Consideration on future applications for high brightness γ-ray

"Mini-Workshop on Advanced Accelerator and Laser Technologies for New Generation Light Sources"

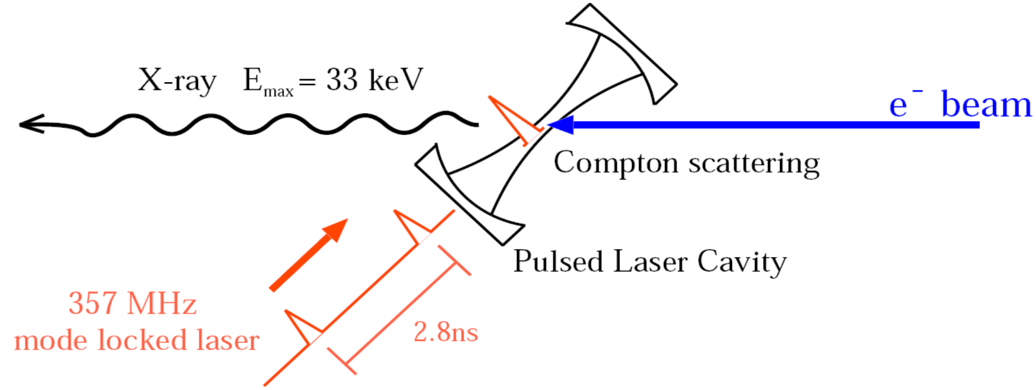
KEK, Junji Urakawa

31st Jan. 2014

The purpose of the mini-workshop is to discuss on the possibility of high brightness γ-ray generation.
We are considering how to diagnose nuclear waste precisely using monochromatic γ-ray and how to generate high flux to determine amount of each species of nuclear waste quickly.
However, I know many participants have another intentions. So, I do not limit our discussion to above issues.

1. Introduction

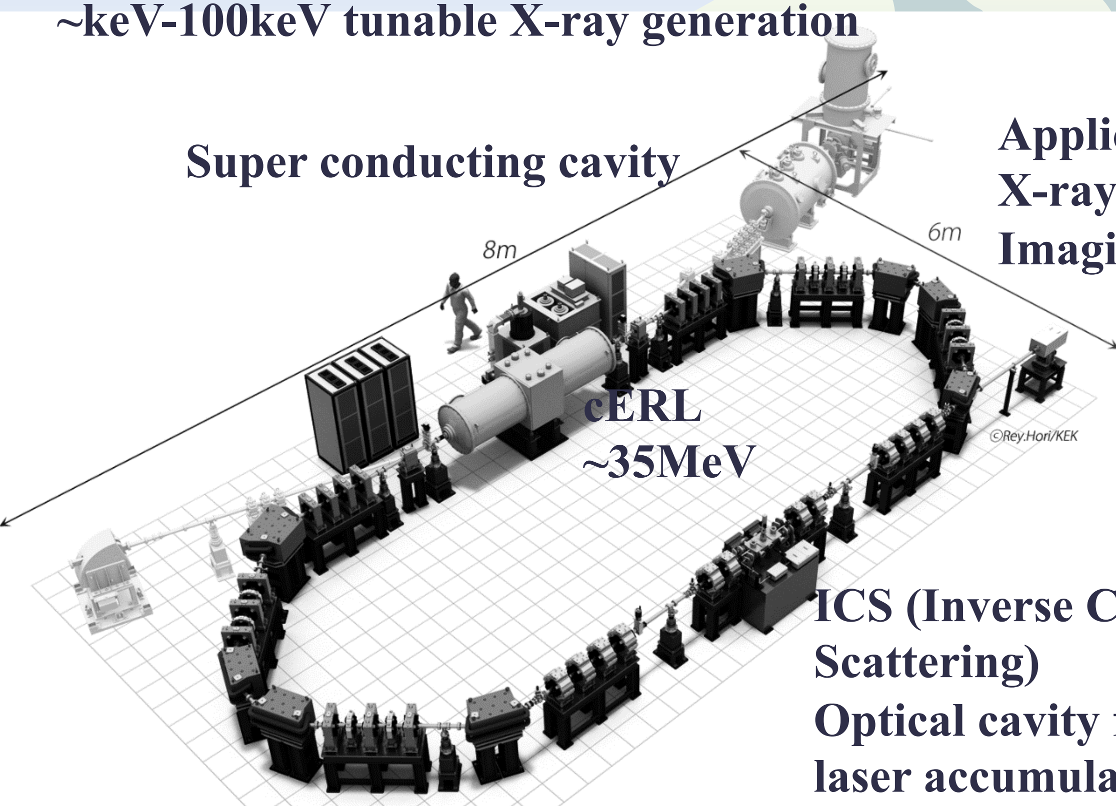
Fundamental Technology Development for High Brightness X-ray Source and the Imaging by Compact Accelerator



ICS (Inverse Compton Scattering)

Purpose of our project

Compact X-ray Source (Peak Brightness 10^{19})
~keV-100keV tunable X-ray generation



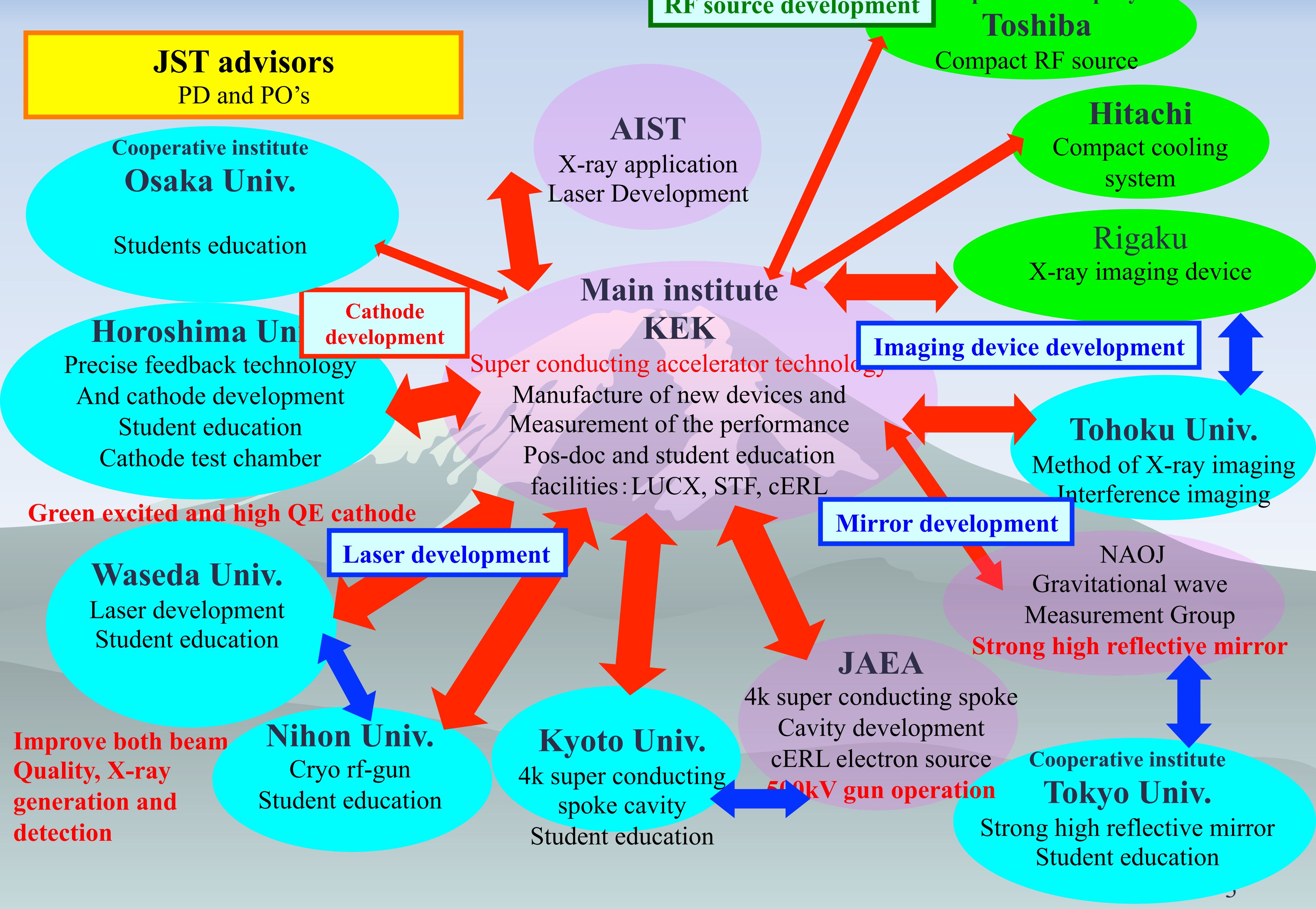
Application of X-ray: Imaging etc.

ICS (Inverse Compton Scattering)
Optical cavity for pulse laser accumulation, collision point

Development of Basic Technologies

1. Multi-alkali photocathode for high average current
2. Cryo-rf-gun
3. ERL
~1MW electron beam
4. ~1MW high-average power laser
5. ~10μm precise collision technique
6. X-ray imaging
7. 4K 325MHz spoke cavity

Research organization and responsibility



Evolution of photon source：X-ray source based on accelerator and laser

2011, ~mJ X-ray pulse is realized

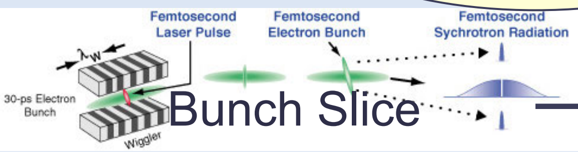
DESY-XFEL
SPring8-XFEL

Next Generation Photon Source

SLAC-XFEL — **2010**

Coherent Ultra-short Pulse, Compact X-ray source

Ato-sec. Science



Bunch Slice

ERL proposal — **2000**

Ultra-high field Science

Third Generation Photon Factory

XFEL proposal

Plasma X-ray

1990 — **Higher harmonic wave : Coherent soft-X-ray**

Femto-sec Science

Chirped Pulse Amplification(1985

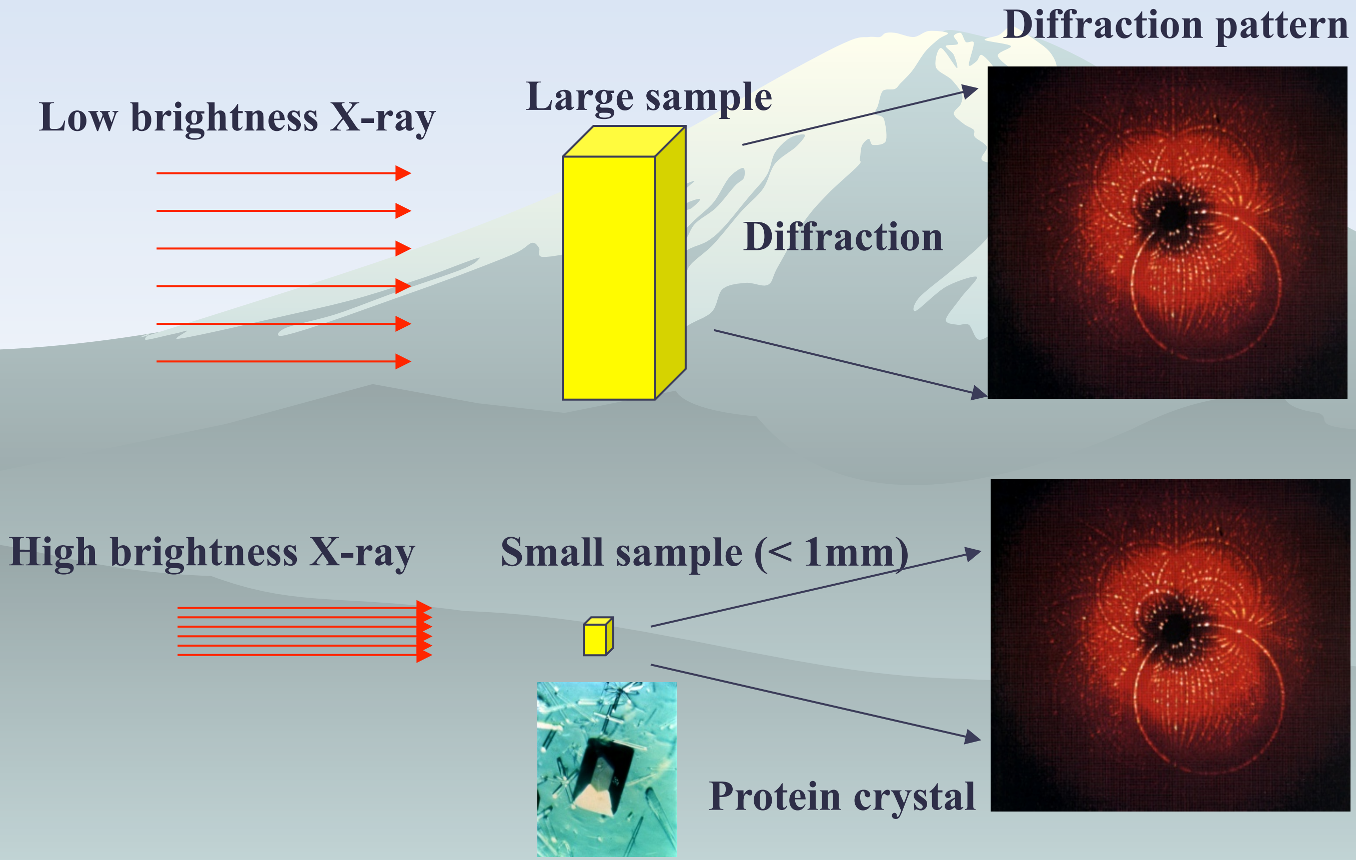
Second Generation Photon Factory

1980

To stronger and brighter photon beam

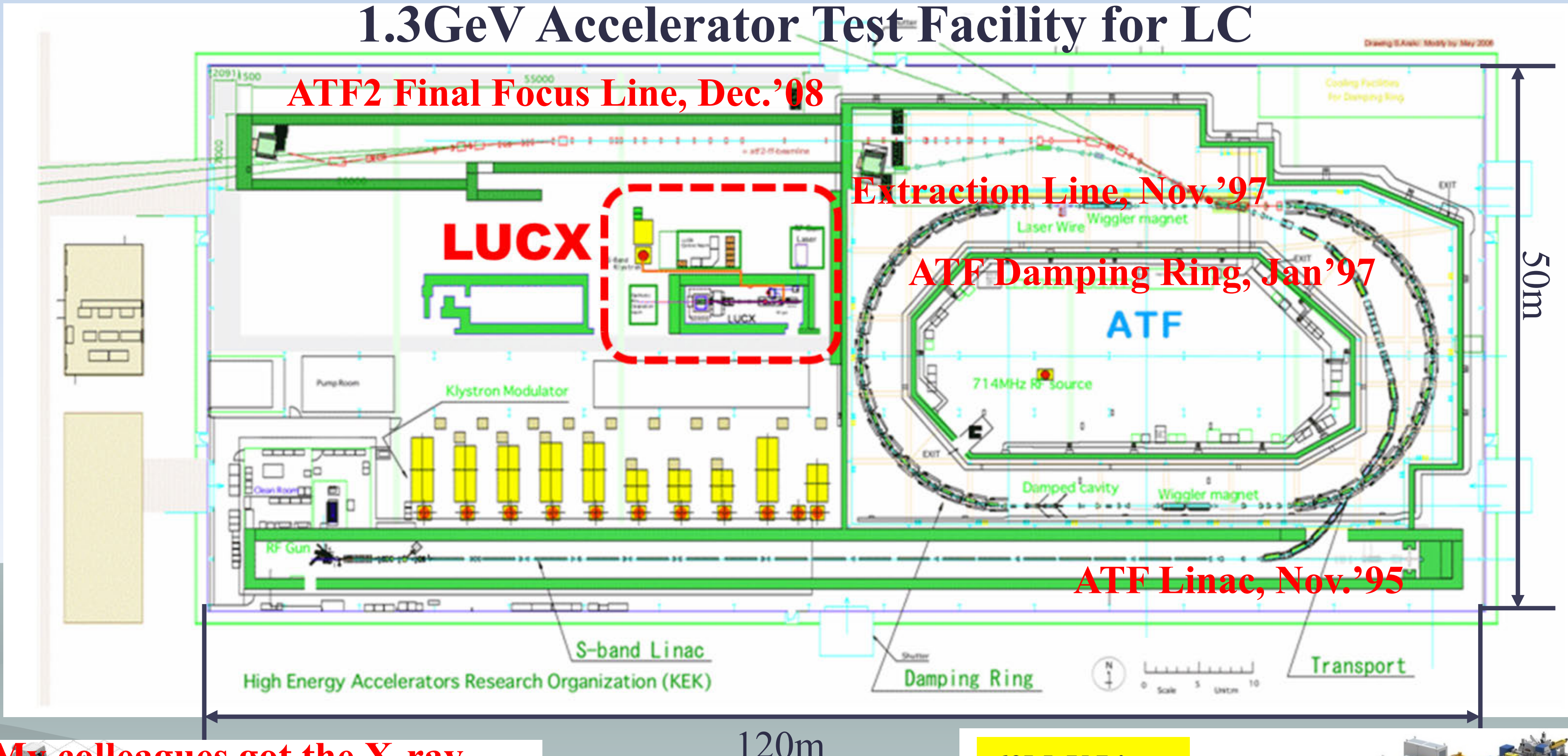
$$Brightness = \frac{photons/\sec}{(\mathrm{mrad})^2\left(\mathrm{mm}^2(source-area)\right)(0.1\%\ spectrum-width)}$$

10μm photon source is considered, which means 0.2 mmmrad normalized emittance.
1mrad angular spread collimation means small energy spread.



Smaller source is realized by focusing laser beam and electron beam at IP. We have to supply low emittance and high intensity electron beam. Our target is Brightness 10^{17} Photons/sec/mm^{2}/mrad^{2} in 0.1%b.w.

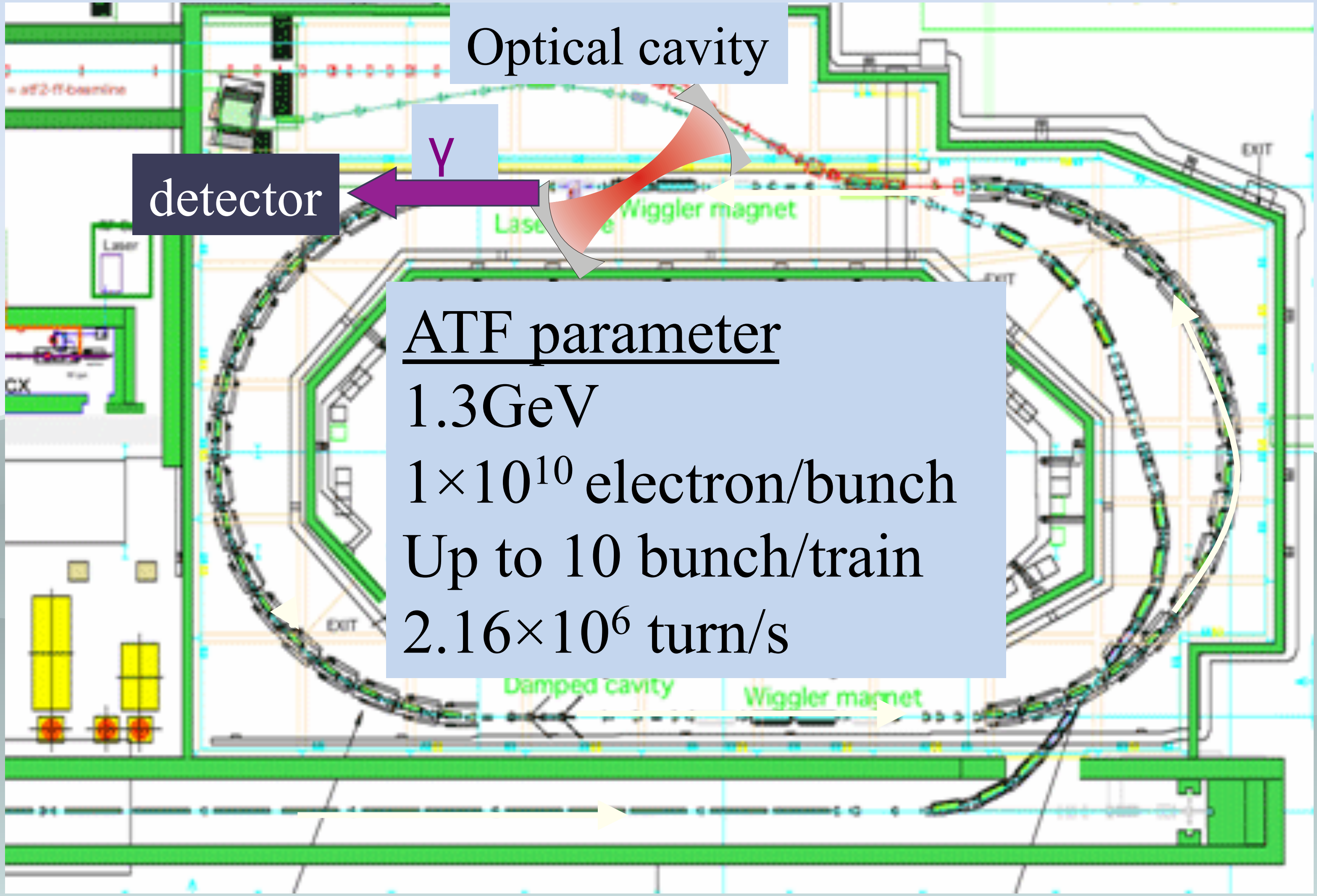
γ-ray generation at KEK-ATF Damping Ring



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

γ-ray generation based on ICS with 3D Optical Cavities

Experiments at the KEK ATF



<u>ATF parameter</u>

1.3GeV

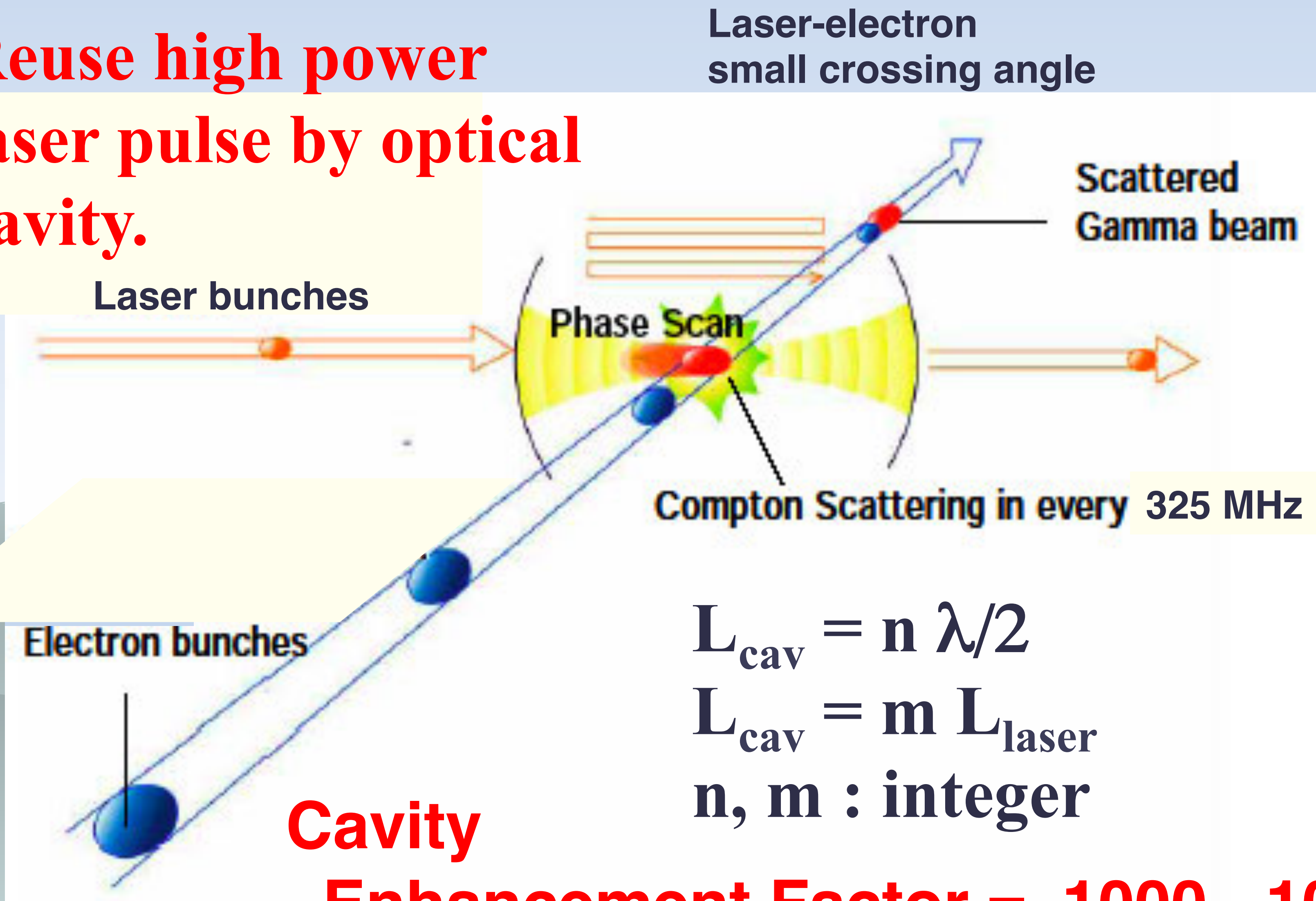
1×10^{10} electron/bunch

Up to 10 bunch/train

2.16×10^{6} turn/s

Laser Pulse Stacking Cavity

Reuse high power laser pulse by optical cavity.



$$L_{cav} = n\,\lambda/2$$
$$L_{cav} = m\,L_{laser}$$
$$n, m : \text{integer}$$

Cavity
Enhancement Factor = $1000 - 10^5$

Storage of laser pulse

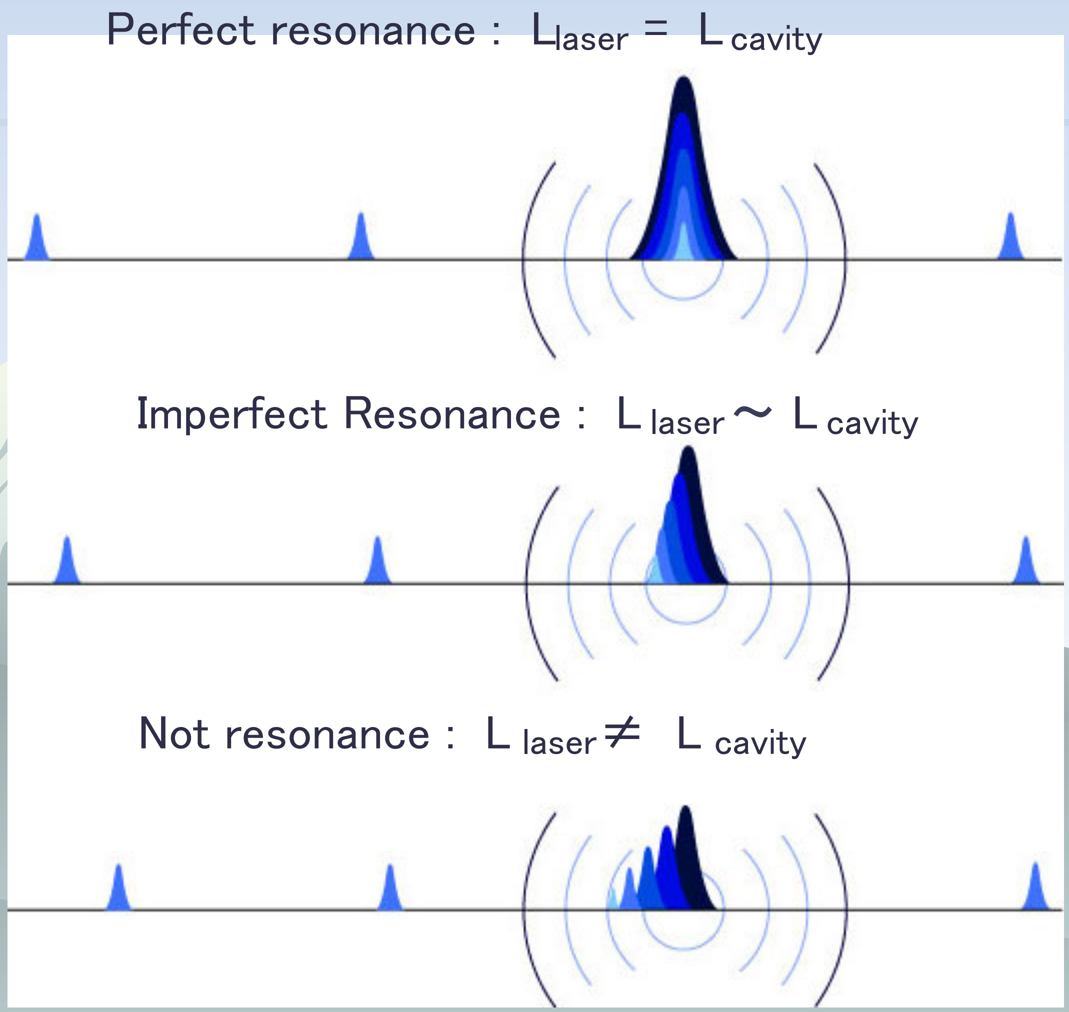
Resonance condition :

The relationship with laser and cavity :

$$L_{cav} = n \cdot \frac{\lambda}{2} \ ,$$

$$\Delta l = L_{laser} - L_{cav} \ , \quad \Delta l = 0 \ .$$

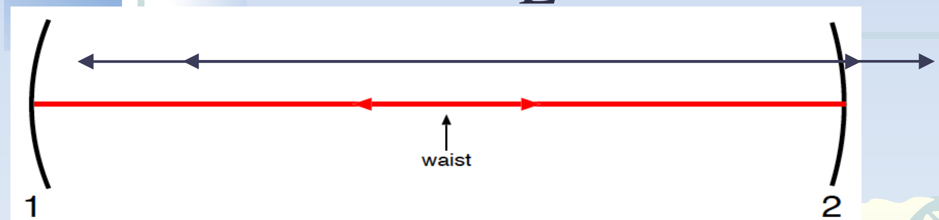
The enhancement factor is the function of reflectivity, Δl and laser pulse width.

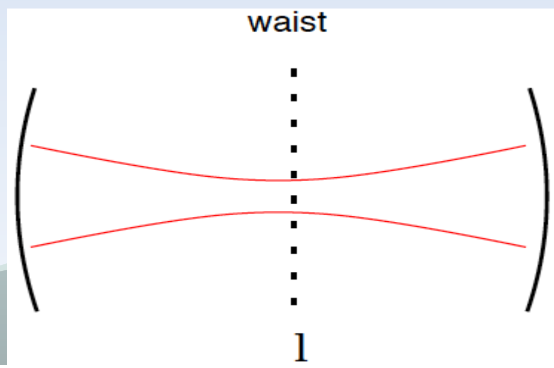


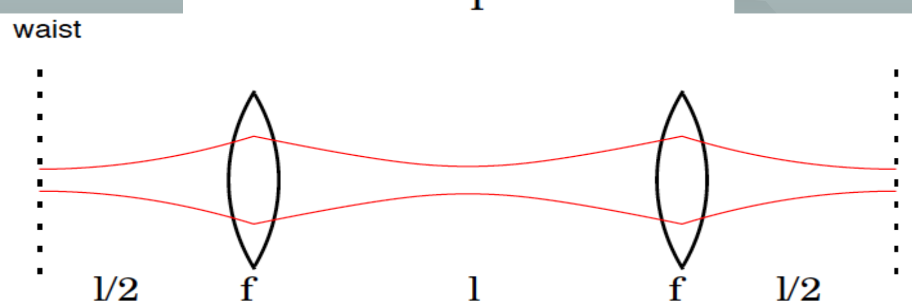
Mirror alignment tolerance

2-mirror cavity

R1=R2=L/2



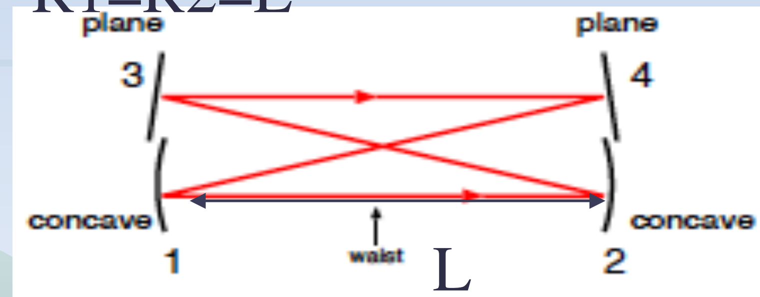


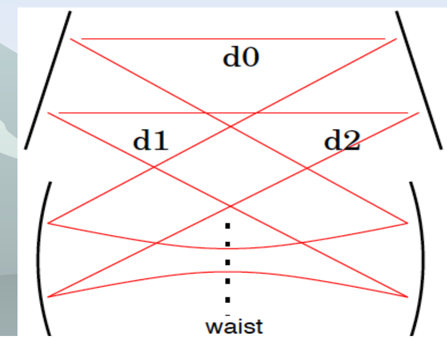


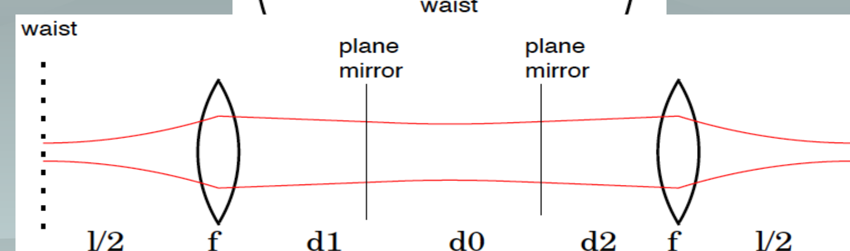
concentric

4-mirror cavity

R1=R2=L

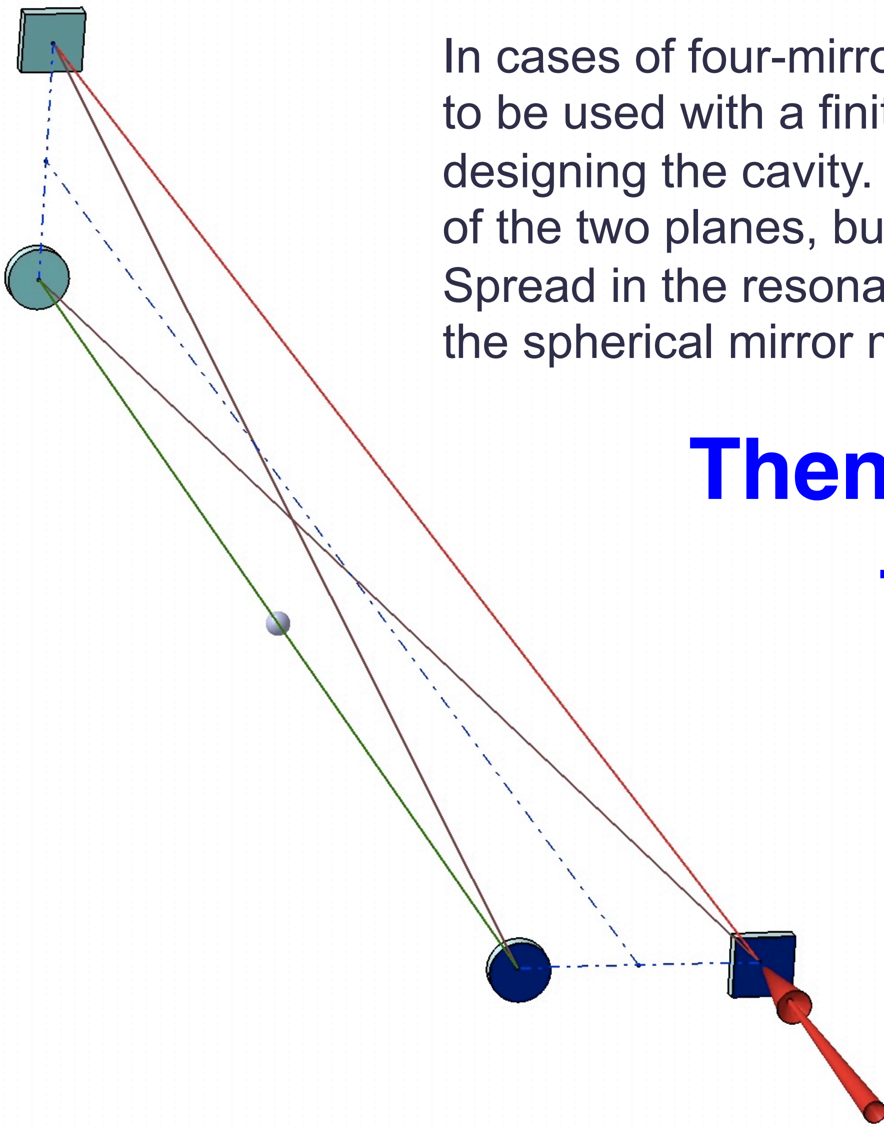






confocal

This astigmatism makes phase spread due to Guoy phase depending on beam waist.



In cases of four-mirror optical cavities, spherical mirrors have to be used with a finite angle. It requires a careful analysis in designing the cavity. Astigmatism changes the optics design of the two planes, but it should not be a fundamental problem. Spread in the resonance condition due to finite spot size on the spherical mirror may limit the finesse of the cavity.

Then, 3D 4-mirror-cavity --> no astigmatism

4 mirror 3D cavities are at the ATF

KEK-Hiroshima
installed 2011.

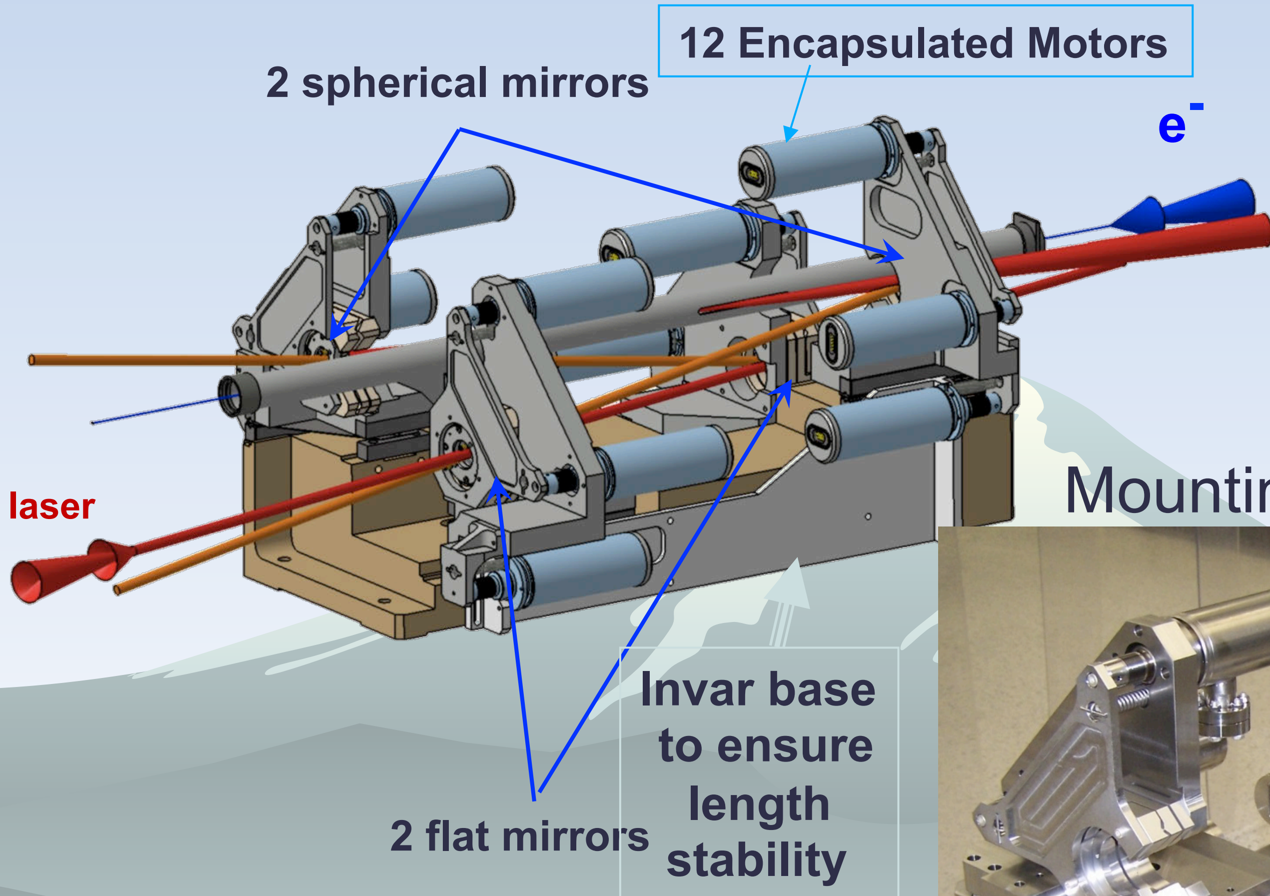
relatively simple control system and employs new feed back scheme.

LAL-Orsay
installed summer 2010.

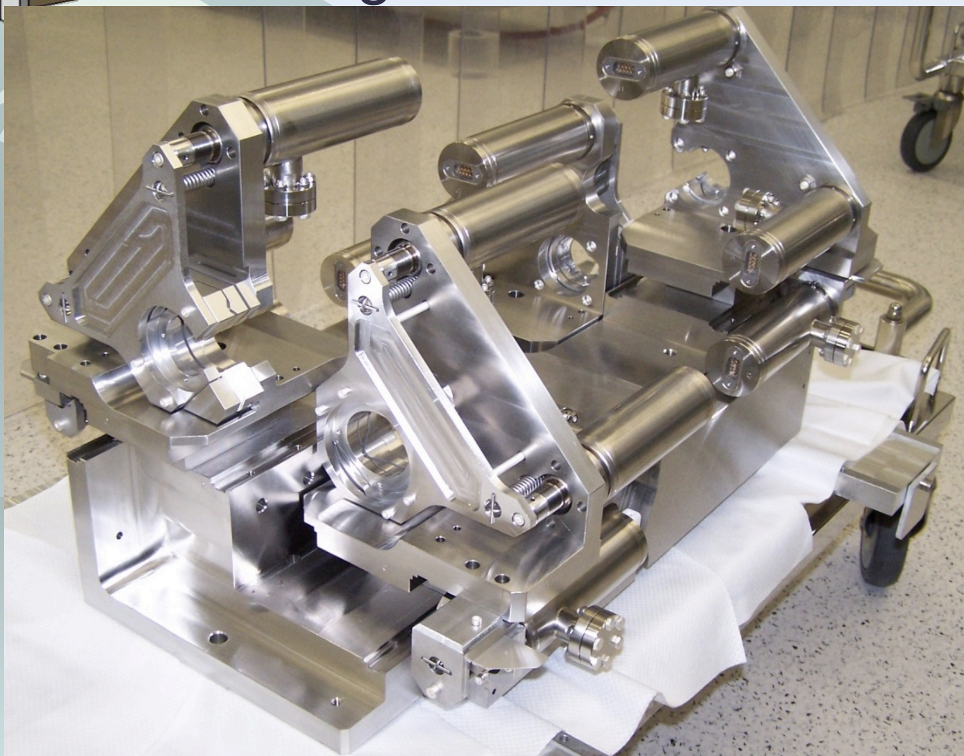
sophisticated control and digital PDH feedback

LAL 3D cavity and laser system were reinstalled in 2013.
LAL achieved 101kW accumulation in the cavity. They confirmed 100% laser pulse injection coupling also.
When 40kW was accumulated in the cavity at the ATF damping ring, ~500γ/bunch were generated, which is corresponding to $10^{10}\gamma$/sec.

LAL Mirror positioning system

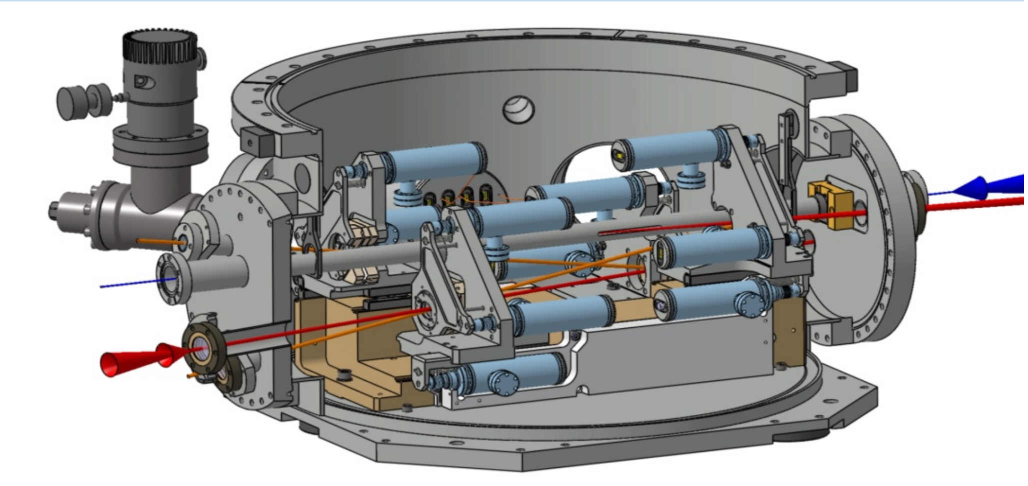


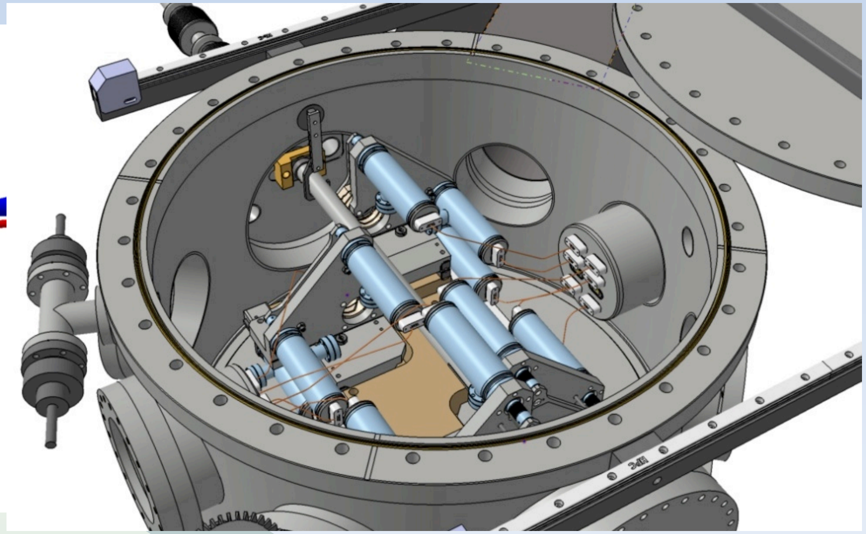
Mounting in class 10 room

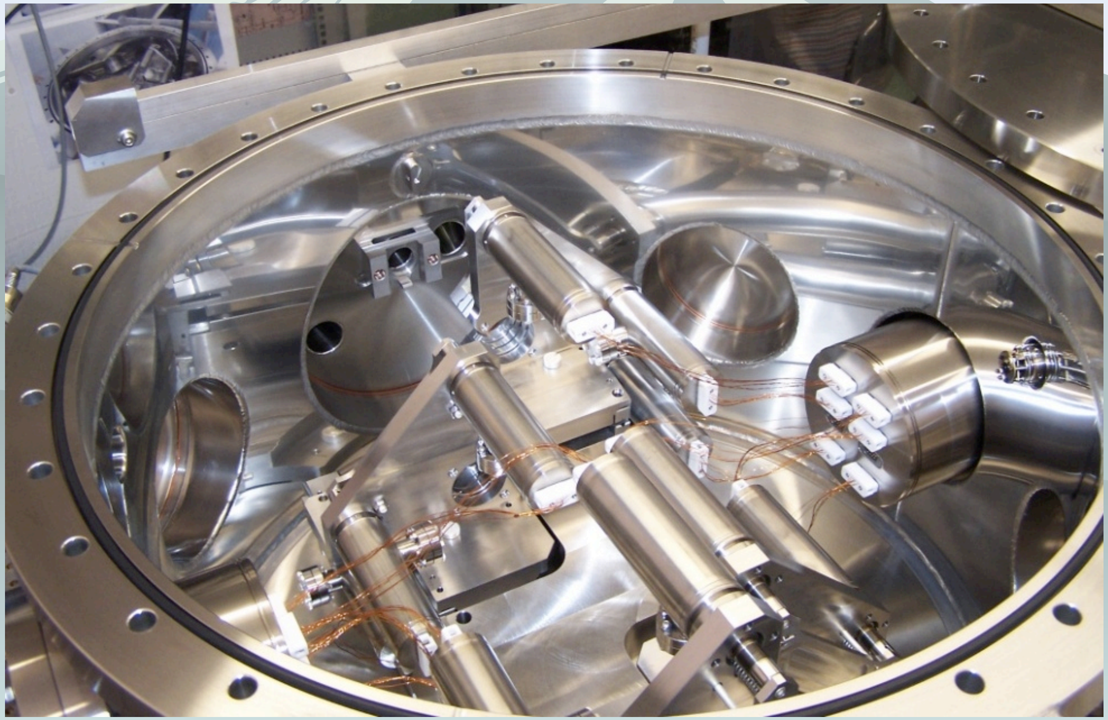


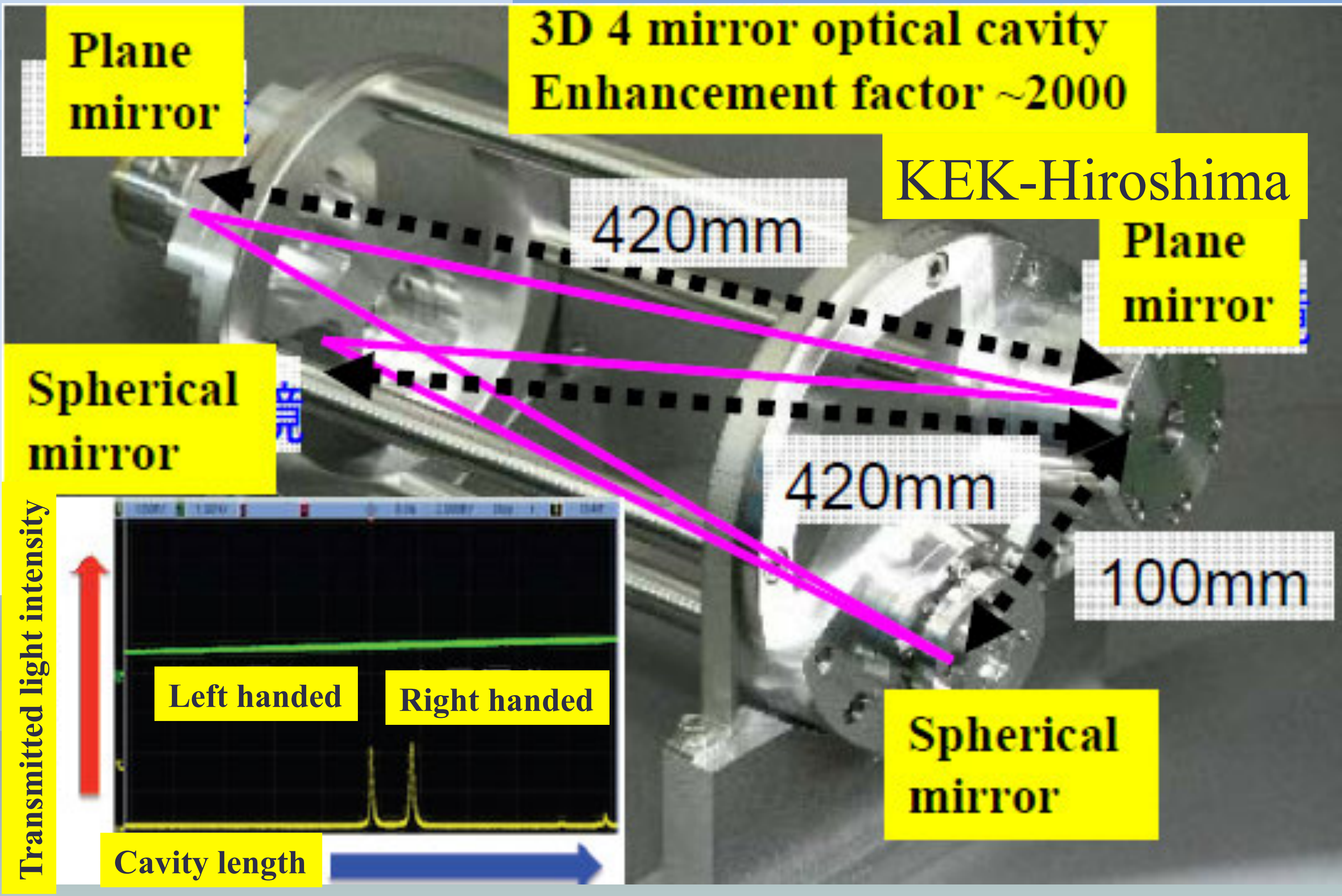
LAL-Orsay

Vacuum vessel for ATF





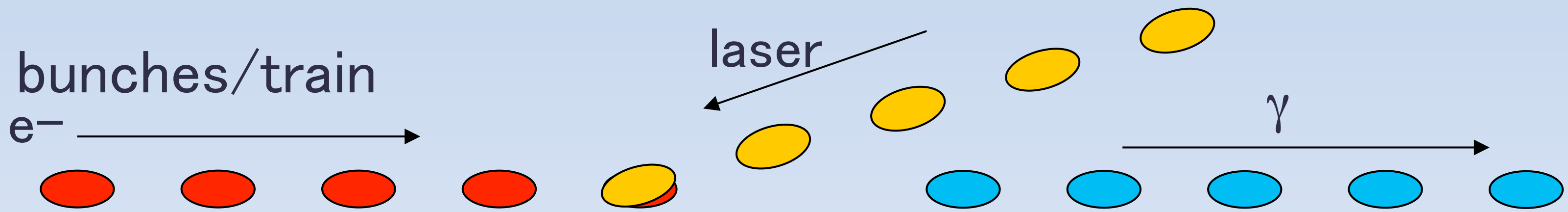




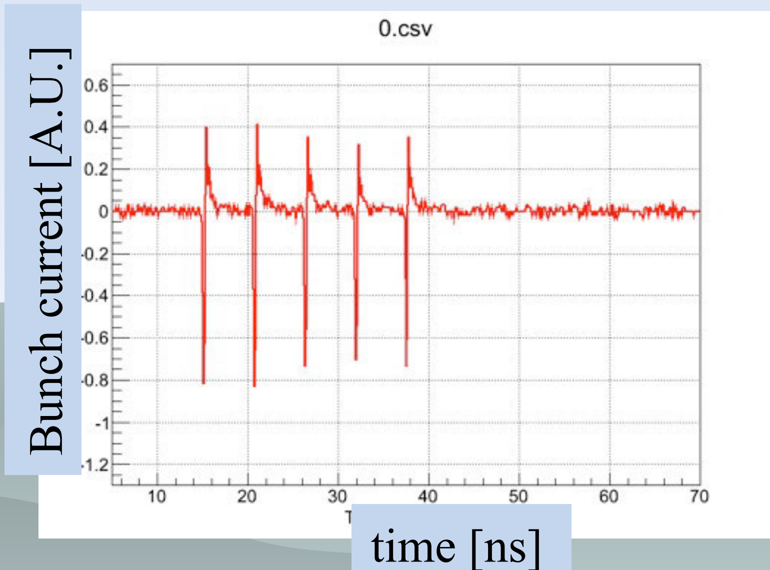
Ca. Finesse 4850, design gain ~2000 was confirmed by generation of gamma-ray in 2012. Also, laser waist size was less than 13μm.

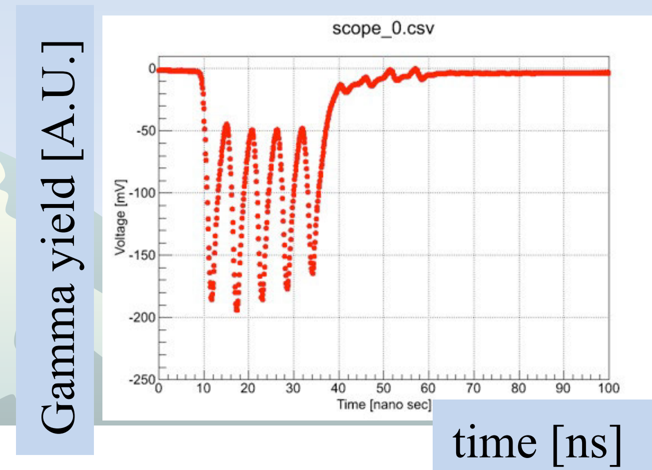
γ-ray Generation

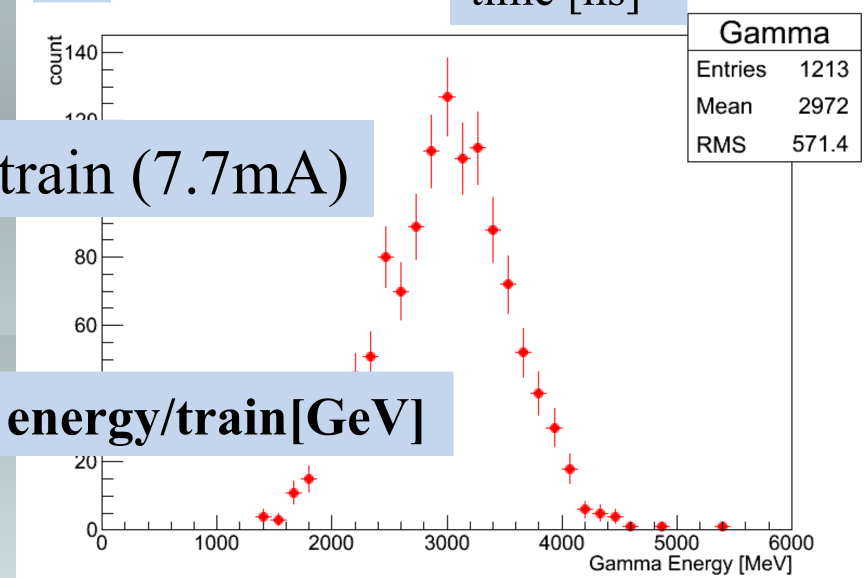
5 bunches/train



5.6ns







5 bunch/train (7.7mA)

Total detected energy/train[GeV]

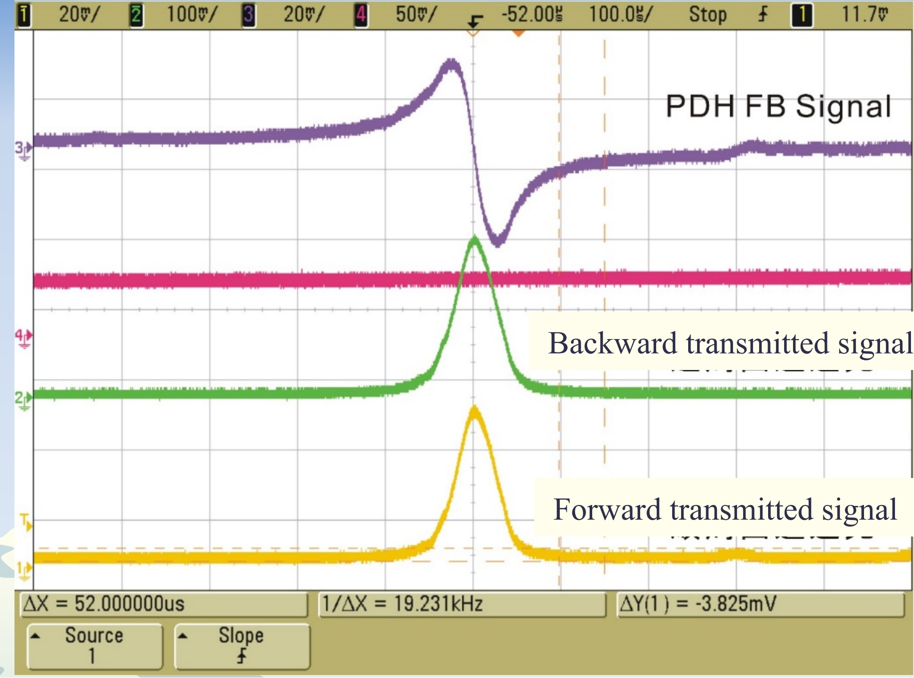
2970±20 MeV

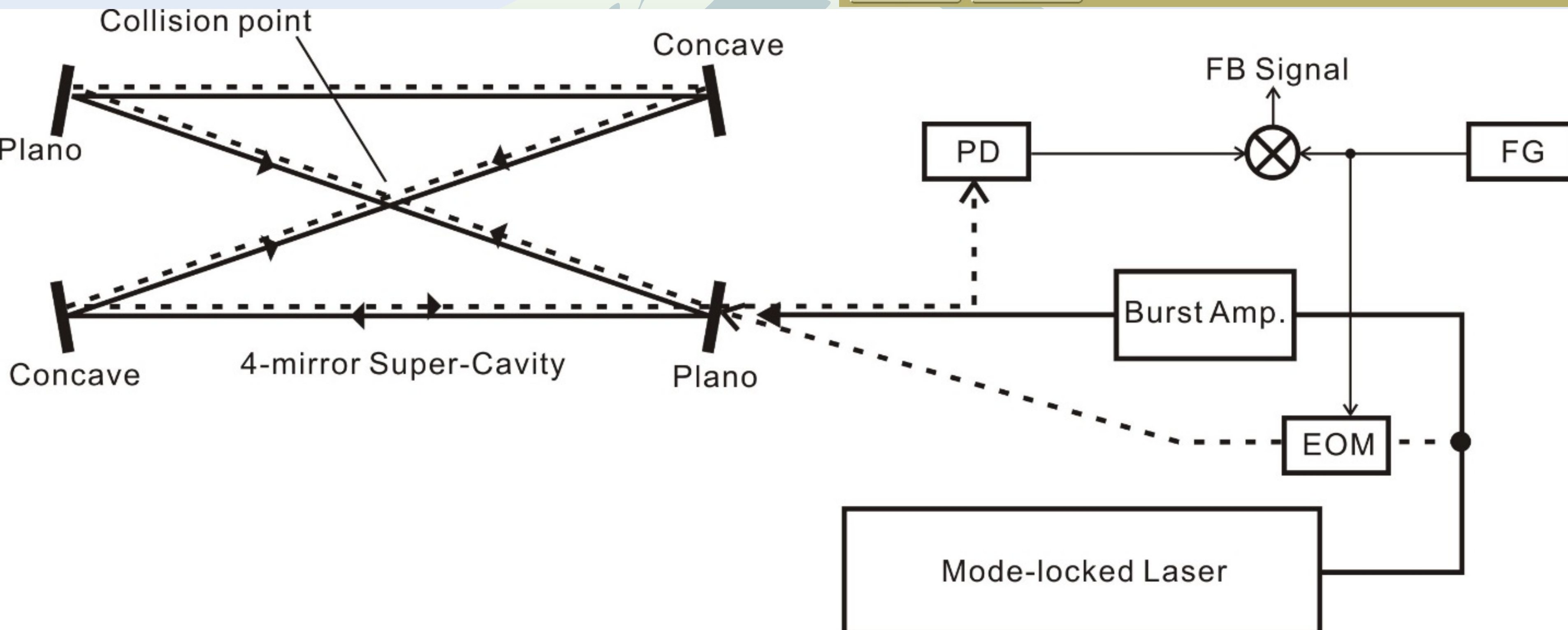
⇒ ~120γs / train

ATF 2.16MHz

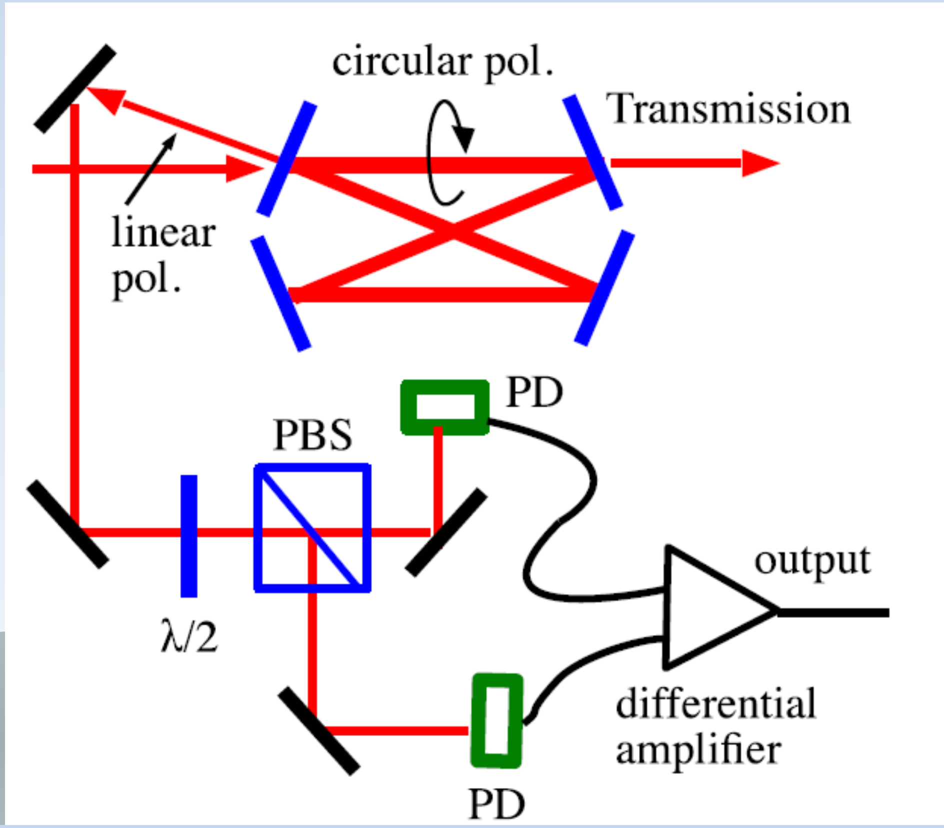
~2.6×10^{8}/sec

Standard Feedback is Pound-Drever-Hall method. We invented forward and backward circulation in respect of electron direction in order to make good PDH feedback signal when burst amplification is on (see below figure).
Then, we will operate our large optical cavity with ~1MW soon.

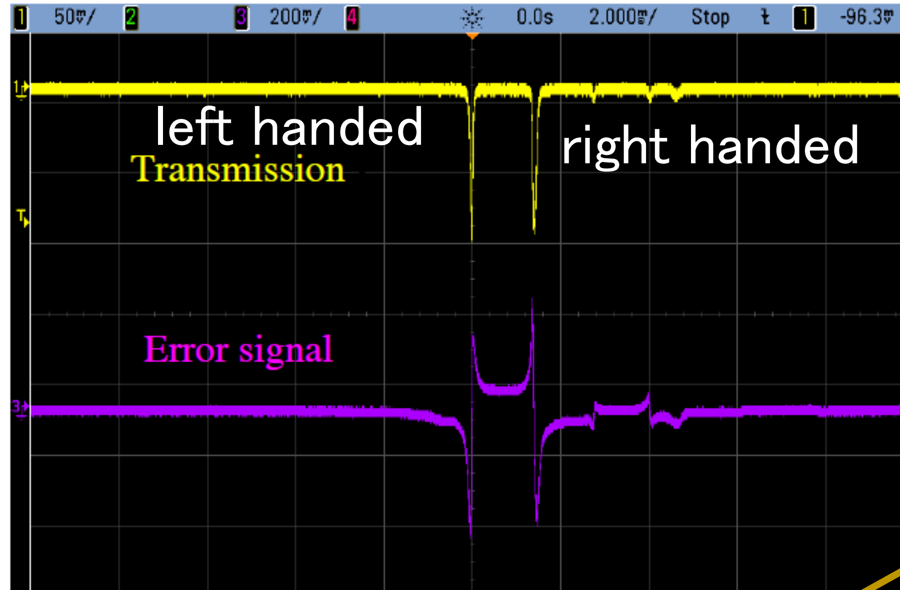


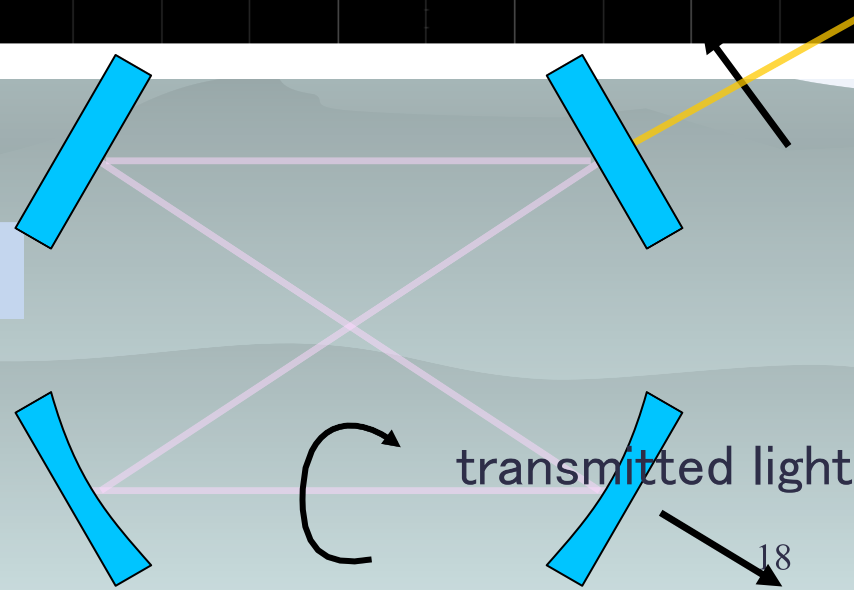


New feedback control using polarization resonance characteristics.



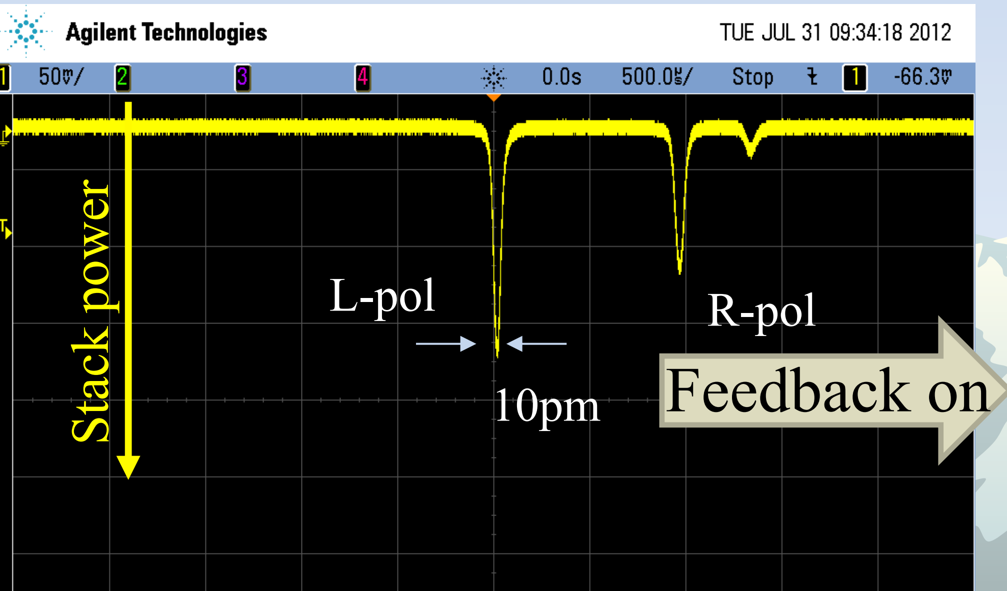
circumference of the cavity

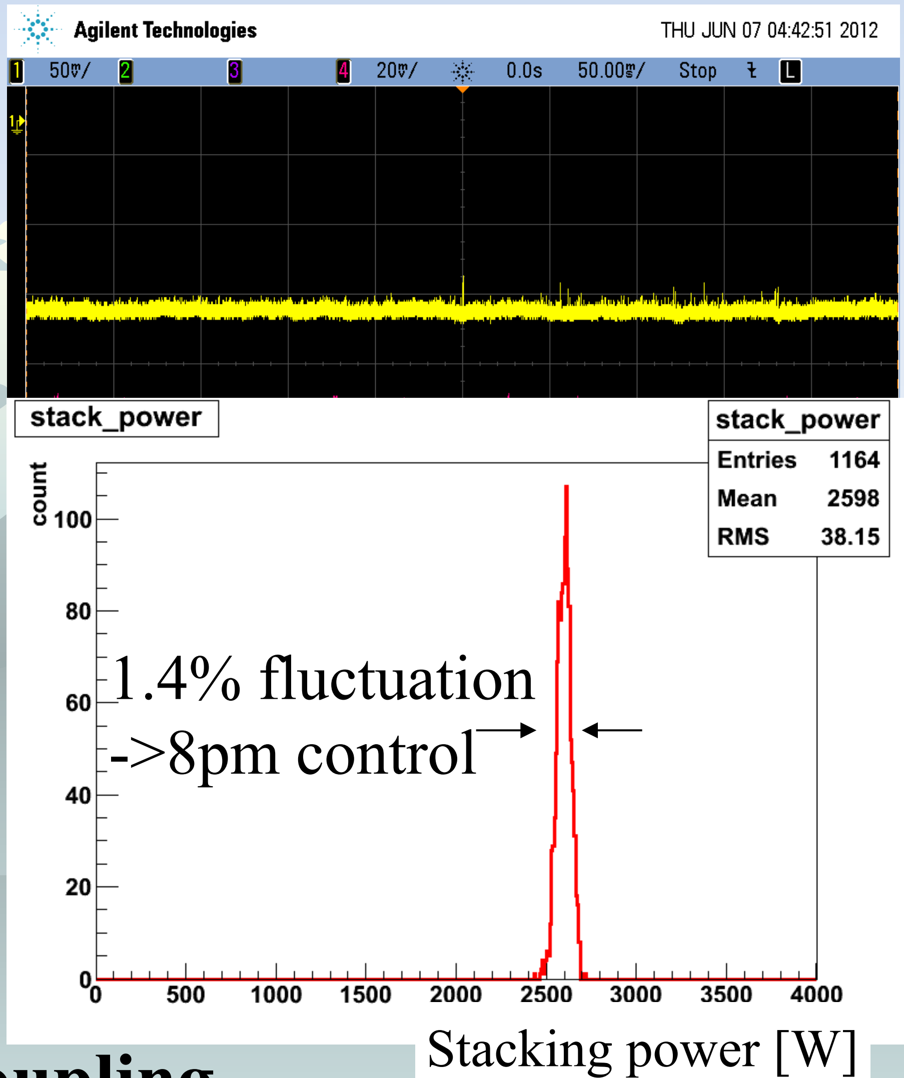




Different slope in left and right pol.

Cavity control accuracy





Laser power = 2.6kW

Timing jitter = 8ps

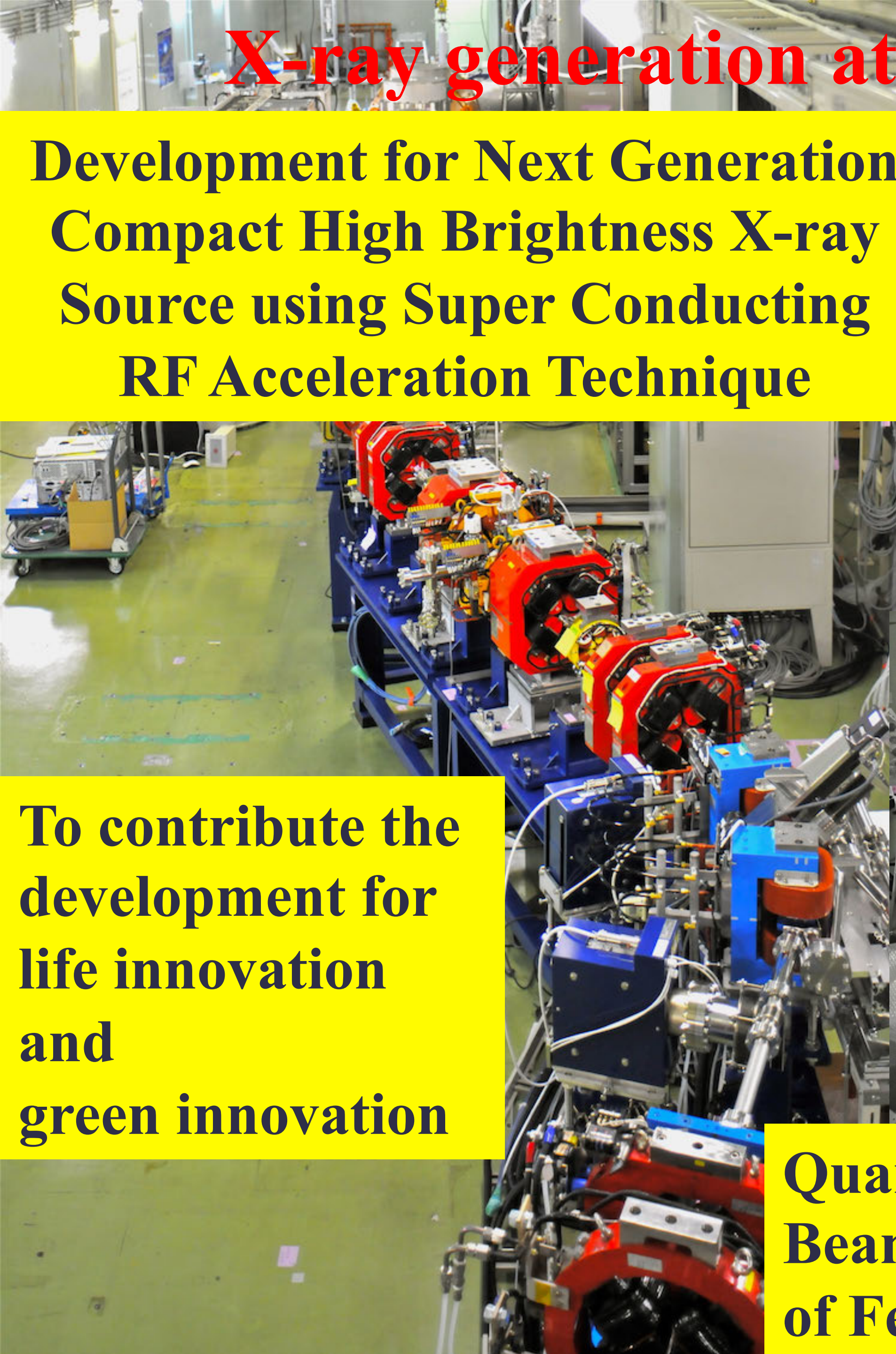
Enhancement 1230

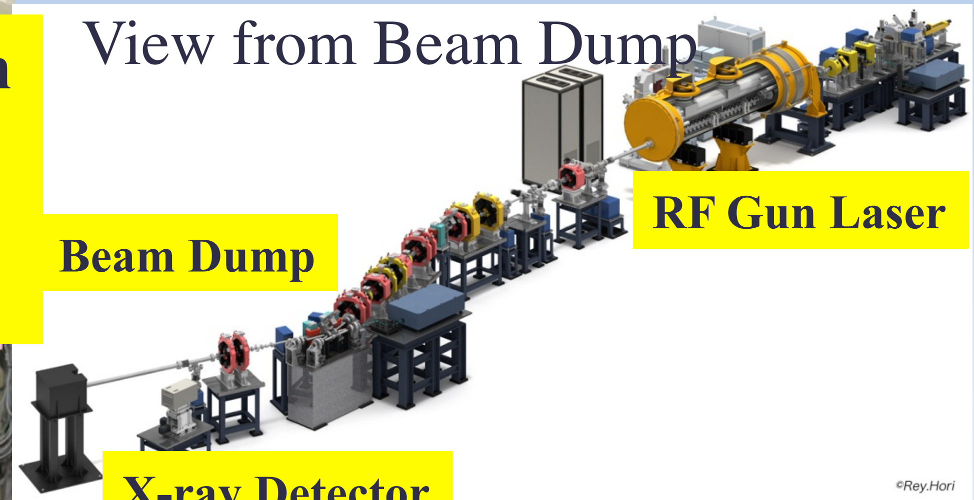
due to mirror

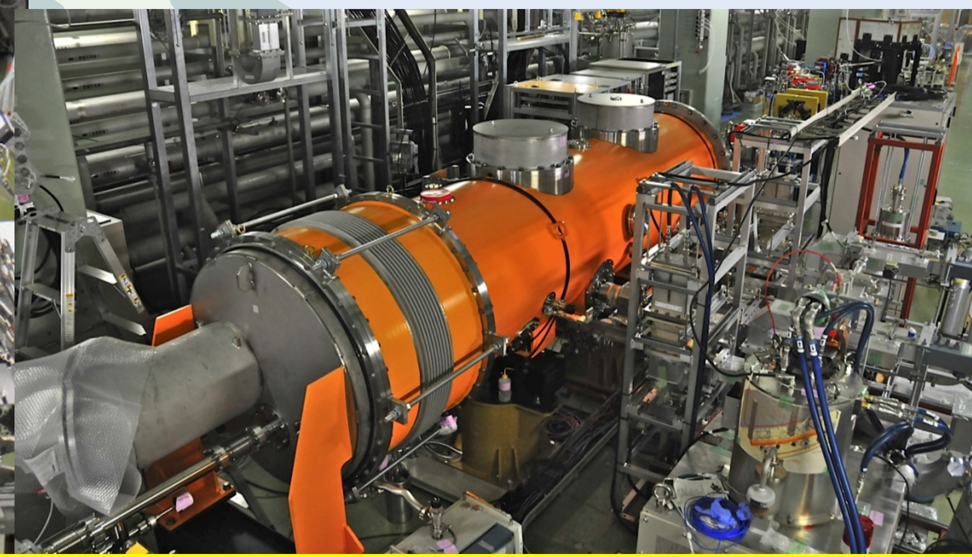
contamination and injection coupling.

X-ray generation at STF and LUCX

Development for Next Generation Compact High Brightness X-ray Source using Super Conducting RF Acceleration Technique



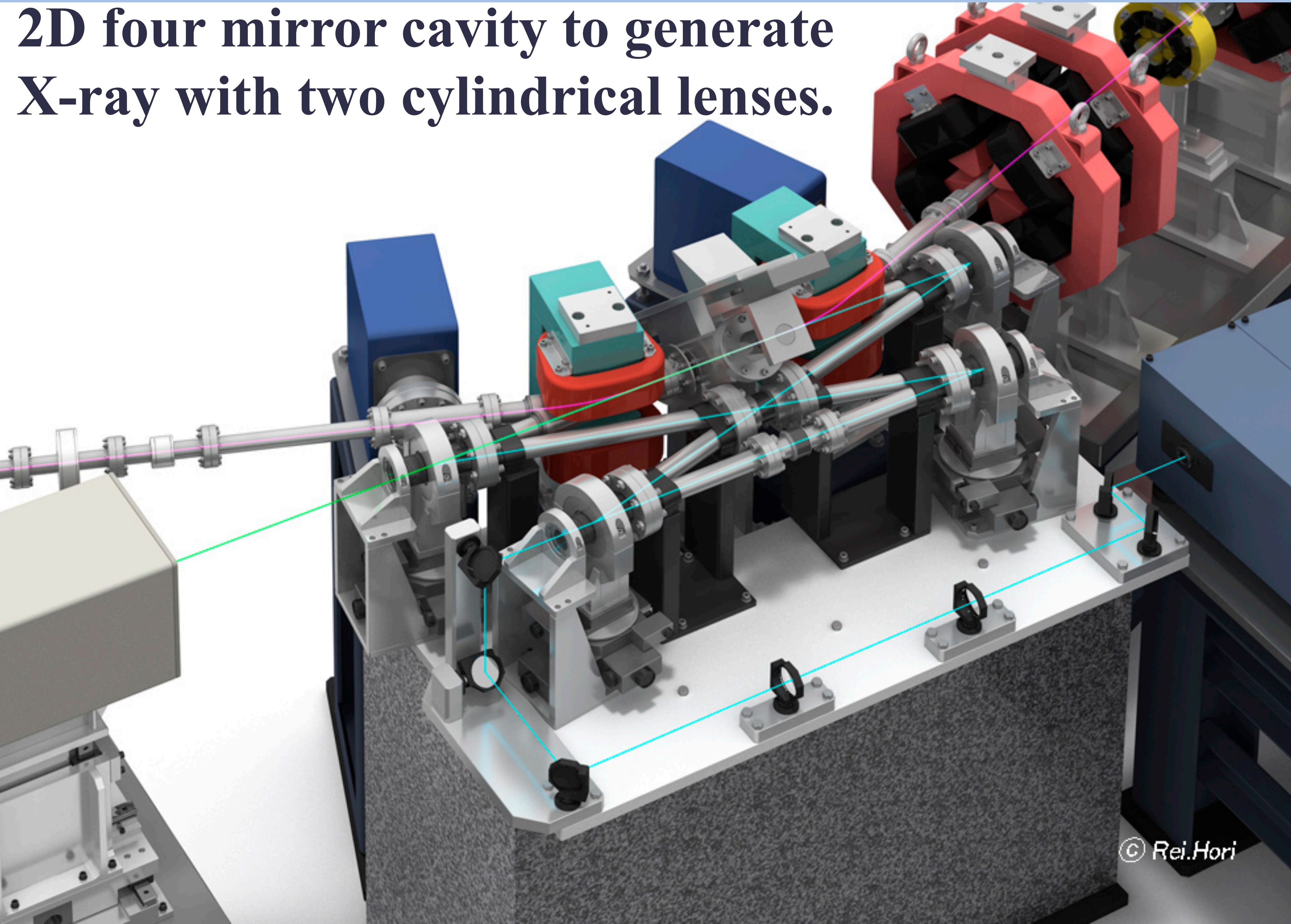




To contribute the development for life innovation and green innovation

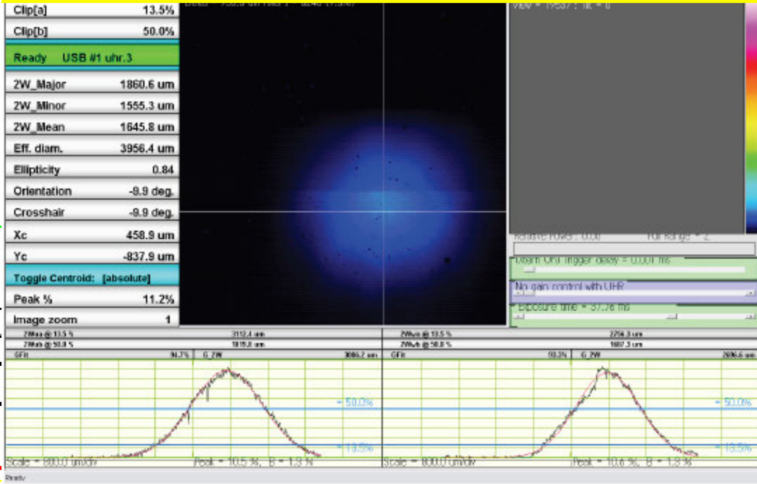
Quantum Beam Technology Program: Beam commissioning started from mid. of February 2012 to March 2013.

2D four mirror cavity to generate X-ray with two cylindrical lenses.

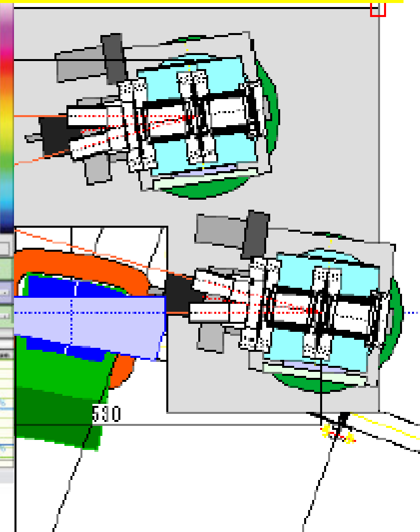


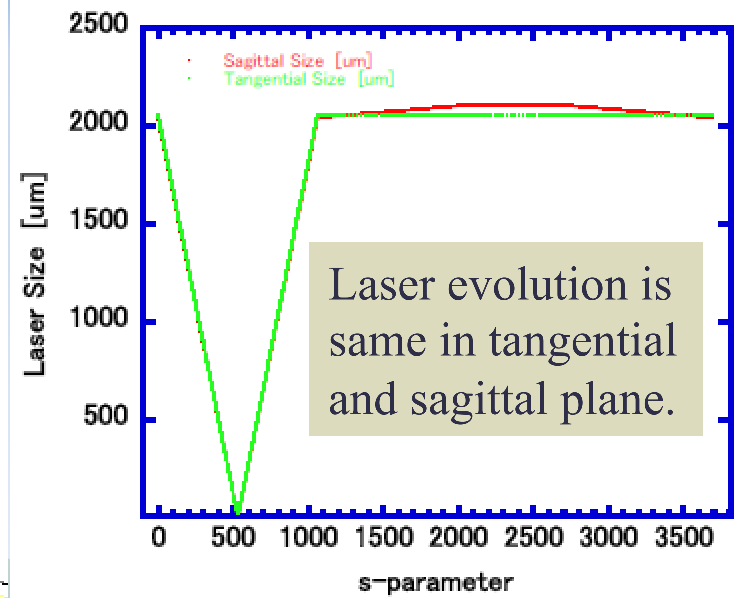
Latest Version Cavity Design

profile of Transmitted laser from cylindrical mirrors.
We confirmed the effect of the cylindrical mirrors.



$2\omega_h$ = 3112.4um / $2\omega_v$ = 2756.3m

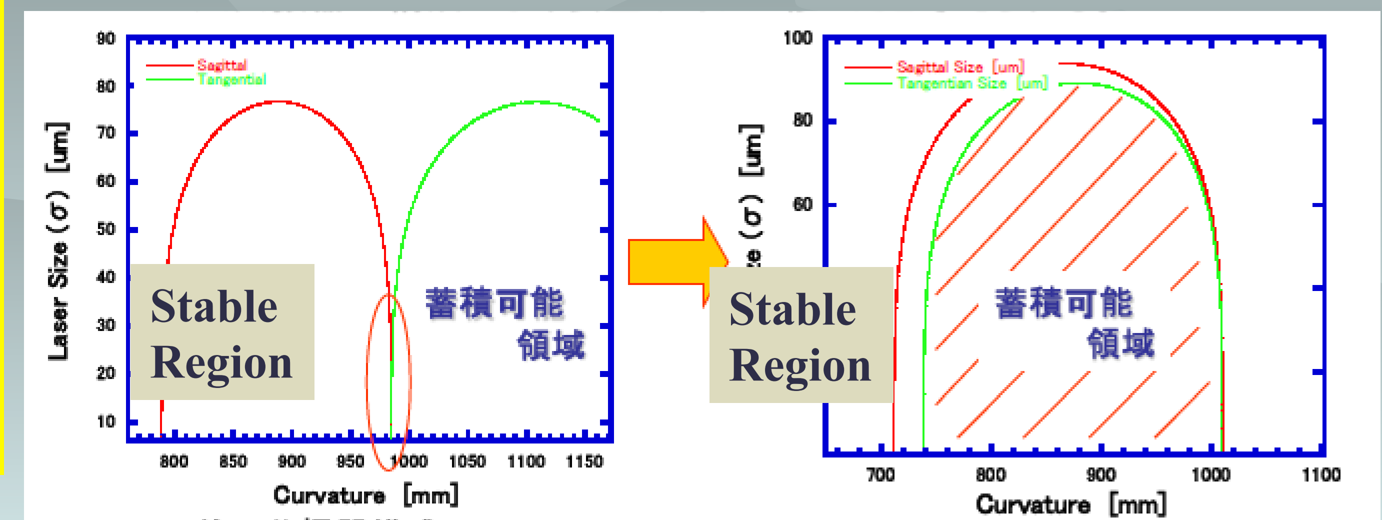




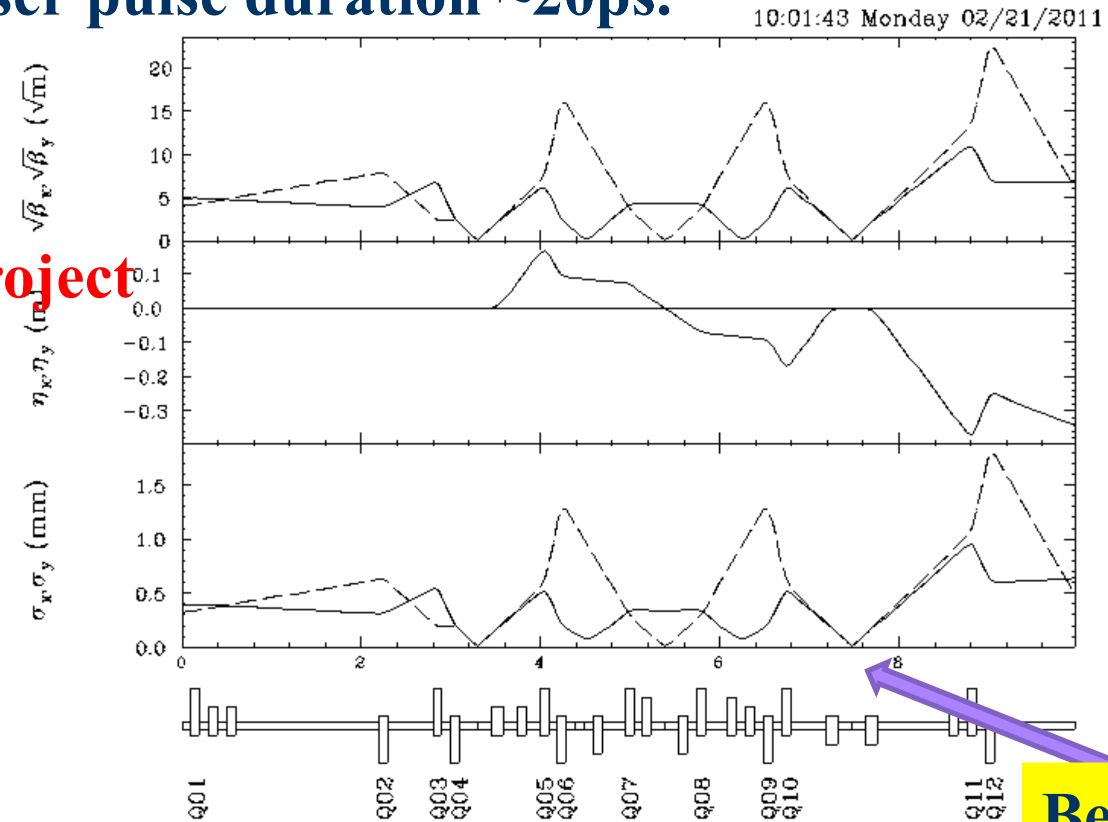
Laser evolution is same in tangential and sagittal plane.

Two laser pulses are circulating with the spacing of 6.15ns in a ring optical cavity.

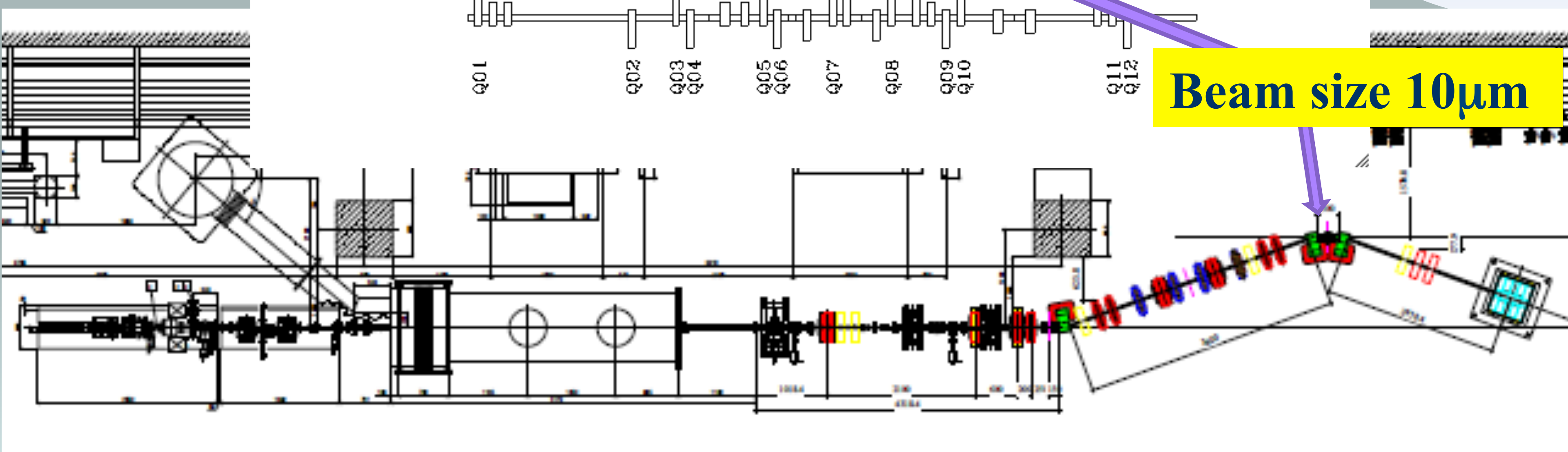
Change to 2D 4-mirror optical cavity with two cylindrical lenses instead of two plane mirrors.



Change to head collision scheme to get another enhancement of 5 and to increase laser pulse duration ~20ps.



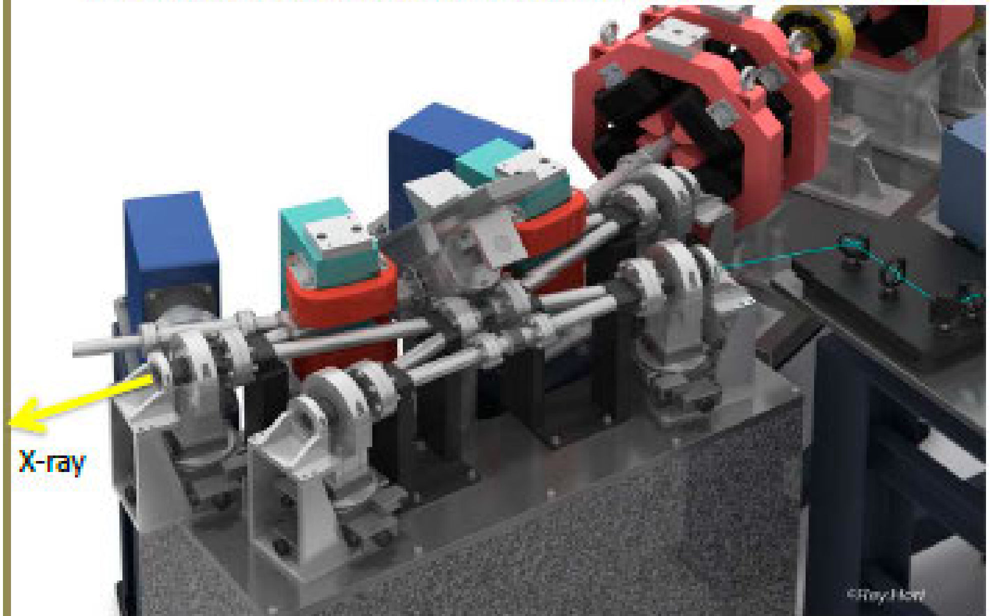
Quantum project at STF



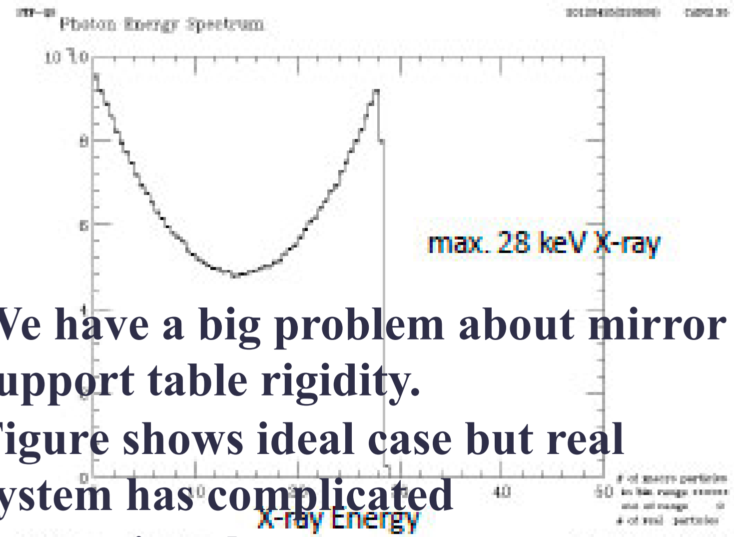
Beam size 10μm

Plan of X-ray generation by Inverse-compton scattering

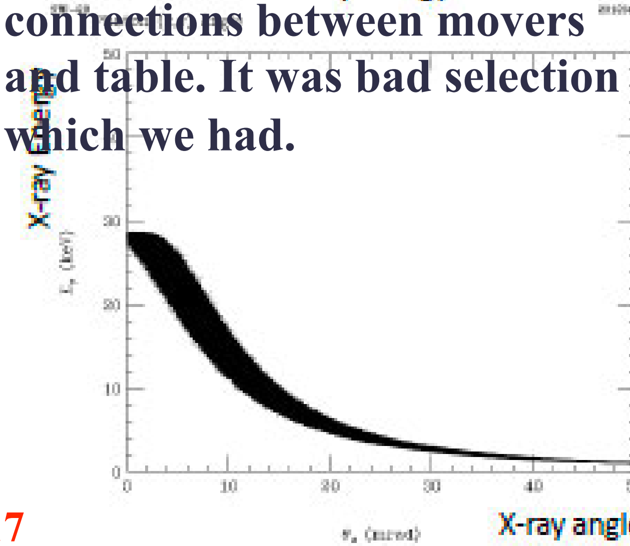
4-mirror laser accumulation, head-on with e-beam



40MeV, head-on collision



We have a big problem about mirror support table rigidity.
Figure shows ideal case but real system has complicated connections between movers and table. It was bad selection which we had.



	Electron	Laser
Energy	40MeV	1.17eV (λ=1064nm)
Energy spread	0.1% (rms)	
Beam size(rms)	10μm	10μm
Pulse width(FWHM)	12ps	12ps
Intensity	61.5 pC/bunch	50mJ/pulse
Number of bunches	162500	----
Emittance	0.5π mm mrad	
Collision angle	0deg (Head on)	
Rep. Rate	5Hz	

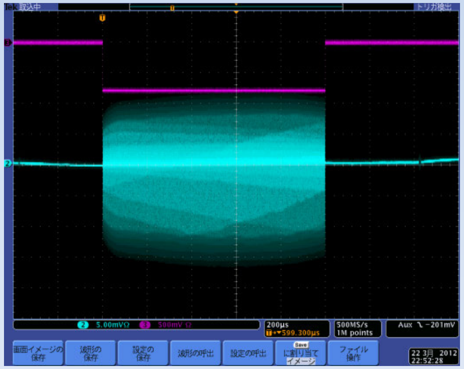
Brightness 10^{17}
Photons/sec/mm^2/mrad^2 in 0.1%b.w

target: 1.3x10^{10} photons/sec/1%bw

Achieved beam at STF for QBT project

07132012 Hayano V1.0

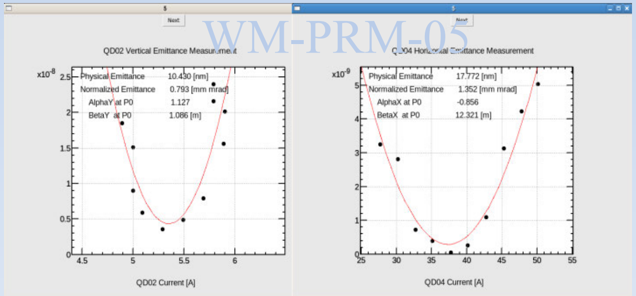
1ms beam from L-band RF Gun



(RF feedback ON) 03.22.2012
50pC/bunch

Min. emittance so far

WM-PRM-05



Date	Normalized Emittance [mm mrad]		RF gun [MW]	SC cav. [MV/m]	Main Solenoid : Main/Backing	UV Laser	Charge [pC]	Energy [MeV/C]
	Vertical	Horizontal						
13/June	0.79	1.3	3.5	14.5, 24.0	306.23 / 100.73	φ1mm	15-25	39.1

Measurement of beam emittance by wire scanner 06.13.2012

Min. beam size@WM-PRM-05

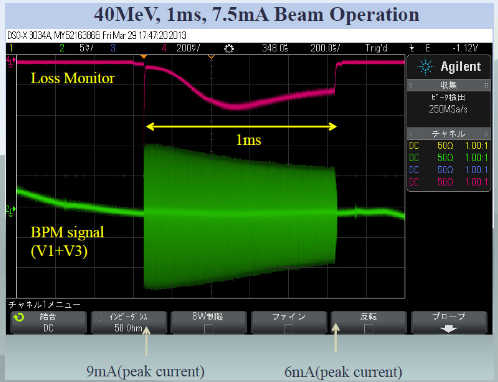
WM-PRM-05で一番小さく
絞れた時。
ただし、WM-PRM-07では
大きかった。

WM-PRM-05
σx: 17.5[µm]
σy: 25.3[µm]

このとき、
WM-PRM-07
σx: 55.8[µm]
σy: 29.3[µm]
(ログブックのデータのみ
画像データなし)

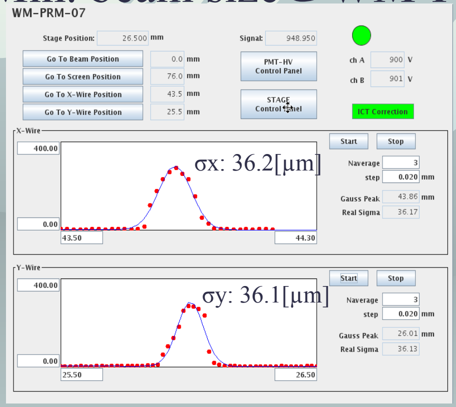
07.04.2012

Accelerated 1ms beam



1ms beam acceleration, 7.5mA
(Gun/SCRF RF feedback ON) 06.08.2012

Min. beam size@WM-PRM-07



07.04.2012

Target size : 10µm

Dispersion measurement

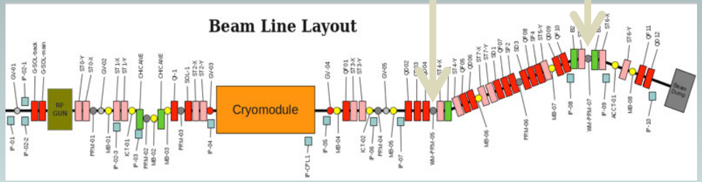
@WM-PRM—05, -07, dispersion measurements
SC phase 240deg 40.58 MeV/c (B1 150.20A)
SC phase 250deg 40.02MeV/c (B1 148.10A)

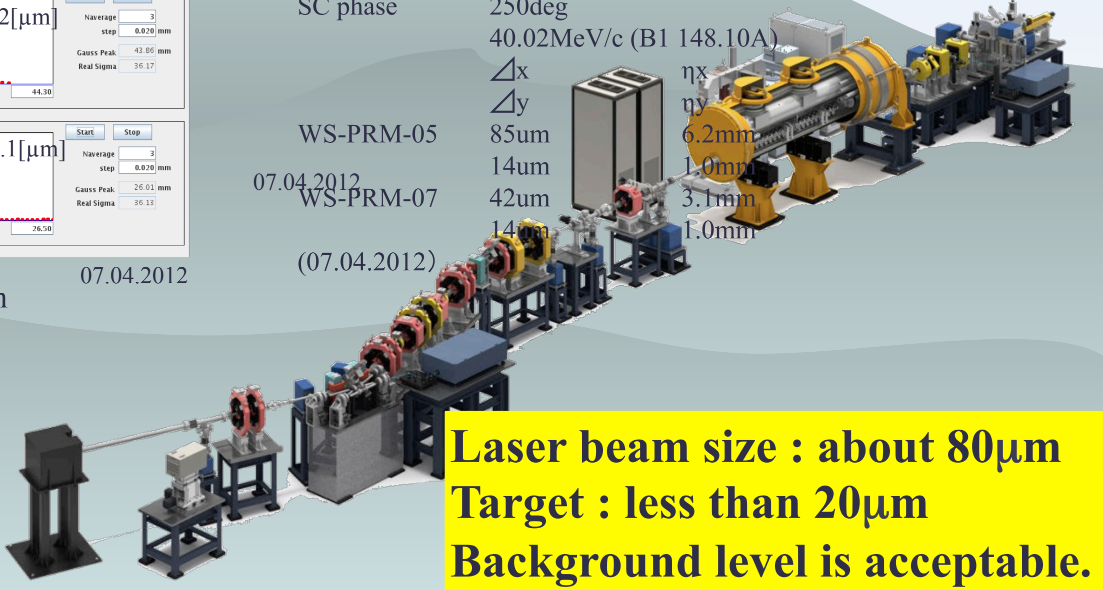
	⊿x	ηx
	⊿y	ηy
WS-PRM-05	85um	6.2mm
	14um	1.0mm
WS-PRM-07	42um	3.1mm
	14um	1.0mm

(07.04.2012)

07.04.2012

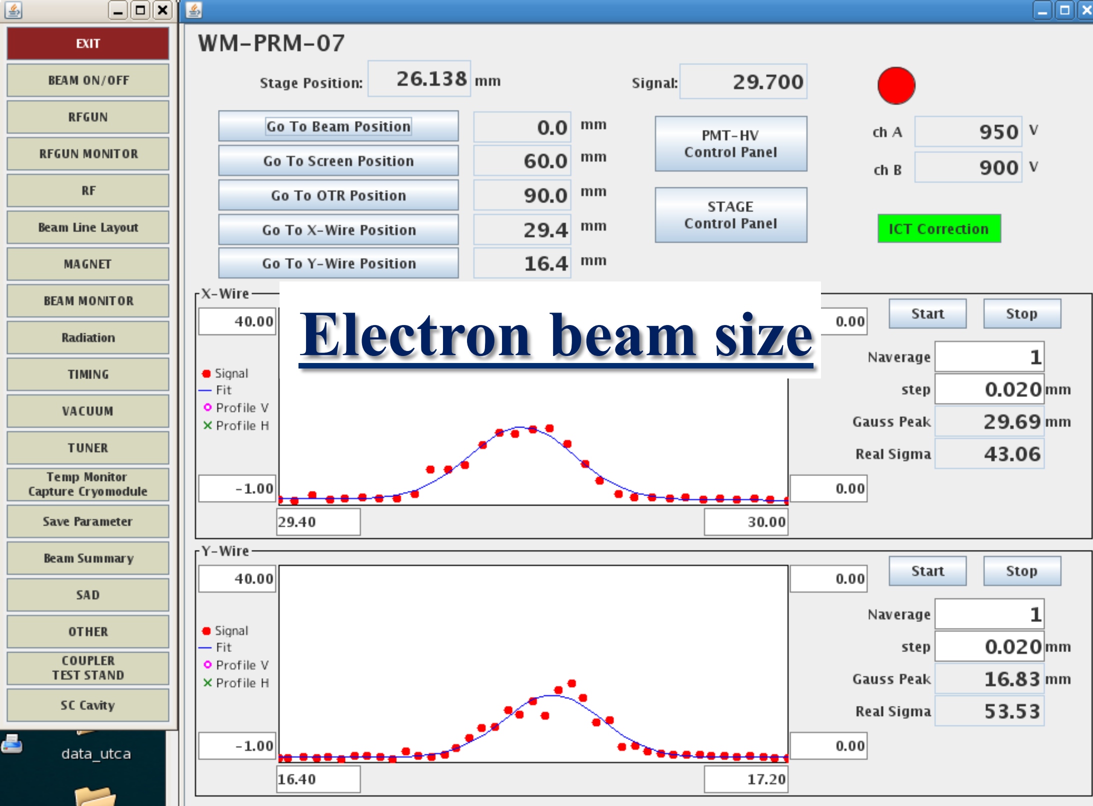
WM-PRM-05 WM-PRM-07





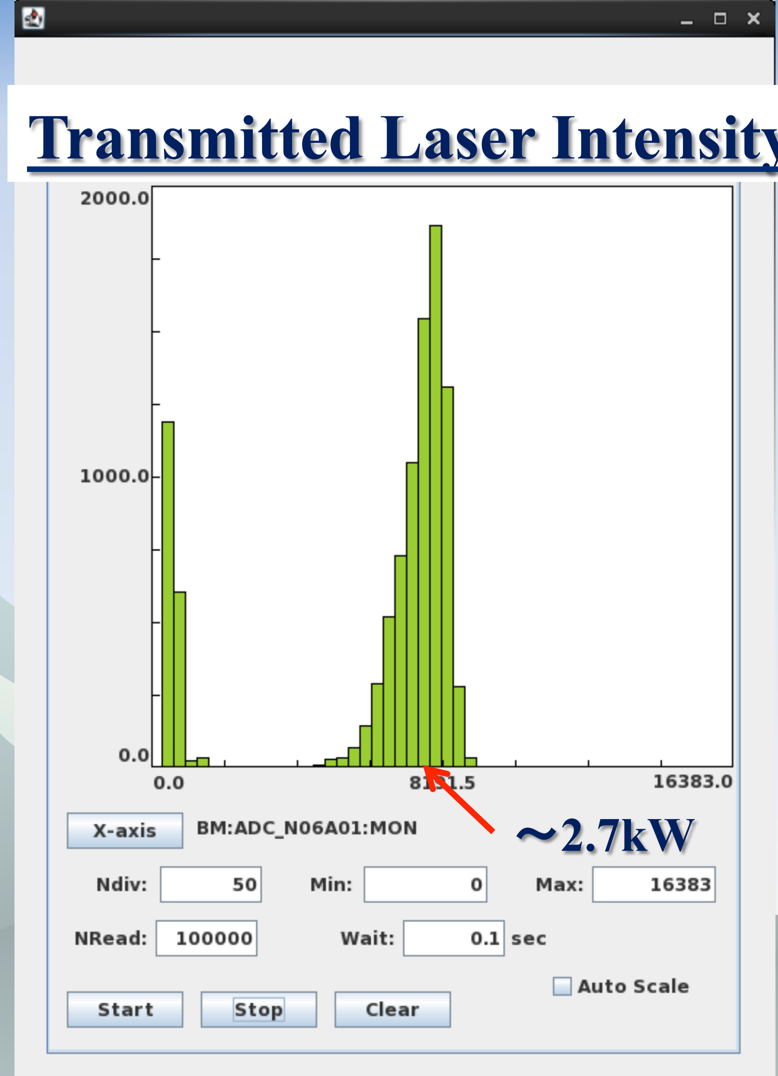
Laser beam size : about 80µm
Target : less than 20µm
Background level is acceptable.

Electron beam size



↑ Wire Scan Result at IP

Transmitted Laser Intensity



↑ Transmitted Laser Intensity Monitor

Typical Collision Condition

Electron Beam : 40MeV

248-bunch

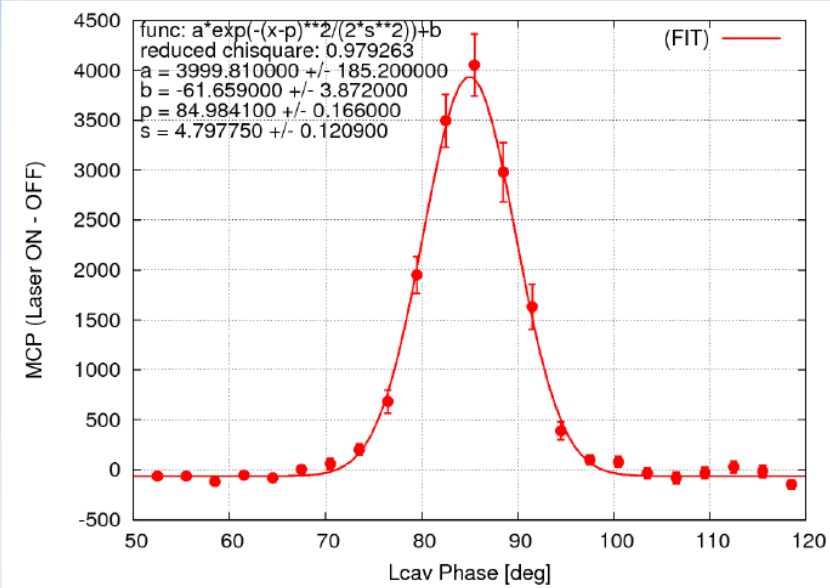
55pC/bunch

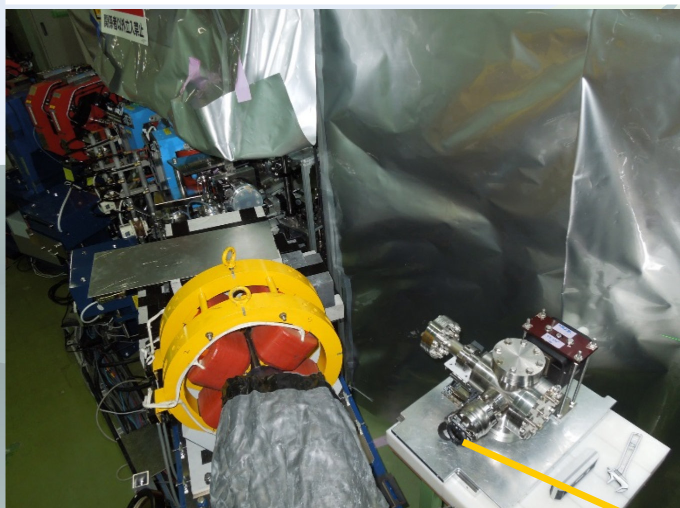
σ_x : 43um/σ_y : 55um

Laser : ~15.4uJ@IP

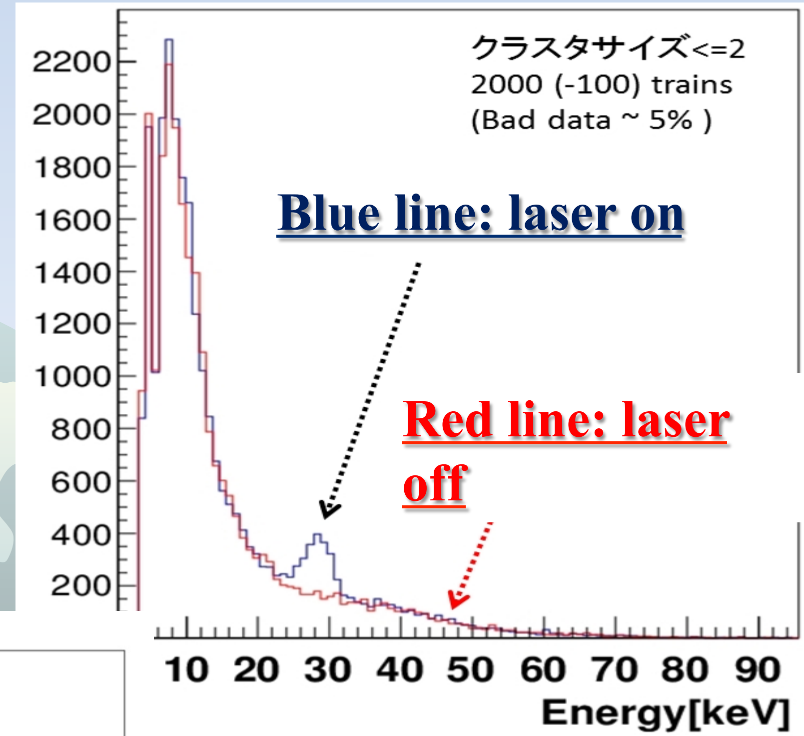
σ : ~ 80um

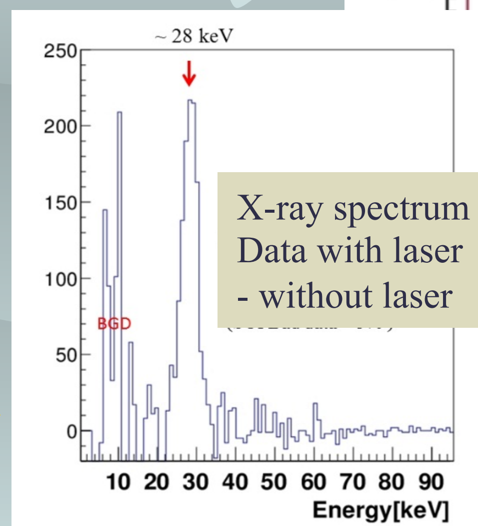
Detected Signal by MCP (22nd Mar. 2013)





Raw X-ray spectrum detected by SOI detector



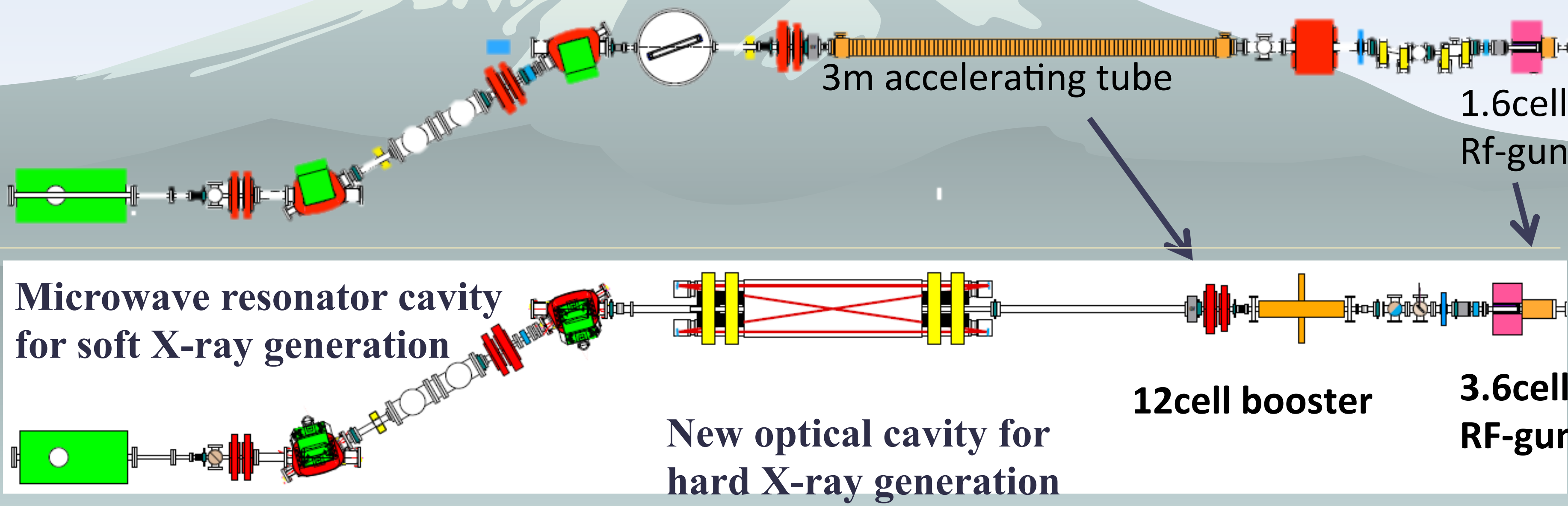


Detected flux 10^6 photons/sec of 28keV X-ray.

Success of 28keV X-ray detection

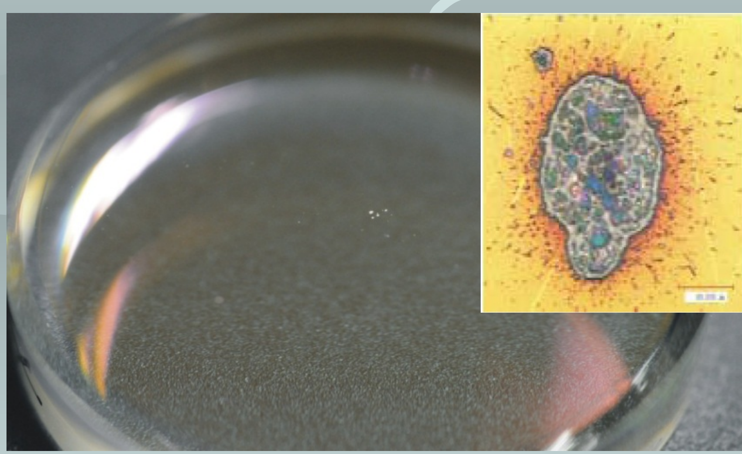
X-ray generation at LUCX

- 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 June 2012.

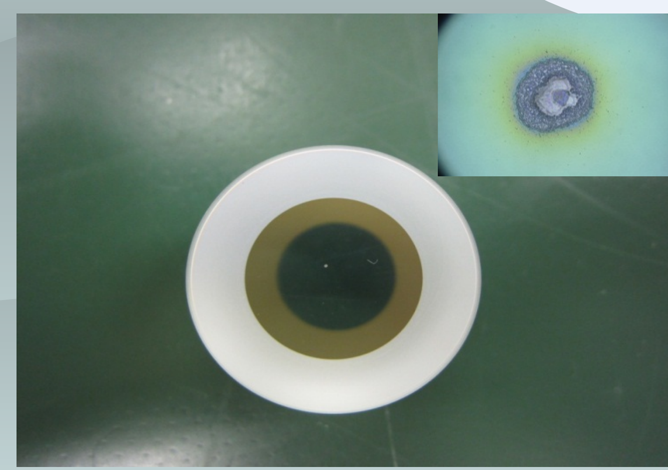


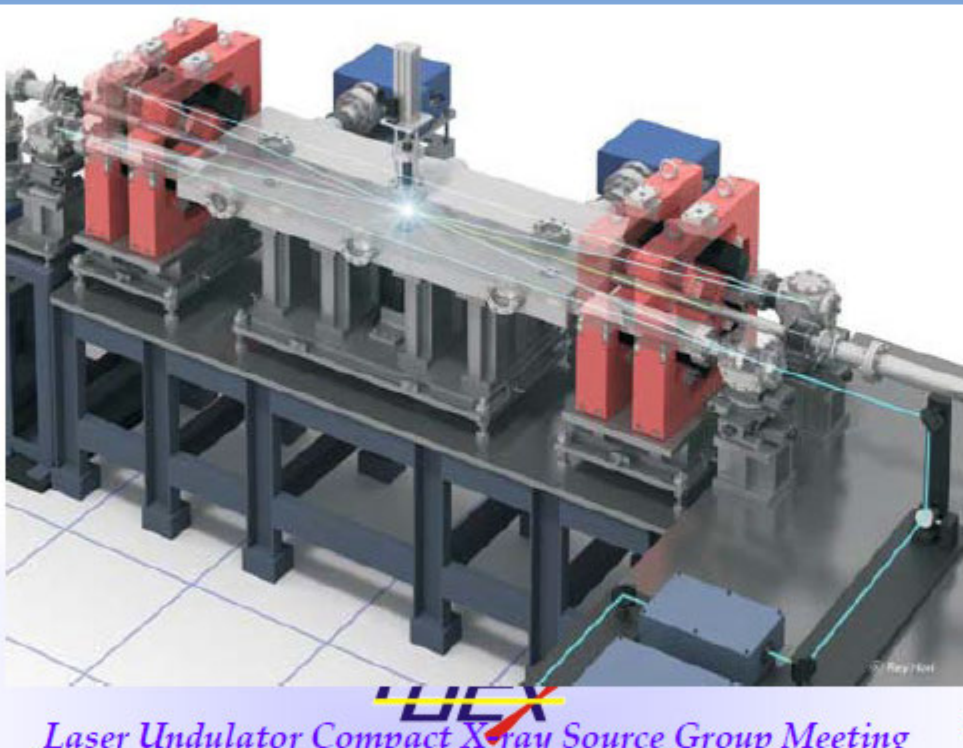
We destroyed the mirror coating many times. First occurred when the waist size was ~100μm with burst amplification and 42cm two mirror cavity. Second occurred when the waist size was 30μm with the burst amplification and the 42cm two mirror cavity. Now we are using 4 mirror cavity with smaller waist size at IP. From our experience, we have to reduce the waist size to increase the laser size on the mirror and need precise power control for the burst amplification. I guess about storage laser pulse energy from 2mJ to 4mJ destroyed the mirror coating with the waist size of 30μm. Also, we found the damaged position was not at the center.

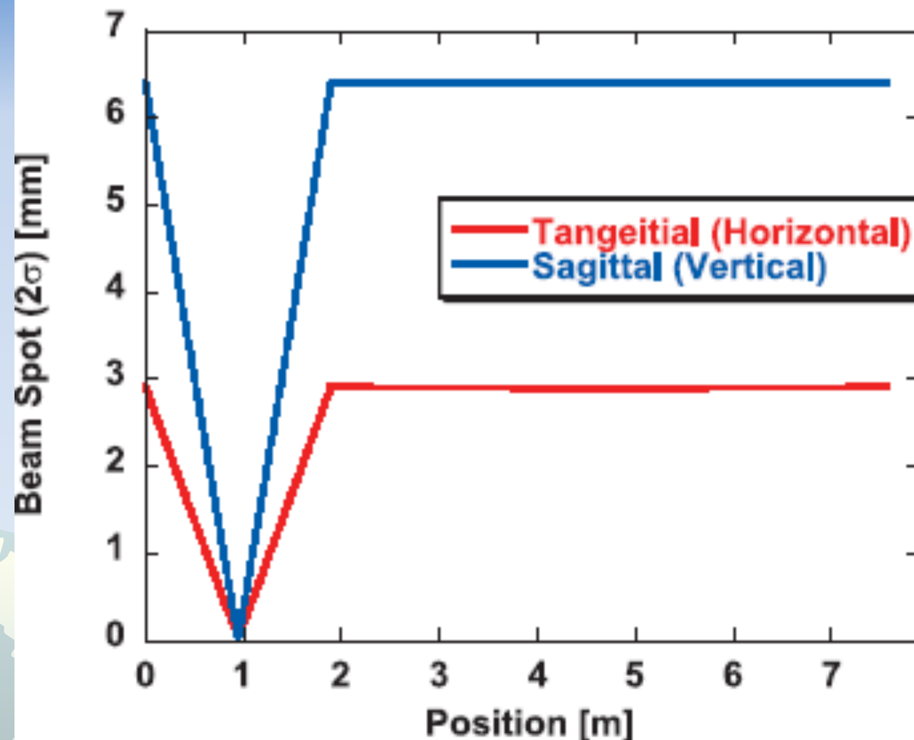
2008



2011

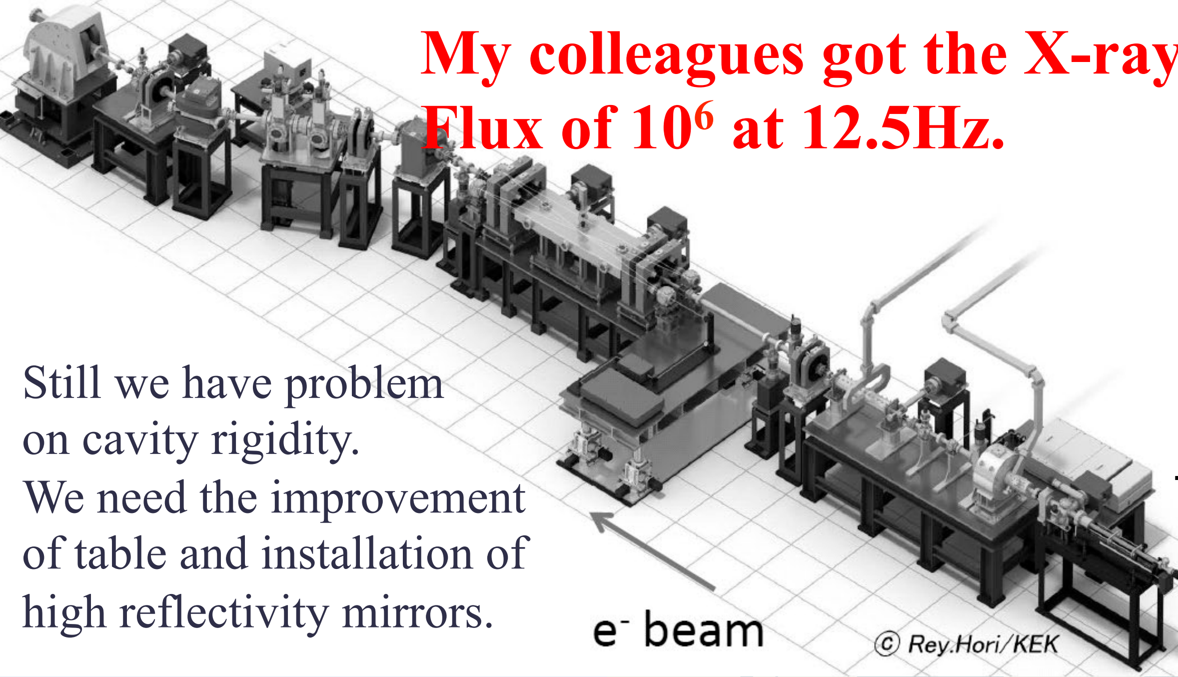






One turn length : 7.56m, horizontal laser waist size : ~100μm in 2σ,
Crossing angle : **7.5 degrees**, vertical laser waist size : **~50μm in 2σ,**
Horizontal laser size on laser injection plane mirror : 2.92mm,
Vertical laser size on laser injection plane mirror : 6.4mm
Laser pulse energy in cavity : 8mJ, distance between concave mirrors : 1.89m, **7.56m means this cavity has 9 laser pulses.**
Use two inch mirrors and increase the threshold damage energy.
Completed this device in September 2012 and started the generation of X-ray from mid. of Feb. 2013.

My colleagues got the X-ray Flux of 10^6 at 12.5Hz.



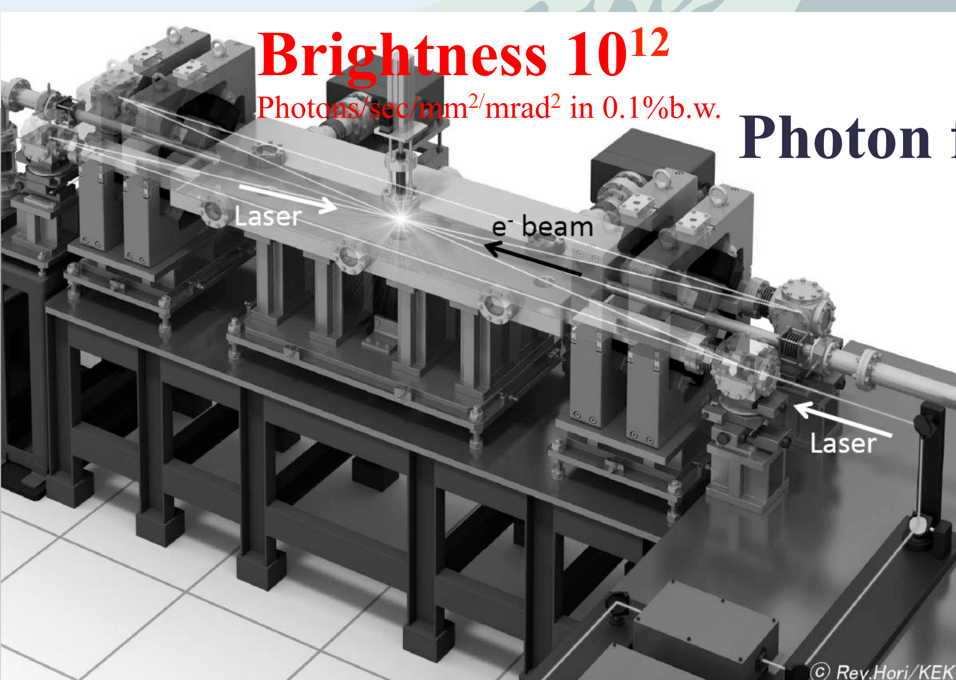
Still we have problem on cavity rigidity.
We need the improvement of table and installation of high reflectivity mirrors.

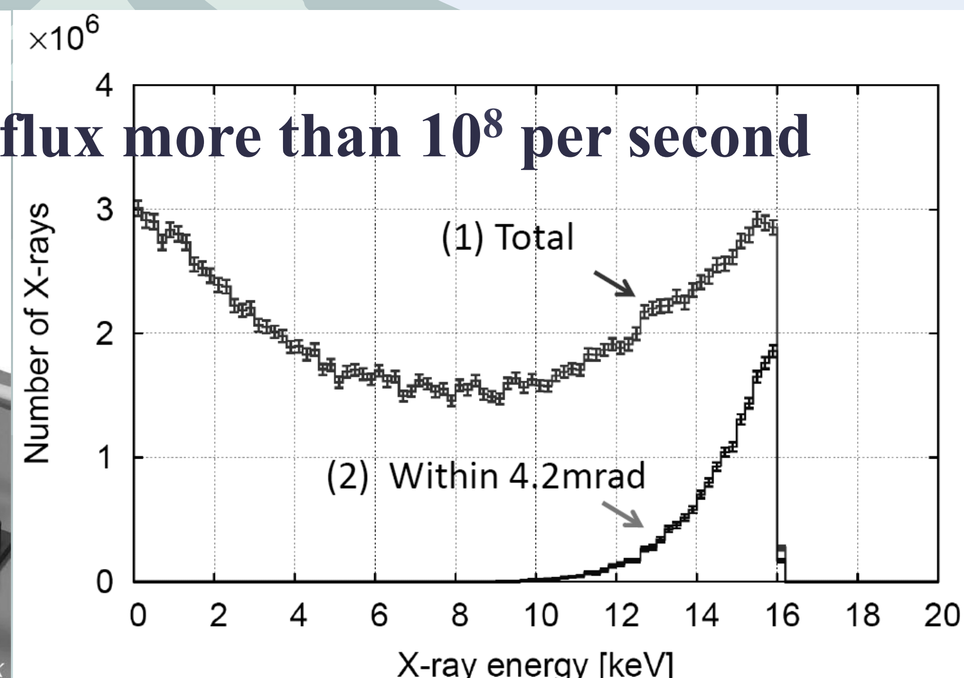
Energy	30MeV
Intensity	0.4nC/bunch
Number of bunch	1000
Beam size at the collision point (1σ)	33μm ×33μm
Bunch length	10ps
Bunch spacing	2.8ns

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

Brightness 10^{12}
Photons/sec/mm^2/mrad^2 in 0.1%b.w.

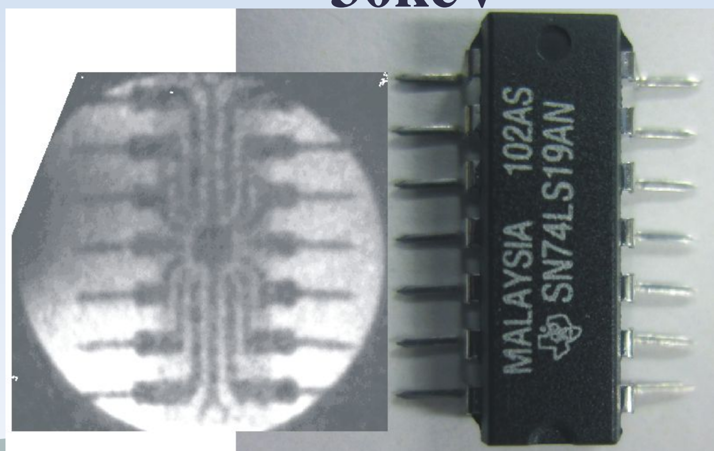
Photon flux more than 10^8 per second



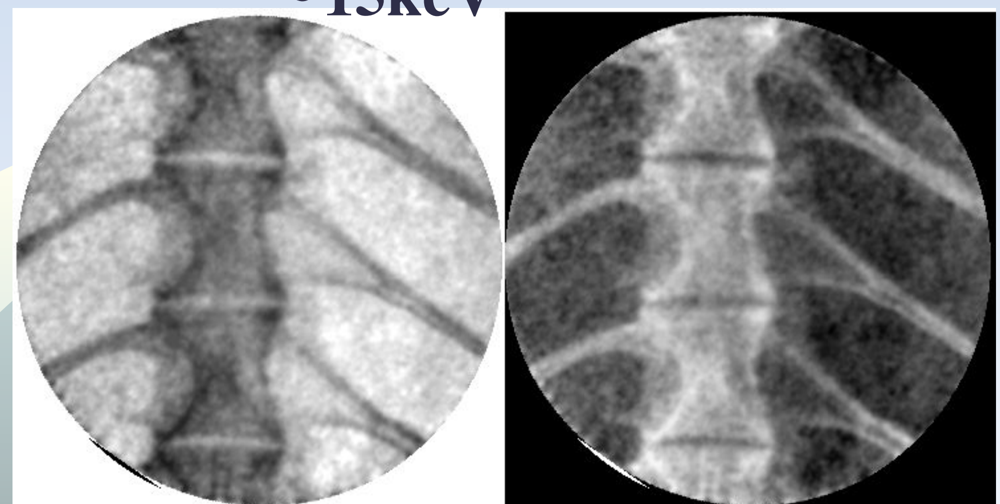


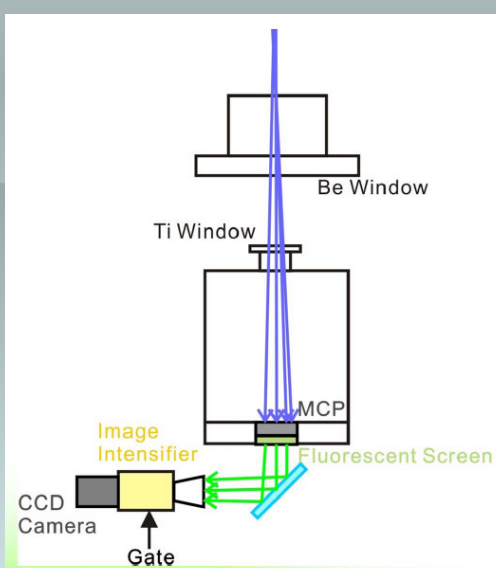
X-ray Imaging by I-MCP+I.I. and SOI
Phase contrast X-ray imaging is next step at LUCX.

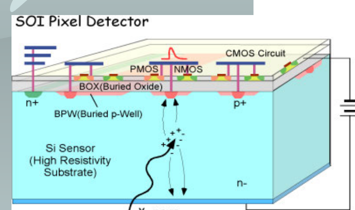
～30keV

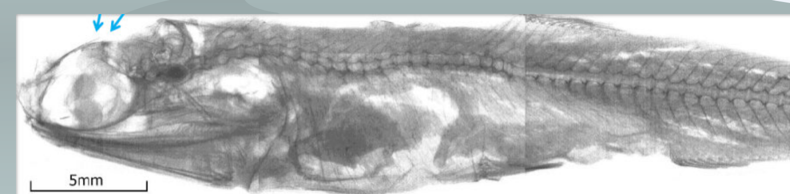


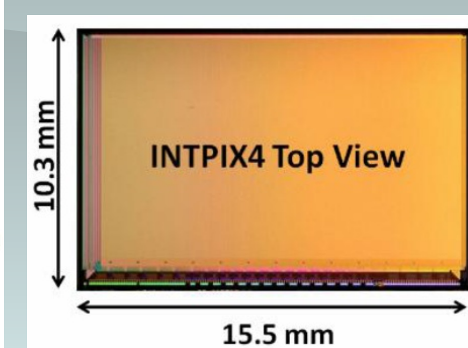
～15keV







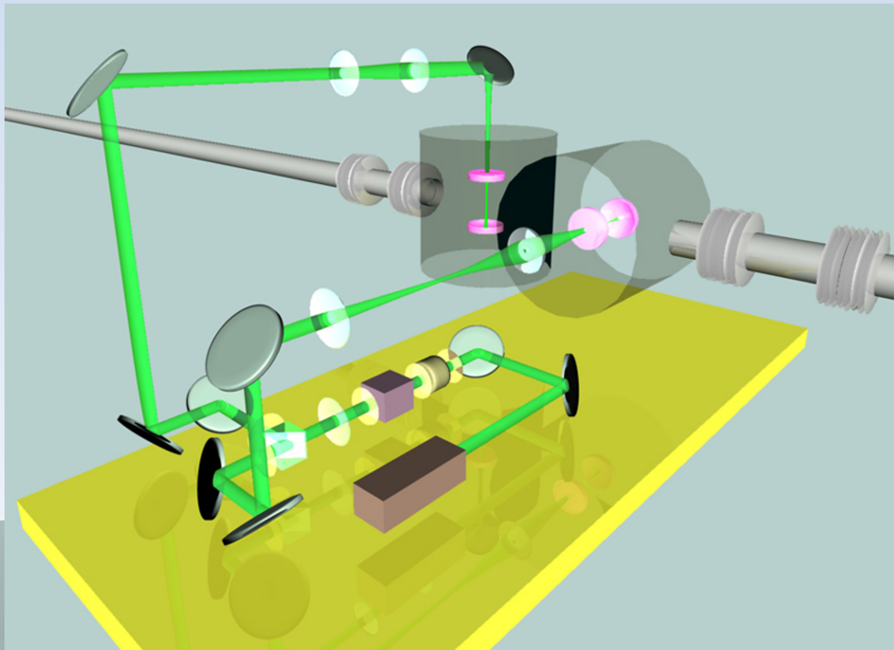


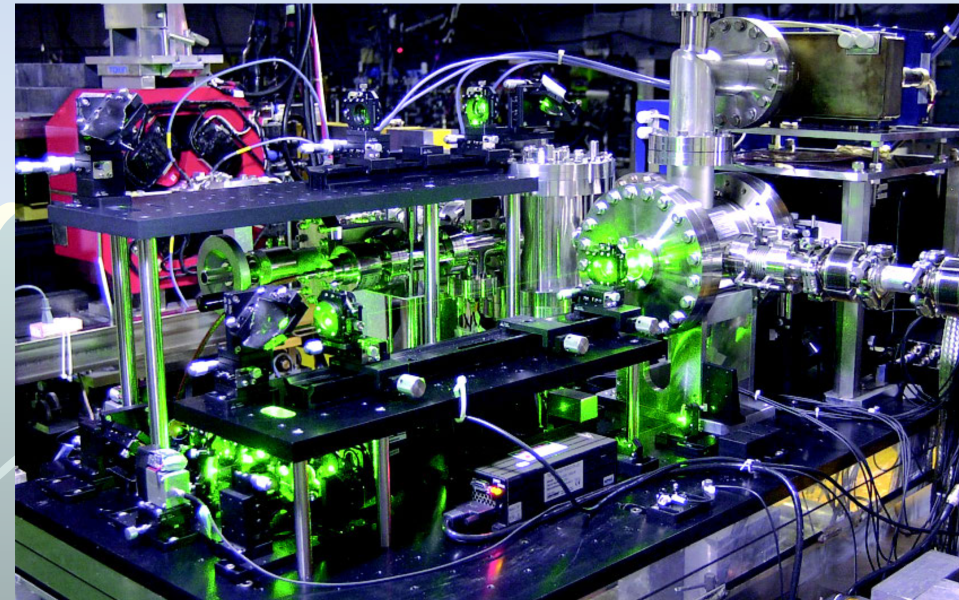


X-ray Imaging by SOI Pixel Detector

Optical cavity development

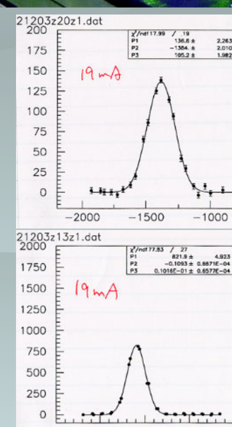
New Laser wire X & Y scan May 2003





Two wire chamber

TEM00 Mode



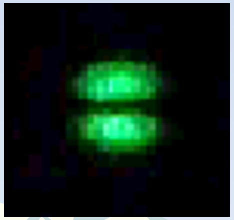
X profile

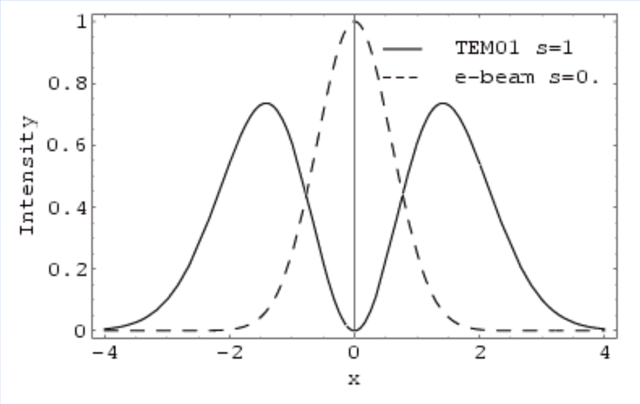
Y profile

Twin peaks laserwire

use TEM01 resonance mode in the optical cavity as a laserwire

good resolution for small beam size

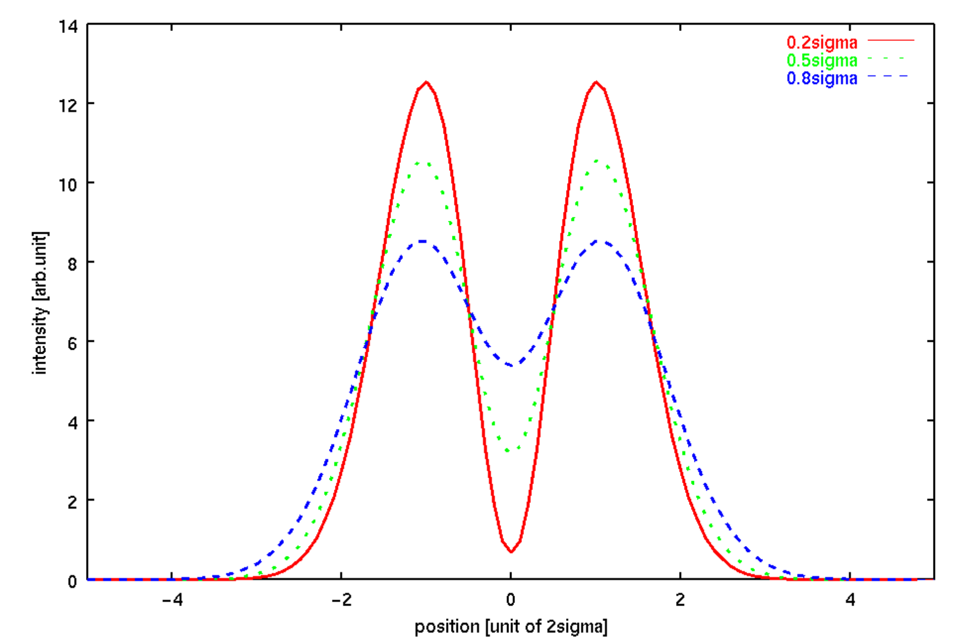




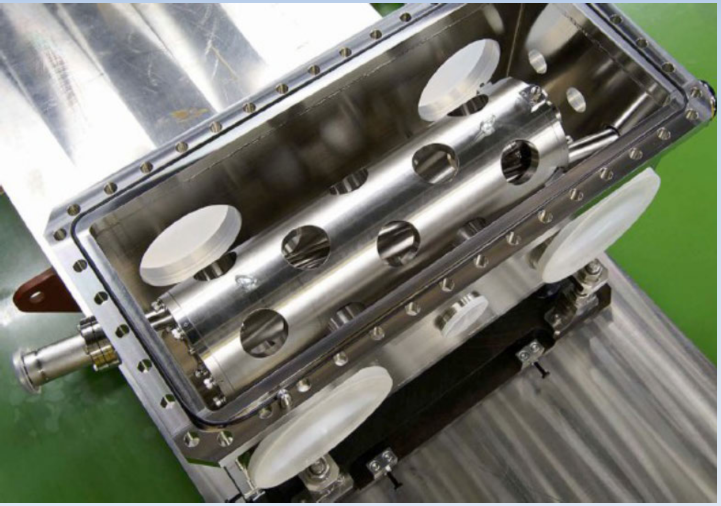
factor 2~3 resolution improvement

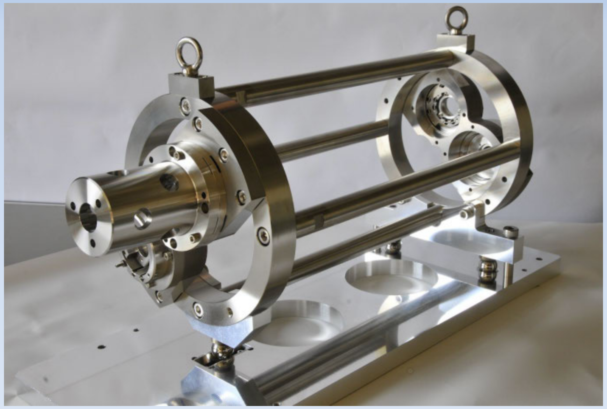
insensitive for beam orbit drift

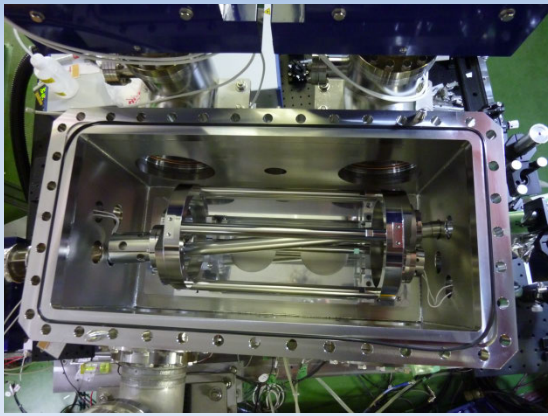
scan free



2-Mirror Cavity --> 4-Mirror Cavity



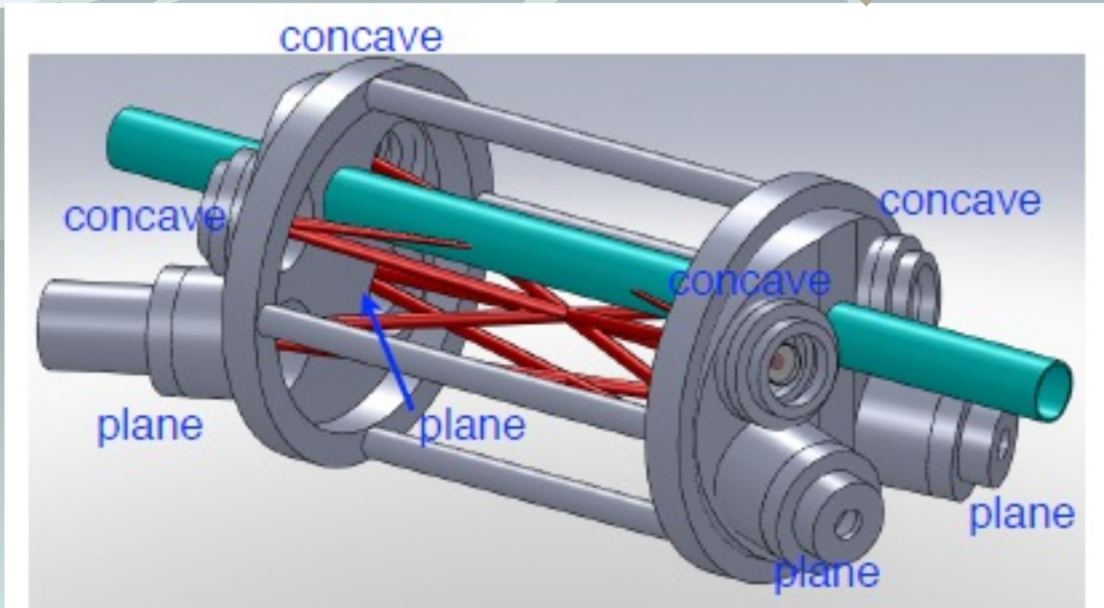




σ_{spot} ~ 13 micron F ~ 4000

σ_{spot} ~ 30 micron F ~ 2000

4-Mirror Cavity can storage the power more than 1MW, which will be possible soon.

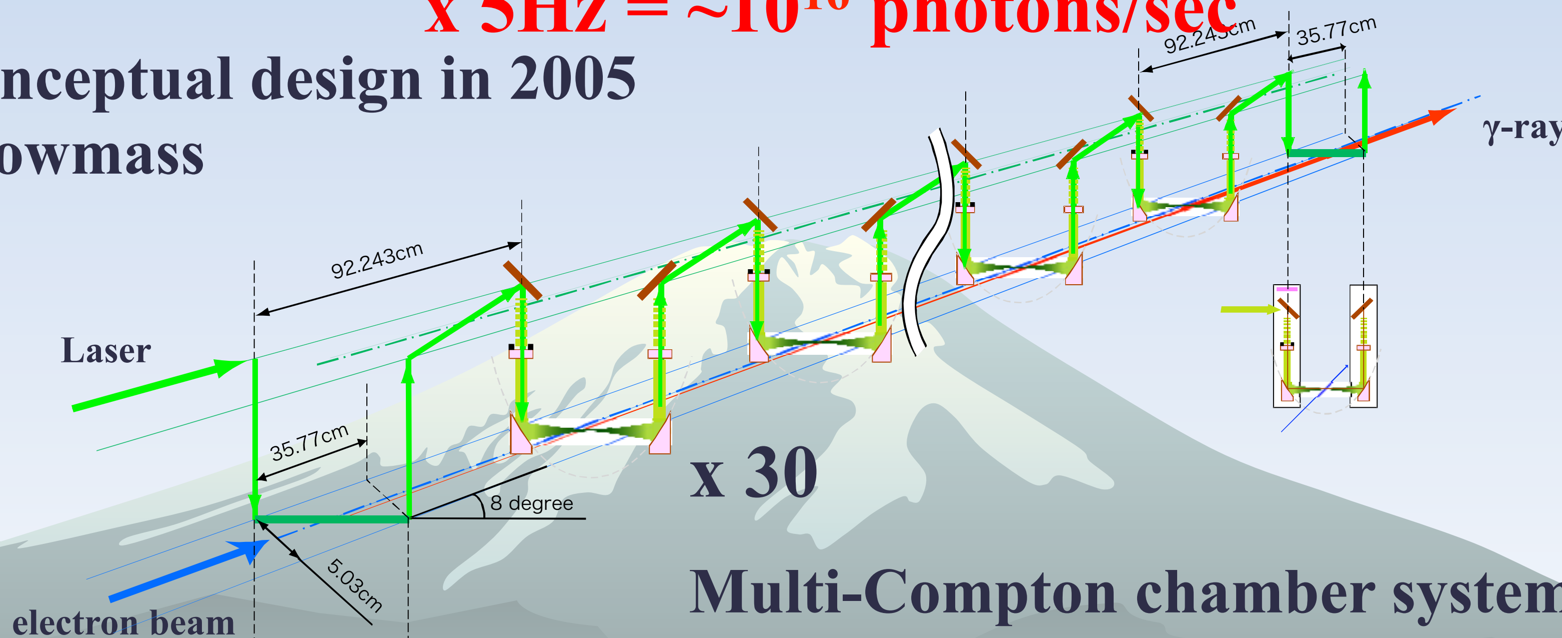


Storage power more than 2MW is possible due to recent study. See H. Carstens et al., "Large-mode enhancement cavities," *Opt. Express*, 21, 11606-11617 (2013). They demonstrated the storage of 400kW with pulse duration 250-fs and 2000 enhancement.

ILC polarized positron source

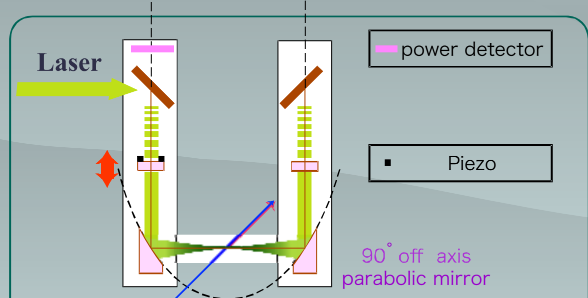
~10^{12} photons with 6.16ns spacing x ~3000 bunches x 5Hz = ~10^{16} photons/sec

Conceptual design in 2005 Snowmass



x 30

Multi-Compton chamber system



x 5 at present

Good progress under R&D

PoP Experiment had been done.

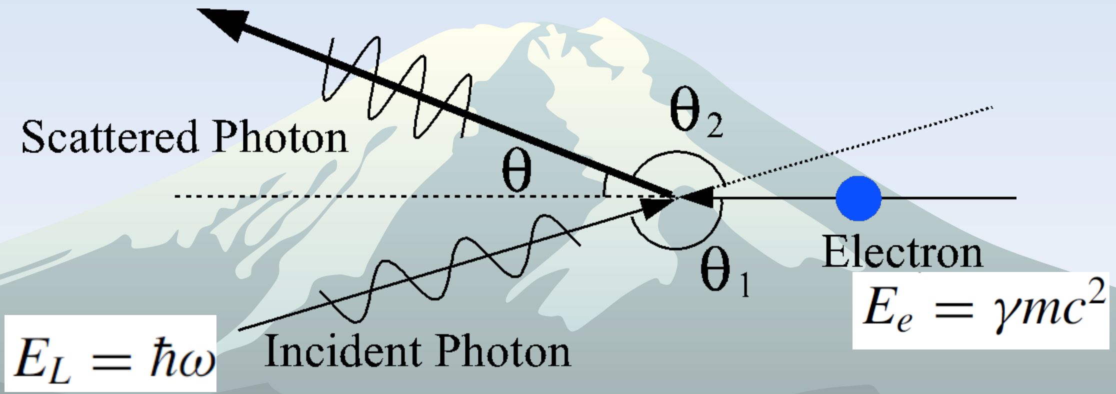
M. Fukuda *et al*. Physical Review Letter, 91, 164801(2003)
T. Omori *et al*. Physical Review Letter, 96, 114801(2006)

Presented by Junji Urakawa
At KILC12, Daegu, Korea
GDE Source, 30min.

Quantum beam : particle beam = electron, proton, ion, neutron

electro-magnetic wave = THz ∼ x-ray → **γ-ray**

γ beam generation based on laser Compton scattering



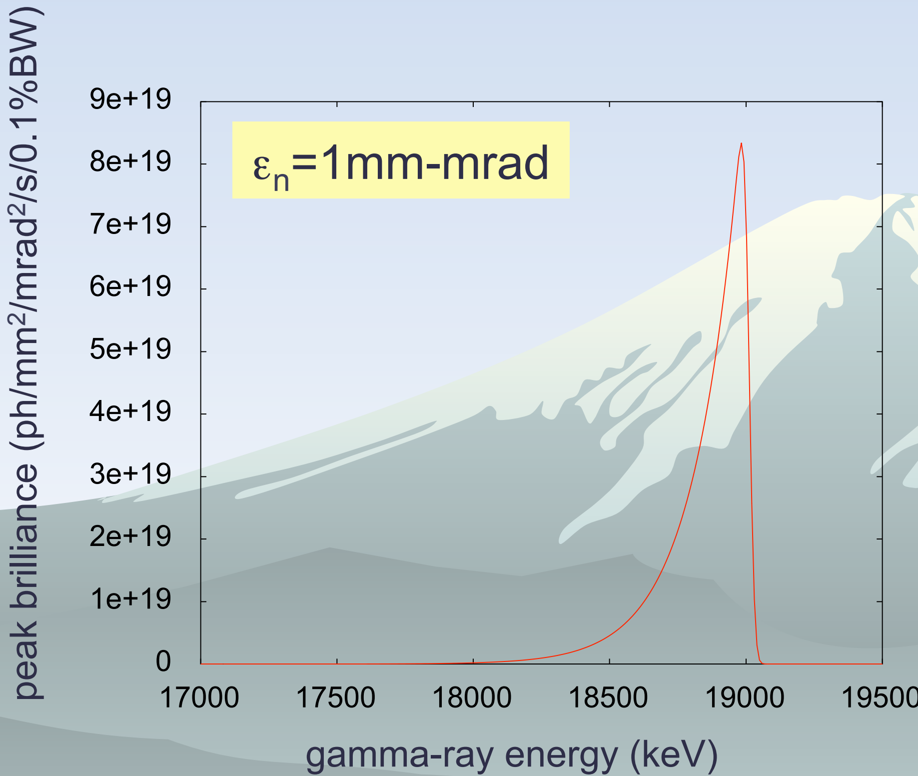
$$E_\gamma \simeq \frac{4\gamma^2 E_L}{1 + (\gamma\theta)^2 + 4\gamma E_L/(mc^2)}$$

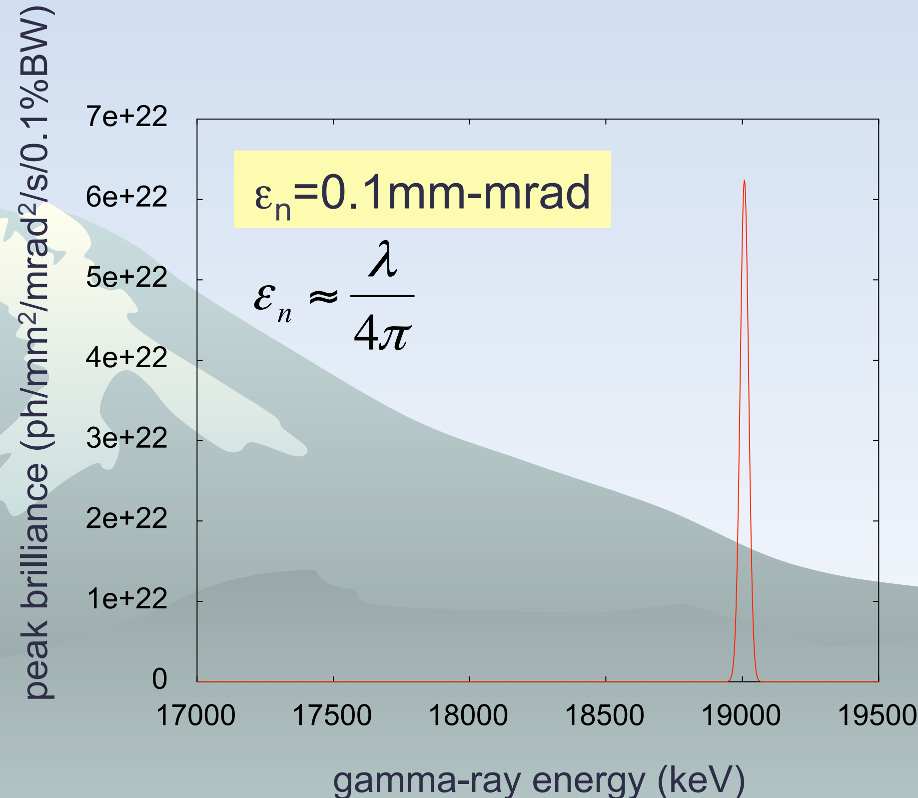
Approximated formula in the case of head on collision.

- monochromatic
- tunable energy
- cone beam
- short pulse

Low emittance → improvement of monochromatic γ beam

Calculation in the case of 1-GeV ERL





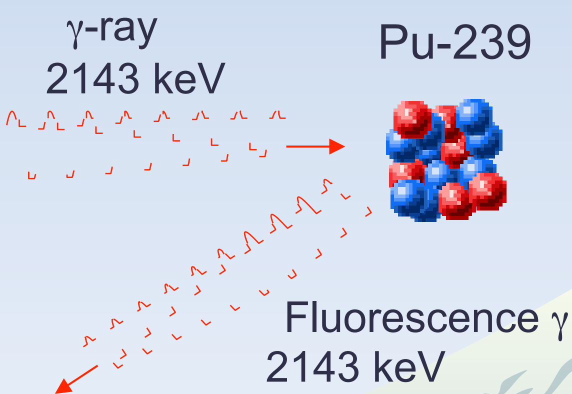
$$\hat{B}_x = \frac{4\times 10^{-15}}{\pi^2}\frac{\gamma_0^2}{\varepsilon^2}\frac{N_e N_\lambda}{\Delta\tau}\frac{r_0^2}{w_0^2}\exp\left\{\frac{\chi-1}{2\chi\Delta u_\perp^2}\left[2+\frac{\delta\omega^2+\delta\gamma^2\chi^2}{2\chi(\chi-1)\Delta u_\perp^2}\right]\right\}\left[1-\Phi\left\{\frac{\chi-1}{\sqrt{\delta\omega^2+\delta\gamma^2\chi^2}}\left[1+\frac{\delta\omega^2+\delta\gamma^2\chi^2}{2\chi(\chi-1)\Delta u_\perp^2}\right]\right\}\right]$$
$$\times\frac{\eta e^{1/\mu^2}[\Phi(1/\eta)-1]-\mu e^{1/\mu^2}[\Phi(1/\mu)-1]}{\mu^2-\eta^2}, \quad (50)$$

calculation by using a formula in [1].

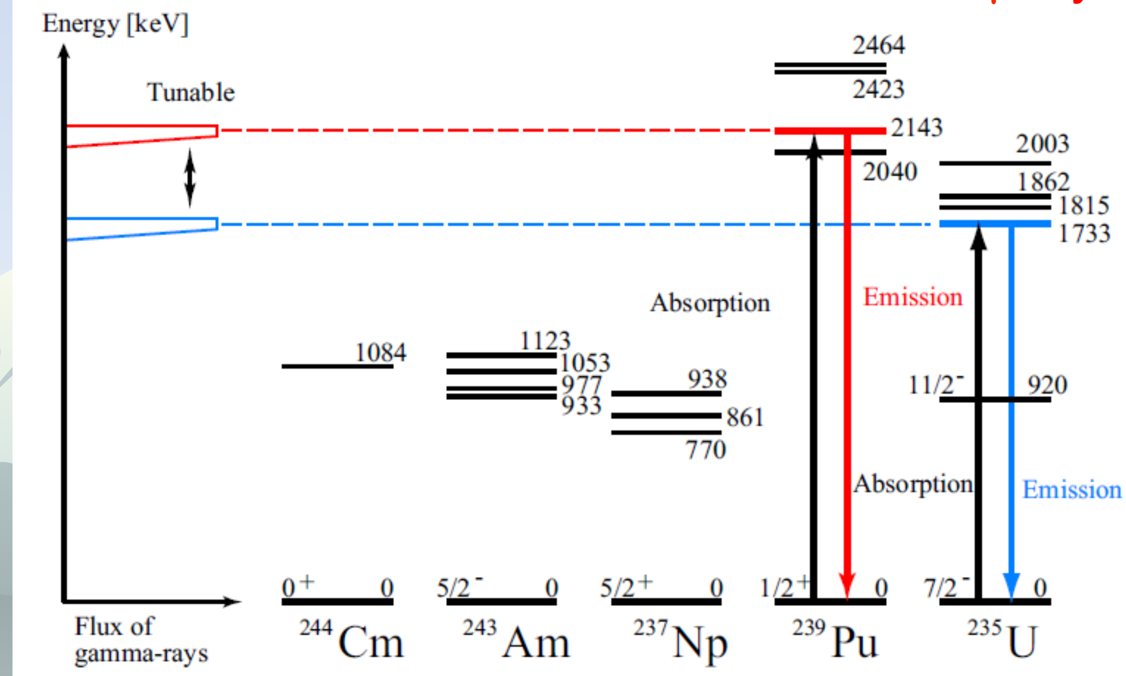
[1] F.V. Hartemann et at. Phys. Rev. ST AB 8, 100702 (2005).

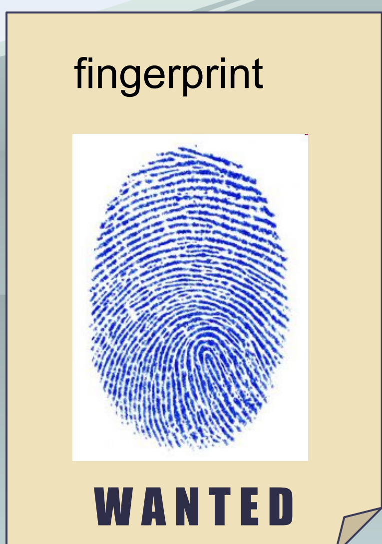
Nuclear Physics using NRF

(**N**uclear **R**esonance **F**luorescence)



NRF based on monochromatic γ-ray





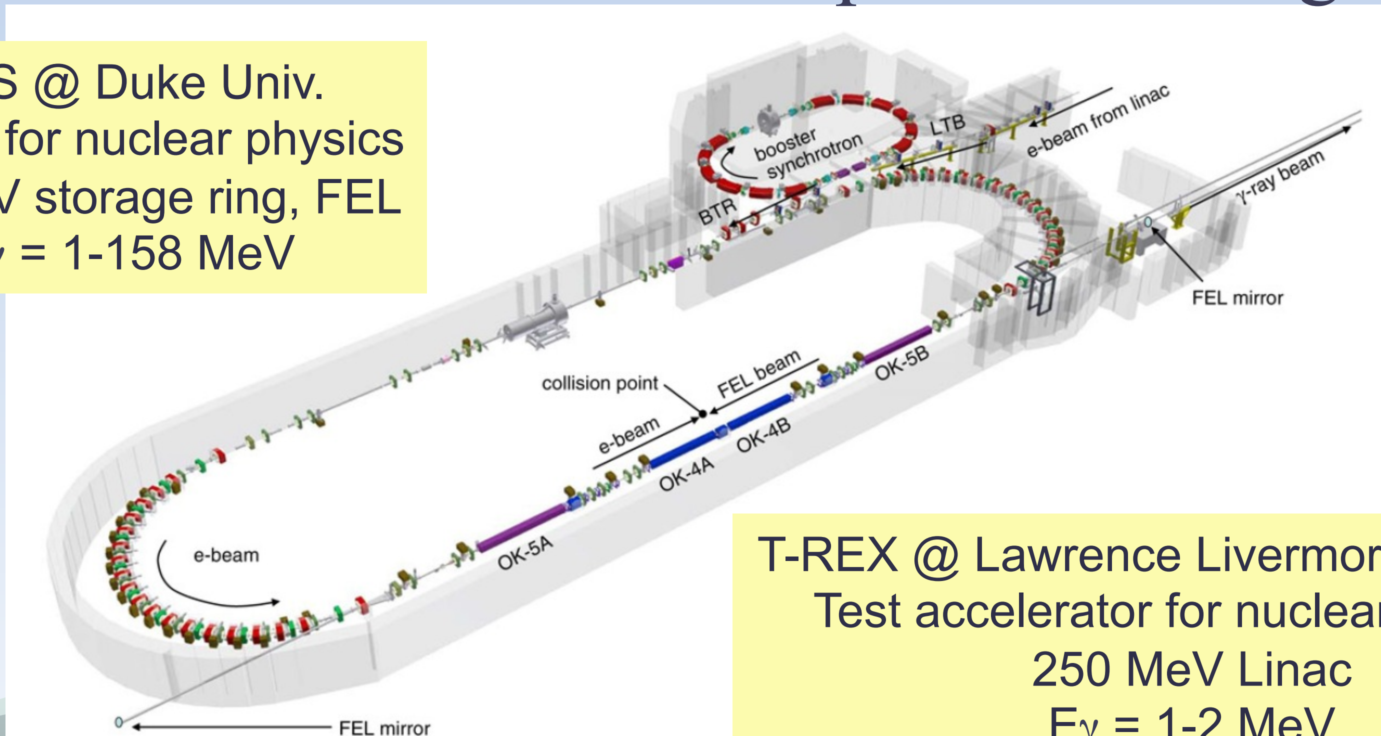
Tunable energy

Monochromatic γ beam ⇒ **Selective Nuclear reaction**

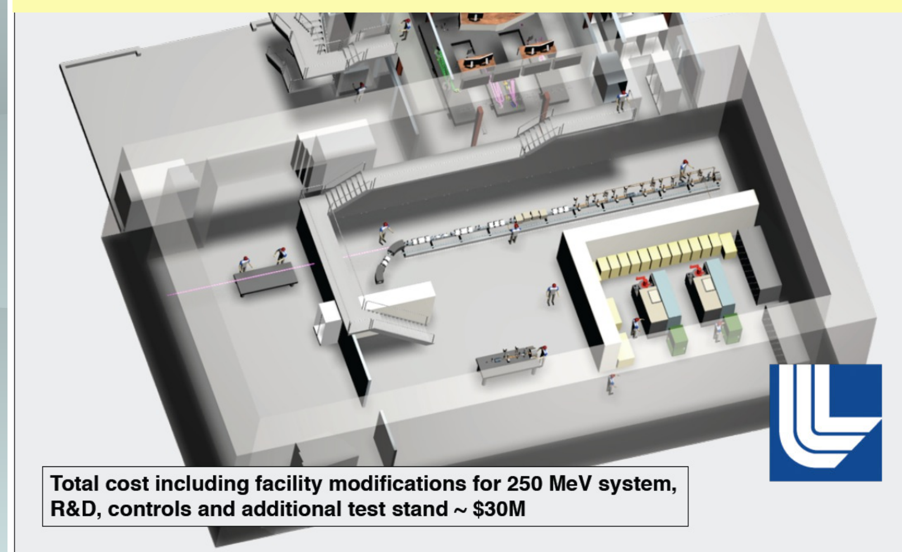
R. Hajima, T. Hayakawa, N. Kikuzawa, E. Minehara, J. Nucl. Sci. Tech. 45, 441 (2008).

γ source based on laser Compton scattering in USA

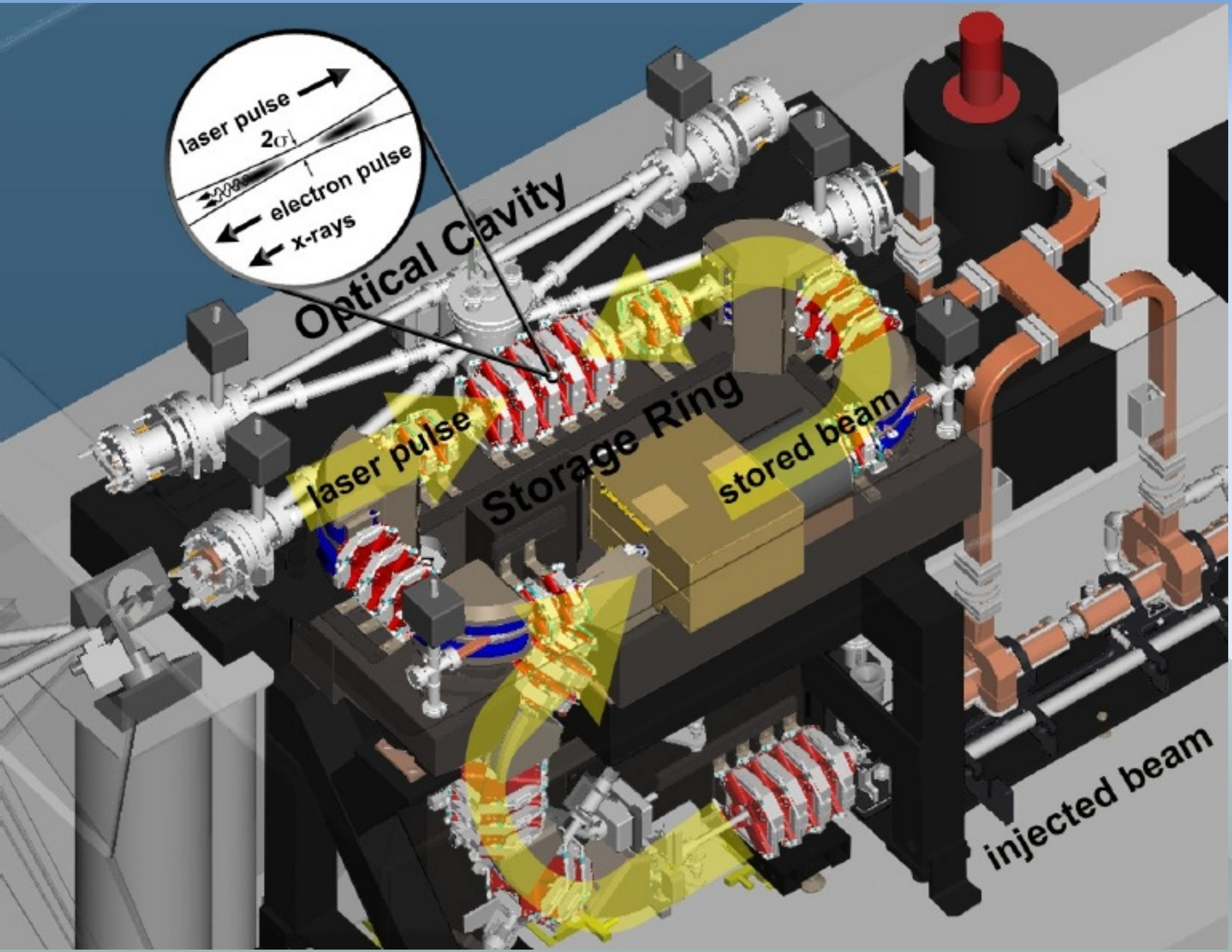
HIγS @ Duke Univ.
Facility for nuclear physics
1.2 GeV storage ring, FEL
Eγ = 1-158 MeV



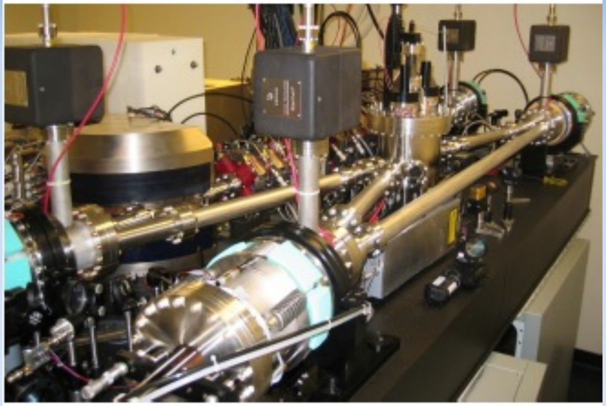
T-REX @ Lawrence Livermore Natl. Lab.
Test accelerator for nuclear security
250 MeV Linac
Eγ = 1-2 MeV

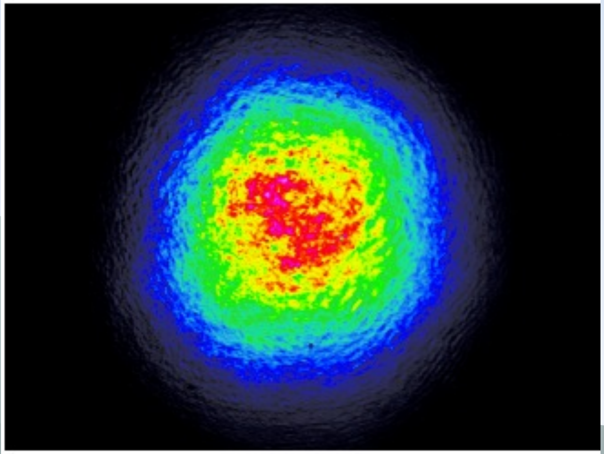


In our country, TERAS, New-SUBARU and UVSOR –II are generating γ beam.
Nuclear physics, Astrophysics, X-ray and γ-ray Computerized Tomography,
Non-destructive measurement of radioactive isotope using NRF,
Non-destructive measurement for chemical materials under cover using 2 color γ-ray,
and so on.



IR Storage Cavity





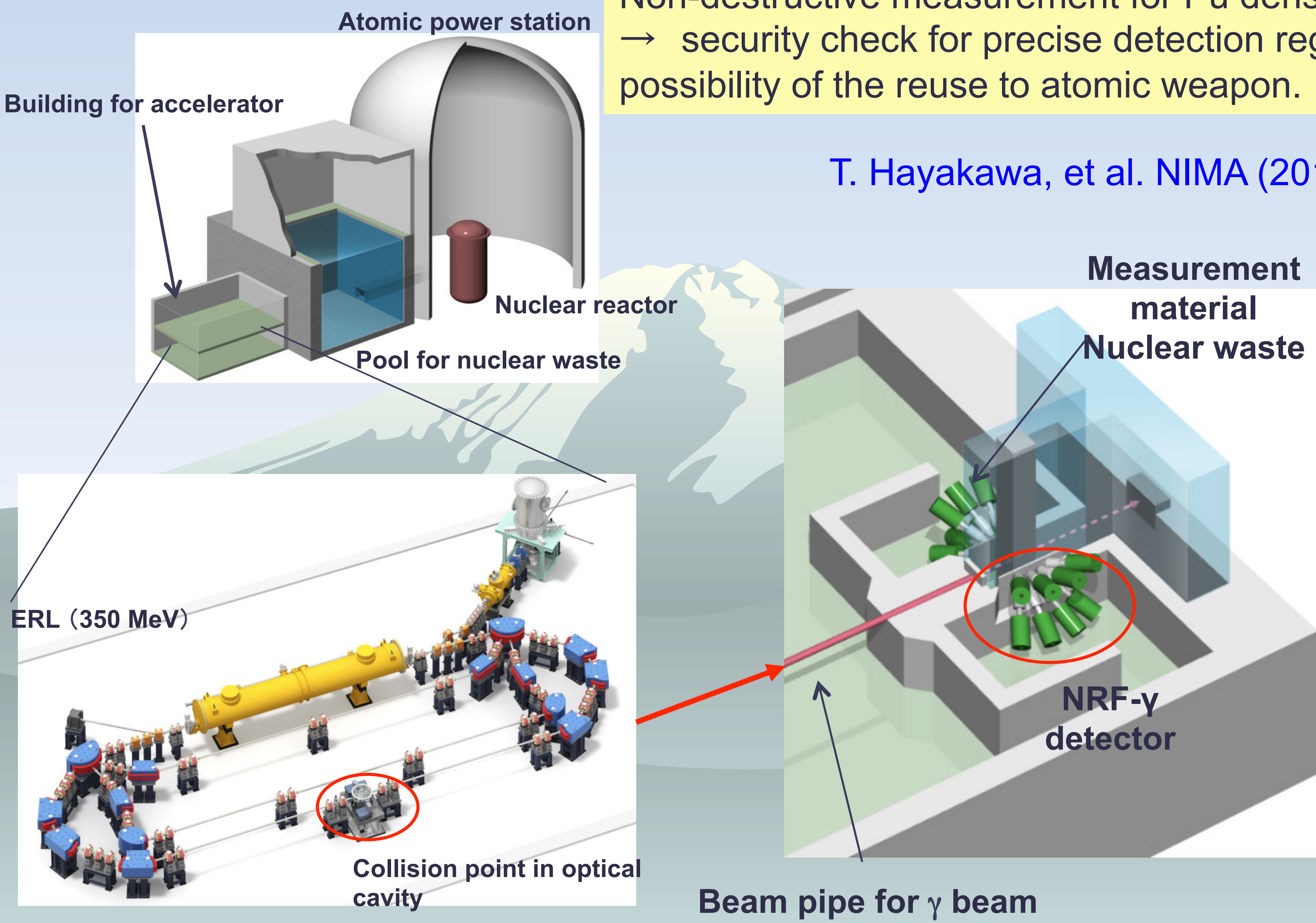
Stored IR Pulse

Pulsed laser beam
1. 25ps pulses & gain ~4000, waist size~60µm (Lyncean Techn., Inc.)
2. 7ps @357MHz (Compton x-ray generation), R&D in progress
Total gain ~70000 with burst mode (cavity gain ~600),
Waist size ~50µm (KEK-ATF-LUCX)

Proposal for nuclear secured facility

Non-destructive measurement for Pu density
→ security check for precise detection regarding possibility of the reuse to atomic weapon.

T. Hayakawa, et al. NIMA (2010).



High reflective mirror development

We made the contract to manufacture 99.999% reflective mirrors with LMA in Lion France. We requested the transmissivity more 2ppm. It means the scattering and absorptive loss are less than ~6ppm.

We bought many mirror substrates from American companies, 1 inch, 2 inch and special sized mirror with sub-A micro-roughness.

In last Feb. 2013, we made the coating at LMA. Before this, we used order-made mirrors from Japanese company ,which has about (99.99+0.005) % with the transmissivity more than 8ppm.

LIGO developed big mirror with loss under 1ppm many years ago.

We have a plan of the development of thin thickness of concave mirror to realize X-ray high transmission.

Development for stronger mirror : We started the collaboration with NAO (Gravitational Wave Observatory group), Tokyo University (Ohtsu Lab.), Japanese private Co., LMA and LAL.

1. Enlarge mirror size : we started the change from one inch to two inch mirror.
2. LMA made mirrors with reflectivity of 99.999% and loss (absorption and scattering) less than 6ppm.
3. We ordered many substrates with micro-roughness less than 1 A to approach low loss mirror.
4. We understood the necessity of good clean room to handle the high reflective mirrors in the case of the mirror which has high reflectivity more than 99.99%.
5. We have to develop how to make the stronger surface which has higher damage threshold.

Measurement of surface roughness for super-polish. Reduce the loss ,which means low absorption and scattering.

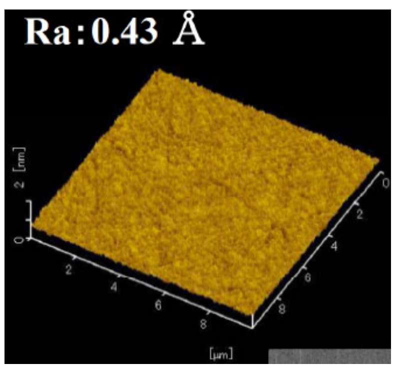
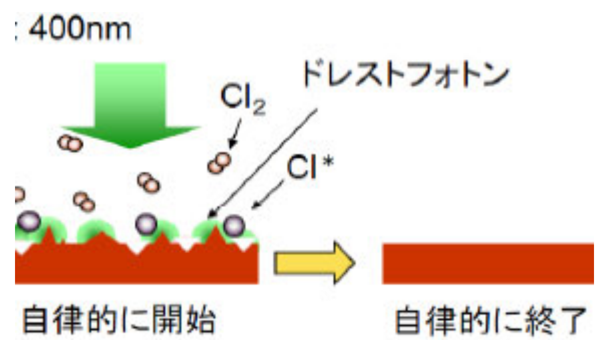


Photo-chemical etching occurred by dressed photon.

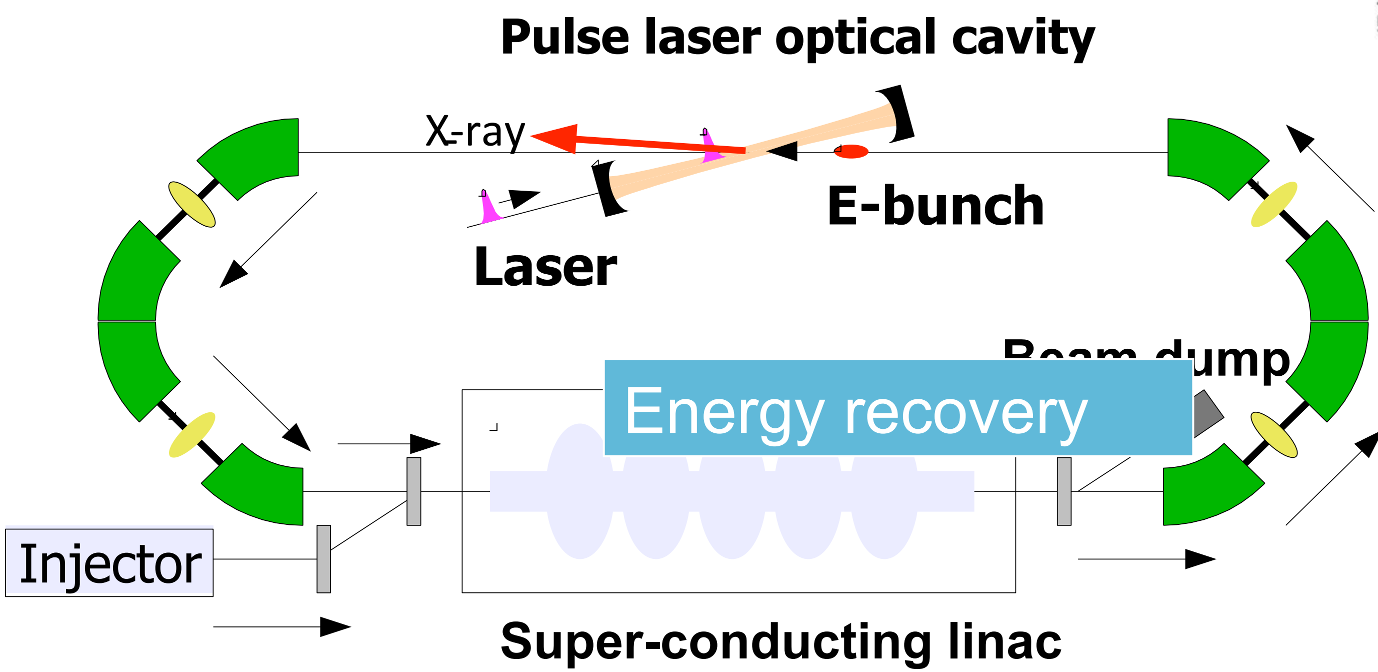


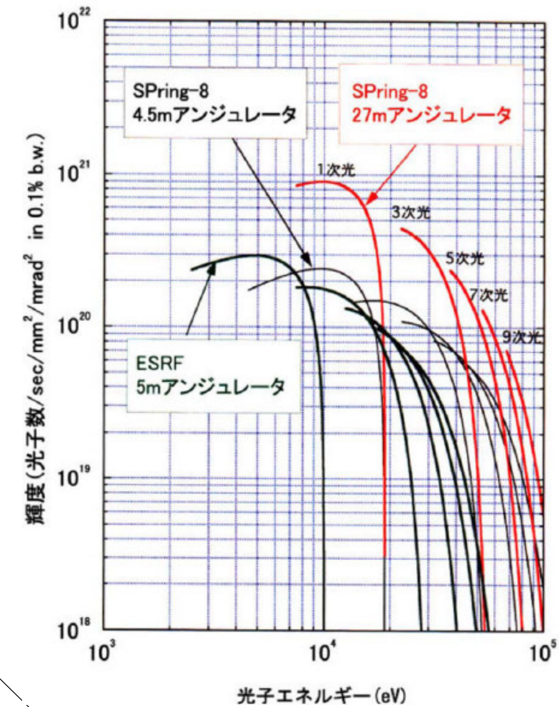
We learnt a lot of things which humidity in Japan is high and makes OH contamination to increase the mirror absorption. 50% humidity is suitable to handle the mirrors, especially high quality mirrors. We confirmed this problem.

7. Future plans and schedule

High brightness X-ray generation at c-ERL
as a demonstration through beam experiment

End of 2014: high brightness X-ray generation experiment at cERL.





SPring-8
World highest
Av. Brightness 10^{21}
Photons/sec/mm²/mrad² in 0.1%b.w.
from 27m undulator at SPring8

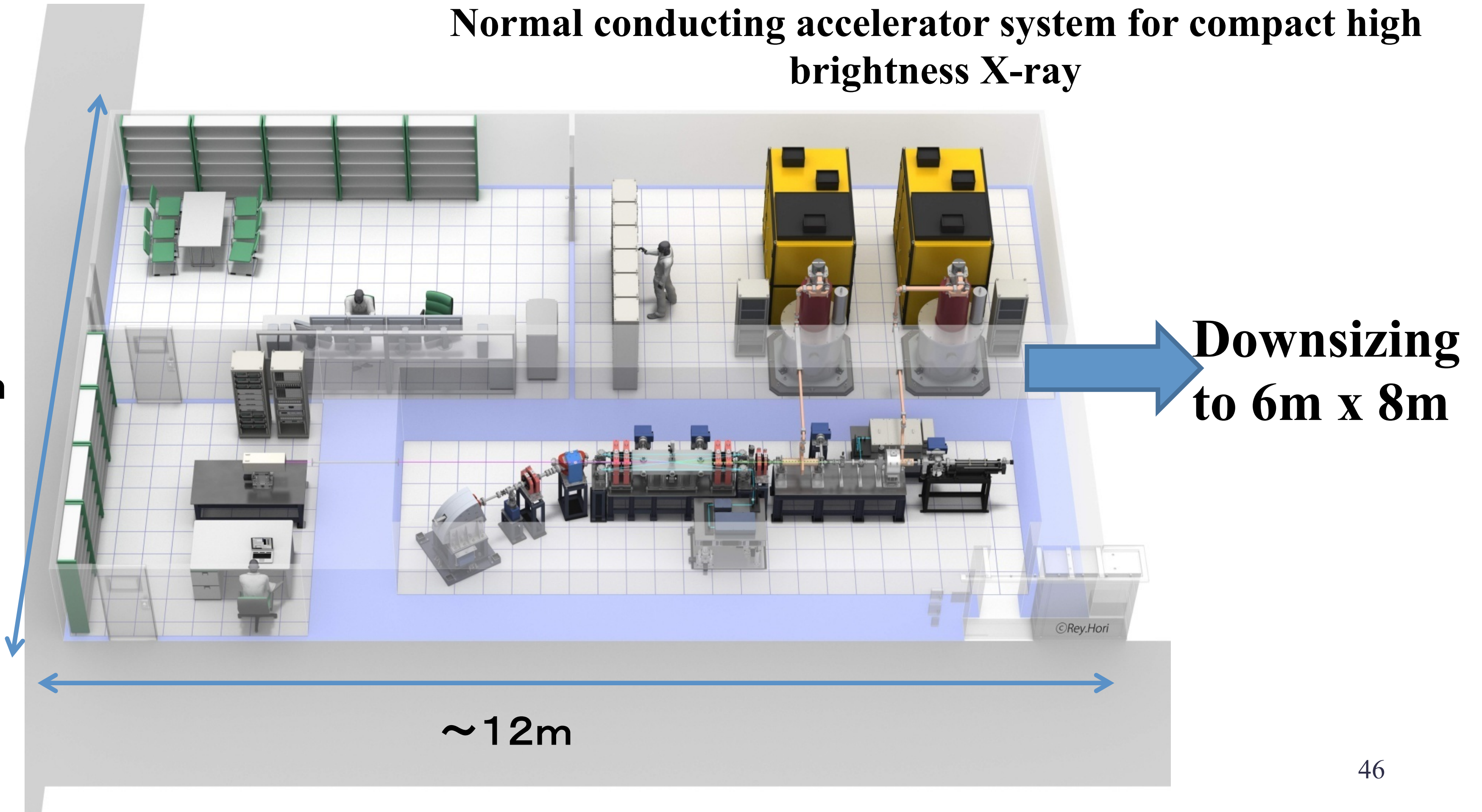
Realize the Brightness 10^{19} Photons/sec/mm²/mrad² in 0.1%b.w. **10^{13} photons/(sec･1%b.w.)**

35MeV electron beam x 1μm laser = 23keV X-ray

New Quantum Beam Technology Program(NQBTP) is supported by MEXT from 2013.8 to 2018.3 (~5 years project).

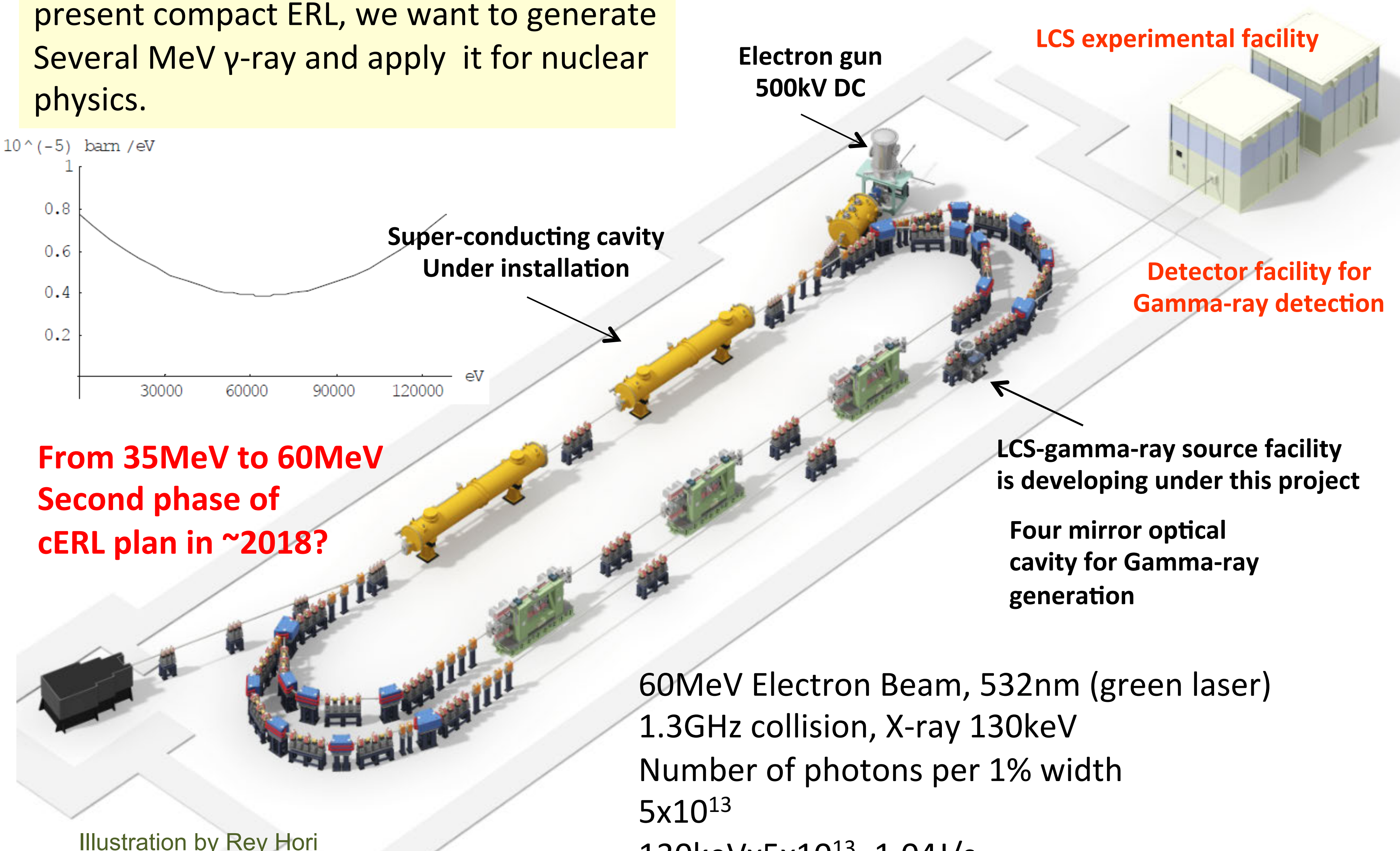
Approved project included two Japanese Companies at least and the development for CW super conducting acceleration technologies. Normal conducting accelerator system and super conducting accelerator system for compact high brightness X-ray source should be realized by joint research with companies.

Normal conducting accelerator system for compact high brightness X-ray



Proof-of principle experiment at compact ERL facility

After add super conduction cavities into present compact ERL, we want to generate Several MeV γ-ray and apply it for nuclear physics.



From 35MeV to 60MeV
Second phase of
cERL plan in ~2018?

Illustration by Rey Hori

60MeV Electron Beam, 532nm (green laser)
1.3GHz collision, X-ray 130keV
Number of photons per 1% width
5×10^{13}
$130\text{keV}\times5\times10^{13}=1.04\text{J/s}$
330 kGy (X-ray size 0.2mm diameter)

Please enjoy the discussion about these important issues.

Thank you for your participation!