# THE MESOTRON - AN ELECTRON ACCELERATOR FOR HIGH FINAL ENERGIES

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# THE MESOTRON, AN ELECTRON ACCELERATOR FOR HIGH FINAL ENERGIES

by

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A b s t r a c t

The circular electron accelerator descibed in this paper is characterized by the following properties:

- The energy gain per turn is an appreciable fraction of the final energy; thus the electrons perform only a small number of turns.
- Electrons in different turns are simultaneously accelerated in linear accelerator structures.
- Electrons of different energies are focussed on separated orbits; thus dc-powered magnets may be used in the circular sections.

Comparison of the proposed accelerator with the conventional synchrotron and the linear accelerator is made and the possible advantages are discussed. The use of superconducting acceleration structures would allow a duty-cycle of 100%. In this case the proposed accelerator is expected to have economical advantages compared to a superconducting linear accelerator of the same duty-cycle for energies up to approx. 60 GeV.

Finally, the possible application for proton acceleration is pointed out.

## 1. INTRODUCTION

This note introduces the concept of a ring-type electron accelerator with high final energy and high duty cycle.

It is only possible to obtain a high final energy in ring accelerators by keeping the synchrotron radiation losses small. This assumes a relatively large energy gain per circuit and a small number of circuits. The total duration of the acceleration is then so short that only constant magnetic fields can be considered for the deflection. These features are in the first place characteristic of the familiar microtron. This type of accelerator, which is capable of development, has already been adapted many times for special applications, including high final energies[1]. However, for final energies in the GeV region it is convenient to use another type of accelerator, having several accelerating sections that are the same for all circuits, while they are connected by beam guides special to each energy.

The characteristic property of common acceleration of particles of different energies and separate paths is summarized by using the term Mesotron as an abbreviation for multiple energy-separated orbits.

In the following section the principle of the accelerator is described, and then a comparison is made with the synchrotron and the linear accelerator, the attainable final energy is estimated, and an example in the form of a 50-GeV mesotron is outlined. Finally, the possible application of the Mesotron as a proton accelerator is discussed.

## 2. PRINCIPLE OF THE MESOTRON

In order to obtain a large energy gain per circuit, the acceleration of the particles takes place in linear accelerators, which are traversed several times. There must be at least two linear accelerators in opposite directions at a certain distance from one another, and it is likewise possible to use several correspondingly smaller linear accelerators distributed around the circuit. The connection between each pair of linear accelerators is through $n$ beam guides, where $n$ is the number of circuits. The separated orbits recombine at the end of these arcs. This is pictured in Figures 1 and 2. All paths have different lengths.

The beam guidance must above all satisfy three conditions:

1. The differences in length of the nominal paths for the various energies must be integral multiples of the h-f wavelength.

2. The arcs must be free of dispersion, to guarantee that the entry of the beam into the next straight section is independent of the particles' energy distribution.

3. The particle trajectories in the arcs must be almost isochronous, but it must be possible to vary the dispersion path length somewhat for phase-focusing . Particles with too small an energy must for example enter the accelerating section earlier than the particle with nominal energy if the falling edge of the h-f voltage waveform is used.

The beam guidance in the accelerating sections must be so arranged that the particles in various circuits, and thus having widely differing energies, remain inside a sufficiently small envelope. The wavelength of the betatron oscillations increases rapidly with increasing particle energy, so that resonance points cannot develop.

The phase focusing depends essentially on the lengthening of the dispersion trajectory. If the beam guidance in the arcs is specially made isochronic, then the energy variations caused by energy and phase differences on injection and in the accelerating sections simply add together. By a proper choice of the dispersion path length it is, however, possible to transform any energy deviation that may be present into a phase deviation, and produce an equalization of energy in the next accelerating section. A preliminary investigation has shown that stable regions exist in the phase plane. The phase focusing has the effect of ensuring that the energy variation of the extracted beam is of the same order as the energy variation at injection and when traversing an accelerator. An additional energy spread is caused by the statistical variations of the beam losses, which in practice only become important in the last half-arc.

The injection in the Mesotron is carried out using a d-c magnet immediately in front of an accelerating section, and the extraction immediately after an accelerating section. Neither of these processes raises any problems, since the trajectories of particles with different energies are in any case separated.

The final energy is found from the product of the energy gain per circuit and the number $n$ of circuits, plus the injection energy and the energy gain in the last accelerator before extraction. Synchrotron radiation losses must be deducted from this sum.

Since all the beam guidance elements are run on direct current, the duty ratio of the mesotron depends only on that of the accelerator sections. Hence the possibilities of this accelerator principle are not exhausted by pulsed linear accelerators. In fact, the mesotron is only fully exploited by using accelerator sections with high duty cycle. If superconducting structures are used it is possible to obtain continuous operation for an appropriate cooling power.

## 3. COMPARATIVE STUDIES

The mesotron will be compared here with the two types of electron accelerator which have hitherto been constructed for high final energies. A comparison is made with both normal and superconducting versions of the synchrotron and linear accelerators.

### a) Comparison of the mesotron with the synchrotron

For a final energy of a few GeV both accelerators have about the same external dimensions. While in the synchrotron one works with a peak field of about 10 kG the mesotron can be operated at higher field strengths as the magnetic field is constant in space and time, but because of the longer accelerating sections it is not significantly smaller.

The construction and operating costs of the accelerator and magnet structure are higher in this energy range for the mesotron than for a synchrotron of the same final energy. For a normally conducting accelerator structure the duty ratio for the mesotron is the same as for the linear accelerator. Hence for this case it is clearly inferior to the synchrotron. In this energy range the use of superconducting structures hardly gives any advantage to the synchrotron because of the time-variable magnetic field, but in the mesotron this can yield a high duty ratio (up to 100%), although it involves a significantly higher expenditure. In this case the improved beam properties must be weighed against the increased costs.

From 10 GeV onward the radiation losses in the synchrotron necessitate a reduction of the magnetic field strength. The most economic solution leads to a diameter increasing as the square of the final energy[2]. Up to about 60 GeV the mesotron dimensions increase linearly with energy, since at 16 kG the radiation loss per circuit reaches the order of magnitude of the energy gained per circuit (see Section 4). It follows that the mesotron is competitive for normal and superconducting structures above certain energies. For high energies, however, the linear accelerator is superior to the synchrotron, and it is then more reasonable to compare the mesotron with the linear accelerator.

b) Comparison of the mesotron with the linear accelerator

The starting point of this comparison is the fact that in the mesotron the accelerating structure is shortened by a factor of $n$ compared with the linear accelerator, but it is necessary to construct $n$ complete circular arcs with deflecting magnets, lenses, and a vacuum system. Of these, the last arc, for the highest energy, will be as intensively equipped as possible. The other arcs can be constructed with less expense, since they correspond to lower energies. The total cost of all arcs could be about $\frac{n+1}{2}$ of the cost of the last arc.

The example of a 50 GeV mesotron discussed in Section 4 shows that for 5 circuits and an acceleration of 10 MeV/m there is a saving of 4000 m of accelerating structure relative to a linear accelerator. On the other hand, according to the above-mentioned example some $(6/2) \times 840 = 2520$ m of magnet structure is required.

If one takes into account the fact that in normally conducting pulsed accelerating sections the space-charge-limited current density in the mesotron is n times smaller than in the linear accelerator, for the same transmitter power, it appears that it is not worth while to build a mesotron for this case.

The comparison is quite different if superconducting accelerator structures are used in both cases. The construction costs for the structure with the appropriate cryostats are much higher than for a continuously running beam guidance system. It follows that in the mesotron the cooling system can be smaller by a factor of n. How decisive this item is for the construction and running costs can be seen from the suggestion for a superconducting version of SLAC[3], where the duty ratio is limited to 6% because of the cost of the cooling. Thus the mesotron could achieve n times this duty cycle for the same cooling power.

Since in this case the current is limited not by the space charge but by the available h-f power, neglect of radiation losses gives the same transmitter power for the same currents in both the linear accelerator and the mesotron.

Thus, by using superconducting structures with a high duty ratio the mesotron can achieve the same beam power as the linear accelerator, with significantly lower construction and running costs.

This superiority of the mesotron over the linear accelerator is limited by the synchrotron radiation, which increases with increasing energy. The highest energy is thus achieved with a small number of circuits and correspondingly longer accelerating regions.

With $n = 2$ circuits a magnetic field strength of 16 kG, which is technically quite realizable, allows one to achieve a final energy of 71 GeV. It results from an injection energy of 3 GeV and two circuits of 30 GeV energy gain each, an additional transit through an accelerator (15 GeV), and a radiation loss of 7 GeV. With a further half circuit the additional energy gain of 15 GeV in the linear accelerator is almost half-compensated by the additional radiation loss of 7 GeV.

If, correspondingly, one selects an energy gain of 6 GeV per circuit for $n = 10$, one obtains a final energy of only 51 GeV. The total synchrotron radiation loss is here as much as 15 GeV. The radiation loss in the last quadrant compensates, at 2 GeV for more than half of the energy gain of 3 GeV in one linear accelerator.

A rough estimate of the cost shows that there is an optimum number of circuits lying between the values 2 and 10 considered above, requiring the smallest outlay as a function of the final energy. Working on the basis of this optimum number, for which it may be expected that the mesotron will show a substantial saving over the linear accelerator, it should be possible to obtain a final energy of about 60 GeV.

If one increases the magnetic field strength, perhaps by the use of superconducting deflecting magnets, then the dimensions of the system are correspondingly reduced but the final attainable energy is also reduced. If, on the other hand, the magnetic field strength is reduced to reach higher final energies, then, as in the case of the synchrotron, this leads to a rapid increase in the dimensions of the mesotron.

## 4. EXAMPLE OF CONSTRUCTION

The problems and technical requirements for a mesotron can be illustrated by the following example of a 50 GeV machine. The details have not been optimized, and the specific figures serve only to give an idea of this type of machine. The construction costs depend heavily on the price of the superconducting structures and on the cryostatic system, the development of which cannot be estimated at present.

The number of circuits is taken as $n = 5$. The energy gained per circuit must amount to about 10 GeV. The accelerating sections are divided into two parts, each representing 5 GeV. With an injection energy of 3 GeV and a field strength in the deflection magnets of 15.5 kG the different half-arcs give successively the values entered in Table 1. The particle energies on leaving the half-arc are calculated allowing for the radiation loss shown in the previous column. In addition, the mean magnetic radii of the half-arcs and their lengths are given, the latter being composed of the lengths of the deflection magnets and the straight sections with lenses (see Figure 2). The half-arcs have been assumed to be composed of $60^{\circ}$ sections here, after which the paths recombine. This yields a mean value of 1.3 m for the distance between the trajectories, so that there is room for lenses for each beam, but the beam can otherwise be led through a common tunnel.

Figure 3 shows a possible configuration of envelopes and dispersion paths in the 10th half-arc, and represents half of the symmetrically arranged

$60^{\circ}$ section. The fact that the dispersion path in the symmetry plane is parallel to the nominal path guarantees freedom of the section from dispersion. The position of the dispersion path can be altered by moving the lens $L_1$ and inserting other lenses behind it. This also changes the length of the dispersion path relative to the nominal path. The beam guidance for half-arcs of low particle energy is changed (see Figure 2) in such a way that there arises a difference in length between the half-arcs amounting to an integral multiple of the h-f wavelength. The properties of the beam course discussed above remain unchanged.

The total radiation loss in the last half-arc is over 2 GeV, most of it being radiated in low-energy quanta. The statistical variations in the number of quanta in the MeV region lead to variations in the radiation loss, which amount to 1-2% of the particle energy, These variations in particle energy are not automatically compensated on the next passage through the accelerator with the corresponding phase. Estimates show, however, that no significant particle loss occurs from this process.

A fraction of the synchrotron radiation from the last part of the arc enters the linear accelerator and reaches the wall there. In order to reduce the wall heating and the additional cooling power needed to deal with it, it is convenient to construct a small part of the deflection magnet with a low field strength. This magnet section also makes it easier to introduce the injection trajectory.

If a FODO channel[4] is used for focusing in the accelerating sections, where the lens separations increase with increasing energy, then calculation shows that for lens separations determined by the first circuit the envelopes for subsequent circuits do not have a very great amplitude. It might be convenient on cryotechnical or h-f-technical grounds to make the lenses equidistant and to adjust the lens strengths appropriately. In each case the number of lenses increases as the injection energy becomes smaller so that an optimum must be found on economic grounds.

The number of betatron oscillations in the beam guides of the accelerating sections decreases with increasing energy. For an acceleration of 10 MeV/m in the example considered here the number of betatron oscillations in the FODO channel is 10.25 for the first circuit and 1.25 for the fifth. The number of betatron oscillations in an arc only changes a little. It is 6 for the last circuit.

The length of the accelerator structure is determined by the desired energy increase per circuit and the energy gain per meter. The conventional value of 10 MeV/m is inserted here so that the accelerator has a length of 500 m on either side. In view of the fact that the development of superconducting linear accelerators is still in its early stages, it appears that an energy gain of 30 MeV/m cannot be excluded[3].

The choice of frequency and oscillation mode in the accelerator structure, allowing for wall losses and breakdown strength[2,5] must be left to further research. A frequency of 300 MHz is chosen for the present example. The problems of radiation reaction are still largely open.

## 5. SUMMARY

The presented principle of a ring electron accelerator offers substantial cost advantages over a linear accelerator by using superconducting accelerator regions and giving a duty ratio of the order of unity and final energies up to 60 GeV. The most important of the remaining problems can be summed up by the following titles:

Superconducting structures and radiation reaction

Beam instabilities

Phase focusing

Optimization.

The first point can be investigated independently of the others. The problems should, however, all be soluble.

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# APPENDIX

## APPLICATION AS A PROTON ACCELERATOR

The above considerations referred to particles in the extreme relativistic energy region. However, the mesotron principle also allows for a certain change in the particle velocity during the acceleration. If the particle velocity differs from the phase velocity in the structure, then on passing through each accelerating section the particle traverses a certain phase region the mean position of which must of course yield a resultant acceleration. The path length differences of the individual trajectories must then equalize this phase displacement.

The energy-dependent velocity of protons automatically produces a phase focusing if the mean phase is on the rising edge of the h-f waveform and the dispersion path is about as long as the nominal path. If this effect is too small, then a shortening of the dispersion paths can dominate the phase focusing.

Consider the following numerical example:

If 2 GeV protons are injected ($\beta = 0.95$), and if the phase velocity in the accelerator structure is 0.975 c, then the largest possible deviation is 2.5%. With an accelerator frequency of 760 MHz this implies a phase advancement of $\pi$ for an accelerator length of 8 m. If 12 accelerating lengths are distributed around the perimeter one achieves initially about 500 MeV/circuit and later 1 GeV/circuit, when the particle velocity is less than the phase velocity.

The higher the injection energy the higher is the efficiency of this accelerator. For $\beta \longrightarrow 1$ the considerations of the previous section are valid without alteration.

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Table 1. Various data for the half-arcs of the 50 GeV mesotron

| Half-arc | Radiation Loss GeV | Extraction Energy GeV | Mean Magnetic Radius, m | Length of half-arc m |
|---|---|---|---|---|
| 1 | 0,01 | 7,99 | 17,19 | 409,80 |
| 2 | 0,04 | 12,95 | 27,88 | 411,10 |
| 3 | 0,12 | 17,83 | 38,45 | 412,40 |
| 4 | 0,24 | 22,59 | 48,82 | 413,70 |
| 5 | 0,42 | 27,16 | 58,85 | 415,00 |
| 6 | 0,66 | 31,50 | 68,43 | 416,30 |
| 7 | 0,96 | 35,54 | 77,44 | 417,60 |
| 8 | 1,31 | 39,23 | 85,75 | 418,90 |
| 9 | 1,68 | 42,55 | 93,28 | 420,20 |
| 10 | 2,07 | 45,48 | 100,00 | 421,50 |
| Extraction | 0,28 | 50,20 | | |

Table 2. List of parameters (some only rough estimates) for three final energies

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| No. of circuits | | | | 5 | | | | |
| Magnetic field strength | | | | 15,5 | | | | kG |
| Energy gain per meter | | 10 | | | | 30 | | MeV/m |
| Final energy | 50 | 40 | 30 | | 50 | 40 | 30 | GeV |
| Injection energy | 3,0 | 2,4 | 1,8 | | 3,0 | 2,4 | 1,8 | GeV |
| Energy gain per circuit | 10,0 | 7,6 | 5,5 | | 10,0 | 7,6 | 5,5 | GeV |
| Radiation loss in last half-arc | 2,1 | 1,1 | 0,5 | | 2,1 | 1,1 | 0,5 | GeV |
| Length of an accelerating region (filling factor 0.8) | 600 | 460 | 330 | | 200 | 150 | 110 | m |
| No.of quadrupoles in accelerator section in the arcs | 82 | 72 | 62 | 240 | 30 | 25 | 22 | |
| Largest magnetic radius | 100 | 80 | 60 | | 100 | 80 | 60 | m |
| Mean radius | 134 | 107 | 80,5 | | 134 | 107 | 80,5 | m |
| Magnet power supply | | | | 5 to 10 | | | | MW |
| Mean extracted current | | | | 10μA (6,2 · $10^{13}$ e/sec) | | | | |
| High frequency | | | | 3000 | | | | MHz |
| Mean generator power | 1000 | 800 | 600 | | 1000 | 800 | 600 | kW |
| Loss power in HF structure for 0.3 duty cycle | 6* | 4,8 | 3,6 | | 18 | 15 | 11 | kW |
| Approx. largest length | 868 | 674 | 491 | | 468 | 364 | 271 | m |
| Approx. largest width | 268 | 214 | 161 | | 268 | 214 | 161 | m |

* The costs of a cooling system for 6 kW are given as 26 million DM in ref. 3 and 48 million DM in ref. 5.

## Figures

**Figure 1.** Overall view.

The diagram is restricted to trajectories in the first circuit (inner) and last circuit (outer), together with injection and extraction trajectories. The half-arcs are divided into dispersion-free symmetric $60^{o}$ sections. Half of one such segment is shown enlarged in Figure 2.

**Figure 2.** Half segment of beam guide ($30^{o}$)

All beam guide elements are drawn for the outer (last) trajectory. Only the deflection magnet and the first lens in each case are shown for the other trajectories.

**Figure 3.**

Envelopes and dispersion paths for a half section of the last half-arc. The second of the dispersion paths $D_1$ and $D_2$ shown is isochronous.

The path difference relative to the nominal path is adjusted essentially by changing L1.

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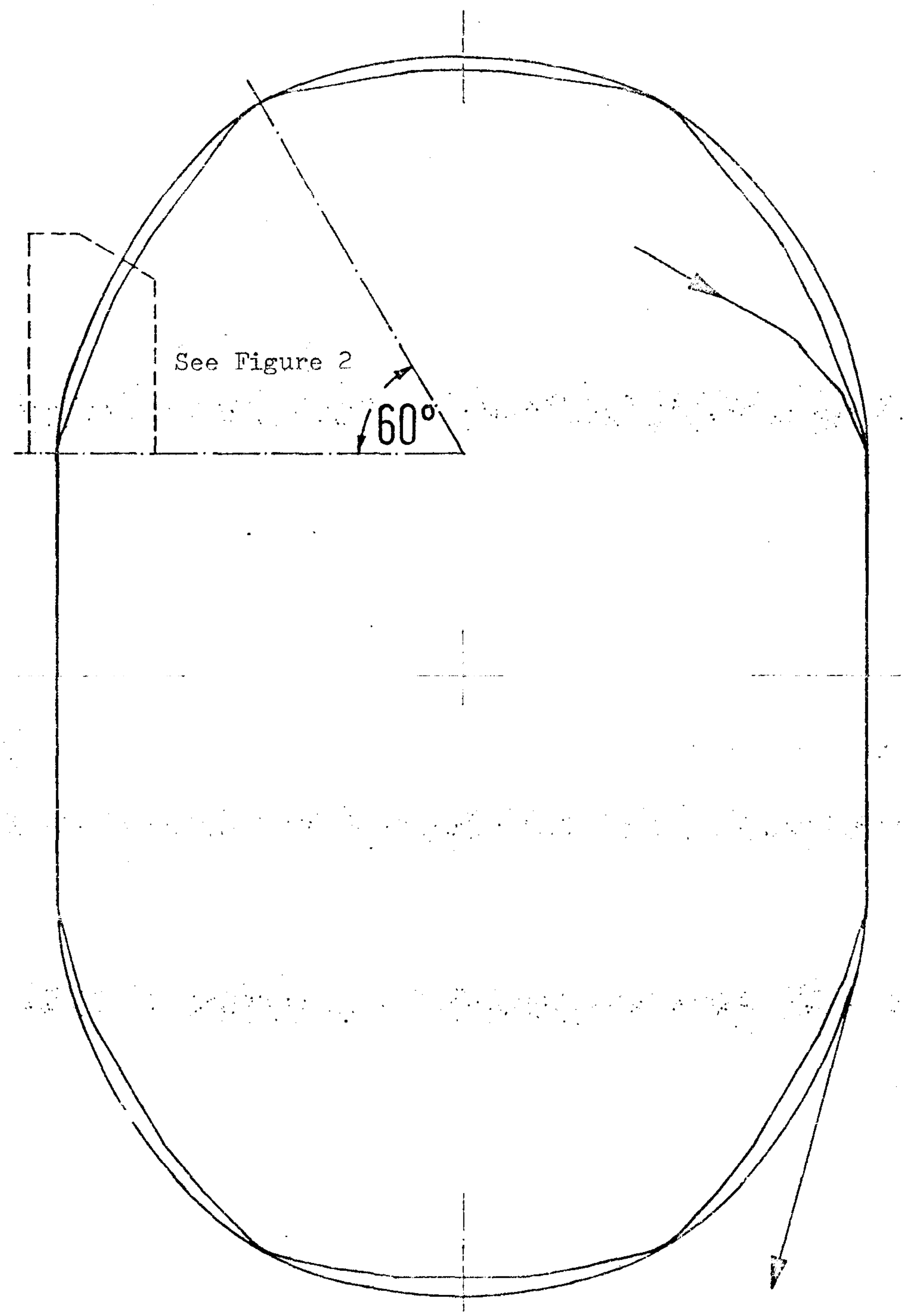


Figure 1. Overall Plan

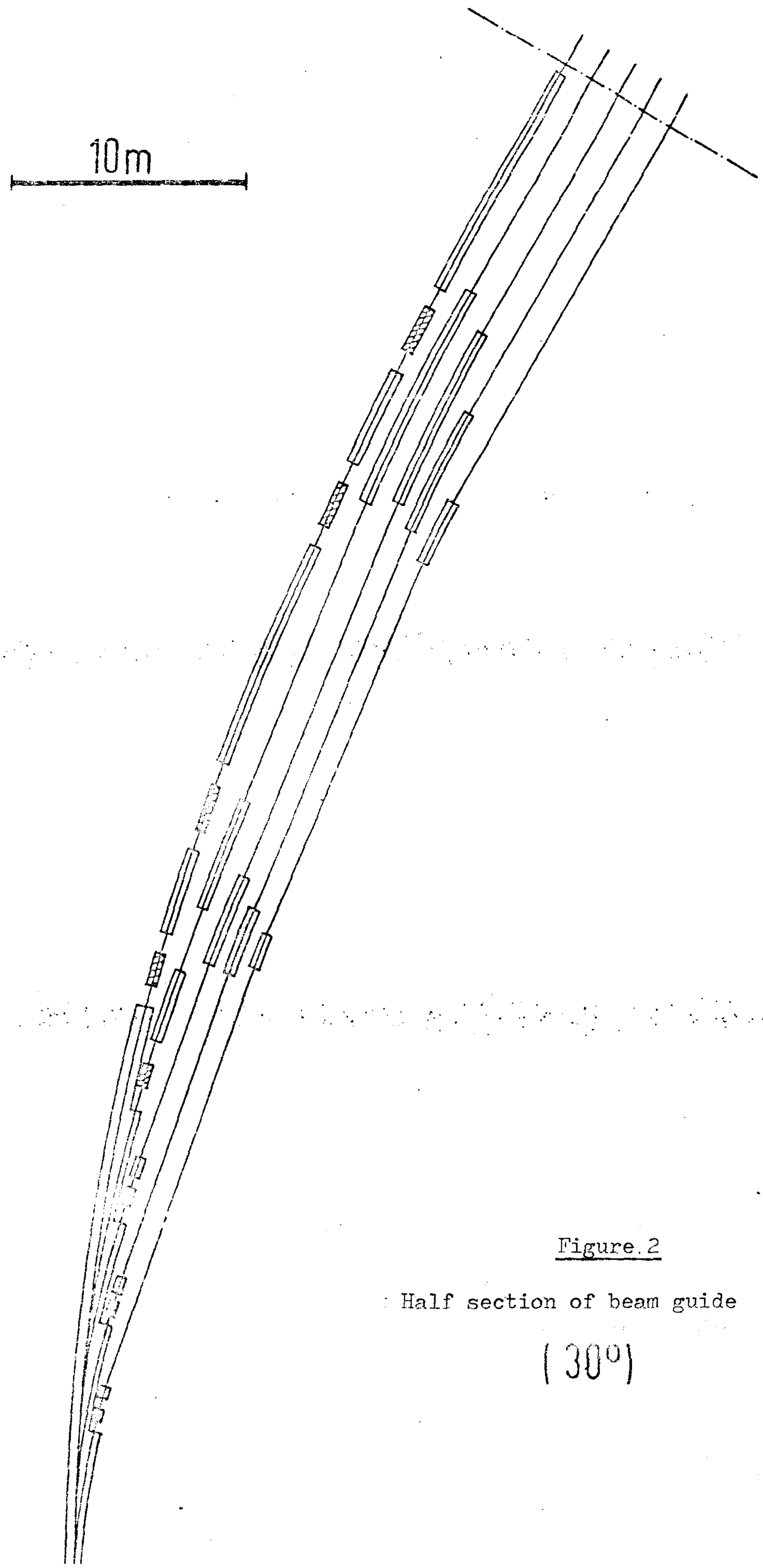


Figure. 2

Half section of beam guide

(30°)

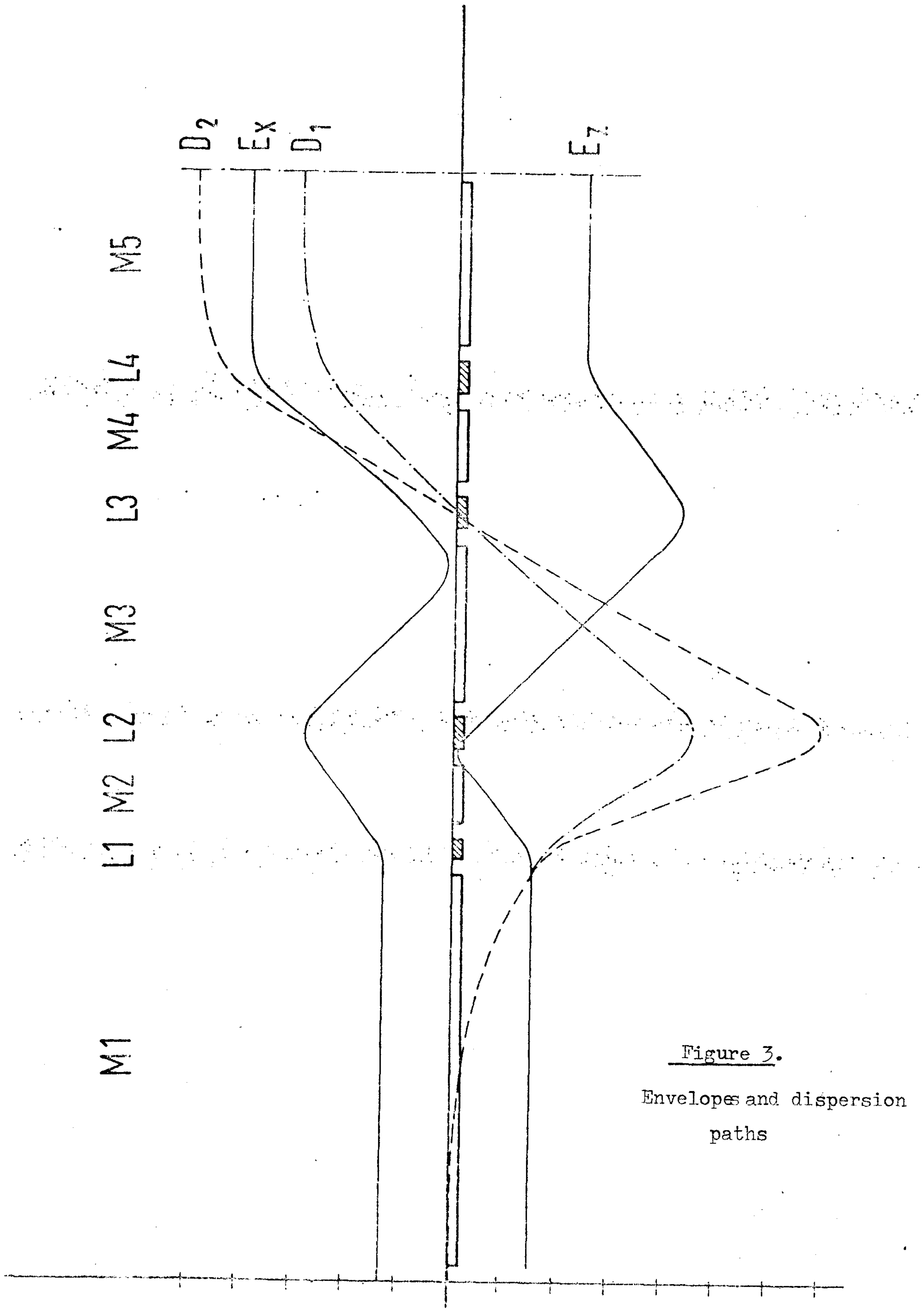


Figure 3.

Envelopes and dispersion paths