ILC Accelerator Introduction

Hitoshi Hayano, KEK  05232019
Configuration of ILC Accelerator

**e+, e- Main Linac**

- **Beam Energy**: $125\text{GeV} + 125\text{GeV} = 250\text{ GeV}$
- **Total accelerator**: 20.5km
- **SRF Accelerator**: 5km + 5km

- **Number of Klystrons**: 218
- **Number of Cryomodules**: 906
- **Number of SC cavities**: 7800

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**Electron source**
- **e+ Linac (5km)**
- **Damping Ring (3.2km)**
- **e- Linac (5km)**

**Interaction Point Detectors**
- **ILD Detector**
- **SiD Detector**

**Positron source**
- **20.5km**

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Higgs particle was found, but no other particle was found up to 1 TeV region.

Study of Higgs particle (coupling to other particles) is urgent.

ILC has the abilities of precise measurements of Higgs.
ILC Accelerator Staging Plan

Step-wise construction and experiment (staging) was proposed, and plan of the accelerator at the beginning is 250GeV.

- **Option A:** (Option A’ 35MV/m)
  - 250GeV tunnel
  - 250GeV accelerator
  - Simple tunnel (no center wall, no facilities)
  - 33.5km

- **Option B:** (Option B’ 35MV/m)
  - 250GeV tunnel
  - 250GeV accelerator
  - Simple tunnel (no center wall, no facilities)
  - 27.0km

- **Option C:** (option C’ 35MV/m)
  - 500GeV tunnel
  - 250GeV accelerator
  - Simple tunnel (no center wall, no facilities)
  - 33.5km

For Option A’, 35MV/m, $Q_0 = 1.6 \times 10^{10}$ is assumed.
Beam Acceleration Sequence

Beam size of collision point

±5.9 nm
±474 nm

Small floor Vibration Site is required

Stiff rock, Deep underground

Turn around
Bunch compressor
Electron Linac
Positron generation
final focus
Interaction Point (IP)
Bunch compressor

5GeV positron damping ring (3.2 km)
5GeV electron damping ring (3.2 km)

Beam start here
beam generation (554 ns bunch spacing)

1ms bunch train mean:
1312 bunch (220 km length)

injection with compressed bunch spacing

1312 bunch (220 km length)

Bunch train compression

beam acceleration in Linac (554 ns bunch spacing)

In Damping Ring (6ns bunch spacing)
: 2.3 km length

Bunch train expansion

extraction with long bunch spacing

Polarised electron source

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Kitakami Candidate Site

Tohoku Area

Morioka

Ichinoseki

Sendai
Kitakami Candidate Site

Boring examination

Extracted Core was Good stiff Granite

Long Granite bed (pink)
ILC Accelerator: Lattice design and tunnel design

ILC250 Accelerator tunnel

Total Accelerator tunnel length
= 20,549.5m (20.5km)

Tunnel Design is on-going
Overall siting plan to fit Kitakami Candidate Site

Access Tunnels
Site-specific design of Access tunnels

AT-10: 1503m
AT-8: 691m
AT+8: 283m
AT+10: 943m
AT·DR (access point to DR): 763m
AT·DH (branch to detector hall): 693m

PM-10
PM-8
Interaction Region
PM+8

Total Accelerator tunnel length = 20,549.5m (20.5km)

Access Tunnels
Detector shaft 1
Utility shaft 1

access tunnels 5
Detector shaft 1
Utility shaft 1
total length 4876m
φ18m depth 75m
φ10m depth 75m
Bird’s eye view of ILC in Kitakami candidate site
Plan of Interaction point

Surface IP campus

Vertical Shaft

Underground Detector Hall

Interaction Point (IP)

Electron accelerator tunnel

Positron accelerator tunnel

5GeV damping ring Tunnel (3.2km)

Access tunnel

©Rey.Hori/KEK

5GeV damping ring Tunnel (3.2km)
surface design
IP area  78,500m²

154kV receive  
154kV to 66kV Trans  
66kV co-generation 

Water chiller & pumps
Air intake/exhaust

research building

LNG for co-generation
He compressor & tanks

IP detector assembly building

ILD&SiD detector preparation building

computing building

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Surface-to-Underground access-tunnel

Surface Access Station

Access Tunnel (10% down-slope tunnel, 1km)

Underground Access Hall

Accelerator Tunnel
Access-station at Surface

- Surface design
- Access stations
- 16,600m² 5 area

Access Tunnel

- Air intake/exhaust

Water chiller, pumps

He compressor & tanks

Temporary Crane

Water chiller, tanks & pumps
Beam acceleration by Superconducting Cavity
Electron Source
Damping Ring
Positron Linac
Electron Linac
Detectors
Positron Source
Beam dump
Beam dump
RF unit (below) is placed repeatedly in a line
Klystron: RF power is generated
Waveguide: RF power is distributed
Cryomodule: 8 cavities are included
Interval of beam bunch
Accelerating field in cavity
It is repeated in 5Hz
Beam pulse length (1ms, 5Hz)
1312 Beam bunchs
RF pulse length
Acceleration gradient
Cryomodule
Beam bunch:
Tunnel layout of ILC Main Linac

Tunnel Layout of ILC Accelerator

- Shield wall (1.5m thickness)
- Concrete shield
- Cryomodule
- Accelerator Tunnel
- Klystron Tunnel
- MARX Modulator
- Multi-beam Klystron
- Digital LLRF controls
Cross-section of ILC Main Linac Tunnel

- **66kV Cables**
- **6.6kV Cables**
- **LCW Supply**
- **LCW Return**
- **CHW S,R**
- **Klystron Tunnel**
- **Accelerator Tunnel**
- **Waveguide**
- **LPDS**
- **Cryomodule**
- **RTML**
- **Shielding Wall**
- **Transport Vehicle**
- **Krystron**

Dimensions:
- 2,200 mm
- 5,500 mm
- 1,800 mm
- 1,500 mm
- 4,000 mm
- 9,500 mm
Cryomodule

Type-A (9 cavities)  604
Type-B (8 cavities + SC-Q magnet)  302

Number of Cryomodules: 906

- Support posts
- Helium gas return pipe (Φ300mm SUS pipe)
- Liquid Helium supply pipe (Φ60mm Ti pipe)
- Thermal shield (Al plate + Super-Insulator)
- Input coupler
- Cryomodule (12.65m)

Cross-section from D. Kostin
Niobium cavity is cooled by 2K Liquid Helium introduced into the jacket, Pulse RF power put into input coupler, resonance tuning done by mechanical Tuner and piezo tuner.
Beam Acceleration by 1.3GHz RF field

Once cavity comes to superconducting-state by liquid helium cooling, Surface resistance become tremendously small, the RF-loss by the RF current on the cavity wall become small also. RF power inside of cavity makes high accelerating field on its axis, and last long dulation.

Yellow lines and pink lines represent accelerating field. Its direction alters 180 degrees by the speed of light velocity. Electron beam also moves by the light velocity, so that electric field direction and electron beam moving direction can be adjusted by choosing appropriate beam injection timing.

$TM_{010} \quad \pi - mode$

1.300 GHz
Technologies for high performance SRF cavity
RF Amplitude & Phase stabilization by digital feedback
Stabilized RF amplitude and phase

Vector sum operation of 7 cavities with LLRF control as an example

Amplitude stability 0.005% rms

Phase stability 0.015° rms
ILC SRF accelerator development

Number of SC cavities in ILC: 7800

Euro-XFEL in Germany (800 cavities)

LCLS-II in US (280 cavities)

Euro-XFEL

DESY/FLASH, Euro-XFEL

Saclay
cryomodule assembly

IHEP/cavity development

PKU/cavity development

KEK/STF, CFF, ATF

RRCAT/cavity development

( SARI/SHINE )

SHINE in China (615 cavities to be fabricated)

ILC accelerator/SRF technologies development by International Collaboration
Test results: **USABLE GRADIENT**

**As received** test

Reasons of Usable Gradient degradation

- Q₀ degradation
  - (except field emission)
- Field Emission
- Break-down

* few cases of power limitation, HOM coupler heating etc.

Average loss from max: ~4 MV/m

<table>
<thead>
<tr>
<th></th>
<th>RI</th>
<th>EZ</th>
<th>Total</th>
</tr>
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<tbody>
<tr>
<td>Tests</td>
<td>375</td>
<td>367</td>
<td>742</td>
</tr>
<tr>
<td>GₐVG (MV/m)</td>
<td>29.1</td>
<td>26.4</td>
<td>27.8</td>
</tr>
<tr>
<td>GₐRMS (MV/m)</td>
<td>7.4</td>
<td>6.6</td>
<td>7.1</td>
</tr>
<tr>
<td>yield @ 20MV/m</td>
<td>89%</td>
<td>83%</td>
<td>86%</td>
</tr>
<tr>
<td>yield @ 26MV/m</td>
<td>73%</td>
<td>59%</td>
<td>66%</td>
</tr>
<tr>
<td>yield @ 28MV/m</td>
<td>63%</td>
<td>45%</td>
<td>54%</td>
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</table>
Test results: Retreatment

"As received" test

In general, first re-treatment is a standard High-Pressure Rinse (HPR)

Second (if required) is BCP

HPR treatment for <20MV/m cavities in XFEL
Extrapolation to ILC - VT

- ILC TDR assumed VT acceptance > 28MV/m (XFEL >20 MV/m)
  - Average of 35 MV/m (XFEL 26 MV/m)
  - Assumed first-pass yield: 75%
  - 25% cavities retreated to give final yield of 90% >28 MV/m (35 MV/m average)
    - 10% over-production assumed in value estimate

**ILC specification : >=90% yield**

<table>
<thead>
<tr>
<th>RI results only (ILC recipe)</th>
<th>ILC TDR (assumed)</th>
<th>XFEL max</th>
<th>usable</th>
</tr>
</thead>
<tbody>
<tr>
<td>First-pass</td>
<td>Yield &gt;28 MV/m</td>
<td>75%</td>
<td>85%</td>
</tr>
<tr>
<td></td>
<td>Average &gt;28 MV/m</td>
<td>35 MV/m</td>
<td>35.2 MV/m</td>
</tr>
<tr>
<td>First+Second pass</td>
<td>Yield &gt;28 MV/m</td>
<td>90%</td>
<td>94%</td>
</tr>
<tr>
<td></td>
<td>Average &gt;28 MV/m</td>
<td>35 MV/m</td>
<td>35.0 MV/m</td>
</tr>
<tr>
<td>First+Second+third pass</td>
<td>Yield &gt;28 MV/m</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Average &gt;28 MV/m</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

More re-treatments - but mostly only HPR
Number of average tests/cavity increases from 1.25 to 1.55 (1\textsuperscript{st}+2\textsuperscript{nd}) or 20% over-production or additional re-treat/test cycles

\[ \text{Xfel cavity results} \] \[ \text{ECFA LC 2016} \] \[ \text{Santander - Spain} \] \[ 31-05-2016 \]

\[ \text{Nicholas Walker \ DESY \ nicholas.walker@desy.de} \]
FNAL CM-2 has achieved the average cavity gradient of 31.5 MV/m with all 8 cavities powered simultaneously.
**Test Accelerator to test ILC cryomodules**

Combined 8 cavities in cryomodules with vector-sum LLRF, were operated at 30.5 MV/m in 2016, just RF filling. **In March 2019, average 32MV/m beam acceleration was confirmed.**
The 1,000m “copper” linac in Sectors 0-10 will be replaced by a superconducting linac, occupying 700m (room to grow).

The SC linac will provide electrons to either or both undulators.

The existing linac in “middle” 1,000m of the tunnel will be left intact (likely use: R&D on plasma wake field acceleration). Electrons from SC linac transported past this linac in a separate channel.

BESAC July 7, 2015 LCLS-II Status
LCLS-II (FNAL, JLAB) will fabricate 35 cryomodule (280 cavities)
Beam Collision
**Electron and Positron collision**

**Beam = group of electrons (positrons)**

**Beam size of collision point**

- **electron**
- **positron**

- Simulation of collision event in ILD

- TPC
  - ECAL
  - HCAL

- *Electron bunch 1312*
  - Length 300μm
  - Bunch spacing 166m
  - Repetition 5Hz
  - Energy 125 GeV

- *Positron bunch 1312*
  - Length 300μm
  - Bunch spacing 166m
  - Repetition 5Hz
  - Energy 125 GeV
Keep the beam size small, keep the collision stable

- **Damping Ring** is to realize beam emittance ultra-small
- **Final Focus Beam Line** is to make vertical beam size ultra-small
- **No-vibration accelerator Floor** requires
  - Deep underground, stiff rigid Rock-base mountain
- **Fast Beam feedback** is to keep beam collision stable

*Fig. by P. Burrows, ATF2 Review 2013*

Pick-up beam deflection signal of outgoing beam caused by beam-beam interaction

Fed back to incoming beam orbit to keep beam-beam interaction maximum.
ATF : Accelerator Test Facility in KEK, Japan

Layout of ILC

1.3 GeV S-band Electron LINAC (~70m)

Damping Ring (~140m)
Low emittance electron beam

ATF2: Final Focus Test Beamline

ATF Damping Ring
Target low emittance is already attained
Development of beam focus with low energy (ATF2)

- **Nano-beam development by international collaboration**
  - 25 laboratories with more than 100 researchers
- **The same optical design of ILC final focus beam line**
- **Scale down of beam energy to 1.3 GeV**
- **Target of beam size**
  - 37 nm vertical size (correspond to ILC 5.9 nm)
- **Recent Status**
  - 41 nm beam size (with FONT Feedback)
  - Parameters dependence to beam size are under research

Beam size monitor using laser interferometer

T. Okugi, ECFA-LCW, Santander June, 2016
ILC political Status of Japan
SCJ committee Discussion for ILC250

MEXT: Minister of Education, culture and sports, Science and Technology Japan

SCJ: Science Council of Japan

Tasks of the committee

- The academic significance of the ILC, importance of the ILC in the elementary particle physics
- Importance of the ILC in the whole academic research
- Significance of the ILC in Japan
- Preparation status for the ILC, budget and human resources necessary for construction and operation

Tasks of the sub-committee

1. Technical feasibility of large facilities
2. Cost evaluation
3. Economic ripple effect
4. Environmental assessment

The SCJ recognizes the importance of the Higgs physics. “It is agreed upon Japanese high energy physics community that the precision measurement of the Higgs coupling is an important one”.

“Judging from the plan and preparatory status of the project presented at the moment, the Science Council of Japan does not reach a consensus to support hosting the 250GeV ILC project in Japan.”

Their main concerns are “Japan’s large share of the overall cost required for the project implementation”, “matter of concern for the implementation of the project (for technical issues)”, and “the uncertainty surrounding proper international cost-sharing with respect to the long-term commitment to large budget allocation”
ICFA/LCB meeting at Tokyo (Mar.07,2019)
Following the opinion of the SCJ, MEXT has not yet reached declaration for hosting the ILC in Japan at this moment. The ILC project requires further discussion in formal academic decision-making processes such as the SCJ Master Plan, where it has to be clarified whether the ILC project can gain understanding and support from the domestic academic community.

MEXT will pay close attention to the progress of the discussions at the European Strategy for Particle Physics Update.

The ILC project has certain scientific significance in particle physics particularly in the precision measurements of the Higgs boson, and also has possibility in the technological advancement and in its effect on the local community, although the SCJ pointed out some concerns with the ILC project. Therefore, considering the above points, MEXT will continue to discuss the ILC project with other governments while having an interest in the ILC project.
ILC (International Linear Collider) uses superconducting accelerator for the electron-positron collision experiment (7800 cavities).

Euro-XFEL (DESY, Saclay, INFN) fabricated 100 cryomodules (800 cavities) for the superconducting accelerator, The cavity performance was very close to ILC requirement.

LCLS-II (FNAL, JLAB, SLAC) is fabricating 35 cryomodule (280 cavities) SHINE (SARI) will fabricate 75 cryomodule (615 cavities) FNAL, KEK-STF is developing superconducting test accelerator, KEK-ATF and ATF2 are developing damping ring and beam focus and achieved 41nm beam size.
Summary

Plan of ILC installation into Tohoku-area are presented. Tunnel, buildings and water&air will be prepared by Japan, High-tech accelerator part will be shared by US, Europe, and Asia.

On March 7, MEXT did not say hosting ILC, but express their interest to ILC. International cost share discussion WG has been started by MEXT, Waiting for listing ILC on “master plan of SCJ”, this year.

ILC is very close to go.
Thanks for your attention
Cost-down of Main Linac

US-Japan cost down R&D

In 2016, MEXT (Japanese government) and US-DOE agreed to have cost-down R&D by US-Japan collaboration, to make ILC realize

ILC 250GeV Cavity Package 7800 unit
US-Japan Cost-down R&D Items

(A-1) Nb material cost-down by Ingod-slicing

Cost down by Mid-RRR-ingod material + slicing to sheet

Development of gradient performance and ensuring Nb sheet strength and press-forming availability

(A-2) High-Q High-G of cavity by N-infusion

Introduction of clean furnace for N-infusion, search of infusion parameter range

ILC operation specification
- 31.5MV/m $1 \times 10^{10}$
- 35MV/m $1.6 \times 10^{10}$
N-dope(2013) and N-infusion(2013) were developed

A. Grassellino et al., 2013 Supercond. Sci. Technol. 26 102001
A. Grassellino et al., arXiv:1305.2182, 1701.06077

**N-dope** 25mTorr N2 @800 deg C, 2min

**N-infusion** 25mTorr N2 @120 deg C, 48hours

High-Q & High-G

Low-loss

TTC meeting (2014/Dec) A. Melnychuk 「Update on N doping at Fermilab」

After this process, ~7μm EP was applied

A. Grassellino 「High grad/high Q via N infusion」 (LCWS2016)

800C

120 degree C N-infusion (3.3Pa = 25mTorr)

48 hours
N-infusion was applied both 1-cell and 9-cell cavities

120 C N-infusion: high $Q_0$ at high gradients

**Single-cell**

**9-cells**

Higher $Q$-factor at higher field may allow for higher duty-cycles and therefore higher luminosity!

A. Grassellino et al., arXiv:1701.06077 (in publication to SUST)
Surface structure of N-dope and N-infusion

Diffusion of N into Nb surface

N-dope

Diffusion of N into Nb surface
around 200 nm

N-infusion

Diffusion of N into Nb surface
20 – 30 μm
High-Q/High-G surface only by baking!!

Repeated on second cavity TE1AES009 (fine grain, AES, WC)

FNAL new receipe June 2018
75 °C baking +120 °C baking reach to 49MV/m

EP+ 75C 4 hrs+ 120C 48 hours

Regular 120C

No N-dpe,
No N-infusion

New Furnace for N-infusion R&D at KEK

KEK new furnace (located at COI)

- Completed at the end of FY2017
- Cryopump for main pump, oil-free pumping system.
- Molybdenum is used for heater, reflector, table etc.
- TMP is used during N-injection, can reach ~2e-5Pa.
- Clean-booth surround entrance door.
# Summary of KEK N-infusion

## Summary of N-infusion @KEK new furnace

<table>
<thead>
<tr>
<th>#</th>
<th>Day (N-inf / VT)</th>
<th>Cavity name</th>
<th># of cell</th>
<th>Nb</th>
<th>Treatment</th>
<th>Results</th>
<th>Eacc (MV/m)</th>
<th>Comment</th>
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<tbody>
<tr>
<td>1</td>
<td>Jun-6 / Jun-21</td>
<td>R-6</td>
<td>1</td>
<td>FG</td>
<td>800C, 3h + 120C, 48h, 3.3Pa N2</td>
<td>No Q-degradation</td>
<td>35</td>
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<td>2</td>
<td>Jun-13 / Jul-2</td>
<td>R-9b</td>
<td>1</td>
<td>FG</td>
<td>800C, 3h + 120C, 48h, 3.3Pa N2</td>
<td>No Q-degradation</td>
<td>26</td>
<td>Quench due to defect</td>
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<td>3</td>
<td>Jun-20? / Jul-5</td>
<td>R-10</td>
<td>3</td>
<td>LG</td>
<td>800C, 3h + 120C, 48h, 3.3Pa N2</td>
<td>No Q-degradation</td>
<td>27</td>
<td>F.E. limited</td>
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### Summer shutdown

<table>
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<th>#</th>
<th>Day (N-inf / VT)</th>
<th>Cavity name</th>
<th># of cell</th>
<th>Nb</th>
<th>Treatment</th>
<th>Results</th>
<th>Eacc (MV/m)</th>
<th>Comment</th>
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<tr>
<td>4</td>
<td>Sep-9 / Oct-5</td>
<td>R-2</td>
<td>1</td>
<td>FG</td>
<td>800C, 3h + 160C, 48h, 3.3Pa N2</td>
<td>Strong Q-degradation</td>
<td>19</td>
<td>No defects found</td>
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<tr>
<td>5</td>
<td>Oct-6 / Oct-18</td>
<td>R-6</td>
<td>1</td>
<td>FG</td>
<td>800C, 3h + 120C, 48h (without N2)</td>
<td>Q-degradation (like J-PARC)</td>
<td>32</td>
<td></td>
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<tr>
<td>6</td>
<td>Nov-23 / Dec-5</td>
<td>R-8</td>
<td>1</td>
<td>FG</td>
<td>800C, 3h + 120C, 48h, 3.3Pa N2</td>
<td>Better Q than reference</td>
<td>36</td>
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<tr>
<td>7</td>
<td>Dec-21 / Jan-23</td>
<td>R-9b</td>
<td>1</td>
<td>FG</td>
<td>800C, 3h + 160C, 48h, 3.3Pa N2</td>
<td>Q-degradation (like J-PARC)</td>
<td>24</td>
<td>Quench due to defect</td>
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<td>8</td>
<td>Jan-31 / Feb-14</td>
<td>AES018</td>
<td>1</td>
<td>FG</td>
<td>800C, 3h + 120C, 48h, 3.3Pa N2</td>
<td>No Q-degradation</td>
<td>38</td>
<td>No reference data at KEK</td>
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