Optimal Tunneling for Future Colliders

Part 1: Tunnel Requirements

Wilhelm Bialowons
Deutsches Elektronen-SYnchrotron DESY · Hamburg

July 17, 2001

TESLA campus area.
Overview

- **Introduction**
  - Linear Collider (NLC, TESLA, …)
  - Hadron Collider (VLHC)
  - Muon Collider and Neutrino Factory

- **Tunnel design**
  - Cut-and-cover versus tunnel
  - Single tunnel versus twin tunnel

- **View into the TESLA tunnel**
  - 20 km of superconducting cavities at 2 K
  - Radiation safety

- **Cooling**
  - Water cooling
  - Tunnel ventilation

- **Power distribution**
  - External or in the tunnel

- **Installation**
  - Mono rail or tram

- **Summary**
  - Van Gogh and the high art of yellow

Over view of TESLA

NLC configuration

Injection scheme for the VLHC

A schematic of a neutrino factory.

Different future High Energy Physics projects.
linacs that minimizes the bend angle needed to transport high-energy beams to one of the interaction regions, the high energy IR. The beam delivery system is sufficiently long to allow the high energy IR to be ultimately upgraded to energies in excess of 3 TeV. A synopsis of staging scenarios for the NLC is given in Table 1.1.

**Figure 1.1**: NLC Configuration.
Overview of the TESLA Linear Collider at DESY in Hamburg.
Overall view of the linear collider North-Northwest of DESY.
Site map of the Linear Collider and XFEL at DESY in Hamburg.
Expanded profile of the Linear Collider area North-Northwest of DESY.

‘The interaction point HERA West is about 20 m above sea level. The axis of the main part of the linac tunnel lies about 8 m below sea level. The straight section HERA West has a slope of about 8 mrad out of the horizontal. Therefore there is a smooth transition from the initial slope into the horizontal direction with a bending radius of about 1000 km. The depth of the tunnel below ground level of about 8 m in minimum and 12 m in average is more than sufficient to guarantee shielding against radiation. The tunnel is below the ground water level over nearly the entire length.’
The Very Large Hadron Collider at Fermilab in Illinois.
I. INTRODUCTION

The fascination of the neutrino sector, how it may be explored, and what we might learn in such a venture has been described in the previous Comment by Stephen Geer [1]. The need to adequately address this sector puts new, and interesting, burdens upon the accelerator builder. True, accelerators have, through the years, produced neutrinos and certainly one can imagine ever-more-powerful proton accelerators that, combined with horns, can produce ever-more-powerful neutrino beams. Can one design and build a facility directly oriented to this new need? Would such a device be superior to conventional neutrino beams and would it permit one to address new areas? The answer to both questions is “yes,” and in this Comment I would like to describe what form such a facility, a Neutrino Factory, might take. See Fig. 1 for a schematic of a facility.

![Figure 1: A schematic of a neutrino factory.](image_url)

I will go into some detail, in this Comment, in describing the components of such a facility, the demands upon each component, the required R&D before undertaking construction of such a facility, and the expected performance of a Neutrino Factory. I shall, also, describe possibilities for up-grade in flux and energy.

The concept of a neutrino factory was proposed, in the mid-seventies, independently, by Kushkarev, Wojcicki, and Collins. It
Overview

- **Introduction**
  - Linear Collider (NLC, TESLA, ...)
  - Hadron Collider (VLHC)
  - Muon Collider and Neutrino Factory

- **Tunnel design**
  - Cut-and-cover versus tunnel
  - Single tunnel versus twin tunnel

- **View into the TESLA tunnel**
  - 20 km of superconducting cavities at 2 K
  - Radiation safety

- **Cooling**
  - Water cooling
  - Tunnel ventilation

- **Power distribution**
  - External or in the tunnel

- **Installation**
  - Mono rail or tram

- **Summary**
  - Van Gogh and the high art of yellow

Different Linear Collider tunnels designs.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>TESLA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radio frequency ( f_{\text{rf}} ) /GHz</td>
<td>1.3</td>
</tr>
<tr>
<td>Accelerating gradient ( E ) / MV/m</td>
<td>23.4</td>
</tr>
<tr>
<td>Active cavity length ( L ) / m</td>
<td>1.038</td>
</tr>
<tr>
<td>Rf pulse length ( T ) / ms</td>
<td>1.370</td>
</tr>
<tr>
<td>Repetition rate ( f_{\text{rep}} ) /Hz</td>
<td>5</td>
</tr>
<tr>
<td>Number of bunches ( n_b )</td>
<td>2820</td>
</tr>
<tr>
<td>Charge per bunch ( N_e ) / 10^{10}</td>
<td>2.0</td>
</tr>
<tr>
<td>Bunch spacing ( T_b ) /ns</td>
<td>337</td>
</tr>
<tr>
<td>Peak rf power per cavity ( P_{\text{max}} ) / MW</td>
<td>0.23</td>
</tr>
<tr>
<td>Number of cavities per klystron</td>
<td>36</td>
</tr>
<tr>
<td>Peak rf power per klystron ( P_{\text{max}} ) / MW</td>
<td>8.7</td>
</tr>
<tr>
<td>Average rf power ( P ) / kW</td>
<td>68</td>
</tr>
<tr>
<td>Overall efficiency / %</td>
<td>60</td>
</tr>
<tr>
<td>Power reserve ( P_{\text{max}} / P )</td>
<td>1.1</td>
</tr>
<tr>
<td>Solenoid power ( P ) / kW</td>
<td>4</td>
</tr>
<tr>
<td>Number of klystrons</td>
<td>584</td>
</tr>
<tr>
<td>Klystron lifetime ( T ) / h</td>
<td>40 000</td>
</tr>
<tr>
<td>Klystron failure ( T ) / h</td>
<td>68</td>
</tr>
<tr>
<td>Total beam power ( P_{\text{beam}} ) / MW</td>
<td>22.6</td>
</tr>
<tr>
<td>Total rf power ( P_{\text{rf}} ) / MW</td>
<td>65</td>
</tr>
<tr>
<td>Cooling water ( V_{\text{max}} ) / m^3/h @ deltaT = 50 K</td>
<td>1120</td>
</tr>
</tbody>
</table>

TESLA rf parameters for the \( E_{cm} = 500 \) GeV baseline design.

The machine length includes a 2 \% overhead for energy management. The primary electric power quoted include a 10 \% regulation reserve.
The main tunnel of the TESLA Linear Collider has a minimum inner diameter of 5 m (5.20 m minus construction tolerances). The main components installed in the tunnel are the cryomodules for the superconducting linac and the beam lines for the dog-bone damping rings, for the FEL laboratory and for the ELFE@DESY (Nuclear Physics) option. In addition there are numerous auxiliary components. The cross section is divided vertically into three parts. One third is for sensitive accelerator and beam line components and for the rf distribution. A walk path is located on the outer side for installation and maintenance. The place for the transport system is in the center above the place for components which need easy access. On the bottom the hot and cold water pipes are installed in a small channel; this channel serves for the collection and detection of leakage water. The klystrons, electronics and vacuum pumps are mounted in special containers, the center of mass of which are just below the hook of the transport system. This allows for easy installation and exchange of components with a relative short lifetime. The transport system is a so-called monorail, utilizing an I-beam fixed at the top of the tunnel. The vehicle is used to transport equipment and persons. The last part is the main walk path. The space above the grids is free at all times and the space below is reserved mainly for the cable connection between modulators and klystrons. The free space is for an escape route and for lines-of-sight for optical survey.
Concept for the TESLA tunnel layout.
NLC rf parameters for the $E_{cm} = 500$ GeV baseline design.
Concept for the S-Band double tunnel layout.

The main components installed in the collider tunnels are the S-band accelerating sections mounted on girders, the beam lines for the low emittance and low energy electron and positron beams and the beam lines for the FEL Laboratory and the ELFE@DESY (Nuclear Physics) operation. In addition there are numerous auxiliary components including klystrons and modulators. During beam operation access is necessary to these components. For example the klystrons and modulators have to be repaired quasi continuously due to the large number and their relatively short lifetime. Thus for the S-Band Linear Collider a double tunnel solution was chosen. A small tunnel with an inner diameter of 2.5 m houses the S-band linear accelerator and the beam lines. A larger tunnel with an inner diameter of 4 m houses the auxiliary components. The tunnels are connected every 25 m by pipes of 300 mm inner diameter. The cross section is vertically divided into two parts. One part is for the linear accelerator and the beam lines. The center of mass of an S-band section is just below the hook of the transport system. This allows an easier installation of most of the components. The transport system is a so-called monorail, utilizing an I-beam fixed at the top of the tunnel. The vehicle is used to transport equipment and persons. The other part is the main walk path, which is free at all times for emergency exit and for the lines-of-sight for optical survey. The auxiliary tunnel is divided horizontally and vertically into two parts. The lower part is reserved for cable connections and cooling pipes. The upper part is reserved for the horizontally oriented klystrons, modulators, electronics, power supplies and distribution, the transport system, similar to that in the other tunnel and for the emergency walk path. The two tunnels are connected by pipes housing the wave guides, which connect the klystrons and accelerating structures.
View into the S-Band Linear Collider tunnel.
View into the S-Band Linear Collider tunnel.
Overview

- **Introduction**
  - Linear Collider (NLC, TESLA, …)
  - Hadron Collider (VLHC)
  - Muon Collider and Neutrino Factory

- **Tunnel design**
  - Cut-and-cover versus tunnel
  - Single tunnel versus twin tunnel

- **View into the TESLA tunnel**
  - 20 km of superconducting cavities at 2 K
  - Radiation safety

- **Cooling**
  - Water cooling
  - Tunnel ventilation

- **Power distribution**
  - External or in the tunnel

- **Installation**
  - Mono rail or tram

- **Summary**
  - Van Gogh and the high art of yellow

**Typical geological properties.**

Tunnel layout for the Linear Collider TESLA.
View into the TESLA Linear Collider tunnel.
**TESLA nine cell superconducting cavity.**

<table>
<thead>
<tr>
<th>Subsections</th>
<th>Strings</th>
<th>Modules</th>
<th>Cavities</th>
<th>Klystrons</th>
<th>Length $L$ / m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modules</td>
<td></td>
<td>10</td>
<td>12</td>
<td></td>
<td>16.604</td>
</tr>
<tr>
<td>Strings</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Subsections</td>
<td>12</td>
<td>1 752</td>
<td>21 024</td>
<td>584 (1 168)</td>
<td>29 090.2</td>
</tr>
<tr>
<td>Linacs</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Number of main components for the TESLA linear collider.
View into the TESLA Linear Collider tunnel.

<table>
<thead>
<tr>
<th>Modules</th>
<th>Strings</th>
<th>Modules</th>
<th>Cavities</th>
<th>Klystrons</th>
<th>Length L / m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subsections</td>
<td>Strings</td>
<td>10</td>
<td>12</td>
<td>584 (1 168)</td>
<td>16.604</td>
</tr>
<tr>
<td>1752</td>
<td>21 024</td>
<td>29 090.2</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Number of main components for the TESLA linear collider.
View into the TESLA Linear Collider tunnel.

<table>
<thead>
<tr>
<th>Modules</th>
<th>Strings</th>
<th>Modules</th>
<th>Cavities</th>
<th>Klystrons</th>
<th>Length $L$/m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subsections</td>
<td>12</td>
<td>10</td>
<td>12</td>
<td></td>
<td>16.604</td>
</tr>
<tr>
<td>Strings</td>
<td>1 752</td>
<td>21 024</td>
<td></td>
<td>584 (1 168)</td>
<td>29 090.2</td>
</tr>
</tbody>
</table>

Number of main components for the TESLA linear collider.
Cross section of the TESLA tunnel.

Construction Costs for the TESLA tunnel

<table>
<thead>
<tr>
<th></th>
<th>HERA</th>
<th>TESLA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner tunnel diameter (d / \text{m})</td>
<td>5.2</td>
<td>5.2</td>
</tr>
<tr>
<td>Tunnel length (L / \text{km})</td>
<td>6.236</td>
<td>33</td>
</tr>
<tr>
<td>Normalized price</td>
<td>12 300*</td>
<td>20 000</td>
</tr>
<tr>
<td>(P / \text{DM} / \text{m})</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Price index (P_{2000} / P_{1981})</td>
<td>1.6**</td>
<td></td>
</tr>
</tbody>
</table>

Scaling law: \(P / \text{DM} / \text{m} = 8 500 + 2 500 \ d / \text{m}\)

\(^*\) The tunnel construction costs of HERA were 76.3 Mill. DM with the purchasing power of January 1, 1981. In the HERA-Proposal the cost estimate of the tunnel construction was 92.5 Mill. DM. The total cost estimate was 654 Mill. DM.

\(^{**}\) Statistisches Bundesamt.
4 Project Cost Estimate and Schedule

The costs for the TESLA project are given separately for the 500 GeV electron–positron linear collider, the X-ray Free Electron Laser (incremental cost for accelerator, beam delivery and the X–ray laboratory), and one detector for particle physics. All costs are given in Euro and in year 2000 prices.

4.1 The Linear Collider

The cost for the 500 GeV linear collider baseline design with one interaction region is

- 3136 million EUR.

The cost for the major subsystems is detailed in Fig. 4.1.1, Fig. 4.1.2 and table 4.1.1.

Figure 4.1.1: Distribution of the accelerator sub–systems in percent of the total cost. The costs of the X-ray FEL laboratory and the detector for particle physics are not included here.
Radiation safety of the tunnel

Position of TESLA tunnel and typical geological properties.

**Assumption for a beam loss:**

Linear loss of **100 W/m** (The average cooling power is 3 W/m!).
During **100 h** per year.

This is a relative loss power of **0.1 % at 125 GeV over 56 m!**

For these assumptions one can calculate the doses per year on ground:

<table>
<thead>
<tr>
<th>Distance between tunnel and ground in m</th>
<th>Doses per year in µSv</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimal covering</td>
<td>8.0</td>
</tr>
<tr>
<td>Average covering</td>
<td>14.0</td>
</tr>
<tr>
<td>Natural radiation dose</td>
<td></td>
</tr>
</tbody>
</table>

A power loss of 0.1 W/m over 5000 h/year leads to a value of a factor of 20 less.
View into a TESLA shaft.
Overview

- **Introduction**
  - Linear Collider (NLC, TESLA, …)
  - Hadron Collider (VLHC)
  - Muon Collider and Neutrino Factory

- **Tunnel design**
  - Cut-and-cover versus tunnel
  - Single tunnel versus twin tunnel

- **View into the TESLA tunnel**
  - 20 km of superconducting cavities at 2 K
  - Radiation safety

- **Cooling**
  - Water cooling
  - Tunnel ventilation

- **Power distribution**
  - External or in the tunnel

- **Installation**
  - Mono rail or tram

- **Summary**
  - Van Gogh and the high art of yellow

---

**Cooling and tunnel ventilation considerations.**
keeps the pressure of the return pipe as low as required by some of the RF system components. The diameter of the tubes, installed on the tunnel floor (figure 8.5.4), is 200 mm over the whole length of the linac tunnel. For operation at 500 GeV the pressure in the supply water pipe is approximately 7.5 bar and goes up to 10 bar at 800 GeV.

The temperature of the return water is 70°C. Therefore the return water tube will be insulated with mineral wool of 70 mm thickness, which reduces the heat loss into the tunnel to about 30 W/m. To minimise the mechanical stress in the tubes due to thermal expansion there are compensators in the tubes. Every six metres is a sliding support and between pairs of compensators a fixed support. The last or direct connections to all elements (e.g. magnets, klystrons etc.) are done by EPDM-rubber tubes. The advantages are: resistance against radiation, high flexibility for the connections, quick installation, direct connection between elements at high electrical potential and grounded tubes.

### 8.5.2 Air conditioning

A ventilation and exhaust system is foreseen for each of the 9 halls along the TESLA site (two end stations, 6 service halls, central site), see figure 8.5.5. Each of the tunnel sections between two halls is operated independently and with 100 % fresh air (no recycling). It is also possible to bypass a hall and feed the air from one tunnel sec-
Figure 8.5.5: Overview of the ventilation system.
Cross section of the TESLA tunnel.

Heat properties of air and concrete

<table>
<thead>
<tr>
<th></th>
<th>Air</th>
<th>Concrete</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density / kg / m³</td>
<td>1.128</td>
<td>2 300</td>
</tr>
<tr>
<td>Heat capacity $c_p$ / kJ/kg K</td>
<td>1.01</td>
<td>1.0</td>
</tr>
<tr>
<td>Heat conductivity W / K m</td>
<td>0.5</td>
<td>1.0</td>
</tr>
<tr>
<td>Velocity of air $v$ / m / s</td>
<td>0.5</td>
<td>1.0</td>
</tr>
<tr>
<td>Heat transport / W / K m @ 5 km</td>
<td>2.2</td>
<td>52.3</td>
</tr>
</tbody>
</table>

Temperature stabilization of a tunnel in an aquifer is much easier than of an tunnel in dry bedrock.
Overview

- **Introduction**
  - Linear Collider (NLC, TESLA, …)
  - Hadron Collider (VLHC)
  - Muon Collider and Neutrino Factory

- **Tunnel design**
  - Cut-and-cover versus tunnel
  - Single tunnel versus twin tunnel

- **View into the TESLA tunnel**
  - 20 km of superconducting cavities at 2 K
  - Radiation safety

- **Cooling**
  - Water cooling
  - Tunnel ventilation

- **Power distribution**
  - External or in the tunnel

- **Installation**
  - Mono rail or tram

- **Summary**
  - Van Gogh and the high art of yellow
<table>
<thead>
<tr>
<th>Site</th>
<th>Position $L$/km</th>
<th>Power $S$ / MVA</th>
</tr>
</thead>
<tbody>
<tr>
<td>DESY</td>
<td>0</td>
<td>10.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Modulators 12.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Damping ring 6.0</td>
</tr>
<tr>
<td>Halstenbek-Süd</td>
<td>5</td>
<td>10.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Modulators 12.8</td>
</tr>
<tr>
<td>Halstenbek-Nord</td>
<td>7.5</td>
<td>10.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Modulators 12.8</td>
</tr>
<tr>
<td>Borstel</td>
<td>12.5</td>
<td>10.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Modulators 12.8</td>
</tr>
<tr>
<td>Ellerhoop</td>
<td>16.5</td>
<td>3.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>FEL-Laboratory 3.0</td>
</tr>
<tr>
<td>Bevern</td>
<td>10.5</td>
<td>10.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Modulators 12.8</td>
</tr>
<tr>
<td>Voßloch</td>
<td>25.5</td>
<td>10.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Modulators 12.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Damping ring 6.0</td>
</tr>
<tr>
<td>Bokelseß</td>
<td>30.5</td>
<td>10.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Modulators 12.8</td>
</tr>
<tr>
<td>Westerhorn</td>
<td>33</td>
<td>3.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sum 186.2</td>
</tr>
</tbody>
</table>


Installed electrical power $S$ for the TESLA Linear Collider.

This value includes redundancy but no reactive power ($\cos \phi \approx 1$) and allows for an energy upgrade. The nominal power consumption is $P \approx 140$ MW.
External power distribution for the TESLA Linear Collider.
110 kV power cable in the TESLA tunnel.
Overview

- **Introduction**
  - Linear Collider (NLC, TESLA, ...)
  - Hadron Collider (VLHC)
  - Muon Collider and Neutrino Factory

- **Tunnel design**
  - Cut-and-cover versus tunnel
  - Single tunnel versus twin tunnel

- **View into the TESLA tunnel**
  - 20 km of superconducting cavities at 2 K
  - Radiation safety

- **Cooling**
  - Water cooling
  - Tunnel ventilation

- **Power distribution**
  - External or in the tunnel

- **Installation**
  - Mono rail or tram

- **Summary**
  - Van Gogh and the high art of yellow

Snap shots of Linear Collider installation.
The TESLA is drilled with a tunnel boring machine similar to the HERA machine is constructed by concrete segments called tubbings. The thickness of the concrete tubbings is 30 cm and the shield diameter of the boring machine is 6 m. At HERA the boring speed was 10 m per day in average and 14 m per day in maximum. A tunnel boring machine is running around the clock, five days a week and 250 days a year. At a shaft 283 m³ soil has to be transported per day in average. A truck can transport 15 m³ of soil. About 20 transports per day are necessary. After two years 5 km of tunnel will be finished and the construction site moves to the next shaft. The length of the tubbings is 1.20 m. A ring consists of seven tubbings. And has a weight of 15 t. Eight trucks deliver the concrete segment from a concrete company.
Installation of a TESLA module with a monorail crane.
Installation of a TESLA module with a monorail crane.
Monorail for TESLA.
Installation vehicle for TESLA.
Overview

- **Introduction**
  - Linear Collider (NLC, TESLA, …)
  - Hadron Collider (VLHC)
  - Muon Collider and Neutrino Factory

- **Tunnel design**
  - Cut-and-cover versus tunnel
  - Single tunnel versus twin tunnel

- **View into the TESLA tunnel**
  - 20 km of superconducting cavities at 2 K
  - Radiation safety

- **Cooling**
  - Water cooling
  - Tunnel ventilation

- **Power distribution**
  - External or in the tunnel

- **Installation**
  - Mono rail or tram

- **Summary**
  - Van Gogh and the high art of yellow

---

Mein lieber Theo,


Ganz der Deine

Vincent

---

The high art of yellow (Die hohe Kunst des Gelben).
Overview

- **Introduction**
  - Linear Collider (NLC, TESLA, …)
  - Hadron Collider (VLHC)
  - Muon Collider and Neutrino Factory

- **Tunnel design**
  - Cut-and-cover versus tunnel
  - Single tunnel versus twin tunnel

- **View into the TESLA tunnel**
  - 20 km of superconducting cavities at 2 K
  - Radiation safety

- **Cooling**
  - Water cooling
  - Tunnel ventilation

- **Power distribution**
  - External or in the tunnel

- **Installation**
  - Mono rail or tram

- **Summary**
  - Van Gogh and the high art of yellow

---

Mein lieber Theo,


Ganz der Deine

Vincent

---

Vincent van Gogh: Das Schlafzimmer in Arles, Rijksmuseum Vincent van Gogh, Amsterdam

The high art of yellow (Die hohe Kunst des Gelben).