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A STUDY OF ELECTRON BEAM WAVE GENERATION

Stanford University

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This report summarizes theoretical and experimental work on electron beams in space. The ~~primary~~ purpose of this work, which was conducted during the interval 29 Dec 83 through 28 Jun 86, was to investigate the possibility of using a modulated electron beam on a space platform as a virtual "antenna" to radiate electromagnetic waves down to the earth's surface. Our study has established a strong theoretical base from which to make predictions of the electromagnetic radiation produced by a modulated electron beam in space, and it has given much new information about the wave and plasma effects produced in the vicinity of such a beam. Although it necessarily leaves some important questions unanswered, it nevertheless provides substantial support for the virtual antenna concept. Further experiments and theory will be required to establish the optimum conditions for radiation from such an antenna.

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1. INTRODUCTION

Early in January 1984, Rome Air Development Center (RADC) issued a contract to Stanford University for a two and a half year study of electron-beam wave generation in space and the subsequent propagation of the waves to earth. The Principal Investigator for the study was Professor P.M. Banks, who heads the Space Plasmas Group. in the Space, Telecommunications and Radioscience Laboratory and the Associate Investigator was Dr A.C. Fraser-Smith.

The study was largely stimulated by the Fast Pulse Electron Gun (FPEG) experiment on the third flight of a Space Shuttle Orbiter (usually designated STS-3 by NASA). which took place during March 1982. The Principal Investigator for the experiment was Professor P.M. Banks and it was managed by the Space Plasmas Group. In addition to the data acquired specifically as part of the FPEG experiment. the Space Plasmas Group also had access to the uniquely complete collection of wave and plasma data aquired by the University of Iowa's Plasma Diagnostic Package (PDP) during operation of the FPEG. The object of the RADC-funded study was to investigate the FPEG and PDP data, both theoretically and experimentally, to determine the conditions under which an electron beam might be used to radiate electromagnetic waves down to the earth's surface.

The study started on December 29. 1983. and concluded on June 28. 1986. Most of its results have now been published, or have been submitted for publication. In the following we summarize the results and document the various publications. A full list of publications by the Space Plasmas Group, together with a list of general references for this report. is given at the end of the text.

In addition to Professor P.M. Banks (P.I.) and Dr A.C. Fraser-Smith (A.I.), the other scientists and engineers who contributed to the research reported here were, alphabetically, Dr R.I. Bush, Dr K.J. Harker, Dr T. Neubert, Mr G.D. Reeves, and Professor L.R.O. Storey.

2. THEORETICAL RESULTS

Artificial electron beam experiments in space only became a subject of keen research interest over the last decade, or so, and thus the theoretical basis for understanding the results of the experiments has only been under development for a short time. During the same time, a number of experiments of increasing complexity have been undertaken, such as the VCAP experiment on the STS-3 flight in March 1982, the SEPAC experiment on Spacelab 1 in November-December 1984, and the Spacelab 2 flight in July 1985. The theory necessary for the understanding of the electron beam experiments has therefore tended to lag behind the experiments.

Beam injection experiments can tell us a great deal about the space environment, but probably one of the most interesting aspects of the experiments from the theoretical point of view is the generation of plasma waves by the electron beam in the presence of the background plasma. By monitoring these plasma wave emissions, such as with the Plasma Diagnostics Package (PDP) developed by the University of Iowa for Space Shuttle experiments, we can learn much about the interaction processes that take place in the beam-plasma system.

The primary motivation for the study of electron beams in space in this study has been the possibility of using the beam as an antenna, i.e., as a generator of electromagnetic waves for communication purposes. The availability of an antenna which uses no wires, but only a modulated beam of electrons in space, offers great potential advantages. Chief among these are long length and thus higher radiation resistance (important for the generation of low frequency waves), and the elimination of metallic ohmic losses.

2.1 PAST WORK

Over the last four years, we have conducted a systematic investigation of the generation of electromagnetic waves by the passage of a pulsed electron beam through a magnetized plasma. This effort was motivated, of course, by the numerous experiments and applications which have been mentioned above. Measurements of the electromagnetic fields generated in these experiments have been made with varying results, which points to the complexity of the radiation process.

Using a simple model for a pulsed electron beam, we have obtained a number of important predictions concerning the nature and characteristics of the fields generated. Basically, there are three main radiation mechanisms that can cause emissions from an electron beam: (1) incoherent spontaneous emission, (2) coherent spontaneous emission, and (3) stimulated emission.

In incoherent spontaneous emission all the electrons radiate independently of one another, giving rise to a radiated power proportional to the number of radiating particles. A number of authors have studied this phenomena in relation to either natural or artificial beams. Their general conclusion has been that incoherent spontaneous emission is not strong enough to give significant radiation from an electron beam of the type currently injected into space from orbiting vehicles.

In coherent spontaneous emission each particle still emits by spontaneous emission, but now the particles are constrained to travel in orbits which force all velocities at each particular position in space to be alike, leading thereby to coherent emission. For a charged particle traversing a magnetoplasma this velocity correlation comes from the fact that all the particles originate from approximately the same region of space and then are constrained to flow along the path of a helix. However, as the beam length increases, these correlations tend to average. If the beam were to remain continuous and become very long, the resulting interference would reduce the coherency to zero. The beam must therefore be broken into segments of the proper length and spacing. This leads to the second criterion for coherent spontaneous emission, namely beam modulation and beam fronts.

In stimulated emission the beam in the presence of the background plasma becomes unstable with respect to wave growth. As opposed to spontaneous emission, emissions are here stimulated by the presence of the wave itself. Since the probability of emission is proportional to the wave strength, the growth rate (in either time or space) is exponential.

Since stimulated emission is not dependent on beam fronts, and hence on modulation, we have not studied this mechanism in detail. Rather, our work on this project has concentrated on coherent spontaneous emission, since the associated coherency gives rise to the required signal strength, and the pulsed character of the beam satisfies its unique requirement for the presence of fronts.

2.2 RESEARCH RESULTS

2.2.1 Radiation from Beams with a Finite Pulse Train.

The first topic studied in this project was radiation from a finite pulse train electron beam. The results of this study were presented in the article "Radiation by Pulsed Electron Beams in Space Plasmas" by *Harker and Banks* [1984a]. The radiation from a single particle traveling through free space permeated by a magnetic field was considered first. This was later generalized to the multiple pulse case. Finally the complete theoretical treatment to describe the radiation field of a finite pulse train of electrons traveling through a space plasma was presented. In order to simplify the theory, the beam length was assumed to be unbounded, i.e., it was assumed to extend from $z = -\infty$ to ∞.

Detailed numerical studies were made of the radiation from the lower hybrid to electron cyclotron frequency. Beam voltages considered were 100V, 1 KeV, and 10 KeV, while the beam current and pitch angle were taken as 100 ma and 30°, respectively. The 1 KeV beam voltage was chosen to simulate the FPEG electron gun used in the STS-3 Space Shuttle flight. The theory showed that the power radiated per unit solid angle per pulse typically lies in the vicinity of the free space value of 1 mW/sr. There is a great variation with angle and frequency, and for certain angles and frequencies it is not uncommon to find radiated powers per unit solid angle of the order of 1 W/sr. In addition, singularities in the power distribution functions, up to three in number, were observed to occur; it was recommended that the conditions corresponding to these singular points should be studied in experiments, since they have the likeliest probability of detection.

This study showed that the successful use of electron beams as radiators and antennas relies on their use at selected frequencies, observation angles, beam duty cycles, beam modulation frequencies, and pitch angles.

2.2.2 Radiation from Long Pulse Train Beams.

Recent experiments have reported the emission of electromagnetic radiation at the modulation frequency of the electron beam when that frequency was in the VLF range. In experiments on STS-3 [*Neupert et al.*, 1982; *Banks et al.*, 1983 and 1984; and *Shawhan et al.*, 1984], modulation of the beam at 3.1 and 4.8 kHz produced emissions at these frequencies and also at their harmonics up to the maximum observation frequency of 30 kHz. Pulse trains typically contained 32,768 pulses. Experiments with modulated beams were also carried out on the SEPAC experiment on board Spacelab-1 in November and December 1983 [*Obayashi et al.*, 1982; *Taylor and Obayashi*, 1984].

To help explain the results of these experiments, our previous theory was extended to cover the the radiation produced by long pulse train electron beams. The details are reported in "Radiation from Long Pulse Train Electron Beams in Space Plasmas" by *Harker and Banks* [1985]. There were several new steps taken in the theory. First, because of the relatively large number of pulses, we extended the earlier theory to cover infinite pulse trains. Second, because most of the observations had been made at frequencies in the range 1 - 30 kHz, we extended our numerical results to cover the region below the lower hybrid frequency. Third, we made the more realistic assumption that the beam extends only from $z = 0$ (the gun position) outward, instead of from $-\infty$ to ∞. Finally, we introduced the assumption that the ability of the beam to radiate, for whatever reason, falls off exponentially with distance. The e-folding distance for this fall-off is a parameter which must be determined from more detailed theories or from experiments. We first derived general results, and then used these to specialize the theory to two cases, the long and short beam, in order to gain as much simplification as possible.

Calculations to determine the radiated power based on the theory were carried out for a range of parameters. One set of computations was made for a voltage of 1000 V, a current of 100 ms and a pitch angle of 30° for comparison with the results of the STS-3 mission with the FPEG. Another set of computations were made for a voltage of 7500 V, a current of 1.6 A, and a pitch angle of 45°. In all cases results were presented for Cerenkov and normal and anomalous cyclotron radiation.

In our theory for finite pulse train beams, after carrying out the mathematical simplification for the radiated power resulting from contour integrations, we are generally left with two integration variables. When the beam is infinitely long, an additional restraint is imposed in the form of the wave-particle interaction condition, which reduces the number of integration variables to one. This was the case discussed in the finite pulse train paper, where the power distribution function was chosen successively to be a function of the frequency, propagation angle, and ray vector angle.

In the present case, the beam is an unbounded pulse train. This introduces a new restraint, namely that the frequency is an integral multiple of the modulation frequency, which again reduces the number of integration variables to one. When the beam is long, the wave-particle condition is again imposed, reducing the number of integrations to zero, and yielding a single angle for each modulation frequency. This is another way of saying that all of the power has been concentrated into radiation at a single polar angle, i.e., within those angles lying on a thin conical surface. Of course, this angle still varies with the system parameters, such as frequency and pitch angle.

2.2.3 Computations using the Long Pulse Train Theory

In this section we wish to report an important parameter study made by L.E. Johnson of Pacific-Sierra Research Corp. Using the long pulse train theory described above, Johnson computed the radiation emission from a modulated semi-infinite electron beam under a wide variety of conditions, many of them representative of the ionosphere [*Johnson*, 1985]. The large number of graphs provide much information concerning the dependence of radiated power on frequency, beam energy, pitch angle, and other basic beam parameters, and on the altitude and other important parameters of the ionosphere. Although there is no general attempt to estimate the radiation produced on the ground, the data provide the basis for making such estimates. One conclusion, that "radiation in the Cerenkov mode may therefore dominate the radiation that actually reaches the ground," is particularly significant because Cerenkov radiation is emitted in the direction of motion of the electron beam. Thus if if is desired to produce signals on the ground, it will be most desirable to direct the electron beam downwards (along the magnetic field).

2.2.4 Near Fields in the Vicinity of Pulsed Electron Beams in Space.

One shortcoming of the above work was that it was valid for the far-field only. This meant that if the beam had a length l, then the theory was only valid for distances from the beam greater than a factor of three of more times l. Since most of the measurements on electron beams in space have been taken within 10 m or so of the electron beam generator, it is clear that further work was needed to be done on the near fields generated in the vicinity of pulsed electron beams.

In order to remedy this situation, a study was made at the near fields generated by a pulsed electron beam. The results of this study were reported at the 21st General Assembly of URSI in Florence, Italy, during August 25 - September 5, 1984, in a paper entitled "Near Fields in the Vicinity of Pulsed Electron Beams in Space" by *Harker and Banks* [1984b]. The most recent results are presented in the paper "Near Fields in the Vicinity of Pulsed Electron Beams in Space" by *Harker and Banks* [1986].

As in our previous studies, the model assumes that the electrons follow an idealized helical path through the space plasma. The total radiation is obtained, again as above, by adding coherently the radiation from each individual electron in the helix, leading thereby to coherent spontaneous emission. The mathematical technique used consists of taking the Fourier transforms in space and time of Maxwell's equations, including the modulated beam current terms which act as the driving mechanism for the interaction. The solution is then obtained by taking the inverse transforms to obtain the electric field as a function of the spatial coordinates. An important feature of the theory is the retention of evanescent waves in addition to the propagating waves used in the far field theory. This gives rise to contributions to the field strengths in frequency stop bands of the far field theory. Field strengths calculated by the theory were calculated for a representative set of values of ionospheric parameters and electron beam current, voltage, and pitch angle and for a range of modulation frequencies extending from the ion to the electron cyclotron frequency. These predictions were found to be in essential agreement with the most recently available experimental data.

2.2.5 Solution for the Steady State Electron Beam.

Up to the end of the work reported in the previous section, our model of the electron beam as a radiator of electromagnetic emissions has been a simple one, namely a group of particles following a single electron helical trajectory and without interaction between neighboring particles. Since the accuracy of any theory for radiation depends, at least in part, on the accuracy of description of the unperturbed beam, an effort was mounted during this study to develop a moment (or fluid) theory for the steady state flow of an electron beam through a background plasma. The moment theory was chosen, since it should be valid as long as the Debye wavelength of the background plasma is less than the beam radius, and yet it avoids the complexities of a full kinetic theory. Our study concerned itself with the motion of the primary beam and the particles of the background plasma, and included plasma temperature and electron and ionizing collisions.

In the initial phase of the moment theory study, the beam was assumed to have axial symmetry about the magnetic field line (i.e., zero pitch angle), and solutions were obtained in specific transverse planes of the beam by ignoring longitudinal variations of the dependent variables in the equations. The method of solution in each such isolated transverse plane was a coupled set of equations, the paraxial ray equation for the beam, and a combined numerical and analytic solution for the background plasma. The analytic solution was based on a series expansion, the expansion parameters being those factors which cause transverse currents to flow in the beam-plasma system. Solutions were obtained in specific transverse planes of the beam, including in particular the gun throat and the region in which the beam has attained neutralization. As a result of these efforts, a good understanding of the beam-plasma equations in a plane transverse to the beam has been attained. The results of this work were presented at the 1985 AGU Fall Meeting in San Francisco in a paper entitled "Steady State Transverse Plane Solutions for Electron Beam Flow in a Space Plasma" by [*Harker and Banks*, 1985].

Because of the termination of the contract at the end of June 1986, the work on moment theory did not proceed beyond its initial phase. The final phase should take into account the interaction between adjacent transverse planes by reintroducing the interaction terms in the axial direction, and the final solution of the problem will probably require an iterative technique in order to take these interactions properly into account.

2.2.6 Numerical Simulation

In addition to the above work, which treats the electron-beam wave generation problem directly, a further theoretical study, using numerical simulation, was made of the motion of a tenuous bunch of fast electrons through a plasma. The object of this latter study was to investigate the experimental observation that, on some occasions, an electron bunch could propagate over large distances with little apparent energy loss, when it might well be expected that the bunch would become unstable and dissipate over a much shorter distance. Clearly, the stability of the electron bunches is directly relevant to the use of pulsed electron beams for wave generation.

A one-dimensional Vlasov code was used in the simulation, and its results indicated that the moving electron bunch was not violently unstable, nor was it linearly stable as it would be if it started in a state of equilibrium (which is not achievable in practice): it was mildly unstable. Further, the mild instability appeared to be responsible for the moving electron bunch shedding a train of nonlinear plasma oscillations. Further details can be found in the publication that resulted from this work [*Shoucri and Storey*, 1986].

3. EXPERIMENTAL RESULTS

The experimental work involved in this study largely involved the analysis of data obtained during the FPEG operations on the third Shuttle flight, STS-3. However, important work was also carried out in connection with the Spacelab-2 flight of August - September 1985, and the second flight of the CHARGE rocket (i.e., CHARGE-2) on 14 December 1985.

In a preliminary study of the wave phenomena observed during STS-3, which was also funded by RADC, we observed a wide variety of harmonic and 'satellite' lines in the vicinity of the electron gun when it was modulated at various frequencies in the ELF (3 Hz - 3 kHz) and VLF (3 - 30 kHz) ranges. The results are discussed in the final report for that effort [*Fraser-Smith et al.*, 1985] (a general introduction to the wave data obtained from STS-3 is given by *Shawhan et al.*, [1984]). Investigation of these wave phenomena was continued during the present study, and the results for the two most frequent modulations in the VLF range (3.25 kHz and 4.87 kHz) are reported by *Reeves et al.* [1987]. An important part of this study was the comparison of the observed wave phenomena and the phenomena predicted by our theoretical work, and by the near field theory of *Harker and Banks* [1987] in particular.

Although there was often good agreement between the amplitudes of the harmonic lines observed during the VLF modulations and those predicted by theory, there were also frequent differences between the two. We still have no explanation for the deviations. Further, although we now have much more information concerning the satellite lines, and some other unexpected low frequency lines that we refer to as 'sub-harmonics,' we still have no satisfactory explanation for their origin. These peculiar phenomena are not confined to the STS-3 wave data, having been observed in analogous forms in both the SPACELAB-2 and CHARGE- data. However, although the phenomena remain unexplained, we have no reason at this time to suspect that they may limit the wave generation capability of a modulated electron beam, since the primary modulation frequencies are always markedly present in our electric and magnetic field data.

The abstract to the *Reeves et al.*, [1987] article, which has not yet been published, is as follows:

> Among the investigations conducted on the Space Shuttle flight STS-3 of March 1982 was an experiment in which a 1 keV, 100 mA electron gun was pulsed at 3.25 kHz and 4.87 kHz. The resultant waves were measured with a broad-band plasma wave receiver. At the time of flight, the experimental set up was unique in that the electron beam was square wave modulated and that the shuttle offered relatively long times for *in situ* measurements of the ionospheric plasma response to the VLF pulsing sequences. In addition to electromagnetic response at the pulsing frequencies, the waves exhibited various spectral harmonics as well as the unexpected occurrence of 'satellite lines' around those harmonics. Both phenomena occurred with a variety of different characteristics for different pulsing sequences.

An unexpected experimental development arising from our work with the STS-3 electron beam was the suggestion that it could be used to produce artificial plasma density structures [*Banks and Gilchrist*, 1985]. This work was not directed toward wave generation and thus was not supported by our RADC contract, but it is relevant because the artificial plasma density structures could possibly be used to perturb wave propagation, both constructively (by redirecting waves to where they are needed) or destructively (by reducing the wave energy along a communication path). Further, there may be other communication applications that we have not investigated.

In addition to the above study of STS-3 data, a considerable effort was made during the Spacelab-2 mission to detect electromagnetic waves on the ground during FPEG operations. Unfortunately, changes were made in the flight path of the orbiter in response to a two week delay in its launch and none of the paths were optimum for observations at Stanford, where our ground equipment was located. A further difficulty was our limited ability to communicate with the orbiter to request particular gun firings during some of the closer passages to Stanford. Measurements were made at Stanford during some intervals of gun firing but under the above constraints and no evidence was obtained for wave generation by the orbiter electron beam. In retrospect, considering the predictions of our theoretical work, we would have been very unlikely to have observed signals on the ground from the 100 mA, 1 keV beam of the FPEG on Spacelab-2 even under the best of circumstances.

An important feature of the Spacelab-2 experiments was the free flight of the PDP, during which time the electron gun was fired. This enabled us to observe waves produced by the electron gun at much larger distances than had previously been possible. Electromagnetic signals were observed clearly on the PDP up to distances of

300 m away from the gun. Some important preliminary results were presented by *Bush et al.*, [1985]. The Spacelab-2 data are still being analysed, but the observations made on the PDP once again provide support for the concept of wave generation by a modulated electron beam.

A final experimental effort in which we took part was the CHARGE-2 rocket flight from the White Sands Missile Range on December 14, 1985. The rocket separated into a mother-daughter pair, connected by a 400 m 'tether' that was gradually deployed during the flight, and an electron gun was operated on the mother while observations of many plasma and wave phenomena were made at the same time on the daughter. This experiment took place too late to significantly influence the work reported here, but it had an important impact on our planning of future work for RADC, since a decision was made by RADC to help support a further flight of the CHARGE rocket (*i.e.*, CHARGE-3) with a new higher-current electron gun that potentially has adequate power to generate electromagnetic waves that can be observed on the ground.

4. SUMMARY

Over the two and a half years of this RADC sponsored project, we conducted a systematic theoretical study of the electromagnetic waves generated by the passage of a pulsed electron beam through a magnetized plasma. Starting with a simple model of the beam consisting of a group of electrons following a single helical trajectory through the magnetized plasma, and assuming no interaction between neighboring electrons, we developed the theory for (1) the (far-field) radiation from a finite pulse train of electrons [*Harker and Banks*, 1984], (2) the radiation from an infinite pulse train of electrons [*Harker and Banks*, 1985], and (3) the near fields in the vicinity of the pulsed electron beam [*Harker and Banks*, 1986]. Computations with the theory in (2) by *Johnson*, [1985] provide information about the energy radiated by an electron beam under a wide variety of beam and plasma conditions, and can be made the basis for estimates of the radiation reaching the ground from electron beam experiments in the ionosphere.

In addition to the above theory, which incorporates a number of simplifying assumptions, a start was made on a more general moment theory for the steady state flow of an electron beam through a background plasma [*Harker and Banks*, 1985]. This more general theory was not completed, due to the termination of our contract, but it could be quickly extended in the future form its present preliminary form if a need for additional theory arose - presumably in response to the observation of differences between the simple theory and experimental results.

In addition to the above theoretical work, and in support of it, an intensive study was made of the electromagnetic fields produced in the vicinity of the modulated electron beam during the VCAP experiments on the third flight of a Space Shuttle orbiter (STS-3). The near field measurements of electric and magnetic fields provided substantial support for the near field beam theory, but they also revealed a number of entirely unexpected beam/plasma interaction effects that still await explanation [*Reeves et al.*, 1987]. More recent measurements, made during the electron beam experiments that took place as part of the Spacelab-2 mission [e.g., *Bush et al.*, 1985], showed that an electron beam could produce substantial electromagnetic fields at distances up to 300 m away from the electron beam generator. This result provides further support for the theory, but, perhaps more importantly, it suggests that unanticipated beam/plasma interactions not included in the theory, or interactions between the fields produced by the beam and the surrounding plasma, are not strongly affecting the electron beam's ability to function as a 'virtual antenna' for electromagnetic waves.

Measurements made on the ground during the Spacelab-2 mission did not detect any electromagnetic signals from the orbiter during operation of its electron gun. However, due to the two week delay of the flight, and subsequent changes in the orbits and other flight parameters, the conditions for detection of signals on the ground were far from optimal. Further, computations based on our theory by *Johnson* [1985], suggest that the radiation from the low powered electron gun (100 W) may be too weak to be easily detected on the ground even under ideal conditions.

Our participation in the CHARGE-2 rocket experiment of December 14, 1985, took place too late for it to impact significantly on the course of the work under this contract. The experiment was important, nevertheless, because it provided additional data on the electromagnetic fields produced in space by a modulated electron beam under different conditions from the Space Shuttle orbiter experiments, and it appears likely to provide a model for a future electron beam experiment (the CHARGE-3 rocket experiment), that will further explore the ability of a modulated electron beam to function as a virtual antenna for electromagnetic waves.

5. PUBLICATIONS

The following is a listing of the publications and other documentation that resulted from RADC Contract No. F19628-84-K-0014:

Banks, P.M., A.C. Fraser-Smith, U.S. Inan, G. Reeves, W.J. Raitt, W.S. Kurth, G. Murphy, R. Anderson, and S.D. Shawhan, Observations of VLF emissions from a pulsed electron gun on the Space Shuttle, *Eos, 65*, 1054, 1984.

Banks, P.M., R.I. Bush, and W.J. Raitt, Observations of electron beam structures on STS-3 and Spacelab-2, *Eos, 66*, 1053, 1985.

Bush, R.I., P.M. Banks, T. Neubert, K.J. Harker, W.J. Raitt, D.A. Gurnett, and W. Kurth, Observations of the effects of electron beam wave stimulation experiments on Spacelab-2, *Eos, 66*, 1053, 1985.

Harker, K.J., and P.M. Banks, Radiation from pulsed electron beams in space plasmas, *Radio Sci., 19*, 454, 1984.

Harker, K.J., and P.M. Banks, Theory for low frequency radiation from pulsed electron beams, Program and Abstracts of the National Radio Science Meeting (URSI), p. 72, Boulder, Colorado, 11 - 13 January 1984.

Harker, K.J., Radiation from a pulsed beam in a plasma, Conference on Beam-Plasma Interactions in Space, Rosario Resort, Eastsound, Washington, August 12-16, 1984.

Harker, K.J., and P.M. Banks, Near fields in the vicinity of pulsed electron beams in space, Abstracts for OS2: Active Experiments in Space Plasmas, p. 56, XXIst General Assembly of URSI, meeting held in Florence, Italy, August 28 - September 5, 1984.

Harker, K.J., and P.M. Banks, Radiation from long pulse train electron beams in space plasmas, *Planet. Space Sci., 33*, 953, 1985.

Harker, K.J., and P.M. Banks, Steady state transverse plane solutions for electron beam flow in a space plasma, *Eos, 66*, 1054, 1985.

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