Review of ERL Projects at KEK and around the World

Norio Nakamura
for the ERL collaboration team

High Energy Accelerator Research Organization (KEK)
ERL Collaboration Team

High Energy Accelerator Research Organization (KEK)

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Norio Nakamura, IPAC12, May 22, 2012
Outline

1. 3-GeV ERL Light Source Project at KEK
2. The Compact ERL (cERL) Project at KEK
3. Review of ERL Projects around the World
4. Summary and Outlook
3-GeV ERL Light Source Project at KEK
KEK Photon Factory (KEK-PF)

PF ring (2.5 GeV)
- SR beamlines: 22
- Insertion devices: 10
  (VUV/SX 5, X-ray 5)
- E = 2.5 GeV, C = 187 m
- Beam emittance: 34.6 nm·rad
- Top-up operation, I₀ = 450 mA

PF-AR (6.5 GeV)
- SR beamlines: 8
- Insertion devices: 5
- E = 6.5 GeV, C = 377 m
- Beam emittance: 293 nm·rad
- Single bunch, I₀ = 60 mA

More than 30 years have passed since construction of both rings.

Norio Nakamura, IPAC12, May 22, 2012
ERL-based Light Source Project at KEK (2 Stages)

1. 3-GeV ERL as VUV and X-ray SR source
2. 6-7 GeV XFEL Oscillator
# Beam Parameters for Operational Modes

<table>
<thead>
<tr>
<th></th>
<th>3 GeV ERL</th>
<th>XFEL-O</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>High Coherence (HC) mode</strong></td>
<td><img src="High%20Coherence%20(HC)%20mode.png" alt="Blue" /></td>
<td><img src="High%20Coherence%20(HC)%20mode.png" alt="Blue" /></td>
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<td><strong>High Flux (HF) mode</strong></td>
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<tr>
<td><strong>Ultra-Short Pulse (US) mode</strong></td>
<td><img src="Ultra-Short%20Pulse%20(US)%20mode.png" alt="Pink" /></td>
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<tr>
<td><strong>XFEL-O mode</strong></td>
<td><img src="XFEL-O.png" alt="Pink" /></td>
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<tr>
<td><strong>Beam Energy</strong></td>
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<tr>
<td><strong>Beam Current</strong></td>
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<td><img src="Beam%20Current.png" alt="Blue" /></td>
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<tr>
<td><strong>Bunch Charge</strong></td>
<td><img src="Bunch%20Charge.png" alt="Blue" /></td>
<td><img src="Bunch%20Charge.png" alt="Blue" /></td>
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<tr>
<td><strong>Repetition Rate</strong></td>
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<td><img src="Repetition%20Rate.png" alt="Blue" /></td>
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<tr>
<td><strong>Norm. Emittance</strong></td>
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<td><img src="Norm.%20Emittance.png" alt="Blue" /></td>
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<tr>
<td><strong>Energy Spread</strong></td>
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<td><img src="Energy%20Spread.png" alt="Blue" /></td>
</tr>
<tr>
<td><strong>Bunch Length</strong></td>
<td><img src="Bunch%20Length.png" alt="Blue" /></td>
<td><img src="Bunch%20Length.png" alt="Blue" /></td>
</tr>
</tbody>
</table>

- **Beam Energy**: 3 GeV, 6 - 7 GeV
- **Beam Current**: 10 mA, 100 mA, 100 mA, 77 μA (typ.), 10 μA
- **Bunch Charge**: 7.7 pC, 77 pC, 77 pC, 77 pC, 10 pC
- **Repetition Rate**: 1.3 GHz, 1.3 GHz, 1.3 GHz, 1 MHz, 1 MHz
- **Norm. Emittance**: 0.1 mm·mrad, 1 mm·mrad, 0.1 mm·mrad, - , 0.2 mm·mrad
- **Emittance**: 17 pm·rad, 170 pm·rad, 17 pm·rad, - , 15 pm·rad
- **Energy Spread**: $2\times10^{-4}$, $2\times10^{-4}$, $2\times10^{-4}$, - , $5\times10^{-5}$
- **Bunch Length**: 2 ps, 2 ps, 2 ps, $\leq 100$ fs, 1 ps

Norio Nakamura, IPAC12, May 22, 2012
Beam Optics of 3-GeV ERL

Preliminary Optics (from after merger to before dump line)

Emittance growth & energy spread increase due to ISR & CSR effects are negligible for both Ultimate and XFEL-O modes.

M. Shimada et al., MOPP019
Tentative Layout of 3-GeV ERL

Assumptions:

- Beam energy
  - Full energy: 3 GeV
  - Injection and dump: 10 MeV
  - XFEL-O: 6-7 GeV
- Circumference: ~1600 m
- Main linac
  - Eight 9-cell cavities in a cryomodule
  - 28 cryomodules (224 cavities)
  - Cavity acc. gradient: 13.4 MV/m
  - Triplet QMs between cryomodules
  - Total length: ~470 m
    (average acc. gradient: 6.4 MV/m)
- TBA cells for ID’s
  - 22 x 6 m short straight sections
  - 6 x 30 m long straight sections
- 300-m long straight section
Simulation of XFEL-O (6 GeV)

Evolution of temporal pulse profile

Example of parameters for XFEL-O

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td>6 GeV</td>
</tr>
<tr>
<td>Bunch charge</td>
<td>10 pC</td>
</tr>
<tr>
<td>Bunch length</td>
<td>1 ps</td>
</tr>
<tr>
<td>Energy spread</td>
<td>$5 \times 10^{-5}$</td>
</tr>
<tr>
<td>Norm. emittance</td>
<td>0.2 mm mrad</td>
</tr>
<tr>
<td>Photon energy</td>
<td>12 keV</td>
</tr>
<tr>
<td>Undulator length</td>
<td>58 m</td>
</tr>
<tr>
<td>Undulator period</td>
<td>19.4 mm</td>
</tr>
<tr>
<td>Gain</td>
<td>43%</td>
</tr>
</tbody>
</table>

Calculated by R. Hajima

Norio Nakamura, IPAC12, May 22, 2012
Potential of 300-m Long Straight Section

Potential of 300-m long straight section (E=3GeV):
1. 300-m Undulator – Spectral Brightness $10^{23} - 10^{24}$
2. EEHG FEL including generation of attosecond VUV/X-ray pulses
3. Harmonic Lasing of XFEL-O

Figure from PRL 108 (2012) 034802.
Light Source Performance

Spectral Brightness

- 3-GeV ERL
  - $\lambda_u = 1.8\,\text{cm}$
  - $L = 30\,\text{m}$

- PF Ring undulators
- PF-AR undulators

$10^{26}$ by XFEL-O

SR Pulse length

- 3-GeV ERL
  - 50 - 100 fs

- PF/PF-AR
  - 30 - 60 ps

Attosecond pulse by EEHG

Calculated by K. Tsuchiya

Norio Nakamura, IPAC12, May 22, 2012
The Compact ERL (cERL) Project at KEK
## Compact ERL (cERL) Project

### Purposes of the compact ERL
- Demonstrating reliable operations of our ERL components (guns, SC-cavities, ...)
- Demonstrating generation and recirculation of ultra-low emittance beams at high currents
- 1\textsuperscript{st} target: 1 mm·mrad for 10mA @ 35 MeV

### Parameters of the Compact ERL

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
</table>
| Beam energy (upgradability) | 35 MeV  
125 MeV (single loop)  
245 MeV (double loops) |
| Injection energy    | 5 MeV (10 MeV in future)                                               |
| Average current     | 10 mA  
(100 mA in future)                                                   |
| Acc. gradient (main linac) | 15 MV/m                                   |
| Normalized emittance| 0.1 mm·mrad (7.7 pC)  
1 mm·mrad (77 pC)                                                  |
| Bunch length (rms)  | 1 - 3 ps (usual)  
~ 100 fs (with B.C.)                                               |
| RF frequency        | 1.3 GHz                                                               |

Commissioning is scheduled to start in 2013.

S. Sakanaka et al., MOPPP018

Norio Nakamura, IPAC12, May 22, 2012
Injector Design

Simulation result from the gun to just after the main linac.

1st goal (1 mm·mrad for 10 mA) is achievable.

Norio Nakamura, IPAC12, May 22, 2012

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Gun DC voltage</td>
<td>500 kV</td>
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<tr>
<td>Beam energy of injector</td>
<td>5 MeV</td>
</tr>
<tr>
<td>Charge/bunch (Current)</td>
<td>7.7 pC (10mA)</td>
</tr>
<tr>
<td>Full width of laser pulse</td>
<td>16 ps</td>
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<tr>
<td>Spot diameter of laser</td>
<td>0.52 mm</td>
</tr>
<tr>
<td>Magnetic fields of solenoids #1, #2</td>
<td>0.0364, 0.0146 T</td>
</tr>
<tr>
<td>Voltage of buncher cavity</td>
<td>105 kV</td>
</tr>
<tr>
<td>Eacc of 1st, 2nd, and 3rd SC cavity</td>
<td>6.84, 7.53, 7.07 MV/m</td>
</tr>
<tr>
<td>Offset phase of 1st, 2nd, and 3rd cavity</td>
<td>29.9, -9.8, -10.0 degrees</td>
</tr>
</tbody>
</table>
Lattice and Optics of cERL

Betatron and dispersion functions (from after main linac to beam dump)

Norio Nakamura, IPAC12, May 22, 2012

35 MeV single-loop ERL

Injection energy: 5 MeV

Chicane for path-length adjustment

M. Shimada et al., MOPP019
Laser Compton Scattering Experiment

Nondestructive measurement of isotopes by LCS $\gamma$-rays at the cERL

3-year R&D program of JAEA was funded from MEXT (FY2011-2013).

- Electron beam = 35 MeV, 10 mA
- LCS photon flux = $5 \times 10^{11}$ ph/s @22keV

- Possible upgrade in future
  - Electron beam = 245 MeV, 10 mA
  - LCS photon flux = $1 \times 10^{13}$ ph/s @1.1MeV

Lattice and optics of the LCS section is being designed.
A laser system including a laser cavity is being developed.

Norio Nakamura, IPAC12, May 22, 2012
Photocathode DC Gun #1 at JAEA

8-hour operation at 510 kV with a segmented ceramic insulator


HV processing with cathode electrode and NEG pumps in place

- HV processing up to 526 kV
- Local radiation problem needs to be solved

Scheduled to be installed in the cERL beamline this autumn

Norio Nakamura, IPAC12, May 22, 2012
Photocathode DC Gun #2 at KEK

Target pressure: \(1 \times 10^{-10}\) Pa
(to preserve the NEA state on the cathode)

• High voltage insulator
  – Segmented structure
  – Special \(\text{Al}_2\text{O}_3\) material (TA010, Kyocera)

• Low outgassing system
  – Titanium chamber, electrode, guard rings
  – Total outgassing rate: \(\sim 1 \times 10^{-10}\) Pa·m\(^3\)/s
    (actual measurement)

• Main vacuum pump system
  – 4K Bakeable cryopump
    > 1000 L/s, for \(\text{CH}_4, \text{N}_2, \text{CO, CO}_2\) @\(1 \times 10^{-9}\) Pa
    (actual measurement)
  – NEG pump
    > \(1 \times 10^4\) L/s, for \(\text{H}_2\) (design value)

• 600-kV HV Power Supply system
Laser System

**Laser system**
- 1.3GHz Nd:YVO4 oscillator
- Yb photonic-crystal-fiber amplifier
- SHG with an external cavity
- Shaping system

**Specifications**
- 532 nm, 2.3 W on cathode for 10 mA → 5W(532nm), 25W(1064nm) at laser room
- 32 ps pulse duration → stacking of eight 8-ps pulses

**Achievements**
- 38 W(1064 nm) at 1.3 GHz with a 1-stage fiber amplifier
- 70 W(1064 nm) at 1.3 GHz with a 2-stage fiber amplifier
- SH generation and pulse stacking

Operation of 10 mA or more is promising.

Y. Honda, TUPPD056

Norio Nakamura, IPAC12, May 22, 2012
SC Cavities for Injector (1)

Cavities for cryomodule

Input couplers

2-cell cavity

All HOM couplers are loop-type

Vacuum Vessel

5K Panel

2K He Jacket

5K Support

80K Base-plate

80K Shield

Vacuum Vessel

5K Duct

5K Panel

2K Return Pipe

80K Base-plate

Input Coupler

2-cell Cavity

HOM Coupler

Cryomodule design

Norio Nakamura, IPAC12, May 22, 2012
SC Cavities for Injector (2)

Results of Final Vertical Tests

Improved RF feedthroughs in HOM couplers increased accelerating gradient (cERL specification: $E_{\text{acc}} > 11$ MV/m).

All the RF feedthroughs were replaced by Type-II’m.

Please see E. Kako et al., WEPPC012, WEPPC015 for details.

Norio Nakamura, IPAC12, May 22, 2012
SC Cavities for Main Linac (1)

9-cell Cavities

HOM Absorber

Input couplers

Cryomodule design

Cryomodule design (side view)

Norio Nakamura, IPAC12, May 22, 2012
Results of final vertical tests

- $E_{acc}$ of higher than 25 MV/m could be achieved in both cavities.
- Cavities satisfied cERL specification ($Q_0 > 10^{10}$ at 15 MV/m)
- Onsets of X-ray were 14 MV/m and 22 MV/m for the cavities #3 and #4, respectively.

- Cavities are dressed with Helium jackets and waiting for installation into cryomodule.

Norio Nakamura, IPAC12, May 22, 2012
1.3 GHz CW RF Sources

- 300kW CW Klystron for injector SCC
- 30kW CW Klystron for injector SCC
- 30kW CW IOT for main SCC
- 20kW CW IOT for buncher

Courtesy: T. Miura

Norio Nakamura, IPAC12, May 22, 2012
Liquid-Helium Refrigerator

Overview of the system

Gas bag

Pumping unit

3000L 液化ヘリウム貯槽

Purifier

Liquefier/refrigerator

2K cold box

End box

Cooling capacity: 600 W (at 4K) or 250 L/h

3000L liquefied helium storage vessel

2K cold box and end box

TCF200 helium liquefier/refrigerator

Norio Nakamura, IPAC12, May 22, 2012
Magnet/Vacuum/Monitor

Norio Nakamura, IPAC12, May 22, 2012

Bending magnet

Quadrupole magnet

Zero-gap Flange

Stripline BPM with glass-type feedthrough

Screen monitor

Slit for emittance measurement

Courtesy: K. Harada, Y. Tanimoto, T. Honda, T. Obina, R. Takai
Construction of the radiation shield is on going and will be completed this autumn.
Road Map of ERL Projects

Japanese Fiscal Year (from April to March)

- **2008**: R&D of ERL key elements
- **2009**: Prep of ERL Test Facility
- **2010**: cERL construction
- **2011**: Beam test and test experiments
- **2012**: Improvements towards 3GeV class ERL
- **2013**: Construction of 3GeV ERL
- **2014**: User run

Present time

Norio Nakamura, IPAC12, May 22, 2012

Courtesy: H. Kawata
ERL Projects around the World
Jefferson Lab

<table>
<thead>
<tr>
<th>Beam Parameters</th>
<th>Specification</th>
<th>Achieved</th>
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</thead>
<tbody>
<tr>
<td>Energy [MeV]</td>
<td>145</td>
<td>160</td>
</tr>
<tr>
<td>Peak Current [A]</td>
<td>240</td>
<td>400</td>
</tr>
<tr>
<td>$\sigma_t$ [ps] at wiggler</td>
<td>0.20</td>
<td>0.13</td>
</tr>
<tr>
<td>$\sigma_{AE}$ [%] at wiggler</td>
<td>0.4</td>
<td>0.3</td>
</tr>
<tr>
<td>$\varepsilon_{x,y}$ (rms) [mm-mrad]</td>
<td>30</td>
<td>7</td>
</tr>
<tr>
<td>$\varepsilon_z$ (rms) [keV-ps]</td>
<td>65</td>
<td>80</td>
</tr>
</tbody>
</table>

- **IR FEL**
  - High power FEL (>10kW)
  - Beam dynamics studies
- **UV FEL**
  - High gain near 700 and 400 nm
  - 3rd harmonics at 10eV
- **THz source**

Norio Nakamura, IPAC12, May 22, 2012
Jefferson Lab

Beam Parameters Specification

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<td>0.4</td>
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Norio Nakamura, IPAC12, May 22, 2012

- Beam dynamics studies
  - UV FEL
    - High gain near 700 and 400 nm
    - 3rd harmonics at 10eV
  - THz source

J-Lab upgrade plan

600MeV 2-turn ERL (for VUV to SX FEL oscillator)
Full-scale ERL with 3 FELs at Novosibirsk

First and second horizontal loops with second FEL (in operation)

Third and fourth loops with IR FEL (under construction)

Novosibirsk ERL with two FELs

RF cavities

Normal conducting RF cavities

1st stage (1-turn 11-MeV ERL)

Single loop in vertical plane with the THz FEL (in operation)

Maximum average current: 30mA (world record for ERLs)

2nd stage (4-turn 40-MeV ERL)

First multi-turn ERL in the world

Novosibirsk ERL with two FELs

RF cavities

Normal conducting RF cavities

1st stage (1-turn 11-MeV ERL)

Single loop in vertical plane with the THz FEL (in operation)

Maximum average current: 30mA (world record for ERLs)
BINP

Norio Nakamura, IPAC12, May 22, 2012

Lasing (2)

New optical cavity
New undulator
Old THz FEL
RF cavities

Novosibirsk ERL with two FELs
Full-scale ERL with 3 FELs at Novosibirsk

Maximum average current: 30mA (world record for ERLs)

First multi-turn ERL in the world
1-stage (1-turn 11-MeV ERL)
2-stage (4-turn 40-MeV ERL)

MARS
Multi-turn ERL X-ray Source
ALICE @ Daresbury Laboratory

Energy: up to 27.5 MeV
Bunch: up to 100 pC
Repetition: up to 81.75 MHz
Bunch train: 100 µs @ 1-10Hz

ALICE (Accelerators and Lasers In Combined Experiments)

Compton Scattering
X-ray generation

Development of SRF module

Gun Ceramic Change (230 → 325 kV)

Norio Nakamura, IPAC12, May 22, 2012
Cornell ERL Project

- 5-GeV ERL light source as extension of CHESS
- R&D for realizing the ERL X-ray source
- PDDR (Project Design Definition Report) ready for submission
5-GeV ERL @ Cornell University

Cornell ERL Project
- 5-GeV ERL light source as eXtendion of CHESS
- R&D for realizing the ERL X-ray source
- PDDR (Project Design Definition Report) ready for submission

Norio Nakamura, IPAC12, May 22, 2012
Injector Prototype @ Cornell University

Achievements:
1) Max. DC-gun voltage: 440kV
2) Max. beam current: 52mA with GaAs
   (world record for photocathode guns)
3) 8-hour operation at 20mA with CsK₂Sb
4) Min. norm. emittance at 80pC: 0.7 mm·mrad
   with core norm. emittance : 0.3 mm·mrad
5) Largest injector-coupler power: 60kW
6) Largest SRF-cavity voltage: 13MV/m

Achieved beam sufficient for an ultra-bright X-Ray ERL

Norio Nakamura, IPAC12, May 22, 2012
BERLinPro @ HZB

BERLinPro: Main Project Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam kinetic energy</td>
<td>50 MeV</td>
</tr>
<tr>
<td>Max average current</td>
<td>100 mA</td>
</tr>
<tr>
<td>Bunch charge</td>
<td>77 pC</td>
</tr>
<tr>
<td>Emittance (norm.)</td>
<td>1.0 mm·mrad</td>
</tr>
<tr>
<td>Bunch repetition rate</td>
<td>1.3 GHz</td>
</tr>
</tbody>
</table>

SC cavity for Main Linac

600 kW beam dump

SC cavity for Injector

BERLinPro
(Berlin Energy Recovery LINAC Project)
First injector beam in 2015

Main Linac (3x7-cell)

6-MeV Injector

SRF Gun
1.5 - 2.0 MeV

Optics for recirculation path

Injector optimization

Halo simulation

Norio Nakamura, IPAC12, May 22, 2012
500 kV DC-gun (with GaAs cathode as the 1\textsuperscript{st} test) design is completed, and is funded by IHEP’s innovation program, its construction is started.

The 1\textsuperscript{st} 1.3 GHz 9-cell ILC type SC cavity (with large grain and low loss) has obtained 20 MV/m; the preliminary design of CW 7-cell cavity is done.

The conceptual design of the 35MeV-10 mA TF is almost completed, and is in the further improvement.
Plan view of Peking University Superconducting ERL Test Facility (PKU-SETF)

To demonstrate energy recovery, ERL-based FEL and radiation sources and ERL key technologies (DC SRF injector & Acceleration module)

Lattice and optics design updated

Norio Nakamura, IPAC12, May 22, 2012
eRHIC (future electron-hadron collider at RHIC)

- $E_{\text{max}} = 30 \text{ GeV (electron)}$, $L = 10^{33} - 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
- 6-turn ERL for acceleration/1-turn ERL for e-cooling
- Total linac length: 200 m
- Max. energy gain per pass: 2.45 GeV
- Accelerating gradient: 19.2 MV/m

SRF Linac

More than 14000 magnets

Compact magnets

Gap 5 mm total
0.3 T for 30 GeV

Norio Nakamura, IPAC12, May 22, 2012
ERL Test Facility at BNL

- Max. energy: 20 MeV
- Max. current: 0.5 A CW
- 704 MHz SRF gun
- 704 MHz 5-cell SC cavity
- Study items:
  - HOMs and BBU
  - Emittance growth
  - Halo
- First beam from SRF gun: September 2012
- First ERL beam: May 2013
Large Hadron electron Collider (LHeC)

Advantages of Linac-Ring option:

1. Higher luminosity potential up to $10^{34} \text{ cm}^{-2} \text{s}^{-1}$
2. Decoupling from LHC operation/infrastructure
3. Higher polarization degree of electrons
4. Reusable SC linacs for other projects

Draft CDR completed 2011, TDR by 2014, first beam by 2022

Norio Nakamura, IPAC12, May 22, 2012
Summary and Outlook

ERL-based Light Source Project at KEK
• 3-GeV ERL with 6-7 GeV XFEL-O
• Possible further upgrades in 300-m straight section
Combination of a multi-GeV ERL and an FEL seems promising.

Compact ERL project at KEK
• 35 MeV single loop for 1st commissioning in 2013
• R&D and construction in progress
Target specifications of key components are being satisfied.

ERL Projects around the World
• 10 - 100 MeV ERLs established as high-power IR and THz sources
• R&D toward future VUV to X-ray light sources and colliders
• Significant progress in ERL technologies and operational experiences
Encouraging us to work on further development for future ERL projects.
Thank you for your attendance in spite of the difficult situation after the Great East Japan Earthquake.

- The 50th ICFA Advanced Beam Dynamics Workshop on Energy Recovery Linacs
- Venue: KEK, Tsukuba, Japan
- Date: October 16 – 21, 2011
- Number of Participants: ~120
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