NICHOLAS C. CHRISTOFILOS: HIS CONTRIBUTIONS TO PHYSICS

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Abstract

Nicholas Christofilos is best known for his discovery of the strong focussing principle in 1949. However he continued making important and seminal contributions to physics until his death. These included the invention of the Linear Induction Accelerator, research in thermonuclear fusion and on applications of physics to National defense. A brief discussion of these accomplishments as related by his friends and colleagues is presented in honor of his memory.

1 THE EARLY YEARS

Nick Christofilos was born in Boston in 1916 to Constantine and Eleni Christofilos, who had immigrated from Greece to the US. In 1923 the family returned to Greece and Nick grew up and was educated in Athens. In a twist of fate Christofilos would return to the US and spend the greater part of his scientific career there. In fact he was extremely proud of his origin and had not relinquished his US citizenship. Yet, it was while living and working in Greece that he conceived and detailed the strong focussing principle and his scheme for plasma containment, two of his most creative and original contributions to science.

Nick Christofilos' technical ability was evident at a young age. He was a gifted youngster who as a hobby built radios and repaired electrical equipment. At age 18 he entered the National Polytechnic of Athens which at that time, was the premier higher education institution in Greece. He graduated in 1938 with a degree in Electrical and Mechanical Engineering and started working for an elevator maintenance concern, and later established his own firm.

The work at the firm seems to have allowed enough free time for Christofilos to immerse himself in the reading of physics texts – principally in German – in the area of nuclear physics and accelerators. By his own account he was particularly influenced by S. Fluegge's "Introduction to Nuclear Physics" (1942) and by A. Bouwers' "Electrical High Voltages" (1938). The war years and Greece's occupation (1941-44) caused further isolation but did not reduce Nick's interest in science. After the war he would use the USIS (United States Information Service) library in Athens to regularly read the Physical Review. Already in 1946 he had developed an accelerator scheme in principle similar to the synchrotron. He was not inclined to publish but instead submitted a patent application both in the US and Greece with copies to Berkeley. That proposal had shortcomings and in the meantime "phase stability" had been discovered by E. McMillan and simultaneously by V. Veksler.

Continuing his involvement with accelerators, in 1949 Christofilos discovered the strong focussing principle in a bold departure from the then accepted technology. Again he spurned publication, in spite of the urging of his friend the physicist Th. Kouyoumzelis, and instead submitted patent applications in the US and Greece [1]. He also sent copies to Berkeley where the paper was passed from scientist to scientist without being understood or appreciated. In the next section we discuss in some detail Christofilos' proposal as it appears in the patent application, a document of extreme clarity and covering a wide range of applications. Nick always considered himself a "practical physicist" and in all his papers the calculation of physical magnitudes and the technical feasibility of his ideas are prominently presented. An example was his early proposal of flywheel excitation for energy recovery in synchrotrons.

2 STRONG FOCUSSING

The application for a patent entitled "Focussing System for Ions and Electrons" was made on March 10, 1950, and the patent was granted in 1956. In Figs. 1, 2 we reproduce the first page of the patent and a figure showing the design of a strong focussing magnet. The author considers a particle moving along the x-axis with restoring forces along the y- and z-axes. He argues that in the case of ideal focussing it should hold

$$F_x = 0 \qquad F_y = -\epsilon_y y \qquad F_z = -\epsilon_z z \tag{1}$$

The restoring forces will be electromagnetic and derivable from a potential, $\vec{F} = \vec{\nabla}\phi$. Since in the region of the beam the potential must obey Laplace's equation, $\nabla^2\phi = 0$, the focussing force has zero divergence

$$\frac{\partial F_x}{\partial x} + \frac{\partial F_y}{\partial y} + \frac{\partial F_z}{\partial z} = 0 \tag{2}$$

It therefore follows that in Eq. (1)

$$\epsilon_y = -\epsilon_z \tag{3}$$

Namely an ideal focussing system <u>does not exist</u>. Instead, one could alternate the focussing between the y and z axes. By definition in a defocussing region the displacement is smaller than in a focussing region, and since the force is proportional to the displacement, the <u>net effect</u> is focussing.

In the patent a continuously varying gradient was considered,

$$F_y = -\epsilon y \sin(\frac{2\pi x}{\lambda}) \quad F_z = \epsilon z \sin(\frac{2\pi x}{\lambda}) \tag{4}$$

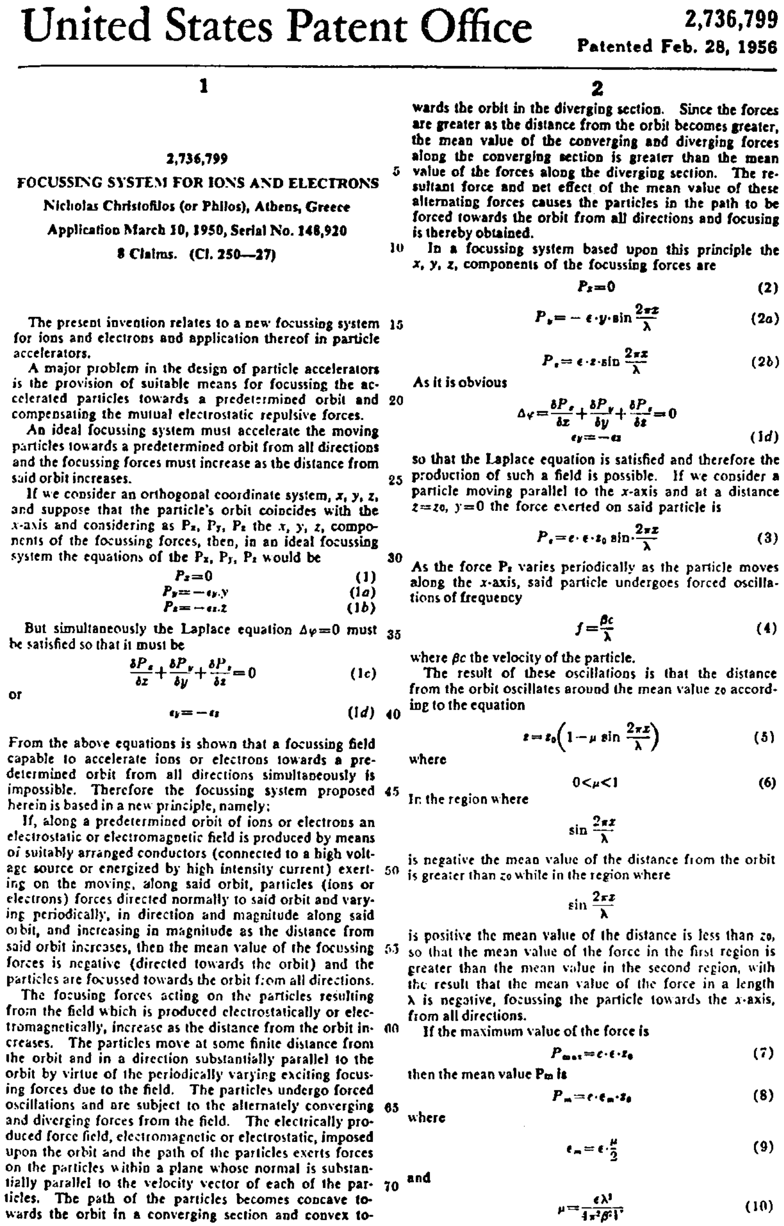
so that a particle injected at $z = z_0$, with $dz/dx = 0$ would follow a trajectory

$$z = z_0[1 - \mu \sin(\frac{2\pi x}{\lambda})] \tag{5}$$

where

$$\mu = \frac{\epsilon\lambda^2}{4\pi^2\beta^2 m\gamma c^2} \tag{6}$$

and $\gamma = E/m$, $\beta = \sqrt{\gamma^2 - 1}/\gamma$ have their usual meaning. Clearly, the stability condition is $0 < \mu < 1$. We recognize the usual formalism for alternating gradient machines simplified by the sinusoidal variation of the gradient.



United States Patent Office

2,736,799
Patented Feb. 28, 1956

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2,736,799

FOCUSSING SYSTEM FOR IONS AND ELECTRONS

Nicholas Christofilos (or Philos), Athens, Greece

Application March 10, 1950, Serial No. 148,920

8 Claims. (Cl. 250—27)

The present invention relates to a new focussing system for ions and electrons and application thereof in particle accelerators.

A major problem in the design of particle accelerators is the provision of suitable means for focussing the accelerated particles towards a predetermined orbit and compensating the mutual electrostatic repulsive forces.

An ideal focussing system must accelerate the moving particles towards a predetermined orbit from all directions and the focussing forces must increase as the distance from said orbit increases.

If we consider an orthogonal coordinate system, x, y, z, and suppose that the particle's orbit coincides with the x-axis and considering as P_x, P_y, P_z the x, y, z, components of the focussing forces, then, in an ideal focussing system the equations of the P_x, P_y, P_z would be

$$P_x=0 \quad (1)$$
$$P_y=-\epsilon_y \cdot y \quad (1a)$$
$$P_z=-\epsilon_z \cdot z \quad (1b)$$

But simultaneously the Laplace equation $\Delta\varphi=0$ must be satisfied so that it must be

$$\frac{\delta P_x}{\delta x}+\frac{\delta P_y}{\delta y}+\frac{\delta P_z}{\delta z}=0 \quad (1c)$$

or

$$\epsilon_y=-\epsilon_z \quad (1d)$$

From the above equations is shown that a focussing field capable to accelerate ions or electrons towards a predetermined orbit from all directions simultaneously is impossible. Therefore the focussing system proposed herein is based in a new principle, namely:

If, along a predetermined orbit of ions or electrons an electrostatic or electromagnetic field is produced by means of suitably arranged conductors (connected to a high voltage source or energized by high intensity current) exerting on the moving, along said orbit, particles (ions or electrons) forces directed normally to said orbit and varying periodically, in direction and magnitude along said orbit, and increasing in magnitude as the distance from said orbit increases, then the mean value of the focussing forces is negative (directed towards the orbit) and the particles are focussed towards the orbit from all directions.

The focusing forces acting on the particles resulting from the field which is produced electrostatically or electromagnetically, increase as the distance from the orbit increases. The particles move at some finite distance from the orbit and in a direction substantially parallel to the orbit by virtue of the periodically varying exciting focusing forces due to the field. The particles undergo forced oscillations and are subject to the alternately converging and diverging forces from the field. The electrically produced force field, electromagnetic or electrostatic, imposed upon the orbit and the path of the particles exerts forces on the particles within a plane whose normal is substantially parallel to the velocity vector of each of the particles. The path of the particles becomes concave towards the orbit in a converging section and convex towards the orbit in the diverging section. Since the forces are greater as the distance from the orbit becomes greater, the mean value of the converging and diverging forces along the converging section is greater than the mean value of the forces along the diverging section. The resultant force and net effect of the mean value of these alternating forces causes the particles in the path to be forced towards the orbit from all directions and focusing is thereby obtained.

In a focussing system based upon this principle the x, y, z, components of the focussing forces are

$$P_x=0 \quad (2)$$
$$P_y=-\epsilon \cdot y \cdot \sin\frac{2\pi x}{\lambda} \quad (2a)$$
$$P_z=\epsilon \cdot z \cdot \sin\frac{2\pi x}{\lambda} \quad (2b)$$

As it is obvious

$$\Delta\varphi=\frac{\delta P_x}{\delta x}+\frac{\delta P_y}{\delta y}+\frac{\delta P_z}{\delta z}=0$$
$$\epsilon_y=-\epsilon_z \quad (1d)$$

so that the Laplace equation is satisfied and therefore the production of such a field is possible. If we consider a particle moving parallel to the x-axis and at a distance $z=z_0$, $y=0$ the force exerted on said particle is

$$P_z=e\cdot\epsilon\cdot z_0 \sin\cdot\frac{2\pi x}{\lambda} \quad (3)$$

As the force P_z varies periodically as the particle moves along the x-axis, said particle undergoes forced oscillations of frequency

$$f=\frac{\beta c}{\lambda} \quad (4)$$

where βc the velocity of the particle.

The result of these oscillations is that the distance from the orbit oscillates around the mean value z_0 according to the equation

$$z=z_0\left(1-\mu \sin\frac{2\pi x}{\lambda}\right) \quad (5)$$

where

$$0<\mu<1 \quad (6)$$

In the region where

$$\sin\frac{2\pi x}{\lambda}$$

is negative the mean value of the distance from the orbit is greater than z_0 while in the region where

$$\sin\frac{2\pi x}{\lambda}$$

is positive the mean value of the distance is less than z_0, so that the mean value of the force in the first region is greater than the mean value in the second region, with the result that the mean value of the force in a length λ is negative, focussing the particle towards the x-axis, from all directions.

If the maximum value of the force is

$$P_{max}=e\cdot\epsilon\cdot z_0 \quad (7)$$

then the mean value P_m is

$$P_m=e\cdot\epsilon_m\cdot z_0 \quad (8)$$

where

$$\epsilon_m=\epsilon\cdot\frac{\mu}{2} \quad (9)$$

and

$$\mu=\frac{\epsilon\lambda^2}{4\pi^2\beta^2 V} \quad (10)$$

Figure 1: The first page of the strong focussing patent issued to Nicholas Christofilos.

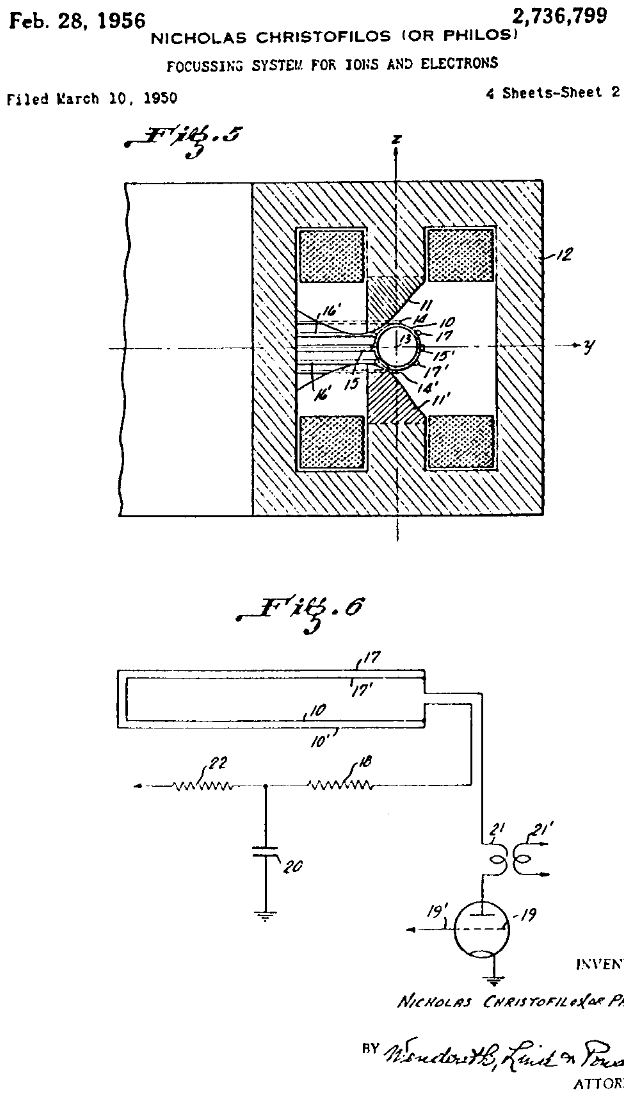

Figure 2: A figure from the patent showing the design of a strong focussing magnet.

To achieve the configuration of Eq.(4) a radially varying magnetic field with index K is proposed

$$B_z = B_0[1 - (1 - R/R_0)K\sin(n\phi)] \tag{7}$$

where R_0 is the equilibrium radius. In the usual way this leads to restoring forces

$$\begin{aligned} F_z &= -z(\beta^2 m\gamma c^2/R_0^2)K\sin(n\phi) \\ F_y &= y(\beta^2 m\gamma c^2/R_0^2)K\sin(n\phi) \end{aligned} \tag{8}$$

as required by Eq.(4). The index K can exceed unity and is related to the periodicity n, through

$$n = \sqrt{K/\mu} \tag{9}$$

The betatron frequencies are given by

$$\omega_z = \omega_0\sqrt{K_d} \qquad \omega_y = \omega_0\sqrt{K_d + 1} \tag{10}$$

where

$$K_d = K^2/2n = K\mu/2 \tag{11}$$

and $\omega_0 = eB_0/\gamma m$ is the orbital frequency.

As an example, Christofilos calculates the parameters for a 6 GeV machine with field index $K = 250$. He shows the important reduction in the beam pipe diameter and the corresponding economy in magnet size. He is concerned about coupling of vertical and radial oscillations and introduces the concept of the quadrupole lens.

Regretfully, Christofilos' discovery went unnoticed for almost three years. Since it did not appear in a physics journal, it did not attract attention and those who received private copies either did not read them, or did not appreciate the importance of the new principle. In 1952 strong focussing was rediscovered by E. Courant and H. Snyder, following a suggestion by M. S. Livingston to examine a lattice with alternately placed C-magnets [2]. This was an independent discovery promptly published and immediately applied to the design of the new accelerators at Brookhaven, Cornell and CERN. In contrast, Christofilos' discovery was made in isolation from scientific colleagues and with only very limited access to the literature.

In 1953 Nick Christofilos visited the U.S. and while reading the Physical Review at the Brooklyn Public Library came upon the Courant, Livingston and Snyder article. He thought that his idea had been used without acknowledgement and rushed to Brookhaven where he was shown around by John Blewett. After some excited discussion it became clear that Christofilos deserved the credit for the earliest enunciation of the principle of strong focussing but also that the Brookhaven discovery was completely independent. Christofilos was immediately offered a position at Brookhaven where he joined the team designing the 28 GeV Alternating Gradient Synchrotron (AGS) under G.K. Green. Eventually a settlement was reached with the Atomic Energy Commission for the use of his patented idea in accelerators then under construction.

3 "ASTRON" AND THE LINEAR INDUCTION ACCELERATOR

Nick Christofilos was an intense and colorful personality. He bristled with ideas and loved to explain them and argue about them. At Brookhaven he contributed to the de-

Plate 2 Nicholas Christofilos, Paul Weiss (left) and Eugene Lauer in front of the 90 foot chamber of Astron in 1964. Courtesy LLNL.

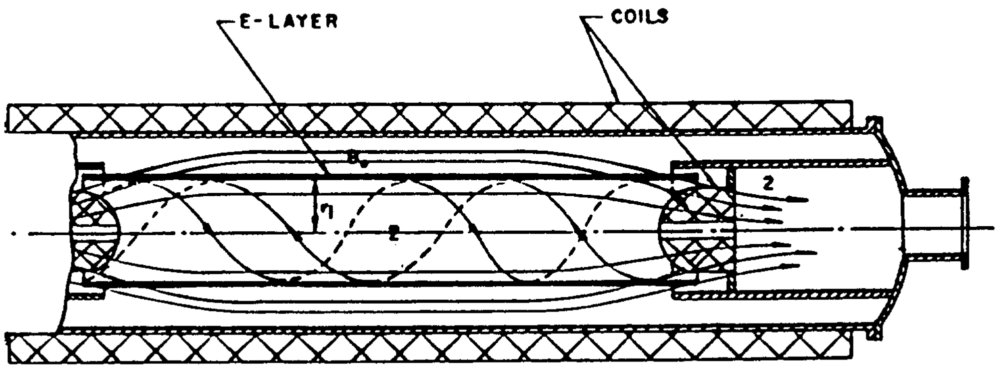

Figure 3: Conceptual Schematic of the "Astron" containment vessel (from Ref. [4]).

sign of the drift tubes for the 50 MeV proton linac [3] but his principal interest was the Astron proposal. Astron is the Greek word for "star" which Nick, appropriately coined for his thermonuclear reactor project. Since all fusion work at that time was classified, it was decided that the work on Astron would be carried out at Livermore (now Lawrence Livermore National Laboratory, LLNL). This led to many amusing incidents until Nick's clearance came through. In one instance he was to present his proposal at a meeting of the "Sherwood project" held in a rented movie theater in Berkeley. While the audience could freely ask questions of the speaker Nick was frustrated since his queries could not be answered. In 1956 Christofilos joined Livermore where he spent the rest of his career.

The fundamental idea of Astron [4,5] was to create closed magnetic lines by establishing a cylindrical layer of electrons at high energy and density. Since electrons and ions would spiral around the magnetic field lines [6] they would remain confined. Furthermore the ions would be heated by colliding with the energetic electrons in the so-called "E-layer". The magnetic lines would by necessity be closed if the field inside the E-layer was reversed with respect to the external field that established the E-layer in the first place. This is shown schematically in Fig. 3. Consider an external axial field B_0 as shown, so that electrons injected perpendicular to the field will follow a circular orbit of radius $R = m\gamma\beta/eB_0$. By appropriate field shaping the electrons can be made to drift axially so as to form a cylindrical layer characterized by a linear density of n_0 electrons/cm. The field generated by this electron layer is directed opposite to B_0 (Lenz's law) and is given by

$$B_{\text{in}} = 2\pi(I/\ell) = 2\pi e n_0 \omega_0 = n_o(e^2 B_0/\gamma m) \tag{12}$$

Therefore "inversion" will be achieved when $\vec{B}_{\text{in}} = -\vec{B}_0$ or

$$n_o = \gamma/(e^2/m) \tag{13}$$

where $e^2/m \equiv r_e = 2.82 \times 10^{-13}$ cm is the classical electron radius. Thus for 50 MeV electrons ($\gamma \sim 100$) the required linear electron density is of order $n_0 \sim 3 \times 10^{14}$ cm^{-1}, a rather demanding condition.

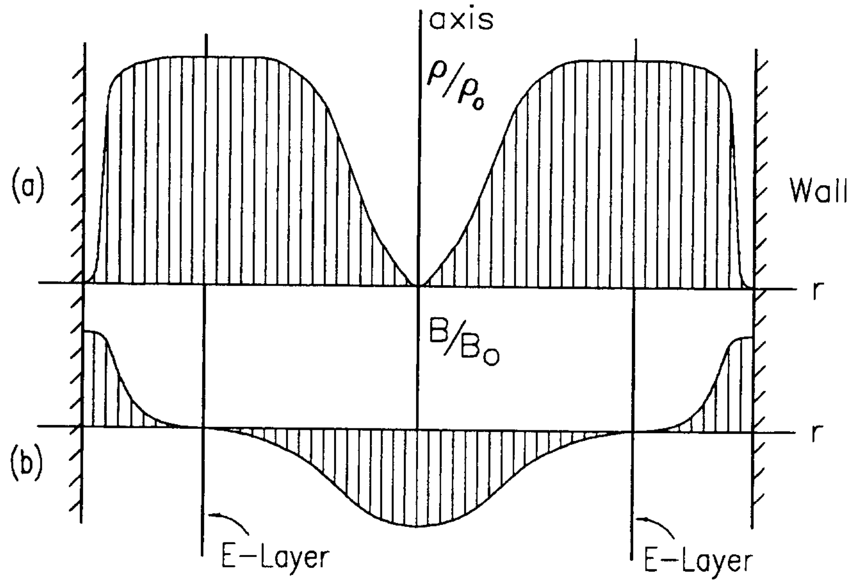

Figure 4: (a) Ion density and (b) magnetic field radial distributions calculated for "Astron" (from Ref. [5]).

A set of design parameters for Astron is given in Table 1. Note that the required external field is an order of magnitude larger than the field seen by the E-layer; the calculated field variation and the ion density are shown in Fig. 4. However the electron density needed for inversion was never achieved because of instabilities in the E-layer, in particular when stacking multiple electron pulses. This in spite of a large effort by many talented physicists who worked on the project. The project was terminated in 1973.

Table 1. Parameters for the Astron Thermonuclear Reactor

E-layer electron energy	50 MeV
E-layer radius	50 cm
B_0	3 T
Length of E-layer	30 m
Plasma temperature	25 keV
(D-T ignition)	8 keV
Ion density	$6 \times 10^{14}/cm^3$
Net electric power output	0.5 GW

The lasting contribution that resulted from the Astron program was the invention and development of the Linear Induction Accelerator. A high current electron source was needed to establish and maintain the E-layer. Christofilos was aware of the inadequacy of travelling wave linacs for this purpose and set out to invent the "induction linac". Again the principle is simple: the electrons pass through a region of changing magnetic flux and gain energy by Faraday's law [7]. A simplified schematic is shown in Fig. 5 where a time dependent magnetic field is excited in a torroidal loop of area A; electrons cross

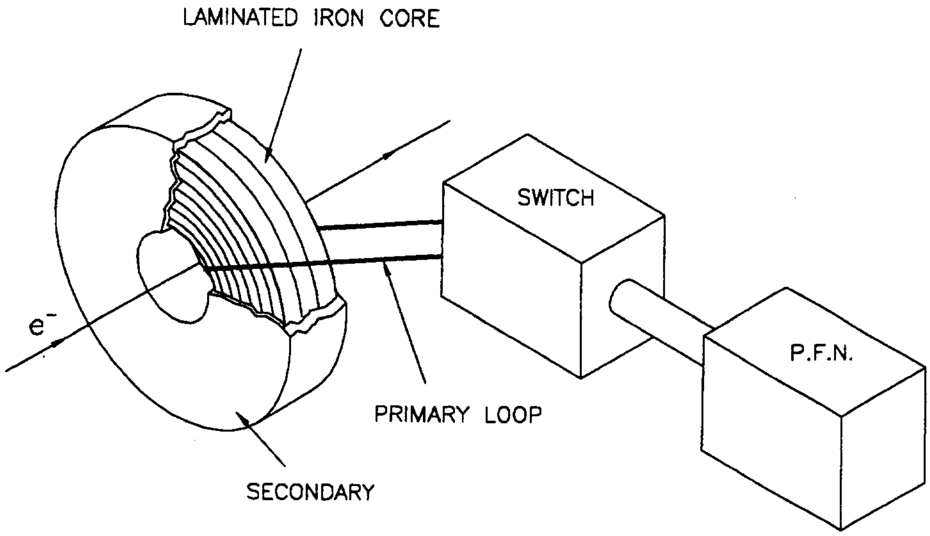

Figure 5: Principle of the linear Induction Accelerator (from Ref. [8]).

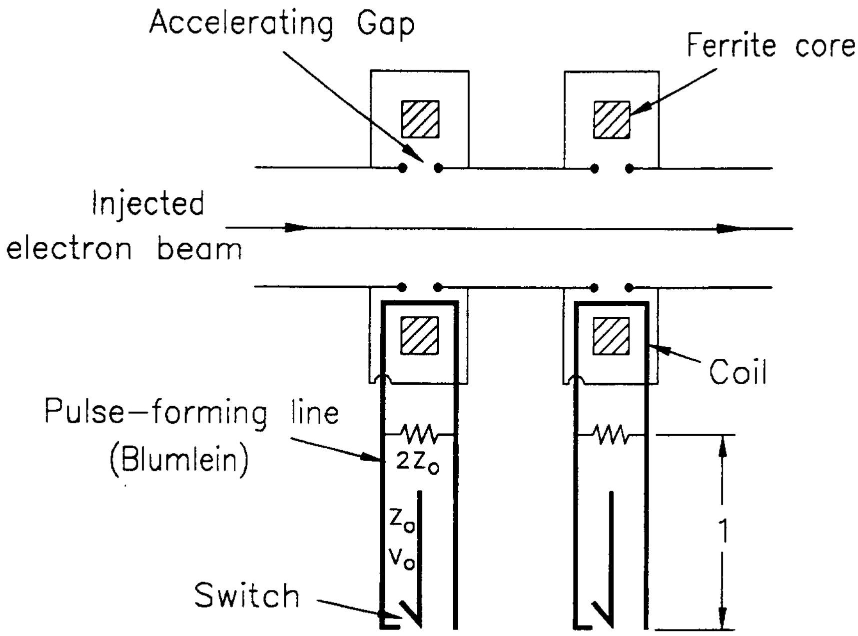

Figure 6: Schematic of a 2-Cavity Linear Induction Accelerator (from Ref. [7]).

Figure 7: The Advanced Test Accelerator. Photograph courtesy Lawrence Livermore National Laboratory.

the center of the torroid so that the energy gained is given by the rate of magnetic field change integrated over the torroid area

$$\Delta E = e \oint \vec{\mathcal{E}} \cdot d\vec{\ell} = -e \int \frac{\partial \vec{B}}{\partial \vec{t}} \cdot d\vec{A} \tag{14}$$

For practical values of $\partial B / \partial t$ and magnetic core area one can easily reach $\Delta E \sim 100$ keV. Several such cores can then be stacked in series to achieve the desired energy.

Induction accelerators are often compared to transformers. In the case of the betatron, the beam is considered as a multiturn secondary which is raised to high voltage by the changing magnetic flux threading the orbit. In the induction linac the beam is viewed as a single turn secondary which can carry high current. In practice, when several induction stages are used to reach the desired voltage, the primary function of the magnetic cores is to isolate one accelerating cavity from the next. This is shown in Fig. 6 which is a schematic of a two-cell linear induction accelerator such as the Advanced Test Accelerator (ATA). A 250 kV pulse is applied directly across the acceleration gap but also excites the ferrite core. This places a high impedance between the pulse feed and its return so that the current loop is closed through the beam [8].

The first induction linac was that used as an injector for Astron. It delivered a 4 MeV pulse at 150 A and was completed in 1964. In 1968 the accelerator was upgraded to deliver 600 A of 6 MeV electrons. A prototype for a second generation accelerator the ETA (Experimental Test Accelerator) began operation in 1979 and was capable of 10 kA of 5 MeV electrons. This was followed by the ATA (Advanced Test Accelerator) which achieved 10 kA operation in 1984. The parameters of the ATA are given in Table 2 and a view from the electron gun end is shown in Fig. 7. Both the ETA and ATA were capable of continuous operation at 1 Hz and of 5-10 pulse bursts at 10 kHz.

Table 2. The Advanced Test Accelerator

Primary Voltage	250 kV
Pulse duration	35 ns
Repetition rate	1-5 Hz
Number of cavities	200
Length	85 m
Electron Energy	50 MeV
Average current in pulse	10 kA
Energy in pulse	18 kJ

4 NATIONAL DEFENSE

A significant part of Christofilos' activities at Livermore was devoted to National defense. He understood the military needs of the country at the height of the cold war and was proud to contribute his vast scientific knowledge and mental agility to such problems. Much of that work especially on directed energy weapons still remains classified. There are today in excess of 200 declassified technical reports which he authored or co-authored while at Livermore. Among the better known of these projects are the "Argus" experiment and the proposal for low frequency communications code named "Sanguine".

In 1957 Christofilos proposed that one could create an artificial belt of electrons around the earth by injecting at sufficient altitude energetic electrons into the earth's magnetosphere [9]. The electrons would spiral along the magnetic field lines but would be reflected at the reentry points due to the "magnetic mirror" effect. This is shown in Fig. 8 and follows from the (adiabatic) invariance of Ba^2 where a is the radius of the spiral and B the local value of the magnetic field. It follows that

$$\frac{p_\perp^2}{B} = \frac{mv_\perp^2}{B} \text{ is conserved and } = m\frac{v_{\perp 0}^2}{B_0^2} \tag{15}$$

and therefore

$$v_\parallel^2 = v_0^2 - v_\perp^2 = v_0^2 - v_{\perp 0}^2\frac{B(z)}{B_0} \tag{16}$$

Thus the axial velocity $v_\parallel$ will go through zero and reverse direction for a suitable increase of the axial field.

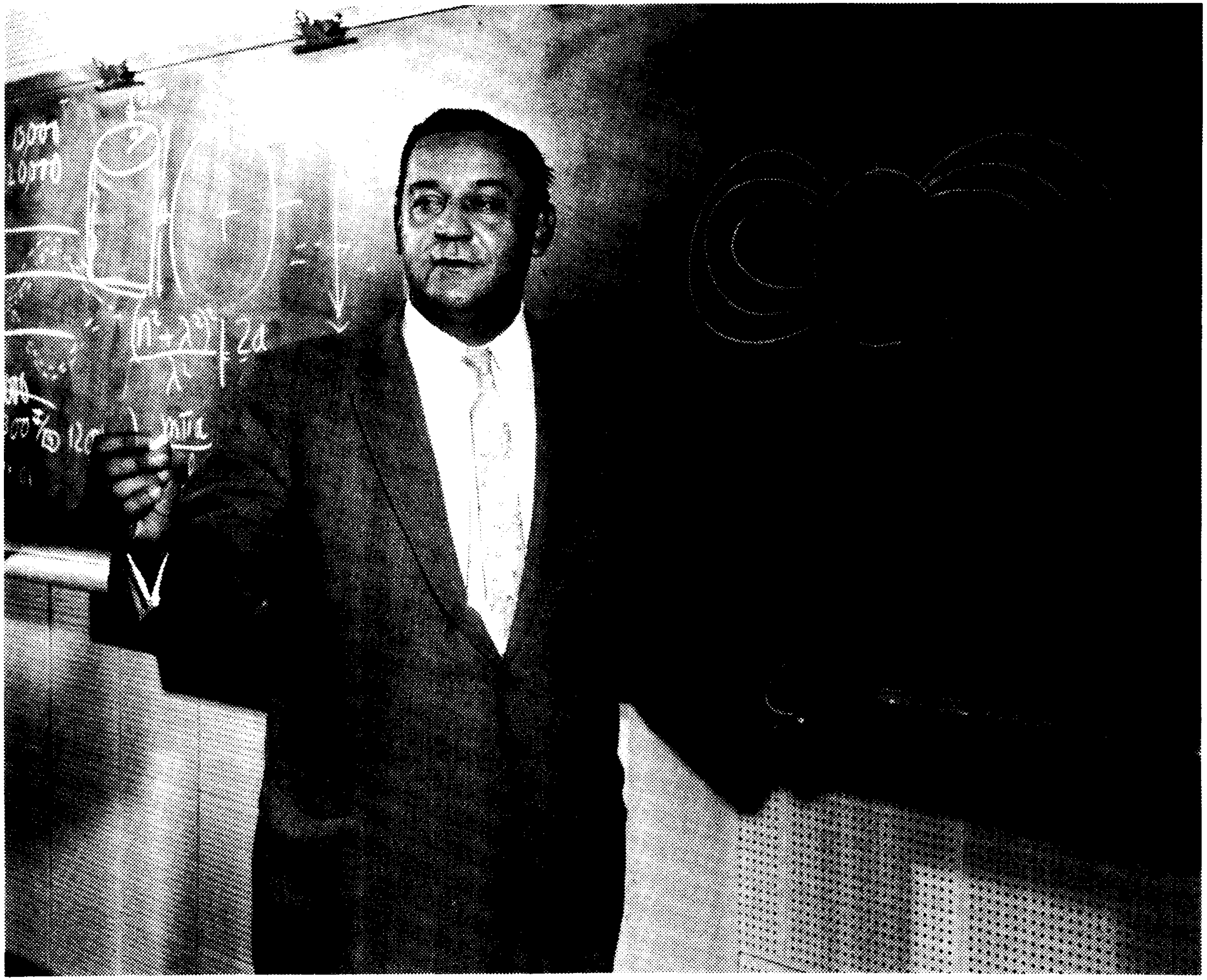

Plate 3 Nicholas Christofilos in 1958 discussing the "Argus" experiment. Courtesy LLNL.

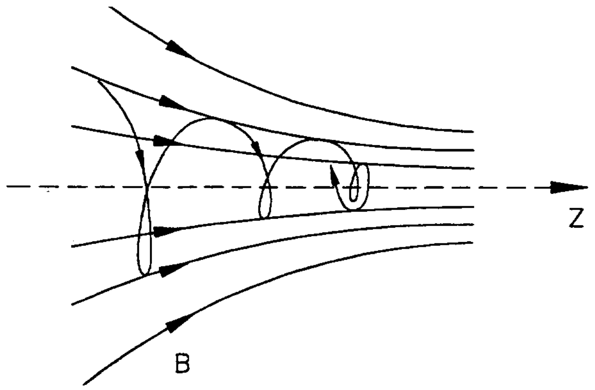

Figure 8: Mirror effect for a trapped particle in an increasing magnetic field.

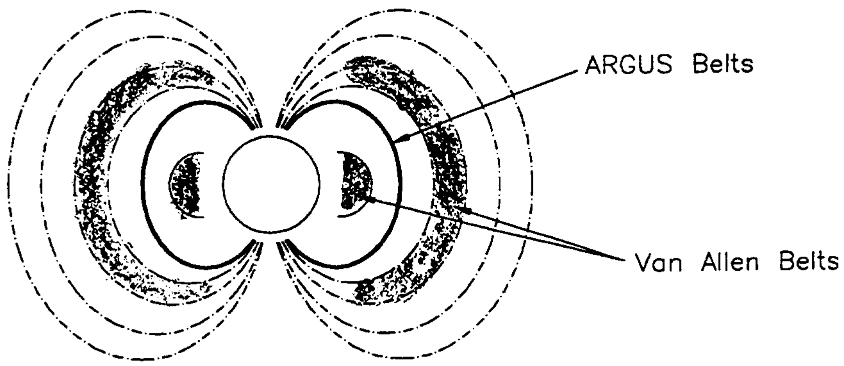

Figure 9: Approximate location of the electron belts produced by the "Argus" experiment.

It is important to note that the Argus proposal was made before the discovery of the Van Allen belts. The source of electrons would be a nuclear detonation and would result in a very dense electron layer which could, for instance, be useful for defense against incoming missiles. The experiment was carried out from August 27 to September 6, 1958 by detonating three small (1-2 kiloton) nuclear devices over the South Atlantic Ocean, at a nominal altitude of 180 km. The radiation was probed by the Explorer 4 satellite which was placed in a near earth orbit.

Minutes after the detonation the radiation could be detected in the Northern hemisphere. Figure 9 shows the position of the Argus belts in relation to the natural Van Allen belts. In total 180 crossings of the sattelite through the artificial electron belts were observed, the typical energy of the detected electrons being 3 MeV; a crossing lasted approximately 30 seconds. The lifetime of the belts, in one case, was as long as 15 days, in excess of the calculated effect. Argus was an experiment on a global scale, and pointed out how vulnerable the earth can be to modern technology.

"Sanguine", was the code name of the U.S. Navy for its project of extremely low frequency (elf) communication with submerged submarines. The idea was to use the Schumann resonances for the propagation of these low frequency waves around the globe. These resonances arise because the ionosphere and the surface of the earth form a waveguide in which TM waves can propagate as shown in Fig. 10. Neglecting the distance to the ionosphere the frequency of the lowest modes is given by

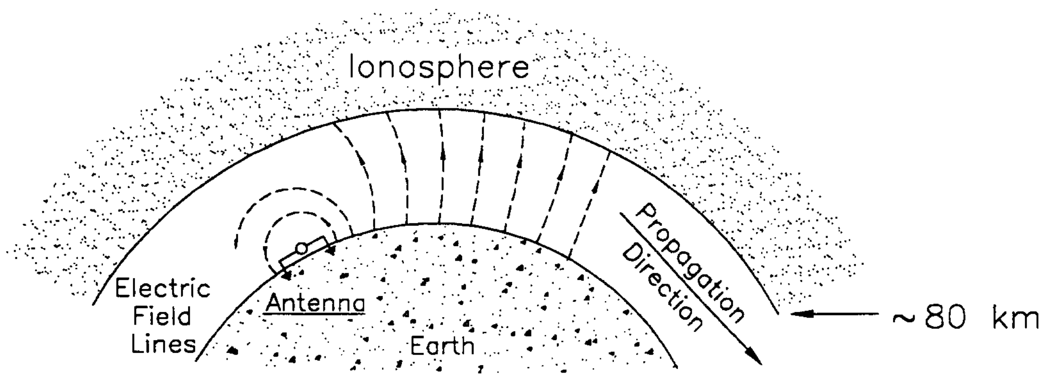

Figure 10: Excitation of a Schumann ELF mode in the earth-ionosphere system.

$$\nu \simeq \frac{c}{2\pi a}\sqrt{\ell(\ell+1)} \tag{17}$$

with a the radius of the earth [10]. The observed frequencies are closer to 8, 14, ... Hz.

The problem solved by Nick Christofilos was how to excite the resonances [11]. He proposed a linear antenna shorted into the earth at both ends. Because of the reflection at the conducting surfaces of the ionosphere and of the earth the antenna is equivalent to an infinite sequence of dipoles and couples effectively into the TM mode. A site in Wisconsin was under consideration for a long time envisaging a 150 km long antenna operating at 40 Hz. It would radiate 4 kW for a power input of 38 MW.

These two examples are typical of Christofilos' practical solutions to problems on any scale. He was a scientific genius ahead of his time and would always seek a novel approach to a problem. Yet he was widely read and had extensive knowledge of the work done by others. The traits of his Greek upbringing stayed with him to the end, evident in his supreme self-confidence, his occasional impatience and in his ultimate generosity to all.

5 EPILOGUE

Nicholas Christofilos died of a heart attack on September 24, 1972 in Hayward CA. Typically, the previous night he had worked late at Livermore. In his life he had been honored in 1963 by the Elliot Cresson medal of the Franklin Institute and in 1959 by the National Science Achievement Award of the American Hellenic Progressive Association (AHEPA). Posthumously the ATA was dedicated in 1980 to his memory. Christofilos was married twice: in 1954 to Elly Christofilos and in 1960 to Joan Jaffray. He left two sons, Nicholas Christofilos, Jr. from his first marriage and Jason Christofilos from the second marriage.

Nick worked extremely hard at his "physics" and was at the Laboratory every day from ten in the morning to midnight. He asked a lot from the physicists, engineers and technicians who worked with him. Through the force of his personality and the example of his own dedication he got extraordinary performance from his team. It is at Livermore that he formed his most lasting scientific friendships and to this day his former collaborators speak of him with great affection. I had met Nick Christofilos only briefly, however it seems to me that his personality is best summed up by the closing paragraphs of his obituary written by his friends, and which appeared in Physics Today [12]:

> "... Many of his ideas were controversial and defending them would sometimes seem to demand more ingenuity and unremitting effort than even his great spirit and energy could sustain.
>
> He was devoted to music, especially Beethoven, whose birthday he shared. He had studied concert piano as a child and when he found time he still played, as he did physics: fortissimo. Intensely preoccupied with work, he made few casual friends. Instead he leaves behind many who admired him greatly and a select group of loyal, close associates who will pursue his dreams. For them, there can never be another Nick."

6 ACKNOWLEDGEMENTS

I sincerely thank the organizers of the school for this opportunity to review for a younger generation of accelerator physicists the work of Nicholas Christofilos. I am heavily indebted to the many persons who shared with me their recollections of Nick and of the early days of strong focussing; in particular to J. P. Blewett, T. Fessenden, K. T. Fowler, S. Humphries Jr., D. L. Judd, and A. B. Langdon. The kind cooperation of Mr. Stephen Wofford of Lawrence Livermore Laboratory in providing the archival material and the photos of Nick Christofilos, is greatly appreciated.

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[9] N.C. Christofilos, Proceedings of the National Academy of Sciences 45, 1144 (1959) and related articles.

[10] See for instance J.D. Jackson, "Classical Electrodynamics", John Wiley and Sons, New York (1975) p. 360.

[11] N.C. Christofilos, "Ocean 1972, IEEE International Conference on Engineering in the Ocean Environment" p. 145. This is a report dated August 29, 1960 and declassified on June 29, 1972. See also related articles.

[12] Physics Today, January 1973 p. 109. Obituary of Nicholas Christofilos by J.S. Foster, T K. Fowler and F.E. Mills.