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"Inverse Free Electron Laser Beat-Wave Accelerator Research"
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I. Summary

In the past year, we have performed an experiment relevant to the IFEL Beat-Wave Accelerator, and we have completed a calculation on the stabilization of the sideband instability in the FEL and IFEL. We have also been in contact with the Omega-P corporation regarding cooperation (as consultant) on their SBIR "Modified Inverse FEL Accelerator" study, which is for use as a low emittance accelerator-injector. A new student is working at Brookhaven as of the time of this writing, studying optical guiding problems connected with the IFEL. In what follows, we shall briefly summarize our findings from the past year's work.

First, we discuss the sideband research. Sidebands are an issue affecting all FEL-related work, and have to do with a "Raman" type instability which develops when the optical power is high and the electrons are undergoing synchrotron oscillations in the bunched electron beam. The issue has come up in connection with the use of a tapered ("variable-parameter") undulator of extended length, such as might be used in an "enhanced efficiency" travelling-wave FEL, or an IFEL accelerator. Indeed, there have been many reports of sidebands from FEL experiments where high power was achieved, notably in an optical resonator. The accelerator aspect has to do with the use of a high power laser that must be used to accelerate electrons in the IFEL and which therefore might drive sidebands that might degrade the high power carrier signal. A few years ago, we reported an FEL experiment which used a tapered undulator to enhance the output of an oscillator; surprisingly enough, the sideband radiations were much reduced in intensity, compared with the untapered

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undulator device. At first, studies suggested the favorable performance was due to our design which used a "fast" (or ambitious) taper.

It is now clearer what mechanism promotes sideband control or suppression as a result of this year's work. The frequency of the most unstable sideband mode varies continuously along the undulator while the peak growth rate itself decreases. Due to this continuous detuning, no single sideband component can grow at maximum rate along the undulator, and hence only a weak and broadened spectrum can emerge from noise. Our calculation has found that an FEL efficiency (for example) of 70% can be obtained with sidebands suppressed by eight orders of magnitude compared with the carrier. The new feature of this physics is a different prescription for the "resonant phase" design of the wiggler: in this case the resonant phase varies along the wiggler rather than remaining constant. This can be done while permitting all of the trapped electrons to remain in the buckets. (The experiment mentioned above did not entirely meet these requirements, so the sidebands were only somewhat reduced in intensity). The IFEL accelerator maintains sideband stability in this model, which is very good news. These new results, by Pila and Bhattacharjee, have been submitted to Physical Review, and have been presented at the 15th International FEL Conference (oral paper) and the Workshop on Acceleration and Radiation from Space and Laboratory Plasmas (Kardamyli Greece) as a poster paper.

We have configured our experimental facility at Columbia to test some of the physics of the IFEL-Beat Wave Accelerator. The IFEL-BWA principle was presented as a publication early in the grant, and has to do with a new type of accelerator. It is a "two-beam" accelerator where an intense low energy ($<1\text{MV}$) beam of electrons is bunched in an undulator by the FEL process. The space charge fields in such a beam can be substantial, particularly if the beam current density is high and the FEL wavelength is long (e.g. microwave). In a conventional IFEL, a fraction of the electrons are trapped into a bucket which is then accelerated by manipulation of the undulator period and/or field (this was studied by us successfully in an experiment completed in the first year of the grant). The IFEL-BWA takes a second electron beam at higher energy but lower

intensity and accelerates it by injecting it into the charge bunches of the FEL. These "test" electrons can be accelerated by increasing the phase velocity of the space charge field, by changing the radius of the wall of the drift tube, for example.

In the past year we have configured our FEL facility as a travelling wave amplifier for a 10kW signal from a 24GHz magnetron. Two experiments were done, one of them quite successfully. We were able to measure the space charge field in the bunches of the FEL, using a specially designed and calibrated probe. At 1MW level of amplified signal, the field in the bunches was about 60kV/cm, peak amplitude, which compares favorably with the 45kV/cm field predicted from our code. We can then scale this field to the saturated power obtainable from the FEL, and increase the beam current density as well to a higher, but still realistic, value. We then project from our data point that an accelerating field of 0.5MV/cm could be readily obtained. These results have been presented at the Workshop mentioned above, and will be published in its proceedings in Physica.

Another experiment was attempted using the same apparatus. In this project, we measured the phase velocity of the space charge field. The measured phase velocity was close to the computed velocity, however, there was microwave interference which interfered with the precision of the measurement. (The phase velocities of the microwave FEL signal and the space charge wave are close, but not identical.) As a result, we did not try the experiment with the tapered waveguide; however, there is a long history of such studies in connection with "collective accelerators", and we are confident that tapering the waveguide walls will speed up the wave.

To summarize our findings in a few words, we have explored various aspects of the inverse FEL accelerator through experimental means. We have found that such acceleration works satisfactorily, and that present codes can be used to design and predict the trapping, acceleration, and energy distribution of electrons. A more technologically-oriented experiment to test limits is now in order, using a standard rf linac facility. "Show-stopping" detrapping and instabilities (e.g. sidebands) have not

occurred. We are now undertaking to understand the physics of guiding high power optical radiation along a lengthy undulator, which is a technical problem of major importance to the IFEL. This will occupy our attention in the next phase of the research, to be done using the experimental facilities at the ATF, Brookhaven.

Preprints of our recent publications have been forwarded to DOE headquarters.

II. Facilities and Personnel

The DOE project has been very helpful to the laboratory at Columbia by providing funds for data acquisition and computing. Recently, an ONR capital equipment grant has provided funding for the purchase of a 4.5GHz bandwidth digitizer which we have used to document solitary waves on the FEL. An accelerator using a solitary wave packet may have some good features; we are continuing our study of this kind of physics with ONR support, and will comment on its application to accelerator physics when more is known.

We have supported one theoretical student (sideband study), one student doing the IFEL-BWA studies, and have started another at Brookhaven. A visiting scientist has joined our group since July, and he will be helpful while Dr. Bhattacharjee is in Japan.

Research results were presented at the FEL Conference, the Workshop (both discussed above) as well as at the Spring meeting of the APS. One of the doctoral students associated with the project has received her PhD in July (LiYi Lin) and is employed at the FEL project at Rutgers.

III. Publications and Presentations

1. "Experimental Test of the Inverse Free Electron Laser Accelerator Principle", Iddo Wernick and TC Marshall, Physical Review A46, 3566 (1992)
2. "An Inverse FEL Accelerator Experiment", Iddo Wernick and TC Marshall, p.292 in "Advanced Accelerator Concepts", J. Wurtele editor, APS Conference Proceedings 279 (1993)
3. "Elimination of the Sideband Instability in Variable-Parameter Free Electron Lasers and Inverse Free Electron Lasers", R.P. Pila and A. Bhattacharjee, submitted to Physical Review; oral paper at the 15th International FEL Conference (The Hague, August 1993); presented at the Spring Meeting of the APS in Washington DC, April 1993.
4. "A Measurement of Space-Charge Fields in a Microwave Free Electron Laser", T.C. Marshall and M.A. Cecere, submitted to Physica and presented at the Workshop on Acceleration and Radiation in Laboratory and Space Plasmas (Kardamyli, Greece, September 1993).

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