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Accelerators and Detectors

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A. Scope

The developing understanding of particle physics, especially in the past 60 or so years, has been largely paced by the evolution of high energy accelerators and detectors. We restrict ourselves to crucial developments in accelerators related to high energy particle collisions. Similarly discussion of detectors will be restricted to those associated with the accelerators and colliders covered.

There exist extensive reviews[2] on our subject. Accelerators and detectors are rather poorly documented in the peer reviewed literature; original source material is largely contained in laboratory reports and conference proceedings and most major accelerator installations have never been comprehensively documented.

B. Growth Patterns of Accelerators and Colliders

Accelerators and colliders can be parametrized by a number of characteristics. The energy of a particle as accelerated in the laboratory is not what is relevant in determining the threshold for initiating a particular elementary particle process. The center of mass energy E_{cm} of two colliding particles of rest masses m_1, and m_2 and total energies E_1 and E_2 respectively, is given by $E^2_{cm} = p_i p^i$ where p_i is the total four-momentum of the particles. For instance, if a proton of energy $E_1=\gamma m_1 c^2$ strikes a proton at rest, then $E_{cm} = [2(\gamma+1)]^{1/2} m_1 c^2$. In the non-relativistic limit only one-half of the incident kinetic energy is available while in the relativistic limit $\gamma>>1$ the center of mass energy grows with the square root of the energy of the incident protons. If two relativistic particles collide head on then $E_{cm}=2(E_1E_2)1/2$ or 2E if the particles have identical energy. These relations demonstrate the energy advantage of *colliding beams*. But as investigations extend to smaller dimensions, the concept of what constitutes an elementary particle changes. At distances with the analyzing power of current colliders (10–18m) quarks and leptons are "elementary." Thus the relevant energy of high energy accelerators and colliders defining its "reach" in initiating elementary particle processes is neither the laboratory beam energy nor the collision energy in the center of mass frame of *composite* colliding particles but is the collision energy in the frame of the center of mass of colliding "elementary" *constituent* particles.

The luminosity defined as the data rate per unit cross section of the process under investigation is another critical parameter. For high momentum transfer events the cross section varies inversely as the square of the momentum transferred. Therefore the luminosity of colliders should increase quadratically with energy in order to yield a constant data rate for "interesting" or novel events. In addition other parameters are of relevance to the experimenter, such as the background conditions, that is particle fluxes other than those originating from the collision under investigation. Then there is the "duty cycle" of the machine, that is the time structure over which collisions occur. Few modern accelerators or colliders produce random collisions uniformly distributed in time. Some accelerators are operating in cycles and most colliders employ bunches of particles rather than continuous beams. The resulting "duty cycle" limits the ability to interpret the time relationship

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[2] *Review of Particle Physics*, *Phys. Rev. D*, **54**, 1996, pp 128 ff (Colliders) and p 142 ff (Detectors).

among products of interaction. Experiments with accelerators either use the primary collisions or secondary beams produced in these collisions; the quality and quantity of secondary beams differ among types of accelerators and colliders.

Last, but unfortunately not least, is the matter of cost. Thus the scaling laws which relate costs to growth of each technology define the historical growth patterns of accelerators and colliders. Figure 1 describes the growth over time of laboratory energy for various particle accelerators.[3] This pattern, first published by Livingston,[4] exhibits important features. An almost exponential growth of laboratory energy with time is fed by a succession of technologies; each technology saturates and is superseded by new technologies. In parallel with this pattern such new technologies have led to a *decrease* in cost per unit of laboratory energy by about four orders of magnitudes over the time period covered by Figure 1.

The more relevant quantity describing the "reach" of accelerators into the unknown is the center of mass energy in the constituent frame shown in Figure 2. In this figure hadron colliders (proton-proton and proton-anti proton) and lepton colliders (electron-electron or positron) are plotted separately. The constituent center of mass energy of hadrons has been de-rated by a factor of about six relative to that of lepton colliders to account for the hadron substructure of quarks and gluons. Needless to say, such a de-rating of colliders using "non elementary" particles can only be an approximation. The internal dynamics of the substructure of composite particles can permit a lowering of reaction thresholds albeit accompanied by a decrease in luminosity. Again, an exponential growth has apparently been sustained over the limited period of time over which colliding beam devices have been successfully constructed, and that growth is comparable for hadron and lepton colliders.

Particle beams striking stationary targets of condensed matter produce effective luminosities many orders of magnitude larger than those attainable by colliding beams. The luminosity growth of colliders is shown in Fig. 3. Thus far this growth has not matched the quadratic growth with energy required to maintain constant data rates.

C. Principles, Categorization and Evolution of Accelerators and Colliders.

Fundamentally accelerators are either *electrostatic* machines where particles are accelerated by traversing once a difference in electrical potential once or they are *transformers* which repeatedly use high-current low-voltage circuit elements to supply energy to a high-voltage low-current accelerating path.

Electrostatic Devices. Early accelerators were discharge tubes fed by conventional high voltage sources. Limitations arise through the ability of the discharge tubes to sustain high voltages and by the availability of high voltage sources. The Tesla coil accelerators were resonant step-up transformers with both primary and secondary resonating at the same frequency. Cascade accelerators, pioneered by Cockroft and Walton,[5] were able to attain voltages in the several hundreds of kilovolts by charging capacitors in parallel and reconnecting them in series. In the Van de Graaff,[6] generator charges were sprayed onto a moving belt and that charge is removed inside a high voltage electrode; this device reached energies near ten million electron volts. The design of discharge columns evolved to permit better voltage distribution and focusing and vacuum practices improved. Electrostatic generators continue to be produced for research in nuclear physics and for medical uses.

Energies above about 10 MeV are not attainable electrostatically. The most important early development to exceed that limit was the *cyclotron* proposed by Lawrence and Edlefsen[7] and reduced to practice by Lawrence and Livingston,[8] using the well known principle that the orbital period of

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[3] For a listing of the relevant machines, see ref. (2). We will cite here only machines at the frontiers of performance.
[4] Livingston, M. Stanley, 1954.
[5] Cockroft, J. D. and E. T. S. Walton, 1932.
[6] Van de Graaff, R. J., 1931.
[7] Lawrence, E. O. and N. E. Edlefsen, 1930.
[8] Lawrence, E. O. and M. S. Livingston, 1932.

non-relativistic charged particles circulating in a uniform magnetic field is independent of energy. Thus if a radiofrequency voltage matching the revolution frequency is applied across a gap placed in such a field, then the particle will gain energy and will spiral out in the magnet.

Cyclotrons developed rapidly in the period before World War II but the decrease in orbital frequency as the particles become relativistic limits the attainable energy. Focusing was first addressed by empirical "shimming" of the magnetic field. A more analytical approach initially by Steinbeck[9] showed that focusing both horizontally and vertically could be obtained by a small radial decrease of the magnetic field, thus generating a further decrease in orbital frequency. These decreases in orbital frequency can only be overcome by extremely high radiofrequency voltages so that the desired energy can be attained in relatively few orbital turns. The 184 inch cyclotron in Berkeley was designed accordingly to attain deuteron energies above 100 MeV but the machine was diverted to military purposes as an isotope separator. In the meantime discovery of the phase stability principle discussed below made this brute force approach unnecessary.

The cyclotron principle fails for *electrons* whose motion becomes relativistic at moderate energies. The *betatron*, invented by Wideroe[10] and first reduced to practice by Kerst,[11] was a transformer in which the energy of electrons in circular orbits was increased by the induced electric field from an increasing flux in a central iron core driven by appropriate windings. The required average magnetic field in the drive core must be twice that of the radically decreasing magnetic field at the orbit of the betatron. Betatrons reached an energy up to about 300 MeV, limited by the radiation loss per turn which increases as the fourth power of the energy divided by the orbit radius; this loss cannot be compensated in a betatron.

In a *linear induction accelerator* individual iron cores are stacked axially and excited through separate driving circuits. This principle permits acceleration of very high intensity electrons, in the kiloamp region.[12] Such devices are still used as x-ray sources for diagnosis of rapid dynamic systems. A linear radiofrequency accelerator was developed by Sloan and Lawrence[13] where an alternating rf voltage was applied across a succession of gaps traversed by a beam, limited to low velocity heavy ions by the low frequency of available RF sources.

A dramatic extension of accelerators and colliders to high energies was made possible by conceptual and technical developments.

a. *Phase Stability*, invented independently by McMillan[14] and Veksler.[15] In the pre-World War II accelerators synchronization between the rf fields and the particle bunches was achieved by "dead reckoning." McMillan and Veksler recognized that the phase of the accelerating rf voltage can be stably " locked" into synchronization with the transit time of particle bunches under appropriate conditions. In a circular accelerator such stability is achieved by the particle bunch crossing an accelerating gap during either on a *descending* or *ascending* part of the radiofrequency voltage, depending on the relation between orbital path length and orbital momentum. This relation depends on the focusing mechanism and the relativistic mass. In a linear accelerator such stability is achieved by accelerating the bunch during the *ascending* part of the radiofrequency voltage. Such stability permits "synchrotron oscillation" about a stable phase.

The principle of phase stability led to diverse applications. In a *synchrocyclotron* particles are injected into a static magnetic field and are accelerated by a radiofrequency source whose frequency decreases to match the revolution frequency as the energy, and therefore the relativistic mass increases, and as the magnetic field weakens as the particle spirals out. Under this condition the particles remain phase-locked to the electric field.

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9 Steinbeck, M., 1935.

10 For a full discussion of the complex of inventions and demonstrations leading to the betatron see: *The Infancy of Particle Accelerators: Life and Work of Rolf Wideroe* by Pedro Waloschek. Vieweg & Sons Publishers, 1994.

11 Kerst, D. W., 1940.

12 Christofilos, N. C., R. E. Hester, W. A. S. Lamb, D. D. Reagan, W. A. Sherwood and R. E. Wright, 1964.

13 Sloan, D. H. and E. O. Lawrence, 1931.

14 McMillan, E. M., 1945.

15 Veksler, V. I., 1944.

In a *synchrotron* particles are injected into a rising magnetic field and traverse a radiofrequency cavity excited at a near-constant frequency.[16] A magnet of only small radial aperture is needed. The particles remain locked in stable phase while their energy, but not their radius, increases with the magnetic field. This is the principle of all of today's high energy circular electron as well as proton accelerators. This includes LEP (at CERN), the world's highest energy electron collider (80 GeV per beam) and the Tevatron at Fermilab, the world's highest energy proton collider. The latter is to be followed by the Large Hadron Collider (LHC) designed to attain 7 TeV proton energy per beam.

All modern *proton linear accelerators* use phase stability and continue to be the device of choice as injectors into today's proton synchrotrons. They operate as accelerators in their own right up to about 1 GeV where high intensity is required.

b. *Strong Focusing*, was invented independently by Christofilos[17], and by Courant, Livingston and Snyder.[18] Focusing in earlier circular machines was attained through radial fall-off in the magnetic field; electrostatic focusing or magnetic solenoids provided focusing in linear accelerators. "Strong focusing" originated from the realization that if a diverging and converging lens of equal and opposite focal strength are separated by a finite distance, then the net focusing effect is positive. A magnetic quadrupole produces focusing in one plane and de-focusing in the plane at right angles. Thus two quadrupoles separated by a finite distance and rotated by 90 degrees relative to one another focus in both planes. This focusing strength varies quadratically with the magnetic field gradient in the quadrupoles and can be much stronger than that of solenoids or that of radial magnetic field gradients.

Strong focusing drastically decreases the needed aperture of proton and electron synchrotrons and of linear accelerators. Thus strong focusing greatly extends the range of particle energies that can be economically attained.

Strong focusing results in particle oscillations about a central orbit whose wavelengths are generally shorter than the circumference of the circular accelerator. This creates the possibility of *resonances* between such focusing oscillations and harmonics of the basic orbital frequency. Also the region in accelerating phase for which phase stability exists can change sign, leading to a transition energy where phase stability vanishes. Such problems can be avoided by appropriate design of the "lattice" of the focusing elements and by rapid passage through transition.

Proton and electron synchrotrons have been configured into colliders leading to the obvious center of mass advantages. Circular colliders are composed of *storage rings* which are synchrotrons storing beams after the magnetic field has reached its final value. Stored electrons require compensation of the radiation loss by cavity re-acceleration. Synchrotron radiation loss of protons is still negligible even at the highest energies attained today, but will become of future importance.

All modern circular colliders use *both* phase stability and strong focusing. Circular electron-positron colliders incur a radiation loss per turn which scales as the fourth power of the energy divided by the orbit radius. If the costs growing linearly with radius are matched with those scaling with the energy loss per turn, then the total cost of an electron-positron collider will grow with the square of the energy. The 27 kilometer circumference electron positron collider at CERN will probably be the highest energy electron *circular* collider ever built. Collisions between linear accelerator beams and beams stored in a storage ring have been considered but thus far studies do not project competitive luminosity.

c. *High Impedance Microwave Devices.*[19] W. W. Hansen invented the electromagnetic cavity in 1937 with the goal of generating high voltage at moderate input power. The invention led to amplifiers, oscillators, cavities to compensate energy loss in circular accelerators, and linear

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[16] If injection into a synchrotron is at a particle velocity not fully relativistic, the frequency can be slightly modulated, for instance by loading of the accelerating cavity with ferrite.

[17] Christofilos, N., U.S. Patent #2,736,766 (1950).

[18] Courant, E., M. S. Livingston and H. Snyder, 1952.

[19] Ginzton, E. L., W. W. Hansen and W. R. Kennedy, 1948.

accelerators, among them the disk loaded waveguide. Operating as an electron accelerator, the phase velocity of a propagating wave in this structure is matched to the particle velocity. The group velocity is tailored to provide a filling time compatible with the pulse length of the radiofrequency source and is designed to provide an appropriate profile of accelerating voltage versus length. The highest energy electron linear accelerator is the SLAC machine operating up to 50 GeV. Beyond that *linear* colliders in which an electron beam from one linear accelerator collides with a beam accelerated by a separate machine are the most promising developments to exceed electron-positron energies attainable by circular storage rings. They require high *average* beam powers and exceedingly small beam cross sections in order to attain the required luminosity. The SLAC linear collider produces collisions between 50 GeV electrons and positrons.

d. *Superconducting Technology*. The availability of superconducting materials enabled another gain in particle energy. For electromagnets the material of choice has been niobium titanium which can be fabricated into multi-strand cables designed to minimize losses during magnetic field changes. Niobium-Tin can sustain higher magnetic fields but its mechanical brittleness has thus far prevented extensive use. The new high temperature superconductors have only limited application in high energy physics, restricted to connections and lead-ins. After extensive development, solid niobium or niobium coatings inside radiofrequency cavities have become practical and reliable and serve as accelerating cavities, both in linear accelerators and as accelerating elements in proton and electron synchrotrons.

D. Accelerator and Collider Limitations

Continued growth of accelerators and colliders is bounded by technical and economic factors. Technical limitations are in the following categories:

a. *Material limits*. Vacuum breakdown and field emission are controlled by practical factors such as surface irregularities, dielectric inclusions, whisker growth, and so forth. These limit gradients in linear accelerators and in accelerating devices in synchrotrons.

Magnetic fields in “warm” magnets are limited by the saturation of iron while those in superconducting magnets are limited by quenching of the superconducting materials in magnetic fields and by the problems inherent in restraining the large forces on conductors in such magnets. Frontiers in this respect have been advanced by the use of super-cooled helium and by metallurgical advances in the production of superconductors and cables.

b. *Non-linear dynamics and collective effects.* The previous sketchy discussion has focused on the behavior of “free space” single particles in “ideal” externally generated electric and magnetic fields. Such motions will be modified by the electromagnetic fields generated by induced currents in metallic envelopes, by deviations of fields from the ideal, generally linear, form and by collective effects of particle groups on the motion of a single particle.

Induced fields and the collective fields of a bunch generate a “wake field” which affects individual particle orbits, both longitudinal along the motion of the particles and transverse to that motion . Wake fields not only effect the shape of a bunch of particles in that the fields produced by the head of a bunch effect the motion of its tail, but they also can result in electromagnetic coupling between successive bunches in an accelerator. In the transverse direction such effects can produce decreased luminosity and outright instability. Luminosity decreases when wake fields dilute the phase space density of the particles in a bunch. Instability can result if transverse displacement of preceding particles induces wake fields which successively deflect succeeding particles further. Such phenomena are complex.[20]

Longitudinal wake fields result in the lengthening of the particle bunch in an accelerator. This can counteract efforts to maximize luminosity in a collider using very short focal length magnets near the interaction region since shortening of the focal length will be ineffective if the bunch length is too large. Transverse instabilities are particularly serious if the transverse

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[20] e.g. see Ref. 1.

displacement of the particle induces fields in either engineered or inadvertent resonant structures. The transverse displacement can induce so-called "higher order modes" in such structures; any discontinuity in a vacuum envelope can enhance transverse wake fields.

The effect of transverse wake fields can be counteracted by a number of measures. The discontinuities in vacuum envelopes can be minimized; focusing strength can be enhanced, thus limiting transverse excursions; the frequency of transverse focusing oscillations can be dispersed among successive sections in a radiofrequency linear accelerator, thus damping a resonant build-up of transverse motion.

The coupling among particle bunches can become coherent as the wavelengths of the Fourier component of the electromagnetic field become comparable to the dimensions of the particle bunch. In this event fields will act coherently and the forces correspondingly increase. The principal countermeasures against coherent instabilities can be external feedback: The electromagnetic field of the particle bunch is sensed by appropriate electrodes and is fed back to deflecting electrodes with a phase to damp the motion. Additionally structures can be designed which damp the relevant higher order modes.

c. *Beam-beam interaction.* Collisions between intense bunches of particles produce electromagnetic forces of one bunch of particles in the other. These forces shift the frequency of focusing oscillation of the particles. If this "tune shift" becomes too large, then the frequency of radial focusing oscillations can shift into regions of instability, as discussed above. Actually the limiting tune shift is set, generally empirically, by non-linear effects in the beam-beam interaction. Thus the permissible tune shift is subject to practical limits which can be minimized by optimized design of the focusing lattice and shaping the beam profile during collision. In addition to the tune shift, the beam-beam interaction in electron-positron linear colliders also produces electromagnetic radiation as each particle experiences the collective electromagnetic field of the opposing bunch. Radiative effects broaden the energy spectrum of the colliding beams and thus make them less useful in elementary particle physics experiments and also produce electromagnetic background.

d. *Beam-"vacuum" interactions.* Interaction of the beams with residual gases or charge clouds in the vacuum can produce background. In addition, if electromagnetic radiation from synchrotron radiation or beam-beam interactions impact the vacuum wall, photo ejected electron clouds affecting particle motions can be formed. Recent analyses[21] show that this can lead to serious instabilities, in particular for the highest energy proton-proton colliders.

e. *Injection.* The design of ion sources in the case of hadron colliders and of either thermionic or photo cathodes in the case of electron machines can affect luminosity. In particular, space charge effects at injection are limiting.

According to Liouville's theorem, the invariant emittance, that is the phase space density times the relativistic factor γ cannot decrease during acceleration, storage, or final interaction in a non dissipative system. Liouville's theorem can be violated if *damping* takes place in the motion subsequent to injection. Such damping can be produced by emission of synchrotron radiation. This fact is utilized in *damping rings* inserted at an appropriate step in an accelerating cycle. Damping can also be accomplished by beam-to-beam *cooling*, where an external beam of small phase volume is permitted to interact with the beam of the accelerator and exchange momentum. Finally damping can be accomplished by feedback in a circular machine by picking up signals from radial excursions and feeding those back onto the orbit at subsequent turns.

Thus the final luminosity may or may not be limited by the phase space at injection, depending on the presence of damping mechanisms.

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[21] Raubenheimer, T. O. and F. Zimmermann, 1995.

E. Future Collider Possibilities.

The previous discussion outlined the principles underlying past and present accelerator and collider systems and identified installations at the current frontier. Existing technology permits limited extension but major advance depends on new technology.

Along conventional lines further extension in energy attainable by large circular hadron-hadron colliders beyond the LHC and larger linear colliders fed by traditional electron and positron linear accelerators appears feasible. Such machines can also become the basis of electron-electron and photon-photon colliders at high energies.

Hadron colliders beyond the LHC face economic limitations and must take synchrotron radiation into account. Therefore such machines require large radiofrequency power and have to face the potential of charge cloud and other instabilities discussed above. At the same time synchrotron radiation will provide damping which may be beneficial in reducing instabilities.

An international effort is addressing construction of a large linear collider, possibly approaching the TeV per beam range. Leading candidates to feed such a device are conventional microwave linear accelerators operating at higher frequency than now in use. In addition superconducting linear accelerators are being explored aiming at improvements in economy and gradient beyond current experience. Finally there exists the possibility of feeding a linear collider by variants of a two-beam accelerator (TBA) principle. Here a high current, low voltage linear accelerator fed by induction or low radiofrequency sources drives a high energy high gradient machine. Energy from the driver is coupled through appropriate transfer structures into the high energy accelerator.

Substituting muons for electrons in circular machines reduces radiation by a large factor while strong and weak interactions of muons appear identical to those of electrons. While the idea is old,[22] optimism has grown that muon colliders of adequate luminosity and background conditions can be designed. Luminosity depends both on initial muon yields and on cooling the muons resulting from pion decay in a practical manner. The background problem is serious due to the large electron fluxes originating from decay of muons in orbit and even decay neutrinos pose a substantial hazard.

In addition to devices which are based on extrapolations of established practice, new technologies are being analyzed. All of these, to be useful for high energy physics, will have to be configured into linear colliders and therefore would have to generate both high energy and high average beam powers. Current research focuses on acceleration by very large intrinsic voltage gradients. Among these are devices using the high fields in intense laser beams.[23] The electromagnetic field in a laser wave in free space cannot accelerate charged particles and therefore research addresses special geometries which generate longitudinal electric field components. Possibilities are the electric field when optical laser beams are diffracted from gratings, when coherent laser beams are crossed to generate a longitudinal field component and similar geometrical arrangements. Other methods utilize the high electric fields contained in plasmas,[24] the high gradients in the wake fields produced by intense particle bunches, and finally the extremely high electric fields which could be generated if plasma waves were excited in crystals;[25] these could be used to accelerate particles channeled in such crystals.

F. Physical Processes in Particle Detection

Charged and neutral particles interact with detector material via limited processes. Charged particles ionize any medium and can radiate Cherenkov, synchrotron, or transition photons. The ionization density, and consequently the rate of energy loss (dE/dx) of charged particles in matter, is

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[22] Work by J. Tinlot, (1970) and Budker et al (1969).
[23] Laser Acceleration of Particles, *AIP Conference Proceedings*, **91**, 1982.
[24] Advanced Accelerator Concepts, *AIP Conference Proceedings*, **335**, 1994.
[25] Chen, P. and R. J. Noble, 1986.

in essence a measure of particle velocity[26]. Therefore measurements of ionization density in combination with deflection in a magnetic field (which determines the ratio of particle momentum to charge) can result in determination of rest mass. The ionization as a function of particle velocity βc has three regions: a) a low velocity region where the ionization decreases roughly as β^{-2} and then levels off to a region of b) minimum ionization; c) a region of logorithmic growth (relativistic rise) which reaches a plateau with $\beta\gamma$ defined by the dielectric properties of the material which affects the relativistically contracted electromagnetic field in its ability to ionize remote atoms.

Neutral hadrons may interact strongly to produce charged particles. Photons may interact electromagnetically via Compton scattering, photoelectric effect or pair production. Neutrinos can generate charged particles with very small cross sections via the weak interaction. At high energies strongly interacting particles produce cascades, and electrons and photons produce electromagnetic showers. Ultimately any detector either senses ionization caused by primary or secondary charged particles or detects secondary photons by photoelectric mechanisms.

G. Detector Components.

1. *Pictorial Detectors* utilize the particle track left by ionization and process the image of that track into a photographic or digital record.

The earliest track detector was the *cloud chamber* which can either produce super saturation following an expansion of water vapor or it can be a continuously sensitive diffusion chamber where a thermal gradient in water vapor leaves a region where condensation forms around an ionizing track. Subsequently photographic *emulsions* were specifically tailored through enhanced silver content to reveal after development particle tracks which are microscopically scanned. A *streamer chamber* produces conditions in which ionization in a gas generates enough light through ion re-combination to permit photographic recording. In a *spark chamber* local breakdown occurs between high voltage electrodes; the sparks can be photographed in a sequence of gaps between electrodes leading to a track in a photograph. In a *bubble chamber* a liquid is expanded leading to a super-heated condition; gaseous bubbles will be formed along an ionizing track which can be photographed.

All these devices greatly contributed to elementary particle physics. Cloud chambers have been major tools in cosmic ray research, including the discovery of the positron. Bubble chambers recorded associated strange particle production and established the foundation of hadron spectroscopy. A limitation of bubble chambers and cloud chambers is that they cannot be "triggered"; they record *all* ionizing events irrespective as to whether the events are novel or are signatures of well known processes. However photography can be triggered to select only events of current interest to limit labor in data analysis . Spark chambers and streamer chambers can be triggered but have inferior location accuracy. All pictorial devices other than the spark chamber permit measurements of ionization density.

Pictorial devices require substantial effort in data analysis; images have to be scanned either manually, semi-automatically, or totally automatically; tracks have to be reconstructed and hypotheses as to the event which may have occurred have to be fitted to the track pattern.

Pictorial devices have largely disappeared from use in elementary particle physics. They cannot handle events produced with small cross sections in the presence of large uninteresting background. They tend to be expensive considering the data analysis effort. Resolving time is generally long. Yet the slowest of these detectors — photographic emulsions — are still in elementary particle physics use because of their unexceeded track resolution near one micrometer. Large emulsion stacks continue to be used in connection with neutrino experiments. Auxiliary electronic detectors can limit the emulsion area to be searched for precise vertex measurements.

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[26] Bethe, H. A., 1932, and F. Bloch, 1933.

2. *Electronic Detectors.*

Scintillation counting. Suitably doped plastics and have long been utilized for position measurement, time of flight measurement, dE/dx, and calorimetry. The scintillation photons from inorganic crystals and wavelength shifted photons from plastic scintillators can either be detected by photomultipliers as high gain, low noise amplifiers of the electrons emitted by the photocathode or by suitable solid state photodetectors. Issues of the number of separate measurements required, operation in magnetic fields, quantum efficiency, size and cost determines the choice of photo detector. Scintillators and photomultipliers still excel at precision timing in applications with modest spatial resolution requirements. For example in the proposed Minos neutrino detector,[27] solid scintillator bars couple their scintillation light to optical fibers using wavelength shifting dopants in the fibers. A variant is the Fiber Tracker, in which optical scintillator fibers form large arrays, with each fiber having an independent photodetector.[28]

Wire drift chambers[29] amplify the few electrons produced by ionization by an avalanche near the anode wires. Electron multiplication near the anode wire produces an easily processed signal which can be timed to produce a variety of precision spatial measurement systems. Electrodes are designed to provide electric fields where the drift velocity can be well understood, and provide small regions of high field that generate the electron avalanche from a primary ionization electron. Chambers range from small detectors to planar or cylindrical arrays of many square meters; 100 micrometer spatial resolution is routinely attained as is multi-track resolution of better than 1 mm. They can operate at the extremely high rates necessary in many fixed target experiments and have been radiation hardened to operate in the harsh environment of high luminosity proton colliders.[30] The coordinate measured by the drift time is normal to the wire. Low precision measurements along the wire can be made utilizing resistive charge division and measuring the signal on both ends of the wires. Higher precision is achieved by small angle stereo, necessitating the association of wire hits with tracks which can be difficult in a busy environment. These systems can be used in a magnetic field for momentum measurement.

Proportional wire systems operate in a mode where the signal is proportional to the primary ionization, thus measuring the energy loss rate of the primary particle in the gas. *Avalanche systems* amplify the primary ionization to saturation, yielding large, very noise immune signals. Such systems using single anode wires in moderate resistivity tubes can give position signals by induction to strips with any geometry on the tube surface.[31] They are widely used for muon detection with active areas of order 1000 square meters.

In a *Time Projection Chamber*[32] (TPC) a sensitive volume is filled with a gas mixture with very low electron attachment cross section. An applied uniform electric field drifts ionization electrons towards a two dimensional array of detectors at one end. Tracks of charged particles are reconstructed from this detector array, with time of arrival at the array providing the third coordinate. The TPC avoids most of the association difficulties of wire chambers and provides digitized pictorial images of events. The TPC has limitations in high rate environments as accumulated slow moving positive ions distort the drift field.

Semiconductor detectors. The development of high resistivity silicon led to pn diodes that can directly detect the ionization caused by the passage of a charged particle. A minimum ionizing particle yields about 80 electron hole pairs per micrometer of depleted silicon, or of order 10^3 electrons in a typical detector. The geometry of electrodes is nearly arbitrary, and detectors range from large area diodes to "microstrips," arrays several cm long divided into diode units of width 25 to 100 micrometers. The overall scale is set by the size of the silicon wafer. Elaborate arrays of microstrips, with sophisticated low mass space frame structures supporting the silicon stable to a few

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[27] Wojcicki, S. *in preparation*.
[28] The DO Upgrade, Fermilab Pub. 96/357-E, 1996.
[29] Charpak, G., 1976.
[30] The CDF II Detector Technical Design Report, Fermilab Pub. 96/390-E, 1996.
[31] Iarocci, E., 1983.
[32] Nygren, D. R., 1974.

micrometers in space are used as vertex detectors. Since it is not yet possible to process complex transistor arrays on the detector wafers and maintain high resistivity, many connections must be made to nearby readout electronics. A vertex detector may have 10^4 to 10^5 channels, so power and thermal management of the electronics, as well as the wire bonded connections, are challenging. Two-dimensional information may be gained by connections to different sets of strips on either side of the silicon, or by using several one-sided arrays.

True pixel arrays are desirable because they give unambiguous space points, even in a dense particle jet. One approach uses Charge Coupled Devices (CCD's) fabricated from high resistivity silicon. The simultaneous advantage and disadvantage of CCD's is that they are read out serially from a small number of readout nodes, thus requiring relatively little electronics but requiring 10's of ms for the readout process. For low interaction rate environments (such as e^+e^- linear colliders) this situation is ideal, and CCD's can provide 20 micrometer sided pixels. Arrays of pixel diodes bump bonded to readout electronics are now being developed for Tevatron and LHC experiments. Such devices incorporate local smart readout to compress data, and can operate at high rates.

Cherenkov radiation detectors. The simplest Cherenkov counters are velocity threshold devices using a medium whose index of refraction has been adjusted so that particles above some velocity generate radiation. The angle of radiation emission measures particle velocity. Focusing devices can send the radiation through a circular slit allowing differential cuts on velocity. Such devices have relatively small acceptance and are used primarily in fixed target experiments. A large step was made with devices that actually image the cone of Cherenkov radiation on a sensitive focal plane to measure the Cherenkov angle. In composite large detectors on the scale of square meters, the focal planes follow the momentum measurement and must detect single photons. In high rate environments, the focal plane might be a pixellated array. The DELPHI[33] experiment at LEP and the SLD at SLAC developed devices that contained low electronegativity, high photo absorption organic molecules in large rectangular quartz walled boxes. The Cerenkov photon converts to an electron in the organic vapor that drifts in an electric field of a few hundred V/cm to a wire chamber at the end of the box. The drift length is read out as time, and the conversion coordinates normal to the drift are read out by the wire number and by charge division on the wire.

Transition Radiation Detectors. A charged particle traversing a boundary between materials differing in dielectric constant will emit photons. Thus detector components of sensitivity sharply increasing with γ can be constructed of sandwiched layers of gas and foils, with a photon detector, usually a heavy gas wire drift chamber, facing the exit surface. In practice such detectors require $\gamma > 10^4$ for adequate signals.

H. Detector Systems.

Detector Systems generally accomplish particle tracking, momentum measurement of charged particles, particle identification and total energy measurement of single particles or groups (jets) of particles. Additionally on-line and off-line data analysis is provided. Since optimal use of the collider has become important, detector systems have grown in geometric acceptance and measurement resolution to maximize information from each event and optimally use collider luminosity. Increases in the number of channels and data rates, and in measurement precision, have augmented costs and sizes.

Fixed target experiments generally include beam definition, target, drift or decay region, and detectors. The size of such experiments ranges from emulsions to the long baseline of neutrino oscillations. While primary accelerated particles are protons and electrons (or their anti-particles), fixed target experiments can utilize secondary beams of long lifetime particles. The experimentalist controls, albeit within limits, beam momentum, momentum spread, spill time, intensity, backgrounds, and experimental geometry. For *collider experiments* almost all parameters save beam energy are fixed by the collider design; in some cases some control of beam polarization may be possible. As a generality, more luminosity, if consistent with background requirements, is always wanted.

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[33] Aarnio, P., 1991.

The basic scale of collider detectors is set by the highest particle momentum to be analyzed. This is defined by the dimensions of the required magnetic analyzer and the range of the most penetrating particles (generally muons).

In general, at the energy frontier, e^+e^- detectors are smaller and simpler than the p-p (or $p\,\bar{p}$) detectors; e^+e^- machines operate at significantly lower energies, and total cross sections are much smaller, and there is usually less demand for forward acceptance with e^+e^- detectors. Radiation hardness and rate requirements are less challenging for e^+e^- detectors; such colliders produce far less than one interaction per crossing. In contrast, the LHC proton collider is expected to have more than 10 events per crossing with a crossing rate of 25 MHz.

1. Momentum measurement; magnet configurations for collider detectors.

The detectors at the CERN Intersecting Storage Rings,[34] the first of the large scale *pp* colliders, used varied magnetic configurations, mostly of modest acceptance. The first large scale cylindrically symmetric detector using a magnetic solenoid was the MKI at SPEAR at SLAC. All subsequent collider detectors except for the UA1 at the SPPS of CERN were cylindrically symmetric, mostly with solenoidal magnetic fields, although toroidal fields for muon momentum analysis have been used. This magnetic configuration leads to coaxial "barrels" of vertex detection, momentum measurement, particle identification, calorimetry, and muon measurement. Geometric variations include endcaps closing the barrels and additional downstream detectors to improve the forward acceptance, which is compromised in the solenoidal geometry.

Magnetic fields of 1.5 to 4 Tesla produced by superconducting solenoids are now used or proposed, as are position resolution of somewhat better than 100 micrometers , leading to tracker radii in the range of 1 to 3 meters.

2. Particle Identification.

Particle Identification generally relies on measurements of velocity (or the relativistic factor γ) or rests on observation of interactions (or their lack). Velocity (or γ) measurements use time of flight (TOF) or the outputs from Cherenkov or transition radiation detectors and observation of ionization density (dE/dx). For sufficiently slow particles, measurement of Time of Flight (TOF) is straightforward. Plastic scintillator with reasonably good geometry coupled to a photomultiplier can give time resolution below 100 ps.[35] The technique is limited by lengths of the flight path and by background.

3. Calorimetry (total energy measurement).

Calorimeters are used to measure the energy and position of hadrons (charged or neutral), electrons, and jets, and to help identify leptons in hadronic jets. Electromagnetic calorimeters must be thick enough to develop, contain, and measure cascade showers induced by electrons and photons. Hadronic calorimeters must be substantially thicker to contain nuclear cascades. Angular resolution of the calorimeter can be critical, and since position resolution is limited by transverse cascade shower dimensions, the calorimeter may become rather large. Calorimeter design requires optimization among performance parameters of energy, angle, and time resolution with radiation hardness, size, and cost. Calorimeters can be sampling or non-sampling, i.e. homogeneous. The sampling calorimeters alternate high atomic number metals for shower development with layers of a sensitive medium, e.g. scintillator, to sample the shower development. Homogeneous devices, practical only for electromagnetic calorimeters, utilize a uniform ionization sensitive medium to both develop and measure the energy of a shower, such as crystals of NaI. Crystals of lead tungstanate have been developed for the CMS electromagnetic calorimeter.

Statistical fluctuations in shower development and the corresponding fluctuations of the ionization in the sensitive medium limit the energy resolution of a sampling calorimeter. Thus the

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[34] Giccomelli, G. and M. Jacob, 1981.
[35] Benlloch, J. M., 1990.

energy resolution will vary as $E^{1/2}$ and as $t^{1/2}$ where E is the incident particle energy and t is the thickness of the radiator between samples. In homogeneous calorimeters, stochastic processes lead to a fractional energy resolution which varies as $1/(E)^{1/4}$, but leakage of the shower from the calorimeter, electronics noise, non-uniformity of light collection, and calibration errors add a constant term (which must be combined in quadrature). Sampling electromagnetic calorimeters achieve fractional energy resolutions in the range 10–15%/$E^{1/2}$ while crystal calorimeters achieve (1–5)%/$(E)^{1/4}$⊕(1–3)%, where E is measured in GeV.

An electromagnetic shower can usually be contained in about 25 radiation lengths, corresponding to 15 cm of lead. Hadronic calorimeters require roughly 10 interaction lengths for containment of hadronic jets, corresponding to 112 cm of uranium or 171 cm of iron. Economics usually dictate a sampling calorimeter with liquid argon, scintillator, or wire chambers as the active medium. In addition to sampling statistics, the resolution of hadronic calorimeters is affected by their relative response to electromagnetic and hadronic showers, usually resulting in fractional energy resolutions of 50–75%/$E^{1/2}$.

Many interesting variants on the basic designs have been developed. For example, liquid argon is extremely radiation hard, but the traditional electrodes of alternating layers of metal have relatively slow response because of their inductance. Folded electrodes in an accordion shape better approximate a transmission line, and have been proposed for ATLAS and GEM.[36] To improve resolution, scintillating fibers can be effectively cast into a lead matrix.

4. On-line Analysis Data Acquisition and Trigger Systems.

Increases in speed, density, and functionality in data acquisition electronics, even *after* the widespread utilization of transistor circuits, are quite impressive. While most early and some modern experiments utilize standardized modular electronics, many larger experiments have improved performance and economics by using custom electronics integrated with the detectors proper. While channel densities are hard to compare, channel counts are shown versus proposal date for several detectors in Figure 4. This growth with only moderate cost increase rests largely on continuing developments in circuit integration and computing technologies.

Most experiments produce raw data rates from the first stages of their electronics far too great to be recorded and subsequently analyzed. Trigger systems select a subset of events for recording, and the data acquisition system compresses and corrects the data and associates data with different detector subsystems for each event. Most trigger systems have a three stage architecture: Level 1 is a fast, relatively simple hardware process that operates at the basic interaction rate of the machine and buffers a subset of events for Level 2, which uses more complex, slower algorithms to further reduce the rate for level 3. Level 3 is usually a set of processors executing much of the nominal event reconstruction code, thus making the full set of analysis cuts available. Level 1 implies fast synchronous buffering of the event data, perhaps with only a subset of the data available to the level 1 trigger processor. Level 2 requires slower, asynchronous buffering of the event data, and may have much of the data available to the processor. Level 3 has complete access to all of the data. The output of Level 3 is stored for offline analysis, with data rates of roughly a megabyte per second.

Data Analysis Systems and Monte Carlo. The computation demands of many collider detectors continue to require leading edge computation technology. Reconstruction of an e^+e^- event may require of order 10^9 instructions, and hadron collider events may need an additional order of magnitude. Most analyses require calculations of acceptances and efficiencies, implying generation and reconstruction of Monte Carlo data sets several times the size of the real data set. Finally, event samples may exceed 10^9 events, and data storage facilities of Pedabytes (10^{15}) are proposed. Fortunately, event computation can easily run on arrays of computers on an event by event basis, and thus parallel "farms" are widely used.

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[36] ATLAS Liquid Argon Calorimeter Technical Design Report, CERN/LHCC 96-41, 1996.

5. The SLD as an Example of a Collider Detector System.

The Stanford Linear Collider (SLC) collides bunches of about 4×10^{10} e^- and e^+ at 120 Hz, with a luminosity approaching 2×10^{30} cm^{-2} sec^{-1}. A linear collider implies a very low true event rate and beam crossing rate; a very small luminous region in all 3 dimensions; and almost negligible radiation damage load on detector components. The SLC final focus system produces beam spots of about 1 micrometer horizontally and 0.5 micrometer vertically. Synchrotron radiation backgrounds are minimized by a masking system requiring multiple reflections for a photon to enter the detector. These features are exploited in the SLD design, shown in Figure 5, to permit a CCD Vertex Detector with about 3×10^8 pixels, a purely computational trigger, and a time multiplexed data acquisition system.

The vertex detector, consisting of ninety-six 18 by 80 mm CCD's, is arrayed around a 25 mm radius Be beampipe. The position resolution of the vertex detector is dominated by multiple scattering at lower momenta. The Solenoidal magnet has an inner diameter of 3 meters and produces a magnetic field of 0.6 Tesla. Charged particle momenta are measured by an 80 layer cylindrical drift chamber extended radially from 20 cm to 1 m, and with a total length of 2 m, arranged in 10 superlayers of alternating stereo angle. The longitudinal coordinate is first estimated by charge division on the anode wires, and then fitted using the stereo information. Momentum resolution of $\Delta P/P = 0.01 \oplus 0.0026\ P\perp$ (GeV/c) is achieved. SLD utilizes a Cerenkov ring imaging detector for particle identification. Three standard deviation separation between P's and K's is achieved from momenta of 1.5 to 5 and 9.5 to 45 and Gev/c, and between K's and π's between 0.35 and 25 Gev/C. Next comes a sampling calorimeter of lead plates in liquid argon, arranged as towers that point projectively towards the vertex. An electromagnetic section is 22 radiation lengths deep, followed by an hadronic section approximately 3 interaction lengths deep. The total calorimeter is not thick enough to contain hadronic showers, but the tails are measured in an iron calorimeter that follows the aluminum solenoid. The iron calorimeter consists of 5 cm sheets of steel interleaved with limited streamer mode chambers (Iarocci tubes). The chamber cathode surfaces are read out, on one side as a continuation of the liquid argon calorimeter towers, and on the other as strips for a muon tracking system. The barrels are closed by endcaps of similar instrumentation.

The luminosity is monitored by small angle Bhabha scattering measured by a pair of highly segmented tungsten-silicon diode calorimeters arranged as cylinders capturing the beampipe about 1.5 m from the interaction point. Electron beam polarization is measured by scattering a circularly polarized laser beam from the electron beam exiting the detector, and measuring the asymmetry of the Compton scattered electrons as the longitudinal polarization of the electrons is changed.

Essentially all electronics was customized for SLD. The basic architecture consists of preamplifiers feeding Application Specific Integrated Circuits of switched capacitor arrays to record each signal waveform. Subsets of this data are fed to a network of microprocessors to compute a trigger. In the trigger architecture described previously, Level 1 is the intrinsic SLC crossing rate, Level 2 is the microprocessor network, and Level 3 was not implemented since an acceptable rate to permanent storage is achieved by Level 2. After a trigger, data still held in the capacitor arrays is multiplexed to digitizers and transmitted via optical fibers to a network of about 600 microprocessors for data correction and compression.

I. The Future

Extension of existing accelerator and collider principles to higher performance requires advances in magnet technologies, superconducting technologies, etc. Detector systems must be able to operate in even more severe backgrounds. Today work on new collider technologies has focused primarily on high gradients and further issues concerning efficient conversion of power from the primary source to the beam must be addressed. Detector and data analysis methods are likely to match this evolution. During the next century of the American Physical Society these proposals should lead to practical designs for collider based physics.

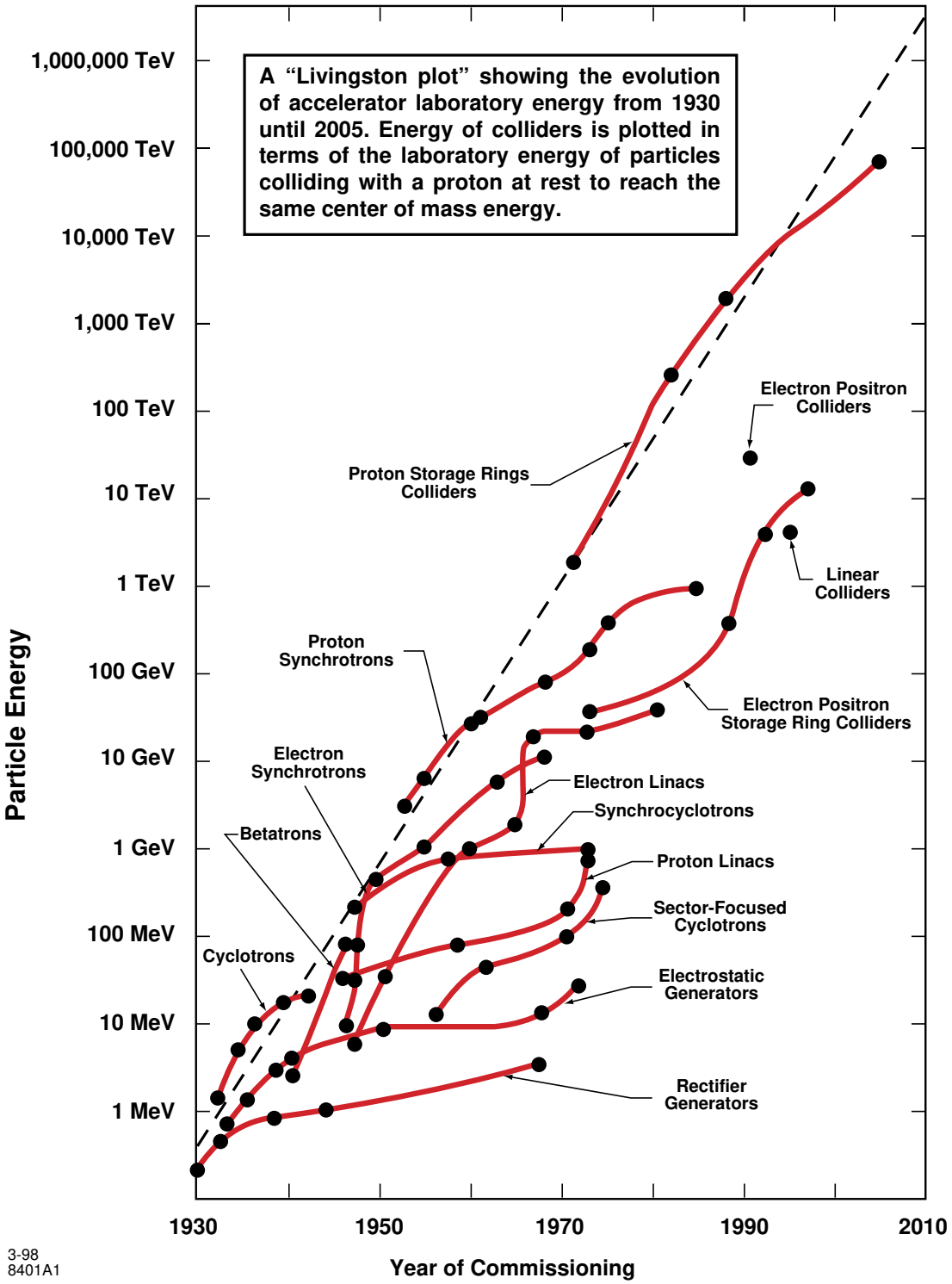
A “Livingston plot” showing the evolution of accelerator laboratory energy from 1930 until 2005. Energy of colliders is plotted in terms of the laboratory energy of particles colliding with a proton at rest to reach the same center of mass energy.
1,000,000 TeV
100,000 TeV
10,000 TeV
1,000 TeV
100 TeV
10 TeV
1 TeV
100 GeV
10 GeV
1 GeV
100 MeV
10 MeV
1 MeV
Particle Energy
1930
1950
1970
1990
2010
Year of Commissioning
Electron Positron Colliders
Proton Storage Rings Colliders
Linear Colliders
Proton Synchrotrons
Electron Positron Storage Ring Colliders
Electron Synchrotrons
Electron Linacs
Synchrocyclotrons
Betatrons
Proton Linacs
Sector-Focused Cyclotrons
Cyclotrons
Electrostatic Generators
Rectifier Generators
3-98
8401A1

Figure 1

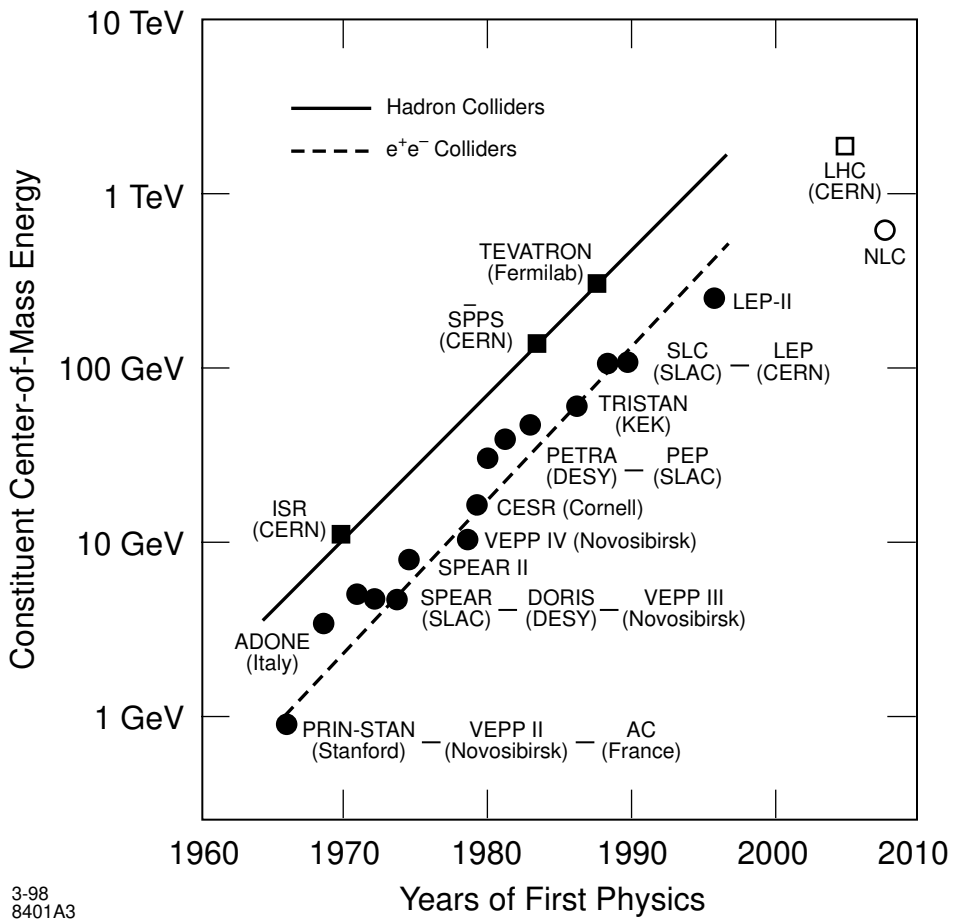

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Figure 2 The energy in the constituent frame of electron-positron and hadron colliders constructed (filled circles and squares) or planned. The energy of hadron colliders has here been derated by factors of 6–10 in accordance with the fact that the incident proton energy is shared among its quark and gluon constituents.

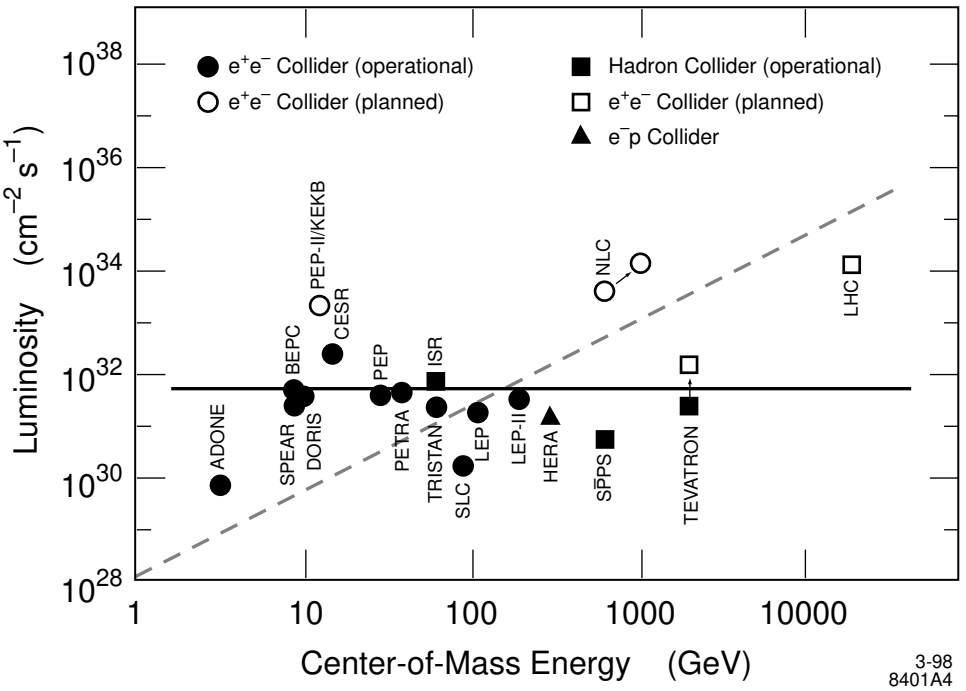


Figure 3 Peak luminosities achieved at existing colliders and values projected for planned or upgraded machines. The dashed line indicates luminosity increasing as the square of the center-of-mass energy. Note that the rated machine energy has been used in calculating the abscissa. (Data updated courtesy of Greg Loew, SLAC.)

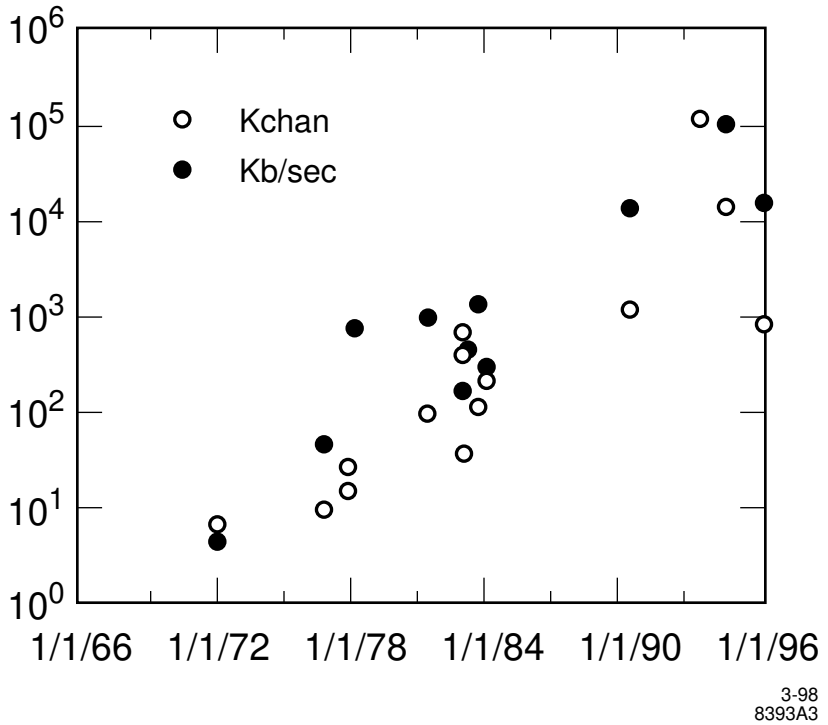
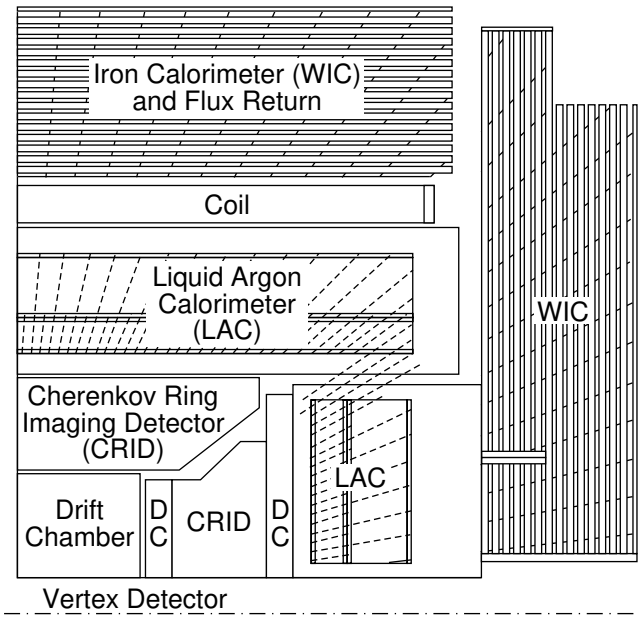


Figure 4 Evolution of the number of detector signal channels with time, indicating growth of collider detector instumentation capability over the last 24 years. The open circles indicate the number of electronic instrumentation channels in thousands. The closed circles indicate the design data rate in kilobytes per second to permanent storage. The date is that of the detector proposal or Technical Design Report; e^+e, pp, and $\bar{p}p$ detectors are included.



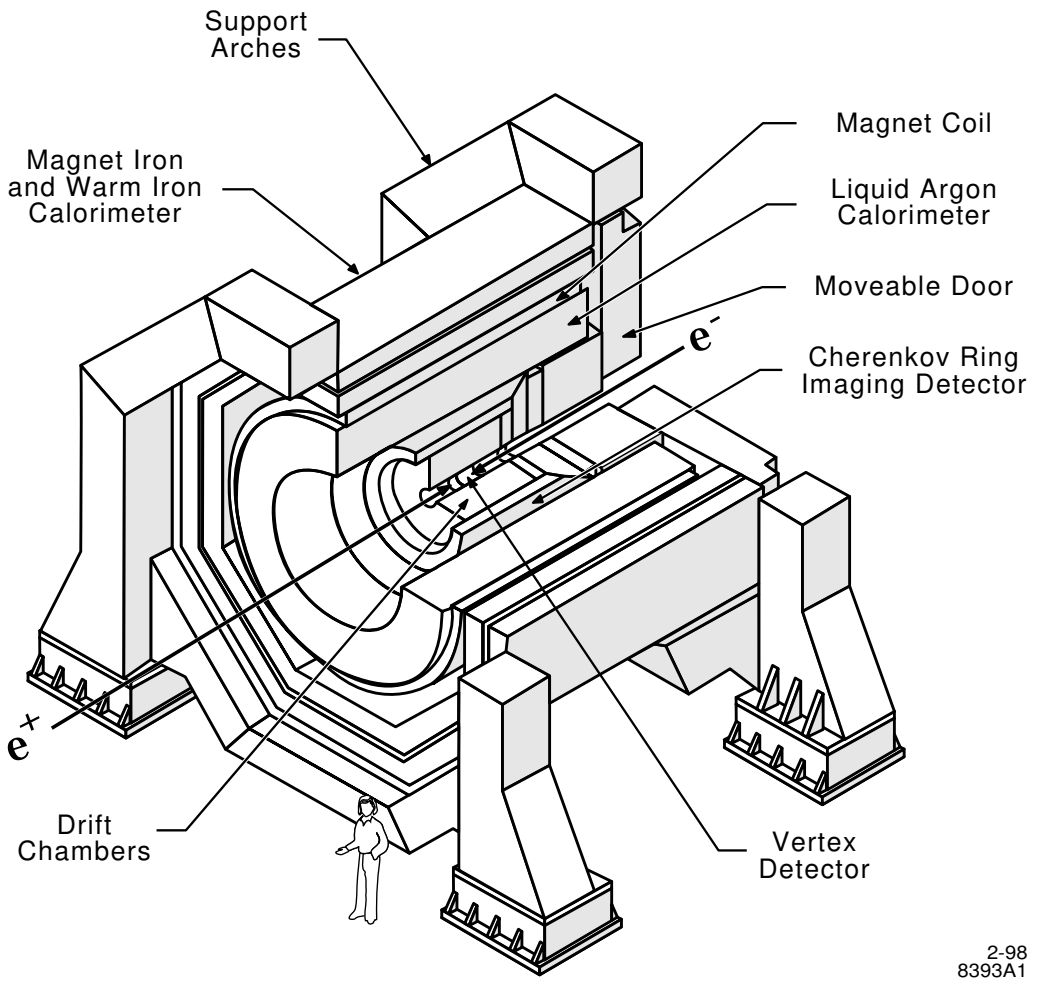


Figure 5 Cutaway and quadrant view of the SLD detector.

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