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HIGH POWER SUBMILLIMETER AND INFRARED RADIATION FROM INTENSE RE--ETC(U)  
1981 S P SCHLESINGER, T C MARSHALL AFOSR-80-0118

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compared with other beam noise for  $\lambda > 1$  mm.

(3) FEL-oscillator operation was conducted at  $\lambda_s = 1.0$  and  $0.6$  mm, as observed by a Fabry-Perot interferometer. Adding this data to the data of prior experiments, we now have a curve showing that  $\lambda_s \sim 1/\gamma^2$  for  $0.4 < \lambda_s < 1.7$  mm, as expected from stimulated scattering. The spectrum shows  $\frac{\Delta\lambda}{\lambda} \lesssim 1-2\%$ , whereas the superradiant spectrum is very wide ( $\sim 13\%$ ).

(4) The power emitted from the laser increases as  $\lambda_s$  decreases; we have observed stimulated emission up to  $\sim 1$  MW, as detected by a calibrated crystal. This estimate is also consistent with a measurement made by a pyroelectric element. Calibration and measurement of insertion losses was done with a  $\lambda = 1$  mm Carcinotron and a  $\lambda = 1/2$  mm  $\text{CH}_3\text{F}$  laser. The coupling from the laser cavity is estimated to be  $\sim 5\%$ .

(5) Signal analysis permitted observation of cavity losses ( $\sim 30-40\%$  pass), filling factor ( $\sim 0.3$ ) and single-pass gain ( $\Gamma_L \sim 1.5 > \Gamma_L$  threshold  $\sim 1$ ). Output from the laser usually consists of a single spike, about 40-50 ns long, although two or three spikes have been observed. It is not yet clear whether these "spikes" are due to fluctuations in electron beam voltage or whether they are caused by a nonlinear mechanism common to conventional lasers involving the pump, scattered wave intensity, and the FEL gain (the latter is sensitive to the beam energy).

(6) In order to evaluate the signal data better, we have begun a "Fox-Li" type numerical analysis of the FEL resonator-including the waveguiding properties of the drift tube and the separation of the mirrors from the drift-tube. This should provide us with a quantitative picture of the radiation structure in the resonator.

## B. Amplifier

We have initiated our program to attempt to measure the dependence of amplification of an input signal on the electron beam's energy. The output of an optically pumped far-infrared laser is optically coupled into the diode and reflected onto the electron path by a mirror in a hollow cylindrical cathode. Construction and testing of the submillimeter source for the FEL amplifier experiment has proceeded parallel to the oscillator experiment. The CO<sub>2</sub> TEA laser "pump" was borrowed from the Lincoln Laboratory and the design of the FIR cavity was supervised by Dr. H.R. Fetterman of Lincoln. After the completion of the oscillator in November the amplifier source was put in place and the extra mirrors, cathodes, ports and undulators were built.

Our first choice of FIR laser medium was the readily accessible and inexpensive C<sup>12</sup>H<sub>3</sub>F, because of the separation of its 496  $\mu$ m output from the mm-cm cyclotron maser radiation which accounts for a "noise" background in any perturbed-IREB experiment. Given the voltage limitations of our Pulserad 220 G ( $\gamma \leq 3$ ), we would need a 6 mm undulator period-or smaller- to amplify 496  $\mu$ m radiation. The 6 mm undulator we built could not withstand even half the pulsed current that was required for modest amplifier gains. We are thus forced to work with C<sup>13</sup>H<sub>3</sub>F and a wavelength of 1.222 mm.

Here, the cyclotron maser does account for a high-level background. In an effort to operate above this background we are running the CO<sub>2</sub> TEA self mode-locked and with the same cavity length as the FIR system so that we obtain regular, high-power spikes separated by 12 ns. To determine gain we will measure the FIR radiation before and after it is passed through the e-beam via a beam-splitter. The amplified signal will be measured in a grating spectrometer with resolution  $\sim 1\%$ . Both detectors are Schottky-barrier diodes and have been supplied by Dr. Fetterman.

### III. Theoretical Research

#### A. Analytical studies

A study was conducted of electron trajectories and their stability when subjected to the magnetostatic fields of a free-electron laser. These include both the uniform guide magnetic field and the spatially periodic wiggler field. The usual model of a wiggler field has only axial dependence and only transverse components; except very near the axis of the drift tube, this violates Maxwell's equations and is hence unrealizable. The motion of electrons is affected by the radial variation and the periodic axial field component of a realizable wiggler. Exact helical orbits were found for relativistic electrons in combined uniform guide field with realizable wiggler, in cylindrical geometry. It was discovered that the parameter that measures the size of the orbital helix also measures the imparted quiver motion on which the laser gain depends, which explains the need for a realizable wiggler theory in practical cases. A perturbation and stability analysis of the orbits was made, giving the trajectory of an electron that starts from any position and velocity in combined guide and wiggler fields, with corrections for realizability and harmonics of practical bifilar wiggler windings. The helical orbits were found to be either strongly unstable or else exhibit secular growth in time.

The exact helical orbits are being studied further and beams of electrons in realizable wigglers are under investigation to develop corrected laser gain characteristics.

## B. Particle simulations

The orbit of a test electron moving down a wiggler has been studied numerically; included in the analysis are: (a) finite beam current and space-charge; (b) finite radial and axial field inhomogeneity due to the wiggler; (c) transient effects entering the wiggler. We have examined the "temperature" of the test electron by calculating  $\langle \Delta \beta_z \rangle = \left\langle \frac{\Delta v_z}{c} \right\rangle$ , the velocity fluctuation of the electron along its orbit (this is relevant to the temperature of the ensemble, which determines the applicability of cold beam (Raman) physics to this FEL situation). It is found that one can prevent the beam energy spread from growing beyond  $\sim 3\%$  if the wiggler amplitude is kept small ( $B_{\perp} \lesssim 1/2$  kG) and one avoids either the "magnetoresonance" ( $2\pi\beta c/\ell = \frac{eB}{\gamma mc}$ ) or its harmonics. Harmonic effects ( $2\pi\beta c/\ell = n \cdot \frac{eB}{\gamma mc}$ ) involve a finite Larmor radius interaction between the particle and the inhomogeneous fields. The range of guiding magnetic field ( $B_0$ ) in which the beam deteriorates due to this interaction becomes rather broad because of the long extension of the wiggler ( $\sim 60$  cm).

## IV Publication and Talks

### A. Published

1. "The Collective Free Electron Laser", D.B. McDermott and T.C. Marshall, p. 509, in "Physics of Quantum Electronics, vol. 7, "Free Electron Generators of Coherent Radiation", editors Jacobs, Pilloff, Sargent, Scully, and Spitzer. Addison-Wesley (1980).
2. "The Free Electron Laser - A High Power Submillimeter Source", T.C. Marshall S.P. Schlesinger, D.B. McDermott in Advances in Electronics and Electron Physics, vol. 53, p.47; C. & L. Morton editors; Academic Press, (1980).

3. "Enhancement of Stimulated Raman Backscattering by Magnetoresponse Effects" D.S. Birkett and T.C. Marshall, Phys. Fluids 24, 178 (1981)

B. To Appear

1. "Free Electron Lasers Based Upon Stimulated Raman Backscattering: A Survey", T.C. Marshall, Plenum Press, Majorana Series (1981), S. Martelluci, editor.
2. "A Submillimeter Free Electron Laser Experiment", D.S. Birkett, T.C. Marshall, S.P. Schlesinger, D.B. McDermott. Special FEL issue, IEEE J. Quant. Electr. July 1981, A. Szöke, editor.
3. "Electron Orbits and Stability in Realizable and Unrealizable Wigglers of Free-Electron Lasers", P. Diament. Physical Review A. (1981).

C. Technical Talks

|    | <u>Author(s)</u>                               | <u>Title</u>                                                   | <u>Meeting</u>                                           | <u>Abstract Reference</u>           |
|----|------------------------------------------------|----------------------------------------------------------------|----------------------------------------------------------|-------------------------------------|
| 1. | McDermott<br>(Invited)                         | "Collective Free Electron Laser Experiments"                   | APS/Chicago<br>1/80                                      | Bull. APS<br><u>25</u> , (1980)     |
| 2. | Marshall<br>(Invited)                          | "The Raman FEL"<br>(A Series of 3 lectures)                    | Erice Conf.<br>Majorana<br>Summer Sch.<br>Scicil<br>8/80 |                                     |
| 3. | Diament                                        | "Realizable vs. Unrealizable Wiggles for Free-Electron Lasers" | APS/Plasma<br>11/80                                      | Bull. APS<br><u>25</u> , 989 (1980) |
| 4. | Birkett, McDermott<br>Marshall,<br>Schlesinger | "Free Electron Laser Oscillator-New Results"                   | APS/Plasma<br>11/80                                      | Bull. APS<br><u>25</u> , 989 (1980) |
| 5. | Grossman, Marshall                             | "Orbits of a Test Electron in a Wiggler"                       | APS/Plasma<br>11/80                                      | Bull. APS<br><u>25</u> , 989 (1980) |

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| 20. ABSTRACT (Continue on reverse side if necessary and identify by block number)<br>The first quarter of Calendar 1980 was spent installing and testing the newly acquired long-pulse well-regulated Physics International Pulserad 220 unit (1 Mev. 20 KA 100 nsec). The balance of the year was spent on the first phase of the FEL long pulse oscillator experiment and the beginnings of an investigation of the FEL amplifier. Wavelength and power were measured as a function of electron energy and current. Theoretical work included an exact analysis of particle dynamics in a true wiggler and the formulation of a simulation of a pump oscillated test particle in a plasma background, the latter study yielding |                                            |                                                                                     |  |

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new insights into finite Larmor radius effects.

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