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A Far Infrared Super Radiant FEL

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Abstract The basic physics, results of 3–D simulations, and relevant parameters for the design of a far infrared FEL, which operates in the SASE superradiant short bunch regime, are presented. It is shown that a quite interesting device can be easily developed, with rather new features, producing coherent laser pulses with ~10 psec duration and around 7 MW peak power.

Keywords Free-electron lasers · SASE · GENESIS 1.3 · BRAFEL

1 Introduction

The Free Electron Laser, FEL, is a radiation source that differs from conventional lasers due to the fundamental underlying physics and two principal properties of their output: tunability and range of frequency operation. Whereas conventional lasers have a small range of tunability, this range can be very large in the FEL both in theory and in practice. The FEL also operates very well at the extremes of the spectrum where conventional lasers either cannot operate or generate only relatively low powers: for far infrared, $\gtrsim$100 micron, and for short wavelengths, from ~10 nm to 1 Å.

Decreasing the operational wavelength of an FEL increases considerably both the costs and required technology. Recently developed projects at 1 Å can be expected to cost in excess of 1 billion USD. On the other hand far infrared FELs, such as BRAFEL (Brazilian Free-Electron Laser) proposal, require much simpler technology with costs of the order of 1 million USD.

Here we propose to build a novel far infrared radiation source, referred to as BRAFEL, working in the Self Amplified Spontaneous Emission (SASE) short bunch superradiant regime, to generate tunable, coherent radiation pulses from 40 to 200 μm, with peak power levels in the MW range and time duration around 10 psec.

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2 The concept of High Gain SASE Superradiant FEL

The BRAFEL proposal consists of three main components: A photo-cathode electron source; a Radio Frequency (RF) accelerating structure and a permanent-magnet undulator, sometimes also referred to as a 'wiggler'. The photo-cathode generates pulses of electrons which are subsequently accelerated in the RF accelerator to relativistic velocities. Following the accelerator, these pulses are injected into the undulator where they are forced by the periodic transverse magnetic fields to undergo a transverse 'wiggling' motion, causing the electrons to radiate independently in the forward propagation direction into a narrow cone of angular width ~γ^{-1}, where γ, is the electron beam relativistic factor. This independent emission is the undulator spontaneous synchrotron emission. However, for sufficiently high beam currents, and with other properties satisfied, an exponential growth of the initial radiation power may develop as the electron beam propagates along the undulator. This exponential growth then saturates yielding radiation powers many orders of magnitude greater than the initial spontaneous radiation. This is the high gain FEL interaction [1]. In the absence of an injected signal, the FEL gain process starts from the spontaneous emission and is called the Self Amplified Spontaneous Emission regime (SASE) [2]. An inherent problem with SASE is that the spectrum and temporal structure are chaotic; the output power being dominated by random spikes in both the temporal and Fourier domains. However, if the electron bunch is sufficiently short in comparison to the interaction cooperation length [3], a single superradiant pulse is generated with power proportional to the square of the number of electrons in the pulse, N. BRAFEL is designed to operate in this regime called SASE short-bunch superradiant emission [3]. Note that short-bunch superradiance should not be confused with coherent spontaneous emission (CSE) [4]. In CSE the electron bunch is shorter than or of the order of the resonant radiation wavelength, and electrons immediately begin to radiate in phase from the start of the FEL interaction with power scaling as N^2. Furthermore, in CSE there is no exponential growth of the radiation. Superradiance is a more complex, cooperative process in which the electron pulse is longer than the wavelength but shorter than or of the order of the interaction cooperation length. The radiation power initially scales as N increasing exponentially to N^2 dependence. Superradiance is a spontaneous process induced by the collective radiation reaction between electrons.

3 Relevant parameters

The spontaneous radiation has a wavelength given by

$$\lambda_r = \frac{\lambda_u\left(1 + a_u^2\right)}{2\gamma^2}, \tag{1}$$

where: λ_r is the resonance wavelength, λ_u is the undulator period, γ is the Lorentz factor, i.e., the electron energy in units of mc^2, and a_u is the undulator parameter given by

$$a_u = \frac{e\overline{B}_u}{mck_u}, \tag{2}$$

where $\overline{B}_u$ is the RMS magnetic field strength of the undulator and $k_u = 2\pi/\lambda_u$. It is seen from Eq. (1) that the FEL is easily tuneable by changing the resonant energy γ and/or a_u.

Tuning via a_u is usually achieved by variation of $\overline{B}_u$ alone, what can be done by altering the gap between the magnet poles of the undulator.

We assume the electron beam consists of a series of individual bunches of rms length l_e.

A fundamental parameter determining the electron beam quality is the normalized emittance which must satisfy the inequality

$$\varepsilon_n \leq \frac{\gamma\lambda_r}{4\pi}. \tag{3}$$

An undulator with curved or canted pole faces provides a uniform focusing channel for the electrons in the transverse plane, such that there is an equilibrium beam radius and the envelope of the electron beam is a constant given by

$$\sigma_e = \sqrt{\frac{\varepsilon_n\lambda_u}{\sqrt{2}\pi a_u}}. \tag{4}$$

Radiation diffraction takes place on the scale given by the Rayleigh range

$$Z_R = \frac{4\pi\sigma_e^2}{\lambda_r}, \tag{5}$$

where σ_e is the RMS radius of the radiation. Under ideal conditions, Z_R should be sufficiently large so that diffraction losses are negligible and 1–D FEL theory will be a good approximation to the FEL performance. It will be seen that this cannot be readily achieved in BRAFEL and 3–D simulations are therefore required.

The dynamical properties of a high gain FEL are governed by the fundamental FEL parameter [1]:

$$\rho \approx \frac{5.7 \times 10^{-3}}{\gamma_r}\left(\frac{I\lambda_u^2 a_u^2}{\sigma_e^2}\right)^{1/3} \approx 10^{-2}\frac{a_u}{\gamma_r}\left(\frac{I\lambda_u}{\varepsilon_n}\right)^{1/3}, \tag{6}$$

where we have used the relation for the beam radius of Eq. (4).

The rate of exponential growth is governed by the gain length which depends upon ρ as:

$$l_g = \frac{\lambda_u}{4\pi\rho}. \tag{7}$$

The high gain FEL regime is obtained when the undulator length $L_u > l_g$.

The ρ-parameter also gives a limitation for the initial uncorrelated energy spread which must be satisfied to achieve a good growth rate:

$$\frac{\Delta\gamma}{\gamma} \leq \rho. \tag{8}$$

4 Self amplified spontaneous emission

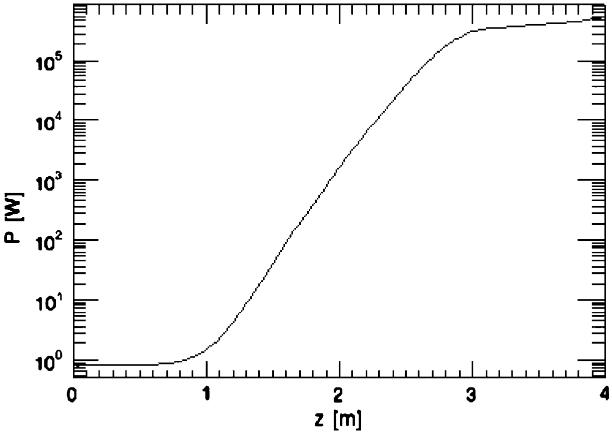
SASE operation of a FEL may be characterized by the following properties:

- Start up is from noise (spontaneous emission)
- Temporal structure and spectrum governed by the cooperation length

  $l_c = \lambda_r / 4\pi\rho$

- Superradiant (SR) spikes have a power $P_{Rad} \propto N^2$
- The number of spikes is given by $N_s = l_e / 2\pi l_c$

Fig. 1 Average power in the radiation pulse as a function of distance through the wiggler.



Hence, the FEL interaction may be characterized into 2 regimes depending upon the electron bunch length: ‘long bunches’ where $N_s >> 1$, and is characterized by incoherent random spiking (e.g. the x-ray FEL projects at DESY, Hamburg and LCLS Stanford); and short bunches where $l_e \leq 2\pi l_c = \lambda_r/2\rho$ characterized by a single SR spike emission with $N_s \approx 1$ and a ‘clean’ coherent spectrum.

BRAFEL will operate in the high gain SASE short bunch superradiant regime.Note that, because $\rho << 1$ in the short bunch limit, the bunch must be sufficiently longer than λ_r to exclude CSE effects.

Typical parameters suggested for BRAFEL are as follows:

$$\gamma = 17, \Delta\gamma/\gamma = 0.1\%, a_u = 1, \lambda_r = 104\mu\text{m}, \lambda_u = 3\text{cm}, \sigma = 0.367\text{mm}, \varepsilon_n = 20\ \pi\ \text{mm mrad},$$
$$I_p = 200\text{A}, Q = 1\ \text{nC total charge}, Z_r = 1.7\text{cm}, \rho = 0.037, l_g = 6.5\text{cm}, l_c = 203\mu\text{m}.$$

3D simulations using the GENESIS code [5] were performed with these parameters and the results are presented in the sequel.

In the set of figures we show the radiation power and spectrum at different positions along the wiggler. It is seen that the exponential regime starts at ~1 m and saturates at ~3 m, with a peak radiation power of ~7 MW.

Fig. 2 Temporal shape of the radiation pulse power as a function of local distance s at saturation z=3 m.

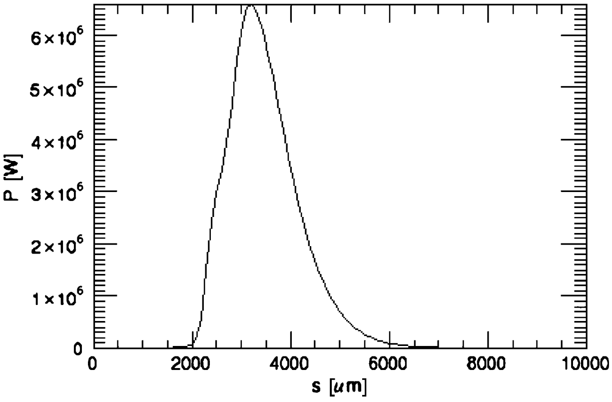
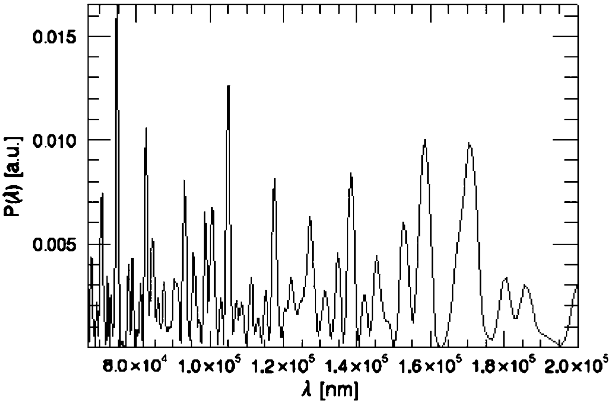


Fig. 3 Spectral power density of the radiation as a function of radiation wavelength at the beginning of the interaction, z<1 m.



From the Figures (1, 2, 3, 4), one can see the evolution from the noisy temporal power and spectrum at the beginning of the interaction z<1 m, to a well defined pulse power of peak ~7 MW and spectrum centered at ~110 μm at the saturation length of z=3 m.

3D simulations have also been performed with different parameter sets shown below at beam energy of γ=25. With these parameters tuning of the radiation wavelength was demonstrated from 48–240 μm, by altering the wiggler parameter. In all cases the following parameters were held constant (at the same value of the γ=17 case): the electron bunch charge at Q=1 nC; the normalized emittance at 20 π mm mrad; and the peak current I_P at 200 A.

A summary of the results for the two cases of γ=17 and γ=25 is shown in Table 1.

For the electron bunch energy of γ=17, the saturation length is ~3 m and for bunch energy of γ=25 the saturation length is closer to ~2 m. In all cases the temporal duration of the radiation output at saturation ranges between 5 and 10 psec.

Fig. 4 Spectral power density of the radiation as a function of radiation wavelength at saturation z=3 m.

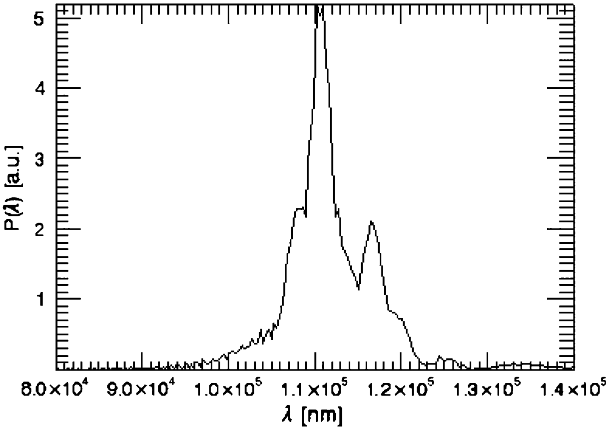


Table 1 Summary of the Genesis 3D simulation results.

γ	a_w	$\lambda(\mu m)$	$\sigma(mm)$	$Z_r(cm)$	ρ	$L_g(cm)$	$L_c(\mu m)$	Peak Power(MW)
17	1	104	0.367	1.7	0.037	6.5	230	7
25	1	48	0.367	3.5	0.025	10	153	13
25	1.7	94	0.282	1	0.043	5.6	174	33
25	3	240	0.212	0.24	0.075	3.2	254	9

5 Conclusions

In conclusion, we have shown that using an electron gun which provides a Gaussian electron pulse with peak current of ~200 A, and total charge ~1 nC, with a modest normalized emittance of ~20 π mm mrad, such as generated by a typical photocathode system, and using only a few meters of wiggler it should be possible to generate far infrared coherent superradiant pulsed output with peak powers up to ~33 MW and time durations between 5–10 psec. With these characteristics the BRAFEL project will provide a FEL radiation source with new and useful properties both from a physical and technological perspective.

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