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COLLECTIVE ACCELERATION OF ELECTRONS AND IONS IN A HIGH CURRENT RELATIVISTIC ELECTRON BEAM

FINAL REPORT

ON

CONTRACT DE-AC02-80ERT10569

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DISCLAIMER

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Introduction

This report describes work carried out on DoE contract number DE-AC02-80ER10569 during the period December 15 1979 to May 31 1992. The report provides a brief summary of the program objectives, summarizes the main accomplishments and concludes with listings of Ph.D degree students supported, and conference and refereed publications.

Technical Program

The original purpose of this research was an investigation into the use of slow space charge waves on weakly relativistic electron beams for ion acceleration. The work had three main objectives namely, the development of a suitable ion injector, the growth and study of the propoerties of slow space charge waves on an electron beam, and a combination of the two components parts into a suitable proof of principle demonstration of the wave accelerator.

Our work focussed on the first two of these objectives. The injector study was based on the use of a collective accelerator in which protons were accelerated by the fields at the head of an intense relativistic electron beam. Typical parameters for the study were as follows:

Electron beam Energy	$600 keV$
Electron Beam Current	$50\ kA$
Pulse Duration	$100\ nsec.$

Peak proton energies of up to 20 times the electron beam energy were achieved. The velocity of a 12 MeV proton is 4.75 x 10^7 m/s and corresponds to a required phase velocity for the slow space charge wave of about $0.16c$. The bulk of the protons had a lower energy, however there were sufficient protons available for the proof of principle wave accelerator.

The development of a suitable space charge wave on the beam and the control of the wave phase velocity proved to be a formidable task, with a considerable effort required to maintain a high enough quality beam and an even greater effort to control the wave phase velocity. Wave growth was achieved by propagating an uniform electron beam with a current of about 1 kA at a beam energy of about 300 keV through a disk loaded waveguide. The cool center portion of the beam was utilized for the wavegrowth experiments. A wave frequency of 1 GHz was used for these experiments. Good coherent wave trains were obtained and propagated stably through the system. Wave phase velocities as low as 0.06 C were obtained occasionally and phase velocities of 0.12 c could be achieved reliably. The electric field in the wave was estimated at up to 22 MV/m.

The observed low phase velocities, which were only obtained for times of order 10 nsec., were considerably slower than expected theoretically. Linear theory indicates that the wave phase velocity only goes to zero when the wave frequency is zero and the ratio of the current to the vacuum limiting current is unity. The observed slowing down was attributed to non-linear propagation and the interpretation confirmed from observations of harmonics of the wave frequency. Experiments were carried out to explore the change in the wave velocity which occurs as the beam to limiting current ratio was decreased. A controlled change in the wave phase velocity is of course required for proton acceleration. Changes in the wave phase velocity were measured and qualitatively followed the expected trends. Discrepancies were attributed to non-linear wave slowing which cannot be readily controlled by changes in the beam or structure geometry. As a result of this we did not suceed in obtaining the required degree of control of the phase velocity to allow us to fabricate a working accelerator and the project was duly terminated in favor of a program which focussed on the generation of ultra high power microwave signals suitable for use in the next linear collider. This program was a natural outgrowth, albeit at higher frequency of the wave studies carried out in the collective ion accelerator research program.

The development of the next linear collider requires the production of ultra high power microwave sources. The sources must not only be very efficient and inexpensive but also must be phase stable. Peak powers of up to 1 GW are required in X band in pulses of order 100 nsec. in duration. Previous electron accelerators have been driven by klystrons which produce up to about 60 MW at S band (2.856 GHz) in a three microsecond pulse. During the past six years we have devoted our main effort to addressing these requirements. We elected to develop an X band traveling wave tube amplifier as a logical extension of our earlier work on the slow space charge wave excitation outlined above. Prior work on high power traveling wave devices had been restricted to the development of Backward Wave Oscillators and no Amplifiers had been built. Our rationale for making the transition to an amplifier was that it was relatively straightforward to visualize the phase control from one amplifier to another for a large array of amplifiers driven by a master oscillator, but it was very difficult to envision a similar system for an array of oscillators. At minimum the oscillator array would take longer to phase lock and the locking would require a much greater fraction of the output power of each device.

Our first amplifier design appeared to work satisfactorily with gains of over 30 dB and with output powers of about 100 MW. A detailed study of its characteristics showed that pulse durations of 100 nsec were achievable and that the bandwidth of the devices were about 30 to 40 MHz. This figure was substantially smaller than expected and our efforts focussed on understanding the bandwidth narrowing over expectations based on known lower power device performance. The phenomenon was traced to finite structure length effects and on deeper study also predicted the development of sidebands in the radiation pattern. These were found experimentally and are the result of preferred wavenumbers for the structures resulting from low Q cavity resonances. The resonances are in turn a consequence of small impedance mismatches at the input and output ends of the amplifiers. Interactions and wave growth occur at frequencies corresponding to the preferred wavenumbers. At power levels of over about 70 MW we find that the sidebands develop and increase in importance as the power is increased. At 400 MW the power in the sidebands was 50 % of the total radiated power.

Attempts to increase the output power above 100 MW lead to oscillation of the amplifier. To overcome this problem we developed a severed two stage amplifier in which the gain could be further increased, reaching ultimately a power output of 400 MW at an efficiency of over 40 %. As indicated above our concerns then turned to the problem of eliminating the sidebands. Towards the end of the contract program we produced a solution to the problem which will be tested as part of a new research program started this month. The solution is based on the development of a slow wave structure with a very low group velocity. In such a structure the TWT may perhaps be better though of as a series of weakly coupled cavities. Preferred wavenumbers should be of no importance in these devices as the input is isolated from the output for a time equal to the structure length divided by the group velocity. This time is comparable to the rf pulse duration consequently thecavity does not get a chance to establish preferred value of the wavenumber. In addition the wave is highly attenuated in transit through the structure much like the regime found in klystrons where the cavities are isolated from each other by extended cut off sections of guide. For the forward going wave the electron beam couples adjacent cavities so the poor coupling in the absence of the beam is of no importance. Finally we note that we have simulated these new structures using the MAGIC code. Results from the simulations confirm that the new structure will eliminate the sidebands.

Approximately a year before the end of the contract we became aware of work in progress at CERN on the use of ferroelectrics as sources of electrons and initiated a low level effort in this area. To date we have used them to achieve currents of up to 70 A at a current density of 70 A/cm^2 in 300 nsec pulses. Current interests lie in determining whether the ferroelectrics will be low emittance sources and how they will perform in rf cavities. Work is continuing on this project.

CONCLUSIONS

Over the duration of the above contract we have completed a substantial body of research on wave growth on intense electron beams. We have reported this work extensively at both conferences and in Journal articles. A listing of the Journal and conference papers arising from this work is appended to the report together with a list of conference presentations. We complete the report with a listing of graduate students who completed their Ph.D. studies on the projects described above.

CONFERENCE AND REFEREED JOURNAL ARTICLES

[1] "Collective Acceleration of Metallic Ions," Appl. Phys. Lett. **36**, 810 (1980) (J.A. Nation, R. Adler).

[2] "The Collective Acceleration of Protons in Relativistic Electron Beam Propagation in Evacuated Drift Tubes," Phys. Fluids **24**, 347 (1981) (R. Adler, J.A. Nation,and V. Serlin).

[3] "Proton Energy Spectrum Diagnostics for a Collective Accelerator," Rev. Sci. Instr. **52**, 698 (1981) (R. Adler, J.A. Nation, and V. Serlin).

[4] "Application of Space Charge Waves on an IREB to Collective Ion Acceleration," IEEE Trans. Nucl. Sci. **NS-28**, 3352 (1981) (G. Providakes, and J.A. Nation).

[5] "Proton Collective Accelerator Studies," Proc. 4th International Topical Conference on High Power Electron and Ion Beam Research and Technology (Palaiseau, France, 1981), **II**, p. 667 (with G. Providakes, J.A. Nation, and V. Serlin).

[6] "Collective Acceleration Processes Using Waves on Electron Beams," ECFA Conference Proceedings (Oxford, 1982) p. 115.(J.A. Nation,)

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[19] "Application of High Power, Intense Electron Beams to Ultra High Energy Electron Accelerators," Proc. 1987 Workshop on New Developments in Particle Acceleration Techniques, ECFA-CAS/CERN-1N2P3, Orsay, France, June 1987, 1, pp. 23-32, (J.A. Nation)

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[23] "Application of Relativistic Electron Beams and High Power Microwaves to Particle Acceleration," (E. Chojnacki, T. J. Davis, J. D. Ivers, G. S. Kerslick, J.A. Nation, and D. Shiffler), Proc. 7th International Topical Conference on High Power Beams - Karlsruhe 1988, II, 870 -875.

[24] "High Power Traveling Wave Tube Amplifier," (D. Shiffler, J.A. Nation, and C. B. Wharton) Appl. Phys. Letters, **54**, (7), 674, 1989.

[25] "A High Power X Band Relativistic Klystron," (T. J. Davis, J.A. Nation, and E. Chojnacki, Proc.1989 Particle Accelerator Conf. **1**,147-149.

[26] "High Power TWT Experiment," (D. Shiffler, J. D. Ivers, J.A. Nation, and G. S. Kerslick), Proc. 1989 Particle Accelerator Conf. **1**,150-153.

[27] "Upper Hybrid Wave Collective Accelerator Studies," (E. Chojnacki,J.A. Nation, and T. J. Davis,) Proc. 1989 Particle Accelerator Conf. **3**,734-736.

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[31] "On the Bandwidth of a Short Traveling Wave Tube Amplifier" (L. Schachter, J.A. Nation, and G. Kerslick), J. Appl. Phys. **68**, (11), 5874-5882, (1990).

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[35] " A high power two stage traveling wave tube amplifier", (D. Shiffler, J. D. Ivers, J.A. Nation, G. S. Kerslick and L. Schacter, J. Appl. Phys 70 (1), 106, (1991)

[36] "Theoretical studies of high power Cerenkov amplifiers", (L. Schacter, J.A. Nation, and D. Shiffler), J. Appl. Phys 70 (1), 114, (1991)

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[24] "A severed High Power TWT Amplifier", Bull. Am Phys. Soc. **34**, 9, 1991, 1989.

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[30] "Recent experiments with high power TWTS," Bull. Am. Phys. Soc., **36**, 9, 2467 (1991).

[31] "Experiments with dielectric slow wave structure high power TWTS," Bull. Am. Phys. Soc., **36**, 9, 2467 (1991).

[32] "Theoretical study of the limiting current in a diode with a ferroelectric cathode," Bull. Am. Phys. Soc., **36**, 9, 2379 (1991).

Ph. D. DEGREE'S

The following students, who have received Ph.D. degrees since 1980, were supported entirely or in part on the DoE Contract.

Richard J. Adler, 1980, Original Employment at AFWL. Research on Radlac accelerator system, Current employment with own company North Star Research,Albuquerque. Small Business working on modulators and pulse power systems

George F. Providakes, 1985, Mitre Corp, First position Technical Staff developing gyrotrons for satellite communications. Present position Department Head UHF/SHF Satellite Communications

Daniel F. Fenstermacher, 1985, First employment Sloan Research Fellow, Center for Science and International Affairs, Harvard University, Current employment: Analyst and AAAS Fellow, International Security and Commerce at Office of Technology Assessment, Washington, D.C.

Shlomo Greenwald, 1987, Cornell University Original employment. Raphael, Research Scientist, Israeli Government, Current employment Cornell University Research Associate, working on rf cavities.

Antonio Anselmo 1987, Varian Co Staff Member doing research in Pulse Power Technology.

Donald A. Shiffler, 1991, First Position Duke University doing FEL Research with John Madey, Assistant Prof. UNM in April 1992

Daniel Koury 1992, Numerical Simulation Specialist for Texas Instruments modelling solid state devices.

Two other former staff completed Post Doctoral Research at Cornell under the aegis of the program. They are:

V. Serlin NRL High Power Microwave Program and

E. Chojnacki now at Argonne National Lab. working on Wake Field Accelerators.