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The Wake Field Transformer Experiment at DESY

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Abstract

The basic principle of *Wake Field Transformation* is to use imploding electromagnetic waves generated by high density electron bunches. One of the most simple structures for a *Wake Field Transformer* is the cylindrical pill-box excited by a hollow beam. The fundamental mechanism will be briefly reviewed. A *Proof of Principle* experiment has been set up at DESY by a group of scientists with collaborators from China, Japan and USA. The layout of the experiment is presented together with a status report and most recent results. Several bunches each of 50 to 100 nC charge have been produced and accelerated to an energy of 8 MeV and bunched down to a length of 1 cm. With a central witness beam a gradient of 8 MeV/m has been measured in a short Wake Field Transformer using six subsequent hollow bunches in one pulse.

Introduction

The principle of the wake field acceleration mechanism has been described in detail in other papers [1,2]. Thus, we recall only the basic points of interest: A high charge driving beam of 1 μC (say) and a central low charge driven beam of 0.01 μC both traverse a special kind of multi cell cavity which we call a *Wake Field Transformer.* In this transformer the driving beam excites wake fields that lead to its deceleration. By proper shaping of the transformer geometry the driving beam excites a wave packet that is subsequently spatially focussed. Thus, there is an increase in field strength proportional to the inverse square root of the volume containing the wake fields. A second pulse of particles entering the transformer focal line with proper delay traverses this concentrated wake field and experiences an acceleration which is much greater than the deceleration of the driving beam. The ratio of acceleration to deceleration we call its *transformation ratio.* Values for the transformation ratio of around 10 are expected in our experiment. Thus, one could accelerate a bunch of electrons to 1 TeV using the wake fields of a 100 GeV driving beam and according to our calculations the accelerating gradient will exceed 100 MeV per meter.

This scheme is considered to be a candidate for the next TeV electron-positron collider. It could be built within a total length of about 10 km if the predicted gradients can be reached.

An experiment with a hollow beam *Wake Field Transformer* has been set up at DESY. A laser driven electron gun produces a high current hollow beam of 10 cm diameter. The beam is bunched in a pre-buncher and accelerated in the following linac. This whole unit is in a solenoid guiding field. The final longitudinal compression is achieved in the high energy buncher. Finally, the beam is fed into the Wake Field Transformer. The energy of the central witness beam passing through this transformer on axis is analyzed in a spectrometer adjacent to the transformer.

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1 Experimental Set Up

In order to study the problems associated with the *Wake Field Transfomer* concept we have assembled an experiment [3,4,5] using a complete linac for generation of the driving beam. We chose a cylindrically symmetric transformer since it should provide high transformation ratios and since it was the only one that could properly be analyzed when first proposed in the year 1982.

The driving hollow beam has a diameter of $10\,cm$. When extracted from the gun the charge should be $1\,\mu C$ over a pulse length of $1\,ns$. Thus, we need $1\,kA$ electron current. The design peak value of the pulsed cathode voltage is $150\,kV$. The beam is accelerated to about $8\,MeV$ and compressed before entering the *Wake Field Transformer*. The overall layout of the experiment is shown in Fig. 1 and the major components will be described below.

Hollow Beam Gun. A laser driven gun was chosen for which the photon energy of the laser light is much lower than the work function of the cathode material. The infrared light beam (wave length $1.064\,\mu m$) produced by a Q-switched Nd:YAG laser (peak power $> 100\,MW$) is focussed onto a ring at the conical tantalum cathode and is absorbed inside a very thin layer. Thus, since the surface temperature increases, thermionic emission and thermionic supported photoelectric emission is possible. The emitted electrons are extracted by a pulsed high voltage and guided by a solenoid field (field strength $\sim 0.2\,T$) through a slit in the anode. A more detailed description of the gun and the emission mechanism and some experimental results are given in a separate contribution to these proceedings [6].

Linear Accelerator. The linac consists of a prebuncher and a chain of four 3-cell cavities powered by a $1\,MW$ klystron ($500\,MHz$) which is pulsed at $25\,Hz$ with $100\,\mu s$ duration. The prebuncher consists of a single cell cavity and a following driftspace. The zero current energy gain is $8\,MeV$ and the measured shunt impedance of the accelerating cavities is $20\,M\Omega/m$. Solenoid coils surround the cavities whereever possible. All cavities are mounted with a periodicity of $\lambda/2$. Additional phase shifters enable the phases to be controlled. The first phase shifter between the prebuncher cavity and the first accelerating cavity adjusts the injection phase. A second phase shifter between the first and the second cavity corrects for the delay in phase owing to the subrelativistic energy of the injected electrons. The third phase shifter at the fourth cavity allows us to generate a variable energy spread which is needed for the high energy bunching mechanism in the antisolenoid. As cavities are located in the magnetic field of the solenoid, multipactoring is much more severe than usual.

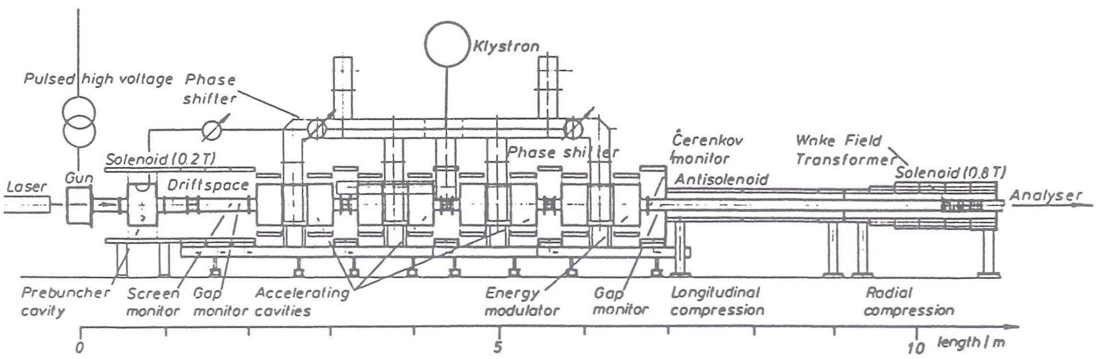

Figure 1: Overall layout of the Wake Field Transformer experiment at DESY.

Shown from left to right: The infrared light beam produced by a Q-switched Nd-Yag laser (peak power $> 100\,MW$*) is focused onto a ring shaped tantalum cathode. The emitted thermionic- and photoelectrons are extracted by a voltage of about* $100\,kV$ *and guided by solenoid fields of* $0.2\,T$ *into the linac. Firstly, the hollow beam is compressed longitudinally in a prebuncher. Then, four 3-cell cavities (*$500\,MHz$*) accelerate it to* $8\,MeV$*. A pulsed klystron (peak power* $1\,MW$*) feeds the cavities. In the antisolenoid further longitudinal compression is achieved. Then the ring is radially compressed by increasing solenoid fields. Finally, the electron ring enters the actual Wake Field Transformer, consisting of 80 cylindrical cells arranged one after another. For monitoring and adjustment of the ring beam, several beam monitors have been set up.*

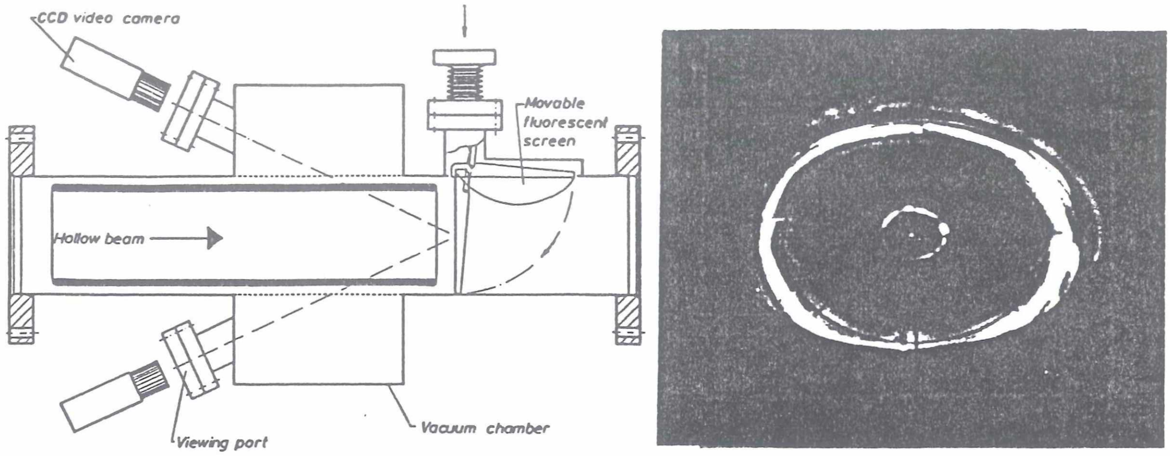

Figure 2: Movable fluorescent screen for monitoring of the hollow beam at the entrance of the linac.
A thin foil of bronze coated with zinc sulphide is pressed against the beam pipe. The hollow beam can pass. If required, the screen can be moved in by a pneumatic system. The projection can be observed by two CDC video cameras (which can be operated in a magnetic field). - A typical photograph of the hollow beam is shown on the left side. The lower part is masked by the beam pipe.

Stable conditions for the prebuncher cavity cannot be achieved owing to the relatively low rf field strength. The field breaks down after aproximately 20 μs. In order to avoid this unstability situation, the rf-power for this cavity is generated separately in a second transmitter and switched off before break down starts. There is an adjustable delay between the prebuncher rf source and the main linac klystron. Thus we can run at a phase where the main linac cavities are at peak voltage, and the prebuncher cavity is still on the rising slope so that no multipactoring occurs.

Measurements of the Hollow Beam. Elements for monitoring the hollow beam are mounted in the drift space of the Prebuncher and at the end of the linac behind the last cavity (see Fig. 1). For the nonrelativistic hollow beam we use a movable fluorescent screen monitor and a gap monitor, for the relativistic beam a gap monitor and a Čerenkov light monitor.

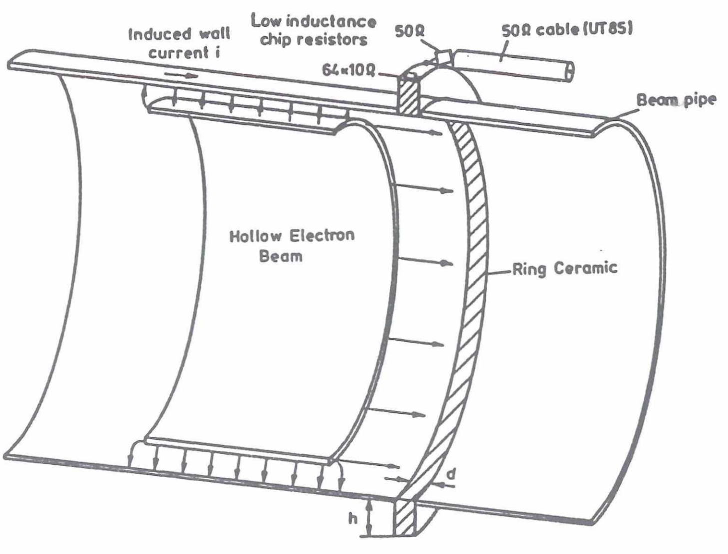

Figure 3: Schematic layout of the gap monitor.
The beam pipe is interrupted by an insulating tube and bridged by 64 10 Ω resistors. Around the circumference of the pipe, 16 pick-ups are fixed. The mean value of the beam current is obtained by a passive network from the signal heights of eight pick-ups. The other eight pick-ups are used for the measurement of the azimuthal distribution of the hollow electron bunches.

A projection of the hollow beam is produced by a fluorescent screen which can be moved into the beam pipe if required and observed by CDC video cameras. The layout of this device is shown in Fig. 2.

A gap monitor measures the wall current induced in the beam pipe. The tube is simply interrupted by an insulating ring and bridged by resistors. The voltage drop across the resistors is proportional to the wall current. For measuring the pulse length of shorter bunches a Čerenkov monitor has been designed. A part of the hollow beam excites Čerenkov radiation in a small quartz wedge. With a light collection system consisting of two mirrors and three lenses the light pulse is guided to the imaging slot of a streak camera. The corresponding peak current must be derived from the signal of the gap monitor mounted near by.

High Energy Buncher. The final longitudinal compression of the hollow beam is achieved in an anti-solenoid. The field strength of the solenoid and of the antisolenoid are equal. The region where the field is radial must be very short. Therefore iron plates are inserted between the coils.

The total effect on the beam of the longitudinal field of the solenoid and the radial end fields is to cause the ring to rotate arround its symmetry axis. As some of the particle energy is now in the circular motion, the longitudinal velocity decreases. The phase of the fourth cavity is adjusted such that the earlier particles are accelerated less than the later ones. Thus the ring can be bunched even at high energies, where classical bunching mechanisms fail.

At the end of the antisolenoid, the rotation is stopped by another inversion of the solenoid field.

Wake Field Transformer. The central part of the whole experiment is the *Wake Field Transformer*. A cross sectional drawing is shown in Fig. 4. An electron ring of 10 cm diameter, 2 mm minor radius, at an energy high enough for it to be relativistic and of total charge 1 μC excites wake field while traversing the transformer through the slot near the outer diameter. The generated wave packet first runs radially towards the outer boundary, is reflected there with reversed sign and subsequently travels towards the center. As the total volume containing the electromagnetic energy is thereby reduced, the field strength is increased inverse proportional to the square root to the volume containing the wake fields. Thus, when the wave has reached the centre, the accelerating field at this location can be 10 to 20 times higher than the decelerating field seen by the particles in the driving hollow bunch. Just to give some idea of the strength of these fields, Fig. 1 shows all wake potentials in the above mentioned device producing an accelerating gradient of 157 MeV/m.

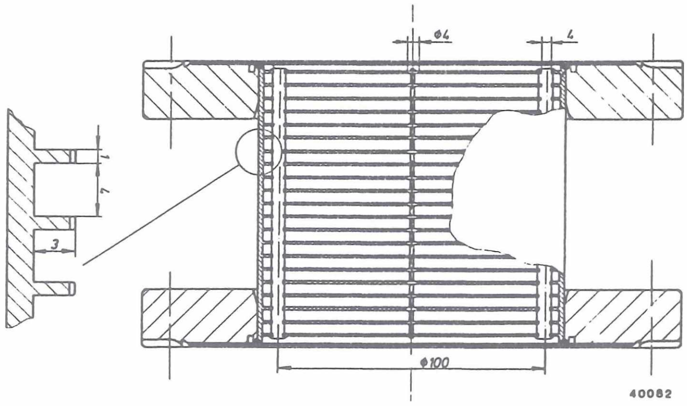

Figure 4: Cross section of one part of the *Wake Field Transformer*.

On the inner wall of the beam tube rebates are turned, on which wake filed are excited by the driving hollow beam. The wake fields are guided by the disks into the center of the beam tube where they interact with the driven beam. The disks are held together by metal strips and form a stack lying normal to the axis of the tube. All parts are made from stainless steel.

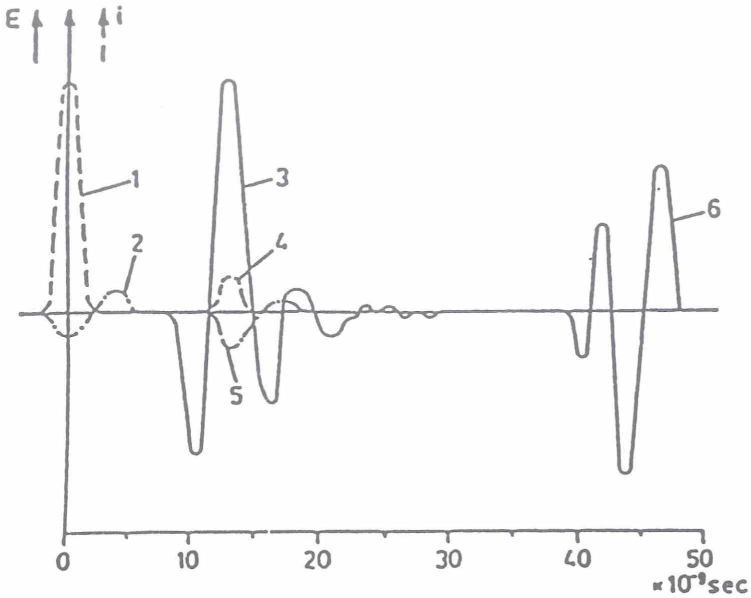

Figure 5: Wake Potentials in a cylindrical *Wake Field Transformer*.

Driving beam: $Q = 1\,\mu C$, $\sigma_{rms} = 2\,mm$, *beam radius* $= 50\,mm$
accelerated beam: $Q = 0.01\,\mu C$, $\sigma_{rms} = 2\,mm$

1... *driving beam density*
2... *driving beam decelerating wake potential,* $W_{min} = 20 MeV/m$
3... *accelerating wake potential for electrons on axis,* $W_{max} = 157 MeV/m$
4... *accelerated beam density*
5... *decelerating wake potential of the accelerated beam,* $W_{min} = 7.3 MeV/m$
6... *accelerating wake potential for positrons,* $W_{max} = 110 MeV/m$

Computer Simulations. The DESY *Wake Field Transformer* experiment has always been accompanied by theoretical studies and computer simulations. Two codes are used for the numerical studies: `WAKTRACK`[7], a fast tracking code including collective effects, is used as an operating tool in parallel with the experiment. It will also be used for investigations on the feasibility of a future *TeV* collider. More detailed investigations, especially in the low enrgy region ($\gamma \leq 20$), are carried out with `TBCI-SF`[8], a new particle-in-cell code. Both programs are described in more detail in another contributions to these proceedings[9].

2 Stage-1 Experiment

In order to investigate step by step the problems concerned with hollow beam dynamics we first omitted the high energy buncher and set up a *stage-1* experiment to get a first proof of the *Wake Field Transformation* concept. The layout of this experiment is shown in Fig. 6.

We are using a transformer which is optimized for the hollow beam size bunched by the linac. The separation of the plates is 1 *cm* and the thickness 2 *mm*. The plates are held by four longitudinal sticks near the slot for the hollow beam. The test beam is produced by a field emission gun which uses the first transformer plate as anode. The cathode consists of a pointed tantalum needle. Since the beam was nonrelativistic only a short transformer could be used: Slow particles are not able to stay in phase with the wake field pulse running at the speed of light. The optimum transformer consists in this case of two cells. Two lead blocks provide shielding against electrons from the hollow beam and parasitic electrons. The energy of the electrons accelerated by the excited wake fields is measured by a decelerating grid method. Only particles with energy greater than the grid voltage penetrate to the zinc sulphide screen and can be detected by a photomultiplier. From the difference with the test gun voltage we can determine the energy rise in the transformer.

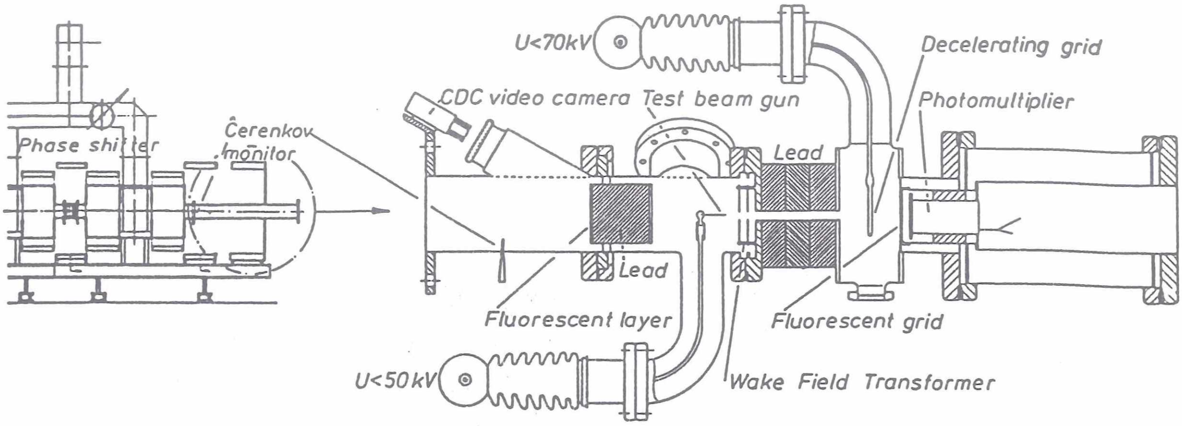

Figure 6: Overall layout of the *stage-1 Wake Field Transformer* experiment at DESY.

A Čerenkov light monitor measures the pulse width of the hollow beam and a gap monitor measures the charge of the subsequent bunches of a pulse. The surface of the first lead block is used as a fluorescent screen for monitoring the adjustment of the hollow beam relative to the slot.

3 Experimental Results of the Linear Accelerator

The study of the properties of the linear accelerator involved many measurements. We have chosen three typical ones for this report.

Azimuthal distribution of the hollow beam. The momenta of the charge distribution within the hollow beam relative to the centre of the beam pipe can be measured by the gap monitor using the signal heights of the eight pick-ups mounted around the circumference of the monitor. The signals for two different currents are shown in Fig. 7. In order to get the correct azimuthal distribution of the hollow beam the different damping of the eight signals due to the different length of the lines and the cross talk between one signal and the others must be taken into account. The relative dipole moment of the hollow beam is less than 20 % in this example.

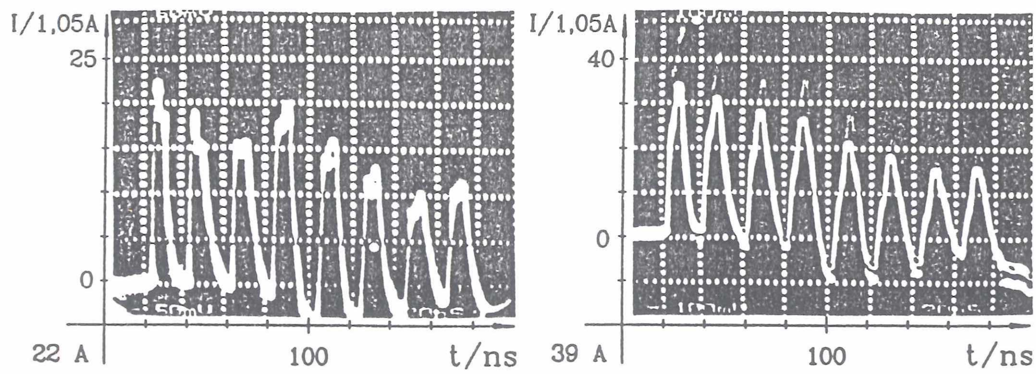

Figure 7: Azimuthal distribution of the hollow beam for two different currents.
Eight signals around the circumference of the gap monitor are delayed by delay lines, added by a passive resistor network and measured by one channel of an oscilloscope. Thus it is possible to measure the eight signals of one pulse simultaneously. On the left photograph a distribution is shown for a hollow beam current of 22 A and on the right photograph for 39 A.

Measuring subsequent bunches. The prebuncher cavity ($\nu = 500\,MHz$) compresses the gun pulse sequence of short bunches within a period length of $2\,ns$ (see Fig. 8). The bunches can be monitored by a gap monitor positioned at the end of the drift space. At relatively high currents ($I_0 \sim 50\,A$) only a weak compression can be achieved due to longitudinal space charge effects. At low currents very short bunches are achieved, whose length approaches the resolution limit of this gap monitor ($\sigma < 50\,ps$).

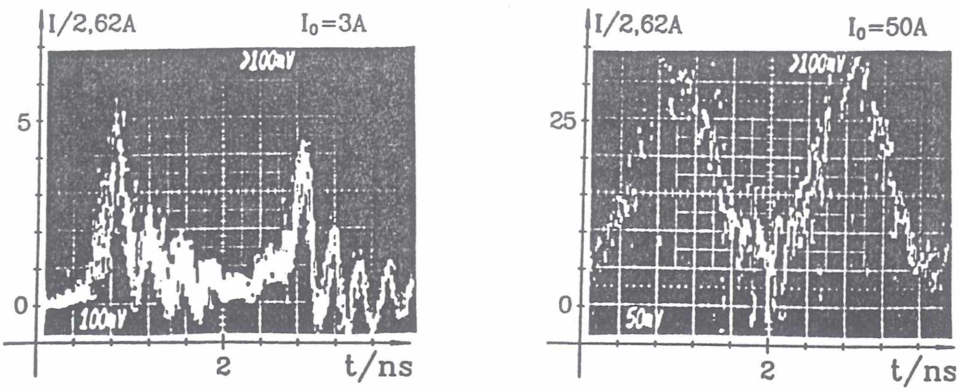

Figure 8: Two bunches of six generated by the prebuncher.

Measurement of picosecond bunches. For measuring short bunches a Čerenkov light monitor has been built. Particles of the hollow beam excite Čerenkov light within a small quartz wedge. The light is detected by a streak camera. Fig. 9 shows a typical signal measured by the streak camera. This is compared with the corresponding response of the gap monitor mounted nearby. It can be seen that the time resolution of the gap monitor has been reached. But, the charge in one of the bunches can be calculated from the integrated signal and together with the length measured by the light monitor, the amplitude of the current can be determined indirectly.

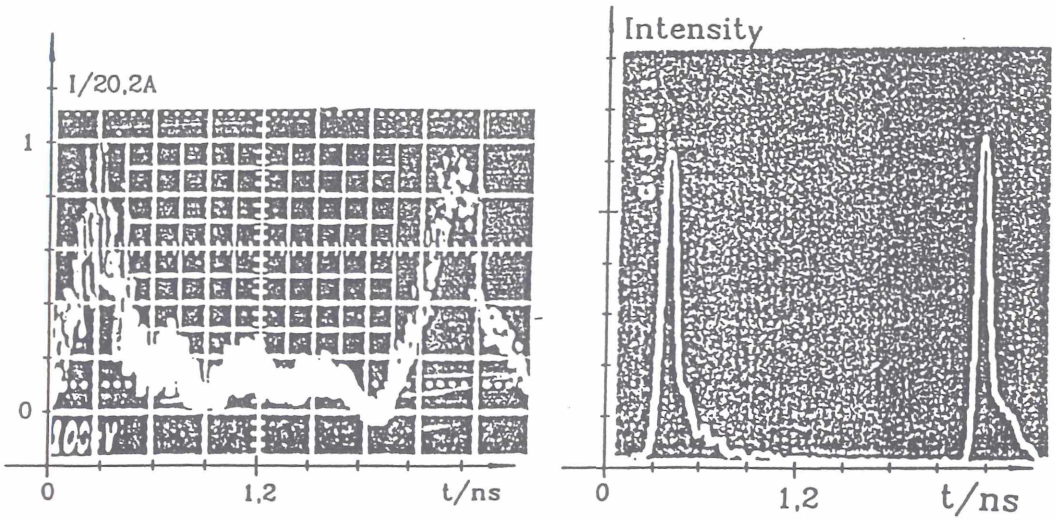

Figure 9: Comparision of the signal response by a gap monitor (left) and a Čerenkov monitor (right).

4 First Experimental Proof of Wake Field Acceleration

In the *stage-1* experimental set up as described above, we first tried to study the problems concerned with steering the hollow beam through the transformer. We were able to generate a current pulse of rms length 1cm and a peak current in excess of 500*A*. The corresponding gun current was 55A, the gun voltage 85kV. The hollow beam consists of a train of six subsequent electron bunches separated by the rf wavelength of the drive linac (60cm). Wake fields excited in the transformer travel continously back and forth radially with a reversal in sign after each reflection at the outmost radial boundary. The travel time for a wake field pulse in the transformer used in this experiment was exactly one fourth of the period of the linac frequency. Thus subsequent ring pulses generate a wake field which adds constructively. For the field at the center there is no difference between six pulses and one pulse with six times the charge.

The beam radius could be adjusted by means of additional power supplies hooked onto the three last solenoids. The beam penetrated through the transformer without significant loss in intensity.

At the end of the linac the hollow beam bunches are much longer than the 2mm that we intend to achieve with the high energy bunching scheme. Thus, wake fields excited by these bunches are significantly weaker than they will be in the final set up as described in Section 1. Even with six bunches we could not expect a change in energy in a transformer placed at this location in the beam line to be high enough to be detectable with a central witness beam running all along the linac. This is because beam loading of the hollow beam and other effects create an energy jitter in the witness beam which is just of the same magnitude as the expected acceleration.

In order to be able to detect even small changes in energy we decided to install a separate witness beam gun with a well defined and low energy. The witness beam dc current was injected at an energy of 20kV into the transformer.

The low energy of the witness beam however has other severe disadvantages. Particles at 20keV are much too slow to stay in phase with the wake field pulse running at the speed of light. In a transformer which is a few times longer than the width of the wake field pulse, the net energy gain of witness particles would average out to zero. The only way to avoid this effect is to make the transformer as short as the pulse width. Following an optimization procedure of maximizing the energy gain as a function of tranformer length we obtained an optimum for a length between 2 and 3cm. We optimized the period length, slot height, central beam hole radius and upper cavity depth for a bunch length of 1cm and obtained a two cell structure, each cell being 1cm long and separated by a 2mm thick metallic disk.

We ran the linac for the above mentioned beam parameters and injecting the witness beam into the transformer. First we switched off the central beam in order to see the background due to secondary photons produced by the hollow drive beam particles. Fig. 4 shows the background signal of the photomultiplier tube.

We than switched on the witness beam and slowly increased the *stopping* voltage on the grid (see Fig. 6) behind the transformer. We expected a maximum acceleration of around 30keV, which we calculated under

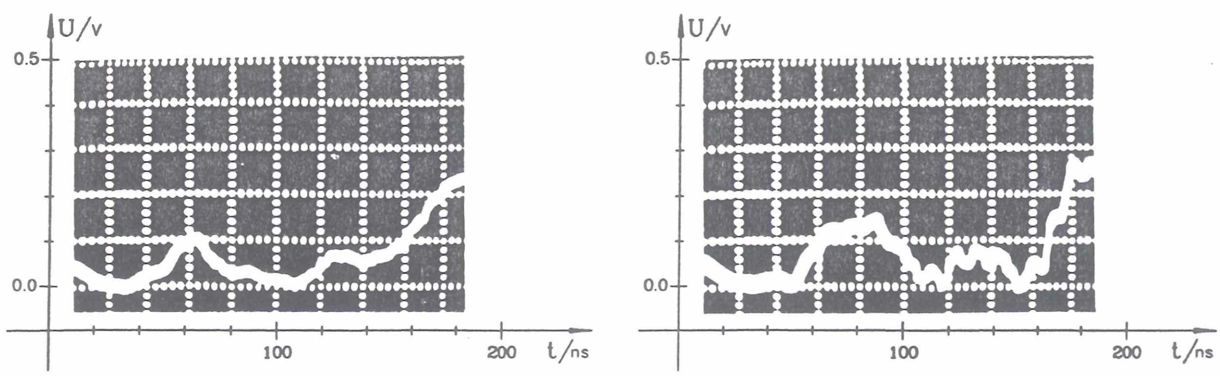

Figure 10: Photomultiplier signal of light produced by electrons traversing the final potential barrier.
Left: *Background signal due to secondary photons created by scattered electrons of the driving beam.*
Right: *Signal from particles accelerated in the wake field transformer.*

the pessimistic assumption that the capture efficiency of the drive linac is only 50 % and that the ring shape is Gaussian [1] in the longitudinal direction. At a voltage of 70kV we were limited by the power supplies but could not yet see any significant decrease of the clear signal from the witness beam particles, see Fig. 4.

Thus we not only had a clear signal of the first particles accelerated by the mechanism of *Wake Field Transformation* but we also found an acceleration higher than expected at least more than 50keV. Thus the charge capture efficiency was better than assumed and/or the bunch shape was narrower than in a Gaussian distribution. This acceleration of 50keV over 2.4cm (which is the length of the transformer including two of the three disks) yields a gradient of **2 MeV/m** for 20keV particles.

It is relatively straightforward to evaluate by means of computer simulation that relativistic particles would be accelerated by these fields at a rate of **8 MeV/m**.

5 Summary

The first experimental proof of the new acceleration mechanism of *Wake Field Transformation* has been completed at DESY. The experiment did show that this scheme is technically feasible.

A number of effects concerned with the unusual beam dynamics of high density hollow bunched beams were studied. The charge densities achieved in this first (not at all optimized) experiment are around 1/10 of the original design values.

Means to improve this situation, such as increasing the laser power, increasing the gun voltage, increasing the width of illuminated cathode area, replacing the present buncher by a subharmonic one etc.., are under investigation.

The *stage-2* experiment will mainly be concerned with the longitudinal bunch compression in the antisolenoid region. In this compressor the bunches will also the significantly improved in their azimuthal symmetry since a local asymmetry at a specific angular position will be smeared out (due to the energy spread produced in the last linac cavity) over all the bunch circumference. This next step will presumably increase the peak intensities by a factor of five and the peak values of the wake fields even by a factor of ten.

In the case of a multi pulse operation which is now being considered, the bunch charge experimentally achieved is in fact high enough for a scheme with 10-20 pulses or even *too* high in a scheme with more pulses.

Also, the multi pulse operation relaxes many beam quality requirements. Whereas longitudinal wake fields add up coherently, in general this is not so for transverse deflecting wake fields since the two classes of modes do not have the same frequencies. Thus for such a multi pulse WFT with more than 20 bunches the existing experimental setup already fulfills the requirements for a real *1TeV Wake Field Tranformer* linear collider.

Acknowledgement

Over the years from 1982 to 1987 a large number of people have contributed to the design and construction of this experiment. We wish to express our deep thanks to our collaborateurs from KEK, S.Ohsawa and K.Yokoya who both spent a year working at DESY, Prof. S.L.Wang from the University of Bejing, K.Bane from SLAC and G.Rodenz from LANL.

Our thanks are also due to many collegues at DESY who were members of the wake field group during the design phase and worked on the beam dynamics and the layout of the experiment: H.C.Dehne, M.Leneke, J.Rossbach and F.Willeke.

Special thanks are also due to M.v.Hartrott (now at BESSY, Berlin) who was with our group for a period of one year and who designed the analyzing apparatus which, as described above was successful.

A great portion of the success of the experiment was due to the intensive help by all the technical groups at DESY: The rf group headed by H.Musfeldt, the controls group headed by F.Peters, the power supply group headed by H.Narciss and W.Bothe, the injection group headed by A.Febel, the civil engineering group headed by K.Sinram and the vacuum group headed by J.Kouptsidis.

Finally, we would like to thank D.Barber for carefully reading of the manuscript.

[1] The actual shape as observed is steeper than a Gaussian bunch and thus presumably creates stronger wake fields.

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