IEEE Transactions on Nuclear Science, Vol. NS-30, No. 4, August 1983

MILLIMETER HIGH POWER SOURCES FOR HIGH GRADIENT ACCELERATORS*

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Abstract

The potential for achieving high accelerator gradients with high power rf sources is evaluated.

I. Introduction

The drive for high energy particle accelerators may come to a halt after the next generation of accelerators unless new technologies can be employed to reduce the size and cost of high energy research facilities. Present and near-present day linear colliders operate at accelerating gradients of 10-20 MeV/m. Under these circumstances, a 300 x 300 GeV linear collider would require a new facility nearly 30 kilometers long. The projected cost and complexity of such an accelerator make its construction unlikely. If accelerator gradients could be increased to 200 MeV/m, a 300 x 300 GeV collider would fit on the SLAC site using existing facilities and, therefore, greatly reduce the accelerator's cost. In this report, we will examine how 1 cm (and shorter) radiation might be used to power conventional accelerator structures and thus might enable one to build a short, 300 GeV collider.

The accelerating gradient (E_a) which can be achieved for a given structure scales approximately as follows:[1]

$$E_a^2 \propto P\,\omega^{1/2} \qquad (1)$$

$$E_a^2 \propto U\,\omega^2 \qquad (2)$$

where P is the power, U is the energy and ω the radial frequency of the rf source. The consequences of this scaling are shown in Table I where the SLAC-SLC[2], a 200 MeV/m version of the SLAC-SLC and a 200 MeV/m, 35 GHz driven accelerator are compared. It is clear that powering a 200 MeV/m structure at 2.8 GHz would be extremely difficult since a 15 KJ rf source would be required. This could be reduced to 3.8 KJ by using a separate drive for each rf feed, but the 35 GHz design, which only requires 100 J/source, looks more attractive.

II. High Frequency Structures

In order to decide whether or not a 35 GHz high gradient accelerator is practical, one must first determine if the structure will withstand high peak power levels without undergoing electrical breakdown or suffering single pulse thermal damage. Rf breakdown is thought to scale linearly with frequency,[3] so by going to 35 GHz, 200 MeV/m gradients should be obtainable without breakdown occuring. Single pulse damage thresholds are more difficult to evaluate, but there is substantial evidence[3,4] that the limit of absorbed energy per unit area scales as the square root of the pulse length. Combining this fact with the following scaling,[1]

Shunt impedance (r)	$\omega^{1/2}$
Area (A)	ω^{-1}
Fill Time	$\omega^{-3/2}$,

we find,[3]

$$E_a^2 \propto P \cdot r \propto \left(\frac{U}{\tau A}\right) A r$$

$$E_a^2 \propto \frac{\tau^{1/2}}{\tau}\,\omega^{-1}\,\omega^{1/2} \propto \omega^{1/4}$$

$$E_a \propto \omega^{1/8} \quad .$$

Thus, the single pulse damage limit also increases with frequency, although very slowly. Rf and pulse breakdown limits are plotted in Fig. 1.[3] These plots represent only crude estimates of the structural limits of high gradient designs, but the advantage of operating at a wavelength just under 1 cm is clearly indicated. The benefits of proceeding to much higher frequencies accrue very slowly.

III. High Frequency Sources

If we assume that an advantageous operating frequency is 35 GHz, we can choose a set of typical operating parameters and proceed to evaluate potential rf sources. Our strawman design is detailed in Table II. An estimate of the dipole wake[5] leads one to predict a large growth of transverse emittance. Increased focusing can reduce this growth as will Landau damping caused by the large energy spread induced by high frequency structures.[5]

Several rf generators have been demonstrated which generate more than 10 MW at frequencies greater than 30 GHz. Many more have produced in excess of 100 MW at about 10 GHz. These generators are enumerated in Table III (a, b). The apparent f^{-2} scaling of power with frequency should be surmountable by utilizing higher voltage relativistic electron beams (taking advantage of the Lorentz contraction) so that short wavelength radiation can be produced with large structures. Both the Naval Research Laboratory (NRL) Free Electron Laser (FEL) and the Backward Wave Oscillator (BWO) (M. V. Lomonosov State University, Moscow) are proceeding along this path. A common characteristic of these devices is that they require high magnetic fields and utilize electron beams produced by pulsed diodes. High magnetic fields are undesirable because they consume energy and add an additional complexity to the source design. If the required magnetic fields are less than 10 KG permanent magnets might be used.

Although high frequency generators have, or soon will have demonstrated the power levels required for high gradient accelerators, they have yet to demonstrate the stability and reliability demanded by accelerators. Table IV compares SLAC klystron characteristics to estimates of a relativistic pulsed diode driven rf source's characteristics. Clearly, major advances must be made in both lifetime and repeatability. Frequency stability would be enhanced if the source could be operated as a power amplifier so that a single, low power, easily stabilized source drives the whole rf system.

IV. Two Beam Accelerator

The tapered wiggler discussed by Kroll, Morton

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* Work performed jointly under the auspices of the U. S. Department of Energy by Lawrence Livermore National Laboratory under contract W-7405-ENG-48 and for the Department of Defense under Defense Advanced Research Projects Agency ARPA Order No. 4395 A#12, monitored by Naval Surface Weapons Center under document number N60921-83-WR-W0113.

0018-9499/83/0800-2754$01.00© 1983 IEEE

and Rosenbluth[14] and demonstrated by Phillips[15] (non-relativistically) has many of the attributes which make it an attractive choice as a 1 cm rf power source. First, it operates as a saturated power amplifier and thus might be capable of long-term frequency stability. Second, it can be driven by magnetically switched induction linacs[16] and is therefore capable of operating at high pulse repetition rates. Finally, it only requires low magnetic fields and can be built with permanent magnets. If we alternate an FEL section with an induction linac section in a manner such that the energy lost to the rf fields by the decelerating electrons is continuously replaced by induction accelerating cores, we might build a steady state FEL. One configuration in which a steady-state FEL is linked to a high gradient accelerating structure is shown in Fig. 2. This two beam accelerator (TBA)[17] operates as a transformer, taking the high current, low voltage (500 A, 1.8 MeV) electron beam produced by the induction accelerator and transforming it (utilizing the FEL) to a low current, high voltage (25 μA, 300 GeV) electron beam. Typical parameters of an FEL suitable for the two beam accelerator are given in Table V. The trapping efficiency (71%) was predicted by a one-dimensional FEL model[18] and was preserved throughout 85 m of equilibrium operation. The low energy electron distribution (assuming the untrapped electrons have been extracted) found after 85 m of operation is illustrated in Fig. 3. The combined FEL/induction LINAC produces more than 500 MW/m, considerably exceeding the requirements listed in Table II.

If we are seriously considering building a two beam accelerator, we must decide on a method for rf phase control and address the problem of microwave "plumbing" at 500 MW. We must also examine the potential instabilities of the coupled high and low energy electron beams. Finally, we must test the tapered wiggler FEL to see if the bunches can be reaccelerated without losing electrons.

V. Conclusion

In conclusion, I feel that mm sources will soon meet the rf power and efficiency requirements of a high gradient LINAC, but a great deal of developmental work must be done to improve the stability and reliability of these sources. The FEL, when combined with TBA architecture and existing induction LINAC technology, has the potential to drive a short 300 x 300 GeV collider.

Acknowledgements

The author would like to thank A. M. Sessler for pointing out the advantages of high frequency accelerators.

TABLE I

Comparison of High and Low Frequency rf Requirements

	SLAC SLC[2]	SLAC	HIGH FREQUENCY
Frequency (GHz)	2.856	2.856	35
Gradient (MeV/m)	18	200	200
Power/Source (MW)	120	15×10^3	4.3×10^3
Energy/Source (J)	120	15×10^3	100

TABLE II

Strawman Design for a 300 GeV + 300 GeV Collider

F	35 GHz
E_a	200 MeV/m
r	shunt impedance ($\pi/3$ jungle gym) 210 MΩ/m
Q	2.6×10^3
L_s	1.5 m
L	1.5 km (1000 rf feeds/accelerator)
P	235 MW/m (12 J/m)
τ_F	50 ns
N	5×10^{10}/bunch
δ	.06
D	.5
σ_z	.5 mm
L	10^{32} cm^{-2} sec^{-1} (at 1 kHz)

TABLE III-a

Demonstrated Sources at Frequencies > 30 GHz with > 10 MW Power

FREQUENCY (GHz)	POWER (MW)	BEAM VOLTAGE (MeV)	BEAM CURRENT (kA)	MAGNET (kG)	REF
40	23	0.4	1.3	20	6
75	35	1.35	1.0	10	7
33	70	0.6	5	10	8
(50)	(140)				8

TABLE III-b

10 GHz rf Sources with Power Levels Exceeding 100 MW

GENERATOR	TYPICAL POWER LEVELS (MW)	REFERENCE
Relativistic Magnetron	100 - 4500	9
BWO	100 - 1000	10
Vircator	100 - 3000	11
Gyrotron	300 - 900	12
Cusptron	250	13

TABLE IV

A Comparison of the Reliability of SLAC Klystrons to Demonstrated High Frequency Generators

	SLAC	TO DATE GUESS
Lifetime	10^{10} pulses	20 - 10^6
Faults	1 in 10^6	1 in 100
Frequency Stability	10^{-7}/hour	Broadband
Amplitude Stability	1%	10%
Rep-Rate	360 HZ	.01 - 50 HZ

TABLE V

A Steady State FEL Operated as a Saturated Amplifier Might Drive a Two Beam Accelerator

FEL Decelerating Gradient	1.6 MeV/m
Equilibrium Beam Voltage	1.8 MeV
Bunched Current	350 Amps
Power Output (Pulse)	570 MW/m
Wiggler Period	10 cm
Wiggler Field	2.7 kG
Equilibrium rf power in FEL	60 MW
Normalized Electron Emittance	.2 rad-cm
Initial Electron Current	500 A
Initial Beam Voltage	2.2 MeV

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Figure Captions

FIG. 1	Estimates of the maximum obtainable accelerating gradient versus frequency as limited by breakdown and single pulse (heating) damage.[3]
FIG. 2	Schematic of an FEL-driven two beam accelerator.
FIG. 3	Electron distribution after 85 meters of a "dc" 1 cm FEL.

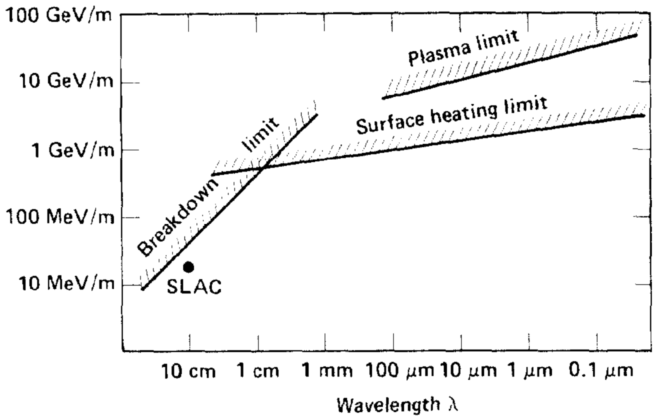

FIGURE 1

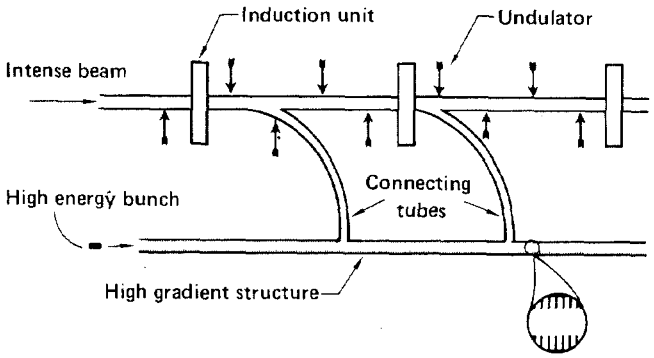

FIGURE 2

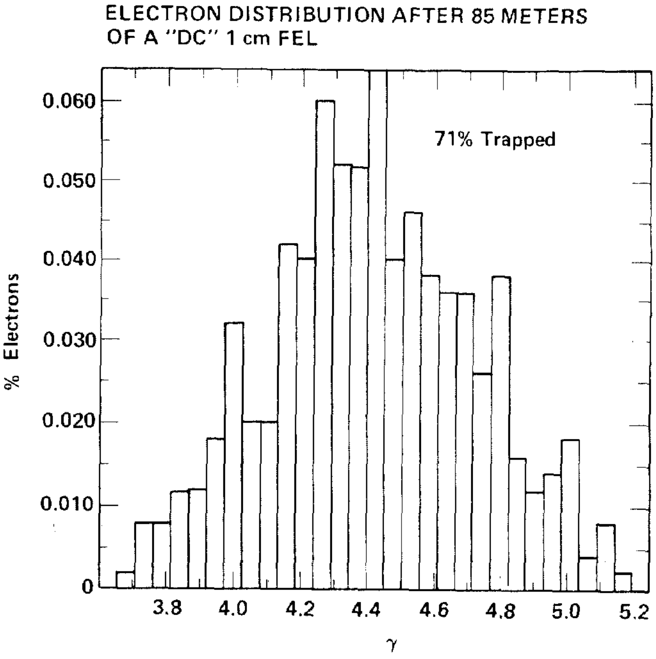

FIGURE 3