A TEST OF SUPERRADIANCE IN AN FEL EXPERIMENT*

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Abstract

We describe the design of an **F**EL **A**mplifier **T**est **E**xperiment (FATE)[1] to demonstrate the superradiant short bunch regime of a Free Electron Laser in the 1 - 3 μm wavelength range starting from noise. The relevance to the LCLS X-ray FEL [1] proposal is discussed and numerical simulations are shown. It is numerically demonstrated for the first time with the 2-D code GINGER, that clean-up of noise in the superradiant regime occurs even at low power levels.

1 INTRODUCTION

Following a suggestion by R. Bonifacio and L. De Salvo, SSRL has been working on the design of an experiment to study the Physics of Self Amplified Spontaneous Emission (SASE) and to explore one of the most important factors: the appearance of superradiant spikes [2]. The design is based on an existing electron source, the SSRL injector for SPEAR. It consists of a low emittance thermionic RF gun, an alpha magnet for bunch compression and three linac sections to provide electron energies between 30 and 110 MeV. The FATE development group considered building a 6 - 8 m long undulator with a period length of 2.5 - 3.6 cm. Measurements as well as numerical simulations of the electron acceleration and transport in the gun to linac beamline indicate that the system should be capable of producing electron bunches with a normalized emittance of 20 to 30 mm mrad, a gamma spread of $\Delta\gamma = 0.4$, and a peak current of 150 A at a total rms bunch length of 240 fs. This gives access to a range of optical wavelengths between about 1 and 10 μm. To be able to detect the longitudinal profile of the optical pulse, we focus on the 1 to 3 μm wavelength range, where highly sensitive solid state devices are available.

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[1] FATE is no longer an active proposal. We will therefore refer to the experimental idea as “FATE-type experiment” in this paper.

2 SUPERRADIANCE

For the proposed experiment, the slippage length L_s is larger than the bunch length L_b. The steady state approximation is no longer adequate for the treatment of the FEL interactions. Slippage has to be taken into account and the FEL will operate in a different, *superradiant* regime of cooperative emission [3].

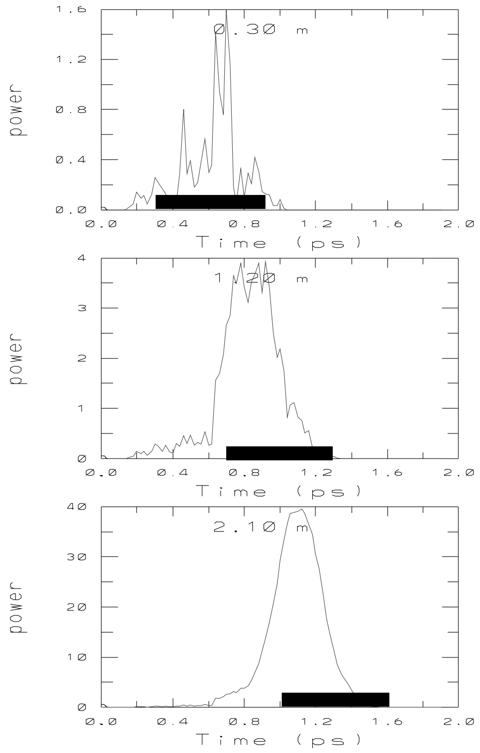

Figure 1: GINGER simulation showing the development of the optical pulse at 3μm. The frame moves at the speed of light. Leading parts of the pulse are shown to the left. The horizontal bar indicates the position of $\sqrt{2\pi}\sigma_s$ of the electron bunch as it falls behind the optical pulse due to slippage.

In this regime the so called clean-up of the spectrum is expected, i.e., the appearance of a single radiation spike will be observed at the end of the undulator. The peak power of

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the spike scales as n_e^2, while the total power scales as $n_e^{4/3}$ as in the steady state regime. n_e is the electron density.

The simulation shows that this clean-up occurs already at an early stage of the amplification process even if the startup is a random series of chaotic spikes at the beginning of the undulator (see. Fig. 1).

The physics of superradiance is new and unexplored. Theory [2] predicts that a single radiation pulse, starting from noise, will develop with peak intensity scaling as the square of the electron current. From a fundamental viewpoint, in the super-radiant regime, the electrons do not radiate by stimulated emission, but by "cooperative spontaneous emission." This is defined as a regime where the electrons radiate coherently because of self-bunching, but the strong slippage inhibits re-absorbtion and saturation. A FATE-type experiment is in a position to demonstrate for the first time this new and unexplored phenomenon in FEL physics.

A FATE-type experiment is of basic importance for the future development of FEL physics and technology in the short wavelength region, i.e. that region of the electromagnetic spectrum where mirrors are not applicable.

In a long bunch (like in the LCLS), the electron pulse breaks into cooperation length regions each radiating a super-radiant spike, independently. Only the envelope, or the total energy, follows roughly the steady state regime. Thus the basic physics of the radiation process is the super-radiance spiking in both the short and long bunch regime, when starting from noise.

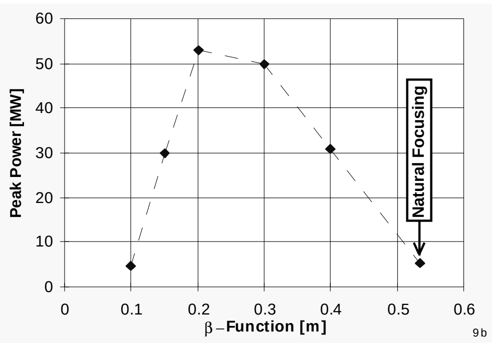

Figure 2: Focusing optimization for planar undulator at 8 m (3 μm).

3 UNDULATOR

For FATE, the undulator was a pure permanent magnet, a NdFeB Halbach-type device with transversely canted poles. In this scheme, canting the poles gives focusing in the horizontal at the expense of focusing in the vertical. Since a Halbach undulator has natural focusing in the vertical, one can obtain half that focusing strength in both the vertical and horizontal, by canting the magnets only a few degrees. One can also arrange a canting strategy that effects a FODO lattice of alternate gradient quadrupole fields.

As indicated in Figure 2, stronger focusing gives much more power output, but it also causes sausaging of the electron beam, which is not fully accounted for in the GINGER simulations. In the FATE design one or two meter sections of undulator would be built, with beam position monitors and dipole correctors between them, so that walk-off errors could be offset.

4 OPTIMIZATION OF THE FATE PARAMETERS

Based on the time dependent 2-D FEL code GINGER [4] an extensive optimization of the FEL parameters has been carried out for both helical and planar undulators. The parameters studied for a range of optical wavelengths λ_r (1 - 3 μm) include the peak current $\hat{I}$ (50 - 250 A), the normalized emittance ϵ_n (10 - 40 mm mrad), the bunch length L_b (80 - 240 fs), the undulator period λ_w (2.5 - 3.6 cm, and 7.7 cm), and external focussing $\beta_{x,y}$ (0.1 - 0.55 m/rad). Table1 lists the optimized FEL parameters. For cost reasons, a planar device was chosen even though a helical device would perform better.

Table 1: FATE parameter list for a 3μm planar wiggler.

Period Length	λ_w	3.0 cm
Magnetic Field	$\hat{B}_w$	1.0 T
Focussing	$\beta_{x,y}$	0.2 m / rad
Emittance	ϵ_n [2]	20 mm mrad
Electron Beam Size	$\sigma_{x,y}$	195 μm
Electron Energy	E	80.5 MeV
Peak Current	$\hat{I}$	250 A
Bunch Length	L_b	240 fs
Coopertion Length	$2\pi\ L_c$	1008 fs
	$L_b/2\pi\ L_c$	0.24
Periods	N_w	270
Pierce Parmeter	ρ	0.0099
	$\lambda_w/4\pi\sqrt{3}\rho$	13.9 cm
Saturation Length	L_s	9 m
Saturation Power	P_s	30 MW

5 UNDULATOR ERROR ANALYSIS

The influence of undulator magnetization and steering errors on FEL performance has been studied using the FRED-3D[5] code, which simulates interaction between the electron beam and the optical field in the undulator of an FEL amplifier. Even though the code does not handle startup from noise and short bunch effects, we expect the results of the error analysis to be relevant for the FATE parameters. The random walk can be partially corrected in FRED-3D by introducing "steering stations", at which the position of the electron beam is measured and a transverse momentum kick is applied to steer the electron beam onto the axis at

[2] The 20 mm mrad expected from the thermionic rf gun is marginal for 3 μm operation. If smaller emittances at similar peak current levels could be obtained, smaller optical wavelength would be accessible.

the next steering station. The position measurement is assumed to be imperfect, with specifiable errors in the accuracy with which the beam position monitors are aligned and the accuracy with which they can measure the beam position. The field errors are chosen from a truncated Gaussian distribution. Fig. 3 shows the effect of random fluctuations of the on-axis peak magnetic field on the relative peak FEL output power after 8 m undulator length when using steering stations separated by 2.0 m for rms steering errors of 50 μm, 200 μm and 2250 μm. The figure shows that the power drops by about a factor of two for a 0.2 % rms field error and small steering errors of 50 μm and 200 μm. The performance drops practically to zero for steering errors as high as 2250 μm.

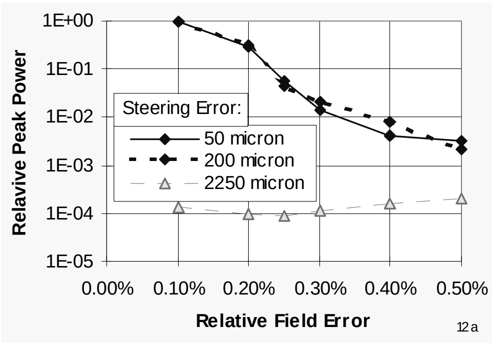

Figure 3: Relative peak power vs. the rms field error.

Fig 4 shows the effect of steering errors for a relative rms field error of 0.2 % with a steering station separation of 2.0 m. Steering errors as high as 0.5 mrad can be tolerated before the performance drops by a factor of two. This does not constitute a real constraint because much tighter tolerances could be satisfied.

6 DIAGNOSTICS

To measure the energy of the FATE output, we planned to use a PbSe detector with detectivity $D^* \approx 10^9$ at room temperature, with which we could see a pulse of as little as 1 nJ of 3 μm radiation. The sensitivity of solid state devices drops as the wavelength increases. Measurements of power would give us evidence of superadiant amplification, but do not reveal the temporal structure of cleanup. Since the FATE pulse is shorter then 1 psec, we do not expect streak cameras to be fast enough. Instead, there are interferometric techniques, such as FROG (Fourier Resolved Optical Gating) [6]. In this technique, the radiation is passed through an interferometer, doubled in frequency with a non-linear crystal, and dispersed onto a 2 dimensional detector, such as a CCD or videcon. The Fourier transform of the resulting pattern yields the pulse shape as a function of time. However, for single shot measurements, about 100 nJ would be required. Below 2.2 μm, doubled to 1.1 μm, an inexpensive silicon CCD could be used, but for 3-4 μm radiation, doubled to 1.5-2 μm, a more costly InGaAs CCD would be necessary, though videcon tubes might also work. It would be difficult to detect cleanup at longer wavelength. There are new, more efficient doubling crystals, like quasi phase matched lithium niobate, that might reduce significantly the energy detection threshold.

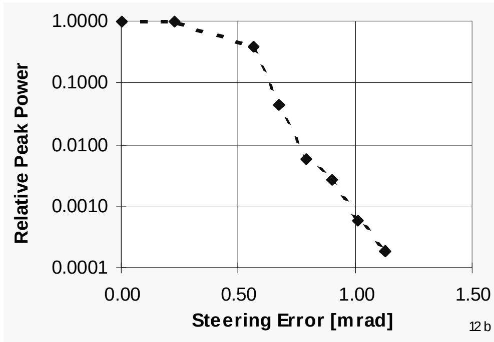

Figure 4: Relative peak power vs. the rms steering error, using 0.1 % relative field error and 2 m steering station separation.

7 CONCLUSION

We have studied the development of the peak power of superradient pulses starting from noise for a range of radiation wavelengths, electron beam currents and electron emittances. The influence of the electron beam parameters, undulator field errors and steering errors on FEL performance for the proposed FATE project has been examined. The parameters of the FATE undulator are optimized to get a resonable peak power for the superradient pulses. The results indicate that the clean-up of the longitudinal optical beam profile into a single superradient pulse occurs even in the case of very small output power.

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