ERL Project
KEK/IMSS

Operational Progress in Compact-ERL and Development of ERL-FEL for EUV Light Source at KEK

ERL project Office, KEK

Hiroshi KAWATA

Contents

- Progress in Compact-ERL
- Design study of ERL-FEL for EUV light Source

cERL Team

High Energy Accelerator Research Organization (KEK)
M. Adachi, S. Adachi, T. Akagi, M. Akemoto, D. Arakawa, S. Araki, S. Asaoka, K. Enami,K. Endo, S. Fukuda, T. Furuya, K. Haga, K. Hara, K. Harada, T. Honda, Y. Honda, H. Honma, T. Honma, K. Hosoyama, K. Hozumi, A. Ishii, X. Jin, E. Kako, Y. Kamiya, H. Katagiri, R. Kato, H. Kawata, Y. Kobayashi, Y. Kojima, Y. Kondou, T. Konomi, A. Kosuge, T. Kubo, T. Kume, T. Matsumoto, H. Matsumura, H. Matsushita, S. Michizono, T. Miura,T. Miyajima, H. Miyauchi, S. Nagahashi, H. Nakai, H. Nakajima, N. Nakamura, K. Nakanishi,K. Nakao, K. Nigorikawa, T. Nogami, S. Noguchi [on leave], S. Nozawa, T. Obina, T. Ozaki, F. Qiu,H. Sagehashi, H. Sakai, S. Sakanaka,S. Sasaki, K. Satoh, M. Satoh, Y. Seimiya, T. Shidara, M. Shimada, K. Shinoe, T. Shioya,T. Shishido,M. Tadano, T. Tahara, T. Takahashi, R. Takai, H. Takaki, O. Tanaka, T. Takenaka,Y. Tanimoto, N. Terunuma, M. Tobiyama, K. Tsuchiya,T. Uchiyama, A. Ueda, K. Umemori, J. Urakawa,K. Watanabe, M. Yamamoto, N. Yamamoto, Y. Yamamoto, Y. Yano, M. Yoshida

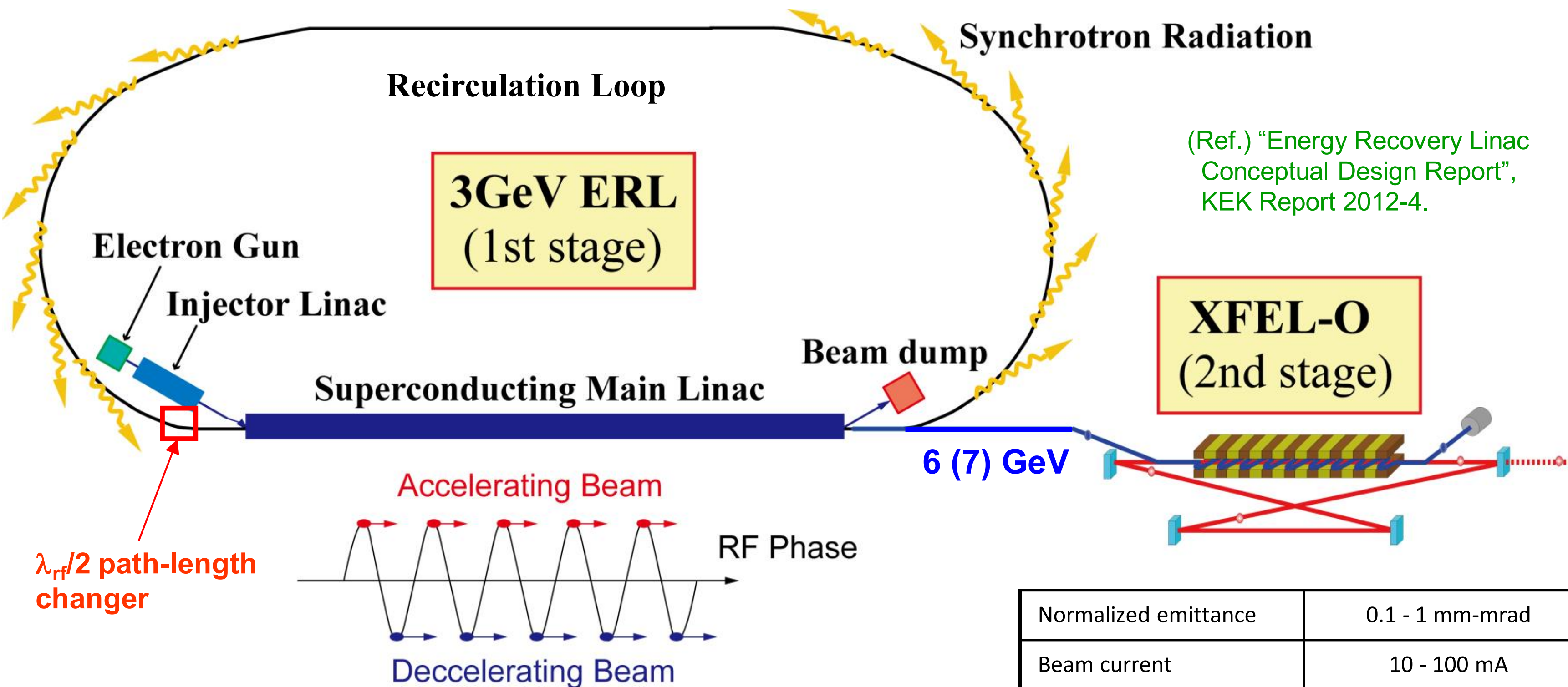
Japan Atomic Energy Agency (JAEA)
R. Hajima, S. Matsuba [on leave], M. Mori, R. Nagai, N. Nishimori, M. Sawamura, T. Shizuma

Hiroshima University
M. Kuriki

The Graduate University for Advanced Studies (Sokendai)
E. Cenni [on leave]

2

Future Plan: ERL Light Source Project at KEK



Normalized emittance	0.1 - 1 mm-mrad
Beam current	10 - 100 mA
Bunch charge	7.7 - 77 pC
RF frequency	1.3 GHz

3 GeV ERL

- Diffraction-limited X-ray source
- Ultra-short-pulse light source
- Driver for XFEL-O (2nd stage)

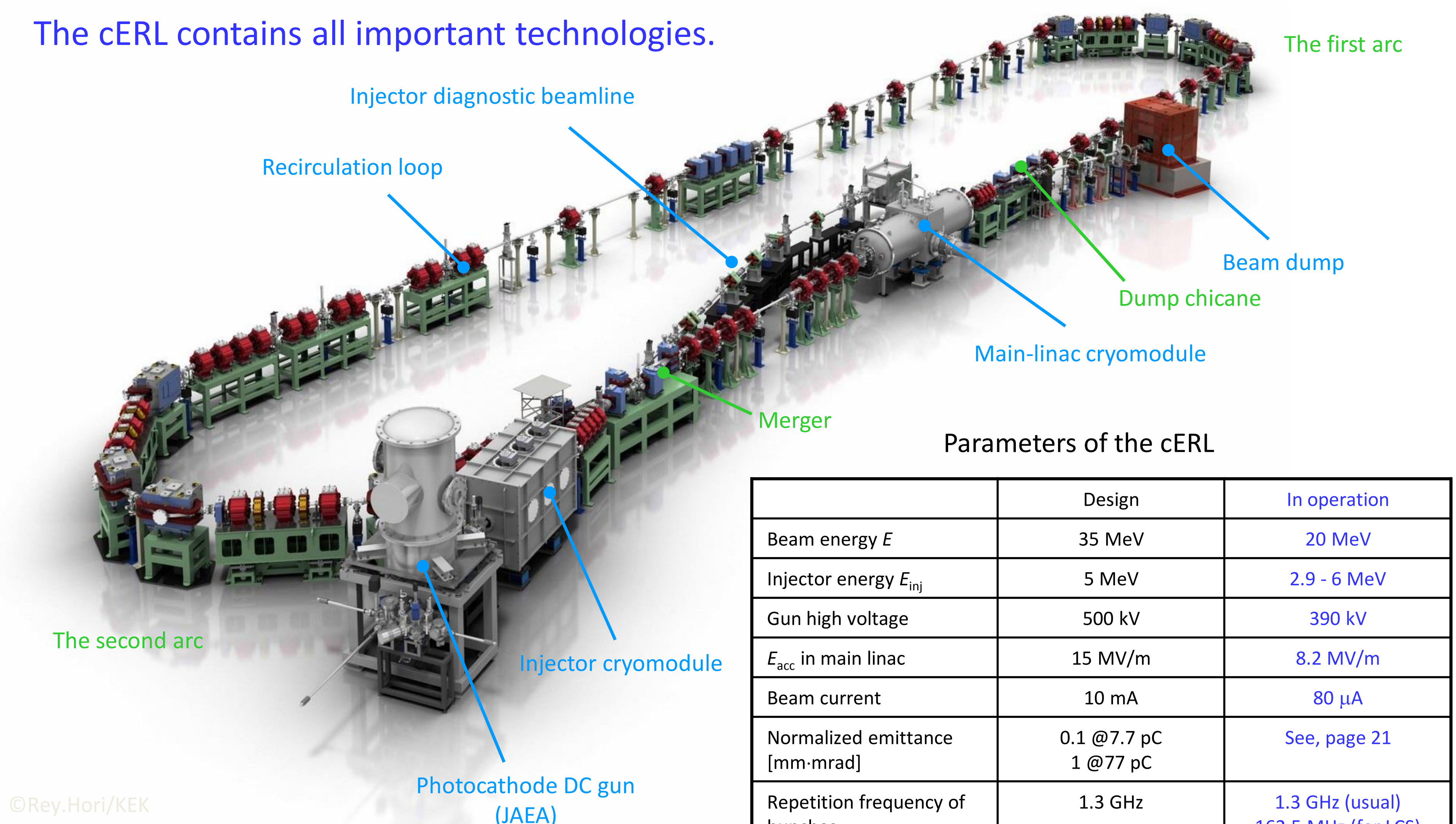
← demonstrate

The Compact ERL

- Injector (low ε, high I_0)
- Main linac (CW, ~15 MV/m)
- Beam dynamics
- Beam losses

The Compact ERL (cERL)

The cERL contains all important technologies.

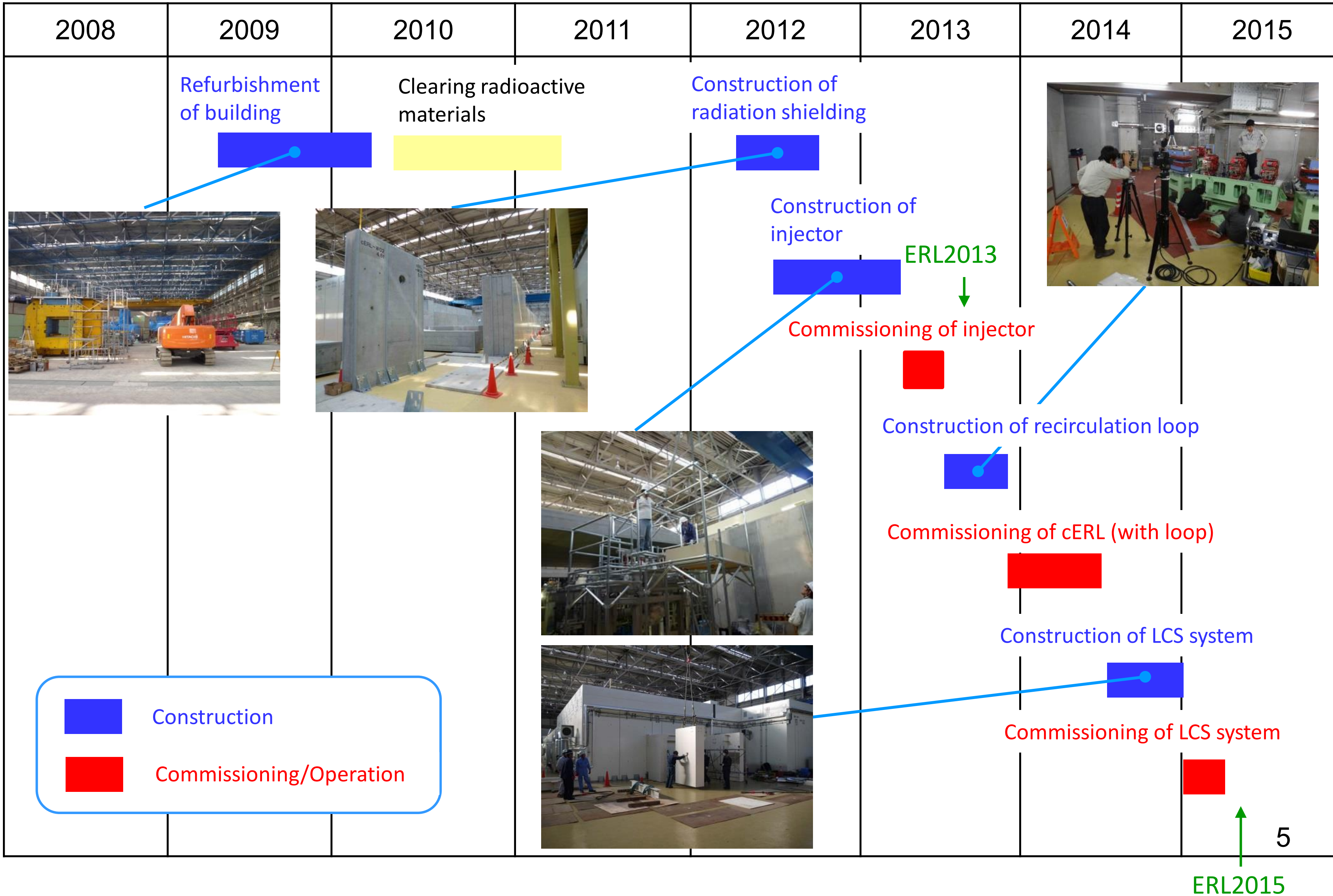


Circumference: ~ 90 m

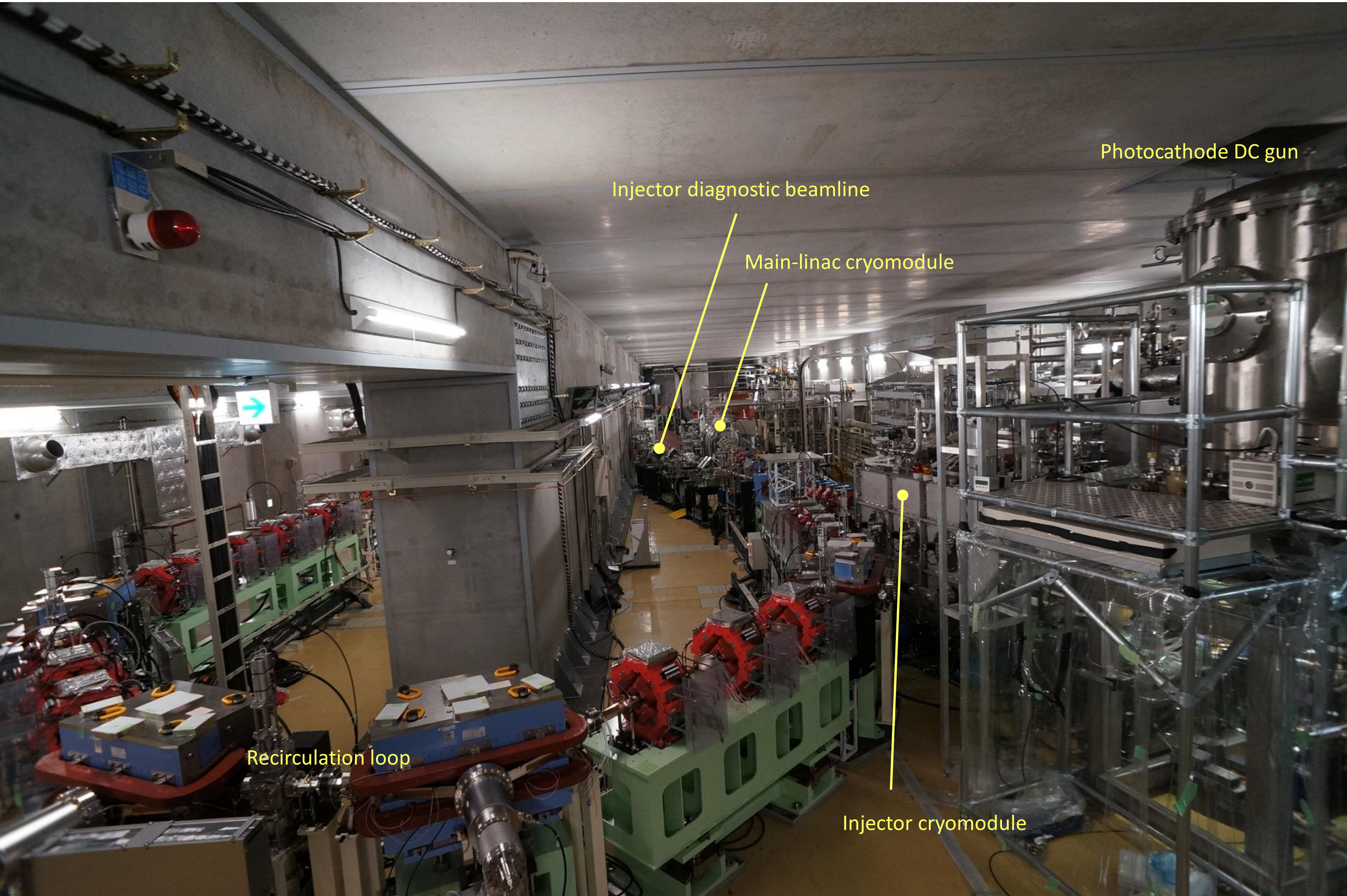
Parameters of the cERL

	Design	In operation
Beam energy E	35 MeV	20 MeV
Injector energy E_{inj}	5 MeV	2.9 - 6 MeV
Gun high voltage	500 kV	390 kV
E_{acc} in main linac	15 MV/m	8.2 MV/m
Beam current	10 mA	80 μA
Normalized emittance [mm·mrad]	0.1 @7.7 pC 1 @77 pC	See, page 21
Repetition frequency of bunches	1.3 GHz	1.3 GHz (usual) 162.5 MHz (for LCS)
RMS bunch length	1-3 ps (usual) ~ 100 fs (compress.)	1-3 ps (usual)
Max. heat load at 2K	80 W	80 - 100 W

Construction and Commissioning of cERL



Picture of the cERL



The First Transportation of Beams to the Dump (Feb. 6, 2014)

Beam energy (E)

- Injector: 2.9 MeV
- Recirculation loop: 19.9 MeV

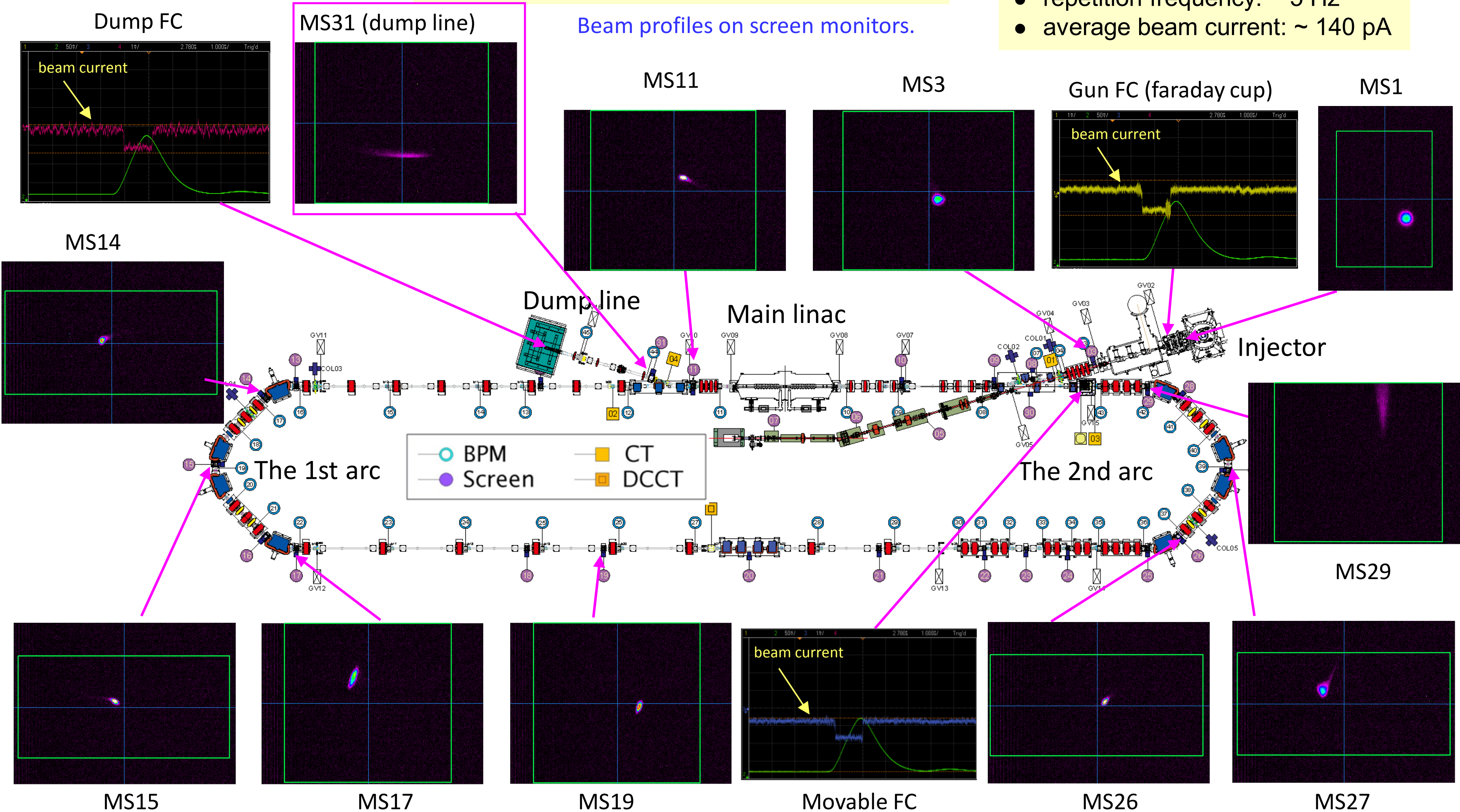
Parameters

- Gun voltage: 390 kV   Buncher: OFF
- Injector cavities: E_{acc} = (3.3, 3.3, 3.1) MV/m
- Main-Linac cavities: V_c = (8.57, 8.57) MV

Beam pulses (macropulse)

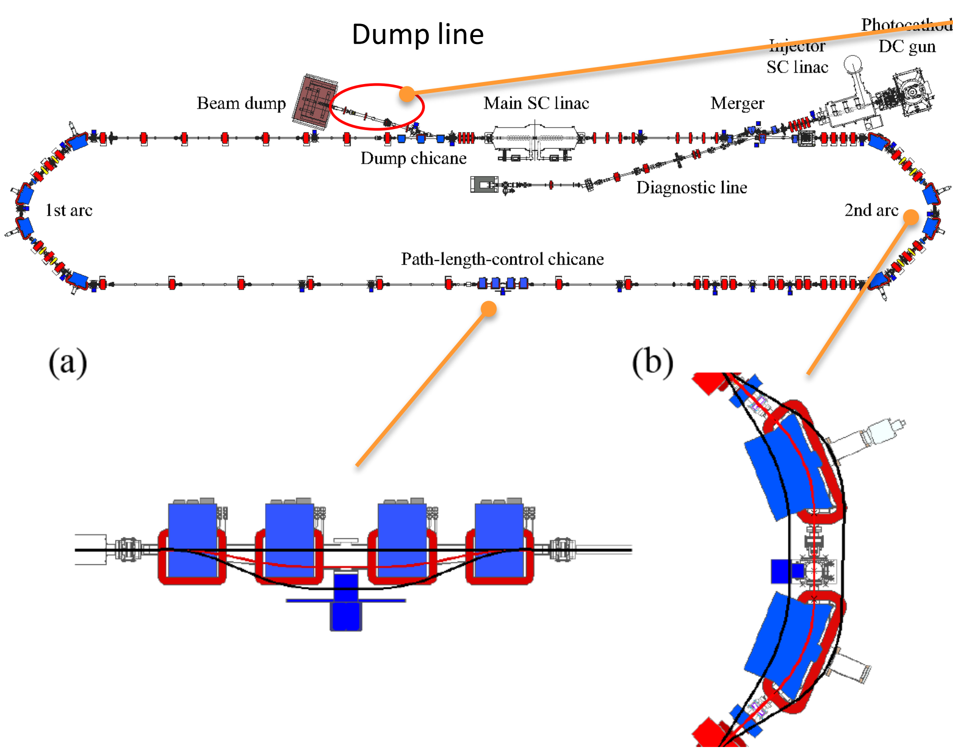
- peak current: ~24 μA
- macropulse width: 1.2 μs
- repetition of bunches: 1.3 GHz
- repetition frequency: 5 Hz
- average beam current: ~ 140 pA

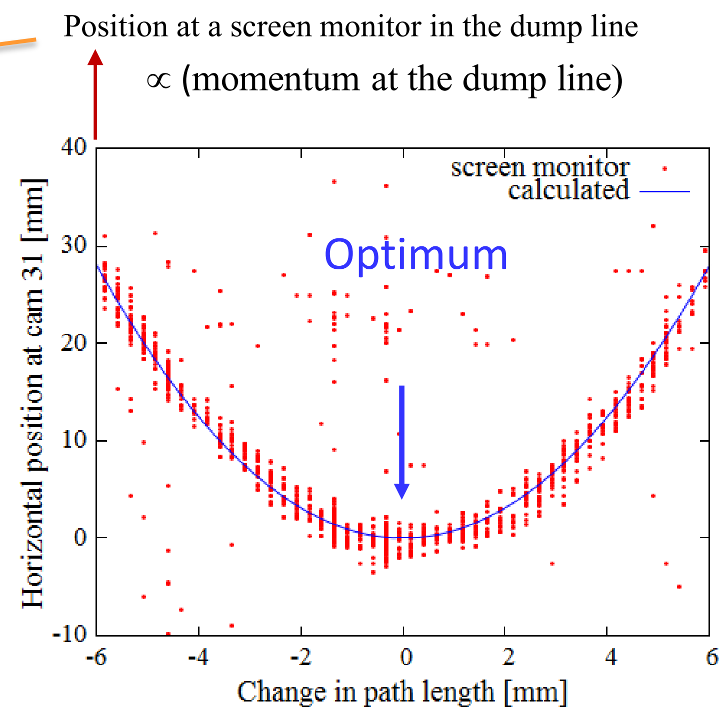
Beam profiles on screen monitors.



Correction of Path Length for Optimum Energy Recovery

- Two measures for path-length correction were prepared
- Path length was corrected so that the beam momentum took a minimum at the dump line





Path-length control chicane

- Tuning range: ±5 mm
- Large hysteresis
- Currently fixed

Orbit bump in the arc

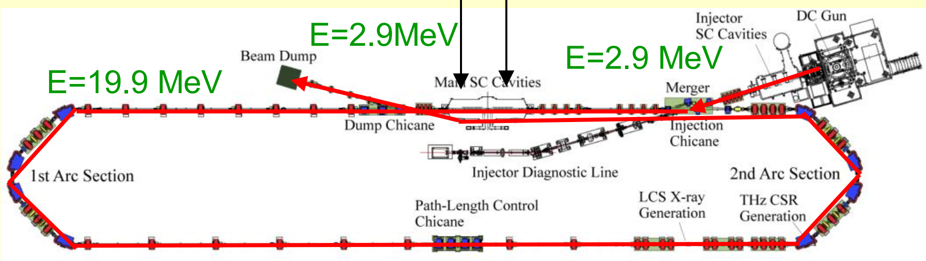
- Tuning range: ±10 mm/arc
- Routinely used

Determination of an optimum path length

Demonstration of Energy Recovery (I_0 = 30 μA)

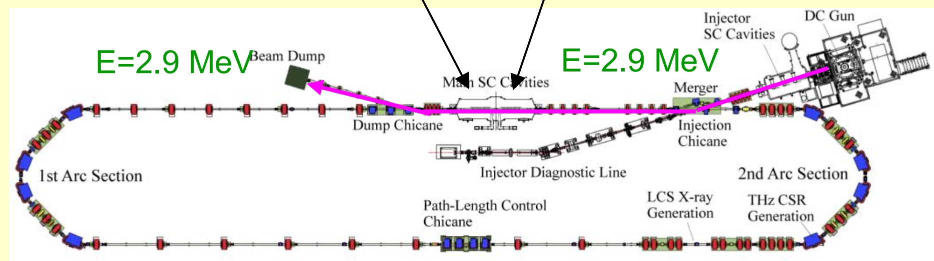
ERL operation

Cavities 1 and 2: acceleration (1st pass) and deceleration (2st pass)



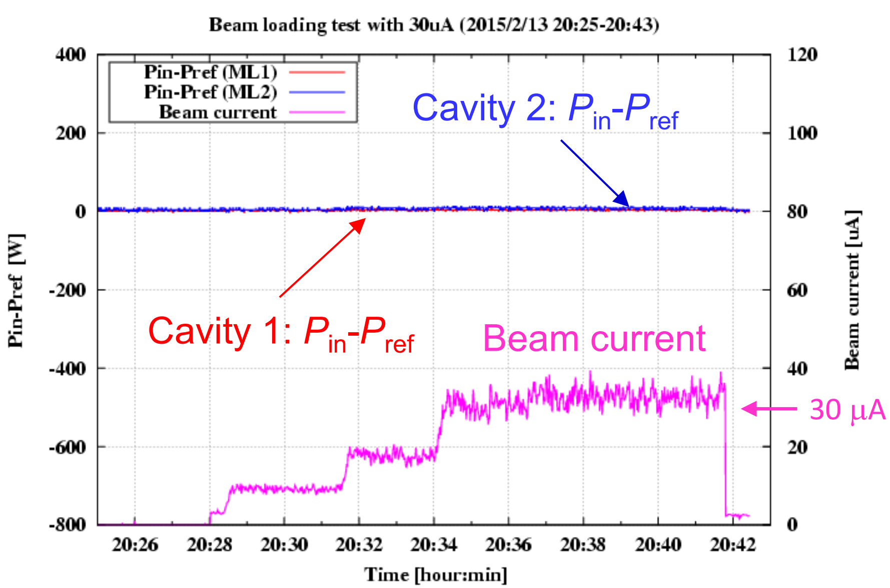
Non-ERL operation

Cavity 2: deceleration (Vc=8.57 MV/cavity) Cavity 1: acceleration (Vc=8.57 MV/cavity)

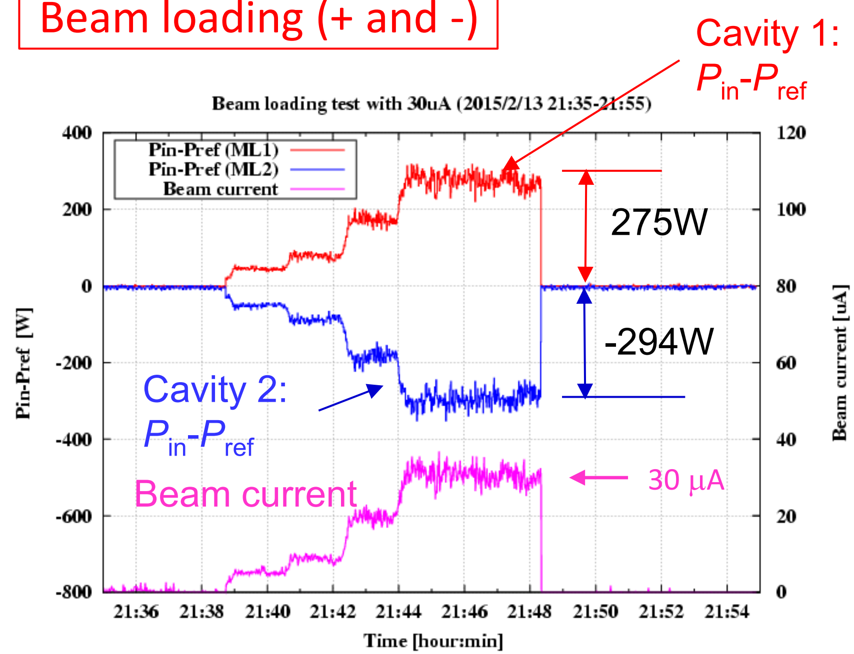


No beam loading

Energy recovery: 100-98.6%
(within accuracy of the measurement)

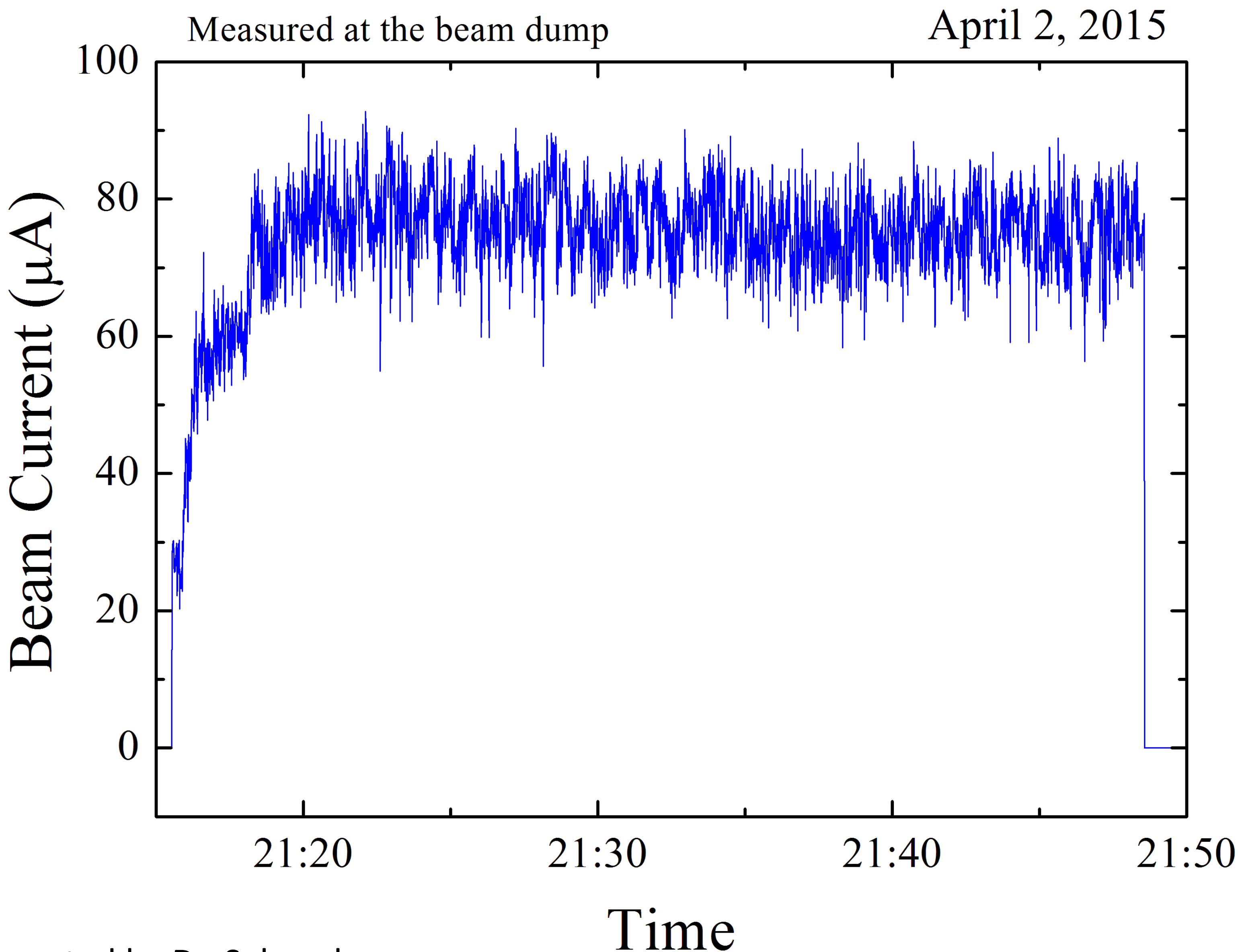


Beam loading (+ and -)



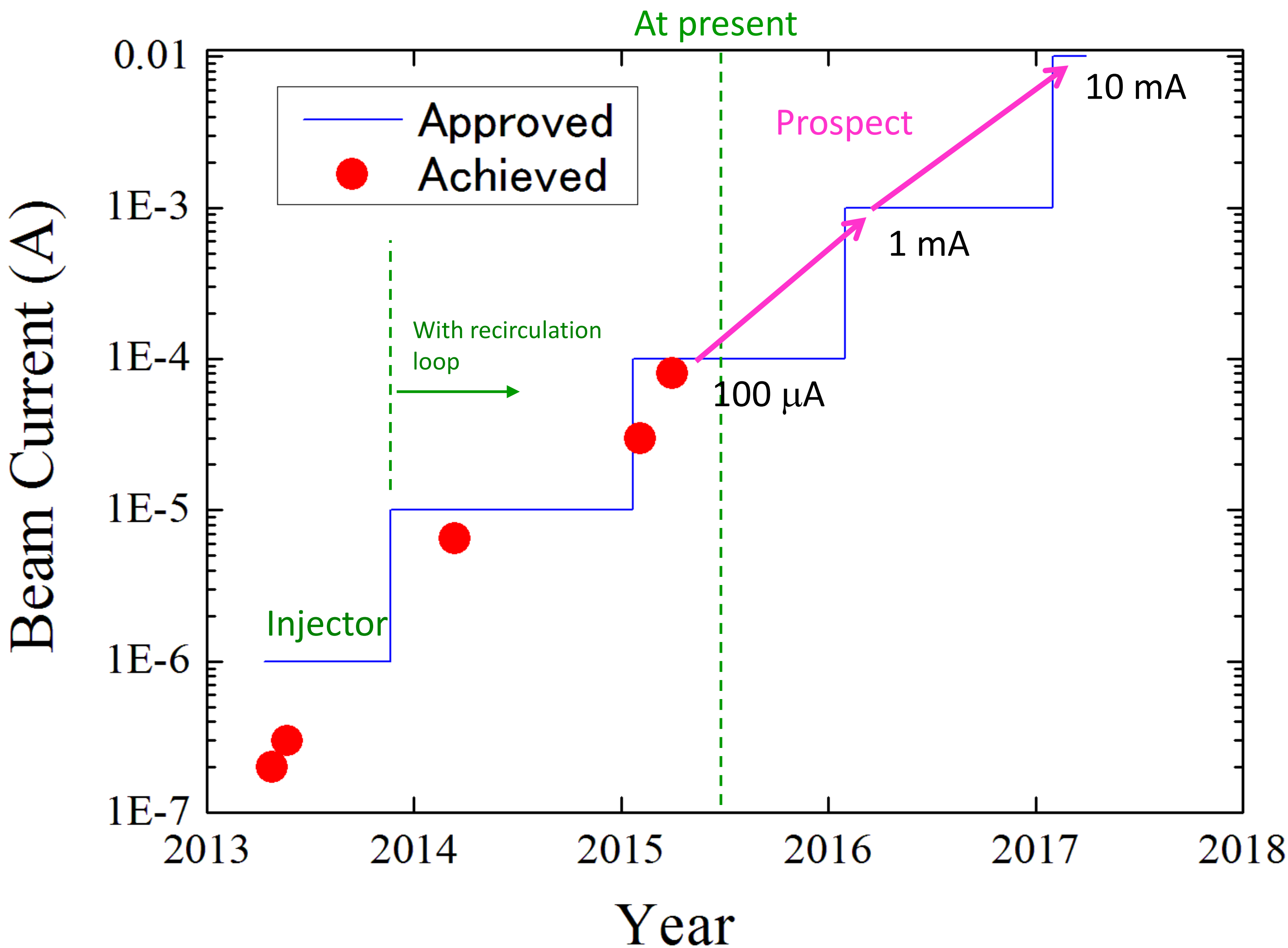
(Power lost in cavity) = (P_{in} : input power to cavity) - (P_{ref} : reflected power from cavity)

Beam Current of 80 μA (CW) was Recirculated



Presented by Dr. Sakanaka

Beam Currents: Achievement and Prospect



Summary and Outlook for cERL

- The Compact ERL was commissioned and is in stable operation.
- Learned many lessons from the commissioning.
- The photocathode DC gun and both (injector and ML) SC cavities are operating very stably.
- Achieved beam current of 80 μA.
- Achieved low beam emittance (< 1 mm·mrad) at low bunch charges (< 0.5 pC/bunch).
- X-ray production from Laser Compton Scattering was successfully demonstrated.

Subjects in the near future

- Lower emittance at high buhch-charges ($q_b \geq 7.7$ pC)
- Beam current: 1 mA ($\rightarrow$ 10 mA)
- Bunch compression (σ_t ~ 100 fs) and THz production

We have established many important technologies for the ERL light source.
We continue to conduct R&D effort on remaining issues such as:

- Improved cavity-assembly technique for higher accelerating gradient
- Mass-production technique for main-linac cavities

Acknowledgment

We have learned much from designs and experiences of JLab IR-FEL and Cornell Injector.
We appreciate useful information and advices from
JLab: George Neil, Steve Benson, Geoffrey Krafft, David Douglas, Kevin Jordan,
Carlos Hernandez-Garcia, Pavel Evtushenko, Vashek Vylet, Andrew Hutton,
Cornell: Georg Hoffstaetter, Bruce Dunham, Ivan Bazarov, Christopher Mayes,
and many other people.
We would also thank the people of ERL community for useful discussions and encouragement.

Design study for high power EUV light source based on ERL-FEL

ERL-EUV Light Source Design Group

(KEK) H. Kawata, Y. Kobayashi, T. Furuya, K. Haga, I. Hanyu, K. Harada, T. Honda, Y. Honda, E. Kako, Y. Kamiya, R. Kato, S. Michizono, T. Miyajima, H. Nakai, N. Nakamura, T. Obina, K. Oide, H. Sakai, S. Sakanaka, M. Shimada, K. Tsuchiya, K. Umemori, M. Yamamoto, S. Chen, T. Konomi, T. Kubo

(JAEA) R. Hajima, N. Nishimori

The design study has been done under collaboration with a Japanese company.

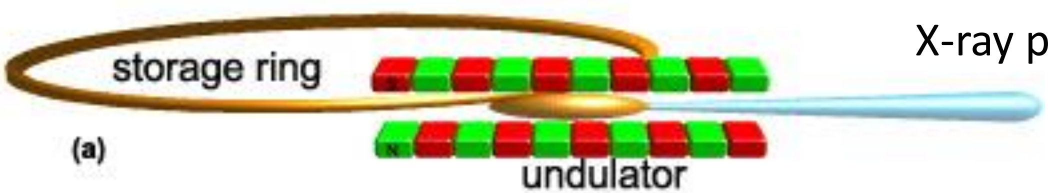
Motivation

- 10-kW class EUV sources are required in the future for lithography

In order to realize 10-kW class EUV light source, ERL-FEL is the most promising light source (High repetition rate (≦1.3 GHz) and high current linac system).

X-ray free electron laser (XFEL)

In case of normal conducting accelerator,
The repetition rate is less than 100Hz



X-ray pulse duration ~ 50 ps

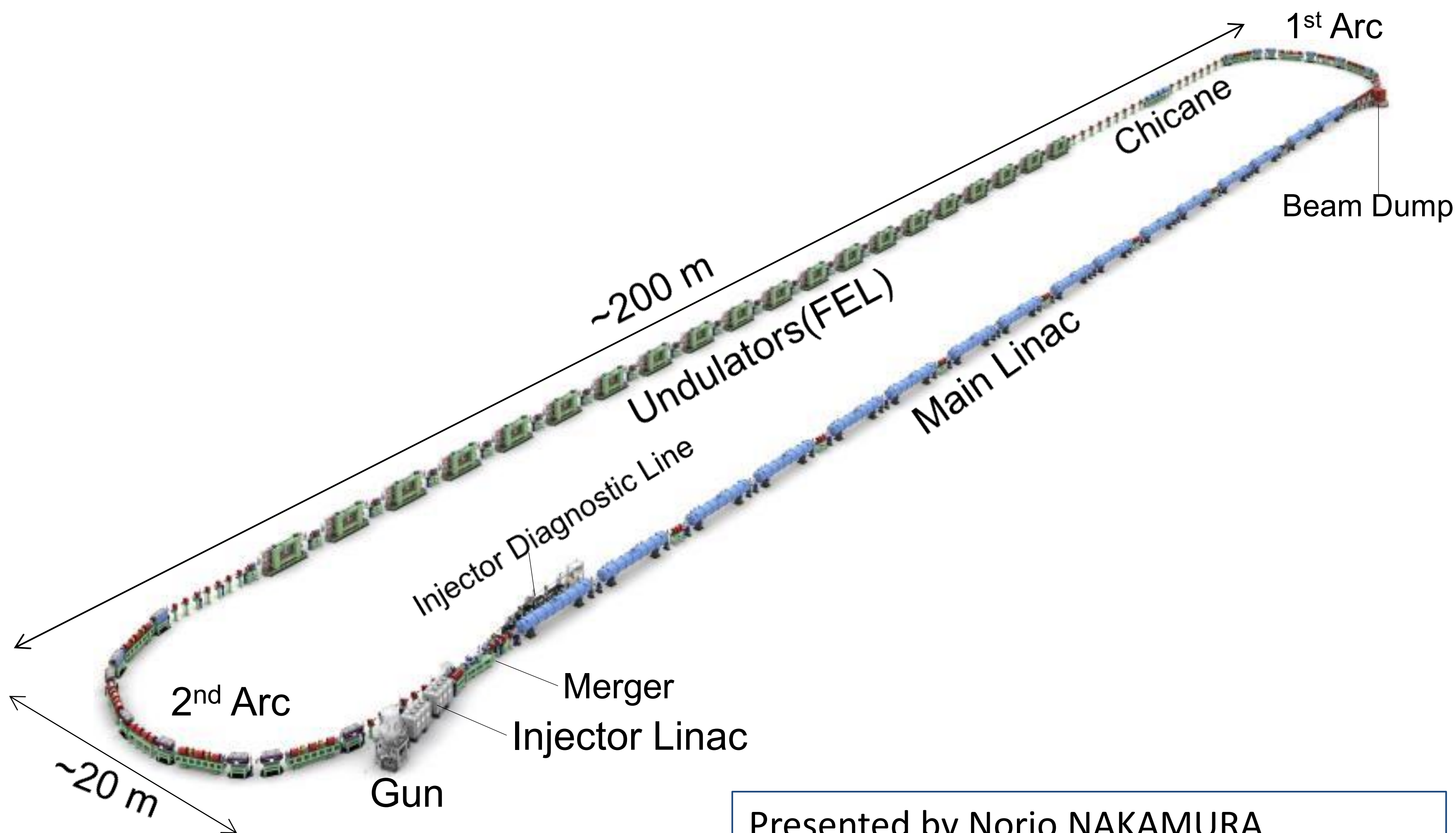
$$I \propto N$$

Micro-bunching -> SASE lasing

X-ray pulse duration ~ 10 fs

$$I \propto N^2$$

Image of ERL-EUV Design



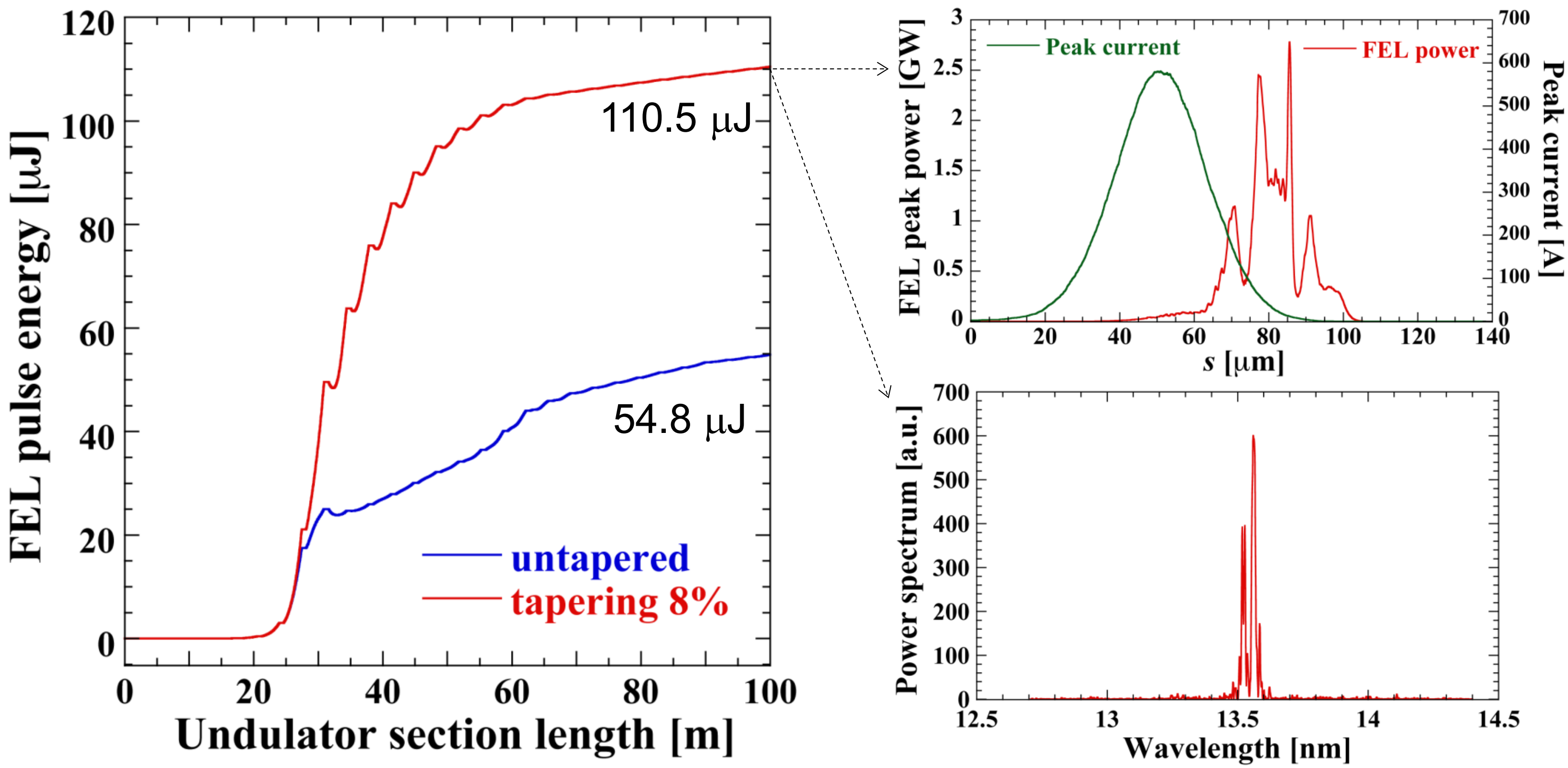
Presented by Norio NAKAMURA
ERL2015（https://www.bnl.gov/erl2015/ ）

Design Concept

- Target : 10kW power @ 13.5 nm, 800 MeV
- Use available technology without too much development
- Make the most of the cERL designs, technologies and operational experiences

FEL Performance

Electron beam parameters: E=800 MeV, Q_b=60 pC, f_b=162.5/325 MHz
Helical undulator parameters: K=1.652, λ_u=28 mm, L_u=2.8m (segment length)
Bunch compression scheme: 1^{st} Arc + Chicane



FEL power without tapering: 8.9/17.8 kW @ 9.75/19.5 mA
FEL power with 8% tapering: 18.0/36.0 kW @ 9.75/19.5 mA

ERL&FEL Parameters

Parameters	Values
Injection Energy	10.5 MeV
Beam Energy	800 MeV
Bunch Charge	60 pC
Repetition Rate	162.5/325 MHz
Ave. Current	9.75/19.5 mA
Energy Spread	0.1 % rms
Normalized Emittance*	0.6 mm mrad
Undulator Period	28 mm
Undulator Gap	7 mm
EUV Wavelength	13.5 nm
EUV output power	18/36 kW

* entrance of 1st arc

Presentation of the feasibility study

2014 International Workshop on EUV and Soft X-ray Sources		
	2014/Nov./3-6	Kako, Hajima
AAA technical workshop	2015/April/14	Kawata
ERL2015 at BNL (USA),	2015/June 7~12	Nakamura
EUV-Litho WS in Hawaii (USA)	2015/June 15~19	Nakamura
NGL Workshop	2015/July/7	Kawata
Particle Accelerator Society of Japan	2015/Aug./4-7	Miyajima
SRF2015 at TRIUNF (Canada)	2015/Sept./13~18	Kawata ←Today
EUV-Source WS in Dublin (Ireland)	2015/Nov./9~12	Umemori

We also start to prepare a committee to establish the consortium to realize the EUV light source in Japan.

Summary & Outlook for EUV Light Source

- Design of ERL-EUV Light Source
  – Injector (gun, SRF cryomodule, tracking)
  – Main linac (cavity, optics, HOM BBU and heating)
  – Arcs and chicane (lattice, optics)
  – Bunch compression simulation
- Performance of the designed ERL-EUV
  – 8.9 kW power at 9.75 mA without tapering
  – 18 kW at 9.75 mA with tapering
- Further design work and optimization
  – Improvement of FEL power
    (tapering, optics, beam&undulator parameters etc.)
  – Bunch decompression simulation