REPORT OF THE PROTON-PROTON COLLIDING BEAM GROUP*

I. RECOMMENDATIONS

The search for the fundamental constituents of matter and the laws which govern them has, over the years, been characterized by exploration of phenomena at a series of ever-increasing energy scales. From atomic and molecular physics at the electron-volt level, through nuclear physics with its MeV scale, to strong interaction physics typified by GeV energies, each stage has led to the opening of a new frontier followed by discovery of rich structures of new particles. At present there are compelling arguments that a new energy scale must be reached below 600 GeV in the center-of-mass, yet the deep inelastic electron-proton scattering experiments at SLAC and early results at NAL indicate that we are still in a transition region.

When the new energy scale is reached, we may again expect to find rich structures of new particles such as W, B, Z, ...etc. As we probe deeper into the structure of particles, we will gain new insights into the dynamics of strong, electromagnetic, and weak interactions. Indeed, we may hope to see all three forces merging into a single interaction.

In order to attain and penetrate into the new energy scale, it is clear that we need large storage rings. Accordingly we have

Recommendation 1. We recommend that the long range goal of NAL be the construction of 2 1 TeV x 2 1 TeV intersecting proton storage rings.

Later in this report, we offer a conceptual design that a large proton-proton colliding beam facility may take at NAL. Such an outline, developed during the limited time available

to us at the Summer Study, may serve as a stimulus for a next phase of study at NAL, but is not intended as a substitute for the serious preliminary design effort. Certain aspects of the design, such as the vacuum system appropriate to a large superconducting ring, received no attention at all in Aspen. Thus, in order to proceed toward the goal proposed herein, we urge

Recommendation 2. We recommend that NAL prepare a preliminary design study on 1 TeV x 1 TeV intersecting storage rings. This study should be done in conjunction with an e-p colliding beam study.

The invention of the proton synchrotron, complemented by the discovery of the alternating gradient focusing principle gave birth to a family of accelerators, each more adventurous than its antecedents, culminating in the NAL machine and its European counterpart now under construction. With the last two machines, the familiar technology of the design and fabrication of conventional magnets has probably reached its ultimate development. It would be difficult to imagine a large machine using conventional magnets which is a nicer balance between the exigencies of economy and performance than the NAL machine.

Looking forward, however, new technology must be developed if new, large-scale, projects are to be realizable given present concerns for energy economy and without an escalation of funding requirements. Fortunately, the superconducting magnet technology, although still not proven on the scale necessary to construct a large accelerator or storage ring, is advancing rapidly and affords hope that substantial economies in electric power and real estate may be achieved.

The construction of large proton storage rings is a natural goal in the technical development of NAL. However, large storage rings will become feasible only if superconducting magnet systems are developed into very reliable operating systems of high efficiency and minimum maintenance. The major superconducting advancements necessary in such a project
should also benefit the National Energy Conservation Program. Valuable experience on the operation of large superconducting magnet systems can be gained first from relatively small external beam line magnet installations and then from the energy doubler. Recognizing this, we arrive at Recommendation 3. We recommend that the present work in the field of superconducting magnets underway at NAL should be pursued with increased vigor.

We believe that present day machine technology simply does not permit us to extrapolate our existing storage ring experience to TeV energies, particularly with a very large system of superconducting magnets as envisaged for these rings. We are then caught in a familiar dilemma: our present technology is inadequate yet without the solid commitment to a real accelerator with high scientific goals the large number of existing efforts in advancing technology lack adequate focus. Without the integrating concept of a real machine to be used by real people for real experiments of great interest to the scientific community, the rate of progress toward the eventual goal proceeds by a sort of diffusion. Therefore, we have Recommendation 4. We recommend that an intermediate step be undertaken in view of the fact that considerable technological experience will be required before embarking upon the construction of an economic and successful 1 TeV machine.

A significant intermediate step would be the construction of a 30-70 GeV proton storage ring located beside the present NAL ring. Collisions would take place between this ring and the main ring or the energy doubler. The development of superconducting magnets with field imperfections small enough for use in large rings would be undertaken in this small storage ring project where study of beam instability and field imperfections would be of major importance in the design of the large rings.
It is central to the recommendation that the small ring not only be suitable for experiments but provide a real advance in the physics. The proposed range of 30-70 GeV colliding with 300-1000 GeV is a significant jump of an order of magnitude in the c.m. energy over the ISR and represents the geometric mean between where we are and where we wish to be in a decade.

There are reasons to hope that the new energy scale may be as low as 100 GeV in the c.m. system. In this case, the small ring colliding with the main ring will undoubtedly discover the new energy scale. Even without this tantalizing possibility, the study of the weak and electromagnetic interactions at these energies will be very exciting. We recommend that a design be carried out for a luminosity of $\geq 10^{34}/cm^2/sec$.

The emphasis should be on the experimental nature of the project. Highest priority should be given to providing flexibility for inserting lattice modifications, beam stacking and acceleration experiments, and other features of importance to the longer range plans. The same philosophy should also apply to the interaction area -- here we strive for the widest variety of experiments in order to gain the broadest experience for the future.

The considerations above lead us to

Recommendation 5. We recommend the construction of a 30-70 GeV storage ring as an attractive intermediate step which interferes minimally with the exploitation of the present facilities. This ring colliding with the main ring or the energy doubler significantly extends the frontier of physics.

The time scale of the small ring is, of course, dictated by funding, the competition for staff time, and the need not to interfere with either the experimental program or other major laboratory projects. A 4-5 year time scale to completion would be ideal -- much longer would be inconsistent with the use of this device as an intermediate step.
II. PHYSICS OF P-P COLLISION

Throughout the study of physics, new frontiers are opened whenever a new basic energy scale is reached. Based on what is already known about weak interactions, we can deduce that a new energy scale must be lower than 600 GeV in the c.m. system. The 2 TeV p-p colliding beam facility will undoubtedly find the new energy scale. There are reasons to believe that the new energy scale may be as low as 100 GeV in the c.m. system. In that case, the small ring colliding with the main ring will discover the next energy scale.

In this section, we calculate rates for various reactions based on the scaling hypothesis for the electromagnetic and weak interactions. We also show the total cross section and multiplicities in p-p collisions at high energy by extrapolating the results from the CERN-ISR.

A. The electromagnetic and weak interactions. Perhaps the richest areas of study at these high energies will be the electromagnetic and weak interactions. An excellent survey of these problems has been published by T.D. Lee\(^{(1)}\) and the salient features will be reviewed here.

In order to estimate the cross-sections at these high energies we use the scaling hypothesis suggested by Bjorken\(^{(2)}\). The scaling hypothesis assumes the absence of any basic energy scale and allows us to write the cross-section from simple dimensional analysis and a dimensionless function depending only on the ratio \((q^2/s)\). We then find:

1. For \(B^0\) production
   \[\sigma (p + B^0 + \text{anything}) = \frac{3\pi}{2m_B^2} f(m_B^2/s)\]

2. For \(W^\pm\) production
   \[\sigma (p + W^\pm + \text{anything}) = \frac{3}{8\pi^2} G f(m_W^2/s)\]
The function $f(x)$ has not been well determined and will be one of the interesting results to come from NAL. For our calculation we will use the form

$$f(x) = \exp(-10x)$$

found by Lederman et al.\(^1\) at BNL energies.

The result of a calculation of $W^\pm$ production is shown in Figure 1. For $W^\pm$ production we note that for a $W^\pm$ mass less than 300 GeV the cross-section is greater than $10^{-33}$ cm$^{-2}$. What will happen by attaining these energies is that we will have reached an energy high enough so that we are looking at a cross-section dependent only on the coupling constants and not dependent on any exponential damping factors.

The same calculation can be extended to the production of heavy dilepton. One finds:

$$\frac{d\sigma}{dM} = g^2 M^{-3} f(M^2/s)$$

where $M$ is the invariant mass of the dilepton. The results of this calculation are shown in Figure 2. Again the advantage of attaining high energy is clearly demonstrated. As one varies the energy it is clear that the range of dilepton mass searched for can be extended quite high. For example, assuming the rings are capable of a luminosity of $10^{34}$ cm$^{-2}$ sec$^{-1}$ and a detection efficiency of 0.1, we obtain 100 events per day for a dilepton mass of 120 GeV.

Perhaps the most important question that can be examined at these high energies is the unitarity limit of the weak interaction. If we examine lepton neutrino production in the interaction

$$p + p \rightarrow E + \nu + \text{anything}$$

we can also estimate the cross-section using the scaling hypothesis. One obtains

$$\frac{d\sigma}{dM} = M^2 \left(\frac{G}{4\pi}\right)^2 f(M^2/s)$$

where $M$ is the dilepton mass.
The results are shown in Figure 3. It is apparent that only by building rings capable of s values of $4 \times 10^4$ (GeV)$^2$ or greater will it be possible to attain invariant masses which exceed the unitarity limit of 600 GeV. This is a prospect which has enthralled high energy physicists since the formulation of the Fermi interaction.

While the above rates depend on the exact functional dependence of $f(x)$, we would like to stress that the results of the calculations are only indicative of the rich structure in elementary particle interactions which, based on our present knowledge, will be attainable upon achieving these new energies. Just as it was true twenty years ago when the multitudinous resonant states were not seen, we can only speculate on the dominant features which will be observed when we achieve these new energy scales.

B. Total Cross-Section and Multiplicity Distributions. One of the most interesting results to emerge from the CERN-ISR is the rise in the total cross-section. Figure 4 demonstrates the presently known data along with a fit to the data consistent with the Froissart bound. Figure 5 shows the rise in charged particle multiplicity observed at energies up to the ISR energies. These effects have either a $(\ln s)^2$ or a $\ln s$ dependence and to investigate the mechanisms in these phenomena it is desirable to extend the energy at least an order of magnitude above the ISR. To extend the energy to those ultimately available at NAL, however, would not only allow us to study the cross-section and multiplicity dependence, but would also investigate the existence of a new energy scale.

C. The Structure of the Proton. There is growing evidence that hard point-like collisions are important in lepton-hadron interactions and possibly hadron-hadron collisions. In this picture one can study the parton-parton collisions via measuring energy and angular distribution of a hadron or a group of hadrons emerging from p-p collisions. An attractive hypothesis is that
the partons turn into jets of hadrons. In this model the detection of jets become easier as the c.m. energy increases.

In the papers attached (SS-73/201, SS-73/197, SS-73/207, SS-73/211) all of the physics is discussed in greater detail and the method of carrying out experiments are also discussed.

III. POSSIBLE DESIGNS FOR P-P FACILITIES

In this section, we summarize conceptual designs for the proton-proton colliding beam facilities at NAL. Further details may be found in the papers appended.

A. $2 (1 \text{ TeV})^2$ Intersecting Proton Storage Rings. A preliminary study of superconducting proton storage rings at energies of 1 TeV x 1 TeV or higher has been undertaken. These rings are designed with conservative magnetic fields (35-45 kG) at the 1 TeV level and would be capable of higher energies as technology is advanced. Conventional magnets with the large power they require were not considered because of their economic infeasibility. The colliding rings are in the same tunnel, one above the other, have 8 interaction straight sections, and in a more detailed study, could incorporate an electron ring.

Two different site layouts of the storage rings are shown in Figure 6. The large rings (Case 1) have a diameter of ~5 km and have very long straight sections (~1 km). If the straight section length is reduced to ~0.5 km these rings can go to energies of 4 x 4 TeV$^2$ at fields of ~90 kG. The smaller rings (Case 2) would be less expensive with their ~2.5 km diameter, though the interaction straight sections (~0.25 km) may not be long enough for all conceivable experiments. It may be desirable to have fewer but longer straight sections instead (say, 4 straight sections of ~0.5 km length). Energies would probably not exceed 2 x 2 TeV$^2$. The detailed parameters for the two sizes of storage rings are given in Table 1.

High-energy storage rings at NAL can operate at constant magnetic fields, thus eliminating the need for solutions to problems associated with acceleration. These problems, though
undoubtedly solvable, would diffuse and enlarge the initial
development effort and possibly detract from the main effort
of development of dc superconducting magnets.

Beams can be injected into the storage rings with the
energies at which experiments will be done. These energies
will range from 300 GeV to 1 TeV. Because there need not be
acceleration, a.c. eddy current losses in the superconducting
magnets and reactive power problems can be avoided. Magnet
tracking and beam instabilities caused by tune changes will
not require sophisticated time-dependent corrections. An
rf system will only be required for injection stacking,
whereas the very low shunt impedance rf systems required for
acceleration are not necessary. Thus acceleration in the
storage rings can be left for a more future development program.

The cost of the storage rings will depend primarily on
the length and number of interaction regions, coupled with the
overall circumference of the rings. Great care must be taken
to insure that the interaction regions are long enough for
experimental versatility without becoming unjustifiably long
and costly. Detailed design effort should incorporate basic
machine lattice properties as standard tools in experimental
analysis. This type of machine-experiment integration will
maximize the usefulness of the storage rings for doing ex-
periments.

A number of interacting regions are necessary for versa-
tility in the experimental program and for high order machine
superperiodicity. If an electron ring were incorporated with
the proton rings, two interaction regions could be devoted to
e-p experiments and the six other regions would be devoted to
p-p experiments, injection and abort systems.

Injection into the storage rings would be done by
momentum stacking (55-73/252). The beam would be fast-
extracted from the main ring or the energy doubler at two
different long straight sections. The injection transport
lines would have to be also superconducting for high-energy
injection. Injection would take place in the non-intersecting region of two of the storage rings' long straight sections. It would take ~130 pulses at 0.4 A/pulse to fill the 5 km rings to 10 A each.

The interaction region would have vertical intersection with low β insertions (SS-73/254), SS-73/258). With low interaction β values of 1 m one gets a luminosity of \(4 \times 10^{34} \text{ cm}^{-2} \text{ sec}^{-1}\) without rf bunching (SS-73/253).

The magnets would have a circular good field region of 4 cm radius. It is believed that this radius is necessary for field error allowance (SS-73/244) and for single beam current limits (SS-73/253).

B. Intermediate-Step Proton Storage Rings In its basic form, this proposal consists of a small (radius ~100 m) superconducting proton storage ring located so that its beam can collide with that of the main ring or the doubler. The tentative parameters are given in SS-73/251 and SS-73/255. A proton energy in the storage ring of 30 GeV would correspond to the relatively modest field of 22 kG - operation to energies as high as 70 GeV (~50 kG) may be feasible.

The storage ring would be filled from the main accelerator at any desired energy up to its maximum by stacking in momentum space (SS-73/255). Subsequently, the storage ring beam would collide with the protons in the main ring or the doubler during each acceleration cycle of the latter machine. It would be possible to stack a beam of 10 A in the storage ring. To obtain equal transverse beam sizes at 30 GeV in the storage ring and at 200 GeV in the main ring the low interaction β values in the storage ring and the main ring should be respectively 1.5 m and 10 m. The beam sizes would then be equal at all corresponding energies, e.g. at 60 GeV in the storage ring and 400 GeV in the main ring.

With the design beam current of 0.4 A in the main ring this gives a luminosity of \(2 \times 10^{34} \text{ cm}^{-2} \text{ sec}^{-1}\) for 30 GeV x 200 GeV and \(4 \times 10^{34} \text{ cm}^{-2} \text{ sec}^{-1}\) for 60 GeV x 400 GeV assuming a head-on beam collision over a length of 1 m.
Variations on this basic theme come readily to mind; particularly the installation of the small storage ring in a long straight section of a main ring (or energy doubler) bypass. These options are discussed in SS-73/257. The possibility of installing the low energy storage ring directly in the main ring is described in SS-73/260. This ring would then have a 1 km radius and a rather low bending field of 2.25 kG at 50 GeV. With one turn injection (0.4 A) into the storage ring one gets already a luminosity of $3 \times 10^{30}$ cm$^{-2}$ sec$^{-1}$ for 50 GeV x 300 GeV.

C. Other Possibilities for Study

As stated in Recommendation 3 above, the design of a large storage ring facility at NAL should include a large (-20 GeV) electron ring as well, so that the very exciting physics of high energy electron-proton collisions may be explored. The synthesis of proton-proton and electron-proton systems into an economical and operationally effective design will require careful study -- some preliminary suggestions are made in the report of the Electron-Proton Colliding Beam Group.

The feasibility of studying the interaction of energetic antiprotons and pions with stored protons received some discussion during the Summer Study, as described in papers SS-73/210 and SS-73/232. Further study is needed to examine these technically complex but extremely interesting possibilities.

Finally, given the large-scale of the projects proposed here, it may be reasonable to contemplate the modifications to the NAL accelerator system that would be required to accelerate deuterons in order to permit the study of proton-neutron and neutron interactions in the storage rings.

REFERENCES

Table I. Parameters of \((1 \text{ TeV})^2\) Proton Storage Rings

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Case 1</th>
<th>Case 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average radius</td>
<td>2.48 km</td>
<td>1.26 km</td>
</tr>
<tr>
<td>Number of interaction straight sections (8)</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Length of straight section (16 straight cells)</td>
<td>960 m</td>
<td>240 m</td>
</tr>
<tr>
<td>Length of curved section (16½ curved cells)</td>
<td>990 m</td>
<td>750 m</td>
</tr>
<tr>
<td>Normal FODO cell length (δφ = 90°)</td>
<td>60 m</td>
<td>60 m</td>
</tr>
<tr>
<td>Dipole length (½ cell)</td>
<td>4 x 5.7 m</td>
<td>4 x 5.95 m</td>
</tr>
<tr>
<td>Dipole field (1 TeV)</td>
<td>34.9 kG</td>
<td>44.1 kG</td>
</tr>
<tr>
<td>Number of dipoles per ring (w/o insertion)</td>
<td>1056</td>
<td>800</td>
</tr>
<tr>
<td>Quadrupole length (½ cell)</td>
<td>3.0 m</td>
<td>2.6 m</td>
</tr>
<tr>
<td>Quad field gradient (1 TeV)</td>
<td>525 kG/m</td>
<td>605 kG/m</td>
</tr>
<tr>
<td>Number of quadrupoles per ring (w/o insertion)</td>
<td>520</td>
<td>264</td>
</tr>
<tr>
<td>Phase advance per cell</td>
<td>π/2</td>
<td>π/2</td>
</tr>
<tr>
<td>Tune (w/o insertion)</td>
<td>65</td>
<td>33</td>
</tr>
<tr>
<td>β_max (normal cell)</td>
<td>102 m</td>
<td>102 m</td>
</tr>
<tr>
<td>β_min (normal cell)</td>
<td>17.6 m</td>
<td>17.6 m</td>
</tr>
<tr>
<td>η_max (normal cell)</td>
<td>1.93 m</td>
<td>2.55 m</td>
</tr>
<tr>
<td>η_min (normal cell)</td>
<td>0.97 m</td>
<td>1.22 m</td>
</tr>
</tbody>
</table>

If Case 1 had 480 m straight sections (8 straight cells) and 1470 m curved sections (24½ curved cells) the dipole field would be 23.5 kG at 1 TeV.
Figure 1. Cross-section for $W^\pm$ production
Figure 2. Cross-section for the production of heavy dilepton.
Figure 3. Cross-section for lepton-neutrino production

\( S = 4 \times 10^4 \)

\( S = 4 \times 10^6 \)
Figure 4. Rise of p-p total cross-section at high energies

\[ \sigma_T = 38.4 + 0.5 \ln^2 \frac{s}{137} \]
Figure 5. Rise in multiplicity in p-p collisions at high energies
POSSIBLE PROTON-PROTON STORAGE RINGS

FIG. 6