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FEL SYSTEM WITH THE LINEAR INDUCTION ACCELERATOR AS THE LASER FUSION REACTOR DRIVER

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1 Introduction

Laser driven inertial confinement fusion (ICF) has perspective to demonstrate ignition of the thermonuclear reaction in the nearest future [1]. Nevertheless, the problem of constructing the laser system meeting the requirements to be the energy driver for commercial ICF reactor is still open. None of the existent laser systems could be used for this purpose, so one should find alternative possibilities to solve the problem of a laser system for commercial ICF reactor.

In ref. [2] it was shown that FEL technique could be used for constructing energy driver for inertial confinement fusion. It becomes possible due to the use of the scheme of multistage, multi-channel FEL amplifier with diaphragm focusing line. This approach combines all the best features of the existent laser and heavy ion approaches. Namely, the use of the accelerator technique reveals a possibility to solve the problems of the efficiency and the repetition rate. On the other hand, the use of optical radiation for the target implosion has been confirmed by the experiments with conventional lasers. As it was shown in paper [2], the present level of accelerator technique R&D allows one to construct FEL based ICF energy driver with the required parameters. So, this proposal could form a base for opening a novel direction of researches in the field of laser systems for inertial confinement fusion.

The scheme of the ICF energy driver, presented in paper [2], was based on a high current RF linac. In this paper we develop the approach of ref. [2,3] and show that FEL based ICF energy driver could be constructed also on the base of the linear induction accelerator (LIA) technique. Nowadays LIA technique is developed intensively in the framework of the researches in heavy ion fusion and promises to generate high energy, high current and low emittance electron beams [4].

2 General concept

The main idea of the proposal is to use multistage FEL amplifier providing a possibility to extract energy from a long electron bunch into a short optical pulse (see Fig.1) [2]. This scheme operates as follows. Linear induction accelerator produces a long electron bunch of duration T_b. At the entrance into the first undulator the optical pulse of duration T_{opt} is combined with the tail of the electron bunch. In the first stage of the FEL amplifier optical pulse is amplified taking the energy off the fraction of the electron beam of the length cT_{opt}. After passing the first undulator, the optical and electron bunches are separated by the magnetic snake: the electron bunch moves along the curved trajectory between the undulators, while the optical beam travels along the straight line. Parameters of the snake are chosen in such a way that the difference of the paths of the electron and optical bunch

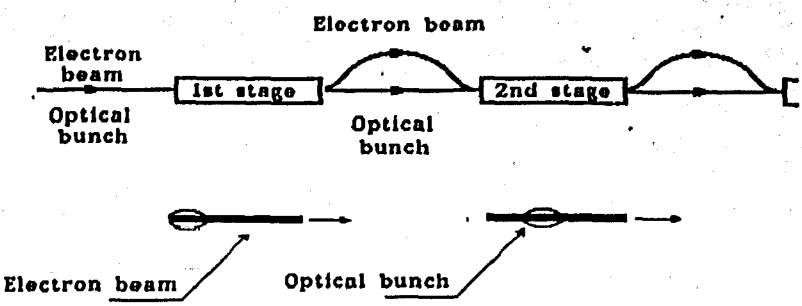

Fig. 1. The scheme of optical power summation.

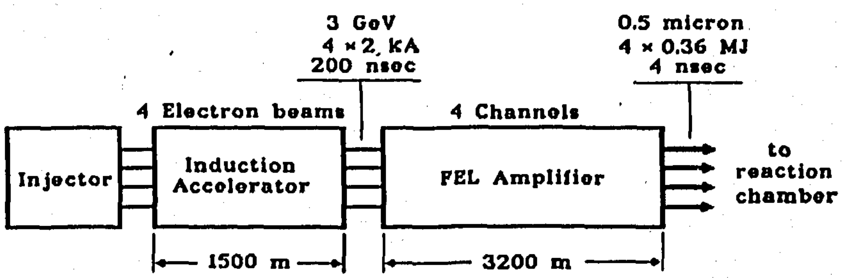

Fig. 2. General scheme of FEL based ICF energy driver.

is equal to cT_{opt}, the length of the optical pulse. So, at the entrance to the next FEL amplifier stage, the optical bunch is synchronized with the next, unperturbed fraction of the electron bunch, etc. The number of the stages of this multistage FEL amplifier is equal to T_b/T_{opt} and the output power of the FEL amplifier exit is much greater than the peak power of the electron beam.

3 Design of the driver

General scheme and parameters of the FEL based ICF energy driver are presented in Fig.2 and Table 1. General parameters of the linear induction accelerator are presented in Table 2. It produces four electron bunches of 200 ns pulse duration with 2 kA peak current and energy of 3 GeV. Each electron beam moves along individual beam transport line inside the accelerator. Total kinetic energy of the electrons at the accelerator exit is equal to 4.8 MJ. Then electron beams are fed into four parallel FEL amplifier channels. Each FEL amplifier channel has appearance of 50-stages FEL amplifier operating at the radiation wavelength of 0.5 μm and amplifies optical pulse of 4 ns pulse duration. Four channels of the FEL amplifier produce optical radiation of 1.5 MJ in each pulse. The

Table 1
ICF driver parameters

Wavelength λ, μm	0.5
Laser pulse length, ns	4
Laser beam brightness, W/cm^2	10^{22}
Total number of channels	4
Total number of stage in channel	50
Energy / pulse, MJ	1.5
Repetition rate, Hz	40
Efficiency, %	12

Table 2
Parameters of induction linear accelerator

Electron energy $\mathcal{E}_0$, GeV	3
Current/beam I, kA	2
Number of beams	4
Pulse duration, ns	200
Local energy spread σ_E/E, %	0.1
Systematic drift of the electron energy along the beam, %/ns	0.1
Normalized emittance ϵ_n, cm·rad	$\pi \times 10^{-3}$
Accelerating Gradient, MV/m	2
Length of accelerator, m	1500
Repetition rate, Hz	40
Conversion efficiency (net power – electron beam power), %	40

brightness of the laser radiation is equal to 10^{22}W/cm^{2}sr. Then four optical beams are expanded and each of them is separated into 16 parallel optical beams, and finally all 64 optical beams are focused on the pellet providing uniform irradiation.

4 Multi-channel FEL amplifier

FEL amplifier consists of 4 separate channels and each of them is multi-stage FEL amplifier providing amplification of a single optical pulse. Each multi-stage FEL amplifier is composed of 50 undulators separated with magnetic snakes. The electron bunch of 200 ns pulse duration is fed into entrance of the first stage of the FEL amplifier together with the single optical pulse of master oscillator (pulse duration 4 ns) which is synchronized with the tail of the electron beam. Then the optical beam is amplified using optical power summation scheme (see Fig.1). Parameters of the undulator of each stage are optimized on effective extraction of the energy off the electrons, taking into account the growth of the optical power from one stage to another. Assuming average efficiency of each amplifier stage to be $\eta_{FEL} = 0.3$, we obtain that the total energy of optical flash is equal to ~ 1.5 MJ.

Peculiar feature of this FEL is that $0.5\mu m$ wavelength radiation is amplified by 3 GeV electron beam which requires the use of the undulators with the period $\lambda_w \simeq 15 - 20$ cm and magnetic field $H_w \simeq 7 - 10$ kGs.

The first stage of the FEL amplifier is destined to amplify signal from the master laser ($W_{ext} \simeq 1$ MW) by a factor of the order of 10^5. It is designed in a standard way, i. e. its undulator has a long untapered section and a section with tapered parameters (see Table 3). Output radiation power at the exit of the first stage is of the order of the electron beam power.

When passing the first stage of the FEL amplifier, only a tail of the electron beam of 4 ns duration interacts with the radiation from the master laser, and the rest part of the beam should remain unchanged. It means, that the value of the master laser power should be much more than the value of the shot noise in the FEL amplifier. Estimations performed in ref. [3] have shown that at the value of the input laser power of 1 MW this effect is negligible.

Subsequent FEL amplifier stage amplify a powerful optical beam and provide small amplification per one stage. They operate in a tapered regime from the very beginning and are designed using a scheme of multicomponent undulator (i. e. prebuncher - dispersion section - tapered undulator). It should be noticed that due to a large length of the FEL amplifier and due to a small field gain in the most number of the FEL amplifier stages, the "optical guiding" effect does not provide focusing of radiation. Effective operation of multistage FEL amplifier is impossible without the use of external focusing of radiation. We solve this problem by using diaphragm focusing line which has a form of periodically spaced screens with holes [2,3,5].

Multistage FEL amplifier operates as follows. In the initial stage a transitional processes

Table 3
First stage of the FEL amplifier

Undulator	
Undulator period λ_w, cm	15
Undulator field H_w, kGs (entr./exit)	10.8 / 9.6
Length of untapered section, m	17.7
Total undulator length, m	64.2
Radiation	
Radiation wavelength λ, μm	0.5
Input power W_{in}, MW	1
Output power W_{out}, GW	480
Efficiency η_{FEL}, %	8

Table 4
50th stage of the FEL amplifier

Main undulator	
Undulator period λ_w, cm	20
Undulator field H_w, kGs (entr./exit)	7 / 4.38
Length of the main undulator, m	47
Radiation	
Radiation wavelength λ, μm	0.5
Efficiency η_{FEL}, %	32
Diaphragm line	
Period L, m	0.5
Radius of the holes R, cm	0.85

take place: the optical power amplification and formation of the optical field eigenmode. After passing some number of stages, the amplification coefficient G becomes to be small and the transverse field distribution is settled corresponding to the ground TEM_{00} mode of the diaphragm line. Investigations performed in refs. [2,3] have shown that this process is lasted approximately $n_0 = 10$ amplifier stages. Average total efficiency of these transitional stages is equal to 0.15 .

Optimization of the parameters of the high efficiency stages has been performed using the following assumptions:

- period of diaphragm line is constant in all the stages and is equal to $L = 0.5$ m;
- total efficiency of each stage is equal to $\eta_{\rm FEL} = 0.32$;
- ratio of the radiation power losses to the radiation power gain is equal to 0.2 for all stages;
- the value of the radiation power losses is controlled by the adiabatic change of the radius R of the diaphragm holes.

According to the results of ref. [3], parameters of the high-efficiency stages can be expressed in terms of the parameters of the last, 50 th stage (see Table 4) as follows ($n = 11, \dots 50$):

$$
\begin{aligned}
l_w^{(n)}[\mathrm{m}] &= 120(n - 0.5n_0 - 1)^{-1/4}, \\
R^{(n)}[\mathrm{cm}] &= 0.33(n - 0.5n_0 - 1)^{1/4},
\end{aligned}
\tag{1}
$$

where $l_w^{(n)}$ and $R^{(n)}$ are, respectively, the length of the undulator and the radius of the diaphragms of the n th stage of the FEL amplifier.

The tapering of the main undulators is performed by a linear law and the depth of the tapering is identical for all the stage and is equal to $| \Delta H_w | / H_w = 0.6$. Average total efficiency of the multistage FEL amplifier is equal to $< \eta_{\rm FEL} > \simeq 0.3$.

Taking into account expression (1) and that the length of the main undulators of the first 10 stages is of about 500 m [3], the total length of the main undulators of all stages is about 2700 m. Magnetic snakes increase the total length by the value of 500 m (10 m $\times$ 50). Contribution of the length of the prebunchers and dispersion sections into the total length is rather small. As a result, the total length of the multi-stage FEL amplifier is of about 3200 m.

5 Quality of optical beam

Parameters of radiation of the proposed FEL system meet all the requirements to the ICF energy driver. First, there is no significant preheat of the target. The radiation power, fed to the target prior arrival of the main pulse, is defined mainly by the superradiation of the electron bunch in the first stage of the FEL amplifier. Undulator of this stage has a long untapered section which provides exponential amplification of a signal by 40 dB. In the case under consideration the FEL amplifier noise is defined mainly by random fluctuations of the electron beam density and effective power of the noise signal at the FEL amplifier entrance is equal to $W_{sh} \simeq 40$ W [3]. Electron bunch generates optical radiation in the first undulator with the power of about 4×10^5 W. This effect does not takes place in the subsequent stages of the FEL amplifier, because undulators of these stages are manufactured with a deep tapering. So during time period of about 200 ns until the arrival of the main pulse with the energy 1.5 MJ, the target will receive the energy of about 0.1 J. As a result, contrast of the FEL based ICF energy driver is about 10^7.

Second, to provide effective focusing of radiation on the target, the laser should provide a high brightness

$$B_l = W_{\mathrm{opt}}/(S\pi\alpha^2),$$

where W_{opt} is the peak laser power, S and α are the square and angle divergence of the radiation at the laser exit, respectively. The FEL based ICF energy driver possesses the brightness $B_l \simeq 10^{22}\mathrm{W/(cm^2sr)}$ which excedds significantly exceeds an ultimate brightness $10^{19}\mathrm{W/(cm^2sr)}$of powerful Nd laser systems. This is connected with the fact that the radiation of the FEL amplifier always has minimal, i.e. diffraction dispersion.

6 Efficiency of the ICF reactor

The efficiency of the proposed ICF energy driver is given by $\eta_{\mathrm{TOT}} = \eta_{\mathrm{ACC}} \times \eta_{\mathrm{FEL}}$. Assuming the efficiency of the accelerator and of the FEL amplifier to be $\eta_{\mathrm{ACC}} = 0.4$ and $\eta_{\mathrm{FEL}} = 0.3$, respectively, we obtain that the total efficiency of the ICF energy driver is equal to $\eta_{\mathrm{TOT}} = 12\%$. To estimate output power of the ICF reactor, one should choose the value of the pellet gain Q. In accordance with results of numerical simulations this parameters may reach the value 200 - 1000 (see, for instance, refs. [6,7]). Assuming that the ICF energy driver initiates thermonuclear explosion with the energy excess by a factor of 200, repetition rate to be equal to 40 cycles per second, the efficiency of thermonuclear power conversion into the electrical power to be equal to 0.4, the ICF reactor heat and electrical power are equal to 12 GW and 5 GW, respectively. The ICF energy driver itself consumes of about 500 MW of electrical power.

7 Discussion

Let us perform cost estimations of the proposed ICF energy driver. As for the cost of the induction linear accelerator, it could be estimated on the base of the cost of the linear induction accelerator developed for heavy ion fusion which should accelerate up to 2.5·GeV energy four Kr^+ ion beams with total current of 20 kA and pulse duration of 100 ns [4]. These parameters are close to the parameters of our numerical example and the costs of the both devices should be quite close. We estimate the cost of four-channel superconducting undulator for the FEL to be about 130 M\$, assuming that the cost of its serial production will be 10 K\$/m. As a result, the total cost of the energy driver will be about 1,500 M\$.

Despite the main elements of the proposed ICF energy driver could be constructed at the present level of accelerator technique, there is no existent FEL amplifier with the required parameters. Moreover, the basic idea of the proposal, namely, a possibility to construct multi-stage FEL amplifier, requires experimental verification. To perform such a verification, there is no need to build a full-scale facility. It may be done, for instance, by constructing a model of the FEL amplifier with the number of amplification stages of about 10. Such a test facility requires RF electron accelerator providing acceleration of 10 electron bunches (bunch spacing of about 4 ns, $\mathcal{E} \simeq 3$ GeV, peak current $I \simeq 2$ kA, emittance $\epsilon_n \simeq 3 \times 10^{-3}$ cm·rad, energy spread $\sigma_E/\mathcal{E}_0 \simeq 10^{-3}$). Micropulse duration of this accelerator may be done rather short, of about 10 ps, in this case slippage effect is almost negligible. The energy stored in 10 bunches will be of about 600 J, so such a test accelerator may operate in L-band RF wavelength range in a regime of stored RF energy. At accelerating gradient of about 25 MV/m, its length will be of about 120 m. An accelerator facility with parameters close to those required is developed, for instance, in the framework of superconducting linear collider project TESLA [8]. Estimated cost of the TESLA accelerator is about 100 K\$/m, so the total cost of 3 GeV test accelerator will be about 12 M\$. We estimate the cost of ten stages of superconducting undulator to be about 25 M\$ (50 K\$/m at experimental production), so all the basic ideas of the proposed ICF energy driver could be verified at relatively low-cost facility.

8 Conclusion

We have shown in this paper that the use of multichannel, multistage FEL amplifier reveals a possibility to solve the problem of energy driver for commercial ICF reactor. It is relevant to underline the main advantages of the FEL based energy driver. The present level of accelerator technique provides a possibility to generate powerful electron beams of high quality which forms a base to obtain high average and peak power of the FEL radiation. Due to the use of accelerator technique there are wide possibilities to steer the length of the optical pulse and achieve very shot pulse duration, $\tau \lesssim 0.1$ ns [2]. There are no physical limitations on the value of the peak and average output power of the FEL amplifier, because the process of amplification takes place in vacuum. Also, due to the latter reason, the radiation of the FEL amplifier has always minimal, i.e. diffraction dispersion. As a result, brightness of the FEL radiation is of the order of 10^{22} W/cm^{2}sr, which exceeds by 3 – 4 orders of magnitude the brightness of powerful Nd-glass lasers. So, we can conclude that the development of the FEL based ICF energy driver could form a novel direction of researches in the field of laser systems for inertial confinement reactor. Moreover, excellent features of the FEL radiation (tunability, high brightness and short pulse length) could form a base for novel approaches in developing of thermonuclear targets.

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