ELECTRON BEAM PUMPED SEMICONDUCTOR LASER FOR PARTICLE BEAM DIAGNOSTICS

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ABSTRACT

Some characteristics of a new technique for accelerated particle beam monitoring are presented. This technique for beam current and pulse duration measurement is based on the electron beam pumped semiconductor laser (EBP-laser) principle of operation. First experimental investigations of 300 μm GaAs primary probe were carried out. Accelerated electron beam pulses with current range 50-500 A, pulse duration 5 μs and energy 200 keV were registered. The system sensitivity in this current range was $5*10^{-3}$ V/A. It was shown that it's possible to apply the thechnique to monitoring of picosecond electron bunches in free electron laser photoinjectors.

INTRODUCTION

High power generation of the ultra-short optical pulse radiation is based on electron beam pumping of a semiconductor laser [1]. Such lasers generate the optical pulses with power 10-50 W, duration 5-10 ps, by pumping current density above 10^5 A/m^2 and electron energy 50-200 keV. The free electron laser photoinjector is worked and developed [2]. The photoinjector electron bunches with current range 50-500 A, bunch duration range 40-200 ps and electron energy range 100-400 keV is achieved. The bunch-to-bunch interval is 10-20 ns with beam pulse duration 200 ns. In present work, the goal of the authors was to research the use of EBP-laser for photoinjector bunches diagnostics. This paper reports results of the first experiments on diagnostic equipment with EBP-laser monitor on the high current accelerator in MEPhI.

SUMMARY OF THE THEORY

In our calculations of radiation power, threshold current and resolution time of EBP-laser we used the monitor structure which is shown in fig.1.

In this structure electron beam is normal to surface of the GaAs crystal, which has thickness H. The optical radiation is normal to side surface. The distance between them is L. For transmission optical radiator the optical fiber with diameter d_f is used. The longitudinal dimention of radiation surface is l_s. In our case it's determined by opening in the collimator. D and d are thickness of active and radiation layer accordingly.

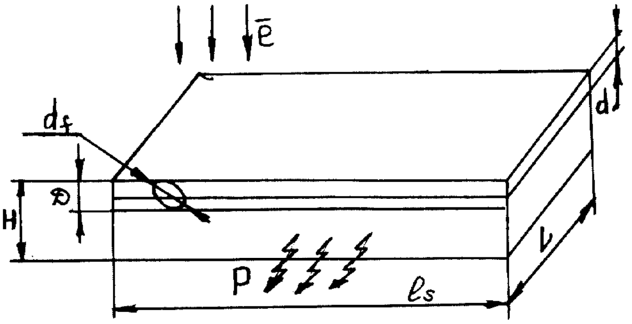

Fig.1. Monitor structure

The optical power of the EBP-laser is defined as

$$P_{opt} = P_{el} \cdot \eta \quad , (1)$$

where

$$P_{el} = \frac{S_c}{S_B} \cdot \frac{EI}{t_i} \quad , (2)$$

S_B is the area of beam cross section and S_c is the area of opening in the collimator.

The laser efficiency can be expessed as [3]

$$\eta = \eta_{in} \frac{1-\exp(-\alpha L)}{\alpha L} \cdot \frac{1-R}{1-R\exp(-\alpha L)} \quad , (3)$$

where η_{in} is the internal efficiency (η_{in}=0.33) α is the dispersive losses in the active layer (α =30 m^{-1}), R is the resonator mirror reflection index (R=0.3). For E=50 keV, I=200 A, t_i=100 ps, $S_B=3*10^{-4}$m^2, $S_c=7.5*10^{-7}$m^2 it's shown, that η =0.05, $P_{el}=2.5*10^4$ W and $P_{opt}=1.25*10^3$ W. The real value P^R_{opt} is less than P_{opt} by three orders because the electron energy distribution is ingomogenious in the active layer. Therefore the layer efficiency must be decreased to 0.01. Moreover P_{opt} is decreased 2 times because the optical radiation is generated from 2 resonator edges. At last, there are the fiber edge deflection losses and the value l_s is much greater then fiber diameter d_f (l_s=0.5 mm, d_f=10 m). So P^R_{opt} isn't more then 1.25 W.

Using the condition of a laser generation the expression for the threshold current density J_t may be written as [4]

$$J_t = \frac{8\pi n^2 \Delta\nu e \mathcal{E} D}{\lambda_0^2 E S \eta_q}\left[\frac{d}{D}\alpha_a + \left(1-\frac{d}{D}\right)\alpha_p + \frac{1}{L}\ln\left(\frac{1}{R}\right)\right] \quad ,(4)$$

where λ_0 is the optical radiation wavelength ($\lambda_0=9.0*10^{-7}$ m), η_q is the internal quant efficiency (η_q= 0.7), n is GaAs refraction index (n=3.34), $\Delta\nu$ is the spontaneous amplification bandwidth ($\Delta\nu=1.5*10^{13}$s^{-1}), e is

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the electron charge, S is the reverse dissipation factor (S=0.68), $\mathcal{E}$ is the average energy for one electron - hole pair creation ($\mathcal{E}$=4.5 eV), α_a=12 sm^{-1} and α_p=210 sm^{-1} are dispersive losses in the active and radiation layers, accordingly. From (4) for E=50 keV, L=1.5 mm, the threshold current density is equal 1.2*10^4 A/m^2. For measuring the electron beam current it is necessary to determine the laser time resolution. The laser generation occurs if the pumping current pulse duration is more then the generation delay time t_d. The delay time t_d can be estimated as

$$t_d = \tau_e \ln \left[\frac{J}{J - J_{t'}}\right] \qquad , (5)$$

where τ_e=10^{-9} s for GaAs, $J_{t'}$ slightly exeeds J_t. The generation delay time t dependence on the electron current density is shown in Fig.2. where $J_{t'}$=1.5*10^4 A/m^2 and J_t=1.2*10^4 A/m^2.

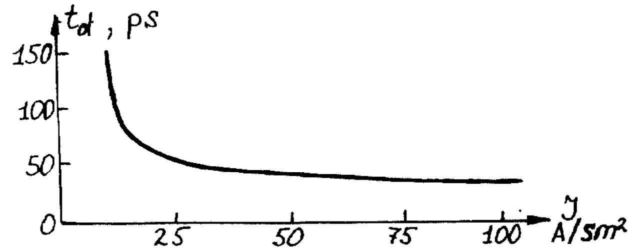

Fig.2. Generation delay time dependence on electron current density.

The dependence in Fig.2. indicates that t_d isn't more then 20 ps at high J. It's known that delay time t_d may be decreased by additional constant pumped current J_c. J_c must be not more then J_t.

To minimize the difference between the optical radiation pulse form and the beam current pulse form, it's necessary, that $t_в$< T. The time T characterises the electron-photon relaxation period and can be determined as

$$T = \frac{2\tau_e}{Y+1}, \quad Y = \frac{J}{J_t} \qquad ,(6)$$

The results of calculation are shown in Fig.3. It is seen that for high Y , the value of T is small (T=20-25 ps).

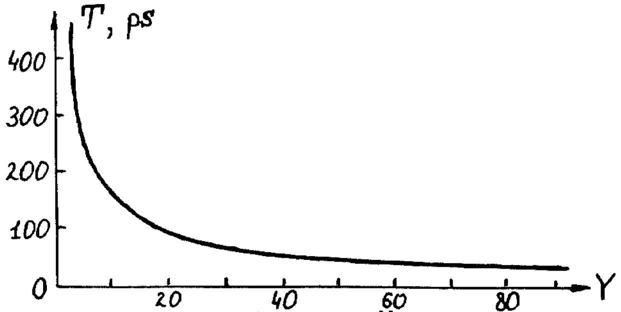

Fig.3. T dependence on Y.

So, if J exceeds $J_{t'}$ significantly and the electron beam pulse duration is enough for laser generation, the pulse form distortion isn't creat. The maximum of pulse distortion should not exceed 20 ps.

MONITOR CONSTRUCTION

The main component of the monitor is GaAs semiconductor crystal. The crystal substrate is placed in a special hollow of a massive metallic substrate (Fig.4). The optical radiation

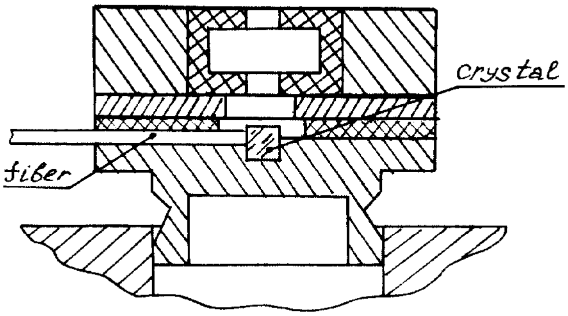

Fig.4. Monitor construction

output is carried into the optical fiber end. The fiber is placed in the V-type channel in a metallic substrate. The fiber is fixed in the channel by a dielectric elastic laying, a metallic plate and a supplementary clamp. The electron beam is transported to the surface of the semiconductor substrate through a collimator. The collimator consists of an aluminium block and a graphite insert with a through opening. To change the electron pumping area on the substrate surface a few graphite inserts with different opening sizes are used. The minimal size of the pumping area is limited by 0.5*1.5 mm^2. To decrease the influence of the secondary electrons a special cavity is inserted into the graphite. The metallic substrate, the metallic plate and the collimator are united in an indivisible construction with 2 screws. The monitor is placed on Faraday cup opening in the vacuum chamber of the accelerator. The monitor construction is provids the optical radiation transmission from a semiconductor laser to the optical fiber. It forms the pumping area on the semiconductor substrate surface and enables to insert different crystal substrates, fibers and graphites.

EXPERIMENT

The experimental work was performed with the high current electron accelerator in MEPhI laboratory of high current beam physics. The samples of the semiconductor laser were prepared on GaAs substrate. The substrate thickness was 300 μm. The vacuum output of the optical fiber is realised on a flat rubber seal. Experiments under vacuum conditions proved that for achiving the limit pressure (10^{-6} mm Hg) such a seal was sufficient. The monitor samples were studied with the high current electron accelerator with electron energy 200 keV, current density range $(15-150)*10^{4}$ A/m^{2}, pulse duration 5 μs. First experiments results are presented in Fig. 5.

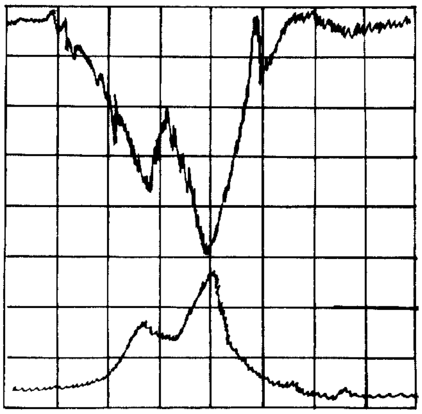

Fig. 5. Experimental results: the upper trace is the beam current pulse (80 A/div, 1 μs/div) ; the lower trace is the EBP-laser radiation (50 mV/div, 1 μs/div).

The optical radiation was transmitted from the laser to a receiver by the 30 m optical fiber. This optical radiation was measured with the avalanche photodiode with sensitivity 27 A/W at wavelength 0.85 μm and was registered by memory - type oscilloscope. The photodiode load resistance is equal 510 Ohm. From Fig. 5. it is seen that the system sensitivity with the electron beam pumped semiconductor laser monitor is $5*10^{3}$ V/A.

CONCLUSION

According to the obtained results the electron beam pumped laser is a useful diagnostic tool for a picosecond electron bunches in free electron laser photoinjector. The pulse duration of photoinjector current can be measured on the basic of this technique. Due to the high time resolution and sufficient sensitivity this detector can be used for particle beam diagnostics.

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