20-TeV COLLIDING BEAM FACILITIES: NEW, LOW-COST APPROACHES

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Introduction

The scope of this paper is to consider the cost of a high-energy accelerator facility and, in particular, innovative ways to minimize cost without sacrificing too much physics. The basic machine for the facility would be a 20-TeV single ring $\bar{p}p$ collider. In the last section, possible additions to this facility are discussed, i.e., a "two-hole" magnet for pp, another ring for pp or $\bar{p}p$, and a 60-GeV electron ring for ep and e^+e^- Z^0 factory. A separate paper considers the additions necessary to have a fixed-target accelerator.

Two assumptions were made at the outset:

1. The total average power for the facility must be less than 100 megawatts. This is as much a social issue (conserve energy) as it is an operating cost limit.

2. The necessary land can be obtained. A "right of way" approximately 1 mile wide around a ring of radius 31 kilometers would contain 40K acres which is a smaller area than some of the cattle ranches in the states where such a facility could be located. In any case, most of the site area would remain available to ranching and other commercial activities.

General Considerations

The limit on power eliminates consideration of conventional magnets. A 1-ft^2 magnet with approximately 1/2 in. radial aperture using aluminum conductor requires hundreds of megawatts of power and implies a capital cost at least twice that of the machines considered in this report. Cold magnets using pure aluminum conductor were not considered. Only superconducting magnets with fields between 2.5 and 10 Tesla were studied in detail. For magnets with magnetic field less than 2.5 Tesla, costs which increase linearly with radius (tunnel, etc.) dominate and make the total accelerator more expensive. Fields greater than 10 Tesla were not considered to be technically feasible on a large scale at this time.

A. Refrigeration

The heat load which the refrigeration system must handle can result from both conductive and radiative transfer of heat from the surrounding environment to the helium temperature magnet (synchrotron radiation will be discussed later). By very careful design of the magnet support structure the conductive heat load can be reduced to the same level or less than the radiative heat load. The support structure can be minimized by using a small amount of cold iron since then magnetic forces between warm and cold are eliminated. According to Ref. 1, the minimum radiative heat transfer one can hope to achieve is ~ 15 mW/m^2 between nitrogen and helium temperature. Assuming an equal load from conduction this implies a 30 mW/m^2 load, or 15 mW/m for a 6-in. diameter magnet. In cryogenics it is not unreasonable to assume a large safety factor; therefore, for this study we use 150 mW/m. The small size of this magnet, the cold iron, and careful attention to the design of the support structure should make it possible to achieve this small heat load. For 2.5 T at 4.6°K and R = 31 km the total power needed to produce the above helium refrigeration is

$$(2\times10^5\ \mathrm{m})\ (150\times10^{-3}\ \mathrm{W/m})\ (600) = 18\ \mathrm{MW} \qquad 2.5\ \mathrm{T}$$

$$(0.5\times10^5\ \mathrm{m})\ (400\times10^{-3}\ \mathrm{W/m})\ (600)\ \frac{4.6}{2.8} = 20\ \mathrm{MW} \quad 10\ \mathrm{T}$$

The factor 600 is for conversion from 4.6° energy to electrical line energy.

In addition, there will be heat losses in electrical leads and peripheral transfer lines, etc., which must be minimized. It should be possible to keep this under 4 MW. Thus the total main accelerator power would be 22-24 MW.

The synchrotron radiation loss per turn per proton is given by

$$\frac{\Delta E}{\mathrm{turn}} = 0.6\times10^{14}\ \frac{\gamma^4}{\rho}\ \mathrm{MeV},$$

where ρ is the radius of curvature in meters of the particle in the magnet. This yields 0.04 MeV/turn (0.16 MeV/turn) for 2.5 T (10 T) magnets. The total radiated power

$$P = \left(N_p + N_{\bar{p}}\right)\ f\ \frac{\Delta E}{\mathrm{turn}},$$

depends on the total number of particles (N_p, $N_{\bar{p}}$) and the rotation frequency (f). For a luminosity of $10^{32}\mathrm{cm}^{-2}\mathrm{sec}^{-1}$ and $N_p = N_{\bar{p}} = 4\times10^{13}$ (1×10^{13}) the total radiated power is 8 kW (32 kW) for 2.5 T (10 T) magnets. If this radiation is absorbed by the cold magnets it corresponds to ~ 5 MW (2.5 T) or 30 MW (10 T) of electrical power for refrigeration, respectively. This is a considerable heat load, and clever ways to remove the heat at a higher temperature should be developed.

B. Magnets

Experience with the Energy Doubler (E.D.) magnets ($40K/magnet) and other superconducting magnets indicates that the main factors affecting the cost are

1. **field × volume** = BLhw, where L is the length of the magnet and h and w are the transverse dimensions of the magnet; since BL is a constant fixed by the energy of the accelerator, the only way to reduce this factor is to decrease the aperture.

2. **magnet ends** where the cryogenic and electrical connections require considerable labor; for the E.D. magnets this factor contributed 30% to 50% of the costs [$(13-20K)/$40K].

3. **number of turns** which for the Energy Doubler contributed $3K/magnet.

4. **unit cost**, painting, measuring, bookkeeping, handling, etc.

In order to minimize magnet and cryogenic costs we have therefore considered very long magnets (low tune lattice) with small aperture (both gap and width) which have few turns. We have also tried to minimize the external dimensions since this affects both material costs and cryogenic load. The consequences of these properties on the beam are considered in the lattice section.

C. Site and Radiation

It would be convenient to have a site flat to within 50 ft or at most divided into two half planes over a very large area. For about $20M, on the order of 10 million yards of dirt can be moved in such a way as to make a "roadway" 25 meters wide and 200 km long (circumference for 2.5 T magnets) flat to within 1 ft. This roadway can be used as a flat area from which to bury the accelerator tunnel. The accelerator tunnel could be a 3-ft diameter pipe. A similar pipe 800 miles long is being buried in Colorado, Wyoming, and Nebraska to transport natural gas. The cost is $165/ft. As discussed in the paper by R. Wilson,[2] this pipe could be interrupted every few hundred meters with a larger manhole to allow entry by people at the quadrupoles. Only a robot would work in the 3-ft tunnel. It would be necessary to dig it up for repair. An alternative tunnel proposed by W. Wenzel[3] would use a neutral buoyancy cryostat in a water pipe.

Six feet of earth cover over the tunnel would make tolerable a single accident where 3×10^{13} protons are lost in one spot, provided that there are the following fences:

1. at ± 50 ft radially from the tunnel (> 100 mr level) there must be an interlocked 8-ft high fence that makes undetected entry very unlikely.

2. at ± 500 ft radially from the tunnel (> 1 mr level) there must be a locked fence with warning signs to keep the general public out.

In order to absorb muons, which in general emerge tangent to the ring, there must be an earth shield which extends horizontally outside the ring for 100 meters. Because of these radiation considerations, it is important to minimize the number of particles in the machine.

To minimize cost there should be only one area (10 km × 15 km) on the ring where all experimental halls, injectors, and accelerator functions are located. An example of such a region is presented in Fig. 1. Since the size of this site compares to the Fermilab site, one might expect the same power usage for the non-accelerator functions (about 25 megawatts).

D. Luminosity

Luminosity requirements are strongly experiment-dependent. In general there are two broad categories: large solid angle experiments which study the details of each interaction, and experiments which limit the acceptance to a specific final state or subset of final states.

For the first category most experiments one can foresee will require tracking charged particles over large volumes, EM calorimetry, and possibly hadron calorimetry. Since it will be very difficult to associate calorimeter signals with interaction vertices, most experiments with calorimeters will be restricted to one interaction per bunch crossing (bunched beam). For a Poisson distribution the maximum number of events with only one interaction will occur when the average number of interactions per bunch crossing equals one ($\bar{n} = 1$). This requirement leads to the conclusion that the machine should have $\bar{n} = 1$ which results in ~ 37% of the crossings having one and only one interaction, ~ 26% having $\gtrsim 2$ interactions and 37% having no interaction. The further requirement that the event rate in the detectors be below 10 MHz limits us to > 100 ns between bunch crossings (total number of bunches $n_B = 6500$) for R = 31 km; f = 1.5 KHz. Taking $\sigma_{p^\pm p} = 100$ mb we obtain for the luminosity per bunch

$$L_{BB} = \frac{\bar{n}}{\sigma_{p^\pm p}} f = 1.5 \times 10^{28}\ \mathrm{cm}^{-2}\mathrm{sec}^{-1}$$

and the total luminosity

$$L = L_{BB} n_B = 10^{32}\ \mathrm{cm}^{-2}\mathrm{sec.}^{-1}$$

The useful luminosity is only

$$L = 0.37 \times 10^{32}\ \mathrm{cm}^{-2}\mathrm{sec}^{-1}$$

Experiments which limit the acceptance to specific final states are those which have a restricted solid angle (e.g., large transverse momentum tracks at 90°) or look at specific particles (e.g., muons which traverse an absorber). In either of these two cases many interactions per beam crossing may be tolerated and luminosities greater than $10^{32}\mathrm{cm}^{-2}\mathrm{sec}^{-1}$ may be useful.

With a single ring $\bar{p}p$ collider it may not be possible to achieve a luminosity of greater than $10^{31}\mathrm{cm}^{-2}\mathrm{sec}^{-1}$ because of the tune spread due to beam-beam interaction. The only way to separate the two beams which seemed feasible during this workshop was to use electrostatic separators to create two undulating closed orbits in the machine. This forces a reduction in the number of bunches in the machine in order to restrict the beam collisions to the desired interaction regions. From the discussions at this workshop it appears that the number of bunches may be limited to a few per wave length around the machine. Thus it may not be possible with $\bar{n} = 1$ to achieve a luminosity of more than $10^{31}\mathrm{cm}^{-2}\mathrm{sec}^{-1}$ for $\bar{p}p$ colliders.

The intersection region for a two-ring machine seems straightforward. With 2 m long, 5 T magnets, it is possible to have "head-on" collisions within a ±13 m experimental area. With such a scheme the bunches will be separated at the next crossing point by 10σ (see Fig. 2).

Injector

The requirements for an injector are:

1. A few $\times 10^{13}$ 1-TeV protons in a few $\times 10^3$ bunches each about 1 meter long in a very small transverse emittance ($\varepsilon_0 < \pi \times 10^{-6}$ mrad normalized).

2. A high intensity ($\sim 10^{13}$ protons per second) 50-100 GeV proton accelerator appropriate for production of $\bar{p}$.

3. Possibility of accelerating $\bar{p}$.

4. 1-3 achievable with maximum reliability and minimum cost ($\lesssim$ $100M excluding salaries, buildings, inflation, and contingency).

A standard scheme of an H^- linac, rapid cycling booster, 1-TeV ring appears to be an efficient and reasonable injector system.

A. Linac

The development at Los Alamos of the RFQ (radiofrequency quadrupole) linac has advanced considerably the technology of linacs.[3] This permits the use of higher frequencies ($>$ 440 MHz instead of 200 MHz) which results in more energy gain per meter. In addition, the Los Alamos work on permanent magnets in drift tube linacs and their development of the disk and washer linac (~1.3 GHz) shows that it is now possible to have a linac system with an average gradient of $>$ 5 MeV/meter. Such a linac would have a 50 mA, 50 microsecond pulse at a 1 Hz rate and an emittance $\varepsilon_0 < 1\pi \times 10^{-6}$ mrad and $\Delta E/E < 0.1\%$. The cost of a 2.5 GeV linac was estimated by the Los Alamos Group to be about \$29M excluding salaries, inflation, building, and contingency.

B. Rapid Cycling Booster

At 2.5 GeV injection energy the coherent and incoherent space-charge limits give an intensity limit of 5×10^{12} protons for $\varepsilon_0 = \pi\times10^{-6}$ mrad. More particles can be accelerated in a larger emittance for $\overline{p}$ production where only the longitudinal emittance is important. This accelerator could be of a design similar to the Fermilab Booster. A 2.5 to 50 GeV, 1-Hz accelerator (r = 0.15 km) would cost approximately \$28M[5] excluding salaries, inflation, and contingency. A bunch spacing of 100 nsec corresponds to 10 MHz rf system.

C. 1-TeV Accelerator

A 1-TeV accelerator constructed with 2.5 T magnets could have a radius of 1.5 km. This could accept 10 pulses (in 10 seconds) "box-car" fashion to load the machine with 5×10^{13} protons. These particles could be accelerated then peeled a la CERN PS-SPS injection to load the large main ring. In principle, with this peeling the transverse emittance could be reduced by up to a factor of 10. The cycle time required for this accelerator would then only be minutes (time between loading p and $\overline{p}$). The cost of such a machine may be as low as \$60M[6] excluding salaries, inflation, and contingency funds. The power usage would be approximately 20 megawatts.

An alternate scheme for low energy injection has been proposed by C. Ankenbrandt.[7] This scheme consists of a low field (4kG, r = 75m) 5-GeV accelerator for H^-. The stripping of the H^- for injection into another ring would be at 5 GeV where the space-charge limit would allow the normalized emittance to be reduced to about $0.5\pi\times10^{-6}$ mrad. For $\overline{p}$ production, the longitudinal emittance can be kept small by stacking beam in the transverse plane (large transverse emittance).

In an alternative proposed by Wenzel,[3] the intermediate booster and 1-TeV accelerator are combined in one rapid cycling variable tune accelerator of full radius.

Accelerator Design

A. Lattice

Various lattices which range from relatively high tunes[8] to low tunes[9] have been considered in the past. Due to the considerations in the first part of this paper, we will pick a low tune of 100 and look at the consequences. Table I lists the parameters for two different machines: (I) 2.5 T magnets shown in Fig. 3 and discussed in the paper by R. Wilson[2] and (II) 10 T magnets shown in Fig. 4 and discussed in the paper by C. Taylor.[10]

B. Magnet Aperture

The apertures (1 in. × 2 in. for 2.5 T and 2 in. diameter for 10 T) for these magnets must be minimum in order to have the lowest cost. The orbit distortions due to alignment and field errors are about 1 cm and can be corrected by correction elements. The good field aperture required by the beam is very small. The magnet aperture will be determind mainly by beam instabilities due to impedances of the vacuum pipe. The instabilities due to resistive wall effects are being studied. We believe the apertures listed in Table I can be used.

Costs

The cost figures presented in this section are rough estimates. In many cases they are scaled from the Fermilab Energy Doubler. R & D costs have not been included.

Table II gives a breakdown of the dipole magnet costs for the Energy Doubler and a 20-TeV accelerator with 2.5 T and 10 T magnets, respectively. In parentheses after each entry the dominant contribution to the cost is indicated (i.e., aperture, radius, field, ends, and turns).

Table III lists some properties and costs for the main accelerator. The dominant contribution to the costs is shown in parentheses.

Table IV is an estimate for the cost of a complete laboratory. The number of buildings is kept to a minimum. An important savings is achieved by having essentially everything concentrated in one area. The 30% included for inflation and contingency is approximately the amount required by DOE (and experience). To within the accurancy of the cost estimates 2.5 T and 10 T are the same.

A separate study indicated that if two rings are necessary it would cost an additional \$200M to put 2 holes in the same 2.5 T magnet (see Fig. 5) and \$250M for the 10 T magnet system. Adding an independent ring of magnets would cost an additional \$500M and \$600M for the 2.5 T and 10 T options, respectively.

The total power requirements for the facility (main accelerator 20 MW, injector 20 MW, experimental areas and site 25 MW) would be ~65 MW.

Thus since size of central area, manpower, and electrical power are similar to Fermilab, total operating costs should be comparable.

Conclusion

We believe that by using some of the ideas presented here and in associated reports at this conference, the cost of a multi-TeV collider can be reduced by more than a factor of 2 from those obtained by a straightforward extrapolation of existing facilities. In fact it appears quite possible to have at least 10 TeV × 10 TeV for less than a billion dollars.

References

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Table I. Accelerator Lattice.

	Doubler	2.5 Tesla	10 Tesla
Energy	1 TeV	20 TeV	20 TeV
Radius	1 km	31 km	8 km
Tune	20	100	50
$\bar{\beta} = R/\nu$	50 m	310 m	160 m
Number of cells	100	400	200
β_{max}	100 m	800 m	400 m
Dipole			
Magnetic field	4.4	2.5 T	10 T
Aperture	7.5 cm diam.	2.5×5 cm^2	5 cm diam.
Magnet Length	6 m	209 m	13 m
Turns	110	2	30
Number	774	800	3200
Current	4.4 kA	25 kA	30 kA
Stored energy	400 kJ	500 kJ	1500 kJ
Quad			
Gradient	76	100 T/m	250 T/m
Aperture	8.8 cm	2.5 cm	4 cm
Magnet Length	1.6	4.1 m	3.2 m
Number	216	800	400

Table II. Dipole Costs.

	Energy Doubler	2.5 T	10 T
Superconductor (aperture, R,B)	$10.0M	$33M	$200M
Iron/steel (aperture, R,B)	2.7	14	50
Cryogenic parts (R, ends)	3.1	50	56
Coils parts (R, turns)	3.7	8	45
Misc. parts (R, ends)	2.2	25	29
Labor (ends, turns)	9.3	51	78
	31.0	181	458

Table III. Accelerator Costs.

	Energy Doubler	2.5T	10T
Dipoles	31	182	458
Quads	6	14	15
P.S., controls, util. (service areas)	20	66	33
Cryogenics (RM/T)	20	50	60
Corrections, detectors (P/βB)	6	30	17
RF (R/τ)	3	12	3
Tunnel (R)	-	200	50
Misc.	7	100	100
Install	7	100	100
	100	754	856

Table IV. Laboratory Cost.

Accelerator	754	856
Injector & $\bar{p}$ source	165	165
EDIA & Test Facilities	125	125
6 Areas	30	30
Low-Rise & Buildings, Util.	50	50
	$1,124M	$1,206M
30% inflation, contingency	330	362
	$1,450M	$1,568M

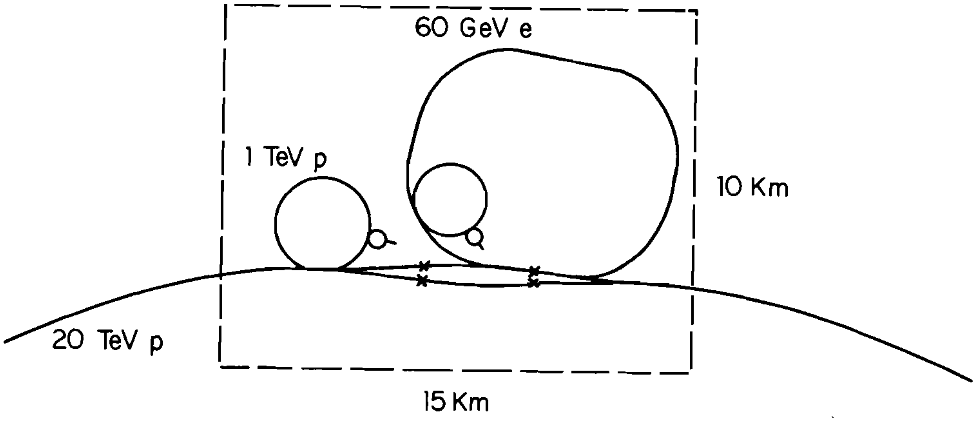


Fig. 1. Central Facility region with 1-TeV injector and 60-GeV electron ring. The x's indicate the four experimental areas.

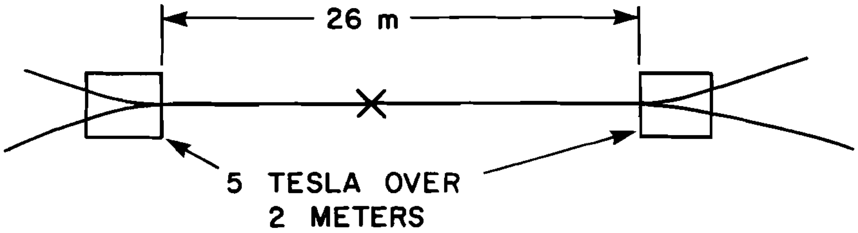


Fig. 2. Possible interaction region.

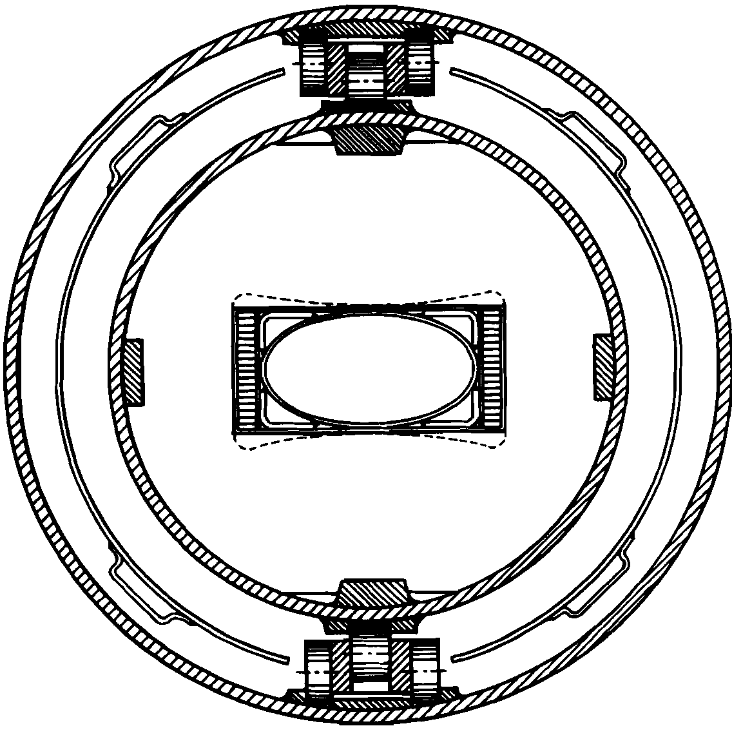


Fig. 3. 2.5 Tesla superferric magnets. (a) dipole magnet.

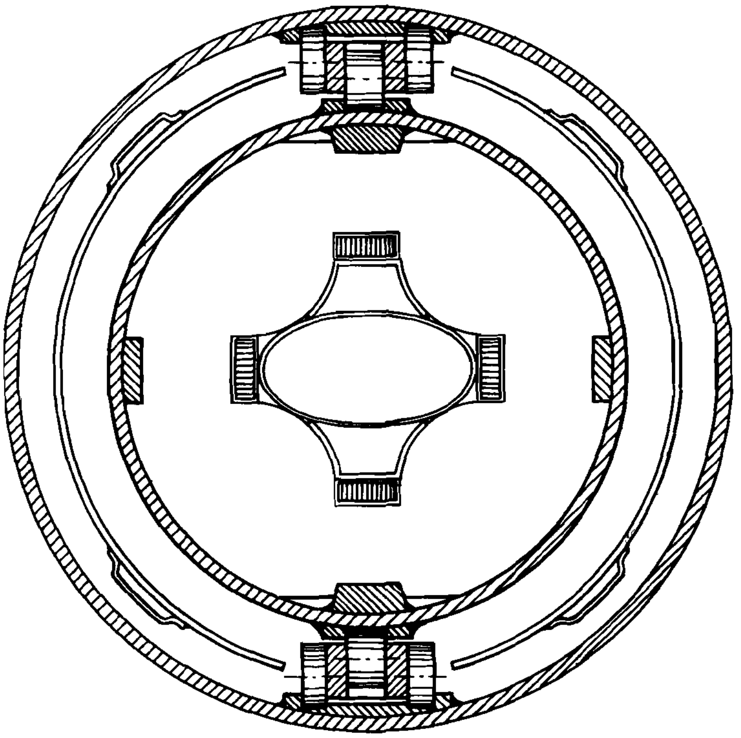
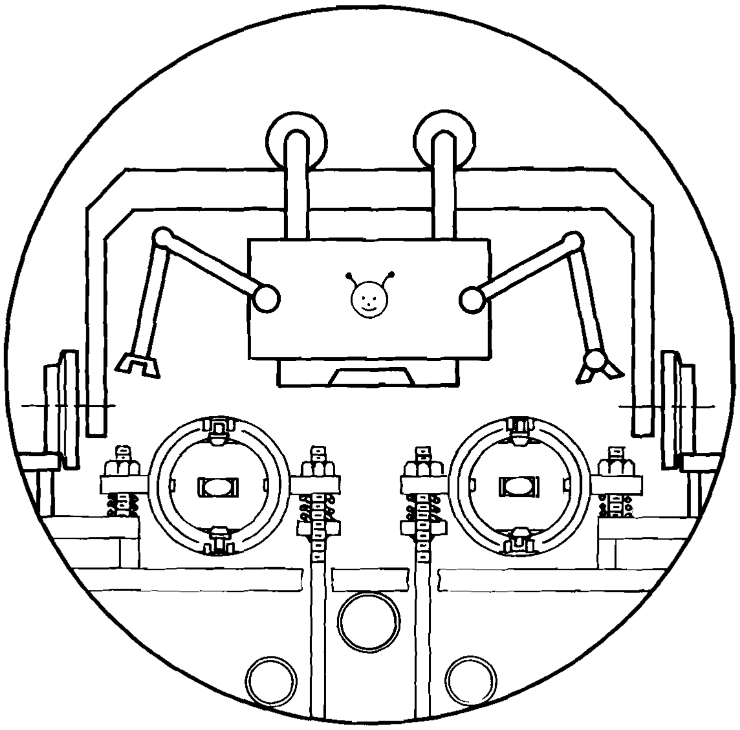


Fig. 3. 2.5 Tesla superferric magnets. (b) 100 T/m quadrupole magnet.



(c) Cross section of the 3-foot "tunnel" and magnets with an artist's conception of a robot.

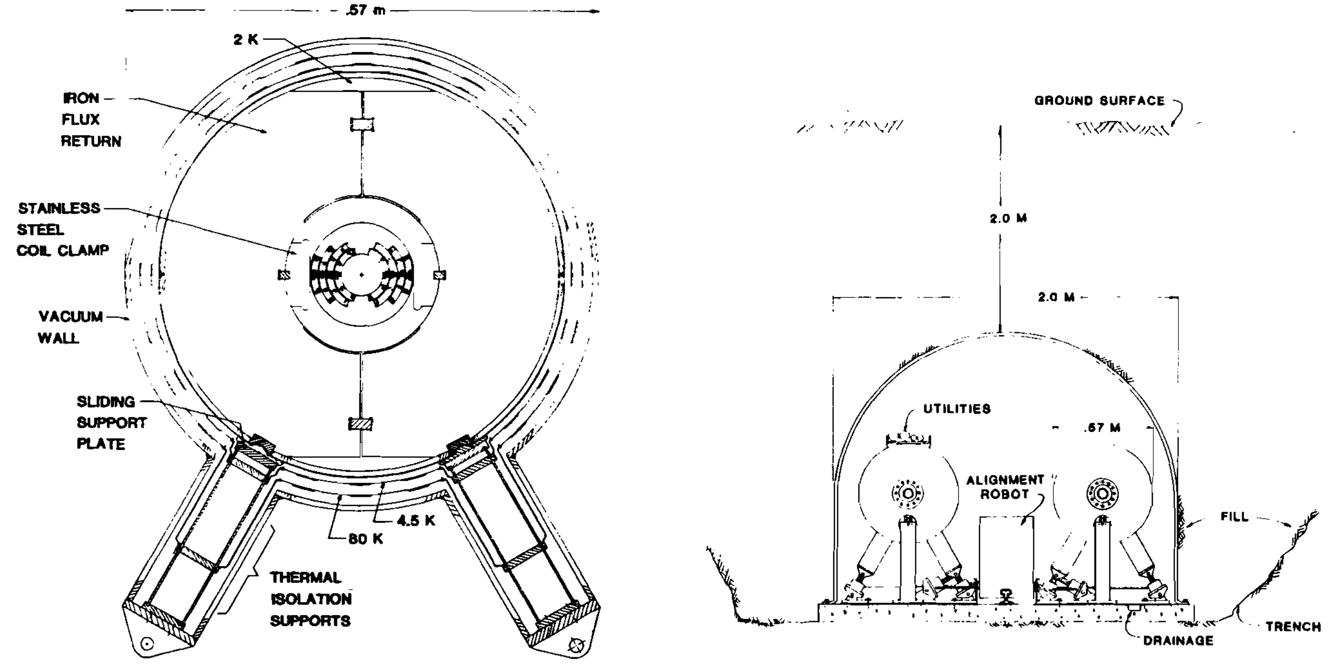
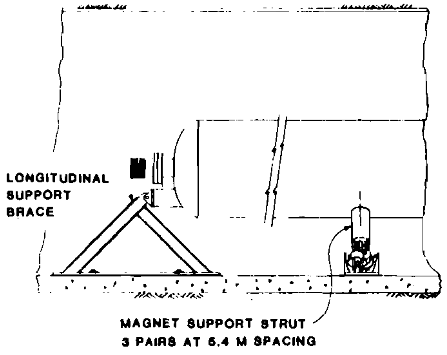


Fig. 4. 10 Tesla superferric magnets.

(a) 10T 50 mm Bore Dia Dipole magnet with "cold" iron and low heat-leak supports.

(b) Schematic Cross Section showing two 10T storage rings in a minimum size tunnel.



(c) 10T Dipole storage ring supports.

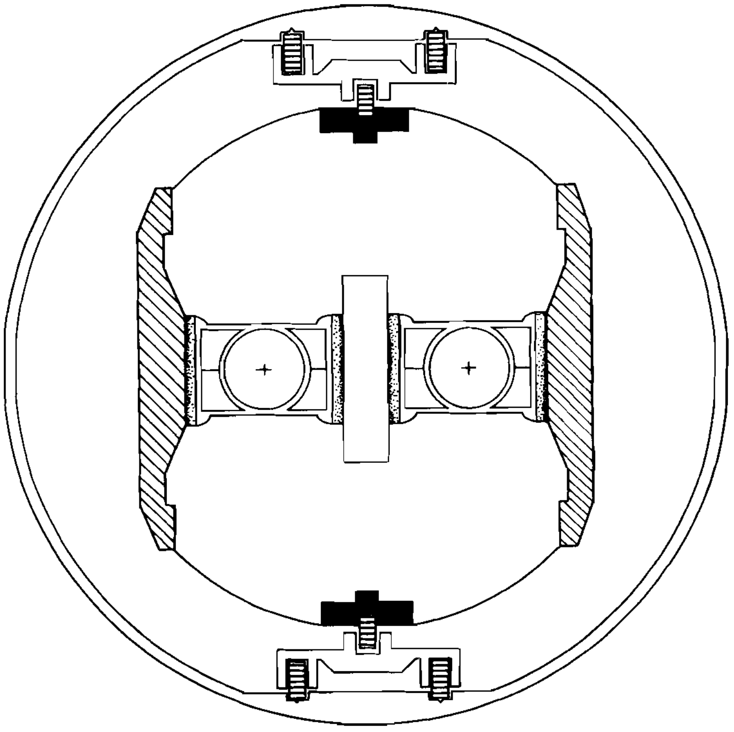


Fig. 5. 2-hole 2.5 Tesla magnet