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A BRIEF SURVEY OF ADVANCED ACCELERATOR R&D EFFORTS*

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1. Introduction

It is apparent that if higher energy accelerators are to be built for a reasonable cost, higher accelerating gradients will be required, and most efforts have been devoted to achieving such gradients. It must also be kept in mind, however, that higher gradients will require higher peak powers from whatever power source is used. The peak powers required are reduced if the wavelength of the accelerating radiation is reduced. If useful luminosity is to be achieved high average power is also needed. Average power is reduced if the beam emittances can be reduced and smaller interacting spots generated. The average power is also reduced if bunches containing larger numbers of particles are employed, but these numbers are limited by the beamstrahlung (synchrotron radiation) at the interaction point. Considerable progress has been made in understanding these questions, but much still remains to be studied.

As an introduction to this subject, we will examine the limits on accelerating fields as a function of wavelength and attempt to place the different schemes on such a plot. We can then examine the constraints applied by beamstrahlung considerations and their influence on the choice of mechanisms.

2. Accelerating Gradient Limits

Figure 1 shows the estimated or known accelerating gradient limits. We know from SLAC experience that at a wavelength of 10 cm, accelerating gradients in excess of 100 MeV/m can be achieved. This is believed to be relatively near to a breakdown limit and this breakdown limit is believed from empirical data to rise as the inverse 7-8th power of the wavelength. Thus

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if the wavelength were reduced to 1 cm, the accelerating gradients of the order of 1 GeV/m might be achieved without breakdown, were it not for the electrical heating of the copper structure. A conventional structure is filled for a pulse duration equal to the cycle time × the resonant $Q/2\pi$. This is called the filling time and provides the highest accelerating gradient for a given power of the rf source. If such a filling time is used with a conventional copper structure, then the field levels at which melting occurs rises as the inverse 1/8 power of the wavelength as is indicated on line b. This limit is set by the thermal conductivity of the metal. As the wavelength is reduced below 100 microns, the filling time has become so short that thermal conductivity becomes of less importance and the maximum temperature is set by specific heat alone. Below this wavelength the maximum accelerating gradient would rise like the inverse one-quarter power (line c), until at some ridiculously short wavelength the filling time is equal to one half cycle and no further increase would occur. The situation for very short filling times is complicated by the finite relaxation time it takes for the hot electrons to transfer their heat to the ions. A single measurement has shown a maximum gradient somewhat higher than that calculated in the simple way. The magnitude of this effect is not known but it should also rise as the inverse one quarter power as has been indicated approximately on Fig. 1 line d. The final line e, indicates the accelerating gradient that could be achieved without melting if instead of filling a resonant cavity for its normal filling time, a radio-frequency pulse of a single half cycle were used. This limit is independent of the wavelength and is, like lines c and d, dependent on the specific heat of the conducting material. If, of course, the accelerating structure is not metallic, then these limits do not apply. A plasma, for instance, could sustain accelerating gradients in excess of any of these limits.

3. Acceleration Mechanisms and Power Sources

In Fig. 2 we attempt to place the acceleration mechanisms in their approximate locations on a plot of wavelength and maximum gradient.

1. Klystron and lasertron driven conventional linac structures. Klystrons and lasertrons as now conceived are restricted to wavelengths of a few cm or longer. At shorter wavelengths the dimenions of the structures become small and the currents and thus power of the devices become too small for our needs. At such wavelengths the accelerating gradients will be limited to around 100 MeV/m.

   Work on lasertrons (which should be cheaper and more efficient than klystrons) is going on at SLAC and in Japan.

2. Free electron laser driven conventional structures. A free electron laser, unlike a klystron or lasertron, can deliver shorter wavelengths at high power. This is because its structure dimensions are not directly related to wavelengths produced. The most efficient use of a free electron laser would appear to be the two beam accelerator arrangement in which the low energy beam that drives the FEL is re-accelerated in an induction unit and reused in subsequent FEL units. If used to drive a conventional linac structure, the wavelength would be restricted to approximately 1 cm or more and the accelerating gradient to of the order of 250 MeV/m.

   Active work on the two beam accelerator is being carried out at LBL and LLL.

3. Free electron laser driven grating structure. The use of the open one sided grating type structures developed for laser acceleration could be used with a free electron laser power source working in the 1 mm to 100 micron wavelength range. Accelerating gradients slightly

higher than those available in the previous case could be achieved.

4. Laser driven grating structures. Carbon dioxide lasers with very high output powers are available with a wavelength of 10 microns. These could be used to drive open grating type structures. Experiments indicate that because of anomolous conduction, accelerating gradients in excess of 1 GeV/m should be possible.

   Work on this possibility is being carried out at Brookhaven, SLAC, Los Alamos and NRC in Canada.

5. Wake and switched field linacs. If a radio-frequency source is employed with delivers a few or even a single half cycle, then far higher fields can be achieved before melting of the accelerating structure occurs. Indeed for a half cycle this limit is approximately 10 GeV/m. Whether breakdown does or does not follow the empirical line (a) on Fig. 1 is not experimentally known, but we will assume that gradients of the order of 1 GeV/m without breakdown with pulse lengths, i.e. λ, in the 1 mm to 1 cm range. Various suggestions have been made as to how to generate these very high peak power single cycle pulses. In the wave field accelerator a single high current low energy bunch from a more conventional accelerator is passed by a periodic structure to generate the pulse. In the switched field case, a laser driven photo diode or laser controlled semiconductor is employed to switch a high current and thereby generate the electromagnetic pulse. In all these cases, some form of radial geometrical focusing has been proposed to couple a large surface area of source to a small volume of accelerator.

Work on the wake field accelerator is being carried out at DESY in Hamburg, Germany. Some work on the photo diode switched power linac is starting at CERN and Brookhaven and a proposal for work on the semiconductor switched power linac has been submitted by the University of Rochester.

6. Plasma wake field accelerators. In the wake field accelerator described above, a periodic conducting structure was needed to generate the wake. In a plasma however a moving charged bunch will generate a wake field behind it without any mechanical structure. This could allow the use of shorter pulses and the gradient would not be limited by heating or breakdown.

   Theoretical work on the plasma wake field accelerator has been done at UCLA and SLAC an experimental program has been proposed at Argonne.

7. Laser plasma accelerators. In this device a powerful laser is employed to excite a plasma oscillation. Laser light is employed at two distinct frequencies with the beat frequency synchronous with the plasma frequency. The resulting charge density fluctuations in the plasma contain large electrostatic fields which are employed to accelerate the particles. Accelerating fields in the tens of GeV/m should be possible employing laser radiation in the 1 to 10 micron region.

   This mechanism was proposed and has been extensively studied experimentally at UCLA . Modeling has been performed at Los Alamos National Lab and theoretical work at many institutions. No particles have as yet been accelerated by this mechanism, but the beat waves have been established and studied.

4. Wavelength Considerations

The choice of wavelength for a high energy electron-positron collider is constrained by considerations of stored energy, peak power, average power consumption and beamstrahlung. The minimum stored energy in any accelerating field is proportional to the accelerating gradient × the wavelength squared. It is clearly minimized by using the smallest possible wavelengths. The average power required for a given luminosity is proportional to the beam emittance × the focusing parameter β divided by the number of particles per bunch N. It is clearly desirable to have a large number of particles per bunch. There is however a limit imposed by consideration of the beamstrahlung, i.e. of the synchrotron radiation that is emitted as one bunch passes through the high magnetic fields induced by the other bunch at the intersection. This limit is also related to the emittance of the beam, the focusing parameter β, and the bunch length, σ_z. The maximum number of particles per bunch once established, imposes a limit on the smallest wavelength that can be employed. If the wavelength is smaller, the stored energy in the structure is insufficient to provide the needed accelerating energy to the bunch. This minimum wavelength is also dependent on the accelerator gradient and is thus represented by a diagonal line on the accelerating gradient vs. wavelength plot (see Fig. 3). A diagonal band has been indicated to cover a range of plausible assumptions about the emittance and focusing. To the right of this band the number of particles that can be accelerated per bunch becomes less and the average power consumption would be excessive. To the left of the band the wavelength is larger than is needed and the peak power and stored energy requirements become excessive. Somewhere there is a cost minimum.

It is unwise at this time to try and draw conclusions from any discussion of this type. It has been presented as an introduction to the potential advantages and disadvantages of the various mechanisms. Only time will tell whether these considerations are the compelling ones. The conclusion will also depend on the different efficiencies. At this point it would appear that the lasertron, free electron laser and switched power driven devices are good candidates for high efficiency. A laser grating device has the capability of high acceleration efficiency, but the laser is not likely to have more than 10%. The plasma devices are far less well understood at this time, and it is too early to make a judgment. Despite their lower efficiencies, however, laser driven devices, both the plasma and grating, are likely to produce the highest energies for a given cost. The lasertron and free electron laser driven devices should be capable of adequate luminosity, but will be relatively more expensive for high energy, and one must wait to see whether the wake field and switched power devices can fill the gap between the two extremes.

5. Recent Progress on Selected Mechanisms

A. The Two Beam Accelerator (FEL Driven)

1. Experimental Demonstration

The free electron laser at Livermore has achieved approximately .8 gigawatts of radiation at a wavelength of 1 cm. About thirty percent of the beam energy was extracted as radiation. The efficiency of the low energy beam induction accelerator was not in fact high, but efficiencies of the order of 70% should in principle be possible. Thus even as now demonstrated an overall efficiency of 20% could be expected. If however the free electron laser is used in a two beam accelerator arrangement, i.e., if after 30% of the beam energy has been removed, the beam is re-accelerated with an induction unit to full energy and this process repeated many times, then the overall efficiency could be as high as 70%. The output power per unit length at the end of the free electron laser was approximately .4 gigawatts/m which is quite sufficient to load an accelerator section with accelerating gradients of the order of 250 MeV/m.

The groups from LBL, Livermore and MIT have performed extensive computer modeling of the two beam accelerator concept and have found no insuperable difficulties. They have also produced a preliminary parameter set for a 1 TeV on 1 TeV electron positron linear collider. Serious cost estimates have not been performed, but scaling from conventional accelerators assuming fixed costs per stored energy, peak power, average power and length would indicate that the cost of such an accelerator could be an order of magnitude less than a conventional linear collider or its equivalent proton proton device such as the SSC.

The LBL, Livermore group plans to test a 1 cm SLAC like accelerating structure and investigate the maximum acceleration gradients They will test the extraction of radiation along the length of the FEL. They would then insert an induction unit to make up the energy loss and follow it by a second FEL section. This would test the true two beam accelerator concept.

Longer range plans would include the construction of a 30 m long section, possibly located at a test beam at SLAC.

B. Laser Grating Linac

Work in this field is being carried out by a collaboration between Brookhaven, NRC in Canada, Los Alamos National Lab, the Stanford Linear Accelerator Center and the University of California at San Diego.

Recent progress has been made in many areas.

1. The question of transverse wake instabilities in a linac structure with such a small wavelength has been investigated, and it has been shown that when Landau damping is employed the basic transverse wake amplification factor is independent of both the wavelength and the accelerating gradient. In this analysis, radio-frequency quadrupole focusing was assumed. The pole tip distances scale with the wavelength and thus the focusing gradient increases with both the accelerating gradient and inversely with the wavelength.
2. An industrial study of a high repetition rate, high efficiency carbon dioxide laser has been completed. The required repetition rates and a 10% efficiency seemed practical.
3. Progress has been made in this study of grating like accelerating

structures. Theoretical work has been done by Kroll and Pickup, and rf modeling has been performed at both Cornell and BNL. Many different such structures have been studied. One consisting of a double row of conducting pill boxes on a conducting surface seems particularly suitable for fields up to the melting limit. Another consisting of four parallel rows of conducting liquid metal droplets might allow accelerating fields higher than the melting limit.

4. It has been shown that both the structures mentioned above will, when operated at a different phase, provide radio-frequency quadrupole focusing. The strength of this focusing is very much higher than that provided by conventional quadrupoles and could be used for the crucial final focus.
5. At NRC, a gold mirror was not destroyed by 2 picosecond pulses of CO_2 radiation that generated surface fields of the order of 4 Gev/m near the surface. The experiment implies that accelerating fields of at least 2 GeV/m should be possible without destruction of a grating structure.

Future plans include:

1. Continuation of theoretical and rf model studies.
2. The construction of prototype structures of both the double pill box and ink jet type. The structures would be tested at low field levels and their resonant properties studied.
3. Breakdown studies at high field levels would be continued at NRC.

4. A 1 GeV test beam will be proposed at SLAC with special collimators to allow a 1 micron spot diameter and a momentum spread of less than 1 MeV. A 10^{11} Watt few picosecond carbon dioxide laser would be provided by the Los Alamos National Lab and synchronized to the short electron bunch at SLAC. A spectrometer would be provided to measure both the change in momentum and transverse focusing. This facility, would also allow experiments on the inverse free electron laser and inverse Cerenkov mechanisms.

C. Wake Field Accelerator

The main work in this field is going on in DESY in Hamburg, Germany.

In this scheme the wake field is generated by a short electron bunch in the form a ring. This ring bunch enters a structure consisting of parallel discs perpendicular to the beam axis over which the ring bunch passes, and a corrugated cylindrical outer wall. The wake fields are generated on the corrugated outer wall and reflected back into the spaces between the plates and focused on the axis. On this axis there are small holes to allow the high energy beam to pass and be accelerated by the focused wake fields. With such an arrangement in which the outer diameter is 12 cm and the spacing between the plates is 4 mm, it is hoped to get an amplification of field of the order of 10 and a final accelerating gradient of 100 GeV/m or more.

Extensive modeling calculations have been performed on this system and a full scale test of the principle is now underway. The test arrangement consists of a laser driven ring photo cathode, a buncher, a 500 MHz conventional accelerating section yielding a final energy of 8 MeV, and a final solenoid magnet that presses the ring bunch both radially and longitudinally. Finally there is the test wake field accelerator.

D. Switched Power Linac

Work on this concept is being pursued at CERN, Brookhaven Lab, and at Rochester, NY.

The arrangement proposed by W. Willis is similar to the wake field accelerator described above. The accelerator itself would consist of discs with the high energy beam passing through holes in their center. Instead, however, of a ring bunch passing over the edges of the discs, a pulse of current is switched at the disc edges in such a way as to induce the required electromagnetic pulse. Two methods for switching this current are being considered:

(a) A photo diode excited by a short laser pulse. The photo cathode consists of a wire between the plates and the current passes from this to one of the plates.

(b) In the other alternative a semiconductor is placed between two plates and a current induced in this semiconductor again by a short laser pulse passing into the semiconductor from the outside.

Modeling work on these systems has started and experimental work on both the photo diode and solid state switching techniques is hoped to begin within a year.

E. Plasma Wake Accelerator

This idea was proposed at UCLA, has been studied theoretically at SLAC. A proposal to study it experimentally has been made by Argonne National Lab.

Unlike the wake field accelerator described in (C), no structure is needed to generate the wake. A short but high current bunch of low energy electrons passing through a plasma will induce a plasma wake behind it that could accelerate a following bunch of higher energy electrons.

In the experiment proposed at Argonne National Lab, a 22 MeV high current electron beam would be employed. An electron bunch of a few millimeters in length containing of the order of 10^{1} particles would be introduced into a low density plasma (~5 10^{14} ions/cm^3). An accelerating gradient of the order of 400 MeV/m is expected and would be probed by a second witness pulse passing through the same plasma.

F. Plasma Beat Wave Accelerator

This idea first proposed in UCLA has been studied theoretically both there and in Los Alamos, and has been demonstrated experimentally at UCLA. Experimental work may soon also start at the Rutherford Lab in England.

The basic concept is to introduce into a plasma a laser beam consisting of two frequencies, whose difference matches the plasma frequency. The beating of the two frequencies causes spatial fluctuation in the light amplitude and thus a spatial fluctuation in the ponderomotive force applied to the electrons of the plasma. The resulting resonant oscillations of the electrons increase in amplitude until losses or density saturation sets in. For a plasma density of 10^{16} particles/cm^3 the density saturation limits fields to 10 GeV/m.

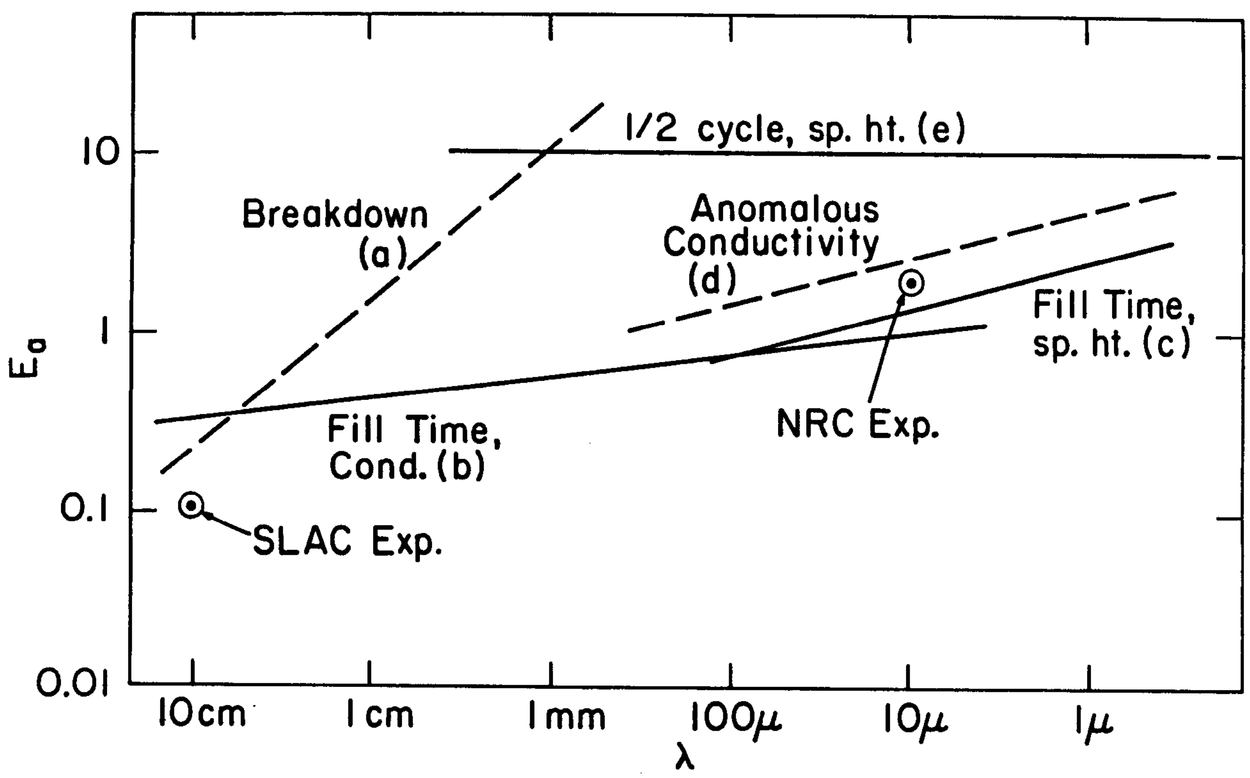
Acceleration continues until the phase has slipped by 180°. This distance being proportional to the square of the laser frequency divided by the plasma frequency. If, however, the particles to be accelerated are introduced at a finite angle to the direction of propagation of the light beam, then the phase can be maintained for an indefinite length. This is known as the "surfatron" idea.

Extensive one and two dimensional modeling has shown that near to the full theoretical accelerating gradient should be achieveable. An extensive experiment at UCLA employing a carbon dioxide laser has excited plasma beat waves which have been diagnosed by Thompson scattering. It was deduced that accelerating gradients as high as 1 GeV/m had been generated over a few mm.

A new experiment has been proposed by UCLA which would induce beat waves over a distance of 20 cm and which would inject 5-10 MeV electrons and accelerate them in the plasma fields.

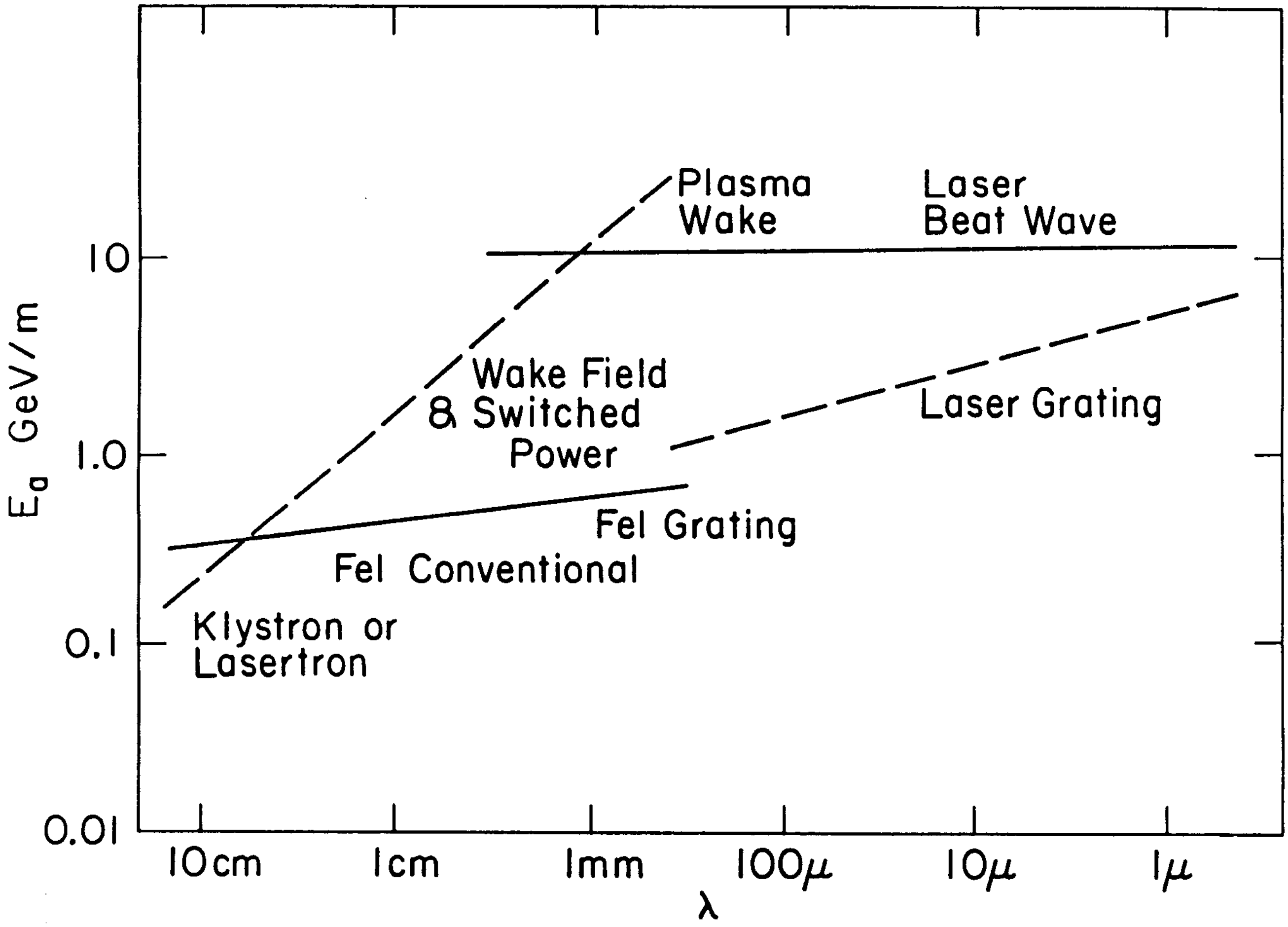
6. Conclusion

This survey has not discussed all mechanisms. Some, like the inverse free electron laser, are known to be unsuitable for very high energies, others like the inverse Cerenkov mechanism are unlikely to be able to preserve the very small emittances required. There are other mechanisms that have only recently been proposed and no doubt more that we have not heard of. Such a survey cannot be complete, but I hope it gives a flavor of the interest and potential of the field. It is generally accepted in the community that it is too early to try and select any particular mechanism for special development. It is my personal opinion, however, that the time is not far off when such a selection should be made. At that time the broad inventive exploration should be continued, but in addition the selected idea or ideas should be pursued in a more active and directed way.



1/2 cycle, sp. ht. (e)
Breakdown
(a)
Anomalous
Conductivity
(d)
Fill Time,
sp. ht. (c)
Fill Time,
Cond. (b)
NRC Exp.
SLAC Exp.
10
1
0.1
0.01
E_a
10cm
1 cm
1 mm
100μ
10μ
1μ
λ

Fig. 1



Plasma Wake
Laser Beat Wave
10
Wake Field & Switched Power
Laser Grating
1.0
E_a GeV/m
Fel Grating
Fel Conventional
Klystron or Lasertron
0.1
0.01
10cm
1cm
1mm
100μ
10μ
1μ
λ

Fig. 2

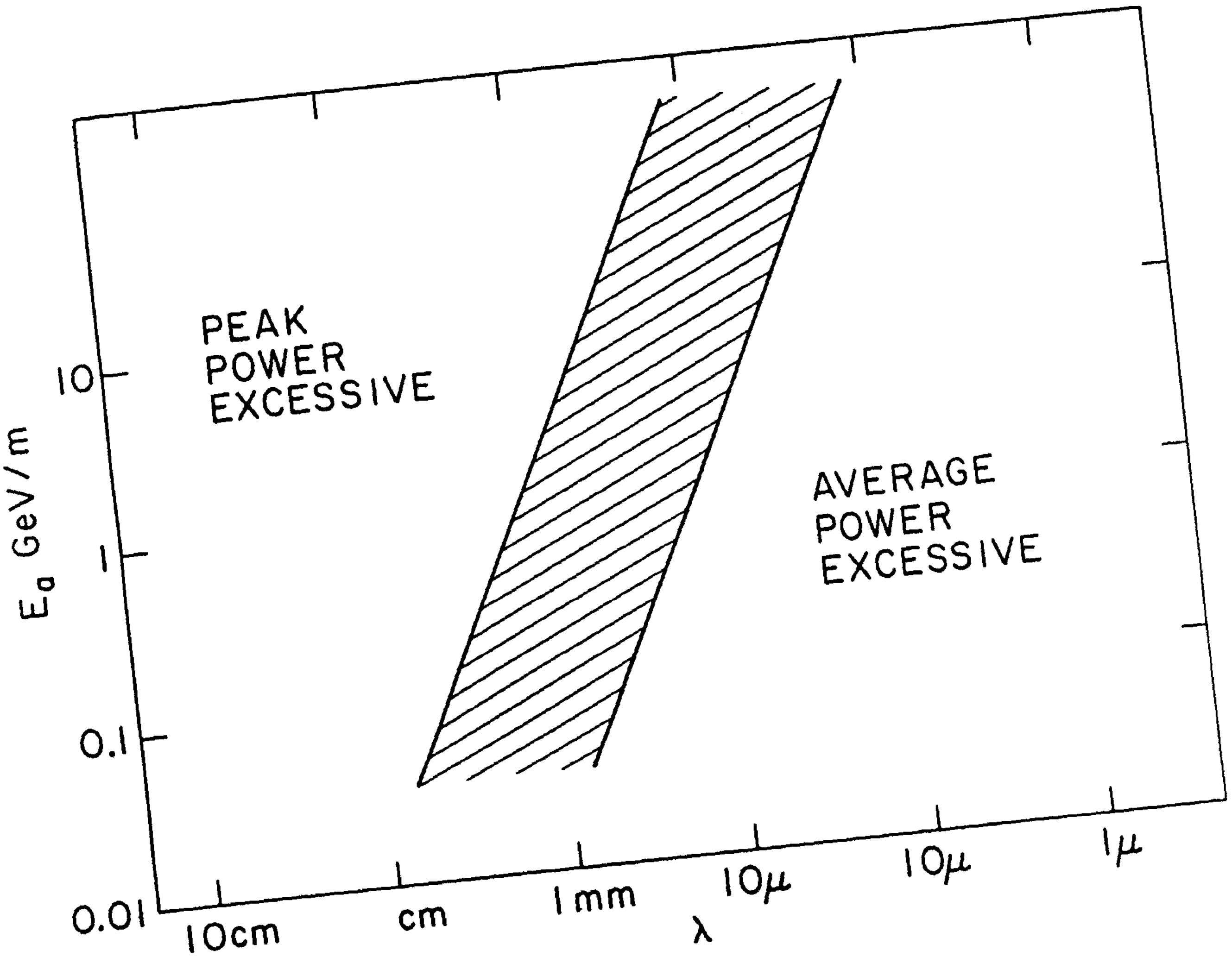

PEAK
POWER
EXCESSIVE
AVERAGE
POWER
EXCESSIVE
E_a GeV/m
10
1
0.1
0.01
10cm
cm
1mm
10μ
10μ
1μ
λ

Fig. 3