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CHARACTERIZATION OF A TRANSVERSE PARTICLE ACCELERATION SYSTEM

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Introduction

The impetus for the development of increased output currents for high energy accelerators is intensifying, due in part to potential applications in defense, energy, and medical technologies. Present limitations to the extension of the capabilities of conventional accelerators include space charge effects, high voltage breakdown, and duty cycle considerations. Although considerable progress has been made in attempting to overcome some of these difficulties,[1,2] interest in new acceleration techniques is increasing. This paper deals with the concept of utilizing the electric field vector of a circularly polarized traveling wave to accelerate charged particles. Since the rotating electric field vector is for the most part transverse to the dominant axial velocity component of the particle, the phase "transverse acceleration system" is used to distinguish this approach from conventional acceleration systems in which the applied electric fields are parallel to the particle velocity.

The possibility of utilizing traveling waves for particle acceleration has been discussed in recent literature[3-6] but the configuration proposed herein has not been widely investigated. Figure 1 contains a schematic of the approach to be analyzed in following sections. Because of the physical similarity to a gyrotron configuration the conceptual device is referred to as a GYRAC (GYrotron Accelerator).

Analysis

The major performance characteristics of a GYRAC device were studied with the aid of a three-dimensional computer code which calculated test particle orbits in the static magnetic and applied radiation field. A very elementary model was used in this initial feasibility investigation. Thus effects introduced by space charge forces, particle radiation loss, cavity transverse field variation effects, and radiation refraction and other off-axis effects have been ignored at the present time, although in principle each can be studied separately. Each of the above effects will tend to degrade the acceleration capability of the device and the magnitude of these effects can indirectly be estimated from the off-resonance behavior study included in this analysis.

The values of the major parameters utilized in the calculations are presented in Table 1. No attempt was made to optimize these parameters in terms of the limitations imposed by present technology in magnet and radiation source design. It should be noted that the radiation and magnetic field values, although high, are achievable over small volumes. In addition, the use of appropriate high energy laser devices should allow very high electric field strengths and the possibility of replacing the static axial B field while preserving the helical particle motion necessary for acceleration[5].

One of the advantages of the GYRAC concept is shown in Figure 2, which illustrates the time history of mono-energetic test particles with different starting phases of the radiation electric field vector relative to the $\vec{\beta}_\perp$ velocity vector. Note that although some particles are initially decelerated, all eventually enter an acceleration phase. Thus the effective "accelerating phase bucket" is 360° and therefore the duty cycle due to the RF is unity. Conventional accelerator "buckets" are typically 10° - 30°, preventing high micro-duty cycles. The initial deceleration of some particles creates an energy spread, as shown in the figure, which can be detrimental in certain applications. This spread can be reduced by injecting the electrons at lower energies, which is desirable from a source point of view.

Figure 3 demonstrates the time and distance scale over which significant acceleration occurs. Electrons are accelerated to about 30 MeV in approximately 4 nanoseconds within an axial distance of slightly over one meter, which is indicative of the potential for compact accelerator systems. The fractional energy spread shown in the figure is approximately 2.3% at $\gamma/\gamma_o = 40$. The actual energy spread ($\Delta\gamma \simeq 1.4$ or ~ 715 kev) remains constant throughout the acceleration process and thus $\Delta\gamma/\gamma$ improves as the particles gain energy.

The previous figures were generated using resonant test particles. When the electron velocity components are not matched to the radiation frequency and phase velocity, then the particles eventually enter the deceleration phase, creating an upper bound on the acceleration efficiency. Figure 4 shows the maximum gamma value attained as a function of the fractional axial and perpendicular velocity deviation from the resonant values. Due in part to the initial 2:1 ratio of $\beta_\perp$ to β_z, fractional changes in the perpendicular velocity are more detrimental than comparable shifts in the axial component. The $\beta_\perp$ sensitivity should be reduced as the injection energy is reduced and gamma approaches unity. Figure 5 shows how the increase/decrease in electron energy is partitioned between the perpendicular and axial velocity components and illustrates the fundamental feature of the acceleration process. The initial energy gain in the transverse direction ($\vec{V}_\perp \cdot \vec{E}_r$) is converted to an axial velocity increase via the pondermotive force ($\vec{V}_\perp \times \vec{B}_r$). Due to the energy spread that is initially produced and the periodicity (axial transit distance for a cyclotron period) it may be possible to tailor the inevitable energy spread in the injected beam to match that shown in Figure 5 and thus reduce the off-resonant effects shown in the previous figure. Beam conditioning should be possible since an energy spread is allowed and beam diameter is not critical in a uniform solenoidal field, thus allowing for fewer constraints on the six-dimensional phase space configuration.

Conclusions

The expected operational properties obtained from an elementary model for a transverse acceleration system for charged particles has been investigated using a three-dimensional particle orbit computer code. The salient features of this GYRAC configuration are listed below, with comments on

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potential advantages over conventional accelerators added where appropriate.

(1) High micro-duty cycle (360° acceleration phase).

(2) Compact axial dimensions relative to output energies.

(3) Potential for very low injection energies.

(4) Transverse acceleration allows the use of high energy lasers for drivers.

(5) Potential for reduced emittance restrictions.

A more detailed analysis is required to determine with greater precision the effects due to space charge forces, axial and transverse velocity spreads inherently present in any particle injection system, and other physical processes which would appear to reduce the ideal performance characteristics of such a device.

References

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TABLE 1. PARAMETERS USED IN CALCULATIONS

PARAMETER		VALUE
Initial electron energy	E_0	~300 keV
Initial gamma	γ_0	1.5925263
Initial axial beta	β_{z0}	0.36
Initial transverse beta	$\beta_{\perp 0}$	0.69
Radiation wave length	λ_0	$5.458149313 \times 10^{-4}$m
Approximate frequency	f_0	~549 GHz
Radiation field strength	$\vec{E}_r$	1×10^8 V/m
Axial magnetic field	B_0	20 T

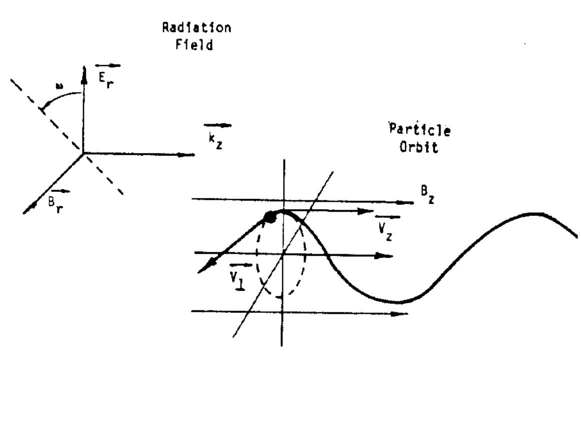

FIGURE 1. GYRAC CONFIGURATION

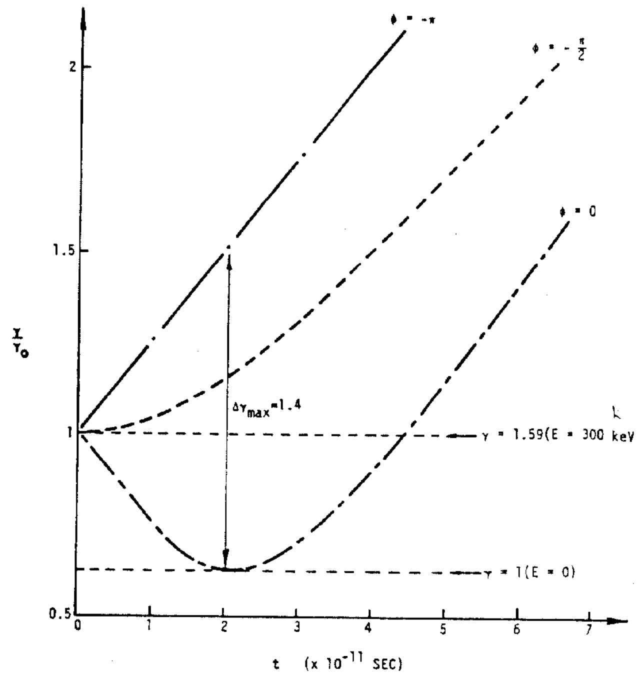

FIGURE 2. CHANGE IN GAMMA WITH TIME FOR DIFFERENT STARTING PHASES

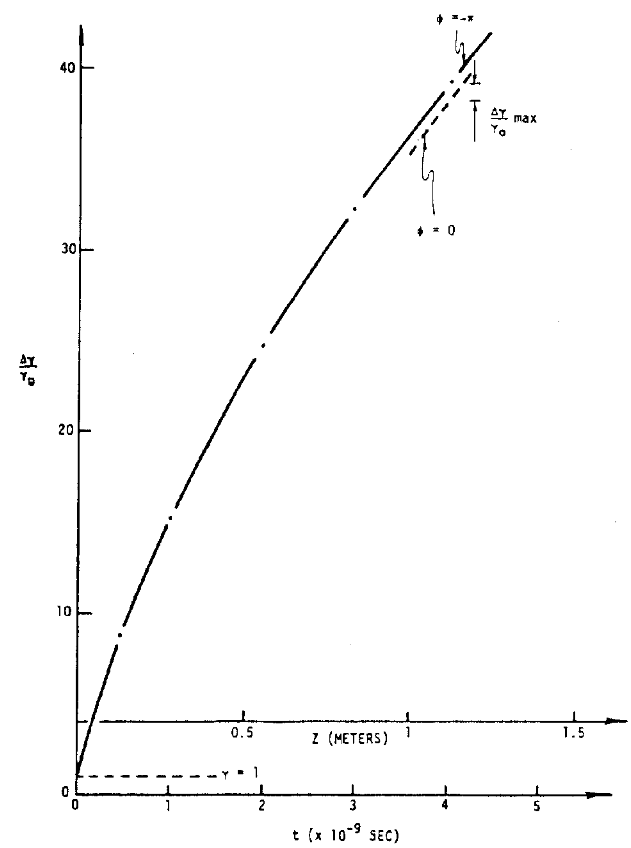

FIGURE 3. ENERGY GAIN (CHANGE IN GAMMA) VERSUS TIME AND AXIAL POSITION FOR MAXIMAL STARTING PHASE

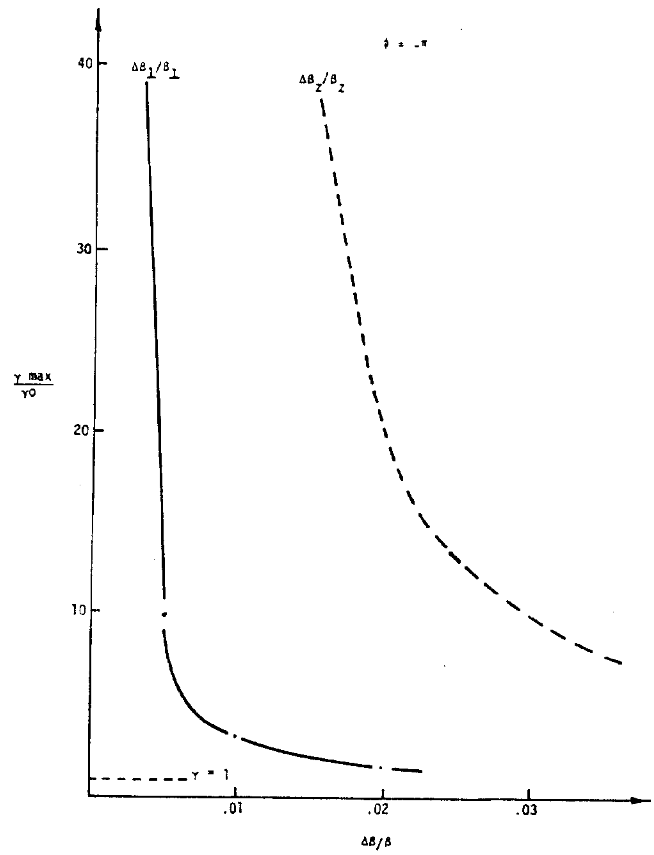

FIGURE 4. SENSITIVITY OF MAXIMUM ACCELERATION TO AXIAL AND TRANSVERSE VELOCITY VARIATIONS

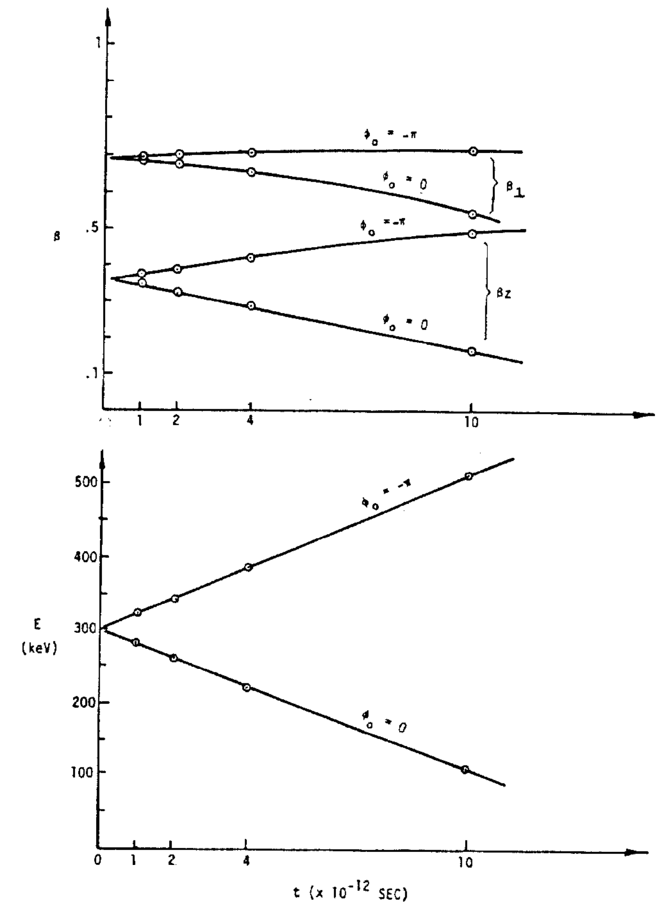

FIGURE 5. VARIATION OF AXIAL AND TRANSVERSE VELOCITIES FOR MINIMUM AND MAXIMUM ACCELERATION PHASES