Internal Report
DESY M-82-10
April 1982

PARTICLE ACCELERATION BY WAKE FIELDS

G. A. Voss and T. Weiland

Abstract

The principle of electron-positron linear colliders seems to be the only method known today for reaching collision energies of a few hundred GeV or higher. The maximum energy in a linear accelerator is given by the average accelerating gradient and the length of the structure. An ultra high gradient scheme is considered using the wake field of a high current driving bunch and suitable structures as transformers. The mechanical constraints are much less severe than in conventional linacs and the gradient may be of the order of 100 MeV/m.

Zusammenfassung

Das Prinzip der kollidierenden Elektron-Positron Linearbeschleuniger scheint die einzige bis heute bekannte Methode zu sein, Energien von einigen hundert GeV und mehr zu erreichen. Die in einem Linearbeschleuniger maximal erreichbare Energie ist gegeben durch die Länge des Beschleunigers und den mittleren Beschleunigungsgradienten. Es wird ein Schema diskutiert für ultra hohe Gradienten, die durch das Streufeld eines Strahles mit hohem Strom erzeugt werden. Mit Hilfe metallischer Strukturen wird das Streufeld auf einen zu beschleunigenden zweiten Strahl transformiert. Die mechanischen Toleranzanforderungen sind wesentlich geringer als in herkömmlichen Linearbeschleunigern und der erreichbare Gradient ist von der Größenordnung 100 MeV/m.

The scheme of linear colliders seems to be the only method known today for reaching collision energies with electron and positron beams in the region of a few hundred GeV and higher. In linear colliders dense single bunches of electrons and positrons are accelerated in linear accelerators and directed against each other. High luminosity is obtained by focussing the beams to an extremely small cross section at the collision point.

The energy of such a device is given by the average accelerating gradient and the total length of the linacs. The collision energy - unlike in electron-positron storage rings - is in principle unlimited because synchrotron radiation losses are absent in linear accelerators. In order to make ultra high energies economically feasible very high accelerating gradients are necessary. For this purpose very high power rf-tubes are being developed at present as well as rf-storage cavities with fast high power rf-switches and special rf-accelerating structures [1].

In this note we consider a different method of acceleration. It is suggested to use the wake field of a very high current bunch of relativistic electrons which can - in a suitable structure - produce much higher accelerating fields than those seen by the bunch itself. At the location of the high field a second bunch with smaller charge can then be accelerated. The structure acts as a transformer for the wake fields.

The energy loss of the high current bunch which generates the wake fields must be replenished at suitable intervals by conventional acceleration methods. This would reduce - in a linear device with two beams - the average accelerating gradient for the high energy bunch. If the transformer ratio of the structure is high enough the increase in obtainable average gradient is still large. No reduction of average accelerating gradient occurs in a three-beam device with alternating sections for the high current beam (producing wake fields - reacceleration) and continuous acceleration of the high energy beam.

There are two obvious aspects to such a scheme: Since both the field generating bunch and the accelerated bunch are extremely relativistic the wake field will always stay in the proper phase with respect to the accelerated bunch. Thus the exact dimensions of the transformer structure are much less critical than those for instance in a conventional linac. Also, since the very high field exists only for an extremely small time at any given point (typically of the order of a few tens of picoseconds), such structures probably allow for extremely high field without breakdown, much higher than those which could be obtained in linac structures.

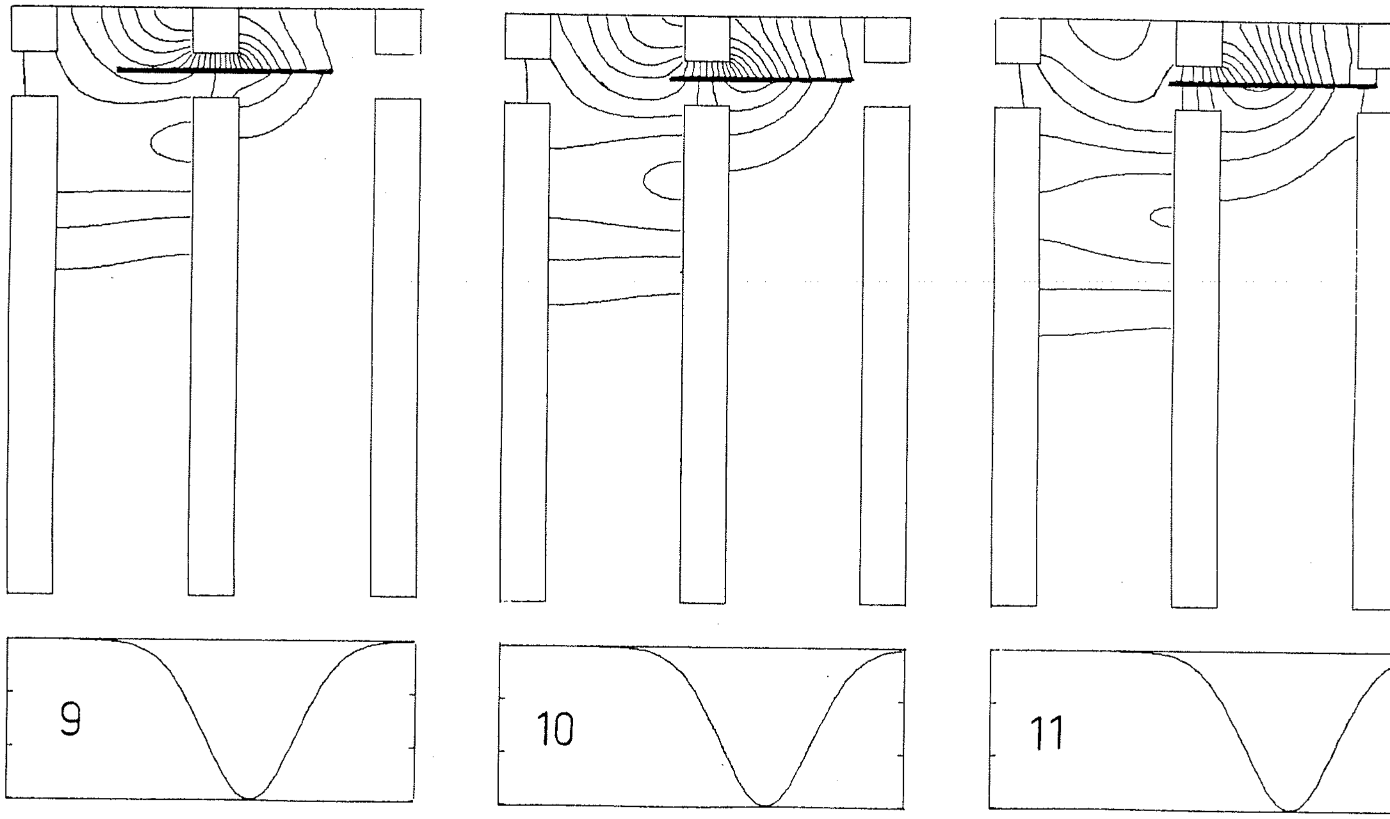
A possible structure which may not be the most convenient one but which has the advantage that the generated fields can be exactly calculated with existing computer codes[2, 3], is shown in Fig. 1.

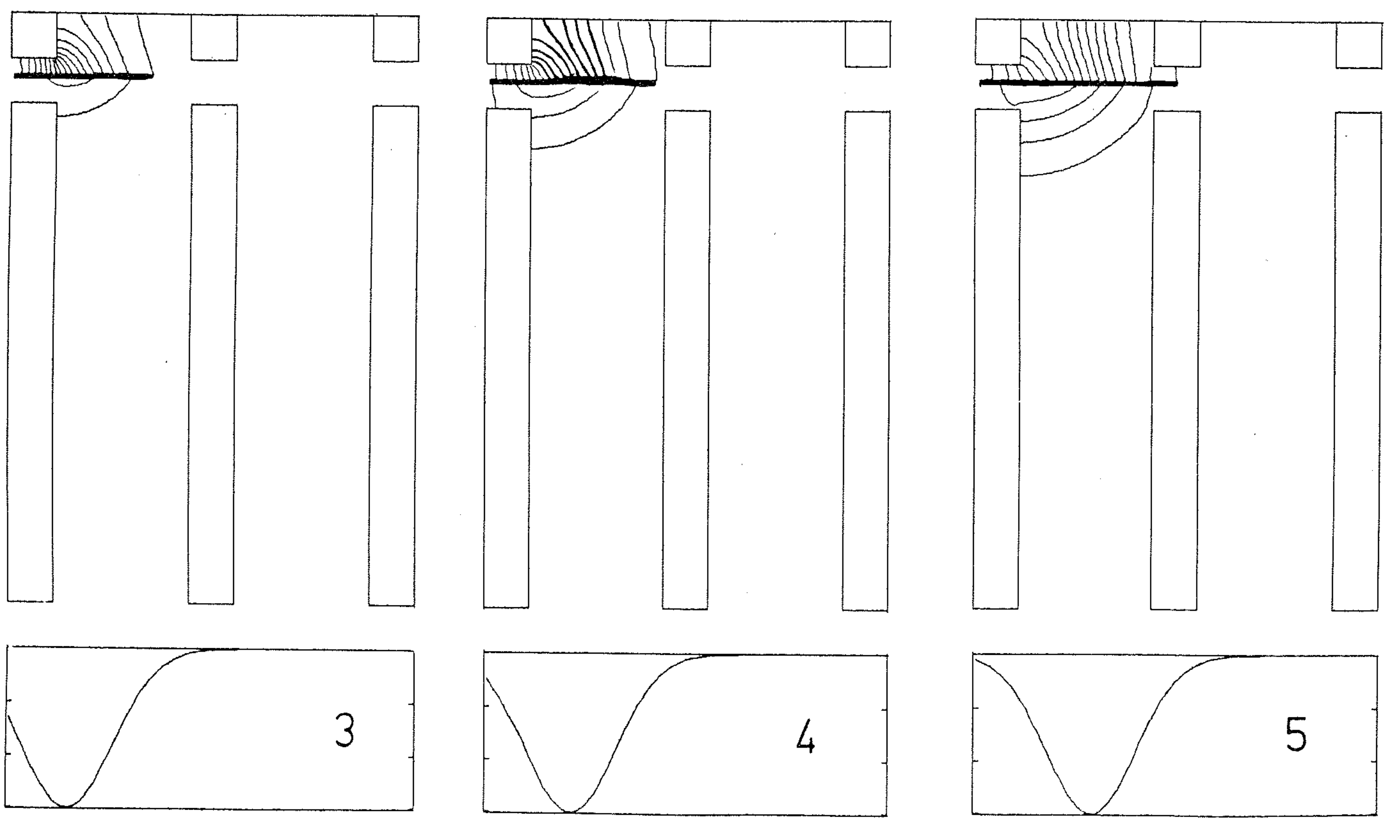
The field generating beam is hollow and has a diameter of 6.25 cm in this example. With a center hole diameter of 0.5 cm the energy gain for particles going anywhere through the center hole is 6 times as large as the maximum energy loss of particles in the hollow outer beam. If the latter has a longitudinal charge distribution (Gaussian) with an r.m.s. length of 0.25 cm, the maximum energy gain for particles in the central region is 100 MeV/m for a charge of 1 μ Coulomb in the field generating bunch. If the accelerated bunch contains 10^{11} particles and has the same r.m.s. length as the driving bunch its energy loss due to excitation of higher order modes will be 6 MeV/m. The maximum energy loss of particles in the driving beam amounts to 16 MeV/m in this example. In Fig. 1 the electric field lines are shown at eleven subsequent time steps during the passage of the driving hollow beam. It can be seen how the wake field is generated at the discontinuities and then travels to the center region of acceleration. A significant increase in transformer ratio may probably be obtained by optimizing the shape of the outer teeth yielding a more coherent reflected wave than the one shown in Fig. 1. The accelerating voltage at the central region and the decelerating voltage in the driving bunch are shown in Fig. 2.

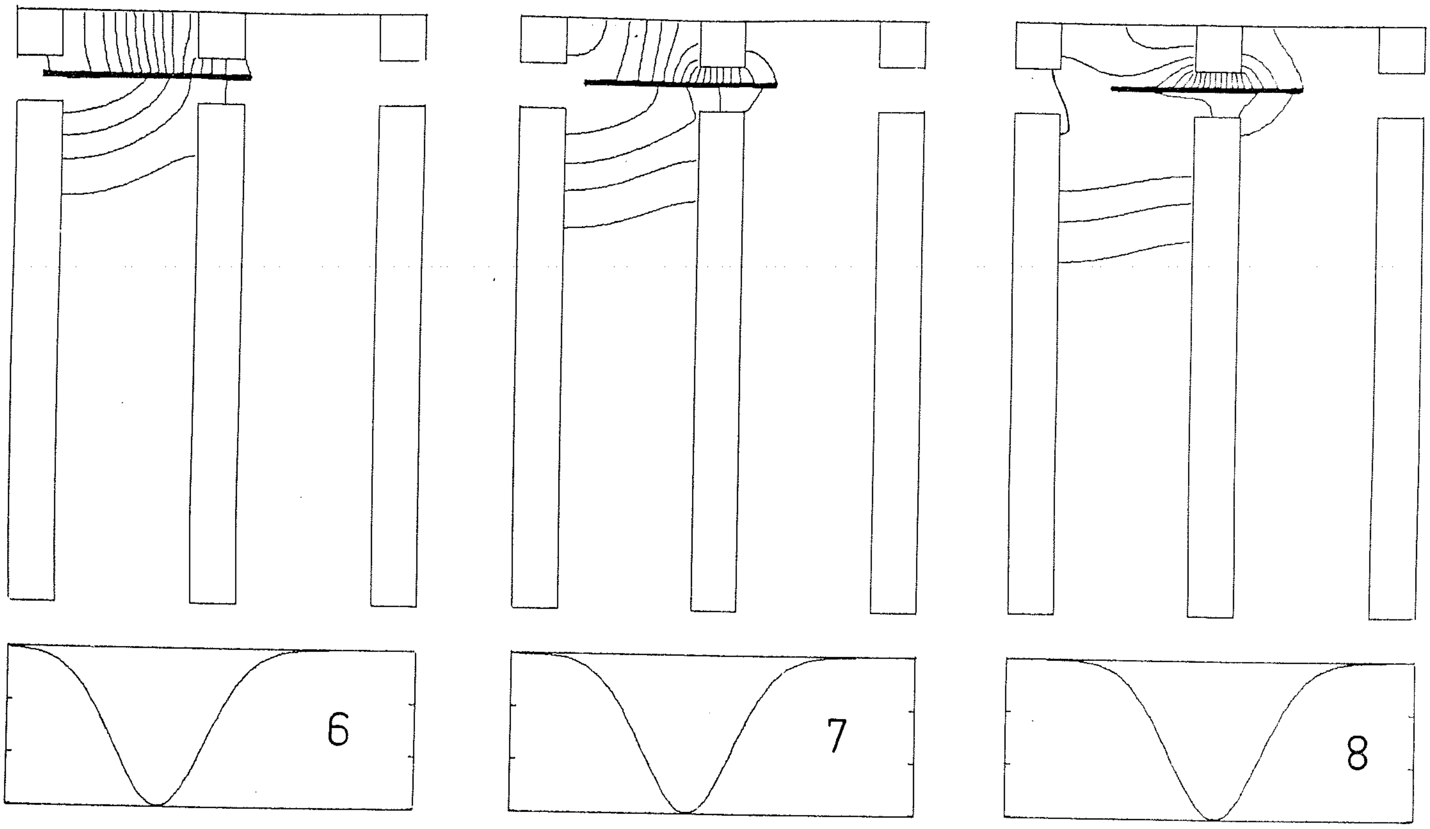
For a given charge in the outer beam the energy gain in the center region is inversely proportional to the structure dimensions. For a given structure the energy gain is of course proportional to the charge of the driving beam and roughly inversely proportional to its longitudinal dimension.

The acceleration of the driving beam may present some difficulties in this case since there exists not yet a simple accelerating structure for hollow beams with such a large diameter. The difficulties due to the hollow beam may be overcome by a similar transformer scheme shown in Fig. 3. A set of driving beams is used for generating the high fields. This scheme also enables more coherent waves since the wake field is cut off from the driving beams in a much smoother way than in the first structure.

A third wake field transformer is considerably simpler: elliptical pill boxes (see Fig. 4) with two different hole sizes at the two focal points allow the driving beam to go through the large holes. The wake fields get focussed at the small holes through which the accelerated beam goes. Since the higher order mode losses scale like $a^{-0.5 \ldots -1.0}$ (a = hole diameter) at a given bunch length the transformer ratio scales like the ratio of the hole diameters with the same exponent as long as the hole is not too large compared to the area of the ellipse. This scheme also provides an easy way for maintaining the full gradient during the reacceleration of the driving beam by means of a second driver as shown in Fig. 4. Two high current beams accelerate the high energy beam in the middle and are reaccelerated in alternating sections with conventional accelerating devices. This scheme is likely to provide similar gradients as the first one with much simpler mechanical transformers and ordinary structures for replenishing the energy lost by the driving beams.


9
10
11


3
4
5



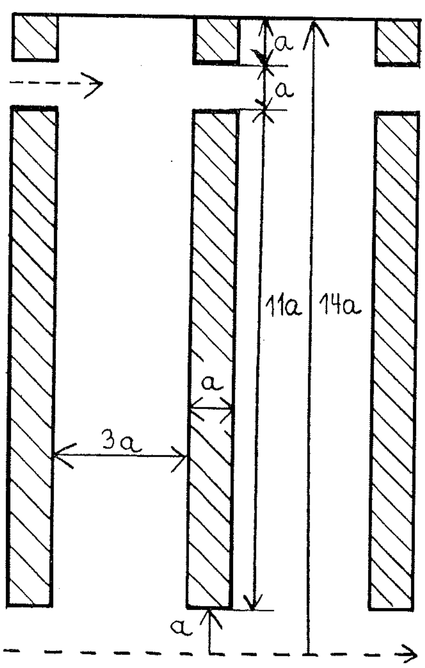
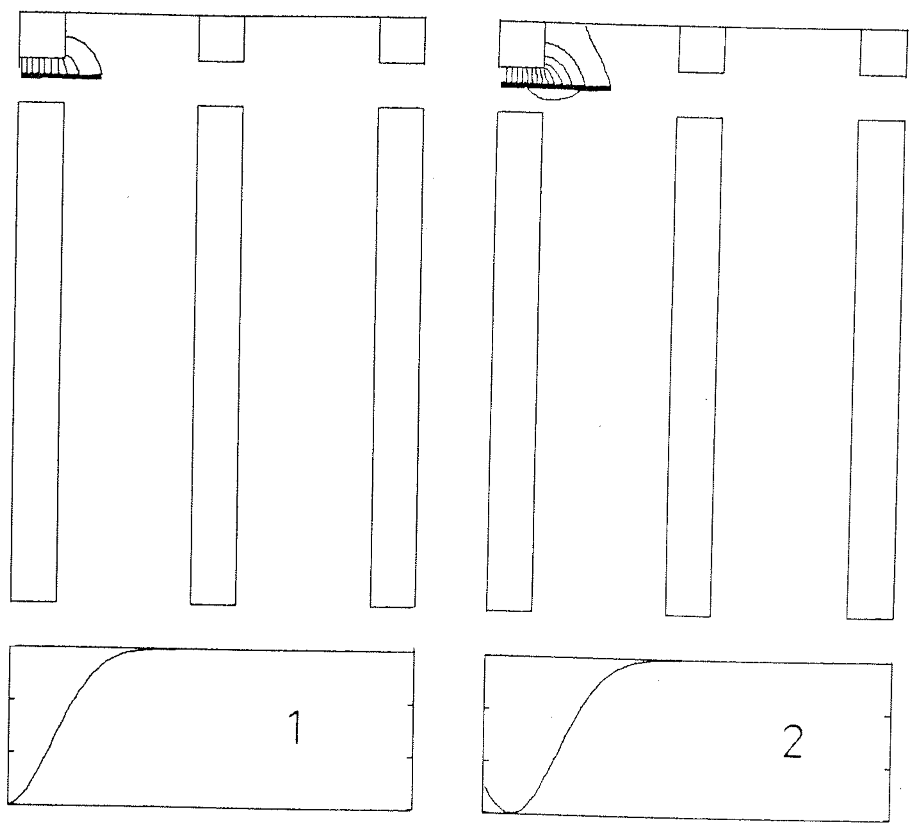


Fig. 1 : The electric field lines at 11 subsequent time steps generated by a hollow beam in the wakefield transformer, a=.125cm, σ=a.



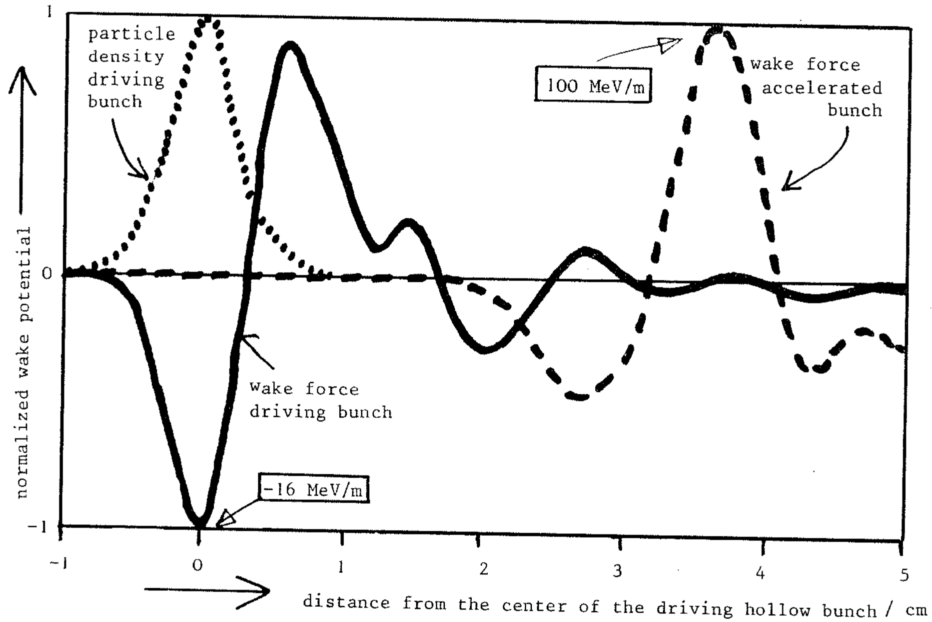


Fig. 2 The accelerating gradient in the center region (max. 100 MeV/m) and the decelerating gradient at the driving outer bunch (max. -16 MeV/m) as a function of distance behind the center of the driving bunch.

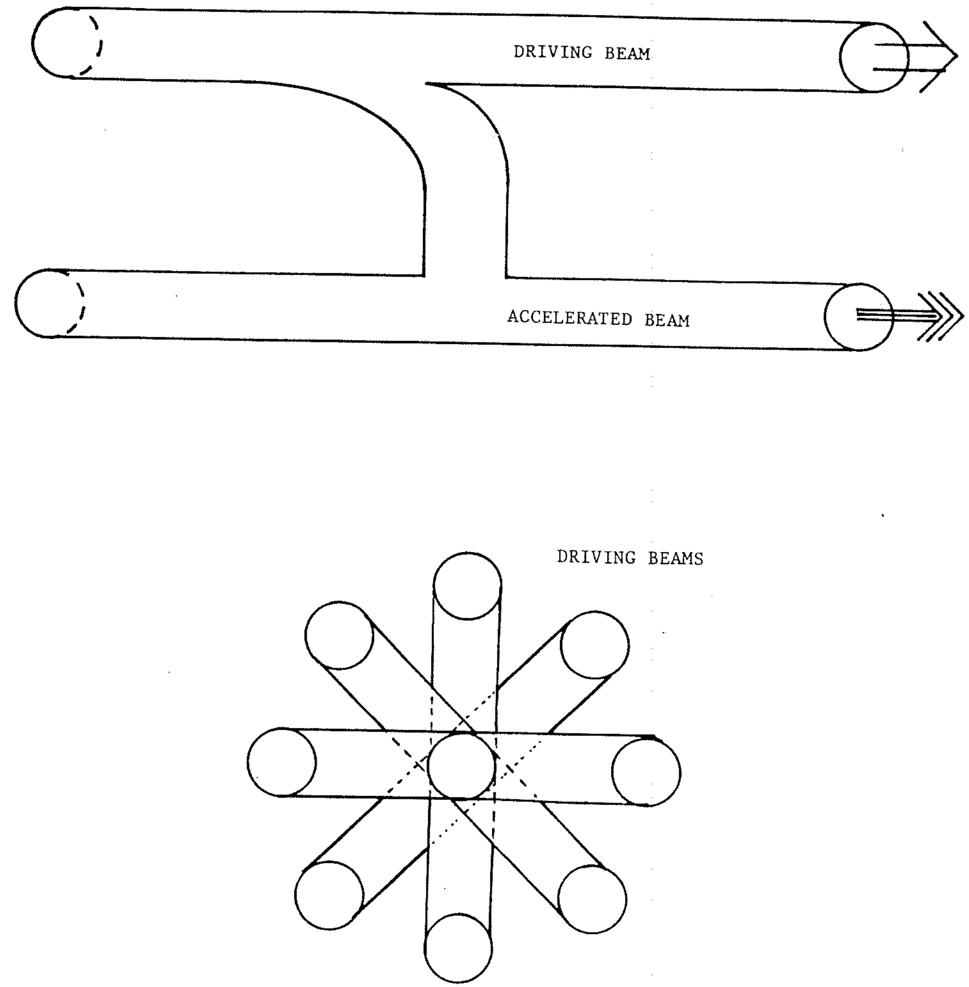
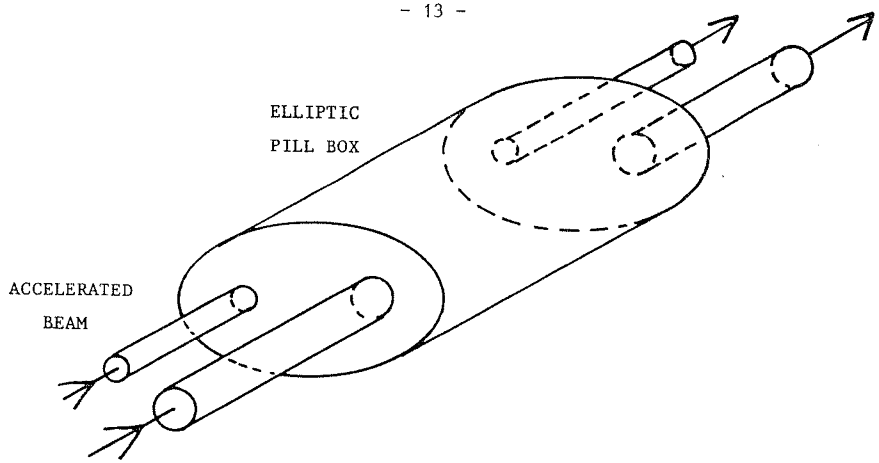


Fig. 3 A simple two-beam wakefield transformer and a possible arrangement for a multiple beam star-transformer based on the two beam principle.



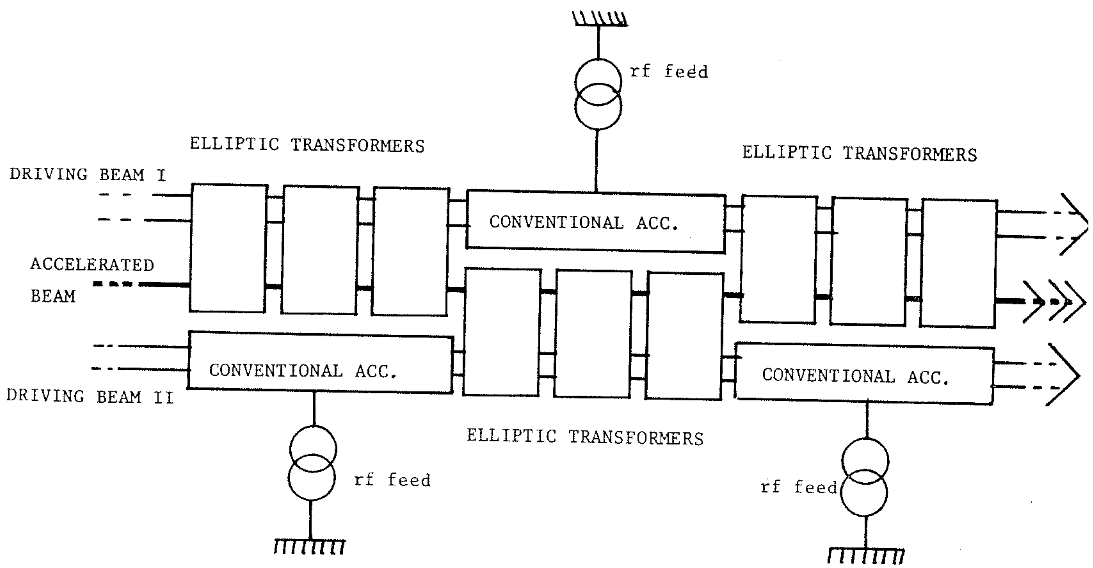


Fig. 4 A two-beam elliptic pillbox acting as a wakefield transformer with a small pipe for the accelerated beam and a big one for the driving beam and a possible layout of a three beam linac with conventional sections for reacceleration of the driving beams

Literature

1) SLC Design Report, SLAC-Report-229
June 1980

2) Weiland, T., Proc. of the XI.-th Internat. Conf. on High Energy Accelerators, Geneva 1980, p.570-575

3) Weiland, T., DESY 82-015, 1982