Title

STATUS OF LBL/LLNL FEL RESEARCH FOR TWO BEAM ACCELERATOR APPLICATIONS

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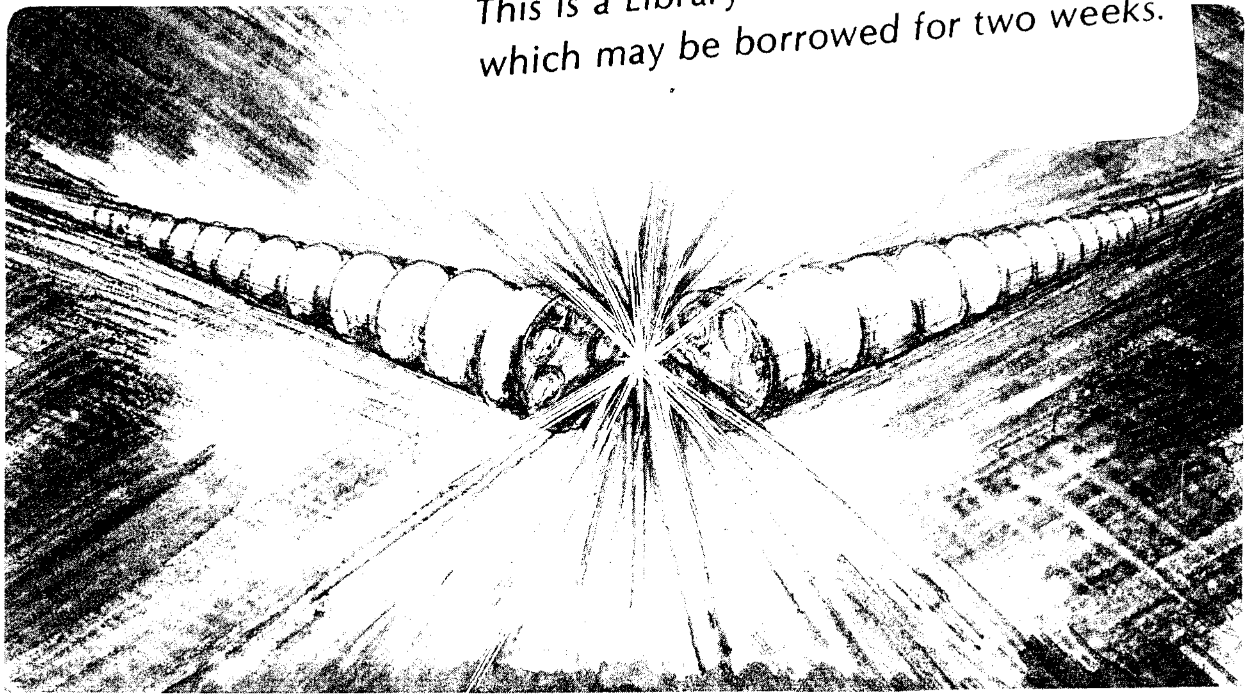

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Abstract

We review the status of free electron laser (FEL) research being conducted at LBL and LLNL as part of a broader program of research on two beam accelerators (TBAs). Induction accelerator-driven FELs for use as power sources for high-gradient accelerators are discussed, along with preliminary cost estimates for this type of power source. Finally, a promising new version of an FEL/TBA is described.

LBL/LLNL FEL Research

Figure 1 shows the principal elements of an FEL-driven two-beam accelerator. The TBA has been discussed in detail elsewhere.[1,2] In collaboration with LLNL, our FEL experimental research program got underway in 1982 with the construction of the Electron Laser Facility (ELF) at LLNL.[3] Several papers[4-8] have summarized the FEL performance of this facility when operated at a ~ 35 GHz, > 1.2 GW power level and also at 138 GHz. Recent papers[9,10] discuss strategies for achieving more efficient wiggler tapering and reducing output noise to < 1%.

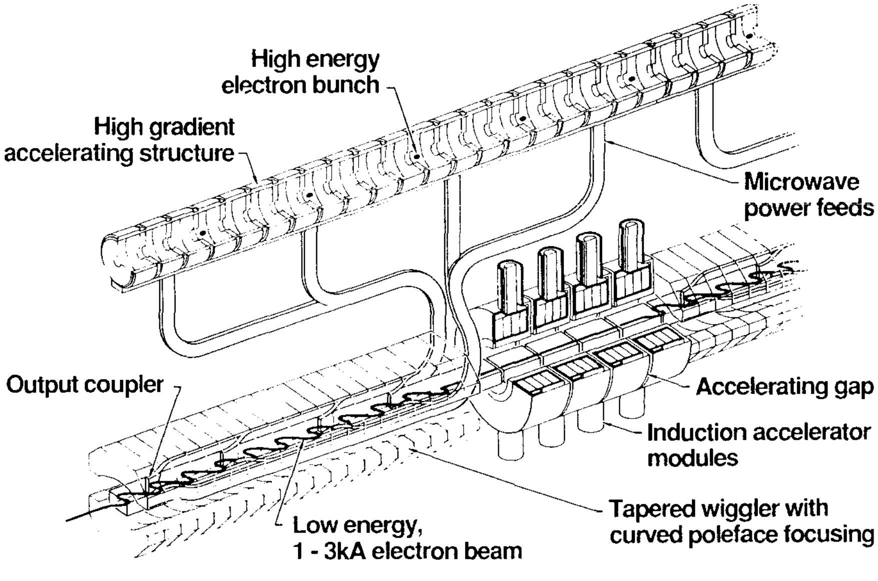

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Figure 1. FEL/TBA Configuration

For practical FEL-driven TBAs, a number of troublesome issues have recently been considered. Solutions have been found for some of these while others await further analytical and/or experimental treatment. Early on, wakefield effects in ~ 15-30 GHz high-gradient accelerator sections were thought to preclude their operation at interesting beam brightness levels for linear colliders under consideration. It has been shown[11], however, that the wakefields can be adequately reduced if three things are done. First, the beam apertures, i.e. iris diameters, must be increased about a factor of two over the dimensions arrived at by standard accelerator design procedures. Second, there must be much more transverse beam focusing than in traditional linacs. This can be supplied by external quadrupoles, or, as has been suggested by W. Schnell, by rf in conjunction with elliptical (alternating) gaps. Third, as pioneered in the USSR[12] and extended by Bane at SLAC,[13] an energy sweep along the bunch is required. Another problem initially thought to be serious but later "solved" involves the large potential FEL gain at synchrotron frequency sidebands. Analysis shows[14] that the synchrotron sideband power is dramatically reduced if the FEL interaction waveguide size is chosen properly. This approach has now been experimentally proven successful.[14]

In the TBA, as originally conceived, not all of the microwave power is removed from an FEL section. A significant amount of remaining power crosses the following beam-reacceleration gap, maintaining a sizeable rf bucket in which all of the electrons are trapped, thus establishing the proper phase in the next FEL amplifier. Several difficulties result from this arrangement for which no satisfactory solutions have yet been found. Another difficulty involves rf handling: the extraction of rf power from the FEL. The interaction waveguide is necessarily highly oversized for the operating wavelength. It is found that the usual techniques, e.g. directional coupling, are impractical and convert power into undesirable modes. We experimented unsuccessfully at ELF with a type of coupler which has septa acting as "scoops" for extracting single-mode power.[15] Different approaches are now under consideration. These are mentioned briefly in a later section that discusses a new FEL/TBA version which avoids many of the problems discussed in this section.

A most serious problem with the original FEL/TBA configuration is its phase and amplitude sensitivity to errors in the wiggler magnetic field, beam energy and beam current.[16,17] For practical machines, parameter stabilities of ≤ 0.1 % would be required. The net effect is to limit realistic TBA section lengths to a few tens of meters, at best, with new beam injectors required at these intervals for "starting over". Feedback compensation schemes have been considered but appear to be impractical.

Regarding the high gradient accelerator (HGA) portion of a TBA, our group undertook a program to demonstrate the successful fabrication of HGA sections for 33-35 GHz operation and test them at ELF to determine their ultimate operating gradients. This work has been summarized elsewhere.[15,18] A high-quality 33.39 GHz, 34 cavity, 10-cm long accelerator, fabricated by the Haimson Research Corporation,[19] is now scheduled to be tested soon at the Massachusetts Institute of Technology, using a developmental cyclotron auto resonance maser (CARM) as a 20-50 MW power source, in a collaboration with G. Bekefi's group.

FEL-Based Accelerator Power Sources

Before the FEL/TBA is fully realized in an actual accelerator, e.g. linear collider, microwave FELs may find an initial application as accelerator power sources. An induction accelerator coupled with a wiggler can readily produce GWs of power. These sources can then be replicated and arranged to periodically drive an HGA in the same manner that multiple klystrons drive long accelerators, e.g. at SLAC. Such sources have been proposed and preliminary cost estimates made, most recently for TeV linear collider applications at 17 GHz[20]. For this study, the assumed collider parameters were as shown in Table 1.

TABLE 1

Linear Collider Parameters

Operating frequency	17 GHz
Collider length	7.41 km
Total rf power required	3.87 TW
Length between rf feeds	1.44 m
rf power/m required	634 MW/m
rf pulse width 50 ns	
Repetition rate	180 Hz
Luminosity (single bunch)	$5.0\text{x}10^{32}$ cm^{-2} sec^{-1}
Luminosity (21 bunches)	$1.0\text{x}10^{34}$ cm^{-2} sec^{-1}

To power this 17 GHz collider, an induction accelerator-driven FEL power source was considered which has the parameters shown in Table 2.

TABLE 2

Power Source Parameters

Beam energy	3.5 MeV
Beam current	3.0 kA
Beam energy stability ($\Delta E/E$)	0.8%
Interaction waveguide size	6.0 x 3.0 cm
Wiggler length	1.7 m
Wiggler period	12 cm
Resonant wiggler field, on axis	4.11 kG
Final wiggler field, after tapering	1.8 kG
Input rf power	80 kW
Output rf power	5.0 GW

For this application, a new, simple, inexpensive permanent magnet and steel wiggler was designed[21]. Also, an "afterburner" was assumed to follow the wiggler to extract a good fraction of the rf energy from the bunched beam before it is dumped.

This is a final relativistic klystron stage where the beam threads a few output coupling cavities producing ~ 2 GW of additional rf power, thereby increasing overall efficiency. For the induction accelerator driver, cost estimates were prepared on three different bases: (1) present technology, (2) a newer small-cell design under development and (3) a projected industrialized version. Estimated costs for the induction driver were, (1) \$1.8M, (2) \$1.5M, and (3) \$0.9M, respectively. The wiggler cost is found to be very small, namely ~ \$80K for a 2.1 m length. Since costs are dominated by that of the induction accelerator, efforts are being made to find ways of significantly reducing this cost.

The TBA concept has always incorporated the idea of periodic reacceleration of the drive beam. This would take place to restore the energy to the beam which had been given up to the microwave field in the FEL sections. Induction accelerator cells would be added to accomplish this. Reacceleration can also be of benefit to the power sources being discussed in this section. For the linear collider parameters of Tables 1 and 2 and assuming the small-cell technology mentioned above, the cost and efficiency of power sources has been estimated.[20] These estimates are summarized in Table 3 for four cases having no reacceleration, then one, two, and three reaccelerations. As can be seen, the difference between no reacceleration and three reaccelerations is an impressive cost saving of \$284 M and an efficiency increase to 32% from 25%.

Improved Version of an FEL/TBA

Recently, a new version of an FEL/TBA has been proposed which avoids a number of difficulties inherent in the original concept.[22] In the new version, a relatively small, stable rf clock signal is provided at the input of each FEL section. At the end of each FEL section essentially all of the rf power is removed and transported to the HGA power input ports. The bunched electrons of the drive beam go on to the next FEL section through the following reacceleration gaps. There is no longer a need for any remaining microwave power to cross these gaps. The advantages that accrue with this configuration are many. In the original FEL/TBA concept, errors in various parameters were cumulative and resulted in the phase and amplitude sensitivities discussed earlier. An analysis of the new version has been made and it has been shown that the FEL/TBA can be designed so that errors do not accumulate. In short, the new FEL/TBA "locks on" to the equilibrium state even if the drive beam energy is initially in error. A full study of this subject is now being prepared.[23] In the meantime, we have begun a search for a practical method for extracting all of the rf power at the end of an FEL section. One method which may be workable is to employ a specially-designed magnet at the end of the FEL. This would introduce a short, brief, achromatic jog of the electron beam away from the centerline, separating it from the microwave field[24] In the beam-free region thus created, centered on the machine axis, an angled "mirror" would then reflect the microwave power out of the machine. In a second method being considered,[25] all but several percent of the microwave power is reflected out of the beampipe by a four-faceted reflector. This also serves as a convenient four-way power divider.

Table 3. Re-Acceleration Various Number of Times

(Assume Small Cell Costs, an RK after burner, and a 3.87 TW total power requirement)

Basic Unit		
Injector (0-1.5 M)	$ 920k	
Accelerator (1.5-3.5 MeV)	$ 620k	
W,R,MD and M*	$ 250k	
Base Unit Cost	$1790k	
Power Output per Unit (5+2)		7.0 GW
Total Cost (553 units)		$ 990 M
Beam to rf Efficiency		67 %
Overall Efficiency		25 %
Single Re-Acceleration		
Base Unit Cost	$1790k	
Accelerator (+2 MeV)	$ 620k	
W,M**	$ 120k	
Unit Cost	$2530k	
Power Output per Unit (10 +2)		12 GW
Total Cost (323 units)		$817 M
Beam to rf Efficiency		73 %
Overall Efficiency		29 %
Two Re-Accelerations		
Base Unit Cost	$1790k	
Accelerators (+4 MeV)	$1240k	
W,M**	$ 240k	
Unit Cost	$3270k	
Power Output per Unit (15+2)		17 GW
Total Cost (228 units)		$746 M
Beam to rf Efficiency		76 %
Overall Efficiency		31%
Three Re-Accelerations		
Base Unit Cost	$1790k	
Accelerators (+6 MeV)	$1860k	
W,M**	$ 360k	
Unit Cost	$4010k	
Power Output per Unit (20+2)		22 GW
Total Cost (176 units)		$706 M
Beam to rf Efficiency		77 %
Overall Efficiency		32 %

*Wiggler, Relativistic Klyston, Microwave Driver, and Microwave Equipment
**Wiggler and Microwave Equipment

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