Fermi National Accelerator Laboratory

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Low-Cost Hadron Colliders at Fermilab
A Discussion Paper

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Disclaimer

Introduction

New more economic approaches are required to continue the dramatic exponential rise in collider energies as represented by the well-known Livingston plot. The old idea of low-cost, low-field iron dominated magnets in a small diameter pipe may become feasible in the next decade with dramatic recent advances in technology:

- advanced tunneling technologies for small diameter, non human accessible tunnels
- accurate remote guidance systems for tunnel survey and boring machine steering
- high T_C superconductors operating at liquid N_2 or liquid H_2 temperatures
- industrial applications of remote manipulation and robotics
- digitally multiplexed electronics to minimize cables
- achievement of high luminosities in p-p and proton-antiproton colliders

There is an opportunity for mutually beneficial partnerships with the commercial sector to develop some of the necessary technology. This will gain public support for this undertaking, a necessary part of the challenge of building a new, very high energy collider.

Much of the material in this discussion paper is taken from a series of talks presented at the mini-symposium “New low-cost approaches to high energy hadron colliders at Fermilab” on May 3, 1996 during the Annual Meeting of the American Physical Society, Indianapolis.

The goal of this paper is to stimulate continuing discussions on approaches to this new collider and to identify critical areas needing calculations, construction of models, proof of principle experiments, and full scale prototypes in order to determine feasibility and arrive at cost estimates.

Project information including announcement of meetings can be found at

http://www-ap.fnal.gov/PIPE/

Historical Note

The concept of building an accelerator in a sewer pipe was clearly presented by Fermilab’s Founding Director, R. R. Wilson at the Snowmass Conference in 1982.[1]

> "Whether the next large proton accelerator (20 TeV ?) is built on a national basis or as an international effort, to be affordable, innovations in construction must be made. The design of a superferric magnet ring buried in a pipe in the ground is explored here to see what reductions in cost might result."
>
> "...superferric magnets (an old idea) have the advantage of simplicity, of being more sparing in the use of superconductor, less sensitive to the position of the superconductor, easier to construct, and perhaps more reliable to use."

Relevant technologies have emerged and grown rapidly since Snowmass 1982. Extrapolations of these technologies can bring this dream to reality in the next 10 - 20 years.

Project Goals

- Define an affordable path to 100 TeV per beam (200 TeV in the center-of-mass)
- One-tenth the cost per TeV (beam energy) of SSC/LHC including collider enclosure. This cost goal is in the range $20M - $40 per TeV. This does not include detector(s), injector(s), and transfer lines which remain approximately fixed costs. Approximately $3B are saved by using Fermilab as injector and supporting infrastructure.
- As few surface accesses as possible, dictated by political as well as cost considerations.

The Collider is logically divided into two sections:

- An accelerator enclosure, deep underground.
- A large on-site human accessible hall contains detector, transfer lines from injector, RF, beam abort, staging areas for the magnet installation machines, etc.

Magnet

The key element in a new large hadron collider is the magnet. For the reasons given above by Wilson we have been concentrating on low-cost, iron dominated superconducting magnets. A promising candidate for the magnet is the "double-C twin bore transmission line magnet" proposed by G. W. Foster, [2,3] shown below.

This magnet has the following characteristics:

- Single turn magnet carrying 60 kA for twin 1.5 cm apertures for a p-p collider.
- Warm iron, warm bore design. Cold mass is small and cool down will be fast.
- Alternating gradient pole tips (no quadrupoles) allow the drive conductor, vacuum system, and iron to be continuous in long lengths, minimizing end costs.
- The coil has many similarities to superconducting power transmission lines. Development of this magnet type parallels ongoing industrial development of High-T_c Superconducting Power Transmission Lines which will come to fruition in this decade.[4, 5]
- Although the beam sees 2 T. the conductor sees $\leq$ 1 T. Presently commercially available high T_c conductors can carry the current density required if the coil is cooled to 20 K. Conductors under development may carry this current at 77 K.
- Due to the symmetry of the design there are no unbalanced forces on the conductor. This simplifies the cold mass support ("spiders") and allows a low heat leak design.

Issues to discuss: pp vs. pp, required luminosities and detector parameters.

Initial parameter sets for 100 TeV x 100 TeV colliders have been developed by Steve Holmes[6] , Wm. Barletta[7, 8], and David Neuffer[9]. Some of these parameters are compared:

		Holmes	Holmes	Barletta	Neuffer
Luminosity Parameters	**unit**	**p-p**	**p-p**	**p-p**	**p-p**
Protons/bunch		**2.50E+11**	**2.50E+10**	**6E+10**	**4.1E+10**
Antiprotons/bunch		**1.82E+08**			
Proton (p) emittance (95%, norm)	π mm-mr	15.00	15.00		1.0 rms
Longitudinal emittance (95%)	eV-sec	2.00	30.00		
Beta @ IP	m	0.25	0.25	1.5	0.1
Injection Energy	TeV	2.50	2.50	10	
Arc Dipole Field	**Tesla**	**2.38**	**2.38**	**2.0**	**2.0**
Circumference	km	931.47	931.47	1160	1000
Rev. Frequency	Hz	321.85	321.85	259	300
Bunches		55,000	55,000	190,000	25,000
Bunch Spacing	m	16.94	16.94	6.1	40
Bunch Frequency	MHz	17.70	17.70		
RF Frequency	MHz	177.02	177.02	400	
Bunch length (rms)	nsec	0.19	0.73		
Momentum Spread (rms)		**5.66E-06**	**2.19E-05**		
Average Current	Amps	0.71	0.07	0.5	
Peak Current	Amps	85.10	2.20		
Crossing Half-angle	mr	0.01	0.01		
Beam size at IP	microns	2.42	2.42		1
Typical Luminosity	**cm-2sec-1**	**8.43E+32**	**3.77E+33**	**E+35**	**E+35**
Interactions/crossing		**7.14**	**31.97**	**13/cm**	

Although at first sight it would appear that pp can comfortably fit in one magnet gap, thereby providing an economy, in fact, the large number of bunches and crossing points requires electrostatically separating the two beams into a double helix which increases the aperture considerably beyond what would be required for one beam. Therefore, if physics justifies a pp collider then a better solution might be to add a second double-C magnet in the same enclosure. This argument probably only pertains to an intermediate energy ring (fed from the Tevatron, and then in turn injecting into the "ultimate" ring). Once one reaches 200 TeV there is no physics difference between pp and pp.

For a possible intermediate ring, built using double-C magnets, two vacuum chambers, instead of being placed in the two gaps of one magnet are placed one each in each magnet. The return current, instead of going through the return cryo pipe energizes the other magnet. The other two gaps are left empty until later conversion to pp.

With the proposed TeV33 luminosity upgrade there will be enough antiprotons available to build a 10^{33} "pipetron." Is 10^{33} enough? Some physics topics will require 10^{34} or even 10^{35} and a detector that can handle these luminosities. This discussion has only begun. It is unclear if there is a physics "niche" for a p-p collider at energy higher than the Tevatron but less than LHC. The advantage, for selected physics, is the q-q subprocess which becomes less and less important relative to gg as cm energy increases.

The current assumption is that there would be one on-site detector running, while another one, displaced transversely, is under construction or being upgraded. This is another issue requiring discussion.

Issue to discuss: double-C magnet vs. H-magnet

H-magnets are not ruled out. The challenge is the large magnetic forces in most designs (although there are coil locations that minimize this problem). With large forces, the "spiders" supporting the cold mass need to be strong and frequently spaced thus increasing the heat leak. A warm-iron H-magnet would require two cryostats for drive conductors instead of one, and would require a third large, cryogen distribution pipe as well. A gradient H-magnet could be considered; otherwise quadrupoles would have to be developed. For pp, two H-magnets would be required.

With an H-magnet, the return current is naturally in the magnet, whereas in the double-C design a separate return lead in the collider enclosure is necessary to avoid creating a disturbing large dipole.   It is also necessary to cross the beams at an even number of crossing points to keep the circumference of the two beams equal and permit a common RF harmonic number. This also requires a return lead. The return current in the C-magnet causes a slight asymmetry (e.g. top/bottom if the return is placed above the collider). This needs to be evaluated and corrected for.

In iron magnets, of either double-C or H- design the energy is in the gap where needed; the proposed 1.5 cm (vertical) x 3 cm gap has a good field region of 1.5 cm x 2 cm. This is to be compared to cosθ designs where the good field region is much less than the physical aperture, and the magnetic stored energy is spread into a large region around the coil.

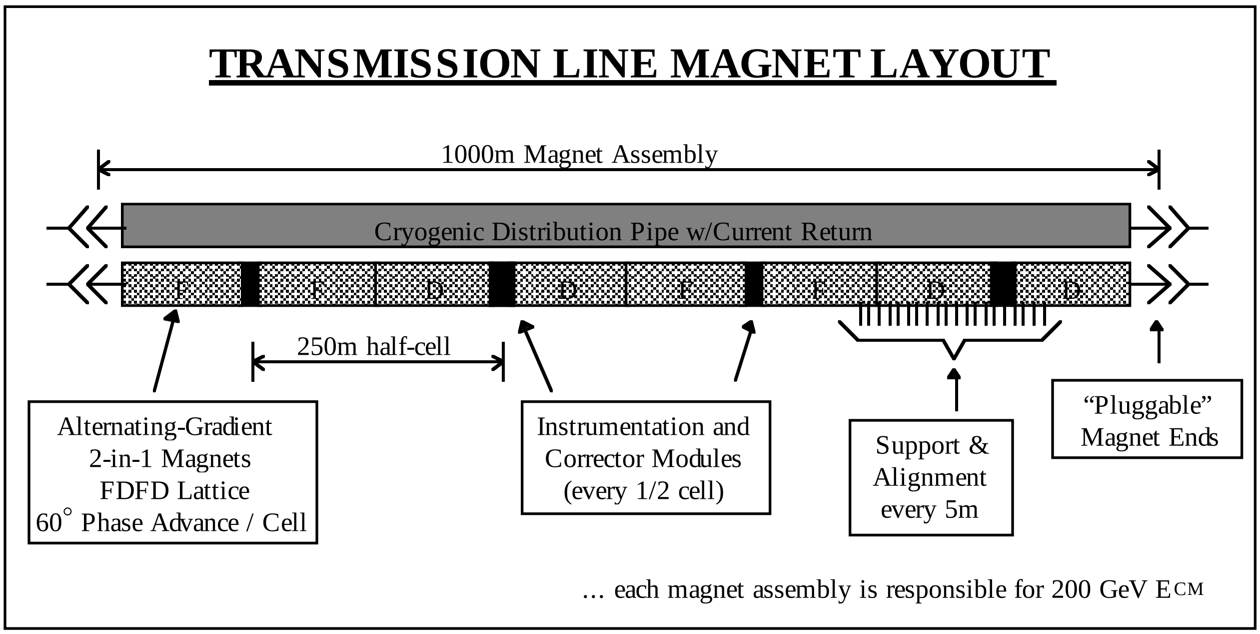
The warm-bore C-magnet has a number of well-known advantages: the field can be mapped prior to beam pipe installation, there is access to magnet pole tips for shimming/trimming/survey and to the vacuum system, BPM's etc., without disturbing the cryogenics. The vacuum system can be easily installed in long lengths into a C-magnet.

Discussion of Extruded Steel Magnet Yokes

It is now possible to obtain solid low-carbon steel extrusions with good tolerances and in long lengths. This is consistent with the current design. ANSYS calculations of eddy currents indicate laminations are unnecessary for a machine with 5-20 minute ramp. [10]

Alternating Gradient Pole Tips and Lattice

Although more discussion will be needed on the lattice, using combined function lends itself to long, identical modules making installation and repair easier. There are no quadrupoles to interrupt the "transmission-line" cryostat, and nearly no interruption of the bend field allowing one to aim for a packing fraction >95%.



An issue needing more investigation is the use of high-saturation alloy pole tips to permit B>2T. This issue will probably be settled by looking at the cost advantage of a slightly higher bending field and smaller circumference.

Neuffer[9] develops several lattices, both separated and combined function, and for phase advance/cell of 30°, 60°, and 90° and half-cell lengths varying from 200 - 300 meters. Holmes[6] proposes combined function with 60° advance and 290 meter half-cell length.

Demonstration/Test Facility

This is now under construction as a joint project of the Technical Support Section and the Accelerator Division. The prototype test setup uses a single 60 kA current loop, and

will provide 2 T field in two 1.5 cm magnet gaps. To avoid high current cryogenic leads the current loop is driven as a shorted single turn secondary winding on a transformer (built from an old accelerator magnet).

The goals are to:

- Demonstrate "transmission-line magnet" concept using helium cooled conductor.
- Provide a test bed for field quality demonstration and pole tip development.

Be compatible with an eventual upgrade to high-Tc conductor.

The Nuclotron, an existing super-ferric synchrotron

There is an existing operating super-ferric magnet synchrotron, the "Nuclotron" at J.I.N.R., Dubna (Russia).[11] It has a conventional separated function lattice, and accelerates particles to 6 GeV/nucleon. The cold-iron H-type magnets operate over a field range of 0.03 T to 2.0 T or a factor of 67. The builders of that machine have made an extrapolation using their design to a "pipetron"[12] with a total heat leak (at liquid Helium temperature) of 500 mW/meter.

Accelerator and instability issues

Gerry Jackson in his talk at the Indianapolis meeting[13] outlined some of the accelerator dynamics issues that need to be addressed in considering this very high energy, and low revolution frequency collider.

To avoid tune modulations at harmonics of the local line frequency (60 Hz), he proposes, as does Barletta[7] to make the revolution frequency an integer harmonic of the line frequency.

One of the potentially most serious issues is emittance growth driven by noise. This noise spectrum rises logarithmically as the frequency becomes lower. There are two approaches to this problem; both must be investigated:

- Passive suppression of emittance growth by mechanically mounting the magnets to isolate them from sources of rapid motion and/or cryogenic/electrical system design eliminating sources of noise.

- Active suppression using feedback. This requires extremely low noise pickups and preamplifiers and damping times that are short compared to the nonlinearity induced decoherence times. Suppression of electroacoustical noise in a 100 TeV machine is also discussed by Lambertson.[14]

Problems of emittance growth due to noise have been observed in the Tevatron and this problem has been systematically studied and the sources of growth eliminated or reduced in importance. Even though its circumference is 1/160th of the “ultimate” Pipetron, experiments in the Tevatron can be used to verify calculations and test feedback schemes.

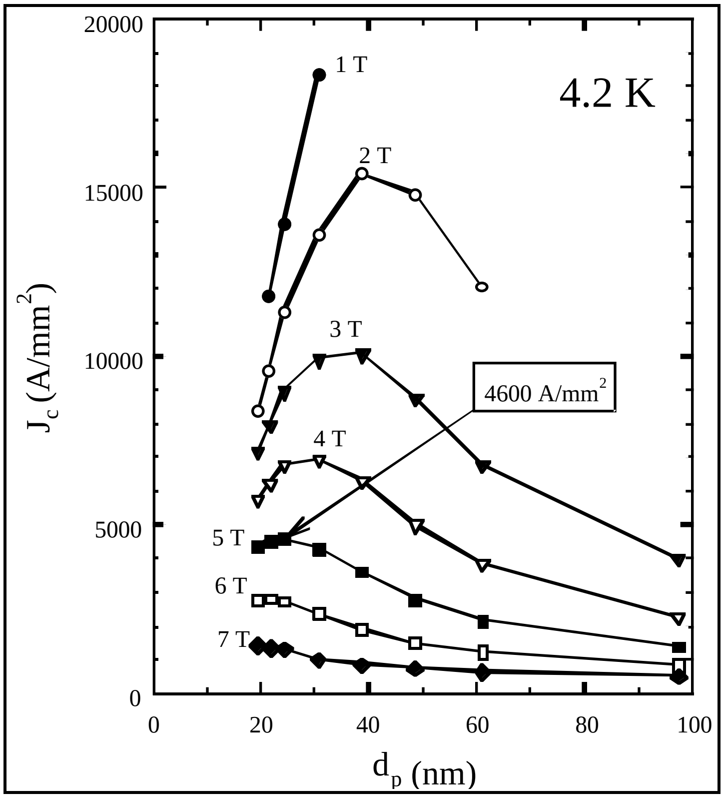
Magnet aperture requirements will be partly determined by the resistive wall instability and what method is used to deal with it.

Work has continued on accelerator physics issues since the Indianapolis meeting. W. Chou has developed parameter lists and surveyed the major issues confronting the pipetron.[15, 16] P. Colestock has made preliminary calculations of beam lifetime.[17]

Discussion of Superconducting Cable

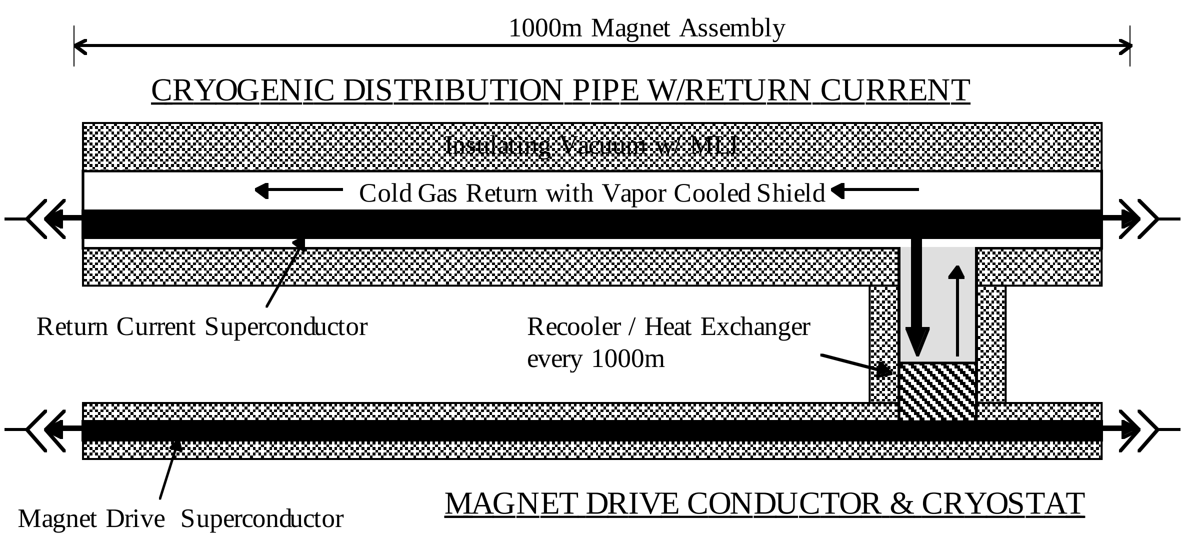
Current status and a comparison of low T_c and high T_c materials was summarized by Larbalestier.[18] Low temperature superconductors (LTS), available today, are NbTi and Nb_3Sn. In the former, artificial pinning centers (APC) are still experimental. The graph from Larbalestier’s talk shows J_c (in amps/mm^2) vs. dp (pinning center spacing in nanometers) from 1 to 7 T for Nb-47wt%-Ti (APC with 24 vol% Nb of pins), showing a new world record for current densities for round strand. This material is attractive in the double-C design where the field at the conductor is relatively low. Note that <4 mm$^{\mathbf{2}}$ of APC conductor would be required for a liquid He based system.

High temperature superconductors (HTS) are a key technology today that was not available to the SSC or LHC. Multifilamentary BSCCO conductors are commercially available now; BSCCO-2212 and BSCCO-2223 when they are operated at <20K offer enormous capability. Their current carrying capacity is high and rather independent of field. BSCCO-2223 is currently being used at Pirelli Cable Corporation under an EPRI/DOE contract to develop a prototype superconducting power transmission line.



The initial design of the Pipetron double-C magnet calls for a single turn carrying 60 kA. Prototype biaxially aligned YBCO monofilament tape conductors exist and are being developed at Los Alamos and Oak Ridge National Laboratories, and in Japan. 1 cm wide Los Alamos tape has a critical current at 77 K and 0 field of about 200 amps, so 300 conductors wrapped around a 1 inch diameter pipe would provide a 50 kA cable.

Commercially available conductor for use in LN_2 cooled transmission lines is getting better all the time. A liquid nitrogen cryogenic system is *much* cheaper than helium and *much much* cheaper than superfluid He which will be used in LHC. Liquid hydrogen is also an attractive possibility especially since our goal is to have the accelerator enclosure non-human accessible and probably fill it with dry nitrogen gas.



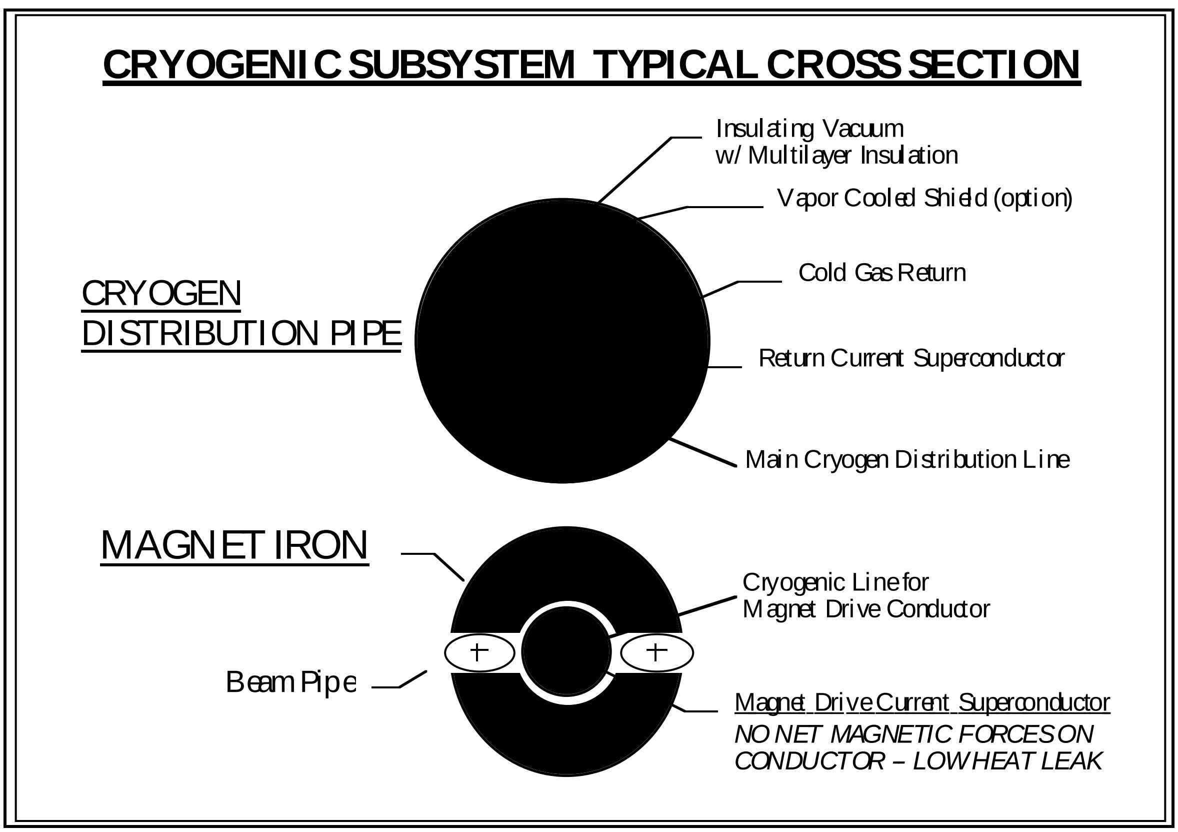
Cryogenics in the double-C design

Cryogenics baseline parameters were presented by Mazur at the Indianapolis meeting[19]. Also some preliminary calculations have been done by McAshan [20, 21]. A baseline is based on 60 kA lines (one drive loop, one return loop) using NbTi superconductors. The length of one cryogenic loop is 40 km, requiring a building and 18 kW refrigeration plant every 80 km. Thus for a 100 TeV collider, approximately 1000 km in circumference, 12 above ground refrigeration plants would be required. With a cryogenic efficiency of 1/200 (about 1/2 Carnot), this translates to 3.6 MW or for the 100 TeV collider, a total of 43 MW of wall power. If LN_2 was used the wall power would be < 3 MW.

After each 1000 meter long magnet module is placed a 3 meter long recooler. Assuming a heat leak of 50 mW/meter is attained, the temperature rises from 4.3 K to 4.6 K from one end of the magnet module to the other. Inside the accelerator enclosure will be three lines for the cryogenic system:

- the drive conductor line in the magnet
- the main liquid cryogenic transfer line
- a warm gas return line which consists of a 10 cm diameter uninsulated pipe

The warm gas return line is used for cooldown and quench recovery. The total heat leak budget is 200 mW/meter (for magnet and return). Multilayer insulation results achieving this low value have been published by several authors.



Challenges in the cryogenic system

- connections and remote assembly
- thermal contraction of the cold components (we may use invar pipe in the magnet)
- electrical insulation of the magnet drive conductor
- controls and instrumentation
- achieve low heat leak on the large scale required.

The effect of HTS on the cryogenic system

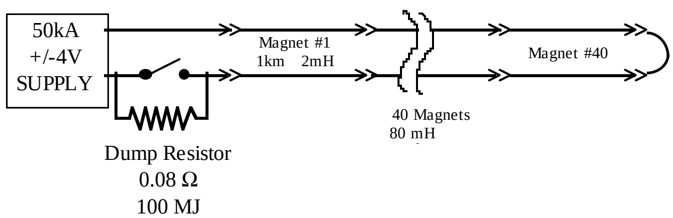
When HTS become available with suitable properties at acceptable costs (that may already be true), it may be possible to use hydrogen (or even nitrogen) refrigeration. The hydrogen refrigerator will be smaller, less expensive, and to have lower operating costs than the helium refrigerator. The piping in the tunnel is also substantially cheaper for the HTS cryofluids. Hydrogen has a latent heat of 450 joules/gram, 22 times that of helium. Consequently, the flow rates required for the same heat leak are smaller and the pipe sizes required in the main transfer line in the collider enclosure are considerably smaller resulting in substantial cost reductions. Mazur's paper[19] compares pipe sizes.

line radius, cm	He	H_2
liquid line	3.4	1.1
cold gas	8.5	3.7

Quench protection parameters have been worked out by Koepke[22] and were presented at the Indianapolis meeting. The type of superconductor (LTS or HTS) is not yet determined so Koepke has used a universal approach that depends only weakly on the critical temperature of the cryogen. The superconductor is in good electrical contact with cable copper area of 1 cm^2. The design of the quench system/power supply system is mainly driven by the allowable peak temperature, assumed to be 500 K, and the peak voltage to ground, assumed to be 2 kV.

MAGNET POWER SUPPLY AND QUENCH PROTECTION SUBSYSTEMS

- Ring is Electrically Divided into 40km (4 TeV)
- Each Section Contains 40
- Peak Drive Current = 50kA
- Total Inductance = 80 mH (= 2 mH / 1km magnet)
- Stored Energy 100 MJ (= 2.5 MJ / magnet)
- Ramp Time = 1000 secs (= 17 mins)
- Ramp Voltage = 4V (= 50 kA * 80mH / 1000 sec)
- Peak Ramp Power = 200kW (= 50 kA * 4V)
- Dump Resistor R_{DUMP} = 0.08Ω
- Dump Time Constant L/R_{DUMP} = 1 second
- Peak Voltage to Ground During Dump = ±2 kV
- Conductor Quench Current Capability = 1250 MITS



Power supplies and switched series resistors are evenly spaced to minimize voltage to ground. The 40 km loops assumed for the cryogenic (helium based) system are also reasonable for the power supplies and dump resistors.

Synchrotron radiation

As the energy increases beyond 20 TeV per beam, synchrotron radiation can have a substantial positive impact on collider performance. This was explored for a 30 x 30 TeV p-p collider with 10^{34} luminosity at the Workshop on Future Hadron Facilities in the U.S., July 6-10, 1994.[23, 24, 25] With a magnetic field of 12.5 T, damping times were 4.7 hours transverse and 2.3 hours longitudinal. However, one must remove the heat load generated within the cold bore magnets. Beyond 30 TeV per beam and at luminosities above 10^{34}, synchrotron radiation becomes a serious, if not fatal problem for the cold bore $\cos\theta$ dipole.

A summary of Turner's[26] talk at the Indianapolis meeting follows. He starts with Neuffer's parameters[9] although his beam tube diameter of 4 cm is larger than has been assumed elsewhere in this discussion paper. Damping time is 20.7 hrs, so this will play a minor role in shrinking the emittance during the store, since it is anticipated that store times will be roughly half-day. The synchrotron power radiated is 0.21 watts/meter. This is relatively weak compared to contemporary electron rings and has both advantages and disadvantages. The decrease in photon intensity in the "pipetron" compared to electron storage rings is compensated by a slower cleanup rate for the vacuum system, so similar linear pumping speeds are required.

Either distributed ion pumps or NEG strips (see next section) with lumped ion pumps look technically feasible for the 200 TeV superferric warm bore pp collider.

Beam tube conditioning times to achieve vacuum limited luminosity lifetime > 100 hours and scattered beam power < 0.1 watts/meter globally and < 1 watt/meter locally are reasonably short. More investigation is need to set the limits on beam power allowed by the superconducting transmission line.

There appear to be large safety margins for ion desorption stability and beam induced multipactoring.

Vacuum system in the double-C design

Ishimaru [27, 28] has based his design on the double-C magnet and an aluminum alloy vacuum pipe. It has the features of low cost and high reliability. Continuous aluminum extrusions can be obtained in long lengths: >250 m. The chamber is periodically anchored to the iron to control thermal effects. One of the key design features is to have no bellows. Finite element analysis has shown that this system will work. The chamber, 1.5 mm thick, is an aluminum alloy extrusion. It is a clad structure with 100 microns of 99.99% pure aluminum on the inner surface (to reduce resistive wall effects).

A high-conductance side chamber for pump down contains the distributed non-evaporable getter (NEG) pump, a standard solution for electron machines. An outgassing rate of approximately 10^{-13} Torr-liters/sec/cm^2 can be achieved utilizing chemical cleaning process procedure at 70^{o}C, and a 1 hour mild baking at 350^{o}C during NEG strip activation.

In the center of each 250 meter length (at β_{max}) will be placed the x-y beam position monitor (BPM), lumped ion pumps for pumping noble gasses, a roughing port, the NEG strip power feedthrus. At the end of each magnet (1000 meter) will be placed a quick disconnect, and a gate valve. The magnet can be built and inserted into the accelerator enclosure under vacuum.

Geology of the Fermilab Region.

Gross[29] has described the suitability of the Fermilab site and region around it for a new large collider project. Site conditions at Fermilab are well understood. The Illinois State Geological Survey (ISGS) has extensive data on the regions under consideration from several hundred-thousand drill holes, and additional data compiled when there was active consideration given to siting the SSC in Illinois. Neighboring mid-West states have similar extensive information relevant to a large project of this sort.

There are predictable rock and tunneling conditions, relatively homogenous rock mass, seismically stable with no movement in recorded history. There is a vibration free environment, important to minimize emittance growth problems. There are no settlement problems at the depths being considered.

Even the largest ring we have considered, 1100 km in circumference is still in glaciated terrain. The Silurian dolomite under Chicago and the Ordovician dolomite under Fermilab are quite uniform. The large regional extent of dolomite can serve as an excellent host for a tunnel or horizontal drill hole in the Fermilab region.

There is extensive local tunneling experience: >72 miles of tunneling experience in Chicago, using TBM's (tunnel boring machines); 266 shafts constructed for TARP (Tunnel and Reservoir Project). The total volume of rock excavated with TBM's in the Chicago area already greatly exceeds that required for the 100 TeV machine.

Rock Mechanics: the directions of fracture planes are favorable to N-S and E-W straight tunnels. The fracture planes that generally run diagonally to these directions may not be a problem for the small tunnels or drill holes proposed for the pipetron.

The spoils from dolomite excavation are a commercially valuable commodity. Immediately south of the Fermilab site there is an underground quarry (mine) which has tunneled down into the dolomite to obtain dolomite gravel for road and civil construction.

Trenchless Technology

Iseley[30] describes Trenchless Technology and its rapidly growing importance as a practical solution to expansion and repair of underground utilities. This is an area where not only can the pipetron benefit from this technology as its capabilities expand but can also be a catalyst to this environmentally crucial industry.

There are two competing commercial technologies with potential application to the pipetron: microtunneling and horizontal directional drilling. These technologies have emerged in recent years, motivated in part by the need to build new and rebuild old infrastructure with minimum surface disturbance. These technologies are already in the billions of dollars/year category and growing rapidly. Applying reasonable extrapolations to these rapidly growing methods one can envision them applied to the next large collider.

Tunneling is done every day. Tunneling is most economical if the geological conditions are well documented and uniform. The geology in the Fermilab region is exceptionally well documented. The Silurian dolomite under Chicago and the Ordovician dolomite under Fermilab are quite uniform and superb hosts for tunnels or drill holes. Trenchless Technology is rapidly growing in importance as a practical solution to expansion and repair of underground utilities.

Features of Microtunneling

- a trenchless technology for constructing pipelines to very close (± 1 inch) tolerances.
- a remotely controlled, laser guided, system; personnel entry not required. Microtunneling is essentially a scaled-down version of the “Tunnel Boring Machine” (TBM) technology used to bore the Chicago Deep-Tunnel project, and later, a portion of the SSC tunnel.
- used to install pipelines in a single pass operation in lengths up to 2,000 ft, and in diameters from 6 in. to 10 ft.
- typical production rates are 30 to 60 ft/day; rates of >200 ft/day have been achieved.
- can be used in a variety of ground conditions from soft clay to rock, above or up to 100 ft below the water table.
- microtunneling costs continue to drop.

Microtunneling issues for the pipetron

Cutters for a hard rock tunneling machine need to be changed periodically and this leads, with today’s technology either to manned access or to a very large number of vertical shafts.[31] Even extrapolating to the future, we might need an access point as often as every 2 km. There are concepts under discussion that would make it possible for two microtunneling machines to pass each other; thus one could be pushing ahead, while the other one is brought back for servicing. These are difficult problems and require considerable R&D effort to solve, but would have a large payoff to industry.

Removing the “muck” is another challenge. Current methods are using a conveyer, dump cars (as in mining technology) or a slurry. Slurry is not practical for long distances because hydraulic impedance increases as bore is longer and weight of the cables/hoses mounts up. Conveyers were used for a distance of 6 miles in the SSC project.[32] More discussion and design work is needed, but at this juncture, the leading idea is installation of rails as the microtunnel machine advances and then use these rails both for muck removal during enclosure construction and later for magnet installation.

Most microtunnels have been straight. Microtunnels that go in curves and follow terrain (as our large collider will likely do) are just beginning to be built, mostly in Europe. Robot theodolites for microtunneling applications are being marketed by DYWIDAG, one of the prime contractors for the SSC. In experimental microtunnels (non-human access), 1.6 m diam, 500 m long, $\pm$ 1 cm accuracy is being achieved.[33] There is active experimentation with inertial guidance, but so far gyro drift rates are too large.

The first microtunnel in the U.S. was done in 1984. Atalah and Hadala[34] have compiled the cumulative installed microtunneling in North America (in kilometers) of all types with projections for 1996 and 1997. This graph shows the rapid growth of the industry, with a doubling time of ~ 2.5 years.

Features of Horizontal Directional Drilling

- Is a U.S. invention developed primarily for oil and gas exploration, in contrast to microtunneling where until recently the advances have come mainly from Europe and Japan. The application of horizontal drilling to the discovery and productive development of oil reserves has become a frequent event over the past 5 years. Thousands of horizontal wells are drilled each year. The cost of horizontal drilling continues to drop.

- May be more likely to work for us than boring using a microtunneling machine because already today, much longer distances between access shafts are possible. Michels Pipeline, one of the large U.S. companies, has drilled 5200 feet.[35] Horizontal drills up to 5 miles are being planned.

- Usual technique is to drill a 10 - 12 inch diameter pilot hole and then back ream from it and enlarge the hole. The drill string is then used to pull the finished pipeline into the ground from the far end of the hole. Diameters up to 48 inches are being done.

- Generally goes from the surface, down at 30^{o} - 45^{o}, under, e.g. the Mississippi River, and then back up to the surface. A downhole instrument package provides location of the drill bit so that the hole's direction can be controlled.

- Can drill through rock at high speed. (> 10 m/hr). Often drilled by a fluid-driven motor mounted downhole directly above the bit. The hydraulic fluid is the “drilling mud” used as a slurry to remove cutting spoils to the surface.

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Horizontal Drilling Issues

The biggest problem with horizontal drilling is the accuracy, currently $\pm$ 1-2 feet. Density variations in the rock cause the drill to veer from the desired direction. This is clearly not good enough for our application at this time, although the distance between access shafts is much greater than with microtunneling. However, there is active research underway in improving accuracy of guiding the drill head. There is a large economic incentive for pipeline companies to eliminate kinks and jogs in their pipelines since this minimizes pull-back friction, and allows longer bores. There is increased frequency of drilling multiple laterals, of interest to us for “sidings” and “alcoves.”

Ground water and enclosure liners

In a glaciated region, groundwater is typically present in the glacial drift and in the uppermost few meters of bedrock. In the bedrock beneath Fermilab, the rate of movement of groundwater varies by three orders of magnitude, from 1,000 ft/year in the aquifers to only 1 ft/year in the Galena-Platteville dolomite. The dolomite of the Galena-Platteville does not yield much water whereas the sandstone is a high quality aquifer. Therefore, the dolomite is attractive as a potential host for a tunnel or horizontal drill hole for an accelerator project. Some major tunnels under the cities of Milwaukee and Chicago, constructed in the dolomite, have such low seepage rates that they are unlined.

Are liners needed? This depends on the rock, and as indicated in the discussion above, seepage rates are very low in the dolomite layers some 300 ft below the surface in the Fermilab region. Probably we do need a liner. Current R&D efforts in the microtunneling industry are aimed at remotely installed liners, either spray on or liners that are in arches that can snap together. Commercial grouts and epoxy sealants exist which can make the tunnel virtually leakproof.

The Construction Challenge.

In order to interact more closely with the Trenchless Technology industry Fermilab has joined the North American Society for Trenchless Technology which represents this rapidly growing multi-billion dollar industry. As we develop the parameters and concepts further we will at the same time explore partnerships with industry to work on innovative ways for

- longer distances between shafts
- “umbrella” machines which “unfold” at the cutting face
- remote cutter changing for microtunneling machines
- remote liner installation
- long-distance muck removal strategies
- guidance
- terrain following

The Collider Enclosure

Preliminary enclosure cross sections were presented by Mike May [36] at the Indianapolis meeting. For discussion purposes we assume a diameter of 3 to 4 feet. As indicated above we do not yet know whether the microtunneling or horizontal directional drilling approach will be chosen. Regardless of this choice, one could consider dividing the collider construction into 2 phases:

phase I -- enclosure construction
phase II -- collider installation

During phase I we might relax the stringent "non-human accessible" requirement, in which case cost optimization might indicate a larger diameter pipe. In current practice, 36 inch (90 cm) is regarded as the minimum diameter for manned access into long industrial pipelines in Europe and in the U.S., and 32 inch (80 cm) in Japan[37].

Electrical services need to be provided for the "toy" train that does muck removal, and the remote control mechanisms that install and repair accelerator components. One concept has bare, high voltage bus either on the ceiling or bottom of the enclosure, with the tunnel vehicles extracting power from the bus, much as is done with a subway. What needs to be decided is what is the maximum voltage that can be handled subject to the problems of dirt and moisture. It is assumed that the vehicles themselves will carry step-down transformers.

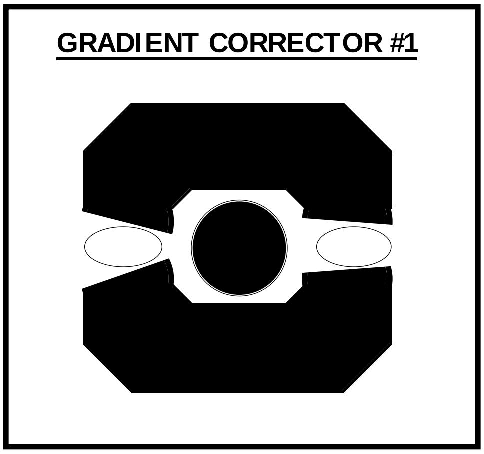
Robotics (more correctly remote handling) are now being used for repair of sewer pipes ranging from 8 to 30 inch in diameter with access every 300 - 400 ft via manhole. The robots cut holes, put in patches, cut roots out, install new lateral connections, etc. This is a rapidly expanding billion dollar/year industry. Visual Robotic Welding has been developed at Fermilab and used to repair beam pipes. Remote operations will benefit by the use of virtual reality. [38] The operations challenge will be to learn a new way of working on accelerators with increased emphasis on reliability, redundancy, and fault tolerance.

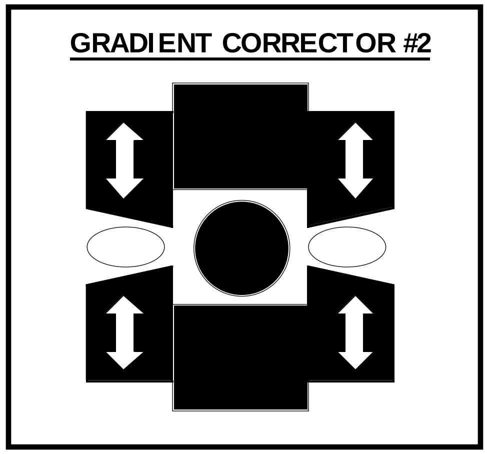
Surface penetrations

As discussed above, a first look at cryogenics and power supply/quench protection requirements indicates that an access shaft and surface building will be required every 80 km around the ring. Depending on evolution of the tunneling/boring industries and detailed cost optimization not yet done, additional accesses to the surface may be required. Clearly the fewer of these the better. Some of these additional access shafts may not need human access, but would be bore holes for surveying, or running cables of various kinds down to the enclosure.

Monitoring and control

There is room here for a great deal of innovation to reduce costs and increase reliability. Can one (or a small number of) multiplexed fiber optic link control and monitor the entire collider? What about radiation damage to the fiber and the electronics? As mentioned above we anticipate simple packages containing ion pump, ion pump power, beam position monitor, beam loss monitor, and electronics for all of this every 250 meters. This frequency is not absolutely required but gives redundancy. Correction magnets could be simply iron C-blocks of the required pole tip shape, driven by the same 60 kA main drive conductor, and moved (even during the ramp) by stepping motors. The illustration is an example on how the gradient (and thus the tune of the collider) could be varied.





An electron option[39]

Given a very large radius of curvature enclosure, one may well ask, if, in the CERN tradition of LEP/LHC, one couldn't put an e^+e^- collider in the same pipe. This is an interesting idea that needs discussion. Simple minded E^4/R scaling from LEP allows an e^+e^- collider in the pipetron enclosure to be above the t t and possibly Higgs threshold for the same total RF voltage as LEP II. The required dipole strength is only 100 Gauss.

The path to 200 TeV in the Center of Mass

There are many possible paths between today and what might become a reality 20 years from now. Considerable discussion and hard work is needed to choose the best path.

Some of the issues:

- is there an accelerator physics need for an intermediate injector ring?
- is there a high-energy physics justification for an intermediate energy ring?
- given LHC what should that energy be?
- magnetic field range with usable good field; this determines injection energy.
- what are reasonable filling times and ramp rates?
- should we maintain antiproton-proton capability in the next (intermediate) stage?

Holmes[6] goes from the Tevatron to a 2 TeV site filler/buster, and then a factor of 50 magnetic field change in the large collider. The Tevatron only operates over a range of 7 in magnetic field. The SSC originally was to have operated over a range of 20 but that was later changed to 10. HERA runs over a factor of 21. Conductor dominated SC magnets are limited by persistent currents whereas iron dominated magnets are not. The Fermilab Main Ring operated at one time over a range of 57, and the Nuclotron magnetic field range is >60. But there are differences between those machines and the pipetron. the Main Ring and Nuclotron are not storage rings; the Tevatron and SSC are superconducting but use cosθ dipoles with field defects from persistent currents.

Next steps

Begin a vigorous R&D plan to attack, in parallel many of the issues: work on accelerator dynamics, develop the physics case and the preliminary detector parameters, do R&D on magnets including the use of HTS, and together with industry work on tunneling and robotics.

Form partnerships with the private sector and start building public support. To gain this support:

- The cost, measured in $/TeV must be significantly lower than other projects, and also in absolute terms must be a reasonable amount. A very preliminary look at the major cost drivers (quantities of superconductor, mass of the magnet, complexity, vacuum system, collider enclosure volume, stored energy etc.) give rise to optimism that this goal is achievable. Both capital and operating costs are important.

- There must be real benefits to society from the R&D leading to this project and also in its execution. The benefits from developing technology which allows one to decommission high-voltage surface power transmission lines, and replace them with underground robotically tunneled and maintained HTS transmission lines, are obvious. Other benefits might include shared use of the collider enclosure for infrastructure. The capabilities developed may open new markets for the private sector.

Study and hard work over the next few years will determine if the “pipetron” meets these criteria.

This project was conceived with the aim of pushing the energy frontier a factor of 100 further than it is today. It will rely for its success on the synergy between the physics goal of reaching 200 TeV in the collision center-of-mass, and the economic and environmental goals of the trenchless technology, superconducting power transmission, and industrial robotics industries.

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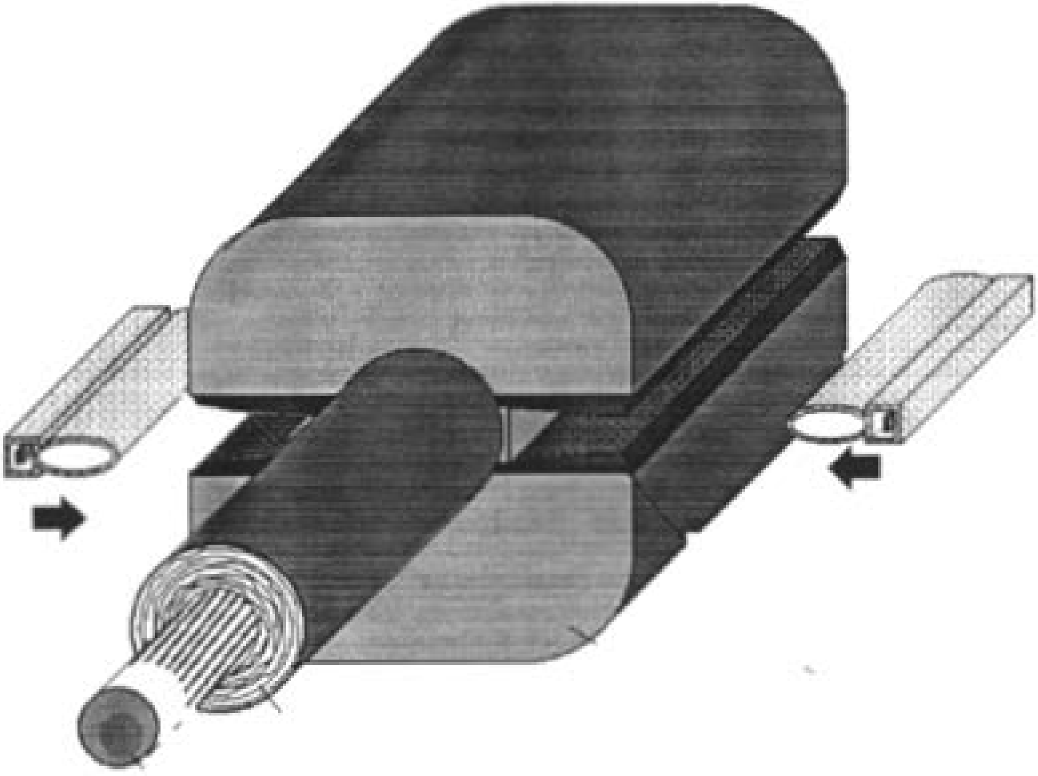
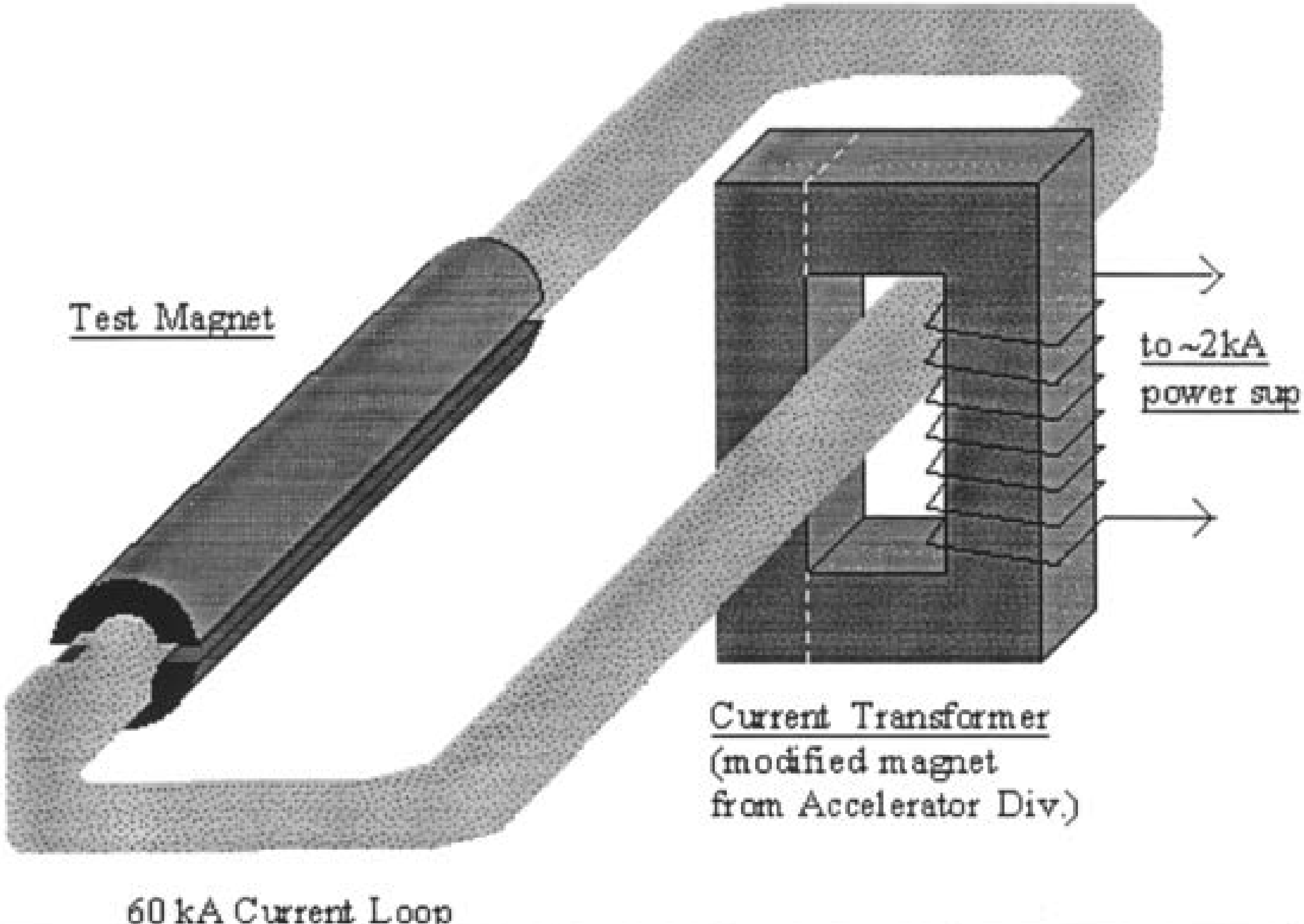
"Double-C" Twin Bore Transmission Line Magnet

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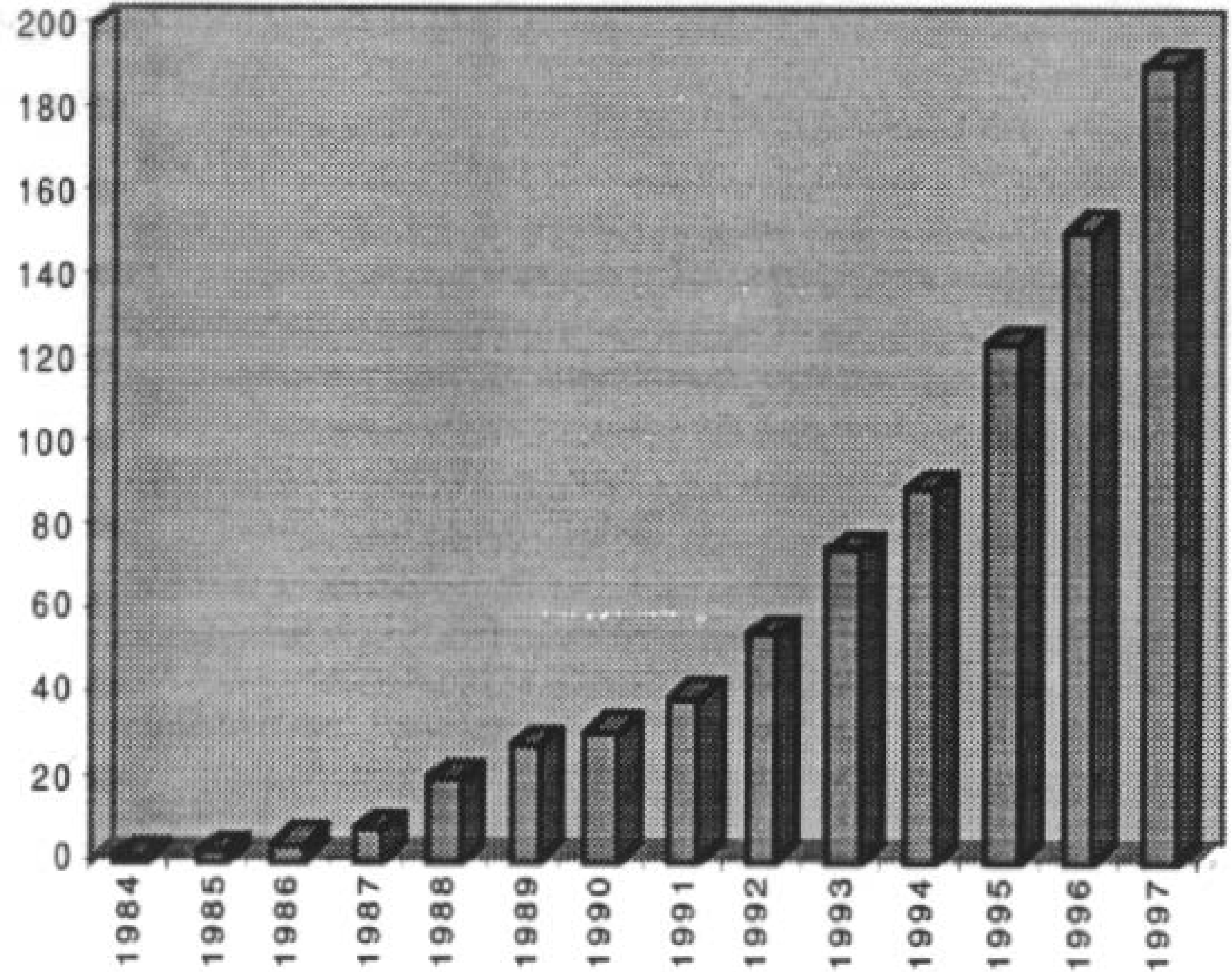
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