Introduction to Beam Physics and Accelerator Technology
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This list contains a set of articles that are recommended as choices for the critical paper review, which we discussed and practiced in class. They were chosen because of their historical importance, because they contain significant scientific and technical advances, or because they describe interesting applications in various fields, such as nuclear and particle physics, medicine, art, etc. The papers are ordered by year of publication.

List of Recommended Papers for the Critical Review

Widerøe: A New Principle for the Generation of High Voltages

Rolf Widerøe. "A New Principle for the Generation of High Voltages." In: *Arch. für Elektrotechnik* 21 (1928), p. 387.

Annotations: First experimental demonstration of resonant acceleration. The second part of the paper describes the concept of the betatron and experimental attempts to implement it.

Sloan et al.: The Production of Heavy High Speed Ions without the Use of High Voltages

David H. Sloan and Ernest O. Lawrence. "The Production of Heavy High Speed Ions without the Use of High Voltages." In: *Phys. Rev.* 38.11 (Dec. 1931), pp. 2021–2032. ISSN: 0031-899X. DOI: 10.1103/PhysRev.38.2021. URL: https://link.aps.org/doi/10.1103/PhysRev.38.2021.

Abstract: A method has been developed for the multiple acceleration of ions to high speeds without the use of high voltages. The ions travel through a series of metal tubes in synchronism with an oscillating electric potential applied alternately to the tubes such that the electric field between tubes is always in a direction to accelerate the ions as they pass from the interior of one tube to the interior of the next. The ions are thereby successively accelerated to speeds corresponding to voltages as many times greater than the high frequency voltage applied to the tubes as there are tubes. In the present experiments a high frequency voltage of 42,000 volts at a wave-length of 30 meters applied to 30 such accelerator tubes in line resulted in the production of a current of 10^{-7} amp. of 1,260,000 volt singly charged Hg ions. The surprising effectiveness of this experimental method for the generation of intense beams of high speed ions is due to the development of simple, convenient and effective methods for focusing and synchronizing the ions as they pass through the accelerating system. The present experiments show that ions having kinetic energies in excess of 1,000,000 volt-electrons can be produced in this way with quite modest laboratory equipment and with a convenience surpassing the direct utilization of high voltages, that the limit to the attainable ion speeds is determined mainly by the length of accelerating system and the size of the high frequency oscillator system, and consequently that the production of 10,000,000 volt ions is an entirely practicable matter.

Cockcroft et al.: Experiments with High Velocity Positive Ions. (I) Further Developments in the Method of Obtaining High Velocity Positive Ions

J D Cockcroft and E T S Walton. "Experiments with High Velocity Positive Ions. (I) Further Developments in the Method of Obtaining High Velocity Positive Ions." In: *Proc. R. Soc. London A* 136.830 (Apr. 1932), pp. 619–630. ISSN: 09501207. URL: http://www.jstor.org/stable/95811.

Cockcroft et al.: Experiments with High Velocity Positive Ions. II. The Disintegration of Elements by High Velocity Protons

J D Cockcroft and E T S Walton. "Experiments with High Velocity Positive Ions. II. The Disintegration of Elements by High Velocity Protons." In: *Proc. R. Soc. London A* 137.831 (Apr. 1932), pp. 229–242. ISSN: 09501207. URL: http://www.jstor.org/stable/95941.

Lawrence et al.: The Production of High Speed Light Ions Without the Use of High Voltages

Ernest O. Lawrence and M. Stanley Livingston. "The Production of High Speed Light Ions Without the Use of High Voltages." In: *Phys. Rev.* 40.1 (Apr. 1932), pp. 19–35. ISSN: 0031-899X. DOI: 10.1103/PhysRev.40.19. URL: https://link.aps.org/doi/10.1103/PhysRev.40.19.

Abstract: The study of the nucleus would be greatly facilitated by the development of sources of high speed ions, particularly protons and helium ions, having kinetic energies in excess of 1,000,000 volt-electrons; for it appears that such swiftly moving particles are best suited to the task of nuclear excitation. The straightforward method of accelerating ions through the requisite differences of potential presents great experimental difficulties associated with the high electric fields necessarily involved. The present paper reports the development of a method that avoids these difficulties by means of the multiple acceleration of ions to high speeds without the use of high voltages. The method is as follows: Semi-circular hollow plates, not unlike duants of an electrometer, are mounted with their diametral edges adjacent, in a vacuum and in a uniform magnetic field that is normal to the plane of the plates. High frequency oscillations are applied to the plate electrodes producing an oscillating electric field over the diametral region between them. As a result during one half cycle the electric field accelerates ions, formed in the diametral region, into the interior of one of the electrodes, where they are bent around on circular paths by the magnetic field and eventually emerge again into the region between the electrodes. The magnetic field is adjusted so that the time required for traversal of a semi-circular path within the electrodes equals a half period of the oscillations. In consequence, when the ions return to the region between the electrodes, the electric field will have reversed direction, and the ions thus receive second increments of velocity on passing into the other electrode. Because the path radii within the electrodes are proportional to the velocities of the ions, the time required for a traversal of a semi-circular path is independent of their velocities. Hence if the ions take exactly one half cycle on their first semi-circles, they do likewise on all succeeding ones and therefore spiral around in resonance with the oscillating field until they reach the periphery of the apparatus. Their final kinetic energies are as many times greater than that corresponding to the voltage applied to the electrodes as the number of times they have crossed from one electrode to the other. This method is primarily designed for the acceleration of light ions and in the present experiments particular attention has been given to the production of high speed protons because of their presumably unique utility for experimental investigations of the atomic nucleus. Using a magnet with pole faces 11 inches in diameter, a current of 10-9 ampere of 1,220,000 volt-protons has been produced in a tube to which the maximum applied voltage was only 4000 volts. There are two features of the developed experimental method which have contributed largely to its success. First there is the focussing action of the electric and magnetic fields which prevents serious loss of ions as they are accelerated. In consequence of this, the magnitudes of the high speed ion currents obtainable in this indirect manner are comparable with those conceivably obtainable by direct high voltage methods. Moreover, the focussing action results in the generation of very narrow beams of ions—less than 1 mm cross-sectional diameter—which are ideal for experimental studies of collision processes. Of hardly less importance is the second feature of the method which is the simple and highly effective means for the correction of the magnetic field along the paths of the ions. This makes it possible, indeed easy, to operate the tube effectively with a very high amplification factor (i.e., ratio of final equivalent voltage of accelerated ions to applied voltage). In consequence, this method in its present stage of development constitutes a highly reliable and experimentally convenient source of high

speed ions requiring relatively modest laboratory equipment. Moreover, the present experiments indicate that this indirect method of multiple acceleration now makes practicable the production in the laboratory of protons having kinetic energies in excess of 10,000,000 volt-electrons. With this in mind, a magnet having pole faces 114 cm in diameter is being installed in our laboratory.

Thomas: The Paths of Ions in the Cyclotron I. Orbits in the Magnetic Field

L. H. Thomas. "The Paths of Ions in the Cyclotron I. Orbits in the Magnetic Field." In: *Phys. Rev.* 54.8 (Oct. 1938), pp. 580–588. ISSN: 0031-899X. DOI: 10.1103/PhysRev.54.580. URL: https://link.aps.org/doi/10.1103/PhysRev.54.580.

Abstract: Bethe and Rose maintain in a recent letter and paper that a maximum energy for the beam from a cyclotron is fixed by the incompatibility of the conditions for resonance and focusing when the relativity increase of mass with velocity is taken into account. It is shown below that, while this result holds for a radially symmetrical magnetic field, it is not necessarily true in general; and that for a field varying with polar angle there is an additional focusing effect. If the relative variation of the field with polar angle is of the order of the ratio of the velocity of the ion to the velocity of light, this focusing effect will compensate the defocusing effect of Bethe and Rose. It is shown further that if this variation has period $\pi/2$, a family of stable periodic orbits exists which are nearly concentric circles. The second order effects due to the simultaneous action of the variations with polar angle of the magnetic field and the accelerating electric field will be considered in a second paper.

Kerst: Acceleration of Electrons by Magnetic Induction

D. W. Kerst. "Acceleration of Electrons by Magnetic Induction." In: *Phys. Rev.* 58.9 (Nov. 1940), pp. 841–841. ISSN: 0031-899X. DOI: 10.1103/PhysRev.58.841. URL: https://link.aps.org/doi/10.1103/PhysRev.58.841.

Kerst: The Acceleration of Electrons by Magnetic Induction

D. W. Kerst. "The Acceleration of Electrons by Magnetic Induction." In: *Phys. Rev.* 60.1 (July 1941), pp. 47–53. ISSN: 0031-899X. DOI: 10.1103/PhysRev.60.47. URL: https://link.aps.org/doi/10.1103/PhysRev.60.47.

Abstract: Apparatus with which electrons have been accelerated to an energy of 2.3 Mev by means of the electric field accompanying a changing magnetic field is described. Stable circular orbits are formed in a magnetic field, and the changing flux within the orbits accelerates the electrons. As the magnetic field reaches its peak value, saturation of the iron supplying flux through the orbit causes the electrons to spiral inward toward a tungsten target. The x-rays produced have an intensity approximately equal to that of the gamma-rays from one gram of radium; and, because of the tendency of the x-rays to proceed in the direction of the electrons, a pronounced beam is formed.

Kerst et al.: Electronic Orbits in the Induction Accelerator

D. W. Kerst and R. Serber. "Electronic Orbits in the Induction Accelerator." In: *Phys. Rev.* 60.1 (July 1941), pp. 53–58. ISSN: 0031-899X. DOI: 10.1103/PhysRev.60.53. URL: https://link.aps.org/doi/10.1103/PhysRev.60.53.

Abstract: The first section gives a general account of the principles of operation of the electron induction accelerator. The second section gives the more detailed analysis of the orbits of the electrons which was undertaken to serve as a guide in the design of the accelerator.

McMillan: The Synchrotron—A Proposed High Energy Particle Accelerator

Edwin M. McMillan. "The Synchrotron—A Proposed High Energy Particle Accelerator." In: *Phys. Rev.* 68.5-6 (Sept. 1945), pp. 143–144. ISSN: 0031-899X. DOI: 10.1103/PhysRev.68.143. URL: https://link.aps.org/doi/10.1103/PhysRev.68.143.

J. Schwinger: On Radiation by Electrons in a Betatron

J. Schwinger. *On Radiation by Electrons in a Betatron*. Tech. rep. Berkeley, CA (United States): Lawrence Berkeley National Laboratory (LBNL), Aug. 1945. DOI: 10.2172/1195620. URL: http://www.osti.gov/servlets/purl/1195620/.

Abstract: Julian Schwinger produced this paper in preprint form in 1945 and, apparently, distributed it only to a few selected colleagues at the time. He later presented the results as a 15-minute invited paper in 1946, at an American Physical Society meeting, under the title "Electron Radiation in High Energy Accelerators" (the abstract is published in Phys. Rev. 70, 798 (1946)). Although he published this work four years later in revised form ("On the Classical Radiation of Accelerated Electrons," Phys. Rev. 75, 1912 (1949)), this original version seems fresher and, in some respects, superior to the published one, hence my motivation to make it widely available. For example, the discussion of coherent radiation (shielded and unshielded) included in this version was wholly omitted in the published paper. In addition, this version exhibits many explicit calculations that are of pedagogical value even today for students of synchrotron radiation. But perhaps the most interesting aspect of this paper is that it shows so well the author's superb dexterity in manipulating mathematical expressions to obtain physical conclusions with clarity and efficiency.

Veksler: A New Method of Acceleration of Relativistic Particles

V. Veksler. "A New Method of Acceleration of Relativistic Particles." In: *J. Phys. U.S.S.R.* 9 (1945), p. 153.

Abstract: It is shown that by application of the resonance method acceleration of relativistic particles can be effected in two different ways — by a method of multiple resonance in a constant magnetic field and by a method of adiabatic variation of the parameters of the accelerator. In accelerators with a constant magnetic field stability of the acceleration process can easily be attained. It is proved that in the method of adiabatic variation acceleration of the particles is possible for any law of variation of the magnetic field (or frequency). It is established that in the adiabatic accelerator electromagnetic radiation does not violate the stability and, therefore, very high energies can in principle be attained in this type of accelerator.

Bohm et al.: The Theory of the Synchrotron

D. Bohm and L. Foldy. "The Theory of the Synchrotron." In: *Phys. Rev.* 70.5-6 (Sept. 1946), pp. 249–258. ISSN: 0031-899X. DOI: 10.1103/PhysRev.70.249. URL: https://link.aps.org/doi/10.1103/PhysRev.70.249.

Abstract: In accelerators of the type discussed by Veksler and McMillan (e.g., the synchrotron and synchro-cyclotron) the motion of particles can be described in terms of stable oscillations about a synchronous orbit. Expressions are worked out for the frequencies of these oscillations, and for the way in which their amplitudes are damped as the energy is increased. The effect of radiation losses on the damping is discussed. It is shown that the synchrotron can advantageously be operated as a betatron until the electron velocity is close to that of light; the dee voltage is then turned on and the machine works as a synchrotron for the remainder of the acceleration. The transition from betatron to synchrotron operation proved to be quite efficient. Formulae are given for the distortions of the orbits by azimuthal asymmetries of the magnetic field. The results are illustrated in terms of the California synchrotron.

Goward et al.: Experimental 8 Mev. Synchrotron for Electron Acceleration

F. K. Goward and D. E. Barnes. "Experimental 8 Mev. Synchrotron for Electron Acceleration." In: *Nature* 158.4012 (Sept. 1946), pp. 413–413. ISSN: 0028-0836. DOI: 10.1038/158413a0. URL: https://www.nature.com/articles/158413a0.

Wilson: Radiological Use of Fast Protons

Robert R. Wilson. "Radiological Use of Fast Protons." In: *Radiology* 47.5 (Nov. 1946), pp. 487–491. ISSN: 0033-8419. DOI: 10.1148/47.5.487. URL: http://pubs.rsna.org/doi/10.1148/47.5.487.

Elder et al.: A 70-Mev Synchrotron

F. R. Elder, A. M. Gurewitsch, et al. "A 70-Mev Synchrotron." In: *J. Appl. Phys.* 18.9 (Sept. 1947), pp. 810–818. ISSN: 0021-8979. DOI: 10.1063/1.1697845. URL: https://aip-scitation-proxy.fnal.gov/doi/abs/10.1063/1.1697845%20http://aip.scitation.org/doi/10.1063/1.1697845.

Abstract: A synchrotron for the production of 70-Mev x-rays has been built and tested. The general mode of operation, and various features of its design and construction, are discussed. Some preliminary information on the characteristics of the electron and x-ray beams is included. This work has been supported by the Office of Naval Research.

Van De Graaff et al.: Electrostatic Generators for the Acceleration of Charged Particles

R J Van De Graaff, J. G. Trump, and W. W. Buechner. "Electrostatic Generators for the Acceleration of Charged Particles." In: *Reports Prog. Phys.* 11.1 (Jan. 1947), p. 301. ISSN: 00344885. DOI: 10.1088/0034-4885/11/1/301. URL: https://iopscience.iop.org/article/10.1088/0034-4885/11/1/301.

Elder et al.: Radiation from Electrons Accelerated in a Synchrotron

F. R. Elder, R. V. Langmuir, and H. C. Pollock. "Radiation from Electrons Accelerated in a Synchrotron." In: *Phys. Rev.* 74.1 (July 1948), pp. 52–56. ISSN: 0031-899X. DOI: 10.1103/PhysRev.74.52. URL: https://link.aps.org/doi/10.1103/PhysRev.74.52.

Abstract: High energy electrons subjected to large radial accelerations radiate considerable energy in the optical spectrum. The distribution of energy in the light from a synchrotron beam has been measured and compared with theory at several electron energies up to 80 Mev. The results indicate reasonable agreement with theory. Measurement of total light output allowed an estimate of electron current in the beam. High speed photography of the light permitted observation of the size and motion of the beam within the accelerator tube.

Ginzton et al.: A Linear Electron Accelerator

E. L. Ginzton, W. W. Hansen, and W. R. Kennedy. "A Linear Electron Accelerator." In: *Rev. Sci. Instrum.* 19.2 (Feb. 1948), pp. 89–108. ISSN: 0034-6748. DOI: 10.1063/1.1741225. URL: http://aip.scitation.org/doi/10.1063/1.1741225.

Abstract: The theory, design, and some experimental results relative to linear electron accelerators are discussed. It is shown that, though the orbits are unstable, this instability is so small as to be negligible in general, provided the electrons are injected at relativistic velocities. Likewise, space-charge spreading may be neglected. The optimum loading design is found for various types of power feeds and curves are given

by means of which any design may be evaluated. A number of illustrative cases are discussed. Operation of a low power, 38-section accelerator is described.

Julian Schwinger: On the Classical Radiation of Accelerated Electrons

Julian Schwinger. "On the Classical Radiation of Accelerated Electrons." In: *Phys. Rev.* 75.12 (June 1949), pp. 1912–1925. ISSN: 0031-899X. DOI: 10.1103/PhysRev.75.1912. URL: https://link.aps.org/doi/10.1103/PhysRev.75.1912.

Abstract: This paper is concerned with the properties of the radiation from a high energy accelerated electron, as recently observed in the General Electric synchrotron. An elementary derivation of the total rate of radiation is first presented, based on Larmor's formula for a slowly moving electron, and arguments of relativistic invariance. We then construct an expression for the instantaneous power radiated by an electron moving along an arbitrary, prescribed path. By casting this result into various forms, one obtains the angular distribution, the spectral distribution, or the combined angular and spectral distributions of the radiation. The method is based on an examination of the rate at which the electron irreversibly transfers energy to the electromagnetic field, as determined by half the difference of retarded and advanced electric field intensities. Formulas are obtained for an arbitrary charge-current distribution and then specialized to a point charge. The total radiated power and its angular distribution are obtained for an arbitrary trajectory. It is found that the direction of motion is a strongly preferred direction of emission at high energies. The spectral distribution of the radiation depends upon the detailed motion over a time interval large compared to the period of the radiation. However, the narrow cone of radiation generated by an energetic electron indicates that only a small part of the trajectory is effective in producing radiation observed in a given direction, which also implies that very high frequencies are emitted. Accordingly, we evaluate the spectral and angular distributions of the high frequency radiation by an energetic electron, in their dependence upon the parameters characterizing the instantaneous orbit. The average spectral distribution, as observed in the synchrotron measurements, is obtained by averaging the electron energy over an acceleration cycle. The entire spectrum emitted by an electron moving with constant speed in a circular path is also discussed. Finally, it is observed that quantum effects will modify the classical results here obtained only at extraordinarily large energies.

E. D. Courant et al.: The Strong-Focusing Synchroton —— A New High Energy Accelerator

Ernest D. Courant, M. Stanley Livingston, and Hartland S. Snyder. "The Strong-Focusing Synchroton —— A New High Energy Accelerator." In: *Phys. Rev.* 88.5 (Dec. 1952), pp. 1190–1196. ISSN: 0031-899X. DOI: 10.1103/PhysRev.88.1190. URL: https://link.aps.org/doi/10.1103/PhysRev.88.1190.

Abstract: Strong focusing forces result from the alternation of large positive and negative n-values in successive sectors of the magnetic guide field in a synchrotron. This sequence of alternately converging and diverging magnetic lenses of equal strength is itself converging, and leads to significant reductions in oscillation amplitude, both for radial and axial displacements. The mechanism of phase-stable synchronous acceleration still applies, with a large reduction in the amplitude of the associated radial synchronous oscillations. To illustrate, a design is proposed for a 30-Bev proton accelerator with an orbit radius of 300 ft, and with a small magnet having an aperture of 1×2 inches. Tolerances on nearly all design parameters are less critical than for the equivalent uniform-n machine. A generalization of this focusing principle leads to small, efficient focusing magnets for ion and electron beams. Relations for the focal length of a double-focusing magnet are presented, from which the design parameters for such linear systems can be determined.

Lawrence: The Evolution of the Cyclotron

Ernest O. Lawrence. "The Evolution of the Cyclotron." In: *Les Prix Nobel en 1951*. Stockholm: Norstedt

and Söner, 1952, p. 127. URL: https://www.nobelprize.org/uploads/2018/06/lawrence-lecture.pdf.

Abstract: Nobel Lecture, December 11, 1951.

Kerst et al.: Attainment of Very High Energy by Means of Intersecting Beams of Particles

D. W. Kerst, F. T. Cole, et al. "Attainment of Very High Energy by Means of Intersecting Beams of Particles." In: *Phys. Rev.* 102.2 (Apr. 1956), pp. 590–591. ISSN: 0031-899X. DOI: 10.1103/PhysRev.102.590. URL: https://link.aps.org/doi/10.1103/PhysRev.102.590.

Symon et al.: Fixed-Field Alternating-Gradient Particle Accelerators

K. R. Symon et al. "Fixed-Field Alternating-Gradient Particle Accelerators." In: *Phys. Rev.* 103.6 (Sept. 1956), pp. 1837–1859. ISSN: 0031-899X. DOI: 10.1103/PhysRev.103.1837. URL: https://link.aps.org/doi/10.1103/PhysRev.103.1837.

Abstract: It is possible, by using alternating-gradient focusing, to design circular accelerators with magnetic guide fields which are constant in time, and which can accommodate stable orbits at all energies from injection to output energy. Such accelerators are in some respects simpler to construct and operate, and moreover, they show promise of greater output currents than conventional synchrotrons and synchrocyclotrons. Two important types of magnetic field patterns are described, the radial-sector and spiral-sector patterns, the former being easier to understand and simpler to construct, the latter resulting in a much smaller accelerator for a given energy. A theory of orbits in fixed-field alternating-gradient accelerators has been worked out in linear approximation, which yields approximate general relationships between machine parameters, as well as more accurate formulas which can be used for design purposes. There are promising applications of these principles to the design of fixed-field synchrotrons, betatrons, and high-energy cyclotrons.

E.D Courant et al.: Theory of the Alternating-Gradient Synchrotron

E.D Courant and H.S Snyder. "Theory of the Alternating-Gradient Synchrotron." In: *Ann. Phys. (N. Y).* 3.1 (Jan. 1958), pp. 1–48. ISSN: 00034916. DOI: 10.1016/0003-4916(58)90012-5. URL: https://linkinghub.elsevier.com/retrieve/pii/0003491658900125.

Abstract: The equations of motion of the particles in a synchrotron in which the field gradient index $n = -(r/B)\partial B/\partial r$ varies along the equilibrium orbit are examined on the basis of the linear approximation. It is shown that if n alternates rapidly between large positive and large negative values, the stability of both radial and vertical oscillations can be greatly increased compared to conventional accelerators in which n is azimuthally constant and must lie between 0 and 1. Thus aperture requirements are reduced. For practical designs, the improvement is limited by the effects of constructional errors; these lead to resonance excitation of oscillations and consequent instability if $2\nu_x$ or $2\nu_z$ or $\nu_x + \nu_z$ is integral, where ν_x and ν_z are the frequencies of horizontal and vertical betatron oscillations, measured in units of the frequency of revolution. The mechanism of phase stability is essentially the same as in a conventional synchrotron, but the radial amplitude of synchrotron oscillations is reduced substantially. Furthermore, at a "transition energy" $E_1 \approx \nu_x Mc^2$ the stable and unstable equilibrium phases exchange roles, necessitating a jump in the phase of the radiofrequency accelerating voltage. Calculations indicate that the manner in which this jump is performed is not very critical.

Robinson: Radiation Effects in Circular Electron Accelerators

Kenneth W. Robinson. "Radiation Effects in Circular Electron Accelerators." In: *Phys. Rev.* 111.2 (July

1958), pp. 373–380. ISSN: 0031-899X. DOI: 10.1103/PhysRev.111.373. URL: https://link.aps.org/doi/10.1103/PhysRev.111.373.

Abstract: The effects of the radiation emission on the motion of electrons in high-energy synchrotrons are analyzed. The damping rates and quantum excitation of the three principal modes of oscillation are derived for strong focusing and constant gradient accelerators. Methods for correcting the radiation effects for strong-focusing accelerators are discussed.

Bargmann et al.: Precession of the Polarization of Particles Moving in a Homogeneous Electromagnetic Field

V. Bargmann, Louis Michel, and V. L. Telegdi. "Precession of the Polarization of Particles Moving in a Homogeneous Electromagnetic Field." In: *Phys. Rev. Lett.* 2.10 (May 1959), pp. 435–436. ISSN: 0031-9007. DOI: 10.1103/PhysRevLett.2.435. URL: https://link.aps.org/doi/10.1103/PhysRevLett.2.435.

Schwartz: Feasibility of Using High-Energy Neutrinos to Study the Weak Interactions

M Schwartz. "Feasibility of Using High-Energy Neutrinos to Study the Weak Interactions." In: *Phys. Rev. Lett.* 4.6 (Mar. 1960), pp. 306–307. ISSN: 0031-9007. DOI: 10.1103/PhysRevLett.4.306. URL: https://link.aps.org/doi/10.1103/PhysRevLett.4.306.

Rose: The Three-Stage Tandem Accelerator

P.H. Rose. "The Three-Stage Tandem Accelerator." In: *Nucl. Instruments Methods* 11 (Jan. 1961), pp. 49–62. ISSN: 0029554X. DOI: 10.1016/0029-554X(61)90010-6. URL: https://linkinghub.elsevier.com/retrieve/pii/0029554X61900106.

Abstract: The position of this new accelerator among the tools of nuclear physics is yet to be determined. Beam currents of 10 mA and energies as high as 30 MeV are probably achievable within the next ten years. The accelerator has all the advantages of constant voltage acceleration. Two forms of the accelerator are described, one with negative ion injection and the other with neutral beam injection. Of the two, neutral beam injection has not only the virtue of having been tried successfully but has the greatest potential for the future. The technical problems associated with the vacuum and ion optics are described and it is pointed out that from an initial 10 mA of positive ions a target current of 191 μA of energetic protons is theoretically possible. Tests with a three stage tandem accelerator are described which show the various loss mechanisms involved in the accelerator. A small beam of 0.3 mμA was obtained, however, at an energy of 15 MeV and with the excellent energy stability of ± 1 in 100 000. Results of experiments in which a neutral helium beam was injected into a tandem accelerator are also mentioned. In conclusion it is shown that neither the vacuum nor the optical problem pose any insoluble problems. Current high vacuum techniques should insure pressures of 10^{-7} torr in the accelerator. Injection of a converging neutral beam should solve the optical problem and high currents will eventually be obtained.

Bernardini et al.: Lifetime and Beam Size in a Storage Ring

C. Bernardini et al. "Lifetime and Beam Size in a Storage Ring." In: *Phys. Rev. Lett.* 10.9 (May 1963), pp. 407–409. ISSN: 0031-9007. DOI: 10.1103/PhysRevLett.10.407. URL: https://link.aps.org/doi/10.1103/PhysRevLett.10.407.

Budker: An Effective Method of Damping Particle Oscillations in Proton and Antiproton Storage Rings

G. I. Budker. "An Effective Method of Damping Particle Oscillations in Proton and Antiproton Storage Rings." In: *At. Energy* 22 (1966), p. 438.

Abstract: A method is proposed for the damping of synchrotron and betatron oscillations of heavy particles, which makes use of the sharp increase in the cross section for the interaction of these particles with electrons at small relative velocity. It is shown that it is possible by this method to compress strongly the proton and antiproton bunches in storage rings, and also to achieve multiple storage of these particles.

E. D. Courant et al.: Transverse Coherent Resistive Instabilities of Azimuthally Bunched Beams in Particle Accelerators

Ernest D. Courant and Andrew M. Sessler. "Transverse Coherent Resistive Instabilities of Azimuthally Bunched Beams in Particle Accelerators." In: *Rev. Sci. Instrum.* 37.11 (Nov. 1966), pp. 1579–1588. ISSN: 0034-6748. DOI: 10.1063/1.1720048. URL: http://aip.scitation.org/doi/10.1063/1.1720048.

Abstract: The transverse electromagnetic coupling of bunches of particles with each other is investigated theoretically, and shown to incorporate the possibility (due to the effect of imperfectly conducting vacuum chamber walls) of coherent instability even when the longitudinal distance between bunches is much larger than the transverse dimensions of the vacuum tank. The modes of oscillation in which the bunches move rigidly are investigated; criteria for stability, and expressions for the small amplitude growth rates under unstable conditions are presented. The case of a single bunch is considered in detail and demonstrated to be stable (even in the absence of Landau damping) provided v lies between an integer and the next higher half-integer, where v is the number of transverse free betatron oscillations occurring in one revolution; for many bunches which are sensibly different in intensity (a criterion for this is presented), all modes are stable provided v satisfies the same restriction. For equally spaced bunches of equal numbers of particles, approximately half the modes are unstable without Landau damping. Numerical examples are presented covering some intermediate situations.

Meer: Stochastic Damping of Betatron Oscillations in the ISR

S. van der Meer. *Stochastic Damping of Betatron Oscillations in the ISR*. Tech. rep. CERN, 1972. URL: https://cds.cern.ch/record/312939.

Abstract: In principle, betatron oscillations could be damped by detecting and compensating statistical variations of the average beam position, caused by the finite number of particles present. It is shown that achieving useful damping in the ISR would be difficult with presently available techniques.

Elias et al.: Observation of Stimulated Emission of Radiation by Relativistic Electrons in a Spatially Periodic Transverse Magnetic Field

Luis R. Elias et al. "Observation of Stimulated Emission of Radiation by Relativistic Electrons in a Spatially Periodic Transverse Magnetic Field." In: *Phys. Rev. Lett.* 36.13 (Mar. 1976), pp. 717–720. ISSN: 0031-9007. DOI: 10.1103/PhysRevLett.36.717. URL: https://link.aps.org/doi/10.1103/PhysRevLett.36.717.

Abstract: Gain has been observed for optical radiation at 10.6 μm due to stimulated radiation by a relativistic electron beam in a constant spatially periodic transverse magnetic field. A gain of 7% per pass was obtained

at an electron current of 70 mA. The experiments indicate the possibility of a new class of tunable high-power free-electron lasers.

Deacon et al.: First Operation of a Free-Electron Laser

D. A. G. Deacon et al. "First Operation of a Free-Electron Laser." In: *Phys. Rev. Lett.* 38.16 (Apr. 1977), pp. 892–894. ISSN: 0031-9007. DOI: 10.1103/PhysRevLett.38.892. URL: https://link.aps.org/doi/10.1103/PhysRevLett.38.892.

Abstract: A free-electron laser has been operated above threshold at a wavelength of 3.4 μm.

Dikansky et al.: Electron Cooling and its Applications in Elementary Particle Physics

N. S. Dikansky, I. N. Meshkov, and A. N. Skrinsky. "Electron Cooling and its Applications in Elementary Particle Physics." In: *Nature* 276.5690 (Dec. 1978), pp. 763–767. ISSN: 0028-0836. DOI: 10.1038/276763a0. URL: https://www.nature.com/articles/276763a0.

Abstract: In recent years, experiments in high-energy physics have shown that one of the most promising means of studying the properties of elementary particles is by colliding beams. First, they open up a region of interaction energies at present unattainable using conventional accelerators. Second, they allow experiments to be performed in extremely clean conditions, when the observed interaction between two colliding particles is not contaminated by the presence of secondary interactions as in the conventional particle accelerator-fixed target scheme. This article describes the electron cooling method applied to proton-antiproton colliding beams.

Tajima et al.: Laser Electron Accelerator

T. Tajima and J. M. Dawson. "Laser Electron Accelerator." In: *Phys. Rev. Lett.* 43.4 (July 1979), pp. 267–270. ISSN: 0031-9007. DOI: 10.1103/PhysRevLett.43.267. URL: https://link.aps.org/doi/10.1103/PhysRevLett.43.267.

Abstract: An intense electromagnetic pulse can create a weak of plasma oscillations through the action of the nonlinear ponderomotive force. Electrons trapped in the wake can be accelerated to high energy. Existing glass lasers of power density 10^{18} W/cm^2 shone on plasmas of densities 10^{18} cm^{-3} can yield gigaelectronvolts of electron energy per centimeter of acceleration distance. This acceleration mechanism is demonstrated through computer simulation. Applications to accelerators and pulsers are examined.

Palmer et al.: Superconducting Magnet Technology for Accelerators

R Palmer and A V Tollestrup. "Superconducting Magnet Technology for Accelerators." In: *Annu. Rev. Nucl. Part. Sci.* 34.1 (Dec. 1984), pp. 247–284. ISSN: 0163-8998. DOI: 10.1146/annurev.ns.34.120184.001335. URL: https://www.annualreviews.org/doi/10.1146/annurev.ns.34.120184.001335.

Meer: Stochastic Cooling and the Accumulation of Antiprotons

S. van der Meer. "Stochastic Cooling and the Accumulation of Antiprotons." In: *Rev. Mod. Phys.* 57.3 (July 1985), pp. 689–697. ISSN: 0034-6861. DOI: 10.1103/RevModPhys.57.689. URL: https://journals.aps.org/rmp/abstract/10.1103/RevModPhys.57.689%20https://link.aps.org/doi/10.1103/RevModPhys.57.689.

Tajima et al.: Crystal X-Ray Accelerator

T. Tajima and M. Cavenago. "Crystal X-Ray Accelerator." In: *Phys. Rev. Lett.* 59.13 (Sept. 1987), pp. 1440–1443. ISSN: 0031-9007. DOI: 10.1103/PhysRevLett.59.1440. URL: https://link.aps.org/doi/10.1103/PhysRevLett.59.1440.

Abstract: An ultimate linac structure is realized by an appropriate crystal lattice (superlattice) that serves as a soft irised waveguide for x rays. High-energy (40 keV) X rays are injected into the crystal at the Bragg angle to cause Bormann anomalous transmission, yielding slow-wave accelerating fields. Particles (e.g., muons) are channeled along the crystal axis.

Mikhailichenko et al.: Optical Stochastic Cooling

A. A. Mikhailichenko and M. S. Zolotorev. "Optical Stochastic Cooling." In: *Phys. Rev. Lett.* 71.25 (Dec. 1993), pp. 4146–4149. ISSN: 0031-9007. DOI: 10.1103/PhysRevLett.71.4146. URL: https://link.aps.org/doi/10.1103/PhysRevLett.71.4146.

Abstract: In this paper, we consider the utilization of optical amplifiers with bandwidth $\Delta f \simeq 10^{14}$ Hz for use in stochastic cooling. It is shown that quadrupole and dipole wigglers can be used as pickups and kickers, respectively. The proposed method increases the application of the stochastic cooling method beyond the traditional area of proton-antiproton cooling. For example, the method has application to electron-positron cooling as well as potential in muon cooling. The proposed method makes possible the independent choice of damping time and source of excitation of emittance, thereby providing a new direction for the design of low-emittance damping rings.

E.D. Courant et al.: Theory of the Alternating-Gradient Synchrotron

E.D. Courant and H.S. Snyder. "Theory of the Alternating-Gradient Synchrotron." In: *Ann. Phys. (N. Y).* 281.1-2 (Apr. 2000), pp. 360–408. ISSN: 00034916. DOI: 10.1006/aphy.2000.6012. URL: https://linkinghub.elsevier.com/retrieve/pii/S0003491600960123.

Abstract: The equations of motion of the particles in a synchrotron in which the field gradient index $n = -(r/B)\partial B/\partial r$ varies along the equilibrium orbit are examined on the basis of the linear approximation. It is shown that if n alternates rapidly between large positive and large negative values, the stability of both radial and vertical oscillations can be greatly increased compared to conventional accelerators in which n is azimuthally constant and must lie between 0 and 1. Thus aperture requirements are reduced. For practical designs, the improvement is limited by the effects of constructional errors; these lead to resonance excitation of oscillations and consequent instability if $2\nu_x$ or $2\nu_z$ or $\nu_x + \nu_z$ is integral, where ν_x and ν_z are the frequencies of horizontal and vertical betatron oscillations, measured in units of the frequency of revolution. The mechanism of phase stability is essentially the same as in a conventional synchrotron, but the radial amplitude of synchrotron oscillations is reduced substantially. Furthermore, at a "transition energy" $E_1 \approx \nu_x Mc^2$ the stable and unstable equilibrium phases exchange roles, necessitating a jump in the phase of the radiofrequency accelerating voltage. Calculations indicate that the manner in which this jump is performed is not very critical.

Zucchelli: A Novel Concept for a $\bar{\nu}_e/\nu_e$ Neutrino Factory: the Beta-Beam

P. Zucchelli. "A Novel Concept for a $\bar{\nu}_e/\nu_e$ Neutrino Factory: the Beta-Beam." In: *Phys. Lett. B* 532.3-4 (Apr. 2002), pp. 166–172. ISSN: 03702693. DOI: 10.1016/S0370-2693(02)01576-9. URL: http://dx.doi.org/10.1016/S0370-2693(02)01576-9%20https://linkinghub.elsevier.com/retrieve/pii/S0370269302015769.

Abstract: The evolution of neutrino physics demands new schemes to produce intense, collimated and pure neutrino beams. The current neutrino factory concept implies the production, collection, and storage of muons to produce beams of muon and electron neutrinos at equal intensities at the same time. Research and development addressing its feasibility are ongoing. In the current Letter, a new neutrino factory concept is proposed that could possibly achieve beams of high intensity, known energy spectrum and a single neutrino flavour (electron-antineutrino or electron-neutrino). The scheme relies on existing technology.

Ackermann et al.: Operation of a Free-Electron Laser from the Extreme Ultraviolet to the Water Window

W. Ackermann et al. "Operation of a Free-Electron Laser from the Extreme Ultraviolet to the Water Window." In: *Nat. Photonics* 1.6 (June 2007), pp. 336–342. ISSN: 1749-4885. DOI: 10.1038/nphoton.2007.76. URL: http://www.nature.com/articles/nphoton.2007.76.

Abstract: We report results on the performance of a free-electron laser operating at a wavelength of 13.7 nm where unprecedented peak and average powers for a coherent extreme-ultraviolet radiation source have been measured. In the saturation regime, the peak energy approached 170 μJ for individual pulses, and the average energy per pulse reached 70 μJ. The pulse duration was in the region of 10 fs, and peak powers of 10 GW were achieved. At a pulse repetition frequency of 700 pulses per second, the average extreme-ultraviolet power reached 20 mW. The output beam also contained a significant contribution from odd harmonics of approximately 0.6% and 0.03% for the 3rd (4.6 nm) and the 5th (2.75 nm) harmonics, respectively. At 2.75 nm the 5th harmonic of the radiation reaches deep into the water window, a wavelength range that is crucially important for the investigation of biological samples.

Andreotti et al.: Precision Measurements of the Total and Partial Widths of the $\psi(2S)$ Charmonium Meson with a New Complementary-Scan Technique in Antiproton-Proton Annihilations

M. Andreotti et al. "Precision Measurements of the Total and Partial Widths of the $\psi(2S)$ Charmonium Meson with a New Complementary-Scan Technique in Antiproton-Proton Annihilations." In: *Phys. Lett. B* 654.3-4 (Oct. 2007), pp. 74–79. ISSN: 03702693. DOI: 10.1016/j.physletb.2007.08.044. URL: https://linkinghub.elsevier.com/retrieve/pii/S0370269307010076.

Abstract: We present new precision measurements of the $\psi(2S)$ total and partial widths from excitation curves obtained in antiproton-proton annihilations by Fermilab experiment E835 at the Antiproton Accumulator in the year 2000. A new technique of complementary scans was developed to study narrow resonances with stochastically cooled antiproton beams. The technique relies on precise revolution-frequency and orbit-length measurements, while making the analysis of the excitation curve almost independent of machine lattice parameters. We study the $\psi(2S)$ meson through the processes $\bar{p}p \to e^+e^-$ and $\bar{p}p \to J/\psi + X \to e^+e^- + X$. We measure the width to be $\Gamma = 290 \pm 25(\text{sta}) \pm 4(\text{sys})$ keV and the combination of partial widths $\Gamma_{e+e-}\Gamma_{\bar{p}p}/\Gamma = 579 \pm 38(\text{sta}) \pm 36(\text{sys})$ meV, which represent the most precise measurements to date.

Heiner et al.: A Molecular Synchrotron

Cynthia E. Heiner et al. "A Molecular Synchrotron." In: *Nat. Phys.* 3.2 (Feb. 2007), pp. 115–118. ISSN: 1745-2473. DOI: 10.1038/nphys513. URL: http://www.nature.com/articles/nphys513.

Abstract: Many of the tools for manipulating the motion of neutral atoms and molecules take their inspiration from techniques developed for charged particles. Traps for atoms-akin to the Paul trap for ions-have paved the way for many exciting experiments, ranging from ultra-precise clocks to creating quantum degenerate matter. Surprisingly, little attention has been paid to developing a neutral particle analogue of a synchrotron-

arguably, the most celebrated tool of the charged-particle physicist. So far, the few experiments dealing with ring structures for neutral particles have used cylindrically symmetric designs; in these rings, no force is applied to the particles along the longitudinal direction and the stored particles are free to fill the entire ring. Here, we demonstrate a synchrotron for neutral polar molecules. A packet of ammonia molecules is accelerated, decelerated and focused along the longitudinal direction ('bunched') using the fringe fields between the two halves of a segmented hexapole ring. The stored bunch of cold molecules (T = 0.5 mK) is confined to a 3 mm packet even after a flight distance of over 30 m (40 round trips). Furthermore, we show the injection of multiple packets into the ring.

Kopp: Accelerator Neutrino Beams

S. Kopp. "Accelerator Neutrino Beams." In: *Phys. Rep.* 439.3 (Feb. 2007), pp. 101–159. ISSN: 03701573. DOI: 10.1016/j.physrep.2006.11.004. eprint: 0609129. URL: https://linkinghub.elsevier.com/retrieve/pii/S0370157306004431.

Abstract: Neutrino beams at from high-energy proton accelerators have been instrumental discovery tools in particle physics. Neutrino beams are derived from the decays of charged π and K mesons, which in turn are created from proton beams striking thick nuclear targets. The precise selection and manipulation of the π / K beam control the energy spectrum and type of neutrino beam. This article describes the physics of particle production in a target and manipulation of the particles to derive a neutrino beam, as well as numerous innovations achieved at past experimental facilities.

Litvinenko et al.: Coherent Electron Cooling

Vladimir N. Litvinenko and Yaroslav S. Derbenev. "Coherent Electron Cooling." In: *Phys. Rev. Lett.* 102.11 (Mar. 2009), p. 114801. ISSN: 0031-9007. DOI: 10.1103/PhysRevLett.102.114801. URL: https://link.aps.org/doi/10.1103/PhysRevLett.102.114801.

Abstract: Cooling intense high-energy hadron beams poses a major challenge for modern accelerator physics. The synchrotron radiation emitted from such beams is feeble; even in the Large Hadron Collider (LHC) operating with 7 TeV protons, the longitudinal damping time is about 13 hours. None of the traditional cooling methods seem able to cool LHC-class protons beams. In this Letter, we present a novel method of coherent electron cooling based on a high-gain free-electron laser (FEL). This technique could be critical for reaching high luminosities in hadron and electron-hadron colliders.

Emma et al.: First Lasing and Operation of an Ångstrom-Wavelength Free-Electron Laser

P. Emma et al. "First Lasing and Operation of an Ångstrom-Wavelength Free-Electron Laser." In: *Nat. Photonics* 4.9 (Sept. 2010), pp. 641–647. ISSN: 1749-4885. DOI: 10.1038/nphoton.2010.176. URL: http://www.nature.com/articles/nphoton.2010.176.

Abstract: The recently commissioned Linac Coherent Light Source is an X-ray free-electron laser at the SLAC National Accelerator Laboratory. It produces coherent soft and hard X-rays with peak brightness nearly ten orders of magnitude beyond conventional synchrotron sources and a range of pulse durations from 500 to $<$10 fs (10^{-15} s). With these beam characteristics this light source is capable of imaging the structure and dynamics of matter at atomic size and timescales. The facility is now operating at X-ray wavelengths from 22 to 1.2 Åand is presently delivering this high-brilliance beam to a growing array of scientific researchers. We describe the operation and performance of this new 'fourth-generation light source'.

Stancari et al.: Collimation with Hollow Electron Beams

G. Stancari et al. "Collimation with Hollow Electron Beams." In: *Phys. Rev. Lett.* 107.8 (Aug. 2011), p. 084802. ISSN: 0031-9007. DOI: 10.1103/PhysRevLett.107.084802. URL: https://link.aps.org/doi/10.1103/PhysRevLett.107.084802.

Abstract: A novel concept of controlled halo removal for intense high-energy beams in storage rings and colliders is presented. It is based on the interaction of the circulating beam with a 5-keV, magnetically confined, pulsed hollow electron beam in a 2-m-long section of the ring. The electrons enclose the circulating beam, kicking halo particles transversely and leaving the beam core unperturbed. By acting as a tunable diffusion enhancer and not as a hard aperture limitation, the hollow electron beam collimator extends conventional collimation systems beyond the intensity limits imposed by tolerable losses. The concept was tested experimentally at the Fermilab Tevatron proton-antiproton collider. The first results on the collimation of 980-GeV antiprotons are presented.

Machida et al.: Acceleration in the Linear Non-Scaling Fixed-Field Alternating-Gradient Accelerator EMMA

S. Machida et al. "Acceleration in the Linear Non-Scaling Fixed-Field Alternating-Gradient Accelerator EMMA." In: *Nat. Phys.* 8.3 (Mar. 2012), pp. 243–247. ISSN: 1745-2473. DOI: 10.1038/nphys2179. URL: http://www.nature.com/articles/nphys2179.

Abstract: In a fixed-field alternating-gradient (FFAG) accelerator, eliminating pulsed magnet operation permits rapid acceleration to synchrotron energies, but with a much higher beam-pulse repetition rate. Conceived in the 1950s, FFAGs are enjoying renewed interest, fuelled by the need to rapidly accelerate unstable muons for future high-energy physics colliders. Until now a 'scaling' principle has been applied to avoid beam blow-up and loss. Removing this restriction produces a new breed of FFAG, a non-scaling variant, allowing powerful advances in machine characteristics. We report on the first non-scaling FFAG, in which orbits are compacted to within 10 mm in radius over an electron momentum range of 12–18 MeV/c. In this strictly linear-gradient FFAG, unstable beam regions are crossed, but acceleration via a novel serpentine channel is so rapid that no significant beam disruption is observed. This result has significant implications for future particle accelerators, particularly muon and high-intensity proton accelerators.

Peralta et al.: Demonstration of Electron Acceleration in a Laser-Driven Dielectric Microstructure

E. A. Peralta et al. "Demonstration of Electron Acceleration in a Laser-Driven Dielectric Microstructure." In: *Nature* 503.7474 (Nov. 2013), pp. 91–94. ISSN: 0028-0836. DOI: 10.1038/nature12664. URL: http://www.nature.com/articles/nature12664.

Abstract: The enormous size and cost of current state-of-the-art accelerators based on conventional radio-frequency technology has spawned great interest in the development of new acceleration concepts that are more compact and economical. Micro-fabricated dielectric laser accelerators (DLAs) are an attractive approach, because such dielectric microstructures can support accelerating fields one to two orders of magnitude higher than can radio-frequency cavity-based accelerators. DLAs use commercial lasers as a power source, which are smaller and less expensive than the radio-frequency klystrons that power today's accelerators. In addition, DLAs are fabricated via low-cost, lithographic techniques that can be used for mass production. However, despite several DLA structures having been proposed recently, no successful demonstration of acceleration in these structures has so far been shown. Here we report high-gradient (beyond 250 MeV m^{-1}) acceleration of electrons in a DLA. Relativistic (60-MeV) electrons are energy-modulated over 563 ± 104 optical periods of a fused silica grating structure, powered by a 800-nm-wavelength mode-locked

Ti:sapphire laser. The observed results are in agreement with analytical models and electrodynamic simulations. By comparison, conventional modern linear accelerators operate at gradients of 10–30 MeV m^{-1}, and the first linear radio-frequency cavity accelerator was ten radio-frequency periods (one metre) long with a gradient of approximately 1.6 MeV m^{-1} (ref. 5). Our results set the stage for the development of future multi-staged DLA devices composed of integrated on-chip systems. This would enable compact table-top accelerators on the MeV–GeV (10^6–10^9 eV) scale for security scanners and medical therapy, university-scale X-ray light sources for biological and materials research, and portable medical imaging devices, and would substantially reduce the size and cost of a future collider on the multi-TeV (10^{12} eV) scale.

Ratner: Microbunched Electron Cooling for High-Energy Hadron Beams

D. Ratner. "Microbunched Electron Cooling for High-Energy Hadron Beams." In: *Phys. Rev. Lett.* 111.8 (Aug. 2013), p. 084802. ISSN: 0031-9007. DOI: 10.1103/PhysRevLett.111.084802. URL: https://link.aps.org/doi/10.1103/PhysRevLett.111.084802.

Abstract: Electron and stochastic cooling are proven methods for cooling low-energy hadron beams, but at present there is no way of cooling hadrons as they near the TeV scale. In the 1980s, Derbenev suggested that electron instabilities, such as free-electron lasers, could create collective space charge fields strong enough to correct the hadron energies. This Letter presents a variation on Derbenev's electron cooling scheme using the microbunching instability as the amplifier. The large bandwidth of the instability allows for faster cooling of high-density beams. A simple analytical model illustrates the cooling mechanism, and simulations show cooling rates for realistic parameters of the Large Hadron Collider.

Litos et al.: High-Efficiency Acceleration of an Electron Beam in a Plasma Wakefield Accelerator

M. Litos et al. "High-Efficiency Acceleration of an Electron Beam in a Plasma Wakefield Accelerator." In: *Nature* 515.7525 (2014), pp. 92–95. ISSN: 14764687. DOI: 10.1038/nature13882.

Abstract: High-efficiency acceleration of charged particle beams at high gradients of energy gain per unit length is necessary to achieve an affordable and compact high-energy collider. The plasma wakefield accelerator is one concept being developed for this purpose. In plasma wakefield acceleration, a charge-density wake with high accelerating fields is driven by the passage of an ultra-relativistic bunch of charged particles (the drive bunch) through a plasma. If a second bunch of relativistic electrons (the trailing bunch) with sufficient charge follows in the wake of the drive bunch at an appropriate distance, it can be efficiently accelerated to high energy. Previous experiments using just a single 42-gigaelectronvolt drive bunch have accelerated electrons with a continuous energy spectrum and a maximum energy of up to 85 gigaelectronvolts from the tail of the same bunch in less than a metre of plasma. However, the total charge of these accelerated electrons was insufficient to extract a substantial amount of energy from the wake. Here we report high-efficiency acceleration of a discrete trailing bunch of electrons that contains sufficient charge to extract a substantial amount of energy from the high-gradient, nonlinear plasma wakefield accelerator. Specifically, we show the acceleration of about 74 picocoulombs of charge contained in the core of the trailing bunch in an accelerating gradient of about 4.4 gigavolts per metre. These core particles gain about 1.6 gigaelectronvolts of energy per particle, with a final energy spread as low as 0.7 per cent (2.0 per cent on average), and an energy-transfer efficiency from the wake to the bunch that can exceed 30 per cent (17.7 per cent on average). This acceleration of a distinct bunch of electrons containing a substantial charge and having a small energy spread with both a high accelerating gradient and a high energy-transfer efficiency represents a milestone in the development of plasma wakefield acceleration into a compact and affordable accelerator technology.

Pichon et al.: Development of a Multi-Detector and a Systematic Imaging System on the AGLAE External Beam

L. Pichon et al. "Development of a Multi-Detector and a Systematic Imaging System on the AGLAE External Beam." In: *Nucl. Instruments Methods Phys. Res. B* 318.PART A (Jan. 2014), pp. 27–31. ISSN: 0168583X. DOI: 10.1016/j.nimb.2013.06.065. URL: http://dx.doi.org/10.1016/j.nimb.2013.06.065%20https://linkinghub.elsevier.com/retrieve/pii/S0168583X13008367.

Abstract: The New AGLAE external beamline provides analytical data for the understanding of the structure of archaeological and artistic objects, their composition, properties, and changes over time. One of the objectives of this project is to design and set up a new non-invasive acquisition system increasing the quality of the X-ray spectra and reducing the beam current on sensitive materials from work of art. To that end, the surface and the number of PIXE detectors have been increased to implement a cluster of SDD detectors. This can also provide the possibility to accomplish large and/or fast maps on artifacts with a scanning of the beam on the sample. During the mapping, a multi-parameter system saves each event from X-ray, gamma and particle detectors, simultaneously with the X and Y positions of the beam on the sample. To process the data, different softwares have been developed or updated. A first example on a decorated medieval shard highlights the perspectives of the technique.

Corde et al.: Multi-Gigaelectronvolt Acceleration of Positrons in a Self-Loaded Plasma Wakefield

S. Corde et al. "Multi-Gigaelectronvolt Acceleration of Positrons in a Self-Loaded Plasma Wakefield." In: *Nature* 524.7566 (Aug. 2015), pp. 442–445. ISSN: 0028-0836. DOI: 10.1038/nature14890. URL: http://www.nature.com/articles/nature14890.

Abstract: Electrical breakdown sets a limit on the kinetic energy that particles in a conventional radio-frequency accelerator can reach. New accelerator concepts must be developed to achieve higher energies and to make future particle colliders more compact and affordable. The plasma wakefield accelerator (PWFA) embodies one such concept, in which the electric field of a plasma wake excited by a bunch of charged particles (such as electrons) is used to accelerate a trailing bunch of particles. To apply plasma acceleration to electron-positron colliders, it is imperative that both the electrons and their antimatter counterpart, the positrons, are efficiently accelerated at high fields using plasmas. Although substantial progress has recently been reported on high-field, high-efficiency acceleration of electrons in a PWFA powered by an electron bunch, such an electron-driven wake is unsuitable for the acceleration and focusing of a positron bunch. Here we demonstrate a new regime of PWFAs where particles in the front of a single positron bunch transfer their energy to a substantial number of those in the rear of the same bunch by exciting a wakefield in the plasma. In the process, the accelerating field is altered — 'self-loaded' — so that about a billion positrons gain five gigaelectronvolts of energy with a narrow energy spread over a distance of just 1.3 metres. They extract about 30 per cent of the wake' s energy and form a spectrally distinct bunch with a root-mean-square energy spread as low as 1.8 per cent. This ability to transfer energy efficiently from the front to the rear within a single positron bunch makes the PWFA scheme very attractive as an energy booster to an electron-positron collider.

Adli et al.: Acceleration of Electrons in the Plasma Wakefield of a Proton Bunch

E. Adli et al. "Acceleration of Electrons in the Plasma Wakefield of a Proton Bunch." In: *Nature* 561.7723 (Sept. 2018), pp. 363–367. ISSN: 0028-0836. DOI: 10.1038/s41586-018-0485-4. URL: http://www.nature.com/articles/s41586-018-0485-4.

Abstract: High-energy particle accelerators have been crucial in providing a deeper understanding of fundamental particles and the forces that govern their interactions. To increase the energy of the particles or to reduce the size of the accelerator, new acceleration schemes need to be developed. Plasma wakefield acceleration, in which the electrons in a plasma are excited, leading to strong electric fields (so called 'wakefields'), is one such promising acceleration technique. Experiments have shown that an intense laser pulse or electron bunch traversing a plasma can drive electric fields of tens of gigavolts per metre and above—well beyond those achieved in conventional radio-frequency accelerators (about 0.1 gigavolt per metre). However, the low stored energy of laser pulses and electron bunches means that multiple acceleration stages are needed to reach very high particle energies. The use of proton bunches is compelling because they have the potential to drive wakefields and to accelerate electrons to high energy in a single acceleration stage. Long, thin proton bunches can be used because they undergo a process called self-modulation, a particle–plasma interaction that splits the bunch longitudinally into a series of high-density microbunches, which then act resonantly to create large wakefields. The Advanced Wakefield (AWAKE) experiment at CERN uses high-intensity proton bunches —— in which each proton has an energy of 400 gigaelectronvolts, resulting in a total bunch energy of 19 kilojoules —— to drive a wakefield in a ten-metre-long plasma. Electron bunches are then injected into this wakefield. Here we present measurements of electrons accelerated up to two gigaelectronvolts at the AWAKE experiment, in a demonstration of proton-driven plasma wakefield acceleration. Measurements were conducted under various plasma conditions and the acceleration was found to be consistent and reliable. The potential for this scheme to produce very high-energy electron bunches in a single accelerating stage means that our results are an important step towards the development of future high-energy particle accelerators.

Bogomilov et al.: Demonstration of Cooling by the Muon Ionization Cooling Experiment

M. Bogomilov et al. "Demonstration of Cooling by the Muon Ionization Cooling Experiment." In: *Nature* 578.7793 (Feb. 2020), pp. 53–59. ISSN: 0028-0836. DOI: 10.1038/s41586-020-1958-9. URL: http://www.nature.com/articles/s41586-020-1958-9.

Abstract: The use of accelerated beams of electrons, protons or ions has furthered the development of nearly every scientific discipline. However, high-energy muon beams of equivalent quality have not yet been delivered. Muon beams can be created through the decay of pions produced by the interaction of a proton beam with a target. Such 'tertiary' beams have much lower brightness than those created by accelerating electrons, protons or ions. High-brightness muon beams comparable to those produced by state-of-the-art electron, proton and ion accelerators could facilitate the study of lepton–antilepton collisions at extremely high energies and provide well characterized neutrino beams. Such muon beams could be realized using ionization cooling, which has been proposed to increase muon-beam brightness. Here we report the realization of ionization cooling, which was confirmed by the observation of an increased number of low-amplitude muons after passage of the muon beam through an absorber, as well as an increase in the corresponding phase-space density. The simulated performance of the ionization cooling system is consistent with the measured data, validating designs of the ionization cooling channel in which the cooling process is repeated to produce a substantial cooling effect. The results presented here are an important step towards achieving the muon-beam quality required to search for phenomena at energy scales beyond the reach of the Large Hadron Collider at a facility of equivalent or reduced footprint.

Hunault et al.: Thirteenth-Century Stained Glass Windows of the Sainte-Chapelle in Paris: An Insight into Medieval Glazing Work Practices

Myrtille O.J.Y. Hunault et al. "Thirteenth-Century Stained Glass Windows of the Sainte-Chapelle in Paris: An Insight into Medieval Glazing Work Practices." In: *J. Archaeol. Sci. Reports* 35 (Feb. 2021), p. 102753.

ISSN: 2352409X. DOI: 10.1016/j.jasrep.2020.102753. URL: https://linkinghub.elsevier.com/retrieve/pii/S2352409X20305447.

Abstract: The restoration of the four northern windows of the 13th century Sainte-Chapelle in Paris from 2011 to 2014 has offered a unique opportunity to investigate the chemical composition and color of medieval glasses. This impressive corpus, covering a total surface of 660 m^2, was created in a record time of a few years. The glasses from ten selected panels were analyzed using non-destructive and non-invasive techniques, with a specific consideration for the color of the glasses. Ion beam analyses performed at the New AGLAE facility enabled revealing that all ancient glasses are "potash" type glasses made from plant ashes, likely beech, in agreement with previous results on off-site panels. The multivariate analysis of major and minor elements demonstrates the presence of compositional clusters with a small variability suggesting the identification of bundles of glasses. The coloration of the glasses was measured by optical absorption spectroscopy, using a mobile spectrophotometer over the entire UV–visible-NIR energy range. The color palette is made of six colors assigned to typical medieval recipes. The chromophores of the different glasses are identified by combining the chemical composition, optical absorption spectroscopy and colorimetry. Colorless, yellow and purple glasses arise from the subtle redox equilibrium between manganese and iron. Their reduced usage shows their uncertain production. Blue glasses are colored by Co^{2+} using saffre from the contemporary German mines, green glasses are colored by Cu^{2+} and Fe^{3+} using high concentrations of copper and red glasses are striated glass colored by metallic copper nano-particles. Glass matrix and chromophores form compositional clusters, which are spread among the panels of the four windows suggesting that the glazing of these four windows was run simultaneously by the same atelier using the same supply of glass.

Shiloh et al.: Electron Phase-Space Control in Photonic Chip-Based Particle Acceleration

R. Shiloh et al. "Electron Phase-Space Control in Photonic Chip-Based Particle Acceleration." In: *Nature* 597.7877 (Sept. 2021), pp. 498–502. ISSN: 0028-0836. DOI: 10.1038/s41586-021-03812-9. URL: http://dx.doi.org/10.1038/s41586-021-03812-9%20https://www.nature.com/articles/s41586-021-03812-9.

Abstract: Particle accelerators are essential tools in science, hospitals and industry. Yet their costs and large footprint, ranging in length from metres to several kilometres, limit their use. The recently demonstrated nanophotonics-based acceleration of charged particles can reduce the cost and size of these accelerators by orders of magnitude. In this approach, a carefully designed nanostructure transfers energy from laser light to the particles in a phase-synchronous manner, accelerating them. To accelerate particles to the megaelectronvolt range and beyond, with minimal particle loss, the particle beam needs to be confined over extended distances, but the necessary control of the electron beam's phase space has been elusive. Here we demonstrate complex electron phase-space control at optical frequencies in the 225-nanometre narrow channel of a silicon-based photonic nanostructure that is 77.7 micrometres long. In particular, we experimentally show alternating phase focusing, a particle propagation scheme for minimal-loss transport that could, in principle, be arbitrarily long. We expect this work to enable megaelectronvolt electron-beam generation on a photonic chip, with potential for applications in radiotherapy and compact light sources, and other forms of electron phase-space control resulting in narrow energy or zeptosecond-bunched beams.

Jarvis et al.: First Experimental Demonstration of Optical Stochastic Cooling

J. Jarvis et al. "First Experimental Demonstration of Optical Stochastic Cooling." In: (Mar. 2022). arXiv: 2203.08899. URL: http://arxiv.org/abs/2203.08899.

Abstract: Particle accelerators and storage rings have been transformative instruments of discovery, and, for many applications, innovations in particle-beam cooling have been a principal driver of that success. Beam cooling reduces the spread in particle positions and momenta, while keeping the number of particles constant, and combats diffusive effects, thereby enabling particle accumulation and the production and preservation of intense beams. In the case of particle colliders, cooling increases the likelihood of observing rare physics events. One of the most important conceptual and technological advances in this area was stochastic cooling (SC), which was instrumental in the discovery of the W and Z bosons at CERN and the top quark at Fermilab. SC reduces the random motion of the beam particles through granular sampling and correction of the beams phase-space structure, thus bearing resemblance to a Maxwell's demon. The extension of SC from the microwave regime up to optical frequencies and bandwidths has long been pursued as it could increase the achievable cooling rates by three to four orders of magnitude and provide a powerful new tool for future accelerators. First proposed nearly thirty years ago, Optical Stochastic Cooling (OSC) replaces the conventional microwave elements of SC with optical-frequency analogs and is, in principle, compatible with any species of charged-particle beam. Here we describe the first experimental demonstration of OSC in a proof-of-principle experiment at the Fermi National Accelerator Laboratory's Integrable Optics Test Accelerator.

Kroll et al.: Tumour Irradiation in Mice with a Laser-Accelerated Proton Beam

Florian Kroll et al. "Tumour Irradiation in Mice with a Laser-Accelerated Proton Beam." In: *Nat. Phys.* 18.3 (Mar. 2022), pp. 316–322. ISSN: 1745-2473. DOI: 10.1038/s41567-022-01520-3. URL: https://www.nature.com/articles/s41567-022-01520-3.

Abstract: Recent oncological studies identified beneficial properties of radiation applied at ultrahigh dose rates, several orders of magnitude higher than the clinical standard of the order of Gy min^{-1}. Sources capable of providing these ultrahigh dose rates are under investigation. Here we show that a stable, compact laser-driven proton source with energies greater than 60 MeV enables radiobiological in vivo studies. We performed a pilot irradiation study on human tumours in a mouse model, showing the concerted preparation of mice and laser accelerator, dose-controlled, tumour-conform irradiation using a laser-driven as well as a clinical reference proton source, and the radiobiological evaluation of irradiated and unirradiated mice for radiation-induced tumour growth delay. The prescribed homogeneous dose of 4 Gy was precisely delivered at the laser-driven source. The results demonstrate a complete laser-driven proton research platform for diverse user-specific small animal models, able to deliver tunable single-shot doses up to around 20 Gy to millimetre-scale volumes on nanosecond timescales, equivalent to around 10^9 Gy s^{-1}, spatially homogenized and tailored to the sample. The platform provides a unique infrastructure for translational research with protons at ultrahigh dose rates.