ACCELERATION OF CHARGED PARTICLES BY COHERENT LIGHT. A SURVEY ON PROPOSED METHODS AND APPLICATIONS

R. Rossmanith

Abstract Since about 12 years acceleration of charged particles by coherent light is discussed. This paper tries to give a short summary of the proposed accelerating technologies and of the possible applications: generation of coherent light up to the X-ray range, high energy physics applications and short-time physics in the femtosecond range.

I. Introduction

In the last few years lasers with extremely high output power were developed. With so called Q-switch techniques the total energy of a laser was concentrated to within a few nanoseconds. Output powers of several 10 GW were achieved. Very soon another technology was developed: the locking of longitudinal modes by an intracavity passive modulator (1). The total energy of the laser is concentrated to within a few picoseconds, with external compression to even less than one picosecond (2). The power of one pulse is several GW. For nuclear fusion experiments (3) lasers with output powers of several 100 GW and efficiences of about 10 % are under construction. This figures are higher by several orders of magnitude than the power achieved in the microwave region used for accelerating charged particles. Therefore accelerating particles by coherent light becomes more and more interesting in high energy physics.

In principle, two different kinds of RF-accelerators exist: the linear accelerator (linac) and the circular accelerator (synchrotron). In a linear accelerator the electrons are emitted by a glow-cathode and accelerated by a TM travelling or standing wave. The largest existing linear accelerator SLAC, Calif. has a length of about 3 km and a maximum energy of 21 GeV (4). This correspondens to an average energy transfer of 7 MeV per meter. The maximum average energy transfer is limited by the transmitter power and the limited Q-value of the cavities. In order to

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achieve higher energy transfer values superconducting cavities were proposed (5). But up to that time the higher Q-value did not effect higher energy transfer since the particle beams detunes the cavity. The superconducting linac at Stanford University even has only one half of the energy transfer of the SLAC linac.

In a synchrotron the particle beam is forced by bending magnets into a circular orbit. Each time the particle beam enters the cavity it is accelerated. This technique saves money and area for particles with high masses e.g. protons. For electrons and positrons most of the RF power is dissipated by synchrotron radiation in the bending magnets. Therefore circular accelerators for electrons in the 20 and 30 GeV region would have circumferences between 2 and 3 km. Otherwise the costs for RF power are too high. Concluding our review on electron linacs and synchrotrons, an upper economic limit will be about 30 GeV, though physics at higher energies still is interested.

Using for acceleration coherent light instead of bounded RF-waves the energy transfer at output power densities of 100 GW/cm^2 could be 6.14 MeV/cm. This energy transfer would reduce the length of SLAC by about a factor of 100 (34 meters instead of 3 km), or, rather, the end energy of a 3 km laser linac will be 2.1 TeV (2100 GeV) instead of 21 GeV. Therefore accelerating electrons by coherent light let us hope that the magic economical limit of 30 GeV will vanish. This is also valid for beam-beam interaction devices.

But there are a lot of technological problems completely unsolved up to now. The phase velocity of the light beam must be matched to the velocity of the laser beam. This problem is solved in RF technology by using special kinds of waveguides. Since phase velocities less than the velocity of light are only possible in bounded systems, the dimensions of the light accelerator are not larger than the wavelength of the light. This seems to be a big technological problem. The electron beam accelerated by coherent light waves has different physical properties than a beam accelerated by RF-frequencies. Since velocity matching is only possible within a small part of the laser wavelength the electron beam is bunched with a bunch length of one femtosecond (10^{-15} sec) or even less. This will be a step towards femtosecond physics, similar to the step to picosecond physics made by mode locked lasers (1).

The electron beam has transverse dimensions in the order of one wavelength due to phase matching. This high particle concentration makes it possible to produce coherent photons on the surface of an optical grating (Smith-Purcell effect (6)). The frequency of the coherent photons emitted by electrons near a grating depends on the energy of the electrons. With highly relativistic electrons (100 MeV or more) coherent photons up to the X-ray region can be produced. The emitted power depends on the proximity of the electrons to the grating. With a narrow beam a coherent X-ray source of sufficient power can be produced. This is of general interest, since the production of coherent X-rays by stimulated emission seems to be very difficult.

II. Acceleration of particles with velocities less than c

The first proposals were published 1962 by Shimoda (7) and A. Lohmann (8). Shimoda's idea was to construct a cavity similar to the well known RF-cavities but using light instead of RF. The walls of the cavity are mirrors. But Shimoda's proposal could not completely solve the problem of phase matching. Lohmann pointed out that phase matching can be done by evanescent waves. The formula describing the change in velocity vs. energy is given by Einstein's formula (fig.1):

$$v = c \sqrt{1 - \frac{1}{\left(\frac{E_{kin}}{m_o c^2} + 1\right)^2}} \qquad (1)$$

v ... velocity of the electron

c ... velocity of light

E_{kin}. kinetic energy of the particle

m_o .. rest mass of the particle

Evanescent waves occur at the boundary of two different media, e.g. total reflection between glass and vacuum. A wave travelling in z-direction with phase velocity v_p and an amplitude depending on x is described by the equation

$$U(x,z,t) = f(x)\ \exp\ (-i\omega(t-z/v_p)) \qquad (2)$$

This equation must be a solution of the wave equation

$$\nabla^2 U - (n/c)^2 \frac{\partial^2 U}{\partial t^2} = 0 \qquad (3)$$

The combination of (2) and (3) yields

$$\frac{d^2 f(x)}{dx^2} + f(x)\ (\frac{n\omega}{c})^2 \{ 1 - (c/nv_p)^2 \} = 0 \qquad (4)$$

A solution of (4) is

$$f(x) = Be^{\alpha x}$$

$$\alpha = (\frac{n\omega}{c})\ \sqrt{-A} \qquad (5)$$

$$A = 1 - (\frac{c}{v_p n})^2$$

For $A < 0$ equation (5) becomes

$$U(x,z,t) = \exp\ (-\alpha x)\ \exp\ (-i\omega(t-z/v_p)) \qquad (6)$$

$$\alpha \ldots \text{real}$$

Solutions of (6) exist only in the proximity of $x = 0$. Therefore this waveform is called evanescent waves. The phase velocity of an evanescent wave is less than c (5). The generation of an evanescent wave is demonstrated in fig.2. The phase difference between two incoming rays is 360 degree or one wave length. The incoming and reflected wave must be continued in the vacuum due to Maxwell equation with a wave length

$$\lambda' = \frac{\lambda_o}{n\ \sin\beta} \qquad n > 1 \qquad (7)$$

At total internal reflection

$$n\ \sin\beta > 1 \qquad (8)$$

The wavelength is smaller than the vacuum wavelength. Therefore (8) fulfills the conditions of an evanescent wave.

The electric evanescent wave is accompanied by a magnetic field. The magnetic field moves the particle away from the glass-vacuum boundary (fig.3). This effect can be compensated by using two parallel plates of glass. The electric fields add and the magnetic field subtract (fig.4).

Matching between electrons and light waves occurs, when the phase velocity is equal to the electron velocity. From equations (1) and (7) a condition for the reflecting angle can be derived

$$\beta(z) = \arcsin \frac{1}{n\sqrt{1-\frac{1}{\left(\frac{E_{kin}}{m_o c^2}+1\right)^2}}} \qquad (9)$$

In fig.5 this function is drawn for glass ($n = 1.5$). The maximum possible value for β is 90 degree. The lowest possible energy for phase matching is therefore 171 keV. The particles must be accelerated by one or two preaccelerator stages to that energy.

In an evanescent wave preaccelerator one has to use a medium with a higher refractive index: e.g. $Ba_2NaNb_5O_{15}$. (refractive index 2.263 at 1.06 μ). The minimum acceptable energy is 60 keV. The acceleration from zero to 60 keV can be done by an electrostatic preaccelerator.

Since the velocity of the electrons change nonlinearly with energy, the phase matching is very difficult. One possibility of matching is demonstrated in fig.7. The incoming laser beam is focused by a nonlinear lens. The curvature is computed for a refractive index of 2.263. The total length of the preaccelerator depends on the total energy of the laser beam. For power densities of 2 MW/cm^2 the total length of the preaccelerator is 6.2 cm (energy ramping from 60 to 200 keV). For 10 MW/cm^2 the total length is about 2.8 cm.

After passing the first stage the electrons are accelerated by a glass evanescent wave accelerator up to 10 MeV. At 10 GW/cm^2 the total length of this stage is 5.2 cm. All three stages together (electrostatic preaccelerator, optical preaccelerator and final optical accelerator) do not exceed a length of 20 cm. The total equipment is sketched in fig.8.

The maximum current is limited by the space charge effect at low energies. A rough estimation can be made by assuming that one electron is deflected by the total charge of the other electrons. The deflecting force is compensated by a small part due to the magnetic forces acting between the particles. The total force acting on one particle is

$$F_{total} = \frac{eq}{r^2} - \frac{eqv^2}{c^2r^2} \qquad (10)$$

e ... charge of one electron

q ... charge of the electron bunch

r ... distance between deflecting charge and electron

This force must be compensated by the magnetic field H of the laser beam

$$F_{magn} = \frac{1}{c}\, e\, vH \qquad (11)$$

Equations (10) and (11) give a formula for the maximum current per bunch:

$$q_{max} = \frac{r^2 \frac{v}{c} H}{1 - v^2/c^2} \qquad (12)$$

In the case of preaccelerating with 2 MW/cm^2 and an injection energy of 60 keV the maximum charge per bunch is $2.1 \cdot 10^3$ e su or $2.5 \cdot 10^{12}$ electrons. The accelerated average current is 1.2 mA even when the laser is flashed each second for only one nanosecond. Flashing the laser with 50 Hz an average current of 60 mA can be achieved. This is an optimistic estimation, since other limitations e.g. intra beam scattering are neglected. But this demonstrates another advantage of the laser accelerator: acceleration and focussing fields are produced by the same wave. The focussing fields are much stronger than in conventional accelerators. Therefore particle densities are higher too.

The exact calculation of the bunch length is very difficult. The generation of small bunches due to acceleration will be discussed by means of an oversimplified model. Assuming that all particles are entering the accelerator at the same time but with different velocities, the energy gain of the particles after one wavelength is given by

$$\Delta E = eU_o \int_0^{\lambda} e^{i(\omega t - kz)} dz = eU_o \frac{\sin\left(\left(\frac{\omega}{v_{part}} - K\right)\lambda\right)}{\left(\frac{\omega}{v_{part}} - K\right)\lambda} \tag{13}$$

U_o ... strength of the electric field

λ ... wavelength of the accelerating field

$v_{part} = \frac{z}{t}$ velocity of the particle (assumed to be constant within one wavelength)

The maximum energy gain is given to particles within the area

$$v_p \approx \frac{2}{3} v_o \tag{14}$$

v_o ... phase velocity of the laser beam

After travelling through n wavelengths this area becomes smaller

$$v_p \approx \frac{v_o}{1 + \frac{1}{2n}} \tag{15}$$

Particles being out of phase at the injection will disappear completely. But the real bunch length will be longer than the computed one due to residual gas and intra-beam scattering and beam oscillations. Beam oscillations are caused by the electromagnetic forces of the bunch and the magnetic laser field similar to the well known betatron oscillations in a synchrotron. The oscillations are nonlinear, since the electromagnetic forces change rapidly with energy and the focussing force depends nonlinearly on the amplitude of the oscillation. Concluding these remarks, a bunchlength of less than one tenth of the accelerating wave length is expected.

III. Possible applications of the 10 MeV accelerator

As nearly all nuclear physics experiments up to 10 MeV are already done by conventional accelerators, experiments only possible with a laser accelerator can be done in two other areas: generation of coherent light in the VUV and X-ray regions, and short-time physics.

a) Generation of higher harmonics

Toraldo di Francia ([9], [10]) has demonstrated, that the electromagnetic field of a charged particle can be described by a set of evanescent waves: the velocity of the particle is less than c. Therefore the phase velocity of the electromagnetic field is less than c too. In chapter II the generation of evanescent waves by plane waves at the boundary of two media has been explained. In the same manner evanescent waves in vacuum can produce plane waves in a medium with $n > 1$, as an evanescent wave in vacuum yields (equation 5)

$$A = 1 - \left(\frac{c}{v_p}\right)^2 < 0 \qquad (16)$$

The evanescent wave is transformed into a plane wave, when

$$A' = 1 - \left(\frac{c}{nv_p}\right)^2 > 0 \qquad (17)$$

Following Toraldo di Francia, effects transforming evanescent waves from a moving particle into plane waves are called "Cerenkovian effects". Two different Cerenkovian effects are known: the first one is the simple inversion of the accelerator drawn in fig.2. The particle beam moves along the surface of a medium with a refractive index larger than 1. The plane wave in the medium travels at an angle ϕ to the direction on the electron:

$$\cos\phi = \frac{c}{v_p n} \qquad (18)$$

This is the well known formula describing Cerenkov radiation.

The bunches of the electron beam have a bunch length of one tenth or even less of the accelerating wave length due to phase matching condition. Assuming that this pulse train passes along a surface, two different kinds of Cerenkovian radiation are produced: the first one is produced by each bunch indepently and gives rise to a radiation described by equation (18). But the bunches have a defined repetition rate. The repetition frequency and the haromics of the repetition frequency produce evanescent waves too. With the laser linac, frequency multiplication can be done similar to the well known multiplication in crystals (11). But in crystals the frequency multiplication does not exceed the third or fourth harmonic. Using sharply limited bunches the electron beam will transport harmonics up to an order of 10. Coherent light can be produced up to that region, where the Cerenkov medium begins to absorb, or where the refractive index is unit. An upper limit is given at the lower end of the vacuum ultraviolet range. Going to higher frequencies another Cerenkovian effect can be used: the Smith-Purcell effect (6). A plane wave falling onto a grating is diffracted by the angle β. The wavelength of the diffracted wave in the direction parallel to the grating is

$$\lambda_{\parallel} = \frac{\lambda_o}{\sin\beta} \tag{19}$$

From diffraction theory β is defined by

$$\sin\beta = \frac{m\lambda_o}{s} \tag{20}$$

s ... spacing of the grating
m ... order of diffraction

Combining equations (19) and (20) yields

$$\lambda_{\parallel} = \frac{s}{m} \tag{21}$$

For large m $\lambda_{\parallel}$ fulfills the conditions of an evanescent wave. In the inverted process, electrons passing close to the grating will produce plane waves. In the case of a reflection grating the emitted wavelength is (9)

$$\lambda = \frac{s}{m} \left(\frac{1}{\beta} - \cos\psi \right) \tag{22}$$

where ψ is the angle between the electron path and the direction of the emitted plane wave.

Evanescent waves produced by a grating were used to test experimentally the acceleration of electrons by laser radiation (12). This experiment failed, perhaps due to imperfect phase matching (13).

The brightness of the emitted radiation (brightness = power per solid angle and per unit emission surface) is

$$B = 2\pi I \; eF \frac{m^2}{s^2} \frac{\beta^3 \sin\psi}{(1-\beta\cos\psi)^3} \exp\left(-4\pi m \frac{a}{s} \frac{\sqrt{1-\beta^2}}{1-\beta\cos\psi}\right) \tag{23}$$

I ... electron surface current

F ... number describing the efficiency of the grating

a ... distance between electrons and grating

A reasonable amount of light is only emitted when both a and the beam diameter are small. But this is exactly the advantage of the laser linac.

Frequency up-conversion can be done in a similar way as described in the former case. But reflection gratings can be used up to the soft X-ray region (about 5 AE). Up to the VUV range bunch repetition rate coherent radiation can be produced. Beyond this limit coherent X-rays are emitted by electrons having higher energies than 10 MeV (100 MeV or even higher) due to formula (22). The method of accelerating electrons to energies higher than 10 MeV will be described in the last chapter.

So the laser linac will be an excellent instrument to study coherent emission of electromagnetic radiation up to frequencies where the probability of stimulated emission is very small compared with spontaneous emission.

b) Applications in short time physics

The laser linac is a source of particle bunches with a bunchlength between several 100 attoseconds (10^{-18} sec) and several femtoseconds (10^{-15}) with a constant repetition rate. With mode locked lasers picosecond laser pulses were produced and molecular relaxation processes were studied. With this new source similar experiments with electronic relaxation processes can be done.

IV. Acceleration of highly relativistic electrons

Independently from each other two similar proposals for accelerating electrons of energies higher than 10 MeV have been published (14), (15).

In both proposals electric and magnetic waves of the laser beam are separated by the generation of standing waves. In fig. 9 the field pattern of a standing wave is drawn. In this case the electron is accelerated by one half wave and de-accelerated by the second one. In order to achieve acceleration the amplitude of the second half wave must be reduced. In conventional accelerators this is done by drift tubes surrounding the particle trajectory. At light frequencies the drift tubes must be produced by optical methods, for instance by a spatial modulation of the light wave in the direction of the particle trajectory. This can be done by interference gratings or holograms. Csonka (15) calls this special kind of hologram "template". It can easily be demonstrated that such a space modulation is possible (14). The field distribution of a parallel beam diffracted by an obstacle is given by the diffraction integral (Fraunhofer approximation):

$$U(\alpha) = \text{const.} \int_{-\infty}^{+\infty} f(\xi) e^{-ik\alpha\xi} d\xi \tag{24}$$

k ... wave vector

α ... angle of the diffracted beam

$U(\alpha)$ ... field strength in the direction of α

$f(\xi)$ ... tramsmission function of the obstacle

For a grating sketched in fig.10 formula (24) becomes

$$U(\alpha) = \sum_{m=-n}^{+h} \int_{md-s/z}^{md+s/z} e^{-ik\alpha\xi} d\xi =$$

$$= \frac{2\sin(k\alpha s/z)}{K\alpha} \cdot (1 + \sum_{n} \cos(ndK\alpha)) \tag{25}$$

Formula (25) represents a series of lines modulated by a sin x/x function. The width of the lines is

$$\Delta\alpha \approx \frac{\lambda}{nd} \tag{26}$$

For high n an accelerating field demanded above can be produced. In practice not a plane grating but a cylindrical grating surrounding the beam trajectory will be used.

The magnetic field will alternately focus and defocus the particle beam: the laser accelerator works as a conventional alternating gradient synchrotron (AGS).

The applications of the highly relativistic accelerator will lie in high energy physics. The physicist are especially interested in colliding beam facilities. At present storage rings are being used in colliding beam experiments. Two particle beams circle in opposite direction and collide in two or more points. Storage rings up to 5 GeV are already existing or under construction. The next generation of storage rings with maximum energies between 20 and 30 GeV and a circumference between 2 and 3 km are in discussion. Instead of conventional storage rings two laser linacs could be used. The total length of a laser colliding beam facility working at 30 GeV does not exceed a length of several ten meters, depending on the power density of the laser. A characteristic figure of a colliding beam facility is its luminosity: the number of particle interactions at unit cross section: (16)

$$L = \frac{N_1 N_2}{A} T \tag{25}$$

L ... Luminosity

N_1, N_2 ... number of particles in one bunch of the colliding beams

A ... square of the cross section of the bunch in the interaction region

T ... number of bunches per unit time

It was demonstrated in chapter I that each bunch can trasport $2.5 \cdot 10^{12}$ particles. The cross section is assumed to be 1 μ. With a laser colliding-beam facility flashed each second for one nanosecond the luminosity will be $2 \cdot 10^{38}/\mathrm{cm}^2 \cdot \mathrm{sec}$. Conventional storage rings have luminosities between 10^{28} and $10^{31}/\mathrm{cm}^2 \cdot \mathrm{sec}$. And there is another advantage: the maximum luminosity is limited in conventional storage rings by instabilities due to the long lifetime (several hours) in the ring. With a laser linac such instabilities cannot occur.

V. Conclusion

The possibility of the acceleration of charged particles by coherent light is discussed. The combination of electric acceleration and magnetic focussing fields produced by the same light source generates particles beams with high densities and small beam dimensions. This outstanding property makes it possible to study the production of coherent light at frequencies up to the X-ray region. On the other hand the high power density of the laser field would shorten the accelerator length by a factor of 100 or even more compared with conventional accelerators. With less money higher energies can be achieved. Two laser accelerators can be combined to a colliding beam facility with luminosities several orders of magnitude higher than in conventional storage rings.

VI. Literature

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FIGURE CAPTIONS

Fig.1: v/c vs.energy for electrons

Fig.2: Creation of evanescent waves at the boundary of two media

Fig.3: Electric and magnetic fields of an evanescent waves

Fig.4: Acceleration of particles with two evanescent waves

Fig.5: Angle of diffraction β vs. electron energy. Medium glass ($n = 1.5$). Minimum acceptance energy 171 keV.

Fig.6: Angle of diffraction βvs. electron energy. $n = 2.263$. Minimum acceptance energy 60 keV

Fig.7: Nonlinear lens for matching electron and laser phase velocity for energies between 60 and 200 keV ($n=2.263$)

Fig.8: Schematic drawing of a laser accelerator with an end energy of 10 MeV. Total length $\approx$ 20 cm

Fig.9: Field distribution of a plan standing wave

Fig.10: Diffraction grating

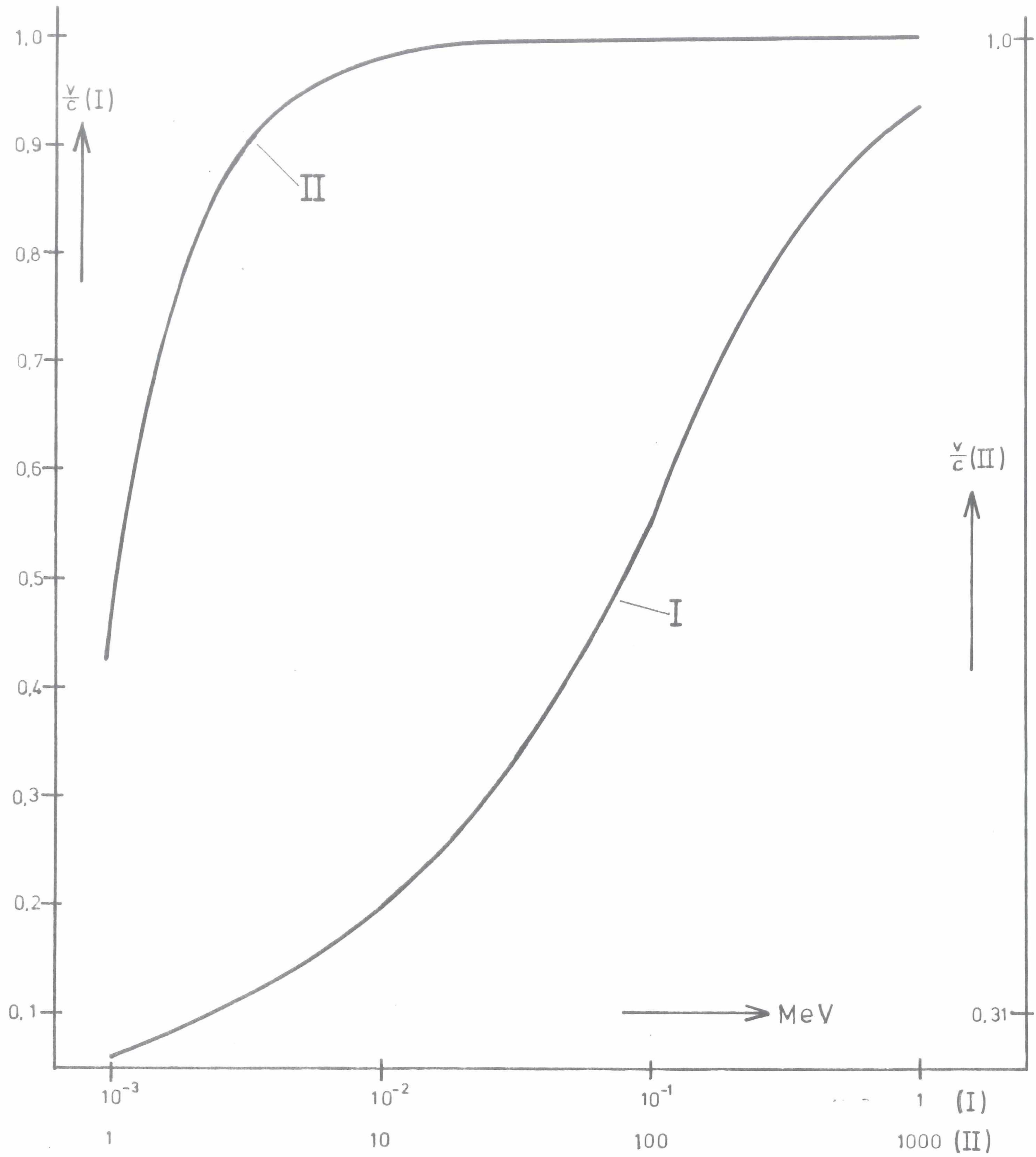

1,0
0,9
0,8
0,7
0,6
0,5
0,4
0,3
0,2
0,1
v/c (I)
v/c (II)
II
I
MeV
1,0
0,31
10^-3
10^-2
10^-1
1
(I)
1
10
100
1000
(II)

FIG. 1

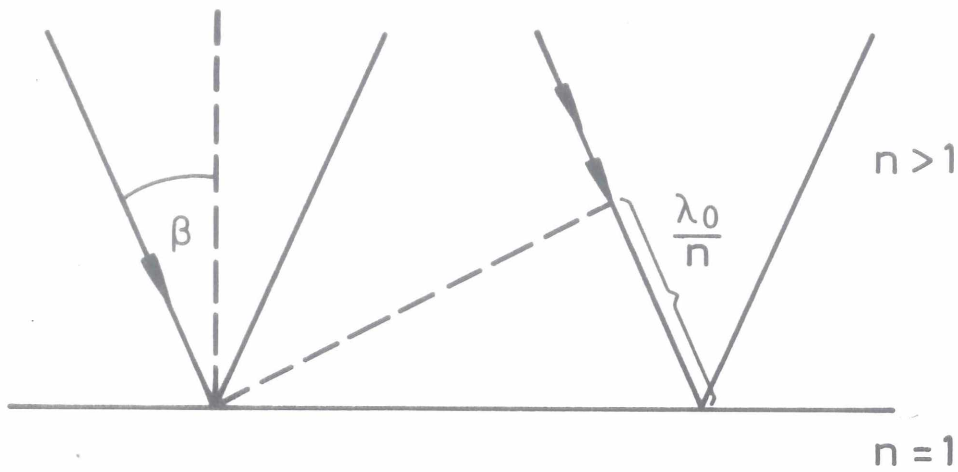


Fig. 2

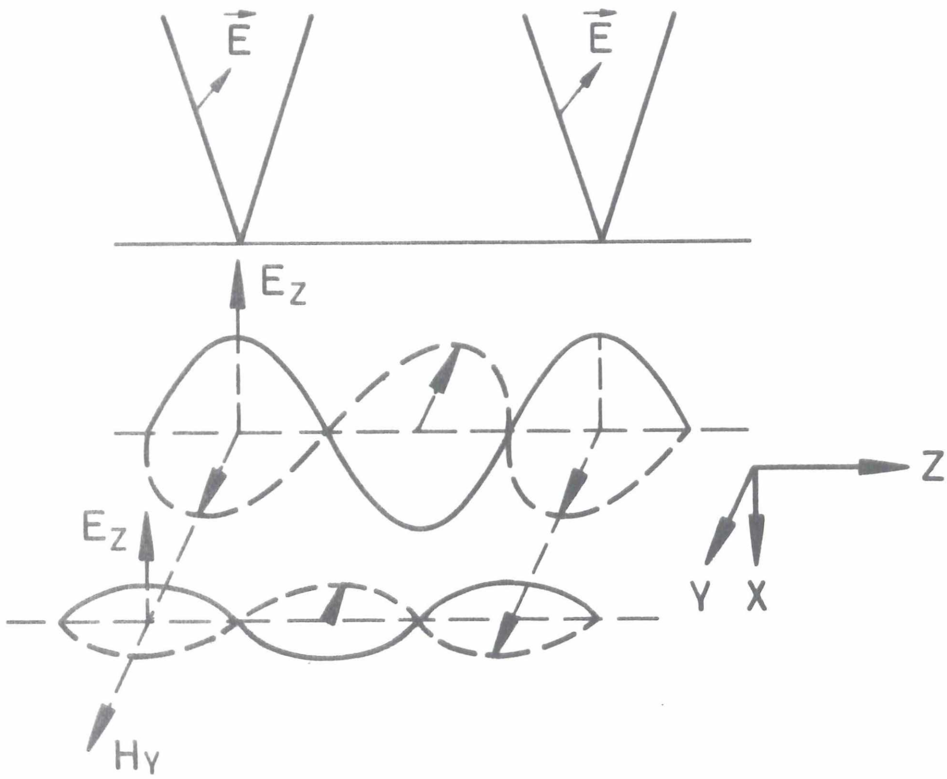
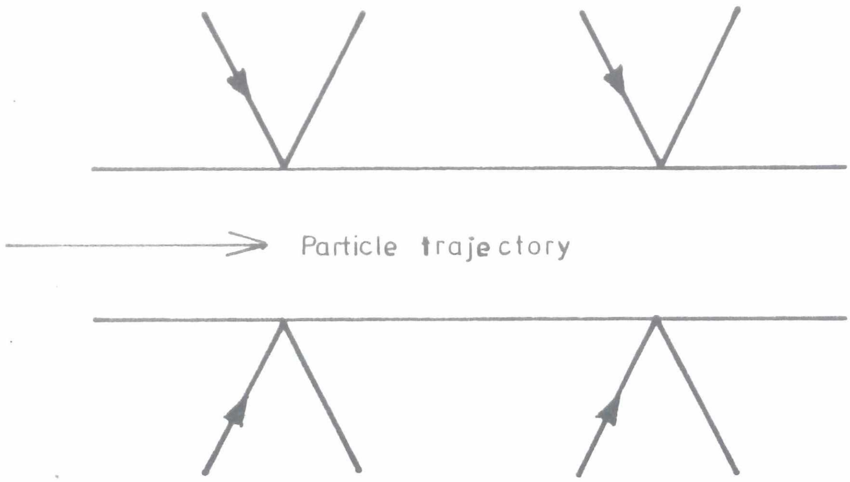
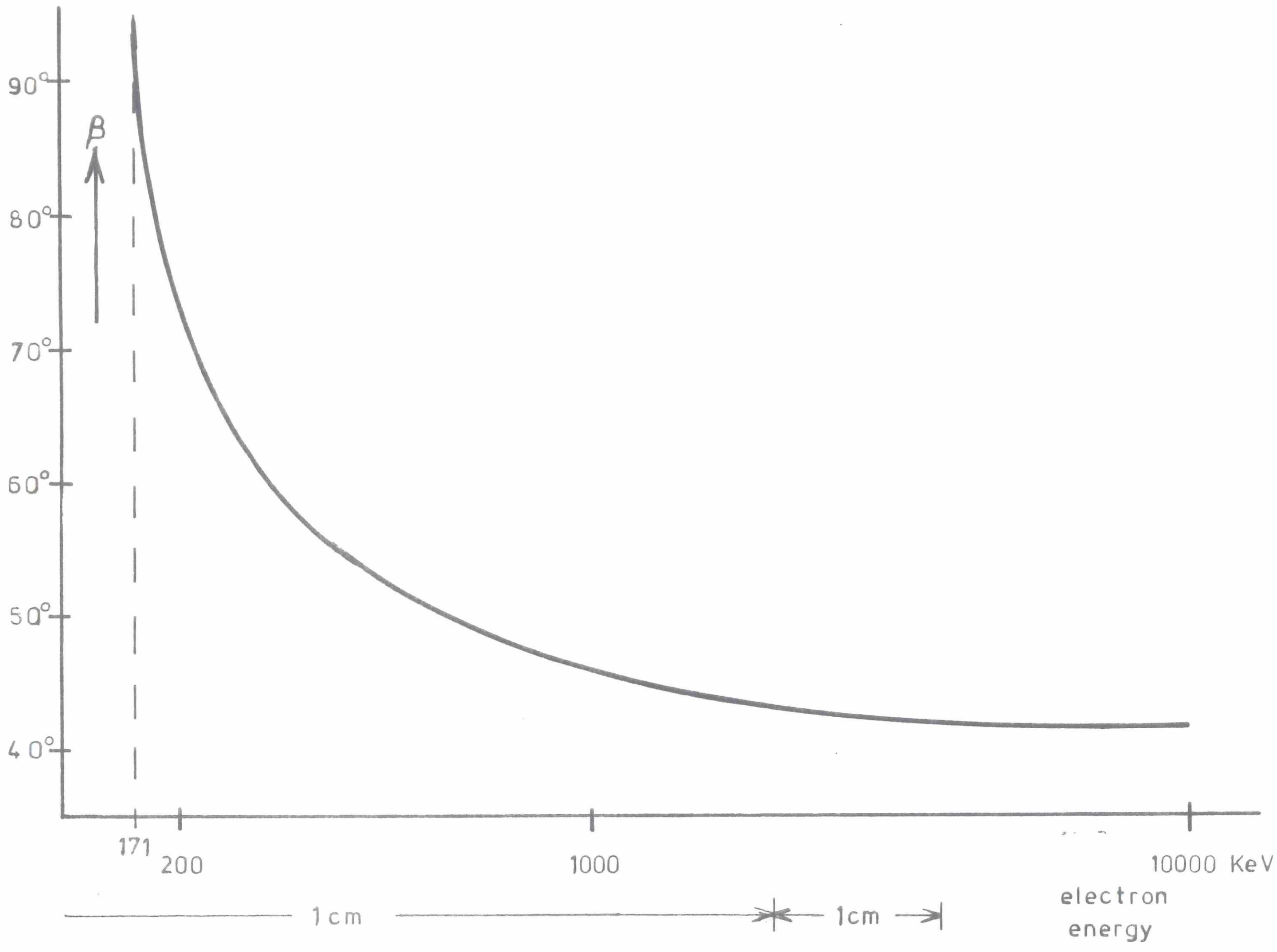


Fig. 3



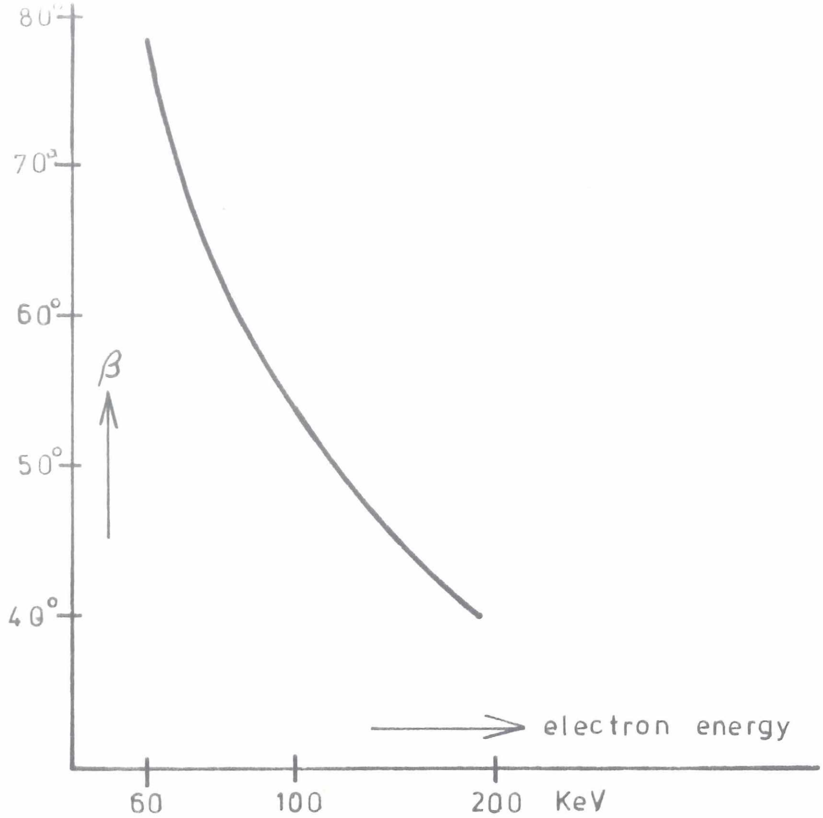
Particle trajectory

FIG. 4



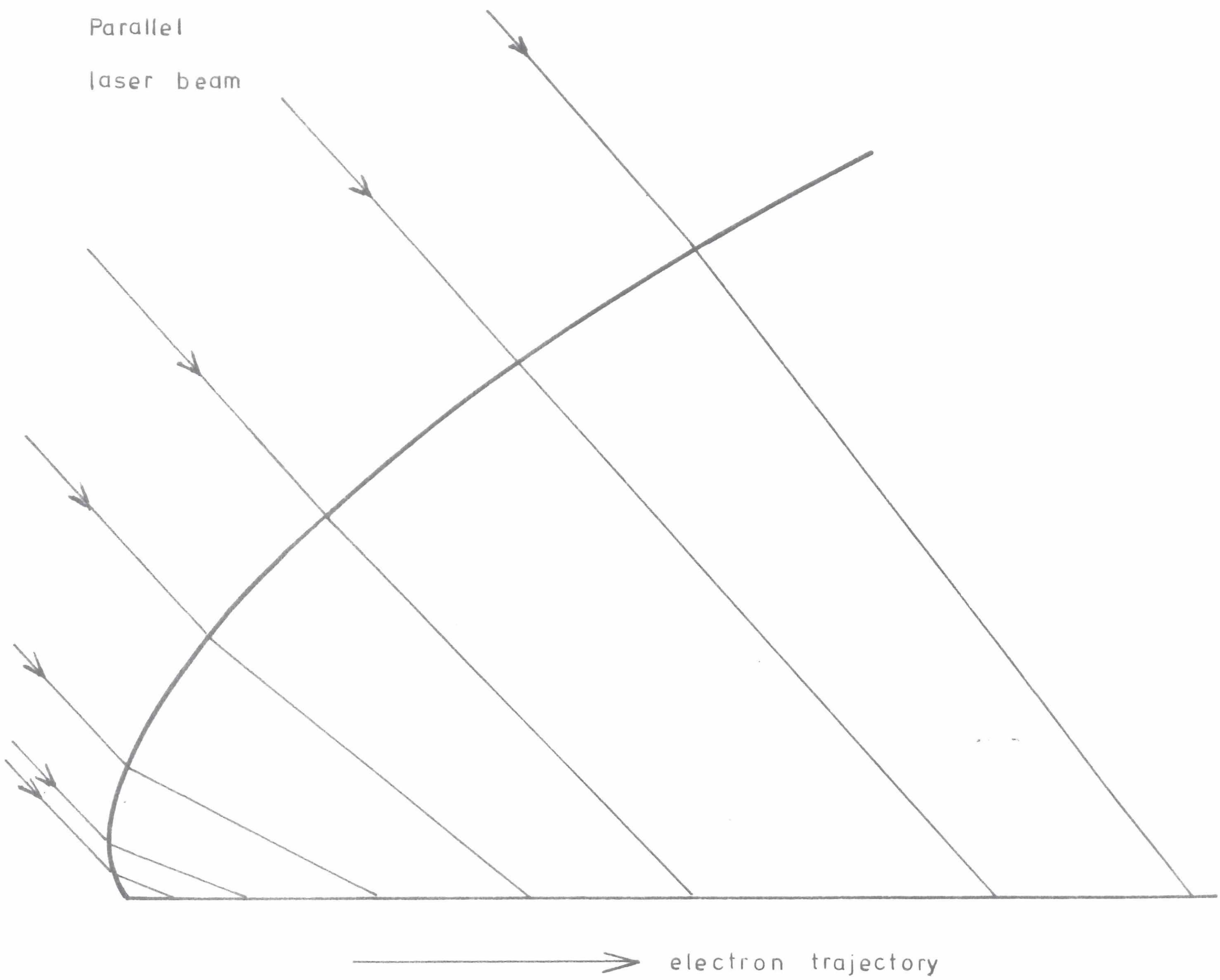
90°
80°
70°
60°
50°
40°
β
171
200
1000
10000 KeV
electron energy
1cm
1cm

FIG. 5



80°
70°
60°
50°
40°
β
electron energy
60
100
200
KeV

FIG. 6



Parallel
laser beam
electron trajectory

FIG. 7

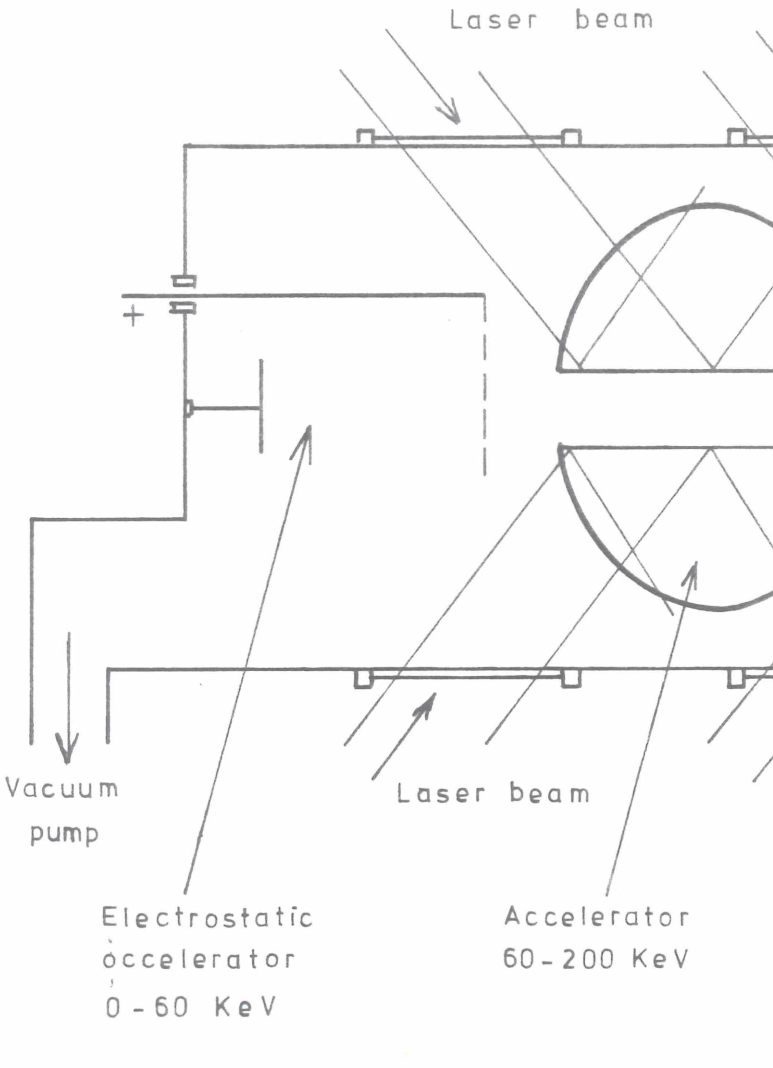
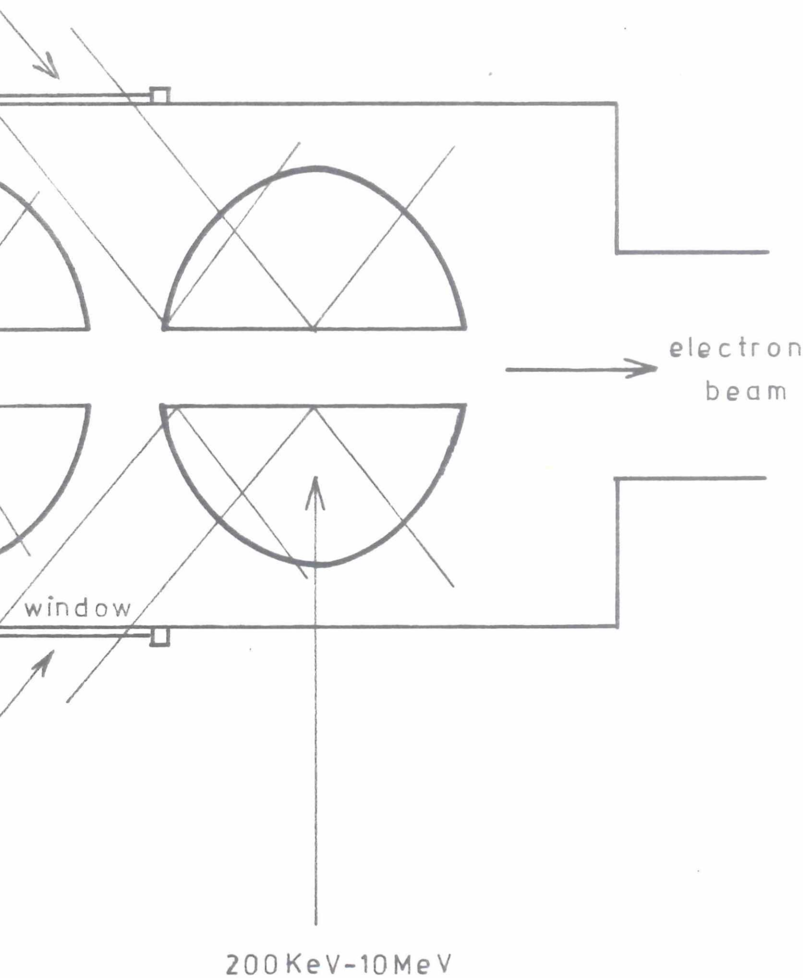

Laser beam
+
Vacuum
pump
Laser beam
Electrostatic
accelerator
0 - 60 KeV
Accelerator
60 - 200 KeV

FIG. 8


electron
beam
window
200KeV-10MeV

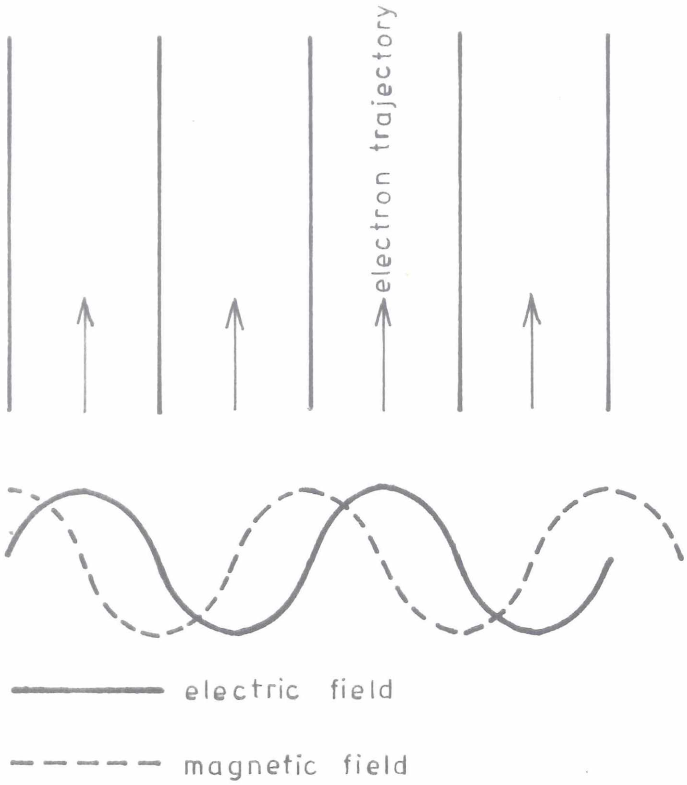

electron trajectory
electric field
magnetic field

FIG. 9

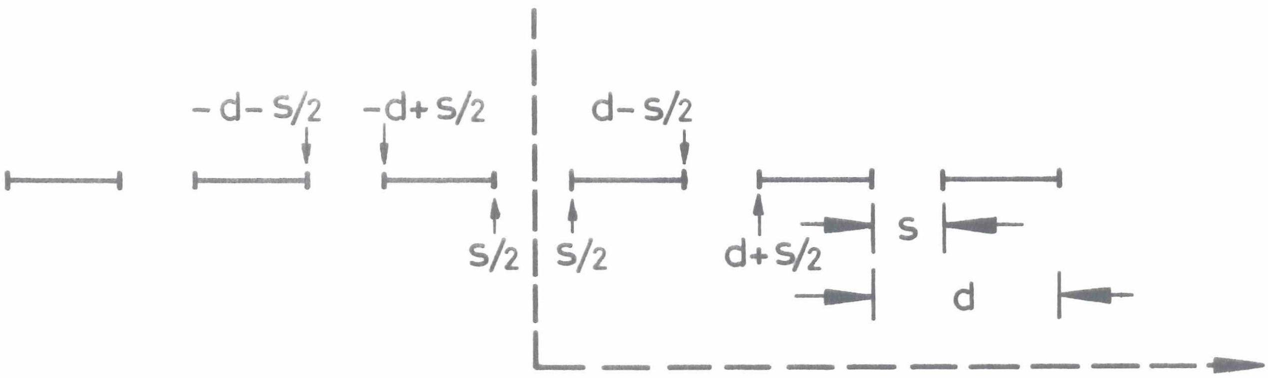

-d- s/2
-d+ s/2
d- s/2
s/2
s/2
d+ s/2
s
d

FIG. 10