Magnet Installation and Human Presence in the Tunnel

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ABSTRACT

For the Rally Large Hadron Collider (RLHC) there are proposals for low and high field designs. We discuss here the low field option. Within this option there are proposals for very small diameter tunnels (1m or so in diameter) and for more conventional bored tunnel (diameter of 3 m and larger). Installation and maintenance work can be thought of to be performed in the traditional way (by people) or by fully automated and remote controlled systems (robots). There are three viable combinations of tunnel size and automation:

Small Tunnel and robots
Large tunnel and robots
Large tunnel and human workers.

We explore here the last combination, large tunnel and human workers. Before choosing an option the other two combinations need also to be explored. The decision will be based on expected reliability and cost.

I. TUNNEL

A. Tunnel Size

With present technology the lowest cost tunnel is one of 3 m diameter or more, bored at high speed, with conveyorized muck removal. Muck removal can occur as far as several km apart. Muck removal shaft spacing is optimized for cost of conveyor systems ($ 300/ ft) and cost of trucking the muck to the point of use (e.g. road building). The vertical muck removal shafts are approx. 3 m in diameter. We assume they are 3 km apart.

Given such a large tunnel size it is possible for humans to do most of the tasks of accelerator installation and maintenance. However, this imposes certain requirements on tunnel amenities. The additional requirements for human occupancy are listed and costed. They are surprisingly mild.

B. Communication in the Tunnel

Wireless digital communication at high speed is becoming a major industry. We expect to use this technology for continuous communication between the main control room and all systems, vehicles, and workers in the tunnel.

C. Tunnel Traffic

Tunnel traffic includes the magnet installation vehicle (“magnet mover”) and people traffic, e.g. installation, surveying, and maintenance crews. We assume that all workers use a vehicle; there will be no pedestrian travel, except in the close vicinity of a vehicle.

II. MAGNETS

A. Magnets, Magnet Factories

Magnets are 25 cm x 25 cm in cross section. Based on this analysis we expect that they will be 250 m long (see length discussion below). Their mass is 460 kg/m. The return conductor cryostat is mounted on top of the magnets to control the stray field produced by the loop formed by the magnet and return conductor. It is expected that the return conductor cryostat will be fabricated using a continuous process and in very long lengths. The return conductor cryostat connects to the external cryo system only infrequently (every 40 km).

Beam vacuum pipes will be pre-installed in the magnets. All vacuum spaces will be pre-evacuated and the NEG pump strip will have been activated.

Magnet factories are skinny long buildings, about 300 m long by 50 m wide. There will be six factories, located next to the six major access tunnels. Magnet parts (iron, pipes, etc.) can be delivered by truck, eliminating the constraint of rail access.

B. Access for Magnet Installation

Magnets can bend on a radius of 200 m for an elongation of 1 part in 2000 for the steel and vacuum chamber. In steel this corresponds to a stress of 10 kpsi, just within the elastic limit of soft iron. In aluminum it will be about 4 kpsi.

For a tunnel 100 m below the surface, a perfectly shaped vertical “S-curve” access tunnel is approximately 350 m long. This shaft is quite steep at the mid-section, nearly 70%, and can only be negotiated by a vehicle moved by rope or other position control. If a friction wheeled vehicle is to be used (e.g. pneumatic tired), then the slope should be held to 5%, and the length becomes approximately 2 km.

For a 50 TeV on 50 TeV machine the circumference is 555 km. The number of magnet accesses comes from balancing the cost of the accesses (and land acquisition) against the cost of buying the magnet movers and operating them. A rough guess compromise might be:

Machine circumference	555 km
# of vehicle accesses:	6

(Note that something like 6 shafts will already be needed for boring machine entry)

Length each access way	2 km

Total access way length	10 km
Maximum magnet trip in tunnel	46 km
Average trip	23 km
Magnet Mover speed	25 km/hr
Average round trip time	1.85 hr
Total # of 250m long magnets	2111

Using just one magnet movers per access, it takes only 651 hours trip time to install all magnets.

This does not count loading/offloading times and other overhead.

This total time is not unreasonable. Even with only a 25% actual travel time, this amounts to 2600 hours, which is just a little over one single-shift year with six crews.

C. How Long should a Magnet be ?

We assume here 250 m long magnets.

Magnet length affects many details of fabrication, installation, and magnet replacement. None of the costs change critically with magnet length.

It is assumed that the magnet conductor and cryostat are assembled in a near-continuous fashion. The iron is delivered in truck-length blocks and assembled at the major access factory sites into a continuous magnet.

Considerations are:

--beam tube vacuum valves at magnet ends (4 valves per magnet at about 2 k$/valve

--cost of rail siding/magnet factories. Building length is proportional to magnet length. Costs include:

HVAC
lighting
worker walking time
hoisting equipment

--magnet production yield/ rework

--magnet warm testing

III. TUNNEL VEHICLES

A. Number of Traffic Lanes in the Tunnel

Each magnet access can support two magnet movers, one heading upstream and one downstream. six accesses can support up to 12 magnet movers without trip interferences. The magnet delivery time is short, as described above. Therefore a single lane in the tunnel is adequate.

B. Tunnel Size and Shape

At the present time the tunnel boring cost has a minimum near 12 to 20 ft diameter. We will assume that the minimum may shift to smaller diameters, and assume a 3 m (9.8 ft) diameter tunnel.

Fig. 1 shows a possible tunnel cross section, complete with a magnet mover. Note that there is no flat floor. A flat floor would add cost. No benefits of a flat floor have been identified.

C. Magnet Mover Design

The magnet mover is a 270m long train. It consists of 25 individually powered cars, each 10 m long, controlled from a personnel car on either end.

All cars are individually powered by batteries, taking advantage of rapid progress in automotive electric battery development. As an example, a one ton total weight passenger car offered for sale now can travel 100 km at 80 km/hr between recharges. The magnet weighs approx. 5 tons per car, travels at 25 km/hr, and needs a range of 100 km. The weight on the return trip would be much less, even when exchanging a magnet (magnet exchange requires two trips or two magnet movers to effect the exchange). We estimate that the battery capacity required for each mover car would equal that of a small passenger car. One would use two such battery packs for redundancy, and to provide ancillary power for lighting and tools. Recharging capability will be available (for other reasons) in the tunnel at 3 km spacings to deal with poor battery conditions or operator error.

The magnet mover supports the magnet once every 5 m, i.e. twice per car. This is the same support spacing as in the tunnel.

Each magnet handler support needs to deal with 2.5 tons, and is designed for 5 ton maximum. Motions are guided by rollers on I-beams and powered through gear motors and chains. Fig. 1 shows the magnet mover in the 3 m tunnel

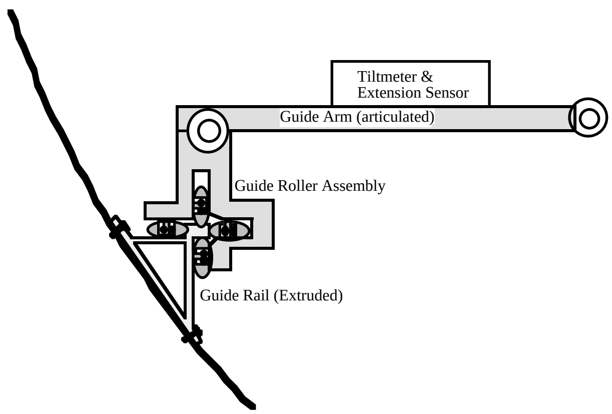
D. Car Design

Vehicle speeds are 25 km/hr maximum. This is a bicycle rider's speed. To protect personnel and equipment the vehicles are guided. Collision protection is visual, by the operator. This is safe since the tunnel is quite straight, with a 720 m line of sight and a time period of 51 sec to approach between two moving vehicles. The operator has a brake time of 25 sec for each vehicle and a minimum brake deceleration of 0.29m/s^2 (0.03 g) with an operator response delay of 2 seconds.

Fig. 1 shows an overall magnet mover car cross section. Passenger cars will have similar wheels and guidance, but a different body design. A passenger car leads and trails each magnet mover train. Small passenger cars may be adaptations of a commercial electric car, equipped with guidance steering.

All cars use the wall mounted extruded aluminum rail for guidance. Guidance is primitive and reliable. Since all turns are quite gentle (200 m is the minimum allowed radius) there is no need to turn wheels or differential gears. A slight side force is enough to "walk" the rubber tired wheels to make them follow the guide rail. This is done by a trolley mounted on an articulating arm at the end of each car (one per car) and an extra one at the front of the train. The trolley simply pushes the cars sideways as needed.

Fig. 2 Guide Rail with Rollers



The trains are controlled from either the leading or trailing passenger car via a multiconductor cable and a computer station. All cars have limited local computing for sensor data acquisition and analysis and local drive motor and positioner control. Drive motion control of cars is adapted from the system used in commercial passenger electric vehicles.

All personnel cars are in constant digital and voice communication with the main control system. Their on-board computer displays all vehicle locations and work activity locations in the tunnel.

1. Passenger Cars

Passenger cars come in three designs, basic work car, personnel protection car ("Pod"), and construction car. Both the basic work car and the pod car can be used to control a magnet mover train.

The basic work car is the equivalent of a large cab pickup truck.

The personnel protection car is used where an additional level of protection is required, e.g. when the magnets are full of cryogens. The personnel protection car has a cab that can be air sealed, and carries compressed breathing air sufficient for 4 person-days of breathing. Oxygen generators may also be used if found advantageous. This car also has extra battery power and a redundant drive system for assured evacuation in either direction (i.e. a range of 92 km).

2. Construction Car

Up until the guide rail is installed, electric vehicles with gravity-referenced guidance. will be used. A tilt sensor controls the wheels to keep the car at the center of the tunnel. Manual guidance can be selected where needed, e.g. on level floor at the factory. These are modified commercial electric cars.

3. Magnet Mover: Motion and Control

The installation motion of the positioners on each car must:

•bring the magnet within the guidance (funnel) range of the stand

•control lifting/lowering/sideways speed at all times to match that of the neighboring cars to avoid excessive loads on the positioner and on the magnet

•be under complete control, including backtracking, at all times

•keep the operator and control program informed at all times of all relevant parameters.

A two-man crew does the positioning. They will not be able to observe all 50 stand locations at all times. The information must be presented to their control computer. Complete remote operation is not a large step beyond this, but appears not to offer huge advantages.

The magnet positioners (2 per car) have lateral and vertical motion capability. To place the magnet accurately the car must know its own position. The lateral car position is given by the guide rail. The guide rail will be surveyed at all stand locations in both horizontal and vertical planes. The guide rail trolley will have some range of compliance. Some crude sensing may be required to measure that extension/ contraction number. The magnet mover car's height above the guide rail is obtained from an inexpensive tilt sensor mounted on the guide arm. Such sensors are now coming into wide use in consumer products. A second tilt sensor measures the transverse "roll" of each car. Knowing the rail coordinates at both guide points and the car's roll, 5 of the 6 coordinates describing the car's position are known. The sixth, displacement along the track, needs to be determined only at one location along the train, e.g. at the magnet interface. The car's computer will use the appropriate calibrations and do the math to relate the sensor outputs to the needed installation motions.

The positioner motion is done by geared stepper motors via chain drives. Positioners are read wrt. the home position which is the storage position while the train is moving. A microswitch indicates that position to the computer. This storage position is along the center of each car. Positions are determined by counting stepper pulses.

The motor currents are monitored for a crude measurement of the both the horizontal and vertical load forces. If this is not sufficiently accurate, strain gauges can be added to the load bearing support rails. The roll sensor of each car can be calibrated to measure the torque exerted by the magnet as it moves away from the storage position. This torque provides an additional consistency check on the load force determination (It also detects tire problems). Note that the car batteries are installed at the radially inward edge of the magnet mover car to act as counter-weights when lifting the magnet.

IV. Tunnel Utilities

A. Tunnel Power

The accelerator system requires electric power for instrumentation, vacuum pumps, and correction magnets. The power requirement will be

• instrumentation 100 W per 250 m module

• ion pump (max. during pumpdown) 20 W per 250 m module

• Correction magnets (currents or motors) 130 W per 250 m half cell average

• pump cart (during installation only) 20 carts * 1000W = 20 kW per 5 km section to be pumped (20 magnets, each 250m long). Rough pumping of magnet interconnects takes only a few hours at the most, so 20 kW per branch circuit is enough.

• Dehumidifier, 6 kW every 3 km

Total power requirement 3 kW/km continuous plus 20 kW per branch circuit initially.

For the 92 km between feeds (46 km max. branch circuit length) we need 170 kW installed power. This is too much power to transmit at 480V/3ø. It will be sensible to use a 7 kV power cable, with a 20 KVA transformer to 208V/3ø at every vertical shaft (3 km). Outlets occur every 250m.

B. Tunnel Air System

The tunnel air system must:

• Assure breathable air

• Warn of and remediate undesirable atmospheres:

Explosive (Methane)

ODH (CO2, cryogens)

Poisonous (CO)

Radioactive (Radon)

• De-humidify the tunnel

The tunnel volume is huge when compared to work crew breathing requirements. Each person requires approx. 50 l/min air. The daily requirement would be 7 m^3, corresponding to 1 m worth of tunnel length.

Undesirable atmospheres drive ventilation requirements. A 0.5 m/s air circulation around the tunnel will be maintained by axial blowers, located at each vertical shaft. Air makeup at a slow rate is done at the 6 major accesses. The purpose of the air circulation is:

• prevent the buildup over long times of local sections with unbreathable or toxic air

• effect air monitoring by placing monitoring stations at the vertical shafts only (3 km separation; 6000 sec sampling delay maximum)

• average out the humidity; this serves to create redundancy and load leveling over the de-humidifiers.

Personnel protection includes several levels, all minimally intrusive to the work environment:

• personnel vehicles have air monitoring and alarms

• personnel vehicles can be sealed and carry breathable air

• air monitors at shafts communicate to personnel vehicles warnings about any abnormal air quality

The air circulation system will require a total power of 500 kW.

C. Legal Considerations

The tunnel is not an OSHA workplace. It is either a mine or a confined space. The protective measures proposed here meet OSHA “confined space” requirements:

• unexposed observer--> monitoring from main control room

• air quality monitoring--> vehicle air monitors, circulating air/ stationary monitors

• constant communication with unexposed observer--> wireless communication in place

• training--> personnel will be trained in any case

(We’ll need to find out more about mine safety techniques and requirements)

D. Tunnel Lighting

There will be no permanent tunnel lighting for most of the tunnel. Personnel will always use electric vehicles which have ample fluorescent (or other efficient) lighting on their roofs, shining up and bathing the tunnel in light sufficient for work. In addition the vehicles will have aimable worklights and bring temporary lighting units, e.g. halogens on tripods for unusual lighting requirements. Vehicle batteries will be adequate for a full shift of work lighting and have safety switches to maintain sufficient charge in the batteries for the return trip.

E. Water Infiltration and Removal

Wherever rock quality allows, the tunnel will remain un-lined. We expect the rock surface to be protected with a tough coating, such as shot-crete, and oversprayed with a white latex paint for reflectivity to improve lighting.

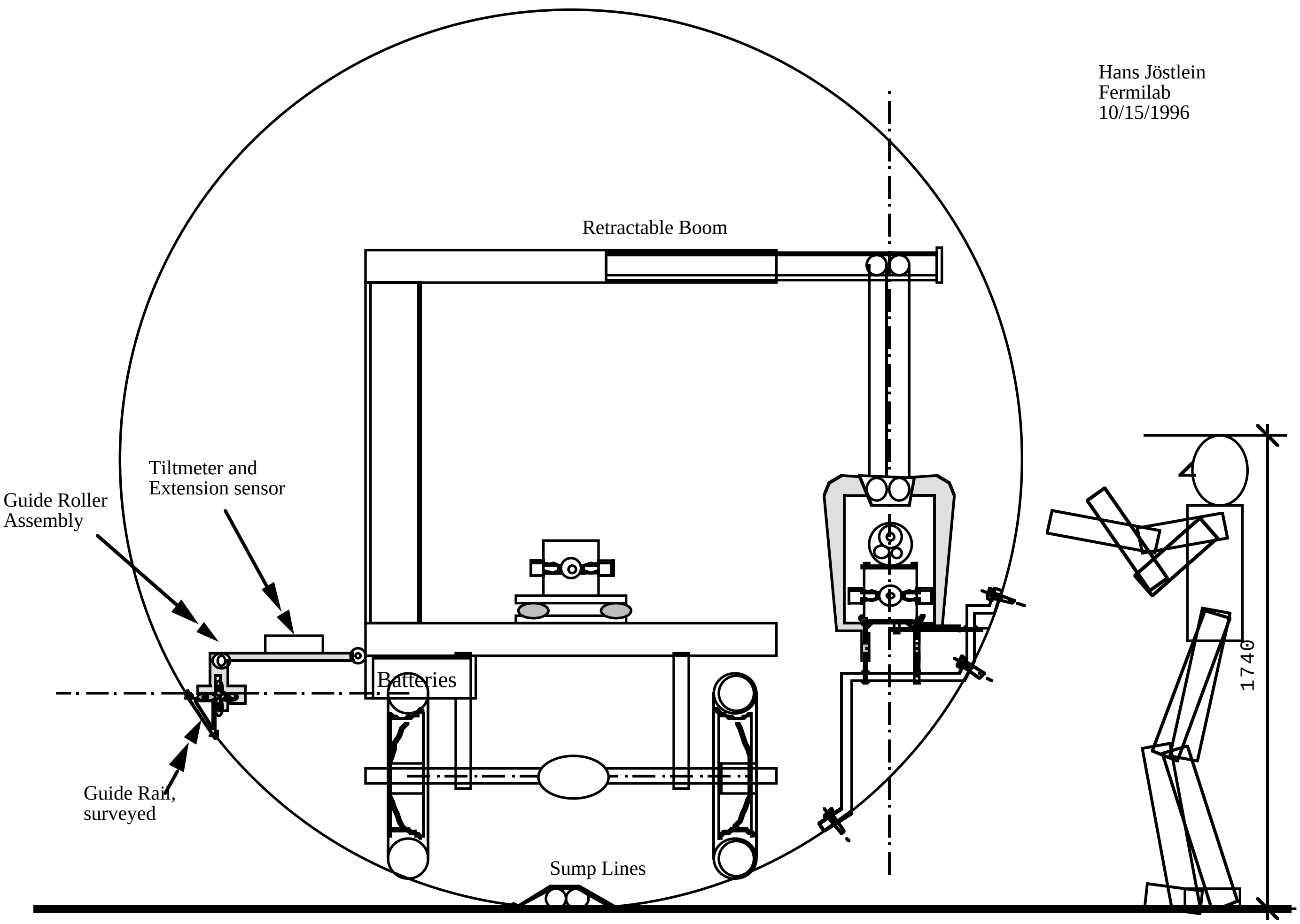
Places with heavy water infiltration will have to be lined. The remaining small water leaks will be tolerated and dealt with by sump pumping. In a round tunnel water typically flows down the walls rather than dripping from the ceiling. There is no flat floor, and the water runs to the bottom of the tunnel. If evaporation from the puddles and run-off “creek” is a concern, an inexpensive cover (such as shown in Fig. 1) can be put in place. Every 250 m there is a sump pump. The sump pump is a standard domestic type submersible pump discharging into a discharge collector pipe that traces the bottom of the tunnel. The pipe is a 3” Sch. 60 PVC pipe. The sump pumps sit in a small hole in the floor, created with a jack hammer right after the tunnel has been bored. Sump pumps are redundant; if one fails, the neighboring pumps take up the load. The discharge collector pipe terminates in a lifting station at each vertical shaft (3 km spacing). where the water is pumped to the surface. Alternatively, at each shaft location a high pressure pump forces water from the local discharge header into a pipe that takes the water to the nearest major access.

V. CONCLUSION

We have explored the consequences of using a tunnel that is accessible to people. We propose ways of installing and aligning magnet stands, and of installing magnets. We also address other tunnel systems such as water removal and air and power systems.

Many of the techniques proposed here are amenable to further automation if that is cost effective. The total manpower identified for the magnet installation is under 100 man-years of largely low-to-medium skilled labor. Any potential manpower reduction appears not to support the engineering effort that would be required to automate such a complex operation, even with the large number of items involved.

We also conclude that the incremental cost of making the tunnel accessible to humans is very modest, essentially limited to providing personnel vehicles, some with personnel protective equipment. It is expected to be well below 1 M$ for the whole project.



Really Large Hadron Collider, Low Field: Tunnel with Magnet Vehicle