COHERENT RADIATION DIAGNOSTICS FOR SHORT BUNCHES

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Abstract

Investigating the longitudinal charge distribution of electron bunches using coherent radiation has become an important diagnostic technique at many accelerators. The principle of the method and some example applications from the FLASH free-electron laser in Hamburg will be described in this article.

INTRODUCTION

The longitudinal charge distribution in an electron bunch is an important characteristic for many particle accelerators and storage rings: the gain length of a free-electron laser (FEL) depends on the peak current of the bunch, and thus, for a given charge, on the bunch length (a typical value is 15 µm/50 fs); the slicing-technique for producing ultra-short x-ray pulses at third-generation light sources relies on producing and controlling a very short longitudinal structure in the bunch through interaction with a laser (90 µm/300 fs); high-energy physics machines need to achieve a sufficiently short bunch to avoid luminosity degradation due to the hourglass-effect (600 µm/2 ps).

Manipulating the bunch to get a desirable and short charge distribution is a complicated procedure and typically requires, for an FEL, several bunch compression steps involving complex longitudinal dynamics. Stable lasing is only achieved for a well-tuned machine. Measuring the longitudinal profiles, and thus guiding the tuning, is a very important ingredient for efficient machine running, as is the preservation of a once-found good machine setup using feedbacks.

Time-domain methods for measuring the longitudinal structure with resolutions in the 50 fs range exist, though typically require involved set-ups, for example high-power transverse deflecting cavities (that need special optics to attain maximum resolution and are thus are not parasitic to normal machine operation), or techniques based on electro-optic principles. Coherent radiation diagnostics (CRD) allows a different approach to this measurement task by working in the frequency domain. No individual technique is currently giving all the information that is needed, and therefore several approaches to longitudinal diagnostics are often employed in parallel.

The notion that the bunch charge distribution affects the emission spectrum is known for a long time, though only starting around 1990 the application for beam diagnostics has been investigated.[1] See [2] for further references on original works.

This article will give a brief introduction to the principle of the diagnostic technique, followed by an overview of some of the experimental arrangements that are currently employed. By no means a complete coverage is intended or possible. The focus will be on studies and results from the FLASH free-electron laser at DESY, Hamburg.

PRINCIPLE OF CRD

The basic relation of coherent radiation diagnostics connects the radiation emission spectrum of a bunch of electrons, $\mathrm{d}U/\mathrm{d}\lambda$, to that of a single-electron, $(\mathrm{d}U/\mathrm{d}\lambda)_1$, by

$$\frac{\mathrm{d}U}{\mathrm{d}\lambda} = \left(\frac{\mathrm{d}U}{\mathrm{d}\lambda}\right)_1 \left(N + N(N-1)\,|F(\lambda)|^2\right). \tag{1}$$

N is the number of electrons in the bunch, $F(\lambda)$, the *form factor*, the Fourier transform of the normalized bunch charge distribution $S(z)$,

$$F(\lambda) = \int_{-\infty}^{\infty} S(z) e^{-2\pi \mathrm{i} z/\lambda}\,\mathrm{d}z. \tag{2}$$

Here, charge distribution and form factor are considered only for a line charge. A non-vanishing transverse extend influences the emission spectrum, although only weakly due to the strong collimation of the radiation for highly relativistic particles, unless the transverse extend is very large with respect to the wavelength. Transverse effects are studied in [3, 4].

The effect of coherent enhancement is illustrated in Fig. 1. For wavelengths comparable to the bunch length or larger, the spectral intensity is strongly amplified, as a large part of the bunch electrons emits coherently. The enhancement of the spectrum extends to shorter wavelengths for shorter bunches, and the shape of the spectrum depends on the shape of the charge distribution. Coherent radiation diagnostics uses this effect to deduce information about the bunch length or bunch shape. The derivations of the basic relations are given in detail in [5].

EXPERIMENTAL BASICS

Any setup that uses coherent radiation as a diagnostic tool includes as a minimum a source of some kind, some

[1] The first description of coherent effects is made, to the authors knowledge, in an originally unpublished paper in 1945 by Schwinger within the context of synchrotron radiation, including also a discussion on shielding. The paper has been reissued in [1].

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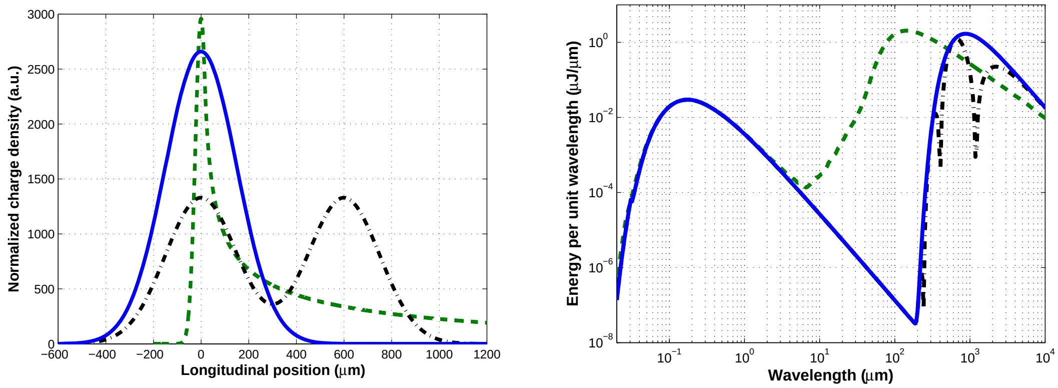

Figure 1: Example for coherent enhancement. On the left, three different bunch shapes are shown, on the right the effect on the emission spectrum after Eq. 1 for 1 nC bunch charge. As single-electron spectrum, synchrotron radiation for circular motion is taken.

beam line to transport the radiation, and a detector. Additional components for a more detailed analysis of the radiation, like spectrometers, are often added, some of which are mentioned in subsequent sections.

Radiation sources

All processes that result in the emission of radiation from an electron are in principle suitable for the purpose of CRD. At FLASH, for example, synchrotron, transition and diffraction radiation are used so far, and a dedicated tunable electromagnetic infrared undulator is currently being installed [6]. The choice of source depends very much on the desired application, as the spectral characteristics and the influence on accelerator operation vary.

A fully parasitic source, not influencing accelerator operation at all, is synchrotron radiation if taken from an existing bunch compressor or bending magnet. This source covers a wide wavelength range. The emission spectrum, especially at long wavelengths, is complicated, as the usual spectrum derived for circular motion in free space is not valid for the comparatively short bending magnets in a bunch compressor (edge effect) and the typically flat vacuum chambers (cut-off) [7, 8]. Also the coherent enhancement can be affected if a bunch only moves on an arc instead of a circle [9].

Transition radiation is significantly more intensive and can be reasonably well calculated for realistic geometries [10]. It is, however, destructive (even for a thin radiator, the emittance is degraded strongly). A fast kicker is used at FLASH to extract a single bunch for beam diagnostics with transition radiation, allowing quasi-parasitic operation if longer bunch trains are used.

Diffraction radiation is parasitic if the gap in the radiator is sufficiently wide to prevent wake fields from disturbing subsequent bunches. Due to the gap, however, short wavelengths are strongly suppressed [10], and this source is thus not suitable for investigations of short bunch structures.

Smith-Purcell radiation essentially combines the source with a spectrometer [11], as the emitted frequency depends on the observation angle. It requires, similar to diffraction radiation, a radiator close by the beam, rising the question of wake fields and the emission of short wavelengths.

Undulator radiation is a narrow-band, high-intensity source, in principle rendering a spectrometer for analysing the radiation obsolete. Attention has to be paid to higher harmonics if a wiggler-like spectrum is obtained from a high-K device.

Radiation transport

The emitted radiation has inevitably to be coupled out from the accelerator vacuum into a measurement setup, requiring some form of radiation transport beam line. To avoid absorption from water vapour that is prominent in the infrared, evacuation of the whole setup is desirable, though only a fore vacuum on the order of 0.1 mbar is needed for distances up to several 10 m. A window then has to separate the fore-vacuum from the ultra-high accelerator vacuum. Thin foils of polyethylene have a good wide-band transparency, though often are considered to be too fragile from a machine safety point-of-view. Other plastic materials, like for example TPX that has the advantage of being transparent in the visible, have also been used. Crystalline quartz (cut perpendicular to its optical axis to avoid birefringence) is frequently used, but its useful transmission range extends only down to 80 μm. The only fully satisfactory material with almost constant transmission of 70% from the visible up to at least millimeter waves is diamond. It is also a strong material, so that 0.5 mm thick windows of 20 mm aperture withstand atmospheric pressure. To avoid etalon interference, such a window is typically wedged with a angle of up to 1°.

As the design of the beam line usually requires full attention to diffraction effects, Fourier optics codes (for example ZEMAX) are used. Although the application and working of such a code is in principle straightforward, care must be taken to implement the source correctly.

Detectors

Broad-band infrared detectors are bolometric, that is their primary detection mechanism is heating due to absorption of radiation. A subsequent effect then converts the temperature change into an electric signal.

Widespread use is made of pyroelectric detectors that use a change of polarization of certain materials like $LiTa0_3$ with temperature. Such a detector is essentially a capacitor of a few square millimeter area and a thickness between 30 µm and 100 µm. Radiation enters through the transparent top electrode, is absorbed, and the resulting surface charge or voltage from the polarization change is detected. Etalon interferences due to the relatively weak absorption in the far infrared are pronounced, as shown in a measurement in Fig. 2. Wedged crystals could overcome this problem, but have so far not been made.

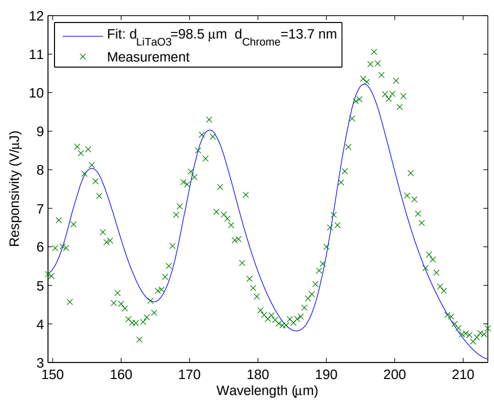

Figure 2: Response of a pyroelectric detector. The fit describes absorption in a stack of a thin Chrome top electrode, a $LiTa0_3$ crystal and a thick gold back electrode. The optical constant of $LiTa0_3$ are not known precisely, limiting the quality of the fit.

Pyroelectric detectors are intrinsically fast, and are used at FLASH with suitable read-out electronics to measure infrared radiation in long trains of up to 600 bunches with 1 MHz repetition rate. Response speeds exceeding 1 ns have been demonstrated elsewhere [12]. Since all pyroelectric crystals are also piezoelectric, mechanical vibrations excited by the absorption of short, intense infrared pulses result in ringing, typically at frequencies of several 100 kHz, depending on crystal geometry [12].

Another broad-band, room-temperature detector that is used frequently is the Golay cell, an opto-acoustic detector. The heating of a closed gas volume and subsequent pressure increase is detected optically via the flexing of a thin membrane. It is expected to have a much flatter response, showing no resonance structures like a pyroelectric detector, as the Golay cell has some similarity to a black body cavity. Measurements similar to those from Fig. 2 support this for the wavelength range 100 µm to 160 µm, though indicate non-uniform response around 3 mm [13].

Orders of magnitude more sensitivity are possible with cooled bolometers, essentially due to the decreased heat capacity of materials at low temperatures (liquid Helium) and the fast change of resistivity with temperature in the transition region from normal to superconducting state. A superconducting hot-electron bolometer was shown in [14] to have a time constant faster than 25 ps. Wide bandwidth operation of such a detector into the mid-infrared is usually not possible due to the steeply increasing heat load from room-temperature black body radiation. Cold filters are employed to limit thermal radiation from reaching the detecting element.

BUNCH COMPRESSION MONITOR

The simplest application of coherent radiation diagnostics uses the frequency-integrated intensity as a relative measure of bunch length. An example from FLASH is shown in Fig. 3: Transition or diffraction radiation from a screen is coupled out through a crystalline quartz window and transported to a pyroelectric detector.

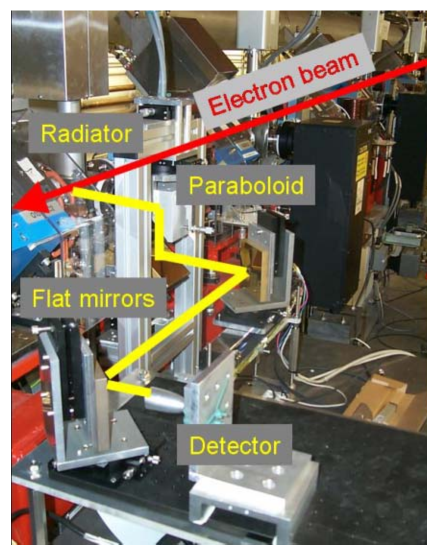

Figure 3: Bunch compression monitor setup at FLASH.

This compression monitor is installed after the first magnetic bunch compressor of FLASH. According to Fig. 1, the total radiation intensity increases with shorter bunches. The degree of bunch compression is adjusted by changing the acceleration phase of the acceleration module in front of the bunch compressor. A scan of this phase versus the intensity registered by the pyroelectric detector is shown in Fig. 4. Note that the curves obtained with synchrotron radiation from the last bunch compressor dipole magnet and with diffraction radiation from the set-up Fig. 3 are very similar except for the amplitude. Different pyroelectric detectors, different optics and only a simple alignment have been used, indicating the robustness of the method for determining maximum compression.

Such a scan, especially the deduced maximum compression phase, is used routinely at FLASH to establish the

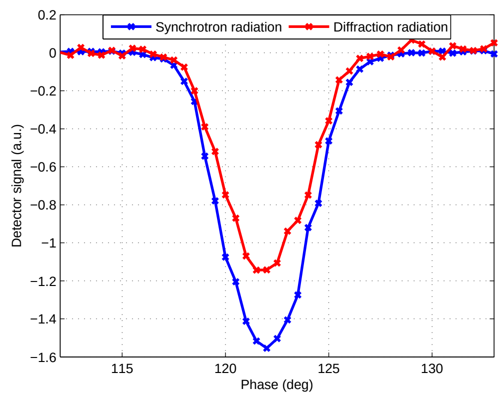

Figure 4: Phase scan with two bunch compression monitors at FLASH. The varied phase is that of the accelerating module in front of the bunch compressor.

per se arbitrary setpoint phase scale. A typical phase for SASE operation is several degrees away from maximum compression, thus allowing a simple feedback algorithm to stabilize the compression by regulating the module phase. This is an indispensable tool at FLASH to counteract drifts on the time-scale of some 10 seconds or longer. Despite the restricted wavelength range due to a crystalline quartz window, the phase found for maximum compression agrees well with the value expected from simulations.

A compression monitor based on using a ceramic gap as radiation source and diode detectors working up to several hundred GHz is proposed for the first bunch compressor of LCLS [15].

BUNCH SHAPE RECONSTRUCTION

By using the full spectral information instead of the frequency-integrated intensity, a more complete determination of the bunch profile is possible. Through knowledge of the single-electron spectrum and the bunch charge, at first the magnitude of the form factor $|F(\lambda)|$ can be deduced from (1). Inverting the Fourier transformation (2) to get the charge distribution is then possible if both amplitude and phase of the complex form factor are available. Although a strict solution of this phase-reconstruction problem is not possible, the Kramers-Kronig relation gives a handle to solve the problem from a practical point of view satisfactorily [2, 5, 16]. If the complex form factor is expressed as $F(\nu) = |F(\nu)| \exp(\mathrm{i}\Theta(\nu))$, then

$$\Theta(\nu) = \frac{2\nu}{\pi} \int_0^\infty \frac{\ln(|F(\nu')|/|F(\nu)|)}{\nu^2 - \nu'^2} \, \mathrm{d}\nu' \qquad (3)$$

yields a phase, the so-called *minimal phase*, that is compatible with the measured form factor amplitude. Although this solution is not necessarily unique, in practice the requirement to extrapolate the measured data to zero and infinite frequency, and the measurement errors are a more serious problem of the reconstruction process than the non-rigorous mathematics.

It is usually difficult to assess the single-electron spectrum precisely. It requires detailed knowledge of not only the radiation generation process in the actual experimental setup, but also of the distortions of the spectrum by the beam line and by the response of the instrument used to measure the spectrum. In some cases it has been possible to measure the incoherent spectrum over a certain wavelength range by assuring that the bunch is long enough to suppress coherent effects [17], but otherwise it is necessary to resort to simulations.

An example for a bunch shape reconstruction at FLASH is given in Fig. 5, taken from [18]. Here, synchrotron radiation from the first bunch compressor was transported to an experimental station outside of the accelerator tunnel, and the spectrum measured with a Martin-Puplett interferometer. The result is compared to a streak camera measurement using the visible part of the synchrotron radiation spectrum at the same beam line.

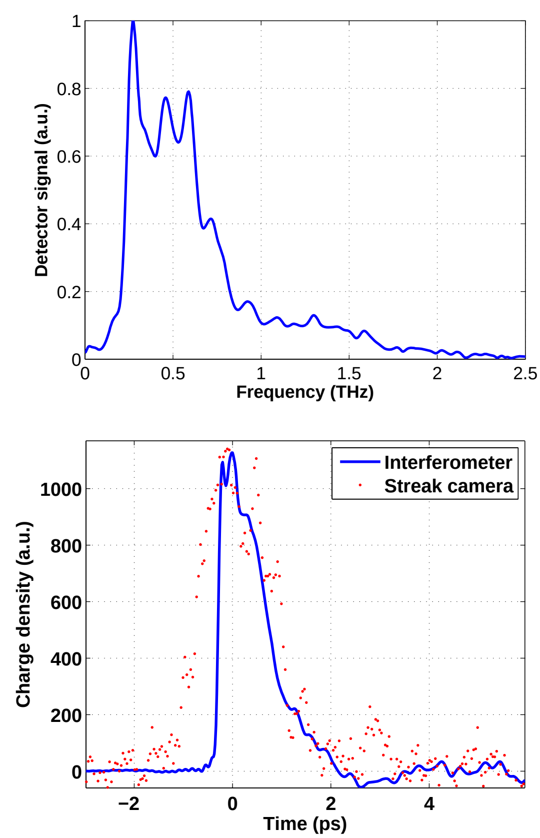

Figure 5: Example for a bunch shape reconstruction at FLASH. On top a measured synchrotron radiation spectrum, below the reconstructed charge distribution. The streak camera measurement has been made at the same synchrotron radiation beam line using visible light.

The streak camera resolution is limited to about 500 fs, the frequency-domain method mainly by the presence of a crystalline quartz window. Although an acceptable agreement is found, the amount of work in correcting the measured spectrum and finding suitable extrapolations was significant, clearly indicating that full bunch shape reconstruction is still an experimental and not fully independent technique.

Another experimental result for full bunch reconstruction can be found in [19].

SINGLE-SHOT SPECTROMETER

A high variability of the SASE intensity on a shot-to-shot basis is found at FLASH. A thorough investigation using coherent radiation diagnostics requires thus equally fast spectral information, ruling out a scanning interferometer for this tasks. A single-shot spectrometer based on staged blazed gratings was developed at FLASH, allowing a wide wavelength coverage from 4 µm up to some 500 µm. The details of the instrument are described in [20].

Measurements have been carried out at the FLASH transition radiation beamline which is located after the final bunch compression stage and equipped with a diamond window [21]. A phase scan with this instrument is reproduced in Fig. 6. Compared to the frequency-integrating scan from Fig. 4, it shows a much more complex behaviour, and especially a much stronger phase dependency (note that the phase scale in Fig. 4 has an arbitrary offset).

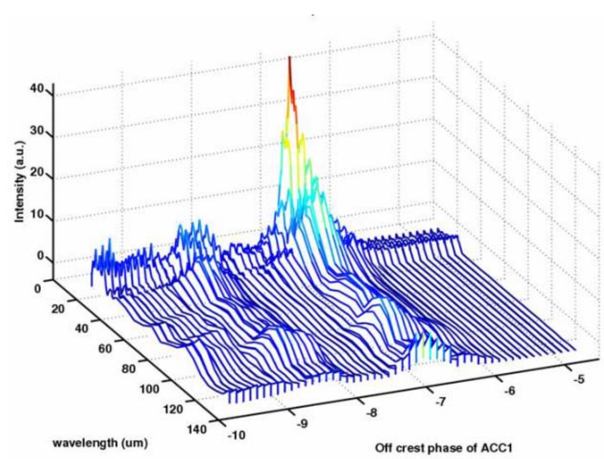

Figure 6: Phase scan with the single-shot spectrometer.

The narrow phase-band that shows high intensity at wavelengths around 30 µm is typically also a good starting point for further machine optimization. SASE performance of FLASH is influenced by many parameters, thus no optimum setting can be suggested by such a measurement alone, but tuning has in several occasions been significantly shortened and improved by using CRD for the initial set-up.

CONCLUSION

Longitudinal bunch shape investigations using coherent radiation are by now a standard tool for nearly all machines operating with short bunches or short bunch features. The tools employed in routine machine operation are, however, invariably non-calibrated, thus giving only relative or empirical information to help setting up a machine. Full longitudinal charge profile reconstruction is still a specialist application, and typically requires significant, dedicated work.

From the experience gained at FLASH, there is a clear benefit from having a wide wavelength coverage with a single-shot resolving spectrometer, especially at the experimental level. With increased understanding of the measured spectra and their dependence on machine parameters, it will likely be possible to restrict the wavelength coverage at a later stage. The benefit, however, comes at the price of a significantly higher hardware complexity, requiring evacuated setups, diamond windows, and well designed optics.

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