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# NEW ACCELERATION SCHEMES AND TECHNOLOGIES*

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## INTRODUCTION

The search for new acceleration schemes and technologies has, in general, been restricted to a search for higher gradient acceleration, and it has been motivated by the aim of reducing the length, and presumably the cost, of new high energy facilities. In particular, it has been argued that very high energy linear colliders will only be practical if much higher acceleration gradients are employed.

Consider a linear collider with center-of-mass energy of 10 TeV (an energy significantly higher than the approximately 4 TeV accessible to the SSC). With the gradient currently used by the Stanford Linear Collider (SLC) of 20 MeV/m, then this collider would be 500 km long. If gradients of 2 GeV/m were employed (as are probably available with some technologies), then the facility could be only 5 km long. No further motivation seemed needed.

Unfortunately, the sheer length of such a 10 TeV collider is not the only technical difficulty. At high energies the fundamental cross sections are smaller, and the required luminosity of the collider must rise. For a 10 TeV machine, a reasonable luminosity would be $1 \times 10^{36}$ cm$^{-2}$ sec$^{-1}$. This is 6 orders of magnitude greater than that of the SLC—in contrast to the only 2 orders of magnitude increase in length that 500 km would imply.

We must therefore ask whether the search for higher gradients is of primary importance, or whether the search for ways to attain higher luminosity should not be emphasized more. At the very least, we must ask whether any technology for higher gradients is also suitable for high luminosity. If the answer is negative, then it does not mean that the technology is of no interest whatever—there may be applications for such a technology in other areas—but it does mean that that it cannot be supported as a potential technology for a very high energy particle physics collider.

The above argument could be challenged on the grounds that we do not absolutely know that cross sections fall with energy. It is only a theory that they do. Unfortunately, the theory is rather fundamental, and even if wrong, it seems hard to believe that the community would recommend a future collider whose expected total

observation would be only a fraction of an event per year. Only if a loophole in the theory is predicted is the situation likely to change.

## ACCELERATION GRADIENT

### *Conventional Structures*

The maximum acceleration gradient $G_{max}$, in conventional structures, is limited by breakdown and dark current. It is not known exactly what the ultimate limit is, but it seems to be given approximately by:

$$G_{max} \propto \lambda^{-1/2}\, t^{-1/4} \quad , \tag{1}$$

where $\lambda$ is the wavelength of the rf field, and $t$ is its duration. For conventional power supplies, it is desirable to minimize the required rf power. For this, the pulse length should be a reasonable fraction (e.g., 30 to 60%) of the decay time $\tau$ of fields in the cavity. For a typical copper structure, $\tau \propto \lambda^{1.5}$, and thus the breakdown limit is given by

$$G_{max} \propto \lambda^{-7/8} \quad . \tag{2}$$

This electrical breakdown limit is shown on Figure 1. Consider the limits (continuous lines) for conventional pulse lengths. We see that at the rf wavelength used at SLAC (10 cm) the maximum gradient is of the order of 100 MeV/m, compared to the SLAC gradient of 20 MeV/m. SLAC is not yet at the limit. In addition, it appears that if the wavelength is lowered to of the order of 2.5 cm, then the maximum gradient will have risen to the order of 200 MeV. These numbers are still uncertain, but the trend is probably correct.

We see that as the wavelength is reduced, then breakdown is less of a problem; but there are other limits, as also indicated in Figure 1. The continuous line labeled (b) indicates the limit when the copper surface of the structure melts, and the continuous line (c) indicates the approximate limit when the pulsed heating of the surface might cause fatigue damage. Because of these limits, the attainable gradient improves only slowly as the wavelength is reduced below about 1 cm.

*Optical Wavelength Structures*

As Figure 1 shows, there is a slow improvement in maximum accelerating gradient as the wavelength falls. The prediction is that the field rises as the 1/8 power of frequency. But if the wavelength is lowered to optical wavelengths of a few microns, then the gain is not negligible. In fact, at optical wavelengths the gain is almost certainly greater than indicated. The pulse duration is then less than the relaxation time for the heat to be transferred from the electrons to the ions. The electron temperature then becomes very high without melting the structure, and the thermal conduction in this condition is enhanced. As a result, it appears possible to sustain surface fields well above 1 GeV/m without surface damage. Whether acceleration is possible at such surface fields is not yet known.

The question of how to build structures at optical wavelengths has been addressed, among others, by Palmer (1). In this paper it is shown that a suitable biperiodic grating, or other biperiodic one-sided bumpy surface, can behave in almost all respects like a conventional accelerating structure. Acceleration over gratings, using laser light, has now been demonstrated at low gradient, and an experiment to study high gradient acceleration is well along.

*Single-Pulse Accelerators*

As we have stated, the continuous lines in Figure 1 are all for pulse trains of the order of the decay time $\tau$. In contrast, the corresponding dashed lines are given for single electromagnetic pulses. It is seen that these limits are much higher than those for the pulse trains, and equal several GeV/m for wavelengths (i.e., pulse lengths) shorter than 2.5 cm (i.e., of the order of 100 psec).

Willis (2) has proposed generating the needed pulses by switching a high voltage gap, and then increasing the amplitude of the resulting electromagnetic pulse by focusing it in a radial transmission line. The switch is excited by a laser pulse, and can be solid state, as has been already demonstrated at low gradient, or a photodiode. It is hoped that a high gradient demonstration will soon be made.

An alternative source of the required pulse is from employing the wakefields left by the passage of a high charge bunch from a primary lower energy beam (3).

*Plasma Acceleration*

Clearly, in plasmas, the breakdown limits and damage thresholds for metal structures do not apply. And it can easily be shown that with quite moderate plasma densities, gradients of many GeV/m are possible (4,5). Many different schemes have been considered in which the plasma fields are excited by: wakefields, the beating of two laser frequencies, or a single short laser pulse. Fields of over a GeV/m have almost certainly been generated, although the observation of acceleration of particles by such gradients has proven elusive.

*Far Wave Acceleration*

Clearly, there is no breakdown limit in a vacuum, far from any material. Acceleration, in this case, is still possible in the presence of periodic magnetic fields (The Inverse Free Electron Laser [FEL]) (6), or in the presence of a fixed magnetic field (Inverse Synchrotron Radiation). Various other schemes have been proposed that do not require the presence of an external field, or any material nearby, but all such schemes, from quantum considerations, can be seen to be multiphoton, or radiation pressure, acceleration. In all realistic cases so far studied, the energy required is excessive and the acceleration is small.

## POWER SUPPLY COST

Several of these ideas could certainly achieve gradients of several GeV per meter, thus shrinking the collider lengths dramatically. But it is not obvious that the highest gradient will yield the most economical collider. In any electromagnetic accelerator, the electromagnetic energy needed per pulse per unit length will be proportional to the square of the accelerating field. The length needed for a given energy will fall linearly with the field, but the total energy needed will still rise linearly with the field. Since the generation of this energy is, in general, expensive, the most economical machine will involve a trade-off between linear and power source costs, and will dictate the

most economical gradient. Figure 2 shows lines of constant costs on an accelerating gradient versus wavelength plot. The dashed line represents the gradient that would give a minimum cost at that wavelength. One notes that this gradient rises, and the total cost falls, as the wavelength gets shorter. Again, we would conclude that very short wavelengths are favored, but this is complicated by the higher cost and lower efficiency of power sources at very short wavelengths. In addition, one finds that considerations of luminosity and tolerances argue against short wavelengths.

## THE LUMINOSITY PROBLEM

### *The Required Luminosity*

High energy colliders are built to study high energy phenomena—that is, the production and decay of high energy states. Unfortunately, as a consequence of quantum mechanics, there is an inevitable relationship between the energy of a phenomenon and its characteristic size and cross section $\sigma$.

$$\sigma \propto E^{-2} \quad , \tag{3}$$

where $E$ is the energy of the phenomenon (i.e., the center-of-mass energy of the fundamental collision). The cross section $\sigma$ of a phenomena tells us what luminosity $\mathcal{L}$ (related to the flux of colliding particles) is needed to achieve a given average rate $dn/dt$ of its occurrence:

$$\frac{dn}{dt} = \mathcal{L}\,\sigma \quad . \tag{4}$$

If we require a given rate of phenomena, independent of energy, then clearly we need a luminosity that rises as the square of the energy. The situation is illustrated by Figure 3. The plot shows the luminosity of some representative electron-positron colliders versus their center-of-mass energies. The line represents a rate of 10,000 events per year (defined as $10^7$ seconds) per unit of $R$, where $R$ is the ratio (of the order of unity) of cross sections to that of the reaction $e^+ e^- \rightarrow \mu^+ \mu^-$. We see that in going from the SLC to a 10 TeV collider , the energy increase needed is 100, compared to the needed luminosity increase of 500,000.

Some might settle for a factor of 10 less than 10,000 events per year per unit of $R$. But since the actual performance of any linear collider is likely to fall below its design (as is the case now with the SLC), it would be unwise to design future machines for lower luminosities.

*Luminosity Generation*

The luminosity of a collider is given by:

$$L \propto \frac{f N^2}{A} \quad , \tag{5}$$

where $f$ is the frequency of bunches colliding, $N$ is the number of colliding particles per bunch, and $A$ is the average transverse cross section of the intersecting beams. There is a limit to how small $A$ can be made, that depends on the emittance $\epsilon_n$ of the beams. And, there is a limit on how large an $N$ can be used without introducing unacceptable energy spread in the collision. Given these limits, higher luminosity can only be achieved by using a higher frequency $f$. But a higher frequency implies a higher average current. If the luminosity is to rise as the square of energy, then the average power will be seen to rise as the cube of that energy. At some point, this becomes a limiting expense. Thus these factors become very important:

1. The design of an electromagnetic power supply with low cost and high efficiency of converting wall power to rf electromagnetic power.

2. Use of an acceleration scheme with high efficiency for conversion of rf electromagnetic power to beam power.

3. Use of an acceleration scheme with the ability to transport very low emittance beams without dilution.

4. And, only when the above considerations are satisfied, use of the highest possible accelerating gradient consistent with minimizing the cost.

*Conventional Structures*

Conventional rf power supplies have an efficiency of the order of 40%, and even higher efficiencies may be possible. The efficiency of coupling this power to a single

bunch can be of the order of 10%, and coupling to multiple bunch could be as high as 50%.

Transverse wakefields, left by the front of the accelerated bunch, which act on the tail, can be a problem, but are correctable by an introduced momentum spread between the head and tail of each bunch. This momentum spread will itself cause emittance blowup unless stringent alignment requirements are met. For rf wavelengths down to a few cm, the resulting alignment tolerances are of the order of 30 $\mu$m, and these do not seem unreasonable.

Conventional rf power supplies and structures, with some development, seem well suited to the needs of high luminosity.

*Optical Frequency Structures*

The shorter the wavelength, the worse the wakefields, the greater the momentum spread needed, and the worse the alignment problem. As a result, one finds that very short, such as optical, wavelengths are strongly disfavored.

Another motivation for considering the use of optical wavelengths has been the availability from lasers of very high instantaneous power. This apparent advantage is, however, offset by the lower efficiency of most lasers. Indeed, it is now often proposed that optical frequency acceleration should be powered by FELs, whose efficiency can be comparable with conventional rf sources. But FELs do not have higher peak powers than a normal frequency klystron driven by the same beam.

*Single Electromagnetic Pulse Acceleration*

In order to transport a beam of very low emittance, and focus it to a stable point, it is very necessary to avoid random deflections. For instance, the natural divergence of a 0.5 TeV beam with normalized emittance $1 \times 10^{-8}$ *meters*, transported in a channel with an average $\beta$ of 100 meters, is $1 \times 10^{-8}$ *radians*. If there are random transverse fields even $10^{-8}$ of the accelerating fields, then the spot will be moved by one $\sigma$. This is a very severe requirement. In particular, it requires that the accelerating field must be exactly aligned along the axis, since minute fluctuations in this field would otherwise deflect the beam.

In conventional structures, the required alignment of the accelerating field is achieved, in part, because of a result from the Panofsky–Wenzel Theorem (7). Strong transverse fields exist in conventional structures, but, as a result of the theorem, for cylindrical symmetry, these fields add together to give zero transverse deflections. The symmetry is partially violated by the input and output ports, but the high resonance $Q$ assures that the field, despite these asymmetric feeds, is substantially symmetric.

In cases where a single electromagnetic pulse is used to accelerate, then the fields are not averaged by a resonance. The symmetry of the fields is then no better than the symmetry of the source. Under these circumstances, whether for switched power or wakefield generated, it is hard to believe that the required control of transverse fields is possible.

In addition, single-pulse structures require much higher instantaneous power than resonant devices. Since a substantial part of the estimated cost of a linear collider is its power supply, it seems unlikely that the much higher power levels required could be provided economically.

*Plasma Acceleration*

The same considerations that disfavor single-pulse acceleration apply even more strongly to plasma devices. The Panofsky–Wenzel theorem does not apply in a plasma, and transverse deflections of the same order as the acceleration are almost bound to be present. These fields can be made to be focusing, but very strong focusing implies extreme tolerances on the alignment and steadiness of those fields. Plasmas are not well known for their steadiness.

*Far Field Acceleration*

Inverse FELs (7), even at short wavelengths, do not have any transverse wakefields, but they cannot be used because the synchrotron radiation, at high energies, results in severe energy loss and emittance blowup.

## CONCLUSION

I am thus forced to conclude that none of the "exotic" acceleration mechanisms are, or will ever be, suitable for high energy linear colliders. One must be careful making such statements. New inventions, or even new optimizations, might lead to different conclusions. But it is hard, at this time, to see how.

The requirements for luminosity do favor superconducting accelerators (8). The wavelengths of such structures can be large, making the wakefields negligible. The damping time being essentially infinite, rf power can be fed continuously from a low power, high efficiency source. Unfortunately, at this time, the highest accelerating gradient that can be realistically achieved is only about 7 MeV/m, and that is just too low. However, the true limit (achieved in small single cavities) is about 40 MeV/m for niobium, and may be as high as 400 MeV/m for the new high temperature superconductors. If such fields could be achieved, then superconducting structures would be highly desirable.

But, for the moment, only room-temperature conventional linac structures appear to be practical.

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FIGURE CAPTIONS

1) Accelerating gradient limits as a function of wavelength. The limits are given both for long rf pulses of the order of field decay times (continuous lines), and for single electromagnetic pulses (dashed lines). Limits are given for: (a) breakdown, (b) surface melting, and (c) surface fatigue damage.

2) Lines of constant costs on an accelerating gradient versus wavelength plot. The dashed line represents that gradient for minimum cost at a given wavelength.

3) Luminosity of some representative electron-positron colliders plotted versus their center-of-mass energies. The line represents colliders yielding 10,000 events per unit of $R$ per year (defined as $10^7$ sec): a reasonable requirement for future linear colliders.

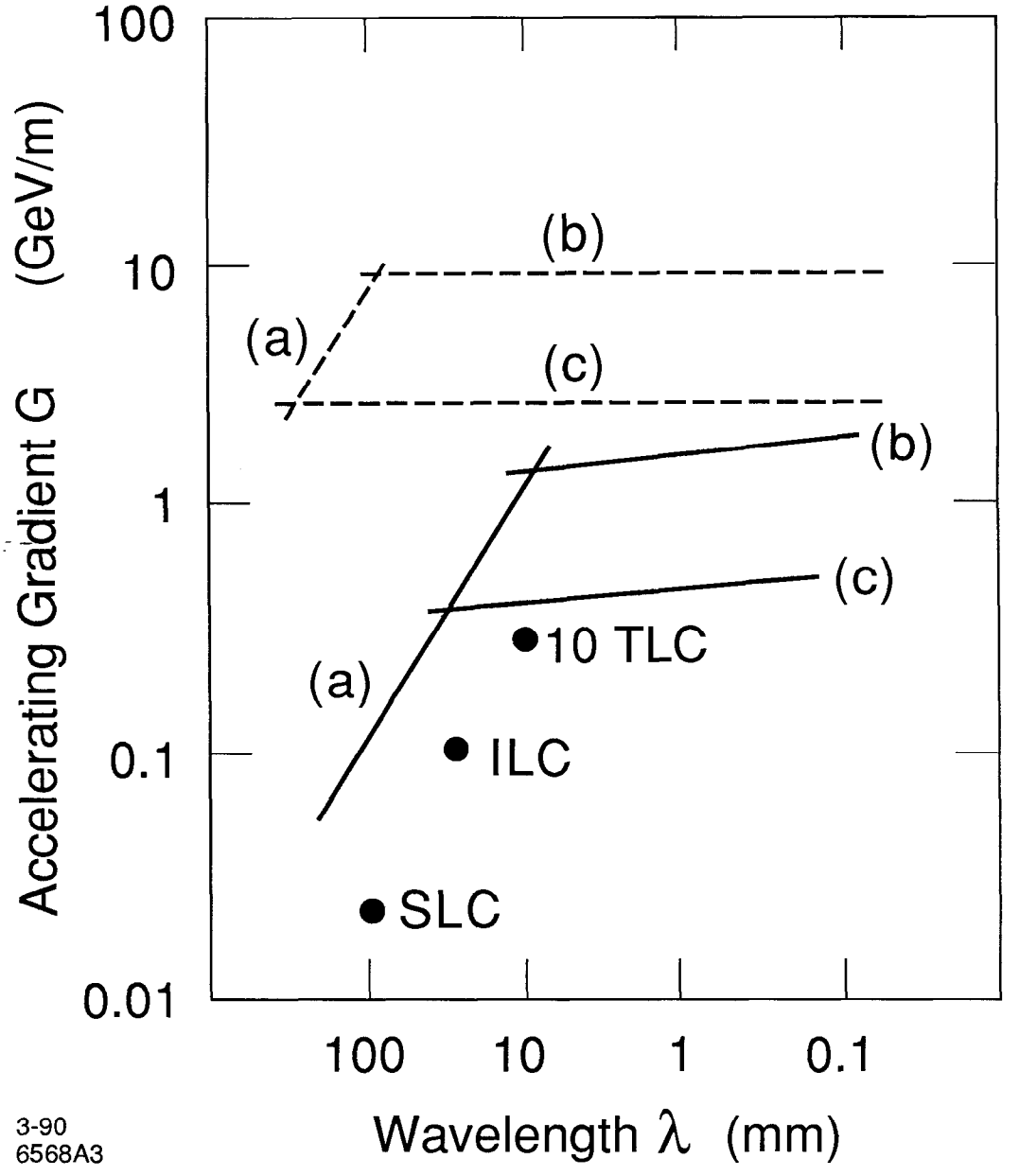


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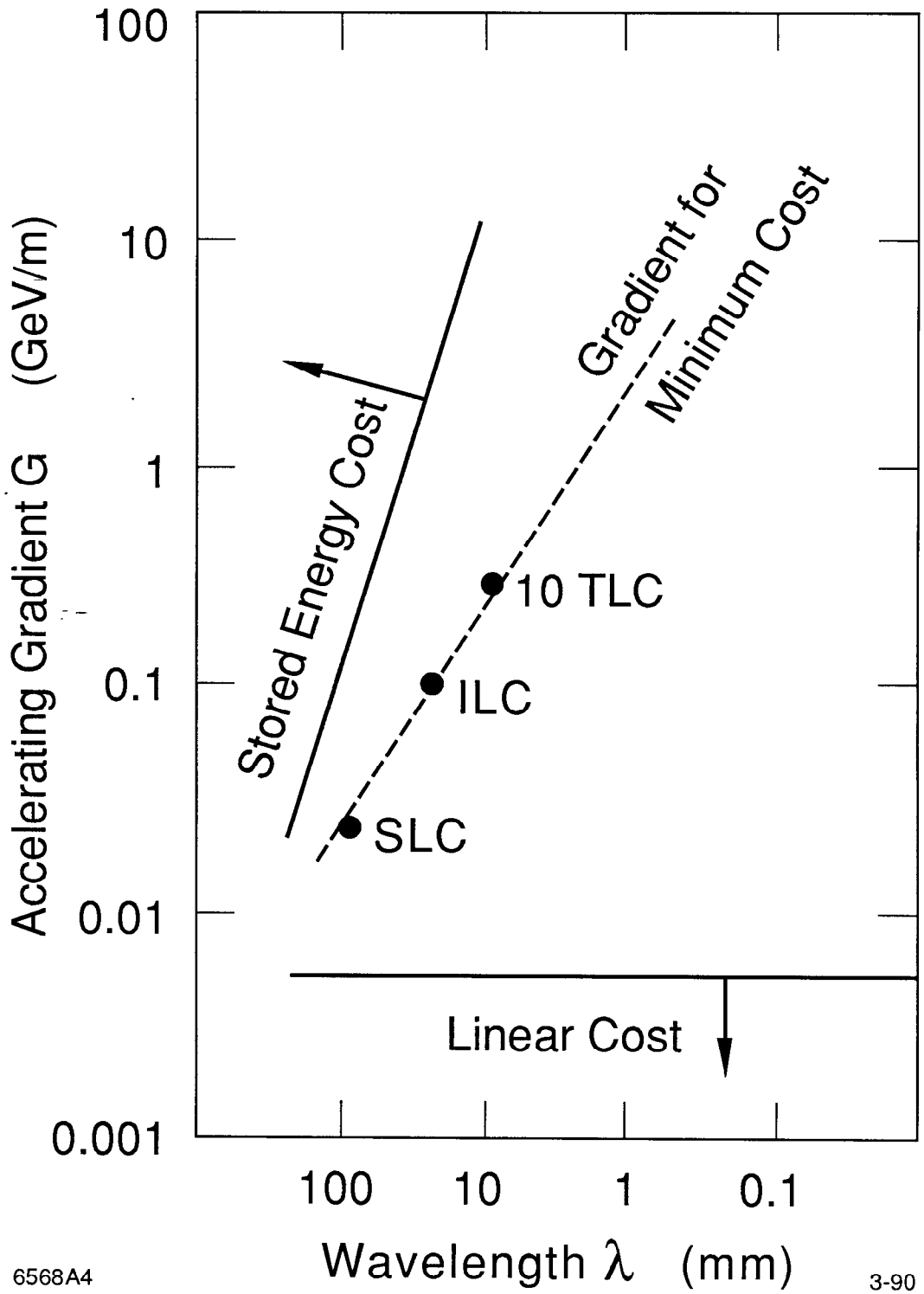
Fig. 1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10
1
0.1
0.01
0.001
Accelerating Gradient G (GeV/m)
Stored Energy Cost
Gradient for Minimum Cost
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ILC
SLC
Linear Cost
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10
1
0.1
Wavelength λ (mm)
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Fig. 2

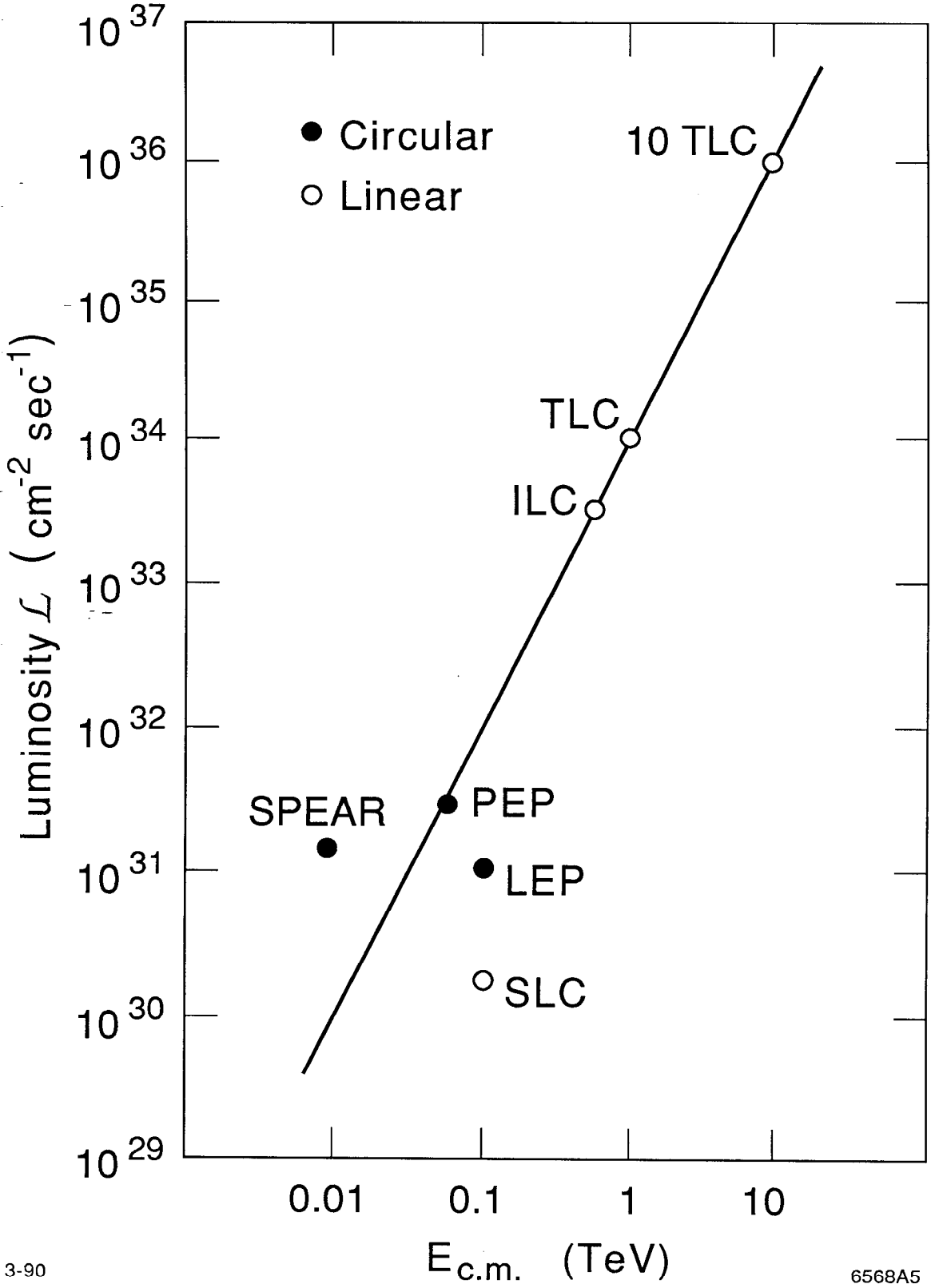


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Fig. 3