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Experiments with electron beam modulation at the DUVFEL accelerator

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Abstract

Recently strong modulation of the electron bunch longitudinal phase space was obtained in the DUV-FEL accelerator at NSLS [1,2]. The chirped beam energy spectra exhibit a spiky structure with a subpicosecond spike separation. A model based on the longitudinal space-charge effect has been suggested as an explanation of the observed effect [3,10].

For characterization of the structure and comparison with the model we performed several experiments [4]. In this paper we present experimental data and discuss them in relation to the model.

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1. Introduction

In our previous papers we described a spiky structure in the chirped beam energy spectra observed while measuring bunch length [1,2]. The horizontal beam profile in the energy spectrometer (6 and 7 on Fig. 1) exhibited modulation with as much as 100 % depth and period of 100 μm (compare with DUV-FEL slippage of 70 μm for the lasing at 266 nm). The interpretation of the spiky structure as the longitudinal density modulation led to the conclusion about inevitable degradation of the FEL performance. However, no real degradation of the FEL output was observed which motivated investigation of an effect responsible for this phenomenon.

A model based on longitudinal space-charge effect was suggested in [3]. According to this model small density clusters in the electron bunch create fluctuations in the static space charge field. Field fluctuations accelerate particles at the head of the cluster and decelerate particles at the tail, creating energy modulation along the

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bunch. This initiates plasma oscillations in the bunch during its travel along the accelerator. As a result, the phase space distribution of the electron bunch at the end of the accelerator is strongly distorted.

Another possible mechanism driving the structure is Coherent Synchrotron Radiation (CSR) instability in the chicane-compressor [5,6]. In this case, coherent radiation emitted by electrons while passing through the chicane creates density bunching along the beam. For DUV-FEL experimental conditions, both numerical simulation [2] and analytical estimates [3] give a small value of the gain for CSR microbunching instability.

The layout of the DUV-FEL accelerator is depicted in Fig. 1. For energy measurements, we use a spectrometer dipole located at the end of the accelerator. A beam position monitor intercepts the beam 30 cm downstream of the dipole, the image on the monitor is recorded, and the transverse distribution in the spectrometer dispersion direction measures the electron energy distribution.

The spectrometer set-up also allows us to measure the bunch length, using the “zero-phasing” technique [7]. In this mode the last linac tank is running off-crest, imparting an energy-time correlation in the electron beam. Measuring a chirped beam’s energy spectrum, one can estimate the bunch length [1].

A Coherent Transition Radiation (CTR) station [8] is located upstream of the spectrometer (Fig. 1). The station consists of an in-vacuum copper mirror mounted on a retractable support. The infrared light is outcoupled into a nitrogen-cooled bolometer by a 3-mirror collection system.

The described experimental set-up gives us an opportunity to characterize the longitudinal phase space only at the end of the accelerator. In our studies, we varied the beam parameters in the beam line upstream and studied the impact of these variations on the measured projections of the longitudinal phase space [4]. In the experiments, we used beam parameters close to regular DUV-FEL operations (charge of ~ 300 pC, bunch length of 4 ps, normalized emittances of ~4 mm mrad).

2. Gradual bunch compression

As discussed in [1], structure appears in an initially smooth chirped beam energy profile after the beam gets compressed. In order to study the dynamics of modulation during the compression process we performed the following experiment. The second linac section was gradually dephased from the on-crest position, providing the energy-time correlation required for compression. The chirped beam energy spectra for every compression ratio are shown in Fig. 2. The first profile corresponds to an uncompressed bunch with a charge of 300 pC. The spike at the head of the bunch (on the left side) is caused by nonlinearity of the phase space due to RF curvature. The beam profile exhibits small amount of modulation with average period of ~900 fs.

In frames (b)-(d) we provided compression ratios of 1.15, 1.53 and 3.30 respectively, by changing the phase offset in the second tank. The small modulation in the chirped beam profile evolved into a highly pronounced structure with a depth of more than 50 %. Another important observation, derived from the profiles, is in the evolution of the modulation wavelength. Though structure shapes differ for consecutive profiles, the average spike separation tends to scale with compression ratio. For instance, in (d), the spike separation is about 250 fs.

This experiment demonstrates the enhancement of the structure during the compression process. The compression decreases the average period of the structure while increasing the peak current in the bunch.

3. Experiment with the chicane strength

The result of the previous experiment leads us to the question of the sensitivity of the structure to the chicane strength. The impedance [9] of CSR in the chicane depends on the bending radius in the chicane magnets and, for the DUV-FEL configuration, it is comparable to the length of the bends. Therefore, for a CSR-mediated effect, the observed structure should be sensitive to the chicane settings.

Changing the chicane strength has two major consequences. First, it changes the compression ratio and, therefore, the bunch peak current. Second, due to the edge focusing of the chicane dipoles, it affects the transverse beam envelope along the accelerator. Thus, changing the chicane strength significantly impacts the beam dynamics, requiring the consideration of many other effects.

In order to create a "clean" experiment we exploit the fact that the compression ratio $1\text{-}h{\cdot}R_{56}$ depends on both the chicane strength R_{56} and the energy chirp h. This allows us to maintain the compression ratio (and the peak current of the postcompressed bunch) while simultaneously changing the bend angle with the chirping tank phase.

In order to maintain the postcompressed beam envelope independent on the chicane settings we designed lattices for any particular chicane settings.

For the experiment we picked three isolines (lines of the constant bunch length on (h, R_{56}) plane) at low (1.8), medium (2.5) and strong (4.5) compression ratio (Fig. 3). The results of the experiment are shown on Fig. 3. For a low compression ratio structure seems enhanced only at the highest chicane strength. At the same time there is no difference observed for the medium compression. For high compression, profiles are dominated by the structure regardless to the chicane strength. We may conclude that, in general, the structure is not sensitive to the chicane strength.

Another important result of this experiment was the close correspondence of the measured values of the bunch length to the calculated ones in any compression scenario. It has also been observed that the measured uncorrelated energy spread is constant along the isoline.

4. Dependence on transverse beam size

As shown in [3], the longitudinal space charge effect has a strong dependence on the beam radius. In the next experiment we tested the sensitivity of the structure to the variation of transverse beam size in the accelerator.

Varying quadrupole triplets, we created three different focusing scenarios. The RMS beam sizes, averaged over the length of the accelerator, were measured as 0.25, 0.5 and 1 mm RMS. Special care was taken to insure that spectrometer resolution stayed constant during the beam size change.

The result of the experiment is shown in Fig. 4. The deep modulation on the chirped beam profile for the smallest beam (0.25 mm) almost vanishes for the largest beam (1 mm) profile. The average modulation period stays nearly constant. This result supports the interpretation of the structure as dominated by energy modulation, caused by the longitudinal space-charge effect.

5. Coherent Transition Radiation measurements

The spectrometer set-up does not allow us to study the bunching content in the longitudinal beam density. Spiky structure in the chirped energy spectrum can be interpreted as a combination of energy modulation and bunching (local longitudinal density fluctuations). We used the CTR station to measure the IR power generated by the compressed beam.

Varying transverse beam size we created two cases of "strongly modulated" and "non-modulated" beam profiles (Fig. 5). All other beam parameters (bunch length, peak current) were maintained constant. The characteristic modulation wavelength was estimated as 90 µm, using chirped bunch profiles. Using an IR bolometer together with low-pass IR filters (cut-off at 40 µm, 100 µm, 160 µm) we measured CTR.

The result of the experiment is shown in Fig. 5. If the observed structure were dominated by the longitudinal bunching we would have to expect enhancement of the measured IR power at the wavelength region of about 90 µm. However, the measurements show no significant difference between these two bunch conditions, indicating that the spiky structure is associated with a modulation in energy, not in density.

6. Conclusion

In this paper we discussed several experiments performed for the characterization of the spiky structure observed in the energy spectra of the compressed bunch. The longitudinal space charge model [3,10] is found to be in a qualitative agreement with the results of experiments. The interpretation of the structure follows as dominated by the energy modulation.

7. Acknowledgements

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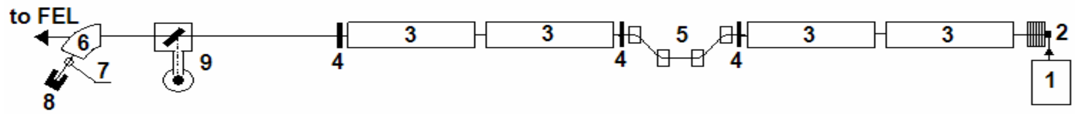

Fig. 1: The DUV-FEL layout. 1 – RF gun drive laser, 2 – RF gun with focusing solenoid, 3 – 3 GHz linac tank, 4 – focusing triplets, 5 – magnetic chicane, 6 – spectrometer dipole, 7 – beam position monitor, 8 – beam dump, 9 – CTR station.

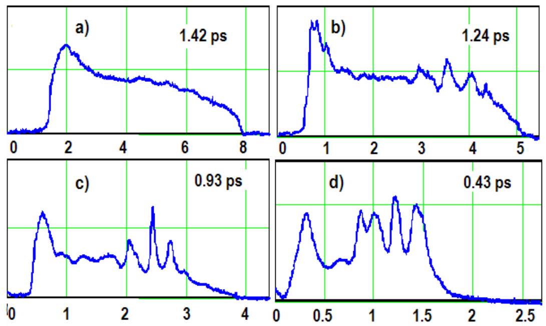

Fig. 2: Development of the structure during compression process. Horizontal axis is scaled in picoseconds.

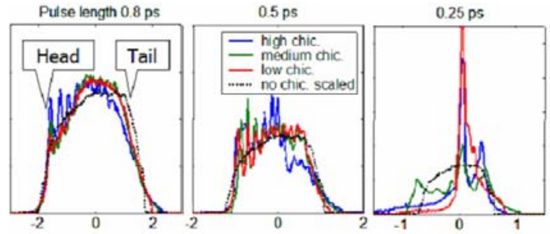

Fig. 3: Chirped beam energy spectra for different isolines

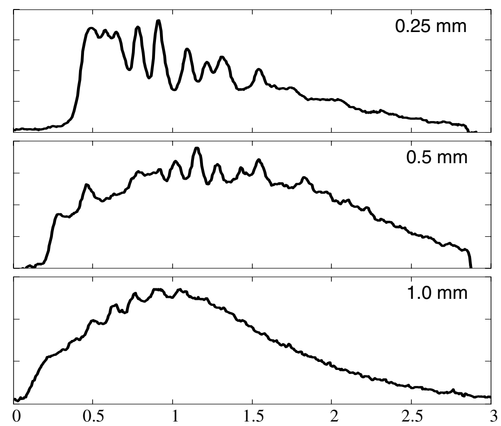

Fig. 4: Chirped beam energy spectra for different average RMS beam sizes

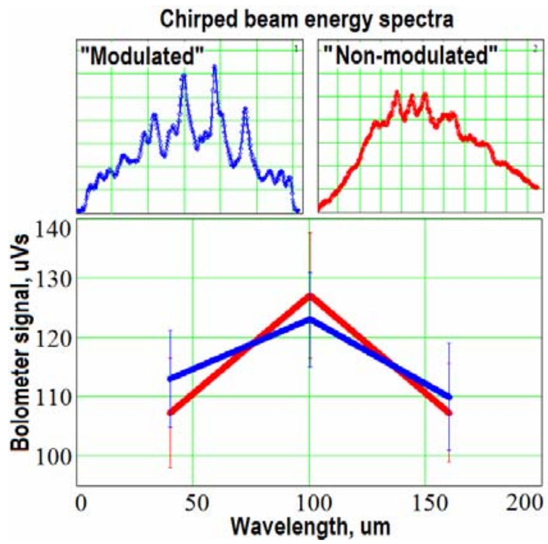

Fig. 5: IR measurements: bolometer signal (μVs) versus wavelength (μm)