The Resonant Wake Field Transformer (RWT)–Collider

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Abstract

Future e^+e^- Linear Colliders with center of mass energies of 2 TeV need average accelerating gradients of 100 MeV/m to be built within a length of 20 km. The gradients required by colliders at this energy range can be economically provided by resonant *Wake Field Transformers*. At the Wake Field Experiment at DESY a 20 cm long transformer section was investigated and the most recent results are presented in this paper. The second part gives a short overview of the present status of research concerning the proposed next stage of a multibunch driver linac with superconducting cavities and long *Wake Field Transformer* sections.

Introduction

Wake Field Acceleration techniques provided by imploding electromagnetic waves, which are spatially focussed in a special transformer [1], as well as the first experimental results have been described in detail in another paper [2]. At the last EPAC a second stage of experiments was proposed, in order to investigate a resonant *Wake Field Transformer* which is a special type of a Relativistic Klystron [3]. The high charge of one hollow driver bunch is divided into several bunches and at the outer boundary excites a mode in a multicell transformer cavity for the resonant addition of Wake Fields [4]. While the train of hollow beam bunches is decelerated, the low charge test beam enters the transformer on axis with a proper delay and is accelerated. The driver beam in the experiment, consists of 5–6 bunches and with a diameter of 10 cm, is guided through the linear accelerator and the transformer section by solenoidal fields. The whole experiment is shown in figure 1.

1 The New Experimental Set Up

To study a longer transformer section, a relativistic test beam and a corresponding energy spectrometer are needed. The space of 8 cm between the 3rd and 4th cavity (see figure 1) was enough to install a field emission gun, including a small bellow and the flanges. Behind the 4th cavity the central test beam must go exactly through the middle of the solenoid–antisolenoid section to avoid the excitation of helical motion, before leaving the last solenoid. Entering the spectrometer, which consists of two quadrupoles and one 30° dipole, the intensity of the test beam is measured with respect to the momentum.

Resonant Wake Field Transformer

The design of the resonant *Wake Field Transformer* has to fulfill several constraints for our experiment. First the resonance frequency must be generally a multiple of the driving frequency. In our case the frequency ratio of the accelerating mode in the *Wake Field Transformer* (WFT) to the repetition frequency of the hollow beam bunches (ν_{WFT}/500 MHz) was eight. Secondly for a given hollow beam radius the outer boundary of the transformer cavity was chosen in such a way, that the decelerating field at the radius of the beam has a local maximum. This provides a strong coupling of the drive beam to this mode at the expense of a low transformation ratio, which was three in our

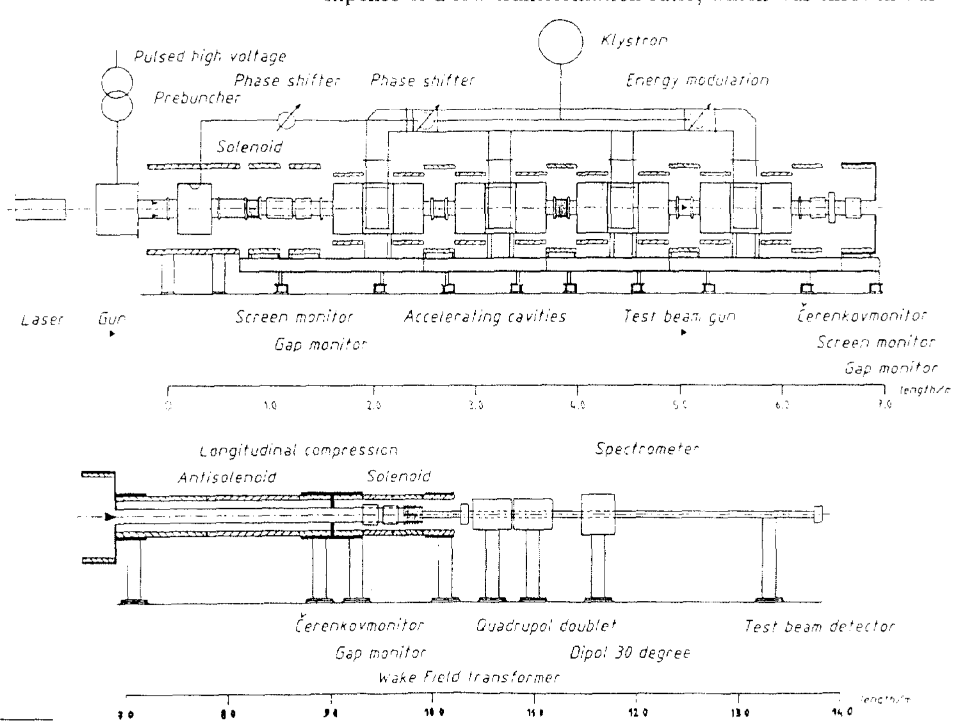


Figure 1: Stage II set up of the Wake Field Transformer Experiment at DESY

Shown from left to right: A laser driven electron gun produces a hollow beam of 10 cm diameter at an energy of about 150 keV. The beam is guided by solenoid fields of 0.2 T along the linac. First, it is compressed longitudinally in a prebuncher. Then, four 3-cell cavities (500 MHz) accelerate the beam to about 7 MeV. An energy modulation provided by the last cavity is used in order to achieve a further longitudinal compression in the antisolenoid. The energy of the central witness beam passing through the resonant Wake Field Transformer on axis is analyzed in a spectrometer adjacent to the linac.

*Now Stanford Linear Accelerator Center, SLAC, California, USA design. However, the idea was to study a longer transformer section rather than to achieve a high gradient.

In the transformer (see figure 2) two glass domes were included to get a reference signal from the antennas which were mounted inside. The first and the last cell are only half cells. The slot for the hollow beam was electromagnetically closed by a grid at the entrance and the exit. With 11+2/2 cells we get a $3\pi/12$ mode, which has the right phase advance, phase velocity and frequency to have a special closed transformer cavity which could be tested in an RF-laboratory; a resonant frequency of 4.01 GHz for the selected mode was measured.

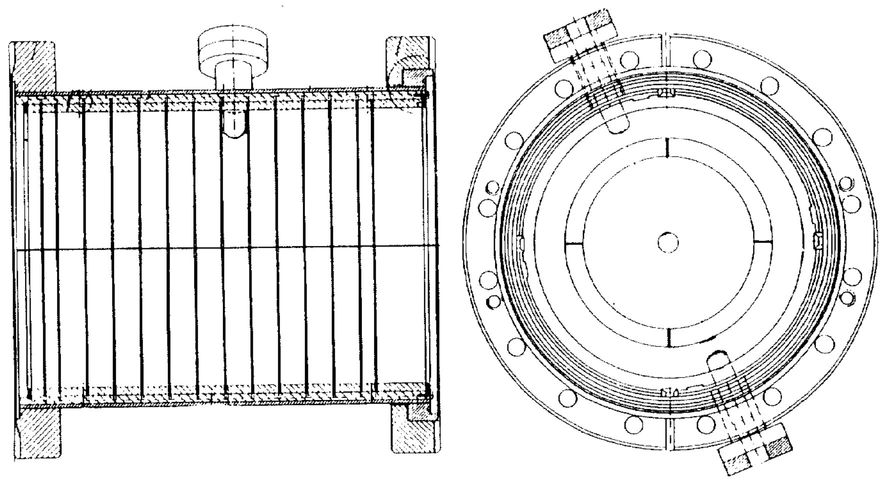


Figure 2: Wake Field Transformer

The resonant Wake Field Transformer consists of 12 (= 11+2/2) *cells. Two glass domes are included in the* 6

Experimental Results

The energy resolution of the spectrometer was calibrated by reducing the accelerating voltage in the fourth cavity.

The corresponding momentum reduction of the test beam could be resolved well below 35 keV/c. In the experiments we could also measure the lowered momentum of the test beam due to the beam loading induced with or without the hollow beam going through the cavities. The Wake Field Acceleration was measured by scraping the hollow beam in front of the transformer (and after the cavities) by a vacuum valve with a hole in its center. In this case the measured intensity peak in the energy distribution of the test beam was broadened (see fig. 3). The test beam bunches are longer than half a wavelength in the transformer and therefore some particles are accelerated while the others are decelerated. With a current of 5–10 A a gradient of 21 MeV/(m μC) was measured with a bunch length of $\sigma_l = 1$ cm. This is in good

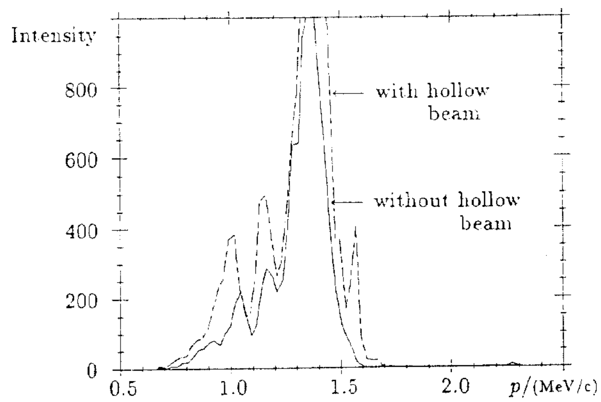


Figure 3: Wake Field Acceleration

agreement with the theoretical value. In addition the signal from the antennas in the transformer were investigated, in order to determine whether the hollow beam optimally excites the transformer. A sampling head was used to resolve the excitation of the 4 GHz oscillation, but especially at higher currents no resonant addition of the field amplitude was found. Due to the increased beam loading in the cavities with higher hollow beam currents, the decreased momentum from bunch to bunch is transformed into a distance variation in the high energy buncher. Therefore the resonant excitation in the *Wake Field Transformer* gets out of phase. A measurement of the bunch distance with a streak camera confirmed this assumption. This leads to reasonable results only with small hollow beam currents of 5–6 A.

2 Further Developments

The decision to use a multibunch driver scheme leads to a completely new concept of efficiency and energy transfer to accelerate the test beam. In our linac a special longitudinal dynamic is chosen in order to realize this optimum. The calculations for the envisaged TeV Collider are presented.

Longitudinal Dynamic

In the driver linac the hollow beam enters the driver cavities at an increasing voltage from bunch to bunch in order to compensate the multibunch energyspread due to the beam loading in the transformers. After the maximum voltage is reached, the central test beam passes the loaded transformer on axis and extracts only a few percent of the stored energy. A second train of hollow beam bunches follows the first one with its phase shifted by 180 degree with respect to the rf. This train is accelerated in the transformer and decelerated in the superconducting driver cavities, which are running in cw-mode. Going through one complete section, which consists of driver cavities and transformers, the energy gain and loss versus bunch number is shown in figure 3 for the driver and the recuperation beam. This idea allows a dedicated recuperation system which reduces the re-

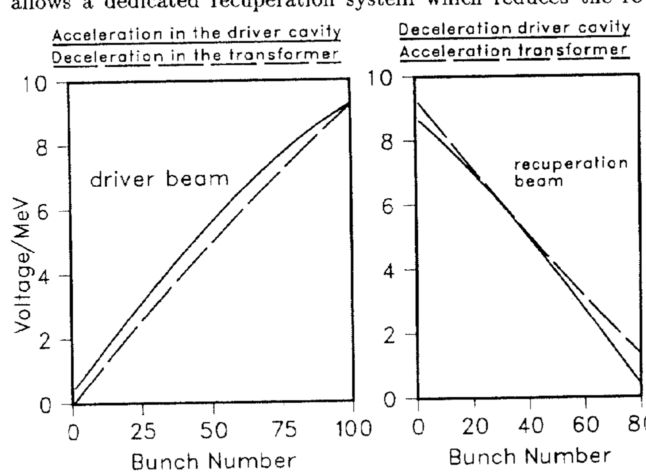


Figure 3: Energy transport in one linac section

cavity parameters			
	driver		transformer
f_1	500 Mhz	f_2	6 GHz
Q_1	3 10^9	Q_2	12000
V_0'	20 MV/m	t	25
bunch parameters			
first beam		recuperation beam	
N_1	100	N_2	80
$q_{bun\,1}$	153 nC	$q_{bun\,2}$	118 nC
gradient,length ratio and efficiencies			
G_{ave}	42 MV/m	Average Gradient	
L_2/L_1	5.0	length ratio	
efficiencies			
η_1	73%	hollow beam to transformer	
η_2	79%	transformer to recuperation beam	
η_3	91%	recuperation beam to driver	
g	2.15	energy gain	
The whole calculation includes parasatic losses			
In η_1 and η_2 wall losses are included			

Table 1: Results for a 500 MHz driver linac and a transformation ratio of t=25.

quired rf-power by a factor of g, with g=1 without recuperation and $(1-\eta_1\eta_2\eta_3)$=1.8–2.5 in our case. Table 1 shows an optimized set up with 500 MHz driver sections (length L_1) and 6 GHz Wake *Wake Field Transformers* (length L_2) [5].

Hollow Beam Gun

From table 1 we can see, that 180 bunches are needed with a charge of $\simeq$150 nC per bunch. Therefore the gun must provide a current pulse with a length of at least 360 nsec. Two possibilities were investigated. The pulse of the laser illuminating the cathode was splitted and optically delayed. This leads to a power puls quadratically decreasing and an extended emission from the

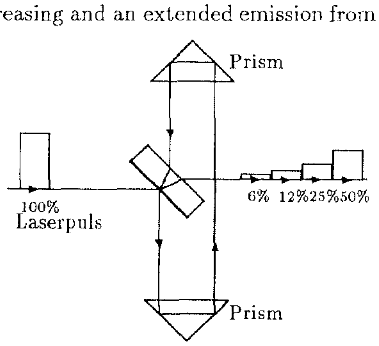


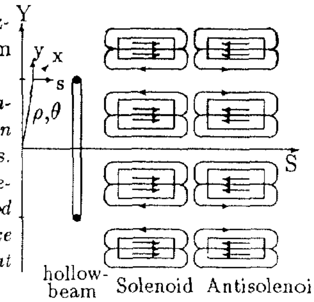
Figure 4: Pulse lengthening by a Photon Storage Ring.
The light pulse of a laser is split and part of the pulse is delayed. The light is reflected by two prisms and coupled out by the beamsplitter.

cathode. The other method uses thin film techniques where a tantalum film, with a thickness of a few hundred nanometer, is evaporated on an insulating ceramic substratum. The temperature of the layer rises fast compared to the length of the laser puls, but thermal diffusion can only take place within the surface. This results in a delayed thermoionic emission. Pulses longer than 30 nsec have been reached [6].

Strong Focussing for Hollow Beams

Up to now, the entire linac was mounted within solenoid coils (see fig. 1) to guide the hollow beam. A concept, using strong focussing, as described for central beams in [7], has the great advantage of field free driftspace and smaller transverse dimensions. Superconducting cavities and long transformer sections can be installed in between the hollow beam lenses. The focussing is provided by permanent magnets which nowadays can have remanent fields of more than 1.2 Tesla. The axially symmetric arrangement of the magnets, leads to a special *solenoid antisolenoid* combination, with a field gradient perpendicular to the reference ring with radius ρ. Solving the equations of motion in

Figure 5: 2-D cut of an azimuthal symmetric hollow beam lens.
Permanent magnets with remanent fields of up to 1.2 T can be used to focus hollow beams. The axially symmetric arrangement provides a special soleniod antisolenoid field, which acts like a lens with fokal length $\leq$ 10 m at hollow beam energies $\geq$200 MeV.



the local frame on a cylinder with radius ρ under the assumption of a thin lens, the net azimuthal rotation vanishes when going through the whole *solenoid antisolenoid*. This is very important, because the inner magnets could be fixed without loosing a significant portion of electrons. Particles on a separated path from ρ with r not equal zero are always focussed towards the hollow beam ring with a focussing strength proportional to $(\gamma/B_z)^2$.

The anology with solid beams is valid for amplitude- and phasefunctions (β(s), μ(s)). In the case of hollow beams they are given on the beam radius ρ and they have azimuthal symmetry going at a given point s once around the reference ring with radius ρ [8].

3 Conclusions

The resonant *Wake Field Transformer* is considered for a colinear, two-beam TeV collider. In comparison with other schemes, the idea of a resonant impedance transformation seems to have many advantages. For example, no separate rf-extraction is needed and the structure is directly filled with the velocity of light by the hollow driver beam. The moderate frequency of 6 GHz in the transformer sections avoids the severe problems with parasitic losses, transverse wake fields and delicate timing problems. Nevertheless it is possible to reach an economic set up for the presented collider. A further advantage is the reduced charge density in the hollow beam bunch, which is 10–20 times smaller than in e.g. the CERN linear collider CLIC [9].

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