DOE/ER/40465--T2

DOE/ER/40465--T2

DE92 000824

Final Report of Proposed Research
on
Advanced Accelerator Concepts

Submitted to
Department of Energy
Washington, D.C.

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Duration of Proposed Research
June 1, 1988 - May 31, 1991

September, 1991

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1 Summary of Proposed Research

This report summarizes technical progress and accomplishments during the proposed three-year research [1] on advanced accelerator concepts supported by the Department of Energy under Contract No. DE-FG02-88ER40465. A vigorous theoretical program has been pursued in critical problem areas related to advanced accelerator concepts and the basic equilibrium, stability, and radiation properties of intense charged particle beams. Broadly speaking, our research has made significant contributions in the following three major areas:

1. Investigations of physics issues related to particle acceleration including two-beam accelerators [2]-[4] and cyclotron resonance laser (CRL) accelerators [5],[6].
2. Investigations of RF sources including the free-electron lasers [7]-[12], cyclotron resonance masers [13]-[18], and relativistic magnetrons [19]-[23].
3. Studies of coherent structures in electron plasmas and beams ranging from a low-density, nonrelativistic, pure electron plasma column [21],[22],[24] to high-density, relativistic, non-neutral electron flow in a high-voltage diode [19],[22].

The remainder of this report presents theoretical and computational advances in these areas.

2 The Two-Beam Accelerator

Significant advances have been made in the two-beam accelerator (TBA) concept. A major problem with the original version of the TBA was the strong sensitivity of the output rf phase to jitter in the system parameters. This difficulty was substantially alleviated by a change in the FEL design [2],[3], so that the rf power is now extracted at the end of each FEL section. This also solved the problem of power transport through the induction cells. Further innovations were made when it was realized [4] that the FEL could couple to a series of short cavities, thus, essentially, making a standing wave FEL. This configuration is interesting not only in that it offers a realization of a method to extract and couple the rf power to the high gradient structure, but also in that it is new way to operate an FEL. Further investigation will be required to see if this FEL has substantial advantages, in non- accelerator applications, over conventional FEL microwave oscillator schemes.

3 Cyclotron Resonance Laser Accelerators

There has been considerable interest recently in laser accelerators [25] with the potential for achieving high accelerating gradient. One such system is the electron cyclotron

resonance laser (CRL) accelerator [26] that makes use of the resonant interaction of a coherent electromagnetic wave with a beam of electrons gyrating in a (guide) magnetic field. An intriguing feature of the CRL mechanism is autoresonance [27],[28], that is, the synchronism between the electrons and laser field is self-sustained in the course of acceleration in an ideal situation so long as the system is initially synchronized. Although recent proof-of-principle experiments [29]-[31] have successfully demonstrated the acceleration of electrons to moderately relativistic energies using microwaves and the technique of tapering the guide field, there are severe limitations posed by laser field dispersion, synchrotron radiation losses, and the available strength of magnetic field in laboratories.

3.1 Investigations of scaling properties in CRL accelerators

The nonlinear interaction of a tenuous continuous electron beam with a traveling electromagnetic wave in the cyclotron resonance laser accelerator is analyzed [5]. using a single-particle model and multiparticle simulation. It is shown that there exist a maximum energy threshold and a maximum acceleration distance, which have not been reported in earlier studies. It is found that the maximum beam energy gain and acceleration distance obey certain scaling laws for optimized systems, that the maximum energy gain is limited primarily by the degree of wave dispersion and is almost independent of the wave amplitude. These scaling laws are important for future CRL accelerator experiments.

3.2 Self-consistent modelling of a 33.3 GHz high-current, high-efficiency CRL accelerator

A detailed design modelling of a high-current CRL accelerator has been conducted in the microwave regime [6], using a three-dimensional self-consistent simulation code — CSPOT [15],[18]. The code takes into account the self-consistent evolution of the

Table 1. Design Parameters for a 33.3 GHz CRL Accelerator

Beam Current	I_b [A]	20
Initial Beam Voltage	V_i [kV]	150
Final Beam Voltage	V_f [kV]	2400
Acceleration Distance	z_m [cm]	100
Initial Axial Magnetic Field	$B_z(0)$ [kG]	5.7
Final Axial Magnetic Field	$B_z(z_m)$ [kG]	10.9
RF Frequency	f [GHz]	33.3
RF Power	P [MW]	50
Operating Mode		TE ₁₁
Waveguide Radius	R_w [cm]	1.88

amplitude and phase of the driving wave due to the cyclotron resonance interaction in the high-current regime. The choice of a driving frequency of 33.3 GHz is based on the available RF source at MIT [32]. For the choice of system parameters listed in Table 1, the simulations show an acceleration efficiency of $\sim 80\%$ and acceleration gradient of ~ 2 MeV/m.

4 Free-Electron Lasers

The physics and technology of free-electron lasers (FELs) are intimately related to the accelerator community because FELs are important applications of particle accelerators and have the potential to power high-gradient rf accelerators, such as in two-beam accelerators [2]-[4]. Under the auspices of this grant, several important aspects of the FEL has be investigated. These have included: (a) theoretical and numerical investigations of the onset of chaos in particle dynamics in free-electron lasers [7]-[9], (b) development of a three-dimensional axisymmetric (TDA) code for free-electron laser simulation [10],[11], and (c) experimental and theoretical investigations of nonlinear effects in a collective FEL [12].

4.1 Investigations of the onset of chaos in FELs

An important parameter characterizing FEL operation is the small-signal gain. According to linear theory [33], the gain increases as the beam density and the strength of the wiggler field are increased. However, in the high-current (high-density) regime and the intense wiggler field (strong-pump) regime, the electron orbits can be modified significantly by the equilibrium self fields of the electron beam and the transverse spatial gradients in the applied wiggler field. This raises important questions regarding beam transport and the viability of the free electron laser interaction process in these regimes.

Under the auspices of this grant, chaotic particle dynamics in free electron lasers has be investigated [7]-[9]. In a field configuration consisting of an ideal (constant-amplitude) helical wiggler field and a uniform axial guide field, it is shown in a model that the inclusion of self-field effects destroys the integrability of the particle equations of motion. Consequently, the Group-I orbits and the Group-II orbits become chaotic at sufficiently high beam density. An analytical estimate of the threshold value of the self-field parameter $\epsilon_s = \omega_{pb}^2/c^2 k_w^2$ for the onset of chaos is obtained and found to be in good agreement with computer simulations.

In addition, the effects of transverse spatial gradients in a realizable helical wiggler field with three-dimensional spatial variations are investigated in the absence of an axial guide field, but including self-field effects. For a thin electron beam ($k_w^2 r_b^2 \ll 1$) and small wiggler field amplitude ($a_w^2 \ll \gamma_b^2$), it is shown that the motion is regular and confined radially provided $\epsilon_s < \gamma_b a_w^2/(1 + a_w^2)$. However, because of the intrinsic

nonintegrability of the motion, the regular region in phase space diminishes in size as the wiggler amplitude is increased. The threshold value of the wiggler amplitude for the onset of chaos is estimated analytically and confirmed by computer simulations for the special case where self-field effects are negligibly small.

The onset of chaos in the FEL particle dynamics poses upper limits on beam current and wiggler amplitude for FEL operation. Further studies are required to examine the effects of chaotic particle orbits on lasing processes, particularly in the nonlinear regime.

4.2 Development of the TDA code for FEL simulation

The TDA simulation code [10],[11] has been developed and is widely used in the FEL community. Presently groups at MIT, CEBAF, LBL, UCLA, BNL and elsewhere are using the simulation to study the performance of various optical FEL systems. The TDA simulation solves the averaged FEL equations with fully three dimensional particle motion and the paraxial wave equation (with azimuthal symmetry assumed for the wave). Versions of TDA now include wiggler field errors and tapering schemes [34], multiple passes [35], and harmonics [36]. There is also a waveguide version of the simulation that can be used to investigate microwave and millimeter wave FELs [37].

4.3 Investigations of nonlinear effects in a collective free-electron laser

A theoretical and experimental study of the nonlinear performance of a FEL amplifier operating in the collective (Raman) regime has been conducted [12]. The FEL generates up to ~ 100 kW of rf power at a frequency of 9.3 GHz and an efficiency of ~ 10 %. Power saturation, efficiency, and synchrotron oscillations are studied as a function of rf input power, electron beam energy, current, wiggler field amplitude, and axial distance with the helical wiggler. The influences of the nonlinear electron motion in the ponderomotive potential and space-charge waves are studied by measurements of the dependence of gain and efficiency on the initial radiation intensity. Good agreement with a nonlinear theory that takes cognizance of electron trapping in the combined ponderomotive and space-charge potential well is obtained.

5 Cyclotron Autoresonance Masers

The cyclotron autoresonance maser (CARM) [38],[39] has received much interest recently as a potential source of high-power microwave and millimeter wavelength electromagnetic radiation. In particular, theoretical and experimental investigations are being conducted to examine the feasibility of the CARM amplifier as an RF source for future accelerators [40]. Under the auspices of this grant, extensive theoretical

and computation investigations have been carried out. These have included: (a) linear and nonlinear analysis of multimode interactions in CARM amplifiers [14],[15], (b) development of a three-dimensional self-consistent code for CARM amplifier and CRL accelerator simulations [5],[15], (c) detailed comparisons between theoretical predictions and experiments [16], and (d) studies of efficiency optimization [13].

5.1 Linear and nonlinear theory of a multimode cyclotron autoresonance maser

One of the most intriguing problems in the generation of coherent radiation using a relativistic electron beam is the interaction of multiple electromagnetic eigenmodes with the electron beam. In FEL oscillators [41] and gyrotrons [42], mode competition determines the temporal behavior of the eigenmodes of the cavity and the radiation spectrum. Multimode phenomena also occur in overmoded amplifier systems, where the temporal dependence of the eigenmodes is usually sinusoidal. In such cases, the eigenmodes evolve spatially as a result of the interaction with the electron beam. A nonlinear multimode theory is indispensable in order to predict the rf power in each mode.

A general formalism of multimode interactions in an overmoded single-frequency CARM amplifier has been developed using a nonlinear self-consistent model and kinetic theory [14],[15]. A complete set of CARM amplifier equations with multiple modes are integrated numerically to calculate the linear and nonlinear evolution of coupled transverse eigenmodes and of the relativistic electron beam. In addition, use is made of the linearized Maxwell-Vlasov equations and the Laplace transform to derive a dispersion relation and amplitude equations for the CARM instability with an arbitrary number of vacuum transverse-electric (TE) and transverse-magnetic (TM) waveguide modes. The Laplace transform analysis allows for analytical calculation of launching losses and the three-dimensional radiation field profile.

It is shown that all of the coupled modes grow with the dominant unstable mode at the same growth rate, but suffer different launching losses. The rf phases of coupled modes are locked in the linear and nonlinear regimes. Simulations indicate that the rf power distribution among the interacting modes at saturation is insensitive to input power distribution but sensitive to detuning.

5.2 Development of the CSPOT code for CARM and CRL accelerator simulation

A three-dimensional, multimode, self-consistent code, CSPOT [14],[15],[18] has been developed for the simulation of CARM amplifiers and CRL accelerators. The code can model a single TE or TM mode, Multiple TE and/or TM modes, cyclotron harmonics, magnetic field tapering, momentum and energy spread, waveguide losses, and various beam loading options. It has been benchmarked against a linear kinetic

theory [14],[15], and has been found in good agreement with recent CARM amplifier experiments [16].

Because the basic equations for the CARM and CRL accelerator are identical, the CSPOT code can also be used for CRL accelerator simulation and design [5],[6]. Unlike a single-particle model, the code take into account the self-consistent interaction between the driving wave and the electron beam, which is important in the high-current regime where the wave amplitude and phase vary substantially in the acceleration process.

5.3 Efficiency enhancement in CARM amplifiers

The efficiency of cyclotron autoresonance maser (CARM) amplifiers with piecewise linear tapering of the magnetic field has been analyzed [13],[18]. In the low current limit, it is found that increasing the magnetic field substantially enhances the efficiency if an effective detuning parameter is positive, while decreasing the magnetic field is advantageous when the detuning parameter is negative. For high current, high gain, CARM operation the efficacy of tapering is found to be reduced in a parameter regime where the normalized saturation wave amplitude becomes of the order of an effective (normalized) detuning parameter.

6 Coherent Structures in Electron Plasmas and Beams

It has been observed in various experiments and computer simulations that the ubiquitous appearance of coherent structures plays an important role in describing the dynamics of nonlinear systems governed by nonlinear partial differential equations. Coherent vortex structures, characterized by strong spatial and temporal correlations, occur in a variety of systems ranging from non-neutral plasmas with circulating electron flow [21],[22], to pure electron plasmas subject to diocotron instabilities in Penning trap configurations [21],[22], [24],[43],[44], to magnetrons [19],[45] and klystrons [46] for high-power microwave generation, to mention a few examples. Under the auspices of this grant, theoretical and computational investigations of coherent structures in electron plasmas and beams have been conducted. These have included: (a) analytical construction and computer simulation of vertex structures in low-density electron plasmas [21],[22],[24] and (b) computer simulation of coherent structures in intense relativistic electron flow in the relativistic magnetron [19]-[23].

6.1 Analytical construction of vortex structures in nonrelativistic electron plasmas

Use has been made of a cold-fluid guiding-center model [21],[22] to investigate the properties of stationary, two-dimensional, rotating vortex structures in a low-density, nonrelativistic electron plasma column. By introducing a stream function and making a transformation from the laboratory frame into a rotating frame, nonlinear vortex structures with an azimuthal dependence of $e^{il\theta}$ have been constructed. For example, for $l = 1$ and 2, the electron density exhibits large-amplitude variations as the radius r or azimuthal angle θ varies. The accessibility and stability of such solutions remain important topics for further investigations.

6.2 Computer simulation of vortex structures in nonrelativistic electron plasmas

In a Penning trap geometry, a nonneutral plasma column is confined magnetically in the radial direction and electrostatically in the axial direction. These plasmas exhibit a rich variety of nonlinear phenomena [22],[24],[43],[44]. In the guiding-center approximation [21],[22], the underlying equations governing the dynamics are analogous to those of an ideal inviscid two-dimensional fluid. The plasma is then well-suited for studies of vortex dynamics and merging. We have constructed a two-dimensional model of the plasma system [24]. Our simulation allows for axial strips of the containing wall to be biased to a fixed potential (analogous to having a nonzero, curl-free, component to the velocity field), which, depending on the initial density profile, deforms the plasma equilibrium, induces a diocotron type motion, or generates a partial or total loss of the plasma.

6.3 Computer simulation of coherent structures in intense relativistic electron flow

In a recent two-dimensional particle-in-cell simulation of the relativistic magnetron [19],[23], it has found that the nonlinear evolution of the system is dominated by the formation of a large-amplitude “spoke” structure in the circulating electron density. The spoke structure persists for hundreds of revolutions and is responsible for efficient coherent radiation generation. Unlike low-density nonrelativistic pure electron plasmas that support vortex structures of an electrostatic type, the rotating vortex structure in the relativistic magnetron is supported by intense relativistic electron flow and is of an electromagnetic type.

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