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The Desertron: Colliding Beams at 20 TeV

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In the field of elementary particles enormous progress has been made over the past decade. The weak and electromagnetic forces have been unified, charm and bottom quarks as well as tau leptons have been discovered, and a theory of the strong interactions in terms of quarks and gluons has been developed. At the same time, a close relationship and interdependence has been established with the fields of astrophysics and cosmology. Most recently, evidence for intermediate vector bosons, carriers of the weak force, has been observed at the European Organization for Nuclear Research (CERN).

Summary. With today's technology, the center-of-mass energy of proton-proton and proton-antiproton collisions can be extended by an order of magnitude beyond that achievable with machines presently in operation or under construction. Such a facility would open a vast new energy region which has been suggested theoretically to contain new kinds of particles and interactions. Several accelerator options, their rate capabilities, and their costs are described.

Further advances in our understanding of the fundamental forces and elementary particles will continue to require the study of particle collisions at ever higher energies. Families of heavier quarks, leptons, and gauge bosons may exist. Particles associated with the spontaneous breaking of gauge symmetry are expected, but have yet to be discovered. These could be simple "Higgs" particles, or more complex families of particles having a new strong interaction called "technicolor." The latter particles would have masses typically in the range of 1 TeV (10^{12} electron volts). For aesthetic reasons, theorists have been drawn to supersymmetric theories which unite bosons (integer spin) and fermions (half-integer spins); such theories predict a multitude of new particles, and these may also have masses in the TeV range, accessible only with higher energies. Spectacular events observed in cosmic-ray experiments further suggest the existence of new types of interactions at very high energies.

Increased energy may also give us a glimpse of the next level of matter. Just as the wide variety of atoms found in nature are all composed of protons, neutrons, and electrons, so have the large number of strongly interacting elementary particles, including the proton and neutron, been explained in terms of quarks and antiquarks. By now, the large variety of quarks and leptons (such as electrons, muons, and neutrinos) suggests that these particles may themselves consist of even simpler building blocks, waiting to be revealed at sufficient energy. In spite of the wealth of theoretical predictions, based on past experience, the most fundamental physics result to come out of this new energy region will likely be something totally unexpected.

Using present-day technology, it is possible to achieve the next order of magnitude in energy with a proton-proton (or proton-antiproton) colliding beam accelerator. Such a machine would be too large to fit on the site of any of the existing accelerator laboratories and may have to be located at a new laboratory, perhaps in a relatively uninhabited area of the western United States. This has led to the machine being referred to as the "Desertron." This name is doubly appropriate as it will explore the beginning of the energy region suggested by some theorists to be a "physics desert," devoid of new phenomena below energies of 10^{15} GeV (1 GeV = 10^9 electron volts). As noted above, however, there are many predictions of "oases in the desert" having completely new types of particles and interactions within reach of the Desertron described here.

Many of the ideas discussed in this article were drawn from a meeting held at Snowmass, Colorado, by the Division of Particles and Fields (DPF) of the American Physical Society. This DPF Summer Study on Elementary Particle Physics and Future Facilities was held 28 June to 16 July 1982. Its purpose was "to assess the future of elementary particle physics, to explore the limits of our technological capabilities, and to consider the nature of future major facilities for particle physics in the U.S." (*1*). It was attended by 150 physicists and covered a broad range of physics, accelerator, and detector topics. More recently (28 March to 2 April 1983) a workshop at Cornell University was organized by Maury Tigner to further explore the feasibility and cost of a proton-proton (or proton-antiproton) collider with 10 to 20 TeV per beam. The conclusions of this workshop reinforced the earlier results from Snowmass.

Evolution Toward Higher Energies

A historical record of accelerator energy as a function of time is shown in Fig. 1 (*2*). Such a plot was first used by Livingston and Blewett (*3*) and shows a series of curves, each for a given accelerator technology. As the various technologies reach "saturation," new ones have been invented such that the envelope of the curves is approximately given by an ex-

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ponential function with a doubling time of 2 years. The graph shows an increase of more than eight orders of magnitude in equivalent laboratory beam energy over the past 50 years. This has been made possible by inventions and improvements in technology which have allowed the cost per unit of energy to be reduced by roughly six orders of magnitude.

The most recent technology to be exploited is that of high-energy colliding beams. The first demonstration of this technology with proton beams (pp) was at the CERN Intersecting Storage Rings (ISR) in 1972. An additional breakthrough in accelerator technology is beam cooling, allowing the generation of intense beams of antiprotons and their subsequent application to colliding beams. Since protons and antiprotons have opposite charge, counterrotating beams can be contained within a single ring of magnets. The highest energy point in Fig. 1 represents the first proton-antiproton ($p\bar{p}$) collider, which began operation in 1981 with 270-GeV beams in the CERN Super Proton Synchrotron (SPS). This high energy was crucial in the recent discovery of events of the sort expected from the production and decay of the intermediate vector bosons (*4, 5*).

Although electron-positron (e^+e^-) circular colliders have yielded spectacular discoveries over the past decade, it is difficult to push them to much higher energies with present technology. Until now, colliding beams have been achieved only in circular machines, which allow the very intense but still tenuous beams to pass through each other many times. The bending of electrons in circular machines requires compensation of the energy lost by synchrotron radiation, which increases rapidly with energy. This results in the optimized cost of such machines scaling as the square of the energy (*6*), while the proton machines lose little energy to synchrotron radiation and their costs scale roughly linearly.

A completely new type of e^+e^- collider was recently proposed (*7*): the single-pass linear collider in which intense bursts of electrons and positrons are accelerated in linear accelerators (to avoid synchrotron radiation), focused to micrometer size, and then collided head-on. This concept is being vigorously developed at the Stanford Linear Accelerator Center (SLAC), where an accelerator R & D project, the SLAC Linear Collider (SLC), is expected to point the way to future very high energy e^+e^- colliders with costs scaling linearly with energy (*7, 8*). At the same time the SLC should provide a copious source of Z^0 intermediate vector bosons and allow a detailed study of their properties.

The different types of colliders are expected to continue to provide complementary particle physics capabilities in the future. The e^+e^- colliders have advantages of simplicity in interpretation of events and a high proportion of "interesting" events, while the pp and $p\bar{p}$ colliders have high rates and will continue to provide by far the highest energy available in the laboratory.

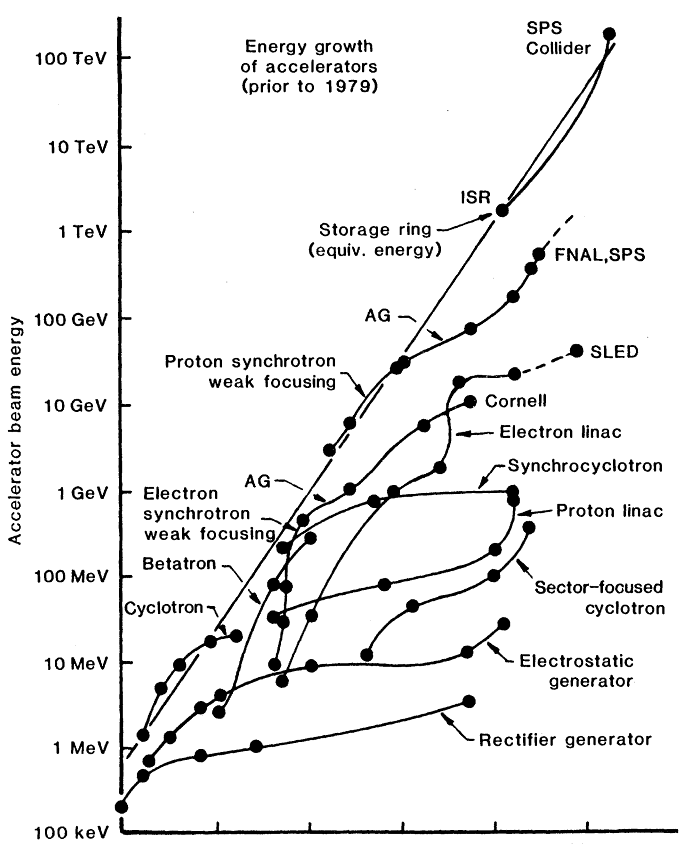

Fig. 1. Livingston plot showing the maximum energy as a function of year for various accelerator technologies. [Adapted from (2)]

Center-of-Mass Energy and Luminosity

Before the advent of colliding-beam machines, high-energy experiments were done with beams interacting in targets which were stationary or "fixed" in the laboratory. The targets were often the proton nuclei in liquid hydrogen. At very high energies most of the beam energy was required just to conserve forward momentum and was thus not available to create massive new particles or to excite new types of interactions.

For fixed-target operation, the available energy, the so-called center-of-mass energy, is given to a good approximation (for $E \gg M_p$) by

$$E_{cm} = \sqrt{2EM_p} \quad (1)$$

where E is the incident beam energy and M_p is the target proton mass in energy units (0.938 GeV). Typical values are E_{cm} = 8 GeV for the 33-GeV Alternating Gradient Synchrotron (AGS) at Brookhaven National Laboratory and E_{cm} = 40 GeV for the Tevatron, the new superconducting accelerator being brought into operation at Fermilab (*9*).

The square root in Eq. 1 makes increases in center-of-mass energy painfully expensive, and this has been circumvented by the use of colliding beams. For colliding beams, Eq. 1 is replaced by

$$E_{cm} = 2\sqrt{E_1E_2} \quad (2)$$

where E_1 and E_2 are the energies of the two beams colliding head-on with one another. In the usual case of $E_1 = E_2 = E$, the laboratory and center-of-mass frames are the same and all of the energy is available, $E_{cm} = 2E$.

For the CERN ISR operating at E = 31 GeV, the center-of-mass energy of 62 GeV is the same as for a fixed-target beam of about 2 TeV (2000 GeV). This equivalent laboratory beam energy has been plotted in Fig. 1 for comparison with previous accelerators. In 1985, the Tevatron together with an antiproton source will allow proton-antiproton collisions at E_{cm} = 2 TeV, equivalent to a fixed-target accelerator energy of 2000

TeV = 2×10^{15} eV, well into the region of cosmic-ray extensive air showers. A fixed-target machine of this energy would be absurd; even with 4.5-tesla superconducting magnets, such as those now being installed at Fermilab, the accelerator would encompass the continental United States (*10*). For a Desertron with 20-TeV beams, the equivalent fixed-target energy would be nearly 10^{18} eV.

The second basic parameter of high-energy accelerators, besides energy, is intensity or event rate. For colliding beams this is expressed as luminosity, $\mathscr{L}$, the proportionality constant giving the event rate for a particular reaction cross section, σ: number of events per second = $\mathscr{L}\sigma$.

For fixed-target operation, this factor is given by the product of the number of beam particles per second times the number of target particles per square centimeter of projected target area. Typical values for large solid angle experiments in secondary beams are 3×10^6 particles per second and 3×10^{24} protons per square centimeter giving $\mathscr{L} \approx 10^{31}$ cm^{-2} sec^{-1}. As discussed in detail below, colliding-beam luminosities of 10^{33} cm^{-2} sec^{-1} or more should be achievable at the Desertron, although not all experiments will be able to make effective use of such high rates (a total of about 10^8 interactions per second).

In addition to colliding-beam operation, the Desertron may well be used for fixed-target experiments. Even though the center-of-mass energy would be only 200 GeV for a 20-TeV beam, this would still be the only direct way to study reactions initiated by high-energy beams of mesons, hyperons, photons, charged leptons, and neutrinos. A study of this possibility was made at the Snowmass meeting (*11*); while fixed-target operation does place some additional requirements on the accelerator design, it appears technically quite feasible.

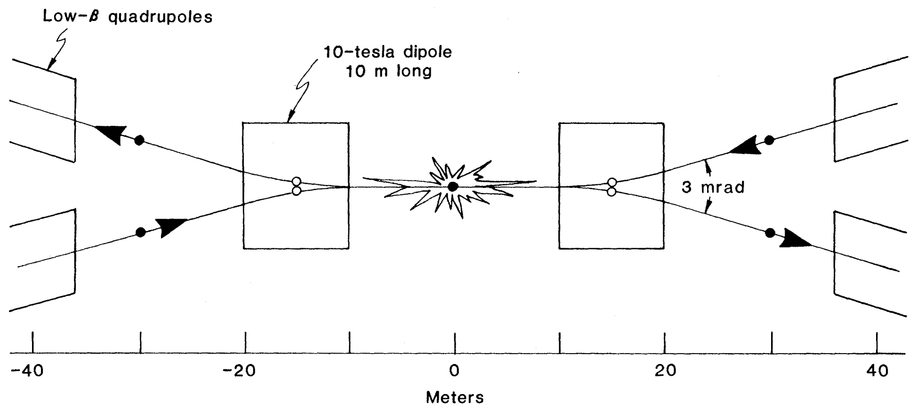

Fig. 2. Sketch of pp beam separation [from (*13*)]. Bunches (solid circles) can be spaced by ~ 30 m and still be separated when they next pass one another (indicated by open circles).

Options for Very High Energy pp and p̄p Colliders

At Snowmass, specific consideration was given to the possibility of building and using proton-proton and proton-antiproton colliders of 20 TeV per beam. This was the energy considered in two earlier studies (*12*) sponsored by the International Committee for Future Accelerators (ICFA). At the Cornell Workshop, colliders of 20 TeV per beam were again the main emphasis, but cost estimates were also made for 10-TeV beams. Although the final energy of such a machine will depend on the site, magnetic field, and resources available, I will also use 20 TeV per beam, 40 TeV in the center of mass, as the example discussed here.

Two technical approaches were pursued by two groups at Snowmass, both under the overall leadership of Maury Tigner (Cornell). Both groups agreed that to keep the electric power consumption to a reasonable level, the magnets would have to be superconducting. The first group (*13*) assumed that high-field magnets, in the neighborhood of 10 tesla, could be used, and the second (*14*) looked into the possibility of using inexpensive low-field (2 to 3 tesla) magnets. While the collider could be built with either low or high field, R & D will be required to determine the optimal field; to be specific, the high-field case will be used as an example here. To bend a 20-TeV beam full circle would require 42 km of 10-tesla dipole field. Adding in space for experimental regions, quadrupole focusing, correction elements, radio-frequency power, injection, and so on would give a circumference of 50 to 60 km, nearly ten times that of the present Fermilab ring.

At these high energies and magnetic fields, synchrotron radiation from protons begins to come into play, primarily with a beneficial value (*15*). The main effect is a damping of the internal motion of the protons within the beam, reducing the transverse phase space, or emittance, of the beam. At E = 20 TeV and B = 10 tesla, the damping time of the emittance would be 6 hours. If no other factors were at work, this would make the beams smaller and more dense, giving an increase in luminosity by a factor of e = 2.72 every 6 hours. Since the rate of damping scales as EB^2, the usefulness of this effect would fall rapidly at lower magnetic fields. Noise, beam instabilities, beam-beam interactions, and so on will eventually limit the growth in luminosity, but the limit is not easily calculable and will depend on details of the machine. The amount of power needed to compensate for the loss from synchrotron radiation is not large, about 15 kW per 10^{14} protons, but care must be taken at the higher beam intensities not to overload the refrigeration system of the superconducting magnets.

For proton-antiproton collisions, large numbers of antiprotons must be collected. This would be done by accelerating protons to roughly 100 GeV and smashing them into a target to produce antiprotons, which would then be focused and collected within a small accumulator ring. The antiproton beam must then be "cooled" to reduce its emittance. This is done for the CERN SPS collider by the so-called stochastic method, with an electronic feedback system, developed at CERN by S. van der Meer, using very high frequencies to damp the internal motion of particles within a beam in a statistical way (*16*). This not only allows the accumulation of more antiproton bunches, but also eventually reduces the beam emittance to the small value needed to achieve dense beams for high luminosity. The Fermilab Tevatron antiproton source (*17*) will use both longitudinal debunching and stochastic cooling to achieve a source strength of 10^{11} p̄ per hour. An extension of this design at the Snowmass meeting led to an estimate of 10^{12} p̄ per hour for the Desertron (*18*). While this rate may eventually become feasible, it was pointed out at the Cornell Workshop (*19*) that it will require considerable R & D.

Two modes of colliding beam operation are possible for a p̄p or pp machine, the first with bunched beams colliding head-on and the second with continuous or unbunched beams crossing at a small angle. Unbunched beam operation results in a better duty factor for the ex-

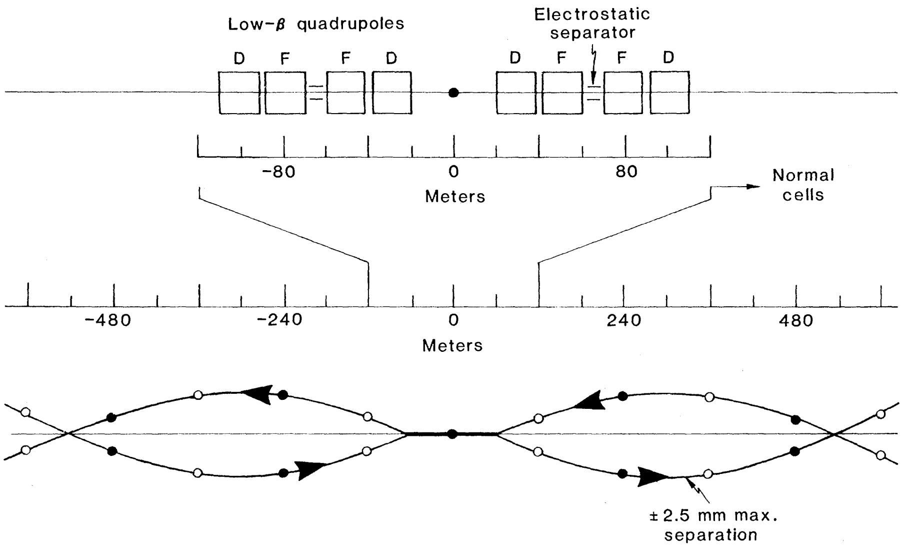

Fig. 3. Sketch of p̄p beam separation [from (*13*)]. For the bunches to be well separated by their next meeting (open circles), they must be spaced apart by ≥ 240 m.

perimental detectors and reduces problems due to certain types of beam instabilities, but requires more beam particles for a given luminosity.

A simple and useful relation for luminosity is best illustrated in the bunched beam case. Long-term beam stability requires that bunches collide at only a few points around the ring in order to minimize the disturbing influence of one beam on the other. The bunches must thus be spaced by a minimum distance such that the orbits of the two beams can be sufficiently separated before the next meeting of bunches (*13*). For the proton-proton case, the two orbits are easily separated by a simple bending magnet, as indicated in Fig. 2. Allowing a free space of ± 10 m for the particle-physics detectors, the bunches can be spaced as closely as $d = 30$ m, giving bunch collisions every $\Delta t = d/c = 100$ nsec.

If $<n>$ is the average number of interactions per bunch collision, the luminosity per bunch collision is

$$L = \frac{<n>}{\sigma_{\rm tot}} \tag{3}$$

and the luminosity per second is

$$\mathcal{L} = \frac{<n>}{\sigma_{\rm tot}\Delta t} \tag{4}$$

For a total cross section of $\sigma_{\rm tot} = 100$ millibarns $= 10^{-25}$ cm^2 and $\Delta t = 10^{-7}$ second

$$\mathcal{L}(\text{pp bunched}) = <n> \times 10^{32}\ \text{cm}^{-2}\ \text{sec}^{-1} \tag{5}$$

The separation of p̄p orbits is more difficult and requires the use of electrostatic separator plates. The example shown in Fig. 3 uses separators 7 m long operating at 65 kV/cm; this results in an orbit separation of up to ± 2.5 mm, sufficient to allow four bunches per betatron wavelength. For the example shown, this would give $d = 240$ m, $\Delta t = 800$ nsec, and

$$\mathcal{L}(\bar{\text{p}}\text{p bunched}) = 1.25 <n> \times 10^{31}\ \text{cm}^{-2}\ \text{sec}^{-1} \tag{6}$$

Typical Beam Parameters

So far, the only accelerator physics used here has been for the relatively straightforward calculation of minimal bunch separation distance. The largest uncertainty in the above formulas for luminosity lies with the number of interactions per bunch collision, $<n>$. While the optimal value ranges from perhaps 10^{-4} to 10^2, depending on the detector technology being used and the physics being studied (*20*), most experiments would probably be carried out within an order of magnitude of $<n> = 1$.

For bunched beams, the luminosity per bunch collision is given by

$$L = \frac{N^2}{4\pi\sigma^2} \tag{7}$$

where it is assumed that each of the colliding bunches has N particles and a gaussian profile in each transverse dimension with root-mean-square width σ. The effective target area of $4\pi\sigma^2$ in the denominator comes from an integration over the product of the densities of the two beams.

The size of the beam is given by its emittance, ϵ, and by the focusing strength of the accelerator (machine parameter β). In the absence of noise and other dilution effects, the emittance is inversely proportional to $\gamma = E/M_{\rm p}$; as an example, take

$$\epsilon = 10\pi \times 10^{-6}\ \text{m}/\gamma \tag{8}$$

as the phase space area containing 95 percent of the beam. While this value is two or three times smaller than that presently obtained in the Fermilab and CERN machines, it should be achievable if sufficient care is taken during the stacking and accelerating processes. Special "low-β" quadrupoles would be used to focus the beams at the interaction regions to give $\beta \approx 2$ m. The root-mean-square width of the 20-TeV beam is then given by

$$\sigma = \sqrt{\epsilon\beta/6\pi} = 13\ \mu\text{m} \tag{9}$$

For $<n> = 1$, this results in

$$N = 1.4 \times 10^{10}\ \text{per bunch} \tag{10}$$

For the p̄p case, a spacing of 240 m around a ring 60 km in circumference requires 250 bunches in each beam and a total of 3.5×10^{12} antiprotons. The corresponding collection time of 3.5 hours at 10^{12} per hour is much shorter than the anticipated several-day lifetime of the beams; with present-day technology, 10^{11} per hour, however, the collection time may be a limiting factor.

A measure of the disruptive effect of one beam on the other is given by the so-called beam-beam tune shift:

$$\Delta\nu = \frac{3}{2}\frac{r_{\rm p}N}{\gamma\epsilon} \tag{11}$$

where $r_{\rm p} = 1.53 \times 10^{-18}$ m is the classical proton radius. For the $<n> = 1$ case, this works out to $\Delta\nu = 1.0 \times 10^{-3}$, well under the upper limit of 5×10^{-3} normally assumed for the design of pp (or p̄p) storage rings. If this is indeed the limiting value, we could increase the number of particles per bunch up to 7×10^{10}, giving $<n> = 25$. Higher values of $<n>$ could be achieved by enlarging the beam emittance and further increasing the number of particles.

For detectors with memory and resolution times well under ~100 nsec, higher useful luminosities could be achieved with continuous (unbunched) proton beams crossing one another at a small angle. For our standard emittance, a crossing angle of 62 μrad would give a luminous region with root-mean-square length ± 0.28 m over which the events would be produced. Intense beams are needed in this case, however. For example, a luminosity of 10^{33} cm^{-2} sec^{-1} (an average of one event every 10 nsec) would require 4 × 10^{14} protons per beam in this mode, about five times that required for the bunched pp case giving the same luminosity ($<n> = 10$ every 100 nsec). The 4 × 10^{14} protons per beam represent a stored energy of 1300 MJ, which could cause considerable mischief if inadvertently missteered. Each beam would also give off 60 kW of synchrotron radiation, which must be extracted from the machine.

A summary of the luminosity and the number of particles per beam required for the three types of operation is given in Table 1 for $<n> = 1$ and 25.

Table 1. Typical time structure, luminosity, and number of particles per beam for three modes of operation. For bunched beams, Δt is the time between bunch collisions; in the unbunched case, Δt is the memory time of the detector, taken to be 30 nsec as an example for this table.

Mode of operation	Δt (nsec)	$<n> = 1$: $\mathcal{L}$ (10^{32} cm^{-2} sec^{-1})	$<n> = 1$: N (10^{14} per beam)	$<n> = 25$: $\mathcal{L}$ (10^{32} cm^{-2} sec^{-1})	$<n> = 25$: N (10^{14} per beam)
Bunched $\bar{p}p$	800	0.12	0.035	3	0.18
Bunched pp	100	1.0	0.28	25	1.4
Unbunched pp	(30)	3.3	2.4	80	12

Physics Trade-Off Between Energy and Luminosity

At Snowmass there was considerable discussion of the relative emphasis to place on luminosity and energy. To explore this question in more detail, a Snowmass group led by Bob Palmer of Brookhaven and John Peoples of Fermilab looked at the effect of luminosity and energy on the rates expected for a set of "bellwether" reactions (*21*). The cross section for each reaction was calculated by using a quantum chromodynamics (QCD) model. In each of the reactions considered, the fundamental interaction is a hard scatter between a pointlike constituent, quark or gluon, in each beam. At the high energies being considered here, the cross sections are expected to be much the same for pp and $\bar{p}p$ reactions.

For each reaction, the Snowmass group calculated the maximum transverse momentum or mass for which 100 events might be observed in 10^7 seconds (approximately one calendar year of running at 30 percent efficiency) for various center-of-mass energies and luminosities. The results for three reactions are shown in Fig. 4.

The signature for hard scattering of quarks or gluons at large tranverse momentum (p_T) would be jets, hot spots of energy deposited in calorimeter cells. Gross deviations from the QCD predictions might reveal the next layer of matter, that is, subunits within the quarks. Even for $<n> = 10$, a Monte Carlo calculation of pile-up in the calorimeter system showed that it should have little effect above a transverse momentum of 10 GeV/c. For $\bar{p}p$, $<n> = 10$ would give a luminosity of 1.2×10^{32} cm^{-2} sec^{-1}, which at E_{cm} = 40 GeV should give 100 events above p_T = 4 TeV/c, a probe of distances less than 10^{-17} cm. For pp at 10^{33} cm^{-2} sec^{-1}, one would collect more than 100 events above 5 TeV/c.

The production of new heavy particles is typified by the calculation of technicolor particles; the example used was the so-called techni-eta, η_T. Here one would have to run at $<n> \approx 1$ in order to identify decay products such as electrons and K mesons. Assuming 10 percent efficiency for observing these heavy particles, one could observe masses up to 3 and 5 TeV for bunched $\bar{p}p$ and pp beams, respectively.

With sufficient dense material near the interaction point to suppress other particles, an experiment to measure the production of muon pairs ($\mu^+\mu^-$) could probably run at 10^{34} cm^{-2} sec^{-1}, allowing observation of pairs with invariant mass above 1.7 TeV. This is an especially clean way to study QCD, as well as to search for new heavy vector mesons $V \rightarrow \mu^+\mu^-$ (first indications of the charm and bottom quarks were seen in this way), and could also be a sensitive indication of a common substructure in quarks and leptons.

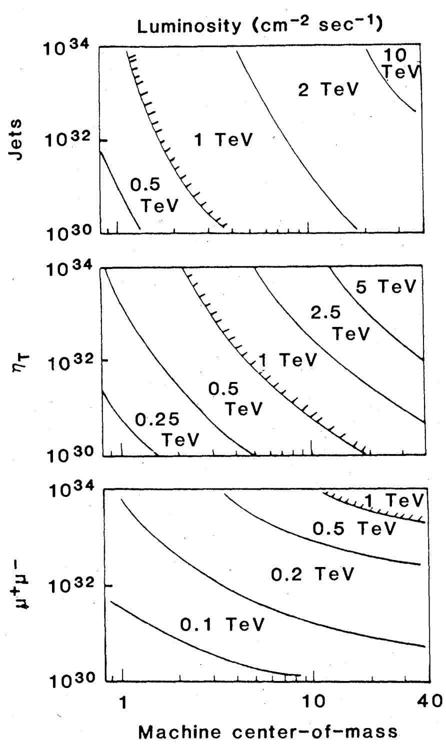

Fig. 4. Contours of M or $2p_T$ giving 100 events in 10^7 seconds. [From (*21*)]

The study of the bellwether experiments indicates that both luminosity and high energy will be important in exploring such physics. At the Cornell Workshop, discussion centered on the use of so-called 2-in-1 magnets, in which the vacuum pipes of both proton beams are contained within a single magnet yoke, with the magnetic field circulating around the yoke, downward through the first aperture and upward through the second. It is believed that the cost for a pp collider system with 2-in-1 magnets is close to that for a $\bar{p}p$ collider, which would require not only a $\bar{p}$ source but also somewhat larger aperture magnets to contain the orbit distortions shown in Fig. 3. Thus, a proton-proton collider, with its inherently higher luminosity, appears possible at about the same energy and cost as a proton-antiproton system; if this is true, we can have both high energy and high luminosity.

Preliminary Cost Estimates

In addition to working out the machine parameters for high-energy colliders, the accelerator groups at the Snowmass meeting also had a first, very rough look at the costs (*22*). This led to an important new perspective that had been lacking in the earlier ICFA studies (*12*).

One group, which I coordinated, looked at the cost of "conventional" colliders, built in much the same style as Fermilab (*13*). There was one important exception to conventionality, however; it was assumed that the use of 10-tesla magnets would be practical. Where possible, costs were estimated by using the initial Fermilab construction cost of \$245 million, mainly spent in the early 1970's; correcting for inflation brings this total up to about \$600 million or \$700 million in today's dollars. Half of this went into the actual accelerators, and a similar accelerator system will be required as the injector to the Desertron. Adding up the various costs gave an estimate of about $2.2 billion in today's dollars for a new laboratory with a single 10-tesla ring for $\bar{p}p$ collisions with 20 TeV per beam.

Although such a facility holds great promise for opening a new realm of exploration and understanding of basic physics, this is an unprecedented sum for a single research facility. It is clearly in the interest of both physicists and taxpayers to explore means by which the cost might be reduced. This was done by a second group at Snowmass (*14*), coordinated by Russ Huson of Fermilab. In particular, this group was inspired by Bob Wilson (the first director of Fermilab, who is now at Cornell) to consider very simple and cheap superconducting magnets with fields in the region 2 to 3 tesla.

The low field considerably reduces the amount of superconductor required and the accuracy with which the coil must be constructed. As homework for the study, Wilson and collaborators had successfully built and operated such a magnet up to 3 tesla (*23*). To further economize, this group suggested reducing the magnet aperture to a minimum, automating production of magnets, making each magnet of maximum possible length to reduce costs associated with ends, and using a larger size of superconductor with fewer turns.

While easier and cheaper to build than high-field magnets, these low-field magnets do require a much longer enclosure or tunnel for the machine, with a circumference of roughly 200 km instead of 60 km. To be economically attractive, the tunnel costs per unit length would have to be brought down considerably from those incurred for previous accelerators. To this end, a "roadway" roughly 25 m wide would be bulldozed flat enough for the accelerator to follow any remaining slow variations in elevation. The 1-m-diameter accelerator enclosure would then be laid in a trench, similar to the laying of a natural gas pipeline, and covered with 2 m of dirt to provide both thermal insulation and radiation protection. Such a small diameter enclosure would preclude easy access by humans, and adjustments would be done by remote control, perhaps with a mobile robot, as whimsically portrayed by Wilson (*23*) (see Fig. 5).

With these techniques, the cost of a new laboratory having a single-ring $\bar{p}p$ collider with 20 TeV per beam was estimated to be approximately $1.5 billion.

At the Cornell Workshop, the cost estimates were reconsidered with the help of consultants. The uncertainties associated with tunnel construction were found to be large due to the range of possible site conditions. The cost estimates and their uncertainties for the various components, when added, gave a final cost estimate of about $1.7 ($\pm$ 0.3) billion for a new laboratory with a pp collider having 20 TeV per beam, in good agreement with the necessarily more uncertain estimates made at Snowmass. A similar estimate for a laboratory with a machine having 10 TeV per beam indicated an overall cost reduction by a factor of about 1.5 from that for 20 TeV per beam. Within the present uncertainties, the cost does not vary strongly with magnetic field, the savings in magnet costs at lower fields being roughly balanced by the increased costs for a longer tunnel.

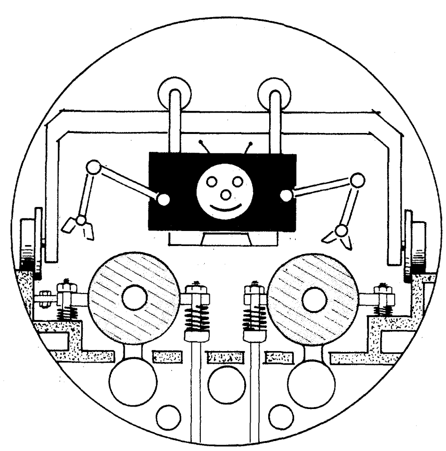

Fig. 5. Cross section of 1-m-diameter beam enclosure, with robot for remote adjustment and maintenance work. [From (*23*)]

Concluding Remarks

The Cornell Workshop (*19*) found that there are several viable approaches to building a 20-TeV collider facility, based on different superconducting magnet designs. There appear to be no fundamental problems of accelerator physics, but intensive engineering development of the magnet designs is needed in order to reduce costs and select the most economical system consistent with reliable operation. Work is progressing on various magnet designs and prototypes, and it is believed that with a reasonable level of effort, construction could begin within 4 years or less. In addition, operation of the Fermilab superconducting ring, which has recently achieved more than 500 GeV (*24*), will provide valuable experience with superconducting magnets.

Probably the most critical parameter of the Desertron is the choice of magnetic field; it determines the size of the site as well as many other aspects of the machine. The diameter of a facility with 20-TeV beams would be about 60 km with 2.5-tesla magnets; for 10 tesla it would be less than 20 km. An area should also be available tangent to the ring for future expansion, including fixed target operation and an e^+e^- single-pass linear collider. For example, an e^+e^- collider with a gradient of 50 MeV/m would require 2 $\times$ 10 km for beams of 500 GeV.

The site must be rather flat, relatively unpopulated (yet near a major airport), with water, power ($\sim$ 75 MW), and land readily available. Potential sites have already been identified in New Mexico (*25*), Arizona (*26*), and Texas (*27*), and other sites will no doubt be found elsewhere.

A crucial question for long-range planning of the field has been whether to build one or more intermediate machines to bridge the gap between the 2-TeV center-of-mass Tevatron collider at Fermilab and the 20- to 40-TeV Desertron. This question was recently addressed by a Department of Energy subpanel on new facilities for the U.S. High Energy Physics Program (*28*). Two possible intermediate machines were considered: a high intensity pp Colliding Beam Accelerator (CBA) of 0.8-TeV center of mass at Brookhaven (*29*) and a 4-TeV $\bar{p}p$ collider at Fermilab built with Tevatron-style magnets (*30*). The subpanel concluded that to avoid interference with a machine of the sort described in this article, which the subpanel called the Superconducting Super Collider (SSC), neither intermediate machine should be pursued (*31*). Indeed, the subpanel recommended "at the highest priority that a major new project be initiated to design and build a proton-proton colliding beam facility exploiting our superconducting magnet technology with an energy goal of 10 to 20 TeV per beam and completion in the first half of the 1990's." At its meeting on 11 and 12 July, the High Energy Physics Advisory Panel unanimously endorsed the subpanel report and its recommendations (*32*).

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Biotechnology in the Marine Sciences

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Genetic engineering holds extraordinary promise for the marine sciences. The potential of the world oceans to feed and sustain humankind has been addressed during the past few decades, clone their genes, so that the stage is set for the realization of genetic engineering's potential in the marine sciences.

A dramatic example of the potential that biotechnological application offers is

Summary. Genetic engineering applied to the production of fish, molluscs, algae, algal products, and crustaceans in natural environments and hatchery systems is still at the rudimentary stage. Cloning systems for producing commercially important chemicals, pharmacologically active compounds, and metamorphosis-stimulating substances present in marine organisms are being sought. Attempts are being made to develop useful drugs from the sea, including antineoplastic, antibiotic, growth-promoting (or -inhibiting), analgesic, and antispasmodic agents. Immediate commercial applications can be expected from engineered systems involving polysaccharide and specialty chemical production, with marine microorganisms as the source of genetic material.

including reports of a huge food source represented by krill in Antarctic waters and by fishery stocks in offshore waters of the world's continents (*1*).

Genetic engineering is being applied to develop the products of fish, molluscs, and crustaceans in natural environments and hatchery systems, although real results are still scant. Streisinger *et al.* (*2*) have produced clones of homozygous diploid zebra fish (*Brachydanio rerio*). Successful aquaculture of many species of invertebrate animals and large populations of shellfish at the larval and intermediate stages has made it possible to

that of marine pharmaceuticals. In a 1977 conference, "Drugs and Food from the Sea: Myth or Reality," investigators described cardiotonic polypeptides from sea anemones, an adrenergic compound from a sponge, and potential antitumor agents from Caribbean gorgonians and soft corals (*3*). More recently, Rinehart *et al.* (*4*) described antiviral and antitumor depsipeptides from a Caribbean tunicate. Extracts prepared from the Caribbean tunicate, an ascidian or sea squirt of the family Didemnidae, inhibit growth of DNA and RNA viruses, as well as L1210 murine leukemic cells. These depsipeptides—termed didemnins after the name of the tunicate family, Didemnidae, from which they are isolated—are closely related but vary in activity. The discovery indicates that the subphylum Tunicata or Urochordata (phylum Chordata) may be an abundant source of bioactive compounds of pharmaceutical interest (*4*). Another tunicate, of the genus *Trididemnum*, when extracted with a mixture of methanol and toluene (3:1), showed activity against herpes simplex virus, type 1, grown in CV-1 cells (monkey kidney tissue), indicating that the extract inhibited the growth of the virus. This antiviral activity may also include antitumor activity. When tested against other viruses, essentially all extracts of the tunicate collected at a number of sites showed activity in inhibiting both RNA and DNA viruses. The suggestion that the extracts might also have antitumor properties was evidenced from their high potency against L1210 leukemic cells. The novelty of the didemnins results from a new structural unit for a complex of depsipeptides, hydroxyisovaleryl propionate, and a new stereoisomer of the unusual amino acid statine (*4*).

In a review of compounds from the sea that act on the cardiovascular and central nervous system, Kaul (*5*) pointed out that drugs of high pharmacologic activity from nature have, in fact, been unsurpassed by synthetic compounds. Drugs from nature, predominantly from plants, include morphine, atropine, and digitalis glycosides. Marine animals and plants have yielded cardiovascular-active sub-

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