POTENTIALITIES OF ELMI DEVICE FOR SUBMILLIMETER GENERATION BY STIMULATED INTERCAVITY SCATTERING IN PLANAR FEM *

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Abstract

Paper describes main features of a project on two-stage generation of submillimeter radiation at the ELMI device. This novel variant of a two-stage scheme is based on stimulated intercavity scattering. In accordance with the scheme, at the first stage a sheet electron beam drives a 2D Bragg free electron maser (FEM) of planar geometry to generate 4-mm pump wave. At the second stage this wave undergoes stimulated scattering at the supplementary electron beam to produce submillimeter radiation. In the paper we describe results of theoretical and experimental investigations of various aspects of the two-stage scheme and some testing experiments on units for realization of this scheme at the ELMI device.

INTRODUCTION

In recent experiments at the ELMI-device the single frequency operation of 4-mm planar FEM with 2D distributed feedback has been demonstrated [1]. These results created a basis for development of a two-stage generator for the sub-mm band. A key feature of the scheme proposed earlier in [2], is the use of two sheet beams with a few kAmps currents that transported in two parallel slit channels with a guiding longitudinal magnetic field, which are connected by a special waveguide. At the first stage one of the sheet beams passing in a slit channel with static undulator magnetic field drives 2D Bragg FEM of planar geometry to generate 4-mm pump wave as well as in the recent ELMI experiments. This intensive 4-mm radiation accumulated in the FEM resonator is transported through the special waveguide to the second slit channel where it is used as an EM-undulator for the secondary stage of sub-mm FEL.

The special waveguide connection will be realized in similar way as it was suggested earlier in the project of multibeam FEM with 2D distributed feedback where it was used for synchronization of radiation generated in different channels [3], [4]. Production of the two sheet beams by one accelerator diode with two cathodes is also similar to the process of operation of the multibeam diode described in Ref. [4].

SCHEMATIC OF PROPOSED EXPERIMENTS

At the first stage we plan to use a FEM with hybrid Bragg resonator which was developed in the recent experiments [1]. Hybrid two-mirror resonator consisting of upstream 2D and downstream 1D Bragg reflectors provides spatial coherence of radiation in a FEL driven by a large-size sheet e-beam [5], [6]. In the ELMI-experiments generated radiation has wavelength $\lambda_0 = 4$ mm with pulse duration up to 0.5 μs. The existence of regimes with high level of the mm-radiation spectral density near the frequency close to one of hybrid Bragg resonator eigen modes during all the pulse has been registered.

One of the typical shots shown in the Fig. 1 demonstrates the FEM operation on the mode with frequency 75.3 GHz. The single mode generation lasts 330 ns.

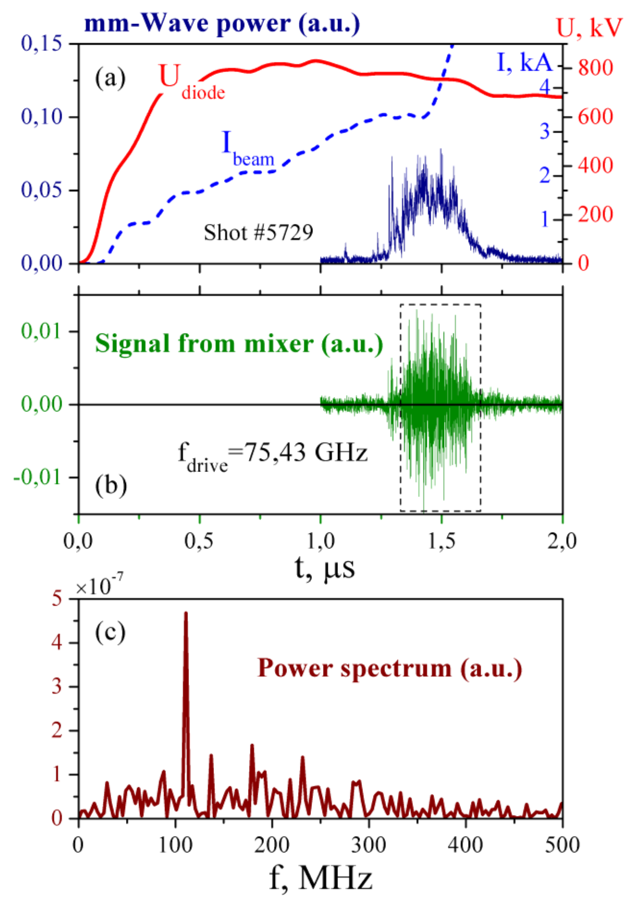

Fig. 1 Single frequency operation of 4-mm FEM: a) diode voltage (U_{diode}), beam current (I_{beam}) and mm-wave power; b) intercarrier frequency signal from heterodyne mixer (heterodyne frequency f_{drive}=75.43 GHz); c) mm-wave power spectrum.

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In a two-stage scheme such mm-radiation as an incident wave should be scattered by the electrons with energy ~1 MeV at the second stage of generation. Using the formula for the double Doppler effect the wavelength of scattered radiation λ will be the following:

$$\lambda = \lambda_0 \frac{(1-\beta\cos\theta_s)}{(1-\beta\cos\theta_i)}, \qquad (1)$$

where $\beta = v/c$ is the electron velocity, θ_i and θ_s — angles of incident and scattered waves with respect to direction of the electron velocity (Fig. 2).

For two cases of back-scattering and 90º-scattering formula (1) gives $\lambda \approx \lambda_0 / 4\gamma^2$ and $\lambda \approx \lambda_0 / 2\gamma^2$ respectively, where $\gamma = 1/\sqrt{1-\beta^2}$ is an electron relativistic factor. The expected wavelengths of the scattered radiation at output of the two-stage scheme are presented in Fig. 2. As it is seen the radiation in the band of 0.1–0.3 mm can be obtained in case of back-scattering of 4-mm radiation whereas 90º-scattering provides radiation wavelength in the band of ~0.2–0.5 mm for γ in the range 2–3.4.

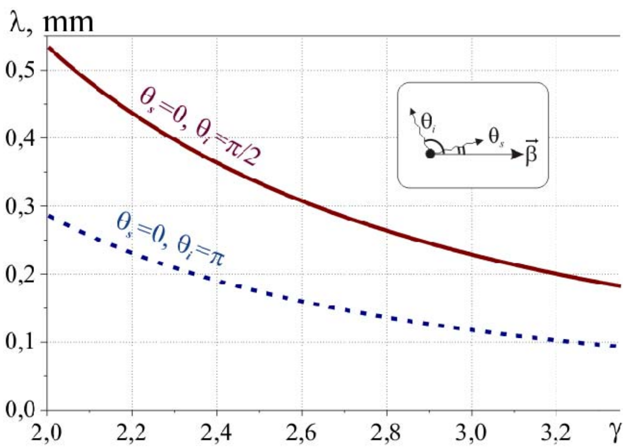

Fig. 2 Conversed wavelength due to scattering of 4-mm radiation on beam electrons as the function of the beam γ-factor

Schematic drawings of experimental realization of sub-mm generator based on two different scattering schemes are presented in Fig. 3 and Fig. 5. For both variants we suppose to use sheet beams with 3–4 mm thickness and 10–20 cm width and a current density more than 1 kA/cm. The e-beams pass the slit channels at presence of longitudinal guiding magnetic field with the strength ~1 T. In the channel #1 of both variants the electrons oscillate in undulator magnetic field and generate 4 mm pump wave. Theoretical studies of planar FEM at ELMI accelerator demonstrates that the electric field strength of 4-mm radiation inside the FEM resonator can amount to 10^5–10^6 V/cm. In Fig. 4 results of simulation of interactivity fields are presented for configuration shown in Fig. 3 (z coordinate is measured along e-beam velocity and 2D Bragg reflector). The 2D Bragg resonator is optimized such a way to increase amplitude of transverse propagating energy fluxes B. These fluxes by connecting waveguides are transported in the channel #2 for pumping electron transverse oscillations.

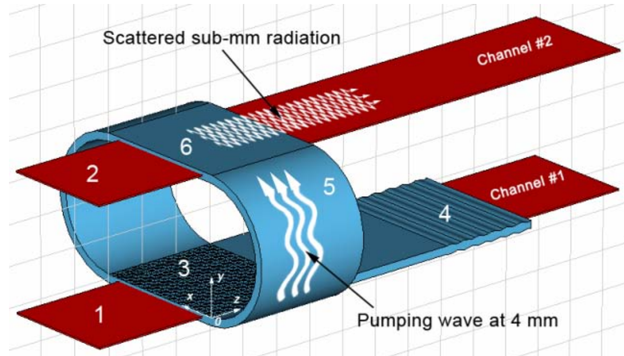

Fig. 3 Scheme of two-stage generation for the band of 0.2–0.5 mm: 1 — sheet REB for driving the planar FEM-oscillator; 2 — sheet REB for mm-wave scattering; 3 — 2D Bragg reflector; 4 — 1D Bragg reflector; 5 — special waveguide; 6 — area of 4-mm radiation scattering on e-beam.

For the first experiments we plan to observe scattered signal amplification in the SASE (self-amplified spontaneous emission) [7] regime in the absence of the resonator (mirrors) for sub-mm radiation. The spatial growth rate for scattered short-wave radiation is given by the expression [8], [9]:

$$\Gamma[\text{cm}^{-1}] = 6.8 \cdot \left(\frac{j_b[\text{kA/cm}]}{\lambda_0[\text{mm}] \cdot b[\text{mm}]} \right)^{1/3} \cdot \frac{a_o^{2/3}}{\gamma}, \qquad (2)$$

where j_b is the linear current density in the second beam, $a_0 = 2.3 \cdot 10^{-8} \lambda_0[\text{mm}] E_i[\text{V/cm}]$ is the pump wave strength parameter, E_i is the pump wave amplitude and b is the gap between the channel plates. For the pump radiation with

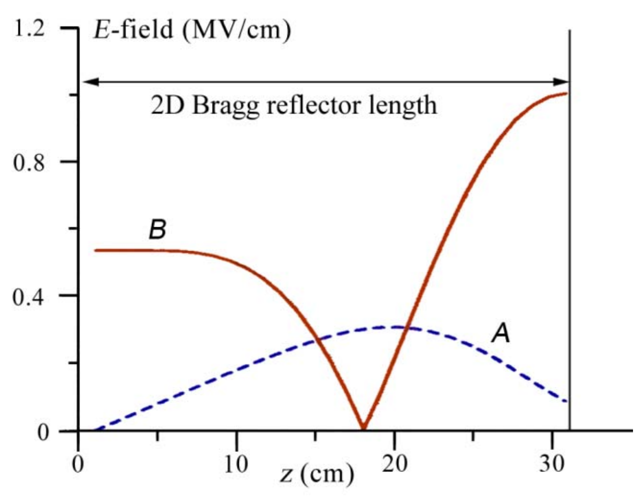

Fig. 4 Results of simulation of 4-mm generation in the 2D Bragg FEM: profile of transverse *(B)* and longitudinal *(A)* propagating partial waves inside 2D Bragg structure.

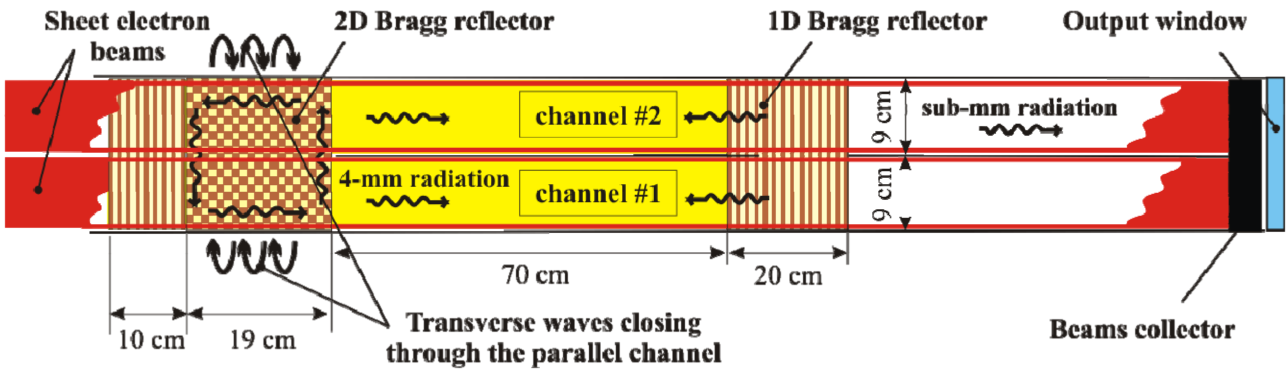

Fig. 5 Scheme of two-stage generation for the band of 0.1–0.3 mm

λ_0=4 mm and E_i =1 MV/cm this parameter is estimated on the level a_0 ~ 0.05–0.1. Thus, for the relativistic factor γ= 3, j_b = 1 kA/cm and b = 10 mm the spatial growth rate of sub-mm radiation is estimated as Γ~ 0.1 cm^{-1}.

Expression for the gain (2) is valid for a "cold" beam with rather small velocity spread

$$\frac{\delta v}{c} << \lambda \cdot \Gamma \approx 0.04 . \tag{3}$$

The required value of the velocity spread can be obtained by an accurate choice of geometry of magnetic field configuration in accelerator diode and an appropriate strength of guiding magnetic field. Analysis of this problem has shown that for experimental conditions of the ELMI-accelerator in order to satisfy (3) we should increase the guiding magnetic field up to 2.5–3 T. In addition to these changes some reconstructions in the accelerator diode and vacuum slit channels should provide appropriate parameters for the first step of two-stage experiments on production of sub-mm radiation in SASE regime. After that it will be possible to use either quasi-optical or some modifications of Bragg resonators to obtain generation regime with corresponding narrowing the radiation spectrum.

One of the problems related with observation of SASE regime in the overmoded waveguide is suppression of interaction with low frequency modes. Such a problem can be solved by using waveguide with variable gap between plates. According to the results of KARAT simulation of 200 GHz SASE (see [2]) the waveguide tapering provides possibility for suppression of low frequency amplification. This result is explained that variation of the waveguide parameters affects more strongly near cut-off modes with the large Brillouin angles.

TWO BEAMS PRODUCTION

As a first step for implementing the two-stage generation scheme we have provided passing of two similar sheet e-beams through the parallel slit channels with the guide magnetic field 1.75 T. The scheme of this experiment was just like one shown in Fig. 5 only that the Bragg resonator has been replaced with the regular planar waveguide. The result of this experiment is shown in Fig. where beams currents measured on the collectors are presented together with accelerator diode voltage. As one can see the traces of beams currents are practically the same. Minor difference can be minimized by varying the cathodes positions in the accelerator diode if required.

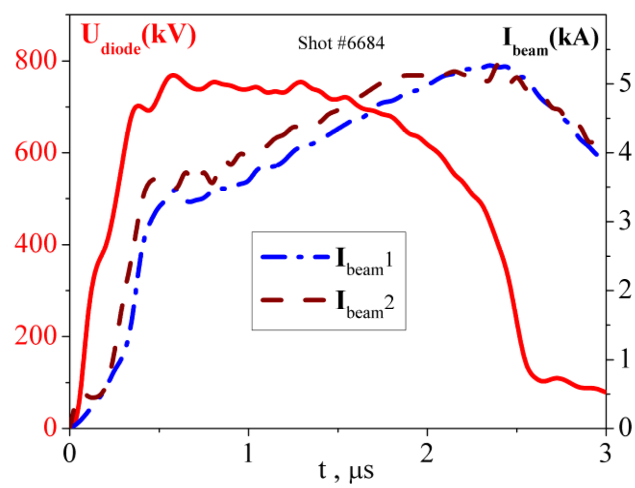

Fig. 6 Production of two sheet e-beams in a common diode with two cathodes and transportation of these beams through the parallel slit channels: U_{diode} — accelerating voltage; I_{beam}1,2 — currents of the beams.

CONCLUSION

Basing on the results of the experiments on generation of 4-mm radiation in a planar FEM together with the results of theoretical investigations and computer simulations, we proposed the submillimeter radiation generator based on stimulated scattering of pumping mm-wave on a high-current sheet REB with electron energy ~1 MeV. Power level up to 1 MW of 100 μm wavelength radiation with 0.1–1 μs pulse duration can be reached by constructing this generator on basis of already operating planar FEM with appropriate technical upgrading at low financial costs. Thus technical implementation of such solution seems to be highly prospective.

ACKNOWLEDGMENT

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