THE FREE-ELECTRON LASER AS A POWER SOURCE FOR A HIGH-GRADIENT ACCELERATING STRUCTURE*

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ABSTRACT

A two beam colliding linac accelerator is proposed in which one beam is intense ($\approx$1kA), of low energy ($\approx$ MeV), and long ($\approx$ 100 ns) and provides power at 1 cm wavelength through a free-electron-laser-mechanism to the second beam of a few electrons ($\approx 10^{11}$), which gain energy at the rate of 250 MeV/m in a high-gradient accelerating structure and hence reach 375 GeV in 1.5 km. The intense beam is given energy by induction units and gains, and looses by radiation, 250 keV/m thus supplying 25 J/m to the accelerating structure. The luminosity, L, of two such linacs would be, at a repetition rate of 1 kHz, $L = 4. \times 10^{32}$ cm^{-2} s^{-1}.

INTRODUCTION

A free electron laser (FEL) is a high-peak-power device which operates over a large range of frequencies and hence allows one to seriously consider operation of an accelerating structure at higher frequencies than are presently employed. The Stanford Linear Collider (SLC) will provide electron-positron collisions at 50 GeV x 50 GeV.[1] Beyond that, one contemplates a collider of (say) 300 GeV x 300 GeV.[2] Such a device, if it were to operate at the gradient of the SLC, 17 Mev/m, would be 18 km long. Thus one is driven to considering very much higher accelerating gradients. To achieve these gradients, and to reduce to a manageable level the energy stored in the accelerating structure one is driven to considering higher frequencies than are used in the SLC.

In this paper we take the accelerating structure to operate at 30 GHz; i.e., at a wavelength of 1.0 cm. Thus we consider just a factor of 10 increase in frequency over that in the SLC and, hence, a factor of 10 reduction in transverse dimensions of the accelerating structure. For the same accelerating gradient we would have, consequently, a factor of 100 reduction in stored energy.

For the accelerating gradient, at this high frequency, we believe we can achieve 250 MeV/m. Taking the accelerating structure to be 1.5 km long yields an energy of 375 GeV. One would also need about 0.5 km of the present SLC accelerating structure, with its associated sources and damping rings, as an injector and hence the

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total length of one linac is 2.0 km. We note that two linacs just fit on the SLAC site (4 km) with the collision point half-way up the site.

Constructing and aligning the accelerating structure (if scaled from the present structure of the SLC it would have a radius of 3 mm and a beam hole of 1 mm!) is a formidable problem. We believe it is not, however, insuperable. Operation at 1 kHz, and with a bunch of 10^{11} particles, would give a luminosity of $4.0 \times 10^{32}\mathrm{cm}^{-2}\mathrm{sec}^{-1}$.

The FEL for powering the structure can be designed to yield 1.0 GW/m which with a pulse length of 25 nsec is more than adequate to power the accelerating structure. The average beam power is 12.0 MW and the power from the mains is (about) 150 MW. Although the average power is high, and could be reduced by considering an even higher frequency, we believe the problems associated with smaller wavelengths are very difficult and unlikely to be solved in time for the next generation of collider. Beyond that, we will have to miniaturize and, hence research on these subjects is called upon.

The FEL should operate in "steady state"; i.e., the electron beam of (say) 3 MeV neither gains nor loses energy as it moves down the FEL. At an energy gain of 1 MeV/m, and a current of 1.0 kA, the FEL-beam is gaining 1.0 GW/m from the induction units, and radiating an equal amount due to the wiggler. The FEL-beam should have a length of 25 nsec so as to give 25 Joules/m.

Thus we are led to two beams traveling the length of the accelerating column (1.5 km). One is the FEL electron beam of 3 MeV, 1.0 kA, and length 25 nsec. The beam travels through induction units and a wiggler. The second beam consists of the 10^{11} electrons which are in a bunch of length 1 mm (so that the peak current is 480 A). This beam is taken to 375 GeV by traveling through the accelerating structure. The two structures are linked by pipes which carry the microwaves over from the FEL to the accelerating structure.

In this report we shall provide the reasoning and calculations behind the concept described in this Introduction. We shall end by suggesting experiments and theoretical studies which need to be done before one can feel confident about actually building the device proposed here. Fortunately, as will be seen, the requisite "proof-of-principle" work is rather modest in extent and cost.

ACCELERATING GRADIENT

In the present analysis we are motivated to obtain as large an accelerating gradient as possible. Just how high the gradient can be before sparkbreakdown occurs is unknown. In fact, this subject was considered by experts at this Workshop on the Laser Acceleration of Particles.[3] A gradient of 80 MV/m has been achieved by SLAC people and the Novosibirsk group has reported achieving 100 MV/m.[4] These gradients were at S-band and it is felt that one will do much better at 30 GHz. Estimates range from 150 MV/m through ("surely") 200 MV/m to ("possibly") 500 MV/m. We take 250 MV/m, but a larger gradient could shorten the device while only 200 MV/m would (in 1.5 km) still give 300 GeV x 300 GeV.

ACCELERATING STRUCTURE

In studying the accelerating structure we follow very closely the work by Wilson.[2] In fact, we really just use the methods of Wilson to study choice of parameters. We shall, therefore, use the notation of Ref. 2 and the reader may have to read that reference in order to understand this section.

Taking a charge bunch of 10^{11} particles, an RF wavelength of 1 cm, and an accelerating gradient of $E_a = 250$ MV/m, one, firstly, has to choose a structure type. We think a Jungle Gym is most suitable for this application and, hence, estimate the parameter k_0 ($E_a^2 = 4k_0w_s$, where w_s is the stored energy per unit length) as 2.5×10^{15} V/C-m. One readily obtains that the structure energy, when it is excited, is 7.8 J/m and that the bunch gains an energy of 4.0 J/m.

The next thing to examine is the transverse wake field, which can be characterized by the parameter A. One readily finds that A is unacceptably large. One can increase the transverse focussing, or lower the frequency, or increase the beam-nearest structure size, (hole-size in a disk-loaded structure). All of these don't have to be done, but it seems convenient to (1) take $\lambda_\beta = 10$ m (It is 100 m in the SLAC.) and (2) take $a = 2$ mm. (It would be 1 mm if we "scaled-down" the SCL structure.) In this case, since A depends upon the parameter, a, as $a^{-3.5}$, we find an acceptable value of A.

Now, however, with the larger value of a, the structure is less efficient and thus $k_0 \approx 1.0 \times 10^{15}$ V/C-m. The stored energy in the structure is now 19.5 J/m. (Alternatively one could decrease the frequency, but I think it is better to keep the frequency high, but make the accelerating structure less efficient.)

The luminosity one can obtain is dependent upon the repetition rate, the bunch length, and the beamstrahlung parameter. Taking $\delta = 0.05$, which is close — if maybe even beyond what experimentalists would find acceptable — yields a bunch length, σ_z of 1 mm. (This is not what one would obtain by simply scaling SLC parameters for there the bunch length will be 1 mm so that scaling would yield 0.1 mm.)

The luminosity, with a repetition rate, f_r, of 1 kHz is 1.2×10^{32} cm^{-2}s^{-1}, but the disruption parameter, D, is 0.90. Thus the lumniosity is enhanced by about a factor of 3 to 4×10^{32} cm^{-2}s^{-1}. The crossing point β^* also has a reasonable value and is 1.04 cm. Finally, the beam transverse emittance $\epsilon_n = 3.0 \times 10^{-3}$ cm, and is also reasonable.

With this long bunch length of 1 mm there will be an energy spread from acceleration of (about) 10%. Thus there is a large (10%) energy spread in the present design. This is a difficulty with all high frequency colliders and there is no way to "get around the problem" and still have a good luminosity (since the luminosity varies as $f_r\sigma_z\delta$ and both σ_z and δ are restricted by the allowed energy spread) unless one contemplates either a higher rate, or a number of bunches per pulse.[5] The higher repetition rate is possible for an induction linac (greater than 1 kHz in possible) but makes the average power consumption probably unacceptably high. A pulse train is always a possibility — as P. Wilson points out —

but is limited by the combination of resistive decay time in the accelerating structure and the cycle-time of particle detectors, so the number of bunches is probably limited to the number of distinct detectors on-line at any time.

FREE ELECTRON LASER

A free electron laser (FEL) can be used to generate the peak power needed to excite the accelerating structure. A rather extensive study has been made at 3 mm and one would expect not very large changes, from that work, at 1 cm.[6] In fact, the design will be easier at 1 cm so that one should be able to accommodate up to 2.0 kA of trapped particles.

On the other hand, induction modules should be able to be made compactly and stacked so that an acceleration of 1 MeV/m is readily obtainable. (Even a gain of 3 MeV/m should be possible.)

Thus, the beam would be given 2 GW/m. We have taken 250 MW/m so either there needs to be less energy gain to the electrons or a smaller current need be employed.

In steady-state, all of this energy will be radiated at 1 cm. Calculations are presently being done on wiggler wavelength, magnetic field, beam energy, current density, etc. Preliminary work, however, indicates that the parameters assumed, here, are quite reasonable.[7]

POWER REQUIREMENTS

The accelerated beam requires an energy of 4 J/m, while powering the structure requires 20 J/m. Thus the beam takes 20% of the energy out of the structure which is not so high as to give concern about instabilities or so low as to be grossly inefficient.

Let us assume an 80% efficiency for powering the structure, so that the FEL must produce 25 J/m. If the FEL is rated at 250 MW/m, then the FEL electron beam must have a duration of 100 ns which is just in the range of accessibility with ferrite cores on the induction linac. One can build such an induction linac with (about) a 50% efficiency from the mains to the beam. Hence, the over-all efficiency is (20%)(80%)(25%) = 8%. If the rep-rate is 1 kHz, and the length of two linace is 3 km then the beam power is 12 MW and the average power from the main is 150 MW.

The above estimate, which is conservative, may be quite conservative. We have designed an FEL which can fill the whole accelerating structure at the required 20 J/m. But the FEL beam, necessary to do this, is only 100 ns long. Thus we envision a 100 foot long, 1-2 kA, beam moving along and powering the accelerating structure. But in the accelerating structure the group velocity can be made large. In this case the pulse of energy can be arranged to move along just with the bunch of accelerated particles. Thus one has only to re-supply resistive losses and beam power losses and the power requirement is very much less than 150 MW.[8]

FURTHER WORK

In order to carry the suggestion made in this paper to the point where it is a serious contender for a linear collider project one must do experimental and theoretical work on a number of fronts:

1. Accelerating Structure

   Computer studies need to be made to see what structure is best at 1 cm and with a large beam hole (2 mm). Presumably one will find that it is a Jungle Gym structure. One needs to determine phase and group velocity so as to accurately evlauate power requirements of the structure. Tuning and tolerance requirements must also be determined.

   Most importantly, one must learn how to fabricate such a structure; first at all and then cheaply. It seems like a Swiss watch, but then we know such watches can be built....

2. Free Electron Laser

   The FEL, of Sessler and Prosnitz, at the ETA will be optimized at 3 mm. One would, probably, build a FEL optimized at 1 cm. Presumably such a device would use electrons of less energy than 4.5 MeV.

   Subsequently, one would want to build a "steady state" FEL of (say) 10 meters length. Such a device could then be used, with an injected beam in an associated accelerating structure, to give the beam (say) an energy gain of 2.5 GeV.

3. Beak-Down Studies

   Of great importance is just what gradient can be achieved before break-down. The FEL at the ETA allows one to do just such studies. They expect 500 MW for (say) 10 nsec which is 5 J. Thus this device can power 25 cm of accelerating structure to 250 MV/m. Of course, one can make shorter devices, etc...

4. Coupling Studies

   One needs to determine, theoretically, a good configuration for coupling the FEL to the accelerating structure. One imagines the FEL being slowly made twice as wide as usual (say) every meter and then the microwave energy is taken away in an over-moded pipe. This concept needs to be refined. Also, there is the very important subject of coupling into the accelerating structure.

   Once again, the FEL at the ETA could be employed for experimental studies.

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4. A. N. Skrinsky, private communication.
5. For example, if the experimental requirement was that $\Delta E/E < 1\%$ then we could consider the (self-consistent) set of parameters: $\sigma_z = 0.1$ mm, $E_0 = 375$ GeV, $f = 1$ kHz, $N = 7.8 \times 10^9$, $\epsilon_n = 3 \times 10^{-3}$ cm, $\beta^* = 0.5$ cm, $\delta = 0.01$, $D = 1.5 \times 10^{-2}$, $L = 2.5 \times 10^{30}$ cm^{-2} s^{-1}. In this case, compared to the example given in the text, there has been a one-order-of-magnitude reduction in $\Delta E/E$, but the luminosity has gone down by two-orders-of-magnitude.
6. D. Prosnitz and A. M. Sessler, "Multimeter Wave Generation by a Single-Pass, Compton Regime, Variable Parameter Free Electron Laser", to be published in the Proceedings of the Conference on Free Electron Lasers, Sun Valley, 1981; UCRL-86258.
7. Cha-Mei Kim and A. M. Sessler, private communication.
8. If, for example, the group velocity were $v_g = c/2$ (probably one would need a Disk and Washer Structure, rather than a Jungle Gym Structure, for this purpose.) then only 1/2 of the structure would need to be excited and the average power would be reduced from 150 MW to 75 MW.