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# REGIME OF MULTI-STAGE NON-RESONANT TRAPPING IN FREE ELECTRON LASERS*

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*Abstract*

We describe three works united by the idea of the non-resonant regime providing an effective trapping in a beam with a great energy spread. (I) Operability of this regime was demonstrated in the high-efficient 0.8 MeV Ka-band FEM-amplifier. (II) In short-wavelength FELs the multi-stage trapping in several consecutive sections can be organized. We describe efficiency enhancement and improving the frequency wave spectrum in multi-stage SASE and super-radiant FELs. (III) The multi-stage amplification of a single-frequency wave signal can provide cooling of the electron bunch.

## NON-RESONANT AND MULTI-STAGE TRAPPING

A key problem in realization of free-electron lasers (FELs) is a small efficiency at the saturated stage of the electron-wave interaction. The averaged radiation loss in the relativistic Lorentz-factor is determined by the so-called FEL parameter, $\Delta\gamma_{rad}/\gamma_0 \sim \rho$, which is typically $\rho \sim 10^{-3}$ for X-ray FELs [1]. A similar condition limits the admissible energy spread in the electron bunch, $\Delta\gamma_{spread}/\gamma_0 \sim \rho$. A known way to increase the efficiency is the use of trapping and adiabatic deceleration of electrons in a tapered undulator. Due to tapering, the energy $\gamma_{res}(z)$ corresponding to the exact electron-wave resonance decreases slowly with the axial coordinate (Fig. 1 a). A fraction of electrons is trapped by the radiated wave, end energies of these particles decrease together with $\gamma_{res}$. In principle, it is possible to exceed limitation $\Delta\gamma_{rad}/\gamma_0 \sim \rho$ in this scheme, but it is difficult to provide trapping of a significant fraction of the beam, if the limitation $\Delta\gamma_{spread}/\gamma_0 \sim \rho$ is not fulfilled. This is because only electrons being close to the resonance with the wave at the beginning of the interaction can be trapped.

The regime of non-resonant trapping [2, 3] can provide an effective trapping in a beam with a great energy spread. In this regime, the wiggler is profiled in such a way that the electron beam is out of resonance with the operating wave at the beginning of the wiggler, and different electron fractions gradually get into synchronism as the wiggler's period decreases (Fig. 1 b).

Recently, the regime of multi-stage trapping was proposed for FELs and for other types of electron devices [4]. In the multi-stage system, the non-resonant trapping is provided several times in several consecutive sections (Fig. 1 c). In each section only a relatively small fraction of the beam is trapped and pass their energy to the wave. However, repetition of this process from section to section involves in the electron-wave interaction almost all particles of the electron beam.

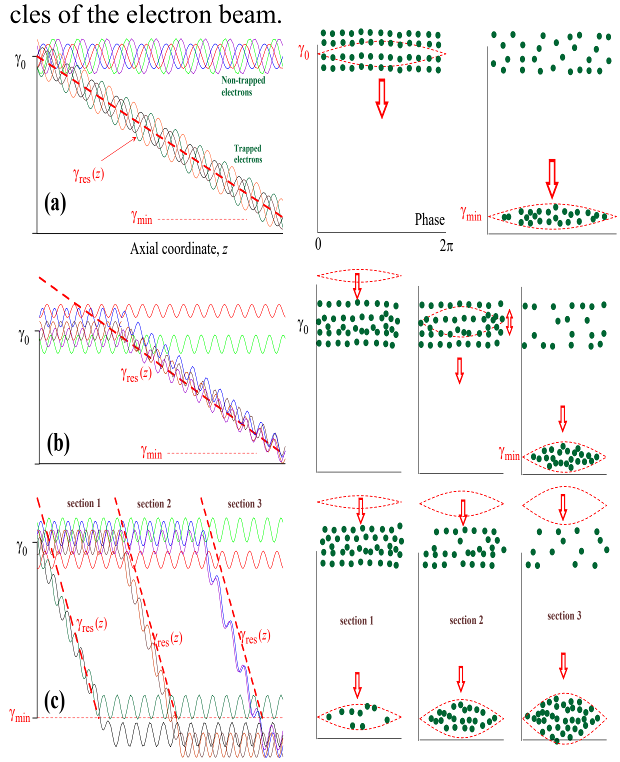


Figure 1: (a) Traditional regime of trapping. (b) Regime of non-resonant trapping. (c) Regime of the multi-stage non-resonant trapping.

## KA-BAND FEM-AMPLIFIERF

The regime of non-resonant trapping has been developed and experimentally demonstrated in Ka-band. In this regime, the wiggler is profiled in such a way that the electron beam is out of resonance with the operating wave at the beginning of the wiggler, and different electron fractions gradually get into synchronism as the wiggler's period decreases.

Examination of this regime in the FEM-amplifier was performed in collaboration between JINR (Dubna) and IAP RAS (N. Novgorod) at the experimental facilities of the linear induction accelerator LIU-3000 [5, 6]. Simulation of the FEM was carried out for the parameters close to the experimental conditions. The regime of a reversed guide magnetic field [7, 8] was chosen; this regime provides a high quality of formation of the helical electron beam in the smoothly up-tapered wiggler.

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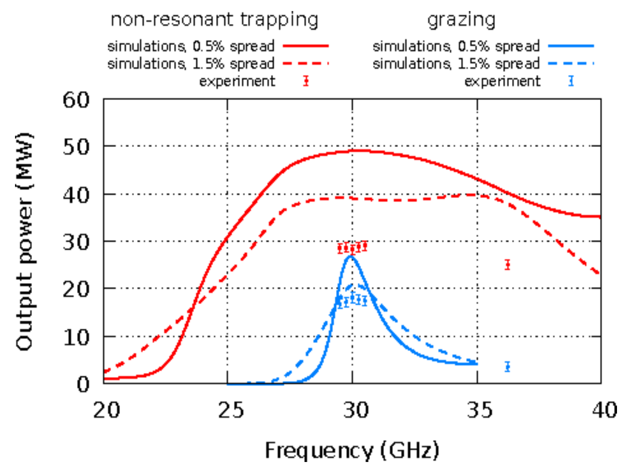

Figure 2: Simulations of the FEM-amplifier: output power versus the frequency for the non-resonant trapping regime (red lines) and grazing regime (blue lines). Experimental results (the output powers measured in the examined regimes) are shown by dots of corresponding colours.

Simulations of the FEM-amplifier were performed in the frame of the model described in [9, 10]. Simulations show (Fig. 2) that the amplification gain is almost independent of the axial velocity spread up to $\Delta\beta/\beta \approx 1.5\%$, which confirms the low sensitivity of the proposed scheme to the spread. For comparison, the more traditional regime of the grazing of dispersion characteristics, which is also capable of providing a relatively wide gain band in an FEM amplifier was studied using a wiggler with a regular winding. In this regime, the axial velocity of the particles is close to the group velocity of the operating wave. Optimization at a central frequency of 30 GHz leads to an output power of 25 MW (a gain of ~35 dB) and a gain band of about ±1 GHz, which is significantly worse as compared to the regime of trapping.

Experiments on FEM amplifiers were based on a 0.8 MeV / 200 A / 200 ns / 1 pulse/s electron beam. Two feeding magnetrons were used: the first one, tunable in the range 29.5–30.5 GHz, and the second one, operating at a frequency of 36.4 GHz. The output power of both magnetrons was attenuated to the same level of 10 kW. In the first experiments, the grazing regime utilizing a regular helical wiggler with a period of 6 cm was studied. As a result, an output radiation power of ~17 MW in 170–200 ns RF pulses was achieved. This power was observed in the whole frequency band of the first magnetron. However, the power decreased down to 3–4 MW, when the second 36.4 GHz magnetron was utilized.

To provide the operation of the FEM amplifier in the non-resonant trapping regime, a helical wiggler of the same length (about 1.5 m) with period profiled from 7.2 cm to 4 cm, was designed. Steady amplification was observed with an output power being noticeably higher than that obtained in the grazing regime. The maximum power amounted to 25–28 MW in 150–200 ns pulses, which had almost the same duration as the beam pulse. It is important that this power level was obtained using both of the driving magnetrons. The parameters of the system were the same when using different feeding sources, which may serve as a kind of modelling of the "instantaneous" amplification band. A comparison of the results obtained in various regimes of the FEM is summarized in Fig. 2. The output power of the FEM in the non-resonant trapping regime exceeds the maximum power obtained in the grazing regime by 1.5 times in the 30 GHz region, and almost an order of magnitude at a frequency of about 36 GHz.

## NON-RESONANT AND MULTI-STAGE TRAPPING

In work [4], the regime of multi-stage trapping was studied for the simplest model of amplification of a single-frequency signal. In this work we show that at definite conditions this regime can be realized in the super-radiant regime and in the SASE regime of FELs (Figs. 3 a and b, respectively). The both regimes represent amplification of initial multi-frequency noise modulation in the operating electron bunch. Figure 4 illustrates sectioned process of amplification of a noise wave signal by a short e-bunch in the regime of the super-radiant FEL. The first section is not tapered, $\gamma_{res} = const$, and the efficiency reaches the saturation in this stage. The use of three tapered sections increases the electron efficiency by an order of magnitude. At the end of the 3rd section, the change in electron energy is approximately the half of the change in the tapered resonant energy, $<\gamma_0 - \gamma> \approx 0.75(\gamma_0 - \gamma_{res})$. This means that ~ 75% of electrons effectively take part in the electron-wave interaction process.

Figure 5 illustrates sectioned SASE FEL process. The first section is not tapered, $\gamma_{res} = const$, and its length corresponds to the saturations of the change in the averaged electron energy, $<\gamma_0 - \gamma>$. The use of four tapered sections increases the electron efficiency by a factor $\approx 25$ At the end of the 5th section, the change in electron energy is approximately the half of the change in the tapered resonant energy, $<\gamma_0 - \gamma> \approx 0.5(\gamma_0 - \gamma_{res})$. This means that ~ 50% of electrons effectively take part in the electron-wave interaction process. It is important also that the process of the multi-stage electron-wave interaction improves the spectrum of the amplified wave signal.

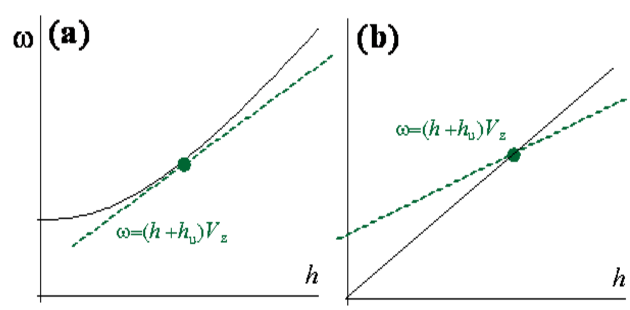

Figure 3: Dispersion diagrams in the regime of super-radiation of a wave packet propagating in a waveguide with a group velocity being equal to the electron velocity (a), as well as in the regime of the SASE amplification of a wave packet propagating in the free space with the speed of light (b).

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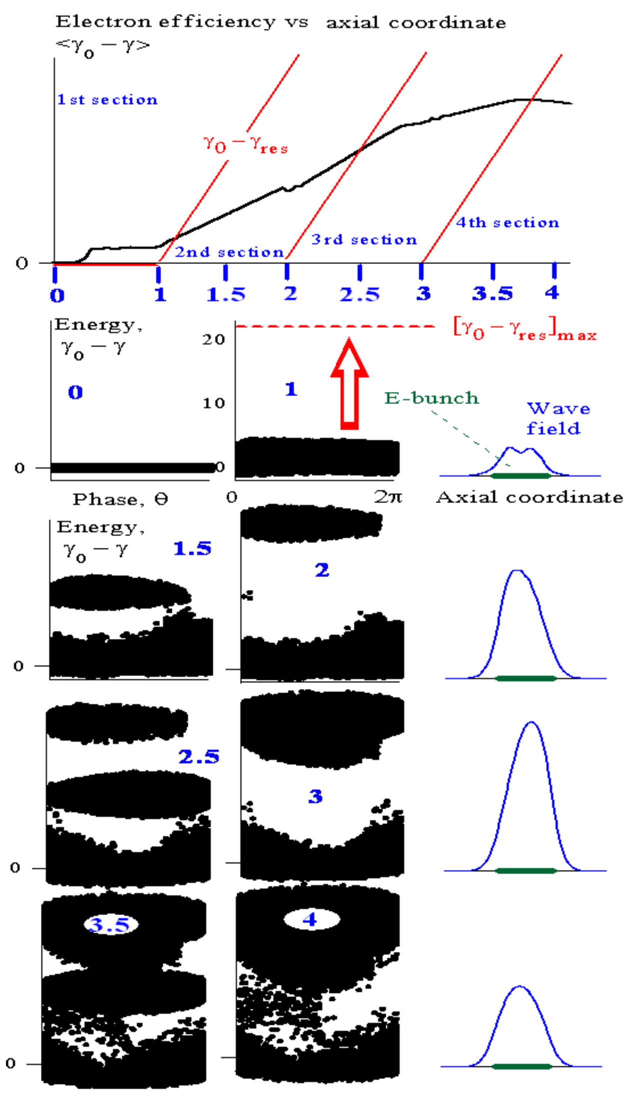


Figure 4: Multi-stage super-radiant process. Averaged change in electron energy versus the axial coordinate, profiling of the resonance energy, distributions of electrons on the energy-phase planes in various parts of the operating region, and distributions of the wave amplitude along the axial coordinate.

## MULTI-STAGE BEAM COOLING

A different way to use the regime of multi-stage trapping is to provide cooling of the electron bunch. In this regime, the electron bunch moves along a cyclic trajectory. At each period of the motion, it passes through an electron-wave interaction system and amplifies there a single-frequency rf-wave signal (Fig. 6). A weak electron-wave interaction is specially provided, so that the initial energy spread in the electron beam is big in the scale of the electron-wave interaction. The tapering of every section is provided such that the resonant energy, $\gamma_{res}(z)$, decreases from maximal initial electron energy down to the minimal one, $\gamma_{max} \longrightarrow \gamma_{min}$. Thus, on the phase plane the "bucket" (corresponding to the resonant electron-wave interaction) at each stage passes the entire electron layer. In this multi-stage process, amplification of the wave leads to the decrease in the energy spread. This can be used for improving of the quality of the operating electron bunched in FELs. If this is true, then this method of the cooling amplification can be an important application of sub-THz relativistic electronics technique.

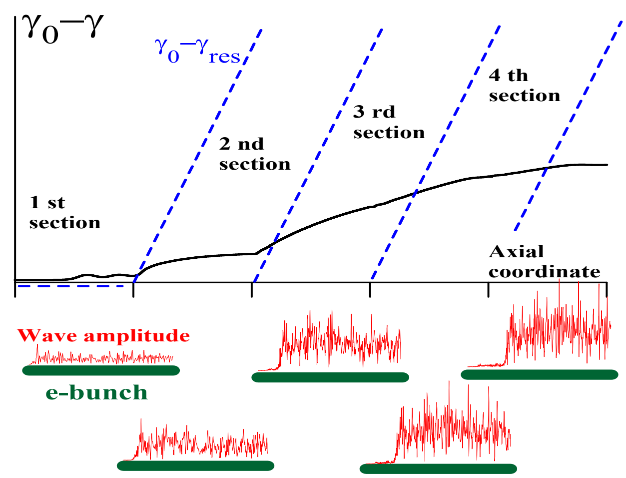


Figure 5: Multi-stage SASE process. Averaged change in electron energy versus the axial coordinate, profiling of the resonance energy, and distributions of the wave amplitude along the axial coordinate inside the electron bunch at outputs of the 1st … 5th sections.

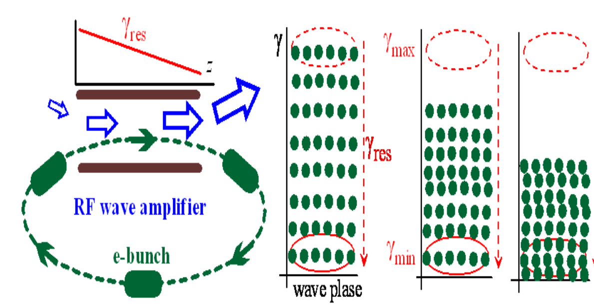


Figure 6: Multi-stage cooling of the electron beam.

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