Powerful 60 GHz FEM with advanced Bragg resonator

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***Abstract* — Project of powerful FEM operating from Ka- to W-band and aimed to accelerating applications is developed in collaboration between JINR (Dubna) and IAP RAS (N.Novgorod) based on linac LIU-3000. The key components to advance the JINR-IAP FEM into short wavelengths are short-period tapered wiggler, which is responsible for high-quality helical electron beam formation, and advanced Bragg resonator with feedback loop including quasi-cutoff wave, which improves selectivity of the resonators over transverse coordinates and allows of the FEM operation with strongly transverse oversize of the interaction space. Present paper describes recent results on the FEM-oscillator at 60 GHz frequency range. In the proof-of-principal experiment narrow-band excitation of the FEM with multi-megawatt power level and the frequency belonging to designed feedback loop of the Bragg resonator was obtained.**

I. INTRODUCTION

OPERATING frequencies of linear electron-positron supercolliders of the next generation are discussed currently from 12 GHz and 30 GHz (CLIC, CERN) up to 90 GHz (SLAC). Advance of the colliders to high frequencies with simultaneous reduction of the RF-pulse duration would lead to increase in accelerating gradients while keeping RF-breakdown strength and moderate level of thermal stress.

Up to now powerful narrow-band 30 GHz FEM-oscillator has been realized in collaboration between JINR (Dubna) and IAP RAS (N.Novgorod) based on induction linac LIU-3000 0.8 MeV / 150 A / 200 ns / 1 pulse/s (JINR). The radiation parameters achieved allows JINR-IAP FEM application to study heating stress effect in high-gradient accelerating structures for the CLIC project [1].

The aim of present work in the frame of JINR-IAP collaboration is advance of the FEM into short wavelength bands and development of the prototypes of effective frequency controllable multi-megawatt power generators operating from Ka- to W-bands for potential accelerating applications. We plan to develop original accelerating structures and to power these structures by the FEM radiation. As a result their joint operability at high power level will be demonstrated and physical process of the collider components under the action of strong pulsed RF-fields will be studied in extended frequency band.

To achieve planning frequencies in JINR-IAP FEM we consider shortening wiggler period up to 3 cm (first stage) and increase in the beam energy up to 1.5 MeV, which can be done at LIU-3000 using additional accelerating sections (second stage). Advanced two-mirror Bragg resonator with quasi-cutoff feedback wave would be responsible for provision of narrow-band operation at high frequencies. In this paper we discuss the key components and progress in theoretical and experimental studies of the FEM.

II. "IMPROVED" SHORT-PERIOD WIGGLER

Induction linac LIU-3000 is exploited as a driver in JINR-IAP FEM. Operation in W-band based on this moderately relativistic electron beam requires shortening of the wiggler period up to 3 cm (instead of 6 cm period wiggler used in previous experiments in Ka-band). Enhance in amplitude of the transverse magnetic field in this short-period wiggler alongside with refining its transverse homogeneity was achieved by optimization of the current distribution in the wiggler winding, which was designed in the form of four helical wires over each period: two bifilar wires for two currents of opposite directions (Fig.1). Computer simulations demonstrated that the winding of such type provides high transverse homogeneous of magnetic field when azimuthal angle between two currents of the same direction at the wiggler cross-section is about 55°.

To improve quality of the helical electron beam formation (for operation in short wavelength bands) the slowly up-tapered wiggler entrance was optimized as well. To avoid residual spatial spikes of magnetic field at the wiggler entrance we examined combination of two traditional methods of the winding tapering: (a) to increase distance of the winding from the axis using conical section and (b) to converge opposite current wires to each other. Results of 3D simulations demonstrate that wiggler with such input section is able to provide smooth rise of the magnetic field amplitude without any parasitic spatial spikes (Fig.2a) that coincide well with the data obtained in "cold" tests (Fig.2b).

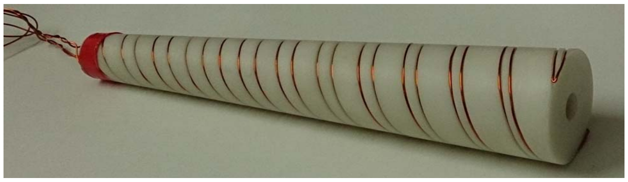

Fig. 1. Photograph of the adiabatically tapered entrance for "improved" short-period wiggler.

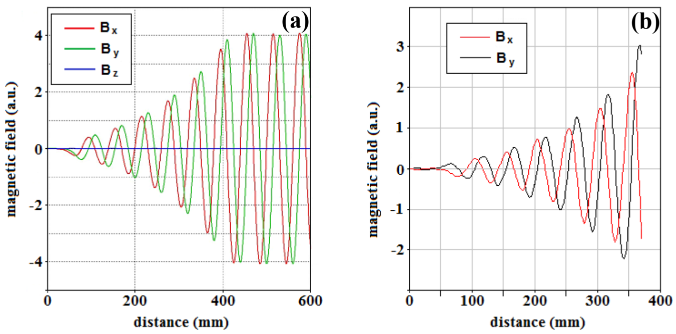

Fig. 2. Results of **(a)** 3D simulations and **(b)** "cold" measurements of longitudinal structure of magnetic field in "improved" wiggler.

III. ADVANCED TWO-MIRROR BRAGG RESONATOR

One more key component for short wavelength FEM is electrodynamic system able to provide stable narrow-band operation in strongly oversize interaction space. To solve this problem we propose to use advanced Bragg structures based on coupling of propagating and quasi-cutoff waves [2]. Implication of the cutoff wave into feedback loop results in mode spectrum purification and improving selectivity over transverse mode index in comparison with conventional Bragg resonators based on coupling of two paraxial waves. Two-mirror resonator scheme with the up-stream advanced Bragg reflector and down-stream conventional Bragg reflector (with rather small reflectivity) allows optimization of the e-beam/RF-wave interaction conditions and decrease in Ohmic losses associated with excitation of the cut-off mode in advanced Bragg structure [3].

For operation at 60 GHz a hybrid two-mirror resonator was designed with advanced up-stream Bragg reflector of 8 cm long having corrugation of 5.3 mm period and 0.3 mm depth, which provides coupling of two counter-propagating waves $TE_{1,1}$ via excitation of the quasi-cutoff wave $TM_{1,2}$, down-stream Bragg reflector of the conventional type of 4 cm long having corrugation of 2.6 mm period and 0.4 mm depth operating via the feedback loop $TE_{1,1} \leftrightarrow TE_{1,1}$ and regular section of about 6 mm in diameter and 20 cm long. Optimization of Bragg reflectors of different types was performed using 3D code CST "Microwave Studio". Results of simulation for the geometry given above are shown in Fig.3.

Simulations of the FEM was conducted using spatial-temporal codes in the frame of original quasi-optical approach of the coupling wave method and demonstrated establishment of narrow-band oscillation regime under designed parameters. With the electron efficiency ~ 7 - 10% the output power can reach ~ 5 - 7 MW and Ohmic losses less than 5% from the radiated power. Simulations show that over full zone of the oscillator self-excitation radiation frequency is close to the frequency of the cutoff wave that provides stability of the oscillation regime in novel FEM scheme.

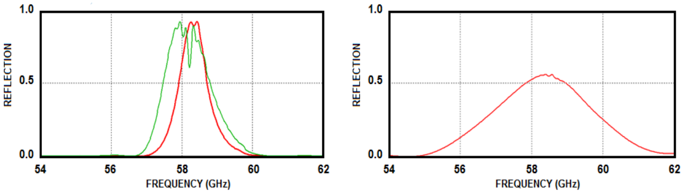

Fig. 3. Results of 3D simulations of reflection of incident $TE_{1,1}$ mode into counter propagating $TE_{1,1}$ mode from **(a)** advanced and **(b)** conventional Bragg reflectors of the length $l_{adv} = 8$ cm and $l_{conv} = 4$ cm (red line in Fig.3a corresponds to corrugation depth $a_{adv} = 0.3$ mm, green line $a_{adv} = 0.4$ mm).

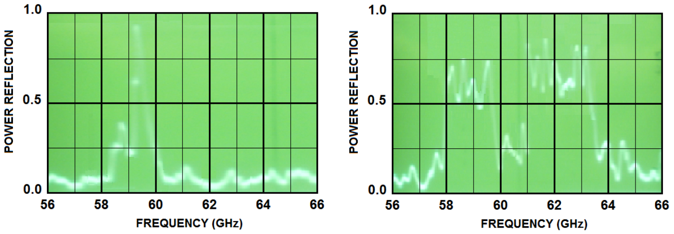

Fig. 4. Results of "cold" tests of **(a)** advanced and **(b)** conventional Bragg reflectors of the length $l_{adv} = 12$ cm and $l_{conv} = 6$ cm.

IV. RESULTS OF THE EXPERIMENTS

Experimental study of novel FEM scheme was performed at LIU-3000. The operating transverse velocity was pumped in 3-cm period wiggler with transverse field of ~ 0.1 T and a reversed guide field of ~ 0.15 T. For the first experimental realization both Bragg structures and regular resonator section were made about 1.5 time longer over the optimal value to increase the resonator Q-factor (to decrease starting current) and to provide fast and certain start of the oscillator.

In accordance with 3D simulations the effective reflection zone in the vicinity of 60 GHz was measured in the "cold" tests (Fig.4). For advanced Bragg structure the reflection band was ~ 0.7 - 0.9 GHz with maximum power reflection more than 90%. For conventional structure power reflection was up to 60% in much broader band. We should emphasize that in conventional Bragg structures some additional ("parasitic") Bragg reflection zones were identified neighboring to operating Bragg zone (in particular, the reflection zone $TE_{1,1} \leftrightarrow TM_{1,1}$ in vicinity of 61 - 64 GHz is shown in Fig.4b). At the same time, in advanced Bragg structure the transverse eigenmodes spectrum is significantly rarefied and no "parasitic" Bragg reflection zones were observed.

In accordance with the simulations stable narrow-band FEM oscillation was obtained in the experiment under designed parameters (Fig.5). Radiation spectrum was measured by means of the cut-off filters set with the accuracy of about 1 GHz and demonstrated the oscillation frequency belonging to the operating feedback loop of the hybrid resonator in vicinity of 60 GHz. With the beam current of about 50 - 70 A the output power (measured by a calorimeter) was amount to 2 - 3 MW that corresponded to electron efficiency of ~ 5%.

The main advantage of the considered FEM scheme is stabilization of the oscillation frequency. This was corroborated by results of the experiment, where oscillation at the designed frequency in the vicinity of 60 GHz was obtained at any wiggler fields from the zone of self-excitation.

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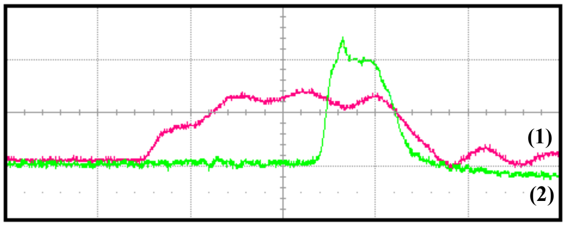

Fig.5. Typical oscilloscope traces in 60 GHz FEM-oscillator: (1) beam current (40 A / div.) and (2) output RF-pulse (1 MW / div.), time scale 100 ns / div.).

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