International Linear Collider Reference Design Report

DESY-Seminar
Deutsches Elektronen-Synchrotron DESY
Hamburg und Zeuthen · June 19 & 20, 2007

Wilhelm Bialowons and Lutz Lilje · DESY & GDE

Outline (1)

- Introduction
- Machine Requirements
  - Overall Layout
  - Parameters
- Electron Source
- Positron Source
- Damping Rings
  - Kicker Systems
  - Electron Cloud and Fast Ion Instability
- Ring to Main Linac
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  - Cavities
  - Modulator
  - Klystron
  - Cryogenic System
- Beam Delivery system
- Value Estimate
- Summary and Outlook
ILC Reference Design Report

~700 Contributors from 84 Institutes

http://www.linearcollider.org
What’s RDR

• Conceptual design report
• With first-stage cost (value, labor) estimation
• Engineering details not yet contained
• Not all based on the present technology
  – Forward-looking
  – R&D needed

• History
  – BCD (Baseline Configuration Document) published in December 2005 at Frascati meeting
  – Rules for cost estimation established in March 2006 at Bangalore meeting
  – First cost compilation in July 2006 at Vancouver meeting
    • Cost reduction effort started
  – RDR draft published in February 2007 at Beijing meeting
Machine Requirements

• Center-of-Mass Energy up to 500 GeV
  – upgradeable to 1 TeV.

• Integrated luminosity in the first 4 years
  > 500 fb\(^{-1}\) (500 GeV equivalent)
  – This corresponds to the peak luminosity
  \(\sim 2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}\)
    • taking into account the availability and buildup of luminosity
      after construction.

• Ability of energy scan in 200-500 GeV
1st Stage: 500 GeV

Schematic Layout of the 500 GeV Machine
## Basic Global Parameters

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<thead>
<tr>
<th>Parameter</th>
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<td>Max. Center-of-mass energy</td>
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<td>GeV</td>
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<tr>
<td>Peak Luminosity</td>
<td>$\sim 2 \times 10^{34}$</td>
<td>cm$^{-2}$s$^{-1}$</td>
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<td>Beam Current</td>
<td>9.0</td>
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<td>Repetition rate</td>
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<td>Average accelerating gradient</td>
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<td>Beam pulse length</td>
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<td>Total Site Length</td>
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<td>Total AC Power Consumption</td>
<td>$\sim 230$</td>
<td>MW</td>
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## Beam Parameters for 500 GeV cms

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<th>Nominal</th>
<th>Low Q</th>
<th>Large Y</th>
<th>Low P</th>
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<td>Number of Particles</td>
<td>2</td>
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<td>Number of bunches</td>
<td>2625</td>
<td>5120</td>
<td>2625</td>
<td>1320</td>
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<tr>
<td>Bunch interval (buckets)</td>
<td>369(480)</td>
<td>189(246)</td>
<td>369(480)</td>
<td>480(624)</td>
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<tr>
<td>Average current</td>
<td>9.0</td>
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<td>6.8</td>
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<td>Norm.emittance at IP x/y</td>
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<td>10/0.03</td>
<td>10/0.08</td>
<td>10(0.036)</td>
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<td>Rms beamsize at IP x/y</td>
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<tr>
<td>Rms bunch length</td>
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<td># of photons of beamstr.</td>
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Range of Parameters

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<td>Linac bunch interval</td>
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<td>Beta at IP (y)</td>
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<td>0.4</td>
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Electron Source

• Requirements
  – Beam structure
    • ~2600 bunches, ~1 ms, $2 \times 10^{10}$ at DR
    • >80 % polarization

• Polarized e- gun
  – Used in SLC for many years
  – Improvements since then
  – Laser for long pulse needed

• Acceleration
  – NC up to 76 MeV
  – SC to 5 GeV
Electron Source System

- Damping Ring
- Energy Compression
- Spin Rotation
- SC e⁻ LINAC (5.0 GeV)
- SC tune-up dump (311 kW)
- 8 x 10 MW
- NC tune-up dump (11.3 kW)
- L-band (β = 0.75)
- TW Bunching and Pre-Acceleration
- Energy Collimation (Vertical Chicane)
- Faraday Cup and Mott Polarimeter (13.5 kW)
- 433.3 MHz
- 216.7 MHz
- SHB
- DC Gun (2x)
- Drive Laser (above Ground)

- 3.2 nC
- 76 MeV - 5.0 GeV
- 5 nC
- 140 keV - 76 MeV
Positron Source

• 3 possible positron generation schemes have been proposed
  A) Standard method: a few GeV electron on target
  B) Undulator scheme: use photons from >100 GeV electron through undulator
  C) Compton scheme: use photons from a few GeV electron through laser-Compton scattering

• B) has been selected as the baseline
  – C) is immature
  – Cost saving by A) is not significant. Physics descoping (no positron polarization)
Positron Source

- **Undulator scheme**
  - Electron beam at 150 GeV

- **Undulator**
  - Helical, superconducting
  - Length 147 m (longer for polarized e+)
    - $K = 0.92$, $\lambda = 1.15 \text{ cm}$, $B = 0.86 \text{ T}$
  - Needs ‘keep-alive source’
    - 10% intensity
    - Share 5 GeV linac
Positron Source R&D items

- **Undulator fabrication**
  - Superconducting
  - Helical
  - pitch 1.15 cm
  - K=0.92 (0.86 T)
  - beam aperture 5.85 mm

- **Target**
  - titanium alloy
  - diameter 1 m, 1.4 cm thick
  - rotating at 100 m/s
  - Eddy current heating if in magnetic field

- **Target region design**
  - quick replacement
    - Redundant target-capture section in the previous design was eliminated for cost reduction
Damping Rings

• Roles
  – Reduce transverse/longitudinal emittances
  – Beam stabilization

• Possible choices
  – Dog-bone
  – (nearly) Circular: ~3 km, ~6 km

• Baseline
  – 6.7 km circular ring
  – One for e+ and one for e-
Damping Ring Location

- Large cost savings since the original BCD
- $1e^{-}$ and $2e^{+} \rightarrow 1e^{-}$ and $1e^{+}$
  - Progress in the electron-cloud problem
- Central injector system
  - Common tunnel for $e^{+}$/e$^{-}$, though transport to main linacs is longer

Now \(\rightarrow\)

\(\leftarrow\) March 2006
DR Remaining Issues

• Injection/extraction kickers
• Instabilities
  – Electron-cloud, Fast Ion, microwave, …
• Dynamic aperture
• Tuning for low emittance

Task Force S3 has been established for DR R&D

• Defining work packages
• Available machines
  – KEK-ATF
  – KEKB, CESR, HERA
Kicker System

- Must extract bunches one-by-one
  - bunch to be extracted next
  - kicker magnetic field
  - position extracted already

- Specification
  - rise, fall time < 3 ns
  - rep.rate 5.5 MHz
  - pulse length 1ms
  - stability < 0.1 %
    - can be relaxed by feedforward
- Fast kicker needed
  - A system with fast pulser and stripline developed at KEK.
  - Unit test done.
Electron Cloud

- Secondary electrons attracted by positron beam causes an instability
- Max. of Secondary Electron Yield (SEY) should be < 1.1
- Possible cures
  - Coating with NEG
  - Solenoids in free field region
  - Grooves on the chamber wall
  - Clearing electrode
RTML (Ring To Main Linac)

Roles

• Transport from DR to Main Linac
• Bunch length compression
  – ~9mm $\rightarrow$ 200 to 300 $\mu$m
• Collimation
• Feed-forward
  – Eliminate beam oscillation from upstream
    • e.g. from DR kicker
• Spin rotation (vertical $\rightarrow$ horizontal)
• Diagnostics
RTML

- ~14 km long transport
- Turn-around
  - needed also for feed-forward
- Spin Rotator
- Bunch compressor in 2 stages
  - 9mm → 300μm (nominal parameters)
  - 9mm → 200μm possible (Low Q parameters)
- Diagnostics and collimators
Main Linac Layout

- Length ~11 km x 2
- Average gradient 31.5 MV/m
- 2 tunnels diameter 4.5 m
Main Linac RF Unit Overview

- Bouncer type modulator
- Multibeam klystron (10 MW, 1.6 ms)
- 3 Cryostats (9+8+9 = 26 cavities)
- 1 Quadrupole at the center
Cavities

- **Baseline: TESLA-type 1.3 GHz**
  - Identical to XFEL cavities
    - Only beamtubes shortened
- **Accelerating gradient**
  - Vertical test
    - $>35 \text{ MV/m, } Q>0.8\times10^{10}$
  - Average gradient in cryomodule
    - $31.5 \text{ MV/m, } Q>1\times10^{10}$
- **With the presently available technology**
  - Average gradient lower than $31.5$ MV/m
  - Spread of gradient large
  - If uniform distribution in $22<G<34$ MV/m, average 28 MV/m
    - Cost increase $\sim 7\%$
High Gradient Reproducibility: S0 S1 Program

- Task Force created and R&D program set up
- S0: establish 35 MV/m in low power tests
  - Single-cell program
    - optimise final surface preparation (e.g. short electr polishing, alcohol rinse, ultrasound grease)
  - Tight-loop process
    - repeated surface treatment with small number of cavities including exchange of cavities among Asia-US-Europe in 2007
  - Production-like process
    - Many cavities with the same recipe
    - Large data set is (will be) available from the XFEL project
      - experience with TTF and FLASH
      - pre-production runs
        » includes industrialisation e.g. Electropolishing at Industry
- Time line
  - Establish high yield well before EDR
- S1: Establishing 31.5 MV/m operational in accelerator modules
K. Saito et al.

(A) CBP+CP+Anneal+EP(80µm) +HPR+Baking(120°C*48hrs)

Ave. $E_{acc}=39.1\pm8.2\,\text{MV/m}$
Scattering: 20%, Acceptability@40MV/m(ACD): 50%

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<th>IS#4</th>
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<td>$E_{acc}$</td>
<td>36.90</td>
<td>31.40</td>
<td>45.10</td>
<td>44.20</td>
<td>48.80</td>
<td>28.30</td>
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<tr>
<td>$Q_0$</td>
<td>1.53e10</td>
<td>8.66e9</td>
<td>9.07e9</td>
<td>5.38e9</td>
<td>9.64e9</td>
<td>1.94e9</td>
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</table>
(D) + EP(20μm) + EP(3μm, fresh, closed) + HF* + HPR + Baking (120°C*48hrs)

Ave. Eacc = 46.7 ± 1.9 MV/m
Scattering: 4%, Acceptability @ 40 MV/m (ACD): 100%

<table>
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<td>Eacc</td>
<td>47.07</td>
<td>44.67*</td>
<td>47.82</td>
<td>48.60*</td>
<td>43.93*</td>
<td>47.90*</td>
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<tr>
<td>Qo</td>
<td>1.06e10</td>
<td>0.98e10</td>
<td>0.78e10</td>
<td>0.80e10</td>
<td>1.17e10</td>
<td>1.0e10</td>
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</table>
‘Qualified’ Vendor Productions: Best Test Results

Average Gradient [MV/m]

- Best
- Best $10^{10}$
- Best FE

Cavity batch

DESY 1st BCP 1400
DESY 2nd BCP 1400
DESY 3rd BCP 1400
DESY 3rd EP+everything
DESY 4 EP
US 1st EP
S1 RF Performance: Compare Acceptance Test with Module Operational Accelerating Gradient

- This is the main motivation for S1
- Improvement on assembly procedures needed
  - Addressed in studies with industry also
XFEL assets: Module Test at DESY

- High gradient modules have been assembled
  - For installation in FLASH
- Test in dedicated test stand possible e.g.
  - Cavity performance
  - Thermal cycles
  - Heat loads
  - Coupler conditioning
  - Fast tuner performance
  - (LLRF tests)
- Part of the ongoing preparation work for XFEL
E.G. CMTB Module 6: 11 cool downs

R. Lange
Alternatives:

• LL-type cavity
  – Lower max. magnetic field at same accelerating gradient
    • Potentially higher gradient > 40 MV/m
  – Under development at KEK and JLab
    • Single-cell test successful with max. over 50MV/m
    • But 9-cell cavities are still poor with max. 29MV/m without HOMs

• Nb material: Large grain
  – Started at JLab
  – Single-cells
    • comparable performance to standard material
  – Full nine-cells fabricated XFEL preparation phase
    • so far only etched (BCP)
    • EP underway
Large Grain Material: EP and BCP

Q₀

1E+11
1E+10
1E+9
1E+8

Eacc [MV/m]

0  5  10  15  20  25  30  35  40  45

1AC3 04.Jan.06 2K bd
1AC4 08.Jun.06 2K bd
1AC3 12.Jul.06 2K bd
1AC4 06.Sep.06 2K bd

Heraeus - EP

BCP

D. Reschke et al.
Modulator

• Baseline
  – Bouncer-type modulator
    • Design at FNAL
      – Has been working for >10 years at TTF at DESY
      – No major technical issues
      – XFEL choice
  – Design improvements (within XFEL industrialisation)
    • More cost-efficient design under way
    • Redundancy of internal components for higher availability

• Alternative:
  – Marx Modulator
    • Under development at SLAC
    • Smaller size
    • No step-up transformer
    • Potentially high cost saving
Klystrons

• Requirements:
  – 10 MW
  – 1.6 ms
  – 5 Hz
  – lifetime for full power >40000 hrs
• Baseline solution: Multi-beam klystron
  – Use multiple beams of low charge
  – Lower space-charge effects
  – Lower voltage (120 kV)
  – Higher efficiency (~65 %)
• Prototypes from 3 manufacturers for the European XFEL (higher repetition rate: 10 Hz)
  – Thales and Toshiba MBKs being successfully tested at DESY at full spec
    • for > 1000 hrs
    • Several klystrons under varying operating conditions at FLASH, PITZ and test stand
• Horizontally mounted klystron needed for small tunnel diameter
  – XFEL develops this with industry
• More lifetime testing going on (eventually also at SLAC)
  – At DESY all tubes which are now in operation do not show signs of degradation
    (no arcing, no perveance drops)
RF Distribution

- 2 outputs from klystron → 2 waveguides of ~10 m long to the other tunnel
- Hybrid splitter (ratio 4:9)
- tap-offs (power fraction to individual cavities)
- circulator (protection against reflected power)
- 3-stub tuner (phase and coupling adjustment)
- Total power loss ~6.5%
- Other design to replace circulator and 3-stub tuner is underway for lower cost and lower power loss
Alternative RF distribution for XFEL
(V. Katalev, S. Choroba)

• Less parts, less space consuming
  – to be tested in FLASH ACC6 soon
Cryogenics System

- 1 cryogenic plant covers 2.5km linac length.
  - Installed power ~4.5MW
- Total 10 plants
  - ~45MW
  - comparable to LHC cryogenics system
BDS (Beam Delivery System)

- From main linac exit to IP (Interaction Point) and to the beam dump
- Roles of BDS
  - Focus the beam to the desired spot size for collision
  - Remove beam-halo to minimize the background events
  - Protect the beamline and detectors against mis-steered beam
  - Diagnostics of the linac beam
  - Safely dump the spent beams
Cost Savings in BDS

- 2IP with crossing angle 20 and 2mrad
  ➔ 2IP with crossing angle 14 and 14mrad
  (small angle scheme in the present design turned out to be significantly expensive)
  ➔ 1IP with crossing angle 14mrad with push-pull detector
- Remove 2nd muon wall
BDS (Beam Delivery System)

- Single IR and push-pull detector
- Total length 4.45 km
- 1 TeV upgrade by inserting some components (no geometry change)
Single IR with Push-Pull Detectors

• Large cost savings compared with 2 IR
  – ~200 M$ compared with 2IR with crossing angles 14 + 14 mrad

• Push-pull detectors
  – Task force from WWS and GDE formed
  – Conclusion is
    • No show-stoppers
    • But need careful design and R&D works
    • 2IR should be left as an `Alternative’
Layout of BDS+DR

Elevation different between DR and BDS is \(~10\) m
Value Estimate

• From Bangalore to Beijing
  – LCWS06 Bangalore, March 9 to 13, 2006
    Value Estimate and Costing Rules
  – VLCW06 Vancouver, July 19 to 22, 2006
    First Cost Estimate
  – ILC06 Valencia, November 6 to 10, 2006
    Cost Reduction
  – BILCW07 Beijing, February 4 to 7, 2007
    Release of Draft Reference Design Report with Reliable Costs
Costing Rules

One common estimate of the “value” and labor including site dependent cost is made. The definition of the “value” is:

1. Cost estimate of the construction cost but no preparation cost.
2. Cost estimate on the basis of a world wide call for tender, i.e. the value of an item is the world market price if it exists.
3. The selection criterion is the best price for the best quality. \textit{value is world market price if exists}
4. One vendor supplies the total number of deliverables. Two vendors for the same package could be chosen for risk minimization. Then the parts depend on the bids.
5. If necessary parametric cost estimate is used for scaling of the cost, i.e. for cost improvement. The cost improvement is defined by the following equation:

   \[ P = P_1 N^a \]

   where \( P \) is the total price of \( N \) units, \( P_1 \) is the first unit price and \( a \) the slope of the curve related to learning. The slope \( a \) is for large \( N \) also the ratio of the last unit price \( P_N \) and the average unit price \(<P>\).

6. No tax is included.
7. No escalation is used. The fixed date is January 2, 2007.
8. No contingency is calculated. The risk will be analyzed separately.
9. One currency with fixed exchange rates is used. The fixed exchange rates are:

   \[ 1 \text{ M€} = 1.2 \text{ M$} = 1.4 \text{ Oku¥} \]

   \[ 1 \text{ M€} = 1.2 \text{ M$} = 1.4 \text{ Oku¥} \]

10. Fixed raw material prices, i.e. for copper, steel and niobium, and fixed prices for power are used. The fixed prices are:
    Electrical work C/W = $ 0.1/kWh (incl. supply cost),
    Copper C/m = $ 1000/100 kg (up to factor three higher for degassed copper),
    Black steel C/m = $ 0.6 /kg (for stainless and magnet steel up to factor three higher).
11. The external labor is included in the value.
12. Internal (institute) labor will be estimated in person hours (1 person year = 1700 person hours).
13. The EDIA\[1\] is included in the item cost.

\[1\] In the U.S. EDIA is the acronym for Engineering, Design, Inspection and Administration. Industry calls this non-recurring engineering (NRE).
High technology: Items such as cavities, cryomodules, and rf power sources, where there will be interest in developing expertise in all three regions, should be estimated separately for manufacture by each region. Costs should be provided for the total number of components …
### System Description: July 18, 2006 - Cost Estimates received for

<table>
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<th>System Description</th>
<th>Common</th>
<th>e-</th>
<th>e+</th>
<th>DR</th>
<th>RTML</th>
<th>ML</th>
<th>BDS</th>
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- First almost complete cost estimate
- Cost just too high!

* = almost complete, missing something minor
Some possible cost reductions (e.g. single tunnel, half RF, value engineering) deferred to the engineering phase.
Scale of International Linear Collider

16,088 SC Cavities: 9 cell, 1.3 GHz
1848 CryoModules: 2/3 containing 9 cavities, 1/3 with 8 cavities + Quad/Correctors/BPM
613 RF Units: 10 MW klystron, modulator, RF distribution
72.5 km tunnels ~ 100-150 meters underground
13 major shafts > 9 meter diameter
443 k cu. m. underground excavation: caverns, alcoves, halls
10 Cryogenic plants, 20 KW @ 4.5o K each
   plus smaller cryo plants for e-/e+ (1 each), DR (2), BDS (1)
92 surface “buildings”, 52.7 K sq. meters = 567 K sq-ft total
240 M Watts connected power, 345 MW installed capacity
13,200 magnets – 18 % superconducting
Total ILC Value and Explicit Manpower

• Total ILC Value Cost $ILCU^* 6.62 \text{ B}

\text{ILCU 4.79 B shared + ILCU 1.83 B } \text{ <site specific>\#}

\text{plus 14.2 k person-years Explicit Manpower}

\text{= 24.2 M person-hours}

\text{@ 1,700 person-hr/person-yr}

\text{\*ILCU(nit) = $ (January 2, 2007) }

\text{\#<site specific> = average of the three site specific costs}
ILC Value – by Area Systems

Main Cost Driver

Conventional Facilities

Components

ILC Units - Millions

0 500 1,000 1,500 2,000 2,500 3,000 3,500 4,000 4,500

Main Linac DR RTML Positron Source BDS Common Exp Hall Electron Source

Global Design Effort

ILC
ILC Value – by Technical Systems

- CF&S
- Cavities & CM
- RF Power
- Cryogenics
- Magnets & PS
- Controls
- Vacuum
- Instrumentation
- Dumps & Collim
- Installation
- e+ specific
- e- specific
- DR specific

ILC Units - Millions

June 19, 2007
DESY-Seminar
## Conventional Facilities

**ILCU(nit) = $ (January 2, 2007)**

<table>
<thead>
<tr>
<th>Region</th>
<th>Total ILCU</th>
<th>Civil Only</th>
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<tr>
<td>Asia</td>
<td>2.25 B</td>
<td>1.38 B</td>
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<td>Americas</td>
<td>2.54 B</td>
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<td>Europe</td>
<td>2.49 B</td>
<td>1.61 B</td>
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</table>
Conventional Facilities

 ILCL Units - Millions

 Shared

 Site-specific
ILC Cost Reviews

• Internal Review of the Cryomodule cost
• Internal Cost Review at SLAC with the participation of an External Review Panel on December 14 to 16, 2006
  – “Methodology is an appropriate basis” for ILC costing
• Machine Advisory Committee Review at Daresbury on January 10 to 12, 2007
  – “…performance driven baseline configuration was successfully converted into a cost conscious design.”
• DOE Briefing on January 17, 2007
• FALC Meeting at London on January 22, 2007
• International Cost Review at Orsay on May 23 to 25
Comparison between TESLA and ILC Cost
Scale of ILC and TESLA

16,088 SC Cavities: 9 cell, 1.3 GHz (TESLA: ~36/26)
1848 CryoModules: 2/3 containing 9 cavities, 
   1/3 with 8 cavities + Quad/Correctors/BPM
613 RF Units: 10 MW klystron, modulator, RF distribution
ML: 562 RF Units (15 to 250 GeV); TESLA 572 (5 to 250 GeV)
72.5 km tunnels ~ 100-150 meters underground (TESLA 37 km)
13 major shafts ≥ 9 meter diameter (TESLA 19 shafts)
443 K cu. m. underground excavation: caverns, alcoves, halls
10 Cryogenic plants, 20 KW @ 4.5° K each (TESLA 12 x 15 kW)
   plus smaller cryo plants for e-/e+ (1 each), DR (2), BDS (1)
92 surface “buildings”, 52.7 k sq. meters (TESLA ~30 k m²)
240 MW connected power, 345 MW installed capacity (145/180)
13,200 magnets – 18% superconducting
## Comparison between TESLA & ILC

<table>
<thead>
<tr>
<th></th>
<th>TESLA TDR / M€</th>
<th>Scaled TESLA TDR / M$</th>
<th>ILC RDR / M$</th>
<th>Difference / M$</th>
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<td>Cryo Plant*</td>
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<td>12 x 100 %</td>
<td>10 x 200 %</td>
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</table>

*TESLA: 12 x 2.2 kW @ 2 K  
ILC: 10 x 3.5 kW @ 2 K  
XFEL: 2.45 kW @ 2 K; 34.35 M€ for Cryogenic System
Summary and Outlook

• RDR Draft published in February 2007
  – Consistent design, though details are still lacking
  – Significant cost savings since the original version of BCD (Dec 2005)
  – Physics scope not reduced (energy, luminosity)
  – Risk assessments underway

• Final RDR to be published soon

• R&D and engineering design issues still remain
  – The next document will contain much more technical detail:
    *Engineering Design Report due 2010*
  – Currently work packages for R&D and Engineering are being set up
    • Move toward a ‘real’ project structure
  – Several of the baseline choices are being tested at the XFEL
    • E.g. klystrons, modulators, LLRF, RF couplers, cavity shape etc.

• The XFEL is a very important stepping stone towards the ILC!
Schematic Layout

Andy Wolski
June 19, 2007
DESY-Seminar

Global Design Effort

e+:
- short straight A (249 m)
- Arc 1 (818 m)
- shaft/large cavern A
- 8 RF cavities
- wiggler
- long straight 1 (400 m)
- small cavern 1
- injection
- Arc 2 (818 m)
- wiggler
- short straight B (249 m)
- Arc 3 (818 m)
- long straight 2 (400 m)
- small cavern 2
- extraction
- Arc 4 (818 m)
- shart straight C (249 m)
- wiggler
- 10 RF cavities
- shaft/large cavern C
- Arc 5 (818 m)
- wiggler
- short straight D (249 m)

e-: counter-clockwise
2 vertical shafts
Fast Ion Instability

- (Non trapped) Ions created from ionization by electrons are attracted by electrons and cause instability

- Cures
  - Low vacuum pressure ~1 nTorr
  - Bunch-by-bunch feedback system
  - Gaps between bunch trains
S1 RF Performance:
LINAC vs. Vertical (Cavity Average Gradients)

- Several Modules met expectations
  - E.g. M4, M5, M7
- M6 did not
  - 2 cavities degraded
  - Large spread in gradients in acceptance test due to time pressure for installation into FLASH
- M3* is a very special case
  - Coupler disassembly wrong
  - Repair with non-standard treatment and no acceptance test on 4 out of 5 ‘repaired’ cavities
  - Time Pressure: Module needed for installation
Interaction Region

- Crossing angle 14 mrad
- Final quadrupole magnets
  - Superconducting (QD0 in detector magnetic field)
  - Out-going beam goes outside
Crab Crossing

- Large crossing angle
  14mrad
- Need to deflect head and tail oppositely
- Crab cavity
  - 3.9 GHz SC
  - phase tolerance ~60 fs
  - prototype fabricated