DISPERSIVE FOURIER-TRANSFORM ELECTROOPTICAL SAMPLING FOR SINGLE-SHOT MODULATION MEASUREMENT IN A PROTON-DRIVEN PLASMA WAKEFIELD ACCELERATOR

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Abstract

The concept of proton-driven plasma wakefield acceleration has recently been proposed as a means of accelerating an electron bunch to high energies with very high field gradients, and a demonstration experiment (AWAKE) at CERN is now under development. For this a clear understanding of the temporal and spatial modulation of the proton driver bunches after propagating through the plasma channel is essential. A single-shot electro-optic sampling system using dispersive Fourier-transform to exploit transverse coherent transition radiation is proposed here to determine the bunch modulation and electric field properties in the frequency domain. Frequencies up to the terahertz region with a resolution of less than 10 GHz are measurable. The system with a closed optical fiber path is based on a semiconductor laser source to achieve easy handling and robustness. The principle idea, estimations of the required sensitivity, and very first experimental results are presented.

INTRODUCTION

Recently, proton-driven plasma wakefield acceleration (PWA) has been proposed as a concept for the acceleration of electron beams up to the TeV-region [1]. Numerical simulations have shown that a 1 TeV proton bunch with 10^{11} protons and an rms bunch length of 100 μm as a driver could indeed excite a large amplitude plasma wave. Surfing the appropriate phase of the wave, an electron bunch reaches energies over 600 GeV in a single passage through a 450 m long plasma. Recent studies [2] [3] have also shown that similar gradients can be reached with a much longer but modulated proton bunch. By using the plasma for the modulation, a strong plasma wave can be generated by a series of micro-bunches. This effect opens the path for immediate experimental investigations and a first test system (AWAKE) is planned using the SPS facility at CERN.

One of the most important parameters are the depth and frequency of the proton bunch modulation after its passage through the plasma channel. Exploiting (transverse) coherent transition radiation by means of electro-optical sampling in the frequency domain could be an adequate way to acquire information about the longitudinal and transverse properties of the modulated proton bunch. Single-shot capability is important because of the relatively large time jitter and shot-to-shot variations of the bunches. To have an easy-to-use and robust system, the distribution of the needed optical signals should be fiber based. Making use of semiconductor lasers is a cheap alternative to conventional laser systems if measurement has to be done at different positions along a hundreds of meters scale beam line.

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TRANSVERSE COHERENT TRANSITION RADIATION

It has been shown [4] that a charged particle passing a metal-vacuum boundary emits transverse coherent transition radiation (TCTR) radially around its trajectory. The emission has a dipole-like radiation pattern with an electric field vector normal to the metal surface. In case of a charged particle bunch the TCTR field is proportional to the particle density. A (periodic) density change at the boundary is imprinted on the TCTR signal as an amplitude modulation even when the bunch current per cross section is constant.

In the described plasma wakefield experiment the bunch radius is modulated with the electron plasma oscillation ($\approx$250 GHz for a density of $7{\cdot}10^{14}$ cm^{-3}) and the TCTR has a spectral component at the same frequency. In a good approximation the radius of the modulated bunch can be described by

$$r(t) = r_0\,(1 + m\,sin(\omega_m\,t)) \tag{1}$$

with r_0 as the mean beam radius, m as modulation index, and ω_m as the angular frequency of the plasma oscillation. With an assumed inner and outer radius of 200 μm and 1000 μm the modulation index is 0.66. These numbers used in a numerical calculation of the TCTR first harmonic signal have shown amplitudes of 40 kV/m at a distance of 40 mm from the beam axis for a typical SPS proton bunch containing 10^{11} protons.

The simulated time domain signal is shown in Fig. 1 (left) for three different distances to the beam propagation axis. The right hand side of Fig. 1 represents the frequency domain response function of the first harmonic for two different modulation indices. The drop in amplitude is larger for a higher modulation index corresponding to a larger time variation of the beam cross section. This can be explained by the loss in longitudinal coherence of the elementary dipoles contained in the emitting surface when the radiated wavelength becomes comparable to the beam diameter variation.

It is planned to place a thin metallic foil perpendicular to the beam axis. Behind the foil small horn antennas with an aperture size of about 5x5 mm^2 ending in a WG10 waveguide will be arranged co-linearly around the

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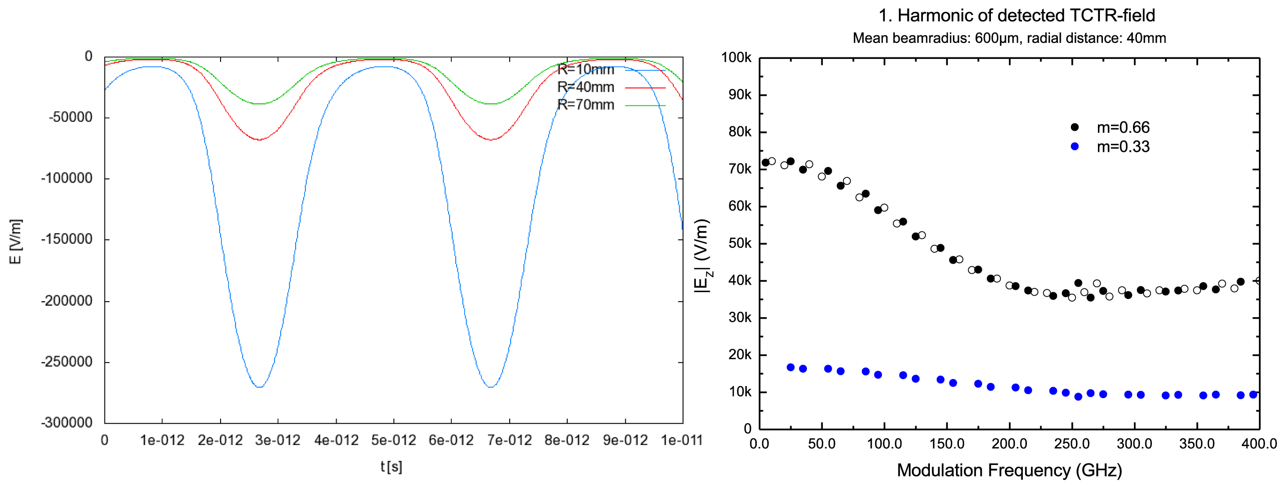

Figure 1: Left: TCTR time domain signal for three different distances (10 mm, 40 mm, and 70 mm) to the beam propagation axis. The modulation index is $m = 0.66$. The bunch energy is 450 GeV with 10^{11} particles in the bunch. The RMS bunch length is 12 cm. Right: Frequency domain response function of the first harmonic for two different modulation indices $m = 0.33$ (Blue) and $m = 0.66$ (black).

exit point of the beam. A small (1 mm thickness) ZnTe-crystal will be positioned inside of each waveguide and used as an electro-optic phase modulator. This sensor configuration will give us the capability to distinguish between different effects like bunch density modulation, bunch displacement or "hosing" from the sum and difference signals. The antenna gain increases the effective electrical field seen by the electro-optic crystal leading to a better sensitivity of the following dispersive Fourier transform (DFT) detection system.

DISPERSIVE FOURIER TRANSFORM

The time dependent amplitude of an electrical field can be imprinted by means of crystals with non-centrosymmetric lattice structure to the momentary phase of an optical signal. This so-called linear electro-optic or Pockels-effect can be found in materials like ZnTe or GaAs and has inherent bandwidth limitations above 5 THz. Phase modulation of a signal leads to the development of new frequency components depending on the modulating signal and can be described by a sum of Bessel functions. For low modulations the process is to the first order linear and equivalent to an amplitude (or intensity) modulation. Under this boundary condition the optical signal spectrum is a two-sided replica of the sampled electrical field spectrum. The amplitude of the first harmonic of the sidebands in the linear regime ($\pi \cdot \hat{V}/V_\pi < 0.5$) can be calculated as

$$|\tilde{a}(f_O \pm f_S)| = \frac{\pi}{2}\frac{\hat{V}}{V_\pi}\hat{a}_O \qquad (2)$$

Herein f_O and f_S are the frequencies of the optical wave and the modulating signal, respectively, $\hat{V}$ is the amplitude of the modulating signal, $\hat{a}_O$ the amplitude of the optical wave, and V_π the half-wave voltage of the electro-optic crystal (about 10kV for ZnTe).

An optical pulse much shorter than the temporal proton bunch length ($\approx$ 400 ps) is used as a sampling signal phase-modulated by the TCTR field. As an example the optical image spectrum of a sampled 100 GHz sinusoidal signal is shown in Fig. 2. Higher harmonics from nonlinearities are also included.

In a next step the amplitude spectrum is transformed to the time-domain by means of a highly dispersive optical fiber (dispersion compensating fiber or DCF). The relative position in time of each frequency component is shifted by a value given by $D \cdot \Delta\lambda$ with D as the dispersion coeffi-

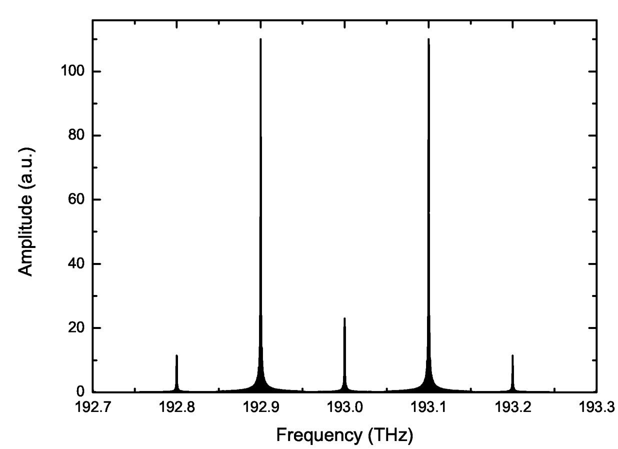

Figure 2: Simulated phase-modulation of a 193 THz signal with a temporal length of 1 ns (FWHM). The modulation signal is a 100 GHz sine-wave with a field strength of 5 MV/m in a 100 μm thick ZnTe-crystal.

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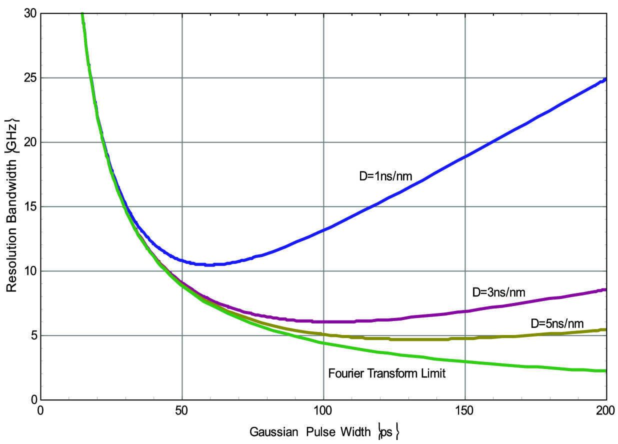

Figure 3: Theoretical frequency resolution of the proposed DFT setup for different dispersion coefficients D. The assumed optical pulsewidth of 100 ps (FWHM) for the laser system using a fiber with a total anomalous dispersion of -3 ns/nm leads to a frequency resolution of about 7 GHz.

cient of the fiber and $\Delta\lambda$ as the wavelength difference to the center wavelength of the optical pulse. The output signal of the fiber is a convolution of the (dispersion broadened) sampling pulse with the time-transformed shape of the frequency spectrum. It can be detected using a fast photodetector and displayed with an oscilloscope. Using a real-time sampling oscilloscope gives the ability to do single-shot measurements. Fourier-transformation using dispersive fibers has been recently proposed and experimentally tested for applications in the field of absorption spectroscopy [5]. Our system differs significantly in the capability to measure externally generated (electrical) signals.

The equivalent bandwidth of the system is given by a convolution of the transformed spectral width using the dispersion coefficient D and the FWHM pulsewidth T_{PI} of the sampling signal at the DCF input. It can be calculated by

$$B_{equ} = \sqrt{\frac{T_{PI}^2 c^2}{D^2 \lambda^4} + \frac{k_P^2}{T_{PI}^2}} \tag{3}$$

Herein λ is the center wavelength of the sampling pulse, c is the vacuum speed of light, and k_P is the time-bandwidth product of the sampling pulse (0.44123 for the assumed Gaussian pulse shape). The calculated bandwidth using equation 3 is shown in Fig. 3 for different dispersion coefficients. One limit is the Fourier limit of the sampling pulse, the other is given by the input pulse width. A higher dispersion coefficient results in a better resolution because of the larger time-domain separation of the pulses. Higher dispersion can be achieved by longer dispersive fibers, but this lowers the sensitivity of the system because of higher attenuation.

Another effect limiting the frequency resolution is the nonlinear wave-coupling in the photodetector. The mixing of two slightly different frequencies will result in additional artifacts superposed on the transformed signal in the time-domain. A detailed discussion is outside the limit of this paper and will be reported elsewhere.

EXPERIMENTAL DFT SETUP

A first experimental setup is shown in Fig. 4. The optical pulses are generated by a gain switched semiconductor laser at a center wavelength of 1553 nm (193 THz). A distributed feedback (DFB) laser or self-seeded Fabry-Perot laser [6] driven by a short electrical pulse to excite only the first relaxation oscillation is well suited. The main advantage of the self-seeding setup is the low optical jitter (<500 fs) and it has been used very successfully for electrooptical sampling systems in the past [7] [8]. The typical pulse length of a relaxation oscillation is in the range between 20 ps and 100 ps, depending on the laser. A subsequent erbium-doped fiber amplifier (EDFA) increases the signal intensity to a level slightly below the nonlinear regime of the following optical fibers. The output signal is filtered by a bandpass centered at the laser wavelength to decrease the broadband noise generated by the amplified spontaneous emission of the EDFA.

In the described here, very first experiment the electro-optic modulation is realized using a traveling wave phase-modulator made out of $LiNbO_3$ for easier use in the laboratory. The bandwidth limit is therefore at about 40 GHz. Later this modulator will be replaced by a ZnTe-crystal. In case of the latter one, the linearly polarized light is transmitted through an electro-optic crystal with 100 μm thickness in a direction perpendicular to the (100)-surface. The polarization axis is adjusted at an angle of 45 degrees to both optical axes of the crystal. With this arrangement for electro-optic modulation in conjunction with the following polarizer one can suppress the unmodulated fraction of the high intensity center wavelength. Only the modulated signal passes through the setup because of the polarization change in the crystal. Using a Mach-Zehnder configuration is an alternative way for base signal reduction, but probably much more difficult to implement. The crystal should be placed inside the mentioned waveguide in the vicinity of the proton beam path to probe the TCTR electrical field.

The frequency-time transformation is done by means of the DCF with a total dispersion of -3 ns/nm followed by a fast photodetector with a bandwidth of 40 GHz and an 8 GHz real-time sampling oscilloscope. To increase the sensitivity of the setup, distributed Raman-amplification in the DCF is proposed [5], but has not been used here.

EXPERIMENTAL RESULTS

First tests of the setup has been performed recently and show good agreement with theory and simulations. In Fig. 5 one can find a comparative measurement between the described setup (black curve) and a conventional grating based optical spectrum analyzer (Yokogawa AQ6370B, red

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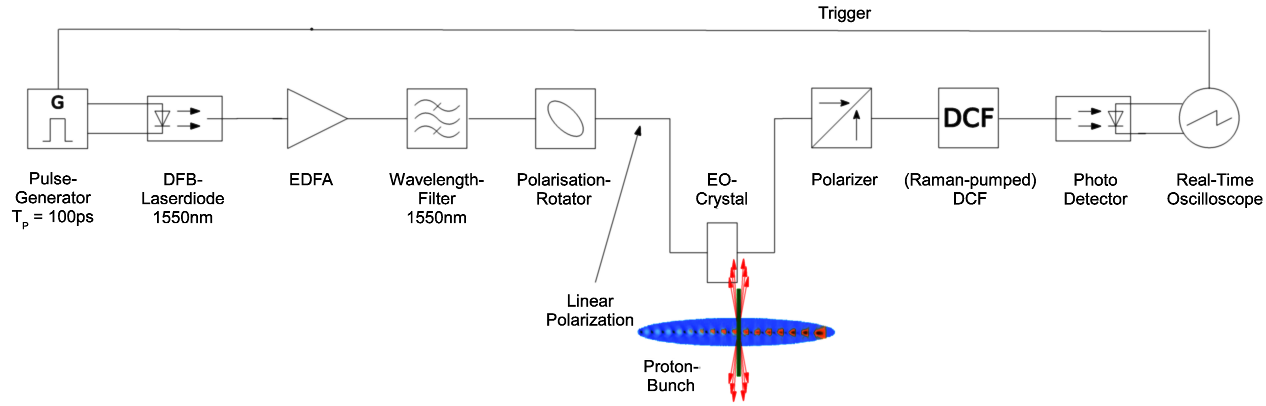

Figure 4: Principle setup for dispersive Fourier transform. A radially modulated proton bunch passes a conductive foil and generates the TCTR (red). The electrical field is causes a phase modulation of a short (100 ps FWHM) optical pulse. The modulated pulse is dispersed in the DCF and detected using a conventional real-time oscilloscope/photodetector combination.

curve). Shown is a phase modulated optical signal with a line spacing of 8 GHz at a center wavelength of 1553,3 nm (193 THz). Clearly visible is the predicted resolution limit of the DFT system for the used sampling pulse width of 100 ps (FWHM). The equivalent sensitivity of the setup is 300 kV/m for a 1 mm ZnTe-crystal. Using Raman amplification this value should be lowered to less than 20 kV/m. Further improvements can be done by using the previously mentioned horn antennas.

SUMMARY

From simulations and first experiments we have seen that dispersive Fourier-transform of short optical pulses with narrow spectral width is a promising concept for single-shot spectral-analysis. Terahertz bandwidths and resolutions below 10 GHz should be feasible using a gain-switched semiconductor laser as a pulse source. Electro-optic modulation can be used to extract the proton bunch modulation information to the optical signal exploiting transverse coherent transition radiation. Considering the simple and robust fiber based setup, the described system appears to be very attractive for multi-point measurements in a harsh environment as a many meter long proton-driven plasma wakefield accelerator will be.

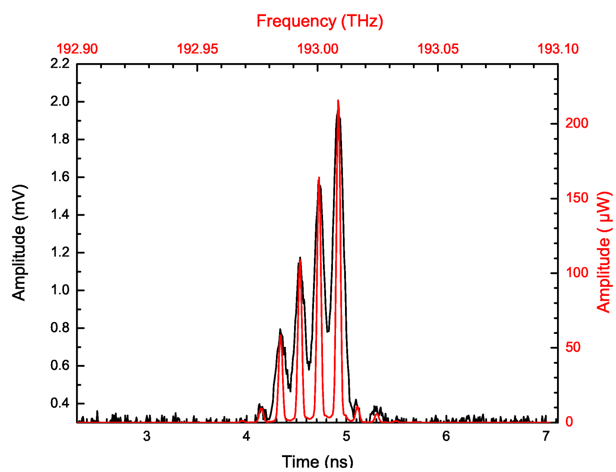

Figure 5: Comparitive measurement of a phase-modulated signal using a conventional grating-based optical spectrum analyzer (red) and the DFT method (eight averaged single-shots, black curve).

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