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A Tribute to Oscar Buneman—Pioneer of Plasma Simulation

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(Invited Review Paper)

Abstract—**Highlights are presented from among the many contributions made by Oscar Buneman to the science, engineering, and mathematics communities. Emphasis is placed not only on "what" this pioneer of computational plasma physics contributed but, of equal importance, on "how" he made his contributions. Therein lies the difference between technical competence and scientific greatness. The picture which emerges illustrates the open-mindedness, enthusiasm, intellectual/physical stamina, imagination, intellectual integrity, interdisciplinary curiosity, and deep humanity that made this individual unique. As a gentleman and a scholar, he had mastered the art of making cold technical facts "come to life." Oscar Buneman died peacefully at his home near Stanford University on Sunday, January 24th, 1993. The profound influence he has had on so many of his colleagues guarantees his immortality.**

I. INTRODUCTION

Oscar Buneman was professor emeritus of electrical engineering at Stanford University, Fellow of the American Physical Society, and a major contributor to the fields of plasma electrodynamics, electromagnetic theory, and numerical analysis. His interests were broad, encompassing microwave tubes to isotope separation to galaxies. He was known as the Father of the Particle Simulation of Plasmas, the discoverer of several charged particle beam and space plasma instabilities that bear his name, and a founder of the field of cosmic plasma physics.

Buneman was to have given a plenary talk at the IEEE International Conference on Plasma Science, Vancouver, British Columbia, June 1993. It is most *apropos* that his chosen title reflected his lifetime work: "Simulation—From Electron Devices to Cosmic Plasma."

II. THE FORMATIVE YEARS

Oscar was born in Milan, Italy, on September 28, 1913, to German parents. He spent his youth in Hamburg, Germany, receiving a classical gymnasium education at the Johannaeum and completing two years of university work. In 1934, he was imprisoned by the Nazis for political resistance. Upon his release in 1935 he went to Manchester University in England, where he completed a study on nonlinear differential equations and received a B.Sc. in mathematics and a M.Sc. in applied mathematics. When World War II began in September 1939, he was interned in Canada with other foreign nationals. Professor Thomas Gold of Cornell University wrote, "He was a marvellous companion in those trying times. He was one of the very few non-Jewish refugees from Nazi oppression in the camp. Evidently he had strong principles and saw the Nazi hell that was being created. He and (Sir Herman) Bondi were the prime movers in the camp university and I certainly learnt a lot more from them than I would have had I remained in Cambridge for those nine months." In 1940 Buneman completed a Ph.D. supervised by Douglas Hartree.

Until 1943 Buneman worked as a postdoc with Hartree on the theory of the magnetron. In the course of these studies, Hartree introduced the innovation of simulating large numbers of particle orbits by numerical integration on his "differential anaylzer." This "analyzer" was a primitive analog computer. Nevertheless, the seed of many algorithms now in use on supercomputers was sown at this time by Hartree and his colleagues, who included Phyllis Lockett and David Copley as well as Buneman. (Hartree's first "differential analyzer" was constructed from an erector set. It used a continuously variable gear and with this device Hartree could mechanically solve self-consistent problems dealing with atomic wave functions and atomic energy levels).

Using these early "simulations," Oscar discovered the bunching of particles in a cavity magnetron; the "Buneman potential" that exists in a frame of reference co-rotating with the particles; and the diocotron instability. It was also at this time that he discovered a voltage threshold for magnetron operation (the Buneman-Hartree criterion). The extremely slow and tedious record keeping used in these "simulations" (Hartree distributed to his colleagues plastic sheets upon which the particles' positions could be noted and then, in the updating process, erased) had a lasting influence on Oscar. Henceforth, he resolved to emphasize *speed* in his algorithms.

In 1944, Buneman worked at the Lawrence Berkeley Laboratory as a member of the British mission to the Manhattan Project. There he continued his numerical modeling, but now focused on ion optics for the CALUTRON isotope separation device. In 1945 he transferred to the Canadian reactor project

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and, in 1946, returned to England to work in the Atomic Energy Research Center at Harwell on neutron diffusion, multigroup models, and Hermitage models. He remained at Harwell until 1950.

III. ELECTROMAGNETIC PHENOMENA IN COSMICAL PHYSICS

Buneman spent the 1950's as a member of Peterhouse College, Cambridge, lecturing in mathematics at the university. (He also pursued his avid love of flying as a solo sailplane pilot with the Gliding Club.) As computers matured, so did Oscar's interests in numerical methods. He interacted frequently with Hartree in this mutual passion. He also published on fundamental classical electrodynamics under the influence of P. A. M. Dirac [1].

It was also during this period that Buneman first turned his attention to electromagnetic phenomena in cosmic plasmas. He seized upon this subject in spite of the lack of observational data supporting the notion of such phenomena in space beyond the earth's ionosphere. Oscar was an enthusiastic participant in numerous conferences devoted to theoretical developments in this then-infant science of space plasmas. He received a personal invitation from Hannes Alfven to attend the International Astronomical Union Symposium on Electromagnetic Phenomena in Cosmical Physics, held August 1956 in Stockholm [2]. Buneman contributed to a program that laid the theoretical groundwork for the eventual discovery of plasmas and electric and magnetic fields in the solar system, in stellar systems, and in galaxies. Over the years, Oscar continued his collaboration with many of the notables at this conference, among whom were H. C. van de Hulst, K. H. Prendergast, B. Lehnert, A. Schluter, E. Astrom, R. S. Pease, T. G. Cowling, A. B. Severny, P. A. Sweet, J. W. Dungey, I. H. Piddington, H. W. Babcock, L. Spitzer, Jr., G. R. Burbidge, I. Biermann, T. Gold, V. C. A. Ferraro, L. Block, E. N. Parker, W. F. G. Swann, W. H. Bennett, L. A. Artsimovich, W. D. Shafranov, I. S. Shklovsky, S. B . Pikelner and W. H. Bostick.

By the mid-1950's, Oscar's hallmark trait of intellectual enthusiasm was already well-developed. When a subject seized his interest, he threw himself into it—mind, body, and soul. It was not enough that he, himself, was excited about it; he insisted on exciting equal enthusiasm for it in his colleagues. In this spirit, Buneman joined forces with Alfven travelling together by train across Europe, advocating the importance of plasma, particle beam, and electromagnetic effects in space. Later, Alfven would use these novel concepts to formulate his Plasma Cosmology [3]. Buneman was no stranger to cosmology; earlier, in 1946, his colleagues at Cambridge, Tommy Gold, Herman Bondi, and Fred Hoyle invented the Steady State Cosmology. It was also at the Stockholm conference that Buneman formed a close friendship with Winston Bostick, then at Lawrence Livermore Laboratory, and a strong advocate of laboratory plasma-galaxy relationships and the plasma cosmology. This friendship grew to include both spouses, lasting until Bostick's death in February 1991.

IV. THE BUNEMAN INSTABILITIES IN PARTICLE BEAM AND SPACE PLASMAS

It was at Cambridge in 1959 that Buneman discovered an instability that developed in two interpenetrating ion streams; his paper in the *Physical Review* led to his acknowledgment as the founding father of the particle simulation of plasmas [4]. While visiting Stanford in 1959 he was stimulated by Tor Hagfors, a visitor from Norway developing the theory of ionospheric backscatter from fluctuations, to work out a new instability in a collisional plasma involving a relative motion between electrons and ions driven by a quasi-dc field in the direction transverse to the Earth's magnetic field [5], [6]. Independently discussed by D. Farley, this instability is frequently invoked in the current literature of auroral and equatorial electrojets [7].

While it was Buneman who first discovered the "slipping stream" or "diocotron" instability, Oscar credited his French colleagues with actually naming it from the Greek word, *διωκειν* meaning "pursue." The phenomenon is observed in cross-field microwave devices in which vortices develop throughout a charged-particle beam when a threshold determined by either the beam current or distance of propagation is surpassed. Alfven used the mechanism in his book, *Cosmical Electrodynamics,* to explain the folding of auroral curtains in the upper atmosphere.

Oscar moved to Stanford University in 1960. Radiophysicists there introduced a new and enduring dimension into Buneman's theoretical activities. The Buneman instability proved to have significance for electron streaming in the magnetosphere, and led to collaboration with T. F. Bell on whistler theory and with L. R. O. Storey, the founder of whistler physics. A Buneman publication on density fluctuations in a plasma whose electrons and ions are at different temperatures proved relevant to the unexpectedly strong backscatter then being detected from the outer ionosphere [8].

V. FROM HAMILTON'S PRINCIPLE TO SPLINES TO VORTICES

The late 1960's and the 1970's were years of exceptional innovation and dynamic growth for Buneman's computational plasma physics group at Stanford. It became a hub of computational physics activity with interests expanding into many technical fields. Regular joint seminars were held in conjunction with the Stanford Computer Science Department on the subject of discrete numerical techniques. Similarly, periodic meetings were arranged with C. W. Birdsall's plasma simulation group at the University of California, Berkeley. Collaborations were established with the computational fluid dynamicists at the nearby NASA Ames Research Center and with the plasma fusion simulators at Lawrence Livermore National Laboratory. Workers in the fields of discrete mathematics and computational physics from all over the world visited, lectured, and learned. It was an exciting time. Buneman's all-encompassing interests and enthusiasm were the driving forces.

An experience of Ralph Lewis illustrates well the dynamics of Oscar's personal magnetism that so attracted innovative researchers. In the early 1960's, Lewis, then working at Los Alamos National Laboratory, was attending a conference at NASA Ames on the subject of collisionless shocks. He attended a presentation by Buneman in which the *apparent* generation of entropy was described as the result of *coarse graining* in a description of collisionless plasma. What made that talk most memorable to Lewis and attracted him to Buneman was not only the *content* of the talk but even more so the *manner* in which it was given. Oscar filled his presentation with eagerness, imagination, and intensity. These are contageous qualities to fellow researchers.

Lewis, along with Ned Birdsall, Bruce Langdon, and Keith Symon, interacted closely with Oscar during this period on a wide variety of related plasma simulation subjects. Oscar helped provide the glue which permitted productive intellectual exchanges among some very disparate and strong-minded individuals. His "glue" was a mixture of curiousity, intellectual integrity, and friendliness.

Themes that ran through much of Oscar's work on numerical simulation of plasmas and fluids at this time were the importance of "coarse-graining" and the need to have "sub-grid resolution" in the computational formulation. Coarse-graining is associated with the data grid which spans the simulation space in particle-in-cell (PIC) codes. Physical function values in the simulation are calculated only at the discrete set of points which make up this grid. Formulas (usually finite-difference formulas) are specified for calculating approximate values of derivatives at the grid points. Sub-grid resolution is required because, using the numerical values at the grid points, one needs to calculate function values and derivatives *between* the grid points in order to move the particles.

Oscar and Lewis had close interactions through a common interest in the application of Hamilton's Principle to derive computational algorithms for plasma simulation. This notion, introduced by Lewis [9], provided a procedure for building coarse graining and sub-grid resolution into a computational algorithm from the outset. The idea is to begin by specifying a functional form, depending on a discrete set of parameters, for representing an approximate solution to the governing equations for the physical problem. This can be viewed as specifying the approximate solution in terms of function values at grid points (coarse-graining) and in terms of an interpolation scheme for values between the grid points (sub-grid resolution). Hamilton's Principle is then used to derive an algorithm for determining the parameters of the approximate solution. One application of this procedure is to derive generalized finite-difference schemes for the Poisson equation. Oscar was very interested in this application and contributed significantly to understanding the properties of one such algorithm for the Poisson equation in comparison to some standard algorithms [10].

Bruce Langdon's stimulating interactions with Oscar began during this same period. He found that Oscar's enthusiasm, his ingenious and elegant numerical methods, and his physical insights literally made the field "fun" for him to work in.

In 1965, Langdon was shown Hockney's paper on fast, direct Poisson solution and its application to plasma simulation [11]. At that time, Langdon had already been introduced to one-dimensional simulations in courses by John Dawson and Thomas Stix. In particular, he knew of Buneman's theoretical and simulation results (previously mentioned) on collisionless dissipation of currents. The mechanism is often called the Buneman instability and is a pioneering example of anomalous resistivity or absorption.

Standard plasma simulation techniques in the mid-1960's used moving sheets of charge, keeping track of the spatial ordering of the sheets during the time integration. This was a slow procedure and did not generalize to more than one dimension. Hockney's paper publicized the Stanford group's work with gridded methods (now generally referred to as particle-in-cell methods or PIC—not to be confused with Harlow's fluid PIC). Their simulations relied on a combination of cyclic reduction and something very close to Fast Fourier Transforms (FFT's) to solve Poisson's equation quickly, to machine accuracy. This was a landmark. Equally important was the Stanford group's use of the mesh for the self-consistent electric field, and the time integration of the particles using that mesh field without explicit regard for nearby particles. This approach became prevalent for most applications in which long-range forces dominate. Also, it generalizes well to multi-dimensional electromagnetic codes, as Buneman may, in fact, have been the first to do, by 1968. Oscar was also a convincing advocate of the time-reversible integration schemes used at Stanford. As a result, these have been the usual algorithms of choice for twenty years, hard to improve on for many practical applications.

At the second Conference on the Numerical Simulation of Plasmas, in 1968, Oscar handed out small packets of punched cards carrying his new invention, a fast non-iterative two-dimensional Poisson solver that used cyclic reduction in both directions. Oscar called it "fast" and "compact," and it certainly was both. His program was less than a page long, uncommented, and even more terse and mysterious than a fast Fourier transform program when one does not know the principle behind it. His multi-dimensional cyclic reduction has been heavily used. It was a real breakthrough and illustrates Oscar's abilities and his habits; cyclic reduction is compact in realization, yet others had not thought of it, and Oscar seems never to have published it himself. It was left to others, such as Buzbee, Golub, and Nielson [12] and Barker [13], to publish papers explaining the algorithm and why Oscar's form of it did not suffer from the limitations of computer arithmetic.

At that same meeting, Oscar told Langdon about his ideas for a multidimensional electromagnetic code in which the conservation laws of electromagnetism had algebraically exact analogues in the computer code. This included Gauss' law, which required a method to form a mesh current that preserved charge continuity. Oscar returned to this topic in recent years, and developed an improved form in 1992 with Villasenor.

Around 1971, flying back to California together from a conference, Langdon told Oscar about the use of splines in plasma simulation. The Stanford group up to this time was still using nearest-grid-point (NGP) weighting, which is fast but a bit bumpy. Langdon used linear or bilinear weighting. That did not seem to interest Oscar much. But splines, which leapfrog past bilinear in a hierarchy of accuracy, did catch his interest. Within a few months, Oscar had worked out many analytic results for using splines in PIC-type applications and was using them in codes.

Higher-order spline particle codes offer the distinct advan-

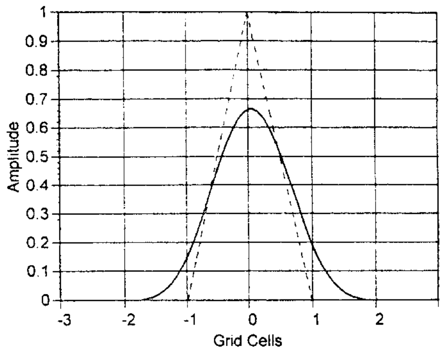

Fig. 1. Comparison of cubic spline shape (solid line) to area-weighted shape (dashed line).

tages of being much quieter and less diffusive than NGP or simple area-weighted schemes [14]–[16]. NGP is equivalent to a zeroeth-order spline model while area-weighting (linear interpolation) corresponds to a first-order spline model. Oscar performed in-depth studies of the relative numerical accuracy and stability benefits of the different order splines through the third-order cubic splines. These building blocks of a finite element (as opposed to conventional finite difference) methodology were so important to Buneman that they deserve some particular elaboration here.

The shape of the cubic spline particle differs from that commonly used in area weighting. Fig. 1 shows the comparison between the two psuedo-particle profiles. In this figure, both particles are centered at grid cell number 0. The dashed line represents the effective particle shape associated with traditional linear area-weighting. In this simple situation, the particle weight will be 1 on the zeroeth cell with no contributions to cells 1 or -1. The cubic spline shape is represented by the solid line. Note that the maximum weight is 2/3 at the cell number 0. However, the particle makes contributions out beyond cells 1 and -1. This form's continuous derivatives up to the third order lead to very smooth and quiet simulations for most situations. As estimated by Birdsall and Langdon, the reduction can be over two orders of magnitude better than the simple area-weighted schemes [17]. Below is the definition of the cubic spline interpolation function scheme:

$$\begin{array}{ll} \text{for Abs}[x] < 1; & S(x) = 2/3 - (1/2)(2-x)\,x^2 \\ \text{for } 1 \leq \text{Abs}[x] < 2: & S(x) = (1/6)(2-x)^3 \end{array} \quad (1)$$

Numerous researchers over the years have discovered the benefits of spline interpolation thanks to Oscar's trail-breaking efforts and vocal advocacy. Steve Brecht, for example, was introduced to them by one of Oscar's disciples at the Naval Research Laboratory, Bob Barker. Brecht was so impressed that he has since applied them to a variety of modeling problems. Over the years, Brecht successfully used them to deal with simulations involving steep plasma gradients, very quiet simulations, and vortex-in-cell simulations. In the steep gradient situations where one may have more than one ion species, particle statistics can become very poor at the base of the gradient where a single particle of a species may get beyond the foot of the gradient. In this situation, the smoothness of the spline shape greatly reduces artificial heating of the simulation. The "quiet simulations" where splines are found to be particularly useful include field-reversed situations, for example when simulating the earth's magnetotail region. Spline interpolation has likewise proven extremely useful in vortex-in-cell (VIC) simulations of such phenomena as the development of turbulence on buoyantly rising bubbles. Brecht used splines in building 2- and 3-dimensional VIC codes [18], [19]. Brecht is now applying the same approach to MHD simulations.

Vortex-in-cell fluid simulations deserve particular mention here. Oscar was fascinated by the close parallel in the mathematics governing plasma and fluid-vortex dynamics. With a twinkle in his eye, he would chuckle that "the numerics are identical except for the scale factor." Oscar delivered a paper in 1970 at the Fourth Conference on the Numerical Simulation of Plasma on the use of particles to track vorticity of fluids [20]. At that time, his concepts were just being formulated. He had determined that such a code had the potential to resolve and simulate fluid instabilities in a more natural fashion than the typical hydrodynamic code. He was correct. Fig. 2 shows the simulation of the Kelvin-Helmholtz instability as simulated with a 2-D VIC code using cubic splines. In this figure, the evolution of three different wavelength perturbations is displayed. In each case, the roll-up of the fluid interface is smoothly and well resolved. Indeed, the long wavelength perturbations show cascade to shorter wavelengths by wave breaking. The smallest perturbation shown is a four-cell wavelength. It will roll up with no numerical dissipation. The 1 and 2 cell perturbations were not shown because the reader cannot see the roll-up on a plot of this scale. However, the code is capable of resolving roll-up down to one cell if sufficient vortex particles are included. Fig. 3 shows the VIC approach applied to a buoyantly rising bubble in three dimensions, as mentioned above. The first plot shows the initial conditions and the evolution of the bubble as the vortex ring is created; only 10% of the particles used in the simulations are being shown in this figure. The grid is extremely crude ($16 \times 16 \times 32$) in the simulation and yet the dynamics of the vortex ring develope and are well resolved by the vortex particles.

VI. SPLASH AND TRISTAN

Operating as human central processing units (CPU's) in the early 1940s, the team of Nicolson, Copley, and Buneman made a number of discoveries including the Crank-Nicolson iteration procedure and the Buneman-Hartree threshold criterion for magnetron operation. The one-dimensional simulations yielded a steady-state but could not account for magnetron operation, or the observed currents which flow across the magnetic barrier. Only when the technique was taken to two-dimensions did Buneman find an instability, not unlike the Kelvin-Helmholtz instability in fluid flow.

In the transition from one- to two- dimensional simulation, iterative methods were abandoned in favor of a Fourier method. It turned out that only a few Fourier harmonics were needed for simulation; the Fast-Fourier-Transform (FFT) was not yet known. Success came to Buneman in the numerical

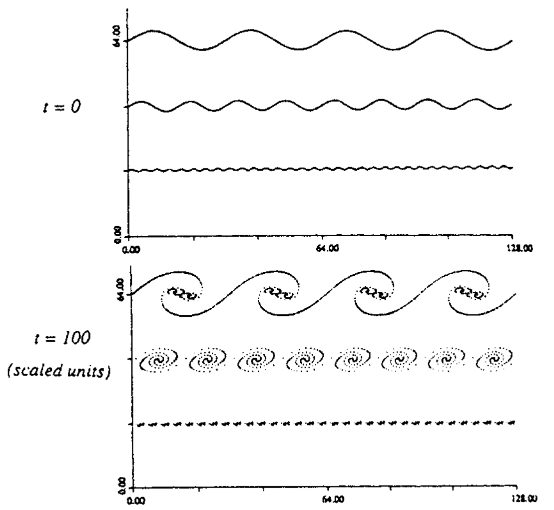

Fig. 2. Three Kelvin-Helmholtz simulations with different initial perturbations at $t = 0$ and subsequent evolution of these perturbations after 100 timesteps.

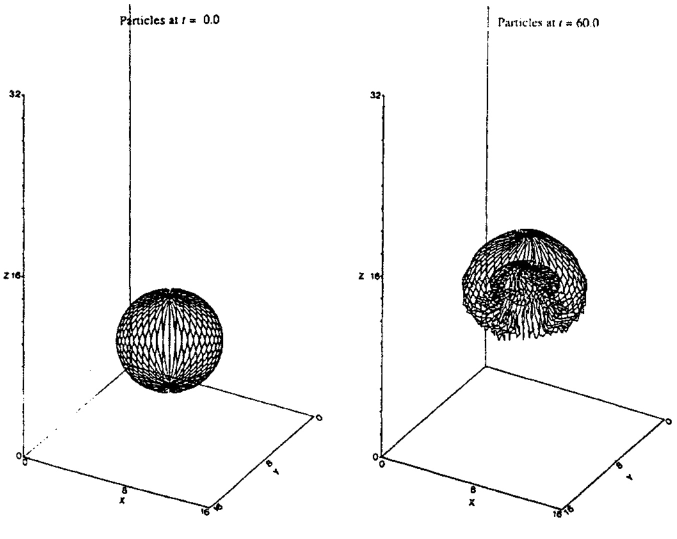

Fig. 3. Time evolution of a three-dimensional buoyantly rising bubble.

observation of the four- and six-wheel spokes of electrons that rotate in the magnetron exciting the high frequencies of the resonators.

In the 1960's and 1970's electrostatic simulations gave way to electromagnetic simulations, and one and one-and-a-half gave way to two and two-and-a-half dimensional simulations. At this time Buneman came under some pressure from his friend Bostick, a physical experimenter and inventor of the term "plasmoid," to do three-dimensional simulations [21].

The world's first fully three-dimensional, fully electromagnetic particle-in-cell simulation code was brought into existence by Buneman's post-doc Chris Barnes and his students, Dale Nielsen and James Green [22]. The code was called SPLASH, an anagram for "Stanford Particle Algorithm Solver." It permitted only 32 cells on a side in Fourier space, but its real-space resolution capability proved many times this, surprising even Buneman [23].

SPLASH employed all the techniques Buneman had learned over the years to make a simulation run as fast as possible. SPLASH was executed at Stanford, from a teletype terminal and modem, but resided at the Magnetic Fusion Energy Computer Center at Livermore. Although CPU time allocation was a concern in moving a quarter of a million particles in three dimensions, it was the notorious CDC7600 computer crashes that really limited how far a simulation could be run and produce recoverable data.

Versions of SPLASH were written for the CDC7600 "supercomputer" that had only a half-million words of memory, and the Cray 1 that had only a million words. In order to permit "interesting" simulations, numerous numerical tricks were required with regard to data treatment. For example, the spatial domain was divided up to process a piece at a time, oddly enough similar to the way researchers handle the data today on distributed memory parallel computers.

Oscar contributed a great deal to methods and applications of elliptic equation solvers and fast Fourier transforms. Nevertheless, he seemed to prefer codes that relied instead on the hyperbolic Maxwell's equations to propagate the correct field information at the speed of light as nature does, instead of instantaneously via elliptic equations or Fourier transforms. The TRISTAN code, used in much of his recent work, is of that type.

As mentioned, Buneman employed fast Fourier transforms and spectral methods for field solving in SPLASH, and later, TRISTAN (Tri-dimensional Stanford code). His reason for doing the entire field update in the transform domain was again related to boosting computation speed and spatial accuracy; namely, to circumvent the Courant condition.

A time-step limitation, the Courant condition is encountered when integrating the full electromagnetic equations over a spatial grid. Because Maxwell's equations (excluding Poisson's equation) are hyperbolic (they contain a natural $\partial/\partial t$ or "update" term), their level of difficulty of solution is of the order of magnitude of the number of grid points. However, this process becomes unstable unless one observes the Courant speed limit, $\delta t < (\delta x)/(c\sqrt{n})$, for $n = 1$, 2, or 3-D meshes of side, δx. In many applications, the units of choice in a simulation may result in a c that is large. In these cases the restriction, $c\ \delta t < \delta x$, forces the time-step, δt, to be unreasonably small resulting in an unreasonably long time for simulation completion.

Buneman was an advocate of the Sommerfeld convention of combining the electric and magnetic vectors into a single complex field vector, $\mathbf{F} = \mathbf{D} + (i\mathbf{H})/c$. The main advantage of this convention is that both Maxwell's curl equations reduce to the single equation:

$$\frac{d\mathbf{F}}{dt} - c\mathbf{K} \times \mathbf{F} = -\mathbf{j} \tag{2}$$

for the spatial harmonic that goes like $\exp(i\mathbf{k} \cdot \mathbf{r})$. Equation (2) is surprisingly similar to the Lorentz equation for particle update:

$$\frac{d\mathbf{v}}{dt} \pm \frac{e\mathbf{B}}{m} \times \mathbf{v} = \pm \frac{e}{m}\mathbf{E} \tag{3}$$

Correspondingly, the solutions to (2) and (3) are also surprisingly similar:

$$\mathbf{F}^{\perp} = \mathbf{j} \times \mathbf{k}/k^2 + \mathbf{F}^{rot} \tag{4}$$

$$\mathbf{v}^{\perp} = \mathbf{E} \times \mathbf{B}/B^2 + \mathbf{v}^{rot} \tag{5}$$

where $\mathbf{F}^{\perp}$ and $\mathbf{v}^{\perp}$ are the transverse parts of $\mathbf{F}$ and $\mathbf{v}$, respectively, while $\mathbf{F}^{rot}$ is a circularly polarized wave rotating at angular frequency, ck, and $\mathbf{v}^{rot}$ is a particle velocity with rotation at angular frequency, $(eB)/(2\pi m)$.

It is through similarities such as these that Buneman recognized opportunities for coding compression and simulation time shortening, albeit, generally, at a cost of readability and portability of the code. (Portability was not an issue in the early 1980s when few computers capable of three-dimensional simulation existed.) While Buneman's elimination of the Courant condition was done at the expense of introducing aliasing and stroboscopic inaccuracies, as well as some difficulties at boundaries, he readily solved these problems by means of highly creative and geometrically interesting interpolation methods [24], including the spline techniques mentioned previously.

To carry out the three-dimensional integrations, Buneman wrote the Newton-Lorentz force in centered-difference form. Then, as shown in (4), he treated separately the particle drift, rotation, and acceleration in the electromagnetic field. Ever mindful of computation time, Buneman was able to reduce the particle rotation algorithm to a minimum number of steps [17], [25].

SPLASH and TRISTAN turned out to be well suited to problems, such as Z pinches and space plasmas, which did not require conducting boundaries. In the 1980's these codes were used to study problems as diverse as the coalescence of exploding wires, synchroton radiation, plasmoid propagation across a magnetic field, cold beam filamentation and heating, coronal loops, current helicing, double radio galaxies, and the structure and magnetic fields of galaxies [26]–[28].

VII. TRISTAN AND PARALLEL PROCESSING

The unique advantages of the spectral method do much to facilitate multi-dimensional PIC simulation on personal computers. Unfortunately, this method does not lend itself well to the parallel computing architectures of modern mainframe computers. This drawback forced a reexamination of the original TRISTAN code.

Data transport, the movement of fields and particles into and out of core, is a dominant concern in 3-D plasma PIC simulations. In massively parallel machines, data transport becomes an even more important issue. Computing efficiency depends critically on (topological or physical) data proximity in the basic procedure of a problem. In massively parallel machines, Buneman noted that "local" algorithms (such as finite difference equations) have preference over "global" algorithms (such as Fourier transforms). For example, the calculation of each single Fourier harmonic requires the entire data-base, an impossibility for parallel processors.

In 1985 Buneman used his own version of the fast Hartley transform, writing TRISTAN directly in Cray Assembler Language (CAL) to gain speed. TRISTAN was an amazingly powerful code. In fact, for the next several years, it was the only fully electromagnetic, fully 3-D PIC code publicly available. [NOTE: At this time, Mission Research Corporation was already running its 3-D, electromagnetic PIC code, SOS, but its availability was restricted]. Nevertheless, TRISTAN remained nearly unused outside of Stanford and Los Alamos. Its lack of widespread acceptance might be traced, in part, to its sparse documentation and the obscure, user-unfriendly CAL coding of some of its key algorithms. Buneman felt that "programming in Fortran was like playing a piano wearing boxing gloves." Nevertheless, try as he might, Oscar was unable to convince fellow simulationists that the need for 3-D simulations was worth learning and programming in CAL. One of the only converts was A. Peratt at Los Alamos who wrote a TRISTAN users manual which described how to set up various beam geometries in CAL.

To take advantage of the reliable, parallel architecture machines, a new version of TRISTAN was written by Buneman, K-I. Nishikawa, and T. Neubert in 1990. This version retained the time-centered second-order particle updating scheme, but integrated Maxwell's equations locally over a cubic mesh [29]. This represented a significant but necessary departure from the inherent beauty of the spectral symmetry of (2) and (3). For portability reasons the new version was written in Fortran and also in C, for use not only on personal computers, but also on connection-type machines. The new version of TRISTAN had two classes of problems in mind: high power microwave tubes and space plasmas.

By the 1990's high power microwave generation schemes came to be dominated by reflex triodes, vircators, reflex klystron oscillators (RKO's), magnetically insulated transmission line oscillators (MILO's), gyrotrons, and backward-wave oscillators (BWO's). These devices are characterized by multiple conductors such as anodes, grids, cathodes, slow wave structures, vanes, and resonant cavities. Unfortunately, as previously noted, conducting boundaries were not permitted in the original versions of TRISTAN. In a novel approach, Buneman sought to correct this shortcoming by modeling conducting surfaces via the forward and return currents they actually carry; i.e., by modeling them using free electrons in "stokes fall" constrained to flow in a specified conducting path. This was one of the projects he left unfinished.

While conducting surfaces are generally absent in space plasma applications, the geometries and plasma flows are no less challenging. Such space applications again became the focus of Oscar's work when he reached emeritus professor status and joined Stanford's STAR Laboratory in 1984. For example, the solar wind and its theoretical discussion dating back to Chapman and Ferraro engaged Buneman's attention in 1990. The more that observational data clarified the time-variable topology of the solar particle stream's interaction with the earth's magnetosphere, the more intractable the theory seemed. With a series of collaborators, among them K-I.

Nishikawa, T. Neubert and D. S. Cai, Buneman duplicated the dramatic kinematics of bow shock formation, the magnetospheric cavity, the magnetotail, and other features known from observation and reproduced the transient behavior associated with the flapping of the solar wind sheet [30].

Buneman lectured at the 1st to 4th International Schools for Space Simulation (1982, 1985, 1987, 1991). At the 4th School in Kyoto, Japan, he demonstrated the fruits of his technique in the form of a computer-generated movie. He gave copies of his transportable code to young space scientists and taught them how to use it on the local supercomputers [31]. His lectures were regarded as most helpful and his enthusiasm inspiring. As recently as 1992, he was lecturing at a space physics symposium in Hawaii. Members of the audience who had never met him previously were amazed that a man his age was so active and enthusiastic in the discussions that arose. All that knew him simply took this for granted.

VIII. MENS SANA IN CORPORE SANO

No discussion of Oscar's life and philosophies would be complete without noting his consistent passion for physical activity. For him, a keen mind went hand-in-hand with a well-conditioned body. Every workday morning, weather permitting, he would be seen pedaling his bicycle five miles down to the Stanford campus from his home in the foothills. He continued this demanding routine of round-trips into late 1992. Similarly, he enjoyed visiting Stanford's olympic-size pool regularly for a vigorous ten-lap workout.

He savored the outdoors. Even at home, he preferred to work and sleep by his pool. On weekends and vacations, his wife, Ruth, would join him in numerous cross-country hikes through scenic wilderness areas. One such hike took place in 1982, backpacking on the John Muir Trail in California's beautiful King's Canyon National Park. Oscar and Ruth successfully hiked south over Mather Pass (elevation, 12,050 feet) which was entirely covered in snow. The trek required ice-axes. They made their way down into the Upper Basin of the Kings River and were on a fairly level stretch of trail at an elevation of about 11,500 feet when Oscar carelessly stepped on a patch of snow near a rock. He had unfortunately forgotten some very elementary thermodynamics: namely, that rocks heat up in the sun and the snow around them melts away, leaving crevasses beneath the surface. The snow gave way beneath his foot, which was then brought to a too-abrupt halt by an underlying rock. Oscar went down with the understatement, "Now I've done it!" Luckily, Ruth was there. An examination of his foot revealed that the skin was not broken but his heel-bone was. He summarized his predicament by noting, "I can't walk." Ruth, however, countered with, "You can crawl." Which he could, and did. With no communications link to the outside world, they walked (and crawled) to a nearby camp site and waited for someone to come along the trail. Shortly thereafter a couple came by who were very happy to carry out a call for help. When Ruth handed them a slip of paper with their names and address on it, the gentleman's eyes opened wide. He exclaimed, "Buneman! Not *the* Buneman of the Buneman Poisson-solver?!?" As it turned out, the hiker was a professor of physics from Tubingen University in Germany. Oscar was chastened by his lapse of physical insight but buoyed by the respect of the chance-met fellow scientist.

IX. CONCLUSION

Buneman taught various courses in electrical engineering, giving them an inimitable mathematical and computational flavor; he also taught courses cross-listed with the computer science department. Resisting the short-cuts of improved high-level languages, Buneman stressed the continued need for meticulous attention to microprogramming. The power of the TRISTAN code is a testimony to the effectiveness of combining basic knowledge of electrodynamics with an intimate understanding of machine fundamentals. Buneman thoroughly enjoyed the digital world. In his last year he improved on the standard algorithm for constructing a pixelized straight line and worked on half-tone graphics. It had been thought that the fast Hartley transform could not be generalized beyond one dimension because the kernel was not separable. Then, during one week in 1986, three different methods were discovered, of which Buneman's was the most elegant and involved a procedure now known to his colleagues as "oscarization." He followed up his discovery by publishing on three, four, and n dimensions.

Roger Hockney, whose dissertation Buneman supervised jointly with Professor Gene Golub, later became a key figure in computational plasma physics in his own right. In 1981, with J. W. Eastwood, Hockney authored what is now considered one of the two standard reference works on particle-based computational plasma physics [25]. They dedicated the book, "To Oscar: Founder of the Subject."

Oscar Buneman was an extremely rare individual. He was set apart from many scientists because he affected science and scientists at many levels. His personal enthusiasm was infectious. His scientific insights have proven to be exceptional, and his colleagues and former students continue to make substantial contributions to the field of plasma physics. Many, many scientists have crossed the active and broad research path of Oscar Buneman. He was a rare man indeed! It was a privilege to have interacted with him.

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REFERENCES

[1] O. Buneman, "Circulation in the flow of electricity: Dirac's new variables," *Proc. Roy. Soc.* A, vol. 215, page 346, 1952.
[2] W. H. Bostick, "Stockholm, August 1956, revisited," *IEEE Trans. Plasma Sci.*, vol. 17, pp. 69–72, 1989.
[3] H. Alfven and C.-G. Falthammar, *Cosmical Electrodynamics.* New York: Oxford University, 1963.

[4] O. Buneman, "Dissipation of currents in ionized media," *Phys. Rev.*, vol. 115, pp. 503–517, 1959.

[5] D. Farley, "Two-stream plasma instability as a source of irregularities in the ionosphere," *Phys. Rev. Lett.*, vol. 10, p. 279, 1963.

[6] O. Buneman, "Excitation of field aligned sound waves by electron streams," *Phys. Rev. Lett.*, vol. 10, p. 285, 1963.

[7] D. Farley, "A plasma instability resulting in field-aligned irregularities in the ionosphere," *Jour. Geophys. Res.*, vol. 68, p. 6083, 1963.

[8] O. Buneman, "Instability, turbulence and conductivity in current-carrying plasma," *Phys. Rev. Lett.*, vol. 1, p. 8, 1958.

[9] H. R. Lewis, "Applications of Hamilton's Principle to the numerical analysis of Vlasov plasmas," *Methods in Computational Physics*, vol. 9, B. Alder, Ed. New York: Academic, 1970.

[10] O. Buneman, "The finite element method and energy-conserving time stepping in simulations," *Proc. of the Sixth Conf. on Numerical Simulation of Plasmas*, Univ. of California, Berkeley, California, 1973.

[11] R. W. Hockney, "A fast direct solution of Poisson's equation using Fourier analysis," *J. Assoc. Comput. Mach.*, vol. 12, p. 95, 1965.

[12] B. L. Buzbee, G. H. Golub and C. W. Nielson, "On direct methods for solving Poisson's equation," *SIAM Jour. Numer. Anal.*, vol. 7, p. 4, 1970.

[13] R. J. Barker, "Advanced techniques for the direct, numerical solution of Poisson's equation," *Banach Center Publications*, Warsaw, Poland, vol. 3, p. 255, 1975.

[14] H. R. Lewis, A. Sykes and J. A. Wesson, "A comparison of some particle-in-cell plasma simulation methods," *J. Comp. Phys.*, vol. 10, p. 85, 1972.

[15] O. Buneman, "Subgrid resolution of flow and force fields," *J. Comp. Phys.*, vol. 11, p. 250, 1973.

[16] A. B. Langdon, "Energy conserving plasma simulation algorithms," *J. Comp. Phys.*, vol. 12, p. 247, 1973.

[17] C. K. Birdsall and A. B. Langdon, *Plasma Physics via Computer Simulation.* New York: McGraw-Hill, 1985.

[18] S. H. Brecht and J. R. Ferrante, "Vortex-In-Cell simulations of buoyant bubbles in three dimensions," *Phys. Fluids A*, vol. 1, p. 1166, 1989.

[19] S. H. Brecht and J. R. Ferrante, "Vortex-In-Cell calculations in three dimensions," *Computer Phys. Comm.*, vol. 58, p. 25, 1990.

[20] O. Buneman, "Vortices, the 'Particles' of fluid and gasdynamics," *Proc. of Fourth Conf. on Numer. Simul. of Plasmas*, Naval Research Laboratory, Washington, D.C., p. 440, 1970.

[21] O. Buneman, "The advance from 2D electrostatic to 3D electromagnetic particle simulation," *Comp. Phys. Comm.*, vol. 12, pp. 21–31, 1976.

[22] O. Buneman, C. W. Barnes, J. C. Green and D. E. Nielsen, "Principles and capabilities of 3D, E-M particle simulations," *J. Comput. Phys.*, vol. 38, p. 1, 1980.

[23] O. Buneman, "Multidimensional particle codes: their capabilities and limitations for modeling space and laboratory plasmas," *IEEE Trans. Plasma Sci.*, vol. 14, pp. 661–665, 1986.

[24] O. Buneman, "Tetrahedral finite elements for interpolation," *SIAM J. Sci. Stat. Comput.*, vol. 1, p. 223, 1980.

[25] R. W. Hockney and J. Eastwood, *Computer Simulation Using Particles.* New York: McGraw Hill, 1981.

[26] D. Nielsen, J. Green, and O. Buneman, "Dynamic evolution of a Z pinch," *Phys. Rev. Lett.*, vol. 42, pp. 1274–1277, 1979.

[27] O. Buneman, "Computer simulation of the satellite photosheath: ESRIN, Frascati, Italy," *ESRO Rep.*, 1970.

[28] O. Buneman, "Internal dynamics of a plasma propelled across a magnetic field," *IEEE Trans. Plasma Sci.*, vol. 20, pp. 672–677, 1992.

[29] A. L. Peratt, *Physics of the Plasma Universe.* New York: Springer-Verlag, 1992.

[30] O. Buneman, T. Neubert and K.-I. Nishikawa, "Solar-wind-magnetospheric interaction as simulated by a 3D EM particle code," *IEEE Trans. Plasma Sci.*, vol. 20, pp. 810–816, 1992.

[31] O. Buneman, *Proceedings of ISSS-4*, Kyoto, Japan, 1992.

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