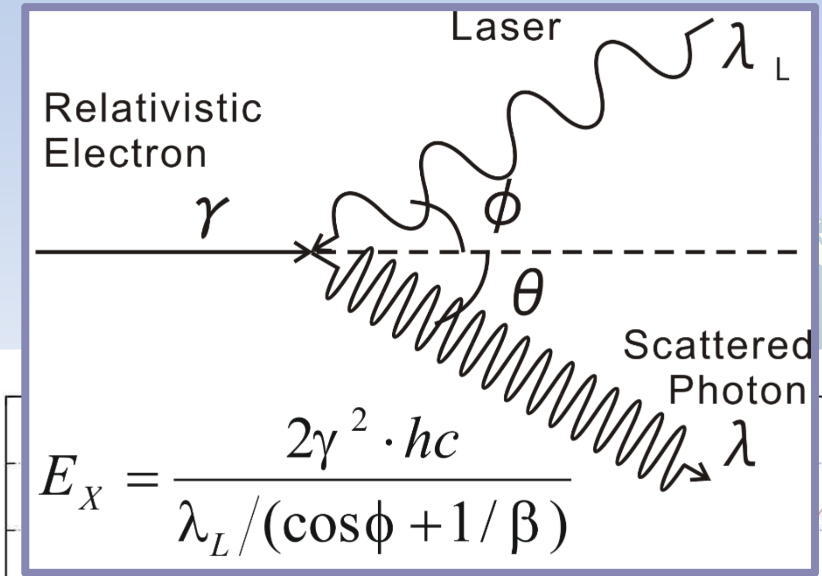
Recent Results on X-ray Generation at LUCX

AFAD-2018 at Daejeon Convention Center (DCC), Korea
KEK, Junji Urakawa

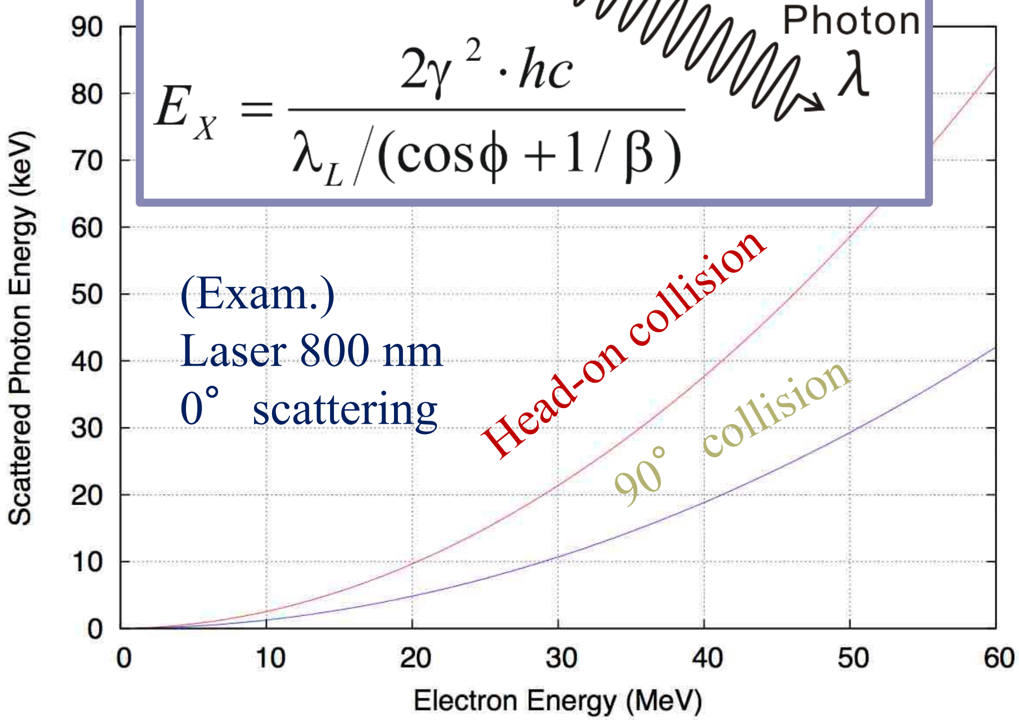
Contents :

1. LUCX (Laser Undulator Compact X-ray)

Laser Compton Scattering (LCS)



$$E_X = \frac{2\gamma^2 \cdot hc}{\lambda_L/(\cos\phi + 1/\beta)}$$



Inverse Compton Scattering

- Laser
- Several 10 MeV electron beam
  (Small accelerator)

Several 10 keV X-ray
(like as large SR accelerators)

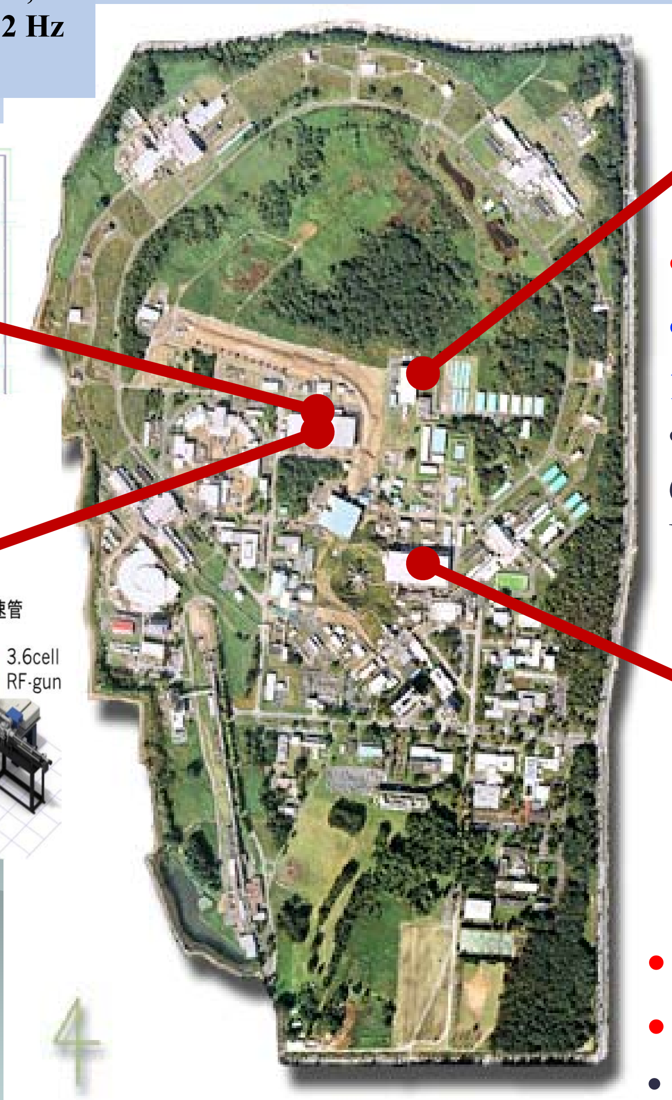
Property of LCS X-ray

- ✓ small source point
- ✓ monochromatic by collimation
- ✓ Tunable Energy
- ✓ short pulse (ps, fs)

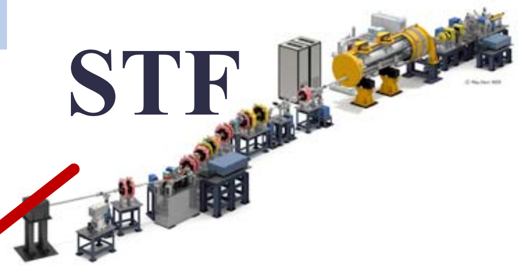
Electron Accelerators in KEK used for LCS R&D

ATF

Electron beam: 1.3 GeV
Intensity: ~2x10^{10} e/bunch,
1 ~ 20 bunches/train, 3.12 Hz
$\varepsilon_{x/y}$ ~ 1.5nm/4pm



STF



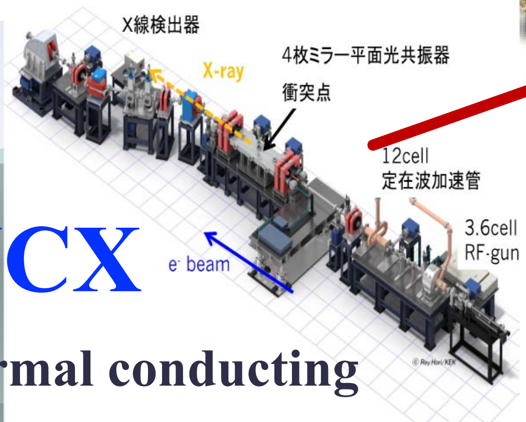
- **Superconducting RF**
- **Pulsed beam:**

1.3 GHz, 1 ms

- Higher energy:

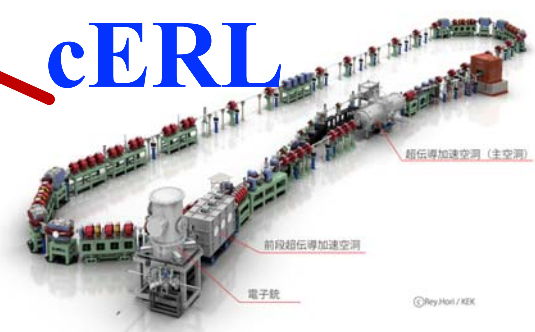
60 MeV → 300 MeV
Under upgrading

LUCX



- **Normal conducting RF**
- **Pulsed beam: 357 MHz - 1000 bunches/pulse**
- **1000 kW pulse laser stacking in optical cavity**
- **24 MeV**

cERL



- **Superconducting RF**
- **CW beam 100 uA → 10 mA**
- **20 MeV**

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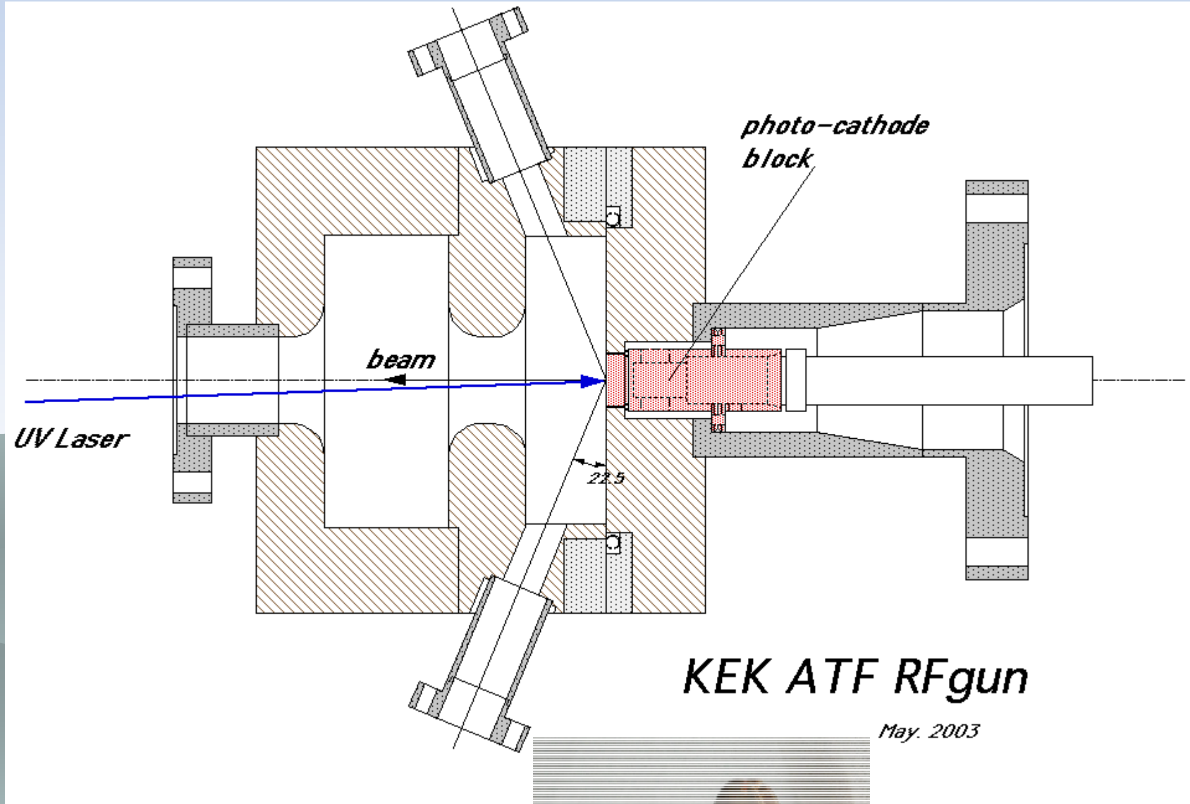
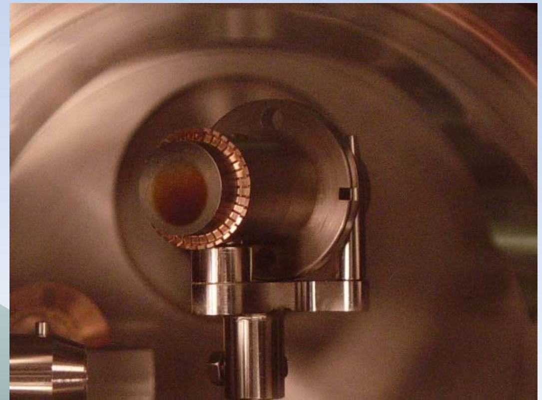
Since we consider the generation of short bunched electron beam, high RF gradient acceleration and short pulse laser to generate photo-electron bunch in the cavity are necessary for the generation of high quality electron beam.
This is a photo-cathode RF gun.

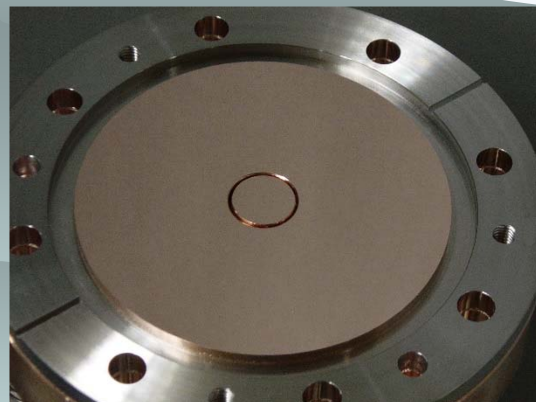
Old RF-gun cavity & cathode block





Cathode block with Cs_2Te coating

Cathode block

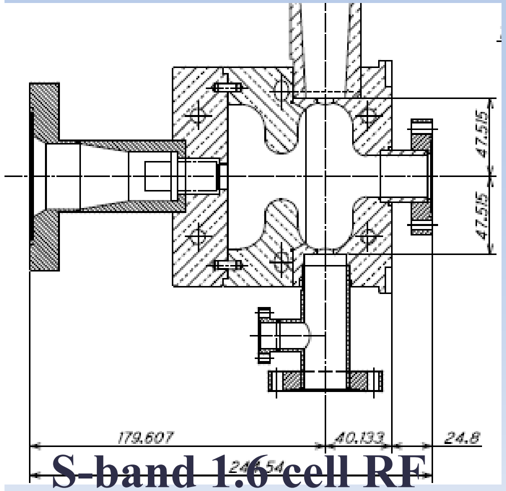


End plate with cathode block

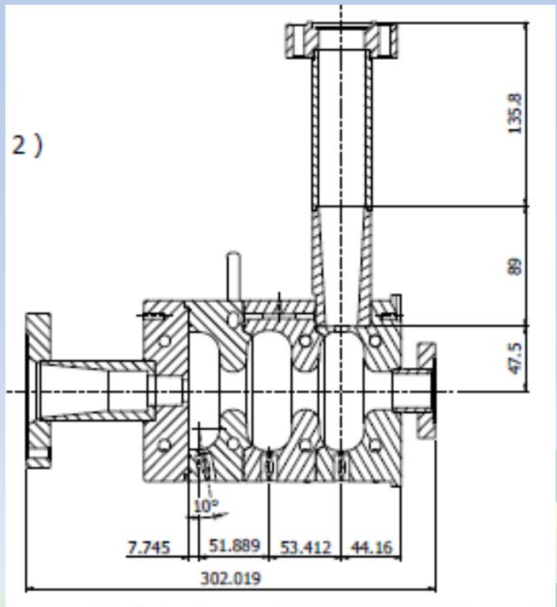
250mm

300mm

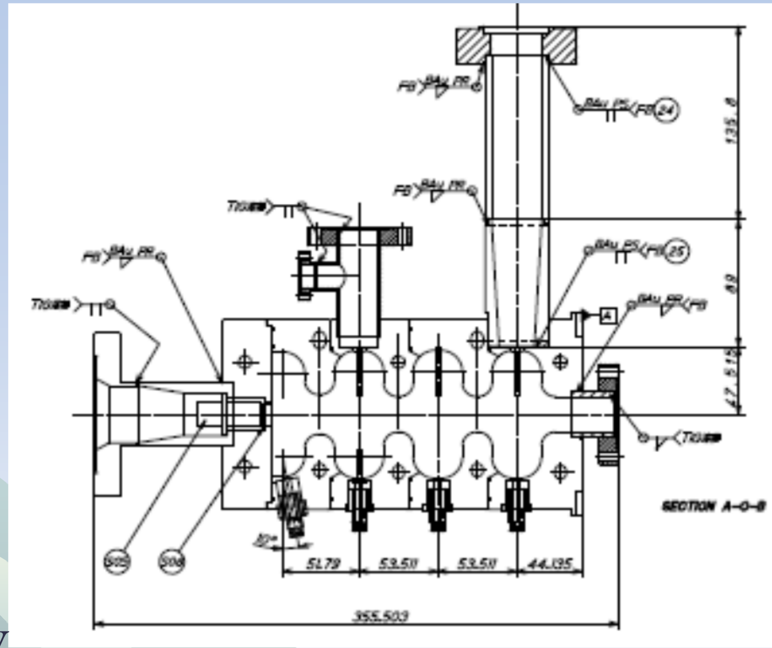
360mm



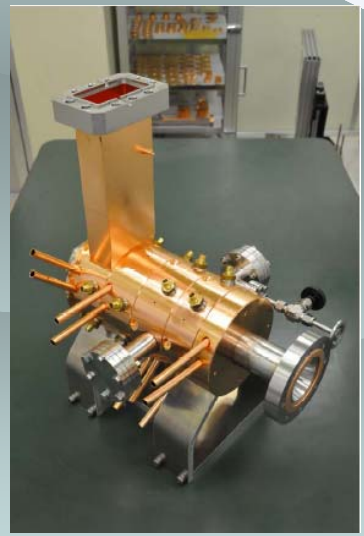
S-band 1.6 cell RF Gun, 100MV/m more Operation 120MV/m, achieved highest accelerating gradient 140MV/m, ~ 6 MeV



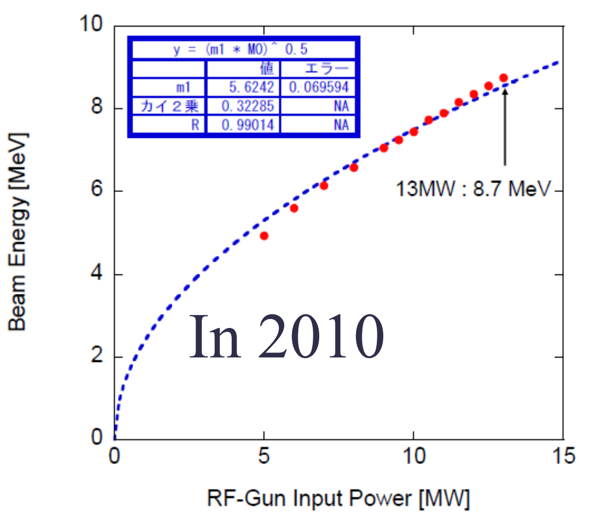
S-band 2.6 cell RF Gun ~ 8MeV

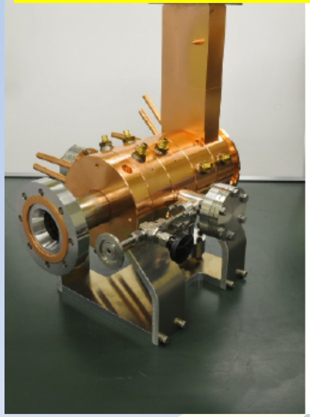


S-band 3.6 cell RF Gun ~ 10MeV

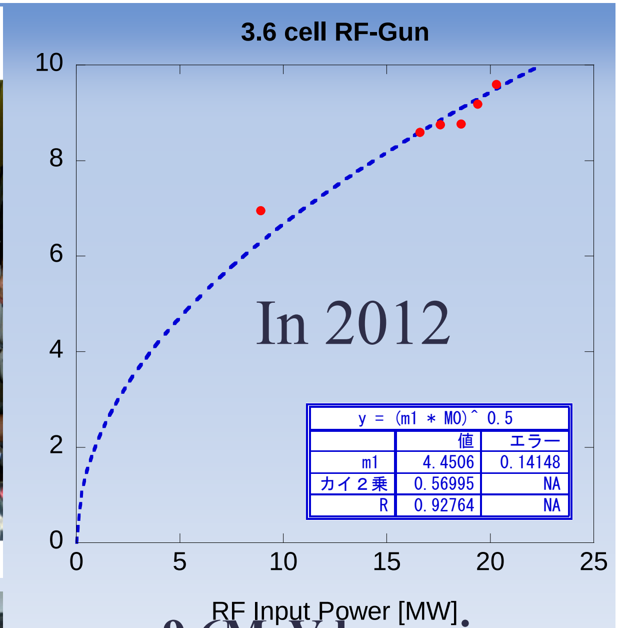


3.6 cell RF Gun Installation

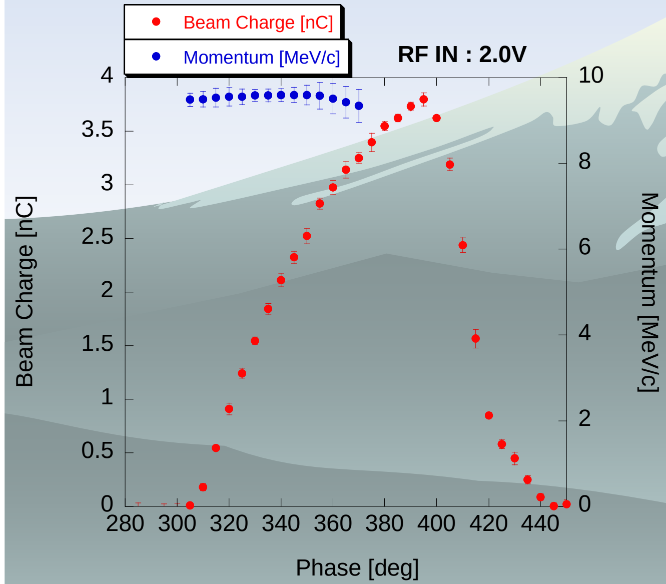


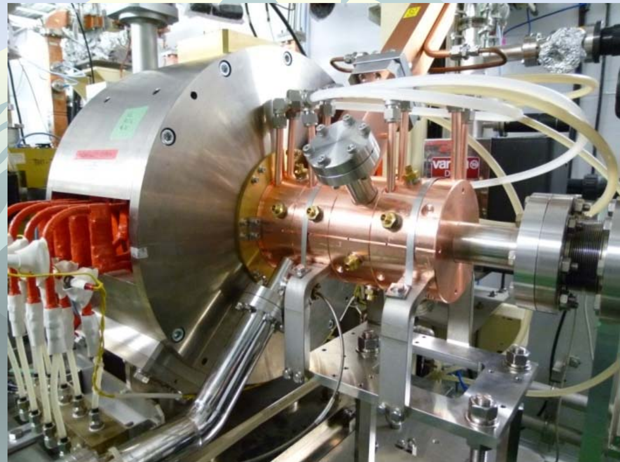


ATF インストールの様子



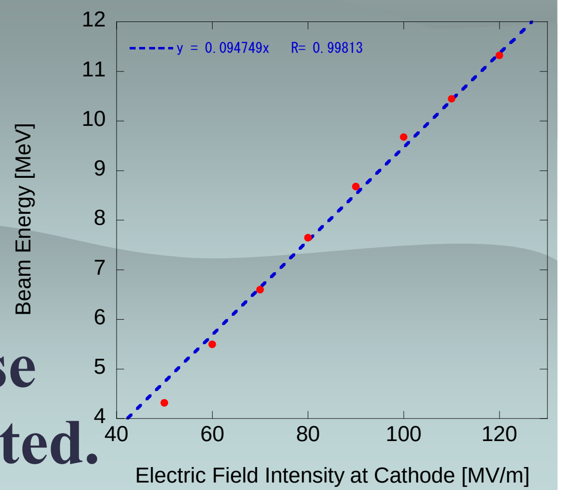
9.6MeV beam in a week RF aging with ~20.3MW RF input power





3.6 cell RF-Gun
Start of beam acceleration test from 1/11,2012.

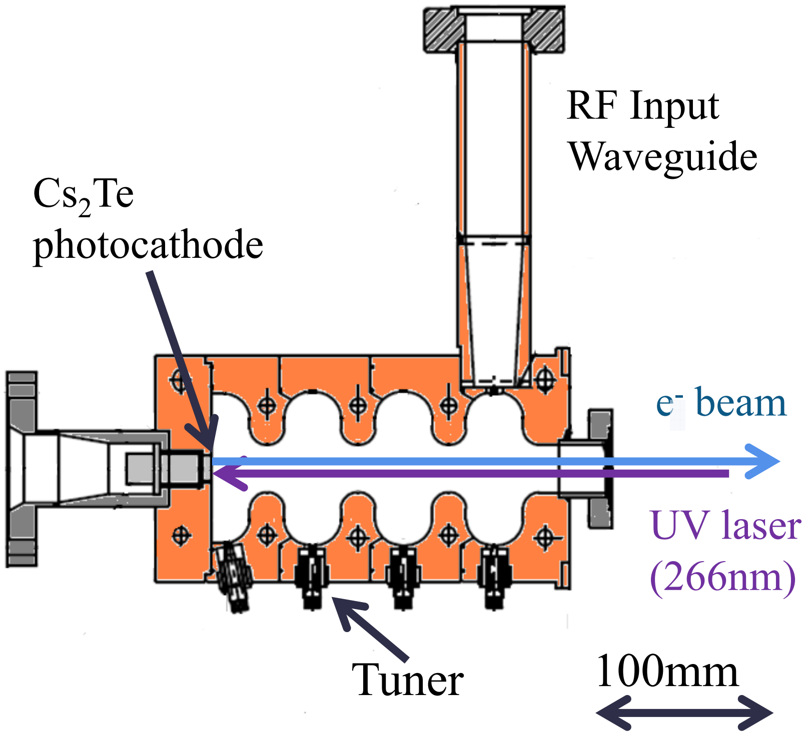
PARMELA SIMULATION

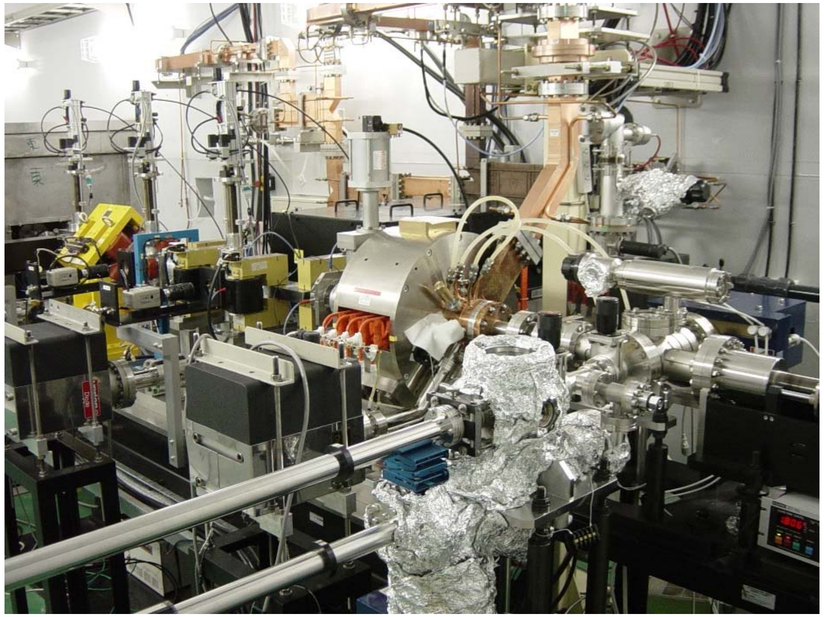


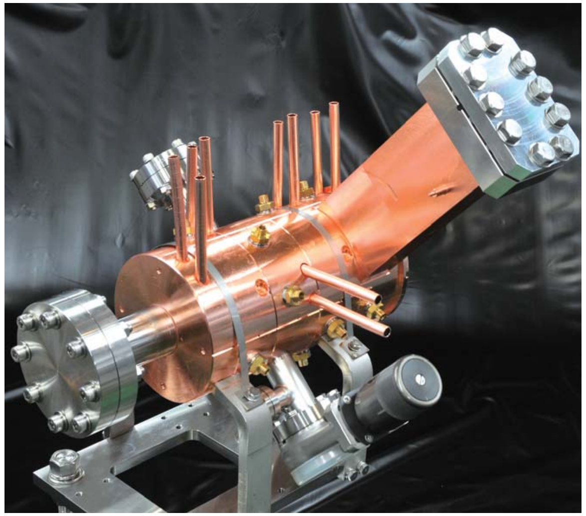
11MeV beam at 120MV/m, from 100bunches/pulse to 1000bunches/pulse beam generation was expected.

LUCX and ATF electron source: 3.6-cell RF gun

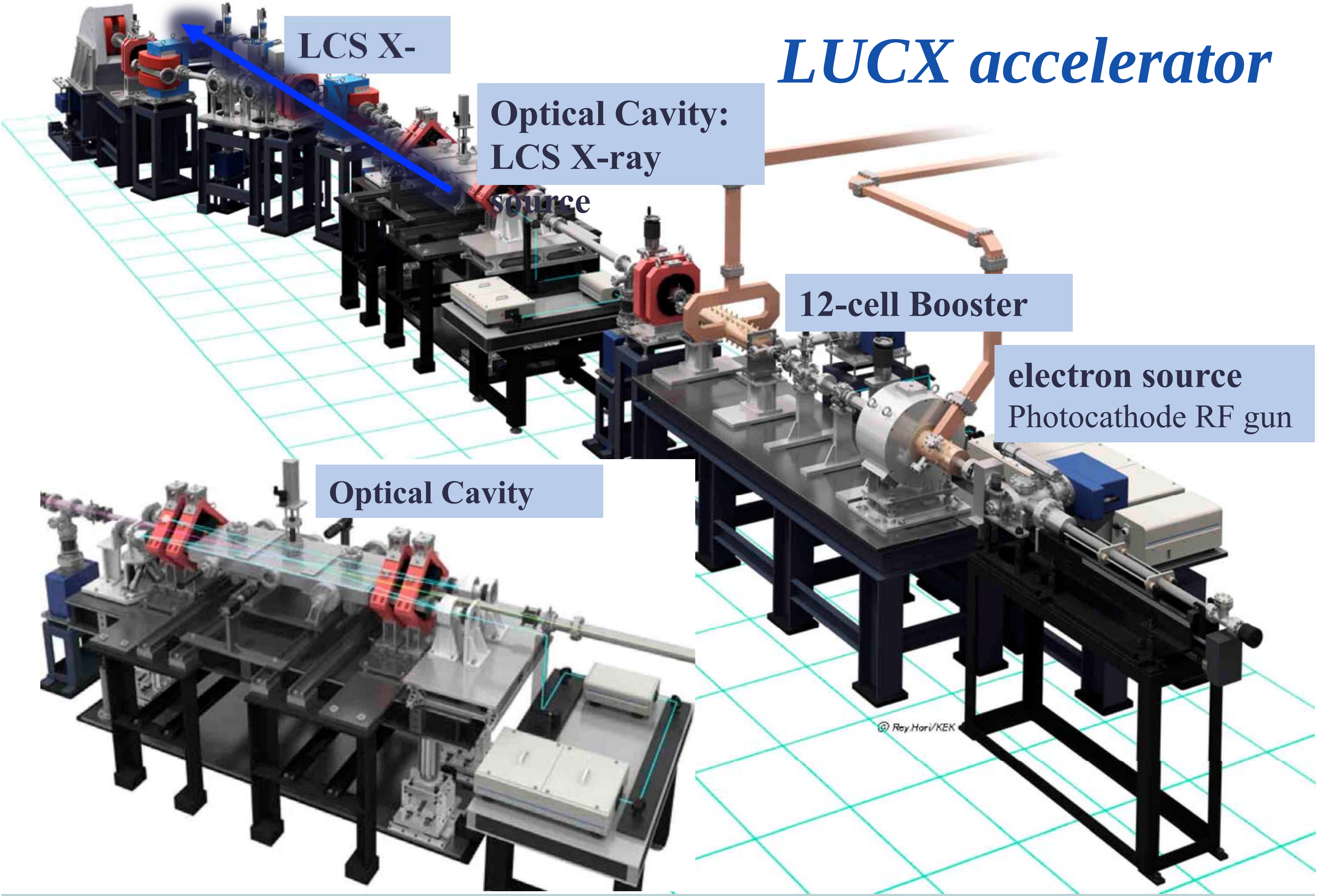
Frequency (π-mode)	2856 MHz
Qvalue	15000
Coupling β	0.99
R/Q	395Ω
Mode separation (π-2π/3)	2.8 MHz







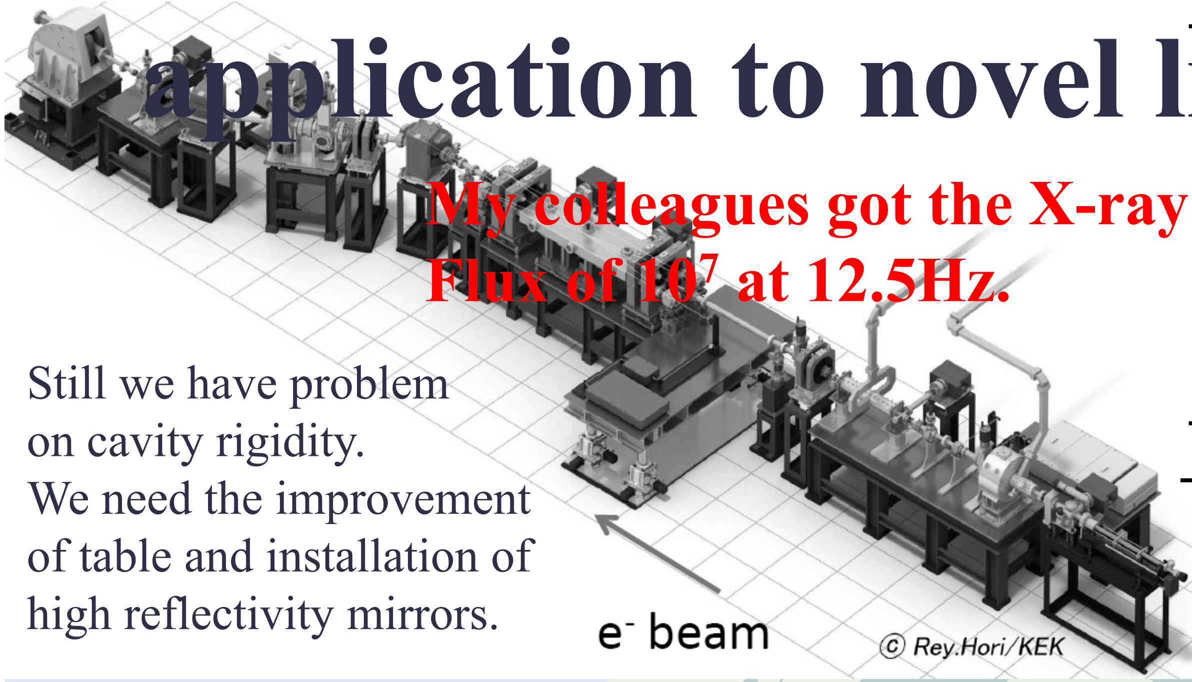
LUCX accelerator



application to novel light sources

Energy	30MeV
Intensity	0.4nC/bunch
Number of bunch	1000
Beam size at the collision point (1σ)	33μm ×33μm
Bunch length	10ps
Bunch spacing	2.8ns

Energy	1.17eV(1064nm)
Intensity	8mJ/pulse
Waist size(1σ)	55μm ×25μm
Pulse length	7ps

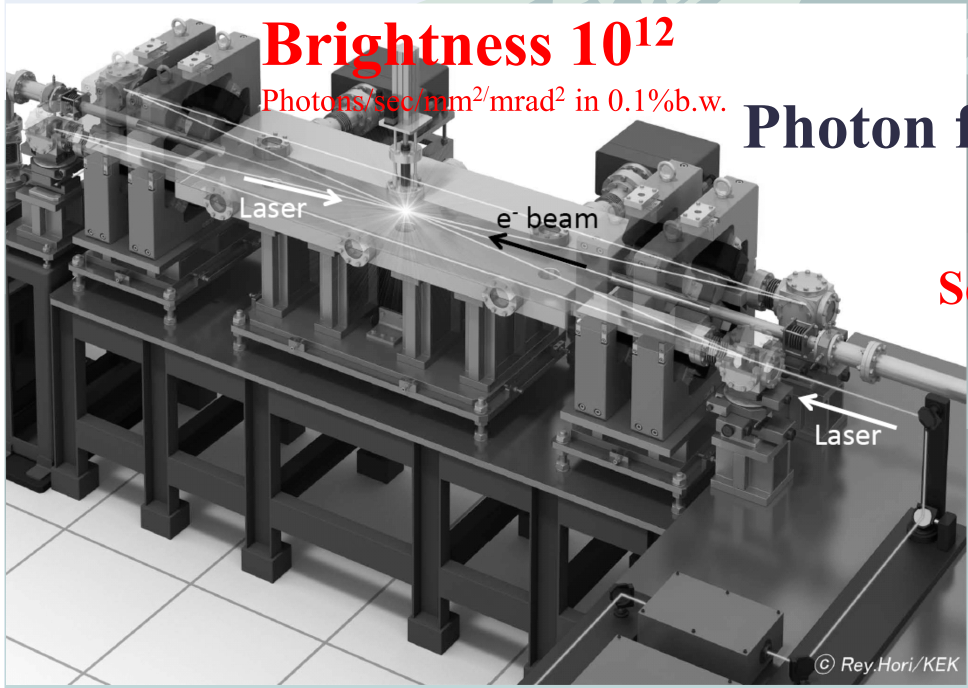


My colleagues got the X-ray Flux of 10^7 at 12.5Hz.

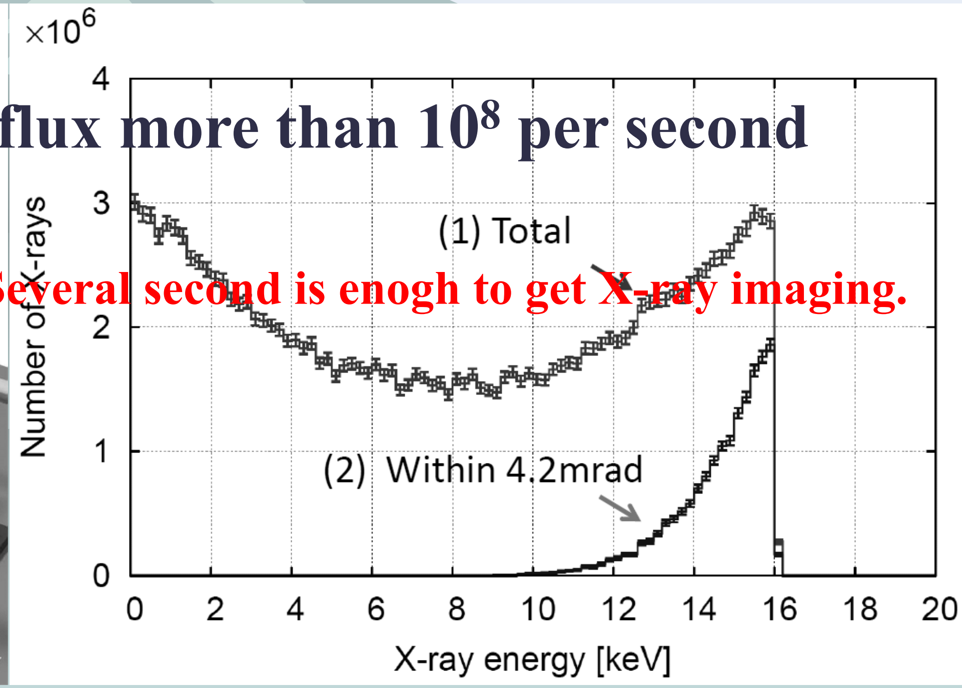
Still we have problem on cavity rigidity.
We need the improvement of table and installation of high reflectivity mirrors.

Brightness 10^{12}

Photons/sec/mm²/mrad² in 0.1%b.w.



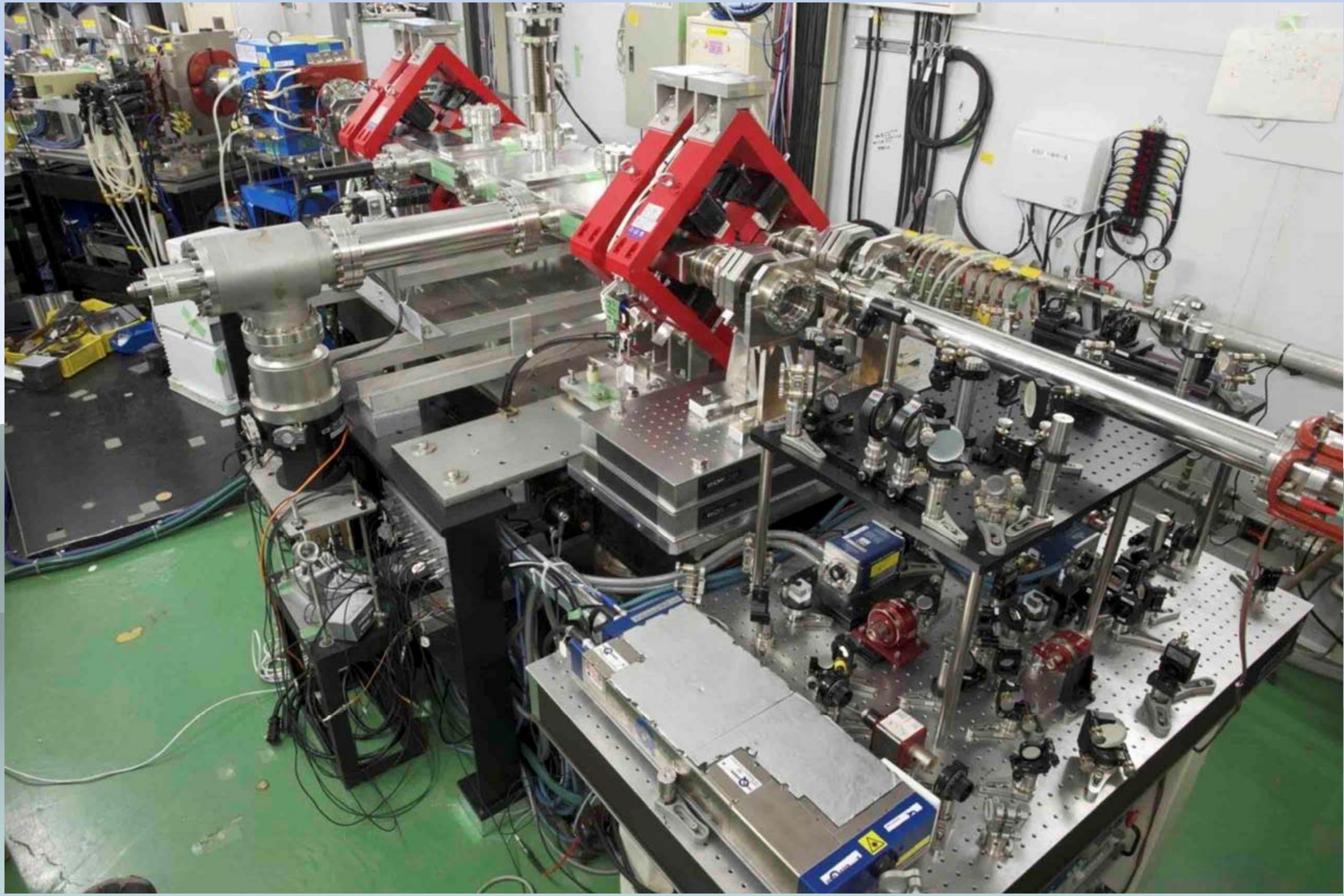
Photon flux more than 10^8 per second



Several second is enogh to get X-ray imaging.

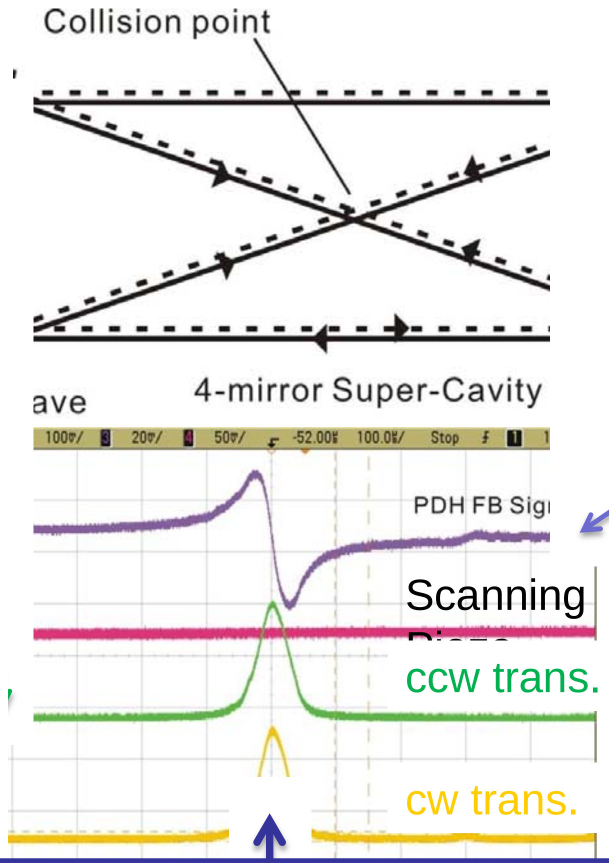
2. Laser Pulse Accumulation with Burst Amplification

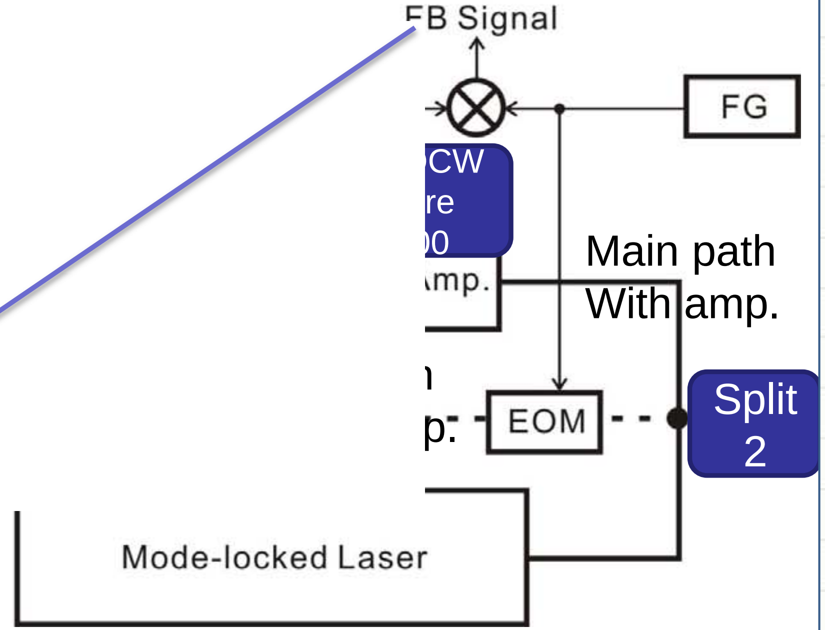
LUCX Optical cavity and Laser system



Burst mode optical enhancement cavity

R. W. P. Drever et al.,
Appl. Phys. B, 1(1983)97.
Use PDH method



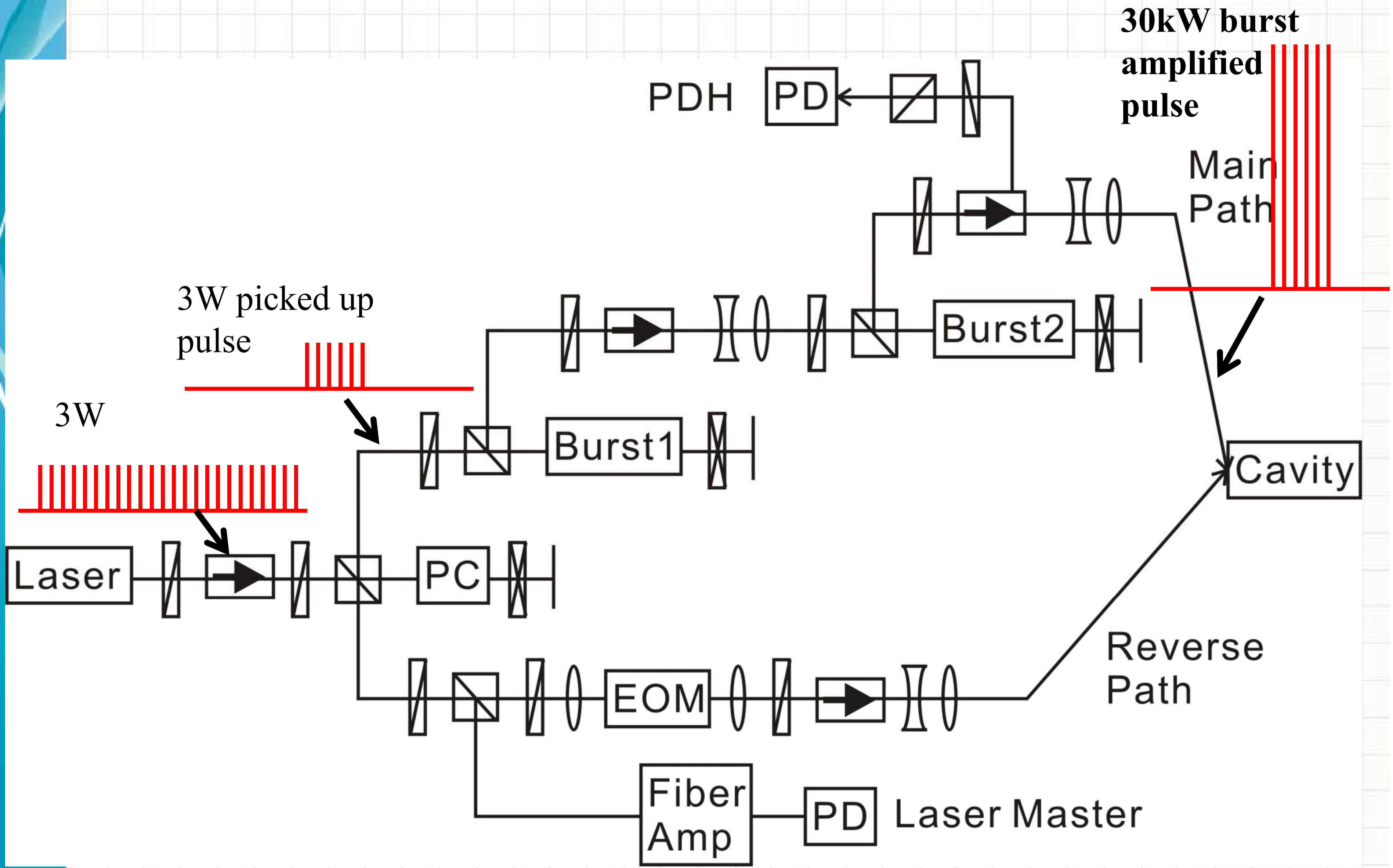


Main and rev. path resonate on same cavity length

1000 times higher peak power can be achieved on electron beam timing, which stabilized by reverse path in the optical cavity.

K. Sakaue (Waseda univ.)

We installed the Pockels cell in order to collect the amplification power at the electron beam timing.

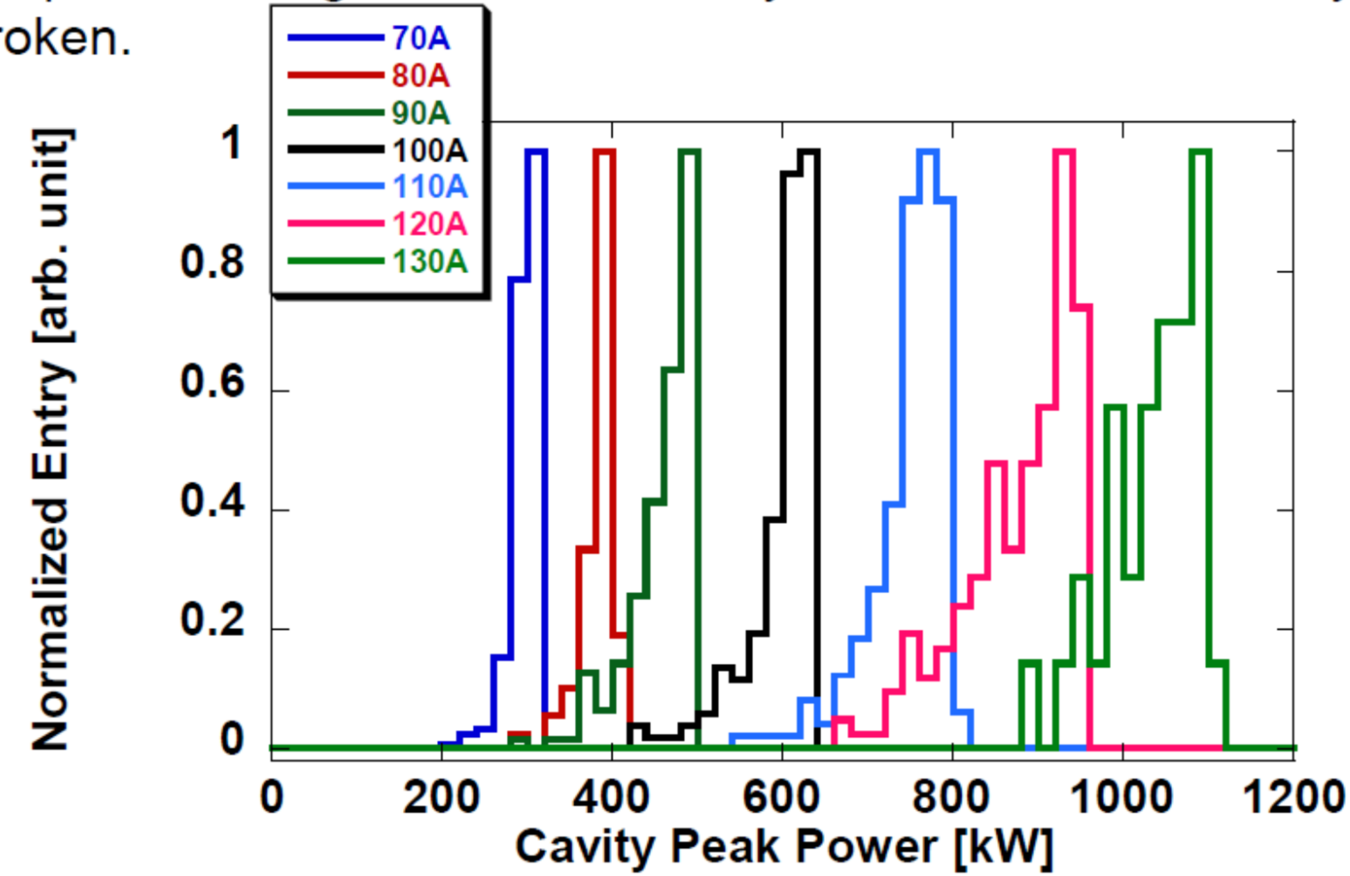


Burst Storage with PC

Histogram of peak power stored in the optical cavity

Power jitter is also small, about 5% in rms

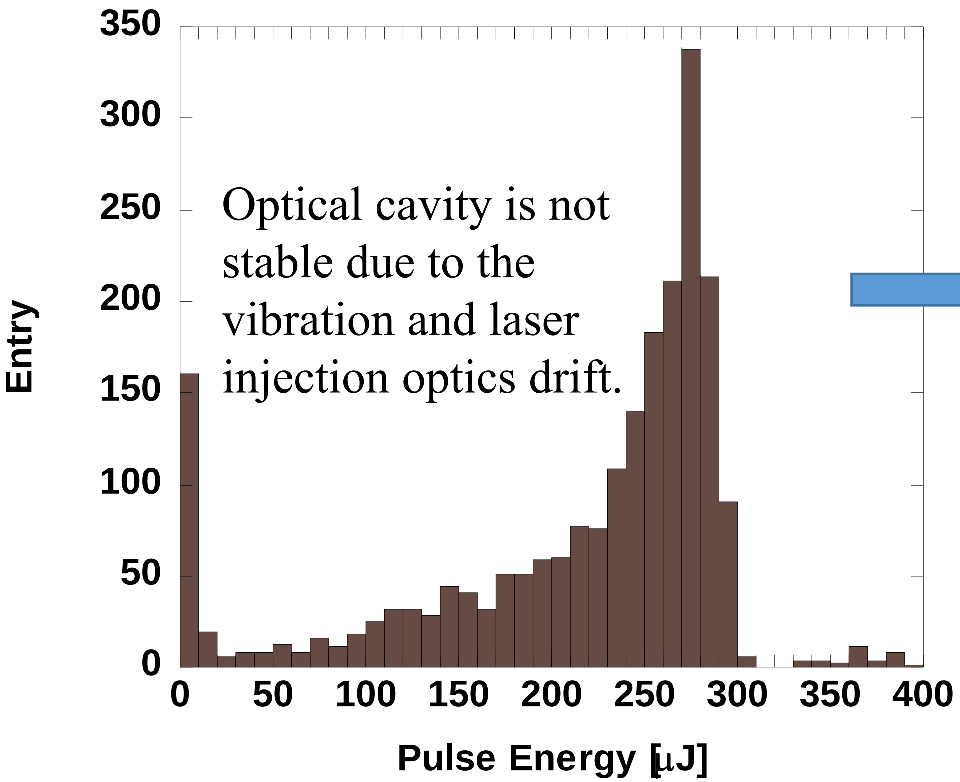
1MW peak power storage was successfully achieved, but the cavity mirror was broken.

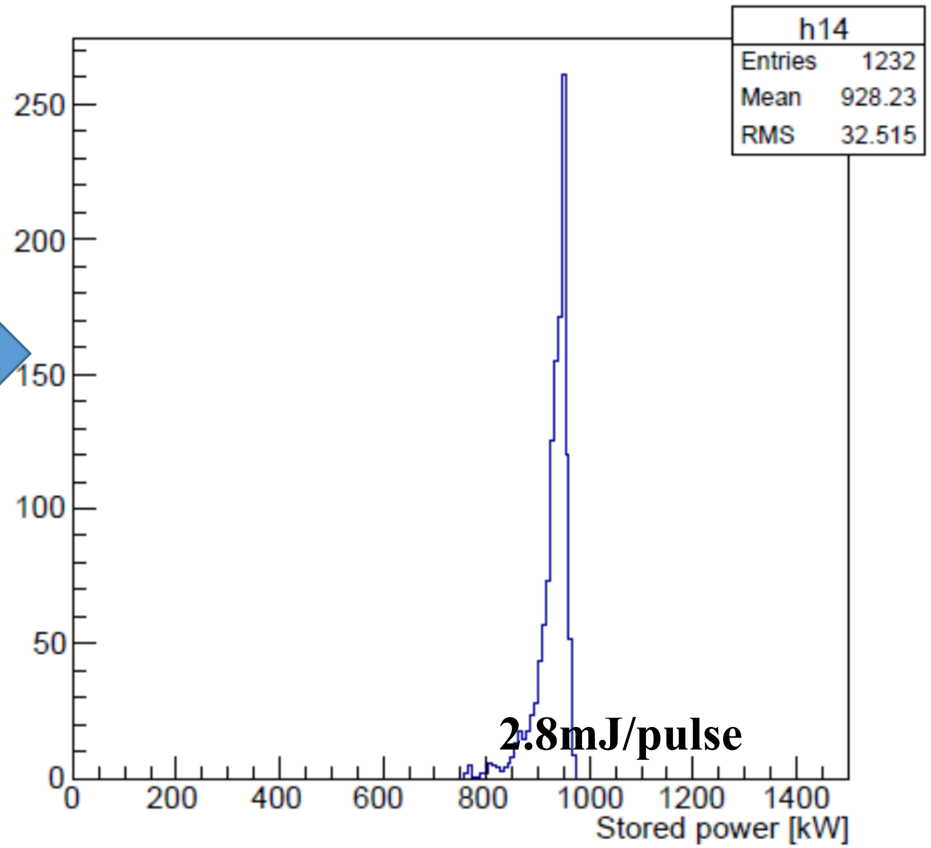


Laser power stability in the optical cavity

Stability of stored pulse intensity: 15% rms
About 0.2nm accuracy of cavity length adjustment was not achieved two years ago.

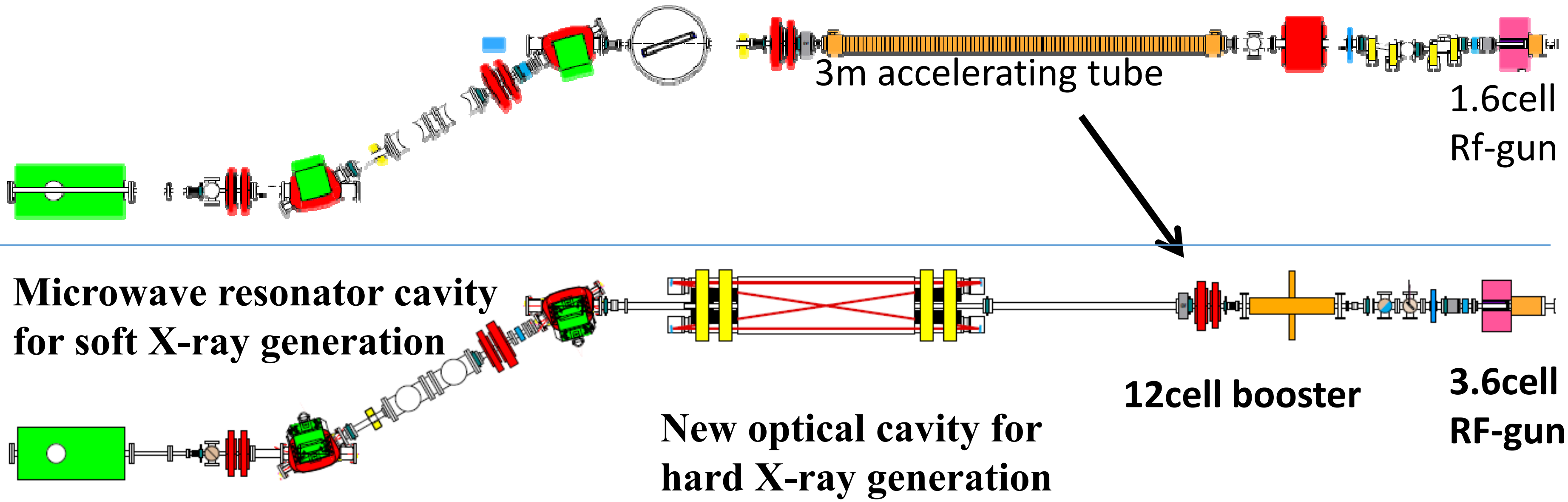
Stability of stored pulse intensity: 3.5% rms
About 0.2nm accuracy of cavity length adjustment is achieved now.



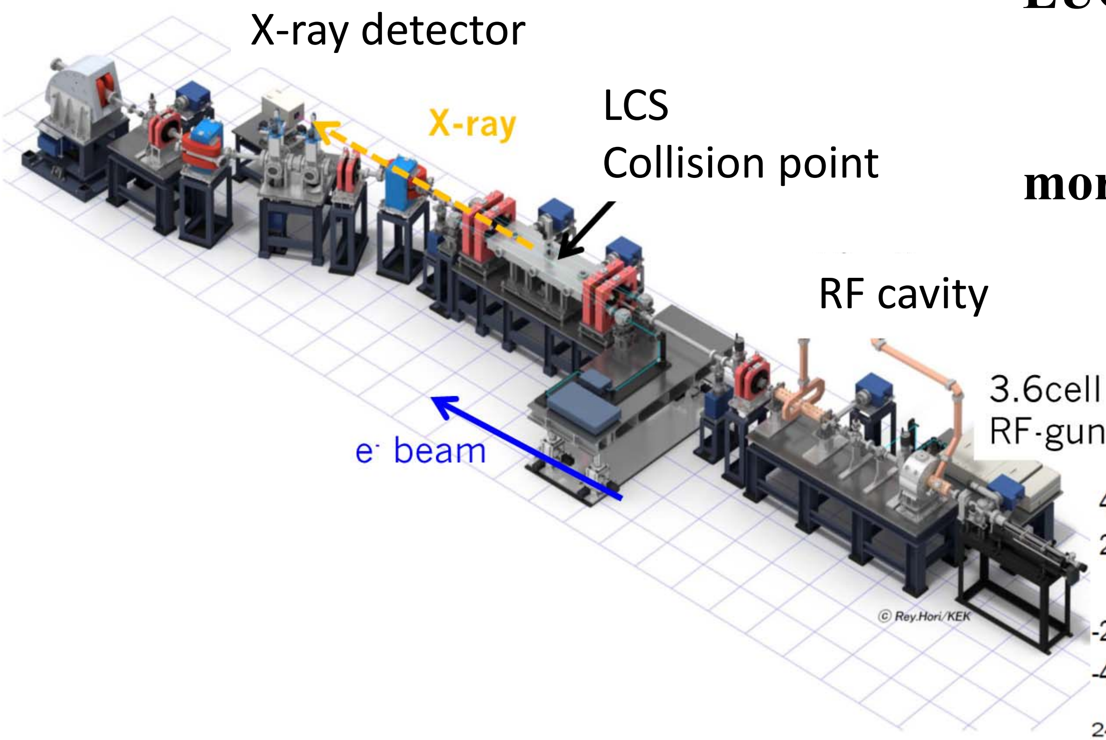


3. Results at LUCX
Four mirror 2D optical cavity to generate X-ray. LUCX Project

- To downsize the accelerator, we have installed a 3.6cell rf-gun and a 12cell booster.
  - 3.6cell rf-gun
    - Beam test has been started from Jan 2012.
  - 12cell booster
    - This booster was installed in last June.

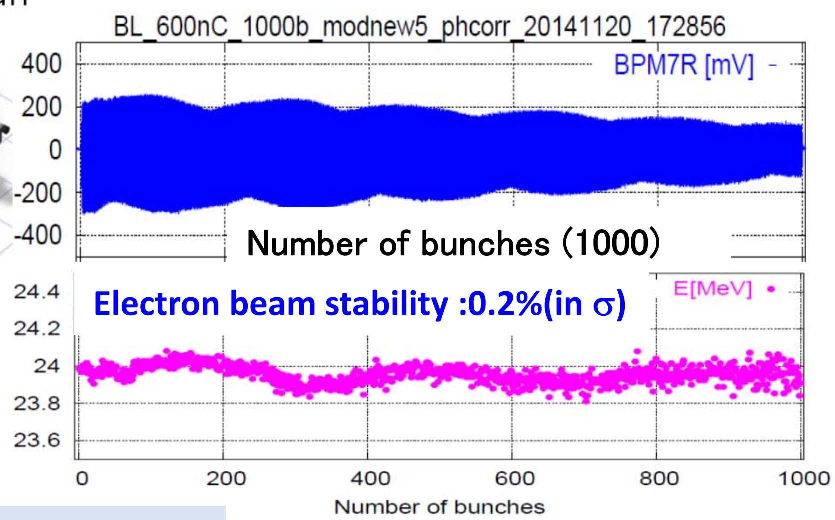


Development of multi-bunch e⁻ beam at LUCX



LUCX beam target:
30 MeV, 357 MHz
bunch spacing 2.8 ns
more than 1000 bunches/pulse,
beam size less than 100μm

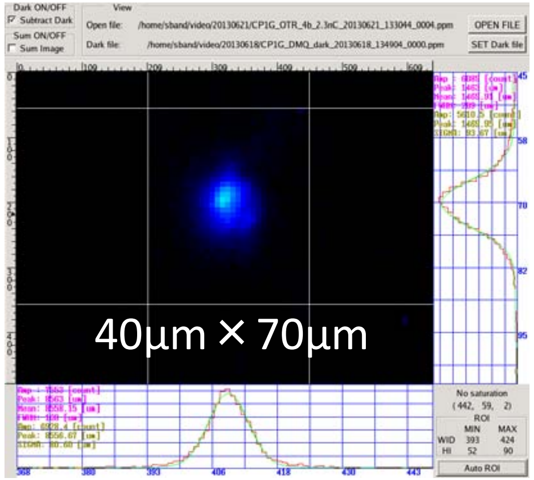
Electron Bunch Charge

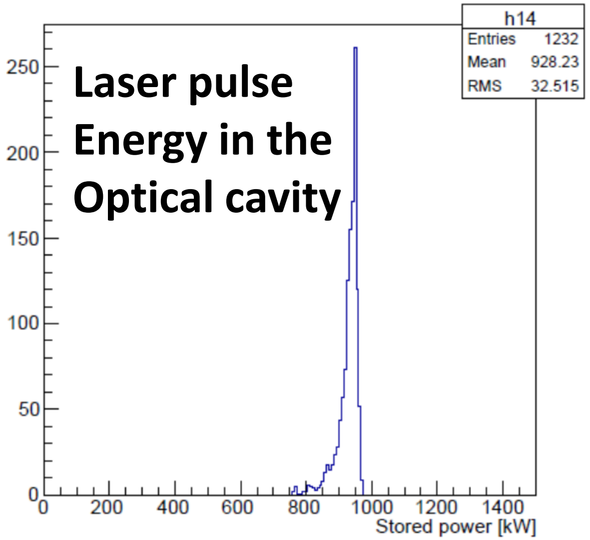


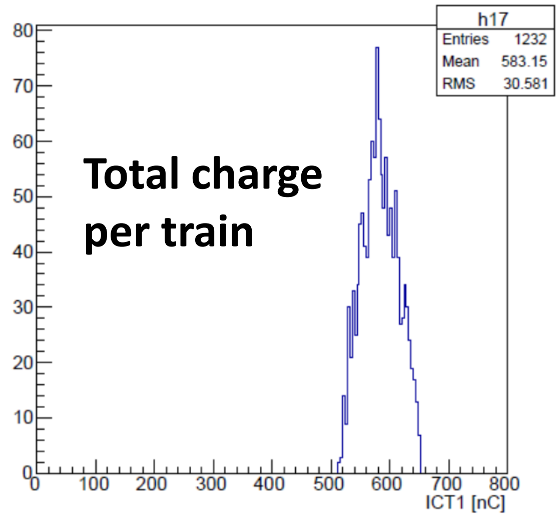
2012: 150 bunches, 90 nC
2013: 300 bunches, 380 nC

2014: 1000 bunches, 600 nC, 24 MeV

Energy compensation by RF amplitude modulation







Summary of Laser-Electron Beam Parameters at the photon-electron collision point

LASER

Wavelength	Repetition	Power	Pulse energy
1064nm	357MHz	1MW	2.8mJ
Size(H)	**Size(V)**	**Pulse duration**	**Col. angle**
60um	25um	7ps	7.5°

ELECTRON

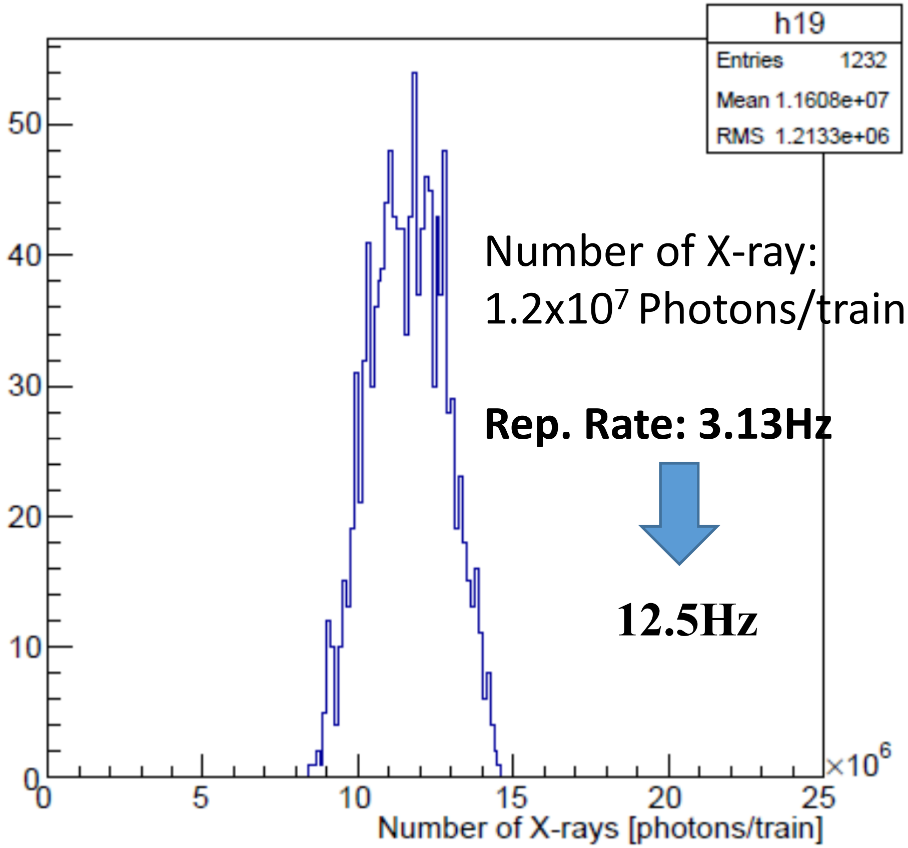
Energy	Repetition	Charge	N. bunch	
22MeV	357MHz	0.6nC	1000	
Size(H)	**Size(V)**	**Bunch length**	**Emi (H)**	**Emi (V)**
40um	70um	15ps	5πmmmrad	6πmmmrad

9keV LCS X-ray Energy

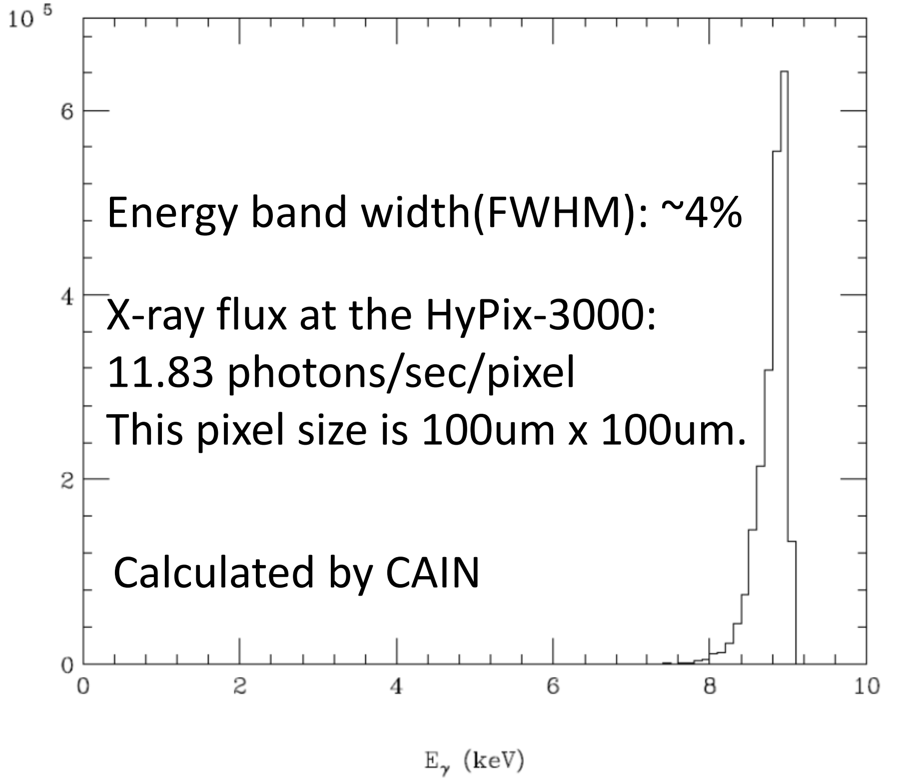
We found the present multi-pixel detector was saturated. This problem will be solved using SOI detector because of the pixel size of 17μm soon.

Measured X-ray intensity distribution and the comparison with CAIN simulation

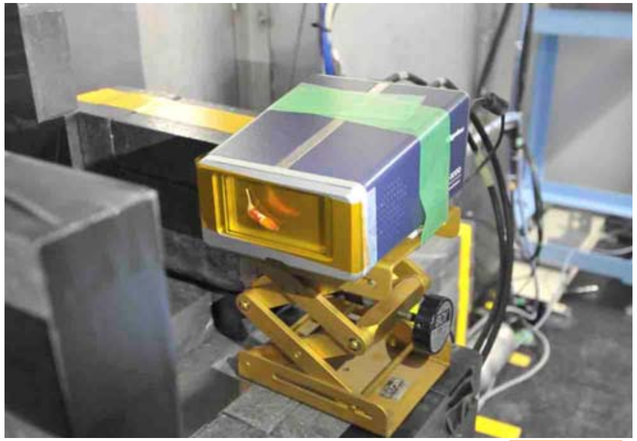
CAIN Simulation assumed following measured values.
Number of X-ray: $3.6\text{x}10^{7}$ Photons/sec
X-ray Energy: 9keV
Source size: 60um x 25um

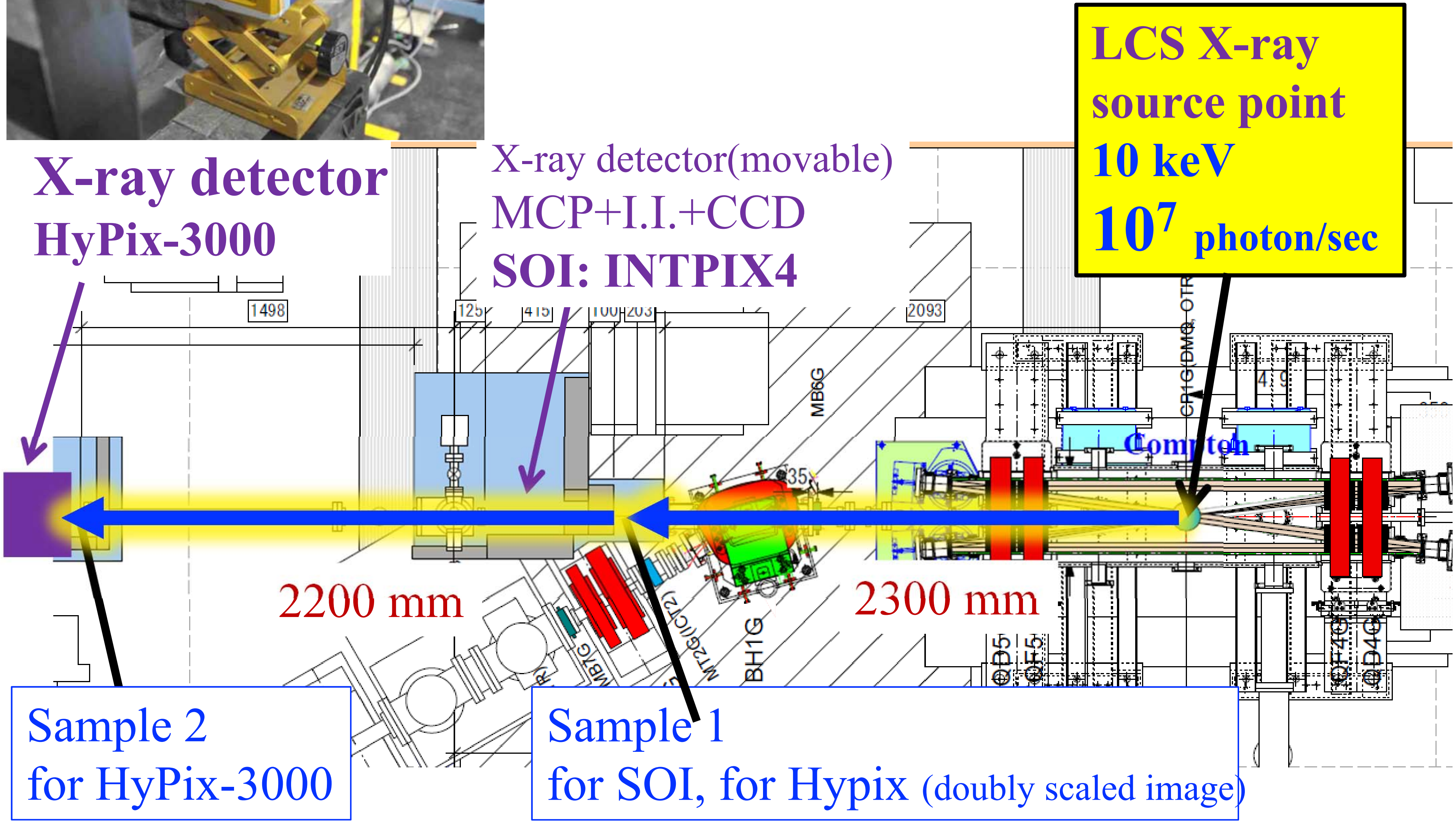


X-ray energy distribution at the HyPix-3000



*LCS X-ray imaging at **LUCX***

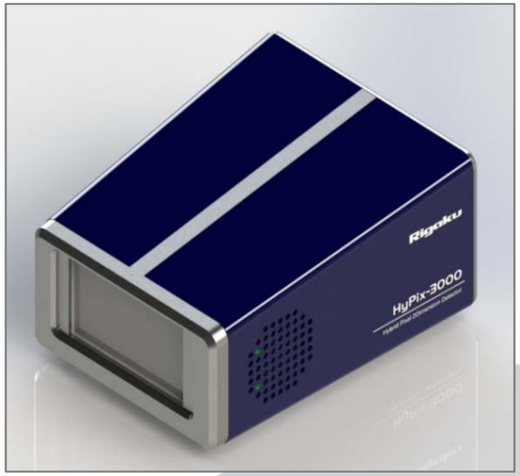




X-ray detector for the X-ray imaging at LUCX/cERL

HyPix-3000 (Rigaku)

High-resolution/high-speed 2D photon counting X-ray detector



Sensors	Semiconductor pixel sensor
Active area	2984 mm² (77.5 × 38.5 mm)
Pixel size	100 × 100 µm
Number of pixels	775 × 385 = 298375 pixels
Threshold	2 ch
	t/zero dead time
	(>1 × 10^6 cps/pixel)
	el (Normal: 16-bit/pixel)
	9%
	zero dead time mode)
	at Cu Kα
	× 180(D) mm
	kg

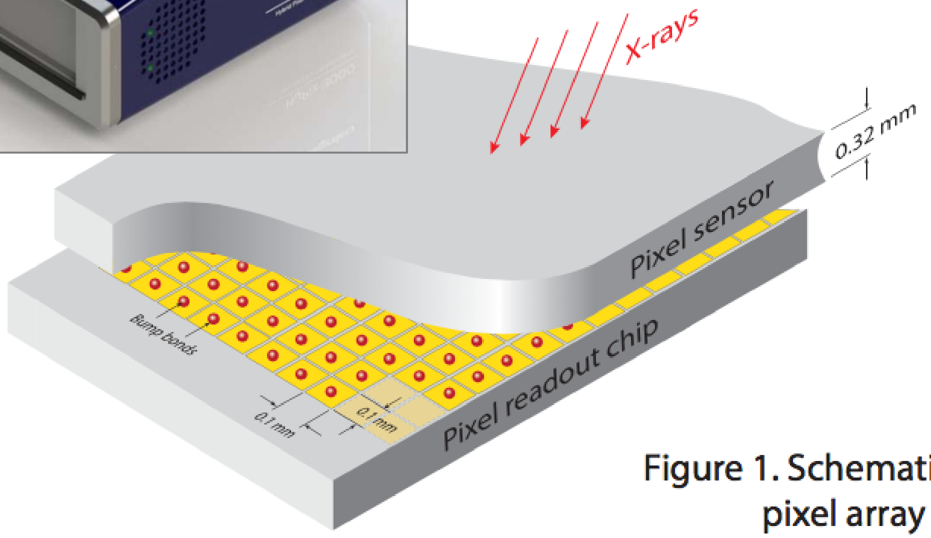
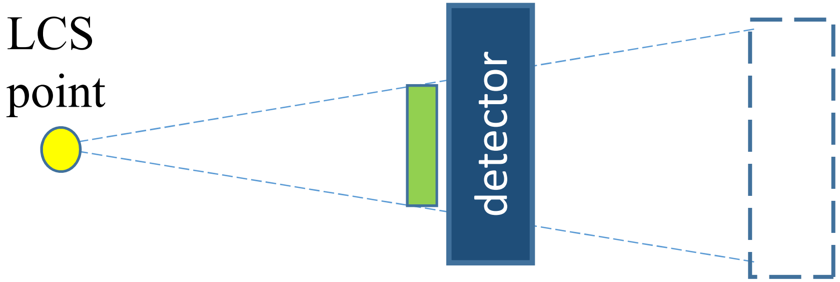
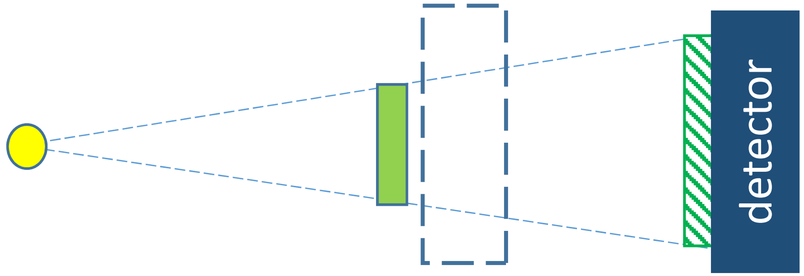


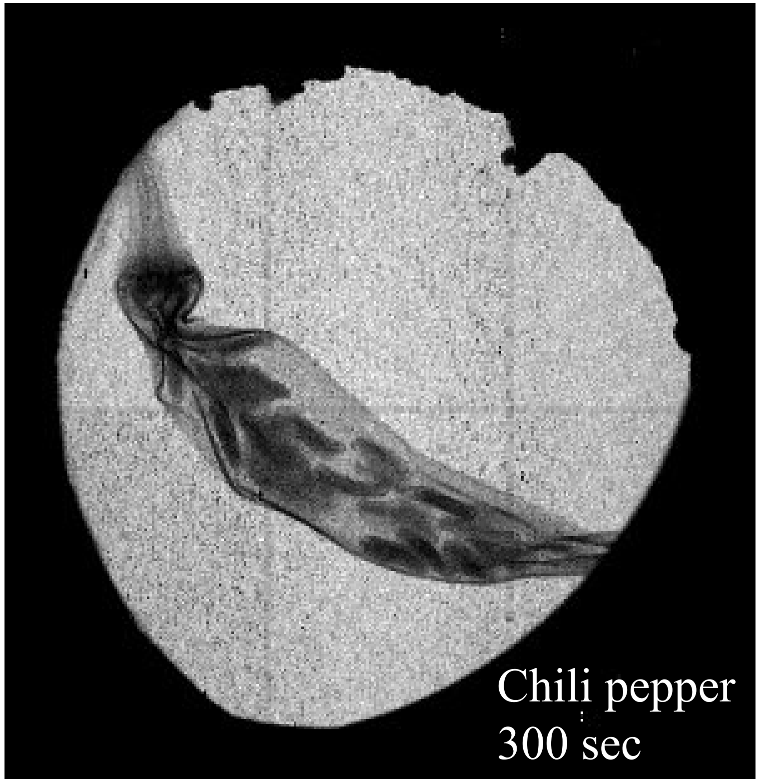
Figure 1. Schematic view of hybrid pixel array detector

*LCS X-ray imaging at **LUCX***

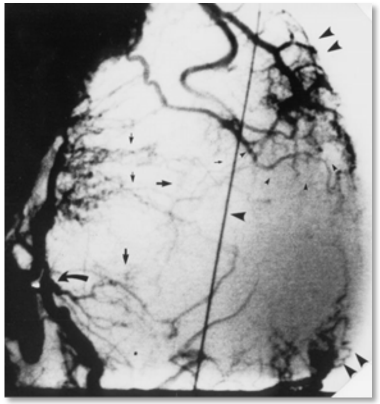
- small source dimensions
- clear expansion of image
- edge contrast enhancement by refraction







Evaluation of present LCS performance

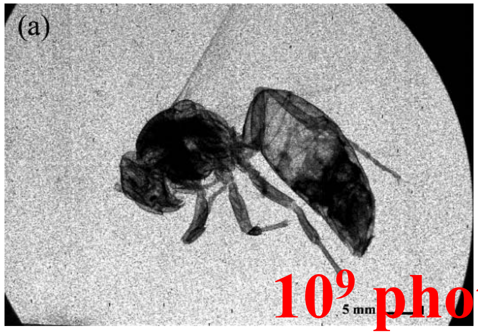


放射光単色X線

SR X-ray (PF-AR)
30 msec exposure
for angiography

LCS X-ray (LUCX)
10 sec exposure
at 10^7 photons/sec

still improving…



LCS X-ray (cERL)
100 sec exposure
at 10^7 photons/sec

Assume the ***angiography*** by LCS X-ray,

need 100 improvement

- *intense electron beam*
- ***intense laser pulse***
- ***smaller beam size***
- *increase repetition rate*
- *…*
- *small crossing angle*
- *higher e- beam energy*
- *…*

integrate challenges!

10^9 photons/sec will be expected at the end of this March.

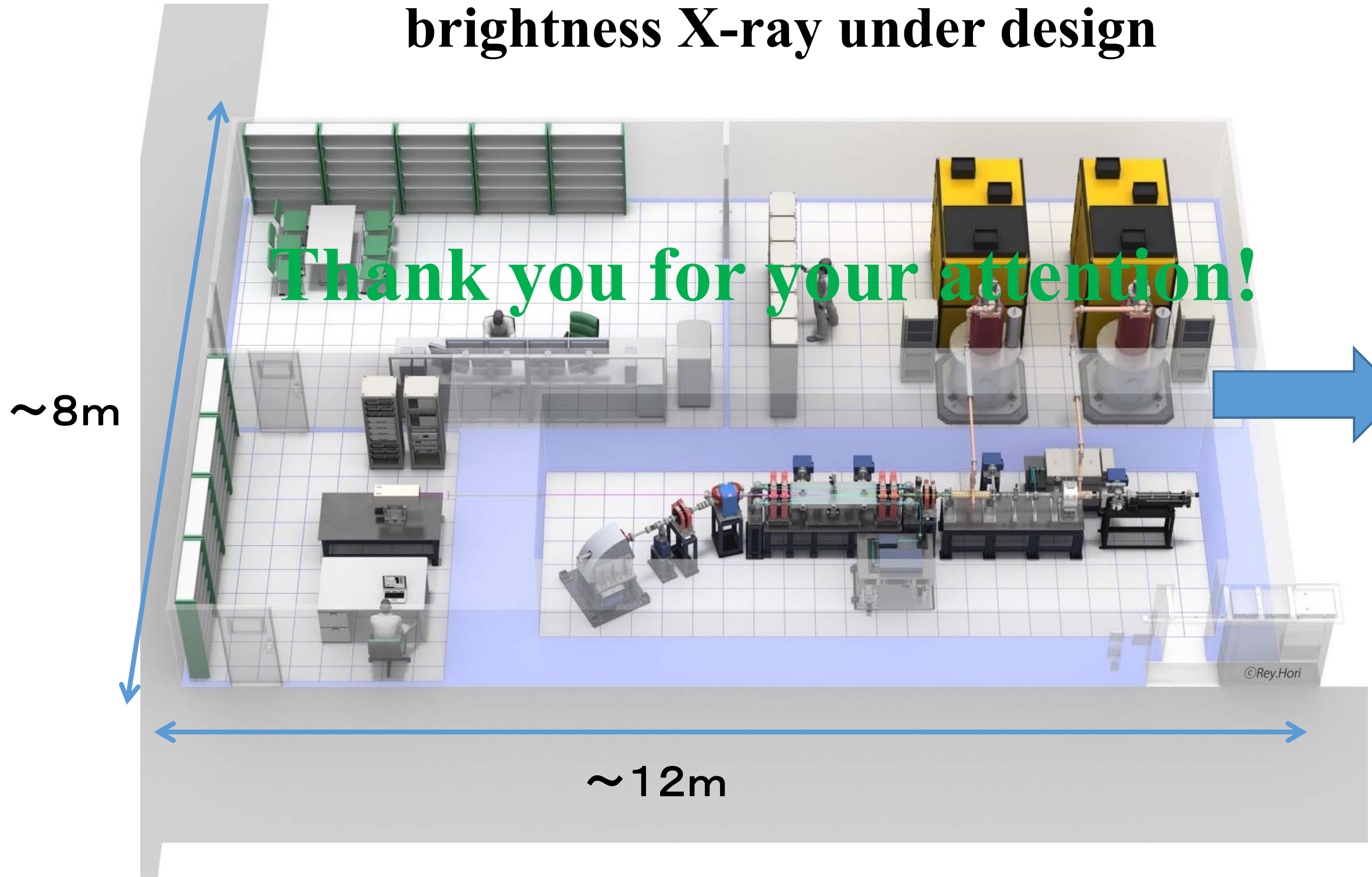
4. Summary

- *We have been developing a X-ray source by a* ***Laser Compton Scattering.***
- *It is a fundamental technology development to realize a* ***compact X-ray source ,****which energy is* ***several tens of keV ,****where a wide variety of application are expected.*
- *Compact LCS X-ray source can be small to fit in universities, industrial labs and hospitals, then will contribute to improve our life.*

To get clear X-ray imaging every second, we have to increase the X-ray flux by factor ~ 10.

High brightness X-ray facility based on LCS

Normal conducting accelerator system for compact high brightness X-ray under design



Downsizing to 6m x 8m by new technologies