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Experimental investigation of a space charge induced modulation in high-brightness electron beam

T. Shaftan
National Synchrotron Light Source, Brookhaven National Laboratory, Upton, NY, 11973
Z. Huang
Stanford Linear Accelerator Center, 2575 Sand Hill Road, Menlo Park, Ca, 94025

Abstract

We present experimental investigation of a collective effect driving strong modulation in the longitudinal phase space of high-brightness electron beam. Measured beam energy spectrum was analyzed in order to reveal main parameters of modulation. Experimental results were compared with simulation, based on the model of space charge oscillations in the beam longitudinal phase space. Measurements and simulation allowed us to determine the parameters range of observed effect in the modulation dynamics.

Introduction

During the last decade a growing demand for a new generation of light sources has initiated research and development of high-gain free electron lasers (FEL)[1]. New light sources are required, having ultimate brightness along with flexible temporal properties of radiation from VUV to soft X-ray wavelength range. These requirements pose serious constraints on allowable quality limits of "active medium" in accelerators-FEL drivers. For successful operation of high-gain FEL, electron beam must have small emittance and low energy spread.

Problems of generation and transport of high-brightness beams caused intensive investigation of possible instabilities, capable of degrading the beam quality. Studies discovered several new effects, specific for high-brightness machines. One of them, Coherent Synchrotron Radiation (CSR) in the bunch compressors, appeared to be a mechanism of dangerous microbunching in the beam longitudinal density [2,3,4,5]. Another instability, wake fields due to vacuum chamber surface roughness [6,7], may dramatically increase the electron bunch energy spread. These and similar effects have been carefully studied and considered at the design stage of various FEL projects. Effective solutions for minimization of their harmful impact on the beam quality were elaborated.

Several years ago two FEL facilities reported observations of a new complicate phenomenon. At the commissioning stage of DUV-FEL (NSLS, BNL) and TESLA (DESY), strong modulation of electron bunch energy spectra has been observed [8,9].

During measurements of bunch length using the so-called zero-phasing method [10,11] energy spectra of compressed bunch exhibited spiky structure with a subpicosecond spike separation. To reveal the main properties of the structure several experiments were proposed and performed [12,13]. In this paper we discuss results of experiment at DUV-FEL (Deep Ultra Violet FEL) facility and their comparison with a developed model of the effect.

The model [13,14] is based on longitudinal space charge effect, which drives small nonuniformities in the longitudinal bunch density into modulation of energy along the bunch. Small density clusters in electron bunch create fluctuations in the static field of space charge. Field fluctuations accelerate particles, located at the head of the cluster and decelerate particles at the tail. This initiates plasma oscillations in the bunch during its travel along the accelerator. As a result, phase space distribution of the electron bunch at the end of the accelerator is strongly distorted. This effect is specific for high-peak current regime, required for achieving high gain in FEL.

Analysis of the model predicts sensitivity of the effect to the beam parameters. In the experiment, described in this paper, we studied dynamics of the modulation with respect to the beam energy, maintaining all other beam parameters constant.

In the first chapter of this paper we describe experimental set-up and present results of the experiment. In the second chapter we discuss numerical simulation, developed according to the model. Using the simulation we calculated amplitudes of energy modulation for different beam parameters and compared it with measured data. In conclusion, we summarize the results of the work.

Experiment with structure in electron bunch energy spectra

The experiment was performed at the DUV-FEL linear accelerator [15]. Electron bunch with 200 pC of charge was generated in an RF gun, driven by 1.3 mm long laser pulse. Bunch was accelerated up to the energy of 71.5 MeV and compressed in magnetic chicane down to length of 280 μm FWHM, which corresponds to 5 times increase in the bunch peak current. The experimental set-up consisted of following chicane two 3 GHz traveling wave accelerating sections (AS) and energy spectrometer, containing a bending dipole with beam profile monitor.

Combination of amplitude and phase of the first section RF wave was chosen in a way to not only change energy of beam centroid, but also simultaneously minimize correlated energy spread, remaining after compression. The second AS has been carefully calibrated to provide a known amount of energy chirp, which the spectrometer transformed into a spatial distribution on the downstream monitor, viewed with CCD camera.

Examples of chirped beam energy spectra (CBE spectra) are shown on Fig. 1. Local brightness in the image is linearly proportional to the local amount of charge. Horizontal coordinate of the beam image is scaled with energy; the position of the image centroid is defined by average beam energy. Electrons, located in the head (tail) of the bunch, gain (lose) energy while traveling through the second AS, but the energy of the beam centroid stays constant. Therefore the bunch gets dispersed along the horizontal axis of the monitor and head (tail) of the bunch gets mapped on the right (left) side of the monitor screen. This set-up is a particular implementation of so-called “zero-phasing” method for the bunch length measurement [10]. Since we can measure both energy and correlated energy chirp along the bunch, this method allows us to calibrate the energy axis in units of time in the bunch rest frame.

The noticeable structure in the CBE spectrum in Fig. 1 was the subject of the investigation. One could argue that the structure on higher energy image looks sharper and, therefore, the modulation amplitude significantly increases with energy. Fourier analysis of the energy spectrum confirms the same conclusion: spectral intensity at modulation frequencies is indeed larger for higher energy. Surprisingly, this conclusion is wrong. Careful analysis of the images on Fig. 1 shows that the modulation amplitude for 50 MeV is bigger than the value of correlated energy spread, imparted by the second AS. This causes “overmodulation” of the structure, which is sketched on Fig. 2. Therefore the CBE spectrum looks smoother for lower energy. In addition, as a measure of the spectrometer resolution, normalized intrinsic energy spread increases at lower energy, which furthermore reduces contrast of image.

As was shown in [14] observed structure must contain a contribution of modulation in longitudinal density, besides energy modulation. The experimental determination of the content of longitudinal modulation is difficult due to absence of high-resolution diagnostics in femtosecond time range. In order to determine if observed structure is dominated by energy modulation we performed two experiments [13].

Using three different focusing solutions with different beam envelopes (0.5, 1.0, 1.5 mm RMS) we measured sensitivity of the modulation to the change of the beam size along accelerator. It was explicitly shown, that the strong modulation, being present when the beam size is small, almost vanishes at a larger beam cross section. Observed structure, if caused by modulation in longitudinal density should not be so much sensitive to the change in transverse beam dimensions. In opposite, space charge dominated modulation must have strong dependence upon the beam size.

In the next experiment we have measured Coherent Transition Radiation (CTR) power from electron bunches with drastically different amount of structure under the same experimental conditions. Measured values of power for several CTR wavelengths did not differ for both cases. This means that spectral content of density modulation is the same in both cases.

The experiments have confirmed the conclusion about the observed structure being dominated by energy modulation.

Manipulating with the first AS, we varied the beam energy from 50 MeV to 110 MeV. All other beam parameters, including length, transverse sizes, charge, etc., were maintained nearly constant during the measurements. Erroneous change in any of these parameters could result in improper interpretation of the experimental results.

A large number of CBE spectra were recorded for every value of energy. Experimental data was analysed in order to retrieve two main parameters of the structure: time period and amplitude. Detail description of the modulation analysis can be found in [16]. For this particular experiment we picked two modulation periods from each of the recorded CBE spectra and averaged over the set of measurements, related to the same energy value.

The number of the modulation periods and modulation wavelength versus energy are plotted in Fig. 3. Frequency bandwidth of modulation lies in the terahertz range. An interesting feature of these dependencies is linear change of the average modulation wavelength with energy. At the same time, the number of the modulation periods linearly decreases with energy, maintaining the product, bunch length, to be constant.

Dependence of the modulation amplitude versus energy is shown on Fig. 4. Average amplitude of modulation is found to be 25 keV or $3\cdot 10^{-4}$ at average energy of 80 MeV. This value may exceed intrinsic energy spread by as much as an order of magnitude. Therefore structure by far dominates over uniform beam distribution and spikes in the images, corresponding to CBE spectra look very sharp.

Comparison with model

To reveal the dependence of the modulation on the beam energy and to explain the effects described in the previous chapter, we built a model, based on the longitudinal space charge effect.

In the frame of the model the first AS was represented as a distributed acceleration together with space charge force, acting at discrete locations along the beam path. The following drift was treated in a same way, except bunch energy was kept constant. Drift distance was chosen according to the real length between first AS and beam monitor. An ensemble of microparticles was tracked through the model set-up for every experimental value of the bunch energy. Space charge forces were included using the formalism developed in [14]. Tracking procedure allowed obtaining the longitudinal phase space distribution of the particles at consecutive locations along the beam path. Final phase space distributions were observed at the actual distance from the end of compressor down to the monitor location.

Note, that only the part of accelerator beginning from the end of compressor was taken into consideration of the model. This assumption is based on the fact that observed CBE spectra for the bunch with compressor turned off exhibited almost no spiky structure. Thus the modulation under study was assumed to be specific only for the regime with high peak current, or compressed bunch regime.

Our experimental set-up did not have the freedom to measure longitudinal bunch parameters at the end of the compressor. Following assumption was the choice of the initial conditions for the particles distribution. We assumed that the initial phase space distribution included a certain amount of density modulation, or bunching. At the same time any initial energy modulation, which might be present in the beam before the compressor, was neglected.

Simulation based on the described model demonstrated development of energy modulation, seeded by initial bunching. The final modulation amplitude depends on modulation wavelength and scales linearly with amplitude of initial bunching.

We used simulation for comparison of the predicted energy modulation amplitude with quantities derived from experimental data. As the experiment revealed a dependence of the measured modulation wavelength on the beam energy, we introduced initial density modulation at the same single wavelength specific for every experimental value of energy. Simulation results for initial bunching amplitude of 6 % are plotted on Fig. 4. This experimental result demonstrates the importance of considering the longitudinal space charge effect as a source of instability in the electron beam. We may conclude, that nonuniformities in the longitudinal bunch density in the range of only a few percent can cause strong modulation of energy along the bunch.

Initial excitation of bunching at a single frequency could not explain the variation of average modulation wavelength with energy. Therefore we used bandwidth-limited noise as a seed in the spectrum of initial density modulation (Fig. 5). Limits for the bandwidth were chosen according to the experimentally observed energy modulation wavelength range. In practice, noise can have different and more complicate spectral shape. Nethertheless, this simplified model of the noise in initial bunching turns out to be capable of explaining the phenomena. As one can see from the plot (Fig. 5), dynamics of the energy modulation, driven by bandwidth-limited bunching, substantially differs for the cases of lower (50 MeV) and higher (110 MeV) beam energies.

The difference between low and high-energy cases comes from two major circumstances. First, plasma oscillation frequency [14] depends on energy and modulation wavelength.

$$\Omega_{SC} = c\sqrt{\frac{2\pi I_0}{\gamma^3 I_A}\frac{|Z(\lambda)|}{\lambda}}\ , \tag{1}$$

where λ is modulation wavelength, γ stands for beam energy and $Z(\lambda)$ is the space charge impedance for coasting beam in free space:

$$Z(\lambda) = i\,\frac{2\lambda}{\pi r_b^2}\left[1 - \frac{2\pi r_b}{\gamma\lambda}K_1\left(\frac{2\pi r_b}{\gamma\lambda}\right)\right],$$

where r_b is beam radius and K_1 is modified Bessel function.

This expression determines phase advances of different harmonics in the spectrum of electron bunch longitudinal distribution. Plasma oscillations at higher frequencies accumulate larger phase advance while the bunch travels down to the accelerator.

Second, the rate of development of energy modulation is determined by space charge impedance in (1). Therefore increase of the beam energy decreases space charge impedance and slows growth of energy modulation amplitude.

It should be pointed out that expression (1) could only be used for the constant energy beam. In reality, beam energy changes during its travel along the first AS, although the AS (3 m) is significantly shorter than the drift (12 m), where expression (1) is valid. Therefore real phase advance would differ from the one predicted by the expression.

At lower energy plasma oscillation phase advance for higher frequencies in the spectrum approaches π, therefore oscillation amplitude in this frequency range is close to zero. As a result, the central frequency of the energy modulation spectrum is shifted towards the low frequency edge. Clearly, the central frequency determines number of oscillation periods in CBE spectrum, which becomes small for lower energy.

At higher energy, the spectral shape of developed energy modulation is slightly distorted towards the higher frequency edge, and the central frequencies of the final energy modulation and initial bunching spectra are almost equal. In this case the period of modulation becomes smaller and, consequently, the number of oscillation periods appears to be large.

Conclusion

This paper describes the experimental characterization of a collective effect in the longitudinal phase space of the high-brightness electron bunch. The essence of the effect is in transformation of initial density perturbations into energy modulation along the bunch. Since RF photoinjectors produce a very “cold” electron beam with small intrinsic energy spread, the modulation significantly modifies the energy spectrum.

Using experimental set-up with two accelerator sections and a spectrometer, we recorded energy spectra of the electron bunch for wide range of energies. The structure in the measured energy spectra was interpreted as a projection of the modulated longitudinal phase space. This allowed us to retrieve the dynamics of the modulation with respect to the variation of the beam energy. Current interpretation is based on several assumptions, due to lack of appropriate beam diagnostics.

Numerical simulation, based on the space charge model of the collective effect, demonstrated good agreement with the measured data. It was shown that longitudinal space charge force essentially modifies the bandwidth-limited spectrum of initial modulation of the beam current. The spectral shape of the developed energy modulation is a product of the spectrum of initial current modulation. The explanation of these dynamic effects lies in the dependence of plasma oscillation phase advance on the modulation frequency.

As a result of experiment we determined main parameters of modulation: spectral range, energy and bunching amplitudes. Amplitude of energy modulation is in the range of several tens of kiloelectronvolts, which may exceed intrinsic energy spread by an order of magnitude. Reconstructed amplitude of density modulation (a few percent) is comparable with measured fluctuations of RF gun drive laser intensity along the 266 nm laser pulse.

This paper presents one of the first steps in experimental analysis of space charge driven modulation in high-brightness electron beams. There is still a lot has to be done for complete characterization of this dangerous effect [13,17]. Once effect is well understood, methods of its treatment will be developed and implemented.

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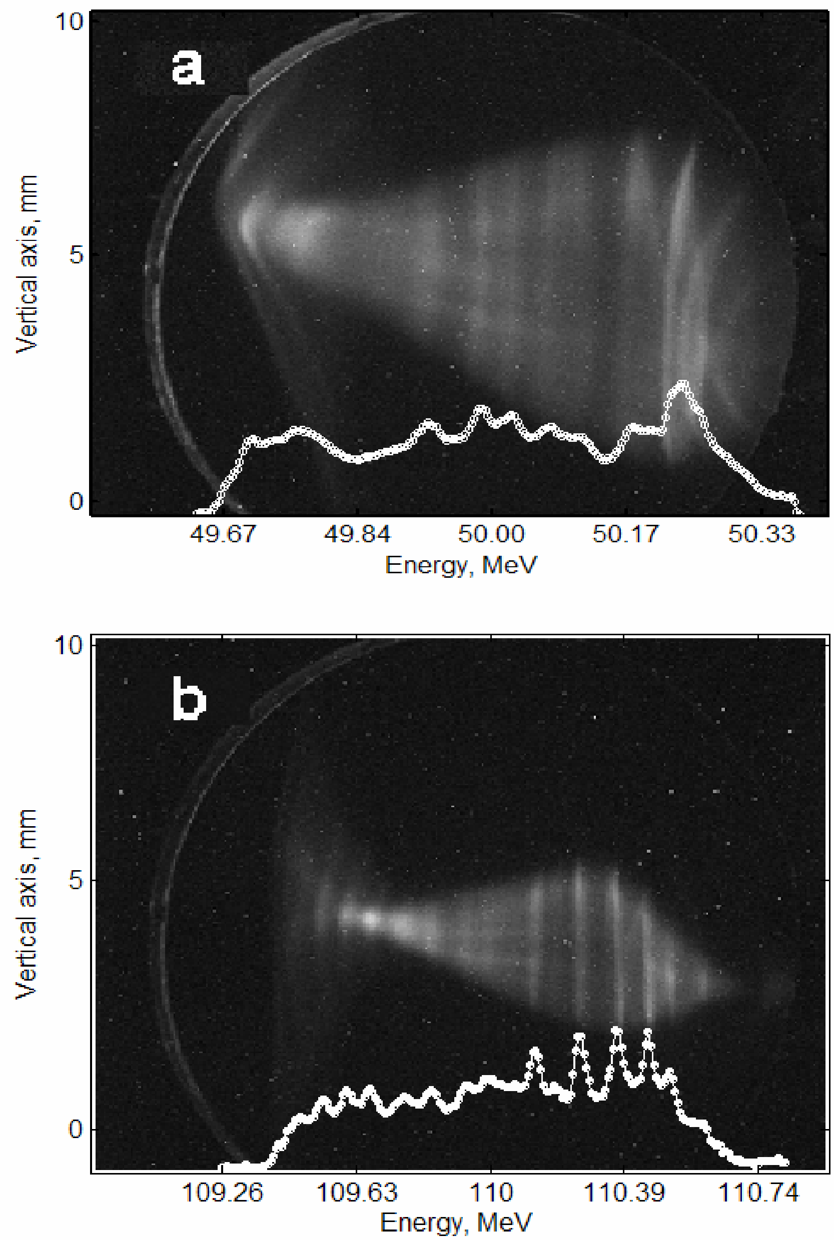

Fig. 1: Transverse beam distributions (images) and chirped bunch energy (CBE) spectra (curves) for 50 (a) and 110 (b) MeV. The CBE spectrum is a projection of the image onto horizontal axis.

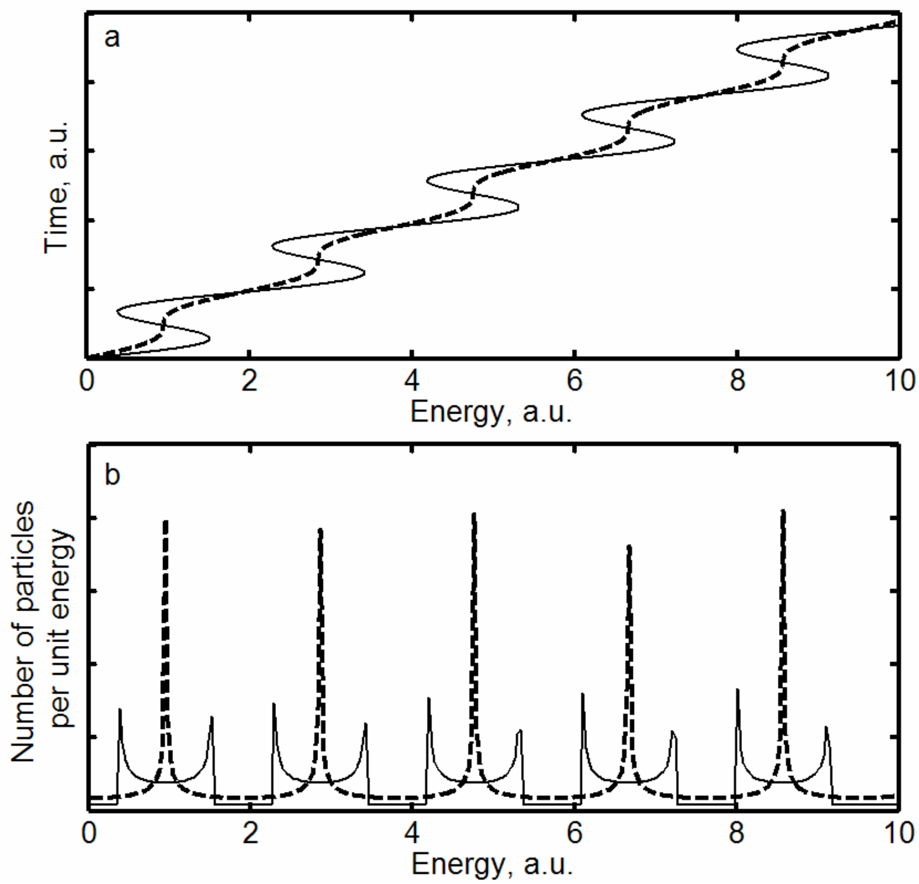

Fig. 2: Sketch of the beam longitudinal phase space (a) and its projections on the energy axis, or CBE spectrum (b). Intrinsic energy spread is neglected. Two beams are shown, one with larger (solid) and second with smaller (dashed) energy modulation amplitudes. Beam with larger amplitude represents "overmodulated" case, i.e. energy along the bunch is not monotonic function of time. Energy spectrum of the beam with smaller modulation amplitude looks significantly more "spiky".

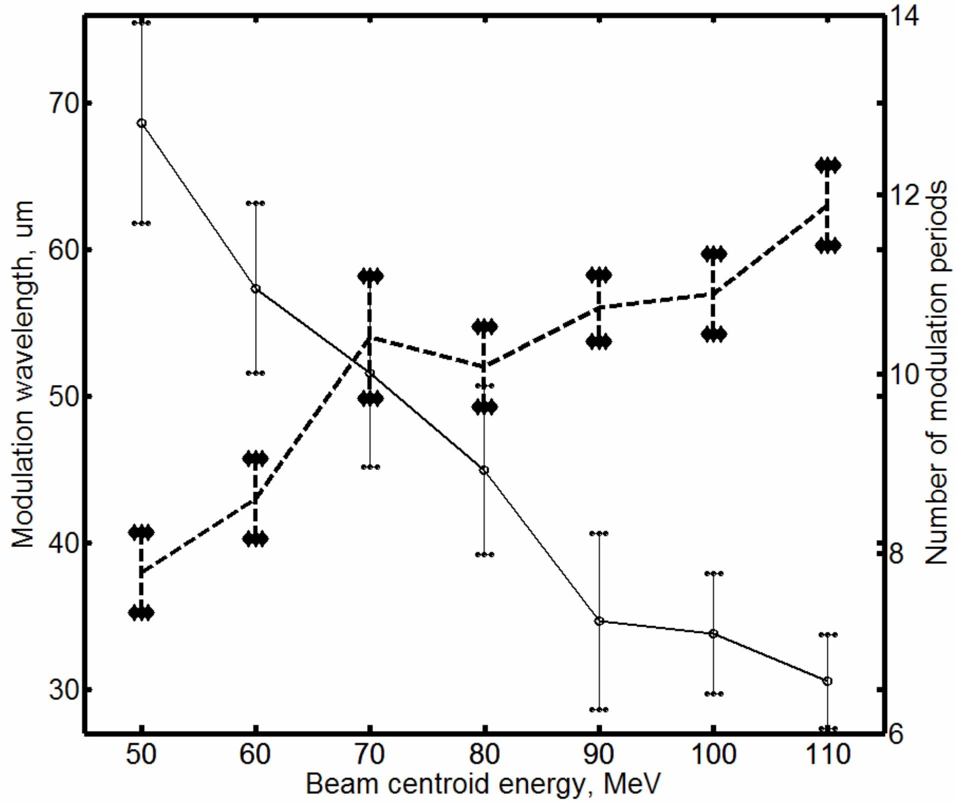

Fig. 3: Measured dependencies of the modulation wavelength (solid) and number of the modulation periods (dashed) versus beam centroid energy.

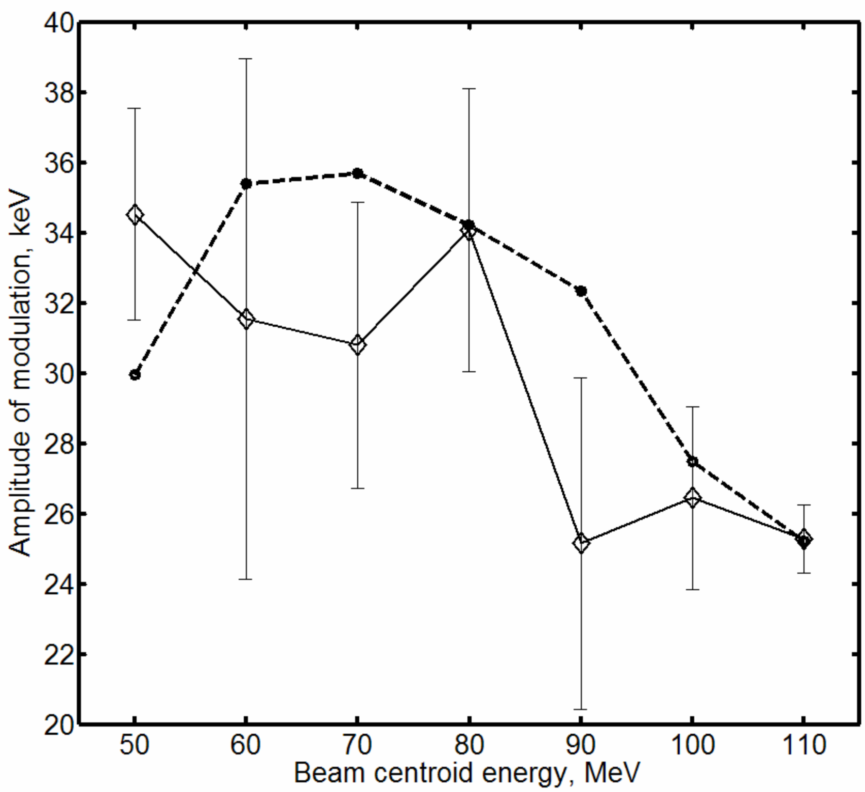

Fig.4: Measured dependence of the energy modulation amplitude versus beam centroid energy (diamonds). Dashed curve shows simulation results, for 6 % value of initial bunching.

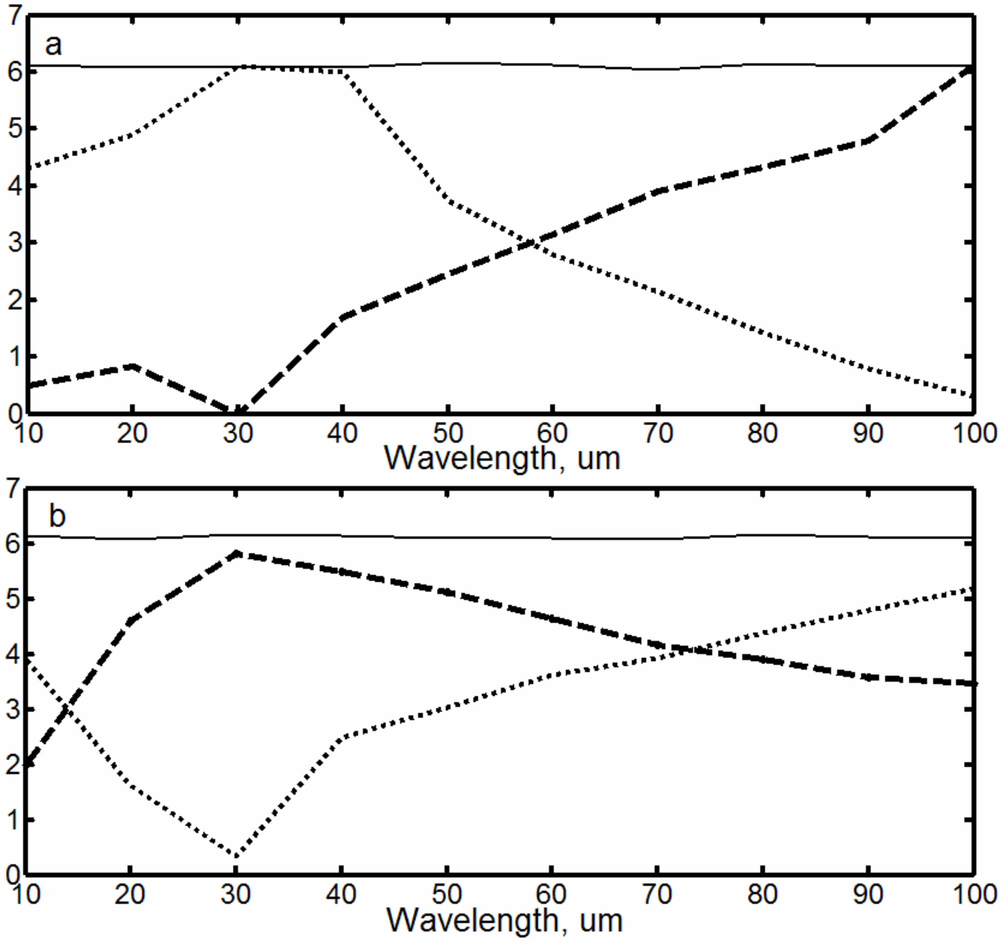

Fig. 5: 1-D simulation results. Normalized initial (solid) and final (dotted) spectral shapes of the density modulation for 50 MeV (a) and 110 MeV (b) cases. Dashed curves – normalized final energy modulation.