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HIGH-ENERGY ELECTRON BEAM-INDUCED IONOSPHERIC MODIFICATION EXPERIMENTS

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13. ABSTRACT *(Maximum 200 words)*

The University of Michigan Space Physics Research Laboratory was given the task of providing scientific investigations of beam propagation physics associated with the injection of a MeV electron beam into the earth's atmosphere. Motivation for this study was driven by the reduction in weight and size of electron beam accelerators in this energy regime to the point which enables them to be flown on balloons, rockets, or spacecraft. Program goals included the modeling of dynamics of MeV electron beams injected from LEO spacecraft into the atmosphere, analysis of the collisional and beam-plasma interactions, and modeling of ionospheric modification induced in the atmosphere, such as enhanced plasma densities, optical emissions and conductivity changes. Results show that, for downward directed beams, radial defocusing of beam electrons due to scattering by the atmospheric neutrals is significantly mitigated by the presence of the earth's magnetic field. In addition, substantial ionospheric modification occurs due to the beam atmosphere interaction, resulting in plasma densities and conductivities significantly above the ambient values. Proposed future work includes the study of optical and bremsstrahlung emissions to be used for diagnostics of beams injected from space, beam propagation dynamics over long distances, and modification of the atmospheric electric potential.

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CONTENTS

1. BACKGROUND

Electron beam (linac) accelerators in the MeV range have been reduced in weight and size to a point that enable them to be flown on balloons, rockets or spacecraft. This opens up the opportunity for a new generation of space-borne relativistic electron beam experiments, as discussed in the AFGL study report by *Banks et al.* [1987]. Acting on the results of the 1987 study, the Air Force solicited proposals under the SBIR program for a sounding rocket experiment module including a linac. A contract was awarded System Planning Corporation (SPC) which is now heading a Phase 2 effort that will lead to a flight-ready sounding rocket module. The beam characteristics of the linac are: I = 100 mA, E = 5.2 MeV, pulse length = 4 μs, duty cycle = 0.1%.

On the background of these activities, the University of Michigan Space Physics Research Laboratory was awarded the present contract by the Air Force to provide scientific investigations of beam propagation physics and atmospheric interactions. The contract was in place at the University of Michigan in May 1993, and work was initiated at the end of that month.

2. PROGRAM OBJECTIVES

At the outset, the following overall goals for the program were defined:

(1) to model the dynamics of MeV-energy beams injected from LEO spacecraft into the atmosphere, including beam-plasma interactions in the ionosphere and collisional interactions in the atmosphere.

(2) to model the modification induced in the atmosphere such as enhanced plasma densities, optical emissions, and conductivity changes.

(3) to assess from such models changes induced in the atmospheric electric structure and under what conditions triggering of upward lightening is likely for beams injected over thunder clouds.

(4) to explore modifications to middle atmospheric dynamics induced by energetic particle precipitation.

(5) to assess the interest in the aeronomy community for an active experiment of this nature.

Because of the transfer of Air Force technical oversight at a mid-point in the contract from ionospheric to space plasma disciplines, not all of the above areas received equal attention. In particular, emphasis was given to areas (1) and (2) with lesser efforts for the others.

3. RESULTS

3.1 BEAM-PLASMA INTERACTION

As the beam exits the accelerator payload, it encounters the ambient ionospheric plasma and is immediately subject to beam-plasma interactions (BPI). A quantitative model of BPI as it manifests in active space experiments has yet to be developed, partly because the problem is a difficult one, and partly because experiments with adequate plasma diagnostics have been relatively few. To develop a model for BPI (funded on other contracts), collaboration was established with Dr. G. Khazanov of the Space Physics Research Laboratory at the University of Michigan. Dr. Khazanov has written a kinetic model based on the Boltzmann equation describing transport of suprathermal electrons in the ionosphere-plasmasphere and energetic auroral particle precipitation. In our first effort, the characteristics of a 10 keV beam was studied under the assumption that Langmuir turbulence elastically scatter beam electrons. It was clear from this study that the more difficult part is to parameterize properly the scattering of beam electrons by Langmuir turbulence. Thus, only elastic back-scattering was considered while experiments clearly show the importance of inelastic scattering. A paper describing the results was published in Geophysical Research Letters [*Khazanov et al.*, 1993].

3.2. BEAM-ATMOSPHERE INTERACTION

3.2.1. Monte Carlo Simulations.

Previous analytical efforts [*Banks*, 1987] were able to identify applicable models of beam atmospheric ionization, associated energy loss, and beam spreading without magnetic field focusing. From this early effort, the importance of including magnetic field focusing effects was identified since beam spreading, due to elastic collision processes, dramatically reduced the expected ionization density. It was, therefore, considered a top priority to investigate magnetic field effects on beam dynamics.

Efforts to model the collisional interaction of a beam with the earth's atmosphere including the earth's magnetic field has been studied in two ways. The first is the adaptation of already existing Monte Carlo algorithms, while the second is an analytical approach. We focused on predictions of energy deposition rates, the spreading of the beam perpendicular to the ambient magnetic field, and the penetration depth of the beam. For this purpose a collaboration was begun with Professors W. Martin, Y. Y. Lau, and with Dr. S. Wilderman, all of the Department of Nuclear Engineering at the University of Michigan.

Two different Monte Carlo transport algorithms have been applied. One is the EGS4 program, which has been used extensively and thoroughly benchmarked by both the high-energy physics and the medical physics communities. EGS4 uses the condensed random walk transport algorithm in which a particle's full transport path is broken into roughly a hundred segments. Aggregate deflection and ionization through each segment is assumed to be described by analytically derived distribution functions, and the full particle path is modeled by successive application of appropriate segment-wise scattering distribution data.

As a means of verification, a more computationally intensive algorithm, which treats all elastic scattering events individually and employs best available differential scattering distribution data, was also applied to this problem. Both simulations produced similar results, and we are satisfied that the algorithms can be used for our purpose.

Simulations were performed with the beam injected vertically downwards from 60 km altitude (the altitude where beam-atmosphere interaction becomes significant at 5 MeV). The atmosphere is modeled as eleven separate 2 km thick 'slabs' composed of 70% N_2 and 30% O_2, and with constant local density. Energy deposition is tallied for cubic regions of volume (1 km x 1 km x 100 m) for simulations without the earth's magnetic field and $(100\ \mathrm{m})^3$ for simulations which include the magnetic field. The energy deposition profiles in altitude and in lateral dimensions are determined in this way.
Simulations of a balloon-borne beam accelerator were also performed with an upward directed beam injected at 40 km altitude.

3.2.2. Envelope Equations

With the cooperation of Professor Y.Y. Lau, we investigated a class of closed form analytical expressions to estimate spreading of relativistic electron beams, the so called "paraxial envelope equations" [*Murphy et al.*, 1992; *Lawson*, 1988; *Lee and Cooper*, 1976]. These equations may be adapted to the case of beam propagation over hundreds of kilometers of distance while accounting for magnetic field focusing effects. The envelope equations utilize a paraxial approximation (i.e., $v_z >> v_r$) to simplify the equations of motion while still tracking the effects important to radial beam expansion. Using the envelope equations, it is possible to allow for expansion effects other than elastic scattering, such as electrostatic self-expansion.

The envelope equations are closed-form analytical expressions to estimate the spreading of relativistic electron beams [*Humphries*, 1990]:

$$\frac{d^2R}{dz^2} = -\left[\frac{{}^{d\gamma}\!/\!{}_{dz}}{\beta^2\gamma}\right]\frac{dR}{dz} - \left[\frac{\omega_{ce}}{2\beta\gamma c}\right]^2 R + \frac{\langle\theta^2\rangle}{R} + \left[\frac{R_o^2\omega_{ce}}{2\beta\gamma c}\right]^2 \frac{1}{R^3} \tag{1}$$

$$\frac{d\langle\theta^2\rangle}{dz} = \left.\frac{d\langle\theta^2\rangle}{dz}\right|_c + \frac{2\gamma}{\gamma^2-1}\langle\theta^2\rangle\frac{d\gamma}{dz} \tag{2}$$

$$\left.\frac{d\langle\theta^2\rangle}{dz}\right|_c = \frac{16\pi NZ(Z+1)r_e^2}{\gamma^2\beta^4}\ln\left[\frac{204}{Z^{0.333}}\right] \tag{3}$$

$$\frac{d\gamma}{dz} = -\frac{2\pi NZr_e^2}{\beta^2}\left[\ln\left(\frac{1}{2}\left(\frac{E^o}{I}\right)^2\beta^2\gamma^2(\gamma-1)\right) - \ln^2\left(\frac{2}{\gamma}-1+\beta^2\right) + \frac{1}{\gamma^2} + \frac{\left(1-{}^{1}\!/\!{}_{\gamma}\right)^2}{8}\right] \tag{4}$$

The beam is propagating in the z-direction, and the radius of the beam, R, is a function of z. These are the envelope equations *per se*, where we have only retained terms that are of significance for the problem at hand. In (1), the first term on the right-hand side represents focusing processes arising from acceleration or deceleration of electrons with position along the z-axis. The second term represents applied magnetic fields, in our case the earth's magnetic field, while the third term describes defocusing processes from scattering and deceleration. The final term represents the defocusing effect arising from the conservation of canonical angular momentum. In the equations, R_o is the beam radius at injection, γ is the relativistic factor, β is v_z/c, c is the velocity of light, and ω_{ce} the non-relativistic electron gyro frequency.

Equation (2) describes defocusing by emittance due to collisions (first term) and deceleration (second term). Here $\langle\theta^2\rangle$ is the mean-squared divergence angle. The small-angle scattering formula is shown in (3), where N and Z are properties of the medium, r_e is the Bohr radius, and γ and β are functions of z. The equations are closed by the Bethe formula (4), which gives the collisional stopping power for relativistic electrons.

It was hoped that the equations could be simplified by the introduction of the so-called Nordsieck length [*Lee and Cooper*, 1976; *Murphy et al.*, 1992]. However, the assumptions under which the Nordsieck length is derived (high-current beams) are not valid for our case, and we are forced to solve the complete set of Equations (1)-(4).

3.2.3. Simulation Results

In the Monte Carlo simulations a beam is injected downwards from 60 km altitude or upwards from 40 km altitude. The upward injection simulates the case of a linac carried on a balloon, and the downward injection the case of a sounding rocket experiment. The altitude of 60 km was chosen to limit the computational effort. The atmosphere above this altitude is relatively tenuous, and little scattering/ionization is experienced above 60 km.

The atmosphere is the MSIS86 model for night-time, mid-latitude conditions [*Hedin*, 1987]. Figure 1 shows the fractional energy deposition of a 5 MeV beam injected downwards from 60 km altitude. The black curve represents the Monte Carlo results, and the red curve represents the results using the Bethe formula. As can be seen, there is very good agreement between the two. The Bethe formula predicts an altitude limit at 42 km; the Monte Carlo results peak here, but they predict that a small fraction of electrons will penetrate to 40 km altitude. The good agreement was anticipated since, after all, the EGS4 code incorporates the Bethe formula.

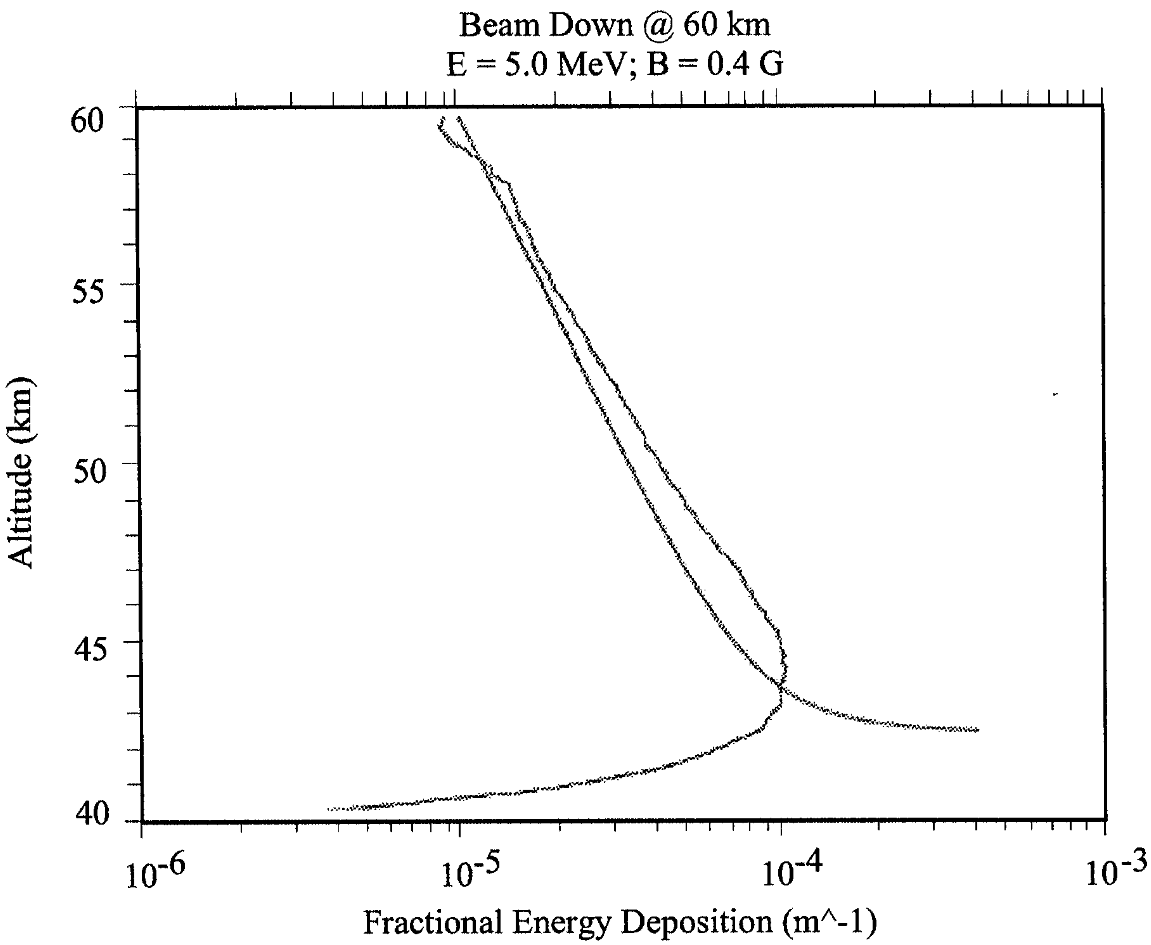

Figure 1. Fractional Energy Deposition: The Bethe formula (red curve) and Monte Carlo Simulation (black curve).

Turning now to the problem of the radial expansion of the beam and the influence of the magnetic field on this expansion, the case of a downward injected beam from 60 km altitude and no magnetic field is shown in Figure 2. The fractional energy deposition as a function of altitude and horizontal distance is shown on a gray-scale together with the analytical results obtained from the envelope equations. We notice an excellent agreement between the two approaches. It is also evident that without a magnetic field, the beam experiences substantial spreading in the horizontal direction, up to 8 km at 42 km altitude. As mentioned earlier, this spreading is caused by diffusion induced by electron-neutral scattering.

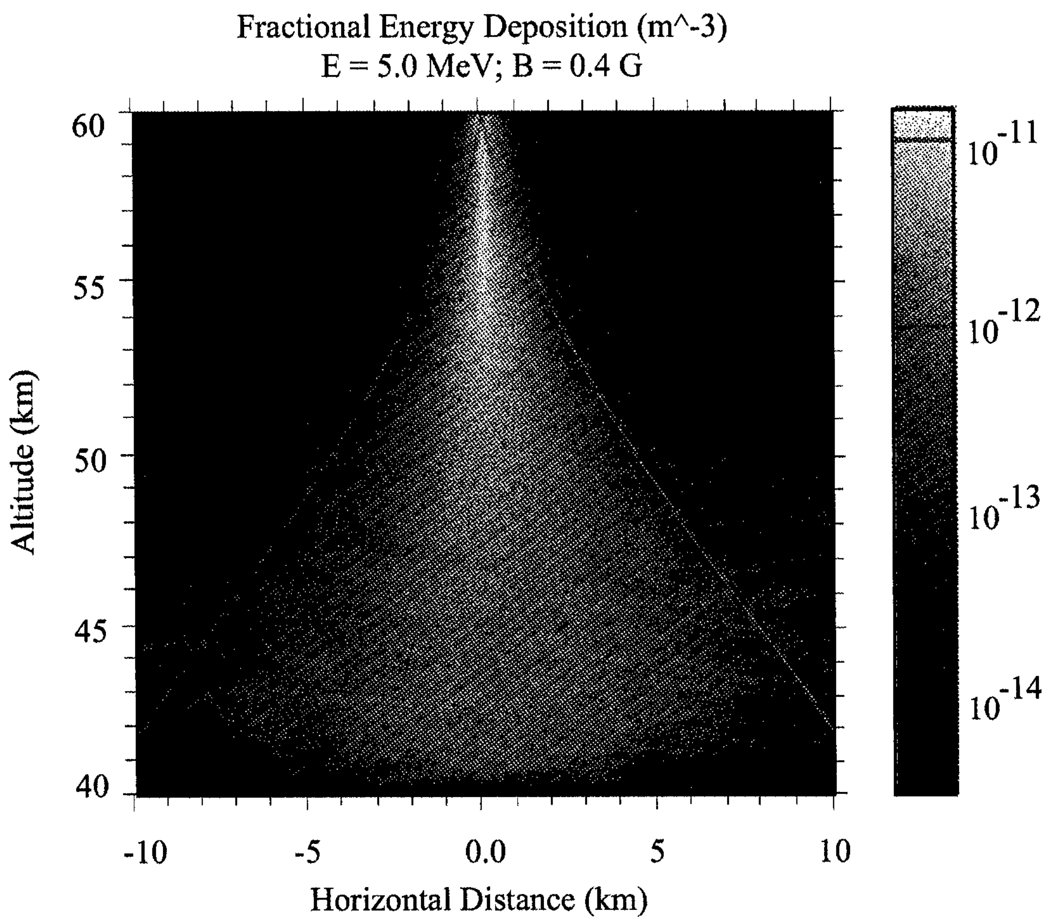

Figure 2. Beam cross-section of fractional energy deposition as a function of beam radius and altitude. The Earth's magnetic field is not included. The simulations are shown on a greyscale and the solution of the envelope equations with the red curve.

The question is now to what extent the magnetic field is able to contain the radial beam spreading, and thereby focus and enhance the perturbation of the atmosphere. A Monte Carlo simulation was run with same beam-atmospheric parameters as those used for Figure 2 except that the earth's magnetic field was included. The result is shown in Figure 3. The beam is now well contained, and the beam radius is within 400 m, which is even less than the 607 m gyro radius of a 5 MeV-beam injected perpendicular to the magnetic field (notice the change of horizontal scale). The analytical results are also in overall agreement, with the exception that the envelope oscillates with altitude.

Fractional Energy Deposition (m^-3)
E = 5.0 MeV; B = 0.4 G

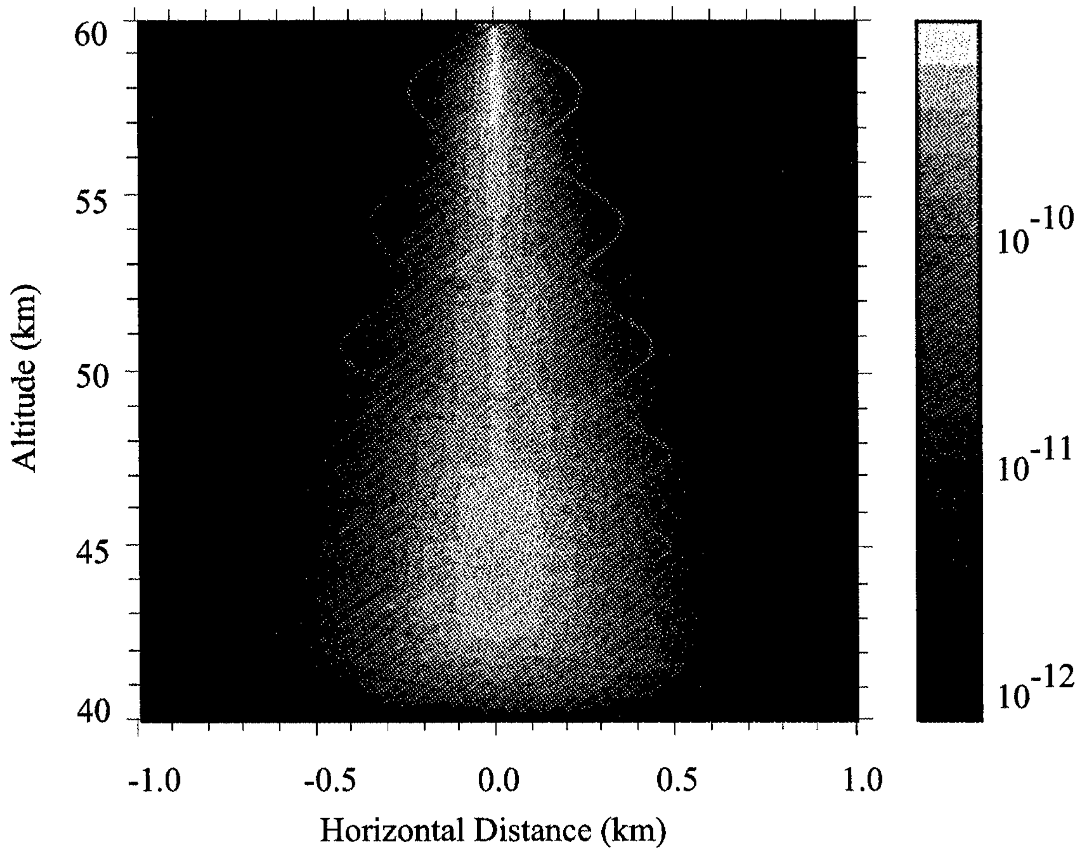

Figure 3. Same as Figure 2, including the Earth's magnetic field.

The oscillations in the analytical solution to the beam envelope equations represent the expansion and contraction of the effective radius of the beam due to the gyromotion of the beam particles. Consider the case illustrated in Figure 4 in which there is no scattering. A particle which starts on the beam axis moves away from the axis as it starts its gyromotion, increasing the beam's radius. As it completes one orbit, it returns to its initial radial position after a time $T = 2\pi/\omega_{ce}$, thus decreasing the beam's radius. When scattering is considered as well, the oscillations are retained. To a first approximation, the wavelength of the oscillations is given by the time required for the particle to complete one gyration multiplied by the axial velocity of the particle. (In actuality this is not exact since the electron will most likely undergo a collision before it completes one gyro-orbit.) This is the so-called "betatron wavelength", given by (in the absence of collisions):

$$\lambda_b = \frac{v_z 2\pi\gamma m_o}{eB} \tag{5}$$

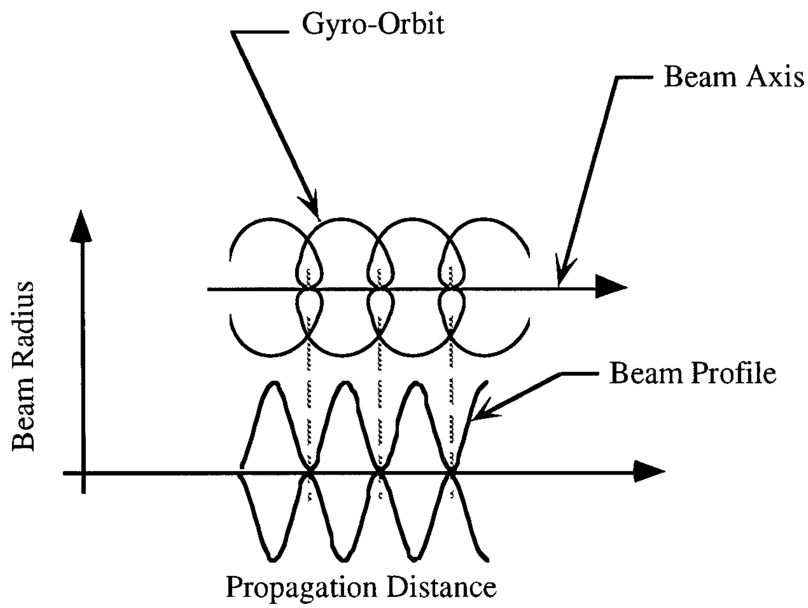

Figure 4. Radial position of the beam particle (shown as the beam profile) varies with position in gyro-orbit.

The oscillations are highly dependent on the initial conditions of the envelope equations. A graphical representation of the solution of Equations (1)-(4) appears in Figure 5 for two sets of initial conditions. Propagation begins at 120 km in altitude in this example, so scattering is not as prevalent. Note that it is possible to center the beam on the gyrocenter of the outermost electron of the beam. In this case, the oscillations do not appear since the radial position of the electron with respect to the beam axis is the same as the radial position with respect to the gyrocenter: a constant. When this is done with the collisions, however, the oscillations are slight near the origin, but increase to their previous severity as the beam propagates down the atmosphere (Figure 6). The reason for this is that the particle does not have enough time to complete one gyro-orbit before it experiences a collision, thus removing the gyrocenter from the beam axis. Therefore, the radial distance of the particle from the beam axis is no longer the same as that from the gyrocenter, and the gyromotion driven oscillations reappear.

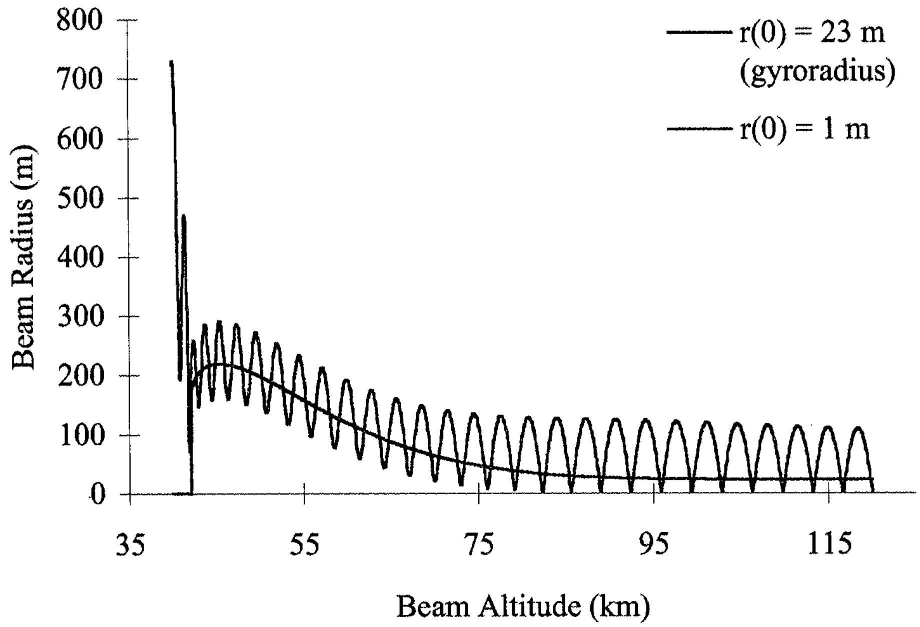

Figure 5. Variation in envelope oscillations between a beam initiated at the gyroradius and one initiated at approximately the beam radial origin.

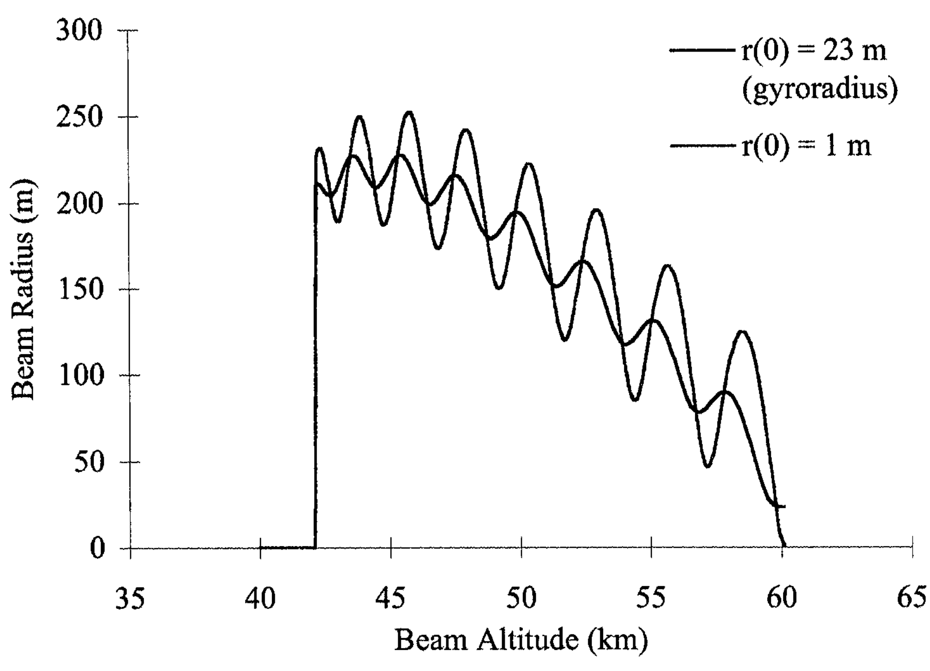

Figure 6. Oscillations remain in the case of collision-dominated propagation, in spite of initially locating the beam's axis at the gyrocenter.

Since the envelope equations are single-particle in nature and track the orbit of the outermost particle, the gyromotion of the particle is preserved, manifested via the oscillations. If many particles are considered, the oscillations are coherent provided the paraxial approximation is applicable. Consider the collection of orbits with slightly varying initial pitch angles in Figure 7. While the orbits are in phase with each other during the initial stages of propagation, they eventually blur into one another farther down the length of propagation. This effect is indicative of the validity of the paraxial assumption of our beam. When the beam is paraxial in nature, the particle's parallel velocity is large compared with the transverse component. In this situation, the pitch angle does not affect the wavelength of the oscillation dramatically. Particles with slightly varying pitch angles will converge on the same spatial coordinate after each gyro-orbit. However, if the particle's transverse velocity is comparable to its parallel component, a difference in pitch angle will result in significantly different parallel velocities. Thus, the wavelengths will differ, and the oscillations will blur.

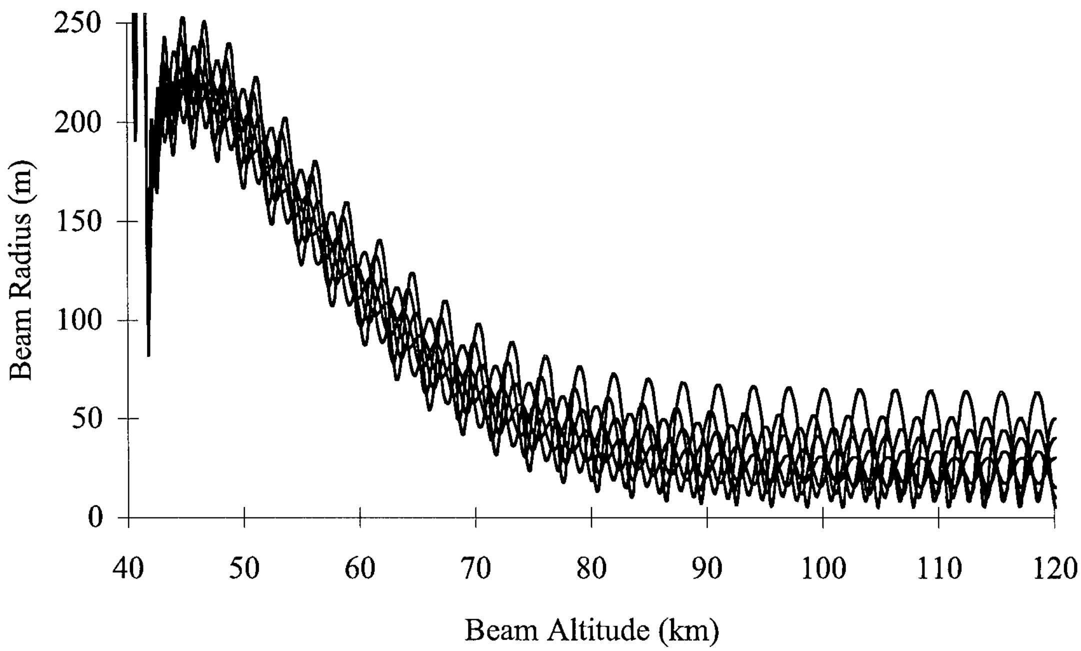

Figure 7. Particle trajectories are coherent with $T=2\pi/\Omega$.

3.2.4 Conclusions

In conclusion, we find:

- Monte Carlo algorithm successfully adapted to atmospheric conditions with magnetic field
- Envelope equations + Bethe's equation can approximate beam-atmosphere interactions in a magnetic field

3.3. ATMOSPHERIC MODIFICATION

Electron Density

From the fractional energy deposition calculations, the electron density can be calculated by assuming one electron-ion pair created for every 35 eV energy loss. The results are shown in Figure 8 for downward directed beams. The beam parameters are those proposed for a sounding rocket experiment funded by AFOSR, where the beam energy is 5 MeV, the beam current 80 mA, and the pulse duration 10 ms. It is assumed that recombination occur on a longer time-scale (ms), so the densities shown are those immediately after one beam pulse injection.

Densities are of the order of 10^8-10^9 m^{-3}, or two orders of magnitude larger than the ambient density. For reference, typical ionospheric peak densities at higher altitude range from 10^{10}-10^{12} m^{-3}. It is probable that higher densities can be achieved during repeated pulse injections. In this case, however, the effects of the rocket velocity across the magnetic field and recombination rates must be taken into account. Such calculations have yet to be performed.

3.3.2. Electric Conductivity

The atmospheric electric conductivity resulting from the beam injection is shown in Figure 9 for downward injection. The background conductivity increases with altitude according to *Volland* [1984], primarily due to the presence of negative ions.

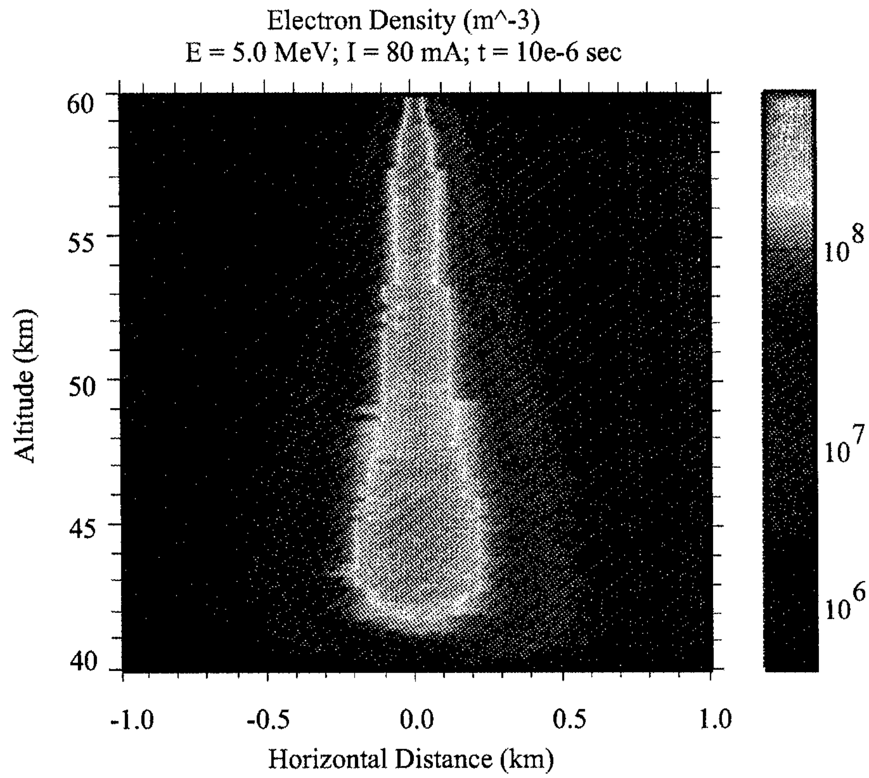

Figure 8. Electron density from Monte Carlo Simulation

The conductivity inside the beam is calculated from the information on the enhanced plasma density. It reaches values of the order of 10^{-9}-10^{-8} S/m, or 1-2 orders of magnitude above the ambient conductivity. It is expected, therefore, that significant modification of the ambient electric potential will be induced in and around the beam. A time-dependent calculation is needed here because of the short exposure and perturbation time of a beam column.

3.4. MIDDLE ATMOSPHERIC DYNAMICS

3.4.1. Introduction

In direct consultations with colleges we have identified two broad science areas for middle atmospheric dynamics:

(a) To determine the effects of energetic particle precipitation on the chemical composition of the atmosphere. Particle precipitation can significantly affect the

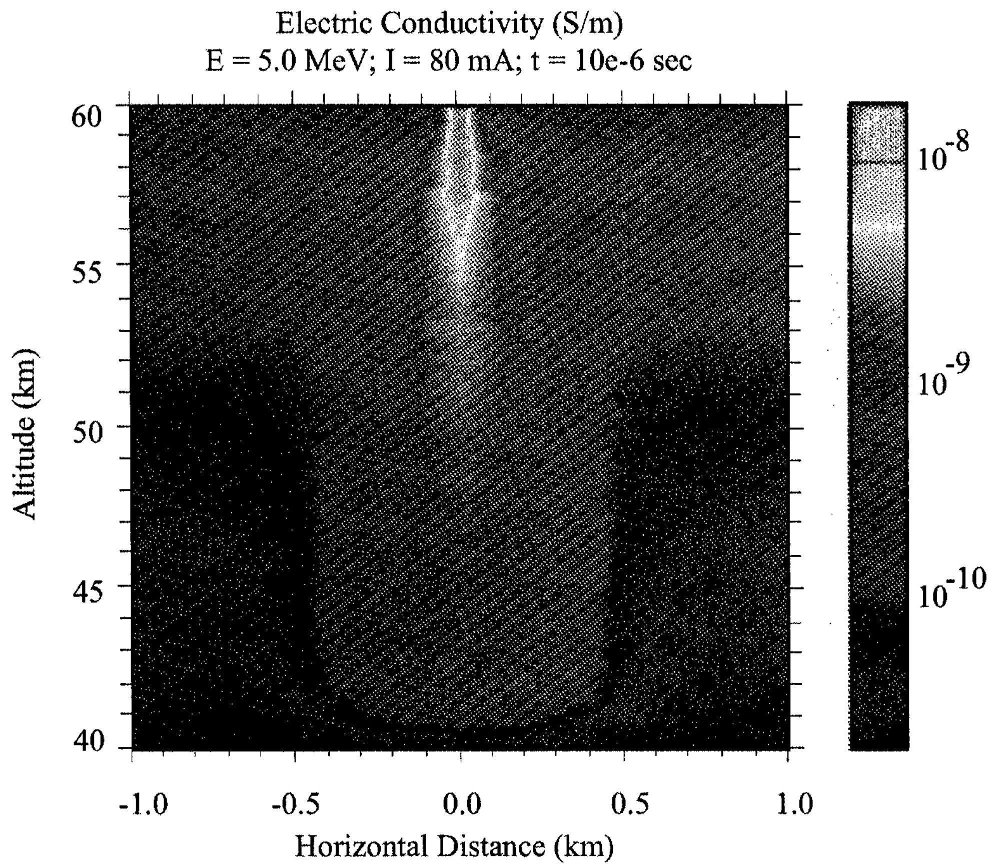

Figure 9. Electric Conductivity from Monte Carlo Simulation.

chemical composition by enhancing ionization and disassociation of atmospheric gases as well as constituent temperatures. Transport of winds and eddy mixing can extend these effects to regions far from those directly affected by the precipitation. Of particular interest are production of odd-nitrogen and odd-oxygen species, since both lead to depletion of ozone in the stratosphere and mesosphere.

(b) To investigate the influence of energetic particle precipitation on the electrical structure of the middle atmosphere. The changing conductivity affects the global electrical circuit and has a direct influence on high-latitude radio communication. Recent reports on upward lightning events [*Franz et al.*, 1990; *Boeck et al.*, 1991, 1992] from the top of thunder clouds underlines the possibility of the idea put forward in our original proposal that MeV beams injected over thunderclouds may possibly trigger upward discharges.

The above items are of interest because of natural precipitation of high-energy particles, particularly in the auroral zone and over the polar caps. In fact, a complete instrument package on the UARS satellite is devoted to the study of the influence of energetic particle precipitation on the middle atmosphere: The Particle Environment Monitor (PEM) which measures electron precipitation in the energy range 1 eV to 5 MeV and proton precipitation in the range 1 eV to 150 MeV. In addition, global images of X-rays produced by Bremsstrahlung (3-100 keV) are provided by a companion experiment.

In addition to UARS, rocket and balloon experiments have been performed in the past to study x-ray emissions, electric fields, electron fluxes, etc., associated with relativistic particle precipitation. There is some uncertainty as to the validity of some models, or, in the case of chemical models, if the dominant processes have been identified. An active space experiment therefore has interest, in particular under the following conditions:

(1) That a beam can be described sufficiently well to allow "calibration" type experiments of natural beam-induced phenomena and
(2) that the beam has sufficient power to create a measurable stimulus of parameters of interest.

For the study of mid-atmospheric dynamics, an experimental configuration consisting of ground-based radar observations of plasma density enhancements, high-altitude balloon observations of electric field perturbations and optical emissions, and a sounding rocket carrying the accelerator and some plasma diagnostics seems an attractive combination. The altitude of the maximum energy deposition of the beam is around 45 km which can be reached by balloons. In certain locations such as Wallops Island, the wind patterns are relatively stable, and it should be possible to launch balloons and rockets in a good relative location [*Holtzworth*, private communication].

3.4.2. Atmospheric Electric Potential

It seems likely that perturbations in the electric fields at balloon altitudes and optical emissions can be stimulated to a degree that make balloon observations of these parameters attractive. The peak beam power of the accelerator is anticipated to be very high, 480 kW, with an average beam power of 480 W. In comparison, the SEPAC electron beam experiment (6.25 keV, 8 kW) flown on ATLAS-1, stimulated aurora of an intensity of about 5 kR when observed by on-board cameras in white light continuum [*Burch et al.*, 1993; *Mende et al.*, 1993].

Perhaps the most spectacular is the possibility that the atmospheric electric potential structure can be sufficiently modified to allow discharges between the beam column and the ambient atmosphere. The recent reports of optical flashes above thunderstorms observed from the space shuttle [*Boeck et al.*, 1992] from ground [*Franz et al.*, 1990], and from aircraft [*Sentman and Wescott*, 1993; *Sentman et al.*, 1995; *Wescott et al.*, 1995], indicate that on occasion, electrical discharges occur naturally above thunderstorms. A relativistic electron beam experiment may, therefore, provide a new means of actively probing upper atmospheric electric phenomena.

To explore this issue further, we calculate the column resistance per unit length, r, from an estimate in *Banks et al.* [1990]

$$r \approx \frac{m_e \nu_{en}}{n_e e^2 A} \tag{6}$$

where ν_{en} is the electron-neutral collision frequency, n_e the electron density in the beam column, and A the beam cross section area. Both the initial electron density in the column and the electron-neutral collision frequency are proportional to the neutral gas density so that r is roughly constant with altitude. Using 50 km as a reference altitude we have $\nu_{en} \approx 10^8 \mathrm{s}^{-1}$, and from Figure 8 that $n_e \approx 10^8$ m^{-3} and $A \approx 10^5$A m^2, which gives $r \approx 360$ Ω/m.

The resistance in the column is therefore substantial, and a modification of the new electric potential structure in the beam column will be established with a time constant determined by the diffusion time of the electric field into the column. An expression for this time constant, τ_c, was estimated in *Banks et al.* [1990]

$$\tau_c \approx \frac{\nu_{en}}{\omega^2{}_{pe}} \tag{7}$$

Using the values for electron density from Figure 8, we find the time constant at 50 km altitude to be $\tau_c \approx 300$ μs. It is of interest to compare the diffusion time of the electric field with the life-time of the ionization enhancement. Electrons are most rapidly lost through attachment to O_2. The electron-negative ion equilibrium time constant is about 23 ms at 50 km altitude [*Banks et al.*, 1990]. The life-time of the electron density enhancement in the beam column is therefore sufficient for the electric field to diffuse into the beam and thereby modify the electric potential structure around the beam.

The average potential difference between ground and the ionosphere is about 300 kV, with the ionosphere positive and ground negative. Most of the potential drop occurs over the first few km altitude where the neutral density is high and the conductivity low. Under fair weather conditions, the electric fields above 50 km altitude are of the order of 0.1 V/m or smaller with a total potential increase from 50 km altitude to the ionosphere of about 1 kV. For the case of an ideal conducting beam column extending downwards from the ionosphere, the potential between the beam and the ambient atmosphere outside of the beam would reach 1 kV at 50 km altitude. With a beam radius of about 200 m, this potential difference corresponds to an average electric field strength of 50 V/m. In comparison, the break-down electric field for discharge in the atmosphere varies from about 10 V/m at 80 km altitude to 10 kV/m at 50 km altitude.

It is possible, therefore, that at altitudes around 70 km and above discharges around the beam may be triggered. The study of these will provide new insights into the electrification of the earth-atmosphere-ionosphere system. In addition, it may be of interest to inject beams over thunderstorm regions to directly probe the electric generator of the earth-ionosphere electric field. In this case, the polarity is reversed and locations above cloud tops are positive with respect to the ionosphere. Averaged potential differences are at values of about 1 kV, and peak potentials are likely to be an order of magnitude larger or more. It is possible, therefore, that MeV beams injected over thunderstorms can trigger upward discharges similar to those observed occurring naturally. Experiments as well as further modeling efforts are clearly needed to explore the potential of linacs in atmospheric research.

3.4.3. Atmospheric Community Interests

Discussions have been held with the following persons, who have shown interest: Dr. Raymond Roble, NCAR (atmospheric circulation and electrical structure), and Professor Robert Holtzworth, University of Washington, (electrical structures-high altitude balloon observations). Other scientists who may have interest but have not yet been contacted: Hugh Anderson, SAIC (beam-plasma interactions), Prof.Ben Balsley, CIRES (electrical structures - radar observations), and chemical reaction paths and ozone: Dan Baker, GSFC, Leslie Hall, Penn State, Charlie Jackman, GSFC, and Linwood Callis, NASA Lewis.

4. FUTURE STUDIES

There are several extensions of the present study that could be of interest both for general research purposes but also for direct support of SLINAC experiments.

The areas that we would suggest for future studies include:

- optical and x-ray emission characteristics of beams injected into the atmosphere - important for the diagnostics of beams injected from space

- beam propagation dynamics over longer distances , i.e. between hemispheres - the lifetime of beam electrons in the plasmasphere is of interest to radiation belt studies and stability of the beam towards wave growth is important for application purposes

- modification of the atmospheric electric potential - further modeling efforts are needed to assess to what extent beams injected from space can be used as tools for the study of the electrification of the atmosphere

5. PUBLICATIONS AND PRESENTATIONS

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