Project of Powerful Broadband FEM-amplifier of 30 GHz Frequency Range

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***Abstract*—Project of powerful 30 GHz FEM-amplifier is developed. With a regular wiggler it would provide 20 MW power in 20% frequency band (grazing regime). Special profiling of the wiggler allows enhance of the output up to 50 MW with simultaneous widening of the band (regime of nonresonant trapping).**

I. Introduction

OVER the past few years, in collaboration between JINR (Dubna) and IAP RAS (N.Novgorod), the FEM-oscillator with Bragg resonator based on induction linac LIU-3000 (0.8 MeV / 200 A / 200 ns / 1 pulse/s) has been realized. At present state, this FEM generates 20 MW / 200 ns pulses at 30 GHz with the spectrum width of up to 6–7 MHz (close to theoretical limit) and high stability of single-mode operating regime. The parameters achieved allow the FEM to be used in several applications, in particular, to study surface heating effects in test cavity which model temperature regime in a high-Q accelerating structure of the CLIC project (CERN) [1].

However, many potential applications of powerful microwave sources require an RF-radiation phase to be controlled. For this purpose, we design the FEM-amplifier project based on LIU-3000. In present paper, the conceptual design and results of simulations of the FEM-amplifier are presented.

Two regimes of wave amplification have been simulated. In the first one, the electrons move along the uniform helical wiggler under the resonance

$$\omega - hv_{\parallel} \approx h_U v_{\parallel}, \tag{1}$$

(ω and h are the circular frequency and the axial wavenumber of the operating wave, $h_U = 2\pi/d_U$, and d_U is the undulator period) with the axial velocity $v_{\parallel}$ equal to the group velocity of the operating wave (so called grazing regime), which results in widening of the amplification band. The second regime is the regime of nonresonant trapping [2], which utilizes tapered wiggler and allows even greater band widening and higher efficiency.

II. Grazing Regime

The parameters of FEM-amplifier simulations are close to ones of the experiments carried out on the base of the LIU-3000 accelerator. In these experiments, the electron is focused by the solenoid with field intensity of up to $H_0 = 0.5$ T. Inside the solenoid, there is an undulator with bifilar winding having a period of $d_U = 6$ cm. Smooth spatial increase of the undulator field is ensured over the first 6 periods by the distributed shortening of the counter-propagating winding currents. In the regular part, the amplitude of transverse undulator field amounts to $H_U \sim$ 0.1–0.15 T. The operating waveguide mode is $TE_{1,1}$.

In the grazing regime, the system parameters provide the coincidence of the axial particles velocity and the group velocity of the operating wave, which equals to $v_{gr} \approx 0.95c$ for the waveguide radius of $R = 0.93$ cm. In this case, the resonance condition (1) is fulfilled in a wide range of frequencies, which ensures the wide amplification band of the FEM.

The simulations results are shown in Fig. 1. For the input power of 30 kW, electron current of 150 A and the accelerating voltage of 0.82 MV, the gain amounts to 25 dB at the saturation length of 1 m in the band of 27–32 GHz, and the maximal output power in the middle of the band reaches 20 MW. Increase of the beam current up to 200 A leads to increase of the gain up to 28 dB and to certain shift of the band to lower frequencies. The initial velocity spread among the particles was taken into account by dividing the beam into fractions having the same energy but different angles of entering the undulator. According to simulations, the efficiency does not decrease for the maximal angle of up to $\alpha_{spr} = 10°$.

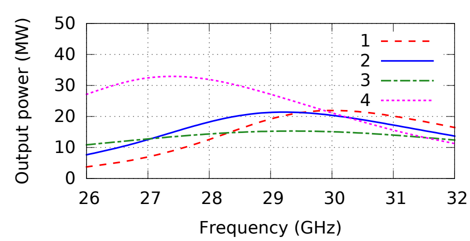

Fig. 1. Output power in the grazing regime for electron current of 150 A and α_{spr} of 5° (1), 10° (2) and 20° (3), and for beam current of 200 A and α_{spr} of 10°.

III. Regime of Nonresonant Trapping

Regime of nonresonant trapping can be realized in a FEM with period, d_U, decreasing along the undulator [2]. In this regime, in the beginning of the interaction the period is greater the resonant one for condition (1) and, thus, the resonance takes place in a certain region inside the undulator. In this region, the particles get trapped by the rapidly increasing wave field and after that are decelerated similarly to more conventional regimes with profiled parameters.

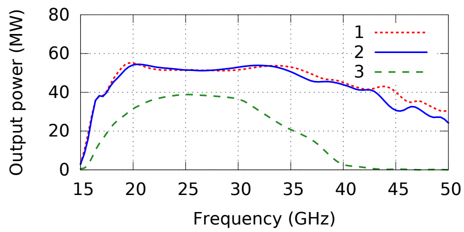

Fig. 2. Output power in the regime of nonresonant trapping for the beam current of 150 A and α_{spr} of 5° (1), , 10° (2) and 20° (3).

The main advantages of the regime are a very wide amplification band and a low sensitivity to the velocity spread. Indeed, the change in the operating wave frequency leads only to shift of the resonance region inside the interaction space, but weakly affects the trapping efficiency. The variations of the axial particle velocities have similar effect. The only demand for efficient trapping is the fast enough increase of the field amplitude in the resonance region, which in turn is determined by the beam current. This means that there should exist a threshold value of beam current from which the trapping and subsequent amplification take place. One more advantage of the nonresonant trapping regime, which is similar to one of conventional regime with profiling, is a relatively high efficiency due to deep deceleration of the electrons in conditions of resonance (1) following the decreasing particles energy. Nevertheless, to obtain such a high efficiency it is necessary to essentially increase the interaction length.

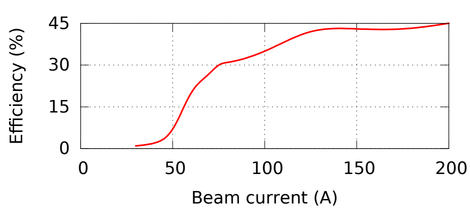

Fig. 3. Dependency of the electron efficiency at the FEM output ($L = 2$ m, $f = 30$ GHz) on the electron current in the regime of nonresonant trapping.

The results of simulations are shown in Fig. 2 and 3. The initial and final undulator periods are chosen to be 8 cm and 3.5 cm correspondingly. The optimal length of the interaction region is increased twice as compared with grazing regime and amounts to 2 m. For the same input power of 30 kW and electron current of 150 A, the gain exceeds 31 dB in extremely wide band, 18–42 GHz, and the efficiency amounts to 35%. Increase of the beam current up to 200 A leads to further increase of amplification gain up to 33 dB inside almost the whole band, and to increase of efficiency up to 40%. Besides, with the increase of the electron current the sensitivity of the scheme to the velocity spread substantially decreases, which is due to dependency of the wave amplitude increment at the stage of trapping of various velocity fractions on the specific currents of these fractions. The threshold total beam current for realization of the regime equals to 50 A (Fig.3).

IV. Broadband RF-Input

To provide effective transportation of the driving signal from 30-GHz range frequency-tunable magnetron into the FEM interaction space a broadband RF-input based on the effect of microwave beam multiplication [3] was designed. This unit makes it possible to provide effective transformation of the input signal into the operating wave of an oversized waveguide over the wide frequency range ($\sim 10\%$) without any obstacles on the electron beam aperture. Results of 3D simulations of the RF-input at the central frequency of 30 GHz are shown in Fig. 4. For this project we plan to use magnetron tunable in the range of 29–31 GHz and we design the RF-input providing signal transformation of more than 90% for the operating $TE_{1,1}$ mode within this band.

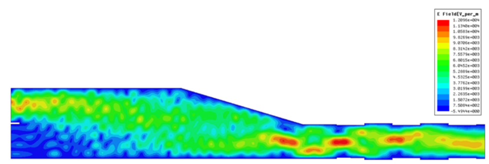

Fig. 4. Schematic diagram and results of 3D simulations of RF-input based on the effect of microwave beams multiplication.

V. Conclusion

The numerical analysis confirms the prospectiveness of using the FEM based on moderately-relativistic electron beams for obtaining high amplification gain (25–30 dB) in wide frequency band (15–20%). It is important that these parameters can be reached in grazing regime in regular waveguide without using special microwave components. Using of specially profiled undulator allows essential increasing of both the gain (up to 33 dB with the efficiency of 40%) and amplification band (up to 80%). The experiments are currently in progress.

Acknowledgment

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References

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