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THE NEXT GENERATION OF ACCELERATORS*

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I. Introduction

I am both an experimental particle physicist and a machine builder, and from both perspectives I am glad to have the opportunity in closing this conference to speculate about the next generations of accelerators. These machines will be very large and will require correspondingly large intellectual, industrial, and financial resources for their completion. Their parameters must be well chosen because as the machines get larger we can afford to build and run fewer of them.

The demand for machines which extend presently available parameters of energy current or particle type is pushed by the need for information in a new qualitative (particle type) or quantitative (energy or current) range in order to answer the most pressing physics questions of the time in which the machine is designed. The information gained in experiments with a new machine serves as a guide to a more fundamental understanding of nature, often by validating one of several competing models which can each explain most of the phenomenon observed with the previous generation of devices. Professors Trilling and Bjorken, in the previous talks, have discussed what we have learned from the present generation of machines and the directions theory has taken based on these observations. I will speculate about the kinds of machines required to test the critical features of current models of the structure and interaction of the elementary particles and to probe more deeply some of the phenomena not explained by these models.

It takes about ten years from the first conceptual design of a new accelerator to first beam on target. The physics questions which the machine was designed to answer must be proposed sufficiently broadly to remain valid after a decade. The machine type and the design must be set to give a sufficiently large extension of parameters to allow answers to be obtained to questions which have not yet even been posed. (There are very few examples of machines whose greatest impact on the development of physics has come through the experiments listed as most important in the physics section of the design report.) Expansion capability must be built into any new design.

The starting point for any discussion of future machines is what we have available now and in Table I, I list the highest energy machines now running, under construction or in advanced design. In the first group, all of the machines except PETRA/PEP have been running for some time and these machines, with the addition of the SPEAR and DORIS e^+e^- machines, have given us the information leading to the current view of elementary particles.

In the second group of machines the Fermilab Energy Doubler is the first attempt to make a large superconducting accelerator. On the present schedule, it should be finished in 1982 and give a moderate increase in center-of-mass energy for fixed target studied.

Table I

A short catelogue of (a) the highest energy now operating; (b) the highest energy machines now under construction; and (c) the highest energy machines now in the advanced design stage.

Particle Type	Machine and Lab	Energy (GeV)	Operation Date
		(a)	
e^+e^-	PETRA (DESY)	18 × 18	Now
	PEP (SLAC)		
e^-	SLAC	35	Now
P	FNAL	450	Now
	SPS (CERN)		
PP	ISR (CERN)	31 × 31	Now
		(b)	
P	DOUBLER (FNAL)	1000	1982
$\bar{P}P$	AA (CERN)	300 × 300	1982
PP	ISABELLE (BNL)	350 × 350	1986
		(c)	
e^+e^-	LEP (Europe)	80 × 80	1988 ?
P	UNK (USSR)	3000	1988 ?
$\bar{P}P$	TEVATRON (FNAL)	1000 × 1000	1985 ?

The CERN Antiprotron Accumulator project uses the stocastic cooling technique to make antiproton bunches of small phase-space, and with these cooled beams of antiprotons CERN will make the first attempt at producing proton-antiproton colliding beams of useful luminosity (10^{30} $cm^{-2}sec^{-1}$). The design maximum beam-beam tune shift of $\delta\nu = 0.005$ is the same maximum tune shift expected for unbunched proton-proton colliding beams. It is not clear that this value of tune shift can be reached in bunched proton beam collisions. The main physics objective of the Antiproton Accumulator project is to find the Z^0 (the neutral carrier of the weak force) which is expected to have a mass of about 100 GeV. Even if the Z^0 exists it is not certain that it can be found in the proposed experiments for the present model implies an event rate for Z^0 production and decay to the most easily observable final states (e^+e^- or $\mu^+\mu^-$) of between 0.1 and 1 event per day. At the lower end of the rate estimates, the Z^0 could be missed in the background.

The third machine on the list of those now under construction is the superconducting proton-proton colliding beam machine ISABELLE. It is expected to have a luminosity of between 10^{32} and 10^{33} $cm^{-2}sec^{-1}$ and this luminosity estimate is not subject to the same uncertainty as is the case with bunched pp collisions.

The third group of machines in Table I are those now under design. Since none of these has been authorized, the completion dates indicated in the table are only guesses. The LEP design is being carried out at CERN. The three TeV fixed target machine UNK is being designed at Serpukov using 40 kg superconducting magnets. Plans for the eventual addition of various colliding beam options are also being made. The third machine, the Tevatron $\bar{P}P$ collider, is a 10^{30} to 10^{31} $cm^{-2}sec^{-1}$ luminosity $\bar{p}p$ colliding beam project at FNAL which will use the FNAL energy doubler ring to contain the high energy beams, and will use a large aperture accumulator ring (most probably using stocastic cooling) now under study.

In the rest of this talk I will discuss some of the physics issues which go into setting machine parameters, and some of the features of the design of next generation electron and proton machines.

II. Electron Positron Machines

(A) Energy

The first question which must be addressed in

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thinking about a new electron-positron machine is that of its energy. We can look at present theoretical ideas to see if there is a reasonably well defined threshold energy for a new accelerator. Figure 1 takes us on an imaginary trip to very high energies in e^+e^- annihilation. In it I have plotted what we might find for R, the ratio of cross sections for mesons and new lepton production vs. the square of the center-of-mass energy (s). The region below $s \approx 100$ is terra firma. Starting at s a bit below 10 it includes the ψ resonance, the threshold for the production of the heavy lepton τ, the ψ' resonance, the threshold for the production of charmed particles and the associated step in R, and the first two of the upsilon states.

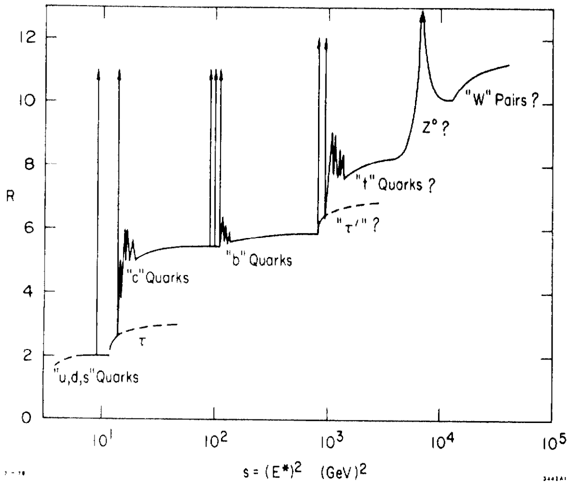

Fig. 1. The ratio (R) of the total cross section for the production of particles heavier than the μ meson to μ meson pair production vs. s, the square of the center-of-mass energy. The region including the three large peaks at around $s = 100$ has been explored and the indicated features seen. The rest is from my imagination.

Beyond $s \approx 100$ is terra incognita. The third upsilon state should be found as should "b" mesons and an associated small step in R. Since new particle families seem to appear at each decade in s, I would guess that the t quark, the charge 2/3 partner of the b which most theoretical models require, will appear at $s \approx 1000$, first with a few narrow resonances and then with about a 20% step in R. We might also find another heavy lepton to complicate the theoretical picture. This region up to $s \approx 1500$ will be the hunting ground of the PETRA and PEP storage rings.

At still higher energies we come to the region where the weak interaction begins to compete with and then to dominate the electromagnetic interaction. At around $s = 10{,}000$, gauge theories would predict the appearance of the Z^0 resonance. At higher energies yet (a few x 10^4 GeV^2), the threshold for charged-vector-boson production will be reached. This high energy region is that which we wish to explore with the next generation of electron-positron machines.

Let us look in a little more detail at the expected phenomenology of the electromagnetic and weak interactions in this high energy regime to see if there are any well defined thresholds to use in determining the minimum energy of the next generation machines. Figure 2 shows the rates expected for production of point-like particles (μ-pair production) in a large e^+e^- machine with a luminosity of 10^{32} cm^{-2}sec^{-1}. The curve shows, as a function of center-of-mass energy, the electromagnetic one-photon annihilation process and two models of the weak interaction (no interference between electromagnetic and weak interactions is included). The Weinberg/Salam model gives a huge resonance peak in the cross section, the location of which depends on the mass of the Z^0. [The predicted Z^0 mass has been slowly increasing with time and now seems to be about 100 GeV ($\sin^2\theta_W \approx 0.2$).] The curve labelled "Fermi" is that expected for an infinite Z^0 mass and a neutral current strength as determined in neutrino experiments (G_0^2 about 12% of G_f^2).

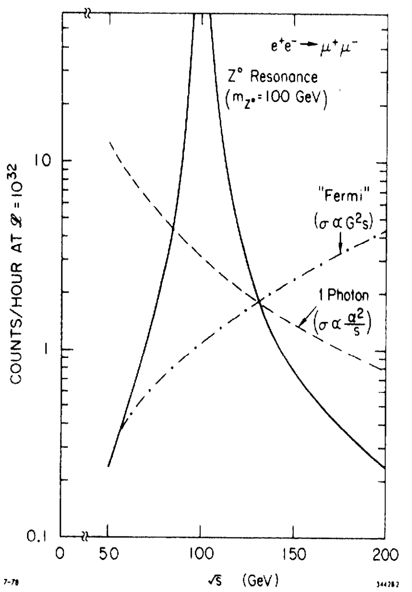

Fig. 2. Counts per hour for μ-pair production at a luminosity of 10^{32} cm^{-2}sec^{-1} vs. center-of-mass energy. The "one-photon" curve give the contribution from the electromagnetic interaction only. The "Z^0" current weak interaction is mediated by a Z^0 of mass 100 GeV and $\sin^2\theta_W = 0.25$. The curve labeled "Fermi" gives the rate for a weak interaction with no Z^0.

Figure 2 defines a minimum energy for the next generation machine in the range of 120 to 150 GeV. Around this energy the weak interaction dominates the electromagnetic interaction, independent of gauge theories or, if gauge theories are correct independent of the value of the Z^0 mass.

A second threshold can be defined in terms of particular models. This threshold is the energy required for the production of pairs of charged W mesons. In the standard model, this threshold energy is about 200 GeV in the center-of-mass.

I conclude that the weak interaction as we understand it today gives only one model independent threshold corresponds to a c.m. energy of 120-150 GeV. We have insufficient information at present to specify the next weak interaction threshold, but it would be desirable to design a new machine such that it's energy could be increased to the 200 GeV region to cover what present theories predict for charged bosons. A machine of ~150 GeV gives an increase of 15-20 in s over that available with PEP and PETRA, and if past experience is a guide we might expect some surprises in hadron physics as well as a more fundamental knowledge of the weak interactions.

(B) e^+e^- Storage Rings

The basic equation governing the design of an electron-positron machine is

$$\mathscr{L}(10^{32}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}) = 12.3\ \frac{\Delta\nu^* P_B(\mathrm{MW})\ \rho(\mathrm{m})}{E_B^3(\mathrm{GeV})\ \beta_y^*(\mathrm{m})} \quad , \qquad (1)$$

where $\mathscr{L}$ is the desired luminosity at each collision point (reaction rate per unit cross section), E_B is the energy of one beam in the ring, P_B is the rf power required to make up for synchrotron radiation losses in both beams, ρ is the bending radius, $\Delta\nu^*$ is realted to the focusing effect of one beam on particles in the other beam at a collision point, and β_y^* is a property of the guide field. Clearly, β_y^* should be made as small as possible, and I will take it to be 0.1 m. It cannot be made smaller than the length of the bunch in the storage ring (5 to 6 cm) nor can it be reduced significantly below 0.1 m without excessively shortening the free space for experiments in the interaction region.

The parameter $\Delta\nu^*$ is the linear tune shift at each interaction point. On the basis of experience with many different kinds of electron storage rings at many different energies, this quantity is independent of the design of the machine and has a maximum value of approximately 0.06 ($\Delta\nu$ for proton rings is thought to be much smaller, approximately 0.005).

Defining a new parameter δ equal to the beam energy in units of 100 GeV, Eq. (1) can be rewritten as

$$P_B(\mathrm{MW})\ \rho(\mathrm{km}) = 136\,\mathscr{L}\delta^3 \quad . \qquad (2)$$

The physics research objectives of the machine specify δ and $\mathscr{L}$. The machine design is generally determined by P_B and ρ, and their product is constrained by Eq. (2).

The beam power and bending radius can be obtained by a process of cost minimization. This minimization yields a radius and a cost for a machine which both scale as the square of the beam energy. If one uses PEP and PETRA unit costs, the circumference of a big e^+e^- machine is given by

$$2\pi R \approx 40(E(\mathrm{GeV})/100)^2\ \mathrm{km} \quad . \qquad (3)$$

New technology, such as rf superconductivity or pulsed acceleration techniques, only changes the constant in Eq. (3). The most optimistic estimate for low cost superconducting rf that I have heard reduces the "40" in Eq. (3) to "30".

Figure 3 shows the cost vs. radius for a 60 × 60 GeV and a 100 × 100 GeV e^+e^- machine built with the same techniques and unit construction costs as used in the PEP and PETRA projects. The minimum in the total costs (including ten years operating power) is quite flat and this flatness allows us to build a machine which may be able to answer the questions not asked but which may be the burning issues of the day ten years from now when the machine first runs. The strategy is to choose an energy slightly above the lowest threshold energy definable now and build a machine with a larger than optimum radius for this energy. The extra costs for this non-optimum radius is small, and the energy of such a machine can be increased if physics warrants it by the application of conventional technology and increased even further by the application of the new acceleration technologies.

This is just the strategy which the CERN group is using in the design of LEP. The LEP machine has a circumference of 30 kilometers which dwarfs the size of the SPS machine. It will probably be designed to turn-on with enough conventional rf to reach 120 GeV in the center-of-mass. An aggressive program to develop superconducting rf systems is being pursued in Europe and if this program comes to fruition the energy of the LEP machine can probably be increased to betwen 200 and 250 GeV in the center-of-mass.

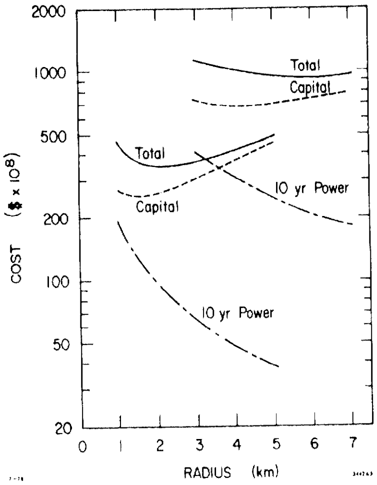

Fig. 3. Cost vs. radius of a 60 and a 100 GeV per beam machine. Costs are based on PEP unit costs in 1976 dollars and do not include office building lab space, etc.

(C) Linear Colliding Beam Machines

The LEP storage ring will probably cost about 10^9 Swiss Francs to construct. Since the scaling laws for e^+e^- storage rings indicate an increase in cost proportional to the square of the energy, it may seem that we are close to the maximum financially practical energy for e^+e^- colliding beams. There may however be an alternate for very high energy e^+e^- collisions -- linear colliding beam systems. Colliding linac beams to produce large center-of-mass energy has been discussed from time to time in the literature (see for example, U. Amaldi, Phys. Lett. B61, 313 (1976)). More recently M. Tigner of Cornell, A. N. Skrinsky of Novosibirsk, and I discovered that we had each been independently thinking about such systems and their performance limitations.

Consider the case of two uniform cylinders of charge of radius r_b and length ℓ_b being fired at each other at a frequency of f Hz. The luminosity in this situation is given by

$$\mathscr{L} = \frac{n^2 f}{\pi r_b^2} \qquad (4)$$

where for simplicity I have assumed that the number of particles in the two beams are equal. In e^+e^- collisions, particles in each beam are bent toward the axis of the other beam by the strong electromagnetic forces as illustrated in Fig. 4.

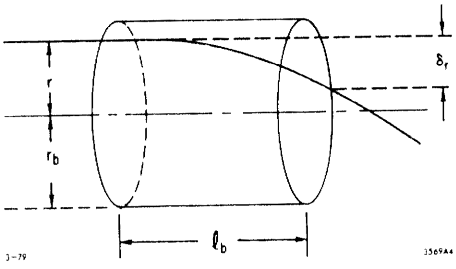

Fig. 4. Geometry of linear colliding beam collision region.

The fractional change in radius of a particle in one beam on passing through the other beam is given by

$$\Delta = \frac{\delta r}{r} \approx \frac{r_e \ell_b n}{2 r_b^2 \gamma} \tag{5}$$

where r_e is the classical electron radius and γ is the energy of the particles in electron rest mass units.

In terms of the parameter Δ the luminosity is given by

$$\mathscr{L} = \frac{2\Delta\gamma n f}{\pi r_e \ell_b} \tag{6}$$

Since the beams are only used once, Δ may be allowed to become very large. The maximum allowable value of Δ is not easy to determine and it will probably take a computer simulation to find it, but for this analysis I will simply take $\Delta_{max} = 1$. At this limit the luminosity is given by

$$\mathscr{L}_{max} \approx 10^{31} P_b\,(\mathrm{MW})\ \mathrm{cm}^{-2}\mathrm{s}^{-1} \tag{7}$$

where I have now assumed Gaussianly distributed beams with $\sigma_\ell = \frac{1}{2}$ cm.

The luminosity defined in Eq. (7) is dependent of energy and only depends on the beam power! This implies that the cost of a machine of fixed luminosity scales like the first power of the energy (the length of the linac required to accelerate the beam increases linearly with energy), while as we have seen earlier the cost of storage ring colliding beam scales as the square of the energy. At some energy, linear electron-positron colliding beam systems must be less costly than storage rings.

A second limit for linear colliding beam systems comes from the emission of synchrotron radiation in the collision process. The fractional energy loss by a particle at the edge of one beam passing through the other beam is given by

$$\left(\frac{\Delta E}{E}\right)_{sync} \propto \frac{E^3}{\rho_B}\,\theta_B \tag{8}$$

where θ_B, ρ_B are respectively the bend angle and radius of curvature of the particle deviated by passing through the other beam ($\theta_B \approx r_b/\ell_b$; $\rho_B \approx \ell_b^2/r_b$). The synchrotron energy loss gives an energy spread in the collision and the maximum value of this energy spread is limited by the physics experiments one wants to carry out. At $\Delta = 1$ the synchrotron radiation induced energy spread is given by

$$\left(\frac{\Delta E}{E}\right)_{sync} \approx \frac{E(\mathrm{GeV})\,\mathscr{L}(10^{32})}{4f(\mathrm{hz})} \tag{9}$$

Thus, a given maximum energy spread sets a lower bound on the repetition rate of the machine.

We do not yet have a positron source to use in this linear colliding beam system. At sufficiently energy we can, in fact, regenerate the required number of positrons from the electron beam after the beam-beam collision. All positron sources now in use (DESY, Frascati, Orsay, SLAC) have to within 20% the same efficiency for positron production and this efficiency only depends on the energy of the particles incident on the positron production target.

$$\frac{n_+}{n_-} = 10^{-2}\,E_i\,(\mathrm{GeV}) \tag{10}$$

For a beam energy of 100 GeV the positrons can be regenerated each pulse after the primary collision by the disrupted electron beam (50 GeV beams can obviously be used if both the electrons and positrons are used to produce a new batch of positrons).

The standard positron sources now in use give beams of large emittance (the normalized emittance of the SLAC positron source is $\varepsilon_n = \pi x x' \gamma = 0.3\pi$ cm, about 100 times the normalized emittance of the SLAC electron source). The positrons can be cooled by radiation damping in a storage ring. For an electron storage ring of tune ν and energy E in the smooth guide field approximation.

$$\varepsilon_n = 0.4\pi\,E^3(\mathrm{GeV})/\nu^3\ \mathrm{cm} \tag{11}$$

After damping, a beam of $E = 0.5$ GeV in a storage ring of $\nu = 2$ will have the same emittance as that of the SLAC electron beam.

A complete linear colliding beam system is illustrated schematically in Fig. 5.

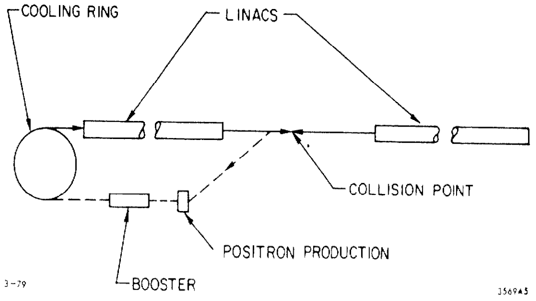

Fig. 5. Schematic of a linear colliding beam system.

It consists of two main linear accelerators, a positron production target, a cooling ring, and a booster to get the positrons to the appropriate energy for injection into the cooling ring. Some parameters for a possible linear colliding beam system with an induced energy spread of 1% using round Gaussian beams of radius σ_r are

E	350×350	GeV
f	2500	Hz
n	10^{11}	
σ_r	1.5×10^{-6}	m
$\mathscr{L}$	10^{32}	$\mathrm{cm}^{-2}\mathrm{sec}^{-1}$

Linear colliding beam systems are still in their infancy. Much remains to be done in the way of system optimization, study of the beam-beam limit, study of the possibility of multiple interaction points and investigation of the stability and phase-space dilution of large linear accelerators. The linear scaling law with energy makes these systems extremely promising and we are pursuing various studies on the subject at SLAC.

III. Proton Machines

(A) Physics

The center-of-mass energy available in a fixed target machine is proportional to the square root of the energy of the beam incident on the target. The center-of-mass energy, the machine intensity, and the variety of beams available determine which of the physics questions described earlier by Professor Bjorken can be addressed with such a machine. Twenty TeV is about as high an energy as I can think about now and I list below the center-of-mass energies of a 20 TeV proton beam on a fixed target, of the 10 TeV neutrino beams which can be generated with such protons, and of some of the other machines now under design or in construction.

Machine	C.M. Energy (GeV)
20 TeV p	190
10 TeV ν	135
LEP	150-200
ISABELLE	700
CERN AA	600
FNAL $\bar{P}P$	2000

This list indicates to me that fixed target machines even at 20 TeV cannot compete in the search for the answers to many of the questions defined earlier. For example, they are not competitive with LEP in searches for new quarks and leptons or for Z^o decay studies. They cannot compete with LEP, ISABELLE, the CERN AA project, or the FNAL $\bar{P}P$ project in searches for new high mass carriers of neutral currents. They can also not compete with the CERN AA, ISABELLE, or the FNAL $\bar{P}P$ in searching out new high cross section effects in proton-proton collisions such as those things hinted at by some recent cosmic-ray data (Centauro events).

On the other hand, such large proton machines may be interesting in studies of meson-nucleon interactions (the proton colliders have no secondary beams); large transverse momentum experiments where the large effective luminosity of the fixed target machines ($\mathscr{L} = 10^{38}$ cm^{-2}sec^{-1}) should allow measurements to be made to much larger p_T than in the colliders; and in the studies of neutrino-proton reactions. The principal interest in big proton machines is probably associated with the various colliding beam schemes which require a large proton machine as an injector.

(B) Machines

With very few assumptions about the properties of the big proton machines, I can describe one. I assume a peak magnetic field of 100 kgauss (not now available but being worked on), an average external beam current of 10^{13} protons per second, and a repetition rate of 0.02 sec^{-1}. Then, with the maximum energy of the beam in TeV, the approximate parameters of the machine are given below.

Circumference (km)	3E
Refrigerator Power (MW)	4E
RF (MV per turn)	2E^2
Total rf Power (MW)	(5-10)E
Peak Stored Energy in Field (megajoule)	1000E
Peak Stored Energy in Beam (megajoule)	75E
Cost (\$ x 10^6)	250E

The numbers for a 20 TeV machine are very large. The circumference is twice that of the LEP design. Nearly 100 MW of power go into the refrigeration system mostly for hysteresis losses in the superconductor. The rf accelerating system requires over 800 MV per turn and a conventional rf system would have an average power dissipation of 100 to 200 MW (clearly rf superconductivity is applicable here as well as in the e^+e^- storage rings). The maximum energy stored in the field at the peak of the acceleration cycle is 20 gigajoules making something of a problem for quench protection. The stored energy in the beam at the peak energy is about 1½ gigajoules, perhaps giving some severe targeting problems. The cost of the 20 TeV machine would be roughly around 5 billion dollars making it unlikely that such a machine will be built by other than an interregional collaboration.

The parameters of a possible set of colliders to be associated with the big proton machine are given in Table II. These numbers were worked out by S. Y. Chen, E. D. Courant, E. Keil, N. N. King, P. McIntyre, T. Nishikawa, and M. Vivargent at the ICFA meeting on limitations of accelerators held at FNAL in October of 1978. The $\bar{p}p$ luminosity is limited by the assumption that the total $\bar{p}$ production rate per day would be the same as for the CERN AA project. A special fast cycling machine the size of the CERN PS or the Brookhaven AGS could increase the $\bar{p}$ yield substantially and allow increased luminosity. The luminosity is also limited by the length of the free space assumed for experiments -- to a first approximation the luminosity is proportional to one over the length of the free space and I personally would gladly trade a factor of 4 in the length of the experimental area for a factor of 4 increase in luminosity.

Table II
Properties of some colliders which can be associated with a 20 TeV proton machines.

Parameter	$\bar{P}$ - P	P - P Bunched	P - P Continues	e - P
E (TeV)	20 × 20	20 × 20	20 × 20	.14 × 20
B (kg)	100	100	100	.7 × 100
n (each bm)	10^{12}	6 × 10^{14}	6 × 10^{14}	4 × 10^{13}
Bunches	4	2400	cont	160
$\Delta\nu$	.005	.005	.005	.06 × .005
Free Space for Exp (m)	±120	±120	±170	±20
$\mathscr{L}$(cm^{-2}sec^{-1})	2.5 × 10^{30}	1.5 × 10^{33}	5 × 10^{32}	1 × 10^{32}

IV. Conclusions

There seems to be no technical barrier to the construction of very high energy machines. New technology such as superconducting rf systems for linear colliding beam machines and acceleration in circular machines as well as high field superconducting magnets will almost certainly be required to keep costs down. Major theoretical efforts will be needed to better understand the non-linear interactions of the beams with guide fields, accelerating systems and vacuum chambers, for these non-linear effects will probably be more pernicious in very large machines than in our present machines.

Our main problem will be finance. We have lived by our wits recently and learned from each generation of machines how to build the next at lower unit costs per meter of magnet, per unit beam energy, per unit center-of-mass energy, etc. LEP will cost less than the SPS. ISABELLE will cost less than FNAL. While this trend will surely continue, the jump in machine parameters in size which will come beyond machines like LEP will almost certainly result in devices more costly than any that have been built before.

I cannot believe the gloomy statements one sometimes hears that the machines now being built will be the last to be built. The governments that support us have many motives (inertia, worries about unemployment, international relations, balance of payments, etc.), but one of these motives is the same as ours -- intellectual curiosity and a desire to know how the universe is made. We do not do a very good job of communicating the intellectual adventure of our work and we should certainly do it better. However, as long as the experiments, theories, and accelerators of elementary particle physics remains central to answering the great questions about the birth of our universe, the ultimate structure of matter, and the relations between and unification of the forces of nature, our field will continue. The next accelerators may be built by a nation, a region, several regions, or the world, but they will be built. I think you and I will have a hand in both building and using them.