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OBSERVATION OF FEMTOSECOND BUNCH LENGTH USING A TRANSVERSE DEFLECTING STRUCTURE

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Abstract

The design of the VUV-FEL at DESY demands bunch lengths in the order of 50 fs and below. For the diagnostic of such very short bunches a transverse deflecting RF structure (LOLA) has been installed which streaks the beam according to the longitudinal distribution. Tests in the VUV-FEL yielded a rich substructure of the bunches. The most pronounced peak in the has a rms length of approximately 50 fs during FEL operation and below 20 fs FWHM at maximum compression. Depending on the transverse focusing a resolution well below 50 fs was achieved.

INTRODUCTION

To obtain enough gain for the SASE process it is necessary to produce peak currents in the order of 4 kA. With the present setup of the machine this can only be accomplished by compressing part of the bunch to 50 fs. Diagnosing such a short pulse poses a challenge to the beam instrumentation. Therefore a transversely deflecting structure is used to streak the beam.

For this purpose a structure formerly used for particle separation in secondary beams is utilized. It has been used before at SLAC under the name LOLA IV [1]. It is an S-band structure operating at a frequency of 2.856 GHz. Operating the structure close to the zero crossing of the field the bunches acquire no net deflection but are streaked vertically. Using a horizontally deflecting kicker one bunch per pulse is steered onto an OTR-screen. This way it is possible to diagnose parasitically one bunch out of a train of several hundred bunches. At SLAC this structure has been used for the same purpose [2,3,4]

SETUP

The setup of the VUV-FEL is depicted in figure 1. The electron bunches are created in an RF-gun and then accelerated in 5 superconducting modules up to presently 450 MeV. Behind the first and the third module there are two bunch compressors used to shape the longitudinal profile of the bunches. The initial bunch length is 1 ps (RMS) which is already long enough to probe the nonlinear rf curvature of the 1.3 GHz L-band cavities. This results in an incomplete compression in the first bunch compressor. The out coming bunch then has two main parts: A very short spike in the head and a tail which resembles the original distribution. The tail however still has an energy correlation imprinted in the first module and reshaped in the bunch compressor. Part of the tail is then compressed in the second bunch compressor to form a short spike with high peak current and good emittance. Depending on the exact phases in the modules #1-#3 the two bunch compressors produce a single or double spike at the exit of the linac. At the end of the acceleration sections, before the collimator system of the undulators, there is the transversely deflecting structure LOLA installed.

The structure is an S-band travelling wave structure. It operates in TE-TM-hybrid mode, so that a combination of electric and magnetic field produces a transverse kick. The maximum equivalent deflecting voltage is 20 MV over a structure length of 3.6 m. The fill-time is 680 ns, so that in a 1 MHz bunch train only one bunch is affected. A downstream OTR screen is utilized to analyse the streak. It is displaced from the centre of the beam pipe so that the beam can pass through. A kicker is used to steer only the bunch in question onto the screen.

To allow for a better synchronization with the master clock, LOLA is tuned to a frequency of 2.856059 GHz, which is an integer multiple of 1/11 of the master clock frequency of 9.027775 MHz. By means of an additional synchronization circuit it is guaranteed that the machine triggers always with a fixed phase relation to this reference [5]. At 9 MHz bunch rate this frequency offset

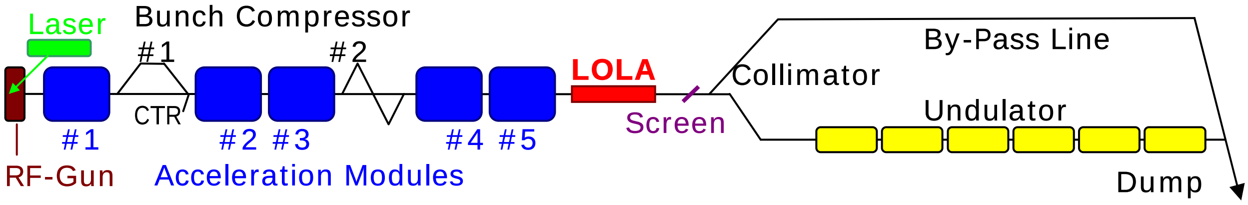

Figure 1: Schematic drawing of the VUV-FEL beam line. At the end of the accelerating section there is the transversely deflecting structure LOLA. It streaks the beam vertically so that on a downstream viewscreen the longitudinal profile of the bunches can be studied.

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such a case each millimetre of vertical dispersion would contribute with 0.3 fs to above resolution.

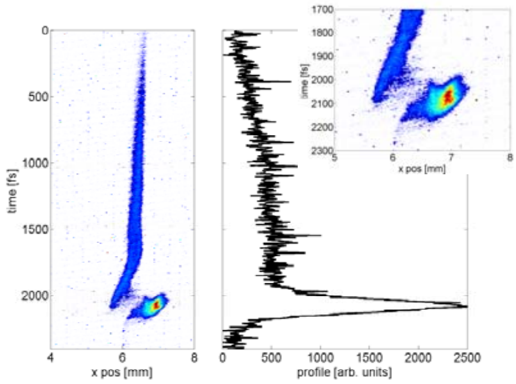

Figure 2: Image of the streaked bunch; inset: zoom on the spike at the head. The streak was approximately 4 fs/px.

results in a phase shift of 36° between neighbouring bunches. This way these bunches would miss the screen and not disturb the measurement.

Because an absolute calibration of the streak based on pure RF measurements did not seem precise enough, one power level was calibrated using the deflection of the beam. The calibration of the other power levels was then scaled according to the relative change of RF power. Relative power levels can be measured much more precisely than absolute levels, so that this method appeared accurate enough. For the calibration a relatively low power level was chosen, allowing for a phase shift of ~7° before the bunch misses the screen. In this way the influence of phase jitter on the calibration is reduced. A streak of 74 pixel/degree or 13.2 fs/pixel was measured. One pixel of the CCD corresponds to 26 μm. A maximum possible streak of 1.8 fs/pixel can be achieved. The optical setup allows for a better resolution than 26 μm.

The beam size at this location is larger, however. The standard beam optics foresee 200 μm spot size (RMS), which would then correspond to a resolution of approximately 15 fs. Unfortunately the spike is also the region of the largest energy spread in the bunch. An energy spread of ~1 MeV (RMS) is not uncommon. In

RESULTS

The transverse deflecting structure LOLA has been used to measure the longitudinal bunch profile while the machine was setup for SASE operation. Two examples are given in the figures 2 and 3. While the performance of the FEL was quite similar in the two cases (approximately 1 μJ photon pulse), the two profiles differ considerably. Both setups were started from a standard setting defined as follows: The acceleration in the first module was adjusted 6 degrees from the maximum compression phase, which is defined by the maximum of the coherent diffraction radiation at a station closely behind the first bunch compressor (see figure 1). The second and third module are adjusted for on-crest operation so that they do not add considerably to the longitudinal energy distribution. The second bunch compressor then creates the spike necessary for the high peak current at low emmittance.

In the first case (figure 2) the module 1 phase was subsequently tuned for less compression, so that no strong peak was produced in the first bunch compressor but only in the second. This would also explain the relatively weak sub-structure of the bunch, because CSR would play a big role only after the second compression stage when it can not influence the longitudinal profile very much.

In the second case (figure 3) the phase was tuned to stronger compression in the first bunch compressor, so that both bunch compressors produce a spike. This results in the double peak structure that can be observed. At the same time there is even more structure to the bunch. This is probably due to wakefield and CSR effects in the first bunch compressor, which can then be translated into a longitudinal modulation in the second compressor stage.

In both cases the width of the peak in the projected profile is measured to be in the order of 120 fs (FWHM). This result however has to be considered preliminary because not all detrimental effects have been considered thoroughly yet. The true width will be smaller than that.

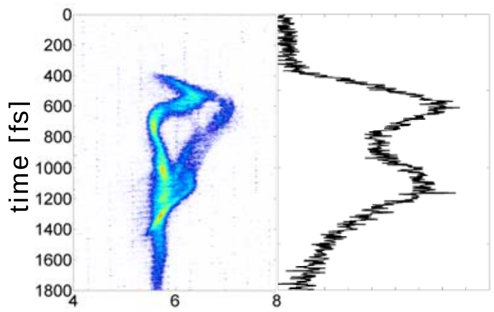

Figure 3: Bunch head with a double peak structure. There is a rich sub-structure of the bunch which shows not only longitudinally but transversely. Note that the streak is opposite to figure 2.

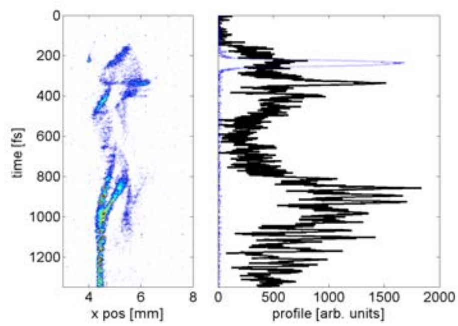

Figure 4: Bunch head with faster streak (2 fs/px) and optimized focusing. The dotted line in the right plot indicates the unstreaked beam size.

For the example in figure 4 the streak was increased and the unstreaked spot optimized for minimum vertical size. Consequently there was no lasing at that time, but the settings were somewhat close to the ones in figure 3. Exact consistency can not be guaranteed, particularly the compression might have been stronger. There is much more structure to be seen than in the previous cases. This appears in part enhanced by a lower intensity of the image which causes darker parts to vanish completely.

The effects that concern the most are the entanglement of the vertical and longitudinal structure of the bunch and the vertical dispersion. As can be seen from the figures 2 through 4 there is a strong variation of the horizontal profile along the bunch. This presumably has to be attributed to the two bunch compressors, which deflect horizontally. Nevertheless it can not be excluded that similar effects show vertically. Since the spike carries only a small fraction of the total bunch charge this can not be checked with the un-streaked beam. In this case the charge contained in the tail outshines the head.

A remedy to this problem might be a tomography in the z-y-plane. For this the voltage in the structure would have to be scanned while the change in profile would be recorded. This procedure is in preparation but is not finished yet. Likewise has the dispersion not been measured nor compensated yet.

The LOLA structure can also be used to monitor the jitter of the beam arrival time. This information is of special importance to pump-probe experiments to be performed with external lasers synchronized to the master clock. The figure 5 shows the shot-by-shot jitter of the bunches measured with a BPM close to the viewscreen.

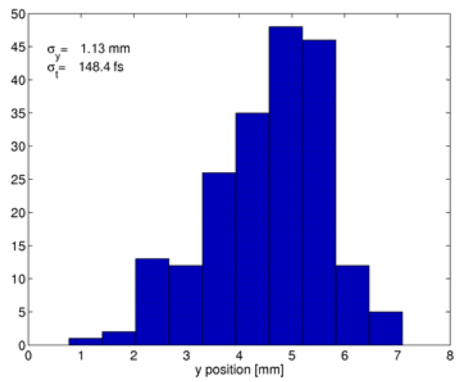

Figure 5: Phase jitter of the beam with respect to LOLA. The jitter due to the high power RF in LOLA is approx. 70 fs.

An RMS jitter of 145 fs (RMS) was measured. Note that this is the jitter of the beam with respect to the LOLA RF which can have a jitter by itself. The largest contribution will be the stability of the klystron, which was found to be in the order of 70 fs (RMS). A similar result for the beam jitter was found with electro-optical sampling (EOS) at a nearby diagnostic station [6]. The main contribution to this timing jitter is expected to be the energy jitter in the first bunch compressor. Evaluation of this jitter delivered compatible results.

CONCLUSION AND OUTLOOK

A transversely deflecting structure has been successfully applied to the beam in the VUV-FEL at DESY. Although some important contributions to the measurement error are not fully controlled yet, the achieved resolution surpasses most other methods already and it can be used in normal operation of the accelerator.

There are plans to exploit more capabilities of this measurement method as well as measurements of slice-emittances. A first attempt has already been made [7], but for best results tomographic measurements are foreseen.

In view of higher bunch repetition rates at later times and in future projects, shorter structures with a shorter fill-time are being envisioned.

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