APPLICATION OF HIGH POWER, INTENSE ELECTRON BEAMS TO ULTRA HIGH ENERGY ELECTRON ACCELERATORS.

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ABSTRACT

We present in this paper a review of the application of pulse power technology to the development of high gradient electron accelerators. Intense pulse technology limits pulse durations to about 100 nsec. Consequently, if we are to use these sources we will require the use of high group velocity structures. We describe in the following sections two approaches to electron acceleration which meet this requirement. The first of these uses high power microwave radiation generated from a pulsed beam in a phase slip accelerator configuration, and the second is a collective accelerator approach in which electrons are accelerated in a fast Doppler shifted upper hybrid mode wave carried on the primary beam. In both approaches one may obtain very high average electric fields for acceleration.

1 INTRODUCTION

Single pulse high power, electron beam generators were first developed at the 30 GW level in 1962[1]. Since that time the technology has been developed to the point where reliable 1 kHz repetition rate operation has been achieved using magnetic switching to control the pulse development[2]. From the point of view of particle accelerators, using pulse power sources as the primary energy source, today's technology exceeds that likely to be required by at least an order of magnitude.

We consider in this paper the use of pulse power technology to generate weakly relativistic kiloampere beams for the generation of high power microwaves for use in a 'conventional' electron accelerator. We also review a new collective accelerator scheme for electrons in which the weakly relativistic intense electron beam is used to support the fast Doppler shifted upper hybrid mode of the beam guide system. In both cases the pulse duration is short and we need to use high group velocity structures or beam modes to efficiently use the primary beam energy for electron acceleration.

The use of high power intense pulsed electron beams for microwave generation has been remarkably successful from the first experiments in 1969[3] to the most recent FEL experiments in which 1.6 GW powers were obtained at 35 GHz[4]. It may well be through this medium that pulse power technology is first used for particle acceleration[5].

It is worth commenting on the differences between conventional microwave sources and those utilizing pulsed power. Most of the pulse power sources developed to date have pulse durations of about 50 to 100 nsec. and consequently will contain only a limited number of cycles of the r.f. wave. Natural bandwidths of the r.f., due to the finite pulse duration, are of order 0.02/f (GHz) where the frequency is given in gigaHertz. Detailed studies have not yet been made of the phase stability of these sources and it is not clear that they will be suitable for the needs of particle accelerators. However, if we accept for the moment the potential suitability of these r.f. sources, then we must still address the types of structures in which they might be used. The short pulse durations imply that we will either have to use low Q or high group velocity structures if the filling time ($2Q/\omega$) is to be made short compared to the pulse duration. Current structures typically use group velocities of order 0.03c and it would be desireable to increase this value by about an order of magnitude. For cavity Q's of order 10^4 the filling time requirement implies operating frequencies in the 30 GHz range. A second and perhaps equally important factor in the design of suitable structures arises from the desire to keep the r.f. field from the walls so the accelerated particles sample the maximum field region whereas the wall fields, which can lead to breakdown, are held as low as possible. This criterion is met in collective beam accelerators where the accelerated particles travel in the region of maximum field and the wall fields are small. A similar class of structures exist for externally driven devices, however the particles must then sample the radial fields within the mode. The phase slip accelerator configuration described below meets both of these requirements5).

2. PULSE POWER TECHNOLOGY AND PARTICLE ACCELERATORS

We have already indicated in the introduction the main requirements imposed by pulse power technology on particle accelerator development. It is worth commenting also on some of the advantages afforded by this technology. All r.f. accelerators use two beams, a low voltage beam for microwave generation and the accelerated beam. These are typically physically separated from each other and coupled by waveguide. The accelerated beam is driven by the fields generated by the coupling of the r.f. generated to a slow wave structure. Fields are usually a maximum at the boundaries of the slow wave structure which typically allow waves to propagate at very low group velocities (~0.03c). Since the typical r.f. pulse duration is 1-2μ sec this presents no problem in filling the structure. In the scenario's reviewed in this paper we consider r.f. pulse durations of order 50-100 nsec. If the module lengths of the structures are not going to be prohibitively short, especially at the higher operating frequencies expected to be used, the wave group velocity must be about or preferably greater than an order of magnitude higher than those in use today. The shorter durations should lead to an increase in the breakdown field strengths and the higher group velocities to a greater separation between the beam and the walls, and hence perhaps, to a reduction in the wake fields. The negative side of this is a possible reduction in the efficiency of the accelerator. Calculations of the elastance of certain novel structures suggest however that it might be possible to obtain elastance figures comparable to those of the scaled SLAC structure.

An approach to the use of high group velocity structures that is of interest for further investigation is the phase slip accelerator. In this device the beam trajectory is rectilinear while the structure, which has a uniform cross section, gently undulates with a sinusoidal or helical variation of the tube axis. In this configuration the particle samples the radial variation of the axial acceleration field and hence the average field gradient felt by the particles is less than the peak field in the wave. On the other hand in such a device the electric fields maximize in the guide and not at the wall so the flashover problems are minimized. The phase slip accelerator described has a very large aperture compared to more conventional slow wave structures so this should lead to reduction in wake field effects although the non axial propagation of the beam suggests that the wake fields may be worse than those found in cylindrically symmetric systems of comparable dimensions.

High group velocities also can be obtained with axisymmetric systems in a synchronous accelerator system. Such a device has all of the advantages of the phase slip accelerator configuration indicated above, i.e. fields a maximum at the beam location, wall fields low, and large aperture systems, and, in addition, does not require microwave plumbing to connect the r.f. source to the accelerator as the acceleration fields are generated at the accelerated beams location. The configuration proposed uses the Doppler shifted upper hybrid mode of a beam in a finite diameter guide. This mode may be closely approximated by Doppler shifted cyclotron oscillations. This is the only eigenmode of an electron beam in a bounded guide which cuts the light line and hence can be used for the acceleration of electrons to ultra high energies without the use of complex phase slip sections. In this device the group velocity of the wave is close to the speed of light and hence well matched to the short duration of pulse power generators. In the following section the basic ideas underlying this device will be presented and specimen parameters presented for an accelerator. Work is currently in progress in first attempts to excite the required mode

3 A HIGH GRADIENT ELECTRON ACCELERATOR

In this section of this report we outline a proposal for a particle accelerator structure which satisfies the criteria presented earlier, namely we have a structure with a short filling time, a high group velocity, and the field is a maximum away from the walls of the device. The accelerated particles sample the field at varying radii throughout the accelerator and the average field is a fraction of the peak (on axis) field in the device. In the particular device proposed one might also expect the wake field effects to be reduced compared to those in other structures due to the overmoded guide used and the relative absence of structure close to the beam. In the proposed device the peak field is off the walls and hence should be better from the point of view of breakdown. The issue of structure design for short duration, high power r.f. pulses is open and the merits of the various competing schemes still have to be evaluated.

The new accelerator configuration proposed uses a periodic undulating waveguide. It is very similar in principle to the IFEL in as much as the electrons slip one cycle of the r.f. wave every period of the structure. The interaction is however through a TM mode and hence is longitudinal and not subject to prohibitive synchrotron radiation losses. The interaction may also be described as a special case of a high group velocity slow wave structure.

We consider a smooth bore waveguide operated in the TM02 mode. The guide axis varies sinusoidally as a function of its position with period Γ and amplitude R_o. Ideally the guide axis will have a helical variation, however, for the sake of simplicity we restrict ourselves to the sinusoidal variation case. We also ignore changes in the waveguide fields due to the curvature of the guide relative to the particle trajectory. This variation is readily included in the analysis and does not alter the basic results significantly. For a guide having an axial variation

$$R(z) = R_o \sin[\frac{2\pi z}{\Gamma}]$$

we compute the force on an electron due to a TM wave traversing the structure as

$$F(z) = eE_o J_o\,(k_c R_o \sin(2\pi z/\Gamma))\cos(\omega t - kz)$$

which averages to zero unless

$$\beta_e = \frac{\omega}{(k + 2nK)c}$$

where K is the wavenumber of the ripple in the guide. If this synchronism condition is satisfied then the force on the electron becomes

$$F(z) = eE_o J_o[k_c R_o \sin(\frac{2\pi z}{\Gamma})]\cos(\frac{4\pi z}{\Gamma})$$

and is plotted in Figure 1. The average of the acceleration field over a period of the structure is shown in Figure 2. In comparison with the IFEL the periodicity of the structure is almost constant, independent of the beam energy, since the wave phase velocity exceeds the speed of light. The same acceleration principle may be invoked using standing waves in a cavity. The use of the synchronism condition leads to an effective field of

$$E(z) = E_{ax} J_o[k_c R_o \sin(\frac{2\pi z}{\Gamma})]\cos(\frac{\pi z}{L})\cos[(k + 2K)z].$$

The value of the acceleration field averaged over the cavity length is plotted in Figure 3.

We have computed the zero-order effects of the wave following the guide geometry rather than travelling in a straight line and the changes are relatively unimportant. The synchrotron radiation has been estimated using the r.f. fields in the actual guide as sampled by the electrons but without including the effects of the wake fields due to the varying proximity of the guide walls. In this approximation radiation losses are unimportant until electron energies in excess of 1 TeV have been achieved.

Table I shows un optimized values of the various accelerator parameters for a 35 GHz wave at the 1 GW power level in the travelling wave case. For a standing wave we obtain comparable acceleration field gradients to those shown at a power level about one order of magnitude lower than that given above. The scaled value of the elastance of the structure is about 6 times lower, for the travelling wave case shown in Table I, than the SLAC disk loaded guide. In the cavity case the elastance is only 3.5 times smaller than that for a scaled SLAC structure.

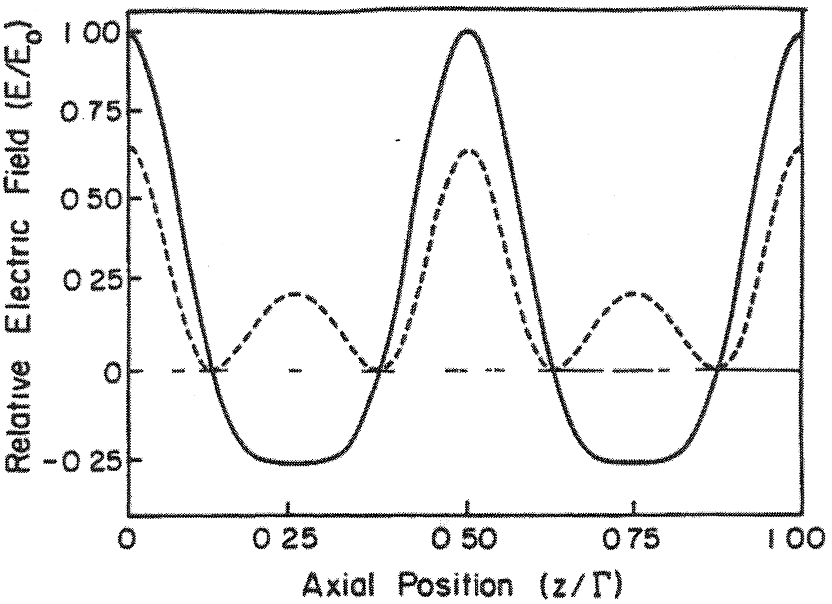

Fig. 1 Local field, normalized to the peak axial field for the TM01 mode, felt by an electron in traversing a period of the undulator. The solid line is for the TM01 mode and the dashed line for the TM02 mode.

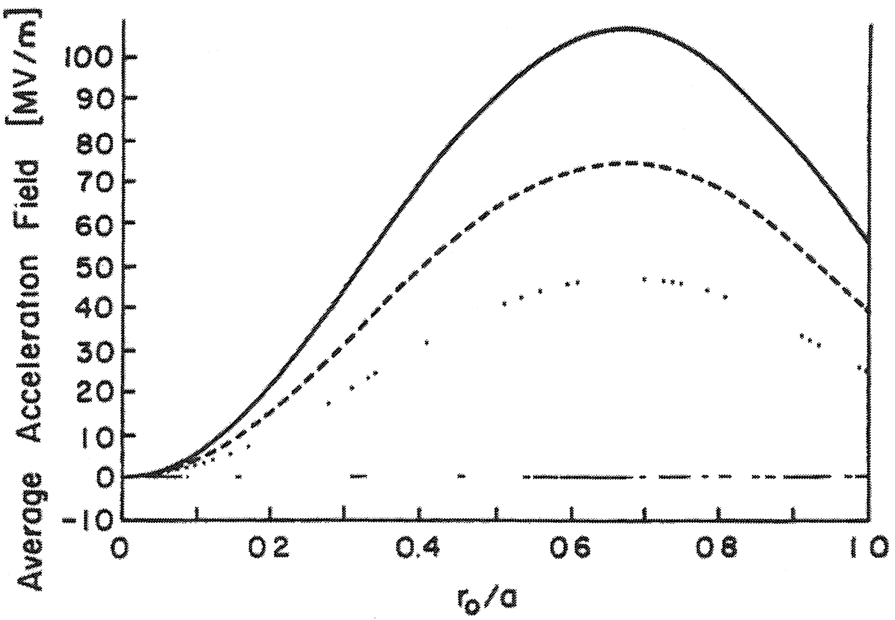

Fig. 2 Average acceleration field in travelling wave accelerator at 35 GHz as a function of the guide curvature R_ρ/a. The three curves are for powers of 1, 0.5, and 0.2 GW respectively.

TABLE I
Parameters for phase slip accelerator

Frequency (GHz)	35
Guide cut-off frequency in TM02 mode (GHz)	33
Module length (m)	3
Power (GW)	1
Pulse width (ns)	50
Peak field on axis (MV/m)	310
Average Acceleration field (MV/m)	100
Undulator Period (cm)	2.8
Wall Modulation (Ro/a)	0.6
Particles per macrobunch	6×10^{10}
Elastance	10^{15}

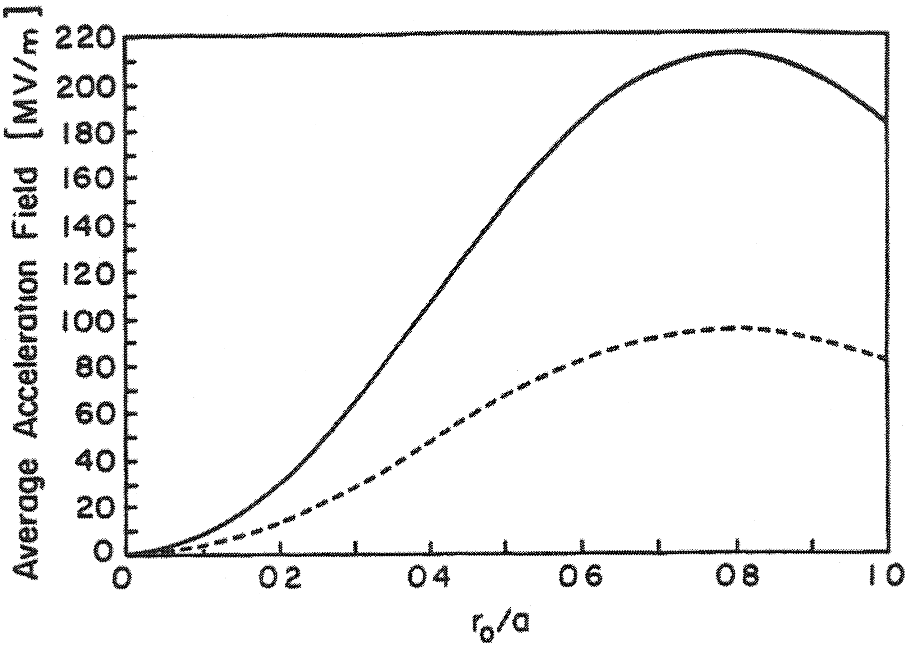

Fig 3 Acceleration field averaged over a cavity length for TM02p mode at 0.5 and 0.1 GW as a function of the guide curvature.

We conclude this section by noting that the same principle may be used to accelerate an high average current beam (~ 10's Amperes) by running at a lower frequency (~ 1.5 GHz). The latter configuration may be especially useful in the future development of high power r.f sources.

4 A HIGH GRADIENT COLLECTIVE ELECTRON ACCELERATOR

Up until now efforts to collectively accelerate particles have been limited to situations where the required particle energy T is less than

$$T = \frac{M}{m}(\gamma_0 - 1)mc^2$$

where M and m are the ion and electron masses respectively and γ_0 the drift energy of the electrons in the primary beam. This requirement arises since acceleration has only been considered in negative energy (slow) waves carried on beams. To accelerate electrons to ultra high energies using the collective modes of an electron beam in a guide requires the use of waves having phase velocities greater than the electron velocity in the primary beam (fast waves). Such a wave will have a positive energy and will require the use of a powerful external source of free energy to drive the wave. It is only in the past two years that we have recognized a way around this problem and have demonstrated the use of a successful excitation technique, albeit for a space charge wave rather than the required mode6). The technique relies on the simultaneous excitation of slow and fast waves so that each may grow at the expense of the other. This process is familiar in the excitation of radiative modes in a free electron laser. We now examine a possible eigenmode for electron acceleration using a weakly relativistic electron beam as the active medium.

We restrict our analysis to the case where the upper hybrid frequency is lower than the cut off frequency for the guide. In this condition we can approximate the fields by use of a scalar potential. The full electromagnetic case is currently being studied in both the linear and non linear regimes7). The analysis assumes a relativistic rigid rotor equilibrium. The relativistic bulk rotation frequency Θ, is given by

$$\dot{\Theta}_0 = \frac{\Omega_c}{2}\left(1 \pm \left(1 - \frac{2\omega_p^2}{\Omega_c^2}\right)^{1/2}\right)$$

To obtain a stable equilibrium one requires that $\Omega_c^2/\omega_p^2 \geqslant 2$ and preferably that the ratio exceeds 3 to preclude the excitation of unwanted surface modes. The analysis uses a two-mass appproximation and the linearized continuity and momentum equations together with Gauss' law. The dispersion relation follows from matching the jump conditions at the beam vacuum boundary and from setting the wave potential on the wall to zero. For axisymmetric waves we obtain

$$\frac{I_0'(ka)K_0(kb) - I_0(kb)K_0'(ka)}{I_0(ka)K_0(kb) - I_0(kb)K_0(ka)} = A(\omega,k)\frac{J_0'(k_\perp a)}{J_0(k_\perp a)} + B(\omega,k)$$

where

$$A(\omega,k) = \left(\frac{(\omega_v^2 + \gamma^2\omega_p^2 - \omega_b^2)(\omega_p^2 - \omega_b^2)}{(\omega_v^2 - \omega_b^2)\omega_b^2}\right)^{1/2}$$

and

$$B(\omega,k) = \frac{m\gamma^2\omega_p^2\omega_v}{ka(\omega_v^2 - \omega_b^2)\omega_b}$$

and k, ω_b, and ω_v, the vorticity frequency are defined by

$$k_\perp^2 = \frac{k_z^2(\omega_p^2 - \omega_b^2)(\omega_v^2 - \omega_b^2)}{(\gamma^2\omega_p^2 + \omega_v^2 - \omega_b^2)\omega_b^2}$$

$$\omega_b = \omega - kv_d$$

$$\omega_v^2 = \Omega_c^2 - \omega_p^2 = (\Omega_c - 2\dot{\Theta}_0)^2$$

respectively. Figure 4 shows a plot of the dispersion relationship together with the space charge waves for a particular set of parameters.

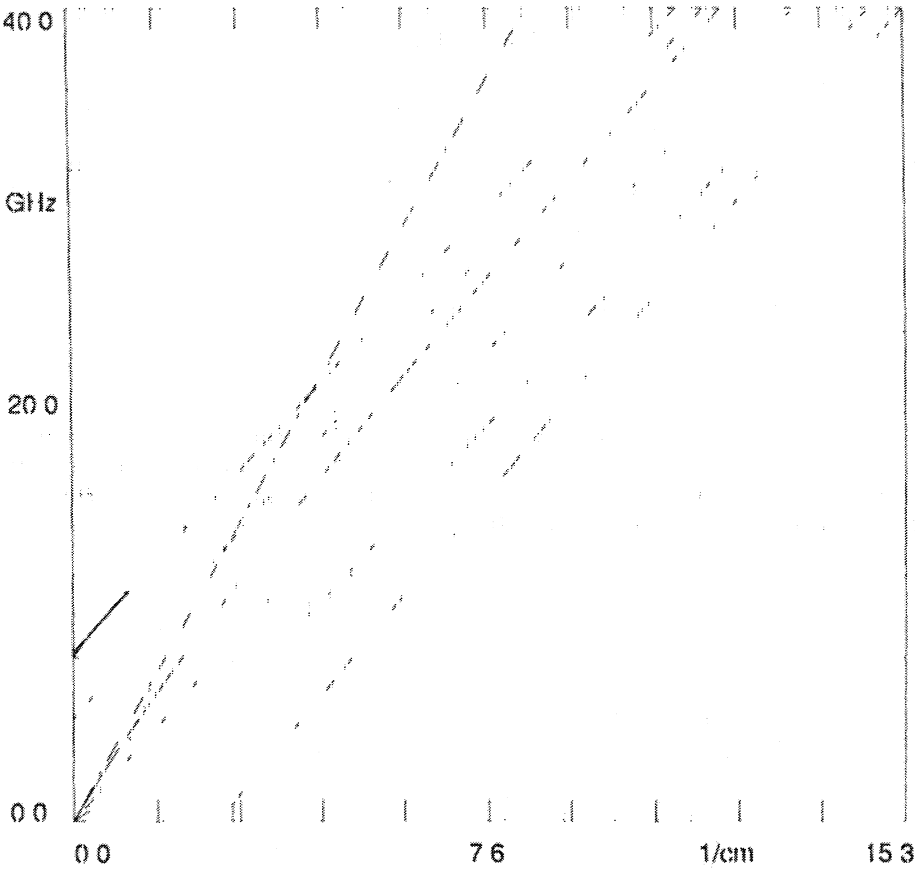

Fig 4. Dispersion relation showing the beam modes. The dashed lines represent the electron drift velocity, the light line and the asymptotic (large ω and k) form for the fast upper hybrid mode.

In this plot the input voltage is 500 kV and the beam current 1.9 kA. The beam radius is one quarter of the tube radius and the cyclotron and plasma frequencies are 11.6 and 6.3 GHz respectively.

We can obtain further information about simple scaling processes if we recognize that the hybrid wave modes may be well approximated by Doppler shifted oscillations at the cyclotron frequency

$$\omega = k v_d \pm \Omega_c .$$

Setting the fast wave phase velocity equal to the speed of light we find that the wave frequency should be approximately given by

$$\omega = \frac{eB_0}{m} \left(\frac{1+\beta}{1-\beta} \right)^{1/2} .$$

Within the framework of this approximation one can obtain an estimate of the fields achievable in the Raman (collective) regime. it should be noted that this is not neccessarily the optimum regime and that two wave interactions, such as those employed in the free electron Laser work of Sessler et al may yield substantially higher acceleration fields.

Assuming that both the slow and fast waves are grown simultaneously and at the same frequency the conservation of wave energy and momentum require that

$$\omega_{fast} = \omega_{slow} \text{ and } k_{\|slow} = k_{\|fast} + \frac{2\Omega_c}{v_d}$$

For a three-wave interaction self trapping of the primary beam electrons in the slow wave will serve to limit the wave growth. The trapping field is given in the electrostatic approximation by

$$E_{\text{trap}} = \alpha \frac{k_z mc^2}{2\gamma_\phi} (\gamma_r - 1)$$

where α is a factor by which the trapping field may be exceeded and represents the effect of the time taken to obtain wave breaking after the threshold field has been exceeded and γ_r the electron energy measured in wave frame is

$$\gamma_4 = \gamma_\phi \gamma (1 - \beta\beta_\phi).$$

We combine the last four equations to obtain an estimate of the self trapping field

$$E_{\text{trap}} = \alpha c B_0 \left(\frac{(2+\beta) - 2(1+\beta)^{1/2}}{\beta} \right).$$

Note that this field is for the slow hybrid mode and that the acceleration field at this condition will be greater than this value by about 40 %. This result follows from a detailed examination of the wave power flow, based on equal power exchange between the fast and slow waves. Typical parameters for two sets of conditions are given in Table II.

Table II
Beam parameters for hybrid wave accelerator

Electron Drift Velocity (c)	0.5	0.6
Injection Energy (kV)	275	500
Magnetic Field (kG)	6.2	5.4
Trapping Field (slow wave)	94	94
Limiting current (kA)	0.9	1.9
Cyclotron Frequency (GHz)	17.3	15.0
Plasma Frequency (GHz)	9.2	9.6
Beam Power (GW)	0.25	0.93
Wave Frequency (GHz)	30	30
Maximum Field Gradient (MV/m) (accelerated beam)	125	225
Elastance	2×10^{16}	6×10^{15}

The final figures in the table are elastance figures for the proposed devices. In this case the energy stored per unit length also includes the kinetic energy of the primary electrons. The elastances are equal to or greater by about a factor of three than those in a scaled SLAC structure.

5 DISCUSSION

We have, in this paper, reviewed some possible approaches to high gradient accelerators for ultra high energy applications. The approach considered is the use of pulse power technology for the generation of weakly relativistic electron beams at about the one to ten gigawatt level. Pulse power technology imposes limits on the duration of these beams, although at the modest powers needed it seems possible to extend the pulse durations to perhaps a microsecond. In this review we have assumed that pulse power beams may be used to either generate high power microwave signals with a high efficiency or may be used to directly generate the wave used to accelerate the electrons in the same location as the beam. In either case we require the use of high group velocities for the waves. This has the advantage of making the structure walls more remote from the beam and probably decreasing the wake fields. In the configurations described in more detail we also find that the wave fields are maximized at the beam location and reduced at the walls. These effects combine to give an enhanced field capability in the accelerator without causing breakdowns.

The trade off for these good effects could be a reduction in the efficiency compared to that in a scaled SLAC structure. We have examined this figure for both approaches and have found that it is possible to obtain scaled elastances of within a factor of 4 for the phase slip accelerator and approximately equal to or even greater than the SLAC figure for the hybrid wave device.

Experiments and further calculations are in progress for both of these approaches to high field gradient accelerators.

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* * *

Discussion

M.Q. Tran, EPFL

1) What is the electronic efficiency η_{el} of the device?
2) Could one consider this concept for amplifiers?

Reply

1) A convient measure of the efficiency is the distance $s = \langle E_z\rangle^2/w$ where (E_z) is the average acceleration field and w the energy stored/m length In this case I use the d.c input, rather than the usual rf energy This figure in the example given is 6×10^{15} and is about a factor of 3 larger than that for a scaled SLAC structure

2) This is a difficult question to answer. The problem is similar to that in an FEL driven two beam accelerator One presumably would have to carry the same modulation through (or a portion of it) from stage to stage in order to phase back the signal along the accelerator Much work is needed to demonstrate the acceleration principle This is one item as yet unresolved

M. Allen, SLAC

Your example of a 500 kV 2 kA beam is in microwave tube language a high perveance beam which usually means low efficiency. Would this be the case with your proposed devices?

Reply

No, the low efficiency you refer to usually results from structure coupling to a beam. In this case the fields are a maximum at the beam However, the self trapping field will decrease as the perveance decreases. The change is fairly rapid but there should still be a wide range of useful perveance for operation. The more difficult initial issue is the excitation of this axially symmetric mode which has, I believe, not been previously studied experimentally.

F. Chen, UCLA

What is the advantage of using the cyclotron mode when a fast plasma wave in the case $\omega_c < \omega_p$ can be used instead? In particular, wouldn't the $B\theta$ of the beam cause ω_c to be non-uniform?

Reply

For a non-neutral beam the fast plasma wave with $\omega_c < \omega_p$ does not exist. Stability requires $\omega_c^2 > 2\omega_p$. The $B\theta$ of the beam accounts for about an 8% variation in the total B and should not be a serious problem.