OVERVIEW ON DIAGNOSTICS FOR X- AND XUV-FEL

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Abstract

Controlling and optimizing the SASE process of X-FEL and XUV-FEL requires detailed knowledge and information about the parameters of the driving electron beam which are of critical influence on the laser performance. Due to the very high peak current, collective phenomena have to be carefully measured and controlled while integral (projected) parameters are of limited use. This necessitates the development of a variety of diagnostics tools to monitor the electron bunch parameters in detailedness beyond the capabilities of conventional systems. Longitudinal bunch structures can be derived from time domain methods like electro optic techniques or using transverse deflecting RF-structures, and from frequency domain methods using coherent radiation. The paper will report on recent developments with special emphasis on single shot and online monitoring capabilities in this field. Other topics will be new concepts and experience in measuring the projected and time-sliced emittance of the beam, high precision beam position monitors and sub-picosecond beam phase and arrival time monitor systems.

INTRODUCTION

Diagnostics for X- and XUV-FEL is a very wide subject and can not, even rudimentary, be covered in a short conference contribution. This paper therefore concentrates on certain areas which are especially demanding and where new developments can be reported. Photon diagnostics is a separate important issue but is completely omitted here.
Single pass FEL, as they are used for the production of X- and XUV radiation, are challenging machines in terms of beam quality and parameter control. On one side, the lasing process depends more or less exponentially on beam parameters like emittance and peak current, on the other side are these parameters subject to a delicate balance between concurrent externally steered and uncontrolled collective effects. Diagnostics has to measure and to control these beam parameters such that optimum FEL operation is achieved. The feedback between the diagnostic tools measuring the parameters and the steering of the machine spans all time scales from the very slow experienced human advice to ultra fast intra-bunch feedback on the microsecond scale. A region of special importance is the longitudinal phase space, since the FEL operation requires high peak currents with good transverse emittance. All the compression mechanisms used and proposed so far will achieve these conditions only for a fraction of the entire bunch

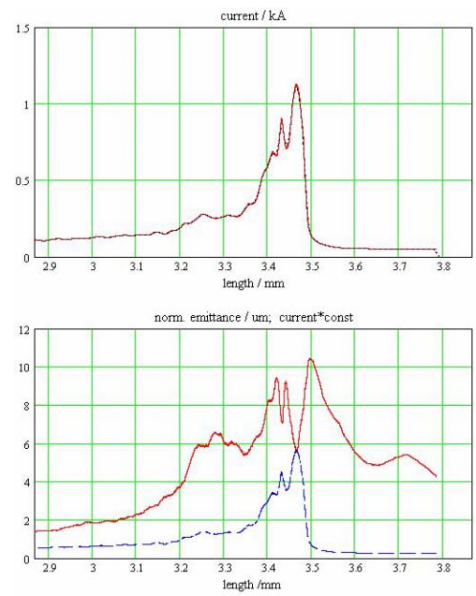

Figure 1: Simulated longitudinal bunch profile and emittance for a non-linear compressor scheme as used in FLASH. The influence of space charge effects and coherent synchrotron radiation on the bunch are included [1].

charge and the longitudinal diagnostic has to be sensitive to the parameters of this specific fraction.

As an example, Fig. 1 shows the result of a comprehensive simulation of the longitudinal bunch profile and emittance for a non-linear compression scheme as used in FLASH [1]. Collective effects like space charge and coherent synchrotron radiation strongly influence the beam parameters and it becomes obvious, that projected values are of very limited use. Diagnostics has to reveal details of the bunch structure and to do so on a single bunch basis since the collective phenomena are of partially 'chaotic' behavior.

BEAM POSITION MONITORS

SASE FEL are single pass machines and thus the trajectory of the electrons is not stabilized due to periodic boundary conditions. It is subject to shot to shot fluctuations and requires meticulous monitoring along the full lengths of the linac. The requirements on accuracy in the injector and main linac sections are of the order a few tens of micrometer which can be achieved by conventional button or resonant strip-line BPMs which are numerously used as workhorses in existing storage rings. Much higher demands on accuracy have to be faced in the undulators. Ac-

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cording to simulations[2][10] , stable SASE operation at X-ray wavelengths (1 $\AA$) requires a well defined trajectory which is reproduced with an accuracy of a few micron. This means that undulator BPMs have to work with sub-micrometer resolution and an overall mechanical stability at the same level. The requirements can be met by cavity BMPs which have demonstrated nanometer resolution during prototype studies for the ILC[13] . For LCLS, X-band BPMs are under development at ANL and SLAC[6] while for the European XFEL, C-band structures working at 4.38 GHz are foreseen[7]. These BPMs will be used in a fast intra-bunchtrain feedback system to correct the beam trajectory actively [8]. Besides the monitors itself, maintaining the required mechanical accuracy requires sophisticated alignment tools and procedures for the undulator section; an overview on the status of the plans for LCLS has been given during this conference[3].

Two specialties in the field of beam position monitors should be mentioned here since they comprise new concepts. One idea is to use the beam induced higher order modes (HOM) in super-conducting cavities to derive information on the beam trajectory. The complex amplitude of the various HO modes depends on the transverse location of the trajectory inside the cavities as well as on its inclination with respect to the cavity axis. Accurate measurement of the HOM amplitude pattern therefor allows to derive these values with an accuracy of a few micrometer and μrad. Test measurements at FLASH[9] have shown the feasibility of the method and impressive first results.

The second field to be mentioned are large aperture BPMs to measure the beam position and size inside the dispersive section of the bunch compressors. The aim is to derive accurate information on the mean energy and energy spread of the beam with single bunch resolution. The accuracy required on the transverse beam center is of the order 5 micron for an energy resolution of 10^{-4} while the width of the beam is of the order 50 - 100 mm. An interesting technique which has been studied recently proposes to measure the arrival time of the signals on both ends of a transverse stripline across the compressor beam pipe with an accuracy on the 10 fs scale[4]. The sum of left and right timing provides the information on the transverse center of the charge and thus the mean energy while the timing difference contains information about the width of the distribution and thus the energy spread. The method to derive timing signals from beam pick-ups with fs accuracy will be described in the next section. An alternative method to measure the transverse distribution in the bunch compressors has been successfully investigated at FLASH; it is based on high resolution imaging of the synchrotron radiation in the UV range produced in the bunch compressor dipoles [5].

ARRIVAL TIME (BEAM PHASE) MONITORS

Monitoring the performance of the machine and providing high precision 'time stamps' for the FEL users requires to measure the arrival time of the electron bunches in front of the undulators with fs accuracy. This is well above the capabilities of conventional RF methods and requires either specialized longitudinal diagnostics (see section on electro-optic methods) or a new type of beam phase monitors as proposed in ref.[11]. These monitors use the rather large beam induced signals from conventional button or ring pick-up electrodes to modulate the intensity of a probe laser pulse with electro-optic modulators (based on 'Periodically Poled Lithium Niobate' structures). These modulators combine a bandwidth of several GHz with high sensitivity and allow to detect the zero crossing of the signal with an accuracy of a few femtoseconds. A test set-up at FLASH has demonstrated very promising resolutions recently. Fig. 2 shows the measured time difference between two bunches of the same bunch train at FLASH. The combined effect of real time jitter and resolution of the phase monitor is of the order 50 fs. A potential drawback of the method is, that it measures strictly the 'center of charge' of the bunch and not the actually lasing part. Ideally, the probing laser of the phase monitor is part of an optical timing system of the machine which avoids any additional timing jitter due to RF synchronization.

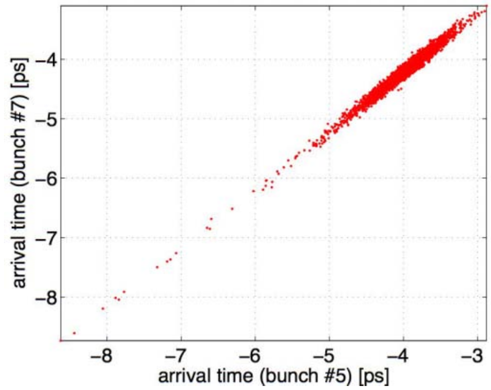

Figure 2: Time difference between two bunches of the same bunch train at FLASH, measured with a phase monitor using electro-optic detection of the zero crossing of a pick-up signal. The combined time jitter and monitor resolution is of the order 50 fs[12].

TRANSVERSE DEFLECTING STRUCTURES

Transverse deflection structures (TDS) are amongst the most powerful and developed tools to measure the phase space distribution of particle bunches. They have been developed at SLAC during the 60th[15] of the last century and used for both, beam separation and diagnostic purposes (e.g. [16]. Operating the deflecting structure close to the zero crossing of the RF, the bunches experience no net deflection but are streaked transversely. Adding a fast transverse kicker allows to send the streaked bunch to an off-axis screen independent of the streak power. If the transverse deflecting structure is combined with a FODO section, quadrupol scans allows to investigate the slice emittance of the bunches. In combination with a dispersive section, the streaked bunch images the slice energy spread of the beam. All future XFEL projects foresee transverse deflecting structures for diagnostic purposes. In the case of the European XFEL, multiple pairs of TDS are foreseen to allow measurements in both transverse planes at different locations along the injector section. An overview can be found in ref. [17].

For operation at zero crossing, the transverse deflection at the screen Δy depends on the longitudinal position Δz with respect to the center as

$$\Delta y = \Delta z \frac{eV}{E_0} \frac{2\pi}{\lambda_{HF}} \sqrt{\beta_c \beta_s} sin(\Delta\psi) \quad (1)$$

with V the total deflection Voltage of the cavity, E_0 the beam energy and $\Delta\psi$ the phase advance between cavity center and screen. It depends on both β-functions at the cavity and the screen and since the temporal resolution of the method is determined by the ratio of $\Delta y/\Delta z$ to the unstreaked transverse size of the beam, the optimal optics for the TDS operation demands large β_c and small β_s. This has to be foreseen during the design of the machine and is not necessarily coincident with the optimal optics for FEL operation.

An S-band TDS operating at 2,856 GHz from SLAC (LOLA IV cavity) has been installed at the FLASH linac and is routinely used for beam diagnostic measurements and to develop the TDS method further. At optimized conditions, a streak power of more than $1mm$ per $100fs$ can be achieved which for a nominal beam diameter of $200\mu m$ would lead to a resolution of about $20fs$ (RMS). Under normal FEL operation conditions, the resolution observed is slightly less. The image of a typical, well compressed bunch is shown in Fig. 3, the width of the charge spike at the bunch head is of the order $150fs$ (FWHM). Fig. 4 shows a bunch fragmented by space charge and CSR due to too high compression (notice the difference in time scale compared to Fig. 3).

Scanning quadrupols in front and after the TDS, the slice emittance of the bunches can be measured; a detailed report on recent results has been given at this conference[18]. If the streaked bunch passes a dispersive section in front of the observation screen, the slice energy spread of the bunch can be derived with high accuracy. The example shown in Fig. 5 demonstrates the complex structure of the longitudinal distribution and the strong coupling between ΔE and z. The bunch head clearly has two well separated peaks in phase-space which almost coincide longitudinally. Such observations are in good agreement with start-to-end simulations and emphasise the necessity of powerful diagnostics for a detailed understanding of the machine. The TDS method can be called semi-parasitic since the observed bunches are lost from the FEL process. The read-out speed is limited by the complex imaging required,

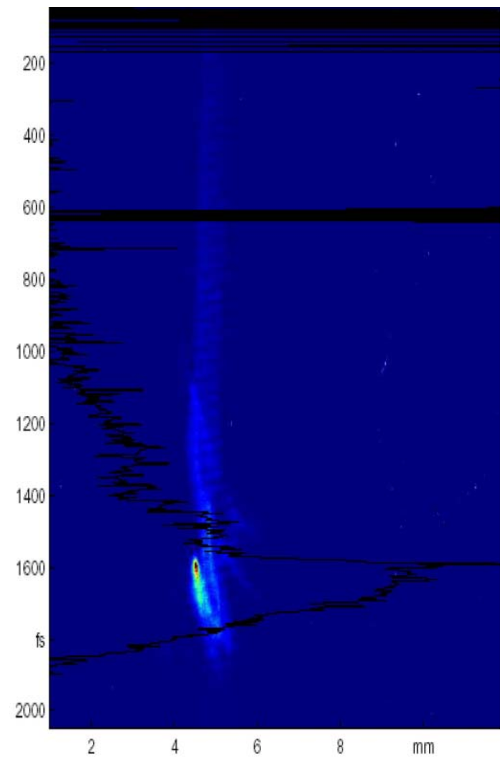

Figure 3: Image of a TDS streaked bunch at FLASH. The phase of the first accelerating module is set such to produce a well formed current peak[14].

the information can not be used for fast feed-back systems.

ELECTRO OPTIC (EO) METHODS

The longitudinal charge profile of the bunches can be probed by detecting their relativistic Coulomb field by means of electro-optic crystals close to the beam trajectory. The optical properties (namely the birefringence) of the crystals is changed proportional to the electric field strength and the cumulative effect on a co-propagating short laser pulse can be detected. In this way, the temporal (longitudinal) structure of the bunch charge is impressed in a polarization modulation of the optical pulse. An overview on the different methods to decode this information is shown in Fig. 6. The scanning delay method is not single shot and can not be used if the temporal jitter of the mean time of the bunch is comparable or even larger than the length of the bunch. Single-shot EO bunch length measurements were pioneered at FELIX [20] with the spectral decoding method (EOSD), the more recently developed spatial decoding [22] and temporal decoding [23] techniques offer higher resolution at the price of enhanced complexity.

The spectral decoding method is of striking simplicity: the probing pulse is stretched to several ps by applying a linear chirp, that is a correlation between time and 'local' wavelength. The polarization modulation due to the EO effect is translated into an intensity modulation by a

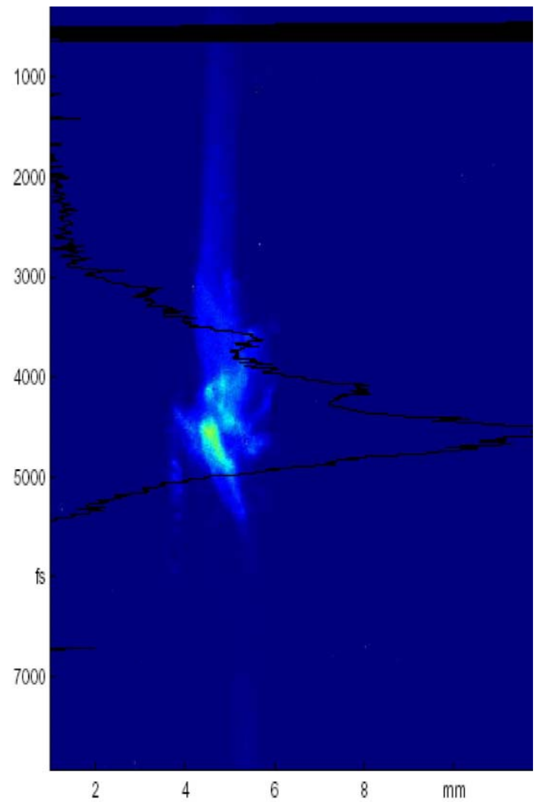

Figure 4: Image of a TDS streaked bunch at FLASH. The phase of the first accelerating module is set too much off-crest, the bunch is strongly distorted by space charge and CSR effects [14].

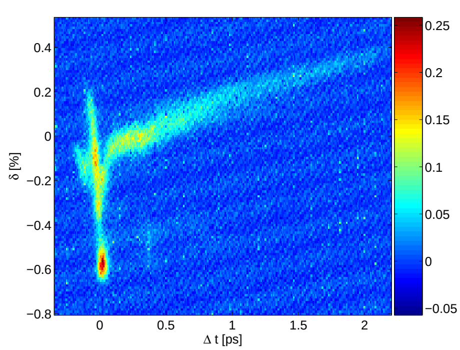

Figure 5: TDS streaked bunch with energy dispersion. The bunch head is contains two separated peaks, less than 100 fs apart and with an energy difference of 0.5 % [18].

set of crossed polarizers, the intensity as function of wavelength, measured with a conventional grating spectrometer, images the longitudinal charge profile. Unfortunately, the method has an intrinsic limitation: the amplitude modulation of the probe pulse creates unavoidably a spectral modulation which mixes with the linear chirp and thus spoils the ’decoding gauge’. For the very fast modulations (that is short pulses), this creates an apparent broadening of the

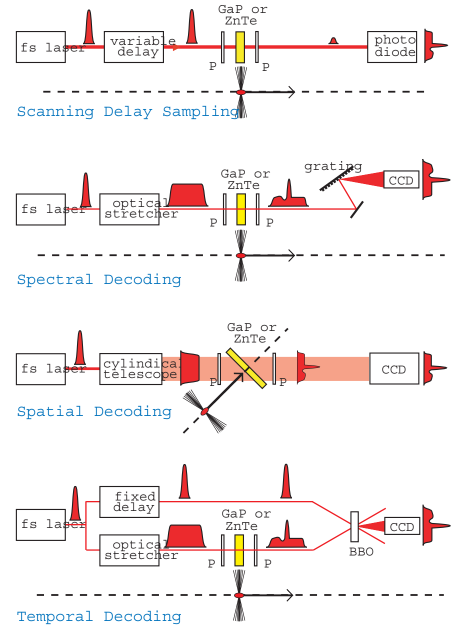

Figure 6: Overview on different methods to decode the temporal information form the laser pulse probing the EO crystal [19].

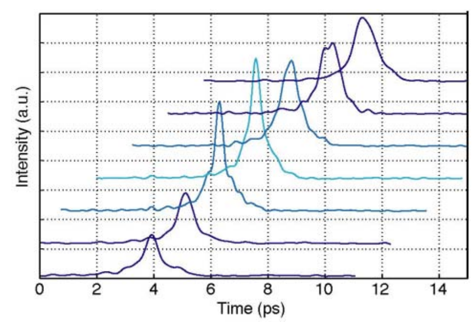

Figure 7: Single shot bunch profiles measured with electro-optic spatial decoding at the SLAC-FFTB using a ZnTe crystal [22].

pulse and even artificial temporal structures. For the typical optical wavelengths of 800 nm and a length of the chirped pulse of a few ps, structures shorter than about 200-300 fs (FWHM) can not be decoded correctly. Nevertheless, the centroid of the bunch can be detected with much higher accuracy (<50 fs) and coarse deterioration (double spikes etc.) can be easily detected. The method has the potential for further developments in the direction to become a routine on-line monitoring system. For that, the expensive and delicate Ti:Sa laser systems used so far have to be replaced by more robust devices (potentially fiber lasers). If the spectroscopy can be done by using a line camera with fast readout, multi-bunch capability can be envisaged for even the 200 ns bunch distance at the European XFEL.

Spatial decoding has been mainly developed at SLAC [22].

The spatially extended short probing laser pulse hits the EO crystal with non-perpendicular incidence, thus a spatial image of the crystal decodes the electric field a different points in time. The method has the great advantage to be free of the intrinsic limits of EOSD but relies on the spatial uniformity of the EO crystal which can be, especially for ZnTe, quite poor. It requires a quite complex optics and imaging system inside the accelerator tunnel but can operate with rather modest laser energy. Fig. 7 shows a result obtained at SLAC using a ZnTe crystal, the resolution of $270fs$ achieved is close to the limit for this material. At FLASH, a similar set up using GaP is installed and resolutions of the order $120fs$ have been demonstrated[21].

Temporal decoding is the most powerful and most complex EO method developed so far. The short laser pulse is split in two halves, one is chirped to a length covering the length of the electron bunch and passes the EO crystal in the beam line. The other one is kept short. The polarization modulation is transferred to an intensity modulation in the usual way, after that the probing pulse hits a non-linear crystal (SHG). There it is merged under a certain angle of inclination with the short 'gate' pulse from the same origin. In the SHG crystal, a second harmonic component is created proportional to the product of both laser intensities, leaving the crystal in a direction well separated from the two incoming components. The temporal information thus is decoded by optical cross correlation as shown in Fig. 8 schematically. Since a non-linear optical process is involved, the method requires much higher laser power (mJ) and thus a complex and expensive laser amplifier system. On the other hand, the method has demonstrated the best resolution so far. At an installation at FLASH, spike widths of the order 100 fs (FWHM) have been measured in good agreement with TDS data recorded simultaneously (Fig. 9).

Single-shot electro-optic diagnostic techniques are rather mature as experiments meanwhile but still in an infant state as routine operation tools. Since they are totally non-destructive and can be applied to any bunch, it is worthwhile to spend considerable efforts to overcome the technical problems to make them more robust an usable as continuously running monitoring tools. The development of optical synchronization systems makes them even more attractive, since they can be directly coupled to them by means of optical synchronization, avoiding any additional jitter introduced by RF components. They are ideal candidates to provide not only detailed information about the bunch structure online but as well to act as extremely precise bunch arrival time monitors and time stamp generators for pump-probe experiments.

COHERENT RADIATION DIAGNOSTICS

The relativistic electrons of the bunches radiate electromagnetic waves whenever their Coulomb field is subjected to changes: synchrotron radiation due to directional changes in the bending sections or transition and diffraction radiation if the field enters regions of changing dielectric

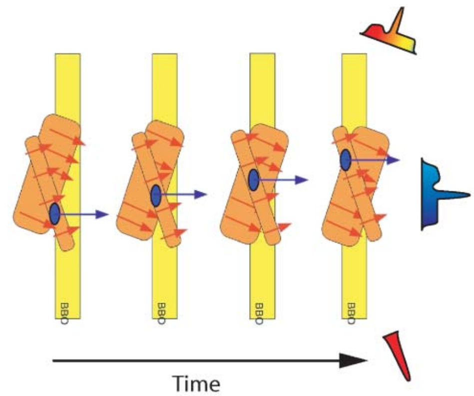

Figure 8: Temporal decoding of the intensity modulation of the probe pulse by spatial cross correlation in a second harmonic (SHG) crystal.

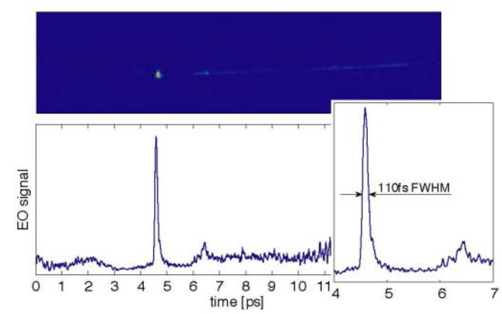

Figure 9: Longitudinal bunch profile measured at FLASH with the electro-optic temporal decoding technique using a 100μm thick GaP crystal [24].

properties. For wavelengths of the radiation longer than the distance of two electrons, these electrons radiate 'in phase' or coherently, the intensity of this coherent radiation scales with the square of the number of contributing electrons and can be a massive effect. More precisely, the radiated power per frequency interval can be written as

$$\frac{dU}{d\omega} \propto N^2 |F_{long}(\omega)|^2 T(\omega, \gamma, r_b, \Theta, source) \qquad (2)$$

with

$$F_{long}(\omega) = \int_{-\infty}^{\infty} \rho(t) exp(-i\omega t) dt \qquad (3)$$

F_{long} is the longitudinal form factor of the bunch, the Fourier transform of the longitudinal charge distribution and T summarizes all other, potentially complex, properties of the radiation source.

The most popular application of coherent radiation diagnostics is to measure a global intensity of the radiation integrating over a certain (normally large) range of frequencies and use the signal strength as an index for the shortness (the 'compression') of the bunch. It should be kept in mind that the information on the bunch length obtained that way is restricted to the wavelength range

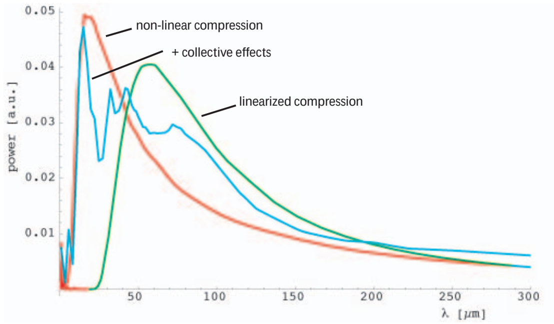

Figure 10: Simulated wavelength spectra of coherent transition radiation for two compression schemes without space charge and CSR effects and for an example of non-linear compression including space charge and CSR effect (data courtesy M. Dohlus).

covered by the radiation detector. If the coherent radiation intensity is observed spectrally resolved, information about the longitudinal form factor and thus the charge distribution can be obtained. For the typical bunch lengths between 10 fs and 100 fs contributing to the FEL process, the corresponding range of wavelengths is in the far infrared from 10 μm to 300 μm. As shown in Fig. 10, the wavelength spectra of coherent transition radiation from ideally compressed electron bunches strongly peak in the region below 200 μm, the position of the intensity maximum directly reflects the length of the current spike[1]. If the bunch is distorted by collective effects, the wavelength spectrum exhibits characteristic substructures which could be used to get information on the strength and nature of the collective phenomena. Despite the fact that a direct reconstruction of the bunch shape from radiation spectra is impossible due to the missing phase information, the wavelength spectra reveal sufficient information to act as 'fingerprints' of the longitudinal bunch structure.

The wavelength range of interest puts a few stringent boundary conditions to the experimental set up: conventional crystalline quartz windows are not transparent for wavelength shorter than about 80 μm and humid air absorbs below 300 μm even over short distances substantially. In consequence, the radiation has to be coupled out of the beam pipe by using a CVD diamond window and the entire coherent radiation set up has to be evacuated or flushed with a dry gas. Conventional IR spectrometers used so far in bunch length diagnostics are Michelson type interferometers measuring the autocorrelation function of the radiation. This method is intrinsically not single shot capable and the information has to be derived in a complex de-convolution process. Recently, a new type of spectrograph has been proposed[25] and assembled which is able to measure wavelength spectra over a sufficiently large range on a single shot basis. The central elements are gratings as dispersive elements and a multichannel detector with fast read out. In a first step, a set of reflective blazed

[1]For a Gaussian bunch, the position of the intensity maximum in wavelength space depends linearly on the temporal width of the bunch

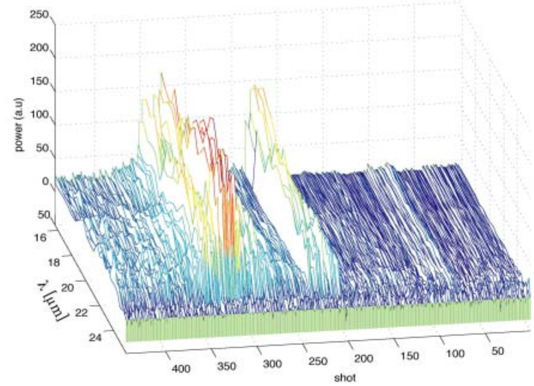

Figure 11: A set of successively recorded single shot spectra in the wavelength range 16-26 μm from coherent transition radiation at FLASH. While recording from right to left, the off-crest phase of the first accelerating module was scanned from zero to about -8 degrees.

gratings has been used to separate different wave length bands and to detect them with single element pyro-electric sensors. Such a device can be used as 'advanced bunch compression monitor' which is much more sensitive to the actually lasing part of the bunch than conventional integrating devices. It has been tested at the THz beam line[28] of FLASH using coherent transition radiation and proven capabilities. More details can be found in ref. [**?**].
The development of a 30 channel fast read out pyro-electric sensor at DESY[29] made it possible to record coherent radiation spectra for single shots online. The device has a sensitivity of about 300 pJ per channel (5σ noise-level) and is almost free of disturbing 'etalon' resonances in the sensitivity in the interesting wavelength range from 1 μm to $1mm$. For this, newly designed pyro-electric sensors have been developed together with industry. The device has been used together with transmission gratings and reflective gratings for fist online single-shot spectroscopy at the FLASH THz beamline[2]. As an example, Fig. 11 shows a set of successively recorded spectra in the range of 16-26 μm while the phase of the first accelerating module was scanned over 8 degrees[27]. Radiation in this wavelength range is produced in two (probably three) narrow regimes of the off-crest phase. One of them is usually used for FEL operation. In contrast to this, fig. 12 shows the equivalent scan for very short wavelengths between 5 μm and 8 μm. No such pronounced bands are seen, the intensity pattern fluctuates from shot to shot and the overall intensity increases with larger off-crest phase angles. This is a very clear indication for micro-bunching on a few femtosecond scale.

Single shot coherent spectroscopy has made a step forward but still to prove its benefits for bunch profile diagnostics and online monitoring. Transmission gratings

[2]The evacuated beamline images transition or diffraction radiation from an off-axis screen over a distance of 20m to outside the linac tunnel. A fast kicker is used to kick individual bunches to the screen, thus the measurements can run in parallel to normal FEL operation.

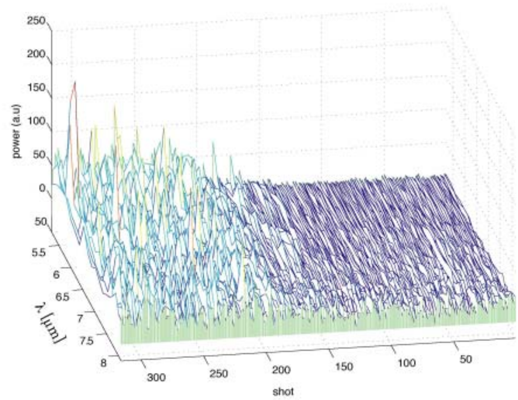

Figure 12: A set of successively recorded single shot spectra in the wavelength range 5-8 μm from coherent transition radiation at FLASH. While recording from right to left, the off-crest phase of the first accelerating module was scanned from zero to about -8 degrees.

offer a wider spectral range but can not reach the shortest wavelengths, reflective gratings span only about one octave in wavelength but have higher efficiency and are available down to the UV region. The natural next step is to 'stage' several reflective gratings with a final transmission grating to span the full range of interest simultaneously. Equipped with fast read-out, these devices can be used even for fast feedback systems.

SUMMARY

Diagnostics for XUV and XFEL requires a variety of new developments on various fields to cope with the very demanding challenges of these machines. Considerable progress has been made during the past years for beam position monitors and especially on the field of longitudinal phase space diagnostics and arrival time monitors. But most of the new methods are still not mature and more or less far from being applicable as routine online tool to control and steer the machine. This is a reach and challenging field for the next years. On top of this, even more sophisticated techniques like the "optical replica synthesizer" are on their way to be explored [30][31].

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