Fermi National Accelerator Laboratory

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Cost Model for a 3 TeV VLHC Booster Tunnel

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Abstract

The Kenny Construction Company was hired on a consulting basis to prepare a detailed cost estimate for construction of a 34 km tunnel to house a 3 TeV low-field VLHC Booster. Their report was submitted in the form of a non-competitive bid including all the backup material used in preparing the bid. This note summarizes our conclusions from their report.

The VLHC (Very Large Hadron Collider) as presently conceived would be a 100 TeV (c.m. energy) accelerator whose two counter-rotating 50 TeV proton beams would originate from the Fermilab Main Injector at 150 GeV. An intermediate accelerator would be needed to "boost" the Main Injector beam energy before injecting it into the VLHC ring. We assume (somewhat arbitrarily) that this machine will have an energy of 3 TeV. It is this 3 TeV "Booster" that we discuss here.

Reducing the $/TeV - Balancing Component Costs We have been impressed with the complexity and the large $/ft cost of the high field magnets of the SSC and LHC. In these projects tunnel costs are not a major cost driver. The potential of lower field (2.0 T) superconducting magnets (super-ferric) with concomitant much lower costs/ft lead us to explore reductions in tunnel costs. The very favorable north eastern Illinois geology with the already extensive local tunneling experience further encouraged us in this direction.

We wish to emphasize that the cost estimate and tunneling technology we describe here reflect today's state of the art *conventional* tunneling technology. It is what we would expect *today* from a competent contractor.

In the last few decades there have been gradual improvements in tunneling technologies which resulted in reduced cost/ft of tunnel. We expect these improvements to continue so that at the time of construction the costs will be further reduced. While the cost for the Booster tunnel that we present here may be acceptable, the extrapolated cost for the much longer VLHC tunnel is sufficiently large that it may preclude its funding. We indicate future paths of development.

Booster Configuration The Booster layout, shown in Figure 1. has a 34 km (21.1 miles) circumference. It can be approximated by two 15.2 km radius semi-circles connected with two 1.8 km straight sections. This layout is based on using 2.0 T magnets to bend the proton beams. The tunnel is bored through the Galena-Platteville dolomite rock formation at an elevation of 97.5 m (320 ft) above mean sea level (msl). At the Fermilab site, this is about 128 m (421 ft) below the ground surface.

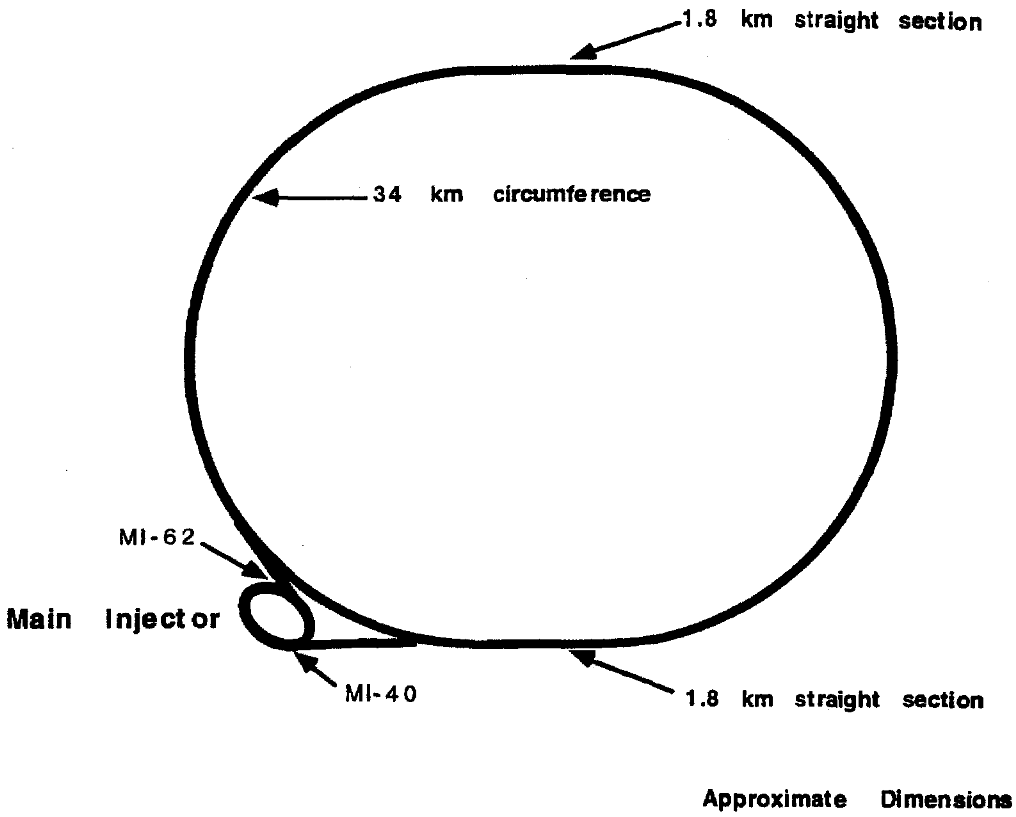

Figure 1 Booster Configuration

It is much easier to bend a 150 GeV beam for injection into the 3 TeV Booster than to bend a 3 TeV beam for injection into the VLHC. For that reason we choose to build the 3 TeV machine near the same depth and in the same rock formation as we will propose for the VLHC.

Beam is extracted from the Main Injector (located at elevation 741 ft msl) in two places. The first extraction is from the MI-62 region into a 2.5 km transfer line sloping downward at 2.9° to become the clockwise rotating beam in the Booster. Similarly beam is extracted from the MI-40 region into a 3.1 km transfer line sloping at 2.4° to become the counter-clockwise rotating beam.

After acceleration to 3 TeV in the Booster, beam is directed into the 50 TeV per beam VLHC located at a similar depth. The VLHC and its injection lines are not shown in the Figure 1. This layout also allows for the possibility of the two beams to be brought into collision in the Booster.

The layout, while not reflecting in detail the eventual accelerator to be built, provides us with a useful basis for understanding the various components in the cost of the tunnel. An example would be the two 1.8 km straight sections. As the accelerator design evolves, these may very well be shortened. Having the detailed unit costs in hand allows us to measure the resulting savings

The Booster configuration shown in Figure 1 is representative of many possible configurations. When this project reaches a stage where construction is seriously contemplated, the final configuration would require input and approval from all potentially effected constituencies.

<u>Geological Setting</u> The northern Illinois geology is characterized by surface deposits composed of a series of glacial tills. Below these deposits is bedrock consisting of sedimentary layers deposited when the area was a vast inland sea. Recent seismic measurements [3] indicate very low background seismic activity. The Metropolitan Water Reclamation District of Greater Chicago [4] has constructed about a hundred miles of rock tunnels in these sedimentary dolomite layers for water conveyance projects. It is in one of these seismicly stable layers that we propose to site the 3 TeV Booster.

Figure 2 shows the geological units plotted along with the elevation of the circumference of the Booster ring ("lampshade"). Note that the proposed tunnel lies entirely in the Galena-Platteville strata. For simplicity we chose a horizontal ring. A slightly tilted ring would aid water drainage. Extensive use has been made of the geotechnical studies[1] done for the Illinois SSC proposal[2]. This report[1] includes most of the needed geological information.

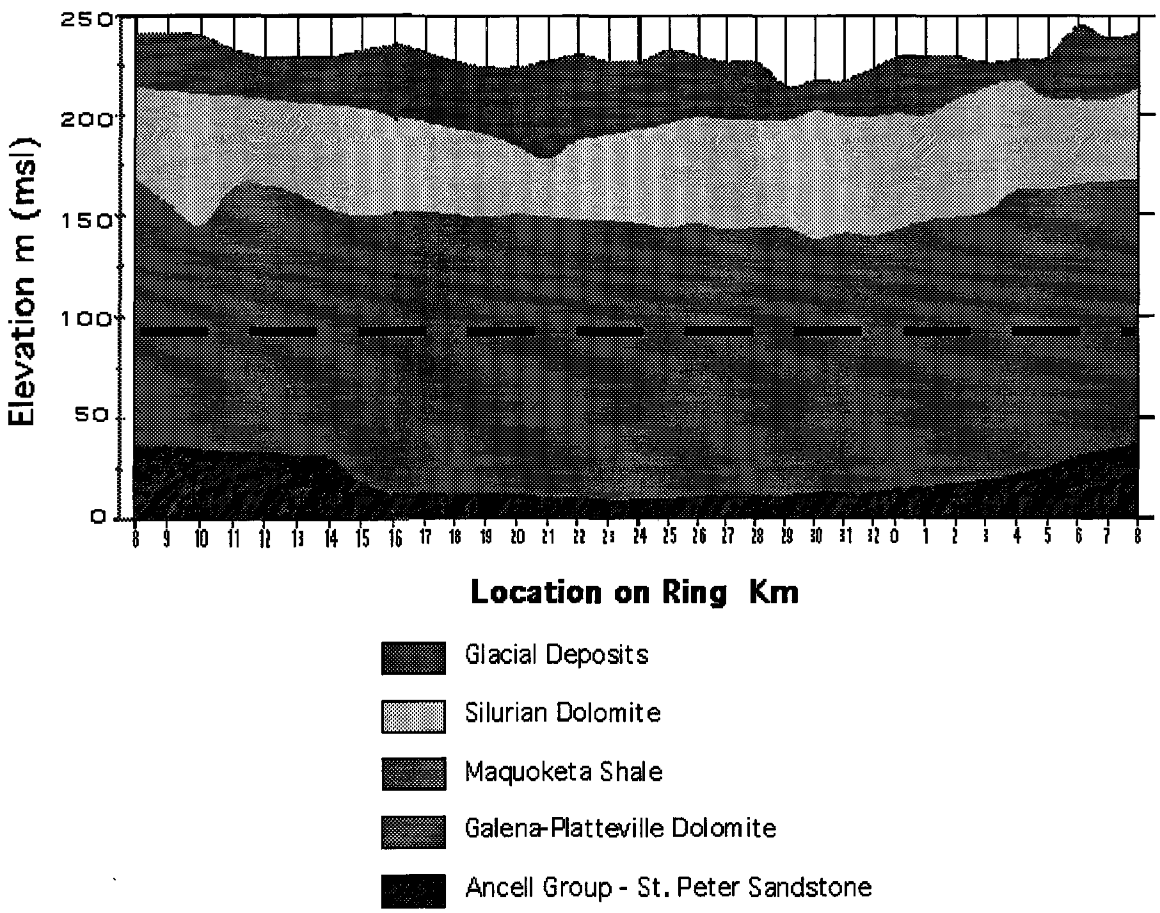

Figure 2 Geology of Booster region
The dotted line indicates the Booster tunnel elevation

Tunnel Specifications We have consulted with the Kenny Construction Company of Wheeling Illinois in estimating the cost of the tunnel for this machine. This company has extensive experience constructing tunnels in similar rock strata in the Chicago area. The Kenny estimate was compiled from a detailed working knowledge of the component costs (materials, labor, etc.) and provided us with valuable insights into the methodology of cost and scheduling of a tunnel construction project. A set of tunnel specifications was compiled (shown in Appendix 1), presented to Kenny, and served as the basis of the estimate.

These specifications include the 3 TeV Booster tunnel as well as the connecting tunnels to the existing Main Injector. The transfer line tunnels make the transition from the surficial glacial materials to the dolomitic bedrock thus requiring tunneling in both hard and soft media.

In order to minimize the tunnel cost, the contractor was allowed to adjust the tunnel diameter. Any size 10 ft or greater was acceptable (12 ft was selected).

A flat 7 ft wide floor (invert) was specified. The invert may contain ducting for drains, utilities, etc. as shown in Figure 3.

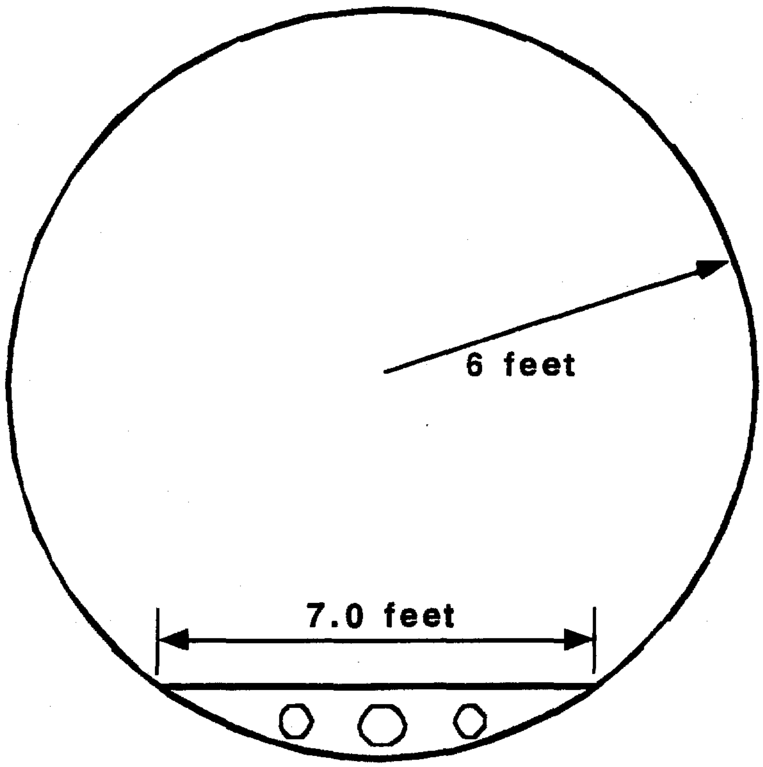

Figure 3
Tunnel cross section

The specifications call for tunnels with water infiltration rates of less than 50 gallons per minute (gpm) per mile. Note that we did not specify a concrete lined tunnel.

Local grouting and rock bolting would be provided as needed by the contractor. In general, it is not expected to be needed for support of the ceiling rock in the tunnel.

Four tunnel access shafts of at least 20 ft in diameter were required (20 ft was selected). Any additional shafts needed for construction and/or safety purposes were to be specified.

Other Considerations Land acquisition costs, which include both underground and surface rights, are intentionally not considered in this document. Clearly, one would attempt to minimize these community intrusions as much as possible. It was assumed that maximum use would be made of the existing Fermilab site.

Our specifications do not call for any dehumidification. The ambient tunnel temperature will be about 55° F and condensation will occur on the walls if warm humid air, typical of Illinois summers, is introduced. An open question is the level of dehumidification that will be needed and its cost.

Kenny Construction Overview A tunnel diameter of 12 feet was chosen by Kenny as the most cost effective size. The tunnel cost per ft is insensitive to the diameter within a range of about 12-14 ft. Here one balances the reduced cost and higher rate of rock excavation using a smaller tunnel with the spatial constraints of transporting the spoils to the surface. The proposed tunnel excavation uses two tunnel boring machines (TBMs) for mining and long conveyor belts (about 5 miles) for the removal of spoils.

The four major shafts required by the specifications in Appendix 1 were augmented by Kenny by 20 additional emergency ingress/egress/utility shafts of about 6 ft in diameter. These shafts are spaced approximately one mile apart as has been done in the Chicago tunnels. They could be filled after the construction was completed.

Construction Cost Summary Table 1 shows the Kenny cost summary. Note that this cost includes both the 3 TeV Booster tunnel and the two connecting tunnels from the Main Injector.

A few descriptive words are in order to help understand Table 1. It is important to realize that the accounting differs from that of a typical Fermilab construction project but does include all the relevant costs. Indirect costs include salaries for project manager, engineering, technical, and office support staff as well as the resources needed (office space, supplies, cars, etc.) to allow them function effectively. Direct costs include labor costs (including fringe benefits) for construction crews, construction related supplies and equipment including the costs for the two tunnel boring machines. Each cost item is separately broken down into the labor and other cost components and summarized in the last column. Note that labor costs represent about one half the total project cost.

Equipment costs are based on the new purchase price minus the estimated salvage value at the time of job completion. Kenny's estimate includes loadout of the muck at the site but not muck disposal costs. Some of the dolomite from the Galena-Platteville layer has potential resale value. Some or all of the disposal costs may be offset by sale of the dolomite. The extent that this is possible will depend on the market at the time that the tunnel is constructed.

Typical contractor profits are expected to be 10-20% of the total project cost. In the item listed as Profit in Table 1 by Kenny, administrative costs including salaries that are not directly associated with the project are also included.

Fermi VLHC Booster Tunnel Cost Summary

Kenny Estimate Sept. 1997

	Total Labor	Equip. Operation	Equipment	Perm. Materials	Supplies	Subcontracts	Total
Indirect Costs							
Gen. & Admin	8,174,313						8,174,313
Office Expenses					966,350	246,600	1,212,950
Ins. & Taxes					4,136,900		4,136,900
Plant & Equip.	1,665,823	412,786	663,980		4,548,426	4,048,632	11,339,647
Total Indirect Costs	**9,840,136**	**412,786**	**663,980**		**9,651,676**	**4,295,232**	**24,863,810**
Direct Costs							
Shaft Exc. Overburden	627,973	80,747	147,750	387,520	28,187	126,610	1,398,787
Shaft Exc. Rock	2,726,251	415,246	614,465	114,182	397,152	118,880	4,386,176
Shaft Lining	1,398,833	140,766	198,860	918,100	88,584	-	2,745,143
Tunnel Excavation-Ring							
Shafts, Starter & Tail Tunnel	2,217,286	251,440		968,600	248,828	4,504,370	8,190,524
TBM Tunnel Excavation	24,042,649	2,461,234	20,244,412	275,650	3,746,390	3,463,868	54,234,203
Conc. Line Starter & Tail Tunnels	645,508	71,191		253,678	30,696	-	1,001,073
Tunnel Excavation-Slopes							
Shaft Excavations	646,419	77,169		78,152	201,100	63,200	1,066,040
Shaft Closure & Backfill	197,019	19,339		96,083	16,515	-	328,956
Softground Tunnel Exc.	764,554	58,239		364,642	98,367	138,310	1,424,112
Mixed Face Drill & Shoot	1,553,045	186,791		280,304	171,384	59,060	2,250,584
Concrete Lining	1,034,017	102,767		747,399	182,626	-	2,066,809
TBM Excavation Rock	4,103,854	427,362	2,765,250	37,888	689,854	476,115	8,500,323
Tunnel Invert Lining	4,471,830	338,740	345,010	3,449,911	489,679		9,095,170
Tunnel Grouting	13,771,783	401,408	367,000	444,675	715,352		15,700,218
Total Direct Costs	**58,201,021**	**5,032,439**	**24,682,747**	**8,416,784**	**7,104,714**	**8,950,413**	**112,388,118**
TOTAL COST	**68,041,157**	**5,445,225**	**25,346,727**	**8,416,784**	**16,756,390**	**13,245,645**	**137,251,928**
PROFIT							**30,000,000**
FINAL BID							**167,251,928**

Table 1
Kenny cost summary in $

From Table 1 and the backup material one can separate out the cost of the injector ramps. Without the injector ramps the unit cost of the 34 km ring is $4068/m ($1240/ft) including the invert. The elimination of the tunnel invert reduces these costs to $3685/m ($1123/ft).

Construction Schedule A nominal construction start date was chosen as 1/5/98. Prices of supplies and labor costs are current as of that date. The estimated construction time is just over three and one half years. No incentives was given for earlier completion, nor were any delays included because of funding limitations.

The first year of construction is devoted to sinking the shafts, lining them with concrete, and setting up the two 12 ft diameter TBMs. A 5 mile long conveyor belt for muck removal is set up for each TBM. Near the end of the first year, the TBMs will start full mining operations. After completion of approximately 1/4 of the tunnel by each TBM, the conveyor belt for each machine will be repositioned to complete the ring tunnel in about August of 2000. The TBMs will then be used for the injector tunnels. The estimated completion date is 8/8/01.

Comments on cost The total cost of such a project reflects not only the cost of the major capital equipment (each of the two TBMs cost $4.0M) but the cost of the muck removal conveyor belts, grouting equipment, etc. bring the total equipment cost to about $20M. The cost estimate of manpower, shafts, starter tunnels, grouting, safety considerations, etc. all make important contributions to the items in Table 1.

Cost reduction or better performance of one item may not directly translate into a cost reduction or better performance of the entire project. This is illustrated by the balance that is needed in the performance of the TBM and the muck removal apparatus.

Follow Up Questions to Kenny Construction Company. After the Kenny's cost estimates were studied a number of questions were put to them.

What are the costs associated with the installation of the 20 emergency ingress/egress/utility shafts and what are the operational and safety implications? The cost of each shaft was estimated to be $234K and while 20 was thought to be optimal in terms of safety, 10 shafts were considered a minimum to insure safety. However, the elimination of the shafts would have other cost impacts. About one half of the potential $2.34M saving would be needed for additional survey, ventilation and concrete conveyance equipment. Potential savings, also scaling profit but not including slower concrete production would only be about $1.3M.

If we were to require working with only two (not four) major shafts, how would this impact costs? The cost of two major shafts ($4.27M) would be eliminated. However additional conveyor belt structures and additional salaries for crew travel time (with fringe benefits) would increase by about $1.16M. There are other unquantifiable items such as the potentially increased failure rate for a horizontal conveyor to operate on a continuous curve for ten miles, inefficiencies of delivering men and supplies to 10 mile headings, and the decreased productivity of concrete operations.

How much would the cost increase if we required a full slip concrete lining? The addition of a monolithic lining bringing the tunnel diameter to 10 ft (1 ft of concrete added) would increase the cost about $360/linear ft. However, grouting costs would also be reduced so the net increase would only be about $300/linear ft. From their previous experience, this would reduce the water inflow from 50 to 10 gpm/mile.

Can you estimate the effect on your cost estimate of a TBM increase in advance rate of 10% ? They estimate that there would be a savings of $1.36M for a 10% increase in TBM advance rate.

The VLHC Ring and Future Directions The VLHC will certainly place much more stringent demands for greater cost containment and improved efficiency. We must explore both incremental advances in the present technologies and newer less conventional options.

Any increase in conventional TBM performance will be of benefit. Better cutter heads and cutter head placement optimized for local rock should be encouraged and will continue to be pushed by local contractors. This has been an ongoing program in the Chicago area as TBMs have been working in similar dolomite layers for over 25 years.

New conveyor belt materials (Kevlar) and other advances have seen conveyors replacing mine cars for muck removal in most tunnels over the last ten years. Certainly, technology which improves the length and reliability of conveyor belts and motors is needed.

Smaller diameter tunnels offer the potential of cost saving since less material need be removed and equipment costs are lower. A limitation here has been on the ability of the muck removal equipment and people to work effectively in a small tunnel. Presently smaller tunnels are not as cheap because of the muck removal costs and the safety of the crew working near the operating conveyor systems. We need to develop a better model for the installation and operational procedures of the VLHC to understand how a smaller tunnel might effect these costs.

Better computer control of tunneling operations will continue to improve productivity and safety. Included are monitoring of TBM performance, maintenance and control of long conveyor belts. Any reduction of labor to check internal operation of equipment as well as early warning of malfunction is of import. Items which effect not only production but also safety are particularly important.

New technology using pneumatic capsules to carry muck have been used in Japan. These offer the possibility of transporting the muck long distances with a high degree of automation and improved safety.

Technology which allows tunneling to be done remotely, thus reducing the labor costs is very attractive. By reducing the number of people underground one not only increases the safety of the operation but also reduces the labor costs. More automated tunneling equipment and muck removal will be explored. Efforts within the mining industry to automate their operations appear to lead the way in these developments.

Appendix 1

Tunnel Specifications for the Fermilab 3 TeV Booster

July 11, 1997

1. The oval **accelerator tunnel** is 34 km in length and is located as shown on the attached diagram. This tunnel is to be bored through the Galena-Platteville dolomite at an elevation of 320 feet above mean sea level (msl). This sitting should be considered approximate.
2. The minimum acceptable **tunnel diameter is 10 feet**; any diameter larger than this will be satisfactory.
3. A total of **four access shafts** adequate for human access and tunnel evacuation will be provided. Two of these should be in the straight sections (i.e. one shaft in each of the four quadrants). The shafts should have a diameter of at least 20 feet. The shaft locations are somewhat flexible such as to minimize surface disruption.
4. The **water inflow** shall not exceed 50 gpm per mile. The tunnels will be grouted as necessary to meet this specification. A pumping facility adequate for the water inflow should be considered as part of these specifications.
5. With the exception of such grouting, the **tunnel interior** will not be finished. A 7 foot floor, or invert, will be constructed at the bottom of the tunnel. There will be the facility for utility (power, controls, drains) distribution within the invert. The floor will be smooth enough to allow material handling and vehicular traffic.
6. Ramps for beam **transfer lines** as indicated on the diagram will be 3 km in length. They connect the Main Injector (714 feet msl) to the 3 TeV Booster and have a slope of about 4%. Their specifications as to diameter, water inflow, .. are the same as for the main tunnel. As indicated, all access points to these lines are on the Fermilab site.
7. **Property Issues.** As much as possible surface work should be on the Fermilab site. An estimate should be made of all surface land needed off of the Fermilab site.
8. **Spoils disposal** should be addressed and costs provided.
9. **Special construction needs.** Any other construction needs, (additional shafts, storage areas, etc.) should be noted and costed.
10. A **construction schedule** should be included.

*R. Bauer is an engineering geologist with the Illinois State Geological Survey

**P. J. Conroy is a geological engineer with extensive experience on Chicago area tunnels. He is an independent consultant.

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2. Site Proposal for the Superconducting Super Collider in Illinois, September 1987.

3. B. Baklakov et al., Seismic Studies for Fermilab Future Collider Projects, to be published in the Proceedings of the 5th International Workshop on Accelerator Alignment, Argonne National Laboratory, Argonne, IL, October 14-17, 1997. Also Fermilab-Conf-97/383, November 1997.

4. Tunnel and Reservoir Plan (TARP). This is now part of the Metropolitan Water Reclamation District of Greater Chicago (MWRDGC)