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FREE ELECTRON LASER SYSTEM WITH 4 MJ FLASH ENERGY FOR THE LASER FUSION REACTOR DRIVER

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1 Introduction

It is generally accepted nowadays that the laser driven inertial confinement fusion (ICF) could demonstrate in the nearest future the ignition process. The next step should be construction of the laser driver for commercial ICF reactor providing the flash energy about 1 MJ, peak power about 100 TW, repetition rate about ten (or several tens) pulses per second and net efficiency not less than 10 %. The laser light wavelength should be shorter than 0.6 μm. None of the existing laser systems could provide the required parameters.

It was shown in refs. [1–3] that the laser driver for commercial ICF reactor could be constructed on the base of free electron laser (FEL) technique. The scale and the cost of the proposed equipment are comparable with the scale and the cost of the equipment for the heavy ion fusion, while the problem of technical realization seems to be more realistic. The approach to construct ICF energy driver based on the use of the FEL technique combines all the best features of the 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 with the experiments with conventional lasers. The only principal problem which should be solved is that of experimental verification of an idea to construct multi-stage FEL amplifier with focusing diaphragm line. It was shown in refs. [1,2] that verification of this idea can be performed at a low-cost equipment. That is why this approach requires detailed study aiming a goal to reduce the scale and cost of a full-scale device, to increase the reliability of the system, etc.

In the present paper we propose a novel scheme of a multi-stage FEL amplifier for ICF energy driver which allows to achieve a higher energy of radiation flash (up to 4 MJ) and ultimate contrast of the laser radiation. It is important that this scheme allows to reduce significantly the requirement on the value of the average current of the driving accelerator with respect to the scheme considered in ref. [1]. The present design uses four accelerators with relatively low average current. Then the beams from these four accelerators are combined into one powerful beam by means of RF technique. A driving beam generation system produces eight electron beams of 384 ns pulse duration, energy of 3 GeV and stored energy of 15.4 MJ. These bunches are fed to the entrance of eight parallel channels of 100-stage FEL amplifiers. At the exit of the FEL amplifiers there are eight optical beams of 384 ns pulse duration with total stored radiation energy of 4 MJ. In the output optical system these optical beams are transformed into 64 optical beams of 7 ns pulse duration and of total stored energy of 3.5 MJ which are fed into reactor

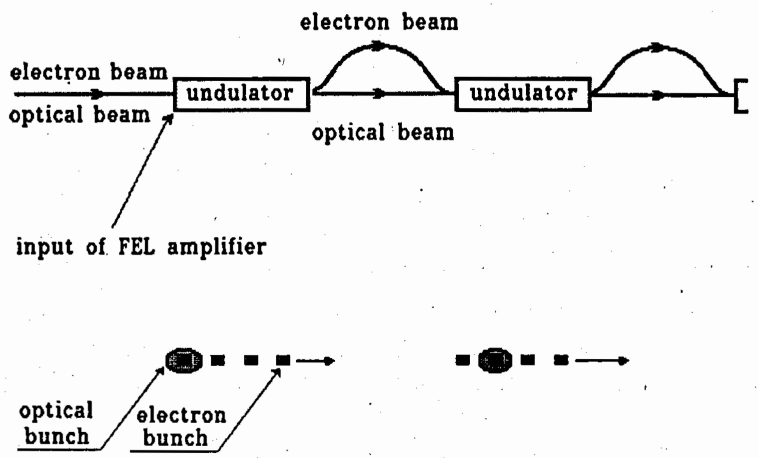

Fig. 1. The scheme of optical power summation proposed in refs. [1,2].

chamber.

In this paper we also study the problem of matching the output FEL radiation with the optical system of the reactor chamber. It was shown that such a matching should be done using optical elements (mirrors, polarizers, Pockel's cells, etc) developed in the framework of the laser fusion program [4].

An important feature of the proposed driver is that four optical pulses are amplified simultaneously in each FEL amplifier channel. As a result, the number of FEL amplifier channels is reduced by a factor of four. On the other hand, such a solution forces to design a more complicated output optical system. Nevertheless, self-consistent economical analysis shows that it results in the reduction of the total cost of the driver by a factor of two with respect to the design presented in refs. [1,2].

2 The scheme of the optical power summation

The laser driver for inertial confinement fusion must deliver the optical pulse with the total energy of about several megajoules within time interval of about several nanosecond. It means that the peak power of laser radiation must be about several thousands terawatts. Such a high peak radiation power could be achieved in the FEL amplifier by means of the optical power summation scheme (see Fig.1) [1–3]. The principle of operation of this scheme consists in amplification of a single short optical bunch by means of a long electron bunch, or a train of electron bunches. As a result, the required value of peak power of the driving electron beam for the FEL amplifier could be reduced to the value about several

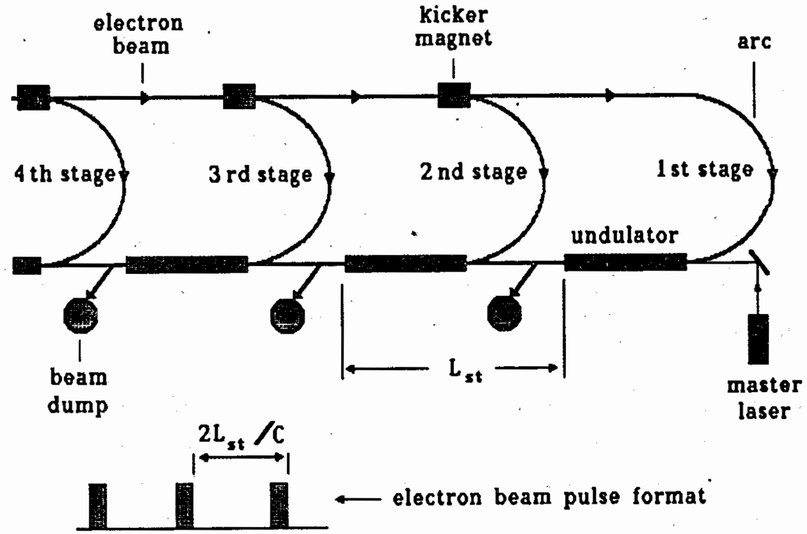

Fig. 2. The scheme of optical power summation proposed in this paper.

terawatts which matches with the present day potential of accelerator technique. It was shown in refs. [1–3] that realization of such a project is technically feasible.

Nevertheless, one of the complicated problem to realize the scheme of ref. [1,2] is the requirement on the high value of the average current of the driving RF accelerator. This is connected with the use of magnetic snakes providing delay between optical pulse and electron bunches which impose a limit on the maximal distance between electron bunches to be about several nanoseconds. In the present paper we consider one more scheme (see Fig.2). The main elements of the scheme are the beam transport line with kicker-magnets, matching arcs and multi-stage FEL amplifier. The scheme operates as follows. The train of N electron bunches (N is equal to the number of the FEL amplifier stages) is fed to the entrance of the beam transport line. The bunch separation in the train is equal to $2L_c$, where L_c is the length of one stage of the FEL amplifier. The first bunch of the train passes the whole beam transport line and is fed to the entrance of the first stage of the FEL amplifier and amplifies an optical bunch from a master laser. At the exit of the undulator the first bunch is directed to the beam dump and the optical pulse is amplified in the second stage of the FEL amplifier by the second electron bunch of the train. The delivering of the second bunch to the second stage of the FEL amplifier is provided by means of switching on the first kicker magnet after passage of the first bunch. The delivering of the electron bunches to the next stages is provided in the same manner.

An important feature of the proposed scheme is that it could operate with a larger spacing of electron bunches. As a result, the requirements on the value of the average current of the driving RF accelerator could be reduced significantly.

Another advantage of the proposed scheme is in providing the absolute contrast of the radiation pulse (i.e. there is no any preheating of the target).

This scheme is more preferable with respect to the FEL amplifier design, because the harmful influence of the synchrotron radiation (the growth of the energy spread due to quantum fluctuation of synchrotron radiation) is decreased by two orders of magnitude with respect to scheme considered in refs. [1,2]. Also the problem of beam dump could be solved in a simple way because each bunch passes only one stage of the FEL amplifier.

In conclusion of this section we should emphasize that effective operation of multi-stage FEL amplifier is possible only when diaphragm focusing line is used to confine the radiation in the vicinity of the electron beam [1,5]. This is connected with the fact that in the most number of the amplifying stages the power gain is small and the "optical guiding" effect [6] becomes very weak to confine the radiation near the electron beam. The diaphragm focusing line has a form of periodically spaced screens with holes. For an axisymmetric line with the period L and radius of the holes $R \gg \lambda$, in the first order of a small parameter $M = (8\pi N_F)^{-1/2}$, where $N_F = R^2/(\lambda L)$ is Fresnel number, eigenfunctions $\Phi_m(r,\varphi)$ have the form [7]:

$$\Phi_m = J_m(k_{mj} r)\exp(-im\varphi), \qquad m = 0,1,2,\ldots \tag{1}$$

where $k_{mj} = \mu_{mj}(1-\Delta_0)/R$, $\Delta_0 = (1+i)\beta_0 M$, $\beta_0 = 0.824$, μ_{mj} is j th root of the Bessel function of the m-th order (i.e. $J_m(\mu_{mj}) = 0$). For TEM_{mj} eigenmode, a fraction of the radiation power losses per passage of one diaphragm is given with the relation:

$$\Delta W_{rad}/W_{rad} = 8\mu_{mj}^2 M^3 \beta_0. \tag{2}$$

When Fresnel number N_F is large, eigenmodes of diaphragm line have rather small diffraction losses. For instance, in a visible wavelength range, at the radius of the hole $R \sim 1$ cm and the distance between the screens $l \sim 1$ m, diffraction losses of the ground TEM_{00} eigenmode are of about 0.01 % per one diaphragm. When the radiation power gain in the FEL amplifier is much greater than diffraction losses in the diaphragm line, the latter one performs mainly focusing of radiation providing the possibility to organize effective undulator tapering.

3 Design of the driver

When considering possible ways of technical realization of the energy driver, we have used only those technical solution which have been used (or are planned to be used) elsewhere. In the process of optimization we have developed the concept of the driver with the main parameters presented in Table 1. The general scheme of the driver is presented in Fig.3 and 4. It consists of three main parts: driving beam generation system, multi-stage, multi-channel FEL amplifier and output optical system.

The driving beam generation system produces eight electron beams of 38.4 μs pulse

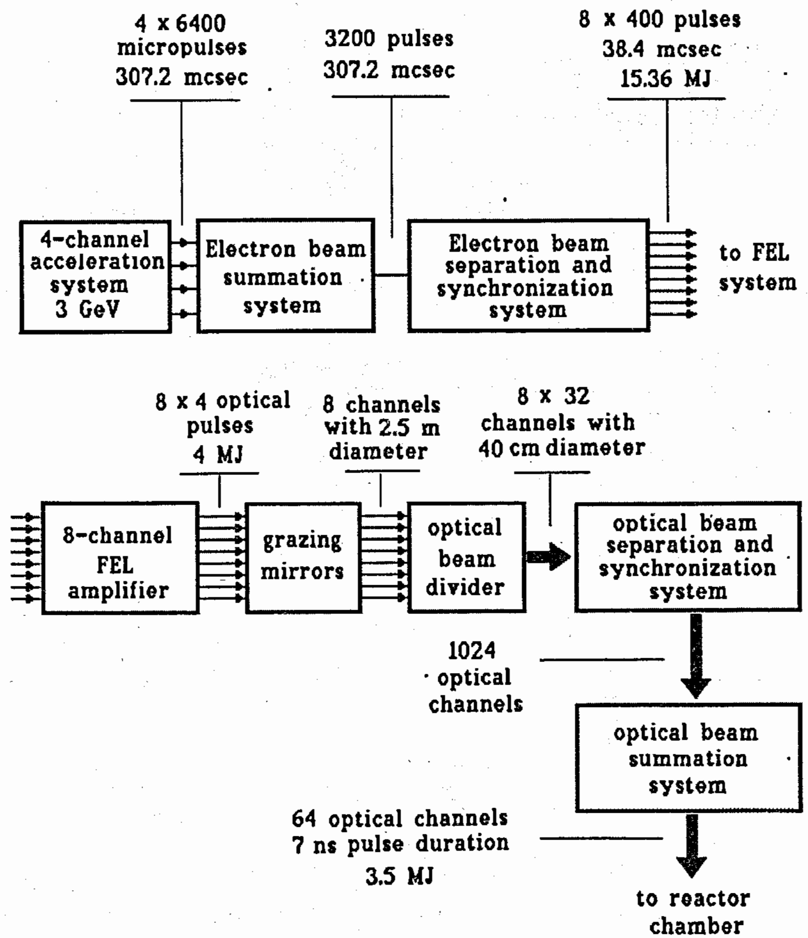

Fig. 3. The scheme of the FEL based energy driver.

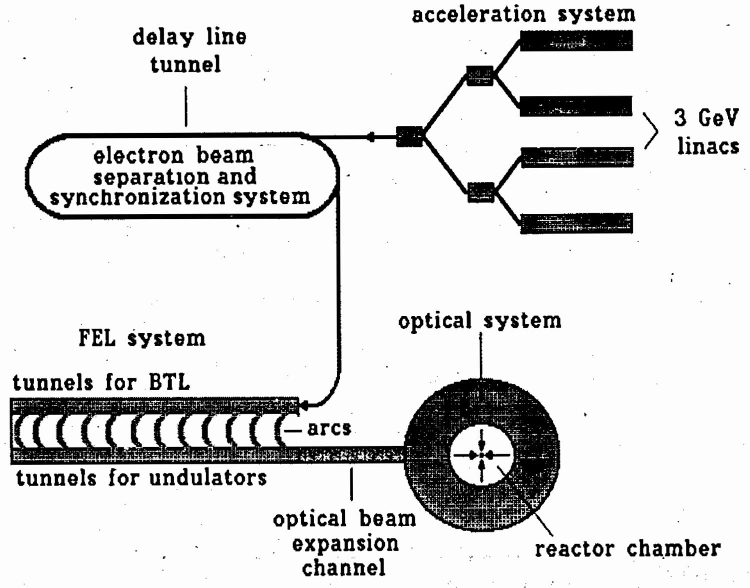

Fig. 4. Layout of the ICF reactor.

Table 1
General parameters of the laser fusion reactor driver

Radiation wavelength	0.5 μm
Laser pulse length	7 ns
Laser beam brightness	5×10^{20}W/cm^{2}sr
Flash energy	3.5 MJ
Repetition rate	10 pps
Net efficiency	10 %

duration, energy of 3 GeV and stored energy of 15.4 MJ. These beams are fed to the entrance of eight parallel channels of 100-stage FEL amplifiers. At the exit of the FEL amplifiers there are eight trains of optical bunches of 384 ns pulse duration with total stored energy of 4 MJ. In the output optical system the trains of optical bunches are transformed into 64 optical pulses of 7 ns pulse duration which are fed into reactor chamber.

3.1 Driving beam generation system

The driving beam generation system consists of four RF accelerators, a beam summation system and a separation and synchronization system (see Fig.3).

3.1.1 RF accelerators

The requirements of the high beam loading define the value of RF accelerating wavelength to be rather large, $\lambda_{rf} = 60$ cm. Accelerating structure consists of separated cavities and each four cavities are fed by one klystron with 32 MW and 100 kW peak and average RF power, respectively, 308 μs pulse duration and 500 MHz RF frequency (see Fig.5). Accelerating gradient is equal to 5 MV/m and total length of each accelerator is equal to 600 m. Peak RF power losses in one cavity are equal to 8 MW (including 1 MW of heat losses).

The general parameters of RF accelerators are presented in Table 2. Accelerators operate at a repetition rate of 10 Hz. During one macropulse duration of $\tau = 307.2$ μs each accelerator produces a train of 6400 electron bunches with total stored energy 3840 kJ. Time diagram of the accelerator operation is presented in Fig.6. Micropulse consists of two electron bunches (peak current $I = 2$ kA, $\tau = 0.1$ ns, $\mathcal{E} \simeq 3$ GeV) separated by 4 ns.

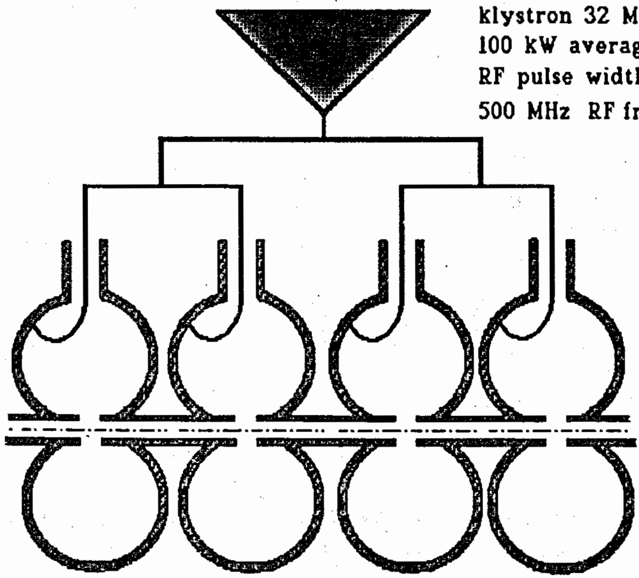

Fig. 5. Module of RF linear accelerator.

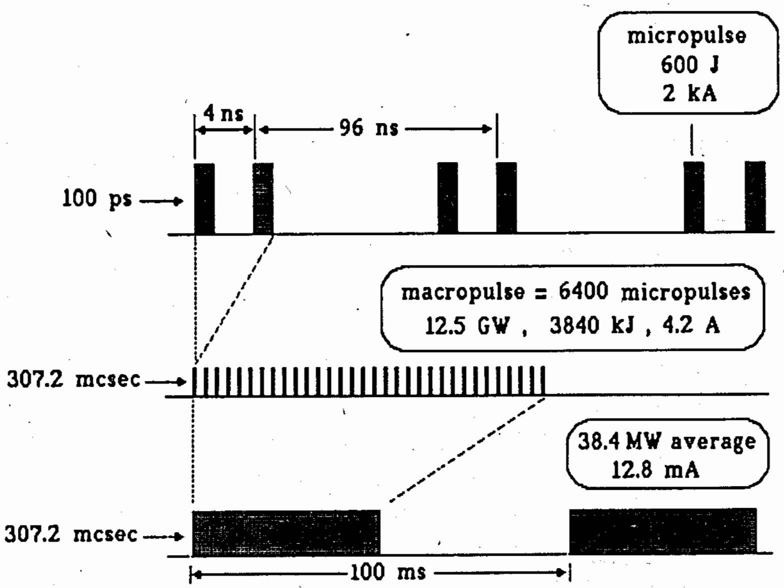

Fig. 6. Electron beam pulse format in RF accelerator.

Table 2
General parameters of accelerator

Electron energy	3 GeV
RF frequency	500 MHz
Accelerating gradient	5 MV/m
Macropulse duration	308 ms
Repetition rate	10 pps
Shunt impedance	5 MΩ/m
Stored RF energy	23 J/m
Q-factor of unloaded structure	2.5×10^4
Wall RF power losses	3.1 MW/m

Time separation between micropulses is equal to 96 ns. Average over macropulse current is equal to 4.2 A. The accelerators have slightly different energies: 2.85 GeV, 3 GeV and 3.15 GeV which is necessary for the operation of the beam summation system (see next section).

Total efficiency of the accelerators η_{AC} (i.e. efficiency of conversion of the electrical power into the electron beam power) is given by

$$\eta_{ACC} = \eta(\mathrm{rf} \to e) \times \eta(\mathrm{klystron}) \times \eta(\mathrm{modulator}),$$

where $\eta(\mathrm{rf} \to e)$ is the efficiency of conversion of RF power into the electron beam power, $\eta(\mathrm{klystron})$ is the klystron efficiency and $\eta(\mathrm{modulator})$ is the efficiency of the klystron modulator. As the beam current is high and the RF pulse duration is much more than the filling time of the loaded structure (of about 1 μs), the efficiency of the RF power conversion $\eta(\mathrm{rf} \to e)$ into the electron beam power is rather large, $\eta(\mathrm{rf} \to e) \simeq 0.87$. Assuming the efficiency of the modulator to be $\eta(\mathrm{modulator}) \simeq 0.8$, the klystron efficiency $\eta(\mathrm{klystron}) \simeq 0.65$, we obtain that the total efficiency of the accelerator is about $\eta_{ACC} \simeq 0.45$.

3.1.2 Beam summation system

To obtain a high value of the average beam current, we use the beam summation system which combines the beams with average over macropulse current of 4.2 A produced by four RF linear accelerators into one beam with average over macropulse current of

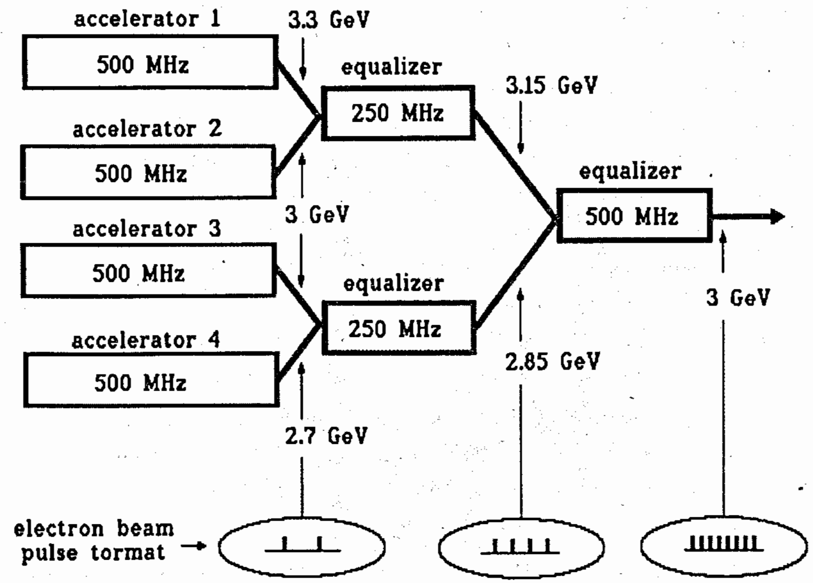

Fig. 7. The scheme of the electron beam summation system.

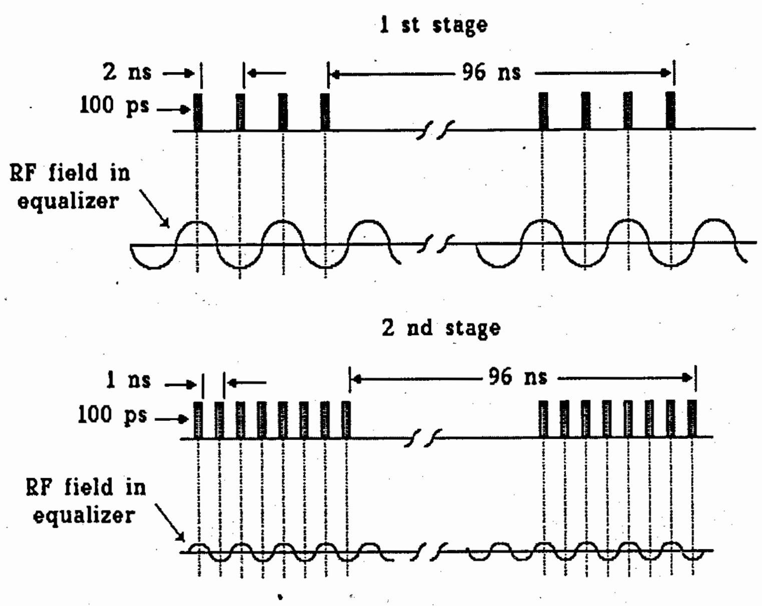

Fig. 8. The scheme of operation of the energy equalizers.

16.8 A. This is performed in two stages (see Figs.7 and 8). At each stage two electron beams with different energies of electrons are combined and then their energies are equalized in a special RF accelerator (equalizer).

The first stage of the beam summation system operates as follows. First, electron bunches from two accelerators with different energies ($\mathcal{E}_1$ and $\mathcal{E}_2$) are combined into one train by means of magnetic system. At the exit of the magnetic system the micropulse consists of four electron bunches with the energies $\mathcal{E}_1$, $\mathcal{E}_2$, $\mathcal{E}_1$ and $\mathcal{E}_2$, respectively. The bunch separation in the micropulse is equal to 2 ns. Then the electron beam is directed to the RF accelerator operating at RF frequency of 250 MHz. The phasing is chosen in such a way, that the bunches with a higher and lower energies are located in the minimum and maximum of RF accelerating field, respectively. As a result, at the exit of the equalizer we have monoenergetic electron beam.

The second stage operates in the similar manner. First, the beams with different energies are overlapped with each other. At the exit of magnetic system the micropulse consists of eight bunches separated by 1 ns. To equalize the energies, the RF frequency of the second equalizer is chosen to be 500 MHz.

The total length of three RF accelerators-equalizers is about 100 m (at accelerating gradient of 5 MV/m). The RF power in these accelerators is used only to achieve the required value of accelerating gradient. As a result, the energy consumption and the

cost of the accelerators-equalizers is much less with respect to those of the main four accelerators.

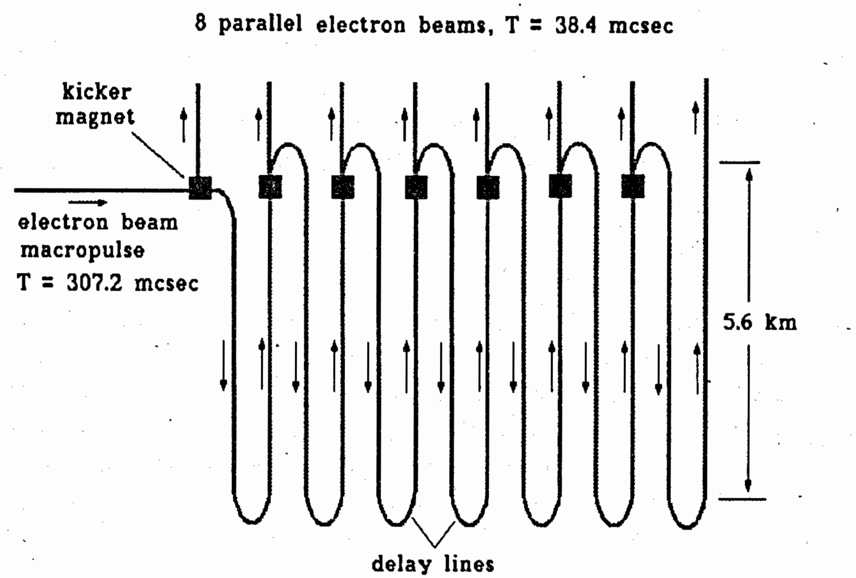

Fig. 9. The scheme of the electron beam separation and synchronization system.

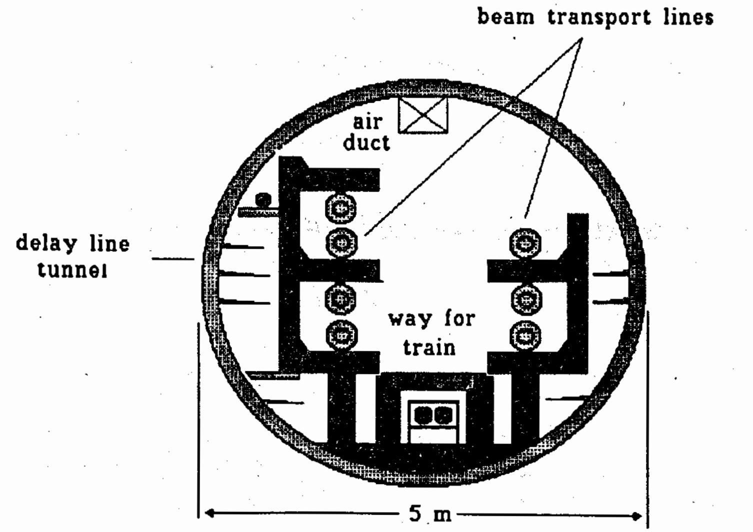

Fig. 10. Layout of the beam transport line in the tunnel of the delay line.

3.1.3 *Separation and synchronization system*

Separation and synchronization system separates the electron beam of 307.2 μs duration into eight parallel beams of 38.4 μs duration. It has the appearance of delay line with the filling time equal to 268.8 μs (see Fig.9). Such a delay line could be placed in two parallel tunnels of 5600 m length connected by arcs with the radius of 50 m. The beam transport line is placed in this tunnel in the same manner as in race-track microtron (see Fig.10). After filling the delay line, seven kicker magnets are switched on simultaneously and we obtain eight parallel bunch trains of 38.4 μs pulse duration.

3.2 *FEL amplifier*

FEL amplifier consists of eight parallel channels and each channel has appearance of multi-stage FEL amplifier with 100 stages of amplification (see Fig.11). The undulators of all stages have equal lengths of 50 m. The total length of each stage is equal to 57.6 m. The principle of operation of this scheme has been described in section 2. The bunch train at the entrance to the beam transport line of each channel consists of 400 micropulses separated by 96 ns. Each micropulse consists of eight electron bunches separated by 1 ns. The time interval between the switching on of kicker magnets is chosen to be equal to

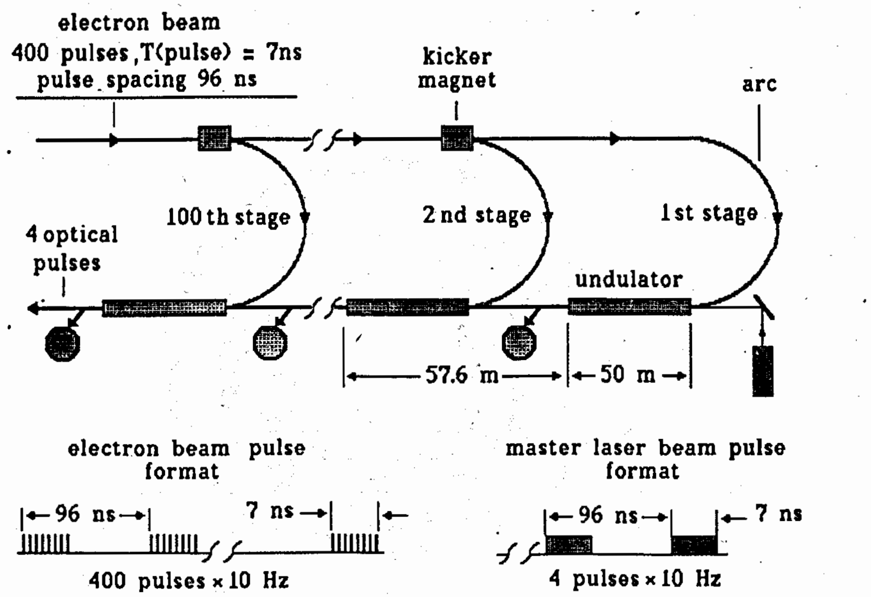

Fig. 11. The scheme of the channel of the FEL amplifier.

384 ns. It means that each channel of the FEL amplifier amplifies simultaneously four optical micropulses with the same time structure. The master laser should produce eight optical pulses of 7 ns pulse duration separated by 96 ns.

3.2.1 *First stage of the FEL amplifier*

The first stage of the FEL amplifier is destined to amplify relatively weak signal from the master laser ($W_{ext} \simeq 1$ MW) 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.

Using numerical simulation code FS2RN [8] we have optimized parameters of the first stage of the FEL amplifier (see Table 3). To provide efficient operation of the first stage of the FEL amplifier the rms energy spread in the electron beam and normalized emittance should not exceed the values of 0.1 % and $\pi \times 10^{-3}$cm rad, respectively. Systematic drift of the mean energy of electrons should be less than 1 %. In the case under study the

Table 3
Parameters of the first stage of the FEL amplifier

Electron beam	
Electron energy	3 GeV
Beam current	2 kA
rms energy spread	0.1 %
Normalized emittance	$\pi \times 10^{-3}$ cm rad
Undulator	
Undulator period	15 cm
Undulator field (enter/exit)	15.3 kG / 13.8 kG
Length of untapered section	17.7 m
Total undulator length	50 m
Radiation	
Radiation wavelength	0.5 μm
Input power	1 MW
Output power	360 GW
Efficiency	6 %

electron beam, produced by the RF accelerator, has finite phase extent with respect to the accelerating RF wavelength. It results in a drift of the mean energy of the particles along the beam about ±0.5 %. Such a drift of the mean energy does not influence on the FEL amplifier operation.

3.2.2 High efficiency stages

Subsequent stages of the FEL amplifier 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). To provide effective focusing of the radiation in these FEL amplifier stages, the diaphragm focusing line is used [1,5]. It has a form of a sequence of screens with holes. When Fresnel number is large, eigenmodes of such a line have rather small diffraction losses.

The detailed study of the multi-stage FEL amplifier is presented in ref. [1]. Operation of the multistage FEL amplifier proceeds as follows. In the initial stages a transitional processes take place: the optical power amplification and formation of the optical field eigenmode. After passing a large 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 focusing line. Estimations have shown that this process is lasted approximately 10 amplifier stages [1]. Average efficiency of these transitional stages is about 0.15.

The scheme of multi-stage FEL amplifier is presented in Fig.11. Each stage consists of planar multicomponent undulator of 50 m length with the period of 15 cm. The length of the main undulator is equal to 48 m. Prebuncher consists of four periods and is separated from the main undulator by dispersion section. The magnetic field in the main undulator is tapered by a linear law. The amplitude of magnetic field at the undulator entrance is equal to 15.3 kG. The parameters of the prebunchers, dispersion sections and undulator tapering are optimized for each stage to achieve maximal efficiency.

Diaphragm focusing line is used to provide focusing the radiation in the high efficiency stages. The period of diaphragm line L has been chosen to be fixed to 10 cm at the whole length of the FEL amplifier. The radius of the holes R is increased adiabatically along the FEL amplifier axis. Optimization of the parameters of the high efficiency stages has been performed using the requirement to keep fixed the ratio of the radiation power losses K to the radiation power gain G: $K/G = 0.1$ for all stages. It was shown in ref. [1] that in this case the FEL efficiency η, the radius of the holes R, the depth of the undulator tapering $\Delta H_w/H_w$ and the radiation power W are increased with the number of the FEL

Table 4
Parameters of 100 th stage of the FEL amplifier

Undulator	
Undulator period	15 cm
Undulator field (enter/exit)	15.3 kG / 6.1 kG
Length of the main undulator	48 m
Radiation	
Radiation wavelength	0.5 μm
Efficiency	36 %
Diaphragm line	
Period	10 cm
Radius of the holes	1 cm

amplifier stage n as:

$$\eta \propto n^{1/3}, \quad R \propto n^{1/3}, \quad \Delta H_w/H_w \propto n^{1/3}, \quad W \propto n^{4/3}. \tag{3}$$

Parameters of the last (100 th) stage of the FEL amplifier are presented in Table 4. The output power is equal to

$$W(100) \simeq 27W_e,$$

where $W_e = 6 \times 10^{12}$ W is the peak power of the electron beam. The electron efficiency (i.e. the efficiency of transformation of the electron power into the radiation power) of the last stage η, the power gain G, the radiation power losses K and the radius of the holes of the diaphragm line are as follows:

$$\eta \simeq 0.4, \quad G \simeq 1.4 \times 10^{-2}, \quad K \simeq 1.4 \times 10^{-3}, \quad R = 1 \text{ cm}.$$

The actual efficiency of the 100 th stage of the FEL amplifier is equal to $\eta_t(100) \simeq 0.36$ (taking into account the radiation losses in the diaphragm line). Parameters of the other FEL amplifier stages could be calculated using parametric dependencies (3). As a result, the efficiency of the multi-stage FEL amplifier (averaged over all stages) is equal to $\eta_{FEL} \simeq 0.27$.

Further we assume that the form of the electron beam pulse is a flat one with the rise and fall time of 5 ps. This will reduce the average efficiency of the FEL amplifier to the value of $\eta_{\rm FEL} \simeq 0.26$.

3.3 Output optical system

The trains of the laser bunches produced by eight channels of the FEL amplifier should be delivered to the reactor chamber. The function of the output optical system consists in transforming of the input FEL radiation (8 beams of 384 ns pulse duration) into 64 parallel laser beams of 7 ns pulse duration. Its operation proceeds in three phases: the expansion of radiation, separation and synchronization of the beams and summation of the laser beams.

3.3.1 The expansion of radiation

Peak radiation power at the exit of each FEL amplifier channel is about 1.6×10^{14} W. To provide the possibility of application of conventional optical elements, the density and the flux of the radiation energy on the optical elements should be less than 30 J/cm^2 and 3 GW/cm^2, respectively [4]. So, at the first stage the laser beams are expanded from the size of 2 cm (at the FEL amplifier exit) up to the size of 2.5 m. Such an expansion is performed in two steps.

At the first step the beams should be expanded diffractionally up to the size of 15 cm. To calculate the required distance, we should remember that transverse distribution of the field radiation is given by the fundamental TEM$_{00}$ mode of diaphragm line. Using Hyegens-Fresnel integral we find that 99 % of radiation power is inside the main diffraction maximum and the boundary of this maximum is given by the value of axial angle of $\theta \simeq 4.4 \times 10^{-5}$. So, the required size of 15 cm of the laser beam is obtained at the distance of the drift space equal to 1.5 km.

After the step of diffraction expansion, the laser beams are directed to the aluminium hyperbolic mirrors and are expanded up to the size of 2.5 m. To reduce the heat losses in the mirrors we use the fact that heat losses at a grazing reflection depend significantly on the polarization of radiation. In the case of a large value of the refractive index n', $\mid n' \mid \gg 1$, the relative heat losses for TE wave (electrical field is perpendicular to the reflection plane) are given by the expression [9]:

$$A_s = 4 \cos\theta Re(1/n') , \tag{4}$$

where θ is the incident angle ($\cos\theta \ll 1$ at the grazing incidence). The heat losses for TM wave are larger with respect to the value given by expression (4) approximately by a factor of $\mid n' \mid^2$. Remembering the fact that the FEL radiation is linearly polarized (see

previous section) we have a possibility to use this opportunity to decrease heat losses in the mirrors.

We choose the incident angle corresponding to $\cos\theta \simeq 10^{-2}$. As a result, the heat losses in the aluminium mirrors are less than damaging threshold of 10^8 W/cm^2 [10]. The angle divergence of the radiation after the mirror is about $\Delta\theta \simeq \cos\theta \simeq 10^{-2}$, so at the distance of 200 m the size of the laser beam will achieve the required value of 2.5 m.

The losses of the laser beam power at this phase of operation of the output optical system are about 1 % and are defined by the condition that hyperbolic mirrors accept only the main diffraction maximum of output radiation.

An important problem is that of extracting the powerful laser beam into the atmosphere. We propose to perform such an extraction at the stage of expansion of radiation. Here we take into account peculiar feature of laser discharge, namely that its threshold decreases with the gas pressure. For instance, for Ne gas, this threshold is 10^{13} W/cm^2 and 10^{12} W/cm^2 at a pressure of 10 torr and 100 torr, respectively [11]. So, the idea is to organize a transition from the pressure of 10^{-8} torr inside the vacuum chamber of the FEL amplifier up to the pressure about 100 torr in the vicinity of expanding hyperbolic mirror. To solve this problem, we propose to use the channel with differential pumping. Such a channel could consist of several chambers separated by diaphragms. At the initial stage of the laser beam expansion the aperture of diaphragms is of the order of 2 cm. To decrease the requirements on the pumping system, pulsed shutters could be used (taking into account the fact that the laser pulse duration is short, 0.4 μs).

3.3.2 Separation and synchronization of the laser beams

This phase consists of two steps. First, the initial eight laser beams are divided into 256 beams with lower density (dividing step). Second, each of 256 beams are transformed into 1024 parallel beams of 7 ns pulse duration (synchronization step). The necessity in the dividing step is defined by the technical limitations of Pockel's cell which is the main element of optical deflector of synchronization step. The present level of optical technology provides the possibility to construct Pockel's cell with aperture not more than 40 cm which requires to separate initial powerful laser beam into large number parallel low-powerful beams.

The scheme of dividing step is presented in Fig.12. The dividing of the beams is performed by polarizers. The orientation of the polarizer is chosen in such a direction that it divides linearly polarized optical beam into two beams with equal power but linearly polarized with respect to each other. One of the beams follows in forward direction and another one deflects due to reflection.

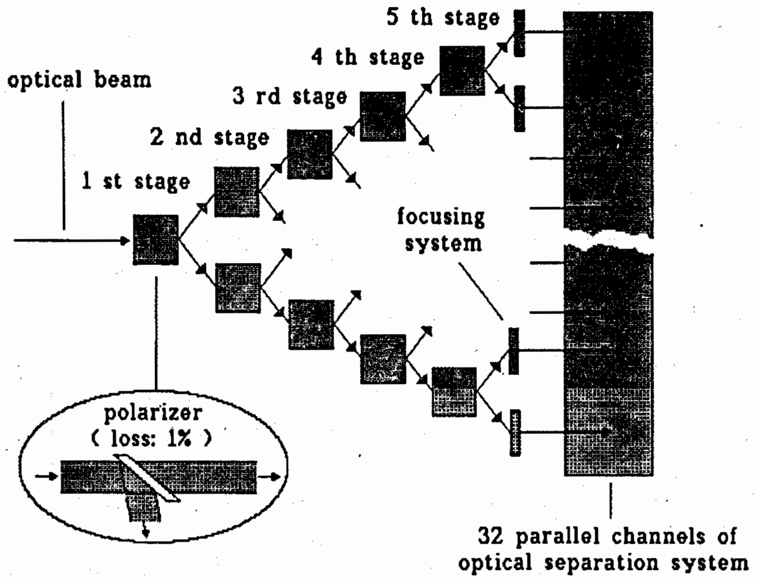

Fig. 12. The scheme of the optical beam divider.

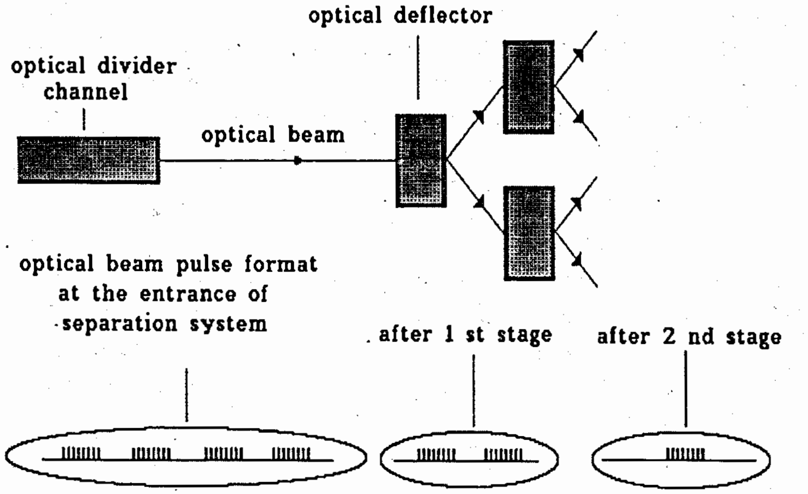

Fig. 13. The scheme of the optical beam separation system.

The dividing is performed by sequential scheme. In this scheme, after k-th stage, there are 2^k parallel channels with 2^k beams in each. At $(k+1)$-th stage, each of 2^k bunches is separated into two beams, etc. The scheme consists of 5 stages, the number of polarizers per one initial beam is equal to $2^5 - 1 = 31$ and the total number of polarizers is equal

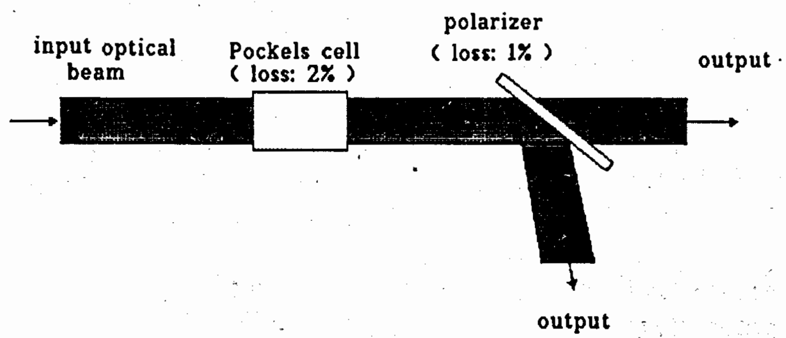

Fig. 14. The scheme of optical deflector.

to 248. The radiation losses in one polarizer are about 1 %, so the total radiation losses in the dividing step are about 5 % [4]. The maximal radiation power flux and energy flux occurs in the first dividing stage and do not exceed the values of 3 GW/cm^2 and 10 J/cm^2, respectively.

After the dividing step we have 256 laser beams. Each beam consists of four sequences of laser pulses separated by 96 ns. Each sequence consists of eight pulses of 0.1 ns duration separated by 1 ns. At the next step we separate 256 laser beams into 1024 laser beams of 7 ns pulse duration (see Fig.13). This is performed by means of optical deflectors which have appearance of Pockel's cells combined with polarizer (see Fig.14). The number of sequential stages is equal to 2 and the total number of optical deflectors is equal to 768.

The radiation power losses in the Pockel's cell and in the polarizer are equal to 2 % and 1 %, respectively [4]. As a result, integral losses of the radiation power at the separation step are about 6 %.

Then 1024 laser beams are fed into optical delay system to providing their time synchronization and then are directed into the system of preparation of output beams.

3.3.3 Summation of the laser beams

In principle, there could be a lot of possibilities to combine 1024 optical beams in order to obtain optimal irradiation of the target. Here we consider one of them. We prepare 64 output beams with the total stored energy of 3.5 MJ and pulse duration of 7 ns. It could be done, for instance, by means of multicomponent mirrors with independent adjustment of the elements (see Fig.15). As a result, we have a possibility to combine 16 laser beams of 40 cm diameter into one laser beam of 160 cm diameter. The radiation power flux and energy flux on the mirrors do not exceed the values of 3 GW/cm^2 and 2 J/cm^2, respectively.

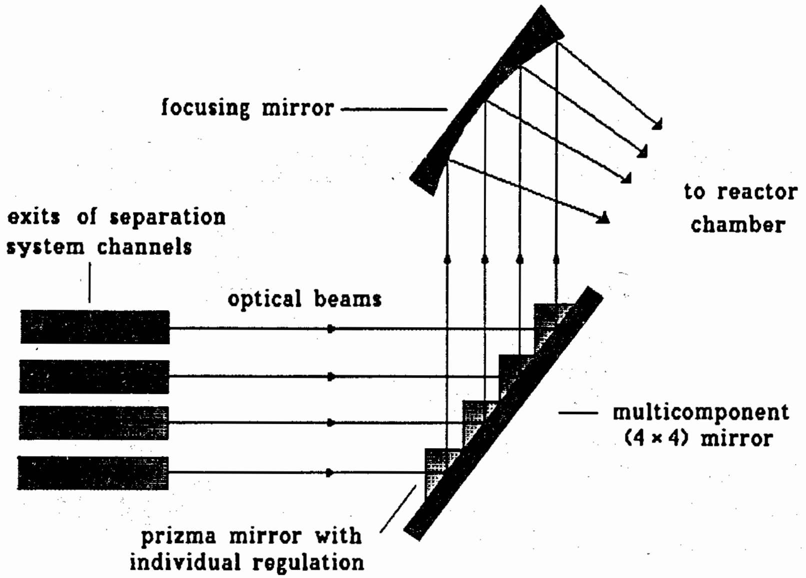

Fig. 15. The scheme of the optical beam summation system.

In the end the output optical system produces 64 laser beams which are directed to the reactor chamber.

In the last to stages, separation and synchronization of the laser beams and summation of the laser beams, multilayer mirrors could be used because of relatively low radiation power flux. Such mirrors possess a high reflectivity. So, following generally accepted practice for ICF driver design [4], we assume the radiation losses in the do not produce any significant contribution into the optical system efficiency.

3.3.4 The efficiency of the output optical system

The efficiency of the output optical system η_{OPT} (or, in other words, the transmission factor) is given by the product of the efficiencies of three phases: expansion phase ($T_1 \simeq 0.99$), separation and synchronization stage ($T_2 \simeq 0.95$) and the stage of summation of the laser beams ($T_3 \simeq 0.94$), and is equal to $\eta_{\mathrm{OPT}} \simeq 0.89$.

3.4 Efficiency of the laser fusion reactor driver

The efficiency of the proposed ICF energy driver is given by

$$\eta_{\mathrm{TOT}} = \eta_{\mathrm{ACC}} \times \eta_{\mathrm{FEL}} \times \eta_{\mathrm{OPT}} \ .$$

The efficiency of the accelerator η_{ACC}, i.e. the transformation of the net power to the electron beam power is equal to $\eta_{\mathrm{ACC}} = 0.45$ (see section 3.1). The efficiency of the FEL amplifier, i.e. the efficiency of transformation of the electron power into the radiation power, is equal to $\eta_{\mathrm{FEL}} = 0.26$ (see section 3.2). The efficiency of the output optical system, i.e. the efficiency of transformation of the FEL radiation into the laser beams suitable for the reactor chamber, is equal to $\eta_{\mathrm{OPT}} = 0.89$ (see section 3.3). As a result, we obtain the total efficiency of the proposed driver $\eta_{\mathrm{TOT}} \simeq 0.10$.

3.5 The quality of the laser radiation

Parameters of radiation of the laser system for inertial confinement fusion must obey to the following requirements: there should not be significant preheat of the target (i.e. a high value of contrast is required); the laser should have a high brightness and there could be a possibility to steer the laser pulse shape and duration. The proposed driver meets all these requirements.

First, the laser radiation of the proposed system provides absolute contrast: there are no sources of radiation power except of the main laser pulse. Contrary to this, in traditional *Nd* glass laser systems this problem could not be eliminated in principle due to the effect of superluminescention.

Second, to provide effective focusing of radiation on the target, the laser should provide a high brightness. The radiation of the FEL amplifier always has minimal, i.e. diffraction dispersion. The brightness of the source consisting of N channels with diffraction dispersion is given by relation:

$$B = 0.27 \times W/N\lambda^2 \ ,$$

where W is the total peak power of the laser system. Remembering that the peak power at the FEL amplifier exit is equal to 1.610^{14} W and then each laser beam is divided into 32 beam, we obtain:

$$B \simeq 5 \times 10^{20}\ \mathrm{W/cm^2 sr}\ .$$

Third, a form of the optical pulse in the proposed scheme could be changed in a wide limits to obtain the required shape and duration. For instance, in the presented specific example (see section 3.3) it could be done simply by changing the parameters of the optical delay lines.

3.6 Cost Estimation

Table 5 presents the cost estimation of the main elements of the driving beam generation system. When estimating the cost of accelerator housing, tunnels and klystron gallery we accepted the cost estimation technique used during realization of the SLC project. When estimating the cost of klystrons, modulators, accelerating structures and beam transport line we have based on estimation technique used in the linear collider projects [12]. In accordance with this technique, the cost of a klystron (modulator) reduces significantly at a serial production (approximately by a factor of 1.5 – 2 when production is increased by a factor of 10). If we assume the number of ICF power stations to be about ten, this requires production of about 10^4 klystrons. As a result, the cost of serial production of the klystron (modulator) could be reduced to the value of 70 K$/unit. We estimate the total cost of the driving beam generation system to be about 600 M$.

Table 6 presents the cost estimation of the main elements of the multi-stage FEL amplifier. The cost of the beam transport line has been estimated on the base of a similar device developed for the linear collider projects [12]. When calculating the cost per meter

Table 5
The cost of the driving beam generation system

	K$/m	Total, M$
Accelerators		
Accelerator housing	10	24
Klystron gallery	5	12
Accelerating sections	15	36
	K$/Unit	Total, M$
2000 klystrons	70	140
2000 modulators	70	140
Rectangular waveguide	10	20
Vacuum & cooling	30	60
Separation system		
	K$/m	Total, M$
Tunnels	8	91
Beam transport line	1	80

Table 6
The cost of the FEL amplifier

	K$/m	Total, M$
Housing (double tunnel)	16	182
Undulators	10	400
Beam transport line	1	45
	K$/Unit	Total, M$
Arcs	30	24
Kicker magnets	20	16
Beam dumps	25	20

of superconducting undulators (including cryostats) for the FEL amplifier we assumed that the cost reduces at a serial production (approximately by a factor of 2 when production is increased by a factor of 10). We assumed also that the cost per meter of a superconducting undulator it is about two time less than the cost per meter of superconducting accelerating modules (developed, for instance, for linear collider TESLA). So, we estimate the total cost of the FEL amplifier to be about 700 M$.

We assume that the cost of the output optical system should be close to that used in the driver for laser fusion reactor with laser diode pumped solid state lasers [4]. The latter system has about one thousand independent amplifier channels and its cost is estimated to be about 200 M$ [4].

The total cost of the FEL based fusion driver consists of three main parts: the cost of the accelerator complex (600 M$), the cost of the multi-stage, multi-channel FEL amplifier (700 M$) and the cost of the output optical system (200 M$). So, we estimate the total cost of the FEL driver for ICF reactor to be about 1500 M$.

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Салдин Е.Л. и др. E9-96-68
Оптическая система на базе лазера на свободных электронах
с энергией вспышки 4 МДж в качестве драйвера
для промышленного термоядерного реактора

В работе развивается концепция использования техники лазеров на свободных электронах (ЛСЭ) для создания энергетического драйвера для промышленного термоядерного реактора [1—3]. Показана возможность создания драйвера со следующими параметрами: длина волны излучения 0,5 мкм, энергия вспышки 4 МДж, частота повторения 10 Гц, полный КПД 10%. Создание такой системы становится возможным благодаря новой схеме суммирования оптической мощности в ЛСЭ-усилителе, предложенной в данной работе. Драйверный пучок для ЛСЭ-усилителя производится ускорительным комплексом, состоящим из четырех СВЧ-ускорителей с энергией 3 ГэВ, работающих на частоте СВЧ 500 МГц с частотой повторения 10 Гц и длительностью макроимпульса 0,3 мс. Особенностью предложенной схемы является то, что для ее реализации требуются СВЧ-ускорители с относительно малым средним током (порядка 4 А в среднем по макроимпульсу). Произведен детальный анализ технических проблем и оценка стоимости драйвера.

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Препринт Объединенного института ядерных исследований. Дубна, 1996

Saldin E.L. et al. E9-96-68
Free Electron Laser System with 4 MJ Flash Energy
for the Laser Fusion Reactor Driver

This paper presents the further development of a concept of a FEL based driver for commercial inertial confinement fusion reactor [1—3]. We have shown technical feasibility of constructing a laser system with the following parameters: laser light wavelength 0.5 μm, flash energy 4 MJ, repetition rate 10 pps and net efficiency 10%. It becomes possible due to the use of a novel scheme of optical power summation. The driving beam for the FEL amplifier is produced by the accelerator complex consisting of four 3 GeV RF linear accelerators operating at RF frequency of 500 MHz, repetition rate of 10 pps and 0.3 ms pulse duration. Peculiar feature of the scheme is that it requires relatively low current RF accelerators (with the average over macroimpulse current about 4 A). Also we analyze in detail technical feasibility of the proposed scheme and estimate the cost of the driver.

The investigation has been performed at the Laboratory of Particle Physics, JINR.

Preprint of the Joint Institute for Nuclear Research. Dubna, 1996