ELECTRON-PROTON COLLIDERS IN THE U.S.

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High energy electron-proton colliders provide a unique opportunity for studying details of the electro-weak interactions, as well as probing nucleon structure at order-of-magnitude shorter distances than in conventional fixed target facilities. The North American based ep group, consisting of several U.S. university and national laboratory based groups as well as members of the Canadian and European communities, has spent the last two and one-half years actively pursuing the goal of constructing an electron-proton collider facility in the U.S. to become operational in the second half of this decade.

We submitted initial proposals to Fermilab in June 1981 (Fermilab Proposal 659 and CHEER). We proposed the building of a 10 GeV electron storage ring tangent to the Tevatron at the area D0 along with an associated detector. These proposals concentrated on detailing the huge physics potential of an ep collider operating at $S = 40{,}000\ \mathrm{GeV}^2$, and on demonstrating that luminosities close to $10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ with longitudinally polarized electrons at the interaction point are obtainable. Proposal 659 contained the first paper design of an electron storage ring capable of attaining greater than 80% longitudinally polarized electrons concurrent with a finite vertical emittance. These proposals were met with some enthusiasm by the Fermilab PAC but were never officially acted upon, presumably because it was felt that the scope of the project was beyond the available resources.

In November of 1981 a proposal was submitted to Brookhaven National Laboratory for a 20 GeV electron storage ring residing within the Isabelle tunnel and colliding at two points with one of the Isabelle proton beams. This proposal formed the basis of the Johnsen Committee Report on the feasibility of doing ep physics in the Isabelle tunnel. At the present time it appears that the Brookhaven management's primary commitment is to a proton-proton collider and that an electron-proton collider would only be considered after pp.

In December of 1981, we submitted a proposal (Proposal 708/719) to Fermilab for a phased approach to ep which could be initiated by the construction of a 5 GeV electron storage ring. Such a machine would allow the implementation of ep physics in the U.S. well before the end of this decade, while also serving as a potential injector for higher energy rings which may then be contemplated. The estimated price tag of \$30 M (ring plus detector) is substantially less than that of the 10 GeV ring. This proposal was met with considerable enthusiasm both from the Fermilab PAC and management. However, concern over possible interference with the startup of the Tevatron I and II programs resulted in the recommendation that such a project should come after $p\bar{p}$.

While the concerns expressed with regard to the availability of operational facilities at the Tevatron are very real, we believe that a schedule which calls for electron-proton collisions at $5 \times 1000\ \mathrm{GeV}^2$ coming after $p\bar{p}$ is not in the best interests of U.S. high energy physics. We believe it is essential to set out immediately on a course which will ultimately lead to an electron-proton collider operating in the range $S = 40{,}000\ \mathrm{GeV}^2$ to $S = 100{,}000\ \mathrm{GeV}^2$. A natural first step would be the construction of the 5 GeV ring described in Fermilab Proposal 719. Collisions

Table 1

Location	Energy (e x p GeV^2)	$\sqrt{s}$ (GeV)	$\mathcal{L}$ ($\mathrm{cm}^{-2}\mathrm{s}^{-1}$)	$\Delta\nu_e$	$\Delta\nu_p$	Polarization (%)	τ_p (min)	Cost (\$ M)
FNAL	5 x 1000	140	4×10^{31}	0.03	0.003		27	17 (e only)
BNL	20 x 400	180	5×10^{31}	0.03	0.002	75%	13	85 (e only)
Tristan (Japan)	25 x 300	170	2×10^{31}	0.03	0.005			
FNAL	10 x 1000	200	4×10^{31}	0.03	0.003	83%	18	40 (e only)
LEP x SPS (CERN)	50 x 300	240	1×10^{31}	0.006	0.0005			
HERA	30 x 800	310	6×10^{31}	0.014	0.0009	~ 80%	~ 15	
FNAL	25 x 1000	320	5×10^{31}	0.03	0.002	~ 80%	~ 15	350 (e x p)

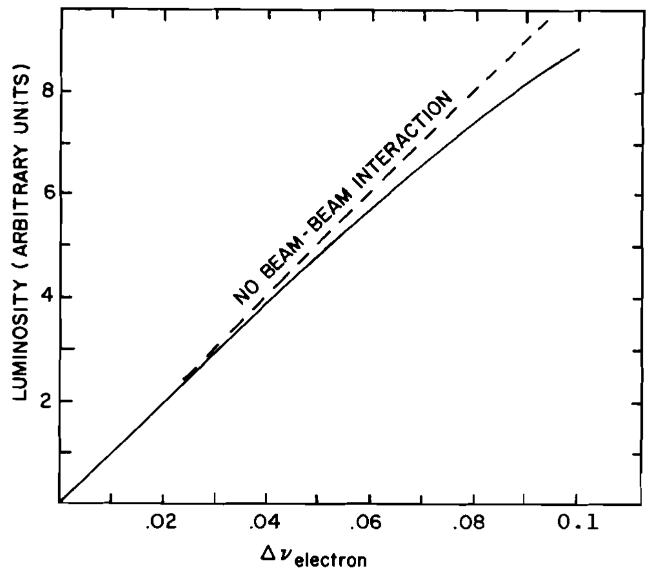

Fig. 1

between electrons and protons, even if for only a few weeks a year, would provide invaluable experience in learning how to operate with this new type of collision.

Machine Parameters

The three most important parameters describing the performance of an electron-proton collider are the center-of-mass energy, the luminosity, and the polarization level with longitudinally polarized electrons present at the interaction point. In some ways energy and luminosity can be traded off to a greater degree than in e^+e^- or $\bar{p}p$ colliders. However, in general one still wants to maximize the energy subject to the constraints of money and technical difficulty. We consider here center-of-mass energies squared in the range S = 20,000 GeV^2 to S = 100,000 GeV^2. The lower limit is set by physics considerations -- it is the energy which gives at least an order of magnitude increase in accessible Q^2 over fixed target lepton scattering experiments at the Tevatron. The upper limit corresponds to the highest energy which can be achieved at a cost of the order of $350 M in an optimized ep collider facility. A general analysis of the costs of electron-proton colliders may be found in the appendices.

In Table 1, we list the various possibilities for rings in the energy range given above. Included in the table are the three rings for which we have prepared specific proposals, the TRISTAN project in Japan, a LEP-SPS collider, HERA, and a 25 x 1000 GeV^2 collider at Fermilab utilizing a new proton ring (included in the cost). Luminosities of all these machines are estimated to be around 5 x $10^{31}cm^{-2}s^{-1}$. However varying assumptions go into these calculations. HERA and TRISTAN are based on non-zero angle crossings between ribbon electron and proton beams. The colliders we have proposed in this country are all based on zero angle crossing and round beams. We have advocated zero angle crossing because it does not require the use of unnaturally short proton bunches, and round electron beams because they provide a better match to the proton beam. Another potential advantage of a round beam is seen in Fig. 1 where we display the dependence of the luminosity on the proton current (i.e. electron tune shift) as calculated for round beams using the computer program of R. Talman of Cornell. Our investigations using this program seem to indicate that the maximum allowable electron tune shift due to the beam-beam interaction may be twice as large for round beams as for ribbon beams. In other words the achievable luminosities may be twice what are indicated in Table 1 if enough protons were available. The tune shift limits in electron-proton colliders in general also appear to benefit from reduced damping times compared to presently operating e^+e^- rings.

Table 1 also shows polarization levels of about 80% with longitudinally polarized electrons at the interaction point. The uniqueness of the electron-proton collider as a tool for studying the interactions of right-handed electrons (or left-handed positrons) has led the proponents of electron-proton colliders to consider the production of longitudinal polarization at a level of greater than 80% to be a requirement of any electron ring design. At present the mechanism of 'stochastic depolarization' is well understood[1,2] as are means of combating it.[3,4,5] In the absence of stochasic depolarization, the limits on the polarization levels achievable (beyond the natural limit of 92.4%) arise from the 'reverse bending' present in the polarization rotators themselves. The depolarization due to this mechanism can probably be limited to 5% per

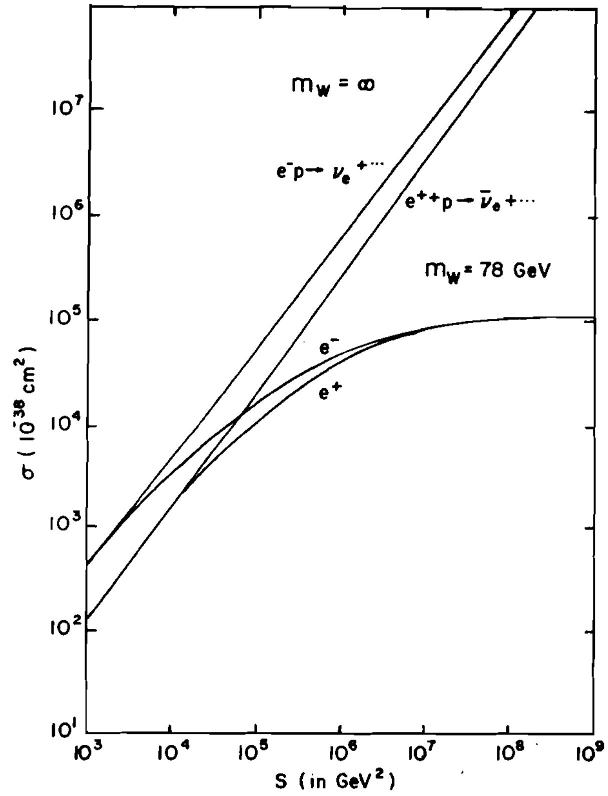

Fig. 2

interaction region.

Details of the cost estimates given in Table 1 may be found in the individual proposals and in the appendices of this report.

Physics of Electron-Proton Collisions

Over the last twenty years, the contributions to our knowledge of nucleon structure which have come from lepton-nucleon scattering experiments have been invaluable. The initial observation of deep inelastic electron scattering and confirmation of approximate Bjorken scaling provided the first direct experimental evidence for the composite nature of the nucleon. This was followed by the discovery of neutral currents in neutrino interactions and the observation of parity violation in polarized electron-deuterium scattering -- two of the most spectacular successes of the Glashow-Weinberg-Salam (GWS) model of the electroweak interaction. With the advent of an electron-proton collider operating in the range S = 20,000 GeV^2 to 100,000 GeV^2 we expect to enter the regime where the electromagnetic and weak interactions become of comparable strength, where the effects of the W's and Z will be clearly seen, and where we will be able to search for modifications to the GWS and QCD 'standard model'. Figure 2 shows for example the total cross section for the reactions

$$e^-p \to \nu_e X$$
$$e^+p \to \bar{\nu}_e X$$

as a function of S evaluated using the standard model. Much of the physics we discuss here will be accessible in complementary ways at other machines planned for the coming decade. However there are also many areas where the electron-proton collider is uniquely suited for observing new phenomena.

One of the most interesting (and perhaps likely) modifications to the standard model one could imagine would be the ultimate evolution of the low energy V-A structure of the weak interactions into a symmetric V-A/V+A structure at high energies. The best limits at present on so-called 'right-handed' couplings come from the measurements of the decay distribution of muons produced from pion decays. The lower limit on the mass of a right-handed W with a standard coupling strength is about 200 GeV. The ability to observe interactions between longitudinally polarized electrons and protons in the ep collider provides a direct measure of the contributions of right-handed W's with masses up to 300 GeV (S = 20,000 GeV^2) or 650 GeV (S = 100,000 GeV^2). In addition the electron-proton collider is unique in its sensitivity to such effects even in the presence of imagined pathologies such as right-handed currents which couple only to heavy quarks.

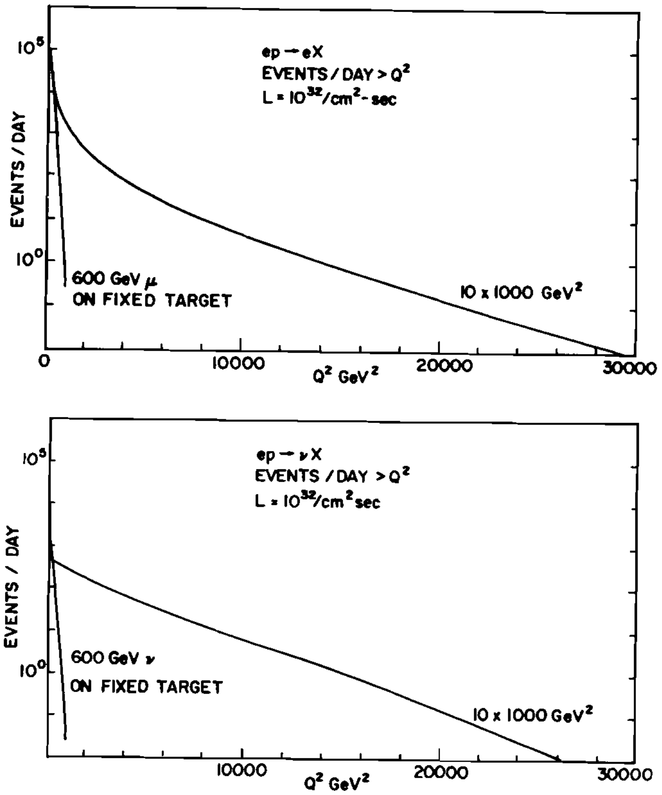

Fig. 3

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Other modifications to the standard model which could also appear in ep

Table 2: Virtual Photoproduction of Heavy Quark States

	Assumed Cross Section	Expected Yield *
1) $\gamma^* \to D^0\bar{D}^0$	500 nb $(1 - \frac{12\ \text{GeV}}{\nu})$	490 K
2) $\gamma^* \to B\bar{B}$	27 nb $(1 - \frac{68\ \text{GeV}}{\nu})$	91 K
3) $\gamma^* \to t\bar{t}$ (20 GeV top)	7 nb $(1 - \frac{893\ \text{GeV}}{\nu})$	21 K
4) $\gamma^* \to t\bar{t}$ (50 GeV top)	1.2 nb $(1 - \frac{5431\ \text{GeV}}{\nu})$	1.3 K

* Yield for an integrated luminosity of 10^{38}cm^{-2} 10 on 1000 GeV ep collisions.

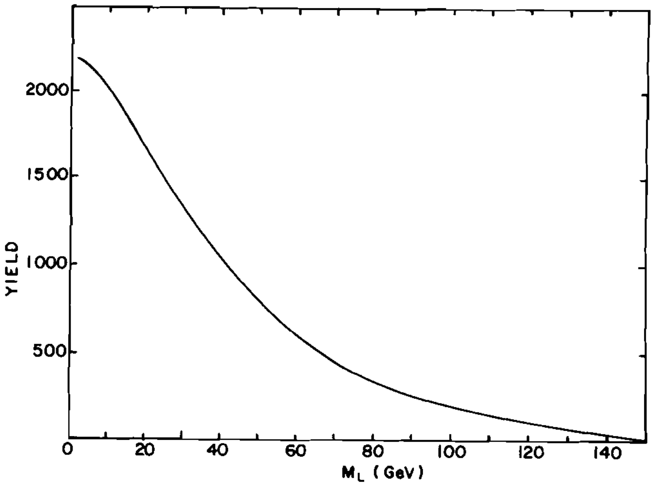

Fig. 4

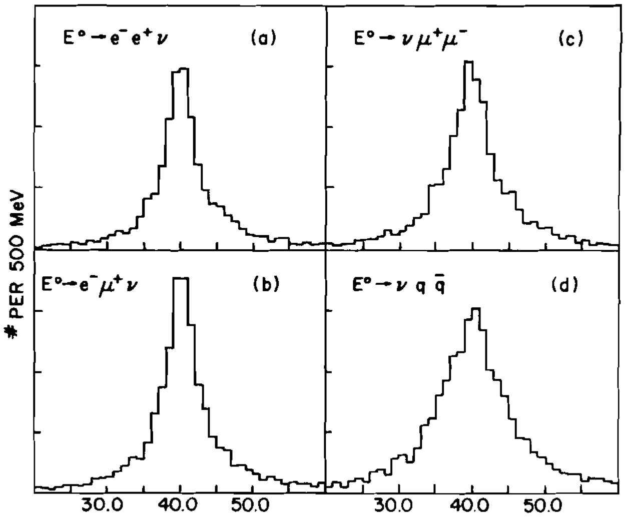

Fig. 5

interactions would be the observation of quark substructure or the appearance of additional W's and Z's. The electron-proton collider will allow us to measure the nucleon structure functions up to Q = 5000 GeV^2 (at S = 20,000 GeV^2) and to look for power law contributions to scale breaking at mass scales of 300 GeV. Such power law contributions could be an indication of quark substructure. However if quark substructure is present it should also manifest itself through the existence of events which look dramatically different from ordinary ep events. Measurement of the scattered electron in the reaction, ep → ex, allows a determination of the direction and energy of the scattered quark on an event-by-event basis. Observation of a jet with a large transverse momentum (say > 100 GeV) relative to this direction would be an unmistakable signal of quark substructure. Study of the Q^2 dependence of the reactions, ep → νx, will allow identification of higher mass W's with standard couplings and masses less than 200 GeV.

Of course the ep collider will also be used to test the standard model by measuring the Q^2 and x dependence of both the charged and neutral current reactions. Figure 3 gives the event yields versus Q^2 for these reactions in a collider operating at 10 x 1000 GeV^2, with an integrated luminosity of $10^{38}cm^{-2}$. The mass of the $W^\pm$ can be measured to ± 5 GeV and the mass of the Z^o to ± 15 GeV through propagator effects.

The electron-proton collider is an ideal place to look for heavy quark states. Such states can be produced either through scattering at high Q^2 off heavy quarks in the nucleon sea, or at low Q^2 through photoproduction. In Table 2, we show the expected yields for the photoproduction of heavy quarks in a run of integrated luminosity $10^{38}cm^{-2}$ at S = 40,000 GeV^2. We assume cross sections which have an energy dependence given by photon-gluon fusion models and a Q^2 dependence which is cut off at the mass squared of the heavy quark. We see copious yields even for a top mass of 50 GeV. Event yields from high Q^2 scattering of the quark sea are comparable to those shown here.

Finally, the electron-proton collider possesses a unique ability to look for such new phenomena as neutral heavy leptons (Fig. 4) and leptoquarks. Neutral heavy leptons could be identified through their decays into final states containing three leptons as in Fig. 5. Leptoquarks with masses < 200 GeV would produce a 'bump' in the measured x distributions at $X = M_{LQ}/\sqrt{s}$.

We summarize in Table 3 the sensitivity of electron-proton colliders to various aspects and modifications to the standard model for three different operating energies. The physics opportunities presented by electron-proton colliders are not only complementary to those expected in other high energy physics facilities planned for the coming decade, but are in many ways unique. They include studies of nucleon structure, the electro-weak interaction, high energy photoproduction of new flavors, and searches for new leptonic states in ways which are inaccessible to other colliding beam or fixed target facilities.

References

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Table 3

S $(GeV)^2$	20,000	40,000	100,000
Q^2_{max} (GeV^2)	5000	7000	10,000
ΔM_W (GeV)	$\pm$ 5	$\pm$ 4	< 4
ΔM_Z (GeV)	$\pm$ 20	$\pm$ 14	$\pm$ 10
Quark Substructure (cm)	6×10^{-17}	4×10^{-17}	2.5×10^{-17}
Right-Handed W Mass (GeV)	300	400	700
Second W Mass (GeV)	200	250	400
Neutral Heavy Lepton Mass (GeV)	75	100	150
Top Quark Rate (50 GeV top)	9 K	27 K	750 K
Lepto-Quark Mass (GeV)	140	200	300

Appendix I

Cost Estimates for 5 x 1000 GeV at Fermilab and 20 x 400 GeV at Brookhaven

We have estimated the costs of both a 5 GeV electron storage ring tangent to the Fermilab Tevatron and a 20 GeV electron ring residing within the existing Isabelle tunnel. The costs have been estimated by identifying the component costs and then adding a fixed percentage to account for EDIA, installation, and contingency. The cost of components is based on experience both at CESR and PEP, as well as on direct calculation. All costs are in 1981 dollars.

Table AI-1 shows the cost estimates of the proposed Fermilab and Brookhaven electron rings. Included in the bottom line are component costs only. EDIA, installation, and contingency probably increase the actual costs by 65%. Both rings use a 100 MeV linac which is assumed to be based on acquired sections of the HEPL Mark III linac. More energy would be needed for positron production. The injector for the Fermilab machine is a 1.5 - 2.0 GeV rapid cycling booster.

Table AI-1

	5 GeV (FNAL)	20 GeV (BNL)
I. Tunnel (w/utilities	\$ 3.1 M	\$11.7 M
II. Magnets (w/Power Supplies)	1.8	10.3
III. Vacuum	1.2	10.
IV. rf	0.8	11.6
V. Controls	1.2	3.7
VI. Linac	1.3	1.3
VII. Injector	1.0	2.0
	\$ 10.4 M	\$50.6 M
EDIA/ Installation	5.2	25.3
Contingency (10%)	1.6	7.6
Circumference	472 m	3834 m
Operating Power	1.2 MW	19 MW

Appendix II

Cost Estimate/Optimization for ep at Fermilab

In conjunction with Fermilab personnel we have made estimates of the cost of building an electron-proton collider facility at Fermilab. The costs of the electron ring are estimated using a procedure described in Fermilab Proposal 719. The proton ring is assumed to be a new ring of flexible dimensions constructed using Doubler magnets. Its cost is estimated on the basis of information provided by R. Lundy and P. Mantsch of Fermilab. Included in the cost estimates are component costs as well as the construction of four experimental areas. Not included are EDIA, installation, and contingency. These last three items probably add 50%-60% to the total cost.

Two cases are considered: 1) electron and proton rings in separate tunnels; and 2) electron and proton rings residing within the same tunnel. A cost optimization is performed for choosing electron and proton ring energies to produce the desired center of mass energy. It is found that the optimized electron energy is a weak function of S and lies in the range 17-29 GeV for the range of S considered (40,000 - 200,000 GeV^2). It is also found that there is little difference in the costs of 1) and 2).

The results of these calculations are given in Fig. AII-1 where we plot on the vertical axis the total cost of an electron-proton collider and on the horizontal axis the electron energy. Shown on the plot are the contours of constant S ($= 4E_eE_p$) and the contours of constant proton energy. Note that the figure can be used either to find the maximum proton energy for fixed \$ and fixed S, or the maximum S for fixed \$ and fixed proton energy. One can also determine the cost (or savings) of raising the proton energy while keeping S fixed. For example we see that raising the proton energy from 1 TeV to 1.5 TeV at S = 80,000 GeV^2 only increases the total collider costs by 12%.

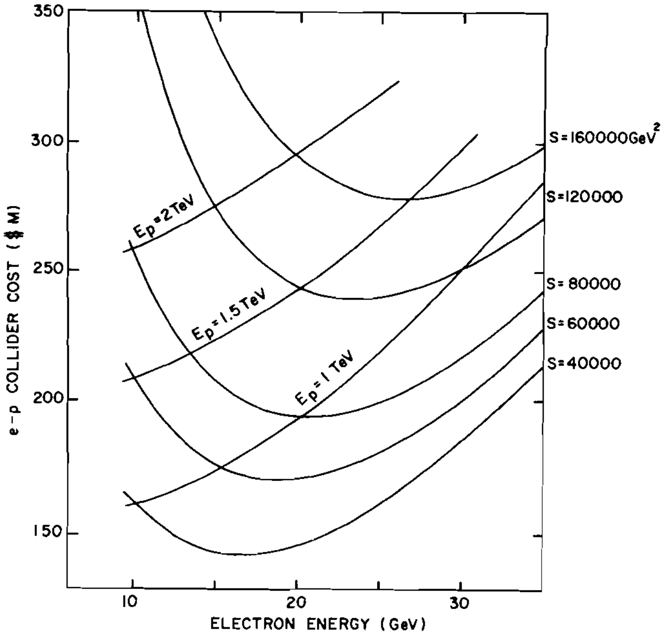

Fig. AII-1

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HIGH ENERGY PHYSICS AT BROOKHAVEN NATIONAL LABORATORY

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Prior to discussing the present and future high energy physics plans at Brookhaven National Laboratory (BNL), I would like to make a few preliminary remarks. In earlier talks we heard about multi-TEV accelerators placed on large expanses of vacant land (deserts) and costing multibillions of dollars. These are fine, worthwhile speculative machines and ultimately the aim is indeed to get to this higher energy domain. However, I remind you that the uncertainty in the cost estimates of such new facilities is of the same order of magnitude as the present total yearly funding of high energy physics, ~$400M. If we can envision such large funding increases, then solving our present funding dilemma should be almost trivial. The present difficulties are illustrated in Figure 1 where total DOE funding for high energy physics since 1967 is plotted in FY 1983 dollars. One notes the disaster from FY 1973 to FY 1975, the partial restoration by FY 1977, and the slow but steady erosion of funding since 1978. In particular, the drop in 1982, which hopefully is being restored in 1983, has been a main detriment to the orderly carrying out of the agreed upon high energy program. In fact it is the shortfall of the 10-20% that is causing the stresses in the community and a restoration of this ~$40M by 1985 would allow for a balanced, complementary, and exciting program in the U.S. To put things in further perspective, I note in Figure 2 the record of past high energy physics projects and their costs. It is interesting to note costs in a fixed year $ (such as 1982) since we tend to recall uninflated numbers. For instance the cost of the SLAC linac project would be $446M in 1982 dollars, not to mention the Fermilab synchrotron project at $659M. For comparison, I note that the ISABELLE Project, as presented to the Trilling Committee, would cost $400M in 1982 dollars; not an unreasonable sum for such a forefront accelerator.

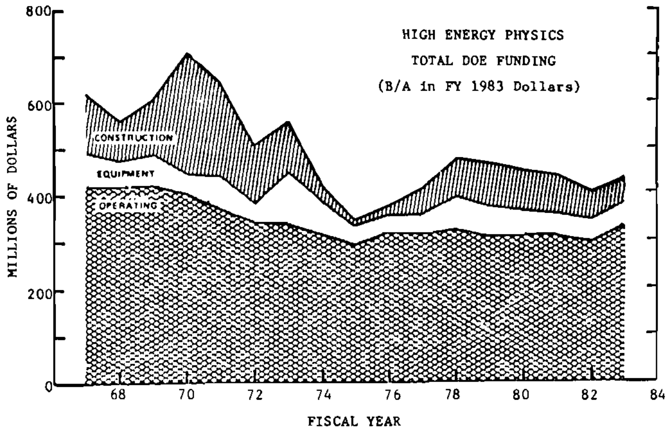

Figure 1.

Record of Past HEP Projects

Device	Site	Const. Start	Init. Test	Cost in Then Yr M$'s	Cost^2 in FY 82 M$
Bevatron	LBL	1949	1954	10	41^3
Bevatron Improvement	LBL	1960	1964	10	41^3
AGS	BNL	1953	1960	31	130^3
AGS Improvement	BNL	1966	1972	49	157
Proton Synchrotron	FNAL	1969	1972	248	659
2 Mile Linac	SLAC	1962	1966	114	446
PEP	SLAC	1976	1980	78	114
CEA	Harvard	1957	1962	10	41
PPA	Princeton	1956	1963	12	49
PPA Addition	Princeton	1961	1965	11	43^3
ZGS	ANL	1959^1	1963	51	209^3

1. Project rescoped in 1961.
2. Based on DOE inflation factors for construction.
3. No inflation factors available prior to 1962. Factor for 1962 was used for prior years.

Figure 2.

The high energy plans at BNL are centered around the AGS and ISABELLE, or a variant thereof. At present the AGS is maintaining a strong and varied program. This last year a total of 4×10^{19} protons were delivered on target in a period of approximately 20 weeks. Physics interest is very strong, half of the submitted proposals are rejected (thereby maintaining high quality experiments) and the program is full over the next two years. The future colliding beam facility will utilize the AGS as an injector and will be a dedicated facility. It will have six intersection regions, run > 10^7 sec/year, and explore a new domain of energy and luminosity. As will be discussed shortly, common to all the considered alternatives is a large aperture proton ring. These possible choices involve pp, ep, and heavy ion variants. The long term philosophy is to run the AGS as much as possible, continuously to upgrade it in performance and reliability, and then to phase it down as the new collider begins operation.

Status and Plans in High Energy Physics at BNL

The aim since 1978 has been to build a pp collider of 400 x 400 Gev with high luminosity, $\geq 10^{33}$ /cm^2/sec. The construction funding levels have been

FY	'78	'79	'80	'81	'82
$M	5	23	41	35	15 = $119M.

The original design as outlined in the White Book of October 1981 would require $259M in 1982 dollars to complete. I noted earlier the deteriorating budget which has caused the present difficulties so that it seems prudent to us to look at ways to reduce the cost of this project. If one normalizes to the 1979 national high energy budget of $300M one notes the following subsequent shortfalls.