# Applications by means of the accelerator technologies based on cERL


**Hiroshi KAWATA**

**(KEK)**

# Contents

- Original proposal of the applications on the cERL
  - Laser Compton Source
  - THz production
- Change the target from academia to industry
- Industrial Application of ERL technology
  - EUV-FEL for Future Lithography
  - High resolution X-ray imaging device for medical use
  - Nuclear security system
  - RI manufacturing facility for nuclear medical examination
- Summary

# Original proposal of the applications on the cERL

- Laser Compton Scattering x- or γ-ray (LCS) production for the future application in collaboration with JAEA
- THz production by means of bunch compression techniques

# Laser Compton Sources Based On Energy Recovery Linacs

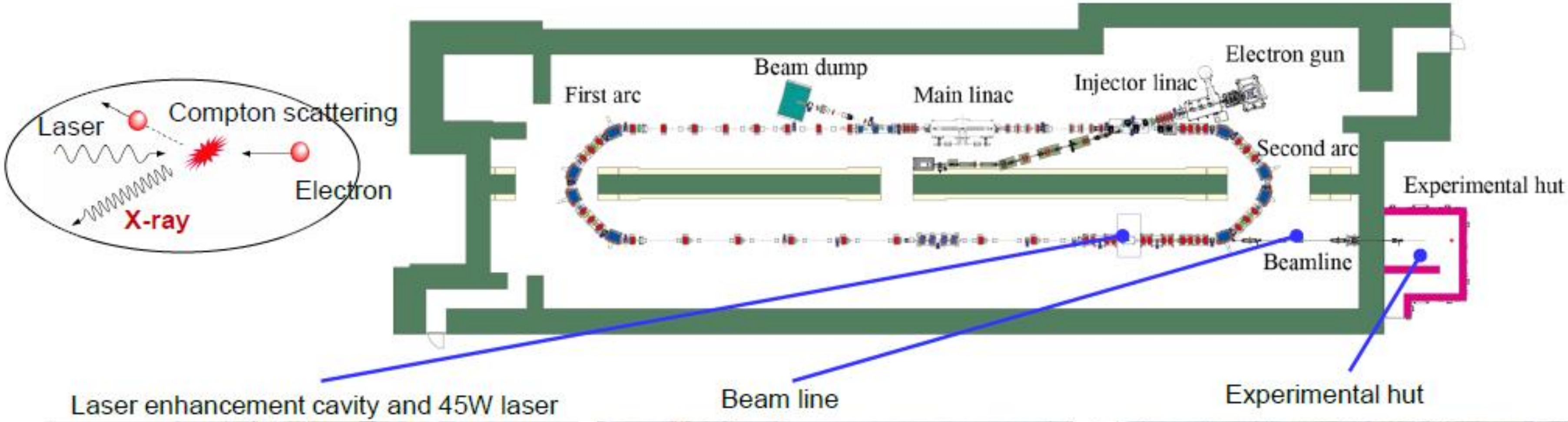
Ryoichi Hajima
Japan Atomic Energy Agency

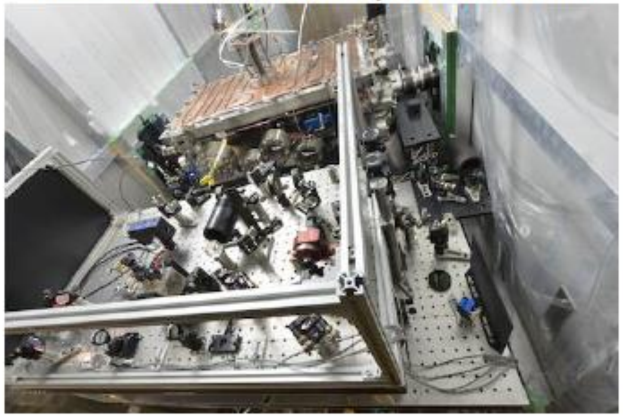
June 10, 2015

ERL-2015 WS

# LCS Experiment at Compact ERL

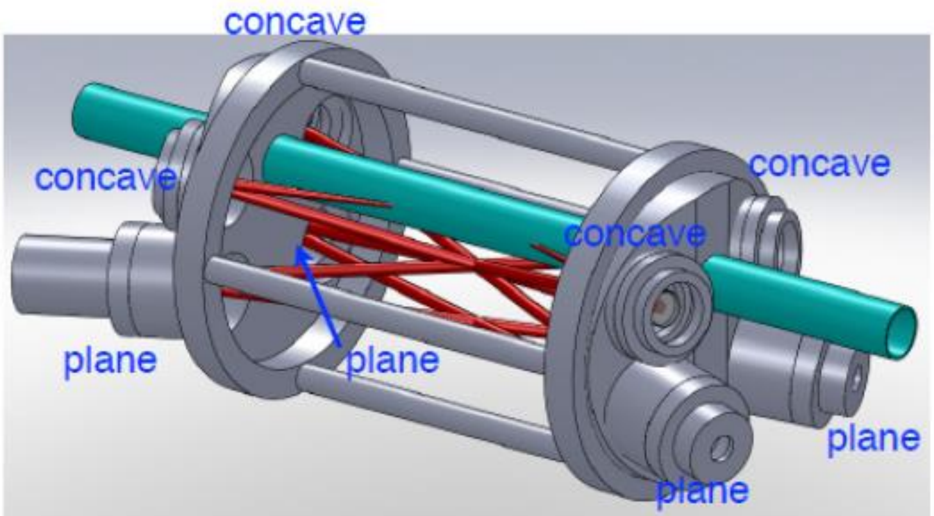
Demonstration of technologies relevant to future ERL-based LCS sources



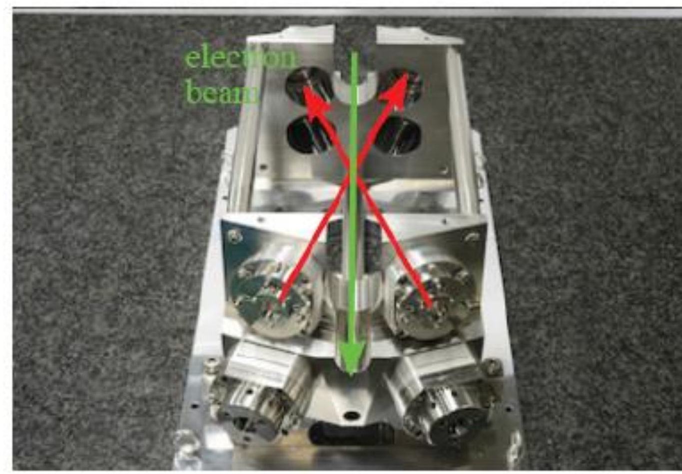
Work supported by:
A government (MEXT) subsidy for strengthening nuclear security (R. Hajima, JAEA), and
Photon and Quantum Basic Research Coordinated Development Program from the MEXT (N. Terunuma, KEK)

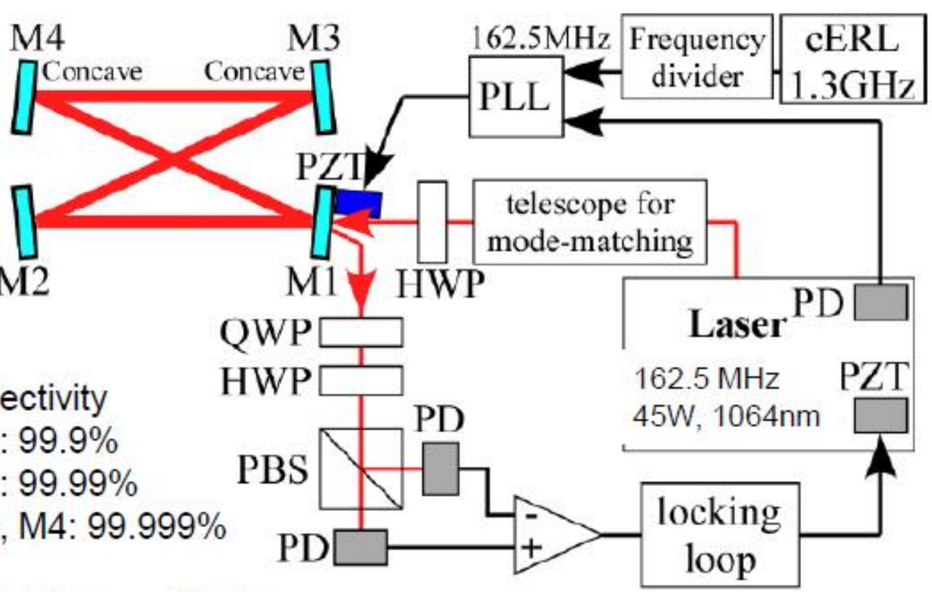
# Laser Enhancement Cavity




Developed by T. Akagi (KEK)

T. Akagi et al., Proc. IPAC-2014, p.2072
A. Kosuge et al., Proc. IPAC-2015, TUPWA-66




reflectivity
M1: 99.9%
M2: 99.99%
M3, M4: 99.999%

waist size: σ=30μm

Can store two beams independently

Fast polarization switch at 325 MHz
or
Double the laser power at LCS

(Single laser for the first experiment)

# Beam Optics for the LCS

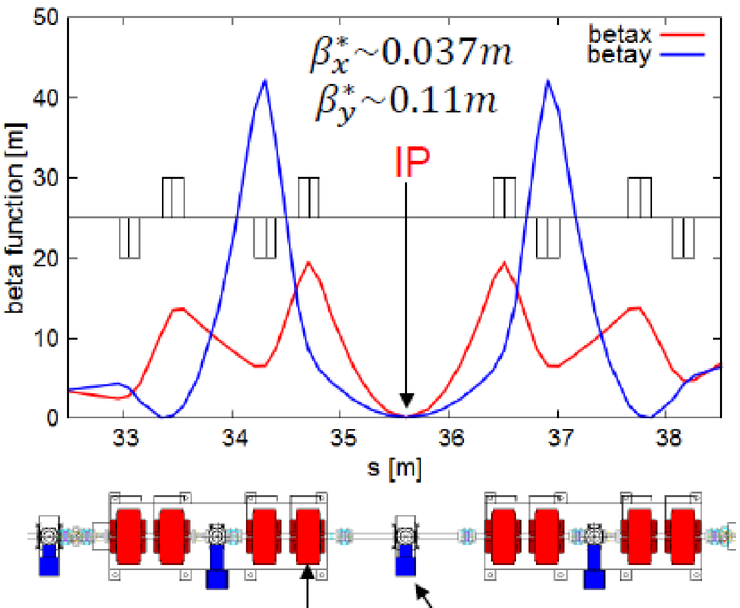
- Low-beta insertion for small beam sizes at IP
- Transport beams to the dump with small beam losses

Beam optics was established

IP: interaction point

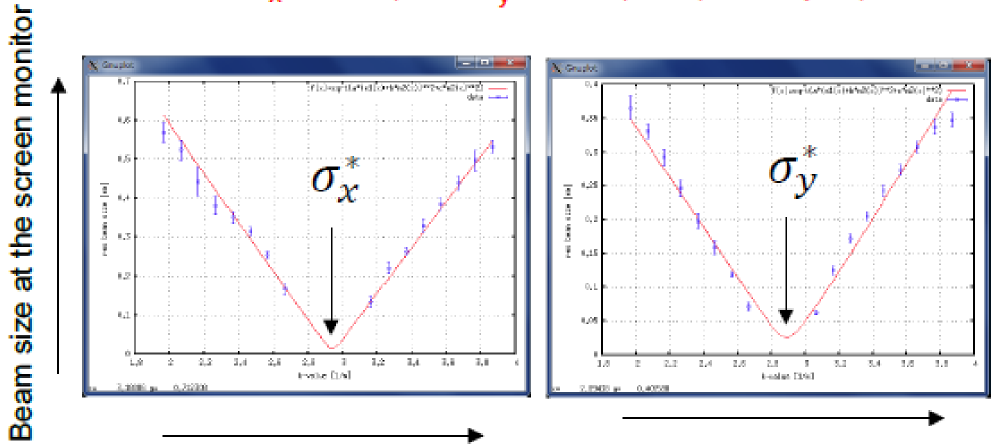
Design optics (example: "70% middle" optics)

$\sigma_x^* = 21\ \mu m$, $\sigma_y^* = 33\ \mu m$ at IP




Beam sizes at IP were estimated from Q-scan data

$\sigma_x^* \sim 13\ \mu m$, $\sigma_y^* \sim 25\ \mu m$ (example)




$\sigma_x^*$, $\sigma_y^*$ < (resolution of the screen monitor)

Bunch charge: 0.5 pC/bunch,

Normalized emittances: $(\varepsilon_{nx}, \varepsilon_{ny})$=(0.47, 0.39) mm·mrad

S. Sakanaka et al., Proc. IPAC-2015, TUBC1

# X-ray Produced by LCS

## Parameters of electron beams:

| | |
|---|---|
| Energy [MeV] | 20 |
| Bunch charge [pC] | 0.36 |
| Bunch length [ps, rms] | 2 |
| Spot size [$\mu$m, rms] | 30 |
| Emittance [mm mrad, rms] | 0.4 |
| Repetition Rate [MHz] | 162.5 |
| Beam current [μA] | 58 |

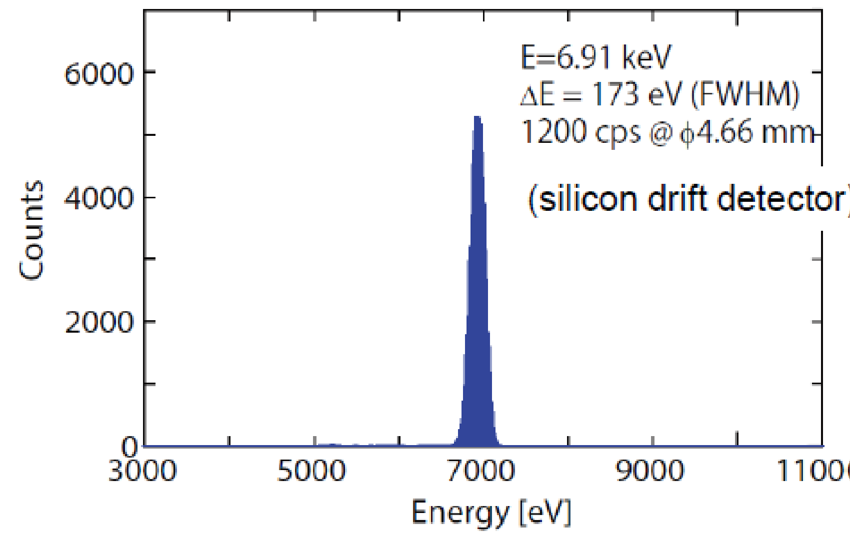
## Parameters of laser (enhanced by cavity):

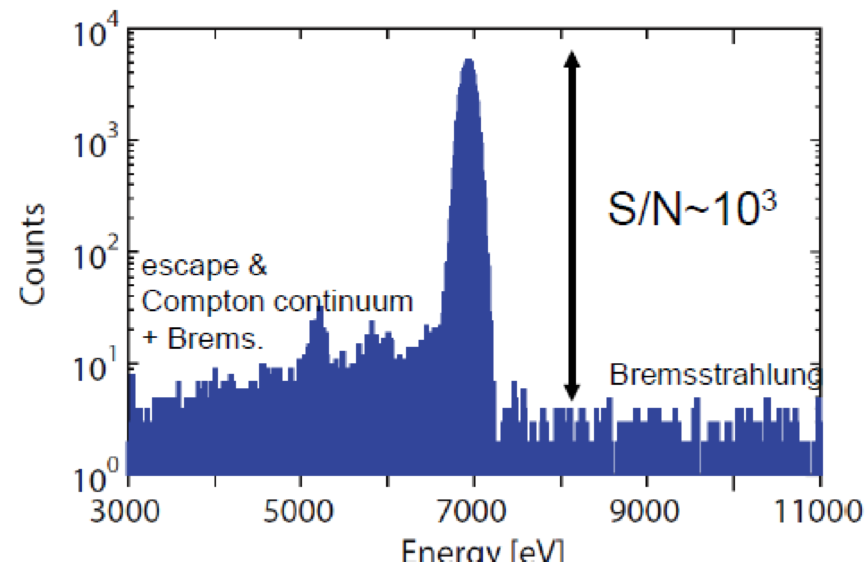
| | |
|---|---|
| Center wavelength [nm] | 1064 |
| Pulse energy [$\mu$J] | 64 |
| Pulse length [ps, rms] | 5.65 |
| Spot size [$\mu$m, rms] | 30 |
| Collision angle [deg] | 18 |
| Repetition rate [MHz] | 162.5 |
| Intracavity power [kW] | 10 |

## Results:

Photon energy = 6.9 keV
Detector count rate = 1200 cps @ϕ4.66mm (*)
Source flux = $4.3 \times 10^7$ ph/s (**)

(*) Detector collecting angle is 4.66mm/16.6m = 0.281 mrad
(**) CAIN/EGS simulations with the detector count rate



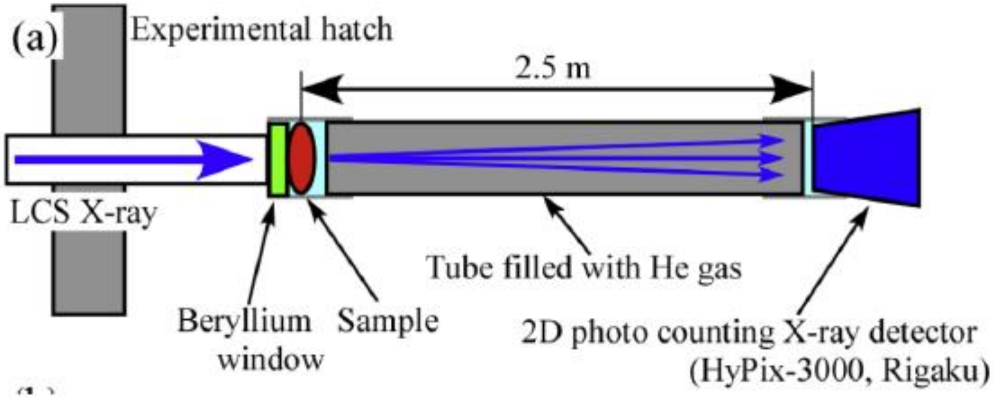




R. Nagai et al., Proc. IPAC-2015, TUPJE002

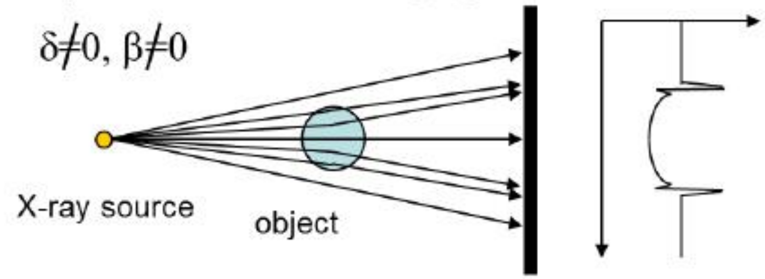


R. Hajima: ERL15

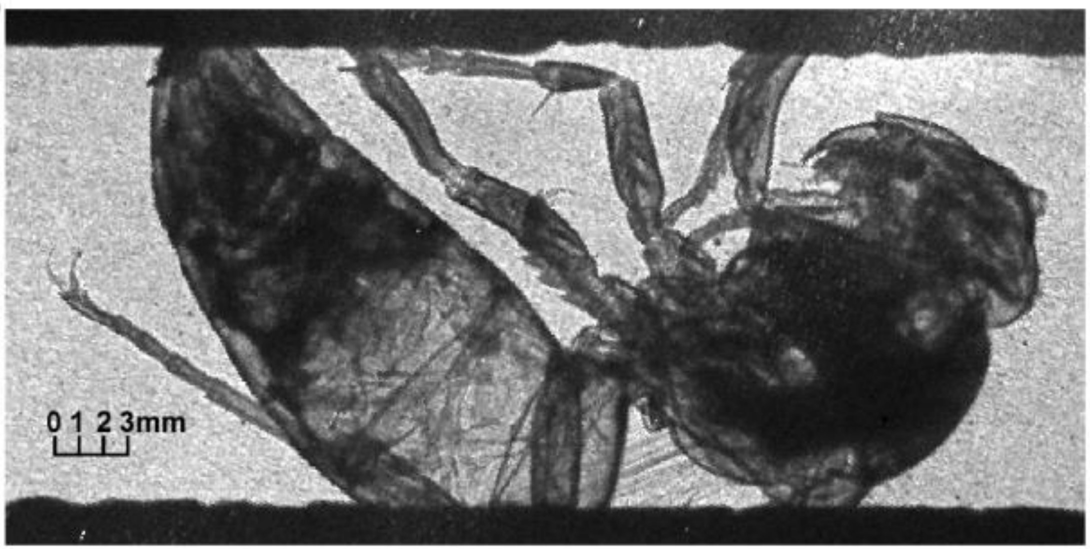
# X-ray imaging with a LCS beam




phase contrast imaging




absorption + refraction
→ edge enhancement




An X-ray image of a hornet taken with LCS-produced X-ray.
Detector: HyPix-3000 from RIGAKU. Detector was apart from the sample by approx. 2.5 m.

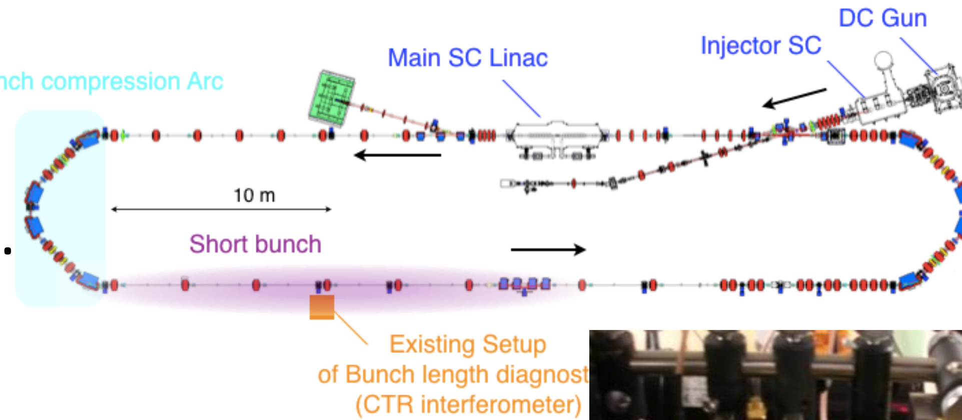
A. Kosuge et al., Proc. IPAC-2015, TUPWA066

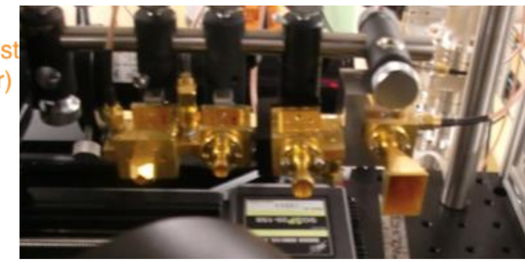
# Production of THz radiation

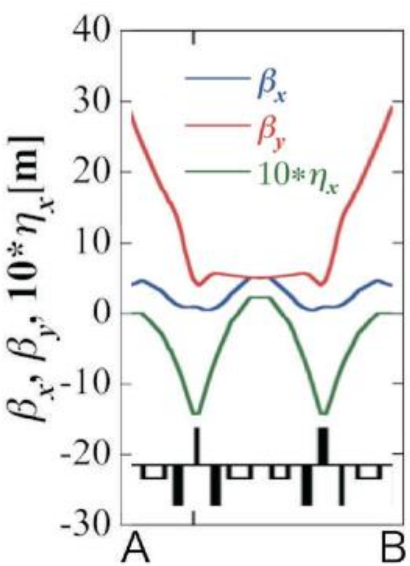
# Bunch compression tuning

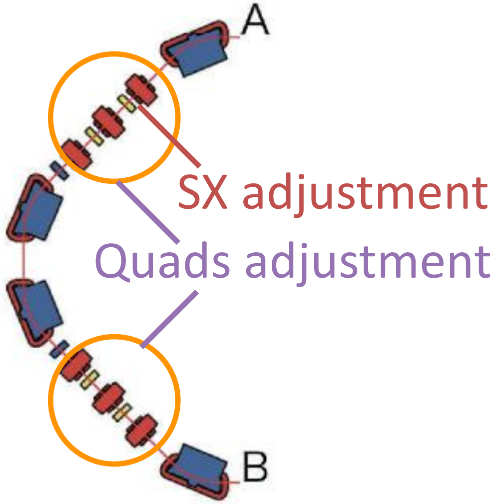
Courtesy of Y. Honda

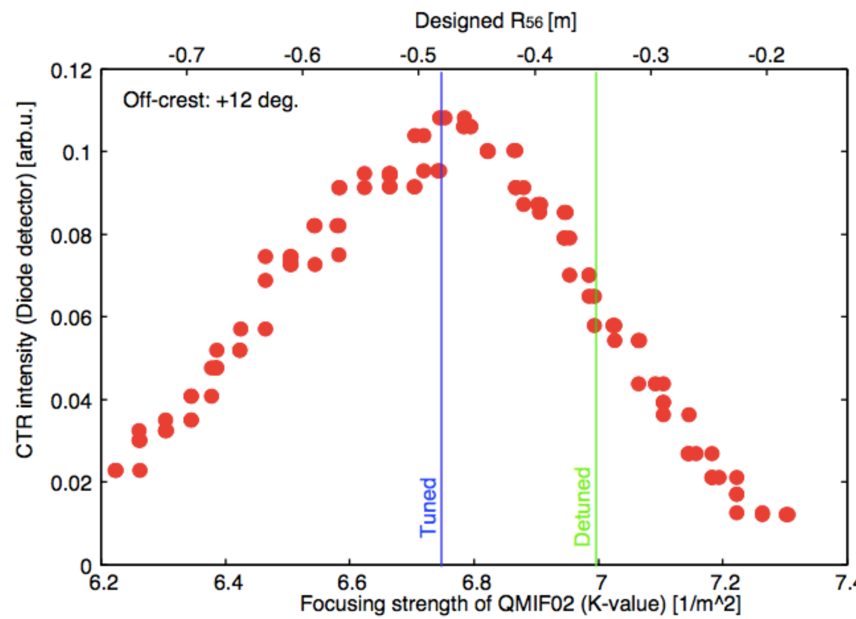
- Beam tuning procedure
  - Set Main linac Off-crest acc.
  - Scan the arc optics
    - R56 by Q combination
    - SX
  - Referring CTR intensity



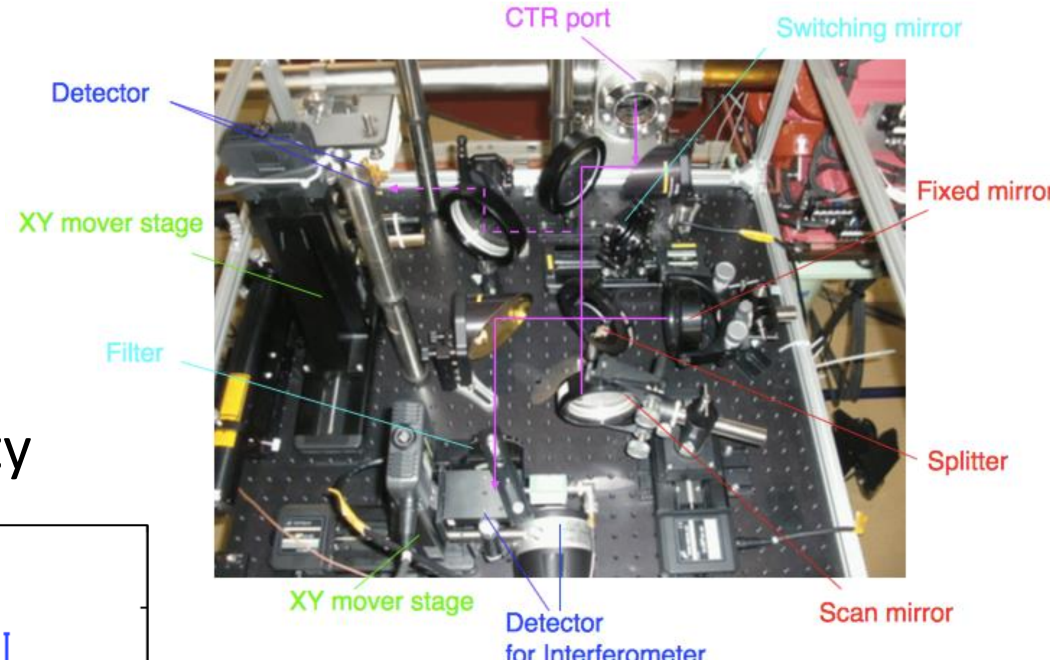


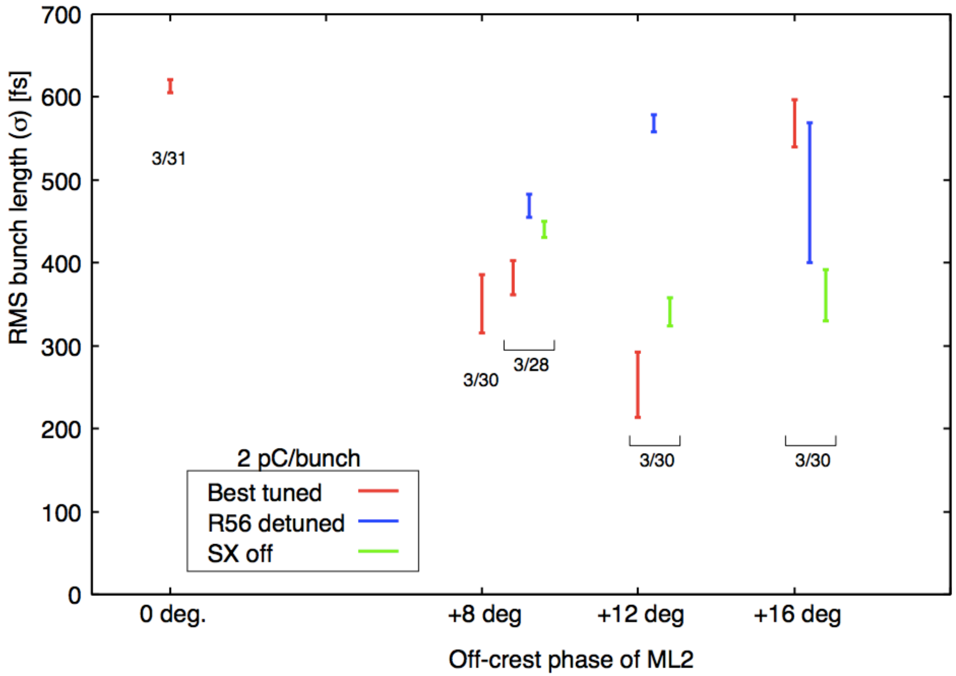



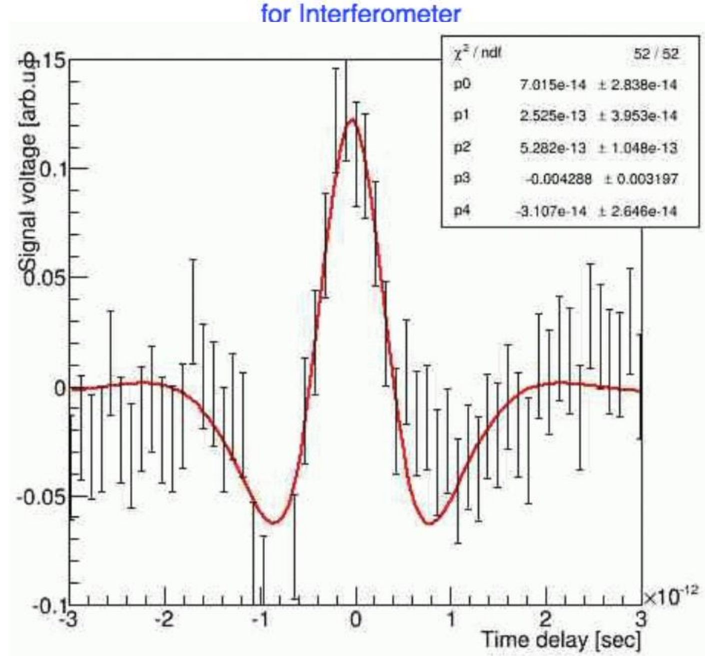
# Bunch length and THz measurement

Courtesy of Y. Honda




- Michelson interferometer at CTR port.
- Spectrum reaching ~1THz
- Bunch length 250fs (RMS) is realized in good reproducibility



# Change the target from academia to industry

2016　The future light source was shifted to the high-performance ring accelerator, so that there is no back ground to continue the ERL R&D.　On the other hand, KEK directorates kept the importance of the R&D for industrial application based on ERL technologies*). High bunch charge test operation was approved at the end of the fiscal year 2016.

2017　ERL project Office was closed in KEK and "Utilization Promotion Team based on Superconductive Accelerator" was kept in Department of future Accelerator and detector technologies in KEK.

*Reference)　KEK Project Implementation Plan (KEK-PIP)
http://www.kek.jp/ja/NewsRoom/Release/20160802141100/
3-2. Other research projects carried out using general funds of KEK
The following projects have up to now been conducted mainly using general funds of KEK. They will be continued on the condition that greater efforts are made to obtain external funding.
・Simulation studies with the existing supercomputer (only up to summer of 2017)
・Industrial application of ERL technology
・

# Industrial Application of ERL technology

ERL gives us a following outstanding performance on Accelerator.

- High current linac-based electron beam
  - Production of the high intense quantum beam
- High quality of the electron beam :

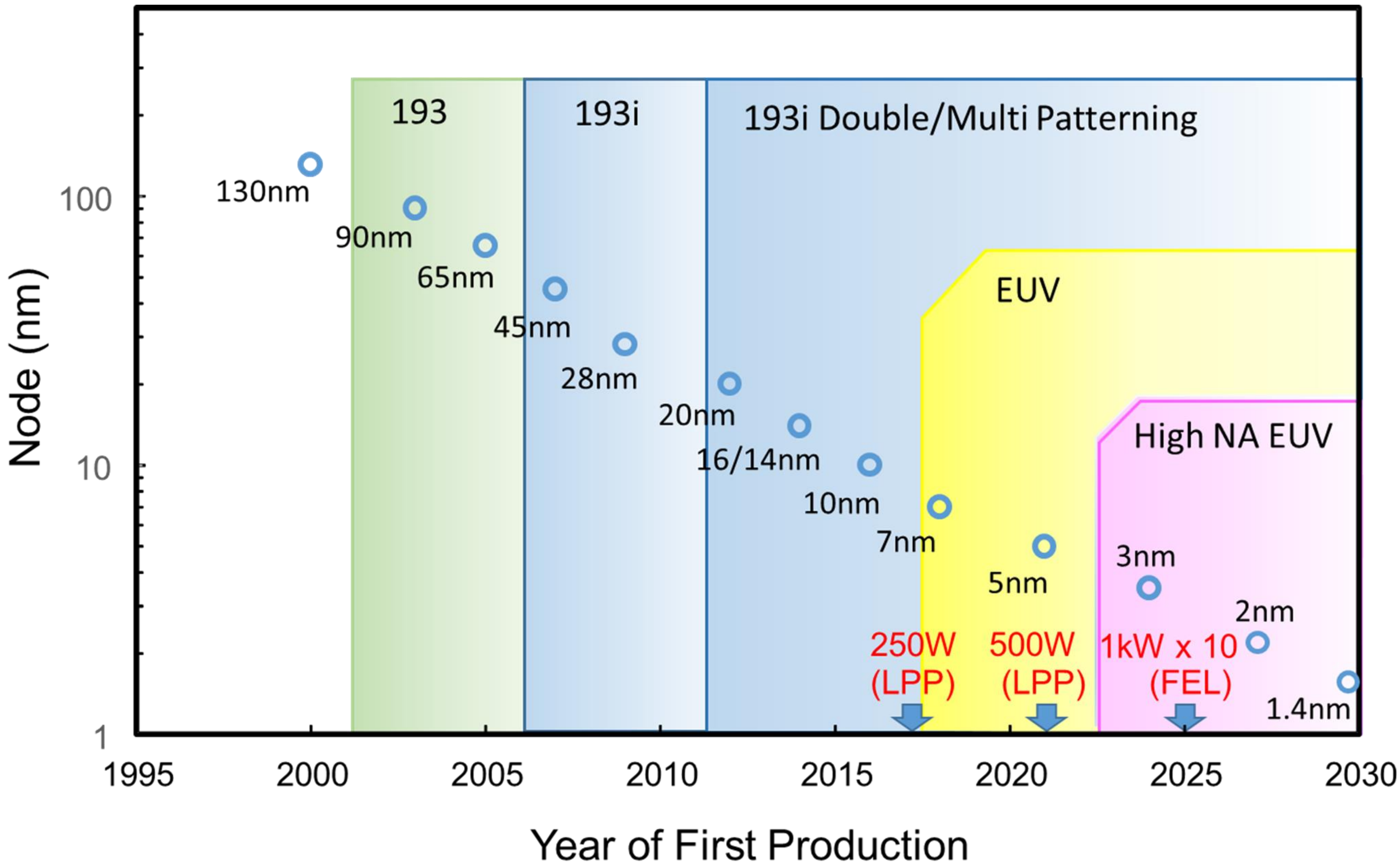
  Small Emittance, Short pulses, and so on
  - The quantum beams have excellent performance on energy and space resolution.

⬇

EUV-FEL for Lithography, High intense LCS sources and so on

# 1. EUV-FEL for Lithography

(Back ground)




Technology node trend of Logic LSI and expected power on EUV light source

# Present Status and Future Development on EUV Lithography

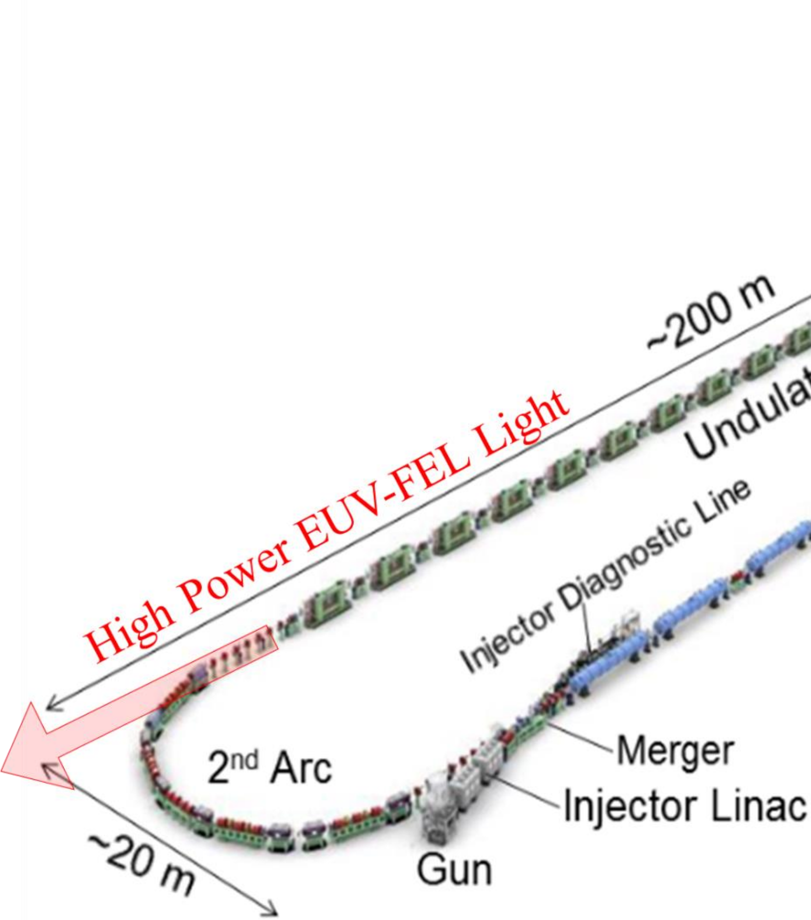
## Present Status

- The technologies on EUV Lithography system based on LPP light source are progressing, now.
- The system based on ~200 W LPP light source is starting point of the production phase.

## Future Development

- It is expected that these on ~1kW source will be necessary to realize the production less than 3nm node, too.
- It is important to develop new type light source to realize higher power than ~1kW, and also the other technologies.

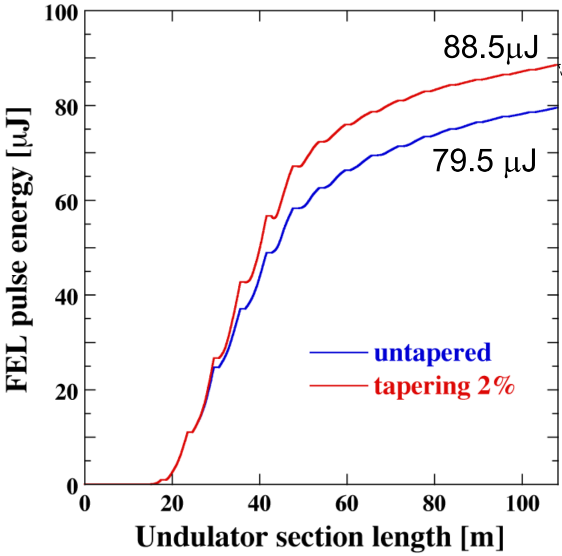
# Prototype design of the EUV-FEL

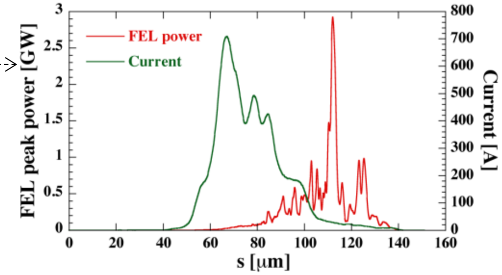


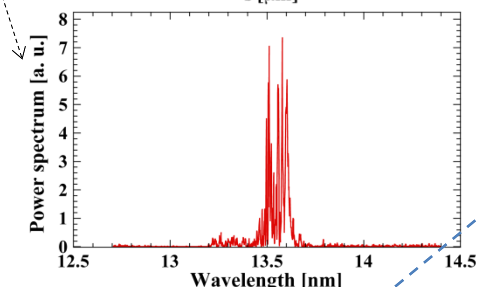

| Items | Achieved values in cERL | Design Values at the EUV-FEL |
|---|---|---|
| Energy for injector (MeV) | 2.9-6 | 10.5 |
| Energy of Accelerator(MeV) | 20 | 800 |
| Charge /bunch (pC) | 0.7-5 | 60 |
| Repetition rate (MHz) | 162.5-1300 | 162.5 |
| Average Current (mA) | 1.0 | 9.75 |
| Emitance for electron beam (mm mrad) | 0.3-1 | 0.6 |
| Gradient of the accelerated energy (MV/m) | 8.6 | 12.5 |
| Wavelength of EUV-FEL (nm) | / | 13.5 |
| Average power of EUV-FEL (kW) | / | Higher than 10 kW |

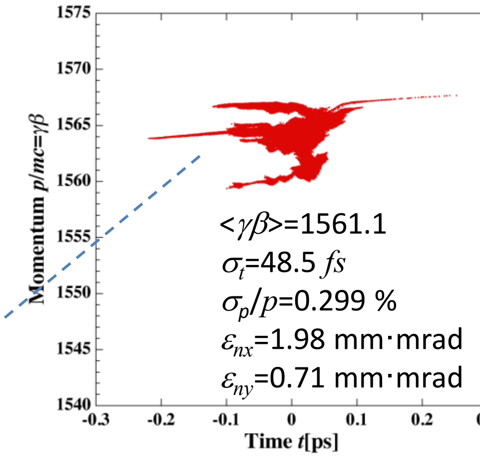
# FEL Performance

BY N. Nakamura: This workshop



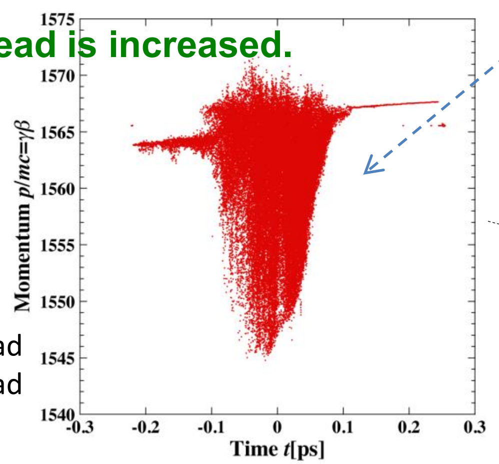



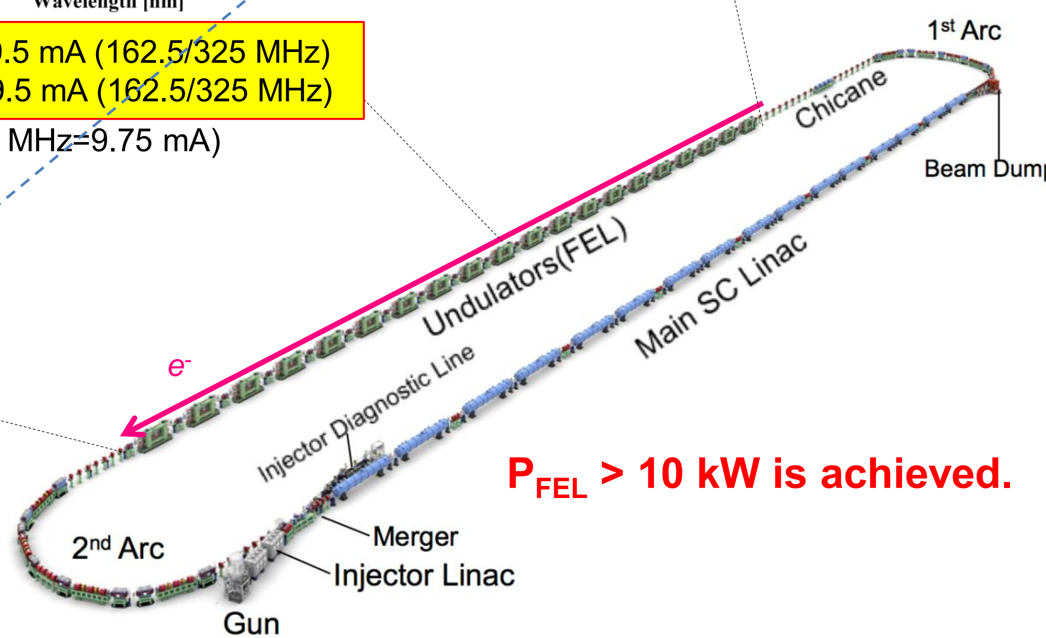

FEL power without tapering: 12.9/25.8 kW @ 9.75/19.5 mA (162.5/325 MHz)
FEL power with 2% tapering: 14.4/28.8 kW @ 9.75/19.5 mA (162.5/325 MHz)

($P_{FEL}$=84 μJ x 162.5 MHz =13.7 kW, $I_{av}$=60pC x 162.5 MHz=9.75 mA)

**Energy spread is increased.**




$\langle\gamma\beta\rangle$=1561.1
$\sigma_t$=48.5 *fs*
$\sigma_p/p$=0.299 %
$\varepsilon_{nx}$=1.98 mm·mrad
$\varepsilon_{ny}$=0.71 mm·mrad




**$P_{FEL}$ > 10 kW is achieved.**

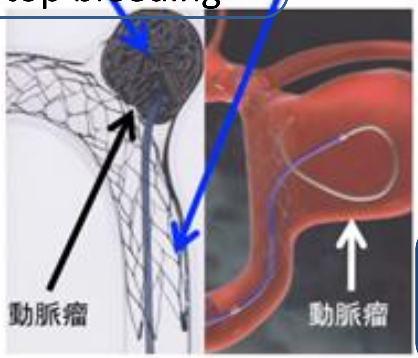
# 2. High resolution X-ray imaging device for medical use

## From the view point of neurosurgery
Courtesy of K. Hyodo

**Intravascular surgery of neurosurgery**

**coil:** Stuffed aneurysm and stop bleeding

Stent: Support stabilizing coil



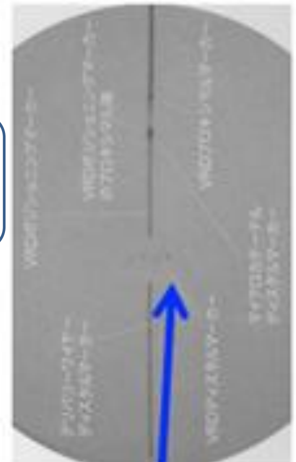
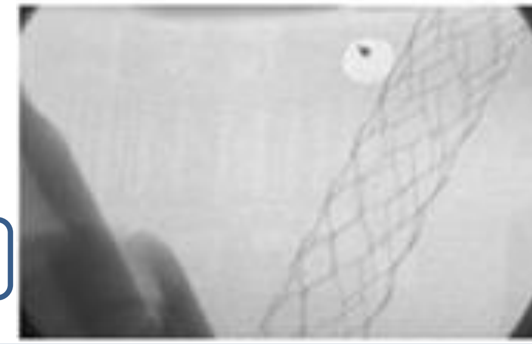



**Image under surgery**
The stent can not be seen

**Using a large synchrotron radiation facility**

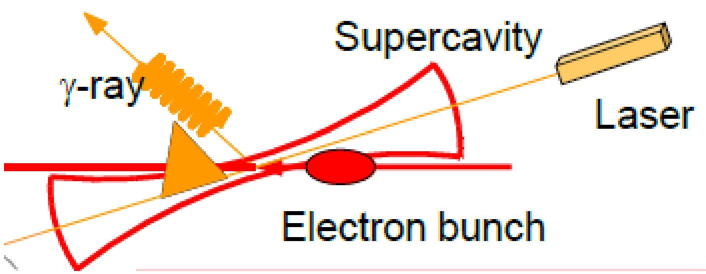
High resolution



Stents can be clearly visualized

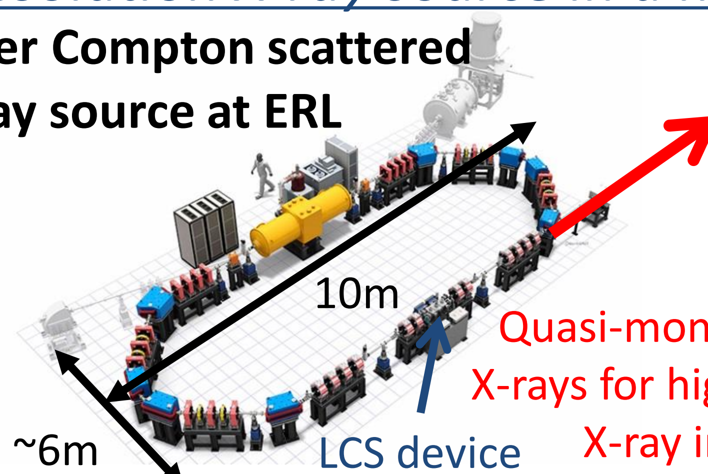
Provided by the Department of Neurosurgery, University of Tsukuba

*If we can make a compact high-resolution X-ray source in a hospital!*




Potential of quasi-monochromatic X-rays for high resolution X-ray imaging by laser Compton scattering (LCS)

**Laser Compton scattered X-ray source at ERL**




Quasi-monochromatic X-rays for high resolution X-ray imaging

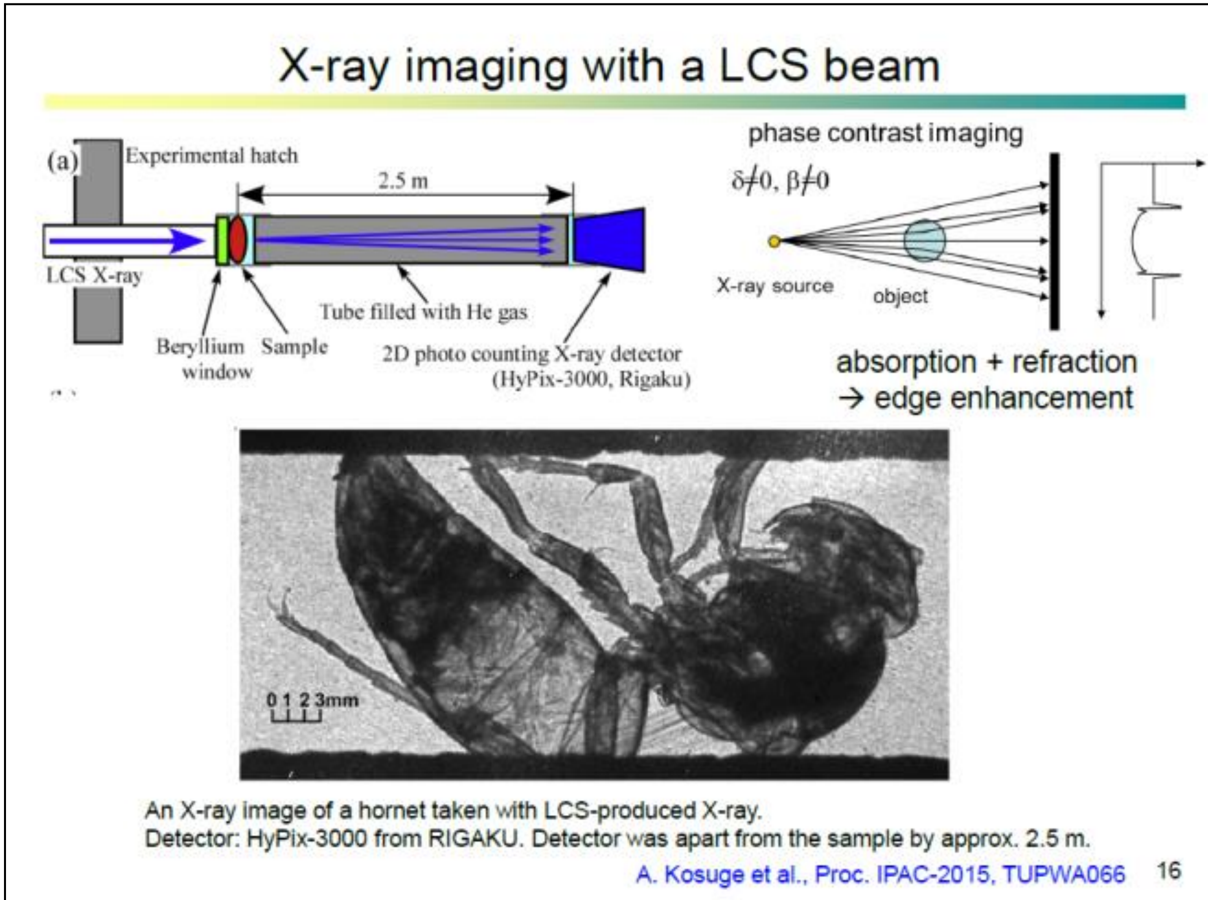
# 2. High resolution X-ray imaging device for medical use

## Feasibility from the experimental result on cERL

Courtesy of K. Hyodo

- Success of LCS at cERL (March/2014) (high resolution X-ray imaging) (20MeV, 0.1 mA, 10kW laser Cavity)

http://www.kek.jp/ja/NewsRoom/Release/20150427150000/




Result of March/2014

X-ray Energy 7keV
Exposure time 600sec

**<u>Main issues for medical application</u>**

1) Too long exposure time
2) Too low Energy

(50MeV, 10 mA, >100kW laser Cavity)

X-ray Energy ~40 keV
Exposure time <0.1 sec

Starting point of medical application

# 3. Nuclear security system

Courtesy of R. Hajima

## (Non-destructive Detection and Measurement of Nuclear Material by Laser Compton Scattering Gamma Ray)

**Necessity of non-destructive detection and measurement of nuclear material**

### 1) Deterrence of terrorism using nuclear material

· Confront terrorism with an international framework (nuclear security summit)

· Border strategy to investigate the nuclear material is essential against nuclear terrorism.

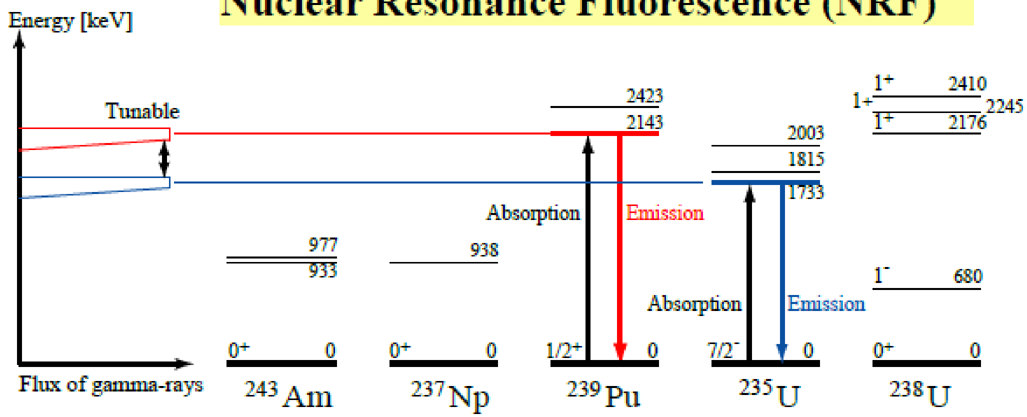

### 2) Nuclear nonproliferation

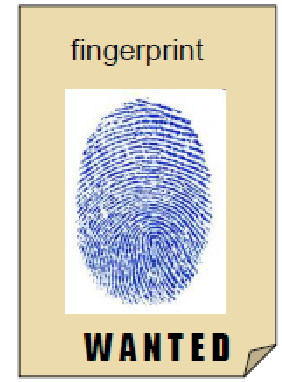
· Melted fuel will be taken from Fukushima Nuclear Power plant from 2021

· Nuclear material measurement of melted fuel is essential

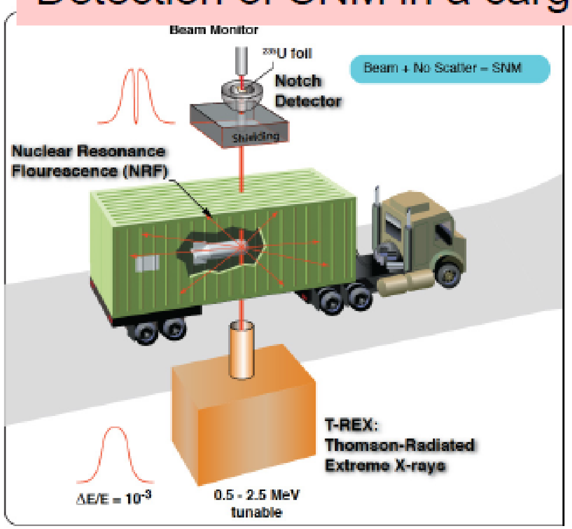
# Nondestructive Detection & Measurement of Nuclear Material

## Nuclear Resonance Fluorescence (NRF)



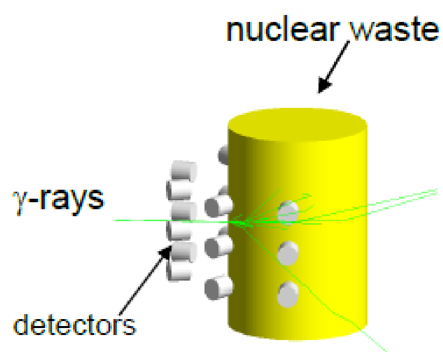




## Detection of SNM in a cargo




SNM: special nuclear material

## Management of nuclear material




detection and assay of isotopes
- -- U, Pu, and Minor Actinides
- -- alpha emitter
- -- difficult to measure by passive assay

R. Hajima et al., J. Nucl. Sci. Tech. 45, 441 (2008)
J. Pruet et al., J. App. Phys. 99, 123102 (2006)

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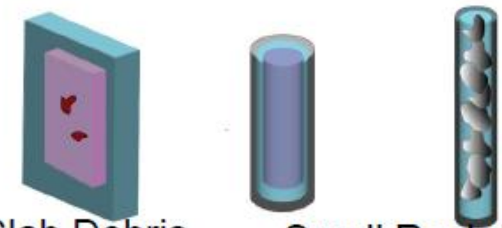
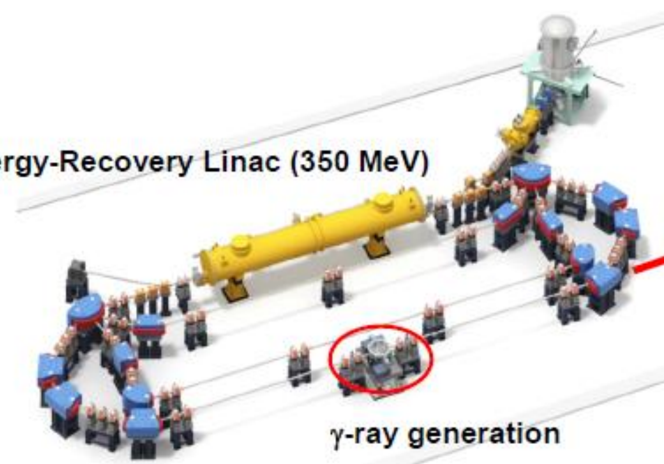
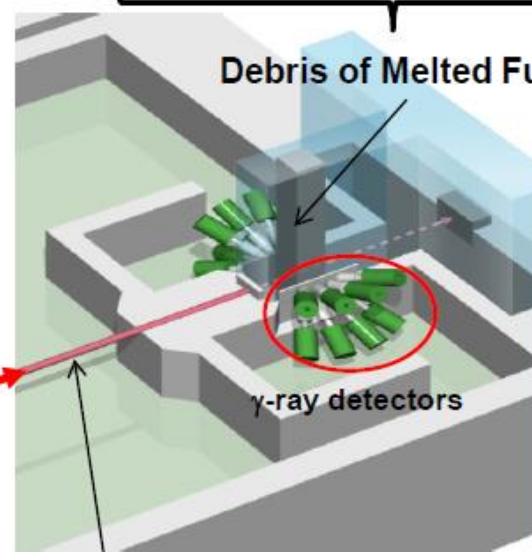
# LCS γ-ray for Fukushima

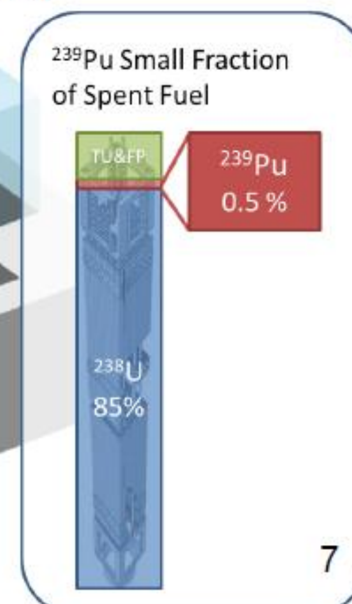
Measurement of Pu in the melted fuel → necessary for nuclear nonproliferation!

removal of debris from the core ~2022






R. Hajima: ERL15

# 4. RI manufacturing facility for nuclear medical examination ($^{99}Mo/^{99m}Tc$)

Courtesy of K. Umemori

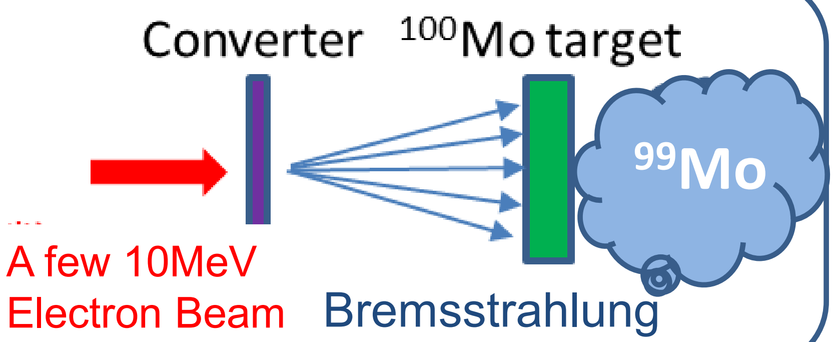
Concern about the stable supply of $^{99}Mo$ / $^{99m}Tc$

- $^{99}Mo$ is almost 100% imported, even though the largest number of applications in nuclear medicine diagnosis
- Problem of the stable air transportation

(Problem caused by volcanic eruption in the past)

- Most $^{99}Mo$ is manufactured in nuclear reactor
- Due to the aging of nuclear reactors, stable supply in the future is a big issue

Development of RI manufacturing ($^{99}Mo$ / $^{99m}Tc$) by using accelerator for stable supply




Required Specification for accelerator

- 20 ~ 50 MeV electron beam
- Several mA to 10 mA

# Summary

- ERL gives us high current linac-based electron beam (~10mA) with high quality of the electron beam such as small emittance, Short pulses.
- The unique performance gives us several important industrial applications.