FEATURES OF FEM FOR TESTING OF HIGH-GRADIENT ACCELERATING STRUCTURES OF LINEAR COLLIDERS*

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Abstract

A millimeter-range FEM oscillator with reversed guide magnetic field and a Bragg resonator was studied as a RF radiation source for collider applications. The configuration with a shift of the corrugation phase is proved to be advantageous. It is demonstrated experimentally that this oscillator is capable of operating at frequencies of ~30 GHz in single-mode regime. The frequency is tuned in interval up to 6%, radiation spectrum width being ~0.1%. The starting mode regime, a novel excitation mechanism was under further study as a possible way to enhance the oscillator efficiency or reduce building-up time of the microwave radiation. Conditions of existence of such regimes are investigated.

1 INTRODUCTION

High-efficiency narrow-band free electron maser (FEM) can be used for the application as pulse microwave power source suitable for testing the high-gradient accelerating structures of electron-positron linear colliders. Such sources must have high enough output power, the narrow radiation spectrum and match the radiation frequency to that of the accelerating structure. FEM oscillator with Bragg resonator with the operating frequency of 30 GHz (corresponding to CLIC collider [1]) is developed and investigated by JINR-IAP collaboration. A feature of oscillator involved is the possibility of precise tuning of the operating frequency. Recent experimental results are presented.

A possible way of enhancement of FEM oscillator efficiency due to employment of additional eigenmode of the resonator is the starting mode regime. Its existence was displayed by Ya.L.Bogomolov and S.N.Vlasov [2] and was shown in simulation in [3]. We investigate the conditions under which this mechanism works in FEM oscillator.

2 PRECISE FREQUENCY TUNING

If an FEM oscillator has a resonator with a shift in the corrugation phase equal to π the fundamental eigenmode is positioned in the centre of the Bragg reflection zone [4]. The frequency of the fundamental mode drifts to the lower edge (or to the higher edge) of the Bragg zone if the phase shift is varied from π to 2π (or to 0).

The FEM oscillator with Bragg resonator is experimentally investigated at JINR using an induction linac LIU-3000 (electron beam energy 0.8 MeV, current 200 A, pulse duration 250 ns). The precise frequency tuning was demonstrated experimentally [5]. It has been achieved by changing the value of the corrugation phase shift due to inserting short rings of different lengths between the Bragg reflectors.

The radiation frequency and spectrum were measured combining two measurement techniques, a narrow-band tunable band-pass waveguide filter and heterodyne mixing. It allowed us to determine the absolute value of the operating FEM frequency with a precision of about 0.1% and obtain precise shape of a RF pulse spectrum.

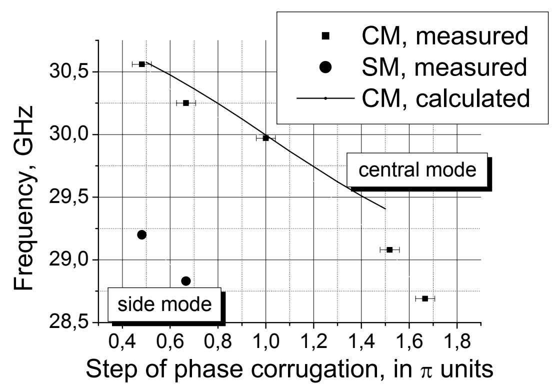

Figure 1: Dependence of the frequencies of the FEM oscillator modes on the value of the corrugation phase shift between Bragg reflectors.

The calculated dependence of the frequency of the central mode (CM) on phase shift between the reflectors is shown in the Fig.1 (upper curve). The experimental data fit to it rather good. The range of phase shift covers most of the Bragg reflection zone of the resonator, so the tuning range of about 6% has been achieved with a precision of about 0.2%. In all regimes the radiation spectrum width didn't exceed 0.1% while the efficiency of generation remained approximately constant.

Besides the central mode, a lower-frequency side eigenmode (SM) of the resonator (positioned just outside the Bragg reflection zone) may also be excited and, indeed, was observed in some regimes at the proper initial mismatches from synchronism (see lower dots in Fig.1). The possibility of its excitation is also confirmed by the simulation results discussed below in Section 3. In contrast, the high-frequency side mode was not observed.

* This work is supported by grants №№ 00-02-17519, 00-02-17232, 02-02-17438 of Russian Foundation for Basic Research and by INTAS grant № 97-32041.
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3 STARTING MODE REGIME

The efficiency of a single-mode oscillator can be increased by increasing the initial mismatch from the beam-wave synchronism up to a certain limit (the boundary of the self-excitation zone). Further the beam-wave coupling becomes too weak and the oscillator doesn't not start up from a noise level.

To obtain more efficient generation, it is expedient to use a "strong excitation" regime (i.e. that of high initial signal). Such a regime can be brought to effect in a resonator for which the eigenspectrum, along with operation mode, contains an additional mode with the somewhat different frequency (particularly, higher for a normal dispersion). Let us define the initial conditions so that the mismatch from the synchronism for the operating mode is beyond the oscillator self-excitation band while the mismatch for an additional mode with higher frequency is rather small. So only the latter mode, named starting one, is available in the spectrum at the initial stage of generation. However the growth of the electromagnetic field in the resonator causes decrease in the beam velocity in the interaction region, which is more favourable for the operating mode.

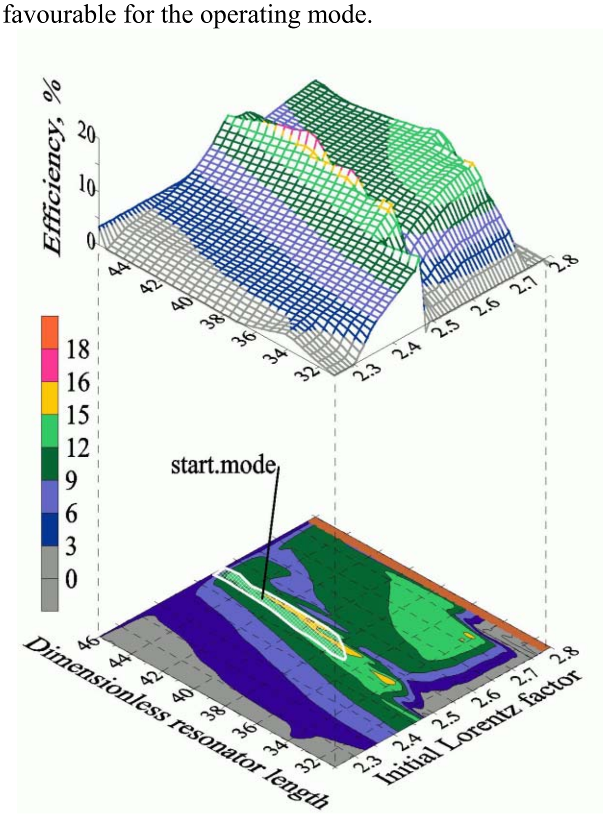

Figure 2: Efficiency of the FEM (regularly corrugated Bragg resonator) versus initial electron beam energy and resonator length of the output Bragg reflector. The feedback coupling factor α = 0.01, guide magnetic field $b_g = -1.2$, wiggler field $b_w = 0.7$ (all values in dimensionless units [3]).

With the excitation of the operating mode the starting mode can be suppressed in the process of non-linear competition. As a result, single-mode regime establishes with an efficiency of energy extraction from the electron beam higher than that could be obtained without excitation of the starting mode (in a single-frequency oscillator).

Here we study the features of the starting mode regime in FEM with a Bragg resonator of two types: 1) regularly corrugated waveguide section; 2) with shift of corrugation phase Δφ = π. A resonator of first type possesses two major eigenmodes positioned at the edges of the Bragg reflection zone: higher and lower frequency (HF and LF). In second-type resonator, along with HF and LF modes, a fundamental one exists in the centre of the Bragg zone (central frequency – CF). First numerical simulations in simple mode of the first-type resonator [3] demonstrated the existence of the starting mode regime and possibility to obtain a considerable gain in the oscillator efficiency.

As the parameter varying the mismatch from the synchronism, the beam initial energy was used (in contrast to the wiggler field amplitude in [3]). It allowed us to reduce the strong effect of the wiggler field changing the beam-wave coupling and therefore to compare the oscillator behavior at two eigenmodes more correctly.

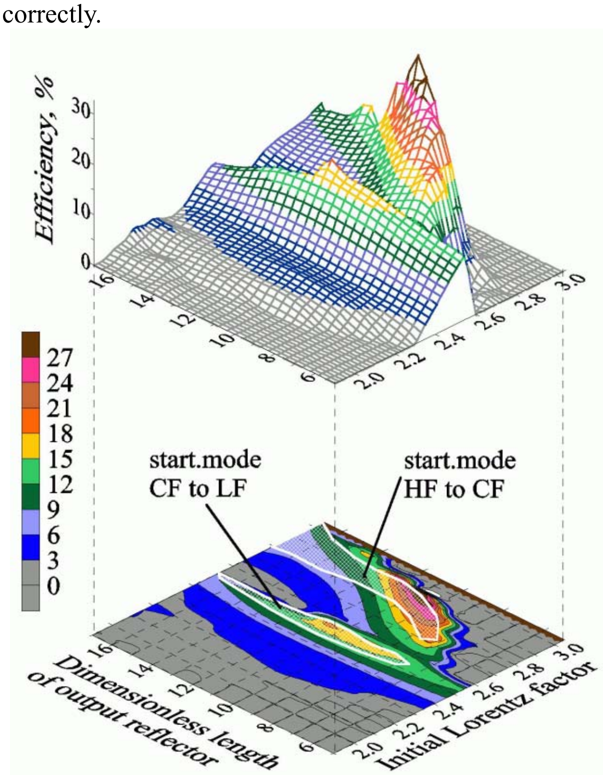

Figure 3: Efficiency of the FEM (Bragg resonator with shift of corrugation phase) versus initial electron beam energy and length of the output Bragg reflector. The input reflector is fixed at the length of $L_1 = 19$, feedback coupling factor α = 0.02, guide magnetic field $b_g = -1.2$, wiggler field $b_w = 0.8$ (all values in dimensionless units).

Numerical simulation was carried out for several values of coupling factor α between forward and backward waves in the resonator at different lengths of Bragg reflectors. This parameter defines both the mirrors reflectivity and the width of the effective Bragg reflection zone (hence, the frequency difference between the resonator eigenmodes). Thus, the neighbour modes may be coupled in different extent. Besides, the Q-factors of eigenmodes depend on α as well as lengths of Bragg reflectors, which were also varied in the simulation.

At a fixed coupling factor α there exists a threshold Q-factor value, over which the self-excitation bands of two neighbour eigenmodes begin to overlap. It provides the conditions of occurring of the starting mode regime. However, too high Q-factors and then the hard intersection of the excitation bands may result in multi-frequency regime where no mode is suppressed in the competition.

Two particular distributions of FEM efficiency for Bragg resonator of both types are presented in Figs.2,3. The coupling factor α for first resonator is chosen twice greater than for the second one because the frequency difference between the nearest eigenmodes becomes approximately the same in both cases. So the comparison of the efficiency dependencies and specifically of the starting mode regimes in both resonators is the most descriptive.

The areas of occurrence of the starting mode regimes are hatched in Figs.2,3. They cover rather narrow ranges in energy, not greater than 0.2 in units of γ. The oscillator demonstrates the peak efficiencies just in the starting mode regimes. In the Bragg resonator with shift of corrugation phase (Fig.3) there exist two separated areas corresponding to radiation jumps of the frequency at different modes.

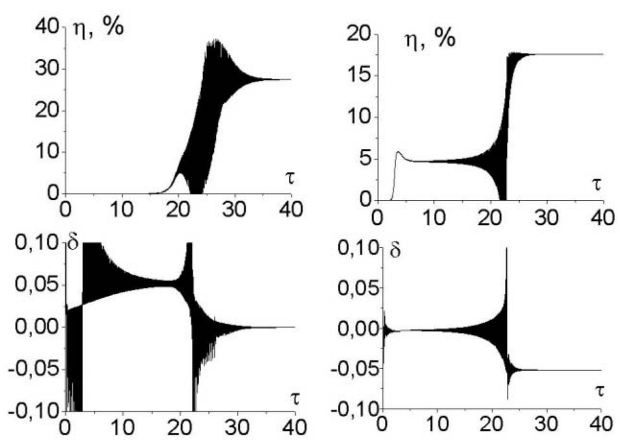

Figure 4: Time dependences of efficiency η and current spectrum of output radiation $\delta = (f - f_0)/f_0$ in the starting mode regime at two different initial mismatches from synchronism. Reflector lengths $L_1 = 19$, $L_2 = 11$, the feedback coupling factor $\alpha = 0.02$, guide magnetic field $b_g = -1.2$, wiggler field $b_w = 0.8$ (all values in dimensionless units). Left: $\gamma_0 = 2.9$ (HF – starting mode, CF – operating mode), right: $\gamma_0 = 2.54$ (CF – starting mode, LF – operating mode).

The highest efficiency is achieved in the resonator with shift of corrugation phase when the ultimate generation establishes at the central frequency (CF) after the excitation of the higher frequency (HF) as a starting mode. Such a regime is illustrated by Fig.4 (left column). Right column in Fig.4 presents a different starting-mode regime (HF to LF) in the same resonator is shown. The efficiency is evidently lower in this case.

Note that single mode regime at the higher frequency in a resonator with corrugation phase shift didn't occur at all. Compared to LF mode having similar Q-factor, for HF mode beam transverse velocity and then beam-wave coupling is lower and excitation conditions turn out to be unfavourable. This fact is in agreement with experiment (Section 2).

The obtained results confirm that the occurrence of the starting mode regime in FEM oscillator requires an optimal intersection of the self-excitation bands of the employed resonator eigenmodes. In order to get that, one have to match the resonator geometry providing suitable combination of the eigenmodes Q-factors and width of the Bragg reflection zone.

4 CONCLUSIONS

It has been demonstrated experimentally that an FEM oscillator with the shift of the corrugation phase is capable of operating at frequencies of ~30 GHz in single-mode regime with the frequency tuning in interval up to 6% at precision of about 0.2%. Over the whole tuning range the radiation possesses narrow spectrum (~ 0.1%), the efficiency of generation remaining approximately constant.

Simulations over wide range of FEM parameters have been performed, areas of existence of starting mode regimes have been determined. Resonator with shift of corrugation phase looks as more preferable configuration. Conditions of the occurrence of the regimes involved are investigated.

5 REFERENCES

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