Development and Operation of the JAERI ERL
(Superconducting Energy Recovery Linac)

E. J. Minehara

FEL Laboratory at Tokai, APRC, Kansai
Japan Atomic Energy Research Institute
What is an Eenergy Recovery linac?

First, I would like to show you collected figures from Prof.T.Smith’s ERL05 Talk!

Then, I would like to talk my JAERI ERL-FEL.
Electrostatic ERL-FELs
University of California Santa Barbara (UCSB)
College of Judea and Samaria, Israel
Korea Atomic Energy Research Institute, South Korea (KAERI)
FOM Nieuwegein, the Netherlands

RF LINAC ERL-FELs (Operating)
Jefferson Lab, Newport News, Virginia, USA
JAERI, Ibaraki, Japan
BINP, Novosibirsk, Russia

RF LINAC ERL-FELs (Planned)
KAERI
4GLS
NHFML-Florida
SACLAY

RF LINAC ERL-FELs (Advanced Concepts)
MAX-lab
TESLA
BNL
Budker
Electrostatic Accelerator based ER-FELs

UCSB [NIM A237 (1985) 203-206]
KAERI [NIM A375 (1996) 28-31]

References = First Lasing
THE UCSB FREE-ELECTRON LASERS
A SOURCE OF TUNABLE, COHERENT, HIGH POWER FAR-INFRARED RADIATION

Center for Terahertz Science and Technology
University of California, Santa Barbara

http://sbfel3.ucsb.edu/
RF Linac based ER-FELs

(History)

S.O. Schreiber and E.A. Heighway (Chalk River)
Double Pass Linear Accelerator - Reflexotron
IEEE NS-22 (1975) (3) 1060-1064

D.W. Feldman et al, (LANL)
Energy Recovery in the LANL FEL
NIM A259 (1987) 26-30

T.I. Smith et al, (Stanford University)
Development of the SCA/FEL for use in Biomedical and Materials Science Research
NIM A259 (1987) 1-7
S.O. Schreiber and E.A. Heighway (Chalk River)

Double Pass Linear Accelerator - Reflexotron

IEEE NS-22 (1975) (3) 1060-1064
D.W. Feldman et al,

*Energy Recovery in the Los Alamos FEL*

Fig. 1. Energy-recovery beamline arrangement.
SCA as configured in 1986 for the Visible FEL Oscillator Experiment

FEL 1986 Oral Presentation
Operating RF Linac based ER-FELs

**JLab** [2004 FEL Conf. Proc., 229-232]
**JAERI** [2004 FEL Conf. Proc., 301-303]
**BINP** [2004 FEL Conf. Proc., 226-228]
JLab 10kW IR FEL and 1 kW UV FEL

**Output Light Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>IR</th>
<th>UV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength range (microns)</td>
<td>1.5 - 14</td>
<td>0.25 - 1</td>
</tr>
<tr>
<td>Bunch Length (FWHM psec)</td>
<td>0.2 - 2</td>
<td>0.2 - 2</td>
</tr>
<tr>
<td>Laser power / pulse (microJoules)</td>
<td>100 - 300</td>
<td>25</td>
</tr>
<tr>
<td>Laser power (kW)</td>
<td>&gt;10</td>
<td>&gt;1</td>
</tr>
<tr>
<td>Rep. Rate (cw operation, MHz)</td>
<td>4.7 – 75</td>
<td>4.7 – 75</td>
</tr>
</tbody>
</table>

**Electron Beam Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>IR</th>
<th>UV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy (MeV)</td>
<td>80-200</td>
<td>200</td>
</tr>
<tr>
<td>Accelerator frequency (MHz)</td>
<td>1500</td>
<td>1500</td>
</tr>
<tr>
<td>Charge per bunch (pC)</td>
<td>135</td>
<td>135</td>
</tr>
<tr>
<td>Average current (mA)</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>Peak Current (A)</td>
<td>270</td>
<td>270</td>
</tr>
<tr>
<td>Beam Power (kW)</td>
<td>2000</td>
<td>1000</td>
</tr>
<tr>
<td>Energy Spread (%)</td>
<td>0.50</td>
<td>0.13</td>
</tr>
<tr>
<td>Normalized emittance (mm-mrad)</td>
<td>&lt;30</td>
<td>&lt;11</td>
</tr>
<tr>
<td>Induced energy spread (full)</td>
<td>10%</td>
<td>5%</td>
</tr>
</tbody>
</table>

# JAERI ER-FEL

<table>
<thead>
<tr>
<th>Output Light Parameters</th>
<th>Achieved</th>
<th>Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength range (microns)</td>
<td>22</td>
<td>22</td>
</tr>
<tr>
<td>Bunch Length (FWHM psec)</td>
<td>15</td>
<td>6</td>
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<tr>
<td>Laser power / pulse (microJoules)</td>
<td>10</td>
<td>120</td>
</tr>
<tr>
<td>Laser power (kW)</td>
<td>0.1</td>
<td>10</td>
</tr>
<tr>
<td>Rep. Rate (MHz)</td>
<td>10.4</td>
<td>83.2</td>
</tr>
<tr>
<td>Macropulse format</td>
<td>10ms 10Hz</td>
<td>CW</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Electron Beam Parameters</th>
<th>Achieved</th>
<th>Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy (MeV)</td>
<td>17</td>
<td>16.4</td>
</tr>
<tr>
<td>Accelerator frequency (MHz)</td>
<td>500</td>
<td>500</td>
</tr>
<tr>
<td>Charge per bunch (pC)</td>
<td>500</td>
<td>500</td>
</tr>
<tr>
<td>Average current (mA)</td>
<td>5</td>
<td>40</td>
</tr>
<tr>
<td>Peak Current (A)</td>
<td>33</td>
<td>83</td>
</tr>
<tr>
<td>Beam Power (kW)</td>
<td>85</td>
<td>656</td>
</tr>
<tr>
<td>Energy Spread (%)</td>
<td>~0.5</td>
<td>~0.5</td>
</tr>
<tr>
<td>Normalized emittance (mm-mrad)</td>
<td>~40</td>
<td>~40</td>
</tr>
<tr>
<td>Induced energy spread (full)</td>
<td>~3%</td>
<td>~3%</td>
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</tbody>
</table>

## Output Light Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength range (microns)</td>
<td>120-180</td>
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<tr>
<td>Bunch Length (FWHM psec)</td>
<td>50</td>
</tr>
<tr>
<td>Laser power / pulse (microJoules)</td>
<td>9</td>
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<tr>
<td>Laser power (kW)</td>
<td>0.2</td>
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<tr>
<td>Rep. Rate (cw operation, MHz)</td>
<td>22.5</td>
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## Electron Beam Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy (MeV)</td>
<td>12</td>
</tr>
<tr>
<td>Accelerator frequency (MHz)</td>
<td>180</td>
</tr>
<tr>
<td>Charge per bunch (pC)</td>
<td>900</td>
</tr>
<tr>
<td>Average current (mA)</td>
<td>20</td>
</tr>
<tr>
<td>Peak Current (A)</td>
<td>10</td>
</tr>
<tr>
<td>Beam Power (kW)</td>
<td>240</td>
</tr>
<tr>
<td>Energy Spread (%)</td>
<td>0.2</td>
</tr>
<tr>
<td>Normalized emittance (mm-mrad)</td>
<td>20</td>
</tr>
</tbody>
</table>

Planned

RF Linac based ER-FELs

4GLS [M.W. Poole et al, PAC 2003]
NHMFL [Proposal to NSF (Jan 2005)]
SACLAY [M.E. Couprie et al, EPAC 2004]
<table>
<thead>
<tr>
<th><strong>Output Light Parameters</strong></th>
<th><strong>Goal</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength range (microns)</td>
<td>3-20</td>
</tr>
<tr>
<td>Bunch Length (FWHM psec)</td>
<td>20-50</td>
</tr>
<tr>
<td>Laser power / pulse (µJoules)</td>
<td>50-250</td>
</tr>
<tr>
<td>Laser power (kW)</td>
<td>1-5</td>
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<tr>
<td>Rep. Rate ( MHz)</td>
<td>22</td>
</tr>
<tr>
<td>Macropulse format</td>
<td>CW</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Electron Beam Parameters</strong></th>
<th><strong>Goal</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy (MeV)</td>
<td>20-40</td>
</tr>
<tr>
<td>Accelerator frequency (MHz)</td>
<td>352</td>
</tr>
<tr>
<td>Charge per bunch (pC)</td>
<td>500</td>
</tr>
<tr>
<td>Average current (mA)</td>
<td>10</td>
</tr>
<tr>
<td>Peak Current (A)</td>
<td>10-25</td>
</tr>
<tr>
<td>Beam Power (kW)</td>
<td>200-400</td>
</tr>
</tbody>
</table>

ERL Prototype

Electron Beam Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy (MeV)</td>
<td>30-50</td>
</tr>
<tr>
<td>Accelerator frequency (MHz)</td>
<td>1300</td>
</tr>
<tr>
<td>Charge per bunch (pC)</td>
<td>&gt;80</td>
</tr>
<tr>
<td>Average current (mA)</td>
<td>&gt;0.8</td>
</tr>
<tr>
<td>Peak Current (A)</td>
<td>~150</td>
</tr>
<tr>
<td>Beam Power (kW)</td>
<td>~30</td>
</tr>
</tbody>
</table>

Output Light Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength range (microns)</td>
<td>3-75</td>
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<tr>
<td>Bunch Length (FWHM psec)</td>
<td>0.1-few</td>
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<tr>
<td>Laser power / pulse (µJoules)</td>
<td>90</td>
</tr>
<tr>
<td>Laser power (kW)</td>
<td>0.9</td>
</tr>
<tr>
<td>Rep. Rate (MHz)</td>
<td>10</td>
</tr>
<tr>
<td>Macropulse format</td>
<td>CW</td>
</tr>
</tbody>
</table>

M.W. Poole et al, PAC 2003 4GLS: A new type of 4th generation light source facility
SACLAY

(ARC-EN-CIEL: Accelerator-Radiation Complex for ENhanced Coherent Intense Extended Light)

1. JAERI FEL Developmental Strategy  3 steps and NEXT

JAERI non ERL and ERL FELs

#1st STEP  Super-Conducting Linac FEL Driver without ERL
1989-1995  Powerful FEL Driver
Other Possible e-Beam Applications

#2nd STEP  Most Powerful FEL Lasing without ERL
1996-2000  Laser beam Applications

#3rd STEP  ERL-FEL  Efficient FEL Lasing  Under Development
2001-2005  Large-scaled Laser Beam Applications
Nuclear Energy Industries

Next STEP  ERL-LS  Conceptual Design and Key Components
JAERI FEL Research Program, Past, Present and Future

JAERI SC-FELs Program and Steps

1990 — 1996
Ideal SC Linac Driver for FELs 100kW

1996 — 1997
FEL Highest Efficiency FEL Highest Power 1kW

1998 — 2001

2002
quasiCW-SC-LINAC FEL

2002
2.3kW Exceed the Goal quasiCW

Energy Recovery CW 20 MeV 200 kW

L/S bands High Eacc qCW-SC-LINAC

60nm Goal
1 GeV 0.1A UV/SX

0.1nm 2005

6nm Goal
6 GeV 0.1A X/HX

2007
ERLSR Energy Recovery Linac-based Light Source

0.1nm 目標
X-ray FEL 2017

10kW Goal 2004

10kW Goal quasiCW

100kW Goal 2005

30kW Goal 2004

1 MW Goal

No Recovery

Full Recovery

CW Industrial Linac Irradiator
Beam Power 10kW—10MW

Industrial Irradiator 2002

Industrial FEL 2006

1 GeV 0.1A UV/SX

10kW Goal 2005

10kW Goal

30kW Goal

1 MW Goal
#1\textsuperscript{st} STEP JAERI Non ERL Super-Conducting Linac FEL Driver

\textsim 100kW Beam Power for FEL Lasing

UHF SC Linac Driver and JAERI FEL at Tokai

Since 2001 April the JAERI FEL was shut-down and was under construction to assemble Energy Recovery Loop.

Old FEL Experimental Hall

Old FEL Main Accelerator Vault
#2nd STEP Toward the Most Powerful FEL Lasing  Up to Over 2kW

High Power FEL Road Map

10 MW
1 MW
100 kW
10 kW
1 kW
0.1 kW
100 W
10 W
1 W
0.1 W
10 mW
1 mW

- Non-Radioactive FEL
- Beam Energy Recovery FEL
- JAERI 2.34 kW
- J Lab 1.7 kW
- JAERI 0.1 kW
- Normal Linac FEL
- Academic / THz Science and Technology
- Academic / Ecology
- Medical Applications
- Photochemistry
- Light and Fine Metal Machinery
- Heavy Metal Machinery / Shipbuilding
- Civil Engineering / Construction
- Energy Beaming
- 10 Times Per Every 2 Years

FELのReinvention

Year

FELパワーティマックス

FEL夏米効率

高強度超放射発振の発見

少数サイクル=高効率=豊富力発振

強度

255フレムト秒 /3.4サイクル
#2\textsuperscript{nd} STEP Toward the Most Powerful FEL Lasing  
Up to Over 2kW

Energy = 16.5MeV  
Bunch charge = 510pC  
Bunch length < 5ps  
Bunch rep. = 10.4125MHz  
FEL l = 16-23\textmu m  
FEL power = 2.34kW  
High-efficiency  \( \eta = 6\% \)

ultrashort pulse  
255fs (FWHM) = 3.4 cycles
#3rd STEP ERL-FEL  Most Efficient FEL Lasing   Up to 10kW

JAERI Energy-Recovery Linac for 10kW FEL

- Natural extension of the original configuration.
- 8 times larger e-beam power.
- Fitting to the concrete boundary.

Energy = 17MeV
FEL : $\lambda \approx 22\mu m$
Bunch charge = 500pC
Bunch length = $\approx 15ps$ (FWHM)
Bunch rep. = 10.4MHz – 83.3MHz
Average current = 5.2mA – 40mA

*after injector upgrade*
JAERI ERL-FEL
Under Commissioning

Main Accelerator
Undulator
Energy Recovery Loop
Merger Magnets
Injection Beam Line
Design of JAERI ERL

Return arc --- triple bend, 180 degree arc.

- Variable $R_{56}$ for energy-spread compression.
- Sextupoles to compensate second-order aberrations: $T_{166}$, $T_{266}$, $T_{566}$.
- Energy acceptance is 7% (full-width) for $\varepsilon_n=30\text{mm-mrad}$. 
Design of JAERI ERL

Injection merger --- two-step staircase.

- Achromaticity is realized by three quads.
- Small angle (22.5 deg.) injection is preferable for small emittance.
- But, performance is sensitive to quads parameters.

Horizontal slit (2.5mm)
Demonstration of Energy Recovery

Beam current at the exit of the second main module.

Bunch interval is 96ns, and recirculation time is 133ns.

RF amp forward power for the 1st main module.

Beam loading is almost completely compensated by energy-recovery.
FEL Lasing with the ERL configuration


FEL power is still low about \( \sim 0.1\text{kW} \).

Gain, loss, spectral measurements have not been done, yet.

Macropulse structures suggest that single-supermode and superradiance appear depending on \( \Delta L \).

Cavity length detuning curve.
Study on CSR-induced emittance growth

CSR in a return arc --- dominant source of emittance growth in ERLs.

New analytical approach -- R-matrix

applicable to design “GeV ERLs”.

R. Hajima, MOP15020.

for JAERI-ERL (17MeV)

CSR effects depends on the beam envelope in the arc.

emittance measurements are in preparation
Upgrading in Injector

Original
0.5nC x 10.1425MHz = 5mA

After
0.5nC x 83.3MHz = 40mA

• New RF sources for the injector.

• New grid pulser for the e-gun

20MHz operation is OK.

IOT-klystrode (50kW)

0.5nC x 83.3MHz = 40mA

P(FEL)~10kW

P(beam)~680kW

50kW 50kW

6kW originally

N. Nishimori et al. (THP-16029)
Improvement of RF Stability — new low-level controllers and reference-signal cables

Phase drift $\sim 3 \text{ deg./}^\circ\text{C}$

Phase jitter $\sigma = 0.78 \text{ deg.}$

Phase drift $< 0.2 \text{ deg.}$

Phase jitter $\sigma = 0.15 \text{ deg.}$
Study on HOM-BBU

Beam break-up by transverse HOM is the dominant phenomenon to limit the ERL beam current.

JAERI-ERL(500MHz) accepts HOM power larger than L-band ERLs.


HOM-BBU is not a matter in JAERI-ERL. But, it is useful to study HOM-BBU for future ERLs.
2. Refrigerator and Cryogenic Operation of JAERI SCA

JAERI Stand-alone Zero-Boil-Off Cryostat = Liq.He Container with refrigerators

A Stand-alone & Zero-boil-off Cryogenics = Big Dewar with Refs
Easiness in Maintenance and Operation of JAERI ERL-FEL

**NonStopLowTempOperation or NoWarm-up Op**

Possible Only for the JAERI Stand-Along & Zero-Boil-Off ERL-SC linac,

1) **Cold Maintenance** for Both Shield Cooler & Recondenser within a few tens minutes
2) **No Liq.He Loss**, 24hours **Over 10-20years Continuous Operation. No need to reload**
3) **No Regulation** of Domestic Pressure Vessel Code required for the Cold Maintenance

**Bonus of the No Warm-up:** (1) **No Conditioning Required** After the first, (2) **Nearly No Deterioration** of all the Cryogenic Components and Conditions, (3) **Always Ready** to fire,
#5 Whole Cryostat System Cold Over Twenty Years/Cold Maintenance

1996–1997 One Year Operation Statistics of Refrigerator

- Unscheduled
  - Stop: 0.82%
  - 3 days: 1.37%
  - 5 days: 1.37%
- Scheduled
  - Stop: 0.55%
  - 2 days

Figure 3a: Statistics of the cryogenic system operation in 1997 Japanese fiscal year.

#6 Non-Stop and Continuous Operation of Cryogenic Refrigerator System Except for Unscheduled Emergency or Power Failure

2.6 Years Operational Statistics / Hours

- Operation from 2001 to 2003: 22360 hours
- 5.6 hours Maintenance
- 1.2 hours Scheduled Failure
- 5.2 hours Unscheduled Failure

Figure 3b: Statistics of the cryogenic system operation in 2001-2003 Japanese fiscal year.
COLD GM Refrigerator Maintenance Pictures

Before the Cold Maintenance

GM Refrigerator Engine in the Cryostat

Lift the GM Engine inside Plastic Bag
Q (T) is linked to the BCS surface resistance

\[ R_s = A f^2 \exp \left( -\Delta / kT \right) \left( + R_0 \right) \]

- \( R_s \): BCS surface resistance
- \( A \): material constant
- \( k \): Boltzmann constant
- \( f \): frequency
- \( T \): temperature
- \( \Delta \): BCS energy gap
- \( R_0 \): residual resistance

1.5 K is taken here as a reasonable lower limit of BCS Q=Q(T) dependence

Diagramm taken from:

Review of Models of RF Surface Resistance in High Gradient Niobium Cavities for Particle Accelerators

P. Bauer
Fermilab, Technical Division

TD-04-014, June 2004

ERL2005  Bernd Petersen DESY
Combination between Zro-Boil Off Cryostat and Large Scale 2K and 4K External Liquefier

#7 Long-Life and Static Pulse Tube /GM Refrigerator System for Idling
Stand-Alone, Zero-Boil Off Superconducting rf Linac FEL Driver

Large Scale Liquefier Cases

JAERI Design

Large N2 Liquefier & Circulating Loop

Shield Cooler PT/GM

24hrs/3 months Continuous Operation x 3 Maintenances
Over-Night Operation 10-20 operators

Unmanned Semi-Infinite Continuous Operation

Liq. He Recondensor

Large He Liquefier & Circulating Loop

#8 External Huge Refrigerator for Routine and High Power Operation

ZBO Refrigerator System for Idling & Routine
Always Running

Shield Cooler Recondensor

ERL Linac Cryostat

External Huge Refrigerator for Routine

Only for
#7 Long-Life and Static Pulse Tube /GM Refrigerator System for Idling Stand-Alone, Zero-Boil Off Superconducting rf Linac FEL Driver

Large-Scale Liquefier Cases
- Large N2 Liquefier & Cirulating Loop
- Large He Liquefier & Cirulating Loop

JAERI Design
- Unmanned Semi-Infinite Continuous Operation
  - 24hrs/3months Continuous Operation x 3 Maintenances Over-Night Operation
  - 10-20 operators

Liq. He Recondensor
- Shield Cooler PT/GM
#8 External Huge Refrigerator for Routine and High Power Operation

ZBO Refrigerator System for Idling & Routine Always Running

ERL Cryostat

Shield Cooler  Recondensor

External Huge Refrigerator Usable for Routine User Operation

Only for High Power
2K Cooling Scheme (simplified)

Primary Power

0.5 bar  T cc out

Cold Compressors

P cc in  T cc in

P bath  JT

T bath = f (P bath)

4.5 K load

40/80 K load

ERL2005 Bernd Petersen DESY
2. ERL Time Table and Required Refrigerator System

**Present Status ERL-FEL 20MeV Quasi CW Operation**
- 4K Zero-Boil Off Small Refrigerator
- 4.2K-32W/50Hz48W/60Hz, 20K-80W, 80K-560W Semi-Perpetual Non-Stop Cooling Operation
- No Liquefier – Like Air-Conditioner, No Commissioning Inspection, No Open Inspection

2005-2006

**Modification ERL-FEL 20MeV CW 4K Hybrid Refrigerator System**
- 4K-200W Large Liquefier+10K/65K-200W Small GM Refrigerator
- Semi-Perpetual Non-Stop Cooling Operation
- Liquefier Regulation, Required a governmental Commissioning Inspection, regular Open Inspection per 3 years

2006-2007

**Construction ERL-LS Prototype 200MeV CW 1.8K/1.6K Hybrid Refrigerator System**
- 1.8K/1.6K-400W Large Liquefier+4K/10K Small GM Refrigerator +65K PT Refrigerator Semi-Perpetual Non-Stop Cooling Operation
- Liquefier Regulation, Required a few governmental Commissionings Inspection every year

2010-2011

**Construction ERL-LS 6GeV CW 1.8/1.6K Hybrid Refrigerator System**
- 1.8K/1.6K-6kW/3kW Large Liquefier+4K/10K Small GM Refrigerator +65K PT Refrigerator Semi-Perpetual Non-Stop Cooling Operation
- Liquefier Regulation, Required a few governmental Commissionings Inspection every year

A Stand-alone Zero-boil-off Cryogenics

=Big Dewar with Refs

The JAERI stand-alone, zero-boil off cryostat has duplex heat shields, and the shield-cooler and Bi-secendenser refrigerators integrated into the cryostat vacuum vessel.
Current Activities:

- Upgrading from Over2 kW to 10kW Class Lasing
- DC gun Capacity Improvement from 5mA to >40mA
- PreAccelerators RF Amplifier Upgrading from 6kW to 50kW
- Main RF Amplifier Upgrading from Transister to IOT CW capability
- Amplitude and Phase Control Circuit Improvement
- Reproducibility and Accuracy Up to 0.1 Degree and 0.1%
- PC-based Control System Upgrading
  - Reliable and High Level Control Capability
- Beam Monitor Upgrading from Destructive to Non-Destructive
- Cable Network Upgrading to Low Temperature Coefficient Cable and
  Temperature Stabilized Network
- FEL Optical Transport System to FEL Experiment Rooms
4. JAERI ERL Future Plans and Programs

Historicals and Strategies
ERLs at JAERI

#1st STEP
Non-ERL SCLinac FELDriver
1989 1995

#2nd STEP
Most Powerful FEL
1996 2000

#3rd STEP
Most Efficient ERL FEL
2001 2005

2007

#4th NEXT STEP
HighPower ERL-FEL

2009 2013

2038

ERL-LS

2007
6GeV ERL light source planned in Japan

linac = 20MV/m x 457m x (300/457)
arc = 12deg. x 15 x 2
straight section = 5m x 20 + 27m x 10 + 270m

ERL light Source planned Site where is located in 140km North East from Tokyo, a several km from Tokai.
6GeV-ERL NEXT Generation Light Source in Japan

SASE-XFEL (option)

seeded-XFEL (option)

Injector

Beam Dump

ERL SC linac
1. Superconducting Energy Recovery Linac (ERL) based FEL and Next Generation ERL Light Source Development

1. ERL-Proof Of Principle Demonstration
   Tunable, Ultra-short, High Average Power, Highly Efficient
   Superconducting Energy Recovery (ERL) FEL, Many Fields of Academic Uses and Industrial Applications

2. ERL Technology and Next Generation Light Source Developmental Program (0.2GeV-ERL Prototype)

   Start the User Experiments and Industrial Applications

1989-2005 Japanese Fiscal Year 20MeV ERL-FEL
2006-2009 JFY 200MeV ERL Prototype
2010-2013 JFY 6GeV ERL Light Source
JAERI ERL Contributions in the Workshop Related with ERL-LS

#1 State-of-the-Art: Optics and Beam Transport  R. Hajima
#2 Linear matrix analysis of electron beam dynamics for the CSR effect in an ERL recirculation loop R. Hajima
#3 Multi-parameter optimization of an ERL injector R. Hajima, R. Nagai
#4 Velocity bunching in a main linac of ERL R. Hajima, H. Iijima
#5 Preliminary result of diamond film secondary-emission cathode T. Nishitani, E. J. Minehara, R. Hajima
#6 Beam-based Alignment with HOM couplers M. Sawamura and R. Nagai
#7 Status of RF system for the JAERI Energy-Recovery Linac FEL M. Sawamura and R. Nagai
#8 Cryostat Design Consideration of the Energy Recovery Super-conducting Linac (ERL) Driven Light Sources and FELs E. J. Minehara
#9 Preliminary Report on Single and Multi-Crystal Diamond Electron Cathodes E. J. Minehara
#10 BBU codes overview M. Sawamura
#11 JAERI gun, and #12 Superlattice GaAs photo cathode T. Nishitani
One Typical Example of our ERL LS Activities of Beam optics and Beam Transport at JAERI

ERL05 State-of-Art Optics and Beam Transport Ryoichi Hajima, JAERI
### Outline

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(Injector will be discussed in WG-1)

#### Beam parameters
- high average current
- small emittance
- short bunch
- stability

Design and optimization methods to obtain beam parameters as we need, without any harmful phenomena.

Technological challenge for each component.
Beam optics & dynamics in ERLs

Advantages of ERLs
- high-average current
- small emittance, short bunch

Beam transport design issues

- Preserving emittance through injector – merger – linac – recirc. loop
- Bunch compression scheme
- Disturbance on beam motions
  - short-range (single-bunch) disturbance = space charge, CSR, wakes
  - long-range (multi-bunch) disturbance = HOM-BBU
Linac focusing optimization

5GeV-ERL design study
CHESS Tech-memo 01-003, JLAB-ACT-01-04

6GeV-ERL design study

$E_{\text{acc}} = 20 \text{MV/m}$

$\Delta f_{\text{HOM}} = 1 \text{MHz}$
Bunch compression during an arc

\[ \rho = 25 \text{m}, R_{56} = 2 \text{cm / cell}, 12\text{-deg-TBA-cell} \times 15 \]

\[ \sigma_t = 3.3 \text{ps} \rightarrow 100 \text{fs} \quad \sigma_{E/E} = 0.34\% \]

- fairly linear compression with second-order correction by sextupoles
- however, relatively large energy spread remains, emittance growth by CSR effects exist.
Velocity bunching in a main linac

\[ \sigma_t = 15 \text{ps} \rightarrow 3 \text{ps} \rightarrow 170 \text{fs} \text{ (after 9-cell x 8-cavity)} \]

- smaller energy spread than compression in a half-arc
- average current is restricted by imperfect energy-recovery
  --- 5mA for typical design.

details are presented at WG2 session.
High power ERL-FEL Applications for Nuclear Energy Industries and Other Heavy Industries

1. Nuclear Reactor De-Commissioning Application

2. Cold-Worked Stress Corrosion Cracking Prevention
   Maybe Applicable to Many Other Fields
Decommissioning of the Nuclear power Plants

Narrow Cutting and Low RI Contamination Using 100kW High Power FEL

Laser Narrow Cutting

100kW High Power ERLFEL

Decommissioning
Nuclear Energy Industry Applications

Prevention of Cold-Worked SCC

Femtosecond laser pulses can remove the cold-working hardened layer without thermal effects.

Repetitive femtosecond laser pulses
Energy fluence of 0.1~1 J/cm²

CWSCC of Core Shroud of BWR Tokyo Electric Company (SUS316L)
JAERI-Femtosecond High Average Power FEL Removes Residual Tensile Stress and Susceptible Materials without Heat Generation- Prevention of SCC and improve BWR lifetime and Safety

Femtosecond High RepitionJAERI-FELIrradiates Low Carbon Stainless Steel to Prevent CWSCC

Core Should

Recirculating ppings

Adopt Cold Worked Compenents

Modified Non-Susceptible Surface (MgCl2 SCC Test Results)
3. Chemical Reaction Control -

Harmful Chemicals Decomposition

Isotope and Element Separation

for chemical processes

 decomposition of PCDD

T. Yamauchi, Kankyo Kagakukai- Shi 14, 567 (2001)

more efficient method --- using chirped FEL pulses

S. Chelkowski et al., PRL 65, 2355 (1990).
Summary

#0 Brief Introduction of ERL Examples
#1 Past and Current Activities of JAERI ERL FEL Development and Operation, Especially About Cryogenics and some items
#2 Activities in the 10kW Upgrading Beam Power from 100kW to 800kW
#3 Preliminary Results of Nuclear Energy Industry Applications CWSCC prevention, Decommissioning in Nuclear Reactors
#4 Some JAERI ERL Activities will be itemized as in the ERL05 Workshop Conceptual Design Activities of ERL-LS like HOM-BBU, CSR etc, PC gun Activities As Key Components