Measurements of Harmonic Wake Fields Excited by Rough Surfaces

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(Received 16 October 2001; revised manuscript received 21 December 2001; published 4 February 2002)

An experiment has been carried out at the TESLA Test Facility linac to investigate the wake fields generated by picosecond electron bunches in narrow beam pipes with an artificially roughened inner surface. The energy structure imposed on the bunches by the wake fields has been analyzed with a magnetic spectrometer. Strong harmonic-wake-field effects are observed as expected from simulations in which the rough surface is modeled by a dielectric layer.

DOI: 10.1103/PhysRevLett.88.074802 PACS numbers: 41.60.Cr, 29.17.+w, 41.85.Ew

Introduction.—The small gap in the TESLA Test Facility (TTF) free electron laser (FEL) undulator magnets restricts the beam pipe diameter to less than 10 mm. The wake potential generated by the short electron bunches of high charge density is expected to be dominated [1] by the residual surface roughness of the undulator vacuum chamber which is in the 0.8 μm range [2]. Since these wake fields have been predicted to have a significant impact on the beam quality in present and future free electron lasers, an experimental verification of the model prediction appeared highly desirable [3]. For this purpose a special vacuum chamber has been built containing six beam pipes with various diameters and different surface preparations, each of which can be placed into the beam line under remote control.

Synchronous mode wake fields.—Wake fields in dielectric waveguides have been studied by various authors, see, e.g., Ref. [4] and the literature quoted therein. A dielectric layer on the inner surface of a beam pipe lowers the phase velocity to the speed of light at a certain frequency, in which case a relativistic particle bunch can excite a single mode propagating synchronously with the beam. Thus a continuous energy transfer can happen between a bunched beam and the mode, leading to the production of a harmonic wake potential of large amplitude. In Ref. [5] it has been shown that the natural roughness of the inner surface of a beam tube may have a similar effect. Extensive numerical calculations have confirmed the dielectric-layer model [6]. The surprising prediction is that in spite of the statistical nature of the roughness pattern a harmonic wake will be produced whose wave number in a circular tube with radius r and roughness depth δ reads

$$k_0 = \sqrt{\frac{2\varepsilon_{\rm eff}}{(\varepsilon_{\rm eff} - 1)r\delta}}\,. \tag{1}$$

The details of the roughness are summarized in an effective dielectric constant $\varepsilon_{\rm eff}$ whose value is of the order of 2. The wake function is harmonic in the longitudinal coordinate s (see Fig. 1)

$$w_0^{\|}(s) = \sqrt{\frac{\mu_0}{\varepsilon_0}}\,\frac{c}{\pi r^2}\cos(k_0 s)\exp[-\alpha(\ell)s]\,, \tag{2}$$

where the damping constant $\alpha(\ell)$ depends on the length of the pipe and to a small extent also on the resistivity of the walls. For further details see [5] and [6]. Synchronous modes in rough beam pipes are also discussed in [7].

In the limit of vanishing surface roughness, one obtains $\lambda_0 = 2\pi/k_0 \ll \sigma_z$, where σ_z is the rms bunch length. Then the energy loss vanishes and the impedance becomes inductive with an amplitude proportional to δ^2 [8].

Resistive wall wake fields become important when the rms roughness is comparable with the skin depth of the metal (about 0.1 μm in aluminum at 500 GHz). These wakes can be neglected in the much rougher test pipes of the present experiment (see Table I).

Layout of the experiment.—The experiment was carried out at the linear electron accelerator of the TTF [9]. The main components of the linac are a radio frequency

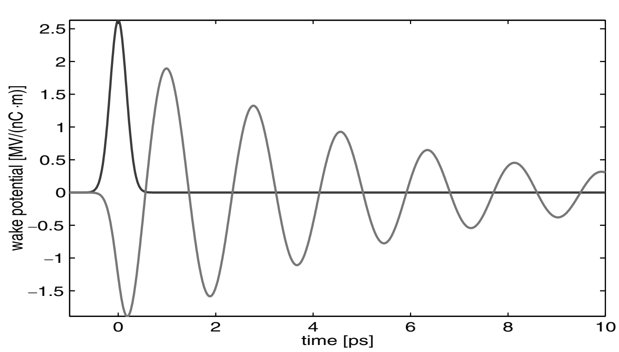

FIG. 1. Longitudinal charge distribution in a Gaussian bunch and the computed wake potential created by a dielectric surface layer [see Eq. (2)]. The bunch head is at the left side. The damping of the periodic wake potential is caused by the finite length and resistivity of the beam pipe. The parameters are $r = 4$ mm, $\delta = 8$ μm, $\varepsilon_{\rm eff} = 2$.

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TABLE I. Parameters of the beam tubes. The parameter δ is the rms depth of the roughness. The wake frequencies f_w have been determined from the energy distribution of the electron bunches. The last column gives the amplitude of the wake potential.

Prep.	r/mm	δ rms	f_w/GHz	$\varepsilon_{\mathrm{eff}}$	ampl./kV
Ref.	4	1.4 μm	...	...	...
Sandbl.	5	8.3 μm	480 ± 27	1.91	39 ± 5
Sandbl.	4	8.3 μm	564 ± 32	1.75	60 ± 5
Sandbl.	3	8.3 μm	658 ± 40	1.73	105 ± 5

photocathode delivering electron bunches of 7 ps rms length, 1 nC charge and an energy of 4 MeV, a 1.3 GHz superconducting (SC) booster cavity raising the energy to 16 MeV, two acceleration modules each containing 8 nine-cell 1.3 GHz SC cavities, increasing the energy to 230 MeV, a magnetic bunch compressor between the two modules, and three undulator magnets with a total length of 13.5 m for the production of FEL radiation in the 100 nm regime. Collimators with 6 mm bore protect the neodymium iron boride permanent magnets of the undulator from radiation damage. For optimum bunch length compression by about a factor of 5, such as needed for the production of FEL radiation, the bunches are accelerated 14° off-crest in the first module. This impresses a position-energy correlation onto the bunch, with the leading electrons having lower energy than the trailing ones. In the magnetic chicane the tail electrons move on a shorter path and thereby catch up with the head electrons. In the second module the beam is accelerated on-crest.

For the observation of synchronous mode wake-field effects, a more moderate bunch compression turns out to be advantageous: a 6° off-crest acceleration in the first module produces a bunch with a very steep rising edge (~100 fs) and a long tail (~10 ps). Then a 14° off-crest acceleration in the second module generates a correlated energy-position distribution in the tail of the bunch (see Fig. 2). The synchronous mode wake fields, which are mainly produced by the sharp front peak of the bunch, can then be observed via the imposed energy modulation in the long tail. There is some resemblance to the pump-and-probe technique in laser physics. Note that coherent synchrotron radiation in the bunch compressor, as well as wake fields caused by resistive walls and cross sectional changes, act mainly on the sharp front peak of the bunch but have little influence on the long tail.

The main component of the experiment is a special ultrahigh vacuum chamber, containing six 800-mm-long test pipes of radii between 3 and 5 mm and with different surface preparations (smooth, sandblasted, grooved), which is mounted behind the undulator. By remote control, any of the pipes can be moved into the electron beam and centered with an accuracy of 0.1 mm. The pipes are composed of half cylinders machined into two flat aluminum plates. This way a controlled surface preparation by sandblasting or grooving was possible. The surface roughness has been measured with a tracer-type measuring device featuring a resolution of 0.02 μm.

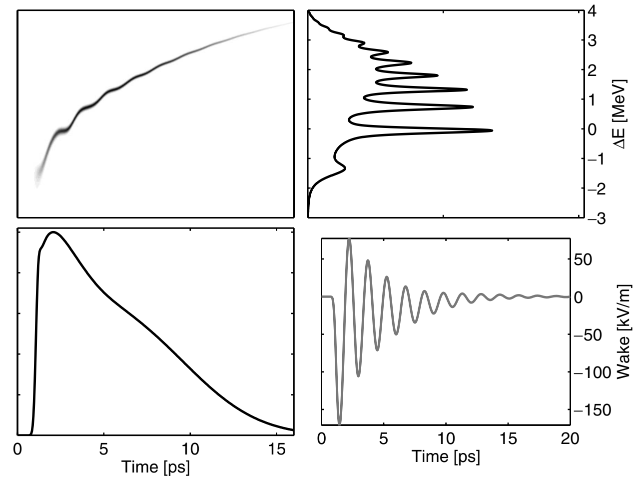

FIG. 2. Simulation of a bunch in longitudinal phase space in the presence of a synchronous mode wake field. The upper left panel shows the bunch in phase space, the lower left shows the projection onto the time axis, and the upper right shows the projection onto the energy axis. The lower right panel shows the harmonic wake field. The periodic energy shift, together with the time-energy correlation, generates the peaks in the energy distribution.

At the entrance, respectively, exit, of the test pipes there is a discontinuous jump in the beam pipe cross section. The wake fields created by such jumps have been studied in [10]. They have mainly a constant impedance with some superimposed weak resonances just above the cutoff frequencies of the pipes, which are all below 50 GHz in our case. These wakes are therefore easily distinguishable from the several 100 GHz wake fields created by the surface roughness.

The electron beam is momentum analyzed in a spectrometer dipole with a 20° bending angle. Optical transition radiation produced at a screen with vertical deflection is imaged by a CCD camera. The horizontal dispersion at the position of the screen amounts to 1 m while the horizontal β function is small (0.25 m). Therefore the width of the horizontal particle distribution on the screen is predominantly given by the energy distribution within the bunch, with a negligible widening caused by the horizontal emittance of the incoming beam ($\varepsilon_N \approx 6 \times 10^{-6}$ m). The momentum resolution of the magnetic spectrometer is $<2 \times 10^{-4}$ at the center of the screen and governed by the intrinsic beam-energy spread of 25 keV. Because of chromatic effects, the resolution degrades to $\approx 5 \times 10^{-4}$ towards the edges of the screen.

Experimental results.—The measured energy structure in the tail of the bunches is shown in Fig. 3. The dashed curve shows the energy distribution obtained when the beam has traversed the smooth reference pipe of 4 mm radius. The observed wide distribution is created by the off-crest acceleration. Superimposed is a slight structure which can possibly be attributed to surface roughness wake

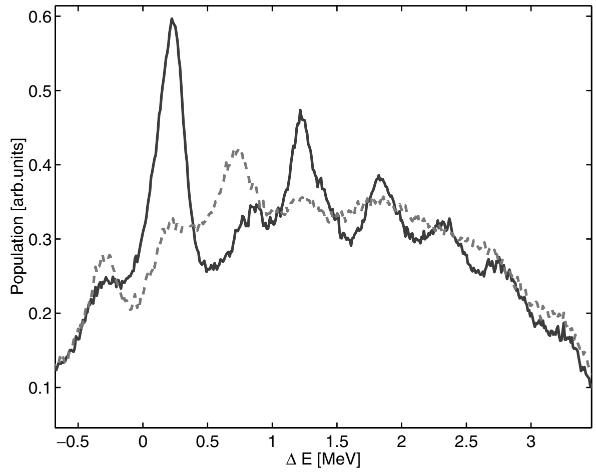

FIG. 3. Energy profile of the tail of a bunch having passed the 4 mm radius test tubes. The dashed curve represents the reference (smooth) pipe, and the solid curve represents the sandblasted pipe. The two pipes are of identical geometry, the only difference is the rms surface roughness of 1.4 μm and 8.3 μm, respectively. The head of the bunch would appear at the left side of the plot but is not visible due to its low energy.

fields in the upstream collimator and undulator beam pipes. The solid curve shows the energy distribution when the beam has passed the sandblasted beam pipe of the same radius $r = 4$ mm. In this case a regular peak structure is visible which can be assigned to a harmonic wake potential: each peak can be identified with a zero crossing of the wake potential with negative slope. We want to emphasize that the only difference between the two cases is the different surface roughness of the two pipes. Figure 5 (below) demonstrates that the regular peak structure becomes much more pronounced when the rough pipe of 3 mm radius is inserted.

A precise determination of the time structure of the distribution is achieved by varying the rf phase of the second acceleration module. This has no impact on the longitudinal bunch profile or on the wake fields. By measuring the resulting changes in the energy separation of the peaks it is possible to resolve their separation in time without making any assumptions about the initial energy distribution. The method works as follows. Consider two peaks in the energy profile which are separated in energy by E_{sep} and in time by τ. When the rf phase ϕ in module 2 is changed by $\Delta\phi$ the change in separation energy is

$$\Delta E_{\mathrm{sep}} = \omega \tau E_{\mathrm{module}}[\sin(\phi + \Delta\phi) - \sin(\phi)] \qquad (3)$$

with E_{module} being the maximum energy gain in the module and ω the rf angular frequency. From the measured values $\Delta\phi$ and ΔE_{sep} the time separation τ of the two peaks can be derived with an accuracy of better than 120 fs. Then $f_w = 1/\tau$ is the frequency of the harmonic wake.

Using this method we have verified that the peaks seen behind the rough test pipes [Fig. 3 and Fig. 5 (below)] have indeed equidistant spacing in time, implying that they are caused by a harmonic modulation of the particle energies. The experimentally determined wake frequencies for the different rough test pipes are summarized in Table I and plotted in Fig. 4 as a function of the pipe radius. Good agreement with the $1/\sqrt{r}$ behavior of Eq. (1) is found. The fact that the time separation of the peaks changes with the pipe radius rules out the vague possibility that the observed regular peak might be due to an initial modulation of the bunch which is only enhanced by the rough pipes.

The observed harmonic wake frequencies agree with the dielectric-layer model prediction for a dielectric constant $\varepsilon_{\mathrm{eff}} \approx 1.75$, while the numerical calculations in Ref. [3] prefer $\varepsilon_{\mathrm{eff}} \approx 2$, corresponding to $\approx$8% lower frequencies. This deviation is still within the estimated errors of our experiment. In the surface roughness model of Ref. [7] higher wake frequencies are predicted ($\varepsilon_{\mathrm{eff}} \approx 1.4$) but it should be remarked that the small angle approximation for the irregularities, used in this paper, is not fully justified for the sandblasted beam pipes of our experiment.

We have shown that the frequencies of the harmonic wakes can be determined in a model-independent way, applying the method described above. Their strengths can be derived with a longitudinal phase space tomography, which is an extension of this method. For a preliminary estimate of the wake-field amplitude a numerical simulation of the whole experiment is carried out. For this purpose the electron bunches are tracked through the entire accelerator. The starting point of the simulation is the charge distribution in the 16 MeV bunches as measured [11] with a streak camera behind the booster cavity. The rms width of the slightly non-Gaussian distribution is 7 ps. The bunches are then passed through the first acceleration module, the magnetic chicane of the bunch compressor, the second acceleration module, the roughened test pipe, and the spectrometer dipole. The wake-field effect in the rough test pipe is imposed as a damped harmonic wave using the frequency determined above. The simulation model

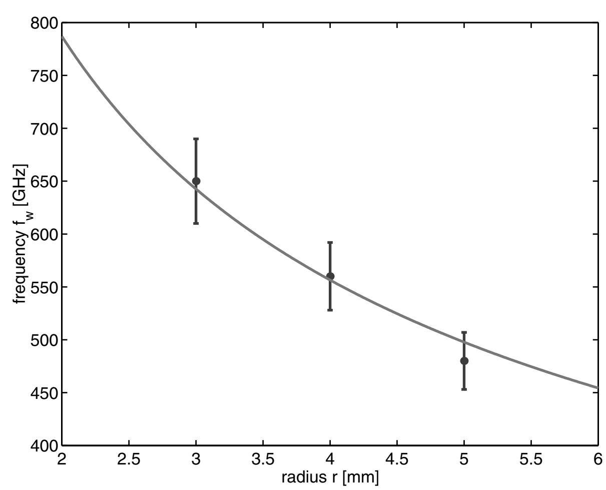

FIG. 4. The frequency of the synchronous mode plotted versus the radius of the beam pipe. The measured frequencies agree within the errors with the $1/\sqrt{r}$ dependence expected from the dielectric-layer model.

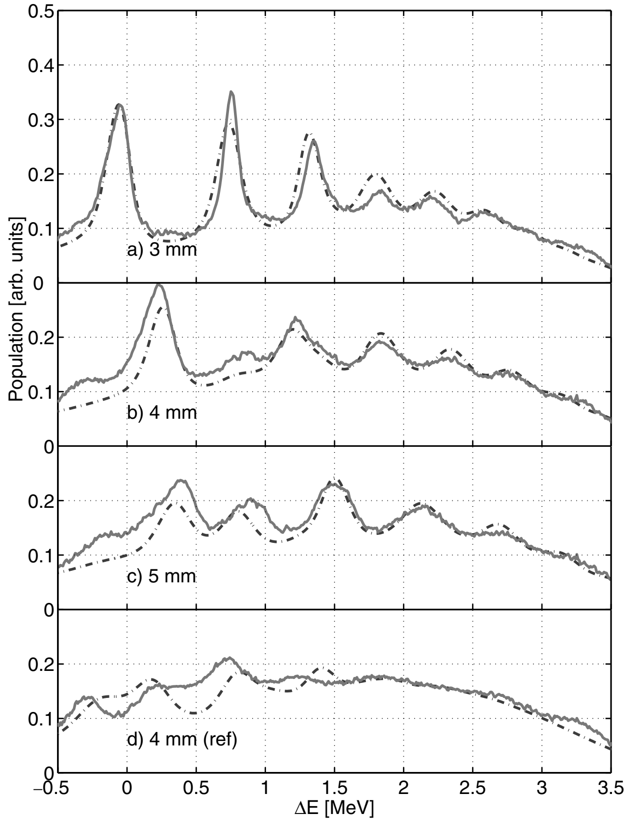

FIG. 5. Energy profiles in the tail of the bunch measured behind different test tubes. (a), (b), and (c) Sandblasted tubes of 3, 4, and 5 mm radius, respectively; (d) smooth reference tube of 4 mm radius. The solid curves show the profiles measured with the spectrometer at the end of the linac. The dot-dashed curves show the simulated distributions. The simulation includes the off-crest acceleration, bunch compression, and surface roughness wake fields generated in the test beam pipes and in the collimator upstream of the setup. The spectrometer resolution is also taken into account.

yields the following preliminary values for the maximum energy shift which an electron in the tail of the bunch experiences during its passage through one of the 800-mm-long roughened test pipes: 39 keV for $r = 5$ mm, 60 keV for $r = 4$ mm, and 105 keV for $r = 3$ mm. The strength of the excitation changes proportional to $1/r^2$, as predicted by the dielectric-layer model, and the damping constants are in the expected range.

To account for possible surface-roughness wakes in the collimator and undulator sections, which may be the origin of the peak structure observed behind the smooth reference test pipe, another dielectric-layer wake is used in the simulation whose frequency and amplitude are adjusted to yield a reasonable description of the energy profile measured with the reference pipe. Simulation parameters, such as the initial charge distribution and the rf phases in modules 1 and 2, are allowed to vary within the experimental uncertainty intervals. The dot-dashed curves in Fig. 5 are the predictions of the model simulation for an optimized parameter set. The agreement with the measured profiles is quite satisfactory, indicating that the basic physics processes are well understood.

It should be noted that our determination of the wake frequency and the maximum energy shift is independent of any specific wake-field model. However, in order to compute the wake function in the conventional units of kV/(pC m) the fraction of charge contained in the leading peak of the bunch and the attenuation coefficient $\alpha(\ell)$ must be known. A detailed analysis is in progress to determine the exact shape of the bunch with a longitudinal phase space tomography.

Conclusion and outlook.—An experiment has been conducted to study wake fields excited by a rough surface of the beam pipe. Evidence is found for the synchronous excitation of a harmonic wake potential. The observed frequencies scale inversely with the square root of the beam pipe radius. The preliminary analysis yields energy shifts inside the bunches of up to ± 100 keV for a total bunch charge of 1 nC. A more detailed analysis including a longitudinal phase space tomography is in progress. The wake fields have also been measured by recording their far infrared radiation. The presentation of these data will be part of a more detailed description of the experiment [12].

The authors thank the TTF team for valuable help in running the accelerator and A. Novokhatski for interesting discussions.

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