide and transmission of the rf through the accelerating cavities), and rf phase and amplitude sensitivity to various imperfections. The LBL group has written many papers on these topics.[7,8,9]

The new version differs from the original version in a very simple, but important manner. In the original version the microwaves surrounding the drive beam were considered to be of large amplitude and flowing through the drive structure from one end of the accelerator to the other (say 5 GW of flowing power). In each period the FEL generated power (say 1GW) which was then removed in an (almost) continuous manner by septa. Thus the drive beam electrons were subject to an (almost) invariant bucket and their dynamics was relatively simple.[5]

In the new version a small rf signal is fed in at the start of each period and amplified by the FEL. At the end of the period the rf is removed and transferred to the accelerating structure. Note, however, that the electrons of the drive beam go on from period to period.

In the remainder of this paper we explore this new version of the TBA/FEL. We first, in Sect. II, develop and study equilibrium and then, in Sec. III, study the sensitivities of the device.

II. Equilibrium

The TBA/FEL is designed and studied using the 1D-FEL equations of motion in a rectangular waveguide. These equations are given in Ref. 5. The dynamical variables are the energy of an electron (in units of its rest energy) γ_i, the phase of an electron with respect to the TE_{01}

electromagnetic wave ψ_i, the amplitude of the electromagnetic wave (in dimensionless units) a_s, and the phase of the electromagnetic wave with respect to a laboratory frame ϕ.

These equations provide stable, and unstable, phase motion in γ-ψ space; i.e. "bucket" motion. Now at the start of each period, a_s is very small and the particles are outside a bucket. At the end of a period a_s is very large and particles are inside a bucket. Can we construct a "steady state"; i.e. a periodic motion that repeats from period to period of the structure? In each period, the motion consists of a "drift" and then a "focus" (but, of course, longitudinally). As one can realize, by analogy with transverse AG focusing, it should be possible to find an equilibrium. We have done just that.

The results of a particle simulation, using the CRAY-XMP supercomputer, is shown in Figs. 3-6. We have designed to 17 GHz and 1 GW every 1.3 meters, as required according to R.L. Palmer, for a 500 GeV x 500 GeV collider giving a multi-bunch luminosity of 10^{34} cm^{-2} sec^{-1}. Parameters for the simulation are given in Tables I and II.

In Fig. 3 we show the variation through one period of the tapered magnetic field . In Figs. 4 and 5 we show the microwave amplitude and phase. The amplitude peaks at about the mid-point of a period, however this large power (~2 GW) is not removed, but is used to provide particle focusing while it is somewhat absorbed during the remainder of the period; the final 1 GW is then removed.

The rapid phase change at the start of a period is a direct result of the equation for $d\phi/dz$ (See Ref. 5) which depends inversely upon a_s. (In the exponential growth region of an ordinary FEL there is no particle bunching at the start of the FEL and $d\phi/dz$ is small even though a_s is small; here, of course, the particles remain bunched and carry that information from period to period so that $d\phi/dz$ is very large when a_s is small.)

Figures 6a,b,c are Poincare Section plots at 1/3 of the way, 2/3 of the way, and at the end, of a period. One can see from these superpositions of motion in many periods that the motion is truly an equilibrium state. More importantly, one can see that there is a considerable region of phase space that is stable. Thus, one doesn't require an excessive longitudinal brightness for this version of the TBA; in fact when we start with an unbunched beam of say 3kA we find that 2kA becomes trapped.

III. Sensitivities

Having obtained an equilibrium it is now a straight-forward process to study the sensitivity of this state to variation of parameters. We are interested in the rf field, characterized by a_s and ϕ, and study its sensitivity to drive beam energy, current, and initial phase. We believe that wiggler field and wave guide dimensions, etc. are sufficiently stable as not to require a study.

In all cases we found a surprisingly small sensitivity. Firstly, we varied the beam current. For a 6% variation (±3%) we found $\Delta\phi = 0.03$ radius, or $(\Delta\phi/\phi) = 0.09(\Delta I/I)$.

Secondly, we varied beam energy and found that for a variation of + 0.1 MeV to - 0.1 MeV (i.e. 0.5%) there was no measurable change in phase ϕ.

Thirdly we varied initial phase of the particles with respect to the initial rf wave (a mis-match) by $\Delta\psi = 0.2$ and, again, found no measurable change in phase ϕ.

Fourthly we studied the sensitivity to random errors in the strength of the re-acceleration gaps. Instead of providing exactly 0.5 MeV we took a Gaussian about 0.5 MeV with a rms spread of 2%. We found that the average phase was as in the equilibrium state with the standard deviation of the phase, $(\overline{\Delta\phi^2})^{1/2} = 0.02$. One can easily make induction units to a 2% accuracy, and 1° phase error is quite acceptable, so again we obtain a strong insensitivity.

In order to understand the insensitivity of the new TBA/FEL we studied a single resonant particle and obtained pretty much the same results as with a cloud of particles. The resonant particle equation are a set of 4 coupled ODEs with varying coefficients so that they are rather complicated. We have not yet pursued this semi-analytic work so we do not yet have a simple description of the sensitivities. It is clear that with "new" rf each period phase errors will not accumulate. Yet the particles carry information from period to period and when there is an error, say in energy, this is mis-information. Yet, as the particle locks on to the equilibrium state, this mis-information is dominated by the (very weak) correct phase information of the input rf signal.

IV. Remarks

We have proposed a new version of the TBA/FEL in which in each period (section) a low level of rf (from a clock) is amplified and then removed, at the end of the period, to the accelerating structure. This new version, in which the rf in each period is de-coupled from all other periods, seems to have decided advantages over the original version in that (1) phase and amplitude of the rf is remarkably insensitive to various imperfections, (2) the rf extraction is simplified, (3) no rf needs to be taken through the re-acceleration cavities, and (4) sideband growth is suppressed.

Our analysis has been in 1-D and must now be extended to two and three dimensions. We don't expect new troubles (especially if the drive beam is energetic enough), but growth of transverse emittance may limit the number of re-accelerations. We need to study the resistive wall instability and learn what limits this imposes (for example, on gap size). (Such studies have been made of the original TBA/FEL.[11])

Further analysis needs to be done to properly understand the sensitivity studies. Also, sidebands need to be studied. We suspect that it will no longer be necessary to have the average longitudinal velocity of the electrons, $v_{||}$, made equal to the rf group velocity, v_g, but it may be advantageous to have the extra stability that this condition implies (as in a distributed-feedback semiconductor laser).

Finally, although a number of items remain to be studied theoretically, and a great deal of experimental work remains to be done, the new TBA/FEL is very attractive and demands further investigation.

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Table I. Parameters of the high-energy beam in a Two-Beam Accelerator.

Energy	500 GeV x 500 GeV
Single-bunch luminosity	5 x 10^{32} cm^{-2} sec^{-1}
Multi-bunch luminosity	10^{34} cm^{-2} sec^{-1}
Frequency	17.1 GHz
Repetition Rate	180 Hz
Gradient	180 MeV/m

Table II. Parameters for the drive beam of a Two-Beam Accelerator.

Period length	130 cm
Waveguide size	20 cm x 3 cm
Initial particle energy	14 MeV
Energy gain per period	0.5 MeV
Beam current	2.2 kA
Wiggler period	26 cm
Maximum wiggler field	3.85 kG
Input power per period	100 kW
Power extracted per period	1 GW
Phase change per period	6 radians

Figure Captions

Fig. 1. Schematic of a two-beam accelerator (TBA). The low-energy drive beam provides power to the high-energy (≈TeV) beam.

Fig. 2. An artist's drawing of the free-electron laser (FEL) version of the two-beam accelerator (TBA). In this version, microwaves are generated from the drive beam by FEL action.

Fig. 3. Wiggler peak magnetic field through one period (130 cm) of the TBA. The period of the wiggler is 27 cm so, of course, the field that the particles fell varies with that period.

Fig. 4. Power in the TE_{01} waveguide mode through one period.

Fig. 5. Phase (with respect to the laboratory) through one period. The phase is taken as zero at the start of the period.

Fig. 6. Poincare (surface of section) plots located at (a) 1/3 point, (b) the 2/3 point of a period, and (c) at the end of a period (just prior to re-acceleration of the particles).

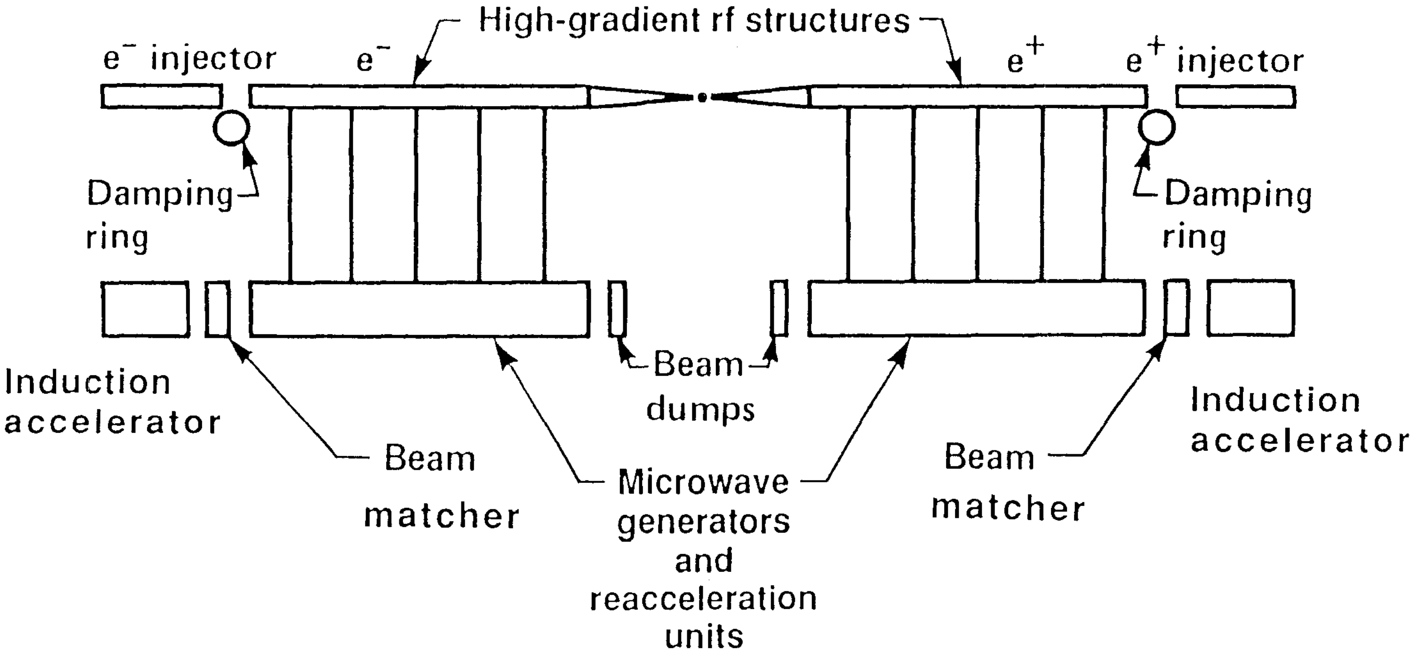

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Fig. 1

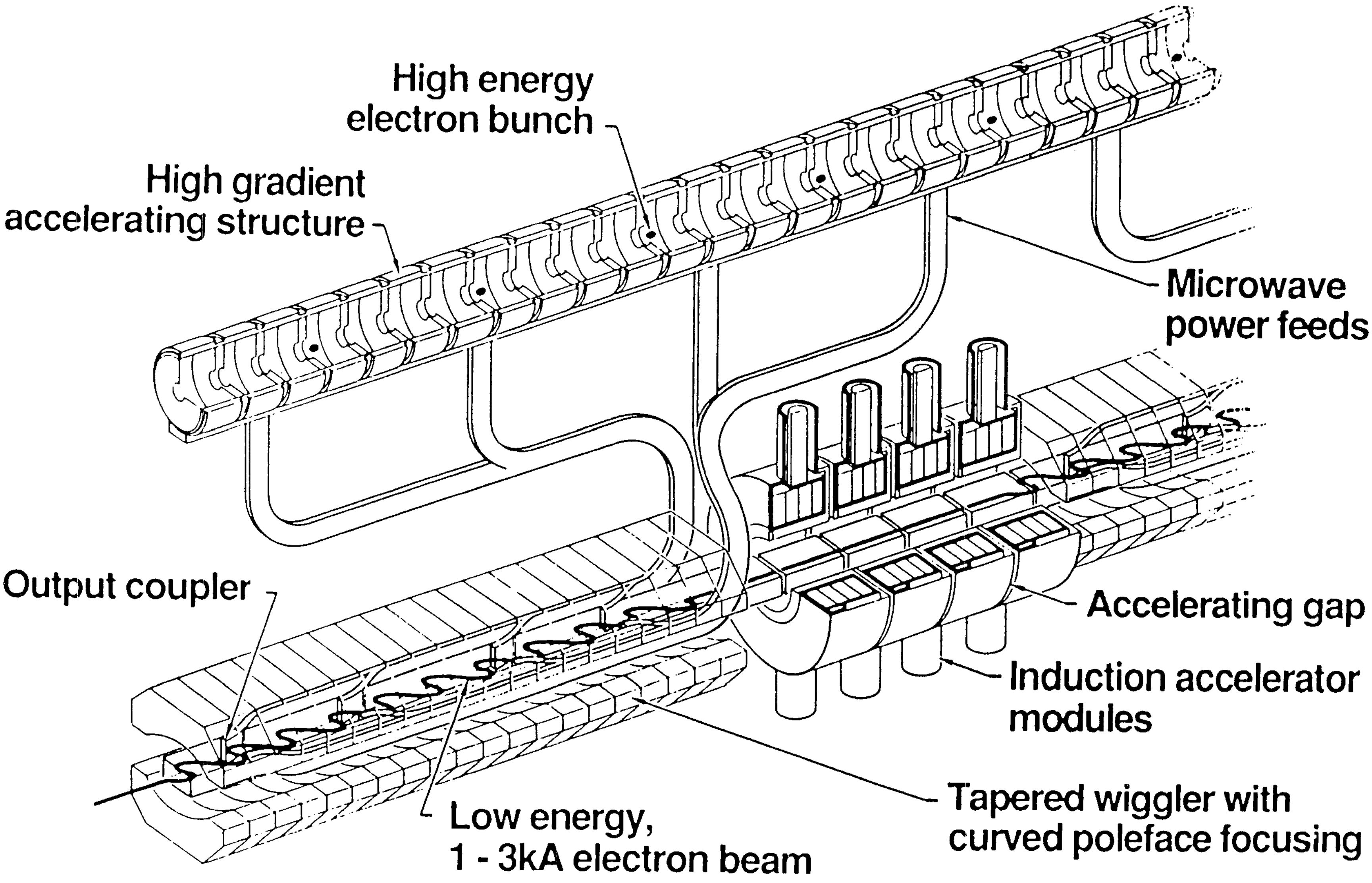

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Fig. 2

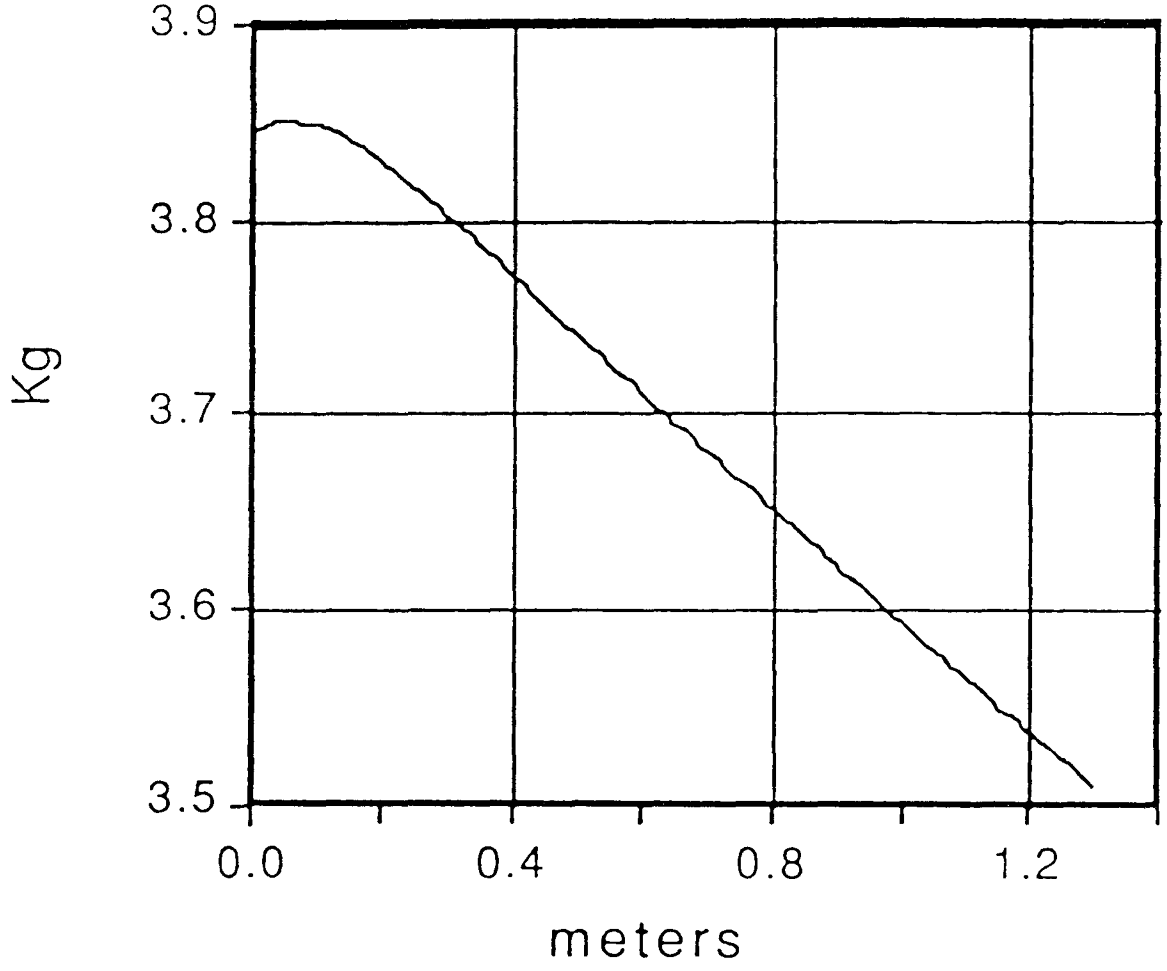

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Fig. 3

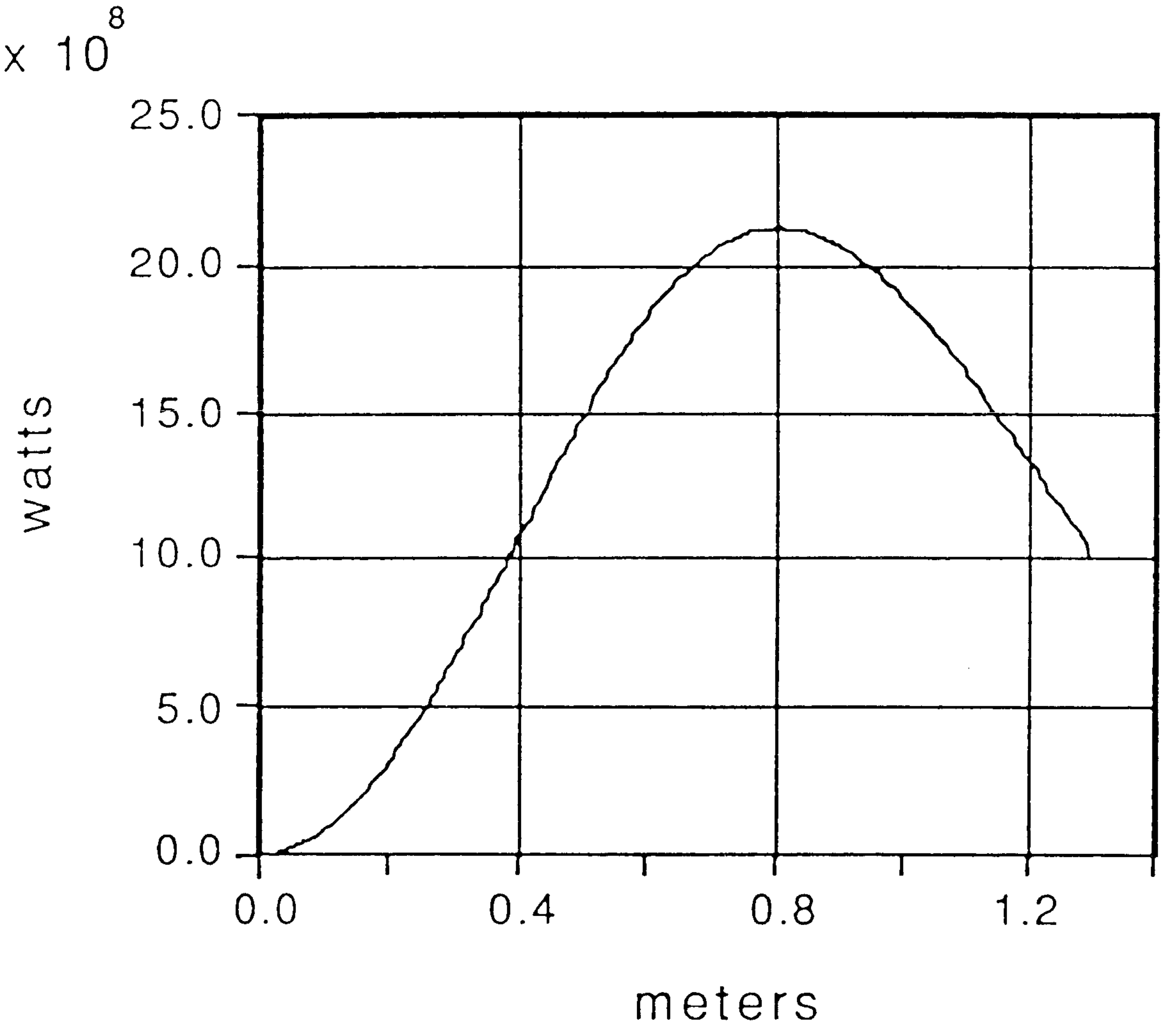

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Fig. 4

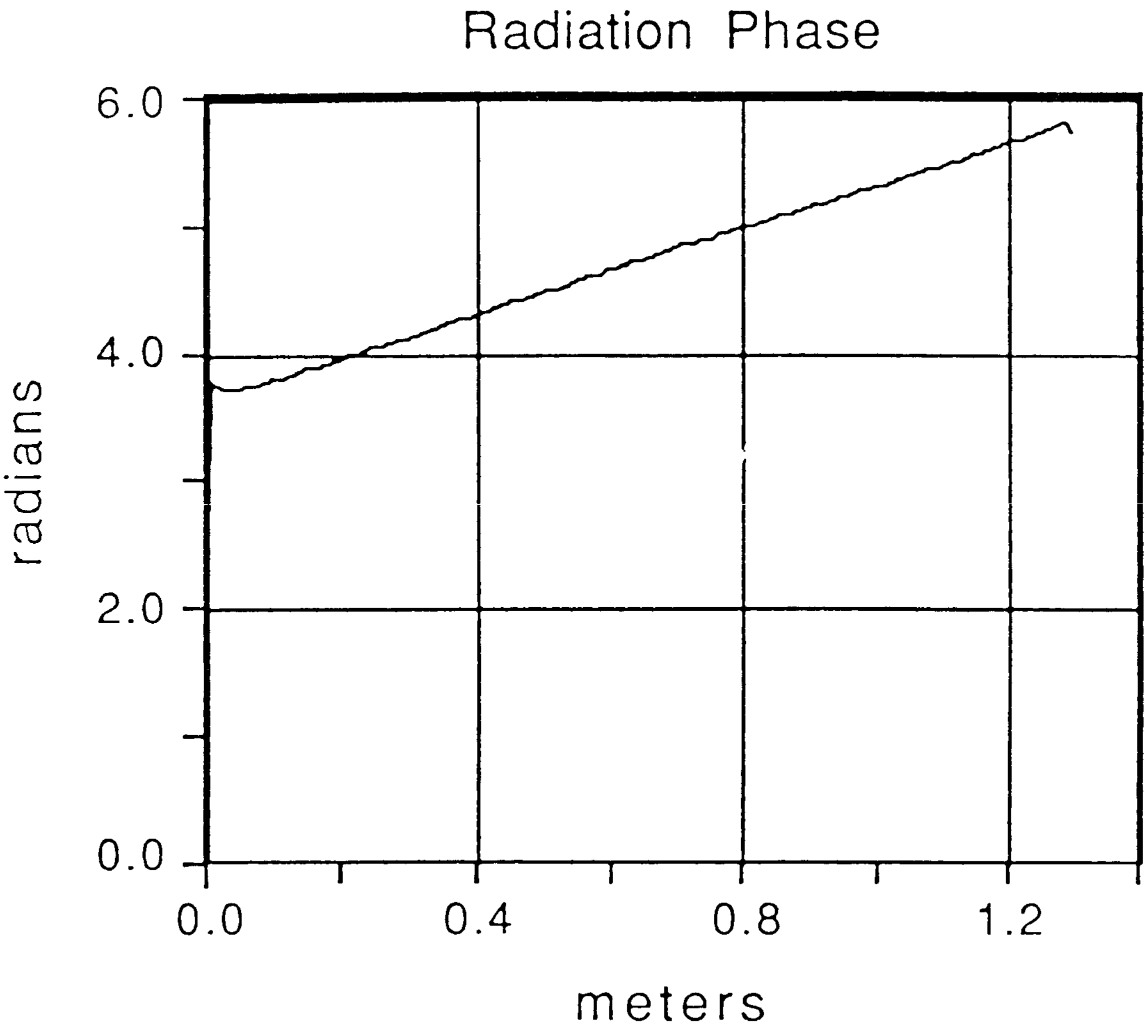

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Fig. 5

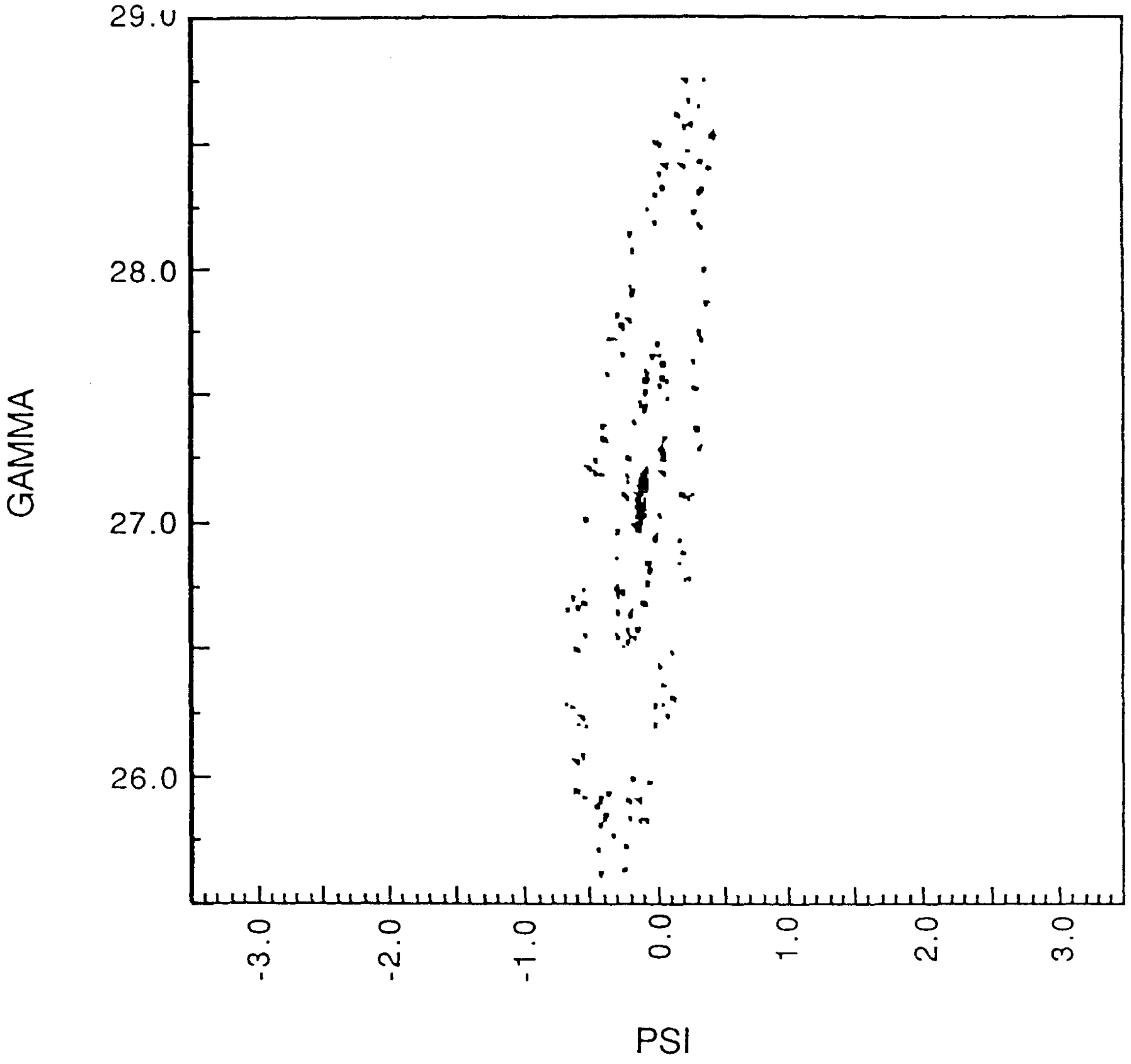

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Fig. 6a

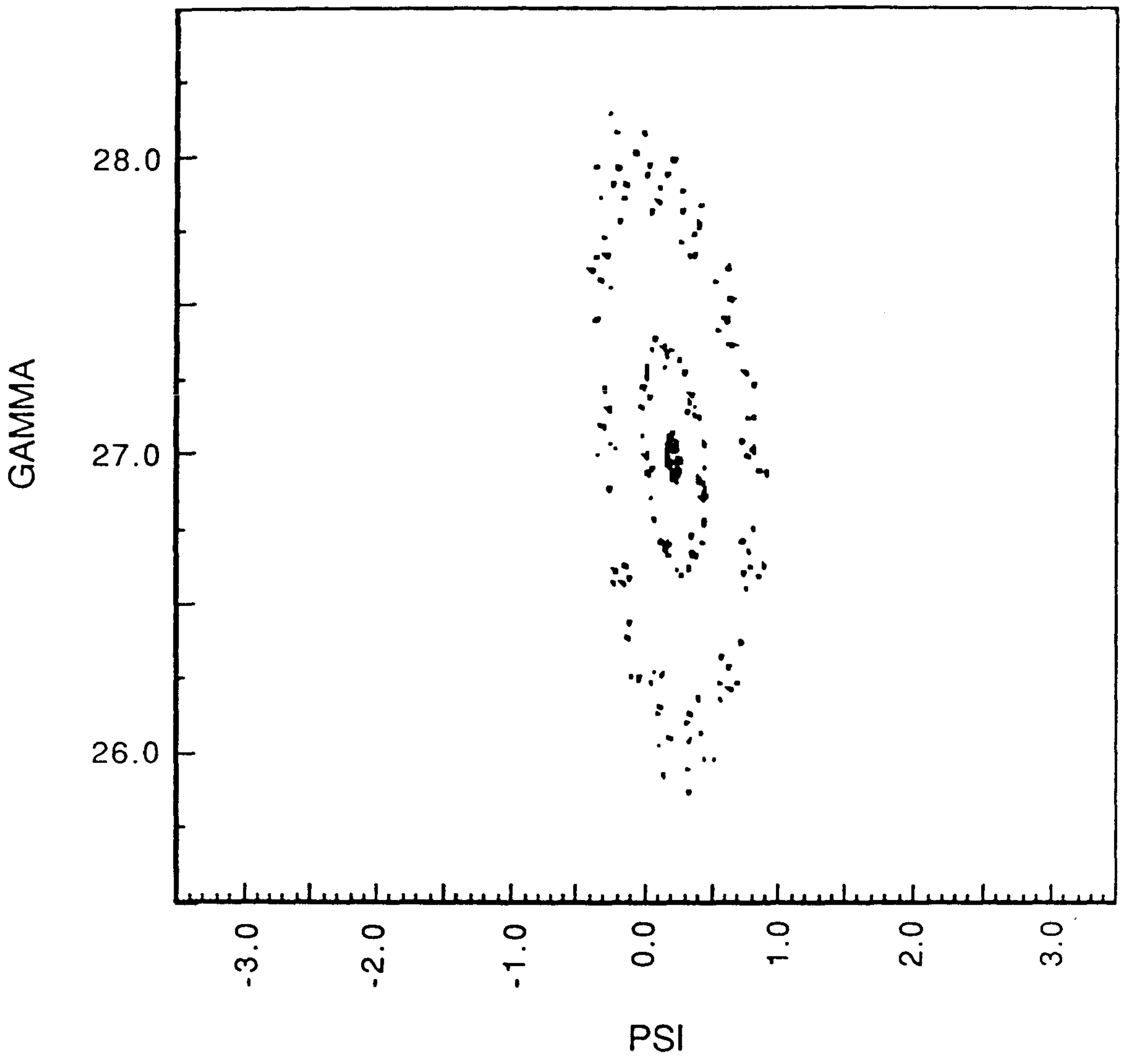

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Fig. 6b

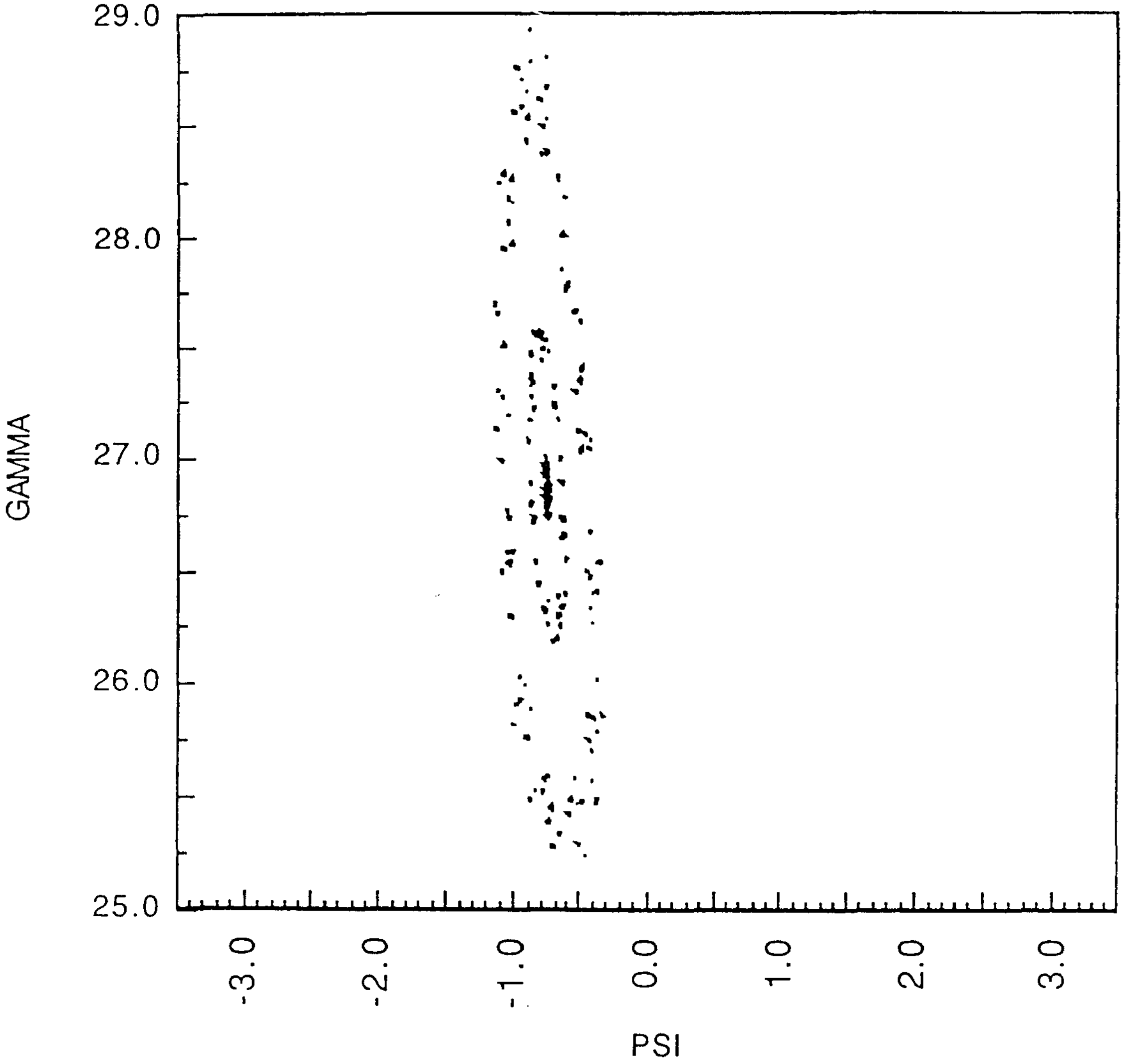

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Fig. 6c