LASER LINAC COLLIDING BEAM ARRANGEMENT AT HIGH ENERGIES

A FEASIBILITY STUDY

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I) Introduction

In an earlier paper (1) a new principle in accelerating charged particles in the focus of a high power laser beam was discussed. It was demonstrated that field configurations in the focus of a laser beam enable single particles to be accelerated which travel along a so-called "acceleration channel" tuned to the particle velocity by a birefringent crystal outside the laser focus. In the following an attempt will be made to investigate whether or not a real particle accelerator based on this idea will be useful in high energy physics. This new acceleration principle will be examined in a colliding beam arrangement wherein two laser linacs are brought to fire against each other. The point around which most interest centres is luminosity and how it will compare with that achieved with conventional storage rings at superhigh energies. The aim is to find out whether a laser colliding beam arrangement with luminosity equal to that of a storage ring will compare favourably with a storage ring with regard to cost. As laser accelerators are still at the stage of discussion, it is of course obvious that all these considerations will have to be of a tentative nature.
The first step is to establish what kind of laser can be used. During this discussion it should however be borne in mind that the rapid expansion in the technology of high power lasers will only permit of a survey of laser types suited to the present purpose. Having defined the possibly usable types of laser, this paper will then be devoted to the investigation of particle beam optics, that is to a discussion for the first time ever of the accelerating of a real beam with finite emittances by means of such an accelerator. Following this discussion a rough estimation of maximum luminosities for a colliding beam arrangement will be given. In the last section a possible physical layout of a 2 x 100 GeV colliding beam arrangement and the costs are discussed. The unsolved problems are collected over the course of the whole

paper and listed in the summary.

II. Principle of Acceleration Channels

Although described in an earlier paper in more detail (1), a survey of the basic idea will be given here. If an electromagnetic wave is used for the acceleration of charged particles, the following two points must be taken into consideration.

(a) Both electric and magnetic fields act on the particle. In order to achieve a satisfying gain of energy, the magnetic field component along the particle trajectory should vanish. This demand can be fulfilled by the use of standing waves where the maxima of the electric and the magnetic field are separated by a quarter wave-length.

(b) When the magnetic component of the electromagnetic field no longer exerts any influence on the particle trajectory, the rapidly changing sign of the electric field strength accelerates and decelerates the particle and the net energy gain can be neglected. Therefore the particle must travel through a field-free region in which the deceleration half-wave cannot reduce the particle energy. A simple field configuration being both periodic in time and space is given by

$$E = E_o \sin(\omega t) \cos\left(\frac{2\pi y}{\lambda'}\right) \qquad (1)$$

wherein λ' is the spatial distance between the maxima of the electric field. Since the energy gain of a particle is given by

$$\Delta E = e. \int E(y)\, dy \qquad (2)$$

the acceleration condition is

$$v_p = \frac{c\lambda'}{\lambda} \qquad (3)$$

v_p = velocity of the particle

λ = wavelength of the laser

For a more detailed discussion see (1). Fields of the form described in equation (1) can be generated in the focus of four laser beams. The four beams are necessary for the production of a standing wave: each beam of Fig. 1 has its counterpart on the opposite side. Two of the four beams generate the field configuration in equation (1). The matching of the accelerating channel to the particle velocity is performed outside the focus by a birefringent crystal. By changing the thickness of the crystals the matching can be accordingly altered.

III. Possible laser systems for a laser accelerator

High power laser systems were especially developed for laser plasma interaction. At the same time as this aspect of physics became more and more important, new and better high power laser systems were developed. At the present moment new and more sophisticated systems are under investigation so that this section is likely to be outdated and the statements to have lost their validity within the next year. In spite of this, a short summary of the high power laser systems presently in operation shall be given at this point for the benefit of accelerator physicists so that they may become acquainted with the problems involved in selecting such a special type of laser. Three examples are described in the following. For a more detailed discussion see e.g. (2).
High power lasers consist of an oscillator laser and several amplifiers as sketched in Fig. 2. A relatively weak beam is generated in the oscillator consisting of a laser-active medium and two mirrors. The amplifiers are built in a similar manner as the oscillator. There is only one difference: they have no mirrors. The laser beam coming from the oscillator is amplified as it passes through the active medium. Since the high light power can destroy the entrance window of the amplifier, the diameter of the beam must become larger after each amplification step. A typical diameter of the beam of the high power laser is 10 to 20 cm.
The oldest high power laser type is the
a) Nd^{3+}glass laser. Glass is doped with Nd^{3+} ions. Glass is the host material, Nd is the lasering material. The lasering wave-length is 1.06 μ (near infrared). Since the laser active material is in the solid state,the laser must be pumped by flashlamps. Compared to electron beam pumped gas lasers this is a serious disadvantage, since the flashlamp emits a broad spectrum whilst the absorption of the laser material is very low. For this reason, the efficiency is about 0.1 %. The efficiency is defined as the relation between the power of the laser light

and the electrical power needed for initiating the laser process. But in spite of this disadvantage this laser type has the following advantages: the emitted laser radiation has a broad bandwidth resulting in pulses with extremely short pulse length. Thus, the total energy of the laser output can be concentrated in high field strength (3). On the other hand the average output power is very low: several minutes have to elapse after each shot to enable the glass to cool down as otherwise thermal stress will cause the glass to shatter. Hence, the Nd glass laser is presumably not the last word in high energy accelerators, but it might nevertheless be used as the first step in the development of a laser accelerator. High power glass laser systems are used in many laboratories see e.g. (4,5). The next possible type of laser for the purpose of acceleration is the

b) CO_2 -laser.

This type is likewise used in many laboratories. An electron excites an N_2 molecule and this molecule transfers its energy to the CO_2. $N_2^* + CO_2 \rightarrow N_2 + CO^*_2$. The excited state of CO_2 is quenched via the emission of a 10.6 μ photon. The pump source is an electron beam leading to an excellent efficiency of 3 to 5 % for nsec pulses and up to 14 % for longer pulses. Since the laser medium is in the gaseous state, the repetition rate can be very high. This laser system has one disadvantage, namely that the wavelength is so far away from the visible range that conventional optics cannot be used. Special IR optics with relatively high absorption losses damp the enthusiasm generated by the high efficiency. Nevertheless this type of laser seems to be better suited for use in a laser accelerator than the Nd-laser. The technology of this laser is well known and highly developed (see e.g. (6,7,8).

c) Iodine photodissociation laser

This laser type is also a gas laser, but is pumped by a flashlamp. CF_3I is excited by the flashlamp to CF_3I^* . This excited molecule dissociates into I $(^2P_{1/2})$ and CF_3. The laser transition is between $I(^2P_{1/2})$ and $I(^2P_{3/2})$. The atom recombines after the laser transition to CF_3I. The wavelength is 1.315 μ. This is an advantage over the CO_2-system. Its disadvantage is the low efficiency of about 0.5 %. At present there is only one high power iodine system which is in operation and that is in Garching near Munich (Asterix III) (9).

In addition to these three "old" high power lasers, several new lasers for high power use are under construction. The types with the greatest chance of success are at the moment the so-called excimer lasers. Excimers are molecules which only exist in the excited state. Thus, for instance, an Xe_2^+ molecule is produced and decays by emission of a photon to the ground state. These lasers are usually pumped by electron beams and therefore have a high efficiency. Their wavelength lies at the high-energy end of the visible spectrum or in the UV region. This laser in a high power version could perhaps combine the advantage of the CO_2 laser (high efficiency) with the advantage of the Nd-laser (wavelength near the visible region). A possible compromise might also be a CO-laser working at about 5μ.

Summarizing this short introduction to high power laser systems, it may be said that the ideal laser for the purpose of acceleration does not yet exist. The best approach seems to be the CO_2-laser. If this latter-mentioned kind is to be employed, then great efforts must be undertaken in order to diminish the absorption losses of the optical elements at this wavelength as will be mentioned later. Hence, one problem in laser accelerator technology will certainly be the further development of high power lasers, not however from the point of view of plasma physics, but from the point of view of accelerator technology.

IV. Elements of electron beam optics in a laser accelerator

In (1) the acceleration of a single electron travelling along the so-called channel is described. The electromagnetic field of the channel is not cylindrically symmetric, but is only symmetric in one plane (Fig. 1). This is a disadvantage of this proposal, since the movement of the particle can only be influenced in the plane in which the channel lies. However, the possibility cannot be entirely excluded that real cylindrical field configurations exist which are simply waiting to be found. This is a problem which will have to be dealt with at some time in the future.

In order to understand the behaviour of a real beam of particles, a computer programme was installed to study the movement of a particle at arbitrary initial conditions. The computer solves numerically the relativistic equation of motion inside the field configuration, of fig. 1. (10)

$$\dot{\vec{V}} = \frac{e}{m}\sqrt{1-\frac{v^2}{c^2}}\left(\vec{E}+\frac{1}{c}(\vec{v}\times\vec{H})-\frac{1}{c^2}\vec{v}(\vec{v}\,\vec{E})\right) \qquad (4)$$

E = electric field, c = velocity of light, e = charge of the electron

H = magnetic field, v = particle velocity, m = rest mass of the electron

In order to achieve an understanding of the problems involved in particle optics, it is necessary to investigate the trajectories and the energy gain of particles injected at different distances from the channel (fig. 3). The energy gain of these particles injected $\lambda/10$ and $2\lambda/10$ away from the centre of the channel is plotted in fig. 4 as a function of the phase. The starting energy is 100 MeV, the maximum possible energy gain is 10 MeV and the channel is tuned to 100 MeV, that is to the energy of the incoming electron.
There are two phases where the electron undergoes no acceleration. In the plot (fig. 4) these two phases are at 22 and 202 degrees, 180 degress apart from each other. The particle trajectories at 22 and 202 degrees are plotted in fig.s 5 and 6. At these very special points the channel acts as a lens focussing or defocussing without acceleration. At the bottom of fig. 4 the focussing and defocussing phases of the channel are marked by D and F. At maximum energy transfer,no transversal force acts on the particles. In the first approximation the energy transfer to the particles ΔE in dependence from the phase can be described for beams near the channel by the formula

$$\Delta E = \alpha E_{MAX.} \sin(\phi) \qquad (5)$$

wherein
E_{max} denotes the maximum energy transfer to the particle and α is a factor describing the influence of the distance of the trajectory from the channel. The point of maximum focussing is separated by 90 degrees from the point of maximum acceleration. It therefore follows that

$$f = \frac{f_{MIN.}}{\cos\phi} \qquad (6)$$

wherein
f_{min} describes the shortest focal length. Since the focussing force has the same magnitude as the accelerating force, the following equation yields for relativistic electrons

$$\lambda/4 / f_{min} = E_{max} / E \qquad (7)$$

E = energy of the particle

This formula is not strictly accurate, as the focussing force is not distributet linearly within the quarter wavelength. Near the channel it is stronger than it is at a distance of a quarter wavelength from the channel, since the focussing strength varies with a local sine function. Thus, if only particles near the channel are considered, formula 7 can be corrected as follows:

$$ {}^{\lambda/4}/f_{min} \approx \frac{\pi}{2} E_{max}/E \qquad (8) $$

or

$$ f_{min} \approx \frac{\lambda}{2\pi} \frac{E}{E_{max}} \qquad (9) $$

These formulae are only approximations, since non-linear effects are completely neglected. In the practical layout the non-linear effects seem to play a more important role and must be considered seriously.
Equation (9) demonstrates that both the focussing forces as well as the acceleration forces in a laser accelerator will be enormous. This can be demonstrated by a simple example in which the maximum energy transfer is 10 MeV as assumed in fig. 4. The laser is a CO_2 laser (10.6μ wavelength) and the electrons have an energy of 100 GeV. From this it follows that the relation E/E_{max} is 10^4, $\lambda/2\pi$ is about 1.7μ which means that the focal length will be about 1.7 cm. This makes optics in the low energy region very difficult, since the transversal forces are very strong and the particles are easily thrown out of the channel. Thus, at low particle energies it is necessary to decrease the energy transfer by decreasing the laser power in the first foci. This is one approach: another would be to produce more complicated particle trajectories. Fortunately this is possible. Fig. 7 demonstrates such particle trajectories where the particles are not allowed to escape. The injection energy is 10 MeV and the maximum energy transfer to the particles is likewise 10 MeV. The particles running outside the channel but parallel to it are first focussed, they then cross the channel and are again focussed. In this way the particles are trapped at lower energies. One must not forget that in the case of transversal stabilized trajectories, only 60 % or so of the maximum energy transfer can be used for acceleration, the rest must be used for the transversal focussing effect.
The next step towards understanding the beam behaviour is to examine the effect of mistuning the channel. The same conditions are used as in

fig. 4 to study this effect. The channel is mistuned to 1 MeV (fig.8), 700 (fig.9) and 500 keV (fig.10).
The curves clearly show the influence of mistuning. Two phase points, A and B, are indicated in fig.s 8,9 and 10 at which the energy gain is independent of the distance of the injected electrons from the centre of the channel. One point is on the focussing side of the plot and the other is on the defocussing side. The reason for the existence of these two points can be explained by the fact that particles having trajectories with an inclination relative to the direction of the channel see another distance of the local minima and maxima in the accelerating structure. For these particles the better matched accelerating structure compensates for the higher field strength in the centre of the channel. In order to demonstrate this phenomenon the energy gain of a convergent particle beam in a mistunned channel has been calculated. The results are illustrated in fig.s 11 and 12. It can be seen that the energy gain of all the particles is nearly identical. This proves the statement that mistuning of a channel can lead to a relatively large acceptance of the accelerator.

One point which has not been dealt with so far is the different energy transfer to particles at different phase position. In the earlier paper (1) the longitudinal stability for particles with velocities less than c was demonstrated. It was shown that particles entering one focus at a phase different from the mean phase can for instance gain more energy, but when they enter the next focus they gain less energy since the particle velocity and the channel tuning are no longer identical. For relativistic particles this remedy against longitudinal energy spread is no longer valid, since a change in energy does not lead to a change in velocity. Obviously another compensation mechanism will have to be found. One of such possible compensation mechanisms can be derived from fig.s 8 to 10. In order to transfer energy to the particle, a series of focussing and defocussing lenses will have to be set up. Such an optical construction will affect the particles in the following manner: in one channel the particles pass phase point A and in the consecutive channel phase point B. The differential quotient of the energy gain in points A and B has a different sign. Particles entering point A earlier accumulate less energy, but since the same particles also enter point B in the next channel earlier, they achieve a higher energy gain and so on. A series of accelerating structures of the type ABABAB..... guarantees not only transversal stability, but also longitudinal stability.

In order to estimate the magnitude of the longitudinal focussing effect, the following calculations can be made. Equation (5) describes the energy gain of a particle

$$E = E_{start} + E_{MAX} \sin\phi \qquad (10)$$

For a particle with a phase deviation $\Delta\phi$ which has passed through one focus there results:

$$E\,(\Delta\phi) = E_{start} + E_{MAX}\,(\sin\phi + \Delta\phi) \qquad (11)$$

After passing through the next focus of type B, the particle has a gain in energy of

$$E\,(\Delta\phi) = E_{start} + E_{MAX}\,(\sin\phi + \Delta\phi) + E_{MAX}\,(\sin\phi - \Delta\phi) \qquad (12)$$

and so on. After passing through n foci, the relation

$$\frac{\Delta E}{E} = \frac{E_{MAX} \cdot n \cdot \sin\phi\,(\cos\Delta\phi - 1)}{E_{start} + n\,E_{MAX}\sin\phi} \qquad (13)$$

is valid. Neglecting the starting energy of the particle the simple relation is obtained:

$$\frac{\Delta E}{E} = \cos\Delta\phi - 1 \qquad (14)$$

As is apparent, a phase deviation of for instance 20^{o} will lead to an energy spread of about 6 %.

Before going any further, it is important that two points should be discussed on a wider basis than was the case up to now. Firstly, discussion has been so far restricted to optics in one plane and this must now be extended to two-dimensional optics. Secondly, the ABAB ..... optics only makes sense at low energies. If the ABAB technique is extended to several 10 GeV, the linac's advantage of small synchrotron radiation losses is forfeited. In other words, answers will have to be found to these two problems before it can be said with absolute certainty that a series of foci can transport and accelerate a particle beam.

The first problem relating to two-dimensional optics is one which can be solved very quickly. A channel defined in let us say the x-y plane does not affect particles having a component of the momentum in the direction perpendicular to this x-y plane. In order to ensure transversal stability in both planes, ABAB ..... configurations must exist in both of these planes, that is AH, BH, AV, BV, AH, BH, ... or similar configurations. AH represents a channel working at the phase point A and lying in the horizontal plane and V stands for vertical. At this stage it is not possible to ascertain what kind of configuration can be used. This must be left to the time when a special laser has been developed and all other technical aspects have been clarified. Suffice it to say for the time being that it is now known that both the horizontal as well as the vertical direction can be stabilized.

The answer to the next question is somewhat more intricate. The acceptance on the low energy side of the laser accelerator must be high, since the beam current of the whole linac depends on the acceptnace of the first accelerating structure: from conventional linear accelerators it is well known that the emittance of the beam decreases with increasing energy: the so-called adiabatic damping mechanism. This mechanism can be explained very easily. The particle is injected with a given forward as well as a given transversal momentum and when accelerated its forward momentum increases whilst its transversal momentum is unaffected, As a result emittance of the beam in the relativistic range shrinks with increasing energy. To calculate the acceptance of the whole linac it is necessary to calculate the acceptance of the first channel. The figures depend on several parameters so that a simple formulae cannot be given. But numerical calculations demonstrate that an acceptance of roughly 2.10^{-3} mm × 10^{-2} rad for a CO_2 laser is expected using a sophisticated combination of accelerating and focussing channels for the first steps. Energy acceptance and phase acceptance were calculated in (1). As demonstrated in this paper the figures are complicated curves depending on the energy of the incoming electron and the tuning of the channel. The best values seem to be about 90 degree phase acceptance and about 5 % energy acceptance for 100 keV electrons. The focussing strength is calculated by equation (9), so that optical calculations for a given laser beam are similar to those for a conventional linac.

If a constant focussing strength (independent of the energy) is provided, the whole beam size would shrink from for instance 2 $\lambda/10$ at 10 MeV to 0.2 $\lambda/10$ at 100 MeV. This will be discussed later in more detail by calculating the luminosity of a colliding beam facility. Thus, the need for AH, BH ... optics vanishes, since the transversal dimensions of the beam can now be neglected. The working points effect electrons guns the brightness is about 10^9 A/cm^2/sterad cf. (12) for energies of 25 keV and higher. Translating this figure into particle numbers we arrive at $6.25 \cdot 10^{27}$ electrons/cm^2/sterad/sec. When making these calculations it should not be forgotten that there is not only a transversal beam limitation as demonstrated in equation (16), but also a longitudinal limitation due to the bunching factor discussed in the previous section. Assuming the bunching factor to be $5 \cdot 10^{-2}$, as revealed by equation (14), then the total number of particles to be transported per second through the laser linac will be:

$$N = 6.25 \cdot 10^{27} \cdot \pi^2\alpha^2 r_s^2 \cdot 5 \cdot 10^{-2}\, \tau_L \cdot V \qquad (17)$$

wherein τ_L is the total pulse of the accelerated electrons and V is the repetition rate of the laser. By combining formulae (15) and (17) the magnitude of the luminosity can be roughly estimated. At the moment we shall have to be content with such a rough approximation, as more exact figures can only be given after sufficient experimental work has been performed. The luminosity is calculated for a CO_2-laser with a wave-length of 10.6 μ and a radius r_s of $2 \cdot 10^{-4}$ cm. Let us assume that the radius of the smallest focus produced by a high energy laser linac (a linac exceeding 10 GeV) has a smaller area than the beam at the injector by a factor of 10^{-6}. This means a shrinking of the linear emittance due to adiabatic damping by a factor of 1000 which seems to be a reasonable figure. A shrinking factor of 1000 would seem to be realistic taking the following points into considerations: in the example following equation (9) a focal length of 1.7 cm for a 100 GeV beam was calculated. Injecting at 100 keV the minimum focal length can be 10 $\lambda \approx 0.1$ mm (CO_2 laser wavelength 10.6 μ). Thus within the linac the focal strength can be increased by a factor of about 200. The decrease of the acceptance will be 2.10^5. Combining both effects one would roughly achieve a shrinking factor of 1000. However, it should be remarked that to really prove this figure, more facts must be assembled regarding the effects of nonlinear focussing and the properties of the laser linac. To take said shrinking due to adiabatic damping into consideration, equation (15) can be reformulated by introducing a shrinking factor Q

$$L = 3.9 \cdot 10^{55}\, \pi^3\alpha^4 r_s^2\, \tau_{INT} \cdot 25 \cdot 10^{-4} \cdot \tau_L \cdot V/Q \qquad (18) .$$

will be somewhere in the region of high acceleration (see Fig. 4 points U and W). At high energies the beam optics can be denoted by the symbols

FH, FV, UH, WH, UV, WV, ..., DH, DV, ... ,

this system being similar to the beam guiding systems which have been known for a long time. Note that the change between U and W is necessary to achieve equal energy transfer to particles at different phase position In summing up this section it may be said that the arguments brought forward fairly conclusively demonstrate that it should be possible to guide particle beams through a laser accelerator. The optics must be different at low and high energies to achieve relatively high beam currents. At low energies the acceptance must be larger to accept as many particles as possible, whereas the acceptance can shrink at higher energies due to adiabatic damping. When the time comes for working out a definite concept for the beam optics, the properties of the laser and the other optical components will have to be into consideration.

V. Luminosity in a colliding laser beam arrangement

In the following section luminosity values will be estimated for a system as sketched in Fig. 13 in which two laser linacs can be seen firing against each other. The luminosity is defined (see (11)) in the following manner:

$$L = \frac{N_1 \cdot N_2}{A} \cdot f \qquad (15)$$

wherein N_1 and N_2 are the number of particles in each of the two colliding beams, and f describes how often per second the collision takes place and A is the transverse area in which the interaction takes place. Since the maximum beam current is limited by the injector in the first steps of the laser accelerator, as revealed in the foregoing section, electron sources with excellent beam properties must be employed, such as are used in modern electron microscopes. The beam current inside an area with a radius of r_s is given by the equation

$$I = B\pi^2\alpha^2 r_s^2 \qquad (16)$$

wherein α is the angle of divergence of the electron beam accepted by the laser accelerator. This figure is limited by the geometry of the focussing elements of the injector. B represents the so-called brightness of the source. For field-

In equation (18) the real interaction time of the two beams has been introduced: τ_{INT} signifies the time at which interaction actually takes place, τ_L the total pulse length of the electron beam and V the repetition frequency of the laser. Working on the basis of an interaction region of 1 cm, (the interaction region can be much more longer in reality) beam pulse length τ_L of 200 nsec, a laser repetition rate of 1 kHz and $\alpha = 10^{-2}$, which from numerical beam trajectory calculations would seem to be a good approach, a luminosity is obtained of about 10^{31} per cm^2 and sec., which compares favourably with luminosities of storage rings presently in operation and those planned for the future.

This is a result of decisive importance showing that the luminosities of laser colliding beam arrangements are not too far removed from those of conventional colliding beam arrangements.

In the preceding sections it was demonstrated that it is possible to accelerate particle beams in a laser accelerator whilst simultaneously generating luminosity of a satisfactory level. In the first part of the concluding section the attempt will be made to give answers to the questions of whether laser systems fulfilling the conditions set forth in the aforegoing are far removed from reality or whether a high energy accelerator with presently available laser systems is a proposition worthwhile considering. In the final part of this section some figures are given as a guide to the cost of such a project.

VI. Physical layout of a laser accelerator

In the first section to this paper it was stated that the ideal laser for a laser accelerator is not yet in existence. In actual fact only one single laser system, the CO_2 laser, has revealed itself to date to be highly reliable and efficient. Unfortunately this system has the drawback that it works at a wavelength of 10.6 μ. From a beam optical point of view this is an advantage since the beam current in the first stages can be very high. From a laser-beam optical point of view, however, this a disavantage since the laser beam can only be accelerated to high energies by passing the particle through a channel several times which means that the optical beam has to be reflected and refocussed for the next channel (Fig. 14). High efficiency can only be achieved if the reflectivity of the reflecting elements is extremely high. The reflectivity of all known optical elements for a wavelength of 10.6 μ is worse than for the visible range (13). Thus, the advantage of the CO_2 laser is lost to a great extent in view of the present-day state of the art in coating technology. This problem may perhaps be overcome by performing experiments in one of the following directions. The suggestions are

a) to increase the reflectivity of the 10.6μ coatings, which would involve a very considerable amount of experimental and theoretical work;

b) to conceive and develop new laser systems in the visible or near visible range (the problems entailed herein will probably be easier to solve than those which are likely to be encountered in developing coating techniques);

c) to reduce the number of necessary acceleration channels by using extremely high power laser systems.

Some kind of compromise will have to be found between these three extremes. Even at the present stage of development it is not possible to say in which direction the compromise will tend and only after an answer has been found to these questions can we make an exact decision as the to the cost and efficiency of a laser colliding beam arrangement. Nevertheless an outline of a preliminary nature can be drawn up for the physical layout and an estimation made of the cost of such a project. We will assume for the present purpose that we have solved the problems of reflectivity and/or developed a more suitable laser system and we have four beams each having a pulse power of 1 GW. The maximum energy gain of one channel will be 2.46 MeV/focus. A 10 GeV laser accelerator,for example, will require at least 4072 foci. As this will exceed the capacity of four beams, we will employ 8 beams, four of which are intended for the horizontal plane and four for the vertical plane. With reflectivities in the range of 99.9 % and using curved mirrors instead of lenses, about 6000 foci can be produced. By reducing the beam power to 1 GW, the mirror will not be larger than 1 cm^2, since the destruction limit of optical elements is somewhere between 1 to 10 GW/cm^2 depending on pulse length and resistivity of the reflecting material (14), (15). The limitation to 1 GW beams means that simple optical elements can be used. From the catalogue prices of high laser power systems it can be seen that the cost of such an accelerator will be in the region of 1 to 2 MDM per 10 GeV. This estimation is very rough since the high precision optical components specified for a final technical layout could cost more than was originally estimated. On the other hand the prises for high power lasers can decrease dramatically when a greater number of them are produced. Nevertheless, although all these considerations are of preliminary nature some idea has been given of the cost of a laser linac as compared with conventional machines.

Thus, a 100 GeV colliding beam arrangement having reasonable luminosity will not be much in excess of 40 MDM, since the cost of a building to house such equipment can be more or less neglected. A 100 GeV laser colliding beam arrangement can be installed in a hall measuring approximately 100 x 25 m which is the usual size of a high energy laboratory. Finally, it is interesting to note that a doubling in energy of a laser colliding beam arrangement merely involves a doubling in price. This is an enormous advantage over conventional storage rings.

VII. Summary

Laser colliding beam arrangements able to yield good luminosity at superhigh energies and at relatively low cost as compared with that of a conventional storage ring may very well be a new and cheaper instrument in high energy physics. At the moment, however, so little experimental knowledge has been collected on the components of laser accelerators that a final layout must be left to the future. It will be necessary to conduct the following experimental work:

a) a more detailed experimental investigation of the accelerating channels;

b) examination of the possibility of generating channels with cylindrical symmetry;

c) an investigation of high energy laser foci and wave front emerging from high power lasers;

d) a detailed study of laser systems other than the CO_2-lasers;

e) an experimental study of materials with extremely high reflectivity;

f) beam optical studies as a consequence of the preceding points.

With this paper the principle direction has been set for future developments in accelerator technology. Since laser accelerators have a good chance of being successful, it is important that detailed work now be commenced in this field.

VII. Literature

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VIII. List of Figures

Fig. 11 Trajectories of a convergent electron beam focussed by a laser lens to the centre of the channel.

Fig. 12 Energy gain of the particle trajectories depicted in Fig. 11. The energy gain for all trajectories is nearly identical. The injection energy is 10 MeV, the maximum energy gain is 10 MeV and the channel is tuned to 700 keV.

Fig. 13 Colliding beam arrangement with two laser linacs firing against each other.

Fig. 14 Optical system for the production of a series of foci for a laser linac. In Fig. 14a a simple arrangement is sketched derived directly from Fig. 1. Fig. 14b shows a more sophisticated system using curved mirrors. One mirror is slightly tilted towards to the opposite mirror.