FERMILAB-CONF-77-184-T

POPAE - A 1000 GeV ON 1000 GeV PROTON-PROTON COLLIDING BEAM FACILITY*

D. Ayres, E. Berger, Y. Cho, T. Collins, E. Crosbie, M. Derrick, R. Diebold, D. Edwards, M. Foss, L. Genens, L. Hyman, D. Johnson, E. Malamud, F. Mills, L. Mo, J. Moenich, S. Ohnuma, J. Purcell, C. Quigg, L. Ratner, A. Ruggiero, R. Singer, R. Smith, S. Snowdon, L. Teng, L. Turner and C. Ward

The Argonne-Fermilab POPAE Collaboration

Argonne National Laboratory, Argonne, Illinois 60439, and
Fermi National Accelerator Laboratory, Batavia, Illinois 60510

Summary

A proposal has been developed for the construction of a 1000 GeV on 1000 GeV colliding beam facility at Fermi National Accelerator Laboratory. To achieve the same 2000-GeV center-of-mass energy with a fixed target accelerator would require a beam of more than 2×10^6 GeV. The total circumference of the facility is 5520 m, including six straight sections, each 200 m long. Injection from the Fermilab main ring or Energy Saver/Doubler (ES/D) will be at the energy desired for interactions, thus avoiding the uncertainty, complication, and cost of accelerating very intense beams in the storage rings themselves. Each ring will require 570 superconducting dipole magnets, each 6.2 m long; the field required at 1000 GeV is 60 kG. For a proton current of 5A in each ring at 1000 GeV, the high-luminosity insertion is designed to give $\mathcal{L} = 4 \times 10^{33} \mathrm{cm}^{-2}\mathrm{sec}^{-1}$.

The proposal[1] was developed during an intensive study from November 1975 to April 1976. This study drew not only on the experience of the CERN ISR[2] and previous Fermilab designs,[3] but also on studies of high energy storage rings made at Brookhaven National Laboratory (Isabelle)[4] and at CERN (LSR).[5]

Reason for Colliding Beams

The great advantage of colliding beams is the very large energy available to produce massive particles or to explore new types of interactions and forces. At fixed target accelerators the center-of-mass energy W increases only as the square root of the laboratory energy E, $W \approx \sqrt{1.88E}$, where both W and E are in units of GeV. For colliding beams the situation is much more favorable, $W = 2E$, where E is the laboratory energy of each of the protons in a head-on collision.

At present, the world's only proton-proton colliding beam facility is at CERN, the Intersecting Storage Rings (ISR).[2] This facility gave an enormous increase in useful energy over that previously available at CERN, up to the equivalent of a 2000-GeV fixed-target accelerator. However, this energy has since been approached by Fermilab and the CERN SPS which are now running routinely at 400 GeV and by the ES/D which will achieve 1000 GeV. For further energy increases, however, colliding beams quickly outstrip the useful energy of fixed target machines, even those that might conceivably be built as part of a World Collaboration. This is illustrated in Fig. 1.

The factor of 1000 increase in equivalent fixed-target machine energy of POPAE over that of the ISR will almost certainly lead to new and interesting phenomena. If we reflect back on the previous factor of 1000, from 2 to 2000 GeV, we find that our whole outlook on elementary particles has been changed dramatically by the phenomena found in this energy range. At POPAE, a further increase of at least 50% is projected for the total interaction rate, and intermediate vector bosons, which mediate the weak interactions, are expected to be produced at the rate of about 10/sec. It seems inevitable, however, that these and other expectations will pale beside the phenomena actually discovered.

Storage Ring Design

The proposed location for POPAE on the Fermilab site is shown in Fig. 2, and results in nearly straight injection lines to the storage rings. These lines will consist mainly of buried vacuum pipe with quadrupole doublets every 150 meters for focusing, and will be relatively inexpensive both to build and to operate. One of these lines will originate at the "Q stub" and the other from a new extraction point at the B straight section.

Some important design parameters are summarized in Table I. The two rings will be housed in a common tunnel and each will have six 720-meter long curved sections, separated by 200-meter long straight sections where the beams are focused and cross one

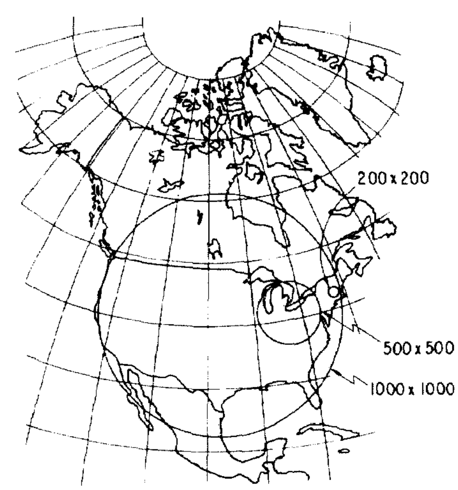

Fig. 1. Size of fixed-target accelerators (with 40 kG dipoles) to achieve the same center-of-mass energy as proton-proton storage rings of the energies indicated (GeV).

*Work supported by the U.S. Energy Research and Development Administration.

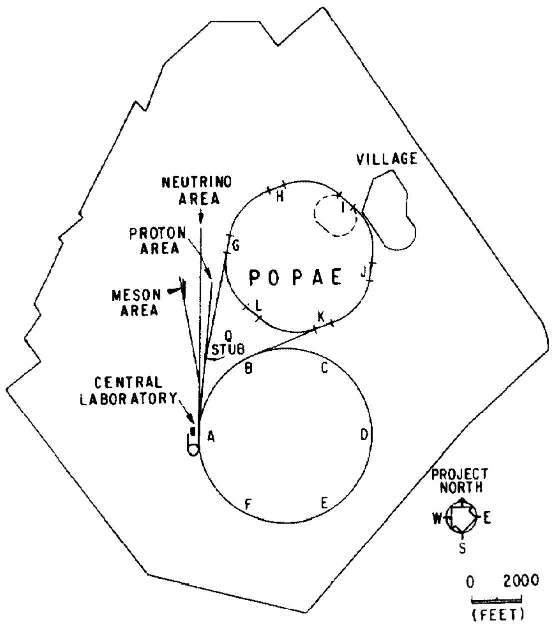

Fig. 2. Location of POPAE on the Fermilab site. The dashed ring shows a possible future location of a 20-GeV electron storage ring for ep collisions.

Table I. Basic POPAE parameters.

ENERGY		
Maximum energy in each ring	1000	GeV
Equivalent fixed-target energy	2100	TeV
LATTICE		
Circumference	5520	m
Insertion length	6 x 200	m
Cell length	72 x 60	m
Cell structure, phase advance/cell	FODO, 90	deg
Tune (typical) ν_h, ν_v	21.84, 22.86	
Transition energy (γ_{tr})	19.6	
Amplitude function regular cell: β-max, β-min	102, 18	m
Maximum dispersion, η	3.6	m
MAGNET SYSTEM		
Number of lattice dipoles/ring	570	
Bending field at 1000 GeV	60	kG
Dipole length	6.17	m
Stored energy per dipole at 60 kG	1.7	MJ
Number of lattice quadrupoles/ring	138	
Quadrupole strength at 1000 GeV	12	kG/cm
Quadrupole length	1.32	m
Vacuum chamber inner diameter (cold bore)	6	cm
REFRIGERATION SYSTEM		
Reliquification of warm gas	1600	ℓ/hour
Refrigeration at 4.5°K	5.7	kW
Power requirement of compressors	3.6	MW
Total liquid helium inventory	165,000	ℓ
INJECTION		
Injected energy/central storage ring energy	.9946	
Number of protons per ES/D pulse	10^{13}	
Emittance of ES/D beam at 1000 GeV: ϵ_h, ϵ_v	0.02π, 0.01π	mm·mr
Longitudinal phase space per bunch at 1000 GeV	0.1	eV·sec
POPAE current/ring	5	A
Number protons/ring	6×10^{14}	
Number ES/D pulses stacked/ring	66	
Momentum spread in stack at 1000 GeV	0.05	%
Stacked beam size at 1000 GeV, V x H	0.8 x 4.6	mm^2
rf frequency of stacking system	53.1	MHz

another. Each 720-meter long sextant is composed of 12 lattice cells, each having eight 6-meter long bending magnets with a field of 60 kG for 1000 GeV operation. The lattice and insertions are discussed in more detail in another paper[6] at this conference; some of the performance parameters are summarized in Table II.

Injection into the storage rings will be handled in a manner similar to that used at the ISR, making use of rf stacking in momentum space. The filling time will range from a few minutes at low energies to about one hour at 1000 GeV. Each ring can store high beam currents at energies between 100 GeV and 1000 GeV, and unequal-energy operation is possible. There is no firm low-energy limit and although the attainable luminosity falls with decreasing energy, some experiments should be possible even below 100 GeV.

The design luminosity, $\mathcal{L} = 4 \times 10^{33} cm^{-2} sec^{-1}$, is two orders of magnitude higher than the values obtained at the ISR. This increase is possible even with a lower proton current because of the high energy; the beams are smaller in size and a smaller crossing angle can be used without the beam-beam tune shift becoming important. There appears to be no hard limit on the stored proton current, and it may eventually be possible to store more than the design current of 5A, possibly yielding $\mathcal{L} > 10^{34} cm^{-2} sec^{-1}$.

Magnets and Vacuum

There are several clear advantages to using superconducting magnets for high energy storage rings. The power saving even for magnets operating at 20 kG amounts to hundreds of megawatts, and the length of expensive underground tunnel can be reduced by a factor of two or three due to the higher fields obtainable. The design field of 60 kG at 1000 GeV is somewhat higher than the 40 to 45 kG design of present accelerator projects, all of which were started several years ago. With the steady improvements in technology, 60 kG superconducting dc dipoles now seem quite feasible, and this field is a worthy goal for the next step in dipole technology. For POPAE, this high field will result both in savings and in reduced sensitivity to various instabilities.

Since protons are stored at a fixed energy, and the high-current beam is not accelerated, several of the design criteria commonly imposed on pulsed magnets can be relaxed. Rectangular monolithic wire or cable can be utilized instead of braid, thus saving the

Table II. Typical performance parameters.

Type of Insertion	Injection-Crossing	High β_v^*	Low β_v^* Large Angle		Low β_v^* Small Angle	High Luminosity
Energy (GeV)	1000	1000	100	1000	1000	1000
Luminosity ($10^{33}/cm^2/sec$)	0.041	0.029	0.12	0.26	2.8	4.5
Tune shift (10^{-3})	3	4	2	0.4	5	4
Crossing angle (mrad)	11	11	11	11	1	1
Free space (m)	±28	±45	±45	±45	±10	±10
$\ell_{interaction}$ (m)	0.2	0.1	0.2	0.1	0.9	0.4
β_v^* (m)	~100	200	2.5	2.5	2.5	1
β_h^* (m)	~ 80	12.4	13.5	13.5	13.5	3
β_{max} (m)	550	680	810	810	810	1080

expense of braiding as well as improving the coil packing fraction. A thick metal bore tube can be employed for mechanical rigidity, without concern for eddy currents which degrade the field quality of a pulsed magnet. A dc magnet also has less stringent requirements on the insulation between superconducting elements, and does not require field corrections that depend on the rate at which the magnet is ramped.

The magnet design adopted for POPAE is described in detail elsewhere.[7] It is similar to a 60-kG dipole magnet built and operated at Saclay, with rectangular coils wound with rectangular conductor.[8] The magnet design incorporates both cold bore and cold iron, as well as liquid-nitrogen-cooled heat shields in the magnet cryostat. The result is a very low heat load on the liquid helium system and a substantial saving on refrigerator costs and power consumption.[9]

The 6-cm vacuum tube bore is substantially smaller than the 8-cm bore proposed for Isabelle. The choice of bore diameter is influenced by many aspects of over-all design such as machine instabilities, vacuum, beam size, etc. In general, a bigger bore helps with various potential problems that may or may not be critical, but it does cost money. POPAE has the option of using a smaller bore, since there is no need to store and bunch the full beam intensity at low energy. Beam instabilities become more important as the beam current increases and, for a given cost, the smaller bore size of POPAE essentially trades luminosity for increased energy. The 5-ampere beam current needed to reach design luminosity will place considerably less stringent requirements on the entire system than does the 40-ampere current achieved at the ISR.

The vacuum will be primarily a cold-bore system, with warm bore only in the straight sections, a natural choice for a ring of superconducting magnets. With high-vacuum preparation of materials, a vacuum of about 10^{-11} Torr will be obtained in the warm-bore sections, while better than 10^{-13} Torr is expected from the cold-bore regions. With high pumping speed of the bore tube at liquid-helium temperature and the relatively low beam current, it should not be difficult to avoid the pressure bump problem seen at the ISR. The vacuum design is discussed in detail in another paper[10] presented to this conference.

Cost Estimate

Table III summarizes the results of a detailed estimate of the cost of constructing and bringing into operation the POPAE colliding beam facility. The construction of this facility at Fermilab takes advantage of the substantial national investment in the facilities of the Laboratory.

For planning and costing purposes, a model set of initial experiments was developed. With this physics program as a guide, experimental halls were designed and included in the estimate for the conventional facilities construction. The cost estimate for the POPAE superconducting magnets made use of current conceptual designs and recent experience with superconducting magnet fabrication at Argonne and at Fermilab.

Table III. POPAE cost estimate (in millions of 1976 dollars).

A. Technical Components			120.8
1. Regular-lattice dipoles		68.3	
a. Superconductor	15.1		
b. Iron and other materials	18.9		
c. Winding and assembly fixtures	2.1		
d. Winding and assembly labor	15.8		
e. Cryostats	16.4		
2. Regular-lattice quadrupoles		8.5	
3. Insertion quadrupoles		5.5	
4. Special bends		1.0	
5. Magnet testing and installation		7.0	
6. Refrigeration		7.5	
7. Vacuum system		6.0	
8. Magnet power supplies		2.0	
9. Correction coil power supplies and control		2.5	
10. RF, beam diagnostics and control		1.0	
11. Injection-line magnets and power supplies		6.5	
12. Control system		5.0	
B. Conventional Facilities			35.4
1. Site work and roads		2.2	
2. Curved-section tunnel		14.0	
3. Research halls		12.0	
4. Injection tunnel		2.2	
5. Service buildings		3.0	
6. Utilities		2.0	
C. Architect-Engineer-Management (20% of Facilities)			7.1
D. EDIA (30% of Technical Components)			36.2
E. Contingency			46.0
F. Total			245.5

The cost of the project was estimated to be $245 M in 1976 dollars.

Since economic constraints may force a reduction in scope, an estimate was also made of the saving which could be realized by lowering the peak energy of POPAE. The 1000-GeV ring geometry is retained (leaving open the possibility of eventual operation at higher energy) and 30 kG, ES/D-type superconducting dipoles are used. Since the magnets are such a large part of the cost, the savings are substantial, and the cost of a 500-GeV on 500-GeV facility is estimated to be $155 M in 1976 dollars.

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