THE TWO-BEAM ACCELERATOR*

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Abstract

The Two-Beam Accelerator (TBA) consists of a long high-gradient accelerator structure (HGS) adjacent to an equal-length Free Electron Laser (FEL). In the FEL, a beam propagates through a long series of undulators. At regular intervals, waveguides couple microwave power out of the FEL into the HGS. To replenish energy given up by the FEL beam to the microwave field, induction accelerator units are placed periodically along the length of the FEL. In this manner it is expected to achieve gradients of more than 250 MV/m and thus have a serious option for a 1 TeV x 1 TeV linear collider. The state of present theoretical understanding of the TBA is presented with particular emphasis upon operation of the "steady-state" FEL, phase and amplitude control of the rf wave, and suppression of sideband instabilities. Experimental work has focused upon the development of a suitable HGS and the testing of this structure using the Electron Laser Facility (ELF). Description is given of a first test at ELF with a seven-cell $2\pi/3$ mode structure which without preconditioning and with a not-very-good vacuum nevertheless at 35 GHz yielded an average accelerating gradient of 180 MV/m.

Introduction

The continuing vitality of high-energy physics research program demands particle beams of ever-increasing energy. However, if a linear accelerator capable of producing a 1 TeV electron beam were to operate at the accelerating gradient of the SLAC Linear Collider (17 MV/m), it would be many kilometers long and would consume prodigious amounts of power. Perhaps, both of these difficulties can be circumvented by using a free-electron laser (FEL) as a source of relatively high-frequency rf power and by operating at a high gradient.

The Two-Beam Accelerator (TBA)[1] is a particular use of an FEL which appears to address these two difficulties while, yet, being a practical device. It is seen as operating at a gradient of several hundred MV/m and at a frequency of about 30 GHz and as being an efficient means for converting conventional electric power into an accelerating potential. Thus, this approach offers the promise of a linac of very high energy and reasonable cost.

The TBA concept can be summarized easily. A high current but relatively low-energy electron beam (of about 20 MeV) (the first beam) traverses a series of undulator magnets and undergoes free electron lasing, and emits intense microwaves. The microwaves are conducted by waveguides to an adjacent beam line where their phasing produces traveling waves with a very high longitudinal electric gradient. The second beam, a low average current of electrons, is accelerated to great energies by the very high gradient. The energy lost to the microwaves by the first electron beam is made up by conventional induction accelerating units located between undulator magnets. This is shown, schematically, in Fig. 1 and described in much more detail in Ref. 2 and 3.

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In this report we shall give the present status of research on the TBA, which we shall do by discussing, in order, various topics.

ELF Results

The Electron Laser Facility (ELF), using the Experimental Test Accelerator (ETA) at Livermore, was built to develop a Free Electron Laser (FEL) at 35 GHz. The apparatus has been described in the literature rather completely[4] and its performance has been documented.[5,6,7]

An FEL is the heart of the TBA concept. Although the TBA concept was developed[1] prior to the successful operation of a high-power FEL; the generation of large amounts of power by an FEL is essential to the TBA concept. An introduction to the literature of FELs may be obtained through a recent review article.[8]

It is therefore most important to appreciate that ELF has now produced 200 MW of power[6,7] and, most recently, more than 1.0 GW of peak power when the undulator was tapered.[9]

Steady-State FEL

The TBA requires an FEL which is operated continuously (in length); i.e. is in "steady state." Energy is pumped in with periodic induction units while essentially continuously being generated and removed. Of course no one has yet operated an FEL in such a mode and we are forced to fall back upon theory and numerical simulations. A careful study of the longitudinal dynamics in such a Steady-State FEL has been given by Sternbach and Sessler.[10]

In Fig. 2 we show phase plots of a TBA. One sees that there is essentially no loss of particles in steady-state operation of an FEL. On the other hand an individual particle undergoes rather complicated motion in longitudinal phase space as is shown in Fig. 3. But the average, over many particles, of this complicated motion is the previously shown phase plot; i.e. contained particle motion.

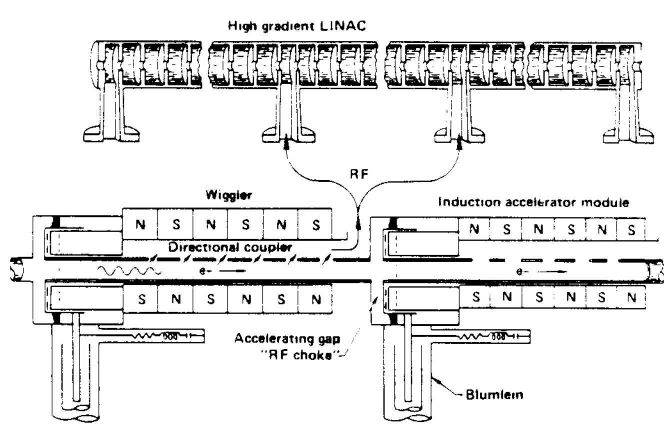

Fig. 1 Schematic of a two-beam accelerator that transfers energy from a high current low-energy beam to a low current high-gradient structure.

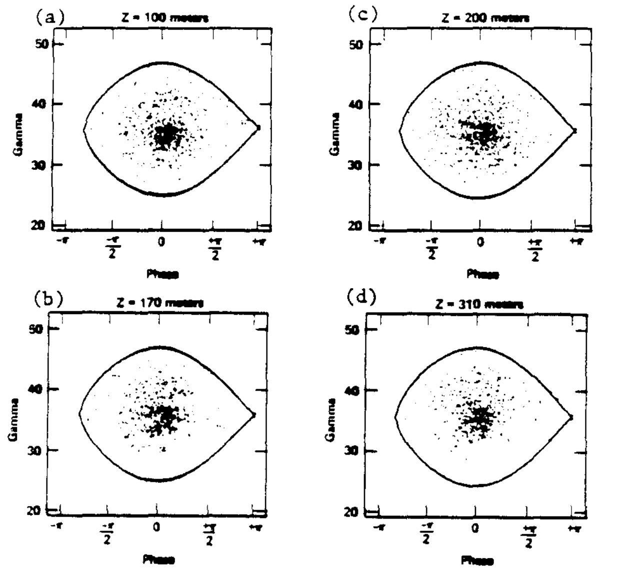

Fig. 2 Longitudinal phase plots of a numerical simulation of a TBA. The parameters are that of a full-scale FEL (Ref. 2) and the phase plots are taken at 100 (a), 170 (b), 290 (c) and 310 (d) meters down the TBA. One sees that steady-state operation is quite possible.

Improved Capture

The particle simulations, of Ref. 10, require that the particles in the FEL portion of a TBA be properly "started" or "captured" into the FEL bucket. After that, steady-state operation poses no particular problems.

The capture has been studied by Sternbach who has, in particular, observed that in a waveguide, with microwave radiation, the boundary conditions can be employed to control the phase velocity of the radiation, and thus optimize capture.[11] This technique can be employed in the initial section of a TBA so as to reduce the "wasted length" devoted to starting up the TBA.

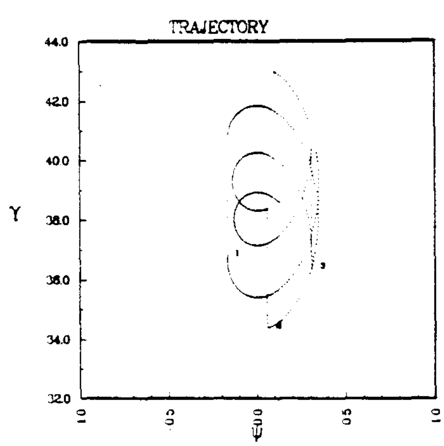

Fig. 3 This shows the actual phase space trajectory of an electron in a TBA. The trajectory begins at the top of the picture. The dashed vertical lines indicate when the electron passes through an induction linac. The numbers indicate the order of the jumps.

Those particles which are not captured must be removed otherwise they will take energy out of the induction units and contribute to TBA inefficiency. Certainly this can be done, but a convenient way to accomplish the separation, in a practical device, has yet to be conceived.

Transverse Effects

Transverse effects in the FEL portion of a TBA have not, yet, been studied very extensively. Conceptually the simplest is transverse effects in the FEL. These should be okay, for parameters are not very different than ELF. On the other hand, a steady-state FEL could bring in new phenomena. As a side benefit of the sideband studies (described in the next section) a 3-D numerical simulation, employing the program FRED, was run by W. M. Fawley for a model TBA. No untoward effects were discovered.[12]

Periodic effects, on electron transverse focusing, was studied by Marks,[13] and shown to produce no unexpected behavior.

The problem of supplying transverse focusing within the induction units has been briefly examined. It is not clear that any focusing is needed ("the beam can be thrown across the gap"). Alternatively, solenoidal focusing could be supplied by locating Helmholtz coils outside the induction acceleration cavities. Since the phase space is rotated slightly there will be "mis-matching" errors at each FEL section, unless the FEL is also "rocked" slightly.

Finally, an optimized design for an FEL beam reacceleration cavity has yet to be carried out. Its overall beamline insertion length must probably be held to 2-3 cm in order not to seriously degrade the TBA's high average accelerating gradient. Moreover, the microwave power loss incurred in crossing a reacceleration gap should be only a few percent. Initial gap-loss measurements indicate that special microwave focusing or guiding will be required to achieve an adequately low loss.

Sidebands

Sideband growth could be significant in a TBA and, consequently, lead to unwanted frequencies. This observation has been made by Rosenbluth, and subsequent numerical simulation studies by Colson have confirmed that it can be a serious problem.[14]

Sidebands arise because there is slippage between the electrons in an FEL and the electromagnetic pulse. They are contained in equations which are the usual Kroll, Morton, Rosenbluth equations for an FEL,[15] modified by replacing derivatives with respect to distance with hydrodynamic derivatives. Thus;

$$\left(\frac{\partial}{\partial z} + \frac{1}{\langle v_\parallel \rangle}\frac{\partial}{\partial t}\right)\gamma_1 = -\frac{\omega a_w a_s}{c\gamma_1}\sin\psi_1 ,$$

$$\left(\frac{\partial}{\partial z} + \frac{1}{\langle v_\parallel \rangle}\frac{\partial}{\partial t}\right)\psi_1 = k_w - \delta k_s$$

$$- \frac{\omega}{2c\gamma 2}\left(1 + a_w^{\;2} - 2a_w a_s \cos\psi_1\right) + \frac{\partial\phi}{\partial z},$$

$$\left(\frac{\partial}{\partial z} + \frac{1}{v_g}\frac{\partial}{\partial t}\right) a_s = \frac{\omega_p^{\;2} a_w}{2\omega c}\left\langle\frac{\sin\psi_1}{\gamma_1}\right\rangle ,$$

$$\left(\frac{\partial}{\partial z} + \frac{1}{v_g}\frac{\partial}{\partial t}\right)\phi = \frac{\omega_p^{\;2} a_w}{2\omega c\, a_s}\left\langle\frac{\cos\psi_1}{\gamma_1}\right\rangle$$

In these equations we use the notation of Refs. 15, 2, and 20. The phase of the rf wave is ϕ and its amplitude (normalized) is a_s. The average longitudinal velocity of electrons is $\langle v_\parallel \rangle$ and v_g is the group velocity of the electromagnetic waves. Note that into the hydrodynamic derivate comes the group velocity of an electromagnetic pulse, although the resonance condition involves the phase velocity. A proper derivation of the ekonal approximation gives, automatically, the group velocity.

These equations have been employed to study sideband growth in the TBA.[16] The growth is very quick, indeed, as can be seen in work by W. M. Fawley shown in Fig. 4. An analytic formula has been obtained by S. S. Yu in the approximation that energy is continuously fed into the particles in a TBA. In that case the growth rate is

$$\Gamma = \left(\frac{\Omega_s}{c}\right) \left(\frac{\dfrac{\omega_p^2 a_w}{2\omega_c a_s \gamma}}{\Omega_s / c} \right)^{2/3} ,$$

where Ω_s/c is the synchrotron oscillation, or bounce, frequency. This analytic formula is in good agreement with the numerical simulation.

Consideration of the physical source of the sidebands suggests a method to remove them;[17] namely to make $v_g = \langle v_\parallel \rangle$. For microwave radiation, where the waveguide is important, it is possible to satisfy this requirement.

In a smooth waveguide of cross section a x b we have for the m,n th mode:

$$v_g \equiv \frac{d\omega}{dk} = \frac{kc^2}{\omega} = \frac{c}{\left[1 + \dfrac{\pi^2}{k^2}\left(\dfrac{m^2}{a^2} + \dfrac{n^2}{b^2}\right)\right]^{1/2}}$$

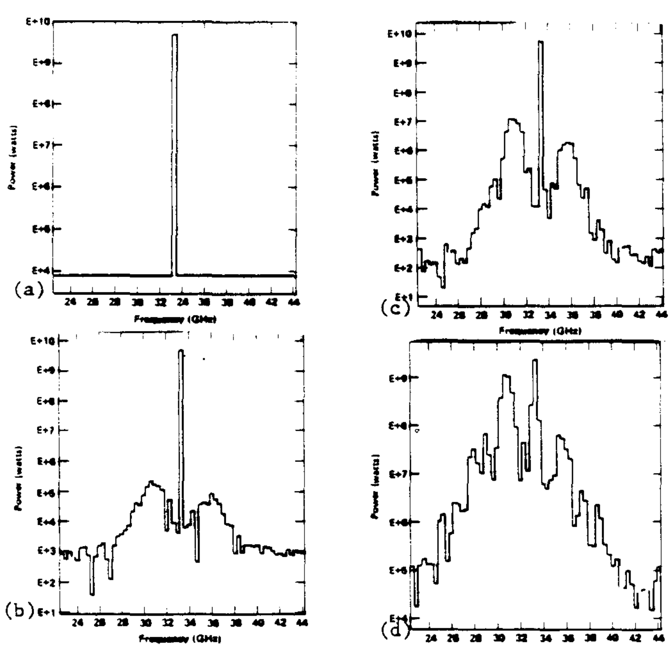

Fig. 4 A numerical simulation, by W. M. Fawley using the program GINGER, which shows the growth of sidebands in only going from 0 m (a) to 6.9 m (b) to 13.5 m (c) to 20.0 m (d) down a TBA. The parameters are those of Ref. 2.

The parallel velocity of electrons is

$$\langle v_\parallel \rangle = c \left[1 - \frac{1 + a_w^2}{\gamma^2} \right] ,$$

and equating these two puts one more condition on TBA design; namely

$$\gamma \approx 2\,(1 + a_w^2)^{1/2}\,(b/\lambda)$$

where λ is the microwave wavelength.

The sideband frequency is given, approximately, by

$$[k \pm \Delta k + k_w]\, z - (\omega \pm \Delta\omega)\, t = \frac{\Omega_s}{c} z \quad ,$$

where $\Delta\omega$ and Δk are the shifts from the fundamental and $(\frac{\Omega_s}{c})$ is the wave number of the synchrotron oscillations of electrons. Letting $z = \langle v_\parallel \rangle t$ and employ the resonance condition of an FEL

$$\omega = (k + k_w)\,\langle v_\parallel \rangle \quad ,$$

and since

$$\Delta\omega = \frac{d\omega}{dk}\Delta k = v_g\,\Delta k \quad ,$$

we have

$$\Delta\omega = \frac{\Omega_s}{1 - \langle v_\parallel \rangle / v_g} \quad .$$

An experiment has observed sidebands at just the position predicted by this last equation.[18] An experiment to study sidebands is planned for ELF.[19]

Note that as $\langle v_\parallel \rangle$ approaches v_g it is predicted that the sidebands move out in frequency, but that the growth rate, Γ, is unchanged. Of course the growth rate must decrease, although just how is not yet known. For example, when the lower sideband approaches -- or even goes beyond -- cutoff there must be a large effect on Γ. To study the phenomenon we must go beyond the usual ekonal approximation made in FEL theory.

Phase Control

Perhaps the largest outstanding TBA challenge is in the area of phase stability and control. An analytical study of the sensitivity of microwave phase to errors in frequency, undulator magnetic field, and FEL beam current and energy has been completed.[20] With no correction, the phase errors resulting from very small, but realistic, deviations from ideal operating conditions are unacceptably large.

The most serious sensitivity is to captured beam current, I, which can be described by the plasma frequency parameter. For an FEL section wave guide a x b we have:

$$\omega_p^2 = \frac{1.3 \times 10^{21}\ I(\mathrm{kA})}{a\ (\mathrm{cm})\ b\ (\mathrm{cm})} .$$

The phase deviation due to an error in ω_p^2 is given by[20]

$$\phi \text{ deviation} = \frac{a_w\, \Delta\omega_p^2 \cos\psi_r}{4\gamma\, a_s\, c\, \omega}\, z \quad ,$$

where the symbols are standard (see Ref. 2 or 19).

The work of Ref. 20 was done in the "resonant particle" approximation; i.e. one-particle. Recently, numerical simulations have been done by Sternbach. This work confirms the validity of the one-particle model. On the other hand, it has disclosed an error in the treatment of Ref. 20 of the response in phase to a change in a_s. The necessary change affects the feedback system proposed, which can, however, with somewhat different numbers, still be made to work.

Hopefully, a system can be devised which is automatic and nearly instantaneous. The system mentioned above is cumbersome and costly. We are now exploring solutions employing ferrite, or even ferro-electrics, which if they can be made to work will be most advantageous. The idea here is to have the waveguide partially filled with material whose magnetic, or electric properties can be readily changed. This will affect the phase velocity of the electromagnetic mode, i.e. its phase, after some distance. The biasing signal should, therefore, be made proportional to phase error and this can be done, instantaneously, by mixing a small sample of the electromagnetic wave with a clock signal.

Wakes

Wake effects in the high-gradient part of a TBA depend upon the inverse cube of the distance from the particles to the nearest wall, and it is proposed to operate the TBA at (say) λ = 1 cm radiation, so that the distance to the walls is ten times less than in SLAC. It was vital, hence, to study wake-field effects carefully and to determine whether or not a TBA could work at the design parameters of Ref. 2. This was done by Selph and Sessler[21] and it was shown that with plenty of (but not unrealistic) transverse focusing in the TBA, a slightly inefficient accelerating structure (where the walls are further removed from the particles than in a maximally efficient structure), and with proper energy variation across the pulse, the wake-field effects are no worse than in the SLC.

Gradient Studies

An initial goal of our TBA experimental program has been to demonstrate ultra-high gradients in an actual accelerating structure in order to increase our confidence in the breakdown gradient scaling shown in Fig. 5. Figure 5 shows a plot of theoretical maximum surface electric field gradient vs frequency for copper rf accelerating structures. In the commonly used disk-loaded waveguide geometry, the average accelerating gradient is about half the maximum surface electric field gradient.

The seven-cell high-gradient accelerator test structure (HGS) shown in Fig. 6 was constructed for testing at ELF. Its method of fabrication and other details have been reported elsewhere.[22] It is a copper $2\pi/3$ mode structure[23] with all cavity and input/output coupler dimensions scaled down from SLAC dimensions.

In this structure, the highest electric field gradient is produced in the input cavity. The ratio of peak surface field to average accelerating gradient is 1.95. A surface gradient of 1.52 GV/m occurs at a power level of 100 MW. The HGS was dimple-tuned (see Fig. 7) to a frequency of 34.6 GHz to match the frequency of the FEL magnetron driver. Figure 8 shows the test arrangement at ELF. The vacuum in the HGS was only marginal, typically in the mid 10^{-5} torr range. Photomultipliers viewing the input coupling aperture and along the HGS axis served as spark detectors.

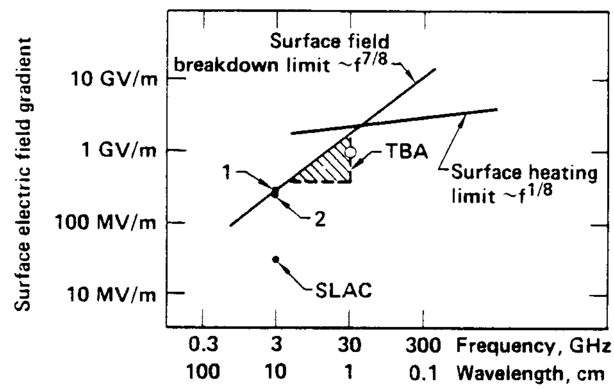

Fig. 5 Theoretical curves, two experimental points, and the operating point of SLAC showing the maximum expected surface field as a function of frequency. Point 1 is by Wang & Loew[24] and point 2 by Tanabe.[25]

Normally, new accelerator structures are preconditioned with pulsed rf whose power level is slowly increased to the rated value. This may take several days or more at repetition rates up to 360 pps. Because of the lack of other high power 35 GHz sources and the ELF repetition rate of 0.5 Hz, there was no opportunity to precondition the HGS. Details of the experiment, and experimental procedure have been presented[7] elsewhere. The best HGS performance achieved was equivalent to an average accelerating field of ~180 MV/m. Considering the marginal vacuum conditions and routine HGS metallurgy, this result is very encouraging.

New accelerator sections are being constructed, by two different techniques: electro-forming and brazing. These sections will undergo a thorough high temperature bakeout and will be tested at a vacuum level of 10^{-7} to 10^{-8} torr. We expect to demonstrate, at ELF, maximum gradients significantly higher than the value quoted above.

Output Coupling

A significant fraction of the FEL microwave power must be periodically extracted and coupled to the

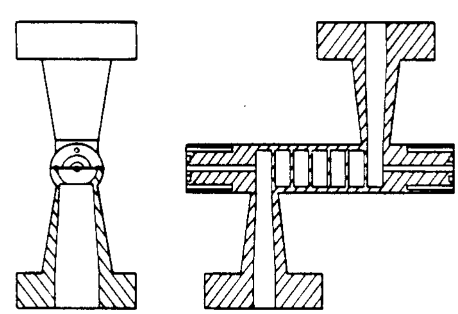

Fig. 6 The high-gradient accelerator test section drawings.

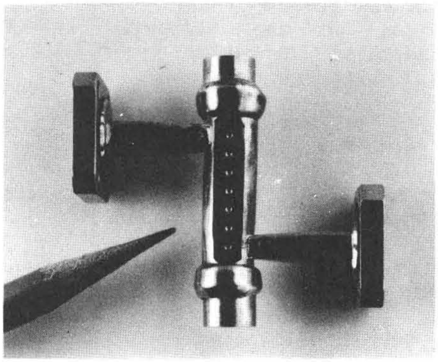

Fig. 7 The high-gradient structure electroformed and dimple tuned.

adjacent accelerator structure in a TBA. This must be done in such a manner that the FEL modal power distribution is not disturbed; i.e., essentially all of the power should continually exist in the desired TE_{01} mode in the FEL.

It does not appear possible to achieve the necessary output coupling in the FEL's oversized interaction waveguide with negligible mode conversion using directional coupling. Our proposed solution is to introduce angled septa into the guide which will function as "scoops" for gracefully removing a fraction of the flowing microwave power. This scheme is shown conceptually in Fig. 9. The scoops are gradually tapered to fundamental waveguide size so that power can be transported to the accelerator HGS without mode conversion.

A septum coupler test section is being constructed and will be tested at ELF.

TBA Parameters

Some TBA studies can be, and will be done, with the ELF facility. We intend to separate the undulator sections and put induction units between some of them.

The next stage should consist of (say) a 30m device. Parameters for such a model TBA have been derived by J. S. Wurtele and are given in Table I.[26] They have, so as to suppress the sideband instability, $v_{group} = \langle v_{\parallel} \rangle$, but with a slightly different height waveguide the growth of the sideband instability would easily be observable. We have not, yet, again produced parameters for a full-scale TBA.

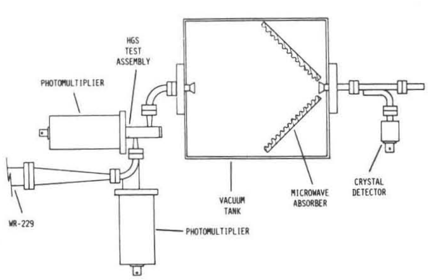

Fig. 8 The high-gradient test arrangement at ELF.

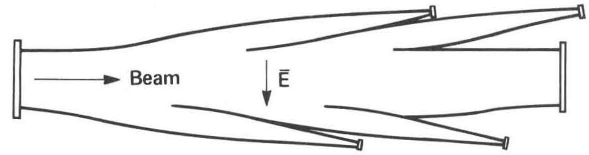

Fig. 9 The septum coupler, with non-linear tapers, designed so as to minimize mode conversion.

Conclusions

Studies to date on the TBA have not revealed any fatal flaws in the concept. Consequently further study and experimental test would seem to be in order. Most notable successes so far are the achievement of (1) more than 1.0 GW from a 3-meter FEL and (2) an accelerating gradient in a very small high-gradient, slow-wave structure of more than 180 MeV/m.

Outstanding problems are numerous at this stage, with (1) control of the rf phase and (2) inhibition of the sideband instability being, perhaps, the paramount subjects. Solutions for both these have been produced on paper, but have not yet been realized in hardware and demonstrated experimentally.

Acknowledgements

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Table I Parameters for a 30 Meter Test Model of a Two-Beam Accelerator

Length	30 meters
Acceleration Gradient	250 MeV/m
Waveguide dimensions	5 cm x 2 cm
High Gradient Structure Filling Energy	10 J/m
Wavelength	1.0 cm
Relativistic Factor γ	10
Undulator Wavelength	16 cm
Undulator Field Parameter a_w	2.3
Relativistic Factor Change	0.55 m^{-1}
Current	2.0 kA
Pulse length	18 nsec
Standing power in FEL	2.0 GW
Period (between induction units)	2 m
Synchrotron period Ω_s/c	4.3 m
RF Field parameter a_s	0.06

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