2 Letters to the Editors

2.1 A Letter to the Editors

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Enzo Haussecker and I just submitted a report "*Influence of Accelerator Science on Physics Research*" (see Sec 2.2) for your consideration to be included in the ICFA Beam Dynamics Newsletter. That report has an intended technical nature and was written as a technical report. After completing the study, however, I have a few comments to add, not as part of the report, but as my personal comments. I am sending them to see if they might also be included in the Newsletter.

1. To me, this report underscores a general lack of recognition of the contributions by accelerator science to the advancement of physics and other sciences. Indeed, the first initiation of this study has been based on the observation that accelerator science has sometimes been considered a supporting science and not quite worthy of its own standing, in spite of the wealth of facts speaking to the contrary. Surprisingly, some of the people who hold that view are accelerator scientists.
2. This study is also triggered by a more recent observation at the start of the operation of the LCLS project. LCLS is an accelerator project based on a profound physics invention of the free electron laser, together with two decades accumulation of prior accelerator innovations that made the operation of this difficult accelerator technology possible. Once completed, it is turned over to the users, who now have acquired a tool whose power exceeds anything in existence by many orders of magnitude. Using this powerful tool, beautiful results were obtained. It would be ironical and incorrect if the accelerator community is not

recognized accordingly as such, as is already apparently occurring when journals such as Nature and Science are readily publishing new results obtained using the LCLS while a submission of the first lasing of the LCLS was rejected. I have to admit that this has been another observation that was with me when I initiated this study.

3. I have one comment on the Bernoulli plot shown in our report. In this plot, one observes a gap around 1970-1975, and another gap around 1995-2004. It is my belief that, to some degree beyond statistics, the first gap reflects a slowing down of nuclear physics, while the second gap reflects a slowing down of high energy physics. Following this second gap, I am expecting that there will be another surge of prizes in the next two decades, and the theme will be photon sciences. Accelerators will again play a pivotal role in that development. Let us hope that accelerator scientists will have an even and fair opportunity to share some of the glory and the recognition when the time arrives. After all, the lack of recognition for accelerator physics will hinder the recruitment of talented physicists into the field, and will impact its future advancement and contribution to science.

I have been fortunate to have Enzo Hasussecker, my summer student of 2010, as my able co-investigator, and I would like to thank him for joining this study.

2.2 Influence of Accelerator Science on Physics Research

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Abstract:

We evaluate accelerator science in the context of its contributions to the physics community. We address the problem of quantifying these contributions and present a scheme for a numerical evaluation of them. We show by using a statistical sample of important developments in modern physics that accelerator science has influenced 28% of post-1938 physicists and also 28% of post-1938 physics research. We also examine how the influence of accelerator science has evolved over time, and show that on average it has contributed to a physics Nobel Prize-winning research every 2.9 years.

2.2.1 **Introduction**

Few would dispute that since the invention of the cyclotron accelerator science has surged in its contributions to research in physics. The extent of these contributions, however, is less well known. A degree of uncertainty exists mainly because until now no one has attempted to evaluate them quantitatively. There are a number of challenges in doing so. One must answer such questions as: How do we establish the existence of an accelerator-science contribution? How do we generate numerical data to provide a reliable measurement of them? By analyzing a well-established index of researches in physics, with well-defined parameters for establishing the existence of accelerator-science contributions, we can take a significant step in answering these questions, minimize uncertainties, and provide a useful and reliable indicator for determining the extent to which accelerator science has influenced physicists and physics. We devise and analyze such an index below.

2.2.2 **Methodology**

We use an index comprised of all Nobel Prize-winning research in physics from 1939 to 2009. Although this sample is somewhat arbitrary, we have chosen it for three reasons: first, the index begins with the Nobel Prize awarded for the invention of the first modern accelerator, the cyclotron; second, Nobel prize-winning physicists have contributed unequivocally to some of the most significant developments in modern physics; and third, Nobel Prize-winning research is "well defined" in the sense that for every Nobel Prize awarded a press release was issued that clearly cites the key justification for the award. This has allowed us to develop a systematic process for collecting Nobel Prize-winning documents for our analysis; we have assembled a total of 331 such documents upon which we have based our analysis.

2.2.3 **Influence of Accelerator Science on Physicists**

2.2.3.1 ***Defining Accelerator Science Contributions***

We begin our analysis by determining the number of Nobel Prize-winning physicists between 1939 and 2009 who were influenced by accelerator science in performing their Nobel Prize-winning research. To determine this number, we must define a criterion for establishing the existence of an accelerator-science contribution on their research.

Criterion 1:

> *There exists an accelerator-science contribution to a Nobel Prize-winning research in physics if and only if there exists a document, authored or coauthored by a Nobel Prize-winner in physics, that explicitly cites the use of accelerator physics or accelerator instrumentation that was developed after 1928*[b] *as having contributed directly to his or her research.*

By applying Criterion 1 to the 331 Nobel Prize-winning documents we collected, we obtained the names of all of the Nobel Prize-winning physicists between 1939 and 2009 who were influenced by accelerator science. Several are obvious, namely, accelerator physicists such as Ernest O. Lawrence, who received the Nobel Prize for Physics in 1939 "for the invention and development of the cyclotron and for results obtained with it"; John D. Cockcroft and Ernest T.S. Walton, who shared the Nobel Prize for Physics in 1951 "for their pioneer work on the transmutation of atomic nuclei by artificially accelerated atomic particles"; and Simon van der Meer, who shared the Nobel Prize for Physics in 1984 for developing the method of stochastic cooling for storage of antiprotons, "which led to the discovery of the field particles W and Z."

Other obvious Nobel Prize-winning physicists who were influenced by accelerator science were nuclear and high-energy experimentalists such as Emilio G. Segrè and Owen Chamberlain, who shared the Nobel Prize for Physics in 1959 "for their discovery of the antiproton" using the Bevatron at the Lawrence Berkeley Laboratory; Robert Hofstadter, who shared the Nobel Prize for Physics in 1961 "for his pioneering studies of electron scattering in atomic nuclei and for his thereby achieved discoveries concerning the structure of the nucleons" using the Stanford Linear Accelerator; Burton

Richter and Samuel C.C. Ting, who shared the Nobel Prize for Physics in 1976 "for their pioneering work in the discovery of a heavy elementary particle of a new kind," the J/Ψ particle, using the SPEAR (Stanford Positron-Electron Accelerating Ring) collider and the Brookhaven Alternating Gradient Synchrotron, respectively; Carlo Rubbia, who shared the Nobel Prize for Physics in 1984 for his "decisive contributions … to the discovery of the field particles W and Z" using the Super Proton Synchrotron at CERN; Jerome I. Friedman, Henry W. Kendall, and Richard E. Taylor, who shared the Nobel Prize for Physics in 1990 "for their pioneering investigations concerning deep inelastic scattering of electrons on protons and bound neutrons" using the Stanford Linear Accelerator; and Martin L. Perl, who shared the Nobel Prize for Physics in 1995 "for the discovery the tau lepton" using the SPEAR collider.

We give the results of our study in Appendix I. Note that the list of names extends well beyond the above accelerator, nuclear, and high-energy physicists. For example, consider the following two case studies in the application of Criterion 1 that reflect the influence of accelerator science on research that superficially appears to be unrelated to it.

2.2.3.2 *Case Studies in the Application of Criterion 1*

Wolfgang Paul, an atomic physicist, was awarded one-quarter of the Nobel Prize for Physics in 1989 "for the development of the ion trap technique." He states in his Nobel Lecture that, "The idea of building traps grew out of molecular beam physics, mass spectrometry and particle accelerator physics…" [1]. He goes on to explain how, "If one extends the rules of two-dimensional focusing to three dimensions, one possesses all ingredients for particle traps," and that "the particle dynamics in such focusing devices is very closely related to that of accelerators…." Paul's Nobel Lecture thus satisfies Criterion 1, so we add his name to the list of Nobel Prize-winning physicists who were influenced by accelerator science.

The astrophysicist William A. Fowler shared the Nobel Prize for Physics in 1983 "for his theoretical and experimental studies of the nuclear reactions of importance in the formation of the chemical elements in the universe." Several of his theoretical studies were based on accelerator experiments, including an important one carried out by Harry D. Holmgren and Richard L. Johnston at the Naval Research Laboratory [2], on which Fowler collaborated and used to support his hypothesis on stellar-fusion processes [3]. Holmgren and Johnston used a Van de Graaff accelerator to produce 2-MeV (million-electron-volt) singly-ionized alpha particles to study the proton-proton reaction chains $He^3(\alpha,\gamma)Li^7$ and $He^3(\alpha,\gamma)Be^7$. Fowler noted in his analysis that, "The large cross-section found for the $He^3(\alpha,\gamma)Be^7$ capture process means that this process will complete successfully with $He^3(He^3,2p)He^4$" [4], and that "it is the completion of the *pp*-chain through $He^3(He^3,2p)He^4$ which is of key importance in the conversion of hydrogen into helium in the theory of stellar nucleogenesis. Only in this way can a star consisting originally of pure hydrogen produce helium through thermonuclear reactions and thus, bring about the first step in nucleogenesis in stars" [5]. Fowler's paper in which he analyzes Holmgren and Johnston's experiment thus satisfies Criterion 1, so we add his name to the list of Nobel Prize-winning physicists who were influenced by accelerator science.

2.2.3.3 *More on Cases Studies and Methodology*

We also note that there are important cases for which there are no statements that satisfy Criterion 1. For example, Gerardus ’t Hooft shared the Nobel Prize for Physics in 1999 “for elucidating the quantum structure of electroweak interactions in physics.” We collected two Prize-winning documents for our analysis: his 1972 paper on the regularization and renormalization of gauge fields [6], and his Nobel Lecture [7], in which he claims that “experiments at the Large Electron Positron Collider (LEP) at CERN … have provided us with impressive precision measurements that not only gave a beautiful confirmation of the Standard Model, but also allowed us to extrapolate to higher energies….” This claim, however, is not sufficient to satisfy Criterion 1, because it implies nothing about his confirmation of the Standard Model and, more importantly, the formulation of his theories concerning electroweak interactions. This is confirmed by his 1972 paper, in which he cites only theoretical work, such as that of C.N. Yang and Robert L. Mills, as having influenced his own. Thus, ’t Hooft was not directly influenced by accelerator science, and we do not add his name to the list of Nobel Prize-winning physicists who were influenced by accelerator science.

Other cases allow us to underscore our distinction between direct and indirect influence of accelerator science on the work of Nobel Prize-winning physicists. We add to our list only the names of those whose work was directly influenced by accelerator science. Consider, for example, the case of Maria Goeppert Mayer and J. Hans D. Jensen, who shared half of the Nobel Prize for Physics in 1963 “for their discoveries concerning nuclear shell structure.” The corresponding press release alluded to Goeppert Mayer’s discovery of high magic numbers (at which protons and neutrons form particularly stable nuclei) and stressed that there was strong experimental support for them [8]; in particular, the neutron beams produced by the University of Chicago cyclotron were used to measure the nuclear binding energies of krypton and xenon. Goeppert Mayer analyzed them in her paper, in which she noted that: “If 50 or 82 neutrons form a closed shell, and the 51st and 83rd neutrons have less than average binding energy, one would expect especially low binding energies for the last neutron in Kr^{87} and Xe^{137}, which have 51 and 83 neutrons, respectively, and the smallest charge compatible with a stable nucleus with 50 or 82 neutrons, respectively. It so happens that the only two delayed neutron emitters identified are these two nuclei” [9]. Goeppert Mayer’s discovery therefore was directly influenced by accelerator science, and her paper on the existence of high magic numbers satisfies Criterion 1. We therefore add her name to the list of Nobel Prize-winning physicists who were influenced by accelerator science.

One might expect that Jensen’s research also was influenced by accelerator science, but this was not the case. His key contribution was his paper on the explanation of high magic numbers [10], in which he explained that a nucleon has different energies when its spin is parallel or antiparallel to its orbital angular momentum. Jensen’s research clearly was influenced by Goeppert Mayer’s discovery, but that means it was influenced only indirectly by accelerator science. Jensen’s research therefore does not satisfy Criterion 1, and we do not add his name to the list of Nobel Prize-winning physicists who were influenced by accelerator science.

2.2.3.4 *Numerical Results*

In proceeding as above in applying Criterion 1 to all of the 141 Nobel Prize winners for Physics in the 71 years between 1939 and 2009, we find that the researches of 39 of them were influenced by accelerator science. Since our sampling methodology has virtually ruled out the possibility that we did not collect a document satisfying Criterion 1 that was authored or co-authored by one of the other 102 Nobel Prize winners, we are inclined to believe that the ratio of 39 to 141 or 28% is an accurate indicator of the proportion of post-1938 physicists who were influenced by accelerator science.

2.2.4 **Influence of Accelerator Science on Physics Research**

2.2.4.1 *Defining the Independence of Researches*

A separate but related problem is to determine the proportion of research in physics that was influenced by accelerator science. This is a separate problem, because it involves a modification of our previous determination, but a related one, because this modification will allow us to restate our earlier findings within the context of research in physics, which provides us with yet another indicator for measuring the influence of accelerator science on them.

We begin by drawing on Criterion 1 to determine all of the works influenced by accelerator science, but this time we do not count the physicists who participated in these researches, but the number of researches themselves, to determine how many were influenced by accelerator science; we then divide this number by the total number of Nobel Prize-winning researches in physics that were awarded in the 71 years between 1939 and 2009. To count these researches, however, we require an appropriate criterion to define their scope to prevent the possibility of counting those that overlap twice.

Criterion 2:

> *The scope of a Nobel Prize-winning research in physics is defined by its motivation as determined by the Nobel Foundation; two researches are independent if and only if they have separate motivations.*

By applying Criterion 2 to each year in which a Nobel Prize for Physics was awarded, we obtain the number of independent Nobel Prize-winning researches for that year. For example, Martin L. Perl was cited as having won the Nobel Prize for Physics in 1995 “for the discovery of the tau lepton,” and Frederick Reines was cited as having won the Nobel Prize for Physics that same year “for the detection of the neutrino.” Thus, there were two independent Nobel Prize-winning researches in 1995.

2.2.4.2 *Numerical Results*

By applying Criterion 2 in this way to all of the Nobel Prizes for Physics, we find that there were 85 independent Nobel Prize-winning researches that were awarded in the 71 years between 1939 and 2009. When we further apply Criterion 1 to these 85 independent researches, we find that 24 of them were influenced by accelerator science. We therefore believe that the ratio of 24 to 85 or 28% is an accurate indicator of the proportion of post-1938 researches in physics that have been influenced by accelerator science.

2.2.5 Influence of Accelerator Science over Time

2.2.5.1 *A Bernoulli Counting Process*

To examine the influence of accelerator science over time, we considered the years in which a Nobel Prize for Physics was awarded to a research that was influenced by accelerator science as successes in a Bernoulli counting process. The probability of a success in any one year then equals the number of years in which a Nobel Prize for Physics was awarded to a research that was influenced by accelerator science, which we have determined by Criterion 1 to be 23, divided by the total number of years investigated, 67. In this case, we investigated only the last 67 years (1943 to 2009), because of the discontinuity owing to World War II. Thus, for the sequence of Bernoulli random variables X_{1943}, X_{1944}, … X_{2009}, the $\Pr[X_i] = 23/67$.

2.2.5.2 *Numerical Results*

The number of trials needed to get one success is a random variable, T, having a geometric distribution with parameter $p = \Pr[X_i] = 23/67$. T can be interpreted as the average time in years between the awarding of two Nobel Prizes for Physics that were influenced by accelerator science. We calculated the expectation of T to be $E[T] = 1/p = 2.9$ years. Thus, on average accelerator science contributed to a Nobel Prize-winning research in physics every 2.9 years.

2.2.5.1 *Plotting the Data*

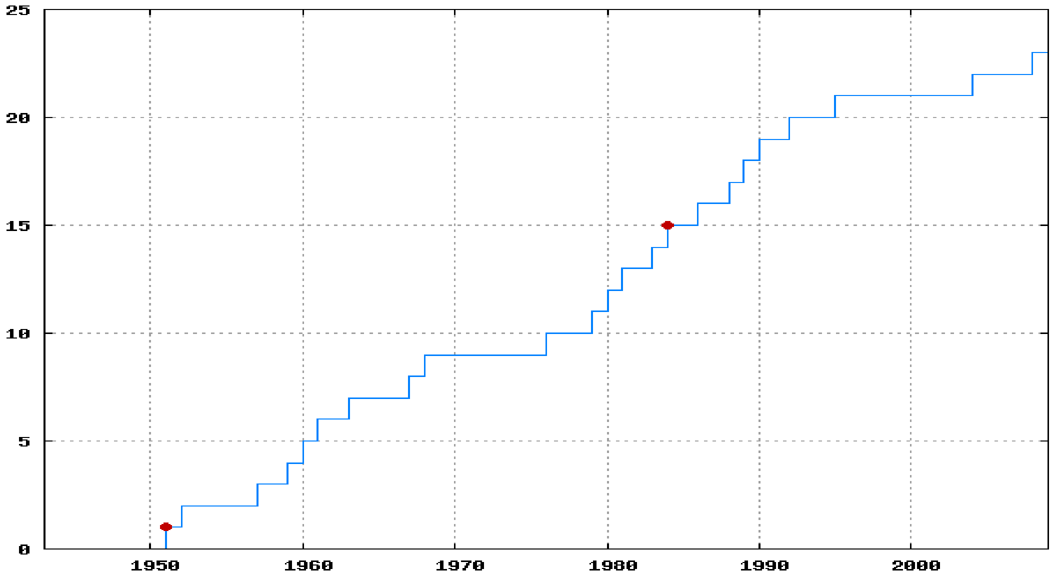

Figure 1: A plot of the Bernoulli count data.

In Figure 1 we see that the Bernoulli-counting process yields a step function that goes up by one unit for each year in which a Nobel Prize for Physics was influenced by accelerator science. The long horizontal lines, for example from 1968 to 1976 and from 1995 to 2004, represent the years in which accelerator science made no contribution to Nobel Prize-winning research; these intervals might be interpreted as a slowing down in recognizing nuclear and high-energy physicists, respectively. The dots indicate the years in which an accelerator physicist was awarded a Nobel Prize for Phyiscs. (Lawrence is not included because he won the Nobel Prize prior to 1943.)

2.2.6 **Accelerators as an Independent Research Discipline**

The percentages of physicists who and researches that were influenced by accelerator science are sufficiently high to support the view that accelerator science is an important contributor to developments in modern physics. This raises the question as to whether there are more accelerator physicists during the past 71 years who were worthy of high recognition in addition to Lawrence, Cockcroft, Walton, and van der Meer, who together constitute only 2.8% of the 141 Nobel Prize winners in physics between 1939 and 2009. This question is beyond the scope of our present study, but we note that there were many important contributions to accelerator science after World War I, as listed in Appendix II [11], many of which supported research in fields other than physics. Perhaps, therefore, it is time to forgo the view that accelerator science is mainly or exclusively a supporting engineering science, as has been argued by some in the accelerator and the high-energy physics communities. Perhaps it is time to treat and accept accelerator science as an independent research field, deserving of distinction in its own right.

2.2.7 **Conclusion**

Our analysis indicates that accelerator science has played an integral role in influencing 28% of physicists working between 1939 and 2009 by either inspiring or facilitating their research. We also determined that 28% of the research in physics between 1939 and 2009 has been influenced by accelerator science and that on average accelerator science contributed to a Nobel Prize for Physics every 2.9 years. This indicates to us that accelerator science should be regarded as an independent discipline worthy of distinction in its own right.

2.2.8 **Appendix I**

Table 1: A list of physics Nobel Prize-winners who were influenced by accelerator science.

Year	Name	Accelerator-Science Contribution to Nobel Prize-Winning Research
1939	Ernest O. Lawrence	Lawrence invented the cyclotron at the University of Californian at Berkeley in 1929 [12].
1951	John D. Cockcroft and Ernest T.S. Walton	Cockcroft and Walton invented their eponymous linear positive-ion accelerator at the Cavendish Laboratory in Cambridge, England, in 1932 [13].
1952	Felix Bloch	Bloch used a cyclotron at the Crocker Radiation Laboratory at the University of California at Berkeley in his discovery of the magnetic moment of the neutron in 1940 [14].
1957	Tsung-Dao Lee and Chen Ning Yang	Lee and Yang analyzed data on K mesons (θ and τ) from Bevatron experiments at the Lawrence Radiation Laboratory in 1955 [15], which supported their idea in 1956 that parity is not

		conserved in weak interactions [16].
1959	Emilio G. Segrè and Owen Chamberlain	Segrè and Chamberlain discovered the antiproton in 1955 using the Bevatron at the Lawrence Radiation Laboratory [17].
1960	Donald A. Glaser	Glaser tested his first experimental six-inch bubble chamber in 1955 with high-energy protons produced by the Brookhaven Cosmotron [18].
1961	Robert Hofstadter	Hofstadter carried out electron-scattering experiments on carbon-12 and oxygen-16 in 1959 using the SLAC linac and thereby made discoveries on the structure of nucleons [19].
1963	Maria Goeppert Mayer	Goeppert Mayer analyzed experiments using neutron beams produced by the University of Chicago cyclotron in 1947 to measure the nuclear binding energies of krypton and xenon [20], which led to her discoveries on high magic numbers in 1948 [21].
1967	Hans A. Bethe	Bethe analyzed nuclear reactions involving accelerated protons and other nuclei whereby he discovered in 1939 how energy is produced in stars [22].
1968	Luis W. Alvarez	Alvarez discovered a large number of resonance states using his fifteen-inch hydrogen bubble chamber and high-energy proton beams from the Bevatron at the Lawrence Radiation Laboratory [23].
1976	Burton Richter and Samuel C.C. Ting	Richter discovered the J/Ψ particle in 1974 using the SPEAR collider at Stanford [24], and Ting discovered the J/Ψ particle independently in 1974 using the Brookhaven Alternating Gradient Synchrotron [25].
1979	Sheldon L. Glashow, Abdus Salam, and Steven Weinberg	Glashow, Salam, and Weinberg cited experiments on the bombardment of nuclei with neutrinos at CERN in 1973 [26] as confirmation of their prediction of weak neutral currents [27].
1980	James W. Cronin and Val L. Fitch	Cronin and Fitch concluded in 1964 that CP (charge-parity) symmetry is violated in the decay of neutral K mesons based upon their experiments using the Brookhaven Alternating Gradient Synchrotron [28].
1981	Kai M. Siegbahn	Siegbahn invented a weak-focusing principle for betatrons in 1944 with which he made significant improvements in high-resolution electron spectroscopy [29].
1983	William A. Fowler	Fowler collaborated on and analyzed accelerator-based experiments in 1958 [30], which he used to support his hypothesis on stellar-fusion processes in 1957 [31].

1984	Carlo Rubbia and Simon van der Meer	Rubbia led a team of physicists who observed the intermediate vector bosons W and Z in 1983 using CERN’s proton-antiproton collider [32], and van der Meer developed much of the instrumentation needed for these experiments [33].
1986	Ernst Ruska	Ruska built the first electron microscope in 1933 based upon a magnetic optical system that provided large magnification [34].
1988	Leon M. Lederman, Melvin Schwartz, and Jack Steinberger	Lederman, Schwartz, and Steinberger discovered the muon neutrino in 1962 using Brookhaven’s Alternating Gradient Synchrotron [35].
1989	Wolfgang Paul	Paul’s idea in the early 1950s of building ion traps grew out of accelerator physics [36].
1990	Jerome I. Friedman, Henry W. Kendall, and Richard E. Taylor	Friedman, Kendall, and Taylor’s experiments in 1974 on deep inelastic scattering of electrons on protons and bound neutrons used the SLAC linac [37].
1992	Georges Charpak	Charpak’s development of multiwire proportional chambers in 1970 were made possible by accelerator-based testing at CERN [38].
1995	Martin L. Perl	Perl discovered the tau lepton in 1975 using Stanford’s SPEAR collider [39].
2004	David J. Gross, Frank Wilczek, and H. David Politzer	Gross, Wilczek, and Politzer discovered asymptotic freedom in the theory of strong interactions in 1973 based upon results from the SLAC linac on electron-proton scattering [40].
2008	Makoto Kobayashi and Toshihide Maskawa	Kobayashi and Maskawa’s theory of quark mixing in 1973 was confirmed by results from the KEKB accelerator at KEK (High Energy Accelerator Research Organization) in Tsukuba, Ibaraki Prefecture, Japan, and the PEP II (Positron Electron Project II) at SLAC [41], which showed that quark mixing in the six-quark model is the dominant source of broken symmetry [42].

2.2.9 **Appendix II**

Table 2: A list of a list of important developments in accelerator science.

Year	*Important Development in Accelerator Science*
1918	Ernest Rutherford discovers artificial nuclear disintegration by bombarding nitrogen nuclei with RaC ($_{83}\mathrm{Bi}^{214}$) alpha particles.
1924	Gustav Ising develops the concept of a linear particle accelerator, and four years later Rolf Wideröe builds the world’s first linac in an eighty-eight-centimeter glass tube in Aachen, Germany.
1929	Robert J. Van de Graaff invents his eponymous generator at Princeton University. In 1959 he also constructs the first tandem accelerator at Chalk River, Canada.

1929	Ernest O. Lawrence invents the cyclotron at the University of California at Berkeley. In 1930 his student M. Stanley Livingston builds a four-inch-diameter cyclotron.
1932	John D. Cockcroft and Ernest T.S. Walton invent their eponymous electrostatic accelerator at the Cavendish Laboratory in Cambridge, England, and use it to produce the first man-made nuclear reaction.
1937	The brothers Russell and Sigurd Varian invent the klystron, a high-frequency amplifier for generating microwaves, and William Hansen is instrumental in its development at Stanford University. In 1935 Oskar Heil and Agnesa Arsenjewa-Heil at the Cavendish Laboratory, but while on a trip to Italy, had proposed a similar device.
1940	Donald W. Kerst constructs the first betatron at the University of Illinois, an electron accelerator that Joseph Slepian and others had proposed in the 1920s.
1943	Marcus (Mark) Oliphant develops the concept for a new type of accelerator, which Edwin McMillan later named the synchrotron.
1944	Vladimir Veksler at the Lebedev Physical Institute in Moscow, and later Edwin McMillan at the University of California at Berkeley independently discover the principle of phase stability, a cornerstone of modern accelerators, which is first demonstrated on a modified cyclotron at Berkeley in 1946.
1946	Frank Goward constructs the first electron synchrotron in Woolwich, England, which is followed by one built at the General Electric Research Laboratory in Schenectady, New York, where synchrotron radiation is first observed, thus opening up a new era of accelerator-based light sources.
1946	William Walkinshaw and his team in Malvern, England, build the first electron linac powered by a magnetron. William Hansen and his team at Stanford University independently build a similar electron linac a few months later.
1947	Luis Alvarez builds the first drift-tube linac for accelerating protons at the University of California at Berkeley.
1952	Ernest Courant, M. Stanley Livingston, and Hartland Snyder at Brookhaven National Laboratory discover the principle of strong focusing, which Nicholas Christofilos in Athens, Greece, had conceived independently in 1949 and had patented but did not publish. Strong focusing and phase stability form the foundation of all modern high-energy accelerators.
1956	The first Fixed-Field Alternating-Gradient accelerator is commissioned at the Midwestern Universities Research Association, based upon a concept that Tihiro Ohkawa, Andrei Kolomensky, and Keith Symon invented independently. In 1938 Llewellyn Thomas had conceived an earlier variation of it.
1959	The first two proton synchrotrons using strong focusing – the Proton Synchrotron at CERN and the Alternating Gradient Synchrotron at Brookhaven – are built. An electron synchrotron using strong focusing had been built at Cornell University in 1954.
1961	AdA (*Anello di Accumulazione*), the first electron-positron collider, is built at Frascati, Italy [43]. It is followed by two electron-electron colliders, the Princeton-Stanford double-ring collider in the United States and the VEP-1 double-ring collider at Novosibirsk, Russia.
1964	Astron, the first induction linac that Nicholas Christofilos had proposed for

	nuclear fusion, is built at a branch of the Lawrence Radiation Laboratory, later renamed the Lawrence Livermore National Laboratory.
1966	Gersh Budker invents electron-beam cooling at the Institute for Nuclear Physics in Akademgorodok, Russia.
1968	Simon van der Meer invents stochastic cooling for cooling antiproton beams. The proton-antiproton collisions studied at CERN lead to the discovery of the *W* and *Z* bosons in 1983.
1969	Vladimir Teplyakov and Ilya Kapchinskii invent the radio-frequency quadrupole linac at the Institute for Theoretical and Experimental Physics in Moscow.
1971	Intersecting Storage Rings, the first large proton-proton collider, begins operation at CERN.
1971	John M.J. Madey invents and builds the first free-electron laser at Stanford University.
1983	The Tevatron, the first large accelerator using superconducting magnet technology, is commissioned at Fermilab.
1989	The Stanford Linear Collider, first proposed by Burton Richter, is built at SLAC. Maury Tigner had developed the linear-collider concept in 1965.
1993	Construction of the Superconducting Super Collider, a would-be largest accelerator in the world, begins in 1989. The project is cancelled by the U.S. Congress in 1993 [44].
1994	The Continuous Electron Beam Accelerator Facility, the first large accelerator using superconducting radio-frequency technology, is built at the facility now called the Thomas Jefferson National Accelerator Facility.
2005	FLASH (**F**ree-Electron **LAS**er in **H**amburg), the first Vacuum Ultraviolet and soft X-ray free-electron laser-user facility, is built at DESY (Deutsches Elektronen-Synchrotron) in Hamburg, Germany.
2008	The Large Hadron Collider with a twenty-seven-kilometer circumference begins operation at CERN.

2.2.10 Acknowledgment

We thank Roger H. Stuewer for his thoughtful and careful editorial work on our paper.

2.2.11 Notes

a. Enzo F. Haussecker is an Applied Mathematics Major at the University of California, San Diego and Adjunct Researcher at the SLAC National Accelerator Laboratory; Alexander W. Chao is Professor of Physics at the SLAC National Accelerator Laboratory.
b. We have defined accelerator instrumentation as being developed after 1928 to omit cathode-ray tubes from our analysis, and to begin with the invention of the Van de Graaff accelerator in 1929.

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