# Chapter 7. Conventional Construction and Facilities

## 7.1 Geology of the Fermilab Region

The geologic studies for the Illinois proposal for the SSC [1,2] concluded that the main tunnel (87 km circumference) and experimental facilities should be sited in the Galena-Platteville dolomite which is a uniform, competent tunneling unit. A subsequent geotechnical study for the Next Linear Collider Project [3] and generic site studies for future accelerator facilities at Fermilab [4] also reached the same conclusion. The only less-than-ideal feature was the depth of construction (approximately 400 feet below the surface) to reach this dolomite layer. However, due to its longer circumference (233 km), a VLHC might extend beyond the region where it is practical, or possible, to site the tunnel entirely in the Galena-Platteville. An earlier geological study for various VLHC configurations was reported by Conroy [5]. There has been substantial experience in the Chicago area [6,7] in tunneling and underground caverns in the Silurian dolomite, Maquoketa shale, and Galena-Platteville dolomite. There is a lack of corresponding local similar experience, or even knowledge of the mechanical/structural engineering properties of the underlying units consisting of the Ancell, Middle Confining unit, and the Franconia formation.

There is a general sloping of the till, Silurian, Maquoketa, Galena-Platteville, Ancell sequence of layers from the West (higher elevation above mean sea level) to the East (lower elevation) to Lake Michigan. However, to the Northwest and West of Fermilab are located the Troy and Rock Bedrock Valleys, where the Silurian, Maquoketa, and Galena-Platteville layers have been completely cut away by glaciers and filled to the underlying sandstones with Glacial drift. The Sandwich Fault Zone lies to the Southwest of Fermilab, passing through Sandwich, Illinois, and running roughly NW to SE. This fault zone does end approximately SSE of Fermilab. To the Southwest of the Sandwich Fault Zone, the underlying Ancell and Middle Confining layers are upthrust to meet the Glacial drift at the bedrock surface, and even the Franconia layer can impact tunnels traversing the fault zone.

The Des Plaines disturbance, as shown in Figure 7.1, is an unusual structure, possibly an ancient meteor impact. The rocks in the disturbance, in an area about 5 ½ miles in diameter, are reported to be intensely faulted. This disturbance was encountered during construction of the TARP tunnels, but did not cause any significant problems.

The study region is in an area of the central mid-continent that is tectonically stable and seismically relatively quiescent. The seismic hazard posed to structures in this region is very low. Active faults are not known in the study area, and the last movement on the Sandwich Fault Zone has been demonstrated to be more than 200,000 years ago. The closest known earthquake source zones capable of producing ground motions of any significance to engineering design or operational requirements are located several hundred miles to the south.

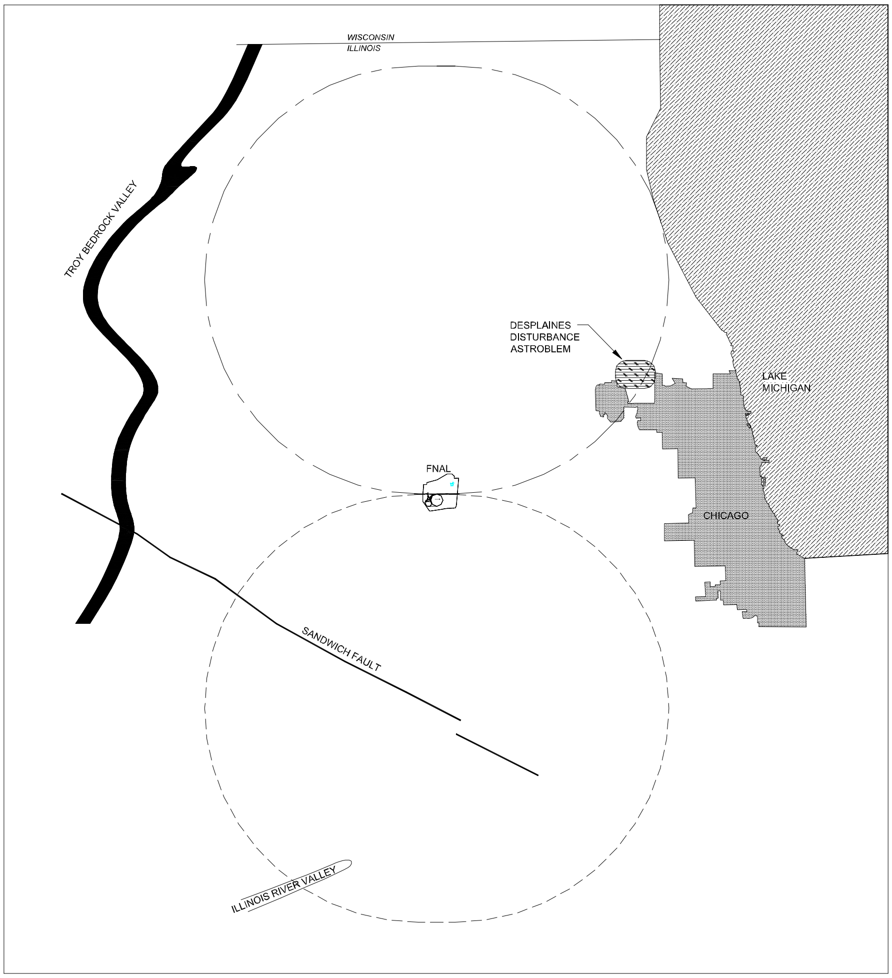


*Figure 7.1. General geologic features of Northeastern Illinois with two alternative ring orientations under study.*

If we restrict consideration to rings that would be contiguous to the existing Tevatron, only a VLHC ring with its center oriented to the North of Fermilab (North Ring) could be completely contained within the Galena-Platteville dolomite. This ring would have a roughly North-South strike axis passing through Fermilab with a tilt of approximately 0.2 % grade to stay within the dolomite. Lake Michigan and the Wisconsin border would bound this ring. Any ring with its center oriented farther to the West (even NNW) would be impacted by the bedrock valleys. Possible rings oriented to the South or West would traverse the Sandwich fault into the strata underlying the Galena-Platteville.

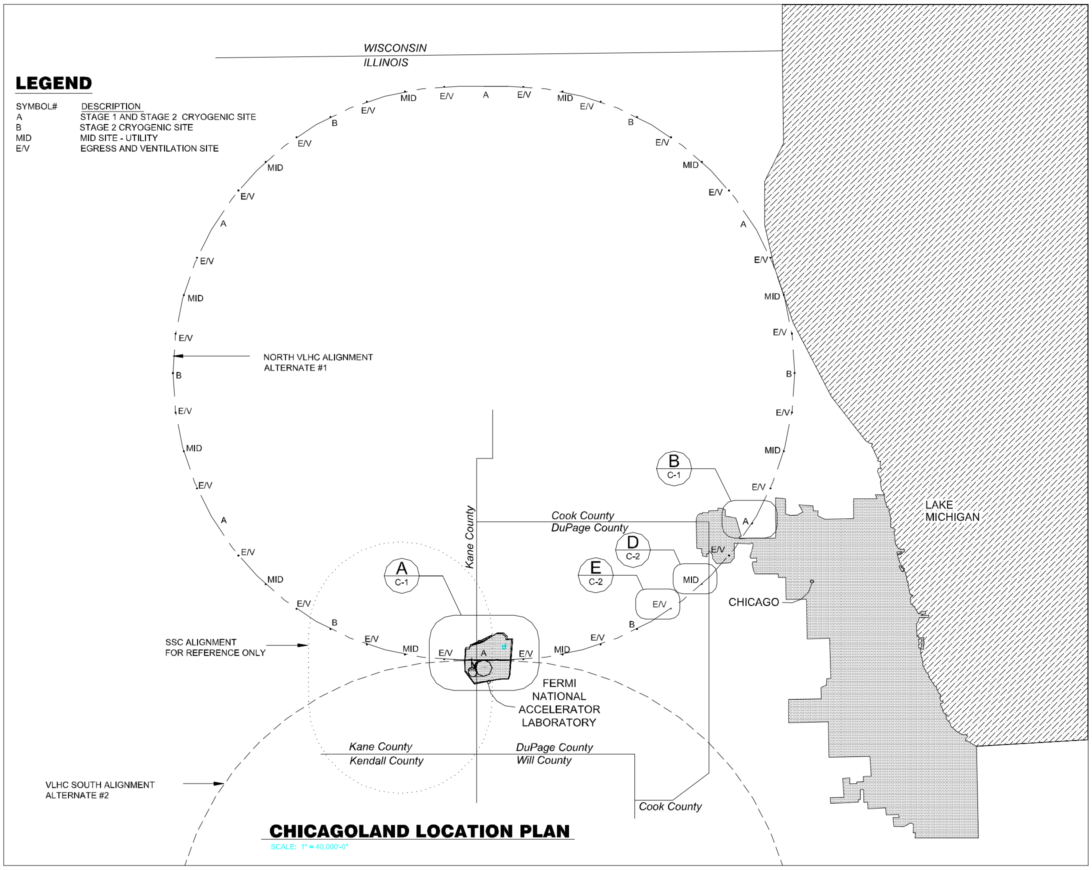


*Figure 7.2. Schematic of the VLHC 233- km racetrack (R = 35 km, two 6-km straights) depicting off-site service areas for North ring configuration.*

Figure 7.2 shows the proposed configuration for the off-site service areas for the North ring. An approximate ring description is two half circles of radius 35 km joined by two long straight sections, each 6 km long. A more precise description of the proposed footprint is the major arcs bend the beams 174 degrees and the remaining 6 degrees of bending occurs in the 6 km, which is a cluster of 5 straight sections separated by four bends. These clustered straight sections are for injection, abort, RF cavities, interaction regions for two experiments, and for the transfers between Stage 1 and Stage 2. Approximately equally spaced around the circumference are 12 cryo sites, labeled A-sites and B-sites. The six A-sites are needed in Stage 1; the full 12 sites are required in Stage 2. Spaced between the 12-cryo sites are 12 addition utility mid-sites.

In order to undertake a tunnel costing and feasibility study for various orientations of a VLHC ring, two layouts and vertical strata lampshades were prepared [8]. The simplest configuration is a tilted (0.2% incline) North Ring, which stays completely in Galena-Platteville dolomite. The second is a horizontal North Ring which transitions between the following media: Maquoketa shale, Silurian dolomite, Maquoketa shale, Galena-Platteville dolomite, and back into Maquoketa shale. The third is a tilted South Ring, which crosses the Sandwich Fault (only once) into the sandstone Ancell aquifer (wet) and the dolomitic sandstone Middle Confining unit and possibly the Franconia formation. These rings are shown in plan in Figure 7.1

and in section in Figures 7.3 and 7.4. Elevation parameters and the percentage of tunneling medium for each of these rings are listed in Table 7.1.

Another design constraint of this costing exercise deals with the positioning and depth of the caverns for the two experimental halls. It is desirable to have these located at the Fermilab site to be able to cluster the long straight sections (for injection/abort and interaction regions) and to utilize the Fermilab campus for the related experiment fabrication and staging buildings, support utilities, and equipment shaft facilities. This also helps to minimize off-site surface land requirements.

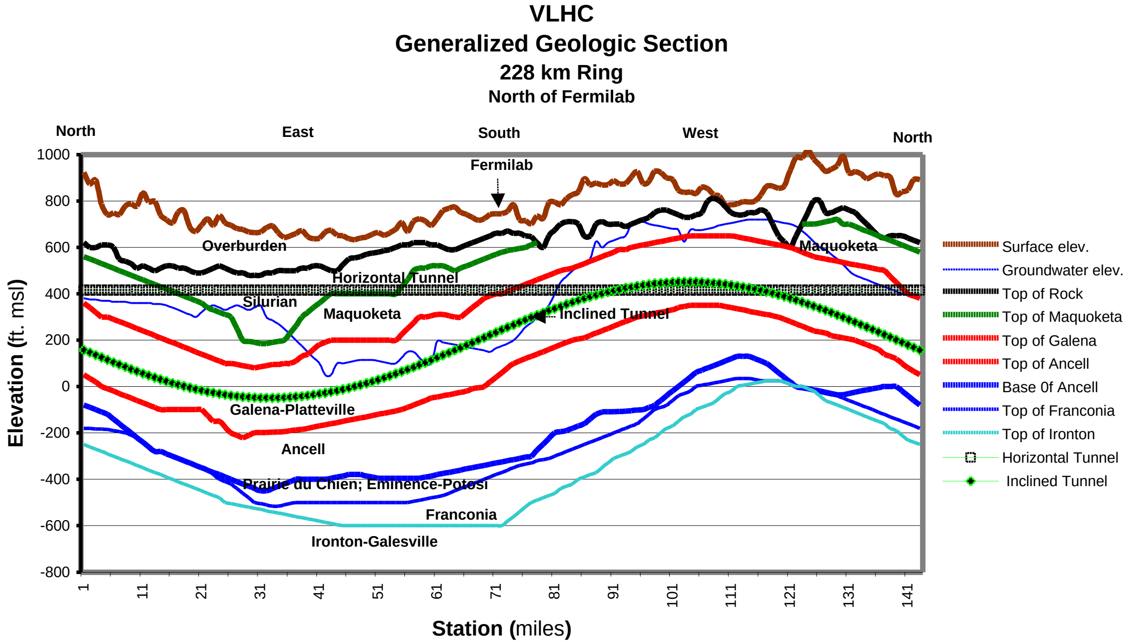


*Figure 7.3. Lampshade diagram for North Ring orientation for horizontal and inclined tunnels.*

Structural features and thickness of the strata supporting the spans of the experimental halls or caverns [2] will determine the elevations at which the caverns can feasibly be sited. This, of course, impacts the elevation of the accelerator tunnel at the site of the cavern. A general rule of thumb is that there should be a depth of rock (dolomite) strata above the cavern at least equal to the span of the cavern. Previous studies [1,2] have concluded that for 75 foot high chambers, roof spans up to 125 feet are feasible using standard methods of roof arching and rock supports. This assumed that the orientation axis of the cavern bisects the major joint sets. The joints run approximately NE-SW × NW-SE so these criteria would be satisfied by VLHC ring orientations to the North, South, or West. Possible options in elevation for the experiment caverns are depicted in Figure 7.5.

*Table 7.1. Elevation parameters and strata fraction for three tunnel models.*

| | **South Ring 0.08 % incline** | **North Ring horizontal** | **North Ring 0.2 % incline** |
|---|---|---|---|
| elevation at Fermilab (ft msl) | 510 | 415 | 244 |
| depth at Fermilab (feet) | 235 | 330 | 501 |
| average depth (feet) | 277 | 371 | 585 |
| r.m.s. depth (feet) | 61 | 99 | 121 |
| minimum depth (feet) | 118 | 219 | 342 |
| maximum depth (feet) | 406 | 603 | 779 |
| **Strata (approximate %)** | | | |
| Silurian dolomite | 29 % | 27 % | |
| Maquoketa shale | 34 % | 27 % | |
| Galena-Platteville dolomite | 21 % | 46 % | 100 % |
| Ancell – St. Peter sandstone | 6 % | | |
| Middle Confining layer: Prairie du Chien, Eminence-Postosi dolomitic sandstones | 10 % | | |

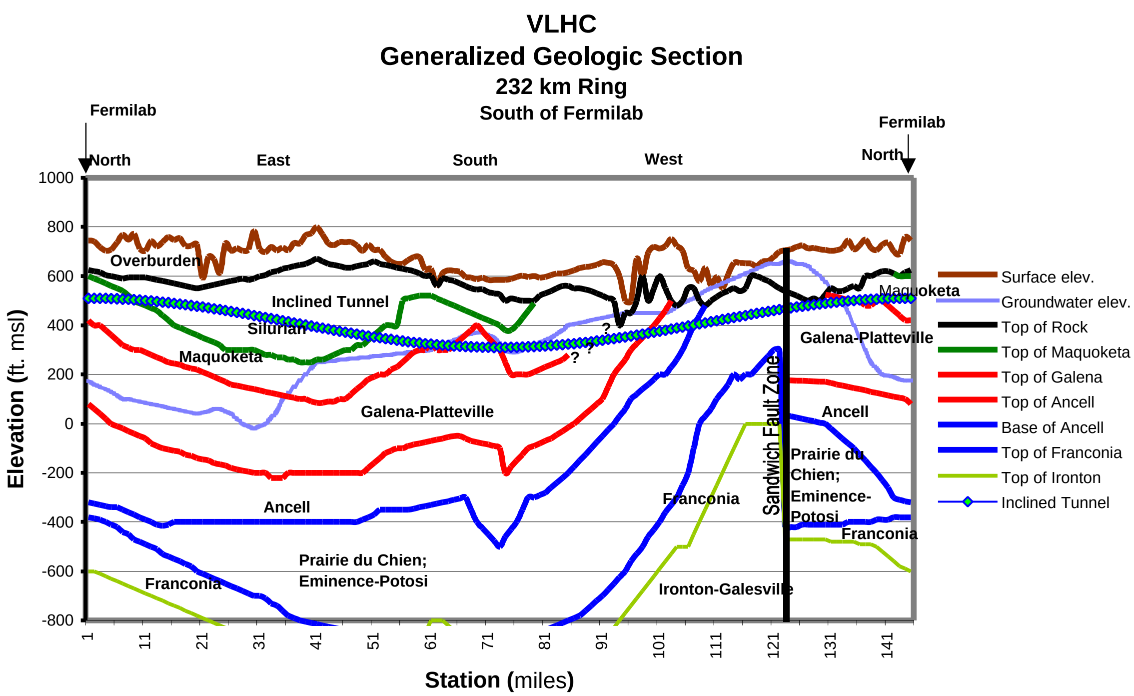


*Figure 7.4. Lampshade diagram for South Ring orientation with inclined tunnel.*

As a working hypothesis for this study, a time scale of 5 years is assumed for completion of the underground construction, including main tunnel, special tunnels, and all caverns and enclosures. It is anticipated that component installation and commissioning in finished sections of the tunnel could be accomplished in parallel with continued construction in other sections. At this stage of the study, engineering design has not begun for any of these underground elements.

Analogously to the 1997 study of a 34 km VLHC booster tunnel by the Kenny Construction Company [9], we have entered into a tunnel costing exercise with CNA Consulting Engineers

[10] to study the expected cost ranges and cost drivers of the three tunnel configurations listed above. By studying the three different tunnels, we hope to learn the unit costs (per mile, per shaft, lined/unlined, etc.) of a tunnel in an excellent media, that of a tunnel transitioning between three different rock media, and that of a tunnel which combines rock media, traversing the Sandwich Fault, and the sandstone and dolomitic sandstones, both within the aquifer, and beyond. These data will allow optimizations and tradeoffs with respect to siting costs. The tunnel cost estimating report will be published elsewhere.

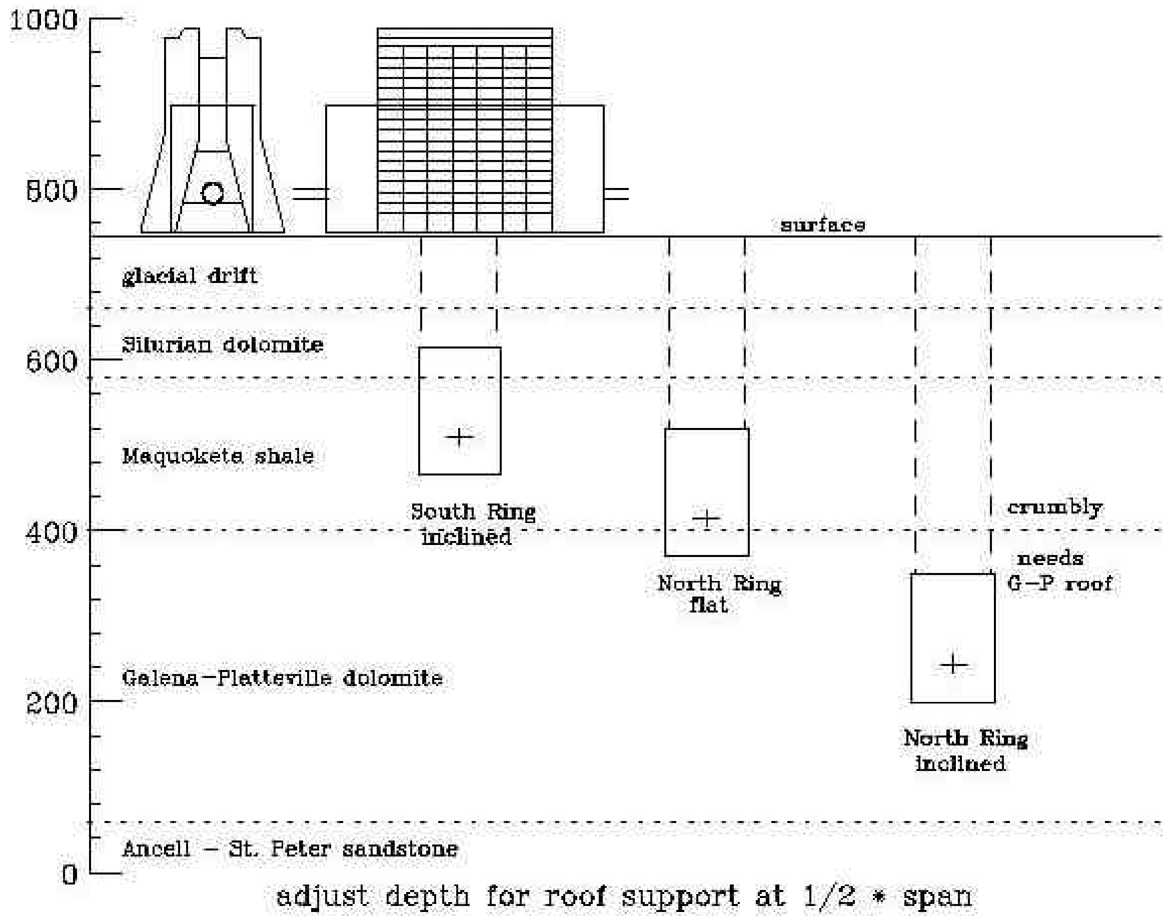


*Figure 7.5. Vertical siting of the experimental halls/caverns (and therefore VLHC).*

## 7.2 Collider Tunnel and Enclosures

Since the largest volume of the underground construction is the main collider tunnel, we will first concentrate on that component. A preliminary 12 foot clear diameter tunnel cross section is shown in Figure 7.6. However, a major purpose of this cost estimating study is to determine the sensitivity of cost to tunnel diameter. As shown in Figure 7.7 the ring will be adjacent to the Fermilab Tevatron. It will serve as the injector to the Stage-1 (low field) ring. The major straight sections will be clustered (5 each cluster) at Fermilab and at the opposite side. Keeping many of these special tunnels, the abort/beam stops, and the experimental areas at Fermilab will optimize utilization of the existing infrastructure and minimize offsite underground construction and shafts. The cluster opposite will contain only the Stage-1 to Stage-2 beam transfer and possibly beam scrapers. Much of these opposite side straight sections can be reserved for future needs. The cluster of straight sections near Fermilab is illustrated in Figures 7.8. and 7.9. Although one configuration for Tevatron injection is shown in these figures and used for the cost estimating exercise, other possible geometry options were discussed in Chapter 4.

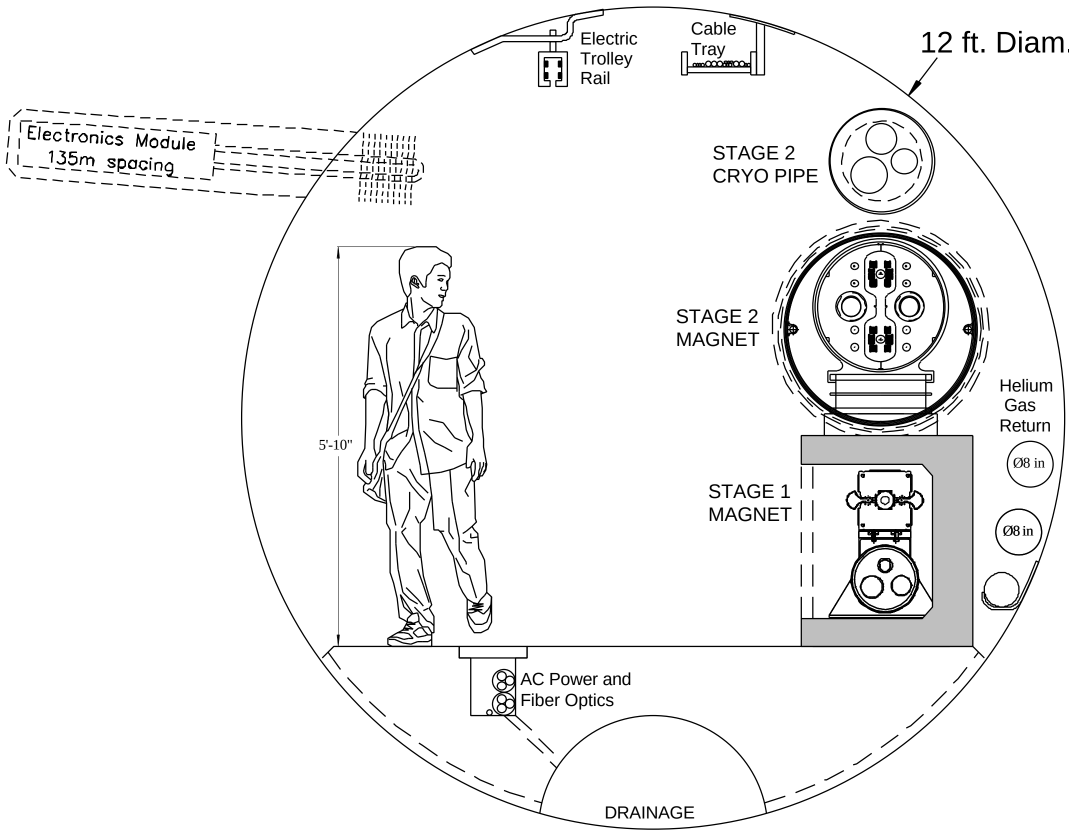


*Figure 7.6. VLHC tunnel cross section showing LF (Stage-1) and HF (Stage-2) colliders. The electronics modules with heat sinks projecting into the tunnel occur only every 135 m.*

The main tunnel will have a minimum finished inner clear diameter of 12 feet with 10-foot wide invert floor (Figure 7.6). Tunnel center alignment will be required to ± 4 inches. The engineering study [10] will estimate the cost differential between 12 and 16 foot diameter tunnels. The tunnel is specified to have an average groundwater influx of not more than 50 gallons per minute per mile. This may require grouting or even lining of some tunnel sections to reduce the groundwater influx to this specification. Dehumidification (< 50 % relative humidity) of the tunnel air will likely be required. The four utility straight sections (injection, abort, RF, and Stage-1 to Stage-2 beam transfers) will likely require additional transverse dimensions, up to 25 feet × 25 feet square cross section. (The SSC design for RF caverns had a 25 foot horseshoe shape). These can be finished by drill and blast after initial tunnel construction by tunnel boring machine. Similarly, at the 12 cryo sites and at the 12 mid-sites, additional underground caverns will be required for tunnel power distribution, cryogenics components, and quench protection systems.

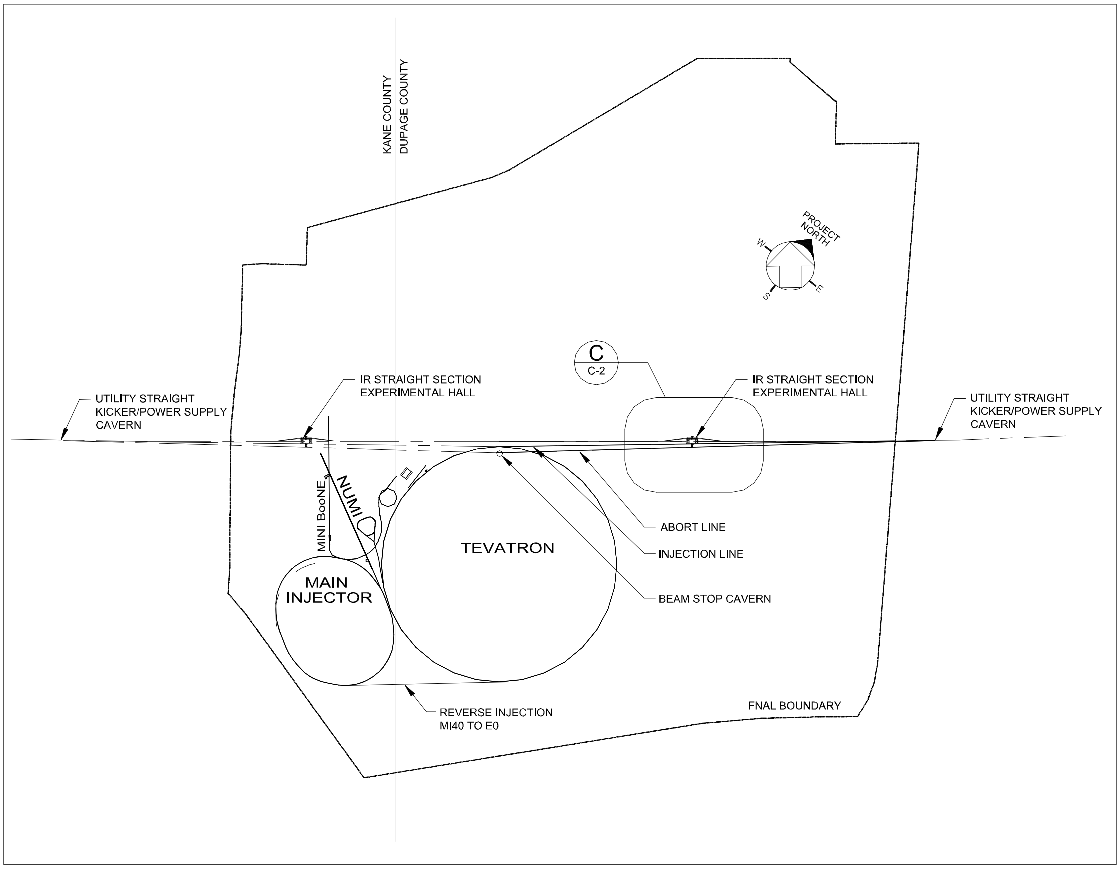


*Figure 7.7. Extraction from Tevatron to North Ring and location of experimental halls/caverns.*

It is anticipated that there will be twelve 30-foot diameter major equipment access shafts, with a clear 6 ft × 30 ft aperture, distributed around the ring at the sites of the 12 cryogenics plants, as shown in Figure 7.2. The rest of the aperture of these shafts will be filled with equipment elevator, cryogenics, power, communications, and sump discharge utilities, plus an isolated emergency egress staircase. There may also be up to 4 magnet delivery shafts for the Stage-2 dipoles (16 meters long) distributed around the ring. Dipoles for both Stage 1 and Stage 2 will access the tunnel through the injection ramps to the surface. There may be a similar additional installation ramp at the cluster of straight sections opposite Fermilab. For tunnel ventilation and emergency egress, there will be approximately 48 E/V shafts (at A-sites, B-sites, mid-sites, plus an additional 24 between) of 15-foot diameter separated by 3 miles maximum. At the Superconducting Super Collider Laboratory (SSCL) the standard was 2.7 miles (see Section 7.8). These egress shafts will be provided with elevators, but, due to the depths, not all will have parallel staircases. The tunnel ventilation system will also provide heat removal cooling for the conventional corrector magnet elements for Stage 1 and their power supplies distributed around the ring.

In addition, at each of the 1710 half-cells, separated by 135.5 meters, there will be a 1-ft diameter × 5-ft deep electronics drawer for instrumentation and power supplies for the correction elements and other local machine components. See Section 7.4.9 and Figure 5.45.

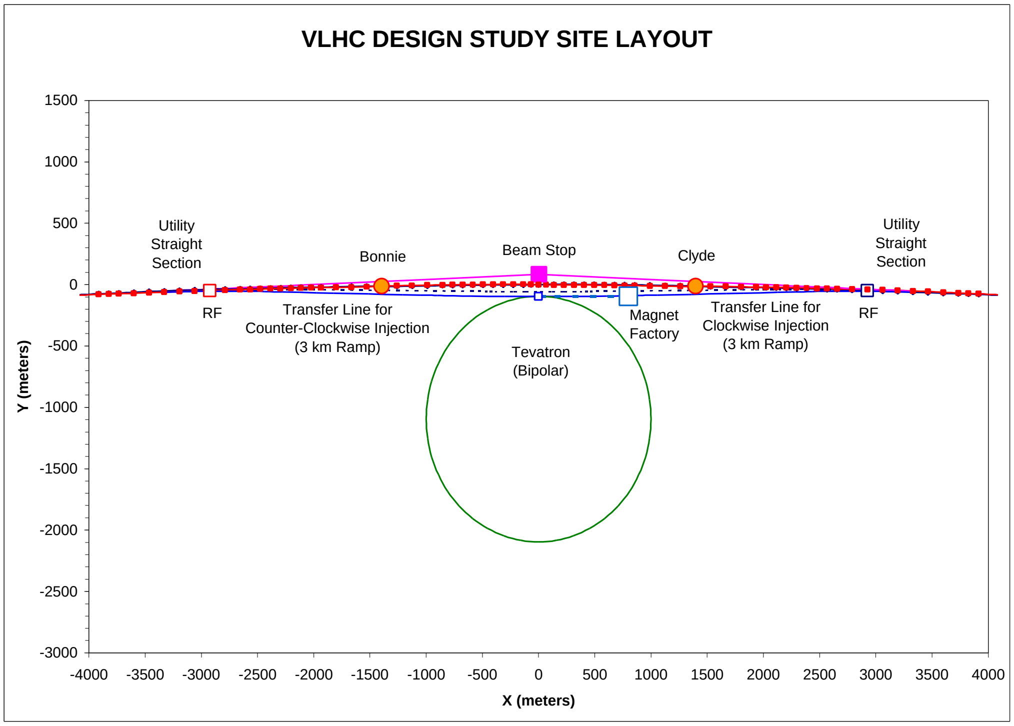


*Figure 7.8. Straight section geometry adjacent to Tevatron. See Figure 7.9 for (distorted scale) details.*

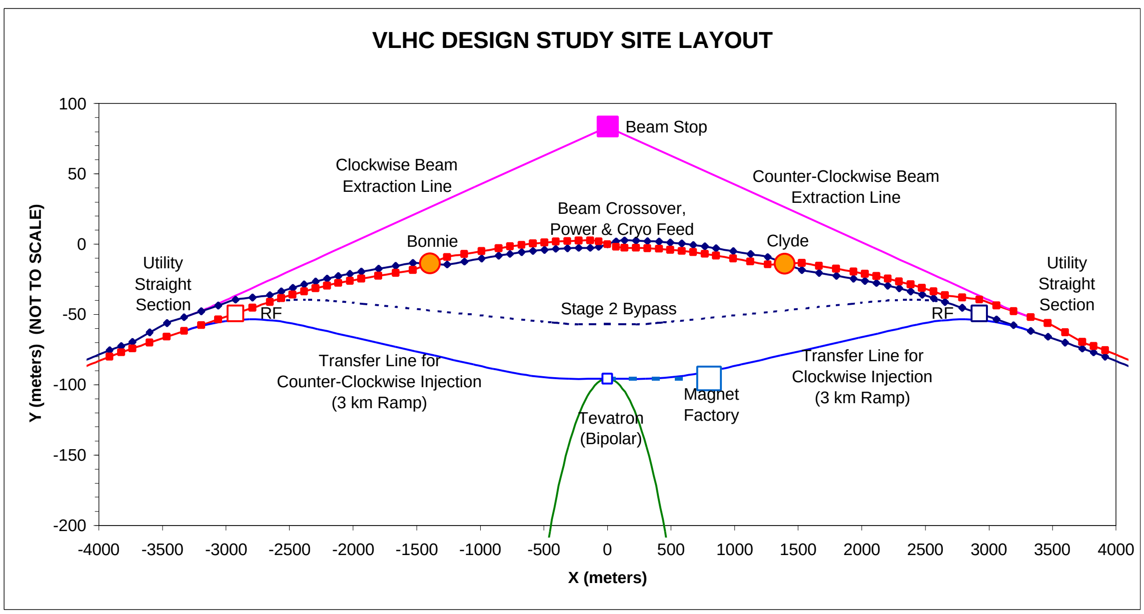


*Figure 7.9. Schematic (distorted scale) geometry of straight sections and Stage-2 bypass line.*

*Table 7.2. Five straight sections and intervening arcs at Fermilab.*

| | |
|---|---|
| Major Arc | 174.375 degrees bend - to/from far side cluster of straight sections |
| Utility Straight<br>1.38 km | CW Stage-1 Injection, CW-1 beam scraping, CCW-1 abort,<br>CW-2 abort, RF cavities with parallel PS and RF Klystron cavern<br>larger tunnel cross section - 25 ft × 25 ft |
| Bend Section<br>1.00 km | 28.419 mrad bend at 35 km radius<br>stub to Stage-2 Low-field ring Bypass tunnel |
| IR Straight<br>1.64 km | experimental hall/cavern - 100 meters long<br>with equipment bypass tunnel - 0.55 km at 25 m bypass |
| Bend Section<br>0.72 km | 20.668 mrad bend at 35 km radius |
| Short Straight<br>0.27 km | CW and CCW beams cross-over, changing magnet apertures<br>may require slightly enlarged tunnel |
| Bend Section<br>0.72 km | 20.668 mrad bend at 35 km radius |
| IR Straight<br>1.64 km | experimental hall/cavern - 100 meters long<br>with equipment bypass tunnel - 0.55 km at 25 m bypass |
| Bend Section<br>1.00 km | 28.419 mrad bend at 35 km radius<br>stub to Stage-2 Low-field ring Bypass tunnel |
| Utility Straight<br>1.38 km | CCW-1 Injection, CCW-1 beam scraping, CW-1 abort,<br>CW-2 abort, RF cavities with parallel PS & RF Klystron cavern<br>larger tunnel cross section - 25 ft × 25 ft |
| Major Arc | 174.375 degrees bend - to/from far side cluster of straight sections |

## 7.3 Injection Line Tunnels (Various Scenarios), Beam Abort Lines, Equipment Access Ramps, and Stage-2 Low-Field Ring Bypass

Options for injecting from the Tevatron to the VLHC are discussed in Section 4.3. For whatever option is chosen, the Tevatron tunnel will have a new line(s) tangential to it. These lines will pitch downward to the VLHC elevation as shown in Figure 7.10. The utility straight section enclosure and interfaces are detailed in Figure 7.11. The major slope of this injection tunnel could be up to 4.2 % grade, sufficiently flat to serve as part of the equipment access ramp(s). There will be an incentive to cross the boundary between glacial drift and bedrock surface as steeply as possible to reduce both complexity of construction and ground water influx at the interface. The beam injection tunnels will also serve as the equipment access ramps which would branch off from the injection tunnels and continue to the surface. It will be important to design and schedule the construction of this geometry to allow VLHC component installation during beam operations of the Tevatron.

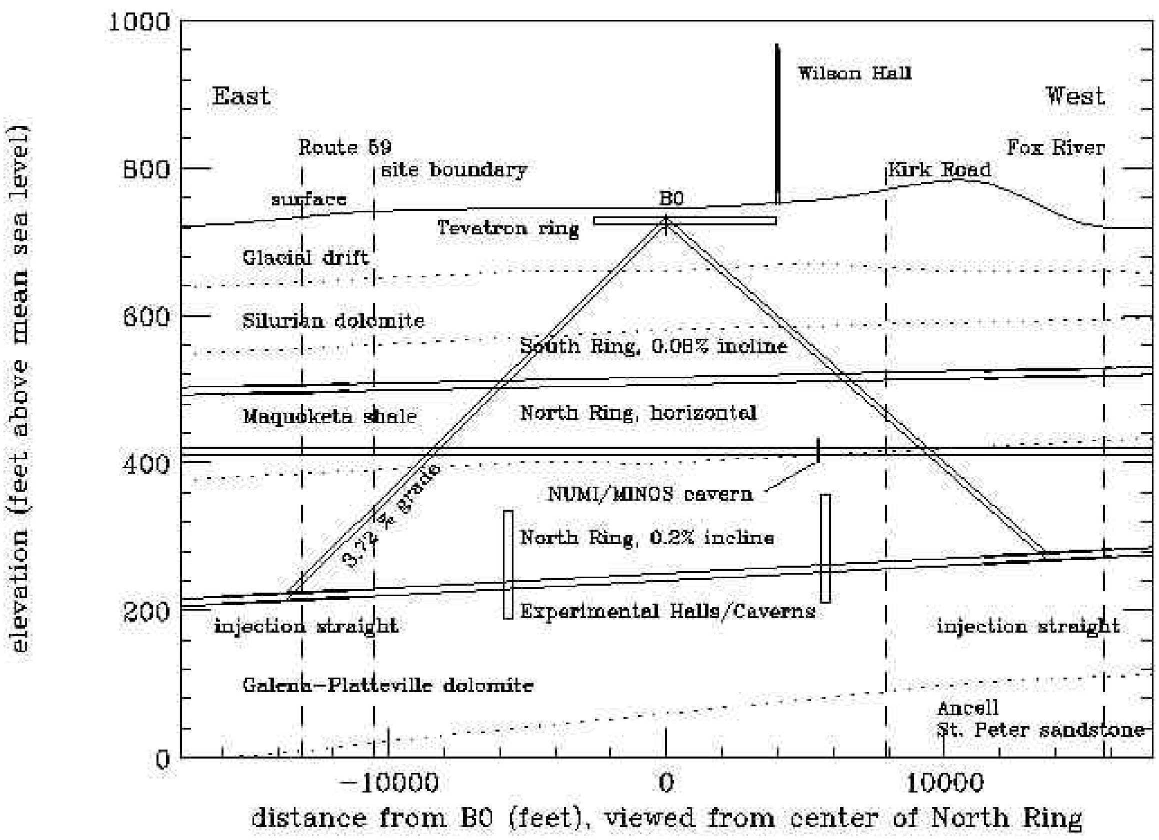


*Figure 7.10. Schematic of injection ramps for inclined North Ring configuration.*

There also will be two sets of straight tunnels connected to the two near-Fermilab Utility Straight Sections. One set will be for the injection lines from the Tevatron to the Stage-1 low-field ring and equipment access ramps to the surface. The other set will be for the abort beam lines of both the Stage-1 and Stage-2 high-field ring. Figure 7.10 illustrates the bipolar operation and extraction from the Tevatron. Table 7.2 also includes the length of arcs for unipolar single beam and unipolar two extracted beams configurations. Some of the lines for injection, abort, and equipment ramps could likely share some common tunnel sections. However, the lines are now listed independently. The interfaces between these tunnels have not yet been designed. To facilitate construction and installation, it will be important to configure the equipment ramps to allow access to the VLHC tunnel while the Tevatron program is in operation.

It is planned to operate the Stage-1 VLHC with the low-field, superferric magnet ring. For Stage 2, a high-field superconducting ring will be added. The low-field ring will serve as injector to the high-field ring. The beam transfer from low-field ring to high-field ring is anticipated to occur in the straight sections opposite Fermilab. In order to remove the second, non-colliding beam and reduce crowding in the experimental areas and also allow possible access to the experimental halls/caverns while the low-field ring is performing accelerator studies, a small section (approximately 7 km) of the low-field ring will move to a bypass tunnel. In Stage 2 additional and stronger bends will be added to the low-field ring in this region to match its beam arc length to that of the high-field ring through the main tunnel. In the current model, stubs will be provided at the 28.4-mrad bend enclosures to allow later construction of this bypass tunnel for the low-field ring in Stage 2. No such bypass is planned for the far-side cluster of straight sections. All of these special tunnel sections are anticipated to be of the same inner finished diameter as that of the main tunnel.

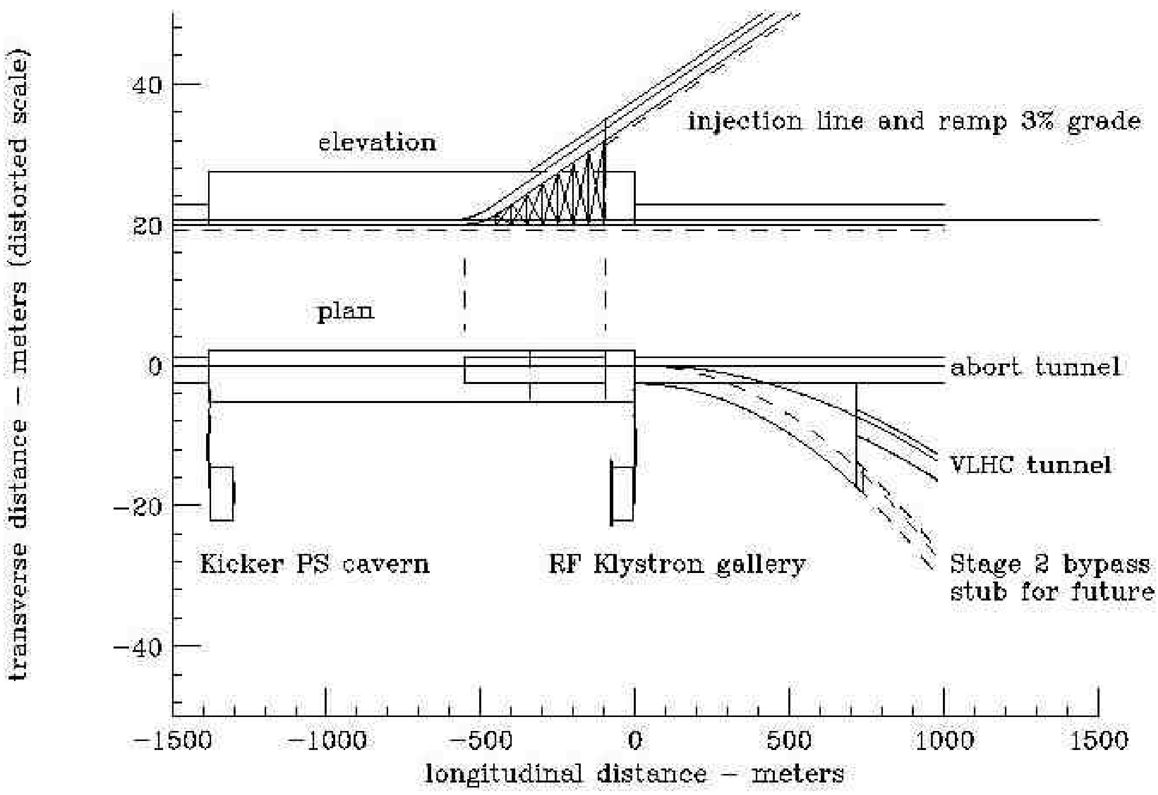


*Figure 7.11. Utility straight section cavern, interfaces, and injection/equipment ramp.*

# 7.4 Accelerator Utility Caverns (Includes Special Requirements For Abort System)

Where detailed specifications were lacking at this time, many of the design features for the SSCL [11] were used as a temporary model.

*Table 7.3. Special tunnel sections (same finished diameter as main tunnel).*

| **Function** | **#** | **Length ea.** | **Comments - all located at Fermilab site** |
|---|---|---|---|
| Access Ramps | 2 | < 1 km | Branch from Injection Lines near surface,<br>up to 4 % grade to surface (745 ft msl)<br>(possibly 1 access on side opposite Fermilab) |
| Abort Lines | 2 | 3.7 km | at tunnel level to common abort/beam stop cavern |
| Injection Lines | 2 | Varies:<br>3.5 km<br>or 5.7 km<br>or 3.7 km | Tevatron (722 ft msl) to VLHC Utility Straight Section<br>(bipolar configuration)<br>(unipolar with 3.5 km radius of curvature)<br>(unipolar with two extracted beams configuration) |
| Exp. Hall Bypass | 2 | 0.55 km | radius = 2.0 km, offset = 25 meters |
| LF Ring Bypass | 1 | 7.0 km | Stage-2 construction only, radius = 2.0 km |

## 7.4.1 Beam Stop Enclosure (1)

A single beam stop enclosure will be located on the Fermilab site at the elevation of the main tunnel. It will house the water cooled beam stop, which will simultaneously service the four rings: low-field CW, low-field CCW, high-field CW, and high-field CCW. The maximum time-averaged power anticipated for the beam stop is estimated to be 100 kW for the Low Field Ring and an additional 200 kW for the High Field Ring. This is based on one full intensity, full energy, two-beam extraction per day. The beam stop enclosure is fed by standard diameter tunnels from the inboard ends of the two Utility Straight Sections at the Fermilab site. By putting all four beam stops at the same location, this plan minimizes the number of places where high energy densities and high radiation fields are encountered, and keeps this under the Fermilab site. The size of the beam stop enclosure will be 16 m × 16 m × 40 m (W × H × L). It will have the necessary shielding and water-impervious retention linings to prevent radioactive contamination of the bedrock or groundwater, either by prompt or residual radiation or by coolant leakage.

A reservoir cavern below the cavern elevation will prevent contamination of the tunnels due to leakage of beam stop coolant. This reservoir cavern will allow monitoring of the radioactivity and other contamination levels before proper discharge. There will be a 30 foot diameter equipment access shaft and a 15 foot diameter personnel access shaft at this enclosure site.

### 7.4.2 RF Klystron Tube Enclosure (2)

SSCL specifications are used in this section. Adjacent to the utility straight sections, the Klystron Tube Galleries house the RF driver tubes and power supplies for the RF cavities. The Klystron galleries are intended to be accessible by personnel for servicing systems during operation. The position of the gallery is illustrated in Figure 7.11. The Klystron Galleries are 25 feet × 25 feet × 240 feet long, serviced by a 30-foot diameter equipment and personnel shaft. This length will accommodate RF-systems for both Stage-1 and Stage-2 machines. They are located a minimum of 30 feet from the accelerator tunnel and are each joined to the RF Cavern by four 30-inch diameter feed throughs, and a 12-foot diameter labyrinth corridor. The total electrical power levels and LCW cooling capacities needed for the RF systems are 4 MW for Stage 1 and an additional 40 MW for Stage 2, distributed over the two enclosures.

### 7.4.3 Kicker Magnet Power Supply Enclosures (4)

SSCL specifications are used in this section. The Kicker Magnet Power Supply Enclosures house the power supplies for injection and abort (at the Fermilab site) and for beam transfer from Low-Field to High-Field Rings (opposite side). These enclosures are adjacent to the four Utility Straight Sections. The position of the enclosure is illustrated in Figure 7.11. The Kicker Power Supply Enclosure is 25 feet × 25 feet × 200 feet long, serviced by a 15-foot diameter equipment and personnel shaft. This length will accommodate both Stage-1 and Stage-2 machines. It is a minimum of 30 feet from the accelerator tunnel and is joined to the Utility Straight Section by four 12-inch diameter feed throughs, and a 12-foot diameter labyrinth corridor. Since the kickers are energized by capacitor discharge at a low duty factor, power requirements are minimum and air cooling seems to be sufficient.

The pairs of Kicker Magnet Power Supply Enclosures and RF Klystron Tube Enclosures at the Fermilab site may be combined into single caverns.

### 7.4.4 A-site and B-site Cryo Systems Caverns (12)

Although most of the cryogenic refrigeration equipment will be located on the surface, caverns will be required at the elevation of the VLHC rings for additional cryogenics refrigeration equipment to compensate for the pressure drop due to gravity. For Stage 1, it is anticipated that there be 6 such caverns of dimensions 40 ft transverse × 20 ft long × 40 ft high located at the A-sites. For Stage 2, it is anticipated that there be 12 such caverns of dimensions 40 ft transverse × 20 ft long × 40 ft high located at the A-sites and the B-sites. Since these caverns will house vital rotating machinery requiring frequent maintenance, they will be located at 30 feet from the tunnel. This will provide adequate radiation shielding to allow occupancy by personnel during operations of the VLHC. At each of these cryo system caverns, there will be approximately 4 penetrations of 30 inch diameter for transfer of cryogens to the VLHC tunnel. There will be a major 30-ft diameter equipment, utilities, and access shaft, along with a Y-shaped switchback for access to the tunnel and radiation shielding. This is depicted in Figure 7.12. There will likely be at least 4 magnet delivery shafts for the Stage-2 dipole magnets (16 meters long) distributed among the A-sites and/or B-sites.

### 7.4.5 Groundwater Collection Caverns and Pumping Stations (6)

The handling of groundwater seepage during the lifetime of the VLHC project will be a major concern. The tunnel design specifies a maximum average of 50 gallons per minute per mile, or a total of 7,200 gallons per minute. This flow will be directed through conduits through the invert floor to six collection and pumping stations at the A-sites of the cryogenics plants. A gentle slope of the tunnel floor is required to drive this water to the collection/pumping sites. It is necessary to be able to collect at least 1 day's flow of groundwater seepage (1.728 million gallons = 277,400 cu. ft. per day for each of 6 pumping sites), in the event of failure of power or water systems. At each of the 6 pumping sites, there will be groundwater collection reservoir caverns. These will have dimensions with a volume equivalent to 65 ft × 65 ft × 65 ft. Emergency back-up generator power will be dedicated for pumping, possibly even a mobile generator. Given this average water influx rate, the power, summed over the 6 sites, for pumping to the surface for the entire tunnel is estimated to be 1.6 MW. If required, any monitoring of groundwater influx for contamination, either conventional or radioactive, can be sampled at the collection caverns before discharge. If advantageous, pumping facilities could be distributed over both the 6 A-sites and the 6 B-sites. To facilitate maintenance, the groundwater pumps should be accessible during accelerator operations. See Figure 7.12.

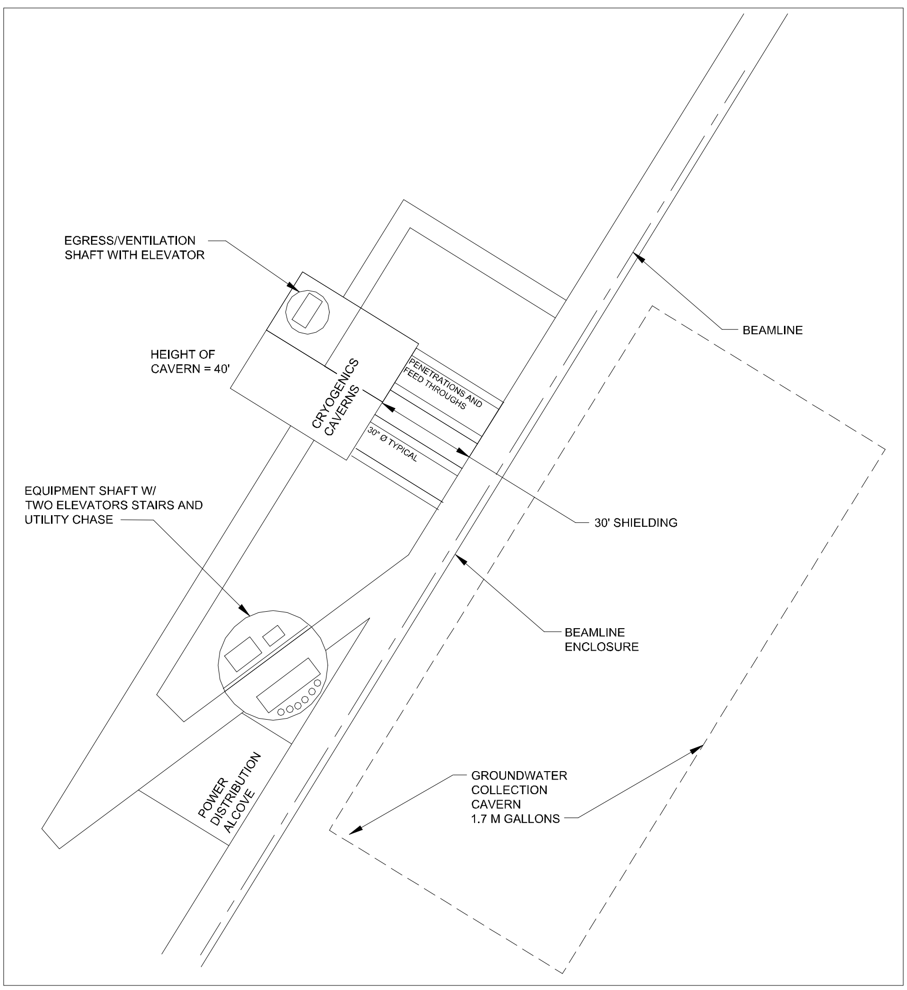


*Figure 7.12. A-site and B-site underground enclosures/caverns.*

### 7.4.6 AC Power Distribution Alcoves (24)

These are alcoves cut into the aisle side of the tunnel wall every 10 km, each 27 ft transverse × 25 ft long × 10 ft high, which house transformers, switch gear, and breakers to step down the 13.8 kV feeders fed through the tunnel from the cryo sites to 480/277 and 120/208 VAC for further distribution around the ring. For redundancy, there will be four 13.8 kV transformers per alcove. All components will be dry, without oil, to minimize fire hazards and environmental concerns below ground. Although the caverns are sized for the full Stage-1 plus Stage-2 complement, half of these components would initially be installed, with the second half installed for Stage 2. This cavern is shown as part of Figure 7.12 and Figure 7.13. These AC power distribution alcoves will be located at the A-sites, B-sites, and mid-sites. There will also be a trolley-type electrical bus on the ceiling, running the length of the tunnel, to provide power for the vehicles for personnel, component transport and installation, and logistical support. This could also provide distribution for welding, temporary lighting, and other applications not requiring high quality power.

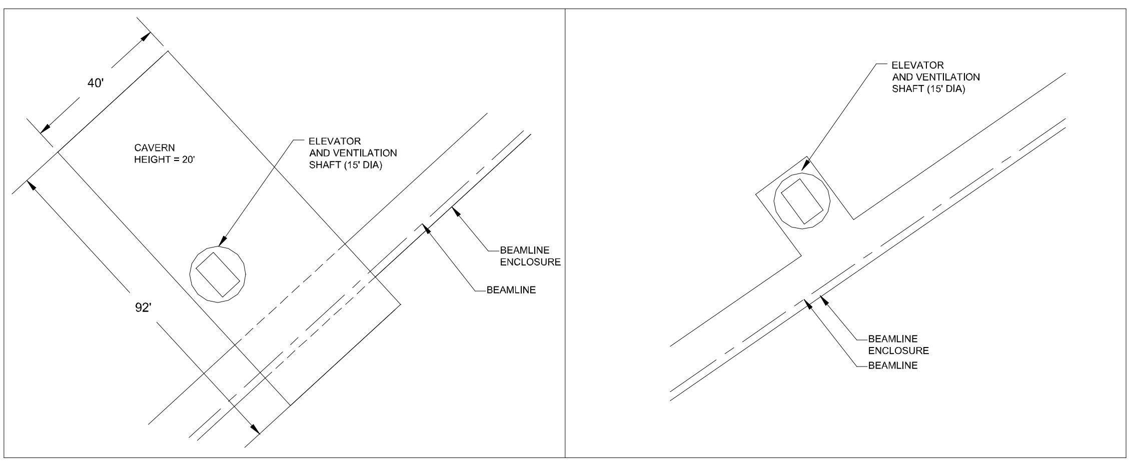


*Figure 7.13. Mid-site and E/V underground enclosures/caverns.*

### 7.4.7 Cryo Valve Alcoves (12)

For each of the 12 mid-sites, between the A-sites and B-sites, there will be small alcoves, 10 ft transverse × 20 ft long × 15 ft high, cut into the tunnel wall behind the accelerator rings with access stairs and catwalks. These allow more room for the installation of the cryogenic turn-around boxes and valves for magnet cool down and flow control and manipulation of bayonet cryogenic couplers. There will be an additional cavern 30 ft transverse × 20 ft long × 20 ft high to house the personnel staircase/beam overpass and a small chain fall crane for equipment. This cavern is shown as part of Figure 7.13. These cryo valve alcoves will be located only at the mid-sites.

### 7.4.8 Quench Resistor Caverns (12) – Stage 2

For Stage 2, quench protection resistors will be placed at the mid-sites. This will require caverns of size 40 ft × 30 ft × 15 ft (W × L × H) to house the resistors and cooling systems.

This cavern is shown as part of Figure 7.13. These quench resistor caverns will be located only at the mid-sites.

### 7.4.9 Electronics Drawers (1710)

Small cylindrical enclosures, 5 ft deep × 1 ft diameter, are bored into the aisle side of the tunnel wall. These will house low power supplies for the trim and corrector magnets for both rings, along with instrumentation and controls. The electronics components will be isolated from the tunnel by a fire/access door, and the small heat load will be cooled by convective cooling of a heat exchanger plate by the tunnel air flow. The electronics drawers will be humidity controlled. The equipment contained in this electronics drawer will be on rolling racks allowing access when extracted into the tunnel aisle. This is illustrated in Figure 7.6.

## 7.5 Experiment Caverns and Bypasses

SSCL specifications are used in this section. There is provision for two experiment caverns and installations in the IR straight sections at the Fermilab site. These caverns, major access shafts, and associated surface structures for experimental apparatus fabrication, staging, and operations, will be located on the Fermilab site to minimize land procurement. The model chosen is that of the designs of the caverns for the GEM and SDC experiments at the SSC [11,12]. It is understood that these caverns were optimized for a 20 TeV × 20 TeV collider, analogous to the Stage-1 VLHC Collider, and specifically not for the 87.5 TeV × 87.5 TeV Stage-2 VLHC Collider. At this stage of this exercise, it is not fully appreciated how the cavern needs scale with collider energy. The current model assumes that there is only one pair of experiment caverns, placed along the tunnel of the Stage-2 ring. For Stage 2, the low-field ring will be displaced through its low-field ring bypass tunnel, away from the experiment caverns. There will not be interaction regions or experiment caverns in the Stage-2 low field bypass. For Stage 2, the experiments will have to upgrade to the four times higher energy. The upgrade will include a vertical change in the position of the interaction point, due to the difference in elevations of the low-field and high-field rings.

Structural features and thickness of the strata supporting the spans of the experimental halls or caverns [2] will determine the elevations at which the caverns can feasibly be sited. This, of course, determines the elevation of the collider tunnel at the site of the cavern. A general rule of thumb is that there should be a depth of rock (dolomite) strata above the cavern at least equal to the span of the cavern. The previous study has concluded that for 75-foot high chambers, roof spans up to 125 feet are feasible using standard methods of roof arching and rock supports. This assumed that the orientation axis of the cavern bisects the major joint sets. The joints run approximately NE-SW × NW-SE so this criterion would be satisfied by VLHC ring orientations to the North, South, or West. Possible options in elevation for the experiment caverns are depicted in Figure 7.5.

Cost optimization of the combination of geology, structural strength of strata, height of dolomite in spans, strength of walls, requirements of radiation shielding, and equipment access all determine the elevation of the experiment caverns and the collider tunnel elevation at the Fermilab site.

The experiment caverns are envisioned to be 30 m × 45 m × 100 m (W × H × L) similar to the SSC model depicted in Figure 7.14.

The current model does *not* have special underground cryogenic plants to service superconducting experiment magnet systems. Special cryo plant alcoves would be added parallel to, and isolated from the experimental halls. Similarly, the experimental halls would be isolated from the accelerator tunnel to minimize the Oxygen Deficiency Hazards associated with the superconducting accelerators.

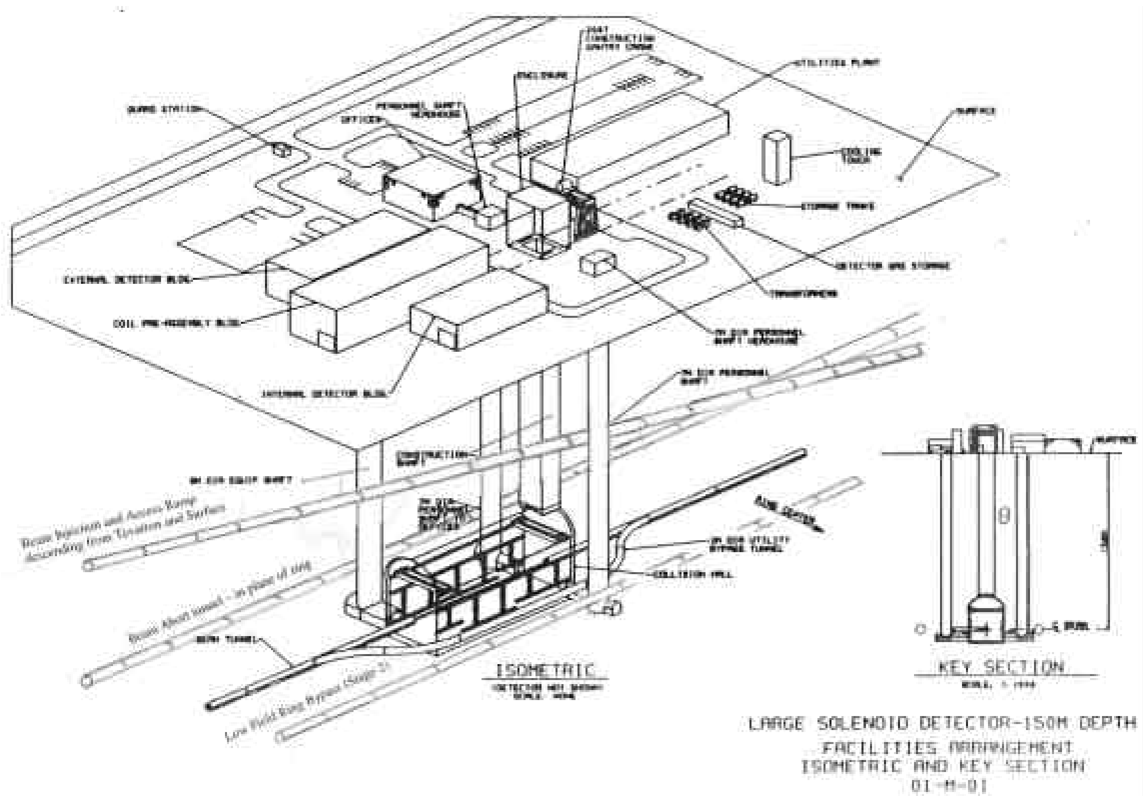


*Figure 7.14. Experimental area, isometric view, modeled on SSC generic Large Solenoid Detector.*

A tunnel bypass, to allow free access and transport of accelerator personnel, utilities, and equipment without entering the experiment caverns will be included. A 25-meter maximum offset can be accommodated with 2-km radius bends over a total bypass length of 550 meters (including the 100-meter length of the experimental halls). This would be of the same diameter as the main tunnel. Likewise, the tunnels for the abort line and the sloped tunnels for the injection lines/access ramps will pass nearby the experimental halls.

*Table 7.4. Experimental facilities (SSC specs).*

| | | | | |
|---|---|---|---|---|
| **SSC Experimental Halls Designs** | | | | |
| **From SSCL-SR-1235 (1994)** | | | | |
| **Underground caverns** | | **GEM IR-5** | **SDC IR-8** | **units** |
| beam depth | | 50 | 50 | meters |
| size of hall (W × L × H) | | 30 × 100 × 45 | 30 × 105 × 45 | m×m×m |
| Cranes | | 2 * 100/20 | 2 * 100/20 | Tons |
| Detector weight | | 11,000 | 40,000 | Tons |
| Surface cranes | | gantry ?? | gantry 100/20 | Tons |
| Heavy load path (on surface) | | 1600 | ?? | Tonnes |
| pit (below beam) | | NA | -13.9 | meters |
| main floor (below beam) | | -13 | -6.8 | meters |
| top of experiment (clears crane) | | +10.5 | +10 | meters |
| Installation shafts (hall to surface) | | 2 * 28 × 18 | 2 * 11 × 18 | m × m |
| **Surface structures** | **GEM North** | **GEM South** | **SDC AB** | **units** |
| Assembly buildings | 64 × 110 | 60 × 110 | 60 × 134 | m × m |
| With high bay | 30 × 110 | 30 × 110 | 30 × 134 | m × m |
| Cranes | 2 * 45/10 | 2 * 35/10 | 50/100 + 2 20/5 | tons |
| Side bays | 1 story | 1 + 2 stories | 1 story | |
| Doors | ?? | ?? | 14 x12 +18x12 | m × m |
| Personnel access buildings | | | | |
| size (free stand head house) | | 13 × 5 | 10 × 11 | m × m |
| Shaft diameter | | 13 × 18 | 9 meters dia. | m × m |
| Other buildings | | EQ access | Detector Ops | |
| size | | 15 × 20 | 24 × 44 2 story | m × m |
| Shaft diameter | | utility 13x17.5 | cable 9 m dia | meters dia |
| Adjacent head house | | NA | 12 × 11 | m × m |
| Utility buildings | | 24 × 80 | 24 × 80 | m × m |
| Shaft diameter | | NA | 10 m dia | meters dia |
| Adjacent head house | | NA | 14 × 14 | m × m |
| Gas mixing building | | 16 × 13 | 17 × 10 | m × m |
| **site footprint** | | 26 | 17 | acres |

# 7.6 Surface Buildings, Utilities, Factories, and Footprints

## 7.6.1 Stage 1

The required surface buildings include the 12 cryogenics service areas, small service areas for the beam stops, RF Klystron tube and the Kicker Power Supply caverns. One of the A-site cryogenics plants and the beam stop and RF Klystron/Kicker PS service areas are anticipated to be on the Fermilab site. In addition, the emergency egress/ventilation shafts will require minimum head houses and footprints, both on- and off- the Fermilab site. The cryogenic service areas will provide equipment and personnel access, collider power supplies, and groundwater pumping stations. For Stage 1, there will be only one plant at each cryogenics A-site. This will minimize the square-feet of building space and power and cooling requirements, and even the land footprint requirements. However, since it seems more appropriate to consider land acquisition as a single activity, the total land needs for the Stage 2 are indicated. The major power and heat load will be for the helium compressors. These requirements, also, are greatly reduced for the Stage-1 VLHC. The choice of cooling methodology, either cooling ponds or air cooling towers, will likely be dictated as much by the local aesthetics of a possibly suburban environment as by cost considerations. There will be one power supply station for the 100 kA magnet bus. This will be located at the cryogenics A-site at Fermilab. It will consist of a building, 75 ft × 40 ft, and an outdoor pad, 20 ft × 25 ft for transformer and oil containment. A superconducting transmission line will carry this current to the tunnel via a vertical shaft.

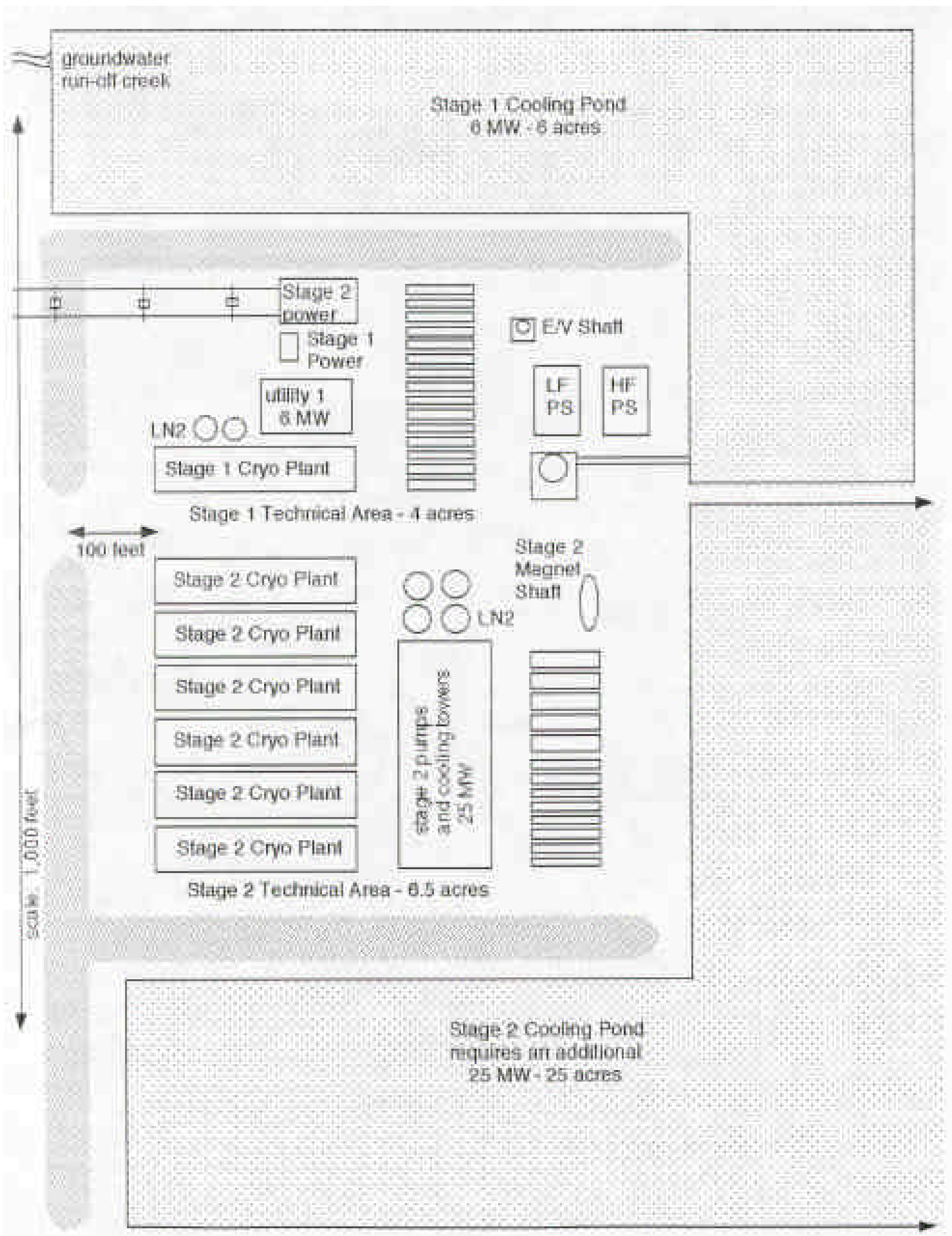


*Figure 7.15. Cryogenics and utility plants at A-sites for Stage 1 and Stage 2.*

Adjacent to the two access ramps at the Fermilab site (and possibly at an additional access ramp opposite), there will be the need for a warehouse, assembly, cryo testing, and storage building for final fabrication of the long magnet and cryogenics systems to be installed in the tunnel. See Section 5.1.6. This building will measure 690 ft. x 460 ft. with a variety of cranes and lifting devices with capacities up to 50 tons. The size, capacity, and complexity of the cryogenics test station/facility associated with these factories for Stage-1 components will be comparable to that of the Fermilab Magnet Test Facility (MTF).

*Table 7.5. Sites, functions, and features.*

| *Site* | *Reference* | *#* | *Function and Features* |
|---|---|---|---|
| **A-site** | Sec. 7.4.4 | 6 | (4) - 30 ft EQ shaft, E/V shaft, AC power distribution cavern, |
| | Sec. 7.4.5 | | - cryogenics cavern, Y-labyrinth, cryogenics penetrations, |
| | Fig. 7.12 | | - beam-on access to cryogenics caverns, |
| | | | - groundwater collection and pumping station, |
| | | | - surface: Stage-1 Cryo Plant, Stage-2 Cryo Plant, |
| | | | Stage-2 Magnet Power Supplies. |
| | | | (1 - at Fermilab, crossover straight) - same as (4) above plus |
| | | | - Stage-1 Magnet Power Supplies & LCW system. |
| | | | (1 – opposite Fermilab, crossover) - same as (4) above plus |
| | | | - LCW system for straight section components. |
| **B-site** | Sec. 7.4.4 | 6 | 30 ft. EQ shaft, E/V shaft, AC power distribution cavern, |
| | Fig. 7.12 | | Cryogenics cavern, Y-labyrinth, cryogenics penetrations, |
| | | | beam-on access to cryogenics caverns, |
| | | | surface: Stage-2 Cryogenics Plant & Stage-2 PS only |
| | | | (undeveloped for Stage 1). |
| **mid-site** | 7.4.6-8 | 12 | E/V shaft, AC power distribution cavern, cryo valve alcove, |
| | Fig. 7.13 | | quench resistor cavern and cooling system |
| **E/V** | 7.2 | 48 | 15 ft diameter shaft, elevator w/auxiliary power system, |
| **(Egress &** | Fig. 7.13 | | HVAC fans, dehumidification, air cooling tunnel heat loads |
| **Ventilation)** | | | (total of 48 includes those at A-sites, B-sites, and mid-sites). |
| **Utility Straight** | 7.4.2 | 4 | Kicker PS Cavern (2 each - at and opposite Fermilab): |
| **Section** | 7.4.3 | | - 15 ft shaft, penetrations to tunnel, Y-labyrinth, |
| | Fig. 7.10 | | - beam-on accessible. |
| | Fig. 7.11 | | RF Klystron Cavern (2 each - only at Fermilab): |
| | | | - 30 ft EQ shaft, penetrations to tunnel, Y-labyrinth, |
| | | | - beam-on accessible, LCW cooling for RF systems. |
| **Beam Stop** | 7.4.1 | 1 | 30 ft EQ shaft & E/V shaft, radioactive water retention, |
| **Cavern** | | | beam stop cooling: 100 kW Stage 1 (plus 200 kW Stage 2) |
| **Electronics** | 7.4.9 | 1710 | 1 ft diameter + 5 ft deep - air cooled by tunnel HVAC |
| **Drawers** | Fig. 7.6 | | |
| **Experimental** | 7.5 | 2 | see Table 7.4 |
| **Caverns** | Fig. 7.14 | | |
| **Magnet Factory** | 7.6 | 1 (2) | one factory at Fermilab, possibly a second at opposite side. |

### 7.6.2 Stage 2

The additional facilities for Stage 2 will include greatly increasing the capacity of the six cryogenics A-sites, adding similar enlarged cryo plants at the six B-sites and increasing the utilities for the RF Klystron/Kicker PS caverns. There will also be Stage-2 magnet power supply buildings, of similar size and utilities to those of Stage 1, located at each of the twelve cryogenics service sites.

A summary of the various sites, their functions, and underground and surface construction features is presented in Table 7.5.

# 7.7 Alignment Issues

## 7.7.1 Tunnel Alignment During Construction

The technology exists today to attain the specified ± 4 inches global positional accuracy (bulls-eye) and relative alignment of the tunnel sections around the ring. This is commonly attained in rapid-transit subway systems and even for elevation of sewer tunnels [10]. This is accomplished with GPS surface measurements translated through normal construction shafts (including horizontal offsets) into a laser reference line and positioning the tunnel boring machine (TBM) relative to that line. By the time of VLHC tunnel construction, it is anticipated that this laser reference and TBM tracking/positioning will be fully computer automated to follow pre-programmed trajectories including curves and slopes within line of sight. Nevertheless, it still will be necessary for the VLHC staff to constantly monitor the construction contractors' tunneling progress, especially with regard to relative alignment of separated tunnel segments being dug simultaneously.

## 7.7.2 Reference Network and Component Alignment

### *7.7.2.1 General Considerations*

This section is a discussion of the errors encountered in machine installation and techniques of building networks for machine alignment. Estimation of possible errors is based on experience from the Main Injector project. Mechanical aspects and specialized alignment tooling are discussed in Section 5.1.8.8.

The ability to transport beam around any synchrotron is directly dependent on how well each component of the machine is installed. The total installation error can be expressed as

$$s^2 = s_n^2 + s_m^2 + s_f^2 + s_s^2$$

where:

- $s_n$ are errors in the network
- $s_m$ are errors due to measurement between control points and magnet fiducials
- $s_f$ are errors due deviation between the magnet fiducials and the magnetic center
- $s_s$ are errors due to stand adjustment.

The errors in the stand adjustment ($s_s$) are a mechanical design issue. There is a trade-off between cost of the stand and the ability to precisely position the magnet. The ability to move a

65-meter long magnet without causing undue stress is discussed in Section 5.1.8.3. Also, the lattice designers should determine how precisely to align the dipoles relative to the quadrupoles for a separated function machine. It may be easier to have a lamination pack that can be added to or subtracted from the magnet once it is installed to make up for errors. Once these values are determined a detailed design for a stand can evolve.

The errors between the magnet fiducial and the magnetic center ($s_f$) are dominated by the quality of the lamination stamping. Experience from the Fermilab Main Injector (FMI) indicates that this can be controlled to ± 0.025 mm. This should be an acceptable error for the VLHC.

The errors between the control points and the fiducials ($s_m$) are determined by the instruments used and the skill of the people doing the measurements. For the Main Injector, a laser tracker was used for the final installation of all magnet elements. This device is a laser interferometer using a set of motor driven mirrors and a feedback system to follow a corner reflector from a base location to a desired spot. The ultimate accuracy of such a device is ±10 microns with an angular resolution of 0.2 milliradians. This is for short distances (less than 50 meters) and in controlled atmospheric conditions. To obtain the best results with such a device a dense network of monuments must be available near the magnets such that multiple and redundant measurements can be made. One of the major advantages of a laser tracker is that a computer logs the data directly thereby avoiding transcription errors. Errors are virtually eliminated if, in addition, a bar code system is in place for the magnets. A database will need to be developed to track the offsets from the magnet to the network. This database will also need to have the values determined from the construction of each magnet and magnetic field measurement.

The dominant error is the network itself ($s_n$). Since ancient Egypt, all survey networks have the same structure. They consist of a set of inter-linking triangles where the distance from the start to any point in the network is determined by either triangulation or trilateration. Triangulation consists of measuring the length of a base line and all the angles of all the triangles. The law of sines is then used to calculate the distances between each vertex (monument) of the triangles. Since the sine of angles near 0 degrees varies rapidly, angles less than 30 degrees or greater than 150 degrees should be avoided. It is obvious that this is impossible inside the VLHC tunnel.

Trilateration consists of measuring the distances between the monuments in a network and at least one angle. These distances are then reduced to a plane coordinate system for error checking. By using a laser interferometer such as a Kern Mekometer errors are (0.2 mm + 0.2 x $10^{-6}$ x distance measured in mm). For the long, narrow geometry of the VLHC tunnel, this is the preferred method.

Using an arc radius of 36,924 meters the longest line of sight (LOS) in the tunnel will be 941.4 meters. The LOS will set the base of the primary network in the tunnel. Given that the magnet end points will be occupied with instruments the exact length of the base line will be slightly shorter. It will be possible to measure from the base line center point to either end point with the Mekometer with an error of ± 0.39 mm. These primary base lines will serve a similar purpose to the Murphy line [13] in the Tevatron. They should be located parallel to the quadrupoles in each section. This will keep the necessary offsets constant for each quadrupole.

In the region of dipoles and quadrupoles the primary network will be densified, that is more monuments will be installed near the magnets to give redundant measurements. The accuracy of these monuments will depend directly on the primary base line. Error analysis of the Main Injector network [14] indicated a tunnel monument position should be better than ±0.3 mm.

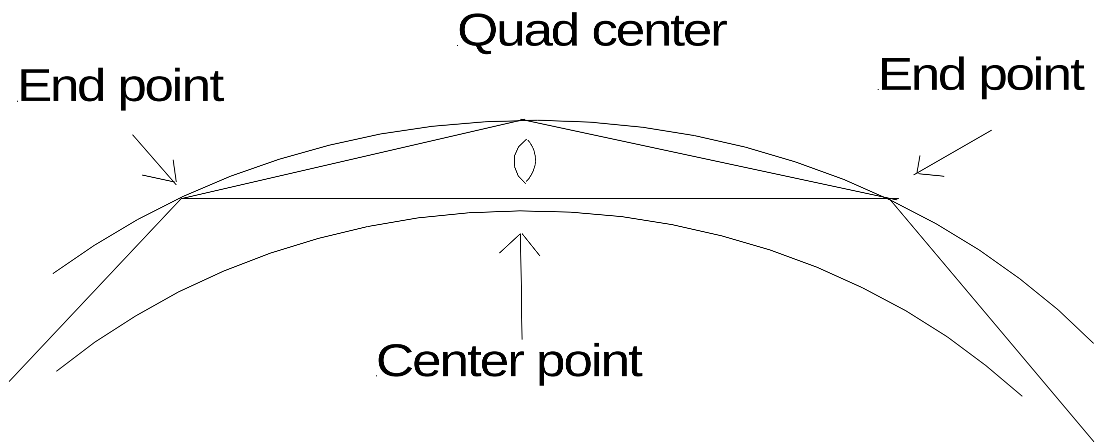


*Figure 7.16. Alignment schematic for technical components.*

In an ideal world, each of these baseline points would have an alignment hole located directly over it so that solid connection to the outside network can be made. This could require, in principle, up to 250 alignment holes. Given the need to minimize surface disruption, fewer alignment holes will be specified. It is important that connection to the surface be made. A strong surface network using GPS and standard survey techniques will strengthen the underground network [13]. At the other extreme, alignment holes directly over the tunnel reference system were not used at CERN's 27-km long LEP/LHC. Instead, the surface control was transferred through vertical shafts at 8 service and experimental areas and then horizontally transferred to the tunnel control network.

Consideration should be given to the fact that IDOT District 2 has been installing a Class I GPS network consisting of 250 monuments [15]. This is in the area north of Interstate 80 and south of the Wisconsin border, west of the Kane-DeKalb county line to the Mississippi River. The errors between the monuments in this area are less than 1 part per 100,000. This can be used as part of the above ground network for the VLHC and save time and effort in the construction phase.

Given the size of the VLHC ring, geodetic techniques will be required to ensure that the above ground network and the tunnel network are designed and installed properly. Care must be taken to account for variation in the geoid and gravity over the entire site. Both will be significant for this machine. It is very possible that there will be significant variations in the local vertical line due to change in the rock density. This needs to be monitored during construction, and measured after the tunnel is complete.

The exact errors in the above ground and primary underground network can be modeled once a detailed lattice and tunnel layout are known.

The requirements for alignment of magnets in the VLHC is approximately 250 µm transverse to the beam with a rotation along the beam axis of under 1 mrad. Achieving the latter is a standard exercise and requires no particular effort. Therefore we concentrate on the first criterion.

Magnets at Fermilab are routinely surveyed to 500 µm. Achieving 250 µm would require careful construction of reference points on the magnets and relating the physical references to the pre-determined magnetic center but neither of these problems involves surveying or alignment. The relevant difficulty arises from aligning magnets over the ring circumference. No matter what magnet one starts from a "random walk" error of 250 µm per magnet adds to large errors over the ring. A standard geodetic check is "closure", that is traversing the ring once and checking the height of the first magnet measured against its height measured at the end of the surveying chain. Surveys in the Tevatron and Main Injector typically achieve a few mm of closure; in the VLHC we might therefore naively expect a few cm, which would be unacceptable.

It is important to note that there are two sorts of error:

- Slow walks over a long distance. These will be controlled by the methods discussed below but can be handled through correction magnets.
- Individually mis-aligned magnets will be caught locally and present no special challenges.

### *7.7.2.2 External Global Network*

Judging from our experience at the Tevatron, we would design exterior monuments to anchor our internal measurements located roughly every few km along the circumference. These exterior monuments could be referenced by a variety of techniques both to each other and to other parts of the accelerator complex. Both horizontal and vertical control can then be transferred into the tunnel from the outside control network. For comparison, Figure 7.17 shows the outside control network for the FMI. One may expect additional control points within the area of the ring for the larger VLHC. Experience with the existing laboratory network shows that we can maintain control to about a millimeter over several miles across the site using techniques developed at Fermilab and SLAC. These points serve to anchor the internal measurements and prevent the random walk from growing out of bounds.

### *7.7.2.3 Internal Control Network*

The FNAL tunnels use a system of tie rods and bolts. The tie rods are placed in the walls of the tunnel and the bolts are placed in the floor. The FMI required 463 wall and floor monuments so we would expect an order of magnitude more in the VLHC. The only significant problem with the system arises from the assumption that the walls and floor do not move relative to each other or to the magnets and that there is no overall twist of the tunnel. The external control network will constrain the size of such effects but it will be necessary to monitor the overall motion of the tunnel. We have seen the FMI tunnel sink by a few millimeters on average since construction with local perturbations of three times this much arising from construction on the site and the loading and unloading of dirt for construction. Again long-wavelength motion is not a significant problem but local twists and shifts are problematic for machine operations.

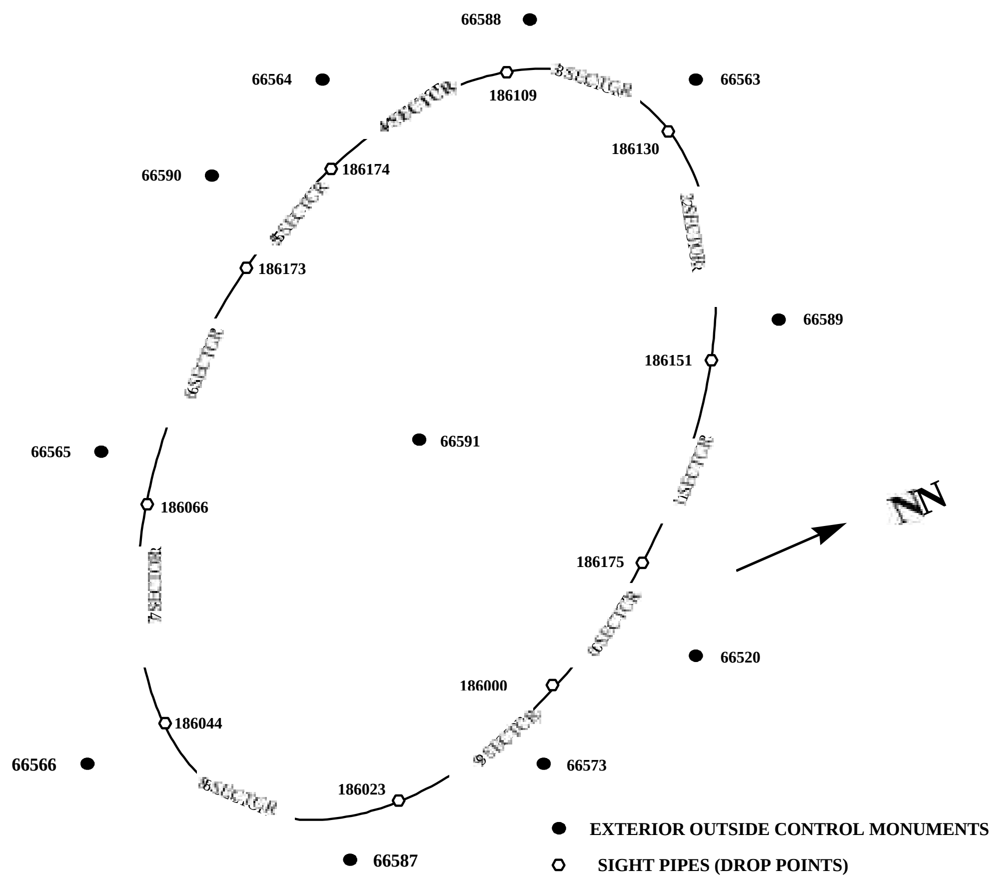


*Figure 7.17. FMI external control, drop points (sight pipes, alignment holes), and sector designations.*

The actual surveying and alignment of the magnets relies on a laser tracker. A laser tracker uses interferometry to locate a magnet in three dimensions. Combined with optical tooling and the tie rod and bolt system we would construct a network as shown below. Three laser trackers reference the tie rods and bolts relative to each other along the tunnel length as in Figure 7.18. In normal operations we do not measure the locations of the magnets relative to the wall control system but this could be added at the cost of increased time. A survey in the FMI or Tevatron takes approximately a week, with an additional week for analysis. We estimate 40 man-weeks for a full alignment of the VLHC. Such work could go on in parallel using multiple crews.

Using this system we believe a survey to the requisite 250 μm locally, with closure of order 1 cm could be achieved by building on the experience in the Tevatron/FMI complex. The most challenging features would be the scale of the effort combined with careful design of the aboveground network and its referencing to the tunnel coordinates.

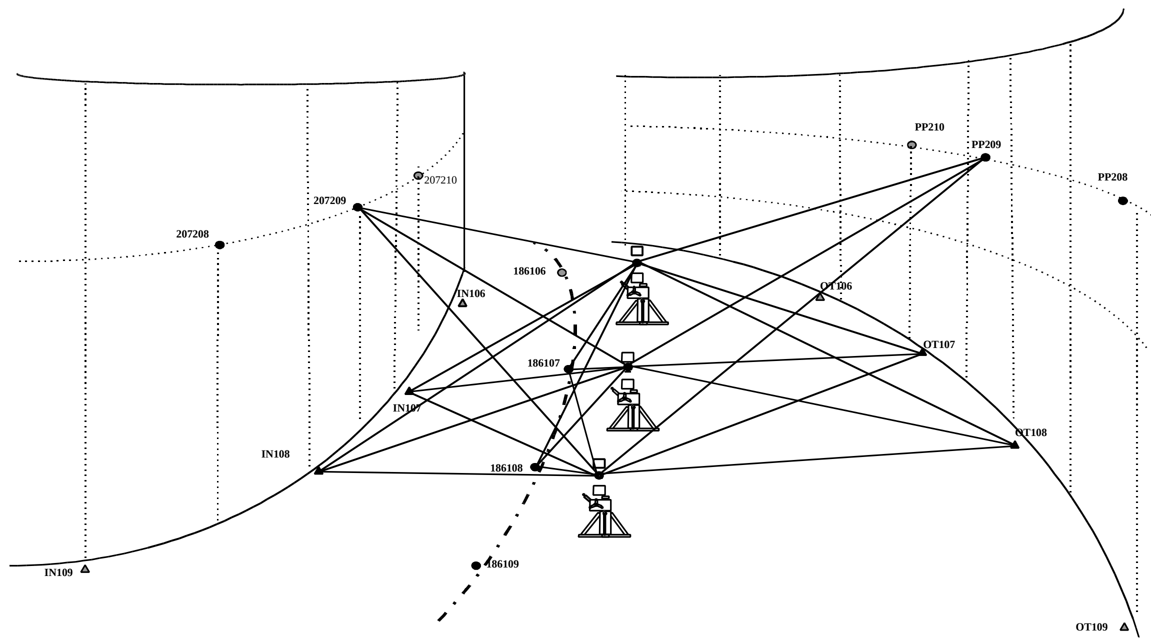


*Fig.7.18. Control stations common to three laser tracker setups in the FMI tunnel.*

We have worked out a preliminary network for the VLHC which allows us to quantitatively estimate the error on an individual magnet relative to the global network as a function of the number of external alignment holes. We can control the global walk to 2.1 mm over 8.5 km of tunnel.

*Table 7.6: Global walk vs. distance between alignment holes.*

| Distance Between Alignment Holes | | | Position Error (mm) |
|---|---|---|---|
| 135 km | => | 2 alignment holes | 7.0 |
| 68 km | => | 4 alignment holes | 4.3 |
| 34 km | => | 7 alignment holes | 4 |
| 17 km | => | 14 alignment holes | 3.2 |
| 8.5 km | => | 28 alignment holes | 2.1 |

## 7.8 ES&H Issues During Construction, Installation, and Operations (Worker Health & Safety, Wetlands Restoration, Muck Disposal, Egress, etc.)

For this exercise, ES&H issues have been merely identified without detailed study or specification of proposed solutions. Most of the ES&H issues both during construction and during operations of a VLHC are discussed for generic new accelerator facilities by the Fermilab Committee on Site Studies [16]. This section is intended to focus on issues peculiar to the VLHC and its scale that are in addition to the issues discussed by that Committee. Although it is anticipated that much further ES&H work will be needed to optimize the costs and operations of a VLHC and satisfy standards to be applicable at the relevant time scales, for the purposes of this study, many of the ES&H requirements of the SSCL [17,18] were assumed for the specifications and costing exercises.

VLHC design/specification issues with ES&H impact start with the finished diameter of the main tunnel. A larger diameter will optimize installation, operations, and maintenance of the accelerator systems, and improve emergency egress and response. However, increasing the tunnel diameter may increase the overall project cost. Personnel access and egress are issues of the number and placement of minor shafts. After much negotiation, the Department of Energy accepted a minimum egress/ventilation shaft spacing of 2.7 miles for the final operating configuration for the SSC. The Chicago area deep reservoir project (TARP) construction required a temporary personnel access/egress shaft serviced by a crane with man-cage at a maximum of 5000 feet from the deadheaded boring face. Such temporary egress shafts are filled-in upon completion and final finishing of that nearby tunnel section.

In this study, it is anticipated that there will be minimum fire and smoke hazards in the tunnel. The main accelerator bus power supplies will be located on the surface. Power distribution transformers, switch gear, and breakers located locally in the tunnel will be oil-free. Smaller power supplies and electronics will be in special fire and smoke resistive electronics drawers, and interconnecting cables of low toxicity and of low smoke generation. The special underground enclosures for RF klystrons and kicker power supplies, cryogenic systems, and the experiment caverns could be equipped with local automatic fire suppression systems and local ventilation systems. The envisioned VLHC cryogenics systems will not use liquid nitrogen. The cryogenic magnet systems will only be energized while the tunnel is unoccupied. The Stage-1 quench reliefs of the liquid helium systems will be through high pressure piping within the cryogenic transfer lines. With reduced fire, smoke, and oxygen deficiency hazards, it is anticipated that during and after installation of the accelerator components, personnel entering the tunnel will carry sufficient oxygen supplies nearby on their motorized access vehicles, removing the need for safety refuges [18]. The SSCL had refuges, each with two hour fire door and two hour emergency air supply for up to 7 people located not greater than 2500 feet apart, between the emergency egress shafts.

After completion of construction, tunnel ventilation will be provided at the 1/3 volume change per hour level during collider operations (unoccupied), and at the 1 full volume change per hour level during personnel accesses for installation and maintenance. This ventilation is needed to purge $C^{11}$ resulting from collider operations and possibly $CO_2$ and Radon naturally released from the tunnel rocks. Flow design, controls, and barriers will have to be designed to isolate ventilation problems.

The handling of groundwater will be a major environmental concern throughout the VLHC project. Much of the tunnel, although below the piezometric surface (water table), will be in the Galena-Platteville dolomite, which is classified as an aquitard. Still, grouting of cracks will be required to reduce the post-construction groundwater influx to workable pumping limits. Other strata such as the sandstone and dolomitic sandstone, below the water table, of the South Ring configuration will be problematic from structural and water influx rate viewpoints and likely will require fully lined tunnel sections.

During tunnel construction, there will be additional water influx rates before tunnel grouting and lining, especially at the injection/equipment access ramps where the long and shallow-angle traversal of the glacial till-bedrock surface interface may be problematic before tunnel lining. There will be the issues of dewatering the aquifer both during construction and operations, prevention of aquifer contamination during construction, and radiological contamination of the soil and aquifer during collider operation. Not only will the volume of water discharged during construction require serious attention, the quality of this discharge, in terms of pH and suspended solids and other environmental limits, will likely be an issue. Engineered solutions will be required for channeling, storage, pumping, and disposal of groundwater influx into existing creeks nearby capable of accepting this water discharge. The VLHC operational specification for groundwater seepage is an average discharge of 50 gallons per minute per mile of tunnel, corresponding to a total of 7,200 gpm total, distributed over 6 pumping sites, each at 1,200 gpm. Optimization studies will have to be undertaken to balance additional construction costs for water exclusion versus operating costs for dewatering costs over the lifetime of the VLHC, including environmental impacts.

The question of possible radioactive contamination of groundwater systems must be addressed. Preliminary estimates of radionuclide concentrations for a single maximum accidental loss at a point of full energy, full intensity beams indicate that for aquitards (such as Silurian, Maquoketa, and Galena-Platteville strata), an exclusion zone for wells of about 100 feet from the VLHC ring will ensure that federal limits for radionuclide concentration in drinking water will not be exceeded. Similar calculations for contamination due to losses in aquifers will need to be undertaken, including specific local water flow migration and dilution models. Preliminary calculations also indicate that even if all radionuclides produced in a single worst case beam loss accident were to immediately be deposited in one of the full groundwater seepage collection caverns, the concentrations of tritium and $Na^{22}$ would be comparable to federal limits for surface discharge. Levels and procedures regarding residual radiation of components and walls, and contamination due to beam losses are part of normal radiological operations of this accelerator.

For the Stage-2 high-field VLHC, each of the 12 remote cryogenics sites will be consuming approximately 25 MW electrical power, mainly to run the helium compressors. This power will have to be dissipated to the environment, either by air-cooling towers, cooling ponds (approximately 25 acres each), or combinations of towers and ponds, depending on the particular environmental needs at each cryogenics site.

The disposal of spoils or muck from the underground construction will be an issue. The spoils will have various fractions of clay, dolomite, shale, sandstone, etc. The Illinois SSC Proposal [19] evaluated four scenarios, three of which were to refill nearby previous mining operations and the fourth was in landscaping around the shafts and remote sites. Sale of the dolomite for use as construction material may, or may not, be feasible, depending on market conditions.

Constructing a tunnel will have major surface impact for personnel and equipment access and muck removal. Some of these surface sites will not be needed, or with reduced footprint, after construction. It will be important to have a plan to return these lands back to the citizens of Illinois in a useable and environmentally acceptable condition.

## 7.9 Model of Construction Schedule

A preliminary impression of a possible construction schedule is based largely on the Kenny study for the 3 TeV VLHC Booster Tunnel [9]. The schedule presented as part of that study included a 34-km circumference tunnel in Galena-Platteville dolomite, four major shafts, and two injection ramps. Other portions of the VLHC civil construction, such as experiment caverns and adits, cannot be extrapolated from the Kenny study, and at this time are only estimates. CNA Engineers [10] are providing costing and scheduling estimates for the entire scope of the VLHC project, including three geological sitings for the tunnel.

This section is intended to provide a straw-man model to begin to understand how the VLHC construction could be accomplished in a finite time scale.

For this schedule, it is assumed that day-one, year = 0, occurs after an Architectural, Engineering, & Construction Management contractor has been hired, the final construction designs have been prepared, land procurements and easements have been obtained, and the bidding process for the construction contracts has begun.

It is envisioned that the VLHC construction will be broken up into some number of underground construction contracts. Geologic factors will be considered to attempt to have each contract utilize only one method of tunnel excavation. As a preliminary model, the 233-km ring tunnel could be broken into 6 contracts of approximately 39 km each, 4 contracts of 58 km each, or 8 contracts of 29 km each. Using the Kenny model [9], the tunnel boring phase (TBM) of these contracts would be 5 years, 7 years, and 4 years, respectively, including one year for contractor mobilization and preliminary shafts before beginning the boring operation. These individual TBM crews could start and end at the A-sites or B-sites. There may be advantages to reconfigure to larger number of smaller, or shorter length/duration, tunneling contracts. In the remainder of this section, 6 TBM crews are assumed for the main-ring tunnel.

In addition, there would be another contractor to handle the more complicated Utility Straight through Utility Straight sections (U2U) plus two more contractors for the experimental halls. It is not apparent whether it is optimal to have the TBM contractors also have responsibility for the adjacent side caverns, or whether that is better handled as separate contracts. Managing all these separate, but somewhat interacting contracts will be a challenging coordination and management task.

Although the VLHC ring has natural 6-fold, 12-fold, 48-fold symmetries, the choice of *two* magnet fabrication plants and associated ramps for transport of the 67 meter long Stage-1 LF magnets implies that with more than 4 tunneling contractors, two or more sections of the tunnel will be isolated, in that magnets cannot be delivered to these isolated sections until tunnel sections between the sections in question and the magnet ramps are completed. This complication in sequencing tunnel construction and magnet installation will imply a undesired lengthening of the time scale for overall VLHC project completion. The alternative is to add a third magnet factory, with 6 tunneling and 6 installation crews all working in parallel.

In Figure 7.19, a tunnel construction and magnet placement schedule is presented for 1/6th (38.75 km) of the VLHC ring. This assumes that four positions for vertical removal of muck/spoils will be used for this section of construction. This would correspond to a maximum of about 10 km of horizontal muck conveyor to reach the vertical take-out shaft. Although contractors could utilize longer horizontal runs, moving the vertical take-out after every 10 km will allow the tunnel finishing tasks, grouting and laying of the invert floor, and the installation of utilities, AC power, lighting, HVAC, etc., and even the beginning of magnet installation to proceed in parallel with tunnel boring.

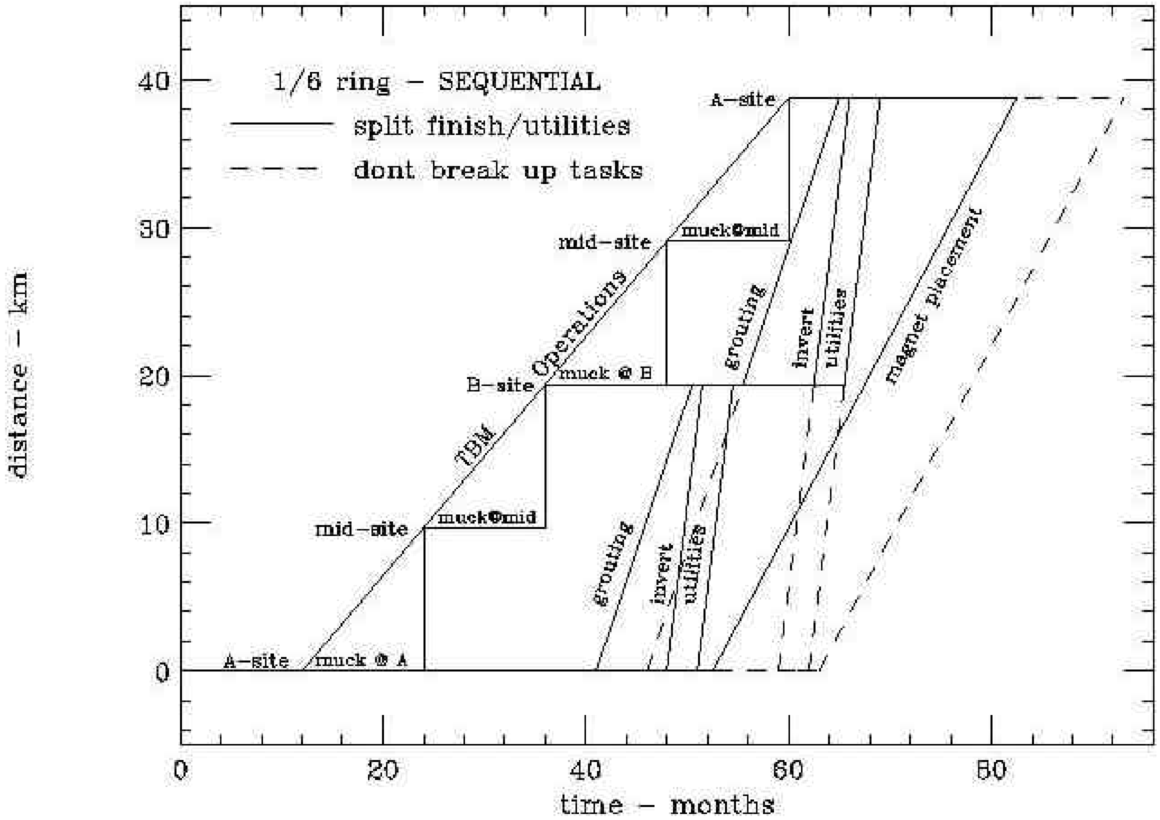


*Figure 7.19. Tunneling schedule for 1/6th of VLHC ring based on Kenny study of a 34-km ring [9].*

This model assumes that the construction of the side caverns can proceed in parallel with minimal mutual interference with nearby TBM operations. This also assumes that the tunnel finishing and utilities operations will begin as soon as boring of the first half of this section is complete. The downside of this early finishing is that these operations will outpace the progress of the tunnel boring and there will be a delay before starting the finishing of the second half of this section. This might incur extra expenses, but it would escalate beginning of magnet installation by almost one year compared to waiting to perform the finishing/utilities operations as one continuous task. (This later start for finishing/utilities, still in parallel with TBM operations, is depicted as the dashed lines in the above figure.)

A more complicated construction area is at the Fermilab site between the utility straight sections (inclusive). A possible scheduling sequence for this U2U section is depicted in Figure 7.20. This would be done by the 7-th TBM contractor in this model. The most time-critical feature is completion of the injection/installation ramps to the surface and the outboard sections of the widened utility straight tunnels in order to be ready for magnet installation. The completion of the RF klystron tube caverns, the kicker magnet power supply caverns, the equipment and utility bypasses around the experimental halls, the abort lines and beam stop cavern, experimental halls, and the stub-outs for the Stage-2 LF ring bypass (to be installed later) will occur after that milestone. Since there are no injection lines at the opposite side magnet factory, the equipment ramp is envisioned to have a much simpler design which could represent a small additional contract or be added to one of the TBM contracts starting from that position. The eighth and ninth underground contractors would have responsibility for each of the two experiment caverns.

A model construction schedule is presented in Figure 7.21. The 3.5 year time scale for construction of the experiment caverns is a pure guess at this time. There is a concern that construction and technical outfitting of the magnet factories will be completed only 3/4 year before tunnel installation of magnets would begin. Finally, the isolated B and E sectors are noted, illustrating how magnets would be filled from the adjacent sectors sequentially. In this report, it has been assumed that there would be 4 crews for magnet installation (one magnet per crew per one shift per day). Cryogenic lines would also need to be installed during this same time period.

## 7.10 Construction Engineering & Design Challenges

Little real engineering study or design has been devoted so far toward the conventional construction aspects of the VLHC. There are several outstanding issues that must be addressed to go beyond the simplified models presented. Of paramount importance is to reduce the overall cost. This can be done by simplifying the underground construction, performing R&D on tunneling methodology [20]. This includes optimizing TBM utilization, especially in the region between utility straights.

There is no design yet for the Stage-2 abort. Its design will impact on the design of the utility straight section cavern or widened tunnel. Other issues to be addressed are the stub for the LF bypass for Stage-2. The LF bypass ring with stronger magnets will cross the enclosure at floor level and will need ramps across the aisle.

There are installation issues to resolve. How many magnet delivery shafts will be needed to install the 16-m long Stage-2 HF dipoles? What are the details of the injection/equipment ramp interfaces to the Tevatron and the surface? The experiment caverns will house enormous detectors deep underground. What are the optimal shaft dimensions for installation and assembly of the detector components?

The optimal size for the Stage-2 experiment caverns where 175 TeV collisions take place needs engineering and physics design optimization of the roof span. The beam heights in the Stage-1 and Stage-2 colliders are different but could be made the same where they pass through the detectors. This would have the consequence of introducing a small amount of vertical dispersion, and its effect would require further study. A better option may be to design the detectors so that they could be adjusted in the Stage-2 upgrade to match the new beam height.

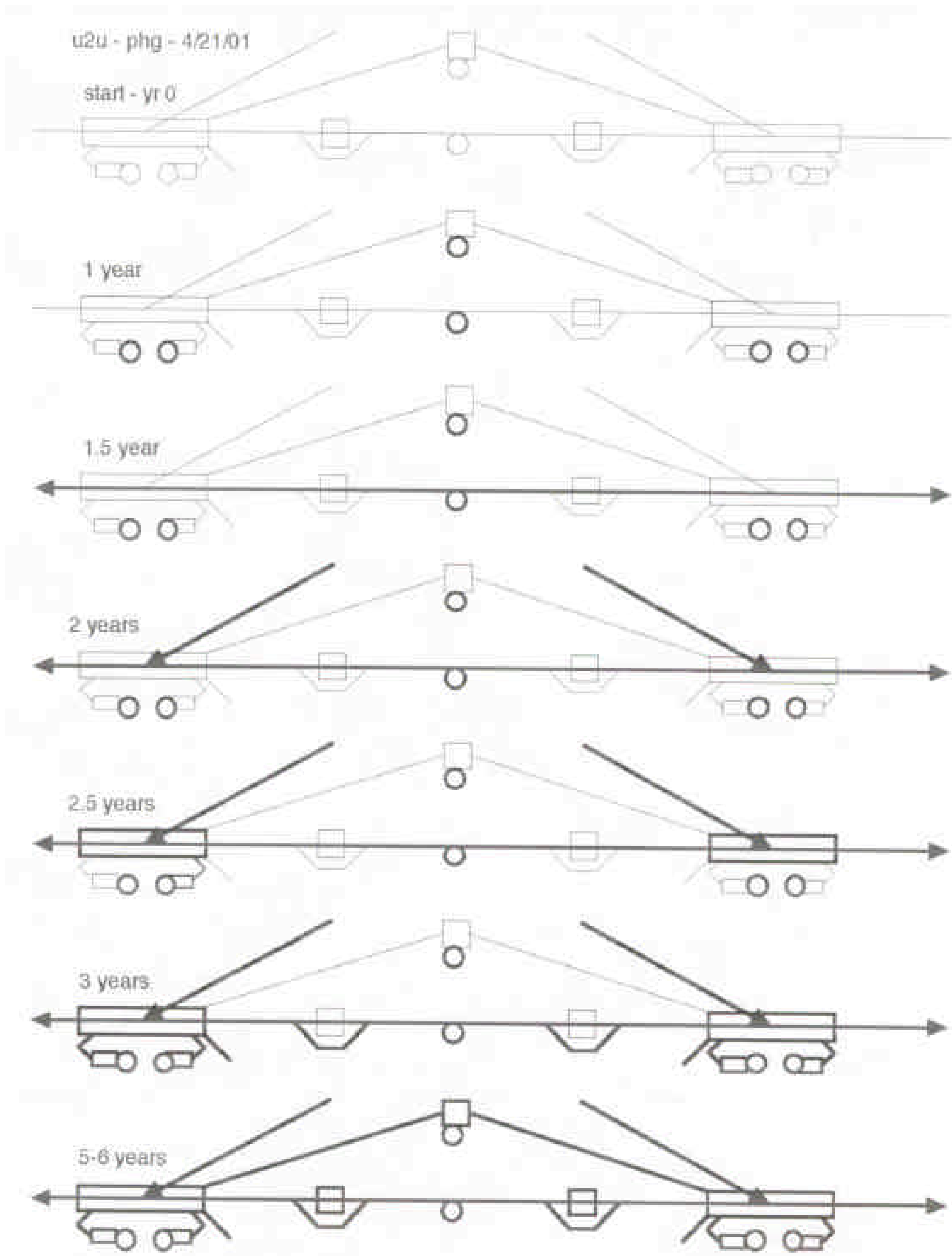


*Figure 7.20. A time-line cartoon depicting progress in the utility straight to utility straight section at Fermilab. Bold indicates completion of civil construction.*

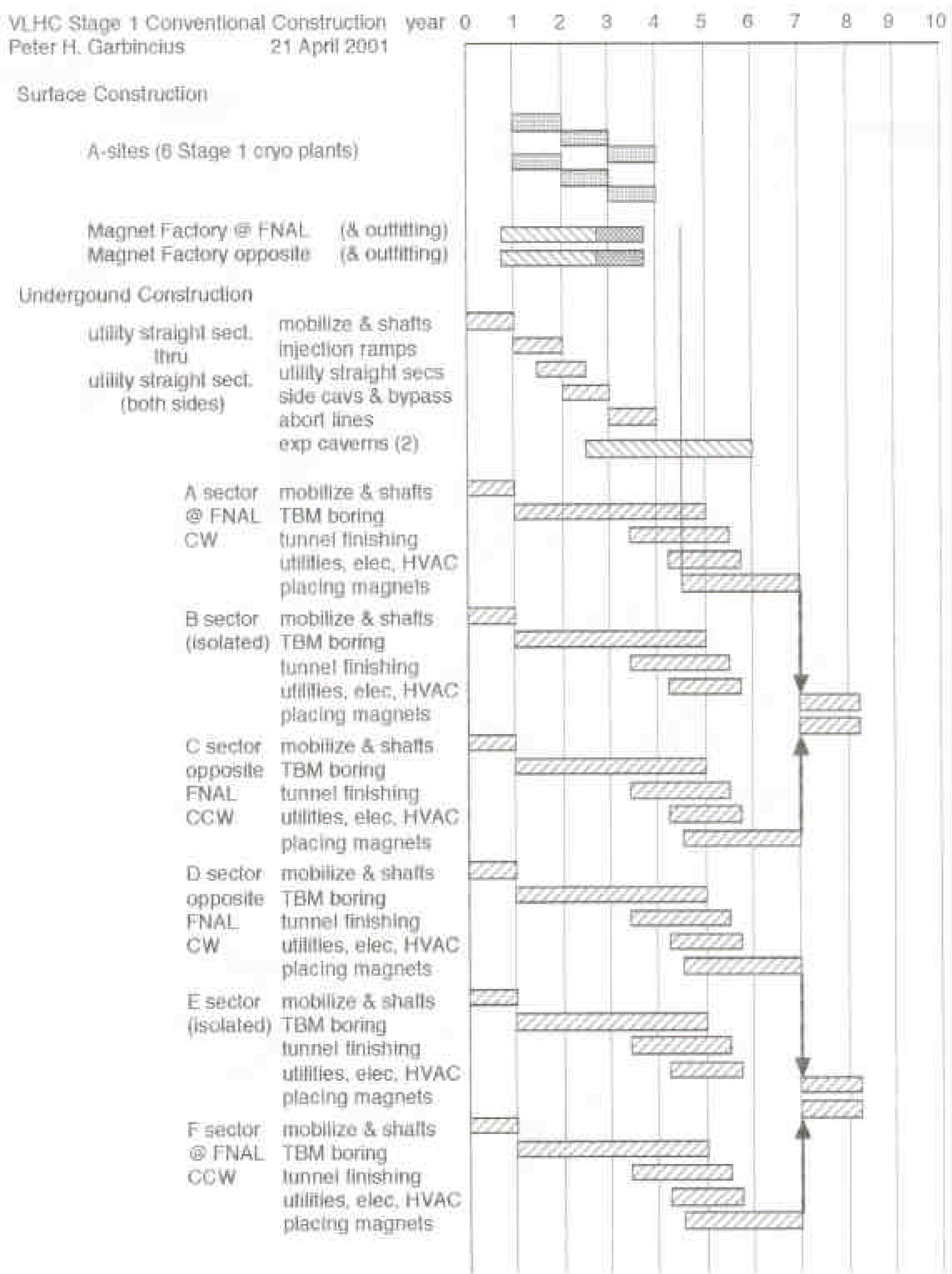


*Figure 7.21. Preliminary schedule for VLHC conventional construction.*

## 7.11 Cost and Risk Reduction

A major cost driver for the overall VLHC construction is the underground tunneling. Any improvement in the technology or methodology of constructing the tunnel is likely to have an impact on reducing the overall cost of the project. A preliminary study has already been completed by the Robbins Company, a major international supplier of tunnel boring machinery [20].

Uncertainties in the cost estimate for the construction reflect the state of knowledge of the underground conditions and quality of the rock, soil, and especially water content. "Average" conditions were assumed in this study. However, before a more realistic cost estimate can be prepared, the particular conditions for a specific proposed site must be quantitatively measured. An optimization between the extent (up-front cost) of such studies and acceptable risk will then be required.

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We also thankfully acknowledge the contributions of Joe Lach (Fermilab) to this study, including sharing his experiences with the Illinois SSC proposal, providing reference materials, and arranging personal contacts and site visits.

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