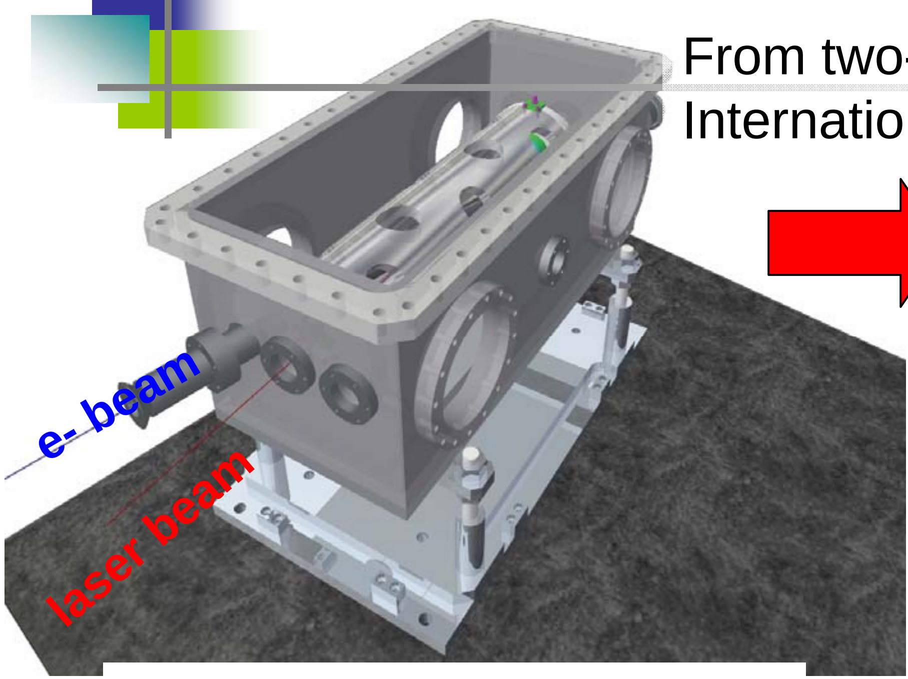
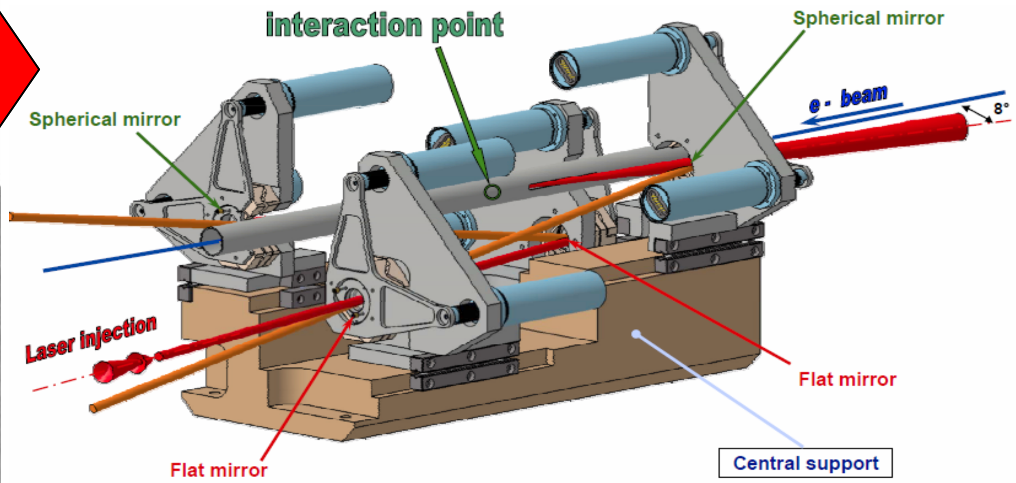
Laser Super-cavity

kek, Junji Urakawa

From two-mirror cavity to four-mirror cavity under International collaboration with LAL.



0.12 mJ / pulse, waist = 60 μm



50 mJ / pulse, waist = 10 μm

1. Short review of pulsed laser stacking
2. Mirror alignment tolerance
3. Resonance condition of a 4-mirror cavity
4. Mirror damage which is caused by peak power density on the mirror.
5. Summary

1. Short review of pulsed laser stacking

Continuous laser beam

1. JLab (CEBAF/polarimeter – gain ~10^4
   Falleto et al. (NIMA459(2001)412)
2. HERA/polarimeter – gain ~10^4
3. KEK-ATF/laser wire – gain ~1000, waist ~5μm

Pulsed laser beam

1. 25ps pulses & gain ~4000, waist ~60μm (Lyncean Techn., Inc.)
2. 7ps @357MHz (Compton x-ray generation), R&D in progress

Total gain ~12000 with burst mode (cavity gain ~600), waist ~30μm (KEK-ATF)

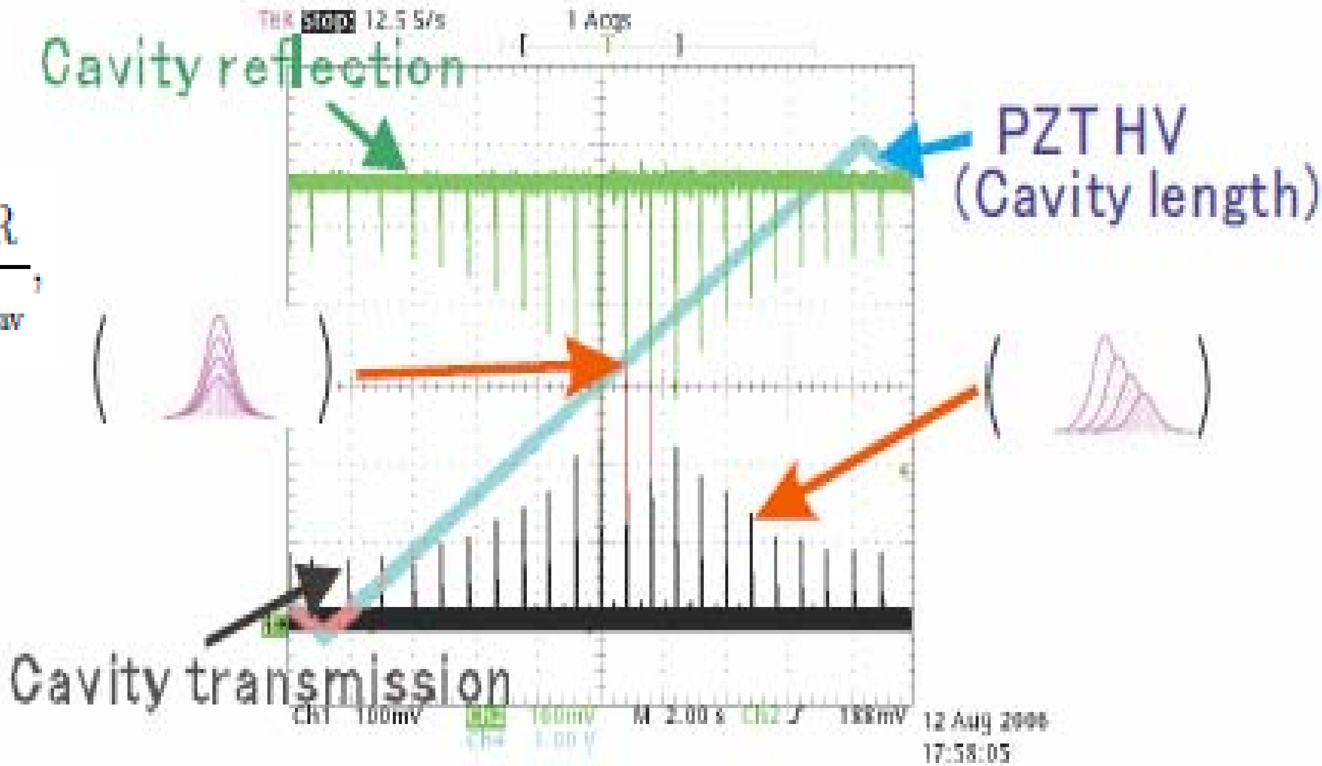
Considering two-mirror cavity,
reflectance R, transmissivity T, and losses L where R+T+L = 1 by energy conservation.
The “bounce number” *b* which is defined from the round-trip power loss in a cavity, $\propto e^{-1/b}$. FSR : free spectral range

$$b = \frac{1}{T_1 + L_1 + T_2 + L_2},$$

$$\mathcal{F} \equiv \frac{\pi \sqrt[4]{R_1 R_2}}{1 - \sqrt{R_1 R_2}} \simeq 2\pi b \simeq \frac{FSR}{\Delta\nu_{cav}},$$

If $R=R_1=R_2$

$$G = \frac{F}{\pi} = \frac{\sqrt{R}}{1-R}$$



Storage of laser pulse

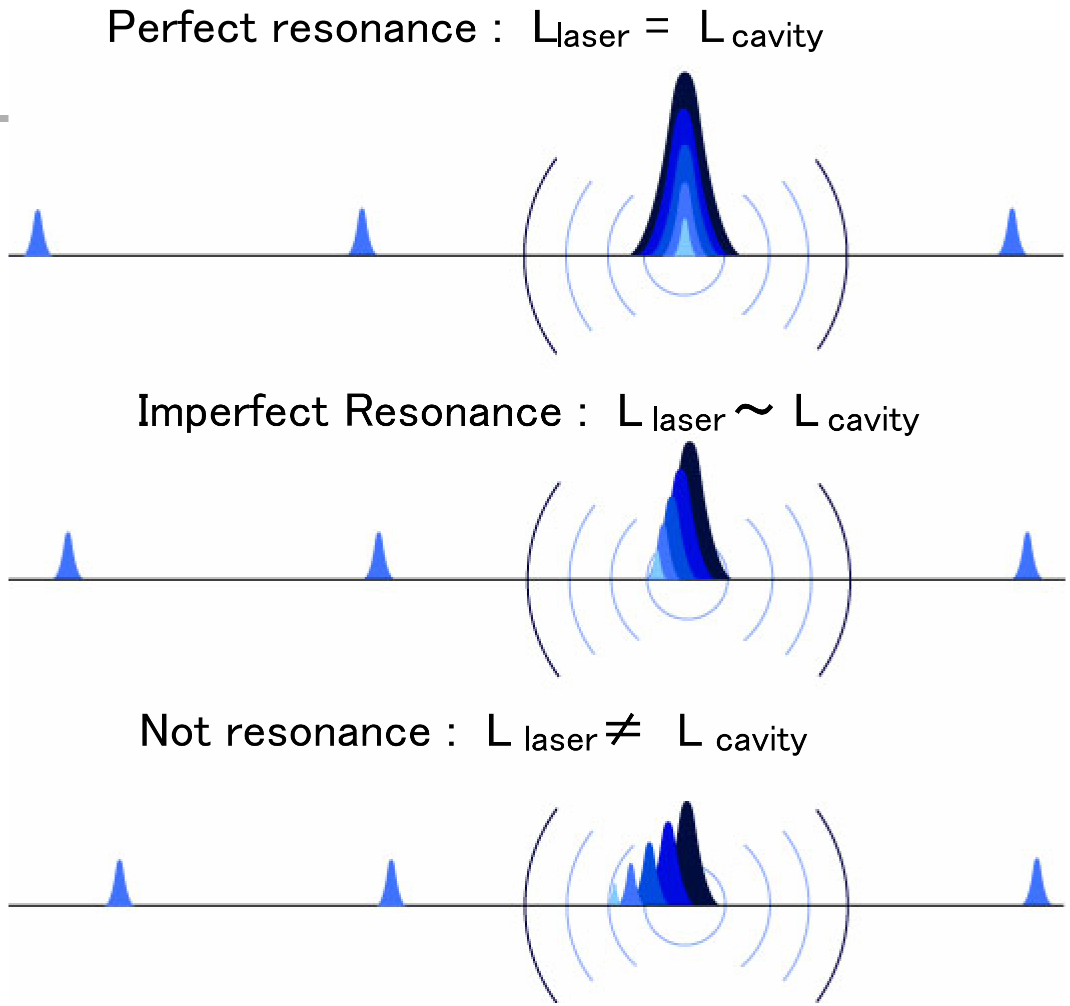
Resonance condition :

The relationship with laser and cavity :

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

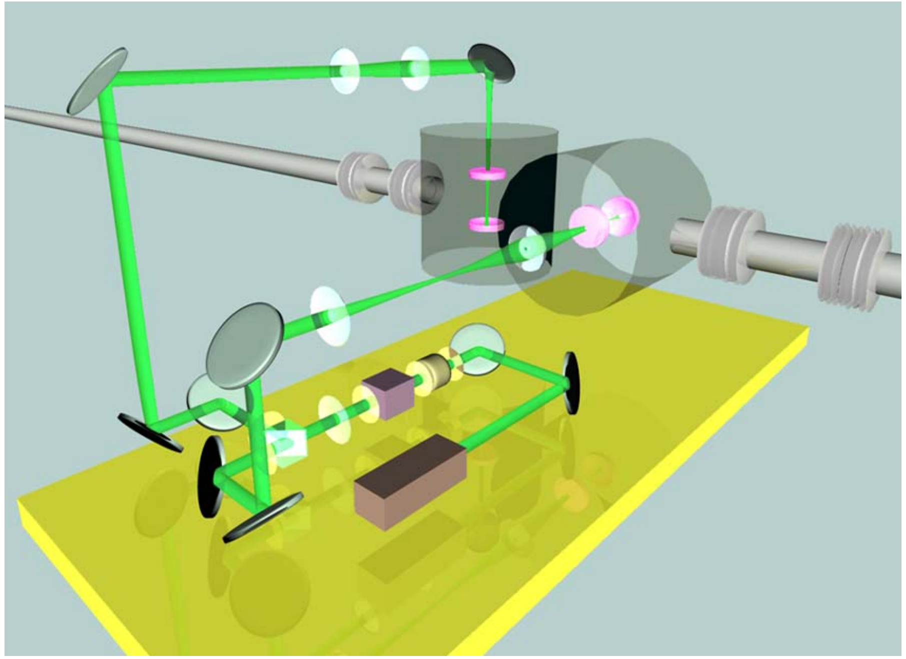
$$\Delta l = L_{laser} - L_{cav}, \quad \Delta l = 0 .$$

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

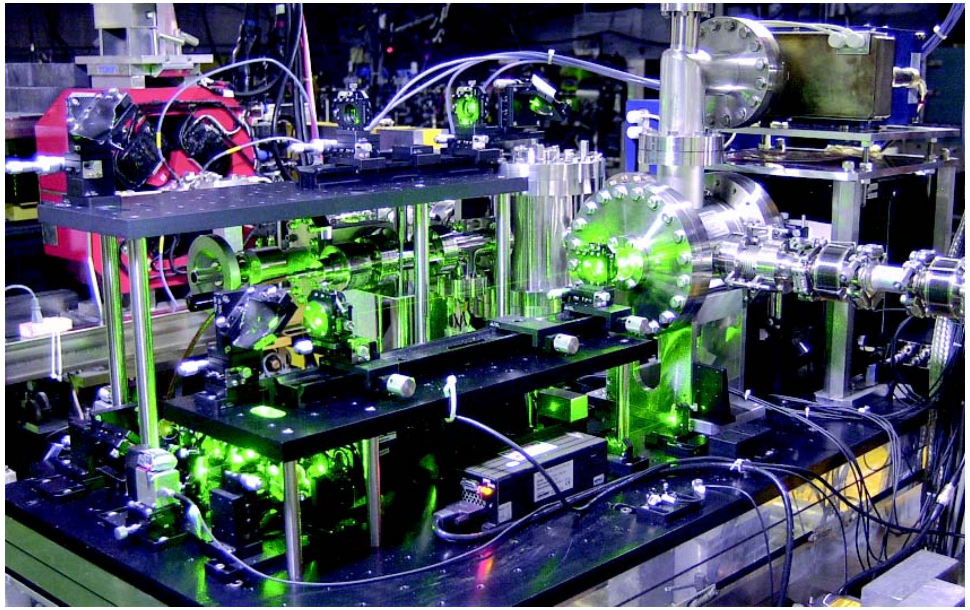


JFY2003

CW Laser wire beam size monitor in DR

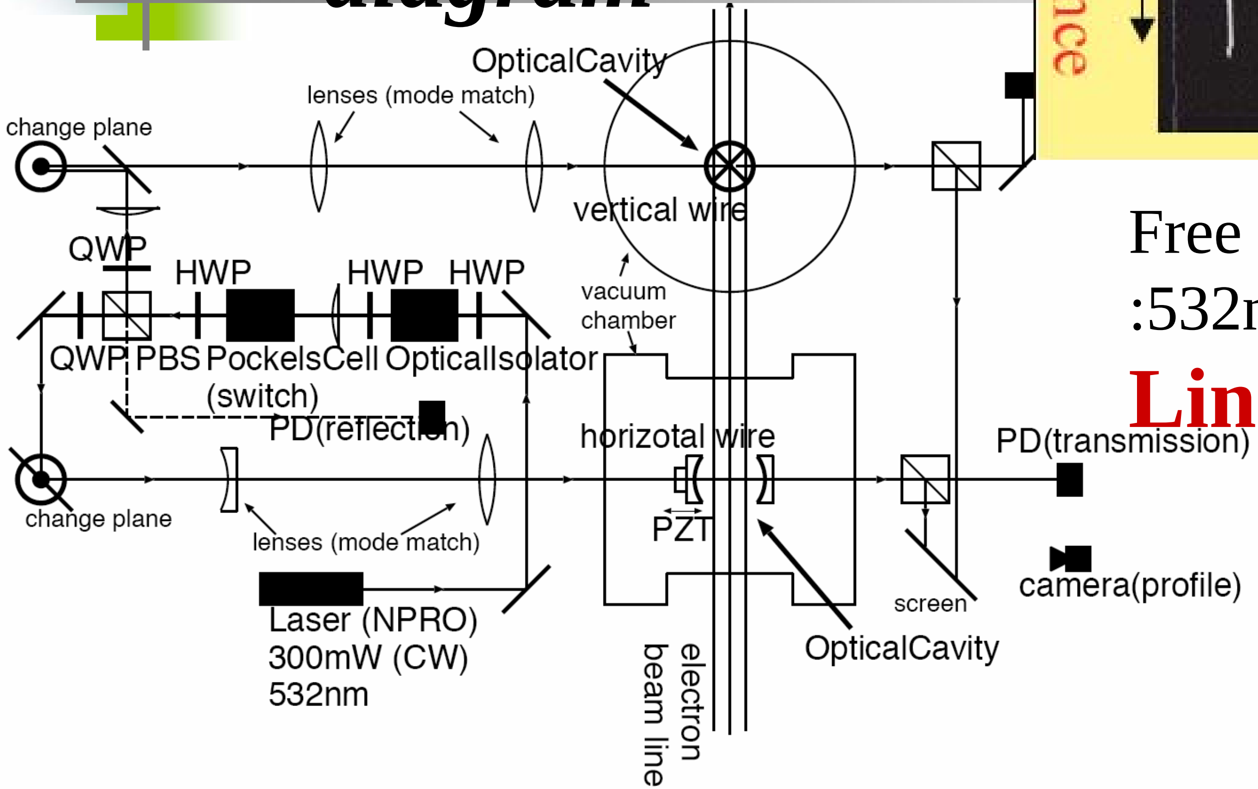


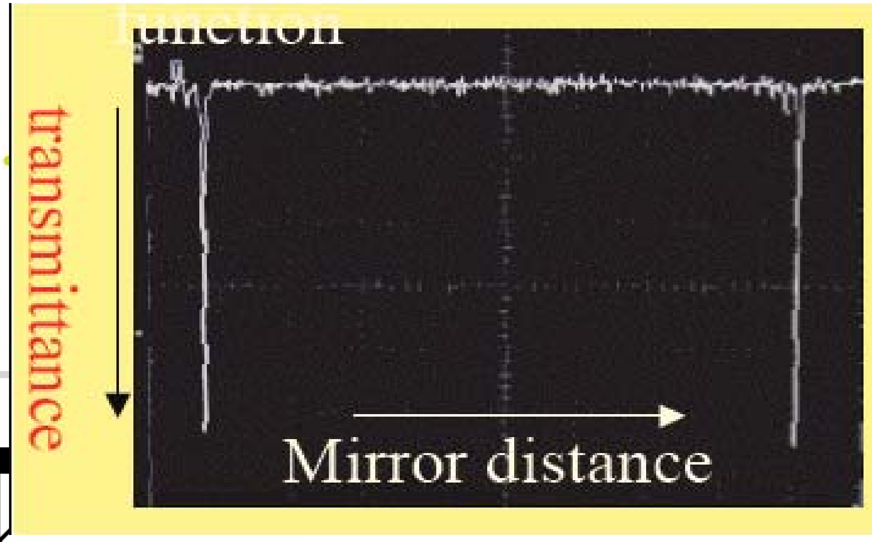
300mW 532nm Solid-state Laser fed into optical cavity



14.7μm laser wire for X scan
5.7μm for Y scan
(whole scan: 15min for X, 6min for Y)

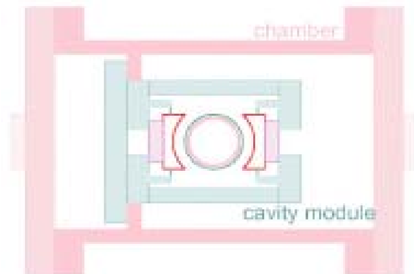
Laser wire block diagram



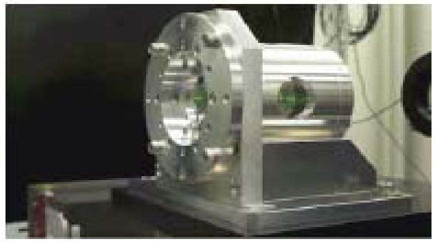


Free spectral range
:532nm/2=266nm

Line width=0.3nm



optical cavity resonance is kept by piezo actuator



Experimental results（Pulse Laser Storage）

Laser:

Mode Lock: Passive
SESAM

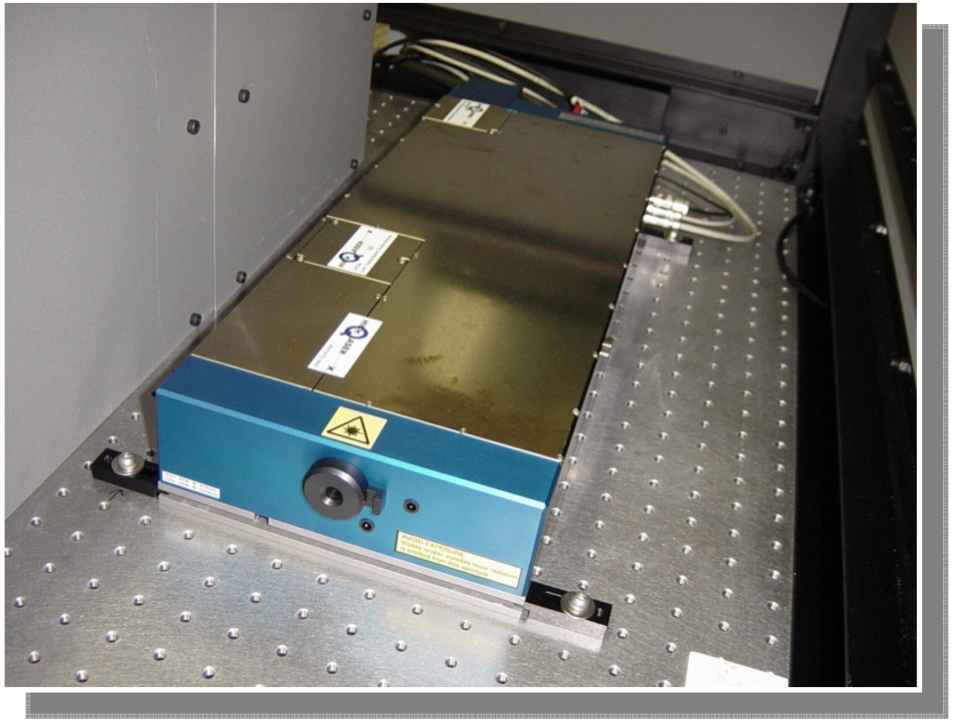
Frequency: 357MHz

Cavity length: 0.42 m

Pulse width: 7.3 p sec (FWHM)

Wave Length: 1064 nm

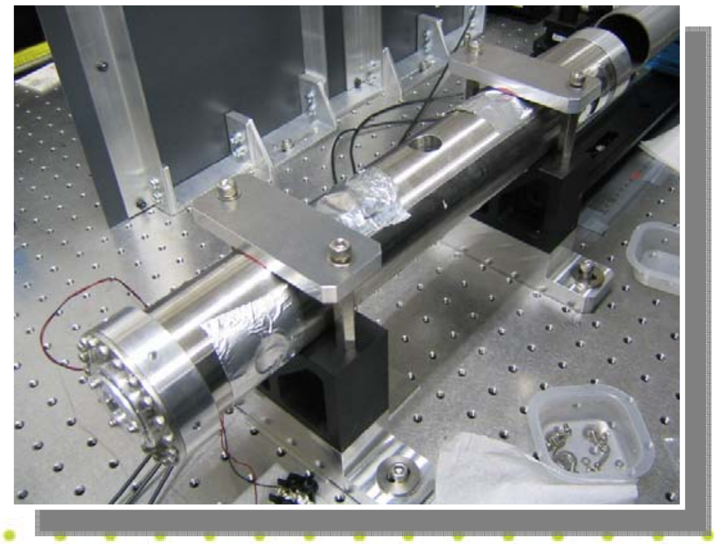
Power: ~ 6W



SESAM: SEmi-conductor Saturable Absorber Mirrors

Ext. Cavity:

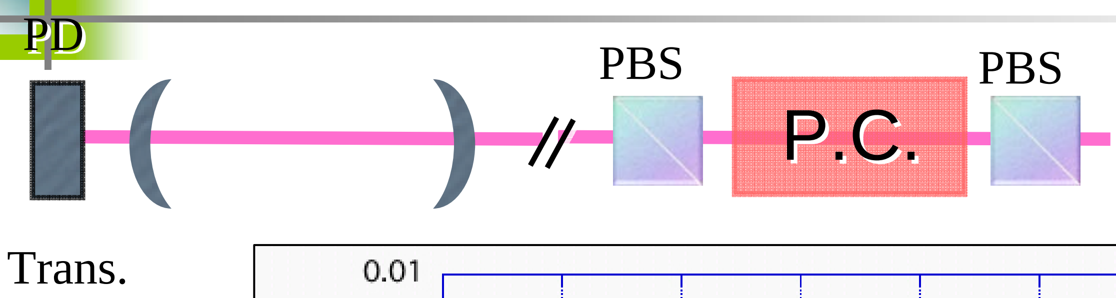
Cavity:	Super Invar
Cavity length:	420mm
Mirrors:	
Reflectivity:	99.9%, 99.9% (maybe, 99.98%)
Curvature:	250 mm ($\omega_0 = 180\,\mu$m)

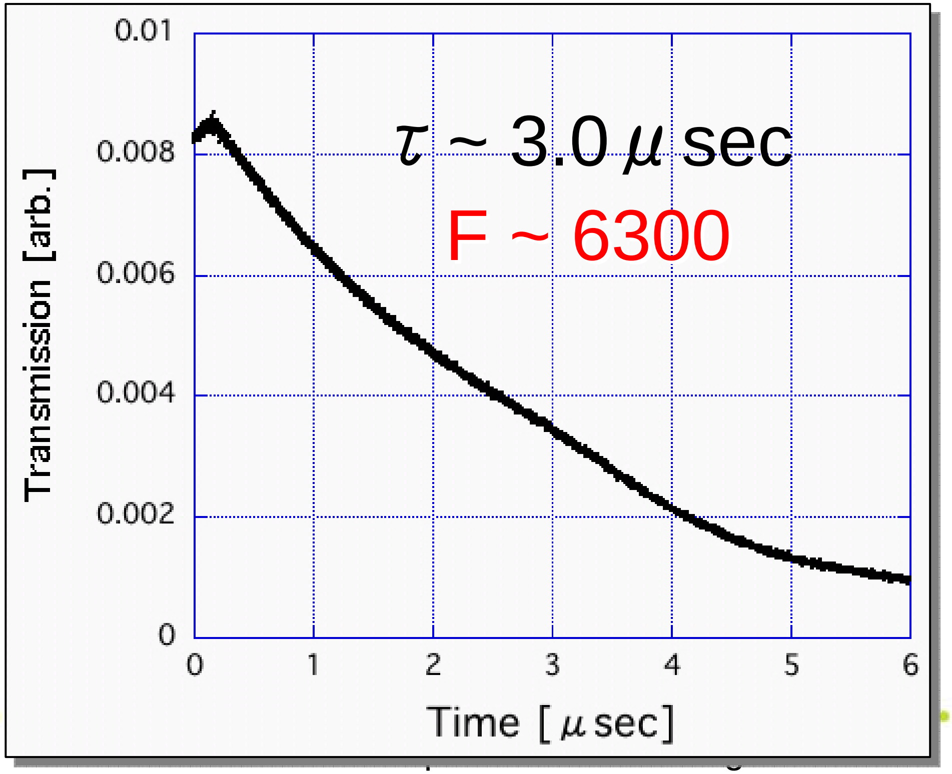


・Finesse: R = 99.98%

$$Finesse = \pi \tau c/l$$

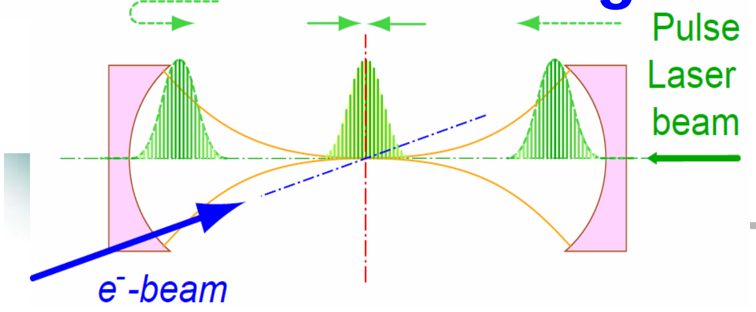
τ :decay time
c: light verocity
l: cavity length





JFY 2004

γ-ray Generation with Laser Pulse Stacking Cavity (Hiroshima-Waseda-IHEP-KEK)



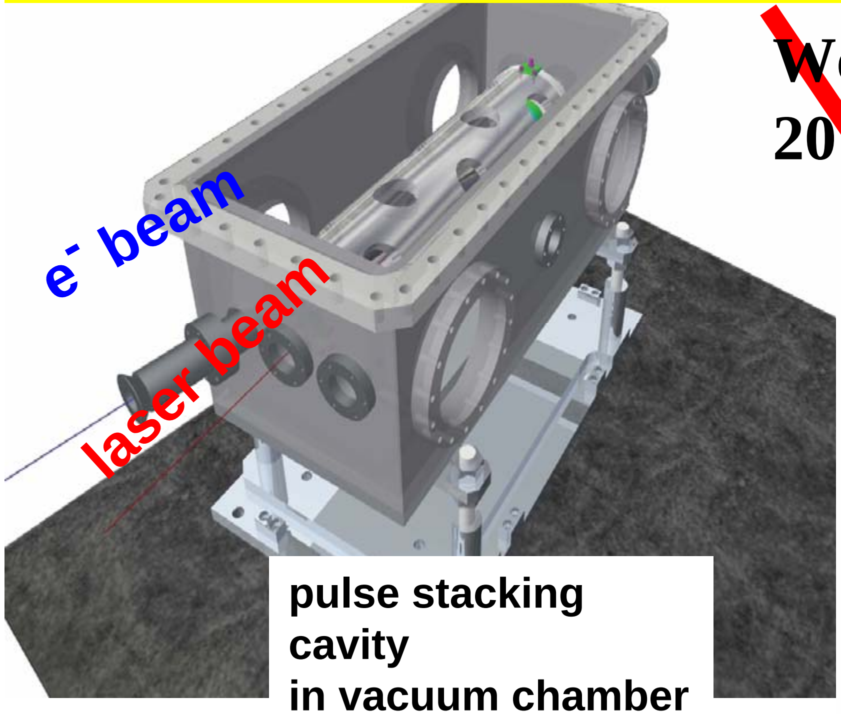
Stack power estimate

date	Finesse	electron	transmitted power	incident power	reflected power	input power	λ	stack power estimate[W]		
		1/pulse	W	W	W	W		by transmi	by input	by cain
8/3/14	200	?		6.2	6	0.2	1.1	-	13	-
8/4/10	218	2.9E+10	0.325	5.3	4.5	0.8	2.5	81	56	42
8/4/15	110	1.5E+10	0.119	5.3	5	0.3	2	30	11	66
8/4/22	486	2.2E+10	1.69	5.3	2.5	2.8	3	423	433	67
	486	2.3E+10	1.64	5.3	2.51	2.79	3	410	432	64
	486	2.6E+10	1.55	5.3	2.55	2.75	3.1	388	425	59

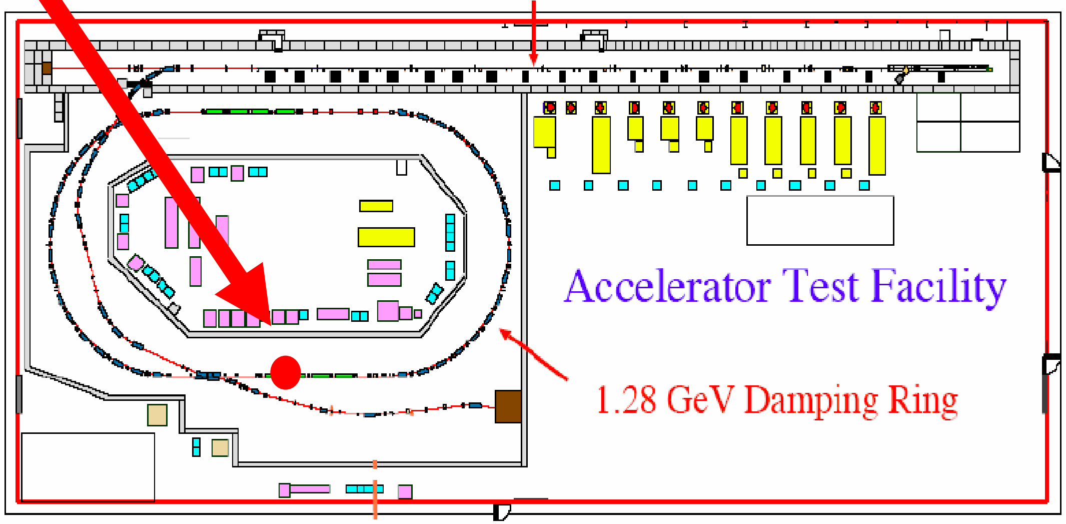
by transmitted power ~ 400W
by reflected power ~430W
by cain with λ=3 ~ 60W

1.Achieve high enhancement & small spot size
2.Establish feedback technology
3.Achieve small crossing angle
4.Get experience with e⁻ beam

We should detect 20 γ's/collision.

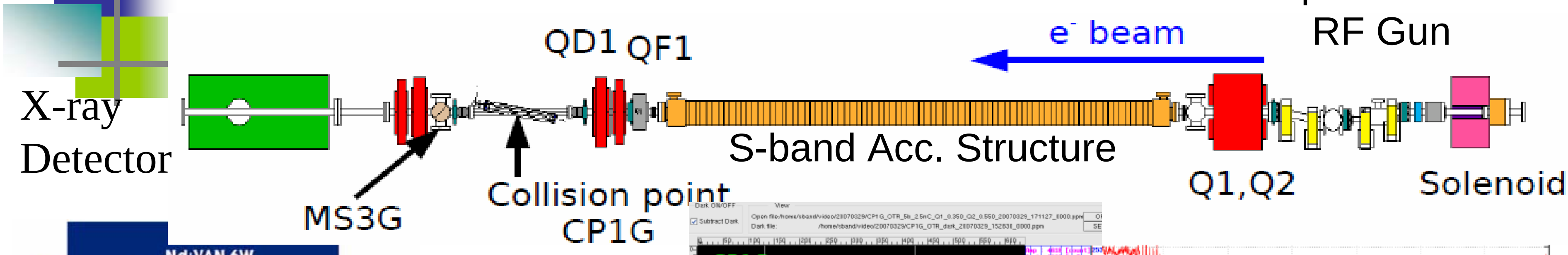


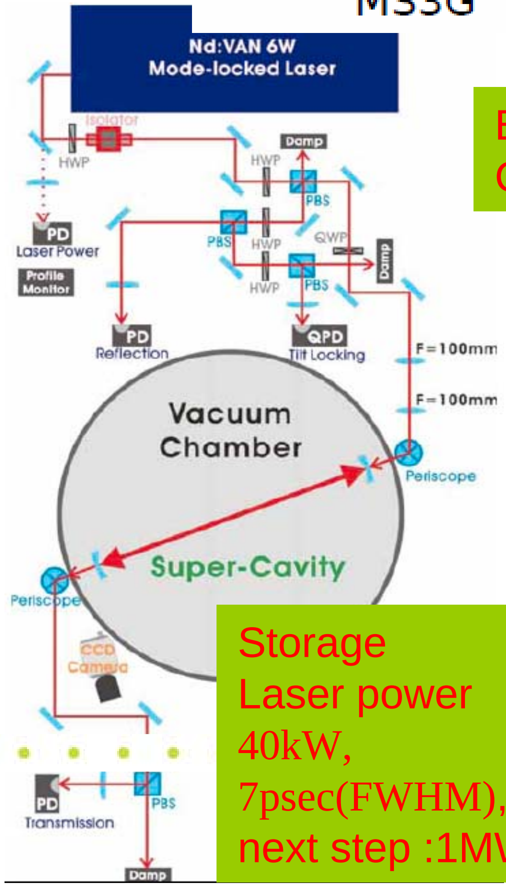
pulse stacking cavity in vacuum chamber



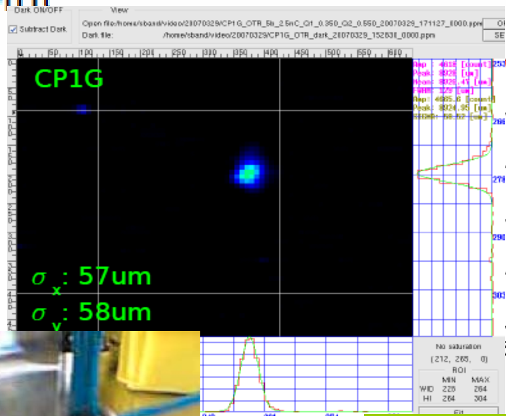
Laser Undulator Compact X-ray (LUCX) Project at KEK-ATF

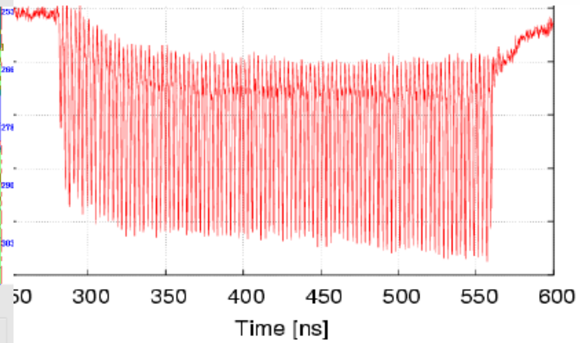
43MeV Multi-bunch beam+ Super-Cavity = 33keV X-ray.





Beam size at CP 60μm in σ





Storage Laser power 40kW, 7psec(FWHM), next step :1MW

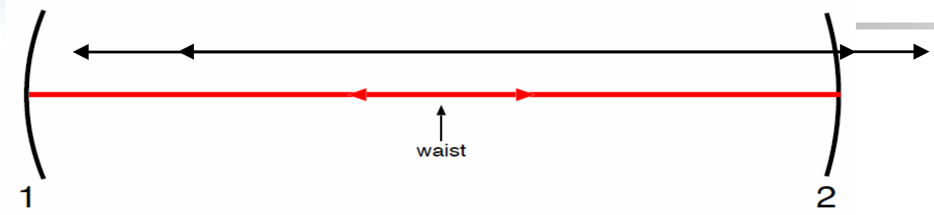
Multi-bunch e- beam 300nC at gun

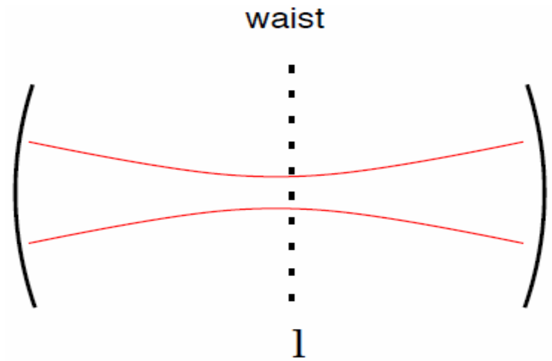
At present, laser waist size is 30μm in σ. We should reduce both beam size at CP down to 30μm.
33keV X-ray generation based on inverse Compton scattering was started from May 2007 with Super-Cavity.

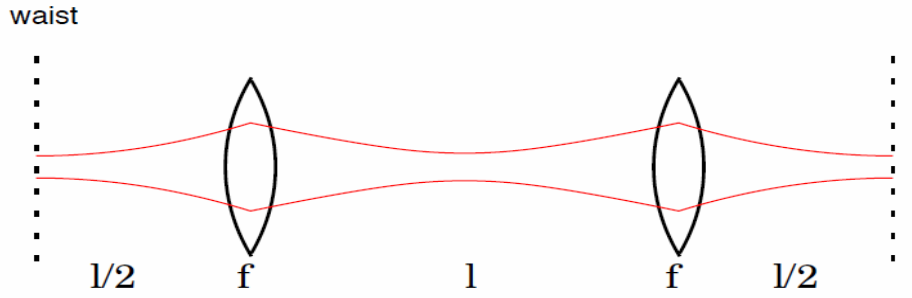
2. Mirror alignment tolerance

2-mirror cavity

R1=R2=L/2 L



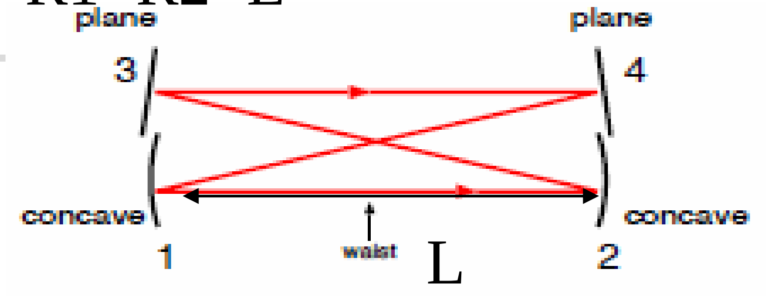


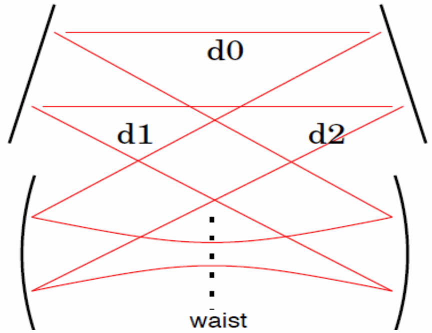


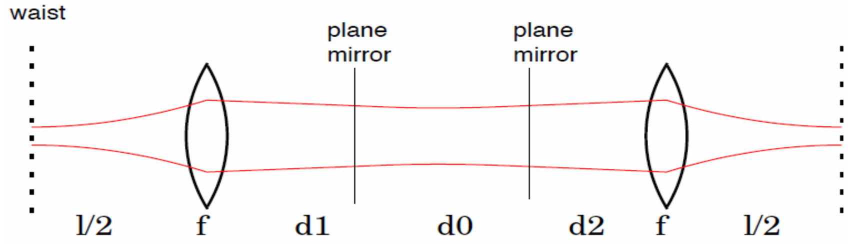
concentric

4-mirror cavity

R1=R2=L







confocal

1. Ignore that laser injection and reflection angle on spherical mirror is not perpendicular (angle between injection and reflection is less than 10 degree. It makes an astigmatism.).

2. Laser wavelength 1064nm, laser waist size 50μm (=two sigma) and assume following table for practical calculation on the tolerance.

	Type of the cavity	Length of one round	Distance between elements
A	Two-mirror	0.21 m	0.105 m
B	Two-mirror	0.42 m	0.21 m
C	Two-mirror	0.84 m	0.42 m
D	Four-mirror ring	0.84 m	0.21 m
E	Four-mirror ring	1.68 m	0.42 m
F	Four-mirror ring	3.36 m	0.84 m

3. Use ABCD-law, TEM_{00} steady-state Gaussian beam formulas of curvature radius of wave front and laser beam waist.

Two-mirror

$$\begin{pmatrix} A & B \\ C & D \end{pmatrix} = \begin{pmatrix} 1 & l/2 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ -1/f & 1 \end{pmatrix} \begin{pmatrix} 1 & l \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ -1/f & 1 \end{pmatrix} \begin{pmatrix} 1 & l/2 \\ 0 & 1 \end{pmatrix}$$

Four-mirror

$$\begin{pmatrix} A & B \\ C & D \end{pmatrix} = \begin{pmatrix} 1 & l/2 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ -1/f & 1 \end{pmatrix} \begin{pmatrix} 1 & d_2 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$$
$$\times \begin{pmatrix} 1 & d_0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & d_1 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ -1/f & 1 \end{pmatrix} \begin{pmatrix} 1 & l/2 \\ 0 & 1 \end{pmatrix}$$

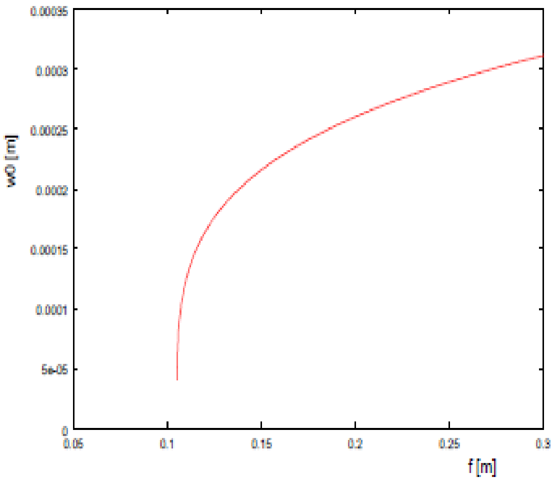
curvature radius of wave front

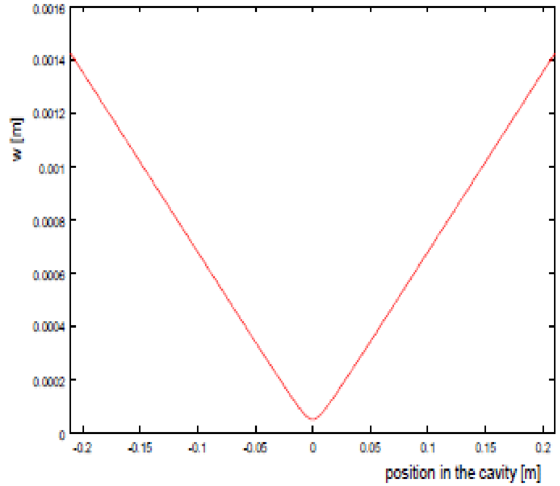
$$R = \frac{2B}{D - A}$$

laser beam waist

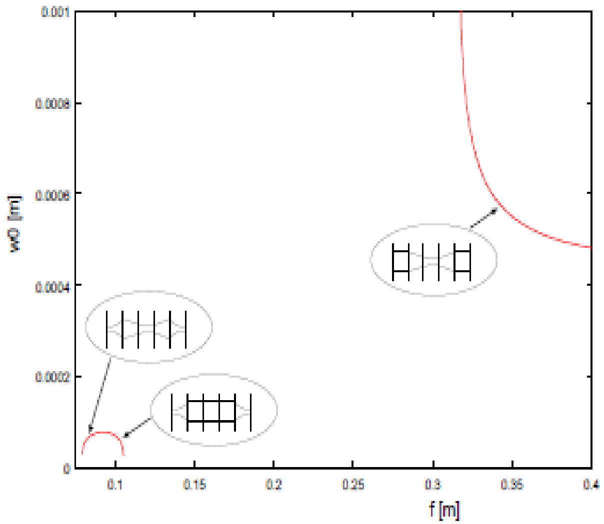
$$\omega^2 = \frac{\lambda}{\pi} \frac{2|B|}{\sqrt{4 - (D + A)^2}}$$

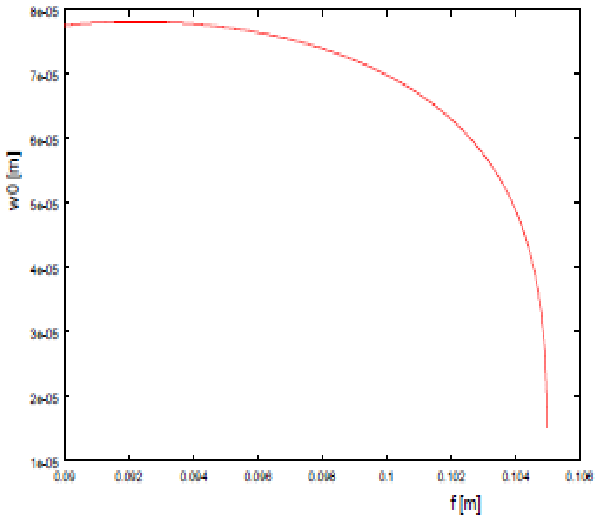
Two-mirror

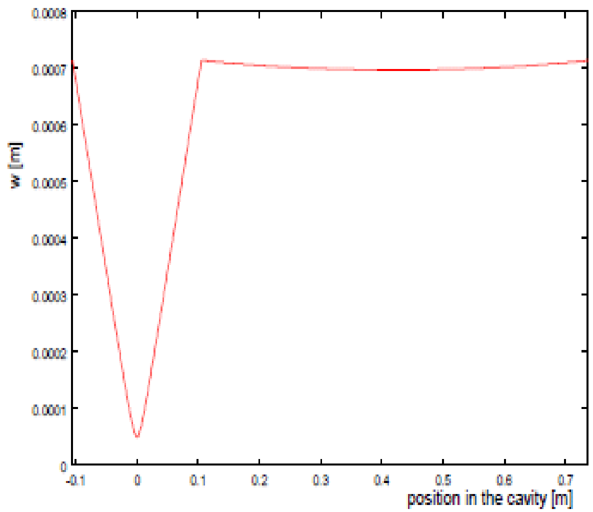




Four-mirror



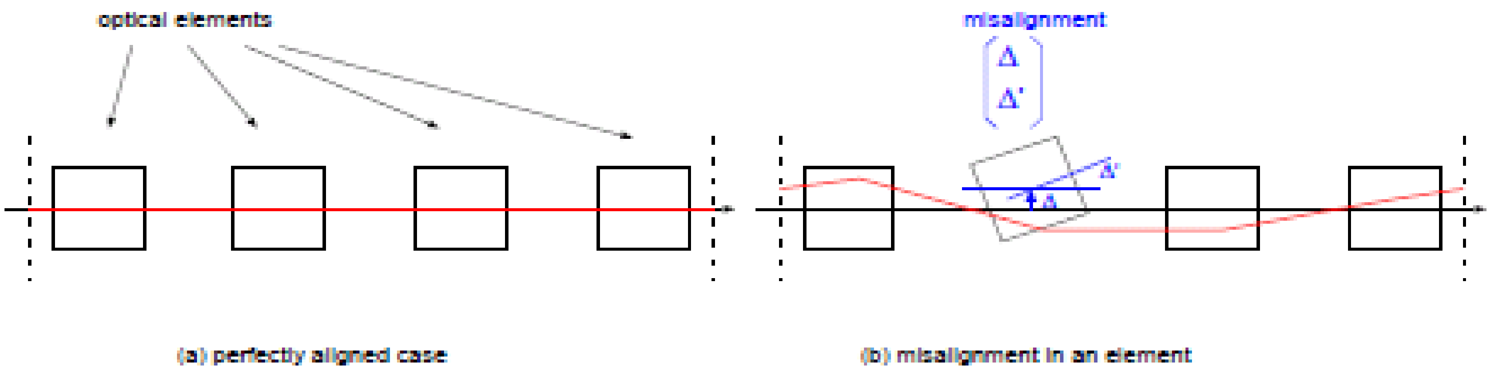




Design for 6 optical cavities with 50μm waist

	Focal length of spherical mirror	Two sigma size on the spherical mirror
A	0.02675 m	0.357 mm
B	0.05275 m	0.713 mm
C	0.10513 m	1.423 mm
D	0.10390 m	0.713 mm
E	0.20947 m	1.423 mm
F	0.419173 m	2.845 mm

Laser position and angle error on spherical mirror due to alignment error of position and tilt of optical element



Extension on ABCD-law

$$\begin{pmatrix} r_2 \\ r_2' \\ 1 \end{pmatrix} = \begin{pmatrix} A & B & E \\ C & D & F \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} r_1 \\ r_1' \\ 1 \end{pmatrix}$$

Thin lens

$$\begin{pmatrix} 1 & 0 & 0 \\ -1/f & 1 & \Delta/f \\ 0 & 0 & 1 \end{pmatrix}$$

Tilt of plane mirror

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 2\Delta' \\ 0 & 0 & 1 \end{pmatrix}$$

Spherical mirror with offset and tilt

$$\begin{pmatrix} 1 & 0 & 0 \\ 1/f & 1 & \Delta/f + 2\Delta' \\ 0 & 0 & 1 \end{pmatrix}$$

Steady state solution

$$\begin{pmatrix} r_0 \\ r_0' \\ 1 \end{pmatrix} = \begin{pmatrix} A & B & E \\ C & D & F \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} r_0 \\ r_0' \\ 1 \end{pmatrix}$$

$$r_0 = \frac{(1-D)E + BF}{2 - A - D}$$

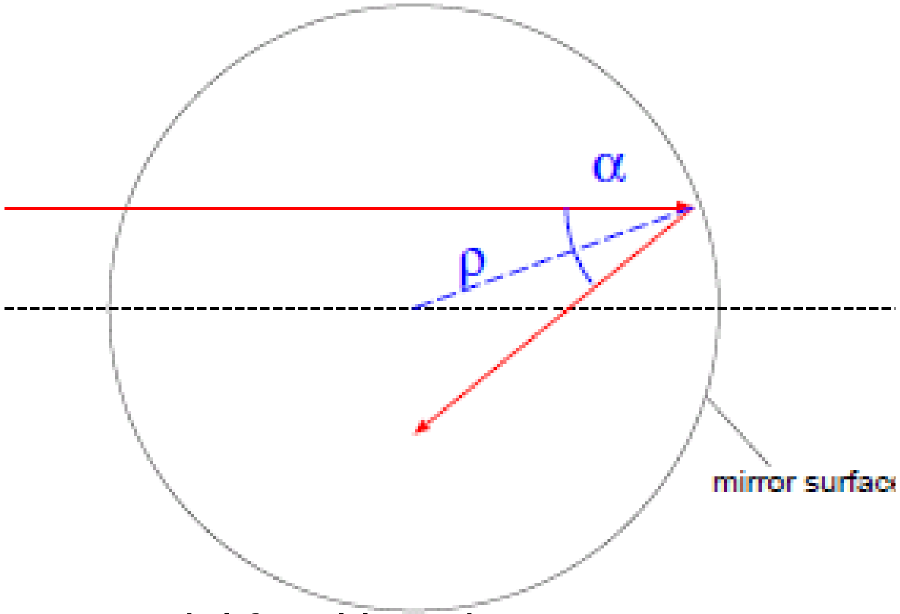
$$r_0' = \frac{CE + (1-A)F}{2 - A - D}$$

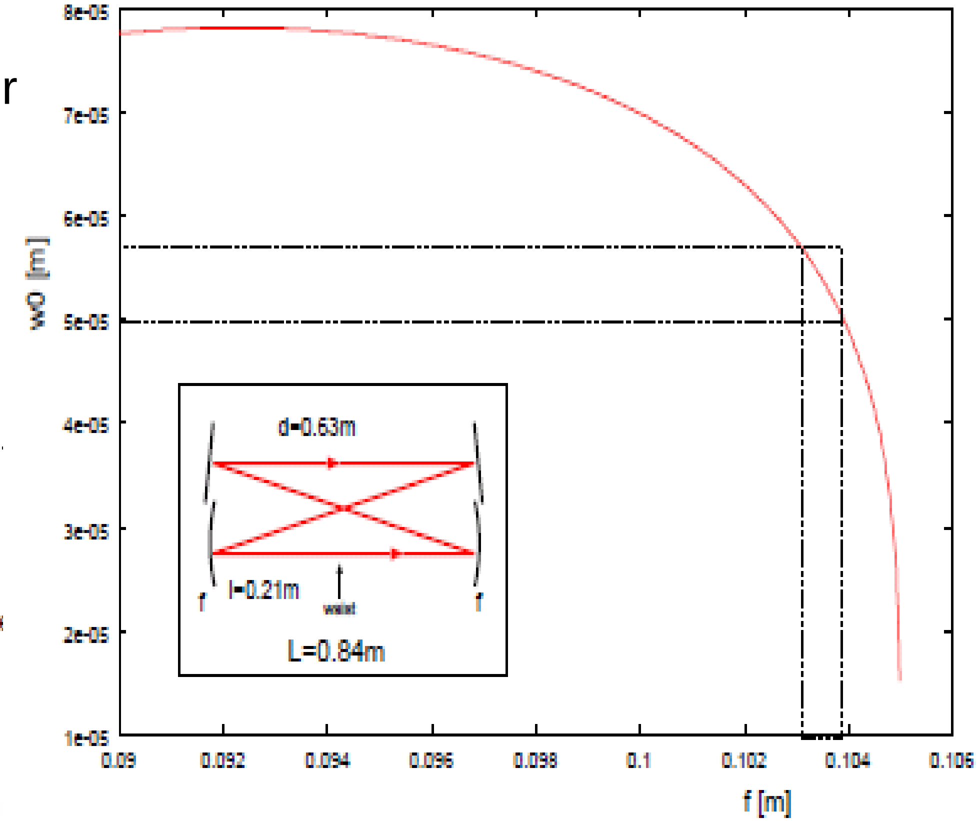
Precise alignment of cavity mirrors is required if we try to realize a small spot size with a concentric 2-mirror cavity. 4-mirror ring cavity can reduce the sensitivity to the misalignment of the mirrors. We estimated the alignment tolerance using a simple model to quantitatively compare the two designs of cavity. **It was confirmed that the sensitivity can be reduced about 2 orders of magnitude in the case of 4-mirror one.**

	misalignment	Position on spherical mirror	Orbit angle on spherical mirror
A	position error 1 mm	26 mm	500 mrad
A	tilt error 1 mrad	1.4 mm	26.8 mrad
B	position error 1 mm	106 mm	1000 mrad
B	tilt error 1 mrad	11.1 mm	106 mrad
C	position error 1 mm	403 mm	1923 mrad
C	tilt error 1 mrad	85 mm	1923 mrad
D	position error 1 mm	1.5 mm	14.9 mrad
D	tilt error 1 mrad	0.3 mm	3.10 mrad
D	tilt error 1 mrad of 3	0.212 mm	1.03 mrad
D	tilt error 1 mrad of 4	0.0045 mm	1.03 mrad
E	position error 1 mm	1.5 mm	7.22 mrad
E	tilt error 1 mrad	0.6 mm	3.02 mrad
E	tilt error 1 mrad of 3	0.42 mm	1.01 mrad
E	tilt error 1 mrad of 4	0.0021 mm	1.01 mrad
F	position error 1 mm	1,5 mm	3.60 mrad
F	tilt error 1 mrad	1.3 mm	5 mrad
F	tilt error 1 mrad of 3	0.84 mm	1.01 mrad
F	tilt error 1 mrad of 4	0.0033 mm	1.01 mrad

3. Resonance condition of a 4-mirror cavity

Reflection angle on spherical mirror





Tangential focal length

$$f_t = \frac{\rho}{2}\cos(\alpha/2)$$

Sagittal focal length

$$f_s = \frac{\rho}{2\cos(\alpha/2)}$$

Guoy phase

$$\Phi(z) = \tan^{-1}(z/z_R)$$

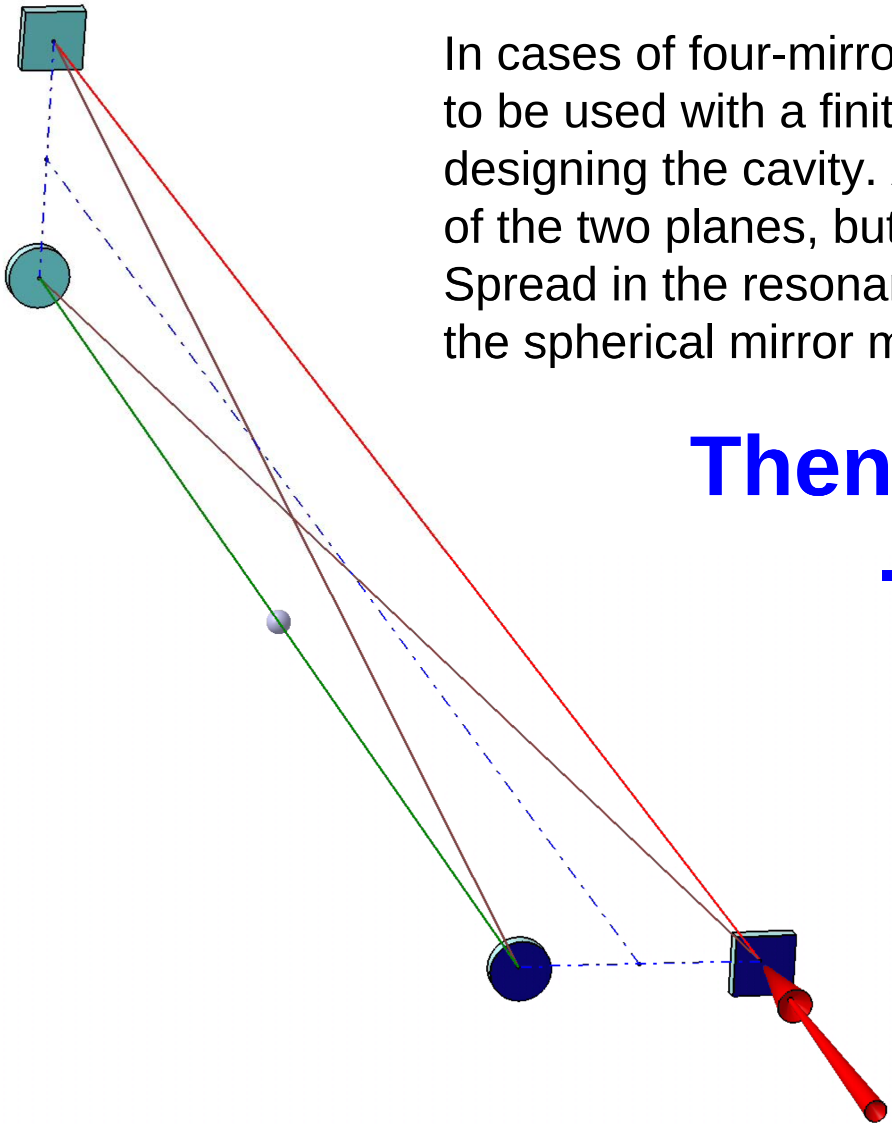
Rayleigh range

$$z_R = \frac{\pi\omega_0^2}{\lambda}$$

W_{0t}=50 μm,
W_{0s}=57 μm

15% difference

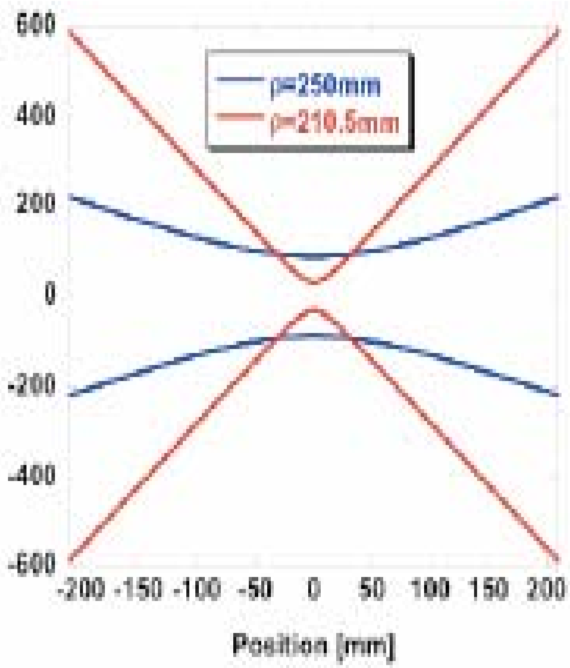
This astigmatism makes phase spread due to Guoy phase depending on beam waist.



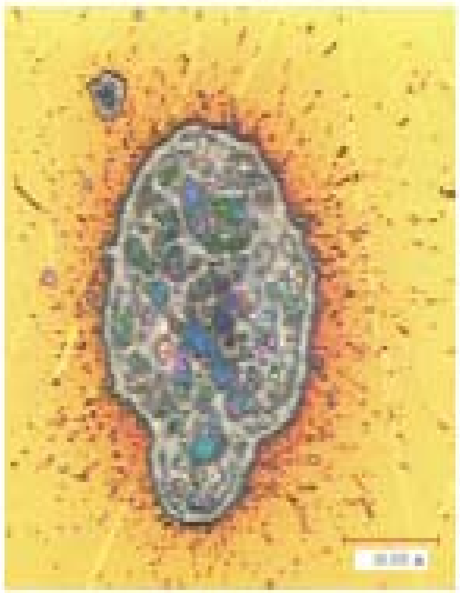
In cases of four-mirror optical cavities, spherical mirrors have to be used with a finite angle. It requires a careful analysis in designing the cavity. Astigmatism changes the optics design of the two planes, but it should not be a fundamental problem. Spread in the resonance condition due to finite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

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

4. Mirror damage which is caused by peak power density on the mirror.



Waist size in sigma from 80 μm to 30 μm



damaged coating size ~100 μm
Depth (p-p) 5.5 μm

Storage average power 40kW or more (maybe 120kW)
Laser size on mirror 440 μm

Then, reduce waist size from 160 μm to 60 μm.
Laser size on mirror 1174 μm

Good coating spherical mirror damage threshold :
Average power density on mirror ~10 MW/cm^2
Peak power density on mirror ~10 GW/cm^2

REO and SOC mirror threshold are a little small : 6.7 GW/cm^2 and 1.6 GW/cm^2

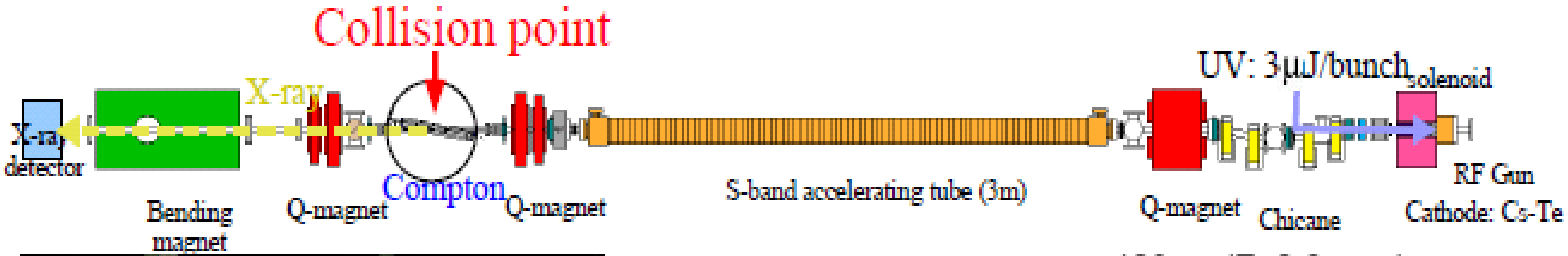
We designed asymmetric reflective mirror configuration to increase the coupling : 99.7% and 99.9% .
Then, we found damaged mirror was low reflective one.

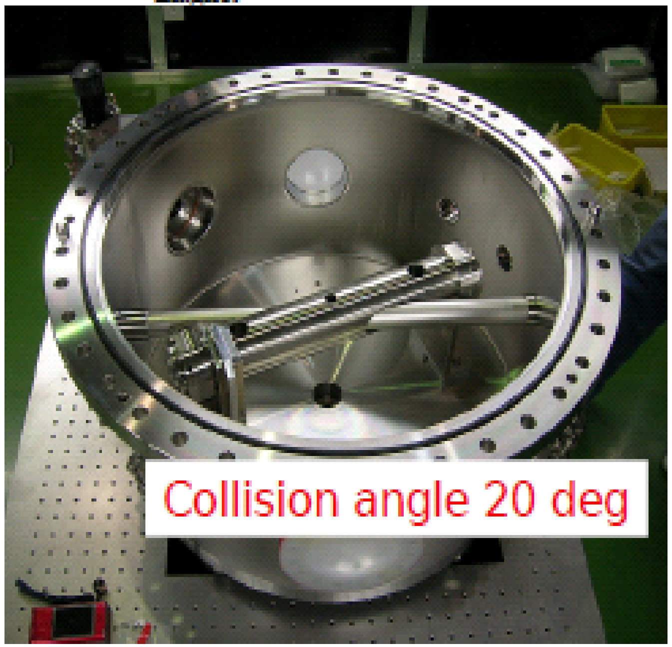
When we introduced burst mode operation for x-ray generation with F.L. pumped amplifier, we might increase average power in the cavity until 120kW. It means ~20GW/cm^2.
Now we keep 40kW average power with larger beam size 1174 μm on the mirror ,which corresponds 0.8GW/cm^2.

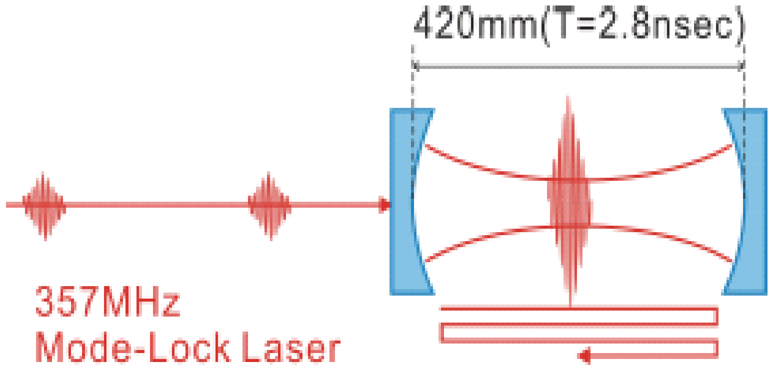
Maybe, burst mode operation is interesting, I show several slides for this.

Pulsed Laser Cavity

The pulsed laser cavity is installed at the collision point.







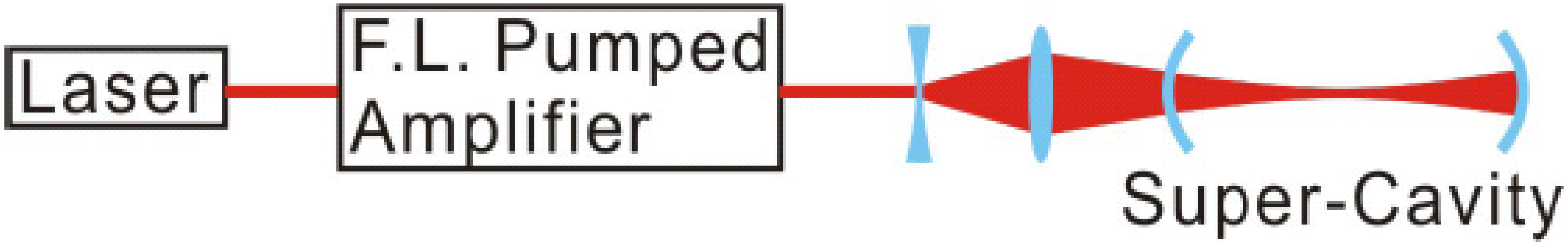
$$L_{cav} = n\lambda / 2$$

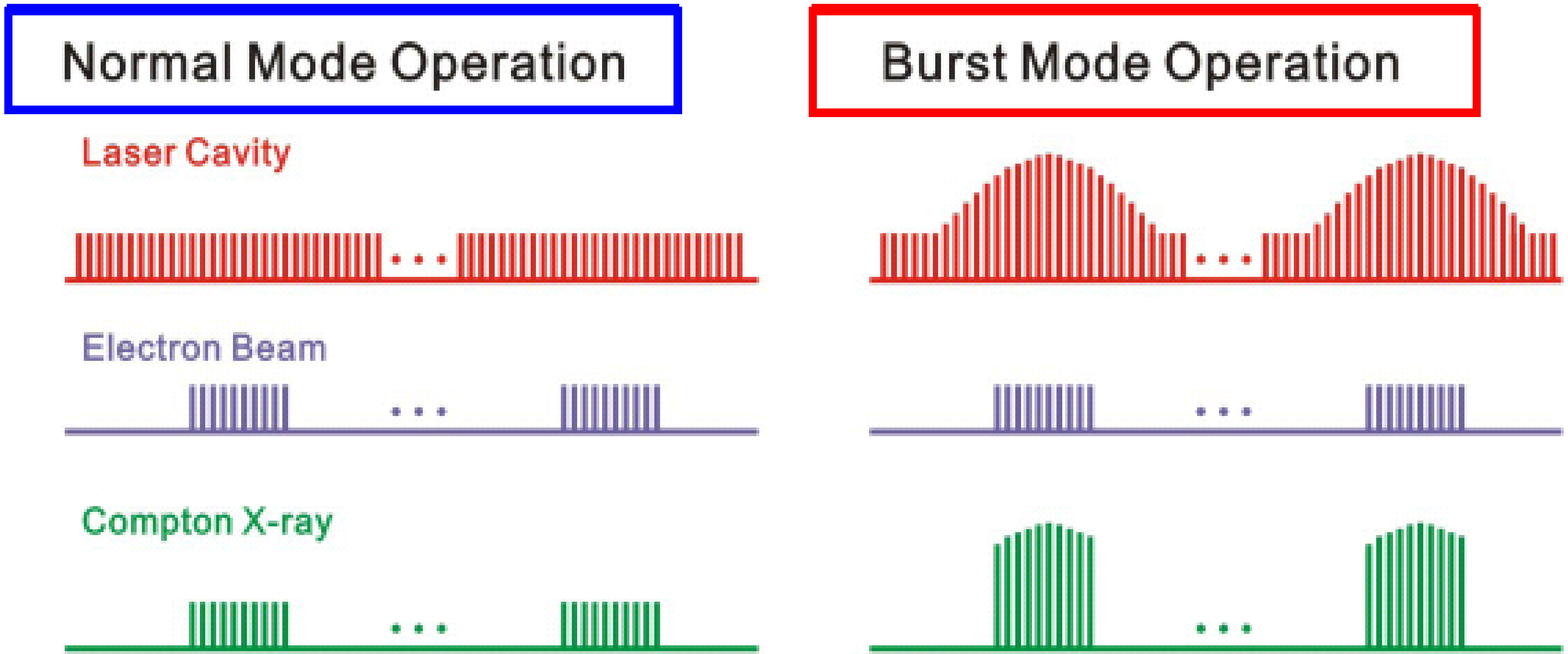
$$L_{cav} = mL_{laser}$$

Pulsed Laser cavity chamber

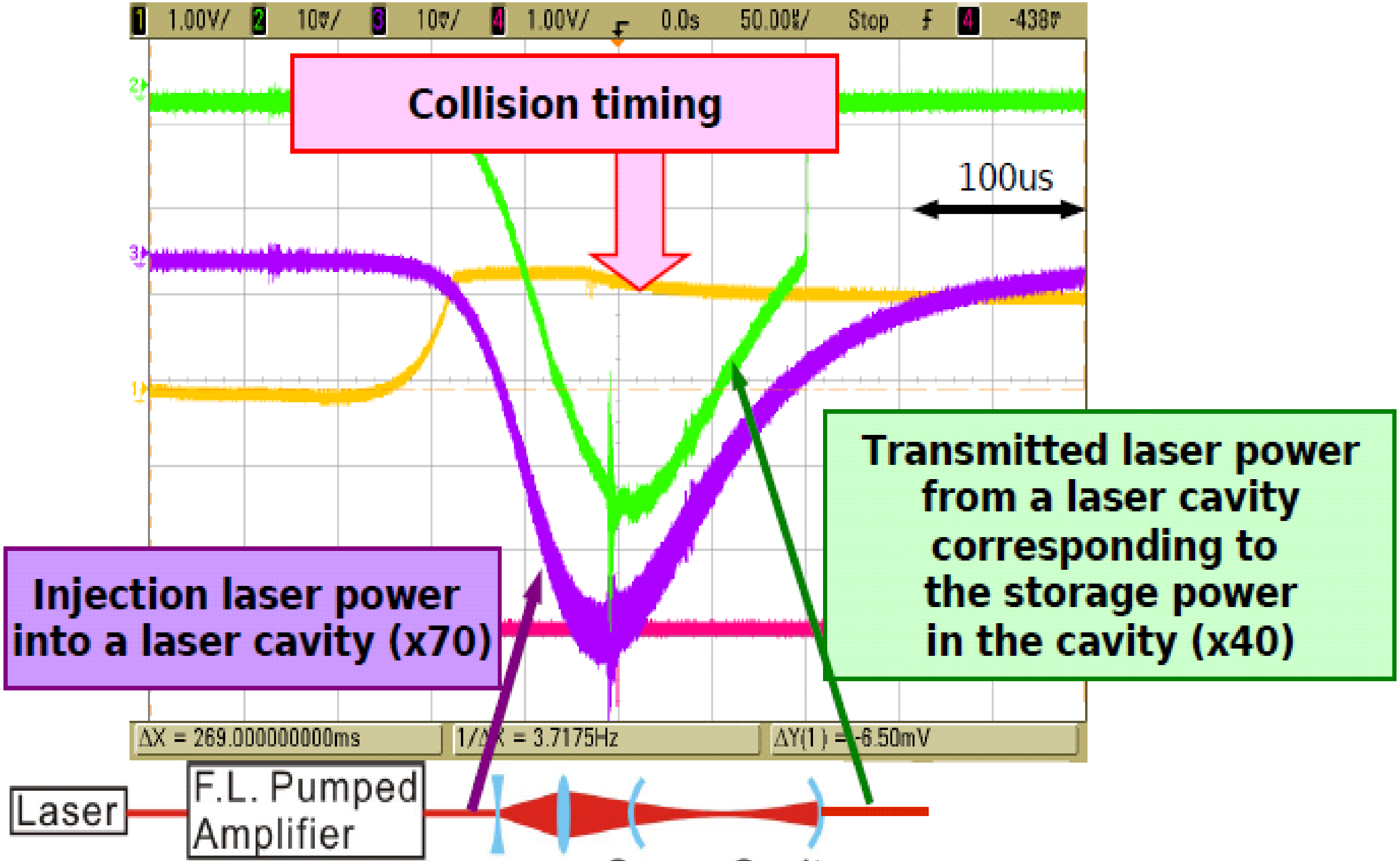
Burst mode Operation

In order to increase the number of x-rays,
A flash amplifier is installed before the laser cavity.



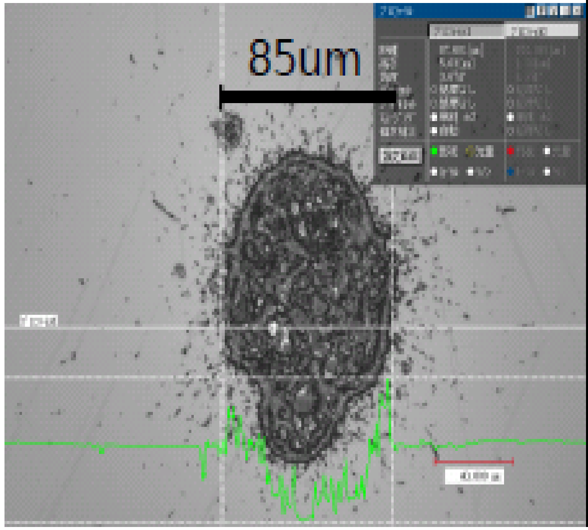


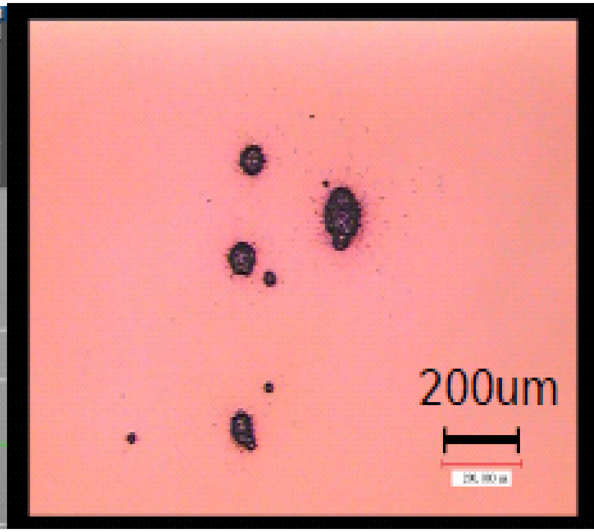
Burst mode Operation

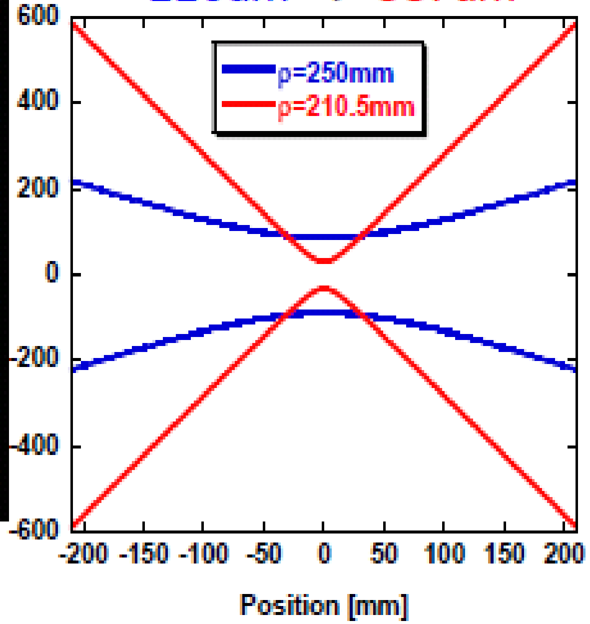


Damage on the mirror in Burst mode

Size on the mirror
220um --> 587um



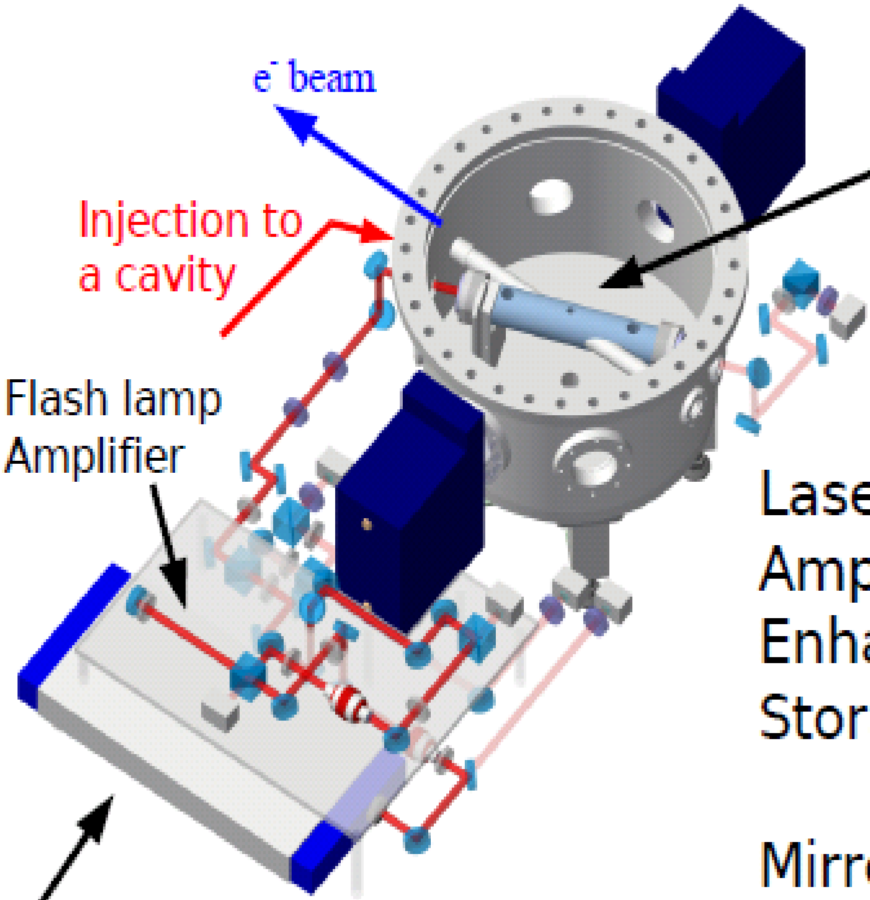




Depth(p-p) 5.5um
Measured by a color laser 3D profile microscope

2Pass Amp Gain	Finesse	Waist Size	Size @ Mirror	Storage Peak Power
70	878.5	30.3μm	587μm	40kW

Burst mode cavity parameters



Laser power	2.5 W
Amp gain (2 pass)	80
Enhancement factor	200
Storage peak power	**40 kW**
	112 uJ/pulse
Mirror curvature	210.5mm
Mirror Reflectivity	99.6%
Waist size	**30.3 um**
Finesse	878.5
Cavity length	420 mm
Pulse length (FWHM)	7ps

5. Summary

1. Establish feedback system to keep the resonance condition precisely.
2. 4-mirror ring cavity has a good tolerance to achieve gain more than 10^4 and waist size 10 μm or less in sigma.
3. Establish accurate alignment with a few μm positioning and a few μrad tilt control.
4. Take care the mirror damage and need safety margin.

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Thank my colleagues (Y.Honda, K.Sakaue and M.Fukuda) for the preparation on related information to this talk.

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