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REVIEW ARTICLE

Greek Fire: Nicholas Christofilos and the Astron Project in America's Early Fusion Program

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Abstract The Astron project, conducted from 1956 to1973 at Livermore National Laboratory, was the brainchild of Nicholas Christofilos, a Greek engineer with no formal physics credentials. Astron's key innovation was the E-layer, a ring of relativistic electrons within a magnetic mirror device. Christofilos predicted that at sufficient E-layer density the net magnetic field inside the chamber would reverse, creating closed field lines necessary for improving plasma confinement. Although Astron never achieved field reversal, it left important legacies. As a cylindrical device designed to contain toroidal plasmas, it was the earliest conception of a compact torus, a class that includes the Spheromak and the FRC. The linear induction accelerator, developed to generate Astron's E-layer, is now used in many applications. Through examination of internal lab reports and interviews with his colleagues and family, this research charts Christofilos' career and places Astron in its historical context. This paper was originally prepared in 2004 as an undergraduate Junior Paper for the Princeton University History Department.

Keywords Fusion · Astron · Nicholas Christofilos · Field reversal · Linear induction accelerator

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Introduction

The second largest building on the Lawrence Livermore National Laboratory's campus today stands essentially abandoned, used as a warehouse for odds and ends. Concrete, starkly rectangular and nondescript, Building 431 was home for over a decade to the Astron machine, the testing device for a controlled fusion reactor scheme devised by an unknown engineer-turned-physicist named Nicholas C. Christofilos. Building 431 was originally constructed in the late 1940s before the laboratory even existed, for the Materials Testing Accelerator (MTA), the first experiment performed at the Livermore site. By the time the MTA was retired in 1955, the Livermore lab had grown up around it, a huge, nationally funded institution devoted to four projects: magnetic fusion, diagnostic weapon experiments, the design of thermonuclear weapons, and a basic physics program.[1] When the MTA shut down, its building was turned over to the lab's controlled fusion department. A number of fusion experiments were conducted within its walls, but from the early sixties onward Astron predominated, and in 1968 a major extension was added to the building to accommodate a revamped and enlarged Astron accelerator. As did much material within the national lab infrastructure, the building continued to be recycled. After Astron's termination in 1973 the extension housed the Experimental Test Accelerator (ETA), a prototype for a huge linear induction accelerator, the type of accelerator first developed for Astron. The second generation of ETA still operates in the extension today, but the original building has outlasted its usefulness and is slated for demolition. For years it has stood empty, waiting for another project to come along and fill its

[1] [6].

space—a massive but little noticed reminder of experiments gone by. In Big Science, projects don't disappear completely; they end, but the traces they leave behind last a long time.[2]

The Astron project was born and died at Livermore, part of the system of big, government-sponsored labs that make up a significant part of the scientific establishment in this country. Entrenched as they have become, the national labs in their present form are relatively young institutions, products of World War II research efforts and the needs of the Cold War that followed in its wake. The first labs to receive the official "National Laboratory" designation, Argonne and Brookhaven, were anointed in 1946, and though "national" was not added to their titles until later, Los Alamos and the Berkeley Radiation Lab were treated from the late 1940s as part of the national laboratory network. Livermore is the baby of the family, created in 1952 at the urging of Edward Teller and Ernest Lawrence for the express purpose of pursuing the hydrogen bomb.[3] When the Astron project was launched in 1956 the lab was still in its infancy, and so Astron grew up along with its parent organization. Astron lived out its seventeen years during the formative period of Livermore and of the national lab system as a whole, a time of constant flux in which the government and the scientists probed and adjusted their new relationship and jockeyed for control. Christofilos, Astron's creator and guiding spirit, spent his career negotiating the tumult that was Big Science in the late fifties, sixties, and early seventies, and his story cannot be disconnected from that broader one. Moreover, in addition to the ebb and flow of attitudes toward scientific research generally, the fusion program, of which Astron was a part, was affected by its own set of external factors. At the same time, Christofilos' unusual personality and proclivities ensured that Astron's story would be distinctive.

The Astron Concept

Christofilos was the devoted leader of the Astron project, his brainchild, for all but its last six months. Astron was a novel approach to controlled fusion, novel because its basic principle, the use of circulating beams of charged particles rather than solid coils alone to generate the magnetic field for plasma confinement, was strikingly different from any

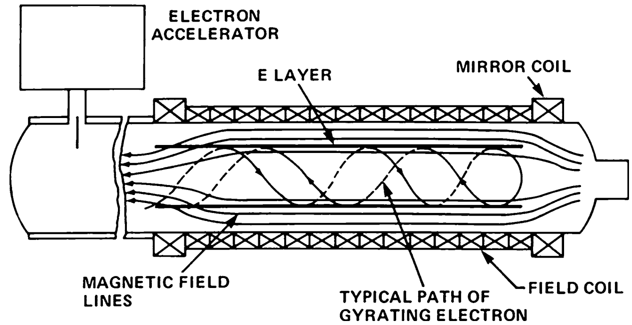

Fig. 1 Gyrations of E-layer electrons trapped in magnetic mirror field (Bromberg, 121)

other concept under study at the time. In Christofilos' design scheme, high-speed electrons were injected into a chamber. The awaiting chamber was rigged with magnetic mirror coils, so that the injected electrons were trapped in a magnetic field and their orbits were bent into a cylindrical shell, which he dubbed the E-layer. Electrons were injected continuously until the current in the E-layer exceeded the external current flowing in the mirror coils, at which point the overall magnetic field produced by both the E-layer and the coils would reverse its direction. When field reversal occurred, the magnetic lines would close back in on themselves inside the chamber, forming a pattern of closed field lines in which plasma could be well contained (Figs. 1, 2). Thus in addition to being a unique *means* of producing confinement, the E-layer also boasted a revolutionary confinement *geometry* of closed, toroid-shaped field lines within a linear machine, with no structure at the center of the torus.

The creativity and comprehensiveness of the Astron design are all the more impressive in light of the inventor's background. In 1953, when he first presented the idea to a panel of American scientists, Christofilos resided in Greece, where he worked as an electrical engineer. He had never had direct contact with the fusion program or any American academic science, and did not hold a degree in physics. Nicholas Christofilos descended on the Big Science scene out of nowhere, and wasted no time making himself at home. He knew that he had big ideas, great ideas, and he expected the Americans to give him the means to pursue them as surely as he expected the sun to rise in the east.

The Path to Astron

To Christofilos, the move to the United States to pursue a career in physics was a homecoming. He had been born in 1916 in Boston, to Greek parents who gave the US a try but could not escape the pull of their native land.[4] When he

[2] In his book *Image and Logic: A Material Culture of Microphysics*, Peter Galison [5] describes and gives a number of examples of the phenomenon of recycling material in the industrial-style post-war labs. His examples include television cameras incorporated into spark chambers, medical X-rays used as films for atomic physics, and preparatory apparatuses for hydrogen bombs blended into other experiments.

[3] [8].

[4] [32].

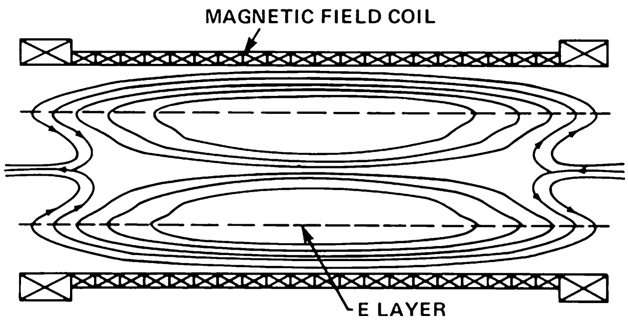

Fig. 2 Formation of pattern of closed magnetic field lines in Astron (Bromberg, 121)

was seven years old, his parents returned to Greece, and so Athens was Christofilos' home for the next thirty years. His precociousness and scientific curiosity were apparent from childhood; soon after the move to Athens he developed an interest in radios and learned to build radio sets and transmitters. As a teen he was a ham radio operator, until the Greek government banned amateur radio transmission in 1936.[5] In 1938 he graduated from the National Polytechnic Institute in Athens with a degree in Electrical and Mechanical Engineering, the only academic degree he would ever receive. After graduation he went to work for a company that installed and maintained elevators. While the common lore of the Christofilos story often enhances the drama of his sudden rise to prominence by referring to him as an "elevator operator," in fact Christofilos worked for the firm as an electrical engineer.[6]

In 1940 the Nazi army invaded Greece, and Athens became an occupied city. Professionally, the German occupation was in essence an extended vacation for Christofilos. His employer, Wisk, Inc., was commandeered by the Germans and forced to forgo the elevator business and repair trucks instead. Christofilos became a supervisor of repairs, a job which to him was child's play, and found himself with a lot of spare time on his hands. He devoted his vacant hours at the plant to a rigorous self-education course in physics. With the Germans in power, German textbooks were easy to come by, and Christofilos pored over *Nuclear Physics Tables* by Joseph Mattauch and Siegfried Fluegge's *An Introduction to Nuclear Physics* (1942), as well as *Electrical High Voltages* (1938) by Albert Bouwers, a book that describes the major American and European accelerators. After the war ended Christofilos opened his own elevator firm, but continued his dalliance in nuclear physics and began thinking up ideas of his own.[7] In 1946 he applied for a patent on an accelerator design similar to the synchrotron, but quickly learned through his reading of physics journals that such an accelerator had already been invented. Undeterred, Christofilos continued to think about accelerators, and in 1948 sent the first of a series of letters to the University of California Radiation Laboratory at Berkeley, in which he proposed an idea for improving accelerator performance through the use of electrostatic focusing and a proton synchrotron.[8] The UCRL staff wrote him a detailed response, pointing out the serious flaws in his design. Christofilos returned to the drawing board and the next year wrote to Berkeley again, this time delineating what he called the strong focusing principle, or as it is more commonly known, alternate gradient focusing. This time his readers at UCRL had less patience with the unsolicited contribution, and filed the letter away without a response. Later, the Berkeley staff would point to Christofilos's makeshift mathematics and claim that they had not understood what he was trying to say in that second letter [45]. Despite Berkeley's silence, in 1950 Christofilos filed a patent application on his invention, which was eventually granted in 1956 as US Patent 2,736,799.

Had they managed to slog through the document, Berkeley scientists would have found an original and significant contribution to scientific knowledge. When a team at Brookhaven National Laboratory reproduced the essence of Christofilos's idea two years later, the discovery was heralded as a breakthrough in accelerator science, sure to vastly improve performance while reducing costs.[9] Brookhaven was and is a leading player in particle physics, and in the early fifties was operating an accelerator called the Cosmotron. The Cosmotron could achieve energy of 3.3 GeV, an impressive number but one that by no means contented the Brookhaven team. They wanted more energetic particles, but calculations showed that a mere tenfold increase in energy would require magnets 100 times heavier–and thus 100 times costlier in terms of raw steel–than those employed by the Cosmotron.[10] It was clear that the next step forward in accelerator energy capacity required a new concept if it was to be economically viable; merely going bigger would not suffice.

The difficulty confronting the Cosmotron was that as the energy of the particles whizzing through it increased, the

[5] [3, 49]. Christofilos apparently returned to his radio hobby during WWII—Fessenden recalls Christofilos telling him that in Nazi occupied Athens, "During the war he listened to the BBC on a little radio he had built [34]."

[6] [36].

[7] That Christofilos opened his own firm is mentioned in Teller to Kraus, April 8, 1959. It is corroborated by an article in the San Francisco chronicle, October 29, 1959, that reports a lawsuit filed against Christofilos by his former business partner for payment of debts related to their firm [47]. The Bay Area press exhibited an odd fascination with all aspects of Christofilos's personal life.

[8] Teller to Kraus; [10].

[9] [19].

[10] [12].

ability of the magnets which controlled the particles to keep them on track deteriorated. There are two basic types of accelerators–linear and ring-shaped–and the Cosmotron was of the ring-shaped variety. This meant that the path particles needed to follow was a circle, not the simple straight line efficiently employed by linear accelerators. Since the natural motion of a speeding particle is a straight line, it is necessary in a ring accelerator to constantly bend the trajectory of a particle into a circular path; this is the task of the magnets which surround the accelerator chamber. At the time of the Cosmotron, the known method of magnetic control was a series of C-shaped magnets, all with the open end facing outward, placed at intervals around the circumference of the accelerator. Under such a configuration, the magnets focused particles very well in the vertical direction but not at all in the horizontal direction, and so at high energies the beams veered off course.

Conceptually, there were two ways of dealing with this problem. One was to accept it, and use brute force–in the form of much bigger magnets–to force the particles back into line. This course was practically ruled out by the tenfold growth of magnet size relative to energy yield. The numbers provided strong incentive for scientists to pursue the other means of dealing with the energy barrier: devise a radical new concept in accelerator design. This conclusion had dawned on Christofilos as he studied accelerators on paper in Athens, and it became apparent as well to three men working hands-on with the Cosmotron at Brookhaven–Ernest Courant, M. Stanley Livingston, and Hartland Snyder. On both sides of the globe the minds devised the same solution. Rather than striving to maximize focusing in one direction, the vertical, as the Cosmotron did, why not alternate between the vertical and horizontal directions, so that the beam was nudged into position from all sides? In his patent for strong focusing, Christofilos proved mathematically that the obvious ideal, simultaneously focusing the beam in both the x and y directions, is physically impossible. However, as he went on to demonstrate, alternating focus between the two axes is the next best thing, and comes far closer to imitating an ideal focus than does y-axis focusing alone.[11] In their paper on the subject, Courant, Livingston, and Snyder showed that "there was no theoretical limit to the energies to which [particles] could be accelerated," simply by alternating the focus more frequently in a given space.[12]

Christofilos was in Greece, still running his elevator installation firm, when Courant, Livingston, and Snyder published their discovery of alternate gradient focusing in the December 1 issue of *Physical Review*. Since the end of the war and the renewed accessibility of American publications in Greece, Christofilos had avidly followed advances in physics by reading journals, especially the *Physical Review*. When he came upon the Brookhaven team's article, he immediately recognized the idea it expressed as fundamentally the same as his accelerator innovation, on which he had a patent pending. Two months later Christofilos headed for the US to stake his scientific claim.

This initial trip, in 1953, seems to have been an eventful one. Christofilos made his way to Brookhaven, where he announced angrily that the idea on which their new accelerator was to be based was *his*, that they had stolen it, and that he had a patent to prove it. He also met with members of the Atomic Energy Commission (AEC), who examined his patent, met with his attorneys, and finally paid him $10,000 for the use of his idea. That was a considerable sum in 1953, but it was a smart investment for the AEC; alternate gradient focusing saved the government an estimated 70 million dollars on the construction of the new Brookhaven accelerator.[13]

Astron Proposed

Christofilos wasted no time in putting his new-found prestige to use. Strong focusing was not the only idea he had worked on during his spare time in Greece; he had a different pet project that he was eager to submit to an American scientific community suddenly willing to listen to what he had to say. He called it Astron after the Greek word for star, because it was a scheme to bring the power of the stars down to Earth. In April of 1953 he attended a meeting of Project Sherwood (Sherwood was the codename for the classified fusion research project) and presented his thermonuclear reactor design. He made his presentation with the unbridled energy that would always characterize him–voice raised, arms flailing with the force of his gestures, wild scribbling engulfing the blackboard.[14] This garrulousness was simply Nick—years later, eulogizing him, his friends wrote that he "played [the piano], as he did physics: fortissimo" [21].

In spite of his crude mathematics (and thick Greek accent,) the audience was intrigued by the ideas Christofilos put forth. Although it was obviously fine-tuned before and during the actual experimentation at Livermore, the Astron idea was painstakingly thought out from the outset; conceptually Astron at its end would differ only slightly from the theoretical machine Christofilos originally proposed in 1953. The brand new scheme laid out before fusionists that day was completely unlike any of the projects they were working on, but Astron was not merely

11 [50].

12 [19].

13 Crease, 220.

14 Teller to Kraus; [43].

clever and original. It struck a chord among the plasma physicists assembled because it offered the prospect, if the gregarious figure before them had done his homework properly, of combating some of fusion's stickiest problems. At the time, two of the predominant fusion ideas under study in America were the stellarator and the mirror.[15] While both teams were still headily optimistic in 1953 and proceeding on the assumption that their devices were stable, each concept had shortcomings that the researchers knew could become problematic. Unknowingly, in Astron Christofilos had developed an idea whose strengths mirrored the precise weaknesses of the existing experiments.

A serious drawback to the stellarator was its sheer complexity. Both the pattern of field lines and the actual plasma tube of the stellarator were twisted into what its inventor, Lyman Spitzer, called a "pretzel" formation. Spitzer expected the unusual shape to combat the tendency in a curved field of the plasma to separate into positively and negatively charged sections.[16] Whether or not the stellarator bore out his predictions experimentally, there was no doubt that its complex geometry would make repairs and adjustments costly and difficult. Astron, like the mirror, had the attractive property of a simple linear configuration that sidestepped the complications of the stellarator geometry. Moreover, the question of the stellarator's stability was very much up in the air. Physicists working on the pinch experiment at Los Alamos had concluded by 1953 that the pinch machine suffered from a severe instability. While neither the stellarator nor the mirror seemed to share the type of severe instability plaguing the pinch, a theoretical analysis of the stellarator indicated that instability could become a problem at high temperatures. Astron, on the other hand, was expected to be stable because the E-layer's extremely energetic electrons provided a current separate from the plasma. This plasma-independent current would, it was hoped, provide "stiffness," a kind of backbone that would stabilize the plasma.[17]

Though the mirror machine was linear and, at the time, expected to be stable, it came with its own essential difficulty: plasma loss out the ends of the device. The mirror was a linear machine, whose concept was inspired by the behavior of cosmic rays trapped in the Earth's magnetic field. The Earth's field is not constant, but is stronger in some points than in others, and the result is that some particles are reflected back the way they came when they encounter the strong sections of the field. In the mirror device, the hope was that many of the plasma particles would be reflected and bounce back and forth between the poles of the machine rather than flying out along the open field lines. Unfortunately, the method's results were middling and end loss continued to be a serious problem. Astron resembled the mirror in its linear configuration, but because each field line completely closed on itself within the device, end loss was not an issue.

Christofilos' idea seemed to combine the best features of the rival existing approaches to fusion—the mirror's shape with the stellarator's closed field lines. While his widely publicized formulation of strong focusing won him the ear of the American physics community, it was the strength of Astron as a concept that convinced the fusion bigwigs and the AEC to pursue his idea. On the one hand Astron was radical, its use of high energy, circulating particles to perform the work of solid coils an original and unexplored idea. At the same time, the men already working with plasmas recognized that it was articulated in terms they recognized, a relative, though perhaps a distant one, of the fusion ideas they already knew. The approach complemented the work already underway in the field, and therefore was something they wanted to pursue.

Even with a consensus among leaders in the field and AEC agreement that Christofilos should be allowed to explore his concept, a sticking point remained. In 1953 fusion was still classified, so working in the field required security clearance that Christofilos did not have. The classification issue had already cropped up once, in an incident that made a lasting impression on Edward Teller, one of the more distinguished members of the panel interviewing Christofilos.[18] Before Christofilos' talk, the assembled group had been discussing classified information and had covered the chalkboards in the room with their calculations. Preparing for Christofilos to enter, a security team carefully scrubbed the boards clean. The meeting was odd to begin with, since classification rules created a situation in which Christofilos did not know how much his audience knew about the topic he was discussing or whether his idea was novel at all, and though his listeners could interrogate him, he was not allowed to ask any questions. Flustered but undeterred, Christofilos plowed ahead and quickly filled the blackboards with equations. As he began to erase his writing to make more space, someone in the room showed him a button to press which raised the boards, uncovering a second layer underneath. As the boards lifted the physicists gasped—the cleaning squad had forgotten to erase the inner boards and the sensitive material from the previous session was revealed before Christofilos' unauthorized eyes.

15 A third concept, the pinch, was investigated at Los Alamos. Very early on, however, the pinch exhibited gross instabilities and was therefore viewed as less promising than the other two major concepts.

16 [2].

17 "Stiffness" is Fowler's terminology. Fowler interview. For pinch instability and stability calculations on the stellarator, see Bromberg, 50–51.

18 [7]. Teller also recounted the story to me in person shortly before he died, and Richard Post relayed it in an interview.

After the short term security crisis was averted, the committee devised a plan: Brookhaven, whose accelerator work was not secret, would offer Christofilos a job. He would work there on the design team for the new Alternate Gradient Synchrotron until he was granted the clearance necessary for fusion work. And while at Brookhaven, he was instructed to continue his theoretical examination of Astron, to bolster the claims that it would work as promised.[19] If all went well, Christofilos's star would soon be born.

This was a time of beginnings for Christofilos. Along with a new career, he began a new family. Before leaving Greece to start his life as a physicist, he asked his girlfriend, Elly, to follow him to America and become his wife. She agreed, and they were married in New York on April 27, 1954.[20] While Christofilos immersed himself in the challenges presented him at Brookhaven, Elly had a harder time adjusting to her new home. Americans struck her as a cold people; she missed the warmth of her Greek community, and the family and friends she'd left behind. Even now, after fifty years in America, her nostalgia for Greece is deep.[21] But for Christofilos, there was never any looking back, and besides, he had found a community that respected and appreciated him for his abilities. Dr. Courant, one of the co-inventors of strong focusing and a colleague of Christofilos's at Brookhaven, notes that at the time that Christofilos joined the lab, no one cared much what fancy degrees anyone did or did not hold. A scientist was judged by what he could contribute, and it was clear that Christofilos's potential was great. In his three years at Brookhaven, he exhibited his vast aptitude and enthusiasm as he played catch-up, learning the complex mathematics, such as Bessel functions, needed to participate in the world of nuclear physics. He also made important contributions to the lab's work, most notably by designing the drift tubes for the AGS.[22]

Astron Realized

Engaging as the work was, Christofilos never forgot his dream machine, the Astron. Courant recalls that he and the others at Brookhaven knew that Christofilos was working on the idea and on getting his security clearance, but that he never discussed it with anyone. Fusion was classified, and Christofilos was extremely conscientious about safeguarding national secrets. According to everyone who knew him, Nick was a "super patriot," unswervingly devoted to serving and protecting the United States in every way he could.[23] Elly reflects that while he had warm feelings toward Greece, the land of his parents in which he was raised and grew to maturity, America had given him the opportunity to do what he loved, to pursue his dreams. America gave Nick power and influence commensurate with his substantial abilities, the extent of which were no mystery to Nick himself–modesty was not among Christofilos' virtues. Loyalty and appreciation for a good turn were, however, and Nick never forgot that America had done exceedingly well by him. As a scientist, he saw it as his duty to address the needs of his nation through innovation, and also through discretion. At Brookhaven he waited patiently for the government to decide he could be trusted with its greatest technological secrets, and in 1956, his patience was rewarded. Nick got his clearance, and he and his family took off for California.

When the Atomic Energy Commission and the Lawrence Livermore National Laboratory decided to pursue the Astron concept, they did not skimp on the resources devoted to it.[24] At Livermore, Astron, with Christofilos as project leader, was inaugurated as the newest of three major fusion projects—the others were the mirror program headed by Richard Post and the pinch experiment led by Stirling Colgate. Thus the move from Brookhaven to Livermore involved a major shift not only in Christofilos' object of study, but also in his position and level of responsibility. Moreover, the two labs had drastically different personalities, a fact which made Christofilos' transition even more dramatic. Brookhaven prided itself on its cozy academic atmosphere, while Livermore, still primarily a weapons lab, was deeply infused with governmental and military industrialism. At Brookhaven Christofilos had worked, as Courant put it, "in a loosely organized team, but [he was] pretty independent. He was…on his own most of the time."[25] Heading the Astron project, on the other hand, placed Christofilos squarely within the lab hierarchy at Livermore, with superiors to satisfy and subordinates to direct. This was a role for which Christofilos was somehow uniquely equipped and ill-suited at the same time. Christofilos had a one-track mind at Livermore–anything that was good for Astron he favored, anything that was not, he fought.[26] While this quality made him a devoted project head, it also made him very much not a "team player," and did not always ingratiate him to the rest of the lab's leadership.

19 Post interview.

20 [48].

21 [32].

22 Teller to Kraus; [33].

23 [41].

24 At the time, the Lawrence Livermore National Laboratory was called the Lawrence Radiation Laboratory, but for clarity I will always refer to it in the text as LLNL.

25 Courant interview.

26 Fessenden interview.

In 1958, the first international fusion conference was held in Geneva, Switzerland. It was called the Atoms for Peace conference, and it stands as a monumental event in fusion history, the moment at which the veil of secrecy lifted and nations around the world shared their progress toward the dream of unlimited thermonuclear energy. The United States, bent on outshining the Soviets, sent a large delegation representing myriad fusion concepts. Although in 1958 Astron still existed only on paper, Christofilos was sent to the gathering to present his idea. The paper he wrote for the Geneva Conference Bulletin was the first published work on Astron. In it, Christofilos laid out his fusion premise, explaining that, because it provides the two necessities of confinement and heating, the "layer of rotating relativistic electrons, hereafter called the E-layer, is the key feature of the Astron concept." He also provided detailed calculations on establishing the E-layer and confining stable plasma within it.[27]

Along with Christofilos's paper, a model of the Astron facility was prepared for display at the conference, which was in essence a large and impressive show-and-tell. Charles Hurley, a mechanical engineer who had been assigned to Astron upon its inception in 1956, designed and built the model and accompanied it and Christofilos to Geneva. He recalls the excitement of that conference, and also his honor to be attending; in those days it was rare for engineers to participate in physics conferences. But Hurley was already, and would continue to be, a crucial part of the Astron project, one of the few people Christofilos trusted completely. Hurley was an experienced engineer when he joined the Astron project–he was one of the Livermore lab's original employees, having moved from the Berkeley Radiation Lab in 1952 when Lawrence launched the new facility at Livermore. But life changed for Hurley when he joined the Astron group. Hurley recalls his years with Astron fondly, as by far the most professionally exciting of his long career, but he also has regrets; the period was a sort of extended leave of absence from his family. Working for Christofilos was a double-edged sword–it guaranteed you challenge and intellectual stimulation that were intoxicating, but it robbed you of any pretensions of life outside the lab.[28]

If Christofilos was a handful for his superiors, he was a truly an ordeal for those who worked under him. Christofilos was a notorious workaholic, regularly on the job until long past midnight, and it did not occur to him that his team might have personal lives with which this Herculean schedule interfered. Moreover, Christofilos himself was a man of extraordinary abilities, with a mind that worked much faster than most, and so his ideas of what human beings could accomplish–even the talented ones Livermore employed–was often not in tune with reality. Hurley and Tom Fessenden, a physicist who worked on Astron early in his career, both recall an anecdote from one of the many times the Astron machine broke down. Christofilos approached the crew of maintenance engineers and asked them how long the repairs would take; they replied that the machine would be down for several days. Christofilos surveyed the work, which consisted of unscrewing and reattaching a number of bolts, and asked the men how long it took to unscrew one bolt. When they answered about 30 s, he announced, "Well then, you should be finished in 3 h!" Christofilos had calculated the number of bolts on the entire machine and multiplied by 30 s. Yet even as his demands were relentless and often unattainable, Christofilos had the sort of charisma as a leader that made people want to live up to his expectations, and drove them to achieve far more than they imagined they were capable of. In large part, it was Christofilos's own utter conviction, his unassailable faith in both the concept of Astron and the ability of his men and himself to make it succeed, that drove his people to work very, very hard.

After the 1958 conference, as construction got underway on the Astron facility, Christofilos and his crew had to deal with the challenges of converting a paper idea into a steel and copper machine. This gave Christofilos opportunities to utilize his talent for invention, for his way of dealing with the scientific problems that crop up in the course of any experiment nearly was always to invent a new gadget or a new methodology as a solution. During the early stages of the project, as the huge and complex Astron device was being assembled, Christofilos' inventor approach was unequivocally beneficial; as the program matured critics began to suspect that his stream of inventions were like Band-Aids being used to patch serious wounds. Among his early and most successful Astron innovations were the resistive wires which lined the Astron tank, and the linear induction accelerator (induction linac) that fed in electrons for the E-layer. The resistive wires were devised in 1959, as a solution to a fundamental problem with the Astron design. Astron consisted of two major sections: the tank in which the E-layer was formed and plasma would, with luck, one day be confined, and the accelerator responsible for energizing electrons and injecting them into the tank. These components were set up perpendicular to one another, so that the accelerator deposited its goods into the side of the tank (Fig. 3). It quickly became clear, however, that once the electrons were injected into the tank and subjected to the force of the external magnets, there was nothing preventing the energetic particles from returning the way they had come, back into the mouth of the accelerator. Christofilos solved this problem by lining the tank with resistive wires, which slowed the electrons

27 [15].

28 [39].

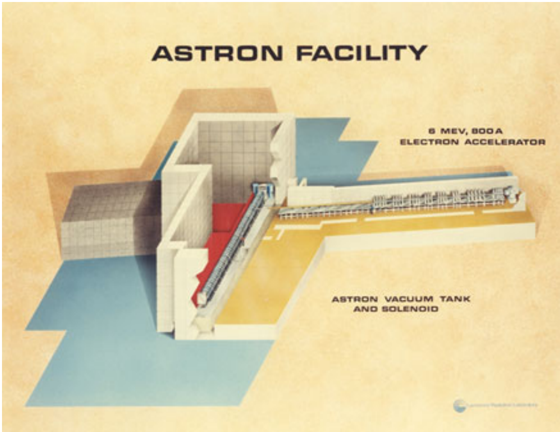

Fig. 3 Plan of the Astron facility (Lawrence Livermore National Laboratory archives)

enough that while they remained relativistic, they did not have sufficient energy to escape the tank's magnetic trap and return to the accelerator.

The other major invention of the construction period was the induction linear accelerator, the heart and soul of the Astron project. Since the Astron design demanded that the E-layer electrons be energized to precise specifications, the accelerator was arguably the most important feature of the Astron design. Nick found existing accelerator types wanting—he needed a linear rather than a circular accelerator, but the familiar linac varieties did not provide the degree of beam precision Astron required. Nick's solution was to apply the principle of magnetic induction, which had been used previously in ring accelerators, to the linac (Fig. 4). The original Astron accelerator, which began operation in early 1964, consisted of 48 donut-shaped magnetic cores surrounding a vacuum tube. Change in flux in the cores produced an electrical field that accelerated electrons according to the desired parameters.[29] While the induction linac was devised to address the particular needs of Astron, it represented, in its own right, a serious contribution to accelerator technology. Today, induction linacs are used, among other applications, in nuclear weapons diagnostics tests.

The Astron induction linac was also involved in a second project during Astron's time. Soon after he invented it, Christofilos pitched the idea of using the accelerator for weapons research to the Department of Defense. The classified project that ensued was called Seesaw, and bore much similarity to the "Star Wars" missile defense program of the Reagan years. The accelerator was used to produce electron beams that were shot into space, with the hope of developing a beam that remained powerful and focused enough to destroy a missile. Christofilos devised characteristically inventive solutions to several problems the experiment encountered, most notably the idea of chopping the beam into discrete pulses that followed each other's trails to counter the tendency of long beams to writhe and come apart. Nonetheless, the experiment never achieved any real successes, and the Department of Defense (DoD) lost interest in it almost simultaneously with the AEC's decision to shut off Astron. While the two programs coexisted, Seesaw affected Astron most markedly in the realm of funding. Christofilos received money earmarked for the accelerator from both the AEC and DoD, while the AEC also funded the other components of the Astron project. Both agencies, however, worried that their funds were being used to promote the other department's project, which created an aura of unease and suspicion around the accelerator. At the same time, DoD involvement meant that Christofilos had a second set of interests invested in his project and a second set of backers to call in for favors. According to Briggs, Christofilos became a master at the art of playing one agency off the other. Finally, his involvement in weapons research set Christofilos apart from the rest of the fusion community, especially as Controlled Thermonuclear Research (CTR) strove to distance itself from fusion's more sinister side, the H-bomb.[30]

The first Astron accelerator was completed in 1963, and was capable of delivering 4–5 MeV electrons at a current of 150 A and a rate of 60 25-microsecond pulses per second. With its completion, Astron at last was ready to go. Great hopes and expectations must have ridden on the Astron's first experimental attempts; they were after all the culmination of nine years of planning and an investment of several million dollars. Astron came at a sort of crossroads in fusion's history, and it was a phenomenon of its time. In the late fifties, the pursuit of fusion was still new and exciting, but it was no longer brand new–it was firmly inside the pale of federally sponsored research. What this meant in practice was that when Astron came along there was enough enthusiasm and optimism for fusion that the government was willing to plunge ahead with new ideas if they promised to deliver a reactor, and there was also bureaucratic machinery in place to inject serious money into the project. In the fusion program's infancy Lyman Spitzer had built his first Stellarator in a retired rabbit hutch; now the initial facility for testing the Astron concept was a subsidiary of Big Science, smack in the middle of one of the major government labs. This was a boon to Christofilos, but it came at a cost. As the price tag on an experiment burgeoned, so did the results demanded of it. The initial results out of Astron were either tepid or promising, depending on who you asked. After some

[29] [18].

[30] [31].

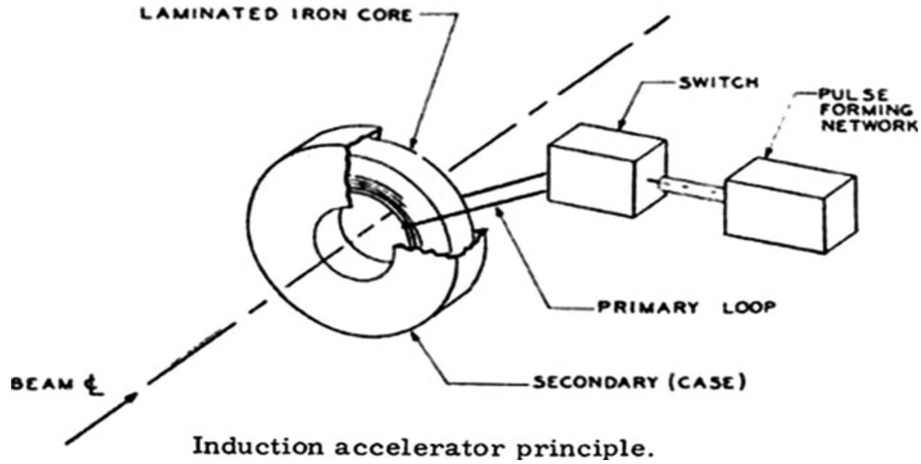

Fig. 4 Induction acceleration principle (Beal et al. "The astron linear accelerator")

hiccupping, of the variety Christofilos claimed was "expected on any new device," the machine came through with results that provided a very basic proof of principle, but little else.[31] The accelerator worked, operating at 4 MeV and 120 A, and a stable E-layer was confirmed, albeit at a paltry 0.05% diamagnetic field strength relative to that produced by the external magnetic mirror coils. Over 100% is required for field reversal and closed field lines. On the most basic level, Astron was a viable concept—E-layers could be created and sustained for a fleeting instant—but the goals of field reversal and plasma confinement were a long way off. In 1964, Astron was a very expensive hunk of metal that could not, in its present state, produce field reversal or even a solid promise of field reversal to come. At least one man, however, had no doubts about the viability of Astron or how to proceed. Christofilos wanted more money.

In his 1964 internal lab report entitled "First Experimental Results from the Astron Facility," after playing up the device's initial outputs, Christofilos delineated a series of hardware improvements that were essential for Astron's performance to live up to expectations. He managed to push through his requests, probably by appealing directly to the lab director, John Foster, and Astron was granted two million dollars to upgrade its brand new equipment.

The Astron team continued experimentation during and in between facility upgrades, and saw a steady but slow improvement in results. By 1967 the group had achieved 6% diamagnetic field, and had overcome a serious "precessional" instability.[32] But there was still no breakthrough, no leap forward in the progress toward full reversal. To merit consideration as a reactor prototype, Astron would have to not only produce full field reversal, but also prove that plasma could be successfully contained and heated to thermonuclear temperatures, as predicted, by the electron shell. But after eleven years of funded development and operation, Astron was far from confining plasmas, and the experiments were still stuck in the first phase, that of developing the E-layer. Typically, Christofilos ascribed the difficulties in experimental progress to inadequate machinery. By 1968 he had decided that the original Astron accelerator was not powerful enough to break through the 6% diamagnetic field barrier they had encountered, and that year, together with Ken Fowler, he wrote a proposal for extension of the accelerator to 6 MeV. Along with the increase in power, he wanted to overhaul the Astron tank and upgrade its vacuum system, and install better diagnostic equipment between the accelerator and the tank.[33]

The co-author of Christofilos's proposal, T. Kenneth Fowler, was at the time the head of the CTR program at Livermore, and was Christofilos's direct superior. Their relationship, however, bore little resemblance to that of a boss and employee. Christofilos and Fowler were close and interacted as equals; Fowler, more than anyone else, mastered the art of persuading Christofilos and keeping him in line. The key to dealing with Christofilos, as Fowler taught Don Pearlstein, another theorist who studied Astron, was to present a problem to him in such a way that he arrived at the conclusion himself. Christofilos never took credit for ideas he absorbed this way; "he knew the idea was yours and exactly what you were doing."[34] Particularly when it came to Astron, Christofilos was touchy about any criticism, but if presented by Fowler's method he would seriously evaluate and even accept negative results calmly. Pearlstein notes that after he mastered Fowler's technique, his daily screaming matches with Christofilos were replaced with productive exchanges.

Fowler came to Livermore in 1967, and soon after his arrival he replaced the retiring Chester Van Atta as head of

31 [27].

32 [28].

33 [30].

34 [42].

the CTR division. For Christofilos, the management change was a happy occasion—it began a new friendship and productive scientific collaboration, and removed a thorn in his side. Van Atta had always been skeptical of Astron and of Christofilos's methodology; he had doubts that Astron was, as Richard Briggs put it, "good science."[35] Van Atta had recruited Briggs to investigate instabilities in the Astron particle beam (Briggs had done his PhD on particle beam instabilities) and generally to evaluate the soundness of the Astron concept. Christofilos's reaction to Van Atta's criticism was to bypass him entirely; during Van Atta's tenure Christofilos took his requests and comments directly to John Foster, the lab director. Briggs observes that mankind was divided into two camps: those who understood Christofilos and those who didn't—those who recognized his vast potential and admired his single-minded devotion to his work, and those who saw his rampant arrogance and fierce temper as a powder keg from which to keep a healthy distance. Christofilos navigated his way through the political morasses of Big Science and national defense by sniffing out kindred spirits and enlisting their support. Van Atta was not a kindred spirit, Foster and Fowler were.

Dark Clouds for Astron

Christofilos got his accelerator upgrade, but not without stipulations. As Astron continued to strive for field reversal, the greater landscape of the fusion program had changed. In the fifties, with America still basking in the afterglow of World War II's stunning technological breakthroughs, the nation's confidence in science, and physics in particular, had been sky high. Fusion researchers, like most government sponsored physicists, found themselves glutted with funding. During the next decade, however, the scientific and political landscapes changed, causing a substantial dip in the federal government's interest in and willingness to fund physics research. The decline of enthusiasm was due in part to roadblocks encountered in the major physics projects of weapons, reactors, and accelerators, and the scientific problems were exacerbated by budgetary pressures. More pressing matters, like the space race, the Vietnam War, and President Johnson's Great Society programs competed with Big Science for funds and usually won. Physicists had to adjust to a new situation in which they had to cut corners and justify expenditures.[36]

In fusion the shift was especially pronounced, as the change in the general mood toward science was compounded by experimental results that were, across the board, far less promising than anticipated. These were coupled with the alarming numbers that came out of the first forays into theory, which cast some doubt on the fundamental feasibility of controlled fusion. The overall reaction of the plasma physicists to the setbacks was not despair, but a stepping back and a switch in methodology. Plasma physics as a field underwent a transformation in the early sixties, from unbridled optimism and a go-for-broke experimental attitude, to a much more reflective, deliberate, and self-doubting sort of research. In the fifties, fusion research had acquired a reputation for being off-the-cuff and impulsive rather than rigorous.[37] The second generation of plasma physicists, epitomized by Marshall Rosenbluth, who over his long career became one of the most respected and adored figures in the field, worked hard to dispel that image. Rosenbluth was a theorist, and he attacked the problem of fusion with deliberation and advanced mathematics.[38] Over the course of the sixties, the importance of theorists in the CTR project steadily increased. New ideas were tested more often by abstract models and less by the earlier practice of experimenting with ever larger and costlier machines.[39] In light of this change in climate, Christofilos' proposal to once again address Astron's performance problems by investing in metal rather than math was met with skepticism.

The skepticism came not merely from within Livermore, but from the fusion overseers in Washington, a fact which was indicative of another fundamental change occurring in the fusion landscape. Though the trend would become much more pronounced a few years later, in 1967 fusion was beginning to feel centralization tighten around it. That year, a newly attentive AEC created an Ad Hoc Panel to review the Astron program.

As the panel's report explained in its forward, the review of Astron was not an isolated event, but part of a shakeup in the AEC's management of the CTR program. The previous year the Commission had completed a thorough deliberation on the fusion effort, no doubt responding to the fact that, between fusion's reputation for sketchy science and excitement over the success of fission reactors, "[i]n the midsixties there was almost no advocacy for the fusion program outside the CTR community itself."[40] What was needed, the Commission concluded in its "AEC

35 [31].

36 Westwick, 16.

37 Bromberg, 135.

38 Rosenbluth was incredibly prolific and over the course of his career devoted attention to virtually every existing fusion scheme. Never convinced that Astron was a viable concept, he was one of Christofilos' most important critics.

39 The rapid evolution of the stellerator from the tabletop Model A to the large Model C is a good example of the early way of doing fusion. For discussion of the stellerator models, see Bromberg, 45–48.

40 Bromberg 135.

Policy and Action Paper on Controlled Thermonuclear Research," was redoubled energy on the project in the context of "increased coordination and cooperation among the various elements of the fusion program." To these ends the report called for establishment of a Standing Committee composed of the directors of the four major CTR labs, the AEC divisional vice-chairman in charge of CTR, and four physicists from outside the program, to oversee and direct the total fusion effort. Since the AEC's goals included improving efficiency and eliminating redundant projects, the Standing Committee formed Ad Hoc Panels to review particular projects whose value, for one reason or another, was questioned. Astron was the fourth project selected for scrutiny.

The panel's mission was to critically examine Astron's premise, difficulties, and progress, and while there was no direct connection between its inception and Christofilos' accelerator proposal, the panel did seize the opportunity to evaluate the accelerator's promise of improvement and cost effectiveness. The accelerator was only a part of its inquiry, however. In truth, the panel's purpose was to judge whether Astron should live or die.

To state that Astron caught the AEC's attention because it was not working, while true, does not fully capture the situation. In 1967 nothing in fusion was working—but Astron was still a large step behind the other projects. While they struggled to shore up plasma confinement time, control instabilities, and reach higher temperatures, Astron was still plugging away at the E-layer, a precondition for plasma confinement experiments. In spite of the theoretical promise Astron offered for plasma stability, by 1967 experience had shown that in plasma physics, nothing was ever easy. It was only realistic to expect that even if Astron could produce a field-reversing E-layer, a long and bumpy road would still stretch between that milestone and a reactor. Considering that the E-layer's magnetic field still hovered at around 6% of the strength needed for field reversal, some in Washington felt that the AEC had received precious little return on the financial investment it had already made and were dubious that further investment would procure better results. When released, the Ad Hoc Panel's assessment made it clear that concerns over the lack of productive output from Astron were not limited to its measurable stats, but also focused on its contributions to general knowledge and understanding of plasma behavior. To a great degree, the panel's criticisms of Astron were thinly veiled disapproval of Christofilos' style as a manager and as a scientist.[41]

In the conclusion of its report, the panel honed in on the gaps in Astron's understanding of its own scientific challenges. The panel members felt that Astron had focused too much on technological issues, mostly having to do with the accelerator, and was neglecting "the study of underlying phenomena."[42] As a result, the reviewers claimed, their task of assessing Astron's potential and optimal courses for improvement was complicated. They conceded to Christofilos that there was no scientific evidence, theoretical or experimental, to suggest that a field-reversing E-layer was impossible or incapable of confining plasma, but they qualified the endorsement of principle with a biting caveat. It was possible, they claimed, that Astron had encountered no knockout blow only because it had avoided looking for one. Compared to other CTR projects, the staff of Astron was light on physicists and heavy on engineers, a fact that, to the panel, symbolized what was wrong with the project. Fusion, as the AEC and much of the internal CTR community conceived it in 1967, was a branch of nuclear physics, a scientific discipline that could and should be taught in classrooms and explored on chalkboards and computers every bit as much as in the laboratory. Christofilos was seen as a maverick, and the CTR leadership was not as willing to accommodate eccentricity as it had been in its youth.

Bold as always, Christofilos insisted on attaching a note to the panel's report delineating his own view of the Astron concept and responding to the panel's main points against it. In his mind, the panel's demand for more thorough theoretical grounding and general caution toward the concept stemmed from the fact that "the fear of future instability of the E-layer and confined plasma has been unduly emphasized while the experimental achievements to date have been very much under stated." In a panel session which Christofilos cites, the Chairman concluded that "the early criticisms of Astron were subjective and not documented" (underlined in original), yet the panel proceeded to base its conclusions on a new set of conjectured instabilities that were, according to Christofilos, equally shaky. Since the fear of instability was far less severe than the panel purported, there had been no cause to invest time and resources in the kind of exhaustive theory the panel deemed necessary. Christofilos also defended the experimental style pursued in Astron, which emphasized, as he freely admitted, expensive facility improvements over methodically documenting the phenomena associated with the functioning machine. He chose this "unorthodox" approach not out of impatience or rashness but because "it was my strong conviction that it was ultimately the fastest way to reach the goals of Astron." Moreover, he delineated a number of calculations and computer models which supported the contention that the facility upgrades were necessary for Astron to perform at its peak. Finally, he

41 Bromberg attributes anti-Astron sentiment to Paul McDaniel, who was head of the AEC's Research Division. Bromberg, 122.

42 [25].

claimed that the improvements, particularly the diagnostic equipment, were essential for Astron to be able to perform reproducible "good physics."[43] In Christofilos' self-account, far from a loose cannon, he was a physicist who made decisions based on solid science, aimed at producing solid science.

The truth no doubt lies somewhere in between. It is the case that Christofilos was never plagued by the doubts that had come to haunt so many of his colleagues, and so he saw no reason to retreat from gung-ho experimentalism. This is not to say that he eschewed theory—he actually performed theory calculations himself on some problems in Astron, a fairly rare occurrence for an experimentalist. In this sense, to some extent the panel's assessment of Astron as dedicated to quick fixes and ungrounded in genuine understanding was unfair. What was unambiguously true, however, was that Christofilos approached difficulties in Astron not with the question of *whether* they could be solved but only of *how* to go about solving them. Harold Furth, an eminent theoretician who was not enamored with Christofilos' ideas or methods, liked to describe Christofilos' attitude toward Astron thusly: Christofilos is a Martian. On Mars, where he comes from, they get all their power from Astron reactors—so he knows it can work! He just doesn't know exactly how.[44] To the panel's mind, that unwavering conviction that Astron was feasible limited the depth to which he was willing or interested in probing Astron's physics problems.

It is striking that Christofilos devoted his entire response to the panel's methodological critiques of Astron and never addressed the panel's major trepidations about the project's physics. Yet the panel's greatest reservation about the future of Astron was a purely scientific issue, one which struck at the question of whether the device could ever be the basis of a commercial reactor. That issue was energy balance—the ratio of the energy a device produced over the energy it needed to operate. Energy balance is a hurdle every fusion concept has to confront; since fusion is not "pure science" but has the end-goal of thermonuclear power plants, it is imperative that a device generate more energy than it consumes. Astron had been touted as a winner in the energy balance equation, because its β (beta) parameter, a measure typically used to assess energy balance, was high.[45] β is the ratio of the plasma pressure to the magnetic field pressure, which is proportional to the square of the magnetic field strength. In most fusion reactor designs, higher plasma pressures mean more thermonuclear collisions and hence more fusion power. Meanwhile, the lower the magnetic field strength the less energy is required to maintain it. Hence high beta should indicate a high return on energy put into a system. The nature of the Astron concept, however, muddled the significance of this equation. Astron relied on relativistic electrons to generate part of its magnetic field, and these electrons radiated away a huge amount of energy. The loss by this "electron synchrotron radiation" did not affect the β parameter, but it did vastly change the actual energy balance calculation. Maintaining an electron shell dense and energetic enough to confine plasma was sure to require more energy than the plasma could produce, even under the best of conditions.

Christofilos was not oblivious to the severity of the energy balance problem. By 1968, however, he was convinced that he had found a solution to the problem. When the time came to develop an actual reactor prototype, he would form his E-layer not from high-energy electrons but from protons, which radiate away considerably less energy. Christofilos laid out this solution, which he sometimes referred to as the "P-layer," in a report for the third International Atomic Energy Agency (IAEA) conference in Novosibirsk, and presumed that he had put the energy balance problem to rest.[46]

Unfortunately for Christofilos, he seems to be the only person who was satisfied with the P-layer solution. If such a layer could be formed, there was no dispute that it would solve the energy balance problem. That, however, was a very big if. Astron had not succeeded in forming an *electron* layer strong enough to reverse the magnetic field, and although Christofilos was correct that there was no evidence that doing so was impossible, there was also no proof of principle that it could be done. With the prospect of a P-layer thrown into the mix, Astron's desperate quest for electron-generated field reversal became only a first step. While Christofilos spoke as if transitioning from an E-layer to a P-layer was like moving from a tricycle onto a two-wheeler, a mere matter of adjusting the same principles to a slightly more difficult problem, the fact was that no technology existed capable of accelerating protons to the parameters Astron would demand. This did not bother Christofilos, whose superb confidence in himself never faltered; he would invent the necessary accelerator technology when the time came, just as he had invented the induction linac to serve the current Astron experiment.

The panel was wary of the P-layer not because they doubted Christofilos' ability to devise a satisfactory accelerator, but because that project was not where they wanted to see him invest his time and their money. It meant a whole new technological hurdle to overcome before Astron could prove itself, and while Christofilos reveled in this sort of challenge, it was the kind of problem from

[43] N.C. Christofilos, "Comments on the Report of the Astron Ad Hoc Panel." February 21, 1968. Addendum to TID 24513.

[44] Paraphrased from interviews with Fessenden and Briggs.

[45] [17].

[46] [24].

which the fusion establishment in 1968 wanted to stay far, far away. In the conclusion of its report the panel wrote, "The limited experimental and theoretical achievements of the Astron Program have resulted…from the emphasis on accelerator and injection technology" rather than plasma physics, and this causal linkage underlies the entire report.[47] A fusion project must study fusion and contribute to the understanding of plasmas, the beleaguered AEC officials declared—it could not be an exercise in accelerator engineering. Ironically, Christofilos' unmitigated devotion to boosting Astron's performance was out of synch with the fusion bureaucrats' vision for the program. The panel set the priorities for the improved Astron facility as first, "better experimental programs to understand the physics, improvement in reliability," and only "as far as consistent with these objectives, higher energy." This ordering was fundamentally at loggerheads with Christofilos' personality as a scientist and as a man. Even after fifteen years working in the American physics establishment, Christofilos retained the mentality of an inventor—he approached problems by seeing where they led and looking for creative ways to overcome them, not by working them through in depth. When he came up with an idea for solving an experimental difficulty, "he'd think through [it] from A to Z, usually in one night."[48] No amount of exhortation from the panel could make him change his spots.

A Reprieve

After the upgraded accelerator was completed in 1969, Astron continued its experimental program under the watchful eyes of the AEC. In compliance with the panel's wishes, and with the support of Fowler, who had headed the fusion theory group at Livermore before taking over as head of the CTR program, the theory group also devoted serious attention to Astron. The theorists used a computer simulation to investigate a problem that had long been haunting Astron—how to "stack" multiple electron pulses from the accelerator to form a single, strong layer. Experimentally, every time the researchers added a second pulse it disrupted the first, and rather than combining the two pulses both became unstable. The theorists were not optimistic about the prospect of pulse-stacking. One young member of the group, Bruce Langdon, developed a simple but, in his view, accurate model of the Astron system which showed that pulse stacking was physically impossible.[49] Christofilos was incensed, and staunchly maintained that the models did not represent real conditions inside the Astron tank because they were two rather than three dimensional. Fowler, in his role as a theorist, came to the rescue. He had proposed in 1968 that the experimentalists add a toroidal field to Astron, produced by cantilevers in the interior of the tank, and in 1971 they finally followed his advice. The rationale for this fix, in Christofilos' words, was that "by adding shear it would be possible to stabilize the plasma with less total circulating current in the E-layer."[50] When tested experimentally, Christofilos found that the toroidal field provided a plethora of benefits, including improved electron trapping. With its help he was able to vindicate his faith in the pulse-stacking principle, as Astron finally successfully stacked two pulses.[51] The resulting E-layer exhibited 15% diamagnetic strength, a threefold improvement over the single pulse results, meaning that he would need to stack less than ten pulses to achieve complete reversal. It was a victory, but still, two pulses was a long way from ten; the finish line seemed to be in sight but was by no means reached.

In 1971, while Astron was working up to its pulse-stacking proof of principle, a group on the other side of the country also had its sights set on field reversal from energetic electrons. Hans Fleischmann headed the Relativistic Electron Coil Experiment (RECE) at Cornell University, the only program outside of Astron based on Christofilos' plasma confinement concept. The primary difference between the two projects was that RECE was trying to reverse the magnetic field with a single, high-current electron pulse—0.5 MeV and 10-20 kA—in place of Astron's weaker repeated pulses.[52] Late in 1971 the Cornell group announced the result Christofilos had spent seven years chasing—RECE had achieved complete field reversal, with a stable electron layer lasting 40 μsec.[53] Cornell's achievement provoked surprisingly little response from Christofilos. He had been moderately supportive of Fleischmann's project, and had loaned the experiment some diagnostic equipment, but had never shown it a great deal of interest.[54] Fowler explains that in Christofilos' mind, by replacing continuous stacked pulses with a huge single pulse Cornell had removed both the challenge and the promise of the Astron concept. Christofilos did not have a shred of doubt that with a strong enough electron layer, the magnetic field would reverse. That was a fact of nature. Creating the layer by Cornell's method, however, was useless, because it could not be the

47 [25].

48 [36].

49 [40]. Convinced that the project's challenges were insurmountable, Langdon left the Astron group shortly after completing his model.

50 [29].

51 Ibid, 8.

52 [20, 35].

53 [14].

54 [35].

basis of a steady-state reactor.[55] Christofilos was obsessively conscious of the economics of fusion and was convinced that only steady-state reactors were commercially viable. As a result he clung doggedly to the pulse-stacking model, striving to create a long lasting E-layer to contain an ignition plasma.[56] Despite Christofilos' personal lack of enthusiasm over Cornell's achievement, RECE's success did benefit Astron by proving conclusively that the concept of field reversal was sound and attainable. It also exacerbated the question of whether or not the monumentally expensive Astron, as it was conceived and operated, could reach the goal Cornell had attained cheaply and with relative ease.

Astron's Last Stand

By 1971, the AEC was growing impatient waiting for an answer to that question. Though the 1968 Ad Hoc Panel's reviews of Astron's finances had showed that the project did not spend more than others of comparable size, the AEC continued to feel that Astron was a black hole, into which money disappeared without producing any payoff.[57] The panel's admonitions had elicited little if any change in the way Christofilos operated Astron, a fact which was fairly predictable from his written reaction to their report. More theory had been devoted to Astron since the 1968 review, but Christofilos had paid little heed to the findings and continued to follow any experimental lead that might produce better field reversal numbers. This experimental impulsiveness was brutal for graduate students trying to put together theses on Astron—they would come in one morning to find that the setup they had been testing for weeks had been changed overnight because Christofilos had a new idea.[58] It was also precisely the kind of thing that irked the AEC. The Standing Committee had recommended in response to the 1968 Ad Hoc report that Astron be reviewed again in a few years, and accordingly in 1971 a second panel set to examining the project. Like the original panel it focused heavily on Astron's experimental methods, and its conclusions were similar but more scathing. "The approach has been," read the report, "to look for ingenious ways to avoid or circumvent difficulties rather than to understand them."[59] For years Christofilos had defended his project with the assertion that no aspect of Astron had been proven impossible, but the reviewers were more concerned with the fact that there was still no conclusive evidence in the opposite direction.

The second Astron review came on the eve of another shakeup within the AEC. In one respect the AEC changes of 1972 reinforced those of 1967, by solidifying the trend toward centralization. At the same time, however, the new leadership set out to reverse the approach to fusion research that the bureaucrats of the late sixties had endorsed, i.e., the extreme focus on basic plasma physics questions. The most important new appointee of 1972 was Robert Hirsch, who took over as chairman of the AEC's CTR Division. Hirsch came into his office with a vision for fusion that revolved around consolidation and progress—he wanted to see fewer fusion projects, each with an enormous budget and on a fast track toward a reactor. Where the previous AEC leaders had felt that the fusion project was plowing ahead irresponsibly, without sufficient scientific grounding for its experiments, Hirsch now maintained that the program had become locked in a mindset of investigating fundamental queries and had lost sight of its goal of producing actual power. He iterated this philosophy in an interview in the *New Scientist,* in which he stated, "My primary personal goal is to get something practical accomplished."[60] In order to improve efficiency and tighten his office's control over research, Hirsch divided the department into the subsections of confinement schemes, research, and development and technology. An assistant director headed each subgroup, and the labs began to receive three separate budgetary allotments, which restricted their ability to divvy funds internally. With his control structure in place, Hirsch set about separating the wheat from what he perceived to be the chaff.

Astron seems to have been on Hirsch's target list from the outset. There was more than a little irony in that fact, since Hirsch was dedicated to moving away from focusing on basic physics problems, the area in which Astron was seen as weakest. Hirsch even advocated a renewed emphasis on the engineering aspect of fusion, precisely the thing that had earned Christofilos so much AEC scorn.[61] Christofilos' much-maligned outlook seemed to jive perfectly with Hirsch focus on the big prize. Astron did not fit, however, with Hirsch's consolidation scheme—he was

55 [36]. The term "steady state reactor" refers to a reactor which can operate continuously and burns a self-sustaining "ignited" plasma. It is opposed to the short-pulse reactor, which creates a short-lived plasma that gives off a burst of energy before it dies and must be rekindled. .

56 Interview with Fowler. For Christofilos' conscience attention to economics, see [16]. Moir and Fessenden also stressed the point in interviews.

57 In 1971 Astron had absorbed approximately 25 million dollars of AEC money over its 15 years of existence. L.D. Smullin, "Report of the Astron Review Committee," March 8, 1972. Quoted in Bromberg, 203.

58 [34].

59 L.D. Smullin, "Report of the Astron Review Committee," March 8, 1972. Quoted in Bromberg, 203.

60 "America's Fusion Director," *The New Scientist*, April 12, 1973, 88. Quoted in Bromberg, 199.

61 Bromberg, 204–205.

looking for quick winners, and Astron was too much of a long shot. Besides, in 1968 at the Novosibirsk conference a relatively new word in the fusion lexicon had captured many imaginations, Hirsch's among them. The word was "tokamak," and it would permanently change the face of fusion, in America and worldwide. The tokamak was a Russian invention, a toroidal device characterized by the presence of strong currents in the plasma itself. When the Russians first announced that their tokamaks had produced confinement times and temperatures far greater than anything anyone had seen before, they were met with extreme skepticism by the rest of the international fusion community. Quickly, however, the results were confirmed, and many American fusionists became tokamak converts. Subsequent experiments continued to boost the tokamak numbers even higher, and so when Hirsch took office he saw the device as the center of his program, the best and quickest hope for a functioning reactor. Creatively off-beat but unproven programs like Astron were, in Hirsch's eyes, distractions from the CTR program's central quest.

Hirsch's approach was controversial at the time, and came under greater fire after the tokamak failed to deliver on the great promise it seemed to hold at the beginning of the seventies.[62] Ken Fowler was a vocal dissenter, and his views represented the main line of opposition to Hirsch's agenda. Essentially, Fowler was not swayed enough by the tokamak to rest all his hopes on its donut-shaped shoulders. His years in plasma physics had convinced him that the problem of controlled fusion was so difficult, and unforeseen challenges so likely, that until one scheme actually proved itself by producing net power, all possible ideas should to be pursued. When Hirsh targeted Astron immediately upon his arrival, Fowler defended Christofilos' program primarily out of his broader belief in the importance of diversity in fusion ideas. With the exception of Cornell, which was a minor program, Astron was the only group researching circulating particle beams as a means of plasma confinement, a concept which Fowler believed was promising and worthy of study.[63] This was true not only in the US but worldwide, a fact which distinguished Astron as "the only unique method [of fusion] being pursued by this country."[64] If nothing else, Astron certainly deserved points for diversity.

The End of Astron

Hirsch's ascension, however, was the final nail in Astron's coffin. After the 1971 panel the Standing Committee had not demanded Astron's immediate termination, but Hirsch's predecessor, Roy Gould, had imposed a tight schedule on the program, including a strict timetable and monthly progress reports on the achievement of the stated goals. Of course, every fusion program ran behind schedule and over-budget, and Astron was no exception. Christofilos' team quickly fell behind, and so when Hirsch assumed control he had a ready supply of ammunition to level at Astron. Gould had set a spring 1973 deadline for a final decision on Astron, but Hirsch was impatient and had no interest in waiting to see what Christofilos could accomplish with his newly renovated accelerator.[65]

On September 24, 1972, after a typically long day in the lab, Christofilos headed for Livermore's Holiday Inn, where he sometimes spent the night to avoid the long commute back to his home in Berkeley. He had met that day with James Schlesinger, the chairman of the AEC, but no record of their meeting remains. The next morning, when he did not show up at work, Christofilos' secretary, Lois Barber, went to his hotel room to check on him. She found him dead of a massive heart attack. Christofilos had always been a workaholic, but in the preceding months, with the progress reports keeping constant heat on his project, he had become frantic in his attempts to achieve field reversal and save Astron and was working nearly round-the-clock. Overweight, a chain smoker, and a heavy drinker, the stress and the hours proved too much for him. He was fifty-five years old [46].

While there was certainly speculation that Schlesinger may have told Christofilos on the day of his death that Astron's days were numbered, none of his colleagues knew the content of the two men's conversations. Bromberg claims that Hirsch had made an absolute decision to terminate Astron in September of 1972, before Christofilos died, but the decision was not made public until December, and she does not cite a source for the claim. Certainly, no one at Livermore was aware of a definite verdict on Astron's fate prior to Christofilos' death. When Astron was at stake Christofilos was a force to be reckoned with—one

62 Much later, Hirsch himself did an about-face on the tokamak issue. In 1997 he wrote an article for *Issues in Science and Technology* in which he asserted that because they produced power so inefficiently tokamaks had no promise as commercial reactors, and that the search for fusion power needed to turn elsewhere. Instead he recommended fusion concepts that lent themselves to smaller reactors—the very types of ideas that he had worked to shut down during his time at the AEC. [13].

63 [4]. Fowler's viewpoint on placing all fusion's eggs in one basket became much more widespread in the 1990s after two decades of relative disappointment from the tokamak. At that point the Department of Energy, which took over the fusion program from the AEC, switched to a policy of funding small experiments with innovative ideas in the hope of finding a better model. The debate is still current, especially regarding the issue of what percentage of the US fusion budget should go to ITER.

64 [23].

65 Bromberg, 201–204.

fusion administrator remarked that "To try to turn off Nick Christofilos' experiment would be like trying to turn off Ernest O. Lawrence's accelerator or J. Robert Oppenheimer's atom bomb project."[66] Christofilos' death produced an unanswerable hypothetical; there remains the possibility, albeit slim, that if he had lived he could he have found a way to keep Astron alive.

Undoubtedly, the decision to shut Astron down had been percolating for a long time; while it may well have been a personal goal of Hirsch's it was not his original idea, and he would have had a hard time pushing it through without the groundwork laid by two reviewing panels over a four-year span. Washington's increasing micromanagement of the fusion program was a necessary factor in Astron's termination, since Christofilos had enough allies and influence within Livermore to keep the lab from cutting his program, at least in the short term. Consolidation of power in the AEC's hands, however, was not an overnight occurrence but a long and gradual process. The timing of Astron's demise, however, was more the result of the program simply running out of excuses for its lackluster results and less of a sudden, dramatic transformation in fusion's relationship with its backers. Still, there is no question that Astron's shutdown was part of a larger trend toward heightened focus on one or two big ideas, under the looming aegis of governmental watchdogs.

The final irony of the Astron story is that the project produced by far its most promising results in its final 6 months, after the AEC had lowered the boom. After Christofilos died Richard Briggs took over the project, which was granted until June of 1973 to finish its final round of experiments and prepare for shutdown. Under Briggs' leadership the Astron group continued to experiment with the toroidal field that had made such a difference in electron trapping. In spite of the fact that Christofilos reported successful trapping and stacking of ten small pulses in his account of experimental results for early 1972, Briggs' crew continued to struggle with pulse stacking. Their final report stated that "buildup of the E-layer by multiple-pulse injection was generally unsuccessful" and noted that at the time of the shutdown they still did not understand what physics problem was limiting the buildup.[67] However, using single pulse injection in a strong toroidal field and high plasma pressure, the team detected E-layers of up to 50% field reversal. Christofilos' absence was a factor in the promising results; since he was preoccupied with stacking, he would probably not have pursued the experiments that got Briggs such good numbers. But without him, there was no one willing or able to use the numbers to fight for Astron, and the project quietly died, its impressive last gasps filed away and forgotten.[68]

Astron's Mark

When Astron shut its doors it did spell the end, as Fowler had warned, of large scale investigation of Christofilos' concept for a particle solenoid confinement scheme. Work at Cornell continued, however. After RECE's field-reversal breakthrough, Fleischmann's group moved on to study ion rings, actualizing Christofilos' proposed switch from E-layer to P-layer. As Astron's critics had predicted, the switch to protons proved immensely difficult, and the group never achieved full field reversal with ions as it did with electrons. The project is in the process of shutting down, because after thirty years of work, the youngest iteration of the project, known as FIREX, has run up against an instability it cannot conquer. John Greenly, who headed the FIREX project, believes that his group's discovery has, at long last, provided proof that the Astron concept is untenable.[69] Whether or not Christofilos, who always walked a fine line between realism and devotion to Astron, would accept Greenly's conclusion, is of course an unanswerable question. If Christofilos' incessant struggle with and notable victories over those who wished to pronounce Astron dead teach anything, however, it is not to underestimate the power of creative solutions over even seemingly intractable problems.

A thornier but more interesting scientific relationship is the one between Astron and a class of machines called Field Reversed Configurations (FRC). Schematics of the FRC's magnetic field lines bear a striking resemblance to Astron, with the field from external magnets reversed by another current so that the lines form closed toroidal regions within a linear device (Fig. 5). In the FRC, unlike in Astron, the field reversing current comes from the bulk plasma itself and not from a separate MeV particle beam [11]. The question of whether or not the FRC was derived from Astron hinges on what is seen as the FRC's essential characteristic: the field line geometry itself, or the method of creating that geometry. In terms of experimental procedure the FRC can be traced quite directly to a machine called the theta pinch, which creates a hot plasma by exposing ionized gas to a rapidly rising magnetic field, inducing a current in the gas. This current rapidly heats the ionized gas to thermonuclear temperatures.[70] Theta pinch

[66] Bromberg, 202. The comment is from Stephen O. Dean, the AEC CTR Division's Assistant Director in charge of confinement systems.

[67] [20].

[68] Aside from Briggs, everyone I interviewed was shocked that the project had ever achieved 50% field reversal. They remembered only the 15% results Christofilos had obtained before his death.

[69] [37].

[70] [1].

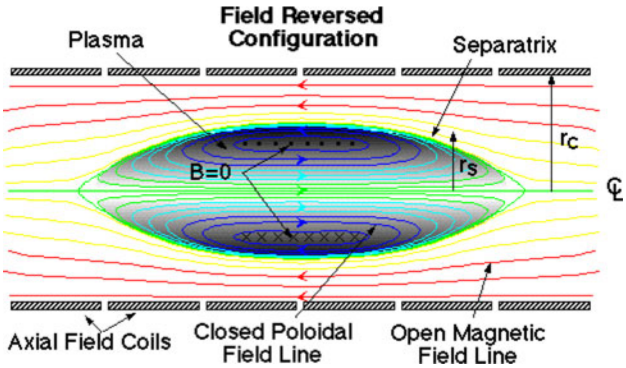

Fig. 5 Formation of closed field lines in the FRC. (http://www.aa.washington.edu/AERP/RPPL/programs/frc_intro.html)

experimentalists had detected very early on that the plasma current created a reversed field, but the field was unstable and was quickly annihilated.[71] The FRC developed when researchers focused in on the reversed field and searched for a way to stabilize it and use it to create a lasting pattern of closed field lines.[72] Whether or not the original FRC scientists had seen the Astron configuration is impossible to establish, although since Astron was a large and prominent project, it is likely that they had. Some of the earliest interest in the FRC concept in America, however, was at Livermore, where Fowler collaborated on the Field Reversed Mirror, and Fowler's interest in the idea did stem from his knowledge of the Astron concept.[73] Alan Hoffman, of the Redmond Plasma Physics Laboratory (RPPL), the only lab in America devoted exclusively to FRC research, claims that the lineage from Astron to the FRC is quite direct. He traces the line of experiments from Astron to the Field Reversed Mirror to Los Alamos' FRX-A and FRX-B reversed field theta-pinch experiments, the direct predecessors of Redmond's FRC work.[74] On the other hand, Hoffman's RPPL colleague, Loren Steinhauer, claims that there is no relation between the Astron and FRC concepts.[75] Steinhauer, however, is interested in a particular quality of the FRC called "self-organization," which was completely absent from Astron. All the documentation I have seen supports the claim that Christofilos was the first person to articulate the concept of a creating a closed field line geometry within a linear device by reversing an external magnetic field. Of course, as Fessenden remarked, no one person invented the wheel. Nonetheless, Astron deserves to be recognized as the progenitor of the reversed field concept, which is seen by some contemporary plasma physicists as the most promising direction toward a fusion reactor.[76]

Conclusion

In one sense, Astron was ephemeral. It was the dream of one man; he conceived it, nursed it through hard times, and when he died it died with him. Astron is a testament to how much influence a single individual's will, stubbornness, persuasion, ardor, and connections can exert, even within a structure as large and diffuse as Big Science. Yet Astron's story is not solely that of Nicholas Christofilos. The project was part of a continuum of political, scientific, and social events, and was also embedded in a web of relationships—personal alliances and enmities, relationships between engineers and physicists, and between different branches of physics. These models, of individual power and of webs of relationships, weave in and out of one another. Christofilos, a man whose only degree was in electrical engineering, who led a multi-million dollar physics project in a government lab and published papers of theoretical calculations on plasma instabilities, himself embodied the juncture of science and engineering that was so central to Astron. His personal career also bridged the discrete worlds of accelerator and plasma physics, disciplines which his Astron concept united in an unprecedented way. Astron was also defined by the thorny intersection of military and civilian research spheres, with Christofilos steering it through the bureaucratic, ideological, and interpersonal morasses of both worlds. The tensions and cooperation of all its various elements are crucial to understanding the way the events of Astron's history unfolded.

As a distinct yet integrated unit within a larger system and a larger story, Astron exemplifies the clash between determination and externalities, between what a person, group, or institution can and cannot manipulate. The story of Astron makes it clear that nothing in science is predetermined, and that scientific experiments can only be controlled to a certain extent. Astron never achieved even its most basic goal, field reversal, and Christofilos' essential vision of a fusion reactor formed from an E-layer will almost certainly never be realized. Nevertheless, Astron introduced crucial ideas—the induction linac and the field reversed configuration—that continue to have power. Christofilos' genius was so eccentric, his story so sensational, and his personality so overwhelming that his

71 [22], T.S. Green, "Evidence for the Containment of a Hot, Dense Plasma in a Theta Pinch," *Phys.Rev. Lett* 5 (1960): 297.

72 The first person to do experiments specifically intended to maintain the reversed field appears to be Kurtmallaev, at the Kurchatov Institute in Moscow [9].

73 [36].

74 [38].

75 [44].

76 [23]. Advantages of the FRC include: potential for high power density, reduced complexity, potential for small-scale reactors, potential for advanced (non-deuterium/tritium) fuels.

character tends to crowd out Astron as its own entity.[77] Yet ultimately, no matter how tightly Christofilos clung to Astron's reins, he could not force the electrons, or the resistors, or the pulser, or any other part of his apparatus, to behave as he wished. No amount of direction, whether from Christofilos, Livermore, or Washington, could completely control the immediate experimental outcome of Astron or the way its legacies played out. The mysteries of physics and the twists of politics and society play as great a role in the course of scientific discoveries as any one man's exertions.

In some form or another, traces of Astron remain. After the project ceased to operate its tank was dismembered, and pieces of it, still lined with Christofilos' distinctive resistive wires, were shipped to other labs. One section ended up at the University of California at San Diego, and still functions there today. Most of the people who work on San Diego's tank have no idea where it came from, and to many of them the term Astron means nothing. Plasma physics does not have an especially good institutional memory.[78] Still, E-layer or no E-layer, traces of Astron are strewn throughout the fusion program and beyond it, into other areas of physics. It is one more example of the peculiar continuity that courses through Big Science.

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[77] Christofilos' significance as an American scientist was recognized by no less than a sitting Vice President and future President. Richard Nixon, "The Scientific Revolution," *Bulletin of the Atomic Scientists* 16:9 (1960): 348.

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