9th International Particle Accelerator Conference IPAC2018, Vancouver, BC, Canada JACoW Publishing
ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-THPAF033

DEGRADATION OF ELECTRON BEAM QUALITY FOR A COMPACT 'LASER-BASED' FEL

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Abstract

Laser wake field acceleration (LWFA) mechanism allows to produce extremely short electron bunches of a few fs length with the energy up to a few GeV in extremely compact geometries. This mechanism provides unique electron beam parameters, in particular, transverse beam emittance (order of 1 π mm mrad), extremely short bunch length (order of a few femtoseconds) and high beam charge (up to 100 pC). The novel acceleration method therefore opens a new way to develop compact "laser-based" FELs. In the frame of this report we discuss basic effects, which lead to degradation of an electron beam quality. The chromatic and collective effects have been analyzed for an electron beam line designed to transport the electrons from the 'laser-driven' source to a FEL undulator. In addition, the SASE FEL performance has been discussed in this report taking into consideration the degradation of the electron beam quality.

INTRODUCTION

The 'laser-wake-field-acceleration' is based on an ultra-high longitudinal electric gradient [1], created by the high-intensity laser pulse focused in a dense plasma (in a gas-jet, gas-cell or capillary target). The ponderomotive force pushes the plasma electrons out of the laser beam path, separating them from the ions. A travelling longitudinal electric field can reach several hundreds of GV/m, which is much larger than the accelerating field achievable in conventional accelerators, making LWFA extremely attractive as a compact accelerator to provide high-energy beams for different applications, including a 'laser-driven' compact FEL [2]. During last decades, a remarkable progress has been made in the field of electron acceleration based on the LWFA concept. For instance, through manipulating electron injection, quasi-phase-stable acceleration, electron seeding in different periods of the wake-field, as well as controlling the energy chirp, the high-quality electron beams in the energy range of 200÷600 MeV with the bunch charge of 10÷80 pC have been obtained experimentally [3].

For the 'demo'-FEL experiment, which is under preparation in ELI-BL [4], the electron beam energy should be in the range of 300÷500 MeV. The goal of this experiment is the demonstration of the 'laser-driven' SASE-FEL using a single section of a 'planar' undulator. The dedicated beamline has been developed to be able to capture the electron beam from the source, transport and manipulate with the electron beam in order to provide required 'slice' parameters of the beam in the undulator. The magnetic chicane [5] has been integrated into the beamline. This setup allows to control the 'slice' energy spread of the 'laser-driven' electron beam. For the 'demo'-FEL setup [4] the initial 'projected' RMS energy spread of 0.5 % is required. It was shown that in this case one can keep the bunch charge below 50 pC for the 'optimum' chicane bending angle of 0.6 degree. For the 'demo'-FEL experiment the saturation length is about 2 m in the case of a 'cryogenic' hybrid undulator.

DEGRADATION OF ELECTRON BEAM QUALITY

Different sources of degradation of the transverse and longitudinal properties of the 350 MeV 'laser-driven' electron beam in the dedicated beamline for the 'demo'-FEL experiment have been considered. The following parameters of the 'laser-driven' electron beam, based on the experimental achievements [3], were used for this analysis: the transverse RMS normalized emittance is 0.2 π mm.mrad; the transverse RMS beamsize is 1μm; the transverse RMS beam divergence is 0.5 mrad; the RMS energy spread of the electron beam is (0.5÷1) %; the bunch charge is in the range of 20÷80 pC and the RMS bunch length is 1μm.

Chromatic Aberrations

The beamline for the 'laser-driven' demo-FEL experiment is based on a combination of quadrupole magnets with high field gradient (the 'capture' block) and the 'momentum' filter [6, 7], which is a set of two 'doublets' of quadrupole magnets with a moderate field gradient and the collimator slit with changeable aperture in the horizontal plane.

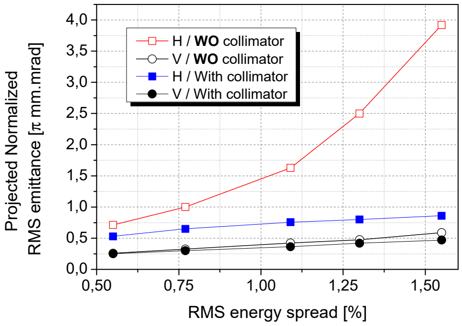

Figure 1: 'Projected' normalized RMS emittance in the horizontal (H) and vertical (V) phase planes as a function of the initial RMS energy spread ($\sigma_{\Delta p/p}$).

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Passing through the ‘momentum’ filter the electrons with large energy spread will create significant ‘halo’ of the beam, caused by the chromatic aberrations. By using an appropriate collimator aperture it is possible to cut these ‘halo’ particles and avoid significant growth of the normalized RMS emittance, caused by large energy spread of the ‘laser-driven’ electrons.

The ‘projected’ normalized RMS emittance of the 350 MeV beam at the end of the dedicated beamline is presented in Fig. 1 as a function of the initial RMS energy spread for two cases: (1) without any collimator; (2) with the horizontal collimator in the ‘momentum’ filter. The ‘chromatic’ aberrations lead to significant dilution of the normalized RMS emittance in the horizontal phase plane, which makes impossible to use such beam for the FEL experiment. By using the ‘momentum’ filter this emittance growth can be eliminated. If the horizontal aperture of the collimator of the ‘momentum’ filter is 400 µm, the RMS normalized emittance in the horizontal plane can be reduced from 4 to 0.8 π mm.mrad for the initial RMS energy spread of 1.5 %, providing the propagation efficiency more than 70 %. For the ‘initial’ energy spread of 0.5 % and the collimator gap of 400 µm the normalized RMS emittances of the ‘laser-driven’ electron beam are 0.5 and 0.25 π mm.mrad in the horizontal and vertical phase planes, respectively. The propagation efficiency of the electron beam in this case is 90 %. The space charge effect was not taken into account for this case.

Space Charge Effect

The ‘demo’-FEL experiment requires the electron beam energy in the range of 300÷500 MeV. The bunch charge of 20 pC and the RMS bunch duration of 2 fs were assumed to estimate the performance of the ‘laser-driven’ FEL in the case of the peak current of 4 kA. The magnetic chicane, integrated into the beamline between the source and the undulator, allows to control the ‘slice’ parameters of the electron bunch. At the same time the bunch duration will be changed by the chicane, leading the variation of the FEL saturation length. In order to keep the required peak current of the electron beam in the undulator the bunch charge from the source should be kept in the range of 20÷60 pC, leading to the ‘space-charge’ dominated regime.

The performed optimization of the R_{56} parameter of the ‘decompressor’ chicane [4] shows that for the initial RMS energy spread of $\sigma_{\Delta p/p}$= 0.5 % the ‘chicane’ bending angle should be in the range of 0.4÷0.8 degree. Variation of the RMS bunch length, caused by the space charge effect, for the fixed bending angle of the ‘chicane’ dipole magnets of 0.6 degree is presented in Fig. 2 (‘black’ symbol).

In addition, the effect of the space charge on the ‘projected’ RMS energy spread is shown in Fig. 2 (‘blue’ symbol). The space charge simulations have been performed by using the 3D space charge routine, implemented into the TraceWin code [8].

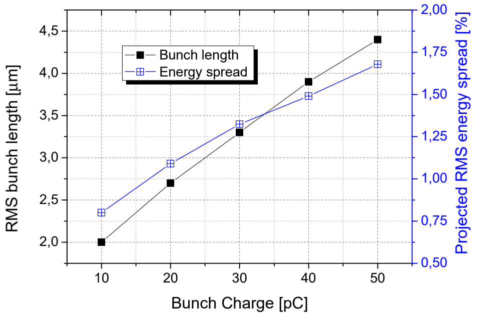

Figure 2: Variation of the RMS bunch length and the ‘projected’ RMS energy spread after the ‘decompressor’ as a function of the bunch charge of the 350 MeV electron beam.

The space charge of the bunched electron beam changes the transverse beam emittance in addition to the effect of the ‘chromatic’ aberrations, discussed above. The ‘projected’ normalized RMS emittances in the horizontal and vertical phase planes as a function of the bunch charge of the initial RMS energy spread of 0.5 % are shown in Fig. 3. The horizontal collimator aperture of the ‘momentum’ filter is 400 µm. The vertical normalized RMS emittance of the beam with the bunch charge of 10÷50 pC increases from 0.25 up to 0.7 π mm.mrad. The propagation efficiency through the beamline depends on the bunch charge (Fig. 3, ‘red’ marks).

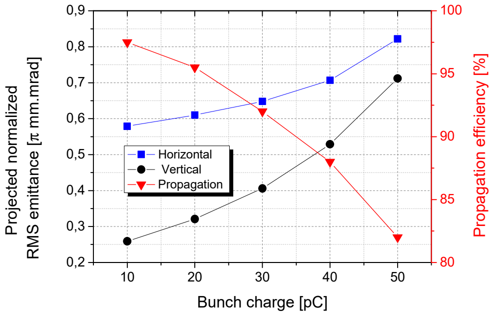

Figure 3: The ‘projected’ normalized RMS emittance in the horizontal and vertical phase planes at the end of the beamline and the propagation efficiency of the 350 MeV electron beam as a function of the bunch charge.

The ‘slice’ length of the electron bunch is determined by the FEL ‘cooperation’ length, which is about 0.3 µm for the considered setup [4]. The average ‘slice’ RMS transverse beam size, the average ‘slice’ RMS normalized emittance and the ‘slice’ RMS energy spread of the electron bunch have been analysed for different bunch charge to use these values for the FEL simulations.

Effect of the Coherent Synchrotron Radiation

The ‘symmetric’ C-type chicane has been considered in order to control the ‘slice’ energy spread of the electron beam for the ELI-BL ‘demo’-FEL experiment. The initial distribution of the ‘laser-driven’ electrons, analysed in the frame of this report, has an uncorrelated energy spread, which can be seen as a worst case scenario for the CSR effect.

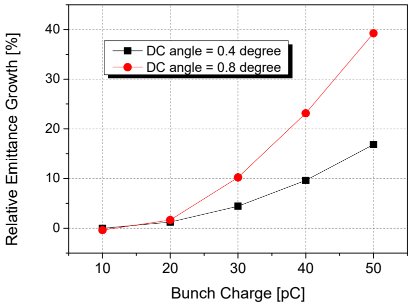

Figure 4: Relative emittance growth of the ‘laser-driven’ 350 MeV electron beam in the horizontal plane as a function of the bunch charge and the bending angle of the chicane’s dipole magnets.

The 1D CSR model, implemented into the ELEGANT code [9,10], has been used to simulate the emittance degradation caused by CSR in the ‘decompressor’ chicane. The validity check for this model has been made by using the ‘Derbeven’ criterion [11]. The 1D CSR model does not include the shielding effect of the chamber, so that one can expect the overestimation of the effect. The model includes the effect of the transverse beam distribution on the amount of the emittance growth due to the energy modulation. The CSR effect leads to the emittance growth in the ‘bending’ horizontal plane. The relative variation of the normalized ‘projected’ RMS emittance in the horizontal plane for different bunch charge and bending angle of the ’chicane’ dipole magnets is presented in Fig. 4 for the case of the 350 MeV beam.

From the obtained results one can conclude that for the ‘optimum’ bending angle of the ‘chicane’ dipole magnets of 0.6 degree [4] and for the bunch change less than 40 pC the degradation of the electron beam properties is caused mainly by the space charge effect itself, especially in the vertical and longitudinal planes. Detailed simulations are required in order to study the combined effect of the space charge and CSR with the shielding.

FEL PERFORMANCE

Taken into consideration the degradation of the ‘slice’ beam parameters caused by the collective and chromatic effects the FEL performance has been estimated for the ‘decompressor’ bending angle of θ_{DC}=0.6 deg by using the SIMPLEX code [12]. Final propagation efficiency of the beam for the bunch charge in the range of 10÷50 pC has been taken into consideration for each bunch charge (Fig. 3). The FEL performance has been studied for the single unit of the ‘cryogenic’ hybrid planar undulator [4]. The total saturation length and the power of the photon flux at the saturation are presented in Fig. 5 for different bunch charge of the 350 MeV electron beam. The minimum saturation length of 2.4 m has been obtained for the beam with the initial bunch charge of 40÷50 pC. The propagation efficiency for such beam is about 85 %.

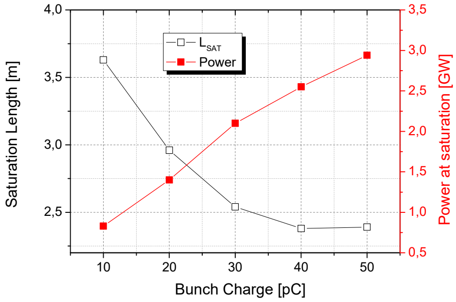

Figure 5: The saturation length and the photon flux power at the saturation for different bunch charge, taken into consideration the degradation of the electron beam parameters, discussed above.

CONCLUSION

For the ‘laser-driven’ electron beam the combined effect of the chromatic aberrations, the space charge and the coherent synchrotron radiation in the chicane leads to significant degradation of the electron beam properties in the transverse and longitudinal planes. By using the moderate bunch charge of 40 pC from the ‘LWFA’ source it is possible to reach the saturation of the photon flux power in a single undulator unit with the length of 2.5 m. The ‘start-to-end’ simulations have to be performed using a realistic initial particle distribution for the LWFA electron beam.

ACKNOWLEDGEMENT

This work has been supported by the project Advanced research using high intensity laser produced photons and particles (CZ.02.1.01/0.0/0.0/16_019/0000789) from European Regional Development Fund.

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