SF 298 MASTER COPY KEEP THIS COPY FOR REPRODUCTION PURPOSES

REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
2/4/98

3. REPORT TYPE AND DATES COVERED
Final Progress Report 5/15/95-11/14/97

4. TITLE AND SUBTITLE
Theoretical and Experimental Investigation of Electron Beam Acceleration and Sub-Millimeter Wave Generation

5. FUNDING NUMBERS
DAAH04-95-1-0336

6. AUTHOR(S)
N.C. Luhmann, Jr., F.V. Hartemann
D.B. McDermott

7. PERFORMING ORGANIZATION NAMES(S) AND ADDRESS(ES)
University of California, Davis
Dept. of Applied Science
228 Walker Hall
Davis, CA 95616

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSORING / MONITORING AGENCY REPORT NUMBER
ARO 34594.1 -PH

11. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.

12a. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

12 b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

Four separate processes for electron beam acceleration and sub-millimeter wave generation have been studied. 1) We have extended our concept that harmonic gyro-TWT amplifiers can stably generate substantially higher power than at the fundamental cyclotron frequency by designing a third harmonic amplifier that is predicted to generate 2 MW with good stability and gain characteristics. 2) A three-cavity TE_{0n} gyroklystron circuit, which is predicted to efficiently generate a peak power of 250 kW with high amplifier performance, has been received from the machinist. 3) The first high energy photoelectrons have been produced in the X-band rf gun. 4) In addition, the previous sixth-harmonic gyrofrequency multiplier that produced 3 kW with 5% efficiency has been upgraded so that it will emit its design value of 150 kW with 30% efficiency.

14. SUBJECT TERMS
Harmonic gyro-TWT Amplifier, cyclotron frequency, gyroklystron, rf gun, phtoelectron gyrofrequency multiplier

15. NUMBER IF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT UNCLASSIFIED	18. SECURITY CLASSIFICATION OF THIS PAGE UNCLASSIFIED	19. SECURITY CLASSIFICATION OF ABSTRACT UNCLASSIFIED	20. LIMITATION OF ABSTRACT UL

Theoretical and Experimental Investigation of Electron Beam Acceleration and Sub-Millimeter Wave Generation

FINAL TECHNICAL REPORT

U.S. ARMY RESEARCH OFFICE

ARO PROPOSAL NUMBER: 34594-PH

GRANT NUMBER: DAAH04-95-1-0336

INSTITUTION: University of California, Davis

DATE OF REPORT: February 5, 1998

PERIOD COVERED BY REPORT: 15 May, 1995 – 14 November, 1997

AUTHORS: N.C. Luhmann, Jr. (P.I.),
D.B. McDermott, and F.V. Hartemann

PRINCIPAL INVESTIGATOR: N.C. Luhmann, Jr.
Chair, Department of Applied Science

MAILING ADDRESS OF P.I.: University of California, Davis
Department of Applied Science
Walker Hall
Davis, CA 94619

APPROVED FOR PUBLIC RELEASE:
DISTRIBUTION UNLIMITED

1. LIST OF REPORTABLE INVENTIONS: none

2. SCIENTIFIC PERSONNEL SUPPORTED BY THIS PROJECT AND DEGREES AWARDED DURING THE PERIOD, 5/15/95 - 11/14/97:

Prof. N.C. Luhmann, Jr.
Dr. D.B. McDermott
Dr. F.V. Hartemann
Ms. L. Laurent (M.S. received)
Mr. J.R. Van Meter
Mr. A.J. Balkcum
Mr. J.D. McNally
Dr. G.P. Le Sage (Ph.D. received)
Mr. A.L. Troha
Mr. E.C. Landahl

3. LIST OF PUBLICATIONS DURING PERIOD, 5/15/95 - 11/14/97

"Operation of a Stable 200 kW Second-Harmonic Gyro-TWT Amplifier," Q. S. Wang, D. B. McDermott and N. C. Luhmann, Jr., *IEEE Trans. on Plasma Science*, vol. 24, no, 3, pp. 700-706, 1996.

"Prebunched High-Harmonic FEL for Short-Pulse 1 THz Emission," D. B. McDermott, F.V. Hartemann, A.J. Balkcum and N. C. Luhmann, Jr., *IEEE Trans. on Plasma Science*, vol. 24, no, 3, pp. 808-815, 1996.

“Transform-limited Coherent Synchrotron Wavepackets in a Chirped Pulse Free-Electron Laser”, F.V. Hartemann, G.P. Le Sage, A.L. Troha, N.C. Luhmann, Jr., and S. N. Fochs, *Phys. Plasmas,* Vol. 3, No. 6, p. 2446, 1996.

“Spectral Analysis of the Nonlinear Relativistic Doppler Shift in Ultrahigh Intensity Compton Scattering”, F.V. Hartemann, A.L. Troha, N.C. Luhmann, Jr., and Z. Toffano, *Phys. Rev. E*, Vol. 54, p. 2956, 1996.

“Theory and Design of a Photoinjector-Driven Chirped Pulse Free Electron Maser”, G.P. Le Sage, H.C. Feng, L.L. Laurent, F.V. Hartemann, N.C. Luhmann, Jr., S.N. Fochs, M.D. Perry, G.A. Westenskow, and J.P. Heritage, *IEEE Trans. Plasma Sci.*, Vol. 24, p. 781, 1996.

“Phase Noise Reduction and Photoelectron Acceleration in a High Q RF Gun”, E.C. Landahl, F.V. Hartemann, G.P. Le Sage, W.E. White, H.A. Baldis, C.V. Bennett, J.P. Heritage, N.C. Luhmann, Jr., and C.H. Ho, accepted for publication, *IEEE Trans. Plasma Sci.*

“High Brightness, X-band Photoinjector for the Production of Coherent Synchrotron Radiation”, G.P. Le Sage, E.C. Landahl, L.L. Laurent, N.C. Luhmann, Jr., F.V. Hartemann, C.H. Ho, W.K. Lau, and T.T. Yang, accepted for publication, *Phys. Plasmas.*

"Stable 2 MW, 35 GHz, Third-Harmonic TE_{41} Gyro-TWT Amplifier," D.B. McDermott, B.H. Deng, K.X. Liu, J. Van Meter, Q.S. Wang, and N.C. Luhmann, Jr., accepted for publication, *IEEE Trans. on Plasma Science.*

"Third-Harmonic TE_{411} Gyroklystron Amplifier," J.D. McNally, D.B. McDermott and N.C. Luhmann, Jr., accepted for publication, *IEEE Trans. on Plasma Science.*

"Results of Three High-Performance Gyro-TWT Amplifiers at UCD: I. 200 kW Second-Harmonic Gyro-TWT; II. Dielectric-Loaded Gyro-TWT with 11% Bandwidth; and III. Slotted Third-Harmonic Gyro-TWT," Q.S. Wang, K.C. Leou, C.K. Chong, D.B. McDermott, and N.C. Luhmann, Jr., Digest of the 1995 Vacuum Electronics Review/ICOPS for the IEEE Plasma Science Conference, Wisconsin, pp. III.23-28, 1995.

"UCD GyroKlystron Program," J.D. McNally, D.B. McDermott, and N.C. Luhmann, Jr., *Bull. Am. Phys. Soc.* 40, 1675, 1995.

"Operation of a 200 kW Second-Harmonic Gyro-TWT Amplifier," Q.S. Wang, D.B. McDermott and N.C. Luhmann, Jr., *Bull. Am. Phys. Soc.* 40, 1724, 1995.

"Stable Operation of a 200 kW Second-Harmonic TE_{21} Gyro-TWT Amplifier," Q.S. Wang, D.B. McDermott and N.C. Luhmann, Jr., *Digest of 20th Int. Conf. on Infrared and Millimeter Waves*, Orlando, Florida, pp. 347-348, 1995.

"Characteristics of a Stable 200 kW Second-Harmonic Gyro-TWT Amplifier," Q.S. Wang, D.B. McDermott and N.C. Luhmann, Jr., Abstracts for *23rd IEEE International Conference on Plasma Science*, IEEE Cat. #96CH35939, p. 205, 1996.

"UCD Harmonic Gyrotron and GyroKlystron Program," J.D. McNally, D.B. McDermott, and N.C. Luhmann, Jr., Abstracts for 1996 Microwave Power Tube Conference, 2E.27, 1996.

"Stable 200 kW Second-Harmonic Gyro-TWT Amplifier Operation," Q.S. Wang, D.B. McDermott and N.C. Luhmann, Jr., Abstracts for 1996 Microwave Power Tube Conference, 3A.3, 1996.

"Harmonic Gyro-TWT Amplifiers for Stable High Power Operation," D.B. McDermott, B.H. Deng, K.X. Liu, J. Van Meter, L. Dressman, Q.S. Wang, and N.C. Luhmann, Jr., Digest of Vacuum Electronics Extended Abstracts, 1996.

"Stable 1 MW, 35 GHz Third-Harmonic TE_{41} Gyro-TWT Amplifier," D.B. McDermott, B.H. Dheng, K.X. Liu, J. Van Meter, L. Dressman and N.C. Luhmann, Jr., *Digest of 21st Int. Conference on Infrared and Millimeter Waves*, Berlin, Germany, 1996.

"High Power Third-Harmonic Gyro-TWT: 2 MW, 35 GHz, Stable," K.X. Liu, B.H. Deng, J. Van Meter, L. Dressman, D.B. McDermott and N.C. Luhmann, Jr., *Bull. Am. Phys. Soc.* 41, 1366, 1996.

"Autororesonant Cavity Acceleration," D.B. McDermott, V.V. Dinh and N.C. Luhmann, Jr., Abstracts for *24th* IEEE *International Conference on Plasma Science*, IEEE Cat. #97CH36085, p. 224, 1997.

"Stable Third-Harmonic TE_{41} Gyro-TWT for 2 MW at 35 GHz," K.X. Liu, B.H. Deng, J. Van Meter, L. Dressman, D.B. McDermott and N.C. Luhmann, Jr., Abstracts for *24th* IEEE *International Conference on Plasma Science*, IEEE Cat. #97CH36085 , p. 223, 1997.

"Gyro-TWT Development at UCD," D.B. McDermott, Q.S. Wang, K.C. Leou, C.K. Chong, and N.C. Luhmann, Jr., *Digest of Vacuum Electronics Extended Abstracts*, 1997.

"Harmonic Gyro-TWT Amplifiers for Stable High Power Operation," D.B. McDermott, B.H. Deng, K.X. Liu, J. Van Meter, L. Dressman, Q.S. Wang, and N.C. Luhmann, Jr., published in *Digest of Int. Workshop on High Power Microwave Generation and Pulse Shortening*, Edinburgh, U.K., 1997.

"High Power Coaxial Ubitron Oscillator: Theory and Design," A.J. Balkcum, D.B. McDermott, N.C. Luhmann, Jr., and R.M. Phillips, Bull. Am. Phys. Soc., vol. 42, p. 1902, 1997.

"Design and Fabrication of an X-Band RF Gun", C.H. Ho, W.K. Lau, T.T. Yang, J.Y. Hwang, S.Y. Hsu, Y.C. Liu, G.P. Le Sage, F.V. Hartemann, and N.C. Luhmann, Jr., Advanced Accelerator Conference, Lake Tahoe, CA, 1996, American Institute of Physics, Woodbury, NY, AIP Conference Proceedings 398, page 705.

4. STATEMENT OF PROBLEM STUDIED

4.1 High Power Harmonic Gyro-TWT Amplifiers

We are trying to extend our concept that harmonic gyro-TWT amplifiers can stably generate substantially higher power than at the fundamental cyclotron frequency in order to produce high performance, stable gyro-TWT amplifiers.

4.2 High Performance Gyroklystron Amplifiers

Varian built and tested a gyroklystron in their early gyrotron program. Although the amplifier yielded respectable performance characteristics, it had significant problems with stability. We have built a similar device with more attenuation to improve its stability and thereby increase the output power level by an order of magnitude.

4.3 Short-Pulse Wideband Emission from RF Photocathode Beams

A novel concept for a powerful source of ultrawideband, transform-limited pulses of coherent millimeter-wave radiation relying on the superradiant synchrotron radiation process in a fast wave guiding structure is being investigated theoretically and experimentally. A compact, GHz repetition rate high gradient photoinjector provides ultrashort relativistic electron bunches that are transversally accelerated by a wiggler in a waveguide. At grazing, where the bunch and group velocities are matched, the duration of the resulting ultrawideband chirped radiation pulses is governed by group velocity dispersion instead of slippage. Because of the intimate connection between the rate of chirping and the bandwidth, the corresponding pulse duration has been shown to be very close to the Fourier transform limit. Theoretical calculations indicate that for our X-band photoinjector parameters (5 MeV, 1 nC, 1 ps) and a short (10 periods) 30 mm-period, 8 kG helical wiggler, peak output powers in excess of 2 MW can be generated, with an instantaneous bandwidth ranging from 120 GHz to 220 GHz.

4.4 Gyrofrequency Multiplier

Gyrofrequency multipliers are an efficient new high power, submillimeter-wave source. The device is driven by an axis-encircling electron beam produced by a cyclotron autoresonant rf accelerator We have investigated the advantages of a cavity accelerator over a nonresonant, travelling wave structure.

5. SUMMARY OF RESEARCH RESULTS

5.1 High Power Harmonic Gyro-TWT Amplifiers

A third-harmonic gyrotron travelling-wave-tube amplifier has been designed and is being built that will extend our concept that harmonic gyro-TWT's are capable of stably generating much higher power than at the fundamental because the threshold electron beam current for the onset of oscillation at the cutoff increases significantly due to the relatively weaker interaction. The concept has recently been successfully demonstrated by our second-harmonic TE_{21} gyro-TWT amplifier, which yielded an unprecedented gyro-TWT output power of 207 kW. The highest power stable first-harmonic gyro-TWT produced 120 kW.

Gyrotron traveling wave tube (gyro-TWT) amplifiers are well suited to generate high power in the millimeter-wave range. The large bore of their fast-wave circuits allows the transport of much higher power than the fragile, periodically loaded, slow-wave circuits of conventional TWT amplifiers. The major problem for gyro-TWT amplifiers has been their poor stability. Since they are usually designed to operate close to the cutoff frequency, where the goup velocity is zero, they often oscillate at this frequency in an absolute instability. However, harmonic gyro-TWT's can be much more stable.

We have developed the design of a stable multi-megawatt 35 GHz, third-harmonic gyro-TWT amplifier, by employing our linear stability and nonlinear large-signal codes. For stability, the TE_{41} circuit is sliced to suppress electromagnetic modes without the desired symmetry and the 100 kV, 100 A electron beam from a magnetron injection gun is placed at the null of the strongest remaining competing (gyro-BWO) mode. The single-stage gyro-TWT is predicted to produce 2 MW with 20% efficiency, 30 dB saturated gain and 3.5% constant-drive bandwidth.

We are in a collaboration with a local company, Micramics, to share the major design projects, which are the electron gun and input coupler. The electon gun and circuit will then be fabricated. The magnet and test-stand from the second-harmonic gyro-TWT experiment will be employed for the third-harmonic amplifier.

5.2 High Performance Gyroklystron Amplifiers

We have constructed an experimental upgrade of Varian's pioneering gyroklystron amplifier. We received from the machinist the three-cavity TE_{0n} gyroklystron circuit, which is predicted to yield a peak power of 250 kW with 50 dB of saturated gain and 39% efficiency. The desired coupling to each cavity has been obtained and their resonant frequencies have been synchronized. The cavity resonant frequencies, coupling, and Q values are within acceptable limits of the simulation parameters and the experiment should proceed within three months.

Gyroklystrons are ideal for high power generation due to their large bore fast-wave circuit as compared to small periodic slow-wave structures. A gyroklystron includes circular waveguide cavities separated by drift regions. An annular electron beam with a high percentage of energy in motion transverse to the axial guiding magnetic field enters the first cavity where a small amplitude wave modulates the electrons' energies. The electrons then enter a drift tube where they ballistically bunch in phase space. Additional gain cavities may be used where the ac electron current drives a wave which further modulates the electrons' energies. Finally, after an optimal bunch has been formed, the electrons enter the output cavity and generate a large amplitude wave due to the negative-mass instability.

It is believed that the drift tube between the two cavities was the source of oscillation in the Varian gyroklystron. Our drift tubes employ a lossy, non-periodic corrugated set of rings, as have been developed for gyrotron magnetic compression tubes. Further, we have added an extra cavity to the Varian design to obtain more gain.

We have also recently designed a third-harmonic, 35 GHz gyroklystron amplifier driven by a conventional magnetron injection gun (MIG) that is a modification of our previous third-harmonic gyroklystron design that employed an axis-encircling Cusp-gun electron beam. The cavity Q was increased to compensate for the reduced interaction strength. Competing modes are suppressed by slicing the smooth-bore circular waveguide cavity to interrupt their wall currents. The guiding center of the moderate voltage MIG electron beam is placed near the maximum of the operating third-harmonic TE_{41} interaction and the minimum of the strongest remaining competing modes. Simulation predicts an output power of 70 kW with 30 dB saturated gain and 20% efficiency.

5.3 Short-Pulse Wideband Emission from RF Photocathode Beams

A simplified beamline setup was used to produce the first photoelectron signals from the X-band rf gun. UV pulses were sent directly down the beamline to the photocathode, and the resulting photoelectrons were collected by a Faraday cup placed immediately after the gun.. To simplify synchronization, rf was derived from the laser oscillator. The phase was coarsely adjusted using a phase delay box. A strong photoelectron signal was seen when within 20 degrees of an optimum input phase. Due to timing jitter and amplitude stability of the laser, the large photoelectron spike was not seen at 10 Hz, but it always occurred at the same time with respect to the trigger. The narrowness of the signal is further evidence that the signal is in fact from photoelectrons, as both dark current and plasma discharge electrons produced much longer pulses in the Faraday cup. Finally, when the laser was shuttered from entering the cavity, the photoelectron signal always went away.

In addition, we have a research effort aimed at developing a cryogenically cooled rf gun. In such a device, the high Q rf gun acts as the master clock for both the rf and laser systems, and the high degree of phase noise filtering in the gun allows the use of a compact, efficient, low voltage (30 kV) microwave source such as a magnetron or a CFA to power the gun. High gradients are still maintained because the Q is very high. We have designed an experimental setup to produce a filtered 70 MHz signal directly from the high power rf gun. Since the ultimate success of the photoinjector project depends on the proper arrival of the fs laser pulse at the gun cathode, deriving the drive signal for the laser system from the cavity itself can help insure that the laser pulses will adjust to any actual changes in cavity rf phase and will eliminate most of the sources of phase noise in the rf system by providing direct synchronization between the laser and rf gun fields. To create the signal, the -80 dB field monitor inside the cavity was combined in a 1 GHz mixer with a local oscillator in the X-band, which differed by 70 MHz from the signal fed into the TWTA. The mixer output then went through a bandpass filter centered at 70 MHz before being displayed along with an FFT spectrum on a 5 GHz bandwidth, 1 Gs/s digital sampling oscilloscope. 70 MHz was chosen because a bandpass filter at this frequency is high enough to reject noise from the thyratron switch, which ranges in frequency from dc to approximately 20 MHz. This technique proved extremely efficient in reducing this and other external noise sources. We first measured the klystron phase by mixing its output directly with a reference local oscillator. When the klystron output was used to power the cavity instead, and the field probe signal was mixed with the local oscillator, the 70 MHz signal shown was much cleaner. Comparison of the two FFT traces shows that the noise sideband was significantly reduced. In particular, the low-frequency sideband due to the PFN overmodulation is clearly eliminated. At this point, where phase noise suppression in the high-Q rf gun has been demonstrated, the next question can be addressed: can the filtered signal from the gun be used to drive the semiconductor laser? The main problem here is that we are dealing with a pulsed (1-2 μs) signal, and the question of how fast the QW laser modelocks must be resolved. As the semiconductor laser is a high gain system, it is hoped that it can track the phase of a pulsed rf clock quickly. This was first demonstrated by mixing two different local oscillators in a mixer with a 1 GHz frequency difference, but with one of the oscillators modulated by a Hewlett Packard pulser. The resulting clean rf pulses with < 100 ns rise time was used to drive the QW laser. Modelocking was achieved with this signal, so the gated oscillator was replaced with the cavity field probe. Again, modelocking was achieved at 0.459 GHz. Thus, direct modelocking of the QW laser system to the rf fields in the energized X-band photoinjector has been demonstrated, encouraging further development of a cryogenic gun powered by a noisy but efficient source where the high Q rf gun itself acts as a master oscillator for the laser system.

5.4 Gyrofrequency Multiplier

A gyrofrequency multiplier uses the intermediary of a rotating spiral-shaped electron beam produced by a gyroresonant rf accelerator to harmonically up-convert (multiply) the frequency of a high power, low frequency microwave source. Our initial unoptimized proof-of-principle experiment demonstrated this harmonic conversion process in a third-harmonic multiplier with the production of 7 kW at 28 GHz with 13% efficiency. In our next experiment, we will remeasure with an upgraded electron gun a sixth-harmonic gyrofrequency multiplier that had been designed to emit 150 kW at 17 GHz with 30% efficiency, but that actually produced only 3 kW with 5% efficiency due to electron gun limitations.

Using our simulation code, the output cavity of a tenth-harmonic gyrofrequency multiplier has been designed to yield 19% efficiency at 600 GHz. The proposed tenth-harmonic multiplier would be driven by our 250 kW, 60 GHz gyrotron. The gyrotron would drive the input cavity and accelerate a 0.5 A electron beam to 300 keV.

In the input accelerator cavity of a gyrofrequency multiplier, low frequency microwaves tuned to the cyclotron frequency accelerate and bunch an initially low energy electron beam to form an axis-encircling beam rotating at the accelerator's frequency. The electrons will then efficiently transfer their energy to an n^{th}-order azimuthal TE mode of the output cavity if the beam and mode are temporally and spatially matched. Temporal matching occurs when the mode's resonant frequency ω is equal to n times the rotation frequency of the beam. The angular velocity of the wave then matches that of the helical beam and each electron enters the interaction cavity at the same decelerating phase. Spatial matching exists when the mode's axial propagation constant corresponds to the pitch of the corkscrew beam. The electrons then remain in harmonic cyclotron resonance with the wave ($\omega = n\Omega_c + k_z v_z$) as they progress through the cavity, resulting in extremely high efficiency.

The gyroresonant rf accelerator that is the first part of the multiplier can be either a resonant cavity or a nonresonant travelling-wave circuit. We have found that both types displays the beneficial property of autoresonance, where magnetized electrons remain in resonance with a traveling wave because their Doppler shift changes to compensate the change in the relativistic cyclotron frequency. It was not fully appreciated that cavities can also display autoresonance. An advantage to operating with a cavity accelerator over a traveling-wave accelerator is the enhancement of the fields by a factor of $\sqrt{Q}$ which yields much stronger acceleration. We have operated a cavity gyro-autoresonant TE_{111} accelerator for the application of RF generation for nearly twenty years. It has produced MeV-level electron beams in a distance of only one wavelength with a modest RF power of less than 1 MW. In addition, one can choose to be in resonance with either the forward or backward wave. A particularly attractive case is where the electrons switch from being in resonance with the backward-wave to resonance with the forward-wave as the axial velocity slows. This leads to an energy gain one order of magnitude higher than in the more conventional case of strictly forward-wave resonance.