Present Status and Future Perspectives of Energy-Recovery Linacs

Ryoichi Hajima

ERL Development Group
Japan Atomic Energy Agency

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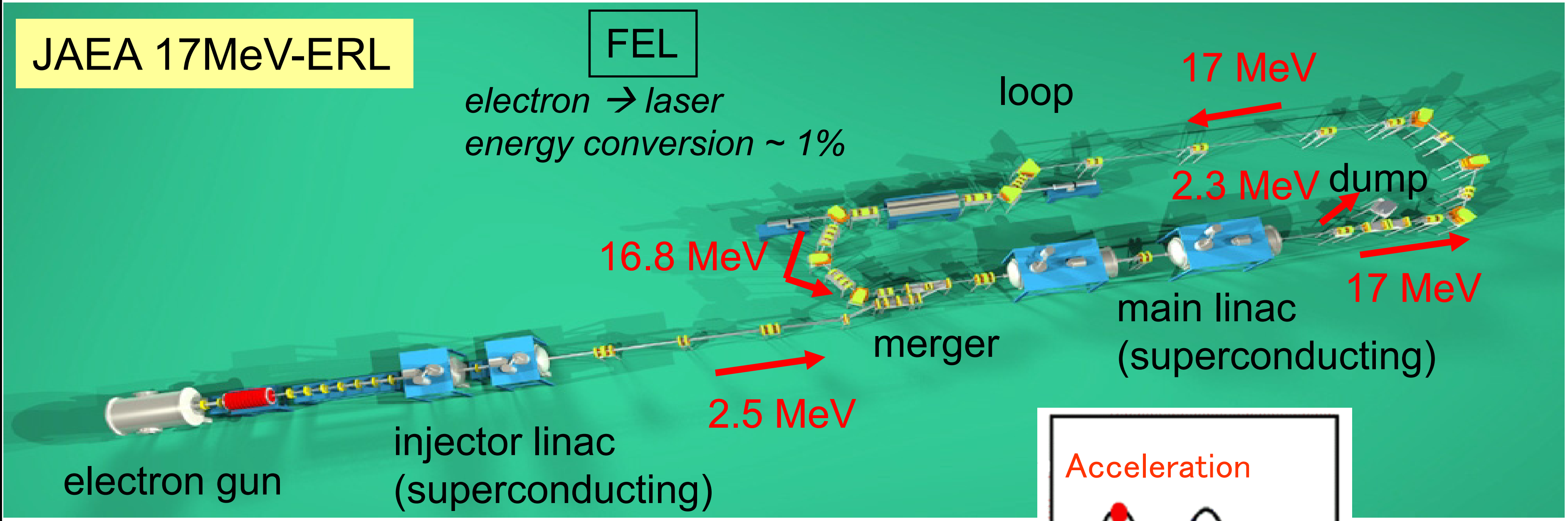
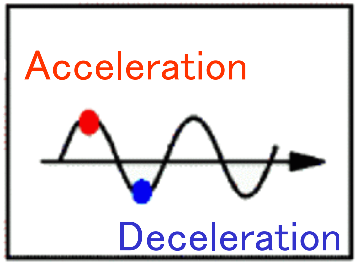
- Michael Abo-Bakr (BESSY)

- the Japanese ERL collaboration team

Energy Recovery Linac





- Energy conversion at FEL ~1% → the spent beam still has ~99% energy.
- Recycling the remaining energy is possible by "deceleration".
- High-average current beams with small RF sources.
- Fresh electrons every turn → high brightness beams

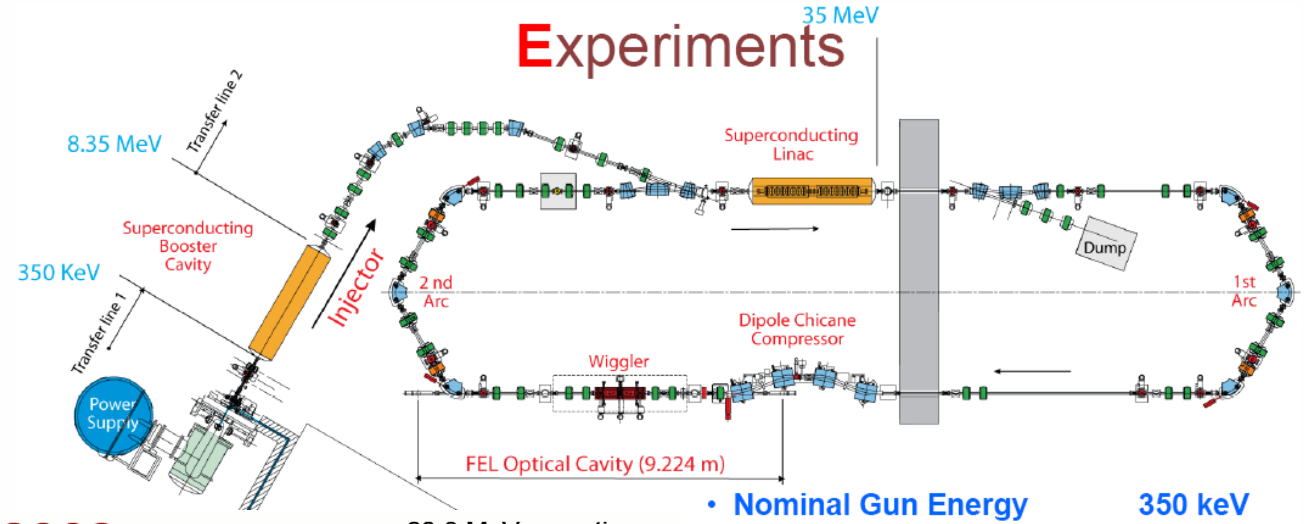
History of ERL

- First proposal of ERL concept
  - M. Tigner (1965)
- Energy recovery at DC acc. (UCSB FEL, 1985)
- Early experiments
  - Stanford SCA FEL, T. Smith et al. (1987)
  - Los Alamos FEL, D. Feldman et al. (1987)
- First successful demonstration of ERL
  - JLAB IR-demo (1999)
- ERL facilities
  - JAERI FEL (2002)
  - BINP FEL (2004)
  - JLAB IR upgrade (2004)
  - Daresbury ALICE (2008)

Welcome to the wondERLand

ALICE

Accelerators and Lasers in Combined Experiments



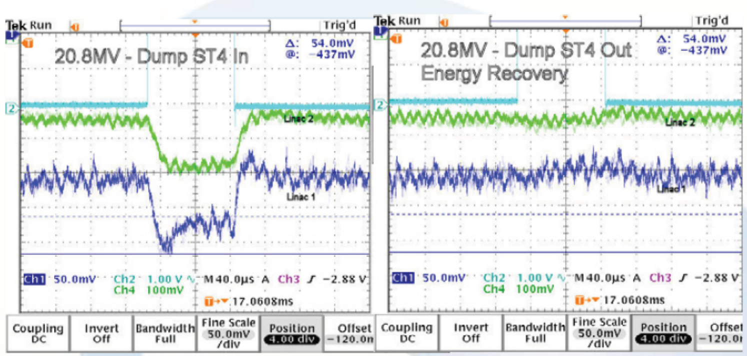
20.8 MeV operation

Energy Recovery

20 December 2008

- **Nominal Gun Energy** 350 keV
- **Injector Energy** 8.35 MeV
- **Circulating Beam Energy** 35 MeV
- **RF Frequency** 1.3 GHz
- **Bunch Repetition Rate** 81.25 MHz
- **Nominal Bunch Charge** 80 pC
- **Average Current** 6.5 mA

(Over the 100 μs Bunch Train)



The green and dark blue traces show the reduction to "zero" in RF beam loading demand on both linac cavities when the beam (duration illustrated by the pale blue signal) is decelerated through the cavities.

First “ERL session” appeared at PAC-2003

Volume 1

MOAL Opening Plenary

MOPA High-Energy Hadron Accelerators & Colliders (HEHAC)

MOPB Sources and Injectors (SAI)

TOAA Multi-Particle Beam Dynamics & Optics (MPBD&O)

TOAB Magnets (MAG)

TOAC Free Electron Lasers & Energy Recovery Linacs (FEL/ERL)

TOPA Light Sources

TOPB Controls & Computing

TOPC Two-Stream Interactions & Collective Processes (TSICP)

TOPD Instabilities & Feedback (INSTAFB)

Since then,
ERL has attracted many attention of the accelerator community

for both future light sources and HEP applications.

ERLs in Operation and Under Proposal

Light Sources

- FELs
  - JLAB (USA), BINP (Russia), ALICE (UK)
- X-ray Synchrotron Radiation Sources
  - Cornell (USA), KEK (Japan), ANL (USA), Berlin (Germany)….
- Laser Compton Sources
  - X-ray JLAB (USA), ALICE (UK), KEK (Japan)
  - γ-ray JAEA (Japan)

High Energy Physics Applications

- E-Cooler and Electron-Ion Collider
  - BNL (USA)
- Polarized Positron Generation by Laser Compton scattering

and more

ERLs for Light Sources

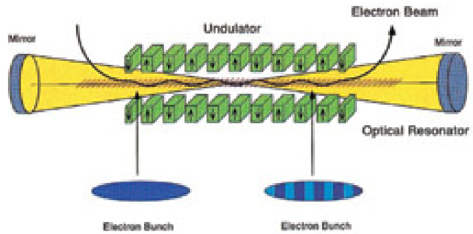
Why ERL?

- High-average current
  → High-flux photons
- Small emittance
  → High-density photons (high brilliance)
- Wide range of e-beam energy
  →10 MeV—10 GeV
  → wide range of photon energy
- Flexible manipulations of beam optics
  → various schemes of photon generation
  → bunch compression to femtosecond

ERL is an ideal device for future light sources

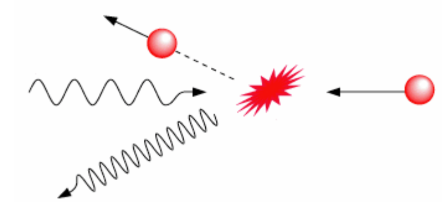
Possible Light Sources Utilizing ERLs

Free-Electron Laser



the only solution to provide femto- or picosecond laser pulses over 10 kW average power
→ industrial applications

Laser Compton scattering

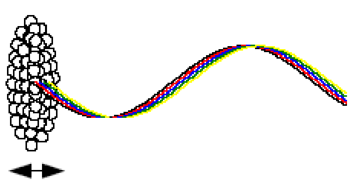


excellent synergy with a laser super cavity
→ compact X-ray sources
high-flux γ-ray sources

meV | eV | keV | MeV

THz | IR | X-ray | γ-ray

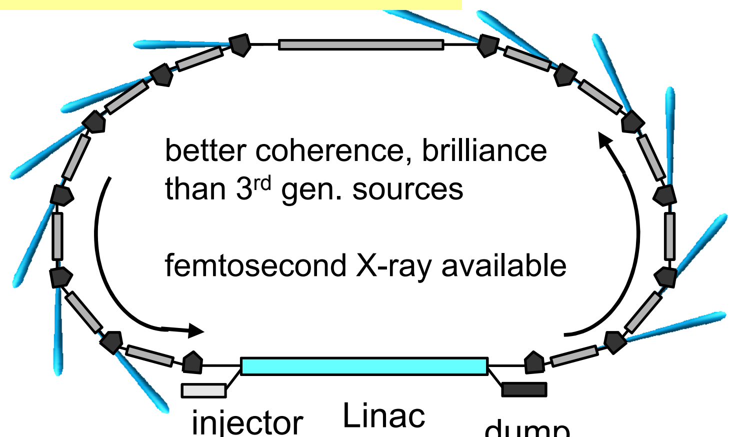
coherent radiation



$\sigma_t << \lambda$ short bunch

flux=1W/cm^{-1}@JLAB-ERL
>10^8 of Glober lamp

synchrotron radiation

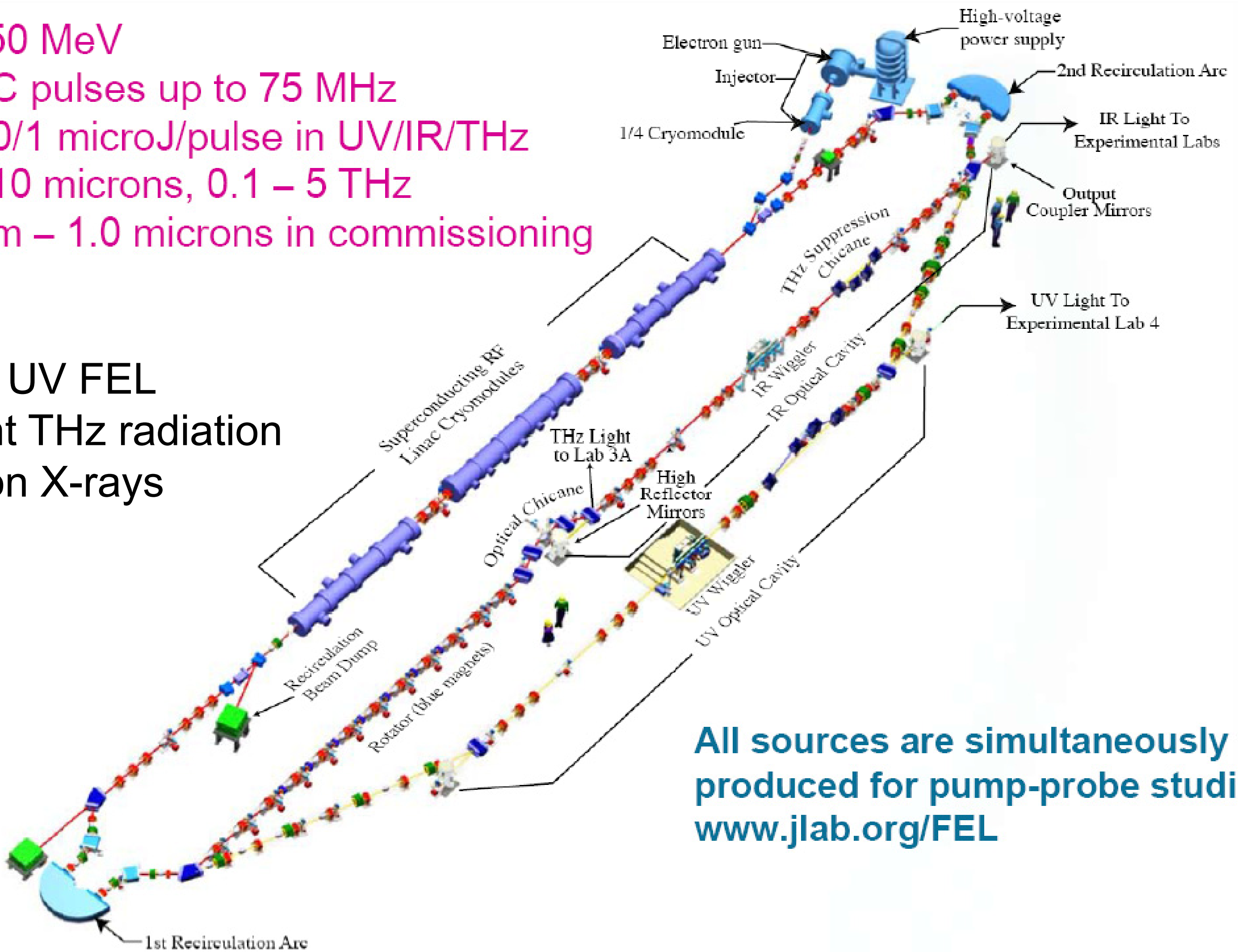


ERL FEL at JLAB

JLab Energy Recovered Linac (4GLS) facility schematic

E = 150 MeV
135 pC pulses up to 75 MHz
20/120/1 microJ/pulse in UV/IR/THz
0.9 – 10 microns, 0.1 – 5 THz
250 nm – 1.0 microns in commissioning

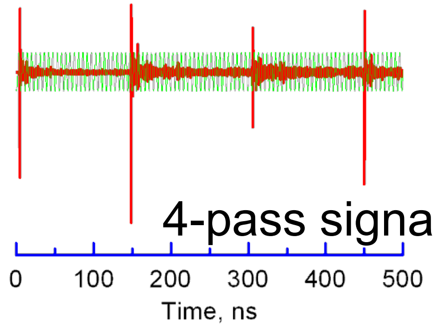
IR FEL, UV FEL
coherent THz radiation
Thomson X-rays



All sources are simultaneously produced for pump-probe studies
www.jlab.org/FEL

Multi-loop ERL FEL at BINP

First Multi-Loop ERL

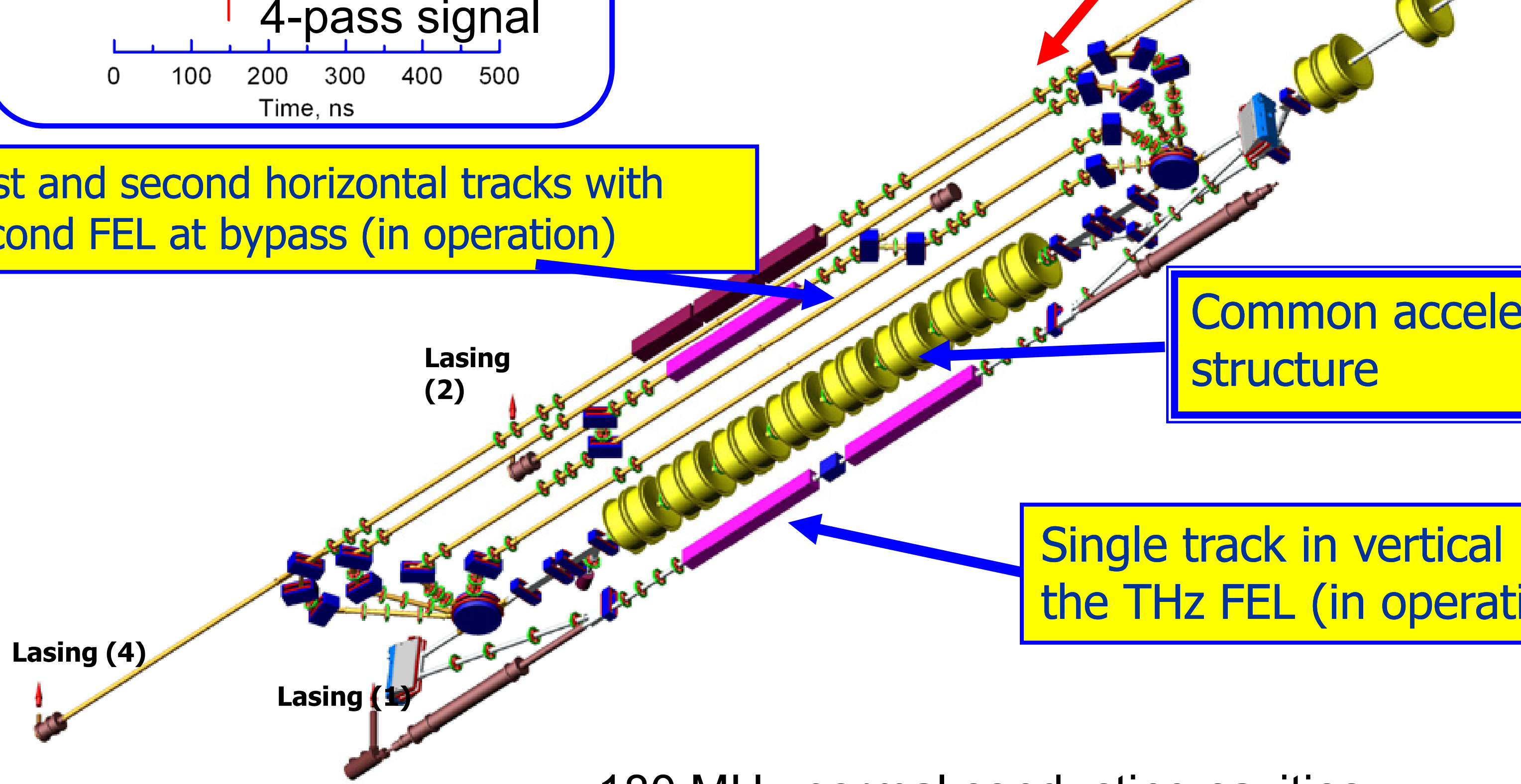


Third and fourth tracks with IR FEL (under construction)

First and second horizontal tracks with second FEL at bypass (in operation)

Common accelerating RF structure

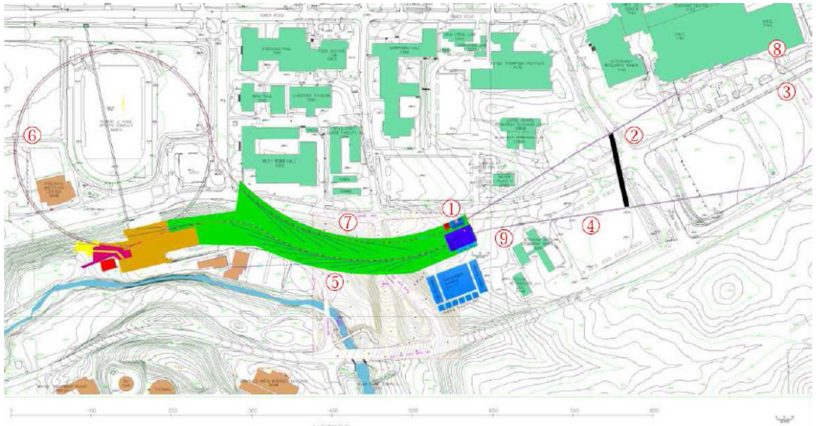
Single track in vertical plane with the THz FEL (in operation)



180 MHz normal conducting cavities
2MeV injection + 10 MeV / turn, 20 mA

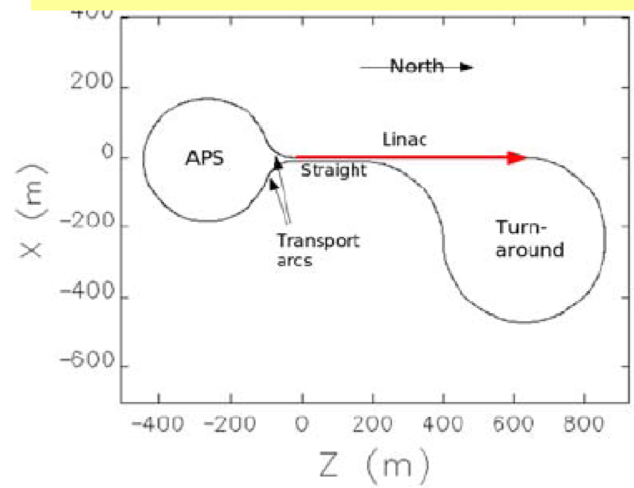
X-ray Light Sources under Proposal

Cornell ERL (5GeV)



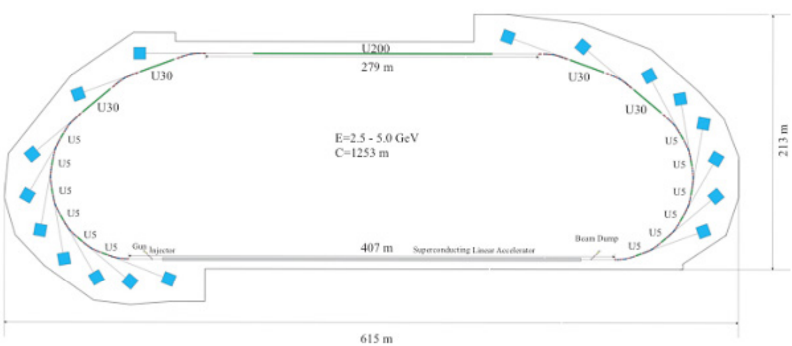
G. Hoffstaetter et al., EPAC-08.

ERL upgrade at APS (7GeV)



M. Borland, AccApp07.

KEK-PF ERL (5GeV)



Berlin,
Peking University
University of Wisconsin-Madison
……

All these facilities aim at producing X-rays with brilliance (coherence) 2-3 orders higher than existing 3rd-gen. sources.

Laser Compton Sources

tunable and quasi-monochromatic X/γ-rays

$$E_X \approx \frac{4\gamma^2 E_L}{1+(\gamma\theta)^2+4\gamma E_L/(mc^2)}$$

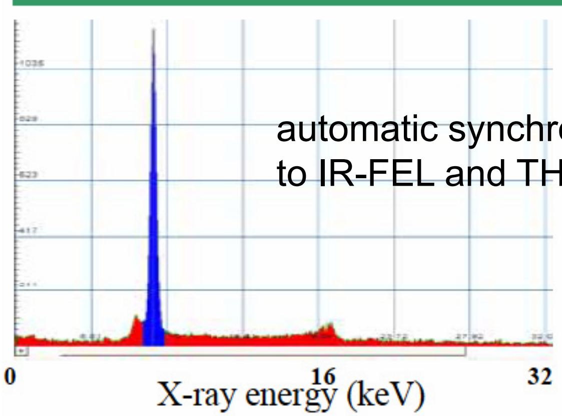
X-ray source

25 MeV + 1μm laser → 10 keV X-ray

- Femtosecond X-ray pulse
- High-flux X-ray
  (synergy with a laser super cavity)

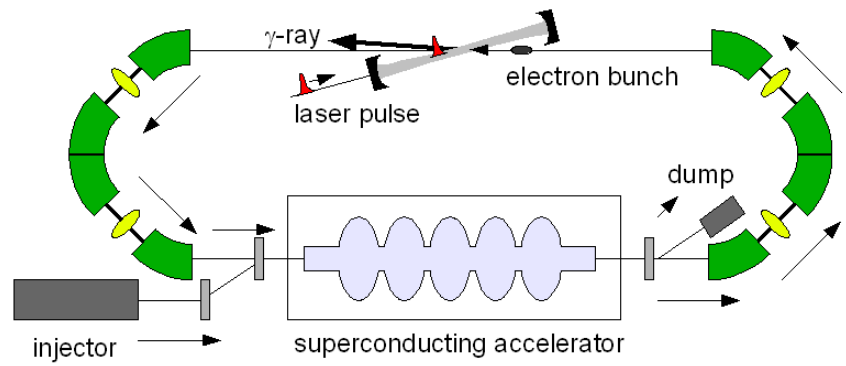
"intra-FEL" Thomson scattering@JLAB

10 keV X-ray > 10^5 ph/sec/0.1% BW



automatic synchronization
to IR-FEL and THz

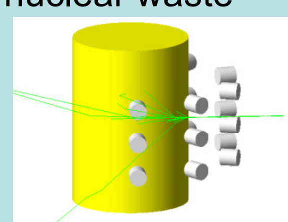
high-flux γ-ray source

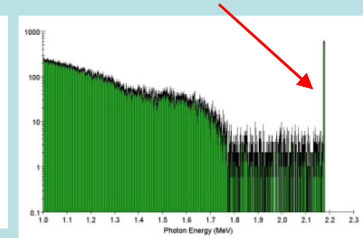


- polarized positron source
- detection of nuclear material

nuclear waste

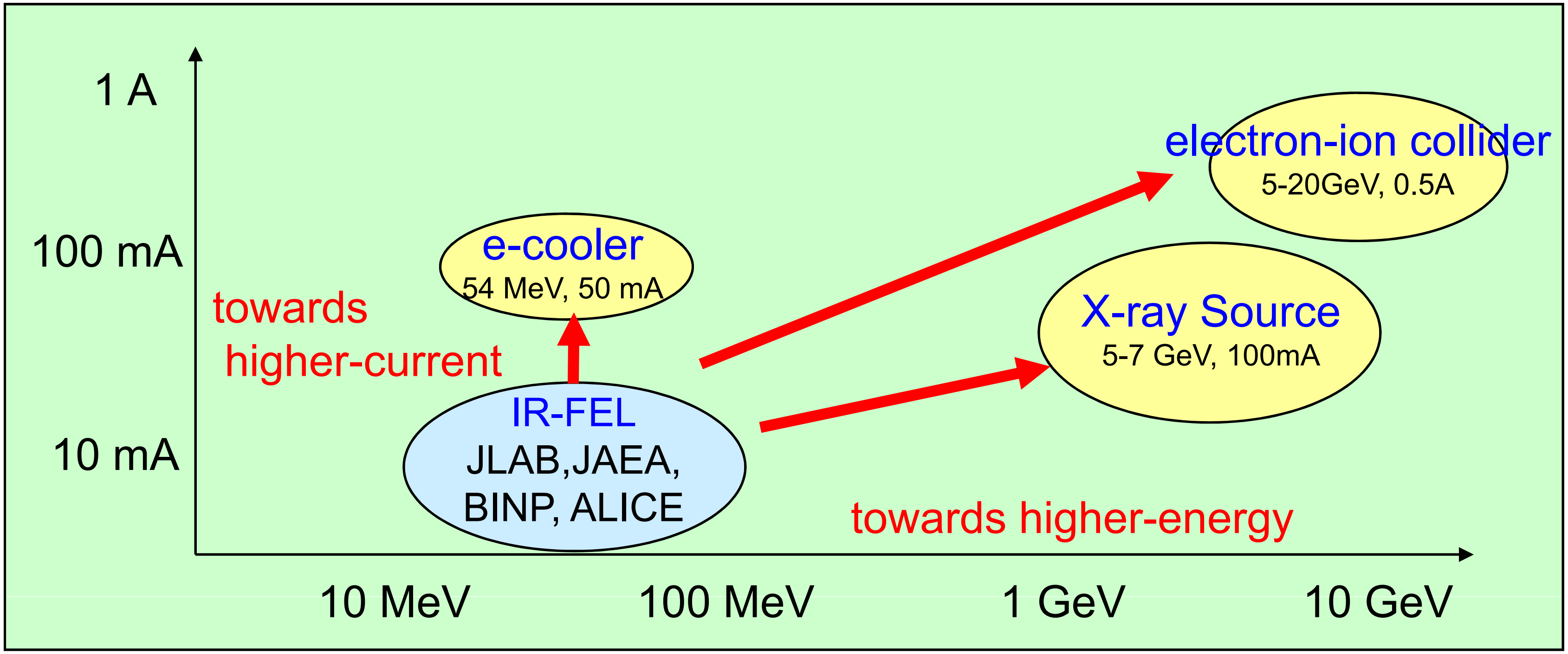
fingerprint signal of U238
= nuclear resonance fluorescence





R. Hajima et al., J. Nucl. Sci. Tech (2008).

E-beam Energy and Current in ERLs



Critical components for future ERL facilities

- electron gun for high-current and small-emittance beams
- superconducting accelerator for high-current beams

ERL Electron Guns

Electron guns for ERLs

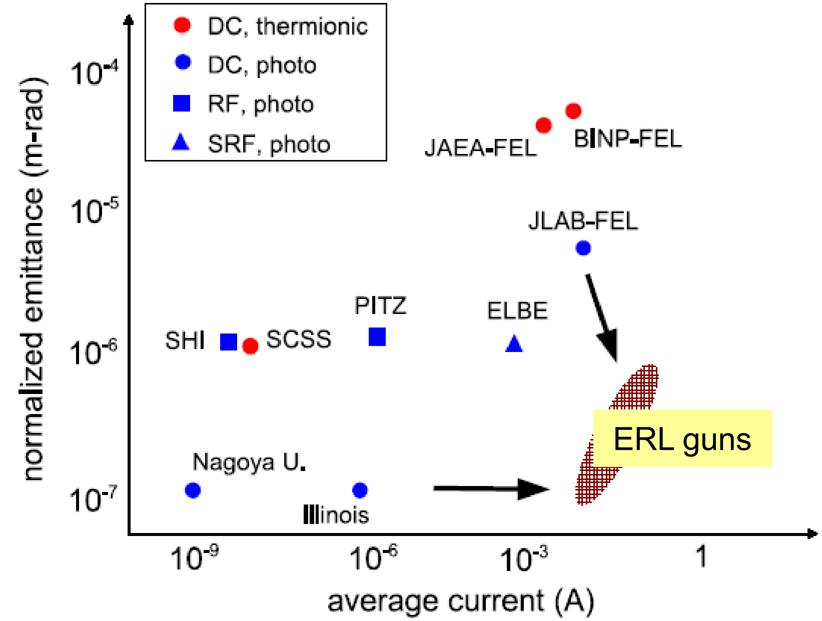
high-average current
small emittance

for X-ray LS

ε_n=0.1-1 mm-mrad, I = 10-100 mA

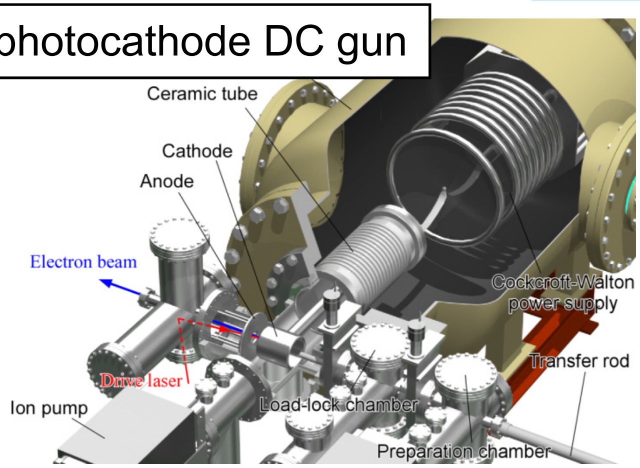
for e-cooler

ε_n=2 mm-mrad, I = 50 mA

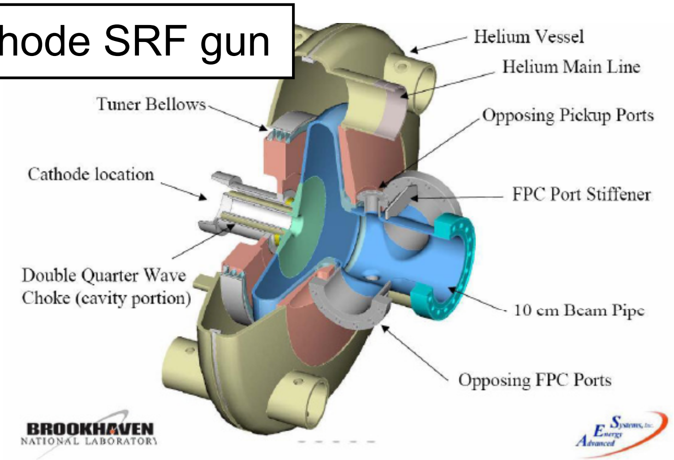


Two approaches

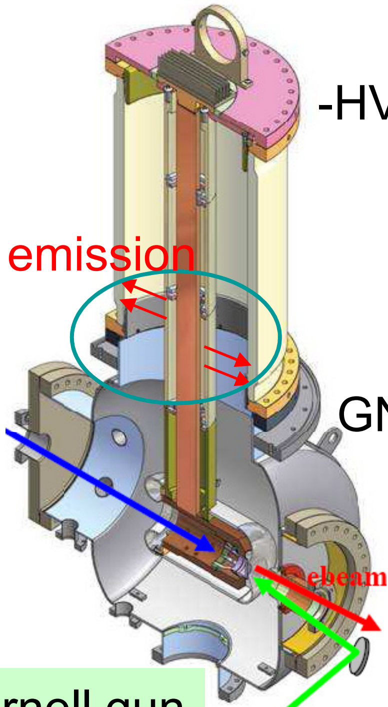
photocathode DC gun



photocathode SRF gun



Photocathode DC gun



Cornell gun

~0.1 mm-mrad is available with a NEA cathode

stable operation over 500 kV is still challenging

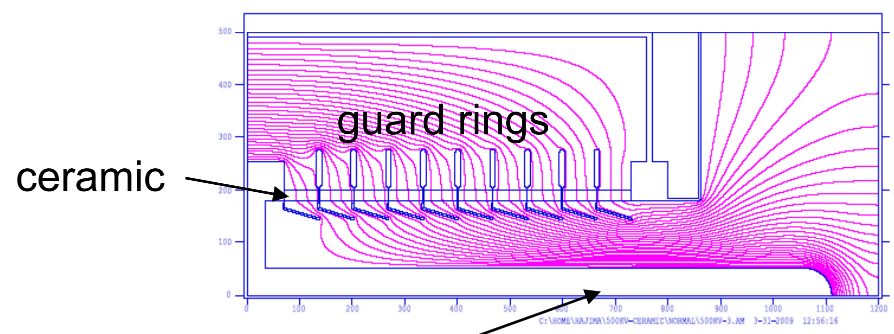
field emitted electrons from the supporting rod hit the ceramic inner surface.

local concentration of electric charge may results in punch-through failure of the ceramic insulator.

possible solutions

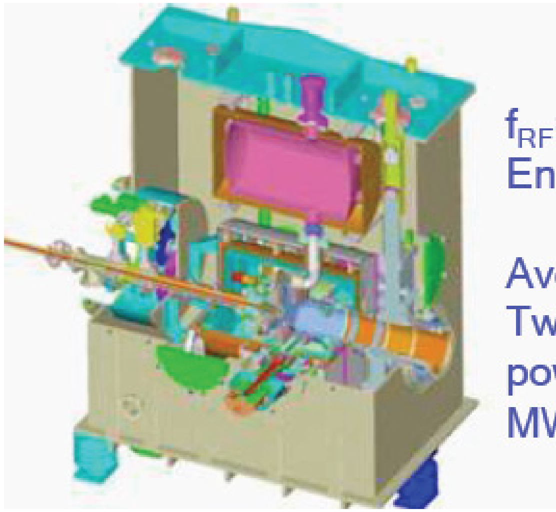
- ceramic with bulk resistivity (Cornell)
- inverted ceramic insulator (JLAB)
- multi-segmented ceramic insulator (JAEA)

multi-segmented insulator at JAEA



Photocathode SRF gun

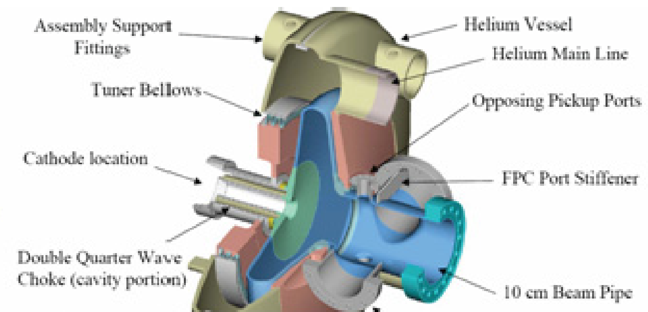
700 MHz half-cell SRF gun (BNL)



Half cell SRF Gun

f_{RF}= 703.75 MHz
Energy=2.5-3 MeV

Average Current: 0.5 A
Two fundamental power couplers: 0.5 MW each



A. M. M. Todd et al., "State-of-the-Art Electron Guns and Injector Designs for Energy Recovery Linacs",PAC2005

Designed for high-charge, high-current operation =1.4 nC, 500 mA

multi-alkali photo cathode (K_2CsSb)
355nm drive laser
2 x 500kW RF coupler
High-Tc SC solenoid

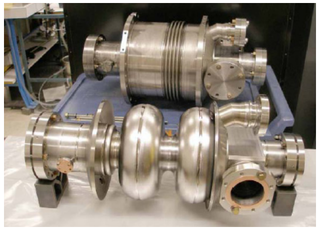
→

1-MW electron beam
direct injection to the linac (w/o booster)
1.4nC, 350MHz, ~2 mm-mrad

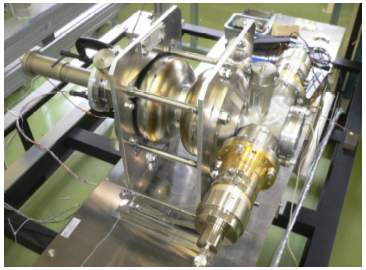
The gun is under fabrication and soon commissioned.

Superconducting Cavity

L-band 2-cell (Cornell)



L-band 2-cell (KEK)



L-band 9-cell (KEK)

Requirements for ERLs

- CW operation
- High-average current >100mA
- Damping of large HOM power
- Moderate gradient 10-20 MV/m
- High-power RF coupler (injector)
- Small microphonics (main)

700-MHz, 5-cell (BNL)

Cavities to fulfill these requirements are under development.

Cornell cavity: in operation at the injector test facility
2-cell, 2x50kW coupler, ferrite absorber@77K

KEK cavity: vertical test in progress, modules complete in 2011
2-cell, 2x250kW coupler, HOM coupler x 6
9-cell, 30kW coupler, ferrite absorber@77K

BNL cavity: first cool down in Mar. 2009, beam test in Oct. 2010.
5-cell, 50kW coupler, ferrite absorber@300K

we can share many technologies with ILC SCA.

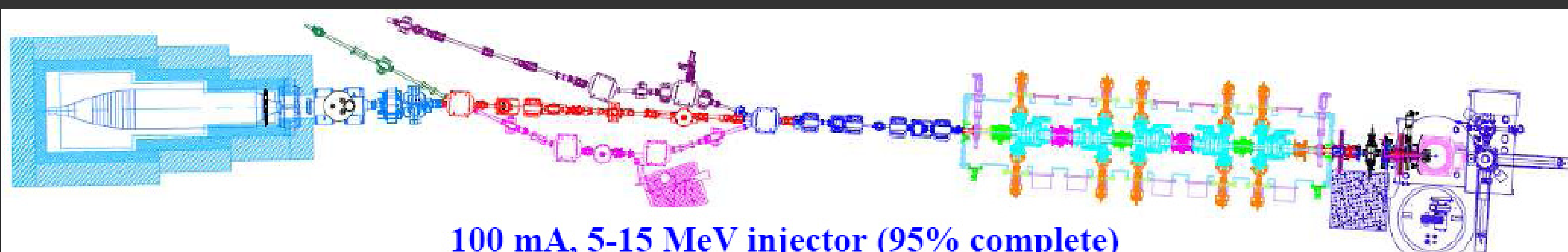
Test Facilities
in operation and under construction

Cornell Injector Test Facility

Cornell University

Timeline

Feb, 2006	the NSF funds the ERL prototype
Jan, 2007	DC gun is built with diagnostics line
Mar, 2008	the DC gun beamline operation stops
Apr, 2008	100 mA SRF module installed; the DC gun is moved and rebuilt for the 3rd time
Jun, 2008	first beam (~5 MeV)
Jul, 2008	~15 MeV
Aug, 2008	the full injector beam experiments begin



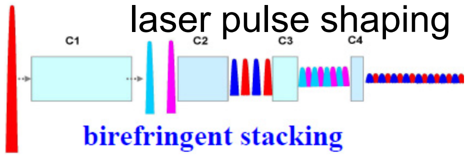
100 mA, 5-15 MeV injector (95% complete)

Results form the Cornell Injector

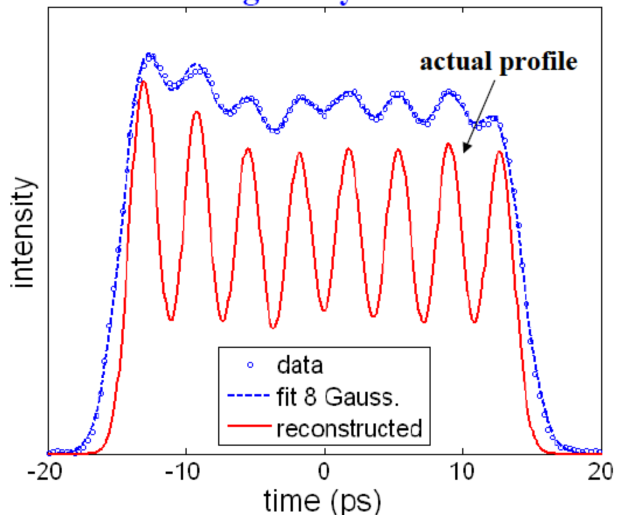
Temporal shaping really works
--- GaAs + 530nm laser

a flat-top electron bunch is preferable for the better emittance compensation

laser pulse shaping



deflecting cavity measurement



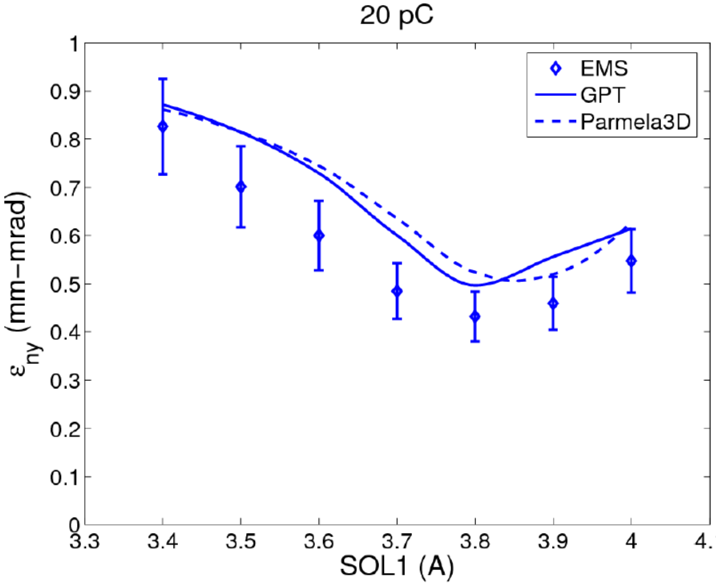
Benchmarking of space charge codes

direct measurements of the transverse space in the space charge dominated regime.

- good agreement with GPT and PARMELA3D
- presence of “brighter core” at 80 pC bunch

  ε_n (100%) = 1.8 mm-mrad

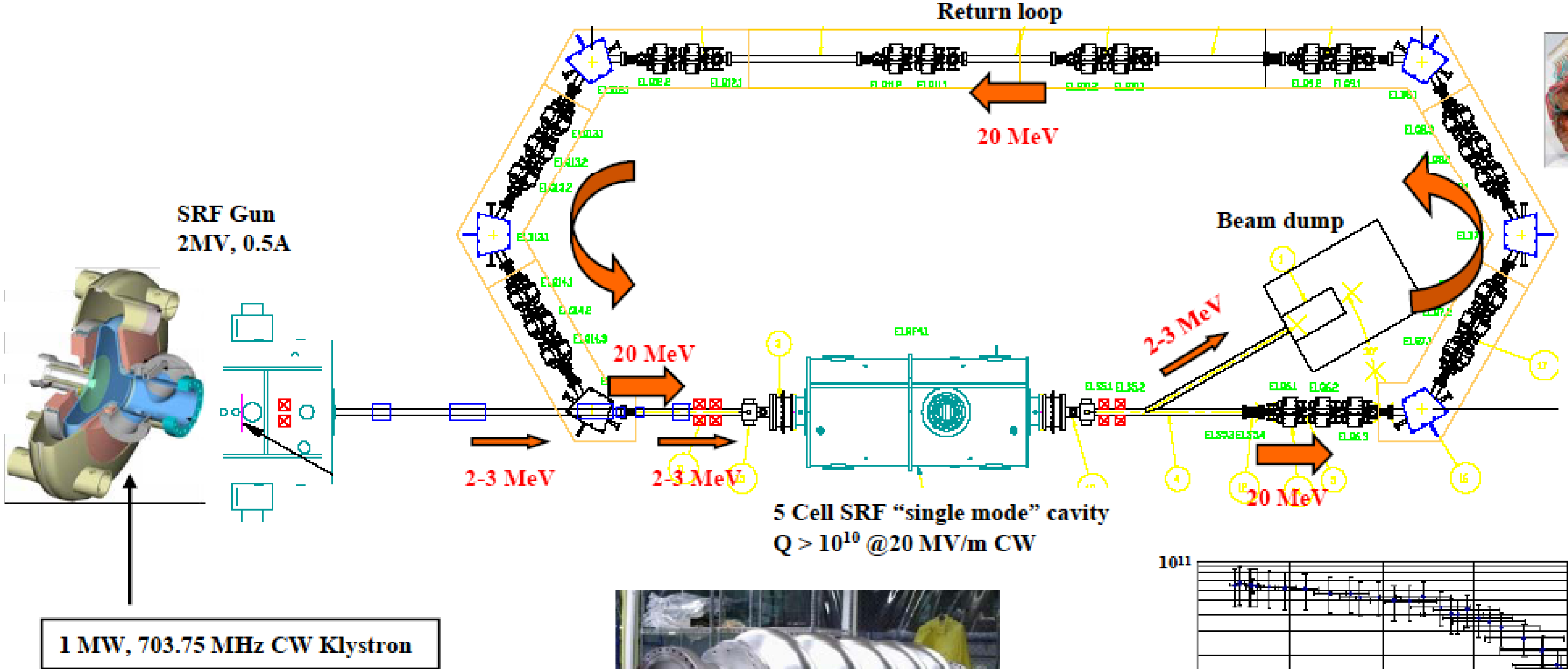
  ε_n (60%) = 0.31 mm-mrad

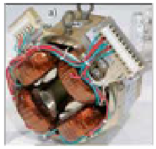


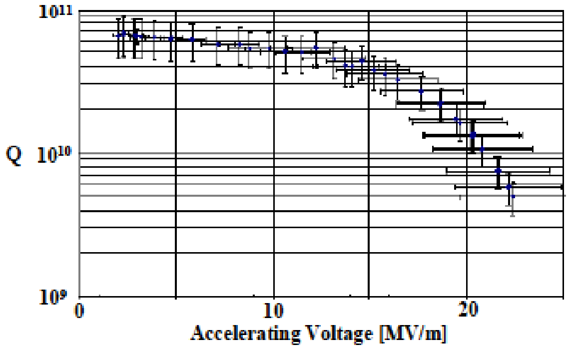
I.V. Bazarov et al., PR ST-AB 11 (2008)

BNL ERL Test Facility

- Test of high current (0.5 A), high brightness ERL operation
- Electron beam for RHIC (coherent) electron cooling (54 MeV, 10 MHz, 5 nC, 4 μm)
- Test for 10 – 20 GeV high intensity ERL for eRHIC.
- Test of high current beam stability issues, highly flexible return loop lattice
- Start of commissioning: 2009 - 2010.







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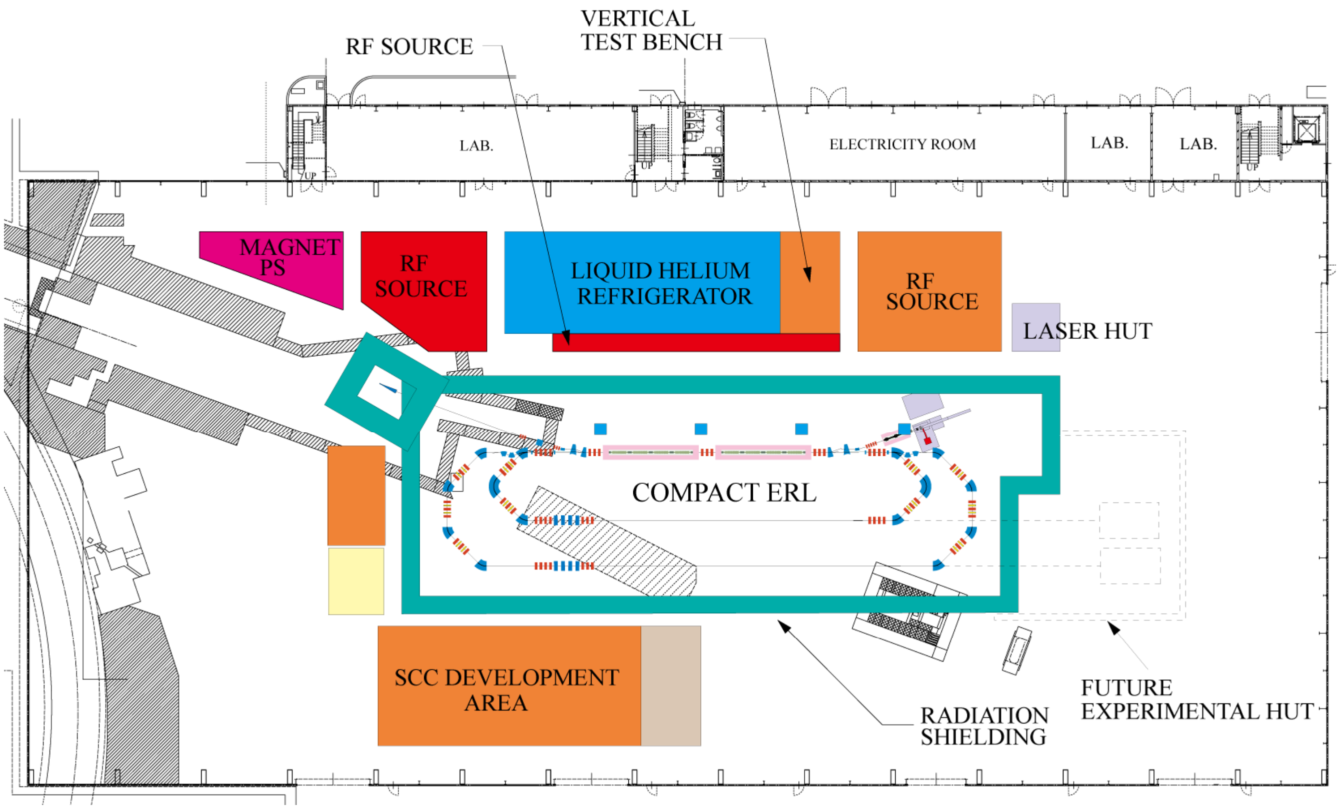
the Compact ERL in Japan



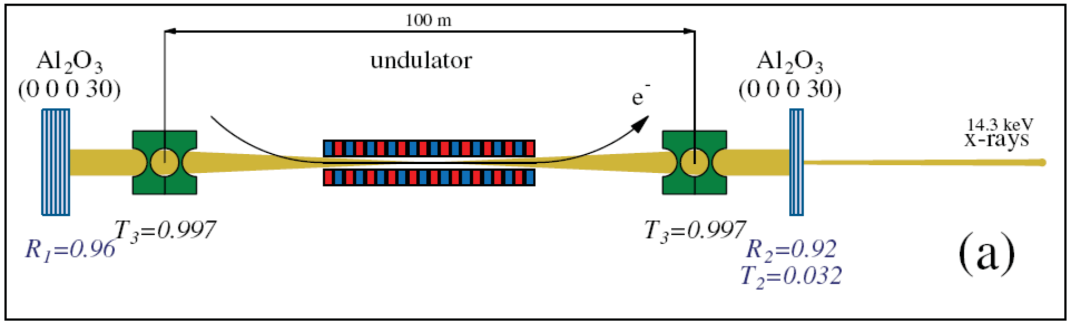
- collaborative project (KEK, JAEA, ISSP, Hiroshima U., AIST, UVSOR, SPring-8)
- test facility for future ERL light sources
- under construction at the KEK-PS counter hall (commissioning in 2012)
- photocathode DC gun, L-band SCA linac (65-125 MeV, 10-100mA)
- future upgrade to 2-loop configuration (~200 MeV)

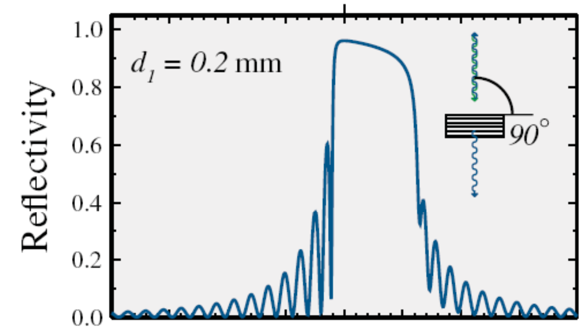
Future Directions

Future research beyond the on-going projects will include

- Pursuing ultimate facilities and new concepts
  - XFEL oscillator (XFEL-O)
  - Coherent electron cooling (CeC)
  - Multi-loop configuration
- Encouraging wider use
  - Low-energy ERLs
  - 4K operation of SCAs

X-ray FEL Oscillator as an option of ERL LS





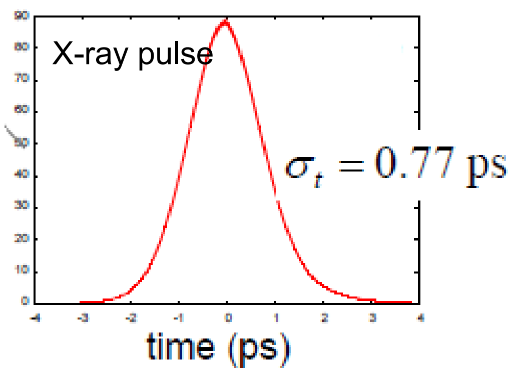
- Narrow-band Bragg mirror + “ERL quality” electron beam = FEL in hard X-ray
- can be installed in an ERL X-ray source.

K-J. Kim et al., ERL-2007 WS
PRL 100, 244802 (2008)

typical parameters

E = 7 GeV, q = 19 pC, σ_t = 2 ps, σ_E/E= 1e-4, ε_n = 0.1mm-mrad
a = 1, λ_u = 1.88 cm, N_u = 3000, $\beta^* = Z_R$ = 10 m

⇒ Gain ~ 20 %



after the saturation:

- Gaussian-like X-ray pulse with narrow band ~2meV.
- B_{av}~10^{26} ph/mm^2/mrad^2/s/0.1% (for 1MHz operation)
- different from synchrotron and SASE-FEL

PAC09

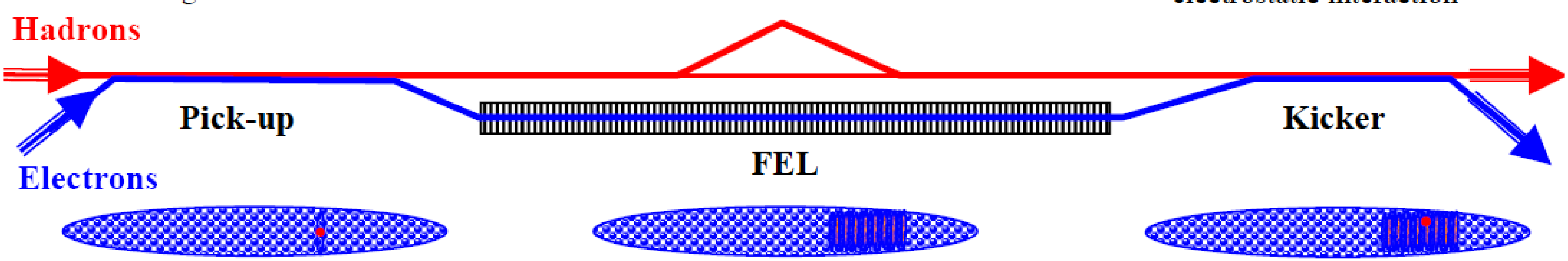
Coherent Electron Cooling (CeC)

- Idea proposed by Y. Derbenev in 1980, novel scheme with full evaluation developed by V. Litvinenko
- Fast cooling of high energy hadron beams
- Made possible by high brightness electron beams and FEL technology
- ~ 20 minutes cooling time for 250 GeV protons → much reduced electron current, higher eRHIC luminosity
- Proof-of-principle demonstration in RHIC using test ERL.

Pick-up: electrostatic imprint of hadron charge distribution onto co-moving electron beam

Amplifier: Free Electron Laser (FEL) with gain of 100 -1000 amplifies density variations of electron beam, energy dependent delay of hadron beam

Kicker: electron beam corrects energy error of co-moving hadron beam through electrostatic interaction



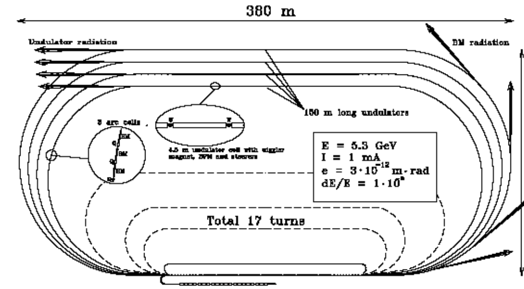
BROOKHAVEN NATIONAL LABORATORY

V.L. Litvinenko and Y.S. Derbenev, PRL 102, 114801 (2009)

Multi-loop ERL

Multi-loop is a very natural extension of ERLs.

small footprint, saving cost



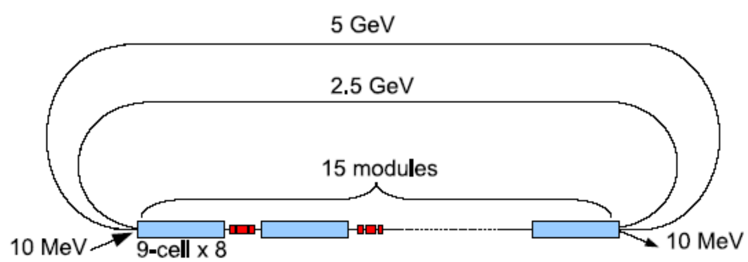
D.A. Kayran et al., APAC-1998.

HOM damping becomes more critical

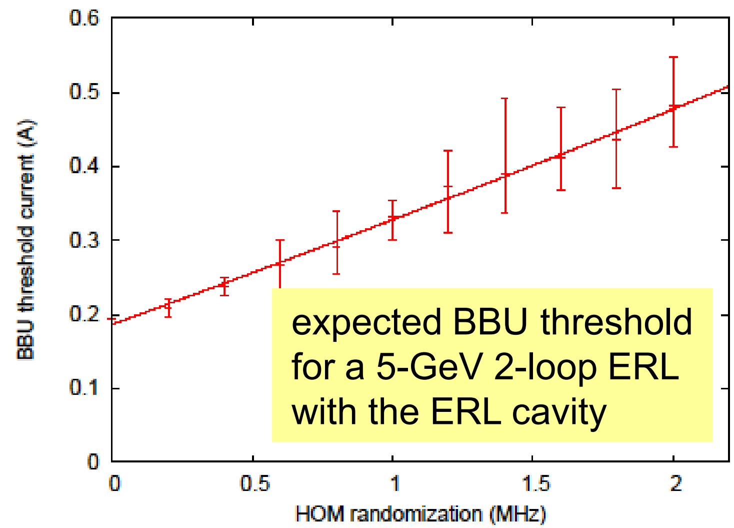
$$P_{HOM} \propto nq^2 f_b$$

n: beams, q: bunch charge, f_b: bunch frequency

recent SCA development may allow larger P_{HOM}



R. Hajima et al., ERL-07



need more studies on beam dynamics & hardware compatibilities

- operation of the multi-loop ERL at BINP will provide helpful information
- 2-loop configuration is planned at the Compact ERL in Japan

Low-Energy Small-Size ERLs

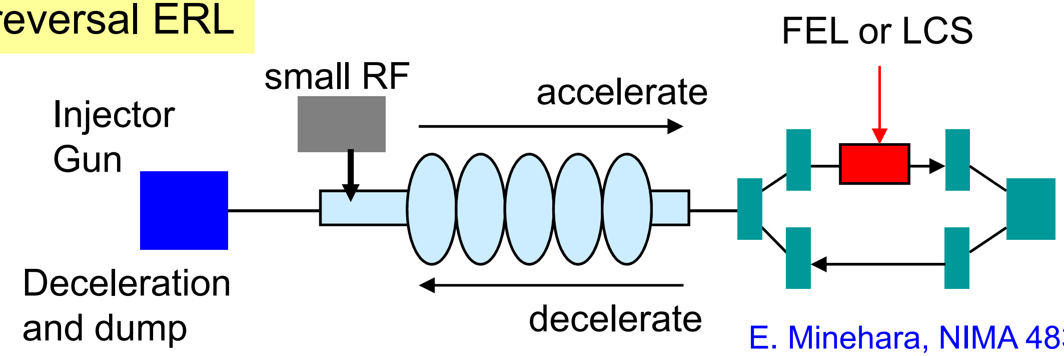
Another important direction will be development of low-energy small-size ERLs.

- Laser Compton X-ray source, infrared FEL, THz source ….
- 20-30 MeV beams are available by a few m long SCA.

To realize such small machines at affordable prices, we need

a small size injector & a small capacity refrigerator

time-reversal ERL

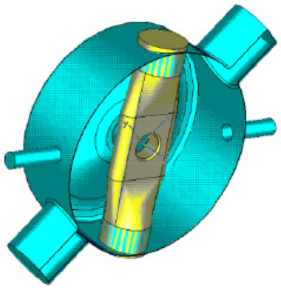


E. Minehara, NIMA 483 (2002)

4K operation of SCA

- spoke cavity (~300MHz)

D.C. Nguyen, LINAC-2006
W.Graves, ICFA Compton WS 2008.



Summary

- Energy-recovery linac is a promising device for future light sources and HEP applications.
  - high-power FEL, X-ray synchrotron, LCS, THz
  - e-cooler, electron-ion collider
- Research of critical components is widely conducted.
  - photocathode DC/RF guns
  - high-current SCA
- Test facilities are in operation and under construction.
  - integration of developed components
  - acceleration/deceleration of high-average current beams
  - pilot experiments
- Future direction beyond the on-going projects will include
  - pursuing ultimate facilities and new concepts
  - encouraging wider use of low-energy small ERLs

Happy 10th anniversary of the JLAB ERL!

On 15 July 1999 the IR Demo lased stably at average powers up to 1.72 kW at 3.1 μm wavelength. Its demonstrated average-power capability is noteworthy, being a full 2 orders of magnitude higher than the previous average-power record for FELs (11 W at Vanderbilt University in 1990 [3]). However, the foremost achievement is a convincing demonstration of the underlying, enabling technology, namely same-cell energy recovery (SCER).

G.R. Neil et al., PRL (2000)