CONCEPTUAL DESIGN OF A FREE ELECTRON LASER SYSTEM AS A LASER FUSION REACTOR DRIVER

E.L. Saldin[a], E.A. Schneidmiller[a], Yu.N. Ulyanov[a], M.V. Yurkov[b]
[a]Automatic Systems Corporation, 443050 Samara, Russia
[b]Joint Institute for Nuclear Research, Dubna, 141980 Moscow Region, Russia

Abstract

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.

1 INTRODUCTION

The laser driver for commercial ICF reactor must provide 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. In this paper we present 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].

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, performed in ref. [4], has shown 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 SUMMATION OF OPTICAL POWER

The main elements of the scheme are the beam transport line with kicker-magnets, matching arcs and multi-stage FEL amplifier (see Fig.1). A 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 $2L_s$, where L_s 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, etc.

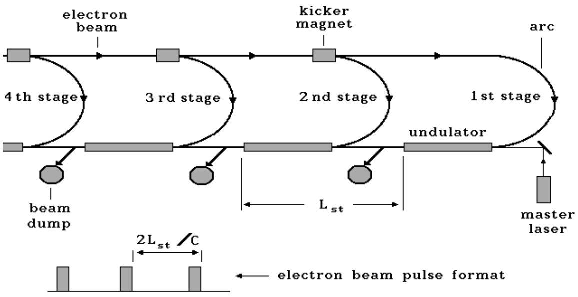

Figure 1: The scheme of optical power summation.

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 [4]. In the process of optimization we have developed the concept of the driver with the main parameters presented in Table 1. The general layout of the driver is presented in Fig.2. It consists of three main parts: driving beam generation system, multi-stage, multi-channel FEL amplifier and output optical system.

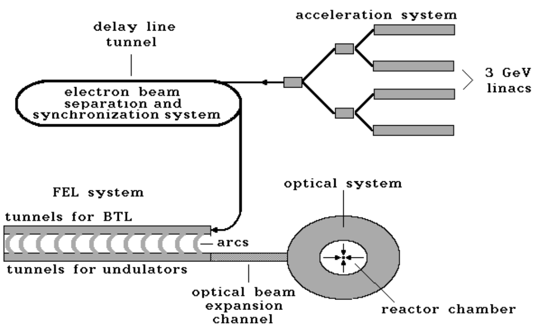

Figure 2: Layout of the ICF reactor.

Table 1: 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 %

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

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. Accelerating gradient is equal to 5 MV/m and total length of each accelerator is equal to 600 m.

The general parameters of RF accelerators are presented in Table 2. Time diagram of the accelerator operation is presented in Fig.3. 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. 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.

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 16.8 A. This is performed in two stages (see Fig.4). 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).

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.5). 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. After filling the delay line, seven kicker magnets are switched on simultaneously and we ob-

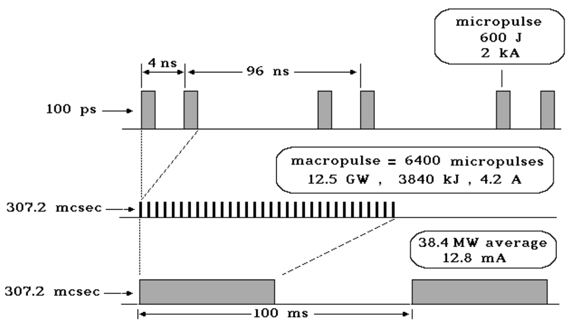

Figure 3: Electron beam pulse format in RF accelerator.

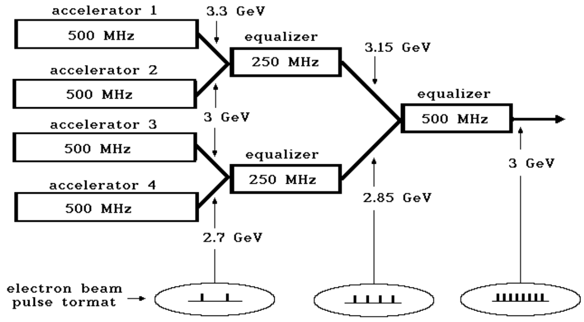

Figure 4: The scheme of the electron beam summation system.

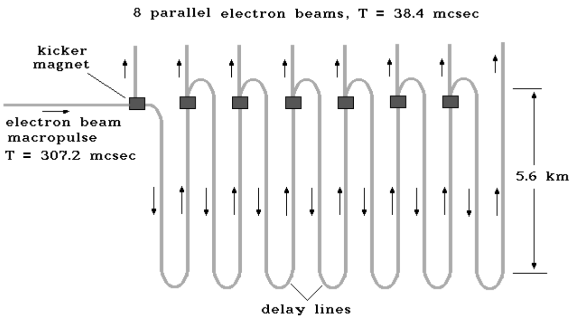

Figure 5: The scheme of the electron beam separation and synchronization system.

Table 2: Parameters of accelerator

Electron energy	3 GeV
RF frequency	500 MHz
Accelerating gradient	5 MV/m
Macropulse duration	308 μs
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

tain 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. 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 384 ns. It means that each channel of the FEL amplifier amplifies simultaneously four optical micropulses with the same time structure.

The first stage of the FEL amplifier is destined to amplify relatively weak signal from the master laser ($W_{\mathrm{ext}} \simeq 1$ 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. 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). The parameters of the prebunchers, dispersion sections and undulator tapering are optimized for each stage to achieve maximal efficiency. To provide effective focusing of the radiation in these FEL amplifier stages, the diaphragm focusing line is used [1, 5].

Optimization of parameters of the FEL amplifier has been performed in ref. [4]. Total efficiency of the multistage FEL amplifier (averaged over all stages) is equal to $\eta_{\mathrm{FEL}} \simeq 0.26$. For illustrations we present in Table 3 parameters of the last (100 th) stage of the FEL amplifier.

Table 3: 100th 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

3.3 Output optical system

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 which are directed to the reactor chamber [4].

3.4 Efficiency and cost estimation

The efficiency of the proposed ICF energy driver is defined by the product of the efficiencies of accelerator ($\eta_{\mathrm{ACC}} = 0.45$), of the FEL amplifier ($\eta_{\mathrm{FEL}} = 0.26$) and of the output optical system ($\eta_{\mathrm{OPT}} = 0.89$) and is equal to $\eta_{\mathrm{TOT}} \simeq 0.10$.

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$). So, we estimate the total cost of the FEL driver for ICF reactor to be about 1500 M$ [4].

4 CONCLUSION

An important feature of the proposed scheme is that it could operate with large 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.

5 REFERENCES

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

[2] E.L. Saldin et al., Nucl. Instrum. and Methods **A361**(1995)317.

[3] E.L. Saldin et al., preprint JINR E18-95-292, Dubna, 1995.

[4] E.L. Saldin et al., preprint JINR E9-96-68, Dubna, 1996.

[5] E.L. Saldin et al., preprint DESY 94-243, DESY, Hamburg, 1994.