THE TWO-BEAM ACCELERATOR: STRUCTURE STUDIES AND 35 GHz EXPERIMENTS*

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Abstract

The Two-Beam Accelerator (TBA) shows great promise for achieving high accelerating gradients, perhaps >250 MV/m, for such machines as electron linear colliders. This paper presents the results of studies of candidate structures for a TBA. Also, the hardware and program for 35 GHz high-gradient testing is described.

Introduction

The Two-Beam Accelerator concept is designed to produce very high energy electrons for a linear collider.[1] A TBA is shown schematically in Figure 1.

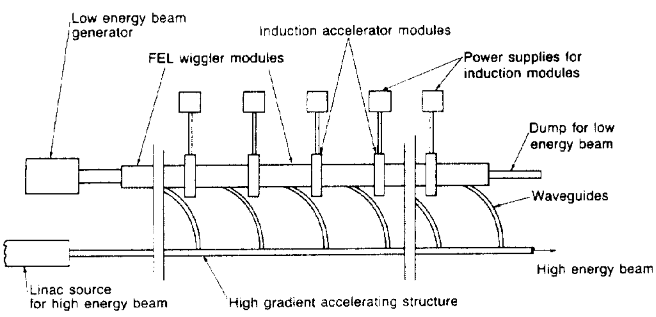

Figure 1 Two-Beam Accelerator

Generally speaking, a TBA consists of a traveling wave high-gradient accelerator structure which is periodically coupled to a single-pass Free Electron Laser (FEL) as a source of high power microwaves. To replenish energy given up by this beam to the microwave field, induction accelerator units are placed periodically along the length of the FEL.

Recent computer studies[2,3] have shown that the FEL can be several kilometers long without significant loss of FEL beam amplitude or quality.

For linear colliders, particle energies of 1 TeV and beyond are being considered. If standard existing techniques, accelerating gradients and rf power sources were used in such a device, it's length and cost would be extremely high. It is widely recognized that the operating accelerating gradient must be significantly increased for such machines to be practical. Operating in the 10-30 GHz range, a TBA shows great promise for achieving such an advancement.

TBA Accelerating Structure Considerations

Figure 2 shows the frequently-seen plot of electric field gradient vs frequency for copper rf accelerating structures. The surface field breakdown limit line has been raised to intersect the points established by recent experiments at SLAC and Varian.[4,5] The Kilpatrick "limit"[6] is also shown for comparison. This criterion was often applied in the past for lower frequency work, but is now recognized as being overly conservative. On the figure, the shaded region indicates an approximate range of applicability of TBA's. As can be seen, a surface gradient exceeding 1 GV/m should be achievable for 30 GHz operation. For a disc-loaded waveguide accelerator scaled to this frequency from SLAC dimensions, for example, this would imply an achievable average accelerating gradient of perhaps 500 MV/m. This is in marked contrast to the 10-20 MV/m average accelerating gradients of present-day S-band accelerators. Finally, we note that for a TBA, this scaling is probably conservative by a factor of at least 2 to 3. This is because the pulse length need only be 20-50 ns, and the breakdown gradient is believed[7] to scale as $\tau^{-1/6}$ to $\tau^{-1/4}$.

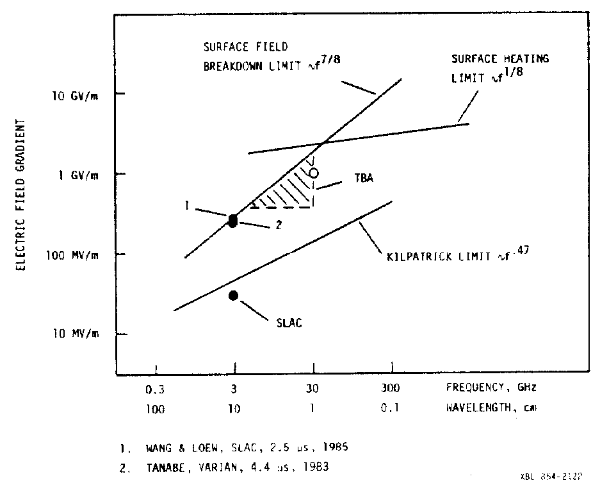

Figure 2 Accelerator Maximum Surface Field Gradients

Basic TBA analysis and design examples have been published elsewhere.[3,8,9] These designs are still evolving as analytical work progresses. A reference set of parameters from a recent 1 TeV x 1 TeV, 30 GHz, TBA collider study[3] is presented in Table 1.

The number of particles per bunch listed in Table 1 would lead to excessive transverse wake field effects in a 30 GHz structure simply scaled from the SLAC dimensions.[10] It has been shown[1] that acceptable performance can be achieved if the center hole diameter is increased to ~2 mm from the SLAC-scaled value of ~1 mm, and if the machine is operated with a short betatron wavelength, e.g., ~10 m. Figure 3 shows Brillouin diagrams for a SLAC-scaled structure (top) operating in the $2\pi/3$ mode (3 discs per wavelength) and a large-hole TBA structure (bottom).[11] To a good approximation, the curves have a cosine shape with zero slope at values of $kL = 0$ and π.

The larger center hole results in a wider passband, which produces larger slopes on the Brillouin curve. Since the slope of the curve equals the group velocity, the operating point must then be shifted near the peak (i.e., near the π mode) in order to reduce the group velocity to the desired value. The slope of the line through the operating point is the phase velocity, which must be equal to c. The disk spacing must be slightly less than one-half wave-

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Table 1 Parameters for a 1 TeV x 1 TeV Two-Beam Accelerator Collider

Low Energy Beam	
Average Beam Energy (Units of mc^2)	40
Beam Current	2.15 kA
Bunch Length	6 m
Wiggler Wavelength	27 cm
Average Peak Wiggler Field	2.4 kG
Beam Power	43 GW
Beam Energy	0.8 kJ
Power Production	2.2 GW/m
Number of FEL Injectors	2 x 2
Power From Mains	160 MW
High Gradient Structure	
Wavelength	1 cm
Gradient	500 Mev/m
Stored Energy	40 J/m
Fill Time	18 ns
High Energy Beam	
Injection Energy	2 GeV
Repetition Rate (f)	0.5 kHz
Final Energy	1 TeV
Length	2 x 2 km
Luminosity	$4 \times 10^{32} cm^{-2} sec^{-1}$
Beam Height (σ_y)	0.14μ
Beam Width (σ_x)	1.4μ
Single Beam Power	8.0 MW
Number of Particles	10^{11}
Disruption (D)	1.3
Beamstrahlung (δ)	0.2
Overall Efficiency (From Mains to HEB)	10%

length, and the waveguide inside cell diameter must be slightly adjusted. The URMEL code[12] is being used to determine these dimensions.

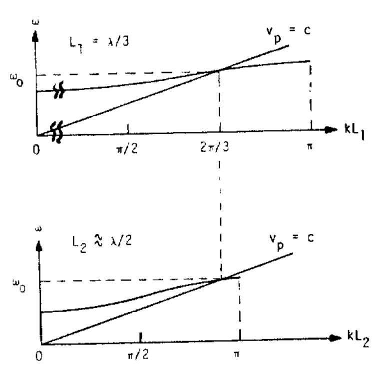

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Figure 3 Brillouin Diagrams for SLAC and TBA Accelerator Structures

High-Gradient Testing at 34.6 GHz

A microwave FEL is operational at the Lawrence Livermore National Laboratory (LLNL) Electron Laser Facility (ELF).[13] This facility is sometimes available to us for TBA high-gradient testing. It has produced 34.6 GHz power in excess of 80 MW for 10-15 nsec pulses.

We are just now embarking on a program for testing several structures on ELF as the operating schedule permits. These tests are aimed at increasing our confidence in the breakdown gradient scaling discussed above. Table 2 lists three waveguides to be tested, their dimensions and the maximum surface electric field referenced to a 100 MW power level. The field scales as the square root of the power and can be calculated from the following expression:

$$P = [abE_p^2/1508][1 - (\lambda/2a)]^{1/2} \quad (1)$$

where a and b are the waveguide width and height, respectively, and λ is the free-space operating wavelength.

TABLE 2 HIGH-GRADIENT TEST STRUCTURES

	DIMENSIONS CM	E_p P = 100 MW MV/M
FULL HEIGHT WR-28 WAVEGUIDE	0.711 x 0.356	86
1/4-HEIGHT WR-28 WAVEGUIDE	0.711 x 0.089	173
1/9-HEIGHT WR-28 WAVEGUIDE	0.711 x 0.040	259
ACCELERATOR SECTION (HGS)	(SEE TEXT)	1520

Figure 4 shows the finished electroformed 1/4-height WR-28 test piece. This is 8.7 inches long. It has two 3 inch long linear tapers in the top wall (only) for transitions to a 1.7 inch long section of reduced height. The intersections of straight and tapered waveguides were broadly radiused to avoid field concentrating regions. Profilometer measurements on the aluminum mandrel indicated that its surface roughness was within the range of 7-18 microinch, r.m.s., in the narrowed region.

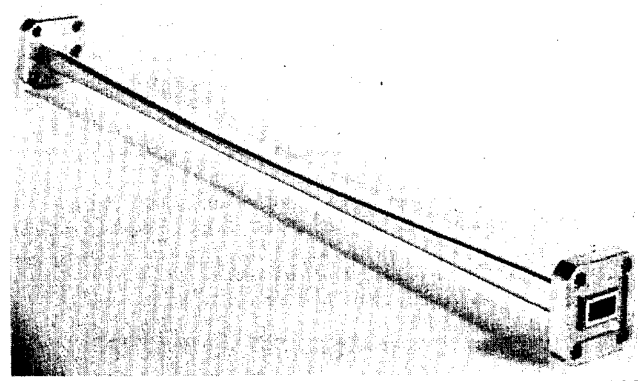

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Figure 4 Quarter-height WR-28 Test Piece

Table 2 also lists the maximum surface field gradient expected in a short accelerator section we have fabricated, referred to a 100 MW power level. We have chosen the disc-loaded waveguide for these initial studies so that a new data point could be established which would confirm the breakdown gradient scaling indicated in Figure 2. Such scaling has maximum credibility when it is applied to identical structures which differ only by a scale factor. Additionally, the chosen structure is easiest to fabricate. We have not seriously considered other types.

Figure 5 shows a diagram of our seven-cavity high-gradient accelerator section (HGS). This was fabricated with all cavity and input/output coupler dimensions scaled from SLAC dimensions by the ratio 34.6/2.856 (GHz) = 12.11. The center-to-center distance between the input and output coupling

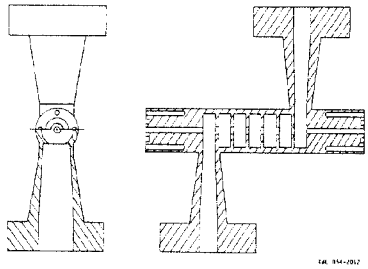

Figure 5 High Gradient Accelerator Test Structure (HGS)

cavities is 0.6828 inches; the overall length is 1.6776 inches. The HGS input and output couplers were both scaled from the SLAC output coupler.

The last cavity in a SLAC accelerating section, number 84, was chosen as the reference for the five center cavities.[14] It has the smallest center hole and in our scaled structure yields the highest electric field for a given power input. The center holes have a full radius and are of the same diameter for all cavities, for ease of fabrication. This means that the highest gradients will be produced in the input cavity. Since the group velocity is well-known (v_g = 0.0065 c) and the ratio of shunt impedance to Q is readily scalable from SLAC performance, the relationship between average accelerating gradient and power is conveniently expressed as:

$$E_a = [(\omega P_o/v_g)(r/Q)]^{1/2} \qquad (2)$$

Finally, the peak surface field, E_p, can be obtained from a ratio well-known for any SLAC-scaled structure:[4]

$$E_p/E_a = 1.95 \qquad (3)$$

The value for the HGS E_p listed in Table 2 is obtained from (2) and (3) using the group velocity given above and the SLAC value r/Q = 45.1 ohms.

The holes through the HGS end cylinders are waveguides beyond cutoff at 34.6 GHz. These permit viewing the interior with a photomultiplier in order to detect sparking when the assembly is under test. The cavity dimensions required for 34.6 GHz are:

center hole diameter,	2a = 0.0626 in
outer diameter,	2b = 0.2659 in
disc spacing,	d = 0.1138 in
disc thickness,	t = 0.0190 in

Our first attempts to fabricate an acceptable structure were based on precision machining of OFHC copper discs and rings, to ±0.0002 inch tolerances, then brazing these together. The assembly was cut in two, lengthwise, and examined under a microscope. The primary problem was in achieving consistent, high-integrity braze joints between the discs and rings. Four trial assemblies were fabricated, each an improvement over the earlier ones. The fourth looked relatively good, probably acceptable, but confidence in our ability to obtain this quality of work repeatedly and reliably was not too high.

Finally, an electroforming approach was chosen and proved successful. Instead of copper rings, aluminum rings were machined which had the correct cavity length and outer diameter. The discs, rings, and coupler sections were aligned and pressed together in a vee-block. The entire assembly was plated with ~40 mils of copper. The aluminum rings were then etched out in a hot sodium hydroxide solution. Figure 6 shows the HGS parts prior to assembly. Figure 7 shows the HGS in a clamp-yoke ready for plating.

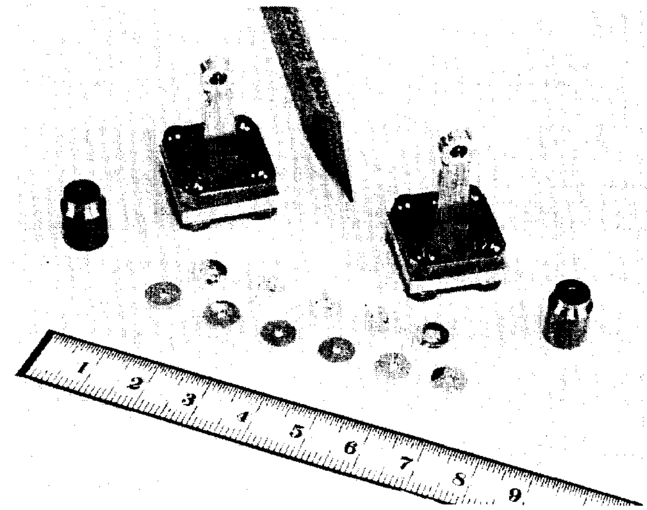

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Figure 6 HGS Parts Prior to Assembly

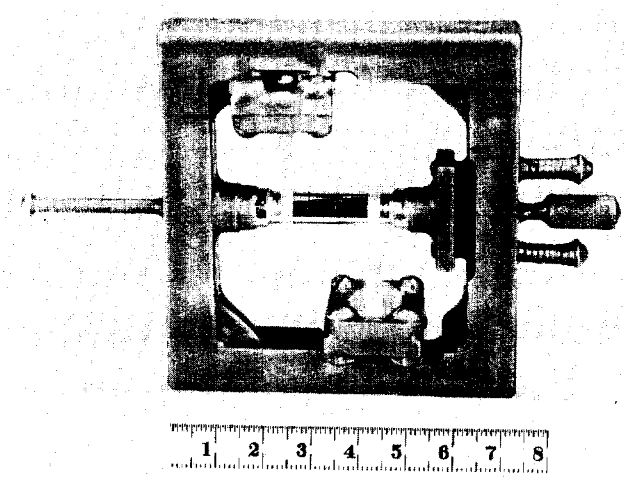

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Figure 7 HGS Ready for Plating

If scaled SLAC machining tolerances were maintained, the tolerances, in microinches, for the 34.6 GHz cavities would be:

2a, 2b:	+60
	-0
d:	~±200
t:	±60

The final HGS discs and rings were machined to ±20 microinch tolerances on a LLNL precision diamond-turning machine. Flatness and concentricity of inner hole and outer diameters were held to <200 microinches. The surfaces were machined to a 1 to 2 microinch r.m.s. finish.

The HGS was bench-tested at a few mW power level using a swept frequency generator. The detected power transmitted through the HGS as a function of frequency is shown in the oscilloscope photograph of Figure 8. The slight dip at the trough between peaks

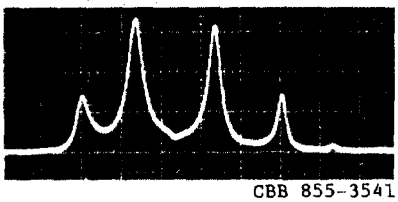

Figure 8 Transmitted Power vs Frequency for the HGS

number 2 and 3 is caused by a calibrated wavemeter located between the generator and the HGS. It was tuned to 34.415 GHz. The frequencies corresponding to the peaks, left to right, are 34.350, 34.380, 34.450, 34.515, and 34.575 GHz, respectively. Our design frequency was 34.600 GHz in order to match the ELF operating frequency. The reason for the general frequency offset is not understood.

The impedance match into the HGS was rather poor, resulting in ~50% reflected power, at best, at the largest transmitted peaks. An investigation revealed that some dimensional errors had been made in the input and output coupling apertures. We are presently correcting this situation by adding properly-sized aperture shims at the coupling irises. We are considering tuning the HGS to the correct operating frequency by internal copper plating using a platinum wire in a copper solution. The wire regions near the aperture holes would be masked to preserve the original finish at and near the holes. As a backup, we plan to start construction of a second HGS with dimensions appropriately modified.

The experimental setup to be used during high-gradient HGS testing on ELF is shown in Figure 9. The vacuum tank ensures a reasonably good vacuum in the HGS and provides about 46 dB of attenuation. Directional couplers and attenuators further reduce the signal to detectable levels (e.g., 1 mW).

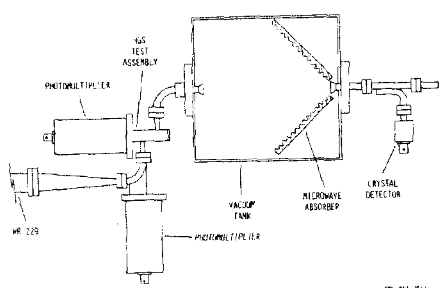

Figure 9 HGS Test Arrangement at ELF

Microwave Output Coupling

In the TBA's FEL, the electron beam is wiggled in the plane of the long dimension of a waveguide which is necessarily very oversized for the operating frequency in order to accommodate the beam. (The present ELF waveguide, for example, measures 3.872 x 1.145 inches.) This is depicted in Figure 10.

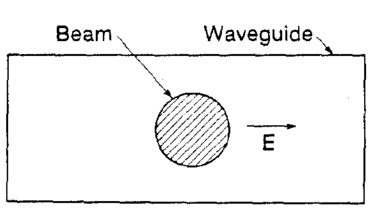

Figure 10 FEL Beam and Electric Field Orientation

A significant fraction of the FEL microwave power must be periodically extracted and coupled to the adjacent accelerator structure. This must be done in such a manner that the FEL modal power distribution is not disturbed; i.e., essentially all of the FEL microwave power should continually exist in the desired TE_{01} mode. Any power converted to other modes by coupling discontinuities represents an undesirable reduction in overall efficiency.

Figure 11 shows an early TBA concept where it was thought that adequate coupling could be achieved with FEL wall apertures. Because of narrow phase margins, each coupling region can only extend over a short length, perhaps 10 cm or so. It does not appear possible to couple the required power out of apertures which span this short a length.[15] In such oversized waveguides, aperture power coupling coefficients can be 30 dB or so smaller than for identical holes in standard waveguide. Moreover, if the waveguide walls are highly perforated or if large apertures are employed, excessive conversion of power to higher order modes will take place.

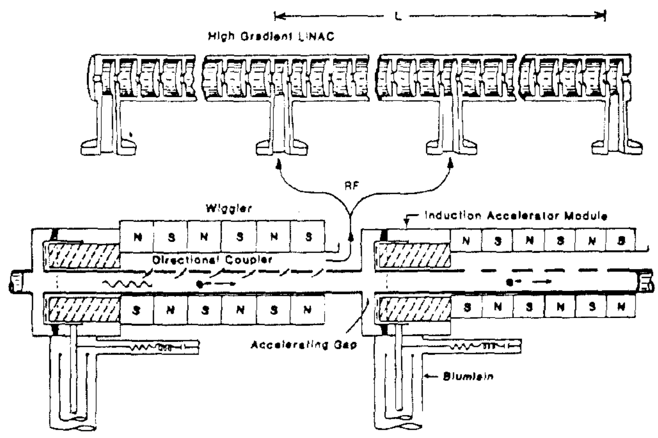

Figure 11 Early TBA Concept With Directional Coupling

It has long been known that a thin metallic septum can be placed in a waveguide perpendicular to the electric field of a TE_{10} or TE_{01} mode, for example, without causing reflections or mode conversion. One of us (R.W.K.) has developed this idea into the septum coupler concept for coupling power out of the FEL.

Figure 12 shows how the basic scheme would work. Septums periodically "scoop" a fraction of the microwave power from the FEL waveguide. The scoop is then gradually tapered to fundamental waveguide size so that power can be transported to the accelerator HGS without mode conversion. Power is naturally coupled out of both sides of the FEL waveguide. This is convenient since it is necessary to feed the HGS symmetrically from both sides in an alternating manner in order to control a beam-deflecting mode in that structure.[14] The FEL waveguide size and septum locations are chosen so as to accommodate the wiggled beam. The beam sees constantly expanding walls. The FEL is designed so that the microwave power increase per unit length from FEL action is equal to the average power extracted per unit length. After a small startup length, the FEL power level thus reaches a nearly steady-state value.

A study of waveguide tapers indicates that mode conversion can be easily controlled in linearly tapered output scoops. In the larger FEL waveguide,

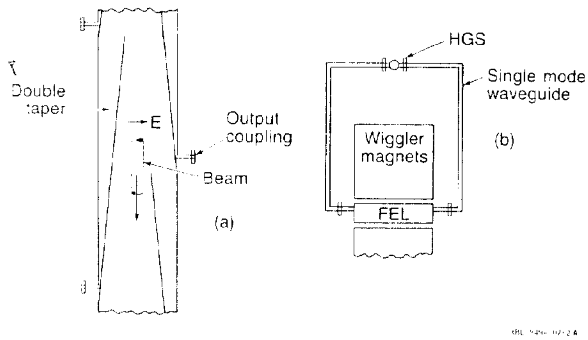

Figure 12 Septum Coupling Technique for Extracting FEL Microwave Power

however, it appears that linearly tapered walls will cause excessive mode conversion. This can be prevented by employing non-linear tapers.[16] Figure 13 shows how this type of section might appear. We are in the process of designing such a structure for testing on ELF. We plan to verify proper power extraction and measure any degradation in the beam transmission, mode conversion, and breakdown threshold.

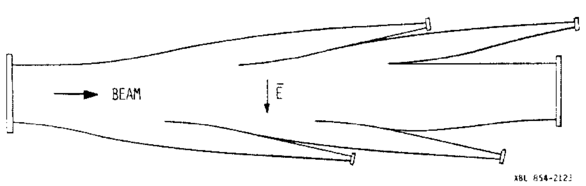

Figure 13 Septum Coupler With Non-linear Tapers

Future Work

It is not yet clear which TBA operating frequency represents the best choice considering scientific, engineering and economic trade-offs. We will be addressing this question and intend to do further high gradient structure testing on ELF at a 17 GHz frequency. In addition, we are studying the important issue of phase and amplitude stability and requirements.[17,18] In 1-1/2 to 2 years, we plan to upgrade ELF by adding a few induction accelerator units so that the combined processes of FEL gain and microwave extraction can be properly demonstrated and studied. Longer-range plans call for the construction of a 30 m prototype TBA.

Acknowledgements

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