The Transient Wake Field Transformer Experiment

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Abstract

The basic principle of *Wake Field Transformation* is to use imploding electromagnetic waves generated by high density electron bunches for accelerating a second pulse of particles. The fundamental mechanism will be reviewed. One of the simplest structures for a *Wake Field Transformer* is the cylindrical pill-box excited by a hollow beam. A *Proof of Principle* experiment has been set up at DESY by a group of scientists with collaborators from China, Japan and the USA. The layout of the experiment is presented together with a status report. In a *Stage-1* experiment several bunches, each of 50 to 100 nC charge, have been produced and accelerated to an energy of 6.5 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 consecutive hollow bunches in one pulse. In a most recent experiment the high energy buncher has been investigated where the bunches have been bunched down to a length of 4 mm.

Introduction

As the principle of the wake field acceleration mechanism has been described in detail in other papers [1], we will only recall the basic points of interest. The idea originated from the observation that wake fields in existing accelerators can produce enormously strong decelerating wake potentials. However, the wake potential for particles at the far tail is positive (acceleration). But, the maximum accelerating potential behind the bunch cannot exceed twice the maximum decelerating potential inside, which is the case for short and longitudinally symmetric bunches. Conditional on conservation of energy the charge in the following bunch must be much smaller than the one in the driving bunch. Both conditions together result an accelerator using this method is not very economical to build.

The situation is significantly improved using the mechanism of *Wake Field Transformation*. Both a high charge driving beam of $1 \mu C$, say, and a central low charge driven beam of $0.01 \mu C$ traverse, at different locations, 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 properly shaping the transformer geometry, the driving beam excites a wave packet that is subsequently spatially focused. 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

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line with proper delay, traverses this concentrated wake field and experiences an acceleration which is much greater than the deceleration of the driving beam. We call the ratio of acceleration to deceleration its *transformation ratio*. The simplest transformer geometry is the circular symmetric hollow beam transformer. Values for the transformation ratio of around 10 are expected for a prototype of this transformer. 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.

1 Experimental Set Up

In order to study the problems associated with the *Wake Field Transfomer* concept we have assembled an experiment [2] 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. The hollow beam gun, the measurements of the hollow beam and the computer simulations are presented as separate contributions to this conference.

High Energy Buncher. The accelerating gradient in a *Wake Field Transformer* is inversely proportional to the square of the driving bunch length. Thus, a short bunch is very important. The final longitudinal compression of the hollow beam is achieved in an antisolenoid. The total effect on the beam of the longitudinal field and the radial end fields is to cause the ring to rotate around 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 higher energies, where classical bunching mechanisms fail.
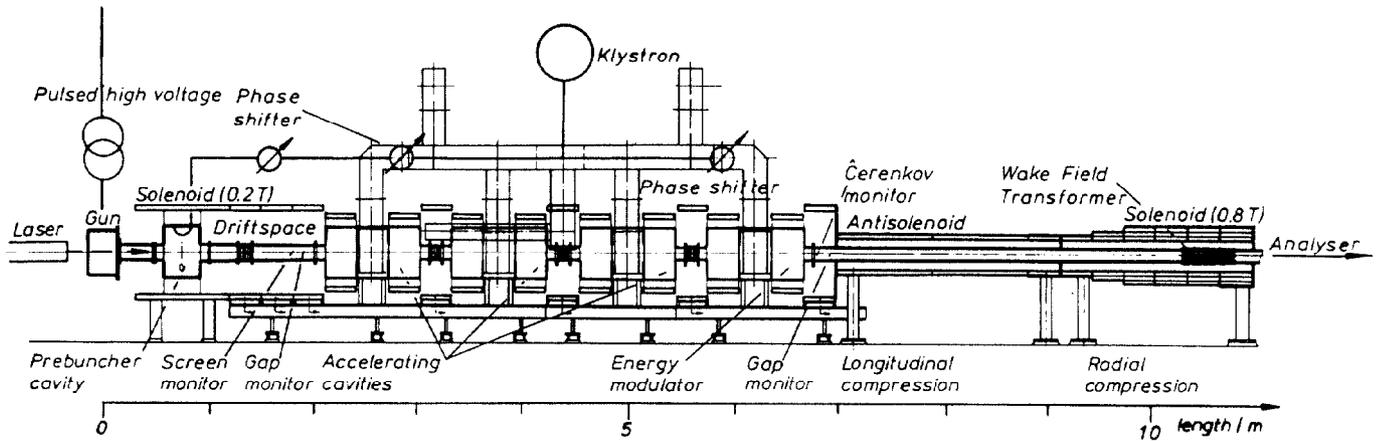
Figure 1: Overall layout of the Wake Field Transformer experiment at DESY.

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. First, 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 in series. The energy of the central witness beam passing through this transformer on axis is analyzed in a spectrometer adjacent to the transformer. Several beam monitors have been set up to monitor the hollow beam: A screen monitor and a gap monitor are mounted in the driftspace of the prebuncher, a gap monitor and a Čerenkov monitor at the end of the accelerating cavities.

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*. 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 fields 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 inversely proportional to the square root of 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, the wake potentials in the above mentioned device produce an accelerating gradient of 157 MeV/m.

Stage-1 Experiment. In order to investigate step by step the problems concerned with hollow beam dynamics, we initially 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. 2. We are using a transformer which is optimized for the hollow beam size bunched by the linac. For several reasons the test beam was nonrelativistic. Thus, 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. The energy of the electrons accelerated by the excited wake fields is measured by a decelerating grid method. From the difference between the grid voltage and the test gun voltage, we can determine the energy rise in the transformer.

2 Experimental Results

In the *Stage-1* experiment we were able to generate a current pulse with a length of 2.5 cm. The corresponding gun current was 55 A at a cathode voltage of 85 kV. From these values we can calculate a bunched peak current in excess of 600 A under the assumption that the capture efficiency of the drive linac is 50 %. The hollow beam consists of a train of six consecutive electron bunches separated by the rf with a wavelength of 60 cm. Wake fields excited in the transformer travel continuously 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 fields which add 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.

We ran the linac with the above mentioned beam parameters and injected the witness beam into the transformer. First, we switched off the central beam in order to see the background due to secondary photons produced
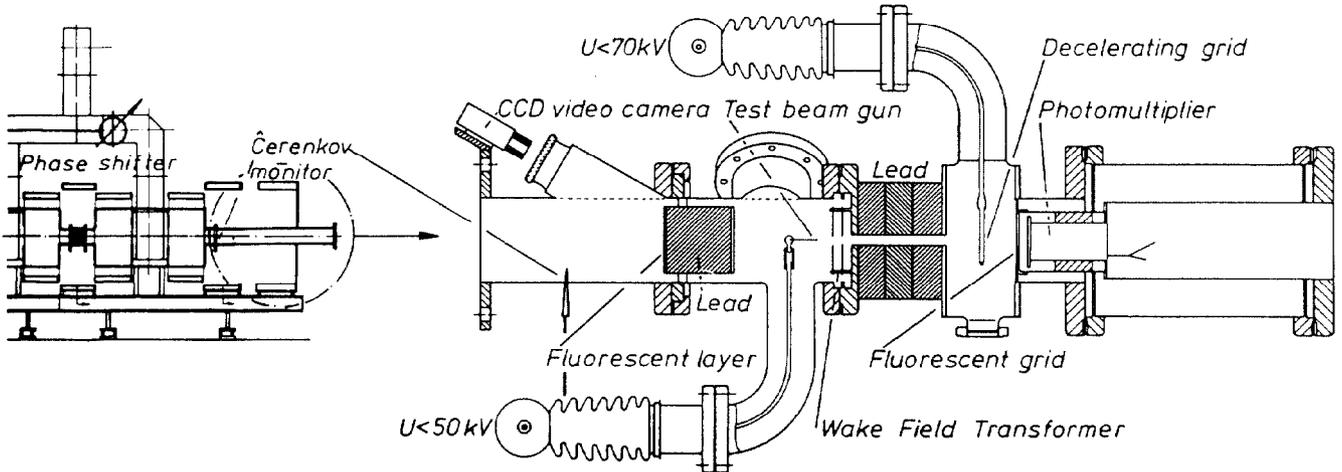
Figure 2: Overall layout of the *Stage-1 Wake Field Transformer* experiment at DESY.

At the end of the linac a stage-1 experiment is mounted. After leaving the last cavity, the hollow beam is monitored by a combined Čerenkov and gap monitor. Then the hollow beam traverses around a lead block with a zinc sulfide which is used for shielding the experiment against parasitic electrons and for monitoring the adjustment of the hollow beam. The test beam is created by a field emission gun. The hollow beam excites the electromagnetic waves in a short Wake Field Transformer consisting of two cells. The separation of the plates is 1 cm and the thickness 2 mm. While these wake fields propagate to the center, the field strength increases where they modulate the test beam electrons. The electrons with an energy higher than the decelerating grid voltage can pass the grid and excite visible light on a fluorescent screen. This light is detected by a photomultiplier.

by the particles of the driving hollow beam. Then we switched on the witness beam and slowly increased the *stopping* voltage on the grid (see Fig. 2) behind the transformer. At a voltage of 70 kV we were limited by voltage break down but could not yet see any significant decrease of the clear signal from the witness beam particles, see Fig. 3. This acceleration of 50 keV over 2.4 cm, which is the length of the transformer including two of the three disks, yields a gradient of 2 MeV/m for 20 keV particles. It is relatively straightforward to calculate by means of computer simulation that relativistic particles would be accelerated by these fields at a rate of 8 MeV/m.

In a most recent experiment we investigated the additional longitudinal compression. Up to now the driving hollow beam has been bunched down to a length of $\sigma = 4$ mm by the high energy buncher.
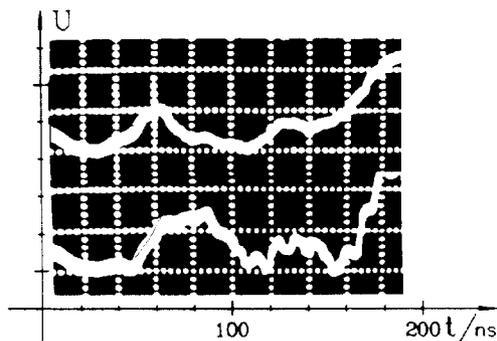
Figure 3: Photomultiplier signal of light produced by electrons traversing the final potential barrier.

Up: *Background signal due to secondary photons*
Down: *Signal from accelerated particles*

Summary

The first experimental proof of the new acceleration mechanism of *Wake Field Transformation* has been completed at DESY. The experiment has shown 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 are under investigation. As a first step we increased the peak intensity by a factor of two to three by using the high energy buncher. By that we expect an increase of the wake fields even by a factor of about five. A proof of the higher gradient with a longer transformer section will start soon.

A multi pulse option called the *Resonant Wake Field Transformer Concept* is represented by a companion paper in these proceedings.

References

[1] G.-A.Voss and T.Weiland, *Wake Field Acceleration Mechanism.* ECFA 83/68.

[2] W.Bialowons, H.-D.Bremer, F.-J.Decker, H.-Ch.Lewin, P.Schütt, G.-A.Voss, T.Weiland, Xiao Chengde, *The Wake Field Transformer Experiment at DESY,* ECFA 87/110.