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THE 'FRESH-BUNCH' TECHNIQUE IN FELS*

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ABSTRACT

The 'Fresh Bunch' technique is being proposed as a method of increasing the gain and power of FEL amplifiers in which the length of the optical radiation pulse is shorter than the length of the electron bunch. In a multi-stage FEL, electron beam energy spread is increased by the FEL interaction in the early stages. In the 'Fresh Bunch' technique, the low energy spread of the electron beam is recovered by shifting the radiation pulse to an undisturbed part of the electron bunch, thus improving the gain and trapping fraction in later stages. A test case for the application of the Fresh Bunch method is demonstrated by numerical simulation. In this particular example we examine a subharmonically seeded VUV Free-Electron Laser. We begin with the generation of harmonic radiation, which takes place over one part of the electron bunch. Then the radiation is shifted by means of a strong dispersive section to a fresh part of the bunch for exponential amplification and tapered wiggler amplification. By starting over with a new ensemble of electrons, the energy spread introduced by the bunching in the fundamental is removed, leading to an increased gain. Furthermore, it is possible to use a much stronger seed in the fundamental without incurring the penalty of a large energy spread later on. We note that more than a single application of the 'Fresh Bunch' method may be done in a single FEL multiplier-amplifier. Thus x-ray wavelengths may be reached by successive multiplication in a chain of FEL amplifiers starting from a tunable seed laser.

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1. INTRODUCTION

In this paper we present a method which leads to significant improvements in the gain and power of multi-stage FELs. This technique can remove the energy spread of the electron beam induced by the FEL interaction in an early stage and thus improve the gain and trapping fraction in later stages.

The principle of this technique is quite simple: The FEL radiation pulse is shifted relative to the electron beam, discarding electrons whose energy spread was increased due to the FEL interaction. It is assumed that the radiation pulse is shorter than the electron bunch length.

This assumption is satisfied in FEL amplifiers (including harmonic generation) which are seeded by a radiation pulse which is shorter than the electron bunch length. Naturally, using a seed which is shorter than the electron bunch means that the whole electron bunch is not used at all the stages of the FEL. However a radiation pulse which is shorter than the electron bunch is sometimes desirable. The overall efficiency is not reduced by the use of a smaller fraction of the electron beam. The large increase in output power per electron guaranties that the FEL will deliver more power for the given electron beam power.

The FEL interaction must generate an energy spread in the electron beam. In a few situations, the interaction may generate an undesirable energy spread. One example is detrapping in a tapered wiggler following an untapered section with an exponential growth. Another is harmonic generation in the FEL [1], [2], [3]. In this case we generate a large energy spread by the bunching of the electron beam at the fundamental frequency using the seed laser. While this energy spread is necessary for the bunching, it degrades the performance of the FEL amplifier section at the harmonic frequency.

The 'Fresh Bunch' technique is used to restore the energy spread in the following way. We begin the FEL operation by positioning the interaction region near the tail of the electron bunch. In the example given above of a laser seeded bunching section, the seed laser pulse will be timed to overlap with the tail end of the electron bunch. Once the initial operation, (in this case the generation of the harmonic radiation), is done then we retard the electron bunch relative to the radiation. This is done by passing the electron beam through a dispersive section of a suitable power so as to delay the electrons by a time equal to at least the length of the radiation pulse. This is equivalent to moving the radiation to an undisturbed, or 'fresh' part of the electron bunch. At this point the radiation starts interacting with a new set of electrons, which have the energy spread as it was before the injection into the FEL, since they did not participate in the previous interaction.

In doing so we gain by wiping out the energy spread which was introduced during the bunching at the fundamental. However we also lose the spatial bunching at the harmonic. This bunching can be recovered relatively fast since a) the radiation is intense and b) a dispersive section may be used to reduce the lethargy distance. We shall demonstrate that there is a net gain in performance which makes the Fresh Bunch technique worth considering.

The Fresh Bunch technique can be applied more than once in a single FEL, provided that the electron bunch is long enough. For example we can do multiple harmonic generation operations to reach x-ray wavelength in an FEL amplifier which is seeded by a conventional tunable laser. After each harmonic generation we shift the radiation to an undisturbed part of the electron bunch thus increasing the gain of the short-wavelength FEL sections. The advantage of this approach over a Self Amplified Spontaneous Emission FEL is in the narrow bandwidth of the generated radiation and in the much shorter wiggler length (since the seed laser can have a very high power). The advantage over an FEL oscillator at the short wavelength is in the elimination of the oscillator's cavity mirrors and in the larger wavelength stability.

THE MODEL FEL

In order to demonstrate the 'Fresh Bunch' technique, we shall present the results of numerical simulations of a model FEL. We establish a 'baseline' case which is the proposed UV-FEL User's Facility at BNL [3]. This baseline is fully optimized in terms of the input laser power, wiggler section lengths, degree of tapering, etc. Setting out from this case we shall proceed to evaluate two additional FEL schemes which use the Fresh Bunch method. The electron beam and wavelength parameters which are common to all three cases are given in Table 1.

In all the cases we input radiation from a seed laser. We assume that this radiation is provided by a conventional, tunable laser which is multiplied by non-linear materials to the visible or near UV. For the purpose of the computation we shall use a single wavelength taken as 3000 Å .

Figure 1 shows a schematic diagram of the FEL system. The radiation and electron beam enter the first wiggler section, (bunching section) which is used to energy modulate the electron beam. This is followed by a dispersion section to produce spatial bunching. Following the dispersion section the beam and (possibly amplified) seed radiation enter wiggler sections which are resonant with the third harmonic of the seed radiation, i.e. 1000Å .

In the harmonic parts of the wiggler the seed radiation plays no role and is diffracted out of the electron beam. The bunched beam proceeds to radiate coherently at the harmonic. This process is characterized by a fast quadratic growth of the radiation power vs. position in the wiggler.

At this point the Fresh Bunch method follows a different course than the baseline case. In the baseline case there is a continuous transition into an exponential amplification. In the Fresh Bunch case the bunching is maximized and the radiation reaches saturation rapidly. Then the saturated coherent radiation is shifted to overlap with an undisturbed ('fresh') part of the electron bunch. This is possible if the electron bunch is longer than the seed radiation pulse. In doing so we lose the spatial bunching at the harmonic wavelength which has been established in the used part of the bunch. This spatial bunching must be re-established in order to proceed with the exponential growth, leading to a lethargy length of wiggler. However we also get rid of the energy spread created by the bunching process in the fundamental.

From this point on the Baseline and Fresh Bunch cases follow the same path. After the exponential growth has saturated we enter a tapered wiggler section to extract additional power from the electron beam.

The structures of the wigglers with all the relevant parameters are given in Table 2. In the baseline case we have made no distinction between the coherent radiation section and the exponential section, since there is a smooth transition from one to the next. Thus the length of both is lumped into the exponential section.

The two cases of Fresh Bunch differ in the amount of input seed laser power. The baseline FEL is optimized in terms of the input laser power, which is 4.2 MW while the first section of the wiggler is 2 m long. A larger seed power would reduce the output power of the FEL due to the large energy spread which is generated at the bunching stage. In the Fresh Bunch cases this limitation no longer applies. Thus we have calculated two cases. In one, the input seed power is essentially the same, 6 MW. To take advantage of the method the bunching wiggler is increased in length to 3.5 m, in order to amplify the seed laser power and produce a stronger bunching. The second Fresh Bunch case uses the same bunching wiggler length as the baseline case and a much larger seed laser power, 42 MW.

The numerical simulation of the FEL was done using the TDA code [4]. This code models the single-pass amplification process in a FEL. It allows for the treatment of the fully three-dimensional electron dynamics, thus taking into account the transverse betatron motion as well as the longitudinal bunching of the electrons. The paraxial wave equation that governs the growth and the diffraction of the self consistent radiation field (assumed to be axisymmetric), is discretized in the radial direction by the finite difference method. The TDA code uses the Runge-Kutta method to solve the coupled equations of electron motion and radiation field evolution. It has been modified to carry out the calculation of the harmonic generation and tested extensively against analytical models [5].

The results of the simulation are summarized in Figure 2. which displays the FEL radiation power on a logarithmic scale as a function of position. The solid line represents the baseline case, [3], [5] with the 3000Å seed at 4.2 MW. The long dash line is the Fresh Bunch case with 6 MW and the short dash line is the Fresh Bunch case with 42 MW seed input power. The origin of the position axis in Fig. 2 is the beginning of the 1000Å wiggler, thus the bunching section and the bunch shifter section are not shown.

All three cases have been optimized. The optimization procedure is described elsewhere [5]. The parameters which are optimized are the seed laser input power and Rayleigh range, the strength of the dispersive section, the taper start position and rate of tapering. The basis for the comparison is an equal wiggler length for the 1000Å section (11 m in all cases) and the same wiggler performance (field and period). The three cases also share the same input electron beam energy, current, emittance and energy spread. The wiggler wavelength and the electron beam energy were chosen to optimize the baseline case and were not changed for the Fresh Bunch case. The beam β function is matched to the wiggler.

The division of the 11 m short wavelength wiggler into its various functional subsections (e.g. the position at which to begin the taper) and the degree of tapering has been done for each case separately. Most significantly, the seed laser input power of the baseline case is optimized. Additional laser power results in less power at the end of the FEL due to an increased energy spread and less input power result in the same but as a result of impaired bunching.

Fig. 2 exhibits four distinct regions in the power vs. position curves. Different radiation growth mechanisms are at work in these regions and it is instructive to identify them. These regions are: 1) Coherent radiation growth; 2) Energy modulation and spatial modulation of the 'fresh' bunch (only in the Fresh Bunch cases); 3) Exponential growth; 4) Tapered section.

The first, rather steep region, is where the coherent generation of radiation takes place. The electron beam enters this region with a strong spatial modulation (at the fundamental wavelength of 3000Å) and the radiation builds up fast. This region is about 2 m long in all three cases.

The second region is a lethargy length which follows the radiation shift operation of the Fresh Bunch technique. This region is obviously missing in the baseline case. Incidentally, this region may be made shorter by the introduction of a dispersive section (an optical klystron technique). We have elected to leave it for the sake of simplicity. It is difficult to pinpoint the exact length of this region. It starts in a clear near zero growth which is about 1 m long, then changes smoothly into exponential growth.

The third region is the exponential growth region. In our calculations the transition point is optimized to yield maximum power at the end of the FEL. In the baseline case the length of the harmonic generation and exponential sections adds up to 7 m. This would make the exponential section roughly 5 m long. In both of the Fresh Bunch cases, the length of the lethargy and exponential region add up to about 2 m.

The fourth and last region is the tapered wiggler, which has been chosen somewhat arbitrarily to be 4 m long in the baseline case. The lengths in the Fresh Bunch cases were chosen such that the total wiggler length in the 1000Å section is equal to that of the baseline.

In conclusion we see that the Fresh Bunch technique results in a considerable gain in power. Alternatively, for a given output power it will result in a significantly shorter wiggler length.

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Table 1. Beam and Radiation Parameters of the FEL Simulation.

Parameter	Value	Units
Electron Beam		
Energy, γ	490	
Current, I	300	Amperes
Normalized rms emittance, ϵ_n	8×10^{-8}	π m radians
Energy spread $\delta\gamma/\gamma$ (FWHM)	0.1	Percent
Radiation		
Input wavelength λ_i	3000	Å
Output wavelength λ_s	1000	Å

Table 2. System Parameters of the FEL Simulation.

	Baseline	Fresh Bunch 1	Fresh Bunch 2
Seed laser power (MW)	4.2	6.0	42
Bunching section			
Wiggler period (cm)	3.5	3.5	3.5
Peak magnetic field (Tesla)	0.765	0.765	0.765
Length (m)	2	3.5	2
Dispersive section			
Magnetic field (Tesla)	0.28	0	0
Length (m)	0.2	0	0
Coherent radiation section			
Wiggler period (cm)	NA*	2.2	2.2
Peak magnetic field (Tesla)	NA*	0.749	0.749
Length (m)	NA*	2	1.5
Bunch shifter section			
Peak magnetic field (Tesla)	NA	0.8	0.8
Length (m)	NA	0.6	0.6
Exponential section			
Wiggler period (cm)	2.2	2.2	2.2
Peak magnetic field (Tesla)	0.749	0.749	0.749
Length (m)	7	2	2.2
Tapered section			
Wiggler period (cm)	2.2	2.2	2.2
Initial peak field (Tesla)	0.749	0.749	0.749
Length (m)	4	7	7.3
Total field taper (%)	1.2	1.6	2.0
TOTAL WIGGLER LENGTH (m)	13.0	14.5	13.0
1000Å WIGGLER LENGTH (m)	11.0	11.0	11.0

*) In the baseline case the coherent radiation section is not distinguished from the exponential section and its length is included in the exponential section entry.

FIGURE CAPTIONS

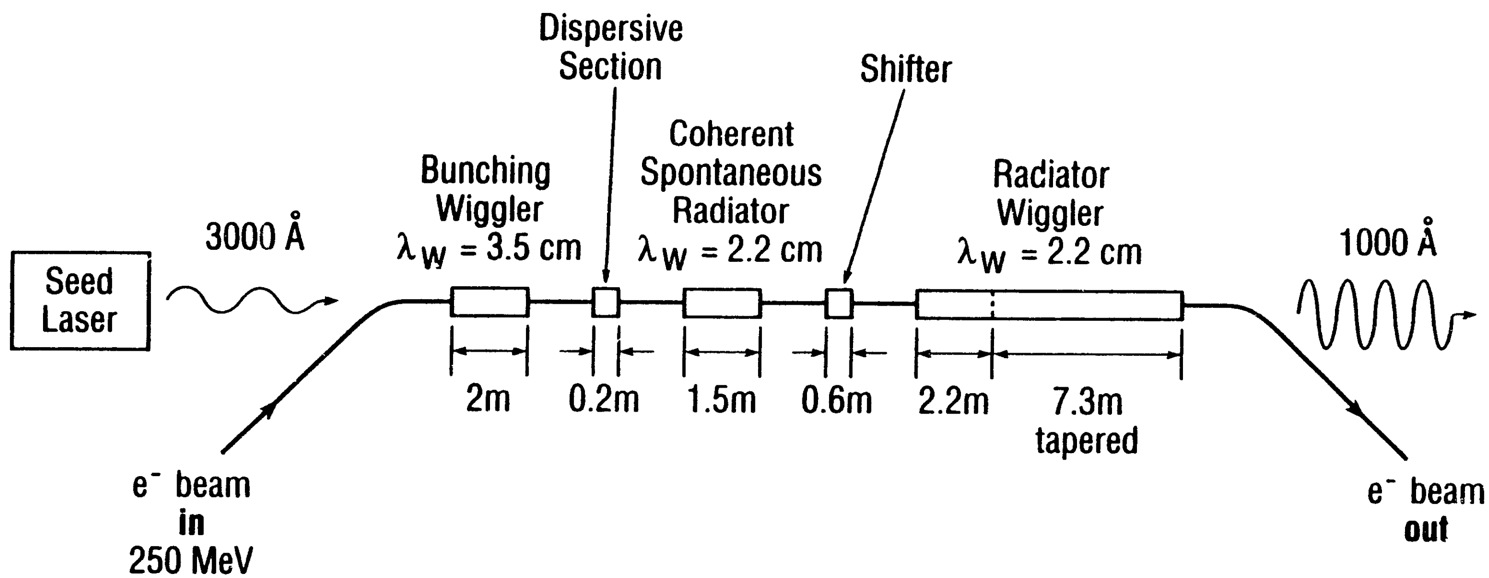
1. Schematic diagram of the FEL system.

2. Logarithm of the radiation power along position in the wiggler of the 1000 Å section for the three FEL cases.

a. Baseline calculation (no Fresh Bunch) and 4.2 MW input power,

b. Fresh bunch case 1 (6 MW input power),

c. Fresh Bunch case 2 (42 MW input power).



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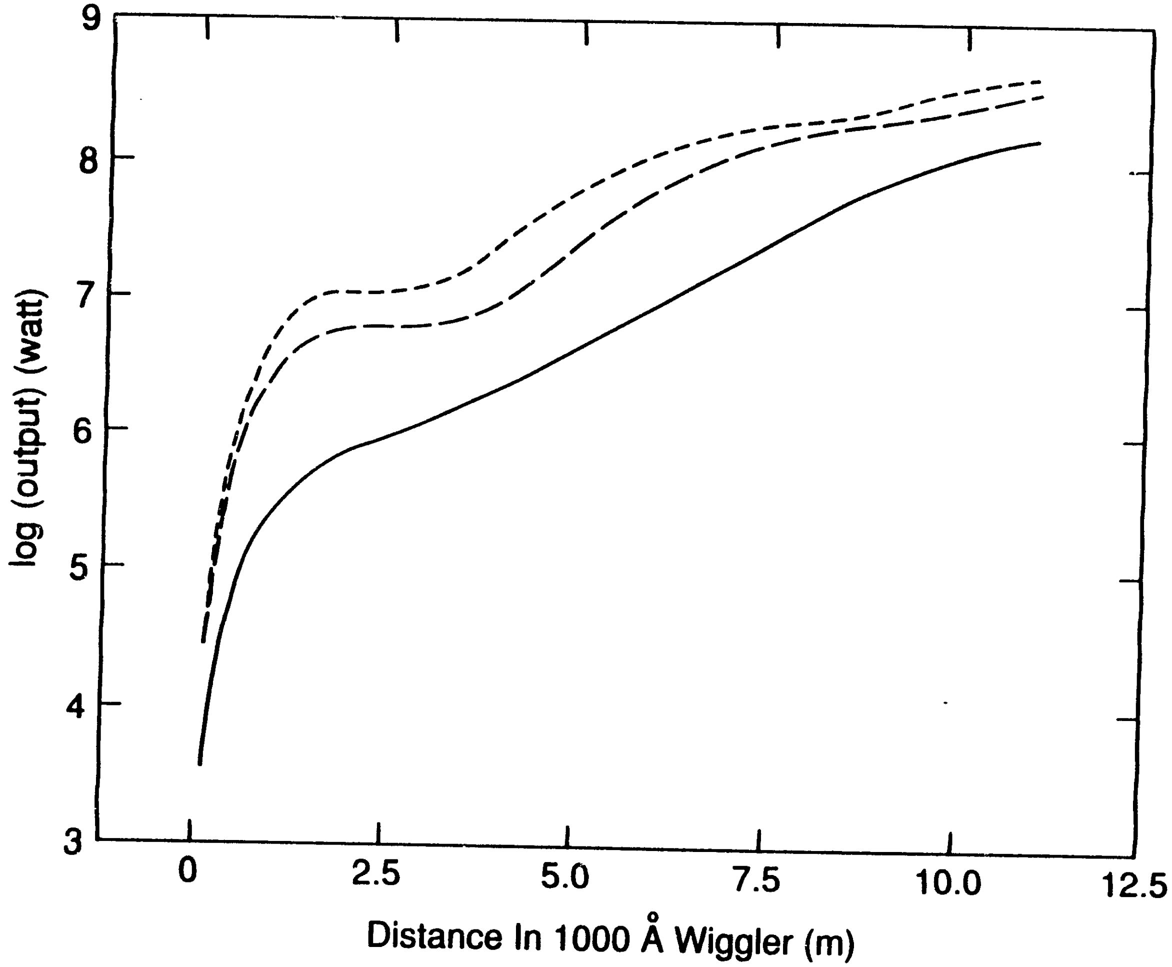

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