DEUTSCHES ELEKTRONEN – SYNCHROTRON DESY

DESY 87-146
October 1987

NEW IDEAS ON PARTICLE ACCELERATION

by

T. Weiland

Deutsches Elektronen-Synchrotron DESY, Hamburg

ISSN 0418-9833

NOTKESTRASSE 85 · 2 HAMBURG 52

DESY 87-146
October 1987

ISSN 0418-9833

New Ideas on Particle Acceleration*)

by

T. Weiland

Deutsches Elektronen-Synchrotron DESY, Hamburg

*) Plenary talk presented at the International Europhysics Conference on High Energy Physics, Uppsala (Sweden) June 25-July 1, 1987

New Ideas on Particle Acceleration

T.Weiland

Deutsches Elektronen-Synchrotron DESY
Notkestr.85, 2000 Hamburg 52, Germany

October 1, 1987

Abstract

Starting with a workshop on laser acceleration in Los Alamos in 1981, a series of workshops in Europe and the USA have stimulated a large number of new (or renewed) ideas for particle acceleration. However, only a few of these ideas have triggered experimental work. With respect to the goal of building a 1+1 TeV linear collider, even fewer of these ideas seem realistic. In order to build a TeV linear collider at a reasonable cost, the development of new methods of particle acceleration is absolutely essential. Such an accelerator does not seem feasible with present day technology. In this paper we will focus on those ideas, which are considered to be *rather realistic* by some experts when comparing them with other ideas.

1 Introduction

The basic ingredients of a linear collider machine are shown in figure 1. Two long linear accelerators accelerate electrons and positrons to the final energy of 1 TeV. Electrons are generated in a conventional source followed by a damping system which reduces the emittance of the electron bunches. Positrons are generated in a target which is bombarded by electrons of medium energy. A damping ring system reduces the emittance to very small values. The emittance is of cruical importance as the final spot size at the interaction point scales as the inverse emittance for a given optical arrangement. In order to keep such a linear collider machine within reasonable physical sizes, the accelerating gradient must be above 100MeV/m. One even more cruical boundary condition is that the total power requirement should not be in excess of 100 Megawatt for example.

Although positron sources and damping rings are reasonably well understood, they form the first big technological problem. In this paper we will mainly deal with (new) methods of accelerating particles at a gradients above 100MeV/m.

A common problem for all linear collider schemes is the beam dynamics in the linac. Collective effects tend to increase the emittance. New focusing and damping mechanisms are under study. By means of recently developed computer codes, one can determine all the parasitic effects and work out the beam dynamics, the focusing needs, the alignment tolerances, etc. Intensive studies are going one at many laboratories.

Also, the beam beam interaction is the subject of theoretical work being done mostly at SLAC and KEK. While the beam dynamics problems in the linac seem to be solvable, the beam-beam bremsstrahlung at 1TeV must be investigated in an intermediate classical as well as quantum regime and is still not fully understood.

However, the realization of a linear collider first needs a practical and economically feasible scheme to generate the necessary gradient over the long linac sections. The *real* problem is the generation of the immensly high peak power, etc.

We will describe only a few out of the many proposals for linear collider acceleration methods, namely those which have already been experimentally studied and some which could be tested with realizable effort.

I do not describe the DESY scheme first because I think it is the best (although I really do). The order in which the ideas are presented is neither an order in my personal preference nor in a historical sense, but simply, determined by the objective to make this paper readily digestable.

However, the comments are certainly subjective and it is recommended that the interested reader also reads a paper from CERN [1] in which he will find a quite different distribution of weights. In order to get an overview of all the ideas presently being discussed, the proceedings of the ECFA workshop held in Paris recommended. [2].

The time dependence of the electromagnetic field that accelerates particles serves as the first category to group the methods being discussed. The field is either *harmonic* or *transient* in time. Nowadays, in the field of High Energy Physics, time harmonic fields are dominantly used: rf cavities in storage rings, linear travelling wave structures such as the SLAC linac, etc. Transient fields are used more for low energy high current beams but now are also being viewed as the principal accelerating field or as the pre-accelerator for some low energy beam that will be used to excite the time harmonic, high frequency field.

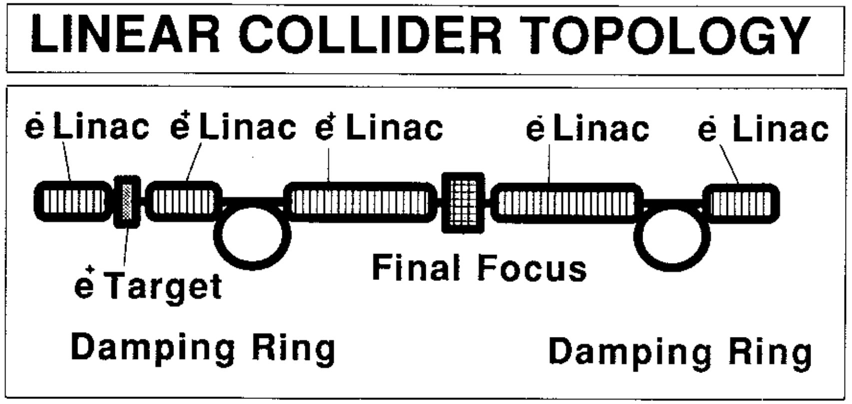

Figure 1: *Principle Layout of a Linear Collider Machine. From left to right: electron source with pre-accelerator, positron target, positron pre-accelerator, positron damping ring, high gradient positron linac, interaction region with final focussing system, high gradient electron linac, electron damping ring, electron pre-accelerator with source.*

2 Transient Field Schemes

Transient wake fields are known as a major source of beam instabilities and performance limitations in high energy physics accelerators, they can have a strength comparable to the fields of accelerating cavities. If the wake fields of an electron beam in some cavity structure were used to accelerate the particles in a following bunch, one could not gain a factor in excess of two (as follows from theory). Thus, the wake fields decelerating a drive beam at a rate of 50MeV/m (say) could accelerate other particles by no more than 100MeV/m. This fact rules out such a scheme a priori. The situation can be improved significantly by means of *wake field transformation* [3].

2.1 Wake Field Transformer

If the driving beam that generates the wake fields traverses a cavity structure at a *different* transverse location than the beam to be accelerated, the above limitation (of a factor 2) can be overcome. Figure 2 shows a *wake field transformer* in which a hollow beam (electron ring) traverses the structure near the outer wall. During the passage, wake fields are excited and radiated toward the radial outer wall. At this wall, the fields are reversed in sign. Subsequently, they travel radially toward the center of the structure. During that radial travel, the volume containing the fields is reduced. Thus the field strength must increase as the inverse square root of the radius.

With realistic dimensions, one easily obtains a transformer ratio of ten to twenty. The inner particles can be accelerated by 200MeV/m by the wake fields of the hollow drive bunch, which is decelerated by only 20MeV/m for example.

The major problem of this scheme (as in almost any scheme) is the generation of a high density drive beam, here the generation of an electron ring beam. In 1984 an experiment was started at DESY to investigate the problems of generating such hollow beams [4]. The overall layout of the experiment is shown in figure 3. Intensive studies on both experimental and theoretical subjects have contributed to the recent first "proof of principle" experimental result. In a very preliminary set up, gradients of over 8MeV/m have been measured. Roughly 10 percent of the design charge per bunch could be achieved. The fact that this number is only 10 percent is mostly due to hardware restrictions in the experiment. In order to make an experiment quick and not too expensive, mostly existing hardware was used. Buncher and linac cavities were by far not optimal for the purpose. In spite of the very limited hardware investment, this result is very encouraging. More details of this unconventional scheme can be found in the paper describing the experiment and the results in more detail. [4].

The remaining missing factor of ten in drive beam intensity can be reached (according to computer simulations) by using a new bunching scheme and more suitable drive linac cavities. Theoretical studies on a design for a new experiment are under way. More experimental work has just been started to improve the hollow beam gun and the pre-accelerator.

A TeV collider could be made of two times ten sections for example, where in each section a new hollow beam is generated, accelerated to 10 GeV, and then sent through a transformer section where it accelerates the high energy bunches to 100 GeV. The length of each section is determined by beam dynamics problems of the driving beam.

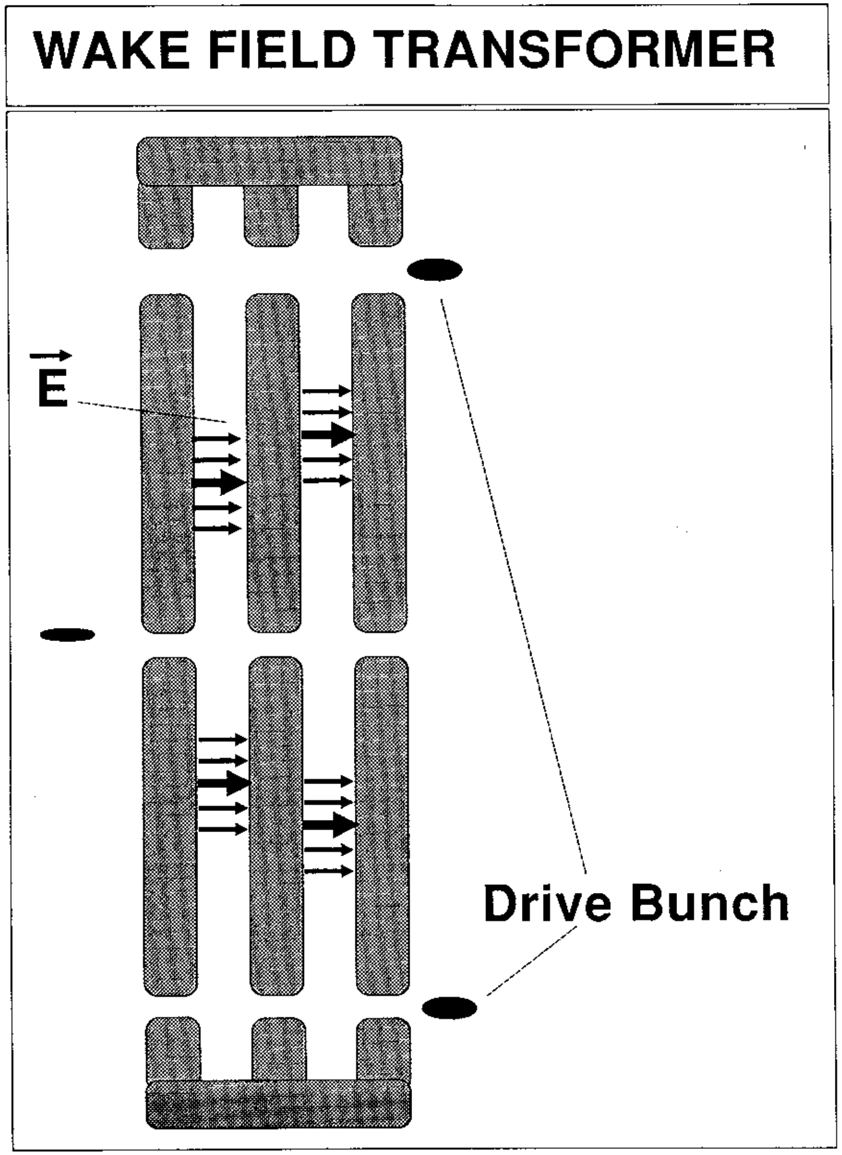

Figure 2: *Wake Field Transformation. A hollow drive beam traverses a cavity-like structure. Wake fields are excited, decelerate the drive beam particles, and subsequently travel toward the center of the structure. Thus, the volume of field is decreased and the field strength increased. The example shown here yields a transformation ratio of ten. Thus, drive beam particles are decelerated by 20MeV/m (say) while particles at the center are accelerated by 200MeV/m.*

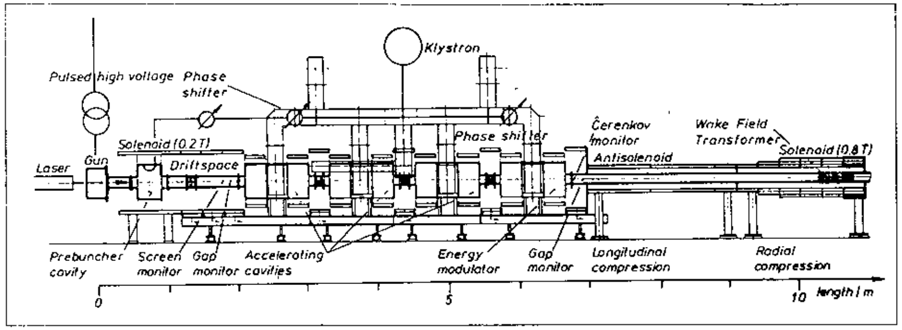

Figure 3: *The DESY Wake Field Transformer Experiment. A hollow drive beam is generated by a laser driven gun. The beam is then bunched and accelerated in a 500MHz linac to 8MeV. Further bunching is obtained at 8MeV by bunch rotation. Finally, the drive beam is brought to a wake field transformer where it will generate high gradient, accelerating fields on axis. The experiment is completed up to the end of the linac. In a first test without hollow beam rotation, an accelerating gradient of 8MeV/m was measured. It is expected that this gradient will significantly increase when the beam will be bunched in the second part of the experiment which is under construction.*

2.2 Switched Power Linac

The switched power linac [5] basically uses the same principle as the wake field transformer scheme. Instead of using a drive beam running all along the linac, a drive beam is generated at each gap by having a charged wire at the outer radial end of the plates, see figure 4. Laser pulses trigger the circular cathodes releasing an electron current which generates an electromagnetic pulse. This pulse then travels toward the center producing there a very high transient field for particle acceleration.

The crucial problem of this scheme is the very high electrostatic field strength needed at the wire surface. The wire must be charged such that a field of the order of 1 GV/m builds up. The triggering process is also very difficult. About 1 Terawatt laser power for every meter of linac is needed.

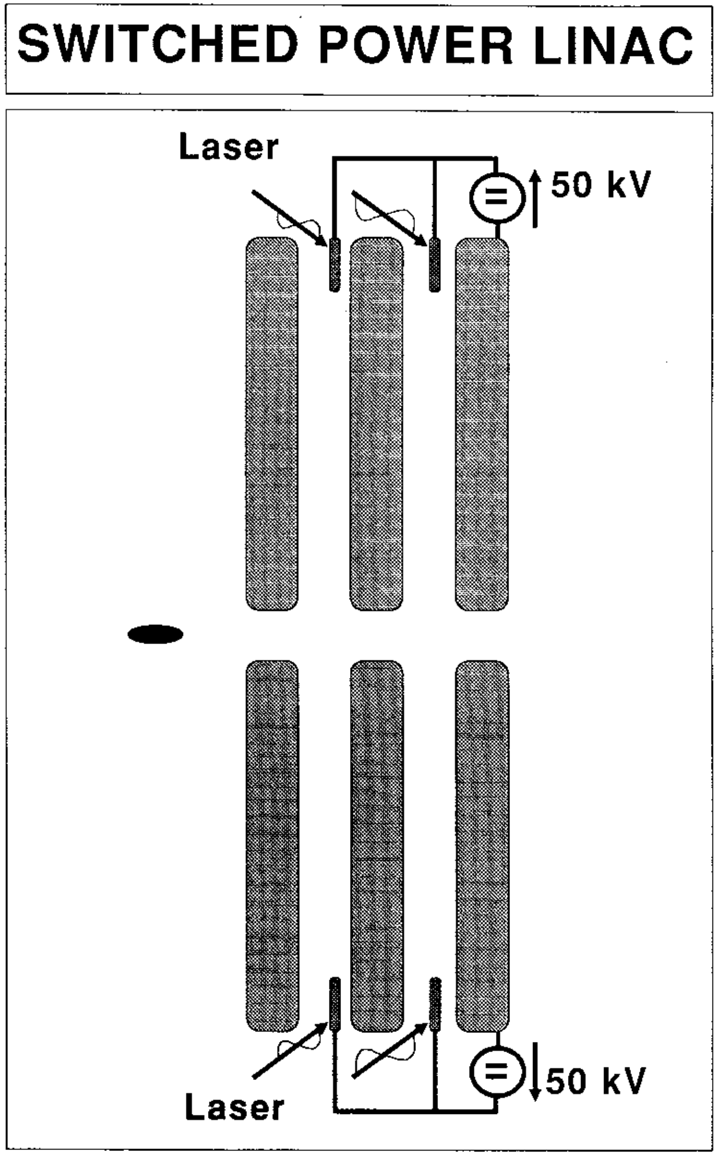

Figure 4: *Switched Power Linac. Charged wires between radial plates are triggered by laser pulses. The released, hollow electron ring current generates a wave travelling toward the center.*

3 Time Harmonic Fields

Following a mixture of fairly well understood physical processes and some more experientially based data, one finds a set of scaling laws that indicate how the various dominating quantities of a rf driven, linear collider scale with frequency. Transverse wake field effects have become known, from the experience at PETRA and SLC, as a very severe limitation in terms of achievable charge per bunch (and thus luminosity). Such effects did cause the current and luminosity limitation in PETRA for a long time. What makes the scaling to higher frequencies even more frightening is that the absolute tolerances that one can realize in the adjustments of accelerator components stays constant from some limit onwards. If the SLC is aligned to an accuracy of 0.02mm(say) at 3GHz, it is not realistic to scale the tolerance simply upwards to 30GHz where one would require 0.002mm and still have 1000 times higher transverse wake field effects. Thus, in a real machine there is even a stronger dependence of wake field effects than the third power given below.

achievable accelerating gradient	$f^{+1.0}$
rf source peak power	$f^{-0.5}$
average power consumption	$f^{-2.0}$
paraisitic wake field effects	$f^{+3.0}$

Table 1: *Frequency dependence of some basic quantities*

If we neglect the collective effects, all remaining laws show that the highest frequency is the best. Currently a range between 10 and 30 GHz is considered.

It should be noted here, that for the accelerated, high energy bunches, a transient field structure, as discussed above, does not look different from a rf linac with a wave length comparable to the disk spacing. Thus, the transient schemes can be compared with respect to beam dynamics with a 30GHz rf linac.

3.1 Accelerating Cavities

A linear rf accelerator has two major components, the accelerating cavity and the rf power source. Figure 5 shows three typical cavity structures and their associated shunt impedances, which are a measure of how much power is needed to accelerate particles by a certain amount of energy. As one can see from this figure, the shunt impedance is not significantly different for the three rather different shapes. However, the shape strongly determines the strength of the parasitic wake field effects. Thus, an overall optimization will probably end in a rather smooth structure with a large aperture [6] and a somewhat lower shunt impedance than what is achievable. For a given cavity shape, the scaling law shows an increase with the square root of the frequency. We can assume to first order that the shunt impedance cannot be improved at a given frequency by optimization.

The next very important question is wether it is possible to maintain fields as high as 100MV/m in such a cavity. Recent experiments at SLAC have shown that this is indeed possible. The higher the frequency is, the higher the achievable field strength is. [7].

3.2 Power Tubes

Assuming now that high fields can be maintained and cavities are optimized to balance the need for high shunt impedance and low wake field effects, we are left with the major question of any time harmonic acceleration scheme, namely, the rf power sources.

SLAC uses in the SLC linac over 200 klystrons with a peak rf output power of 68MW. The principal layout of a klystron is shown in figure 6. In order to generate fields of 100MV/m at 10GHz (say), one needs more than 100MW of rf power per meter linac. Unfortunately, the achievable peak power in a klystron reduces with increasing frequency. One of the main reasons for this limitation is the strength of the space charge forces that prevent the particles in the beam from getting bunched. Obviously, these forces increase with frequency as the spatial distances between particles become smaller. With technology as it is nowadays, a klystron with over 100MW peak power in this frequency range cannot be built. At SLAC there is a program to develop such tubes and the first hardware work has just started. Using more tubes with lower peak power would on the one hand, be an obvious solution but, on the other hand, lead to a very large number of units, some ten thousands (say).

The search for high power tubes has also led to the idea of a *lasertron*, the principle of which is shown in figure 7. It is very similar to a conventional tube with the major difference being that the electron beam bunching is performed by using a bunched laser beam and a photo cathode instead of a continous electron beam and rf bunching. This tube triggered lots of enthusiasm when it was first discussed. Meanwhile the experimental results from KEK [8] and the computer aided analysis at SLAC [9] and DESY [10] have dampened the expectations down to the level of ordinary tubes.

3.3 Induction Linac Klystron

Currently at SLAC a *monster-klystron* [11] is considered. The drive beam is generated in an induction linac. At an energy of some MeV (say), the beam is brought to a normal klystron body with output cavities. The scheme is illustrated in figure 8. First experiments have just started. Problems will certainly be the output cavity that is supposed to extract of the order of 1 GW of power.

3.4 Relativistic Klystron

One of the major drawbacks of klystrons and the lasertron is that the efficiency hardly ever exceeds 50 percent. Half of the beam power is dumped into the collector. This probably triggered the idea of a relativistic klystron, attributed to P. Panofsky from SLAC. Instead of throwing the beam away, one could refresh it again and use it in a second klystron in line with the first one and so on. In order to transport the driving beam over long distances, it is preferable to accelerate it first to some medium energy.

At LBL/LLNL a *relativistic klystron two beam accelerator* is being studied [12]. Induction units, which can efficiently accelerate high current beams, are used to generate a driving beam consisting of a train of bunches. These bunches excite rf fields in special rf

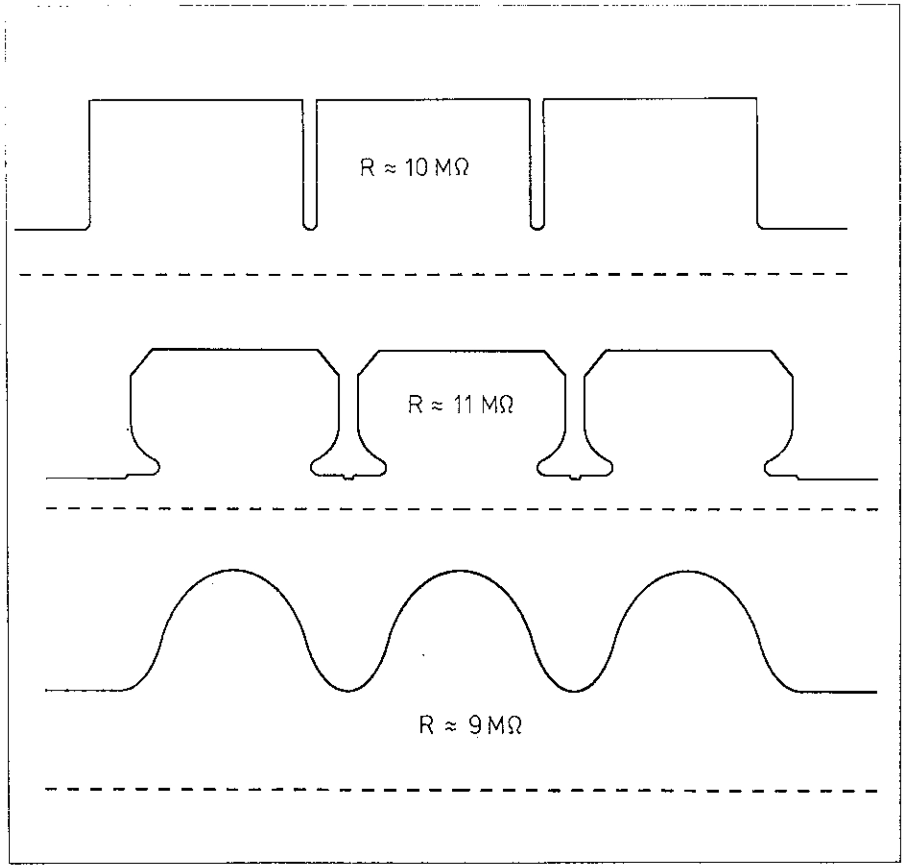

Figure 5: *Three typical shapes of accelerating cavities. The upper most cavity was built 25 years ago for the DESY synchrotron and is still being used as linac cavity in the Wake Field Experiment. It has a measured shunt impedance of* $10M\Omega/m$ *(or 20 in American notation). In the middle, a typical nose cone cavity is shown as it is being used in PETRA, PEP and LEP for instance. The measured shunt impedance is about 10-20 percent higher (These shapes have been obtained by optimizing the shunt impedance by means of computer codes). The third cavity shows the result of an over all optimization. It optimizes the maximum beam current versus rf power taking into account that a somewhat less effective cavity allows much more beam current to be accelerated. After all, not much improvement should be expected from optimization. The shunt impedance is almost a universal quantity for cavities made from the same material, whatever shape they might have.*

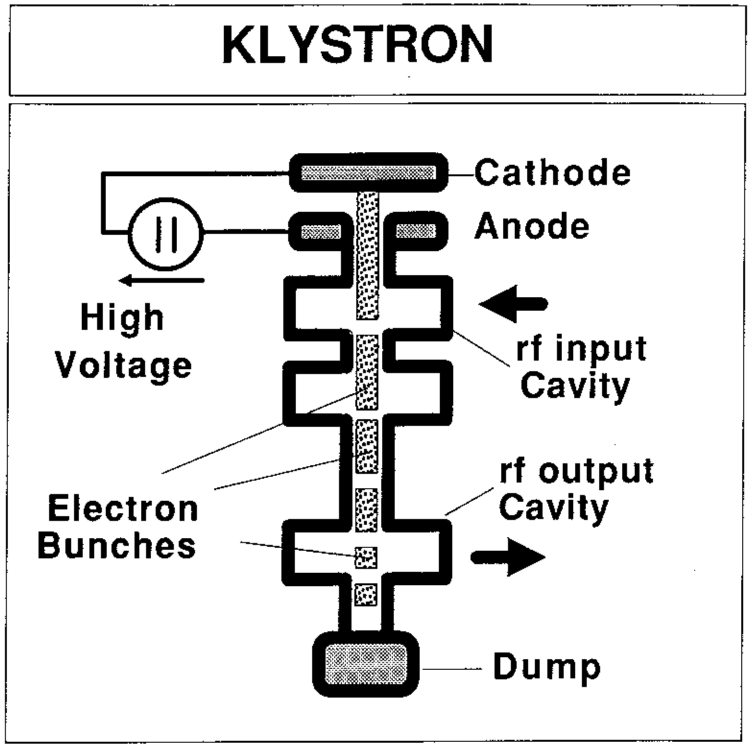

Figure 6: *Principle layout of a rf klystron. A dc electron beam is accelerated in a high voltage gap. Low power rf fields in the cavity modulate the energy and thus the velocity distribution. The beam is bunched and excites rf fields at the output cavity from which the power is extracted.*

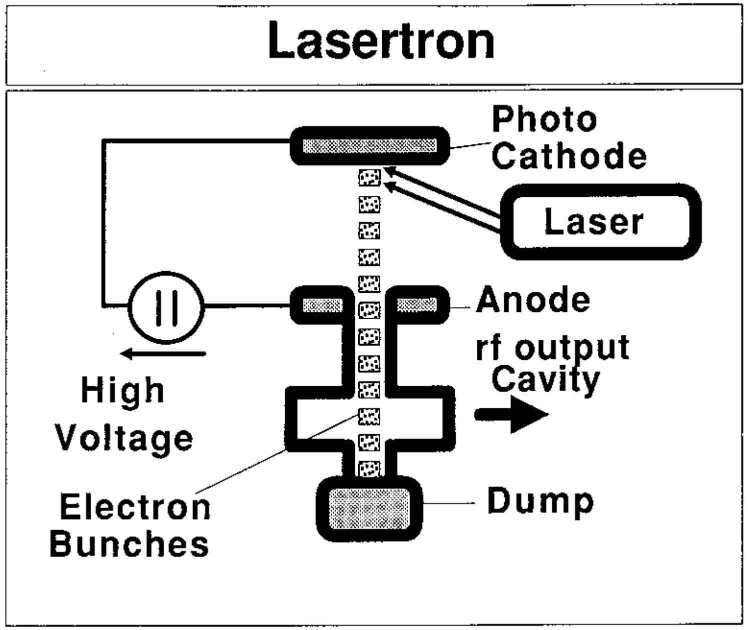

Figure 7: *Principle layout of a Lasertron. A bunched laser beam causes a photo cathode to emit bunches of electrons. A high voltage gap accelerates the bunches. In the output cavity the beam excites rf fields. The power is extracted from this cavity. The main problems are due to space charge forces near the photo cathode. They tend to make the bunches longer and thus less effective in exciting rf fields.*

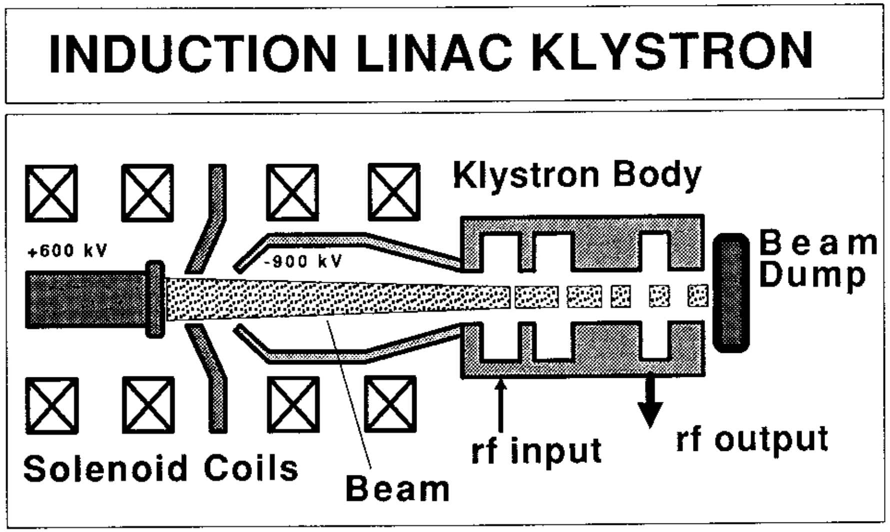

Figure 8: *Induction Linac Klystron. A medium energy, high current beam is generated in an induction linac as the one shown here schematically (the ARC in LLNL). By some mechanism yet to be tested, the beam is bunched and brought to an normal klystron body. Output cavities extract rf power at very high levels, 1GW (say).*

output cavities with low shunt impedance. The rf power is transferred to the high gradient structure running parrallel to the drive beam. Periodically, induction units replenish the energy lost by the drive beam particles. This scheme is illustrated in figure 9.

First experiments are just starting and it is much too early to make relevant comments at this early stage.

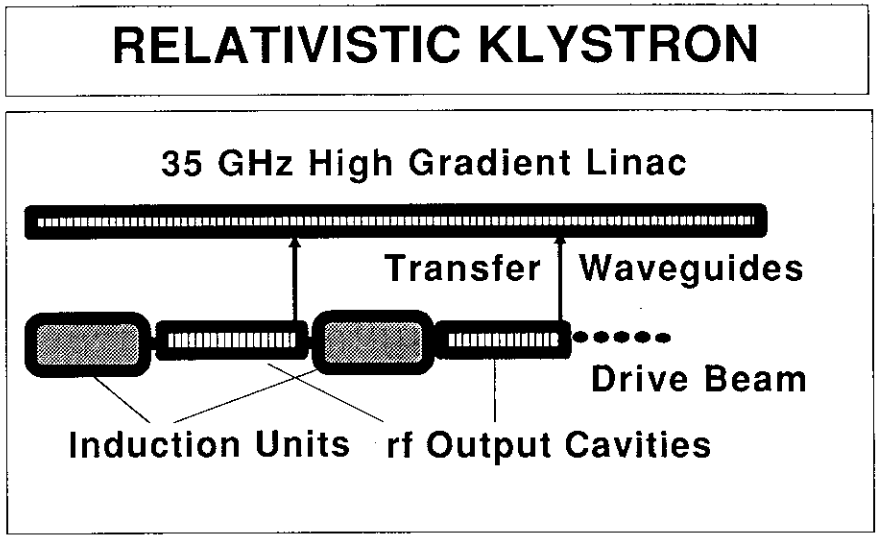

Figure 9: *Relativistic Klystron. A medium energy, high current beam is generated in an induction linac. Periodically, this bunched beam excites rf fields in low impedance output cavities. At some reasonable intervals, the drive beam particles are reaccelerated by induction units.*

3.5 Two Stage Accelerator

At CERN a relativistic klystron is being studied using superconducting rf cavities to accelerate the drive beam (instead of high voltage gaps in an ordinary klystron and instead of using induction units as in the scheme just mentioned above). A train of some ten bunches is first generated once then accelerated to a few GeV. In special low impedance cavities resonating at 30GHz, rf power is generated and guided to the high gradient linac running parallel. The total voltage in the drive beam needed for a TeV collider is in the order of two times 15 GV.

Apart from the difficulties arising from a 30GHz(35GHz) linac, with all its alignment problems, the two latter schemes also rely heavily on the drive beam quality. It yet needs to be shown how one can generate and accelerate about 50 consecutive bunches of 50 to 100nC each, bunched to a length of 1mm rms. So far, no experimental work on this important subject has been started, but might have been started by the time this paper is published.

The major appealing ingredient of this scheme is that it uses superconducting rf cavities, the technology of which is approaching a state where it is becoming conventional. The high efficiency is probably the most important aspect that makes this scheme different from others.

On the other hand, a disadvantage is that a superconducting drive linac must run at a relatively high repetition rate (compared to other schemes). This is due to the fact that the cw operated linac continuosly consumes power, independent of whether a drive beam is accelerated or not. In order to make this cryogenic power not the dominant portion of the total power, one has to operate the system at a rather high repetition frequency of about 5 kHz. Running at a lower repeptition rate will not significantly save power. With a room temperature drive linac, one can simply reduce the repetition frequency and save power almost linearly.

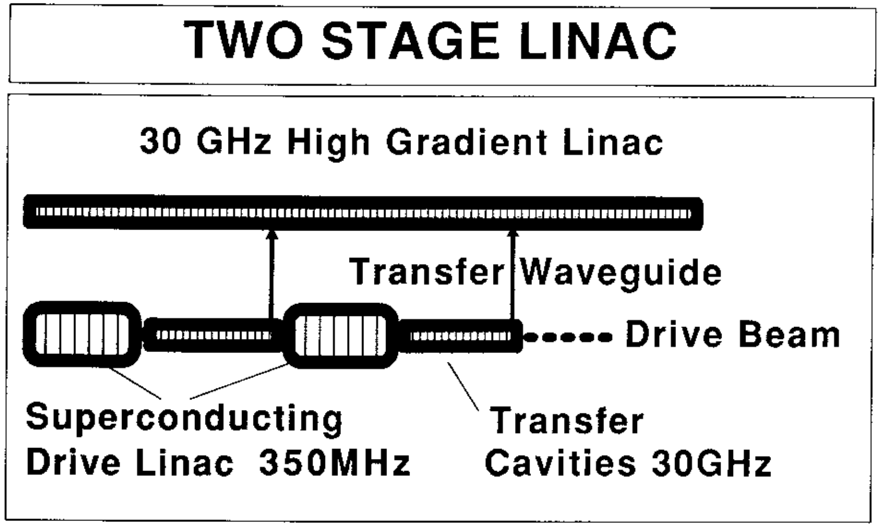

Figure 10: *Two Stage Linac. A train of bunches at 3 GeV excites rf fields in output cavities. The energy lost by this process is periodically replenished by superconducting cavity sections.*

3.6 Two Beam Accelerator

The names given to these different schemes are somewhat misleading. All schemes are *two beam systems*. However, for historical reasons, we call the following idea the *Two Beam Accelerator* [12] because it is known by this name. All the above mentioned schemes extract the rf power by an interaction between the particles and a longitudinal field in output cavities. The drive beam particles may also interact transversely with an electromagnetic field. This mechanism is well known as the *Free Electron Laser*.

In order to use this for rf power generation, one first has to generate a high current, medium energy drive beam. In periodic wiggler sections, the drive beam particles excite rf power by Free Electron Laser action. This power is extracted and guided to a parallel running, high gradient structure. This scheme is one the most advanced ones with respect to experimental work. Using the Livermore test accelerator producing a beam of over 1000 Amperes at 3.5 MeV as drive beam source, a rf peak rf power of 1.8 GW could be generated at 35GHz.

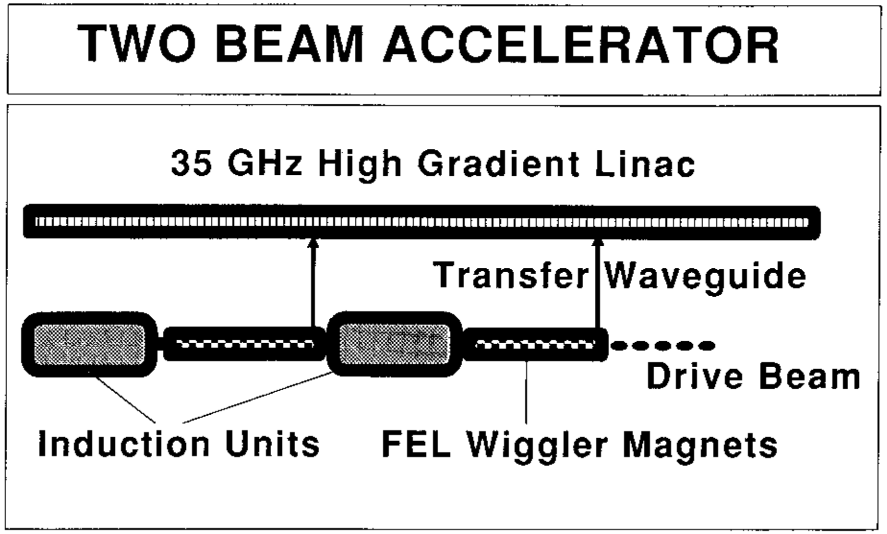

Figure 11: *Two Beam Accelerator. A train of bunches at 50 MeV excites a rf wave in FEL wiggler sections. The energy is extracted and guided to the parallel running high gradient accelerating linac. The energy lost by FEL radiation is periodically replenished by induction accelerator units.*

3.7 Resonant Wake Field Transformer

The scheme of *wake field transformation* can easily be extended from the single pulse transient regime to the resonant regime. Already in the first experiment, a train of six bunches was used. With 50 (say) hollow bunches at 1ns time distance, one could resonantly excite a 2GHz resonance in the wake field transformer of the dimensions shown in figure 12. The major advantage of the resonant wake field transformation is that the transformation ratio is significantly higher than in the transient case. This increase however goes together with a reduction in the actual field strength for a given bunch charge. We find a ratio of **61** for a transformer at 2GHz and 11cm diameter. Thus the driving beam needs 16GV of total volatge to generate a 1TeV beam. The needed charge per bunch is in the order of 50-100nC. Note that the drive linac voltage and drive beam bunch charge are very similar to the case of the *two stage linac* [13].

The drive beam pre-accelerator could be either normalconducting or superconducting. However, it is not yet clear how one can arrange solenoid coils together with superconducting cavities. Certainly, within the range of immediate realization is the use of an ordinary pulsed rf linac at 1GHz. The first bunches in the train are much less decelerated than the very last ones, the necessary energy increases from 0 to 15GV, from the first to the last ring. Thus one can make use of the fact that the volatge in a linac increases almost linearly with time when the power is switched on. Only after some damping times, the voltage saturates. This operational method seems to be very economical as there is no useless powerloss during filling time. Another procedure could be to run the hollow beam gun at a slighlty lower frequency such that the first bunch arrives at zero phase and the last one on top of the voltage in the drive linac.

It is also still being studied how much one would gain by increasing both the drive linac and the wake field transformer resonant frequency. At 3GHz drive linac freqeuncy, the hollow beams are still reasonably large (4cm diameter) and existing power tubes from the SLC could be used right away. Also, one could increase the ratio of the drive linac frequency to the wake field transformer frequency and gain an additional factor in effective transformer ratio this way.

A comparison with other drive linac systems indicates the origin of the limitations. Our numbers are based on **experimentally achieved data.** We assumed 50-100nC per ring at 10cm diameter and 1cm length. In a colinear drive beam scheme the same amount of charge is needed with a filamentary bunch ten times shorter.

After all the *resonant wake field transformer* combines the advantages of the relativistic klystron idea and the "trick" of *geometrical impedance transformation.* It can achieve very high transformation ratios, i.e., ratios between the 1TeV and the drive linac total voltage at relatively low frequencies (1-2GHz). Low frequencies, in turn, allow for easier manufacturing and also strongly relax the tolerance requirements.

Optimization studies are under way, suitable drive linac cavities have already been designed. A first experiment using more bunches in the present set up at DESY is currently under way.

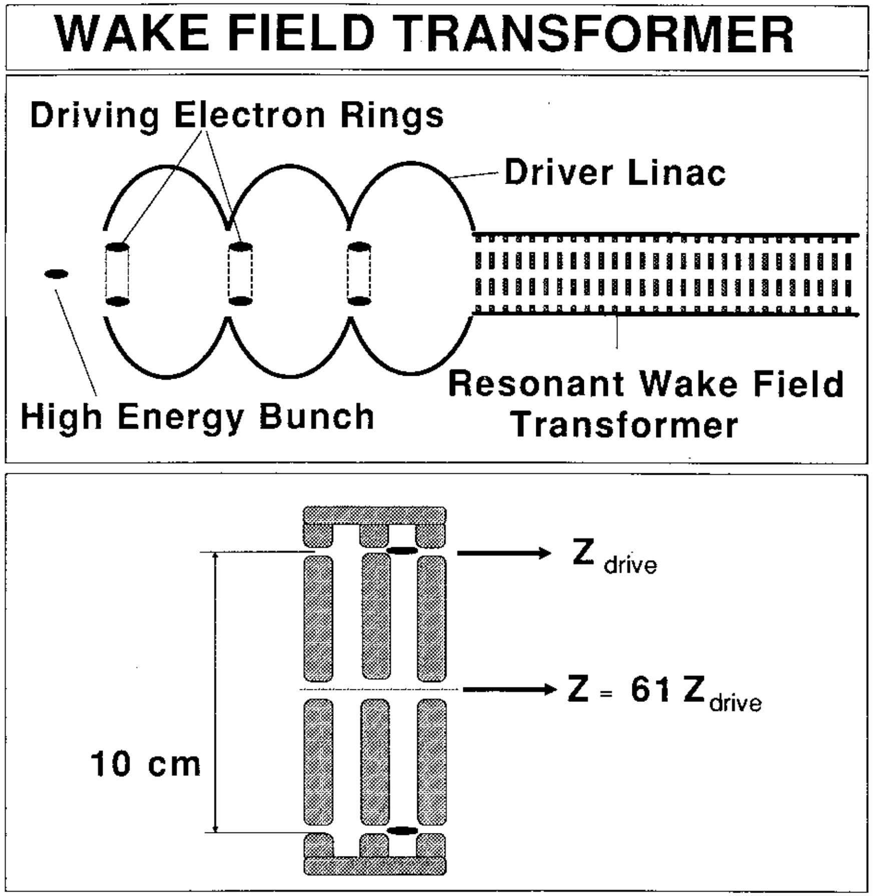

Figure 12: *Resonant Wake Field Transformer. A train 50 to 100 ring bunches, each with 50-100nC charge, excites resonantly a longitudinal mode in the wake field transformer. The impedance of that mode is 61 times lower at the position of the driving hollow beam than on axis. Thus one can generate a total voltage of 1TV using a drive beam of only 16GeV energy. Rings of that charge have been experimentally generated in a train of six pulses (so far). In a first experiment the principle was proven and a gradient of 8MeV/m was measured.*

4 Summary

The reader will certainly get the impression that all these different ideas are, in fact, very similar. This was not the case a few years ago. The presently considered methods of acceleration are the results of a continuous process of investigating many different possibilities, over many years, by many researchers and through many studies.

It is also obvious that during the past few years, ideas have become more and more realistic and closer the technology of today. Nobody still seriously considers plasma accelerators as candidates for the next collider nor the originally enthusiastic ideas on laser accelerators.

The remaining two methods of generating the rf power are by the *transverse electron-wave interaction* in the Free Electron Laser (Two Beam Accelerator scheme) or the interaction of the electrons with a longitudinal field as in all the relativistic klystron proposals. The various latter schemes differ in the methods of drive beam acceleration.

On top of the relativistic klystron idea, the mechansim of *wake field transformation* allows one to drastically reduce the drive beam quality requirements to values that have already been experimentally achieved.

It seems as though there is much more theoretical than experimental work under way on these new technologies. This is an unfortunate situation since the technology being considered is still so much different from what is in use today and that many years of hardware experience will be necessary before one can seriously propose a TeV linear collider.

The next step for all the proposals for acceleration techniques should be a concurrent construction of real test linacs, big enough so one can gather relevant experience with respect to a TeV collider. Thus the final energy of a test linac should be of the order of 10GeV. Theoretical studies are probably already sufficient today to start construction of such test facilities immediately.

Acknowledgement

The author wishes to thank Helen Stokes for careful reading of the manuscript.

References

[1] Final report of the "Rubbia committee" on the long term planning for CERN and CLIC summary report.

[2] ECFA proceedings of the workshop on "New Developments in Particle Acceleration Techniques", Orsay 1987, in print

[3] G.-A.Voss and T.Weiland, DESY M-82-10, April 1982 and Proceedings of the ECFA-RAL Workshop, Oxford, September 1982, ECFA 83/68 and DESY 82-074 November 1982.

[4] W.Bialowons, H.D.Bremer, F.J.Decker, H.C.Lewin, P.Schütt, Xiao Chengde, G.-A.Voss, T.Weiland, this volume

[5] W.Willis, AIP 103, 1985, p.421

[6] T.Weiland, DESY 83-073, 1983

[7] J.W.Wang and G.Loew, SLAC-PUB-4247, 1987

[8] Y.Fukushima et al., INS-Rep.490, March 1984, Institue for Nuclear Study, Univ. of Tokyo

[9] W.B.Hermannsfeldt, SLAC/AP41, 1985

[10] W.Bialowons et al., Proceedings of ECFA workshop on "New Developments in Particle Acceleration Techniques", Orsay 1987, in print

[11] P.B.Wilson, this volume

[12] A.Sessler, Proceedings of the SLAC Linear Accelerator Conference, SLAC-303, 1986

[13] W.Schnell, CERN-LEP-RF/86-06, 1986