GENERATION OF X-RAY FEL LIGHT USING LASER WAKEFIELD ACCELERATED ELECTRON BEAMS

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Abstract

We consider a new class of high gain FELs based on femtosecond electron bunches with extra high current density produced by Laser Wake Field Acceleration (LWFA). The FELs of this kind can be used for generation of high power femtosecond x-ray pulses. We present the results of simulations of FEL operation with some reasonable beam parameters which will be obtained in future. We focus our attention on the advantages which can be gained from the unique possibility of the use of femtosecond hundred-kiloamperes bunches, generated by LWFA. We also consider the impact of the relatively poor electron beam properties on FEL characteristics.

INTRODUCTION

The possibility of the laser wake field acceleration (LWFA) of electron beams in plasma was explored in detail many years ago [1]. Until the present time practical application of this acceleration technique was impossible because of absence of lasers with required parameters. The rapid development of high power laser technique recently gave rise to intensive experimental investigation of LWFA [2]. At present one can obtain the laser peak power up to 1 PW with the pulse duration several tens of femtoseconds. This enables one to expect the creation of laser-plasma accelerators which can provide the peak currents several hundreds of kiloamperes with relatively small slice emittance and energy spread. Such accelerators could have very compact design as the gradient in the laser wake field can reach 300 GeV/m. They certainly would find many applications. One of them could be a source of electron bunches for the compact (tabletop) X-ray FEL [3].

The FEL operation may strongly depend on the details of the 6-D electron distribution function which can not be measured directly. Therefore it seems reasonable to make the LWFA experiments simultaneously with observation of the electron beam radiation from undulator. This way one can optimize the plasma accelerator parameters for the requirements of the X-ray SASE FEL.

In this paper we consider a possible scheme of the combined LWFA and SASE FEL experiment. We discuss some essential physical and technical problems of this experiment. They include space charge and wakefield effects, beam transport and undulator construction. Assuming some reasonable beam parameters which can be achieved in LWFA we obtain the FEL radiation parameters.

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DESCRIPTION OF THE ACCELERATOR AND FEL LAYOUT

Based on the X-ray FEL requirements one can imagine the scheme of the experimental setup which is shown in Fig. 1.

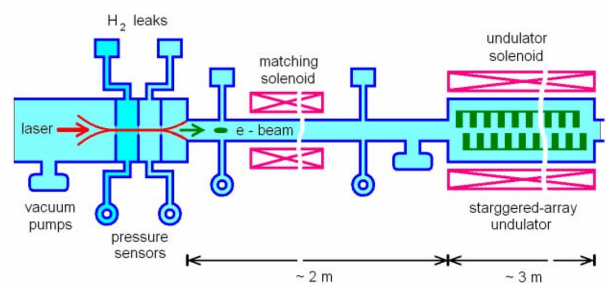

Figure 1. Possible scheme of the combined LWFA and X-ray FEL experiment.

In most of the existing LWFA experiments plasma volume is created in a gas jet or capillary and the transverse laser beam size does not exceed 10 microns [2]. For the laser pulse energy available now it seems worthwhile to increase the transverse laser beam size one order of magnitude and use the gas volume with optimized pressure profile. In addition one can use the gas focusing in the beam transport line after accelerator and inside undulator which matches very well with the electron acceleration in the same gas.

At the scheme presented in Fig. 1 the accelerator region is separated from the vacuum channel by narrow orifice through which the laser radiation is injected into the gas volume. To minimize multiple scattering the gas is hydrogen. The gas pressure is chosen to be ~ 5×10^{-3} atm so that acceleration up to 1 GeV occurs at the distance 10 cm. Additional diaphragms are placed along the accelerator axis. It allows to optimize the pressure profile.

For the compactness of the experimental setup it is desirable to obtain the FEL gain length no more then several tens of centimetres. The electron beam β-function in undulator should be of the same order of magnitude. It can be achieved by applying of gas focusing which works effectively at high beam peak currents. The focusing occurs because the beam electrical field is partly screened due to gas dielectric permeability and beam focuses itself by magnetic field (at high beam currents collective electric field may ionize atoms, and therefore effective permeability will increase). Usually the gas permeability influence is very small but for such big peak currents which can be obtained in LWFA it is sufficient to focus the beam. In our case the required gas pressure is relatively small (~ 100 Pa) and beam scattering can be neglected. To match the beam β-function from the accelerator exit to the undulator entrance one can also use superconducting solenoid.

To obtain X-ray radiation with 1 GeV electron beam one has to use undulator with the period several millimetres. The staggered array undulator seems to be the optimal choice for such small period [4]. The vanadium permendur poles of the undulator can be placed directly to the gas-filled volume. It should be noted that longitudinal impedance of vacuum chamber does not depend on its roughness in the case of short beam and relatively low conductivity of vacuum chamber material. The critical value of the conductivity is determined by the expression $\sigma_{cr} \sim \frac{1}{2\pi}\left(\frac{a}{l_b}\right)^2 \frac{c}{l_b}$ where l_b is the bunch length, a - radius of vacuum chamber, c - speed of light. Taking $l_b \sim 1\,\mu m$ and $a \sim 0.5\,mm$ we obtain $\sigma_{cr} \sim 10^{19}$ which is much higher then copper conductivity. Therefore the undulator poles do not require shielding by smooth metallic plates and thus the gap can be increased which slightly reduces the "resistive" wakefield.

Undulator parameters which have been used in simulations are listed in Table 1.

Table 1: Undulator parameters

Undulator period, mm	3.6
Undulator gap, mm	1.0
Undulator K - parameter	0.3
Longitudinal field, Tesla	1

ASSUMED ELECTRON BEAM PARAMETERS AND SOME KNOWN PROBLEMS

Electron beams obtained by LWFA should have very large correlated energy spread. Electron energy can change from zero to maximum value at the distance equal to the quarter of plasma oscillation wavelength. For the assumed gas pressure $\lambda_p \sim 100\,\mu m$. So the energy difference at distance 1 μm can reach 5 %. On the other hand the local energy spread should not be very large. Therefore in our simulations we assume zero local energy spread and energy chirp 5 % at distance 1 μm.

Utilization of laser beam with larger transverse size allows one to hope that the beam slice emittance can become noticeably smaller then in present experiments. There also may be some correlations between longitudinal and transverse electron motion which can improve FEL operation.

Taking into account all these considerations we assume the beam parameters which are summarized in Table 2.

We also assume homogeneous focusing and constant transverse size of the beam in undulator. As it was mentioned above the focusing in our scheme is realized by beam magnetic field due to the partial screening of beam electrical field in gas. Therefore the transverse space charge defocusing is automatically taken into account.

Table 2: Electron beam parameters

Electron energy, GeV	1
Beam charge, nC	0.8
Pulse duration (r.m.s.), fs	1.5
Peak current, kA	200
Normalized slice emittance, mm×mrad	0.5
Beam transverse size in undulator, μm	8.75
Local energy spread	0
Energy chirp, %/ μm	5

One has to consider carefully the space charge longitudinal wakefield. In our case it is smaller then resistive wakefield and we do not include it in simulations (it depends on current derivative and can be reduced by increase of the bunch length). There is also fast oscillating component of the longitudinal field which is created by microbunching. Its influence is also not very significant because the plasma oscillation length is larger then the gain length.

Another space charge effect which we do not take into account is that the particles with large amplitudes of betatron oscillations gain additional energy in transverse electrical field. This effect creates correlations between electron energy and betatron amplitude which can be favourable for the FEL operation. Unfortunately in our case it is not strong enough for that.

The strongest collective effect which we include in our simulations is resistive wakefield. As the beam length is small we assume that the wakefield is simply proportional to the charge in front and proportionality constant is determined by the undulator gap [5]. The gas pressure is to be low enough to decrease the Cherenkov wakes.

SIMULATION RESULTS

To simulate FEL operation we used the code GENESIS [6]. The results are presented below.

In Fig. 2 one can see the increase of FEL radiation pulse energy (expressed in terms of photon number) in undulator. The gain length at the exponential growth stage (from 1 to 1.75 m) is about 28 cm. Difference between straight and dotted curve illustrates the efficiency degradation due to the resistive wakefield. Influence of the fast component of longitudinal electrical field created by microbunching is illustrated by dashed curve.

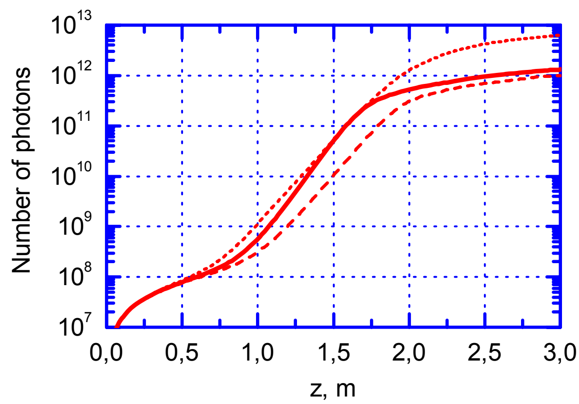

Figure2. Number of photons in the FEL radiation pulse as a function of longitudinal coordinate in undulator. Dotted curve corresponds to the resistive wake free case; dashed curve includes the influence of space charge.

Radiation power and spectral distributions at different positions in undulator are shown in Fig. 3.

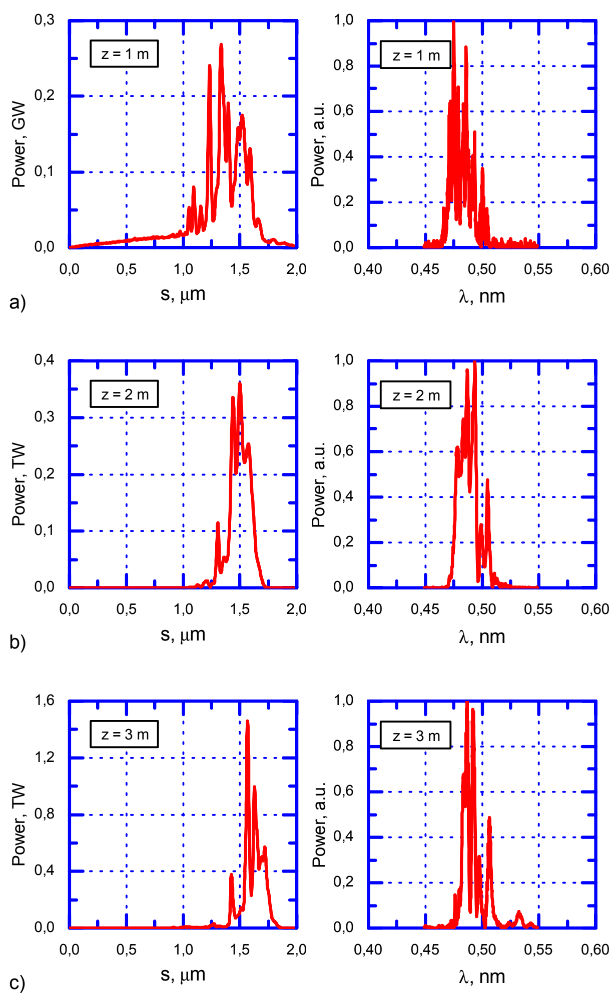

Figure 3. Radiation power and spectral distributions at different distances from the undulator entrance.

The peak power at saturation (3 m from the beginning of undulator) is about 1.5 TW. The spectral bandwidth is rather large which is typical for SASE FELs.

Beam bunching distribution at different stages is presented in Fig 4. The bunching reaches its maximal value at linear stage and starts dropping down at saturation.

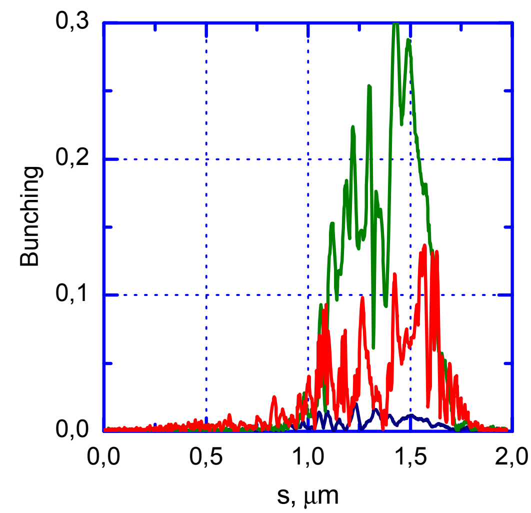

Figure 4. Beam bunching distribution at the distance 1 m (blue), 2 m (green) and 3 m (red) from the undulator entrance.

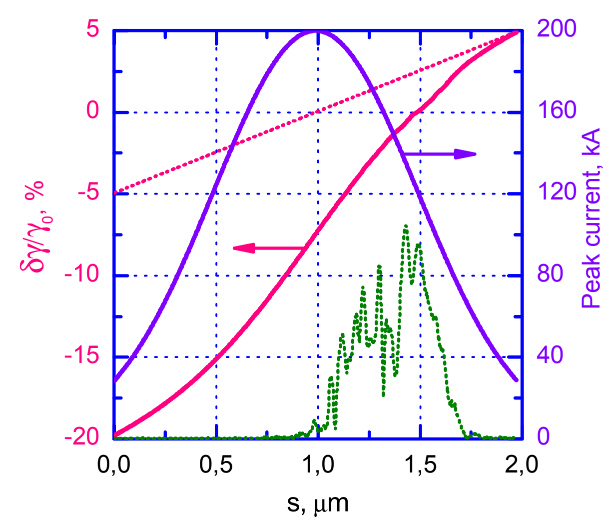

Figure 5. Relative energy deviation created by resistive wake in undulator and initial energy chirp (pink) and beam current profile (violet). Dotted pink curve corresponds to initial energy chirp and green curve shows beam bunching distribution in the middle of undulator.

The resistive wakefield is illustrated in Fig. 5. It is seen that microbunching grows only in front of the beam where the energy deviation is not very large.

The basic FEL parameters are summarized in Table 3.

Table 3: FEL parameters

Gain length, cm	28
Saturation length, m	~3
Radiation wavelength, Å	5
Number of photons	10^{12}
Peak power, TW	1.5
Spectral bandwidth (r.m.s.), %	2
Pulse duration (r.m.s), fs	0.37

CONCLUSION

In this paper we proposed the scheme of test installation for compact x-ray FEL based on laser-plasma accelerator. The main idea is that it is easier to optimize acceleration parameters (laser beam size, plasma pressure longitudinal dependence, etc.) looking at measured x-ray parameters, than to measure details of electron distribution in extremely short bunch with hopefully low slice emittance and energy spread. The lack of reliable data on beam parameters in LWFA makes impossible to predict gain length and power of FEL. Therefore our calculations demonstrate only some set of beam parameters for accelerator optimization. From the other hand, the available peak power of femtosecond lasers and their energy per pulse are increasing from year to year. This gives us the possibility of further LWFA beam parameters improvement (for example, by the increase of the laser beam transverse size for having more homogeneous accelerating field and less focusing aberrations).

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