Particle Accelerators, 1996, Vol. 52, pp. 45–53
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ELECTRON BUNCH LENGTH MEASUREMENTS AT THE S-DALINAC FEL FACILITY*

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(Received 4 September 1995; in final form 3 November 1995)

We report on the measurement of the longitudinal electron bunch distribution of the free-electron laser (FEL) experiment at the superconducting Darmstadt electron linear accelerator (S-DALINAC) facility. The electron micropulse length was found to be (4±0.25) ps FWHM. The bunch shape is most likely rectangular. For the first time the results were established by applying simultaneously two independent methods, an autocorrelation technique using coherent transition radiation in the far infrared and by means of a Hamamatsu C 5680 type streak camera that determined the pulse structure of the 11th and 13th harmonics of the spontaneous emission of the S-DALINAC FEL.

1 INTRODUCTION

The knowledge of the longitudinal electron bunch distribution in electron accelerators has been of great interest during the past few years. It is an important aspect in many research areas such as free-electron lasers, linear colliders and the generation of high intensity radiation sources in the far infrared. The observation of the coherent far infrared transition radiation spectrum[1] as well as autocorrelation techniques using transition radiation[2] made it possible to measure short electron bunches in the order of picoseconds[3] and even in the femtosecond region.[4]

As an important step towards laser operation of the free-electron laser experiment at the superconducting electron accelerator S-DALINAC,[5] the longitudinal electron bunch distribution had to be determined. Therefore, a Michelson interferometer for far infrared transition radiation was installed and put to use in front of the undulator and in addition, a Hamamatsu C 5680 type streak camera[6] having a temporal resolution of 1.5 ps FWHM was applied to determine the time structure of the spontaneous emission. The comparison of the two measurements is particularly important since both methods are known to be prone to errors and often yield questionable results.

* Supported by the BMBF under contract number 05 345 EAI3 and a European Network under contract number SC1-0471-C(A).

A brief introduction to the autocorrelation technique using coherent transition radiation in the first section is followed by the description of both experimental set-ups in the second section. The results of transition radiation and streak camera measurements are presented in the third and fourth section of this paper. A final conclusion compares the results and gives a short outlook on the free-electron laser project.

2 AUTOCORRELATION TECHNIQUE USING COHERENT TRANSITION RADIATION

Transition radiation was first predicted by Frank and Ginzburg[7] as a source of radiation, which is emitted when charged particles cross the boundary of two media with different electrical properties. In the case of relativistic electrons moving from vacuum with dielectric constant $|\epsilon| = 1$ through a metal foil with $|\epsilon| > 1$ the energy radiated in a frequency range $\mathrm{d}\omega$ and solid angle $\mathrm{d}\Omega$ for one electron is given by[8]

$$\frac{\mathrm{d}^2 W(\omega, \vartheta)}{\mathrm{d}\omega \mathrm{d}\Omega} = \frac{e^2\beta^2}{\pi^2 c} \frac{\sin^2\vartheta}{(1-\beta^2\cos^2\vartheta)^2}, \tag{1}$$

where e is the charge of the particle, β is the particle velocity expressed in units of c and ϑ is the angle of emission with respect to the axis of the particle beam. This dipole like radiation is linearly polarized with the electric field vector lying in the plane spanned by the normal to the interface and the direction of observation. The radiation is emitted in a cone with opening angle $\vartheta = 1/\gamma$, where γ is the Lorentz factor.[9] In order to deduce the backward emitted radiation observed in the experiment, one has to change β to $-\beta$ in the formula above.[10] The total energy radiated by a bunch of electrons containing N particles is the sum over the contribution of each electron, and is therefore proportional to the electron micropulse charge. Since transition radiation reaches from the x-ray region[11] to mm waves, this is only true for wavelengths, which are short compared to the electron bunch length. This part of the radiation spectrum is incoherent and results only from statistical fluctuations in the particle density. It can be used to examine individual charged particle effects such as energy, emittance and transverse profile. At wavelengths, which are in the order of the electron bunch length, it was shown that the energy radiated is coherently enhanced.[12] In the case of rf accelerators, where the electron bunch length is in the order of a few millimeters, this enhancement occurs in the mm-range. The total energy radiated by a bunch of electrons containing N particles is then proportional to N^2 and can be expressed as follows

$$\frac{\mathrm{d}^2 W_{\mathrm{tot}}(\omega, \vartheta)}{\mathrm{d}\omega \mathrm{d}\Omega} = (N + N(N-1)f(\omega))W(\omega, \vartheta). \tag{2}$$

Here $W(\omega, \vartheta)$ is the energy radiated by a single electron. The form factor $f(\omega)$ is the magnitude squared of the Fourier transform of the mean particle distribution $S(\vec{r})$

$$f(\omega) = \left| \int \exp\left(\frac{\mathrm{i}\omega z}{c}\right) S(\vec{r}) d^3 r \right|^2. \tag{3}$$

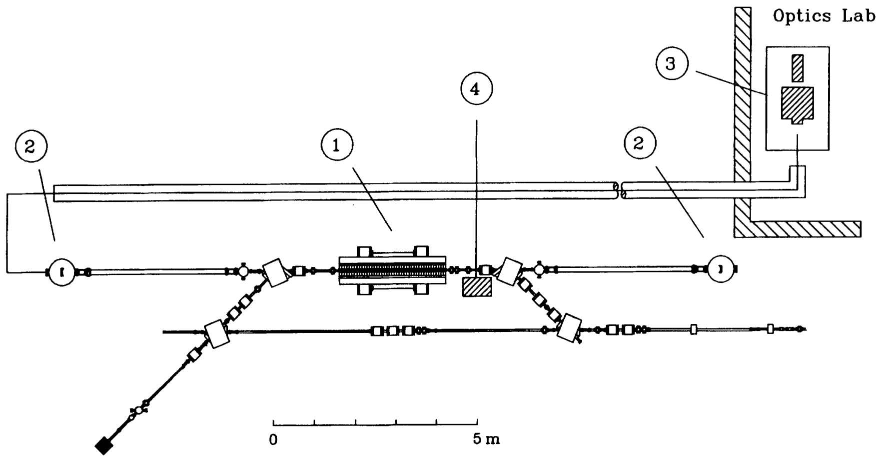

FIGURE 1: Experimental set-ups for the transition radiation autocorrelation and for the streak camera measurements for the FEL experiment at the S-DALINAC. (1) Undulator, (2) mirror chambers, (3) streak camera in optics lab, (4) Michelson interferometer for transition radiation.

One can easily see that $f(\omega)$ describes the coherence of the emitted radiation. The incoherent limit is given for $f(\omega) = 0$ whereas for $f(\omega) = 1$ the total energy is coherently enhanced. This part of the radiation spectrum then contains all the information about the collective longitudinal properties of the particle beam and can therefore be used by autocorrelation or spectral analysis techniques to measure the bunch length of the particles.

3 EXPERIMENTS

The electron bunch length measurements were performed at the 130 MeV superconducting S-band electron accelerator S-DALINAC. The accelerator was operated in the high current free-electron laser mode[13] at a bunch repetition rate of 10 MHz and a beam energy of 31.2 MeV. In the present experiment an additional macro structure of 1 ms duration with a repetition rate of 37 Hz was introduced. The Michelson interferometer for the transition radiation autocorrelation measurements was installed in the FEL bypass in front of the undulator (see Figure 1). Transition radiation was produced by a 25 μm thick Al-foil, which was introduced into the electron beam at an angle of 45°. The radiation was coupled out of the vacuum beam tube through a polyethylene window, collimated and sent through the Michelson interferometer. The interferometer consisted of a 50 μm thick Mylar beam splitter, a fixed and a moveable surface gold mirror and a room-temperature pyroelectric bolometer (Molecron P1-45 with preamplifier) as shown in Figure 2.

When removing the Al-foil the electron beam passed the undulator and produced spontaneously emitted radiation on the axis of the FEL resonator. This radiation was coupled

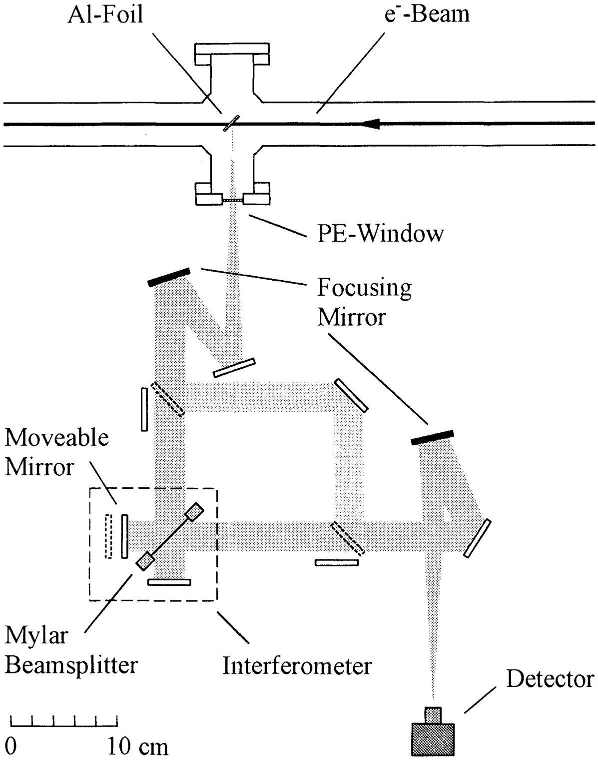

FIGURE 2: Schematic layout of the Michelson interferometer for electron beam autocorrelation measurements using coherent transition radiation.

out of the optical cavity and sent through a 60 meter long transport system to an optics laboratory outside the accelerator hall, where the streak camera was set up in order to avoid possible radiation damage (see Figure 1). The incoming spontaneous emission was focused onto the entrance slit of the Hamamatsu C 5680 type streak camera, which had a width of 15 μm in order to obtain the highest possible time resolution of 1.5 ps FWHM. It was possible to switch simultaneously between the two set-ups so that the same electron beam conditions were available for both measurements.

4 TRANSITION RADIATION MEASUREMENTS

Figure 3 shows a typical interferogram taken by the autocorrelation measurements with the Michelson interferometer. The signal intensity from the pyroelectrical detector is plotted against the optical pathlength difference introduced by the moveable mirror in the Michelson interferometer. The subharmonic injection with the chopper-prebuncher system as well as

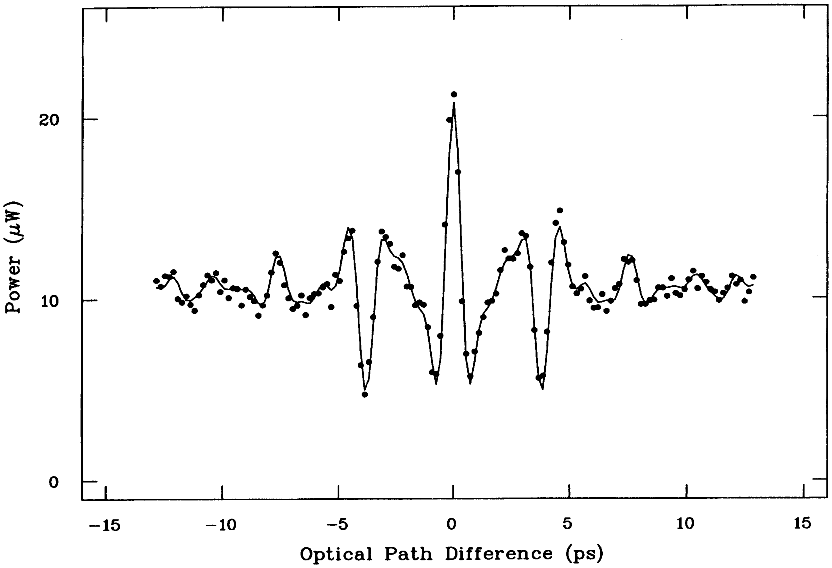

FIGURE 3: Typical interferogram, which was taken with the Michelson interferometer (Figure 2). The solid line represents the symmetric portion of the data obtained by applying a Fourier filter technique.

the superconducting injector linac has been set up for the shortest possible electron bunch operation during that run.

In order to compensate for the frequency dependence of the Mylar beam splitter due to thin film interference effects and absorption in the far infrared and mm range, where the main intensity of the coherent transition radiation occurs, the efficiency of the beam splitter was measured from 20 μm up to 1 mm wavelengths. Measurements of the transmission of the polyethylene outcoupling window as well as the detector response function were performed in the same wavelength range. The cut-off frequency of the detector system was determined to be at 300 GHz. In addition water absorption effects due to humidity have been considered according to [14]. Figure 4 shows the power spectrum of the measured data, which was taken by the technique of Fourier transform spectroscopy, and the efficiency of all components of the interferometer including water absorption. We found three dominant frequency components at 14, 22 and 30 wavenumbers. Even though the phase information, which is lost in first order autocorrelation measurements, can be recovered,[15] in our case the lack of information below 300 GHz (10 cm^{-1}) makes it impossible to reconstruct the exact electron bunch shape. This is illustrated in Figure 5 which shows the efficiency corrected spectral intensity of the transition radiation measurement compared with the power spectrum of a 4 ps long rectangular pulse shape. Nevertheless it was possible to determine the most likely electron bunch configuration. In our analysis the bunch is composed as a histogram containing 21 intervals with a width of 1.25 ps each, according to the measured spectral range from 10 cm^{-1} to 45 cm^{-1}. The measured bunch charge of 3.6 pC

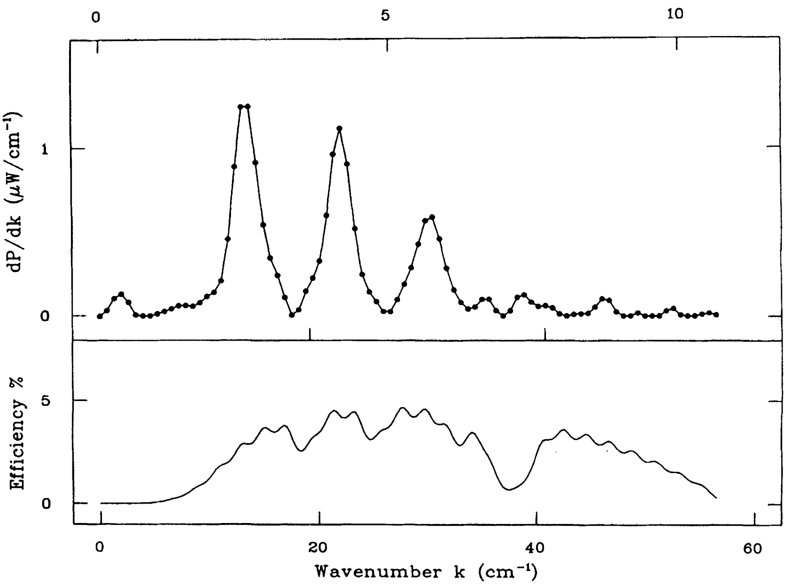

FIGURE 4: Power spectrum of the measured data (upper part) and efficiency of the detector system (lower part). The solid line connects the data points to guide the eye.

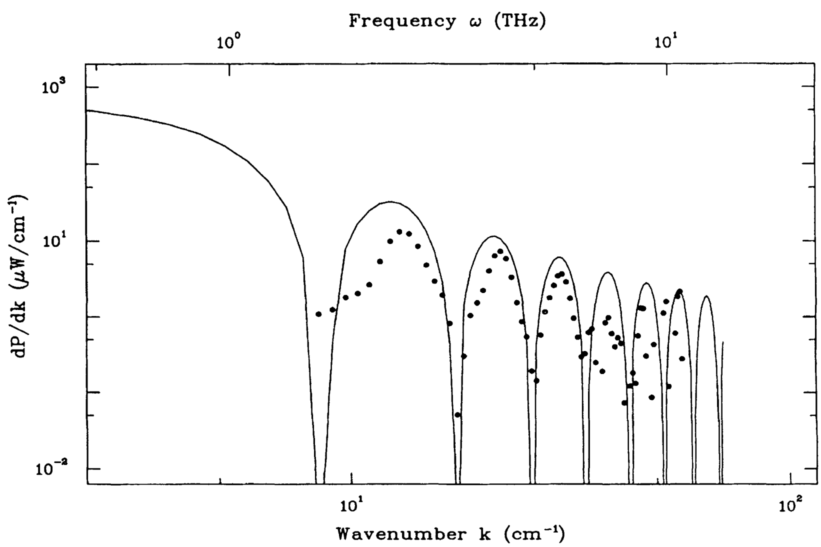

FIGURE 5: Power spectra of the efficiency corrected data (dots) and of a 4 ps long rectangular electron bunch (solid line).

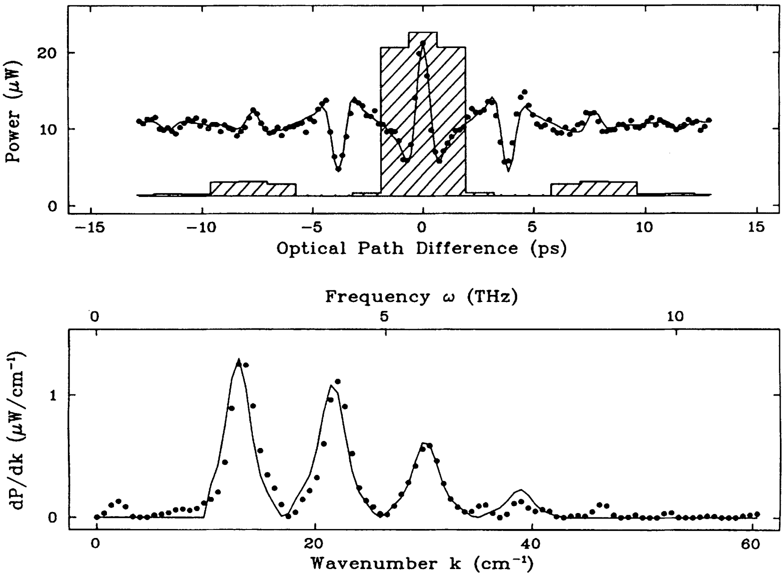

FIGURE 6: The uncorrected measured interferogram is shown in the upper part indicated by dots. The solid line represents the fitted interferogram corrected with respect to the response of the detector system. The most likely electron bunch configuration is shown in shades. The lower part displays the measured power spectrum (dots) in comparison to the spectrum of the fitted electron bunch configuration (solid line).

was taken into account. Power spectra of different bunch shapes were calculated, efficiency corrected, and compared with the power spectrum of the autocorrelation data. In a fitting routine this procedure was repeated until the best agreement of the power spectra was obtained.

It turned out that the electron bunch length in the FEL high current mode at the S-DALINAC facility was (4 ± 0.25) ps with a most likely rectangular shape as shown in Figure 6.

5 STREAK CAMERA MEASUREMENTS

The streak camera measurements were performed with the spontaneously emitted radiation produced by the electrons in the undulator. The accelerator was operated in the same way as for the transition radiation measurements. Since the camera has only been sensitive in the visible wavelength range, we used the 11th and 13th harmonics of the spontaneous emission at 636 nm and 538 nm, respectively. In order to obtain the lowest possible phase jitter, the streak camera was operated in synchroscan mode at the fastest possible time base of 20 ms, where only one macropulse of the accelerator was present. Figure 7 shows a measured streak picture of the spontaneous emission with a total width of 6 ps, which is

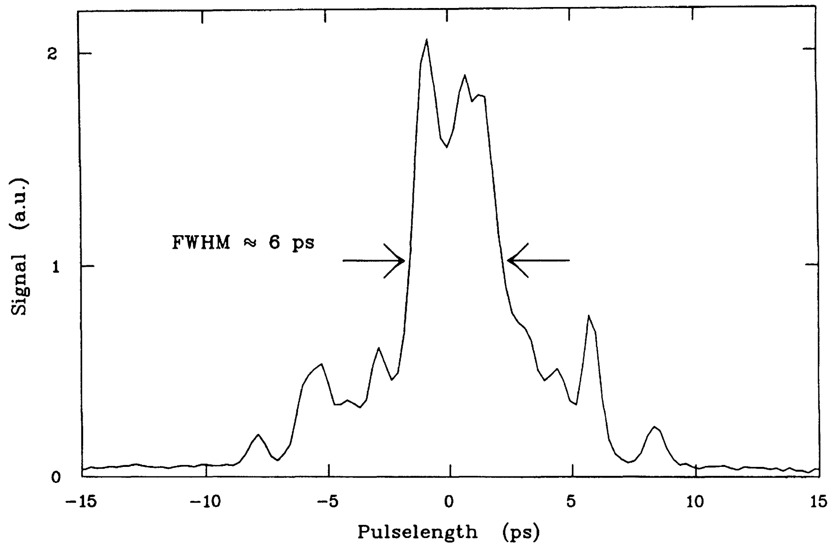

FIGURE 7: Streak camera picture of 11th and 13th harmonics of the spontaneous emission. The measured pulse length was 6 ps FWHM, which results in an electron bunch length of 4 ps FWHM taking the slippage correction into account.

caused by the micropulse time structure of the electron beam and the lengthening of the optical pulse due to slippage effects. In the case of the S-DALINAC FEL the slippage is in the range of 2 ps and thus the corresponding electron bunch length amounts to about 4 ps FWHM with a temporal resolution of the streak camera system of 1.5 ps FWHM.

6 CONCLUSIONS

It has been possible for the first time to measure the electron bunch length in the free-electron laser experiment at the S-DALINAC facility in Darmstadt. It was determined to be (4 ± 0.25) ps FWHM. This result was obtained by the transition radiation autocorrelation and confirmed by the streak camera measurements of the spontaneous emission which shows that coherent transition radiation is an appropriate tool to measure the electron bunch length. It was also for the first time possible to control the bunching process in the injector of the 130 MeV superconducting accelerator in order to reach the shortest possible values for the electron bunch length at that time. Establishing the transition radiation autocorrelation technique for determining the electron micropulse length at the S-DALINAC has certainly been a major step towards the operation of the FEL. It will be used during the upcoming beam times to form the electron beam throughout the accelerator so that the design value of 2 ps electron bunch length, respectively 2.7 A peak current, necessary for lasing is reached.

ACKNOWLEDGEMENTS

We would like to thank K. Berryman, E. Crosson, T.I. Smith and A. Schwettman of the SCA-FEL group at Stanford and D.A. Javoszynski from Bruyères-le-Châtel for many helpful informations and fruitful discussions about the transition radiation autocorrelation measurements. We would also like to thank Mr U. Denzer from Hamamatsu Photonics Inc. for the short term loan and the installation of the C 5680 type streak camera. Many thanks to W. Grill and A. Eifler from the University of Leipzig for the spectral measurements of the bolometric detector and the Mylar beamsplitter. This work has also been partly supported through a Max-Planck-Forschungspreis.

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