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ABSTRACT

Two recent papers [1,2] propose techniques for the generation of very short wavelength radiation from an FEL, with particular emphasis on the possibilities of generating XUV radiation at the ARES superconducting linear accelerator being built in Frascati. The three techniques discussed in refs. 1 and 2 are 1) self-amplified spontaneous emission (SASE); i.e., starting a high-gain FEL amplifier from noise, 2) a high-gain optical klystron, and 3) a sub-harmonic optical klystron (SHOK). In this note, I review each of the proposed techniques.

1. - INTRODUCTION

The first scheme (SASE), the physical basis for which has previously been discussed in the literature[3], involves the generation of 21 and 50 nm light by a roughly 20 m long undulator of 2 or 3 cm period (respectively). The parameters expected for the electron beam from the ARES linac include an rms normalized emittance of 4 or 8 π mm-mrad and an energy spread (rms) of $3.5\ 10^{-4}$ or less at 500-580 MeV. The proposed 21 nm FEL requires some mechanism for focusing the beam that is much stronger than natural wiggler focusing; focusing of the beam by an ion channel (from which the electrons have been expelled by the repulsion of the electron beam) is suggested.

A 3D numerical simulation by the Lawrence Livermore National Laboratory FEL code FRED-3D was used to examine the gain to be expected with the proposed electron beam and FEL parameters. The simulation was done without energy spread, although the very small assumed

IR facility proposed by Barletta and Pellegrini), where the requirements on beam quality, the experimental difficulties, and the costs are smaller by orders of magnitude.

3. - THE HIGH-GAIN OPTICAL KLYSTRON

The buncher-radiator configuration of an optical klystron is proposed in Ref. 1 to overcome the "dramatic effects" that can be caused by the phase difference between the electrons and the signal as they enter the second undulator - the radiator. The dramatic effects are overcome, in this scheme, by discarding the radiation from the buncher before the bunched electron beam enters the radiator. As mentioned above, the suggestion of dramatic effects is based on a misunderstanding of the accuracy with which the spacing between buncher and radiator must be maintained. The authors of Ref. 1 imply that the spacing must be maintained accurately to a small fraction of a signal wavelength, whereas an analysis of the equations of motion across a drift space indicates that the spacing must be accurate only to a fraction of the undulator period. The phase difference produced by a drift space is

$$\frac{\Delta\Psi}{2\pi}=\frac{L}{2\gamma^2\lambda}=\frac{L}{\lambda_w(1+a_w^2)}$$

where λ is the signal wavelength, L is the drift length, and λ_w is the undulator period. In their argument, the authors have left out the Lorentz contraction - the phase matching must be done on a scale of λ_w, not λ. Fig. 1 illustrates the peak intensity achieved in the second undulator with (solid line) and without (dashed line) the initial presence of the signal field radiated in the buncher, as a function of initial phase difference (0 - 2π over an undulator period) between undulator motion and signal electric field; the effect of improper phasing is negligible, as is the enhancement provided by discarding the radiation from the buncher.

Ref. 1 also refers to an improvement of the coherence of emission from the radiator by discarding the (incoherent) radiation from the buncher and permitting the bunched electron beam to radiate by itself ("superradiantly") in the second undulator. The argument for improved coherence neglects the incoherence of the electron beam bunching which reflects (and is identical to) the incoherence of the buncher radiation. No improvement of coherence can be obtained by discarding the buncher radiation.

energy spread does not significantly influence the simulation results[4] (FRED-3D runs usually include non-zero energy spread). The difficulties with the SASE scheme lie largely in the unknowns: the effective input noise power is only known very approximately, the amplified radiation will have a very short coherence length (not well understood), ion focusing can lead to severe emittance growth [5] (the ion-focusing modeled in FRED-3D involves only a very idealized enhancement of axially-symmetric harmonic focusing), and the extremely low energy spread required for high gain at short wavelength has never been demonstrated.

The second scheme of Ref. 1 is a high-gain optical klystron and is a modification of a method proposed recently [6]. The modification is motivated by two misconceptions about the behavior of FEL amplification: first, that the coherence of SASE can be improved by discarding the radiation emitted in an initial bunching undulator, and second, that if the radiation is not discarded, the second undulator in an optical klystron configuration must be positioned to a small fraction of an optical wavelength (rather than of an undulator period).

The third scheme - the SHOK - is motivated by the same misunderstanding of the accuracy with which bunching and radiating undulators need to be aligned. The scheme involves frequency multiplication of an input radiation signal in a single undulator, and requires coupling of a sub-harmonic of the desired radiation frequency to the electrons in the undulator by longitudinal variation of the input sub-harmonic signal. The scheme neglects the much larger gain that will amplify initial shot noise in the fundamental (SASE again). A simple calculation indicates that SASE at the fundamental will easily overwhelm the radiation induced by the sub-harmonic input signal (even with the 10 MW of subharmonic laser light invoked in Ref. 2). Because of the dominance of SASE, the SHOK scheme is identical to the SASE scheme, with the same issues that need to be resolved.

2. - SASE

The 3D simulation of SASE performed at LLNL by W. Barletta and reported in Ref. 1 assumes zero energy spread. The results are not changed dramatically by an assumed energy spread of 10^{-4} (rms). When the energy spread approaches a more conventional value of 10^{-3}, however, the FEL performance becomes extremely sensitive to energy spread, and the 350 MW of 50 nm light after 12 m of undulator is reduced to 50 MW after 20 m (retaining the arbitrary assumption of 100 W of equivalent input noise) [4].

All the difficulties mentioned above - of unknown effective input noise, of unknown radiation coherence properties, of sensitivity to energy spread, and of unknown effects of ion focusing - suggest the necessity of planning experiments at longer wavelengths (like ELFA or the UCLA

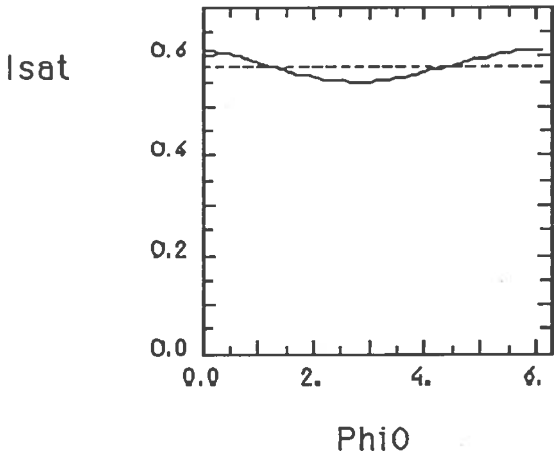

FIG.1 Saturated output intensity (Isat) in the second wiggler as a function of the radiation phase (Phi0) at input to the second wiggler. The dashed line shows the saturated intensity no radiation input in the second wiggler.

4. - THE SHOK SCHEME

The SHOK is another modification of the frequency multiplication scheme proposed in Ref. 6, and is again motivated by the arguments about the relative phasing required between two undulators separated by a drift space. The authors of Ref. 2 propose the use of a single undulator resonant on a harmonic of the desired signal; the desired signal is therefore a sub-harmonic of the input signal and is hence completely out of resonance. Some coupling to the sub-harmonic - hence excitation of the desired signal - is provided by a longitudinal variation of the sub-harmonic signal as the light focuses and then defocuses.

The consequences for the sub-harmonic of being out of resonance are dramatic. In order to saturate an amplifier at 21 nm, the authors propose the use of a 44 nm input signal of 10 to 100 MW and a 27 m wiggler. In their simulations of the SHOK scheme, the authors neglect the ever-present noise at the resonant frequency. A simple calculation indicates that even a few milliwatts (much less than the 100 W assumed for the SASE proposal) of resonant noise will completely dominate the effect of 10 MW of non-resonant sub-harmonic excitation. Once SASE has dominated the sub-harmonic excitation, the FEL behavior will not differ from the SASE scheme discussed above.

5. - CONCLUSIONS

As is well known, there is no easy route to short wavelength radiation from an FEL. The techniques proposed in Refs. 1 and 2 are based on several incorrect arguments about the behavior of an FEL amplifier, and do not provide significantly better ways to generate XUV radiation. A high-gain experiment in the XUV is generally recognized to be premature; the SASE regime should first be tested at longer wavelengths.

6. - ACKNOWLEDGEMENTS

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7. - REFERENCES

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