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CONCEPTUAL DESIGN OF INDUSTRIAL FREE ELECTRON LASER USING SUPERCONDUCTING ACCELERATOR

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1 Introduction

Free electron laser (FEL) history is only 20 years old and the main progress in this field has been achieved during the last ten years. Nowadays there are several tens of the FEL devices operating in the wavelength range from 0.24 μm up to millimeter. Despite a strong competition from the side of conventional lasers, the FEL is recognized now as a unique tool for scientific applications requiring tunable coherent radiation. As the FEL has several excellent features, such as high efficiency, high peak and average power, minimal dispersive, short pulse duration, wavelength tunability a very wide range of industrial applications is contemplated. Taking into account the future perspectives of the FEL, many industrial firms undertake intensive investigations in the FEL technology aiming a goal to construct powerful FELs for industrial applications such as material processing, microlithography, isotope separation, photo-induced chemistry, etc [1,2].

To construct high power FEL for industrial applications, the accelerators should be developed capable to accelerate a high peak and average current at a high quality of the electron beam. Now we see a promising tendency when accelerator technology developed for scientific applications is transferred to industrial applications and the CEBAF project of the FEL for industrial applications confirms this tendency [3]. It is assumed to use this FEL to study various industrial applications such as tailoring the surface characteristics of polymers, composites, ceramics and metals for use in manufactured products.

In this paper we present conceptual design of a high-power FEL complex with the optical output spanning the infrared (IR) and ultraviolet (UV) wavelengths. The design is based on the parameters of the superconducting accelerator to be constructed for the TESLA Test Facility (TTF) in the framework of the R&D work on the linear collider TESLA project [4,5]. The FEL complex consists of three FEL oscillators operating at different wavelength bands (see Fig.1). As a rule, the efficiency of the FEL oscillator, designed by a standard scheme, is rather small, of about several per cent. The use continuous or quasi-continuous driving electron beam from the superconducting accelerator reveals a possibility to use a novel FEL oscillator scheme providing a high efficiency, of about several tens of per cent. It is achieved with the time-dependent tapering of the magnetic field of the undulator [6,7]. The undulator for the proposed scheme is of electromagnetic type and provides a time-dependent and space-dependent change of the field. At the end of the time dependent tapering process, the FEL oscillator efficiency is of about 20 %. So, the proposed FEL complex will produce average output power of about 10 kW in the 0.3 – 20 μm wavelength range.

2 Accelerator

Driving beam for the FEL is produced by a superconducting linear accelerator (see Table 1). The accelerator consists of 8 superconducting accelerating modules. The accelerating gradient is 6 MV/m, rms duration of the micropulse is 2 ps, peak current is 100 A and micropulse repetition rate is 10.4 MHz. Macropulse duration is 0.5 s and repetition rate 0.2 pps (duty factor – 0.1). At the chosen parameters, standard helium TTF refrigerator provides a sufficient reserve capacity and safety margin of operation.

The RF power system of the accelerator consists of two TH 2086 A klystrons operating at 1.3 GHz frequency with output peak and average power 0.6 MW and 60 kW, respectively.

An RF gun with laser driven photocathode is used as an injector producing electron pulses with rms pulse duration of 2 ps, peak current of 100 A (0.5 nC charge per bunch) and 10.4 MHz micropulse repetition rate.

The are two outlets of the beam. The first outlet corresponds to the first stage of the linac (4 cryomodules). The second one corresponds to the full linac (8 cryomodules).

3 FEL System

The parameters of the proposed FELs are summarized in Table 2. The first IR FEL is driven by the electron beam from the first stage of the linac (4 cryomodules, energy 125 MeV). It operates in the 5 – 20 μm wavelength range providing 10 kW of average output power. The second IR FEL ($\lambda = 0.8 - 5$ μm, 20 kW output power) and visible and UV FEL ($\lambda = 0.3 - 0.8$ μm, 10 – 20 kW of average output power) are driven by the beam from the full linac (8 cryomodules, energy 250 MeV).

The FELs use multicomponent undulator consisting of two undulator sections (prebuncher and the main undulator) separated by a dispersion section. The main undulator is a tapered one. The prebuncher, main undulator and dispersion section are composed of electromagnets to permit real time optimization of the gain and efficiency (see section 4).

In the wavelength range 0.3 – 20 μm, the availability of high-reflectivity mirrors indicates that high average power (10 kW level) operation is of a low risk. The optical system for the IR FELs are a straightforward near-concentric cavity. Outcoupling the power is accomplished through a hole in the mirror.

In the visible and UV region the combination of the long FEL optical cavities and small wavelength results in a very high alignment sensitivities. For conventional visible and UV optical resonator design, the sensitivity is below ten microradians and requires a very complicated control system to keep the resonator aligned [8].

To reduce the alignment sensitivity, the resonator of the visible and UV FEL is designed using retroreflection ring resonator technique [9]. The resonator includes two corner cube end-mirrors. A corner cube reflector consists of three mutually perpendicular mirrors. Outcoupling from the resonator is accomplished with a scraper mirror placed in the middle of the back leg. The reflector retroreflects an incident beam independent of the position and direction of the reflector. The alignment tolerance can be improved by at least three orders of magnitude over conventional resonator design. The angle tolerance between the corner cube reflectors is in the range of 10 mrad.

In order to perform exact retroreflections, the facets of corner cube have to remain perpendicular to each other. The angle tolerance between the facets are in the range of one microradian. Since the optics to be aligned at this precision within a small local space about of the corner cube size, it is much easier to achieve the required tolerance compared to that of optics separated by few tens of meters for conventional resonator design.

4 Principle of the time dependent undulator tapering

The proposed FEL oscillator scheme consists of the prebuncher, drift space and main undulator with time-dependent tapering. In the linear mode of the FEL oscillator operation the main undulator parameters are untapered providing effective small-signal gain. When the radiation field in the resonator achieves its maximum, the main undulator parameters begin to change in time. As the depth of the tapering is increasing, the radiation field amplitude in the resonator is also increasing. At some value of the tapering depth the maximum value of the radiation field amplitude is achieved. At this moment the process of undulator tapering is stopped and then the FEL oscillator operates in the stationary regime with an efficiency which is much higher than the efficiency of the untapered case. The time interval required to achieve the high efficiency stationary regime depends on the rate of change of the main undulator magnetic field and may be of the order of several tens of milliseconds or more. Thus, the driving electron beam for the proposed FEL oscillator scheme should be continuous or quasi-continuous and may be generated by a superconducting accelerator.

A detailed description of the proposed method is presented in ref. [6]. Here we illustrate with Fig.2 the dependencies on time of the undulator tapering depth and the efficiency for the FEL oscillator operating at 0.5 μm wavelength. At the end of the time-dependent

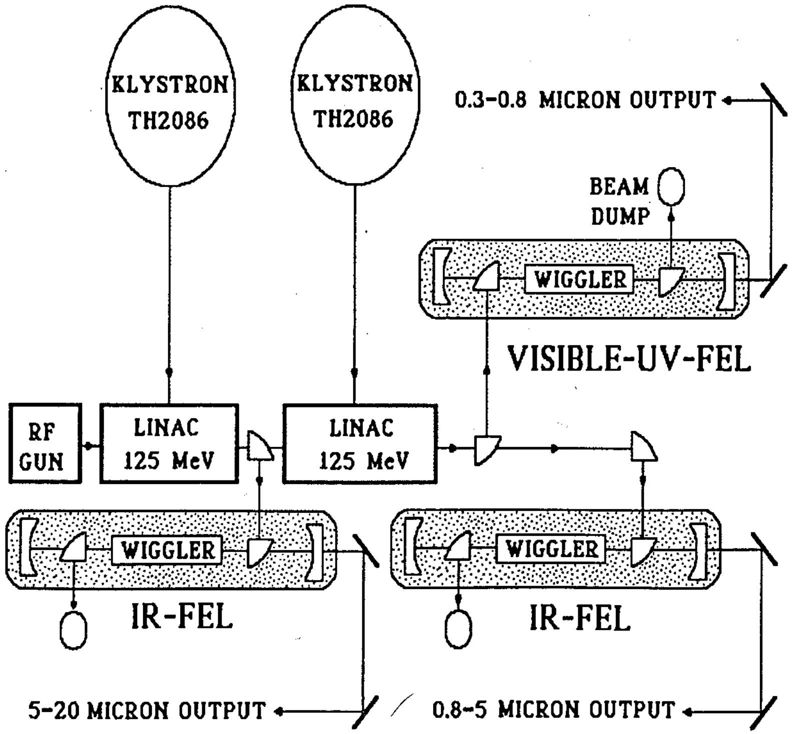

Fig. 1. Conceptual scheme of the industrial FEL.

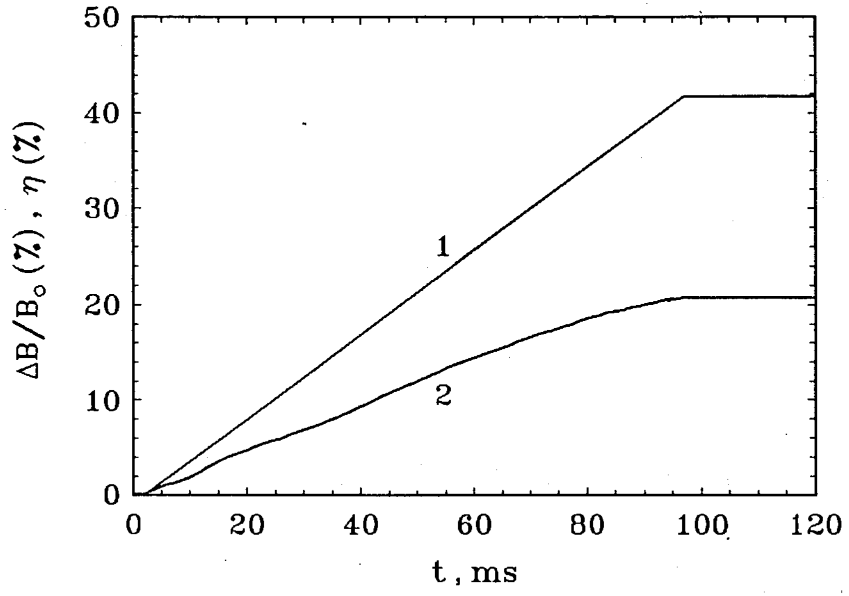

Fig. 2. The depth of the magnetic field tapering in the main undulator (1) and the FEL efficiency (2) as functions of time. Parameters of the FEL oscillator are presented in Table 2 (visible & UV). Operating wavelength is 0.5 μm.

Table 1
Parameters of the accelerator

	1st stage	2nd stage
General parameters		
Energy	125	250 MeV
Number of accelerator cryomodules	4	8
Mode of operation	quasi-CW	
Macropulse duration	0.5 s	
Repetition rate	0.2 pps	
Micropulse duration (rms)	2 ps	
Micropulse repetition rate	10.4 MHz	
Charge per bunch	0.5 nC	
Peak current	100 A	
Average current (over maropulse)	5 mA	
Energy spread $\Delta\mathcal{E}/\mathcal{E}$	0.2 %	0.1 %
Normalized emittance, ϵ_n	10 mm·mrad	
RF power supply		
RF frequency	1300 MHz	
Type of klystron	TH 2086 A	
Number of klystrons	1	2
Peak RF power of klystron	0.6 MW	
Average RF power of klystron	60 kW	
Anode voltage	69 kV	
Operating current	36 A	

Table 2.
Parameters of the industrial free electron laser

	1st stage	2nd stage	
	IR	IR	Visible & UV
Electron beam			
Energy	125 MeV	250 MeV	250 MeV
Macropulse duration	0.5 s	0.5 s	0.5 s
Repetition rate	0.2 pps	0.2 pps	0.2 pps
Micropulse duration (rms)	2 ps	2 ps	2 ps
Micropulse repetition rate	10.4 MHz	10.4 MHz	10.4 MHz
Peak current	100 A	100 A	100 A
Energy spread $\Delta\mathcal{E}/\mathcal{E}$	0.2 %	0.1 %	0.1 %
Normalized emittance, ϵ_n	10 mm·mrad	10 mm·mrad	10 mm·mrad
Undulator*			
Undulator period	12cm	12 cm	6 cm
Maximal undulator field	5.6 kGs	5.6 kGs	5.3 kGs
Number of undulator periods	25	25	100
Number of prebuncher periods	4	4	4
Optical resonator			
Resonator length	15 m	15 m	15 m
Rayleigh length	1.5 m	1.5 m	3 m
Total power losses	5 %	5 %	5 %
Radiation			
Output tuning range	5 – 20 μm	0.8 – 5 μm	0.3 – 0.8 μm
Dispersion	Diffraction limited		
Spectral bandwidth	0.1 – 1 %		
Peak output power	2 – 4 GW		
Average power (over macropulse)	100 – 200 kW		
Average power	10 – 20 kW		
Efficiency	20 %		

*Planar electromagnetic undulator with time-dependent tapering

tapering process ($\tau \simeq 100$ ms), of about 75 % of the particles are tapered in the regime of coherent deceleration and the FEL efficiency $\eta \simeq 20$ % is achieved.

5 Discussion

In the present paper we have considered design of the FEL complex for industrial applications. Peculiar feature of the proposed complex is a high efficiency of the FEL oscillators, up to 20 %. This becomes possible due to the use of quasi-continuous electron beam and the use of the time-dependent undulator tapering [6,7]. High power driving electron beam for the FEL is provided by superconducting linear accelerator. It could be constructed on the base of superconducting accelerating structures which are under development in the framework of the TESLA project [4,5]. Such an approach to the FEL design reveals a possibility of constructing high efficiency and high-power FELs for industrial applications.

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Салдин Е.Л., Шнейдмиллер Е.А., Юрков М.В. E9-96-67
Концепция лазера на свободных электронах
для промышленных применений
с использованием технологии сверхпроводящих ускорителей

В работе представлена концепция комплекса лазеров на свободных электронах (ЛСЭ) для промышленных применений. Комплекс ЛСЭ состоит из трех ЛСЭ-генераторов, перестраиваемых по длине волны излучения от инфракрасного до ультрафиолетового ($\lambda = 0{,}3 \ldots 20$ мкм) со средней выходной мощностью 10—20 кВт. Драйверный пучок для ЛСЭ производится сверхпроводящим ускорителем. Электронный пучок транспортируется к ондуляторам по трем каналам (125 МэВ и 2×250 МэВ). Особенностью предлагаемого комплекса является высокий, порядка 20%, КПД ЛСЭ-генераторов. Это становится возможным благодаря непрерывному режиму работы сверхпроводящего ускорителя и использованию техники вариации параметров ондулятора во времени.

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Saldin E.L., Schneidmiller E.A., Yurkov M.V. E9-96-67
Conceptual Design of Industrial Free Electron Laser
Using Superconducting Accelerator

Paper presents conceptual design of the free electron laser (FEL) complex for industrial applications. The FEL complex consists of three FEL oscillators with the optical output spanning the infrared (IR) and ultraviolet (UV) wavelengths ($\lambda = 0.3 \ldots 20$ µm) and with the average output power 10—20 kW. The driving beam for the FELs is produced by a superconducting accelerator. The electron beam is transported to the FELs via three beam lines (125 MeV and 2×250 MeV). Peculiar feature of the proposed complex is a high efficiency of the FEL oscillators, up to 20%. This becomes possible due to the use of quasi-continuous electron beam and the use of the time-dependent undulator tapering.

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

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