Free Electron Laser as Energy Driver for Inertial Confinement Fusion

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Abstract

An FEL based energy driver for Inertial Confinement Fusion (ICF) is proposed. The key element of the scheme is free electron laser system. Novel technical solutions reveal a possibility to construct the FEL system operating at radiation wavelength $\lambda = 0.5$ μm and providing flash energy $E = 1$ MJ and brightness 4×10^{22} W cm^{-2} sr^{-1} within steering pulse duration 0.1 – 2ns. Total energy efficiency of the proposed ICF energy driver is about of 11% and repetition rate is 40 Hz. Dimensions of such an ICF driver are comparable with those of heavy-ion ICF driver, while the problem of technical realization seems to be more realistic. It is shown that the FEL based ICF energy driver may be constructed at the present level of accelerator technique R&D.

1 INTRODUCTION

One of the possible ways to solve the problem of controlled thermonuclear synthesis is application of inertial confinement fusion (ICF), when thermonuclear fuel is exploded under shocking action of laser radiation. The key problem of such an approach is that of a laser. While the problem of laboratory study of the ICF problem seems to be solvable with conventional lasers, the problem of energy driver for ICF commercial reactor is still open [1].

During last decade significant achievements have been obtained in the field of free electron laser (FEL) physics and technique. FEL devices possess many attractive features. FEL radiation is coherent and tunable, it always has ideal, i.e. diffraction dispersion. FELs are capable to provide a high efficiency of transformation of the electron beam power into the radiation power. Electron accelerators are capable to provide effective transformation of net electric power into the beam power, so one can expect to reach a high level of the total FEL efficiency. Repetition rate of electron accelerators is rather high, up to several hundreds cycles per second. All these features of the FEL indicate that it should be studied as a candidate on a role of the laser for the ICF commercial reactor.

Our investigation has led us to an optimistic conclusion that construction of the FEL system meeting the requirements to be the ICF energy driver is quite possible at the present day level of accelerator technique R&D. It becomes possible due to the use of multichannel, multi-stage FEL amplifier scheme proposed in which the required level of the output power is provided by the use of optical power summation technique. Effective operation of such an FEL amplifier becomes possible due to the use of diaphragm line for focusing radiation. This is the second basic idea.

Using these basic ideas, we have developed conceptual project of the FEL based ICF energy driver.

2 BASIC IDEAS

2.1 *Summation of optical power*

In traditional scheme of the FEL amplifier, output radiation power does not exceed the electron beam power. The peak power of the ICF energy driver should be of the order of several thousands of terawatts which results in enormous values of the electron beam parameters. To overcome this problem, we propose to use multi-stage FEL amplifier which amplifies a single optical bunch by means of sequential usage of several electron bunches. FEL amplifier is composed of a large number N_s of undulators separated with magnetic snakes. The FEL driving electron beam is generated by a linear RF accelerator which produces a train of N_s electron bunches. This train is fed into entrance of the first stage of the FEL amplifier together with the single optical pulse of the master oscillator which is synchronized with the last electron bunch of the train. In the first stage of the FEL amplifier the optical pulse is amplified taking the energy off the last electron bunch. After passing the first undulator, the optical and electron bunches are separated in the magnetic snake: the train of electron bunches moves along the curved trajectory between the undulators, while the optical beam travels along the straight line. Parameters of the snakes are chosen in such a way that the difference of paths of electron and optical bunches is equal to the distance between the electron bunches, so, at the entrance to the next FEL amplifier stage, the optical bunch is synchronized with the next, unperturbed bunch of the train, etc. As a result, this scheme provides a benefit in the peak radiation power of the order of N_s, the number of the FEL amplifier stages, and the peak radiation power can be done much more than the peak power of electron beam.

2.2 *Diaphragm line*

Due to large length of multi-stage 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 multi-stage

FEL amplifier is impossible without the use of external focusing of radiation. In this paper we propose to solve this problem with the help of diaphragm focusing line which has a form of periodically spaced screens with holes and is placed inside undulators. When Fresnel number is large, eigenmodes of diaphragm line have rather small diffraction losses. For instance, in a visible wavelength range, at the radius of the hole about of 1 cm and the distance between the screens about of 1 m, diffraction losses of the ground TEM_{00} mode are about of 0.01 % per one diaphragm. Diaphragm line is rather stable with respect to misalignment of the screens. When the screens are adjusted in the both transverse and longitudinal directions with the accuracy about of 10^{-2} cm (which is usual in the accelerator technique), misalignments do not result in the extra diffraction losses (see ref. [2] for more details).

3 CONCEPTUAL PROJECT

Construction of commercial ICF reactor becomes feasible when the laser system provides energy of laser flash $\gtrsim 1$ MJ, repetition rate $\gtrsim 10$ cycles per second and laser efficiency $\sim 5 - 10$ % at a high quality of laser radiation [3]. In this paper we present conceptual project of the FEL based ICF energy driver.

Table 1: ICF driver parameters

Wavelength λ, μm	0.5
Laser pulse length, ns	0.1 - 2
Laser beam brightness, W/cm^2	4×10^{22}
Total number of channels	64
Total number of stage in channel	90
Energy / pulse, MJ	1
Repetition rate, Hz	40
Efficiency, %	11

General parameters of the FEL based ICF energy driver are presented in Table 1. Its key elements are high-current RF linear accelerator, separation system and multi-channel, multi-stage FEL amplifier. Driving electron beam for the FEL amplifier is generated by linear RF accelerator. It operates at 40 Hz frequency and generates trains of 6400 electron bunches with total stored energy 3850 kJ. Then this train of electron bunches is separated by separation system into 64 trains of bunches which are fed into entrances of 64 parallel multi-stage FEL amplifier channels. Each FEL amplifier channel is a multi-stage FEL amplifier with 90 stages. At the exit of the amplifier, total energy of laser flash is equal to 1 MJ.

3.1 *High-current RF accelerator*

Requirements on the energy of the laser flash, together with the possibilities of the present level of accelerator technique R&D determine the choice of the driving accelerator parameters (see Table 2). Accelerating structure consists of separated cavities and each cavity is fed by separate klystron (peak and average output power 33 MW and 33 kW, respectively). Conversion efficiency of the net electrical power into the electron beam power is equal to $\eta_{ACC} = 0.4$.

Table 2: Accelerator parameters

Electron energy $\mathcal{E}_0$, GeV	3
Beam peak current I, kA	2
Micropulse duration, ps	100
Bunch spacing, ns	4
Macropulse duration, μs	25.6
Energy spread σ_E/E, %	0.1
Normalized emittance ϵ_n, cm·rad	3×10^{-3}
RF frequency, MHz	500
Number of resonstors	4500
Accelerating gradient, MV/m	2
Length of accelerator, m	1500
Shunt impedance, MΩ/m	8
Stored RF energy, J/m	3.7
Q-factor of unloaded structure	2.5×10^4
Q-factor of loaded structure	1.2×10^2
Wall power losses, kW/m	450
Repetition rate, Hz	40

3.2 *Separation system*

Separation of electron bunches is performed by kicker magnets using sequential scheme. In this scheme, after k-th stage, there are 2^k parallel channels with 2^k trains of bunches in each. At $(k+1)$-th stage, each of 2^k channels is separated into two channels, i.e. each train is divided by a half and each half-train is directed into separate channel. Separation scheme consists of 6 stages and 63 kicker magnets. Simultaneous arrival of all trains to the FEL amplifier entrances is provided by using different lengths of channels. Pulse durations of the kicker magnets depends on their place in the separation system and are equal to 12.8 μs, 6.4 μs, 3.2 μs, 1.6 μs, 0.8 μs and 0.4 μs for the 1st, 2nd, 3rd, 4th, 5th and 6th stages, respectively. The value of rise (fall) time is about of 50 ns which results in the losses about of 10 bunches in each separation stage. So the efficiency of separation system is equal to $\eta_{SEP} = 0.9$ and it provides transporting the trains of 90 bunches to each of 64 FEL amplifier channels.

3.3 *Multi-channel FEL amplifier*

FEL amplifier consists of 64 parallel channels and each of them is multi-stage FEL amplifier providing amplification of a single optical pulse (see section 2). Multi-stage FEL amplifier is composed of 90 undulators separated with magnetic snakes. Parameters 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. Average efficiency of the FEL amplifier is equal to $\eta_{FEL} = 0.3$.

The first stage of the FEL amplifier is destined to amplify signal from the master laser ($W_{ext} \simeq$ 1MW) by a factor of the order of 10^5. It is designed by a standard way, i.e. its undulator has a long untapered section and a section with tapered parameters. Output radiation power at the exit of the first stage is of the order of the electron beam power. Subsequent FEL amplifier stages 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 multi-stage FEL amplifier is impossible without the use of diaphragm focusing line.

Peculiar feature of this FEL is that 0.5 μm 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.

A comprehensive analysis of multistage FEL amplifier has been performed in ref. [2]. It was shown that total length of the 90 stages of the FEL magnetic system is equal to 5.5 km (including 900 m of the lengths of magnetic snakes).

3.4 *ICF reactor*

Total efficiency of the ICF energy driver is given with the product of efficiencies of the driving accelerator $\eta_{ACC} = 0.4$, of separation system $\eta_{SEP} = 0.9$ and of the FEL amplifier $\eta_{FEL} = 0.3$ and is equal to 0.11.

Let us estimate output characteristic of the ICF reactor assuming that it is designed by a standard way, i.e. the power of thermonuclear explosion is absorbed by the walls of the reactor chamber, converted into the heat power and then converted into the electrical power. Assuming the pellet gain to be about of 1000 [4], 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 40 GW and 16 GW, respectively. The ICF energy driver itself consumes about of 400 MW of electrical power.

4 DISCUSSION

Let us discuss a possibility of technical realization of the proposed FEL based ICF energy driver.

Construction of the driving RF accelerator is quite possible at the present level of accelerator technique R&D. Concept of the accelerator of such a type has been proposed in ref. [5]. RF power supply of this accelerator may be based at klystrons which are manufactured serially by industry. For instance, L 3775 klystron manufactured by Litton, operates at 430 MHz frequency and provides peak and average RF power 30 MW and 30 kW, respectively. High-brightness injector may be constructed on the base of photoinjector technique [6].

Kicker magnets of separation system have parameters close to those of kicker magnets of the SLC damping ring [7].

Scaling analysis of the existent superconducting undulators indicates that manufacturing of the undulators with required parameters is not a problem [2], [8]. Cryogenic system providing cooling of undulators and magnetic snakes may be designed using a multi-refrigerators system integrated into the cryostat [9].

Nevertheless, it should be emphasized that despite many pieces of the proposed equipment have been developed for other applications, there are no operating FEL amplifiers with the parameters close to those required. 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 about of 10. Such a test facility requires electron accelerator providing acceleration about of 10 electron bunches. Micropulse duration of this accelerator may be done rather short, about of 10 ps, in this case slippage effect is almost negligible. The energy stored in 10 bunches will be about of 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 about of 30 MV/m, the length of accelerator will be about of 100 m.

Experiments, carried out at a such relatively low-cost facility will reveal a possibility to construct in the nearest future a full-scale FEL based energy driver for inertial confinement fusion.

5 REFERENCES

[1] Status reports on ICF laser programs can be found in: Proceedings of the Fourteenth International Conference on Plasma Physics and Controlled Fusion Research (Würzburg, 30 September - 7 October 1992), Vol. 3

[2] E.L. Saldin et al., preprint JINR E9-94-237, Dubna, 1994

[3] J. Duderstadt and G. Mozes, Inertial Confinement Fusion. John Willey and Sons, New York, 1982.

[4] Yu.V. Afanas'ev, N.G. Basov et al., Sov. Pis'ma v Zh. Exp. Teor. Phys., **24**(1976)23

[5] D. Price et al., Proceedings of the 1989 IEEE Particle Accelerator Conference, Vol.2, p.941, Chicago, 1989

[6] K. Batchelor et al., Nucl. Instrum. and Methods **A318**(1992)372

[7] J.T. Seeman, SLAC-PUB-5607 (July, 1991)

[8] L.P. Elias and J.M.J. Madey, Rev. Sci. Instr. **50**(1979)1335

[9] E. Minehara et al., Proceedings of the 8th Symposium on Accelerator Science and Technology, p. 246. Ionics Publishing Company, Tokyo, 1991