COMPARATIVE DESIGN OF SINGLE PASS, PHOTO-CATHODE RF-LINAC FEL FOR THE THz FREQUENCY RANGE: SELF AMPLIFICATION vs. ENHANCED SUPER-RADIANCE

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Abstract

Self amplified spontaneous emission and enhanced super-radiance are discussed and compared as possible configurations in the construction of a single-pass, photo-cathode RF-LINAC FEL source for THz radiation, being developed in Ariel University Center of Samaria. Numerical simulations carried out using 3D, space-frequency approach demonstrate the charge squared dependence of the radiation power in both cases, the characteristic typical to super-radiant emission. The comparison reveals a high efficiency of an enhanced super-radiance FEL, which however can only be achieved with ultra-short (the radiation wavelength long or shorter) drive electron beam bunches at a proper energy chirping.

INTRODUCTION

Tera-Hertz radiation is of interest for a basic science, medical and biological applications, spectrometry, remote detection, and etc. Free-electron lasers (FELs), which often can fit on or scale to the size of a table-top, are able to provide intense coherent electromagnetic radiation over a wide range of THz frequencies. In the present work, we consider a *single pass* FEL (without any oscillator resonant cavity) for production of such radiation. The FEL is designed to be driven by trains of short electron pulses, produced by a photo-injector RF-LINAC. The Israeli RF-LINAC FEL project under development is considered here as an example of such a radiation source [1]. Basic operational parameters of the FEL are given in table 1. Two possible configurations of the FEL are considered and compared in the work: a self amplified spontaneous emission (SASE) FEL, and an enhanced super-radiance (ESR) FEL [2]. The following discussion is concentrated just on the processes taking place in the FEL radiator section (wiggler), leaving aside any consideration of other FEL components.

SASE is a well-known FEL configuration, which is widely used at the far ultra-violet and X-ray wavelengths but also at the infra-red and THz frequencies. An initial spontaneous emission of electron beam is self amplified in SASE FELs, giving rise to a non-linear beam-radiation interaction which results in an exponential growth of the emission up to a saturation. ESR FEL [2] is supposed to utilize a constructive energy-phase correlation [3], what enhances the undulator super-radiant emission of short (a radiation wavelength long or shorter) electron pulses. Energy chirping is a well-known technique used in accelerator physics for density compression of electron pulses. In an ESR FEL, it is suggested to cause a longitudinal density compression of short electron pulses just inside the FEL interaction region, i.e. inside the wiggler.

Table 1: Operational parameters of the THz FEL.

Accelerator	
Type:	Photo-injector RF-LINAC
Electron beam energy:	E_k=3÷6 MeV
Pulse duration:	$T_b \gtrsim 0.1$ pS
Bunch charge:	Q_b=30-500 pC
Wiggler	
Magnetic induction:	B_w=2 kGauss
Period:	λ_w=25 mm
Waveguide	
Rectangular waveguide:	15×10 mm^2

THE MODEL

To simulate and compare between both FEL configurations, 3D space-frequency approach [4] was applied. The method is based on an expansion of the high-frequency electromagnetic field in terms of transverse eigen modes of the medium (free-space or a waveguide) in which the field is excited and propagates. The interaction between the electromagnetic field and the gain medium is fully described by a set of coupled equations, expressing the evolution of mode amplitudes along the interaction region. The model was realized in a numerical code WB3D and has been successfully applied to the analysis of various effects in FEL devices [5]-[11].

A drive electron beam pulse is considered in the model as a consisting of charged electron "macro-clusters" distributed over the beam. An initial distribution of the clusters in the beam is of great importance in simulations of radiation emission processes. Random Gauss longitudinal distribution of a fixed number (N_q=300) of equal charges was considered in the present work. Unfortunately this approach produces an artificial level of spontaneous emission, what prevents from a correct description of radiation build-up process. However this model seems to be adequate enough in description of a coherent emission of ultra-short (much shorter than the radiation wavelength) or highly-bunched electron beam pulses. To improve the description of spontaneous emission and of transition effects, the unified model of electron beam short noise from Ref. [12] was also applied to simulate the initial electron beam short noise in a wide frequency range.

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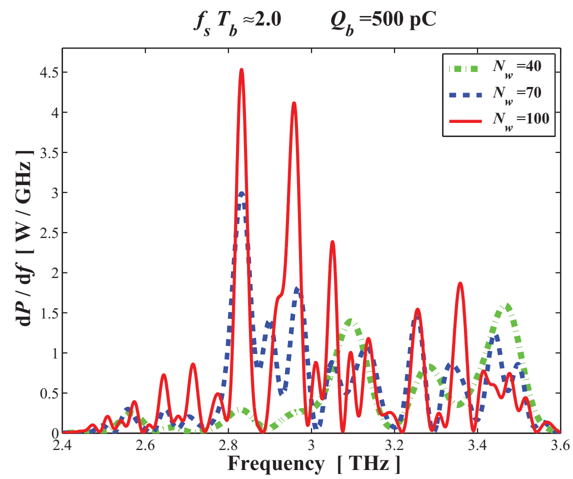

Figure 1: Example of SASE radiation spectrum.

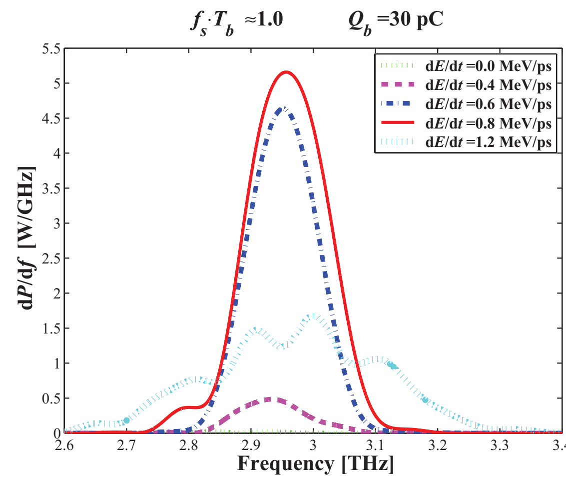

Figure 3: Radiation spectrum of ESR FEL.

THE RESULTS

The simulations were carried out supposing the beam energy of E_k=5.5 MeV, what corresponds to the FEL synchronism frequency of $f_s \approx 2.96$ THz ($\lambda_s \approx 100\ \mu m$).

Typical spectrum of SASE emission is given in figure 1. The example corresponds to the Q_b=0.5 nC electron beam pulse of relative duration $f_s T_b \approx 2$. The unified model of electron beam short noise was applied to simulate an initial distribution of $N_q = 3501$ clusters. Total power of the emitted radiation is demonstrated in figure 2 as function of the wiggler length (in the units of the wiggler's period). The results presented were received in the unified model of electron beam short noise for electron beam pulses of the charges of Q_b=0.1 nC, 0.5 nC, and 1.0 nC. Convergency of the results with the number of macro-clusters considered in the simulations are also shown.

Enhanced super-radiance can be achieved in FELs driven by a train of short electron pulses which are subjected to a controlled energy chirp. Coherent emission of an electron bunch is strongly depressed if the bunch is about the radiation wavelength long or longer. Energy chirp gives rise to a longitudinal density compression of the bunch just while it propagates along the wiggler, enhancing super-radiance [2]. We consider such FEL configuration as a competitor to SASE in construction of compact FELs for the Tera-Hertz frequency spectral range. Simulations of ESR FEL were carried out supposing the L_w=1 m long wiggler (N_w=40 periods); a shorter wiggler can actually be taken, depending on the initial beam pulse duration, and on the energy chirp rate. Figure 3 demonstrates the radiation spectrum of ESR FEL, obtained in the example of the beam charge of Q_b=30 pC, and of the initial relative beam pulse duration $f_s T_b \approx 1$. A proper choice of the energy chirp rate ($\frac{dE}{dt} \gtrsim 0.6$ MeV/ps in the example given) provides a remarkable increase in the total radiation power (about two orders of magnitude) as one can see in the picture. This energy chirp rate level means the total energy variance during the beam pulse of $\frac{\Delta E}{E_b} = \frac{1}{E_b}\frac{dE}{dt}T_b \approx 3.6\%$. Such energy chirping can be achieved in RF-LINAC FEL scheme by means of some phase de-synchronization of the accelerated electron pulses relative to the accelerating electromagnetic wave in the RF-LINAC cavities, similar to the application of the "phase-matching" section within the FEL beam line [3]. Figure 4 shows dependence of the radiation power on the energy chirp rate used.

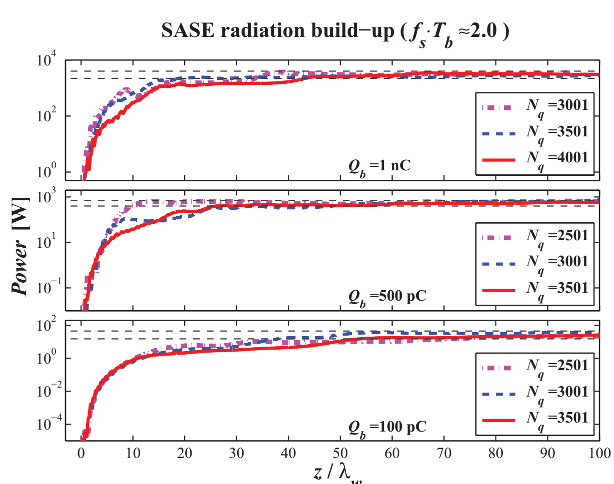

Figure 2: SASE FEL power build-up.

Radiation power obtained in the both FEL configurations considered is presented in figure 5 as a function of the beam charge. Up to considerably high beam charges where space-charge effects reduce a coherent emission, the power in both FEL configurations seems to grow linearly with the beam charge squared what is characteristic to super-radiant emission process.

CONCLUSIONS

Simulations of SASE FEL with initial random Gauss distribution of macro-charges seem to overestimate the saturation power and the saturation length. The unified model of

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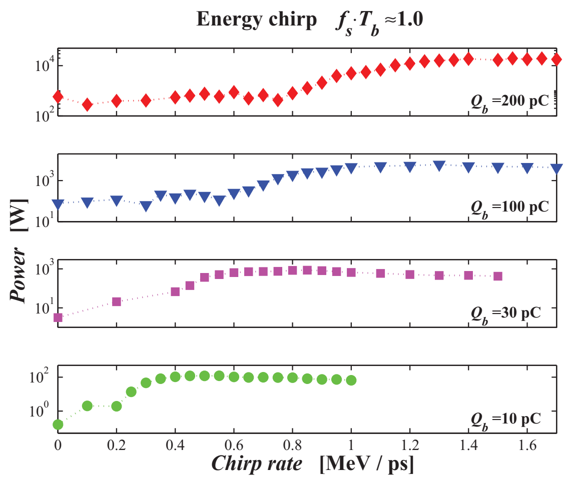

Figure 4: ESR FEL power dependence on the chirp rate.

electron beam short noise [12] is applied instead to a more realistic description of an initial spontaneous emission of noisy drive beam (short noise) and of the transition radiation build-up process. In contrast, nearly the same results were received in simulations of ESR FEL in both models. This difference can be explained by a much stronger bunching taking place in ESR FEL (bunching factor of about 5-6% in comparison with more than 90% at SASE and at ESR FELs, respectively). In ESR FEL, most of the radiation is emitted coherently at the moment of a maximum density compression of the beam pulse; spontaneous emission has a negligible effect at this moment.

A considerably long (about 100 periods) wiggler is required for a SASE FEL in order to enable saturation. The beam bunching is found to be rather weak, and the power of the emitted radiation is much lower than that of ESR FEL driven by electron bunches with similar charges. Spectrum of SASE emission includes a number of narrow peaks,

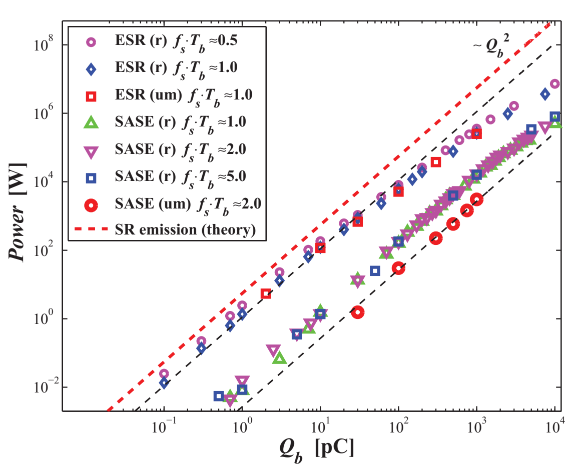

Figure 5: Radiation power of ESR and SASE FELs as a function of the beam charge.

competing each other at saturation. At the range of the beam charges considered, the power of saturated SASE emission is found to demonstrate a super-radiant proportionality to the beam charge squared.

An ESR FEL utilizes short (the radiation wavelength or shorter) electron bunches with a controlled energy chirping. Train of such bunches can be obtained by means of a photo-injector RF-LINAC enabling some phase desynchronization of the accelerated electron pulses relative to the accelerating wave. At a proper chirping, ESR FEL is found to provide a high beam bunching, promising a high efficiency of such radiation source. Unfortunately, destructive space-charge forces emerge to reduce ESR FEL efficiency if overcharged bunches are applied. To overcome this limitation, low-charged bunches at a higher bunch repetition rate can be used. Concluding, ESR FEL seems to be a perspective concept for construction of a photo-injector, THz spectral range RF-LINAC FEL being under development in AUC in cooperation with UCLA.

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