ILC-Americas Workshop
SLAC October 14-16, 2004

Meeting Towards an International Design of a Linear Collider
In preparation of the First ILC Workshop, KEK Nov 13.15, 2004

The TESLA TDR
Machine Design

Carlo Pagani

INFN Milano and DESY
On leave from University of Milano
From the ITRP Recommendation

- This recommendation is made with the understanding that we are recommending a technology, not a design.

- We expect the final design to be developed by a team drawn from the combined warm and cold linear collider communities, taking full advantage of the experience and expertise of both.
The TESLA Mission

Develop SRF for the future TeV Linear Collider

Basic goals

- Increase gradient by a factor of 5 (Physical limit for Nb at ~ 50 MV/m)
- Reduce cost per MV by a factor 20 (New cryomodule concept and Industrialization)
- Make possible pulsed operation (Combine SRF and mechanical engineering)

Major advantages vs NC Technology

- Higher conversion efficiency: more beam power for less plug power consumption
- Lower RF frequency: relaxed tolerances and smaller emittance dilution
Tesla
The Superconducting Electron-Positron Linear Collider with an Integrated X-Ray Laser Laboratory

Technical Design Report

DESY 2001 – 011 • ECFA 2001 -209
TESLA Report 2001 – 23 • TESLA-FEL 2001 - 05

March 2001
About the TESLA TDR Site

TESLA in the Hamburg area

Interaction Points and X-FEL at Ellerhoop

Ellerhoop more quite than HERA

Ground Motion

Ellerhoop

HERA
# TESLA 500 GeV Parameters

From the TESLA TDR

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accelerating gradient $E_{acc}$ [MV/m]</td>
<td>23.4</td>
</tr>
<tr>
<td>RF-frequency $f_{RF}$ [GHz]</td>
<td>1.3</td>
</tr>
<tr>
<td>Fill factor</td>
<td>0.747</td>
</tr>
<tr>
<td>Total site length $L_{tot}$ [km]</td>
<td>33</td>
</tr>
<tr>
<td>Active length $L_a$ [km]</td>
<td>21.8</td>
</tr>
<tr>
<td>No. of accelerator structures</td>
<td>21024</td>
</tr>
<tr>
<td>No. of klystrons</td>
<td>584</td>
</tr>
<tr>
<td>Klystron peak power [MW]</td>
<td>9.5</td>
</tr>
<tr>
<td>Repetition rate $f_{rep}$ [Hz]</td>
<td>5</td>
</tr>
<tr>
<td>Beam pulse length $T_p$ [$\mu$s]</td>
<td>950</td>
</tr>
<tr>
<td>RF-pulse length $T_{RF}$ [$\mu$s]</td>
<td>1370</td>
</tr>
<tr>
<td>No. of bunches per pulse $n_b$</td>
<td>2820</td>
</tr>
<tr>
<td>Bunch spacing $\Delta t_b$ [ns]</td>
<td>337</td>
</tr>
<tr>
<td>Charge per bunch $N_e$ [$10^{10}$]</td>
<td>2</td>
</tr>
<tr>
<td>Emittance at IP $\gamma\varepsilon_{x,y}$ [$10^{-6}m$]</td>
<td>10, 0.03</td>
</tr>
<tr>
<td>Beta at IP $\beta^*_{x,y}$ [mm]</td>
<td>15, 0.4</td>
</tr>
<tr>
<td>Beam size at IP $\sigma_{x,y}$ [mm]</td>
<td>553, 5</td>
</tr>
<tr>
<td>Bunch length at IP $\sigma_z$ [mm]</td>
<td>0.3</td>
</tr>
<tr>
<td>Beamstrahlung $\delta_B$ [%]</td>
<td>3.2</td>
</tr>
<tr>
<td>Luminosity $L_{x+y}$ [$10^{34}cm^{-2}s^{-1}$]</td>
<td>3.4</td>
</tr>
<tr>
<td>Power per beam $P_b/2$ [MW]</td>
<td>11.3</td>
</tr>
<tr>
<td>Two-linac primary electric power $P_{AC}$ [MW]</td>
<td>97</td>
</tr>
</tbody>
</table>
LCs are pulsed machines to improve efficiency. As a result:

- duty factors are small
- pulse peak powers can be very large
TDR Luminosity vs. cm Energy
All cavities at 35 MV/m

Baseline  ●  no additional cost
Upgrade  ●  more RF & cryogenics

\[ L \left[ 10^{34} \text{ cm}^{-2} \text{s}^{-1} \right] \]

\[ E_{cm} \left[ \text{GeV} \right] \]
Site power: 140 MW
500 GeV baseline

Main Linacs
97MW

RF: 76MW

Cryogenics: 21MW

78%

Beam
22.6MW

60%

Sub-Systems
43MW

Injectors
Damping rings
BDS
Auxiliaries

65%
References for TESLA Technology

**CEBAF at TJNAF**

338 bulk niobium cavities
- Produced by industry
- Processed at TJNAF in a dedicated infrastructure

**LEP II at CERN**

32 bulk niobium cavities
- Limited to 5 MV/m
- Poor material and inclusions

256 sputtered cavities
- Magnetron-sputtering of Nb on Cu
- Completely done by industry
- Field improved with time
  \[ \langle E_{\text{acc}} \rangle = 7.8 \text{ MV/m} \text{ (Cryo-limited)} \]
High Quality Control

- **Use of the best niobium (and copper) allowable in the market at the time**
- **Industrial fabrication of cavity components with high level quality control**
- **Assembly of cavity components by Industry via Electron Beam welding in clean vacuum**
- **Use of ultra pure water for all intermediate rinsing**
- **Use of close loop chemistry with all parameters specified and controlled**
- **Cavity completion in Class 100 Clean Room**
  - Final rinsing and drying (UV for bacteria and on line resistivity control)
  - Integration of cavity ancillaries

That is

**New level on Quality Control**
**Optimized cavity design and rules**

*Major contributions from: CERN, Cornell, DESY, CEA-Saclay*

- **9-cell, 1.3 GHz**

**TESLA cavity parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R/Q$</td>
<td>1036</td>
</tr>
<tr>
<td>$E_{\text{peak}}/E_{\text{acc}}$</td>
<td>2.0</td>
</tr>
<tr>
<td>$B_{\text{peak}}/E_{\text{acc}}$</td>
<td>4.26</td>
</tr>
<tr>
<td>$\Delta f/\Delta l$</td>
<td>315 kHz/mm</td>
</tr>
<tr>
<td>$K_{\text{Lorentz}}$</td>
<td>$\approx -1$ Hz/(MV/m)²</td>
</tr>
</tbody>
</table>

**Preparation Sequence**

- Niobium sheets (RRR=300) are scanned by eddy-currents to detect avoid foreign material inclusions like tantalum and iron.
- Industrial production of full nine-cell cavities:
  - Deep-drawing of subunits (half-cells, etc.) from niobium sheets
  - Chemical preparation for welding, cleanroom preparation
  - Electron-beam welding according to detailed specification
- 800 °C high temperature heat treatment to stress anneal the Nb and to remove hydrogen from the Nb.
- 1400 °C high temperature heat treatment with titanium getter layer to increase the thermal conductivity (RRR=500)
- Cleanroom handling:
  - Chemical etching to remove damage layer and titanium getter layer
  - High pressure water rinsing as final treatment to avoid particle contamination

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A dedicated new infrastructure at DESY

- **Scanning niobium material** for inclusion
- **Clean closed loop chemistry** *(Buffer Chemical Polishing - BCP)*
- **High Pressure Rinsing, HPR, and clean room drying**
- **Clean Room** handling and assembling *(Class 10 and 100)*
Learning curve with BCP

BCP = Buffered Chemical Polishing
3 cavity productions from 4 European industries: Accel, Cerca, Dornier, Zanon

Cornell
1995

5-cell

(a) \( \langle E_{acc} \rangle @ Q_0 \geq 10^{10} \)

at \( Q = \text{few } 10^9 \)

\( \langle 1997 \rangle \)
\( \langle 1999 \rangle \)
\( \langle 2001 \rangle \)

(b) \( \langle E_{acc} \rangle @ Q_0 \geq 10^{10} \)

- Improved welding
- Niobium quality control

Module performance in the TTF LINAC
3rd cavity production with BCP

- Still some field emission at high field
- Q-drop above 20 MV/m not cured yet
- Just AC67 discarded (cold He leak)

TESLA original goal

Vertical CW tests of naked cavities
Electro-Polishing & Baking for 35 MV/m

The AC 70 example

**Electro-Polishing (EP)**
- instead of Buffered Chemical Polishing (BCP)
- less local field enhancement
- High Pressure Rinsing more effective
- Field Emission onset at higher field

**In Situ Baking**
- @ 120-140 °C for 24-48 hours
  - to re-distribute oxygen at the surface
  - cures Q drop at high field

**Electro-Polishing & Baking**
- Low Field Emission
- 800°C annealing
- 120°C, 24 h, Baking
  - high field Q drop cured
- High Pressure Water Rinsing

*Vertical and System Test in 1/8th Cryomodule*
Field Emission pushed to very high field

BCP Cavities used in Modules 4 & 5 are in red, EP cavities in blue

Radiation Dose from the fully equipped cavities while High Power Tested in “Chechia”
“Chechia” is the horizontal cryostat equivalent to 1/8 of a TTF Module

Radiation dose producing 50 nA of captured Dark Current: that is the TESLA safe limit giving 200 mW of induced cryo-losses at 2 K

BCP Cavities @ $E_{acc} = 25$ MV/m

EP Cavities @ $E_{acc} = 35$ MV/m

BCP = Buffered Chemical Polishing
EP = Electro-Polishing

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October 14, 2004
Successful Compensation @ 35 MV/m

Cavity detuning induced by Lorentz force during the tests performed in Chechia at TESLA-800 specs

- Piezo-compensation on: just feed-forward resonant compensation
- Piezo-compensation off
**The 35MV/m Cryomodule Test**

**AC72**: one of five high-performance EP cavities

Acceptance test in vertical cryostat

Transferred to

Full 1/8th CM horizontal test (CHECHIA)

- HP coupler
- Tuner (fast/slow)
- full power (system) test

35MV/m

5 \times 10^9
**The 35MV/m Cryomodule Test**

**AC72**: one of five high-performance EP cavities

- Acceptance test in vertical cryostat
- Transferred to
- Full 1/8\(^{th}\) CM horizontal test (CHECHIA)
- Transferred to
- Full 8 cavity Cryomodule
The 35MV/m Cryomodule Test

RF measurements showed no degradation of performance (35MV/m achieved)

RF gradient measurement calibrated using beam (energy spectrometer)

No measurable radiation detected (no dark current)

RF pulse with feedback in cavity 5 (AC72) during beam acceleration

No time for long-term system test due to TTF-II commissioning, but...

35 MV/m EP TESLA Cavity accelerates beam for the first time
Performing Cryomodules

Three generations of the cryomodule design, with improving simplicity and performances, while decreasing costs

Cryomodule Characteristics

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>12 m</td>
</tr>
<tr>
<td># cavities</td>
<td>8</td>
</tr>
<tr>
<td># doublets</td>
<td>1</td>
</tr>
<tr>
<td>Static Losses @ 2 K</td>
<td>1.5 W</td>
</tr>
<tr>
<td>@ 5 K</td>
<td>8 W</td>
</tr>
<tr>
<td>@ 50 K</td>
<td>70 W</td>
</tr>
<tr>
<td>Required plug power</td>
<td>&lt; 6 kW</td>
</tr>
</tbody>
</table>

Sliding Fixtures @ 2 K

“Finger Welded” Shields

Reliable Alignment Strategy
The assembly of a string of 8 cavities

- is a standard procedure
- is done by technicians from the TESLA Collaboration
- is well documented using the cavity database as well as an Engineering Data Management System
- was the basis for two industrial studies.

Technology transfer of the complete established procedure to industry ready for the EU X-FEL.
The module assembly is a well defined and standard procedure.

- experience of 10 modules exists
- the latest generation (type III) will be used for series production (XFEL requires 120 modules)
- several cryogenic cycles as well as long time operation were studied
- the assembly problems occurred are well understood and cured
## TTF Module Installation

<table>
<thead>
<tr>
<th>Module</th>
<th>Installation Date</th>
<th>Cold Time / Months</th>
</tr>
</thead>
<tbody>
<tr>
<td>CryoCap</td>
<td>Oct 96</td>
<td>50</td>
</tr>
<tr>
<td>M1</td>
<td>Mar 97</td>
<td>5</td>
</tr>
<tr>
<td>M1 rep.</td>
<td>Jan 98</td>
<td>12</td>
</tr>
<tr>
<td>M2</td>
<td>Sep 98</td>
<td>44</td>
</tr>
<tr>
<td>M3</td>
<td>Jun 99</td>
<td>35</td>
</tr>
<tr>
<td>M1*</td>
<td>Jun 02</td>
<td>14</td>
</tr>
<tr>
<td>MSS</td>
<td></td>
<td>8</td>
</tr>
<tr>
<td>M3*</td>
<td>Apr 03</td>
<td>3</td>
</tr>
<tr>
<td>M4</td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>M5</td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>M2*</td>
<td>Feb 04</td>
<td></td>
</tr>
</tbody>
</table>
LCH and TESLA Module Comparison

From an LHC Status Report by Lyndon R. Evans
The TTF III Power Coupler

- TTF III Coupler has a robust and reliable design.
- Extensively power tested with significant margin
- New Coupler Test Stand at LAL, Orsay

|                           | frequency | 1.3 GHz
|---------------------------|-----------|----------|
|                           | operation | pulsed: 500 µsec rise time, 800 µsec flat top with beam
| two windows, TiN coated   |           | safe operation, clean cavity assembly for high Eacc
| 2 K heat load             | 0.06 W    |
| 4 K heat load             | 0.5 W     |
| 70 K heat load            | 6 W       |
| isolated inner conductor  | bias voltage, suppressing multipacting |
| diagnostic                | sufficient for safe operation and monitoring |

10 + 30 New Couplers in construction by industry
TESLA Tuners

TTF / X-FEL Tuner

Successfully operated with superstructures
Piezo-tuner integration still pending

TESLA Blade-Tuner
THE TESLA RF Unit

1 klystron for 3 accelerating modules, 12 nine-cell cavities each
LLRF performance in TTF

Principle of RF Control

Operation with Final State Machine

Contributions to Energy Fluctuations

1. Lorentz Force
2. Microphonics
3. Bunch-to-Bunch Charge Fluctuations
4. Calibration error of the vector-sum
5. Phase noise from master oscillator
6. Non-linearity of field detector
7. Klystron Saturation
8. RF curvature (finite bunch length)
9. Wakefield and HOMs

microphonics

Lorentz Force Detuning

Adaptive Feedforward

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LLRF: Operation Example
Phase Adjustment Using Beam Transients

before adjustment

after adjustment

RF vectors during 800 $\mu$s flat top
Multi Beam Klystrons

Three **Thales** TH1801 Multi Beam Klystrons produced and tested

Independent beam design proposed and built by **CPI**. Prototype on test.

**Achieved efficiency** 65%
**RF pulse width** 1.5 ms
**Repetition rate** 5 Hz
**Operation experience** > 5000 h
10% of operation time at full spec's

**A new design proposed by Toshiba looks robust and should reach 75% efficiency**
First prototype under test - Cathode loading < 2.1 A/cm²
Modulators are not a concern

FNAL Modulator at TTF

- 10 Modulators have been built, 3 by FNAL and 7 by industry
- 7 modulators are in operation
- 10 years operation experience

- Work towards a more cost efficient and effective design started
- Hazardous components minimized
- Most components are standard
- Industry is ready to built turn key modulators fulfilling the specs

HVPS and Pulse Forming Unit

Pulse Transformer
RF Waveguide Components

All standard components - Technology well established - Produced by Industry

3 Stub Tuner (IHEP, Beijing, China)

Peak Power = 2 MW

E and H Bends (Spinner)

Peak Power = 0.4 MW

Circulator (Ferrite)

Peak Power = 0.4 MW

Hybrid Coupler (RFT, Spinner)

RF Load (Ferrite)

Peak Power = 5 MW

RF Load (Ferrite)

Peak Power = 5 MW

Peak Power = 1 MW
RF Distribution of Module # 4
The TTF I Linac – 6 Year exp.

- **e⁻ beam diagnostics**
- **undulator**
- **bunch compressor**
- **superconducting accelerator modules**
- **pre-accelerator**
- **laser driven electron gun**

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- **240 MeV**
- **120 MeV**
- **16 MeV**
- **4 MeV**

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**He gas return pipe**
- **beam position monitor**
- **quadrupole package**

**module length 12.2 m**

**input coupler**
TTF II under Commissioning

VUV FEL User Facility

- Linac Commissioning under way
- SASE FEL Commissioning by September this year
X-FEL coming soon

- 50% funded by the German Government - European consensus being established
- **Great opportunity for ILC**
  - Machine reliability according to SRL standards
  - Industrial mass production of cavities (~1000) and modules (>120)
Electron Sources

TDR design has two polarised RF guns
**Positron Source**

- Photons ($\gamma$) produced in undulator by the high energy electron beam upstream of BDS and IR
- Option for polarised $e^+$ with s.c. helical undulator
- Thin target converts $\gamma$ to positrons
- High energy electrons ($> 150$ GeV) required for positron beam
Positron Source

**Advantages**

- significantly reduced power deposition in thin target (~5 kW)
- smaller emittance beam produced
  - less multiple coulomb scattering
  - reduced acceptance requirements for DR
    - no pre-DR foreseen
- much cheaper / less complex than equivalent ‘conventional source’ for TESLA
- Naturally allows upgrade to polarised $e^+$ source

**Disadvantages**

- Requires e-linac with $\geq 150$ GeV
  - TDR solution to use main e-linac
  - coupling e- to e+ production raises questions of
    - operability
    - reliability
    - commissioning strategy
- Never been done before
  - although physics is well understood!
  - E166 experiment at SLAC
Machine Overview - 2

Damping Rings

Beam Delivery System (BDS)

33 km
TESLA TDR Damping Rings

- TESLA bunch train $2820 \times 337 \text{ ns} = 950 \text{ ms}$
  $\Rightarrow 285 \text{ km long}$

- Extract every bunch separately, bunch spacing given by shortest kicker rise/fall time
  $\Rightarrow 20 \text{ ns} \times 2820 \approx 56 \text{ ms} \Rightarrow 17 \text{ km long}$

- Save tunnel cost: DR in main linac tunnel and short return arcs
  $\Rightarrow \text{dogbone}$

Kicker Specs

- 2820 pulses with 3 MHz repetition rate
- 5 Hz repetition rate of macro-pulse

Ripple: $0.05\%$

$0.6 \text{ mrad} \pm 0.05\%$

$0.01 \text{ Tm}$
Dogbone DR Concept

- Need ~ 450m of wiggler for the required 28 ms damping time
  - \( \int B^2dl = 605 \text{T}^2\text{m} \)
  - Permanent Magnet Wiggler with \( B_{\text{max}} = 1.6 \text{T}, \lambda = 0.4 \text{ m} \)
  - Radiated Power (160 mA) over 450 m: 3 MW
- Time varying stray fields at linac beam pulse could be an issue (> 1 mT measured)
TDR Ring-to-Linac (RTL)

- Spin Rotator
- RF wiggler
- Bunch Compressor
- Diagnostics (emittance measurement)
• 1st IP has no crossing angle
• 2nd (optional) IP has crossing angle of 34 mrad for $\gamma - \gamma$ option
• FFS not based on FFTB/SLC design (later reviewed)
Fast Extraction

'single bunch delay' should be achievable

![Diagram showing beam axis and extraction parameters]
Luminosity Stability

- Ground motion
  - vibration; slow drifts
- Fast Intra-Train Feedback
  - beam-beam collision feedback
- Effect of slow drifts
  - Importance of orbit control (BDS: critical)
- High-Disruption Regime
  - beam-beam kink instability makes TESLA 'sensitive'

Brinkmann, Napoly, Schulte, TESLA-01-16
Single Tunnel layout

Tunnel Layout as in the TDR

Reviewed version
TESLA 500 Cost Estimate – 1 IP

3,136 M€ (year 2000 - no contingency) + ~ 7,000 persons · years
Conclusions

- According to his Mission, the TESLA Collaboration improved the SRF Cold Technology up to the level required to be chosen by the ITRP as the preferred technology for the ILC.

- Working prototypes of most of the subsystems have been developed and successfully tested.

- Industry can produce all the components according to specs, and at a price that is under control. Good and well understood specs are increasing the number of possible vendors: Competition.

- Machine design end parameters must be reviewed on the basis of the existing cold technology, its real potentialities and risks.
Conclusions

- The two major advantages of the COLD technology are:
  - The frequency
  - The high conversion efficiency

- At the level of design, construction and qualification of a few complete accelerating modules, TESLA Collaboration did great.

- Working prototypes of most of the subsystems have been developed and successfully tested.

- Final ILC design must reconsider some of the “Historical” parameters, eventually finding a new optimization

- Re-invent or just improve hot water is quite dangerous

- Reliability and availability analysis set up by Tom must be extended and used as a basis for design choices.