Development of an optical cavity system for the advanced photon source based on Compton backscattering

TYL workshop
Seoul
2016.5.19
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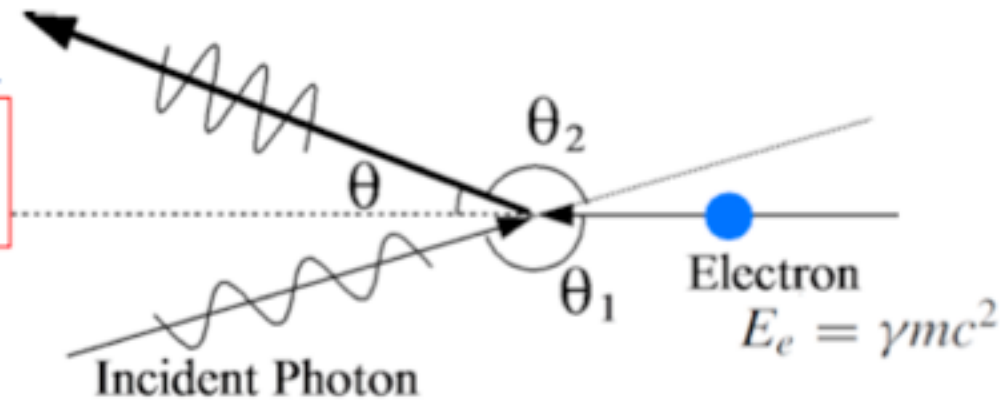
- Collaboration between LAL and KEK
- Both labs have similar projects of Compton photon source.
- Purpose of this collaboration is to exchange experiences in development works of optical cavity systems.

Compton scattering

- A promising scheme to produce an energetic photon beam.



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

(for head-on collision)

- Features
  - Energy scales γ^2; low energy electron beam can produce hard X-ray.
  - 2-body scattering; correlation between angle and energy.
  - Non-destructive; small source and high brightness X-ray.
  - Polarization; easy to control by polarization of laser.

- Difficulties
  - Flux; laser power, beam power
    → laser power enhancement by optical cavity

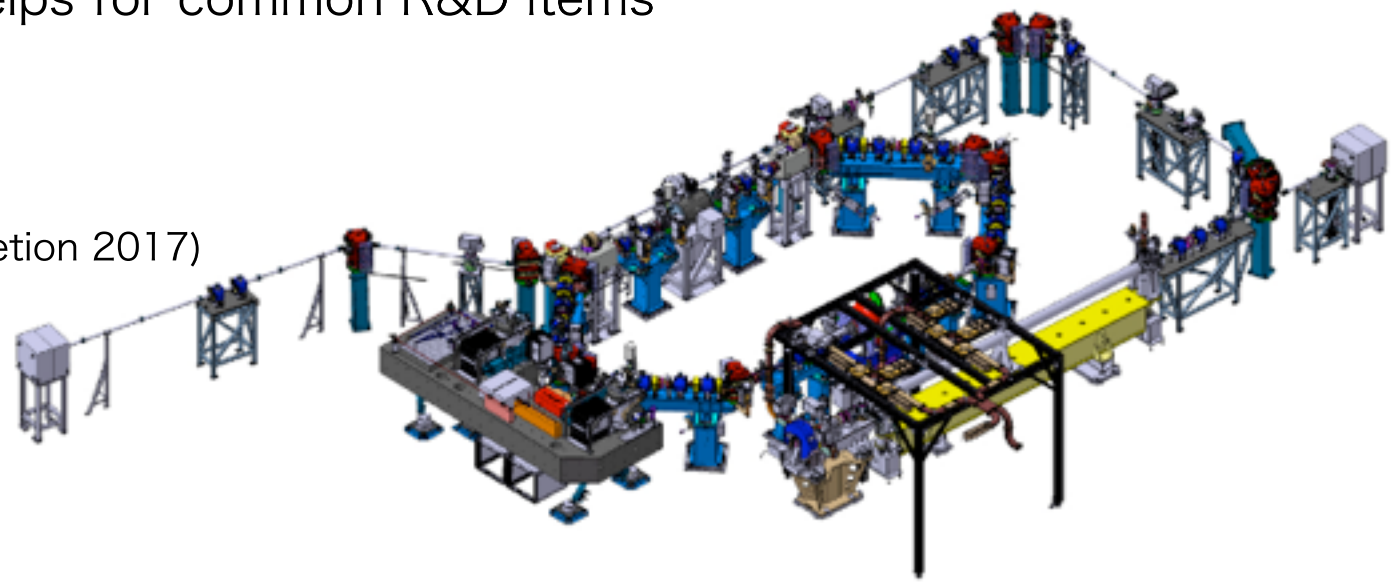
$$F_{total} = \frac{16}{3} N_e N_L f \frac{r_0^2}{w_0^2}$$

electron laser rep-rate size

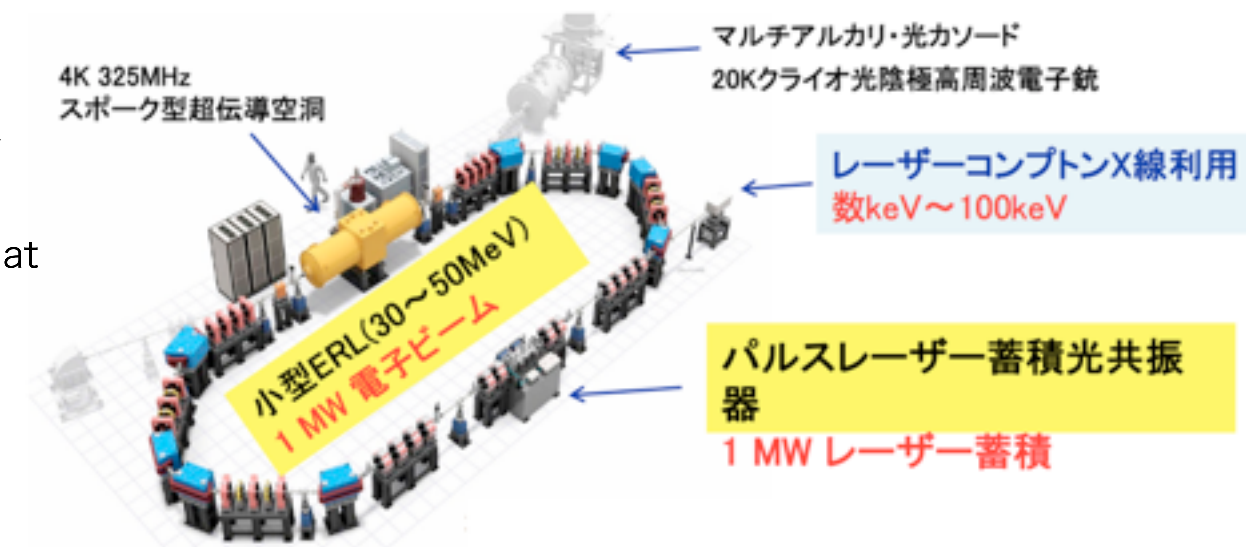
Collaboration

- LAL and KEK have similar projects
  - Both group need high power optical cavity
  - Communication helps for common R&D items

- THOMX in LAL
  - Compact Storage Ring
  - Under construction (completion 2017)

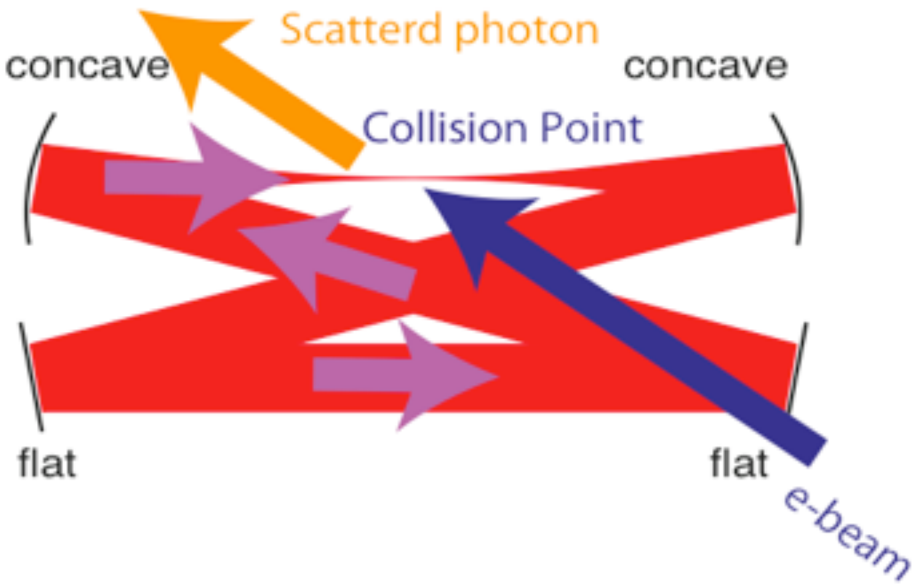


- QB in KEK
  - Compact Energy Recovery Linac
  - Technology development
  - Demonstration of X-ray imaging at existing cERL



Optical Cavity

- Storage laser power for realizing a high power photon target
- Targets of present development work
  - High averaged power; ~1 MW (so far: 10kW)
  - High enhancement factor; >10000 (so far: 1000)
  - Small spot size; ~10 μm (so far: 30 μm)
  - Short pulse; ~100 fs (so far: 5 ps)

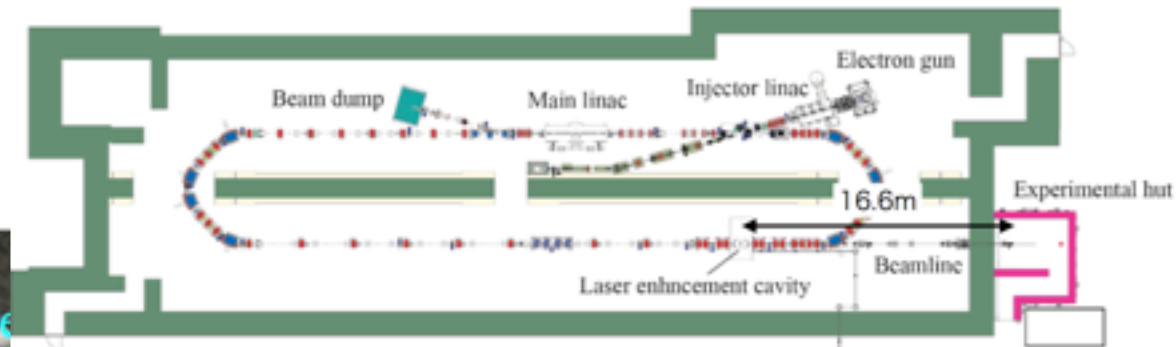


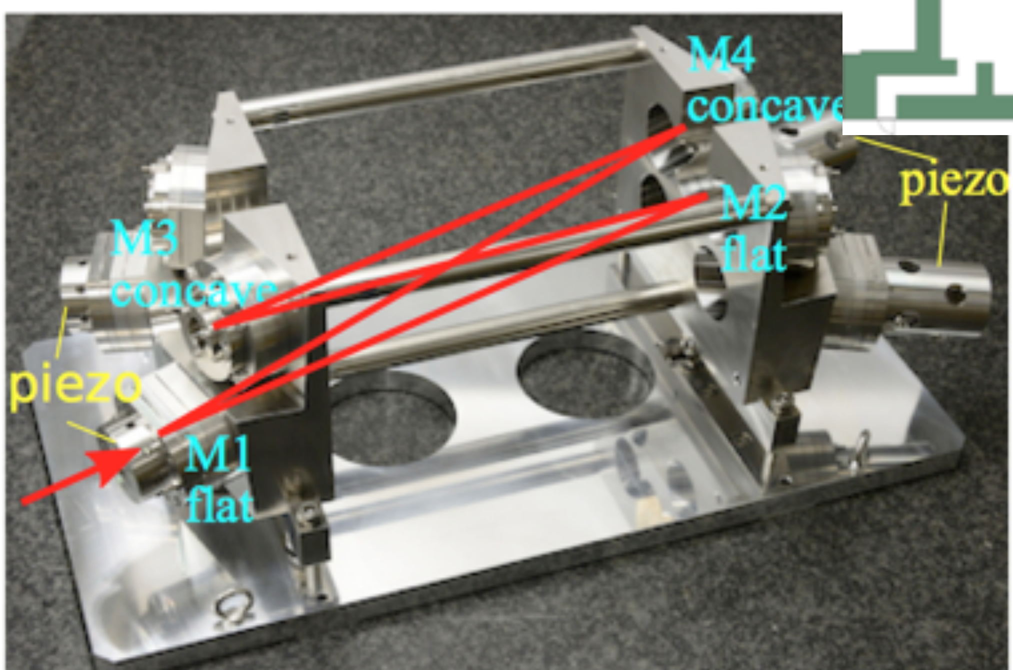
- Difficulties
  - High averaged power; mirror deformation, loss
  - High enhancement factor; cavity resonance control, mirror loss
  - Small spot size; alignment tolerance, cavity design
  - Short pulse; high bandwidth

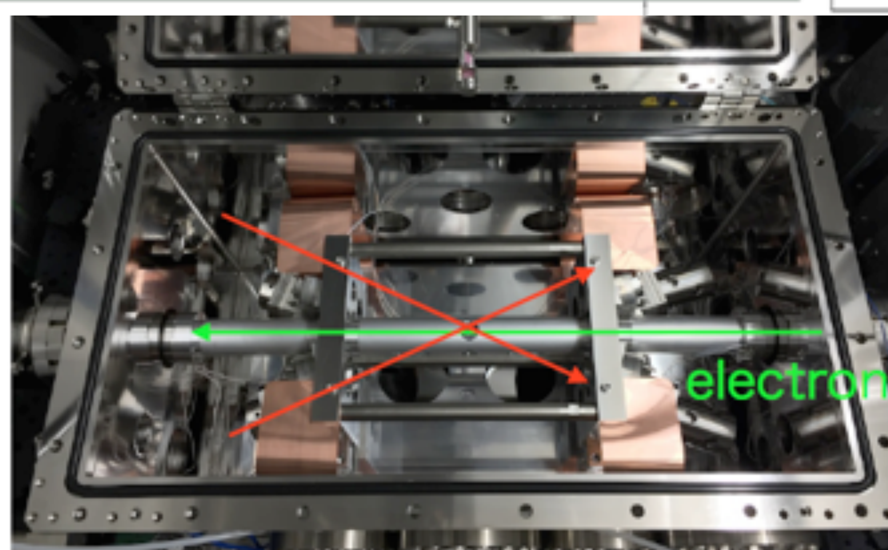
Optical cavity

- Experience in KEK (tested at cERL in 2015)
- Rigid structure for fast installation and reliable operation in an existing accelerator.
- It was good to have experiences so far.
- Finding out problems in the design.
    - Thermal load
    - Mirror deformation
    - Limited tunability

Repetition rate	162.5 MHz
Finesse	5600
Collision angle	18 degree
Spot size at IP (σ_x/σ_y)	20/30 μm
Specification of mirrors	
Substrate material	Fused silica
Diameter	25.4 mm
Reflectivity	
M1	99.9%
M2	99.99%
M3 and M4	99.999%

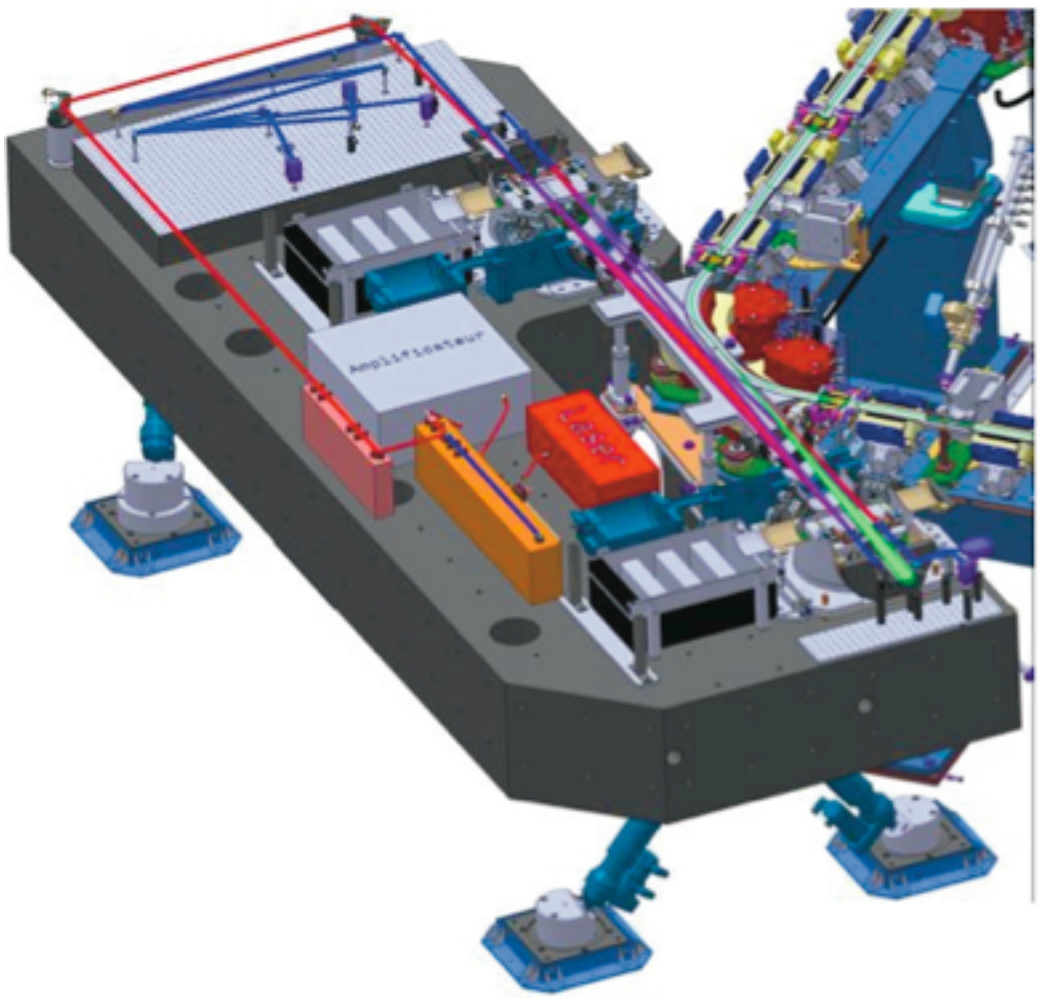


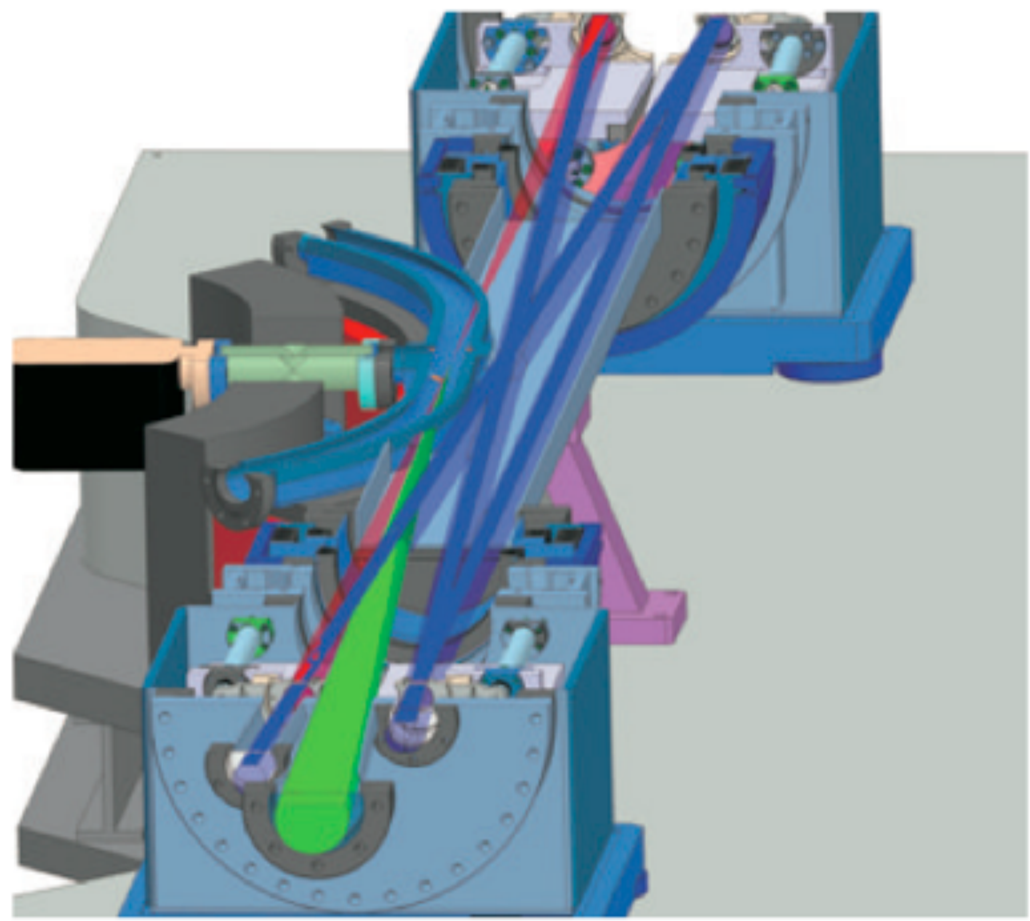




Optical cavity

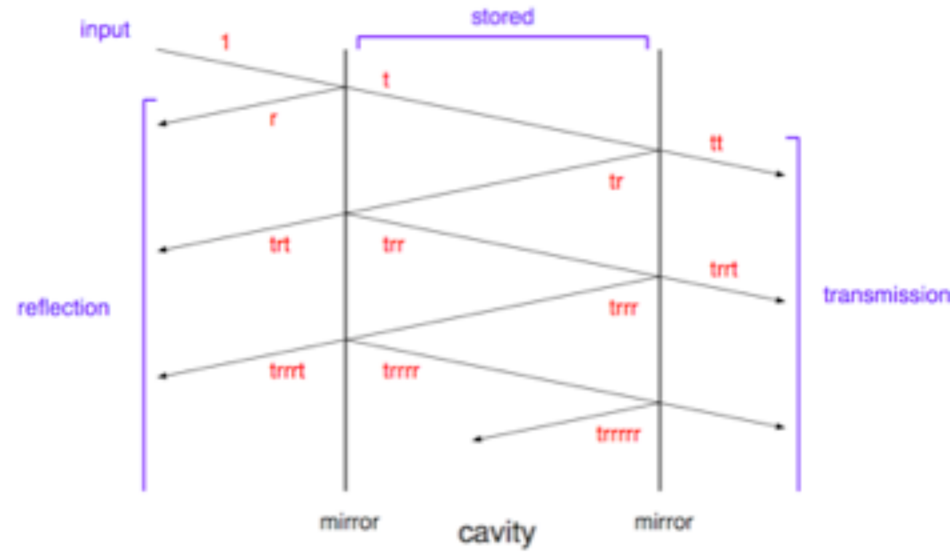
- Design of LAL for THOMX under construction
- Special design combined with beam duct in arc section.
- Complicated but wide-range multi-directional mirror adjustment system.

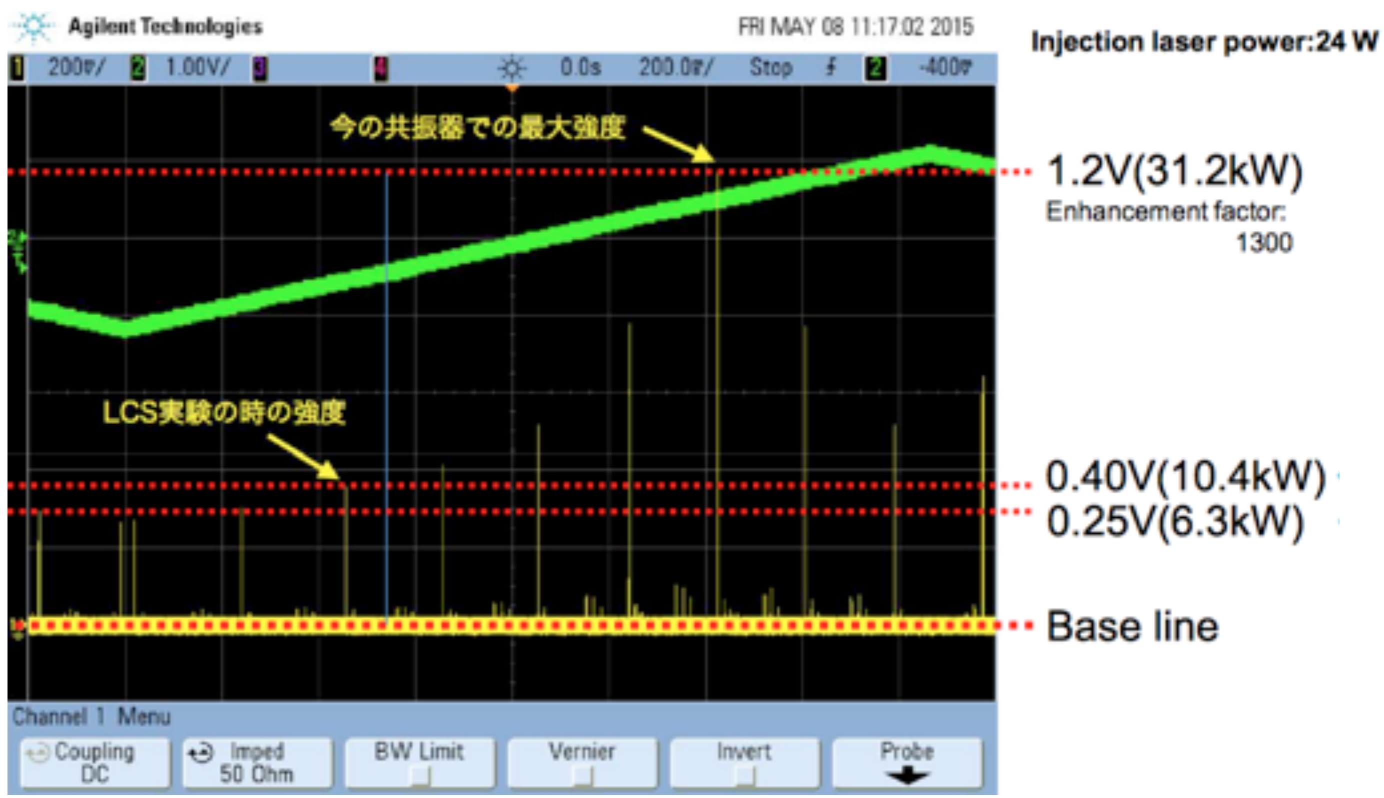




Optical cavity resonance

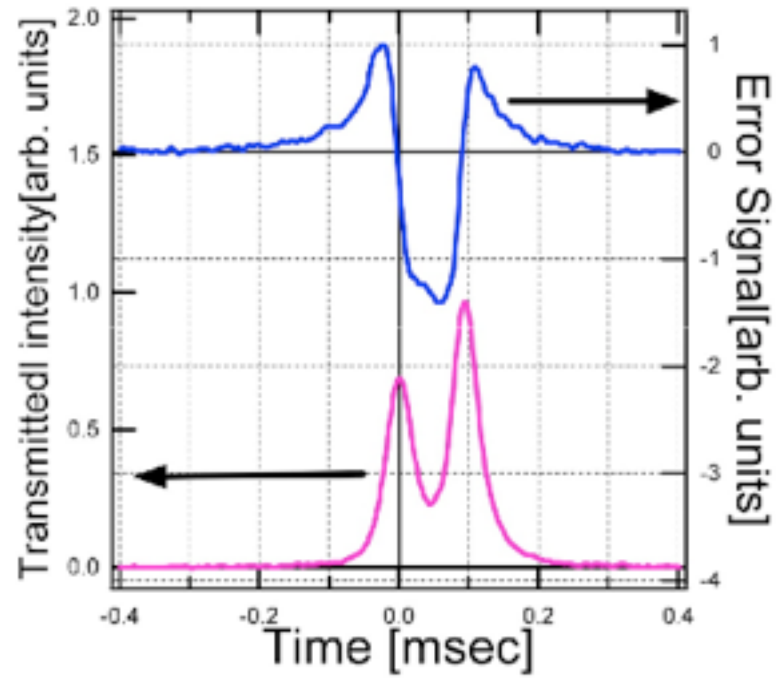
- Resonance peaks
  - High reflectance mirror -> high enhancement factor
  - High enhancement factor -> narrow resonance
- Controlling cavity resonance
  - Precise feedback control to keep the resonance
  - It limits achievable power enhancement
- Technical issue
  - Noise reduction
  - Feedback scheme, bandwidth

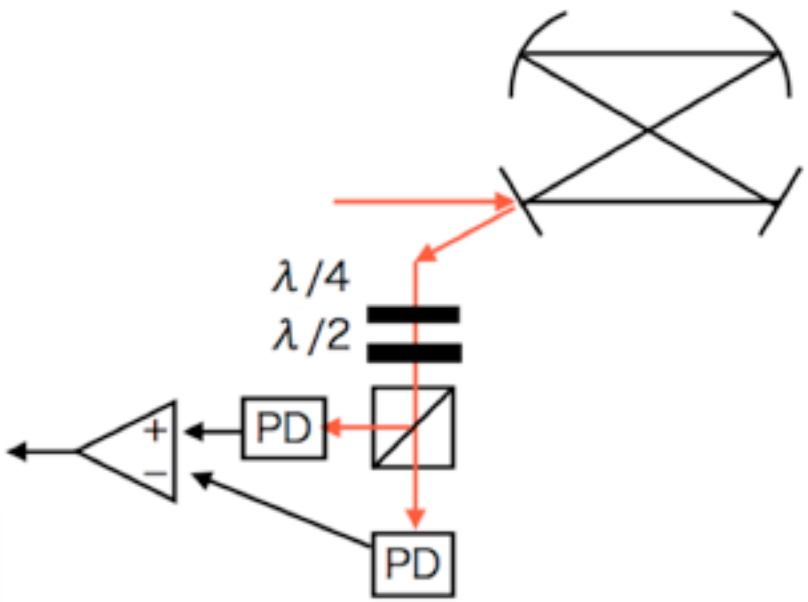


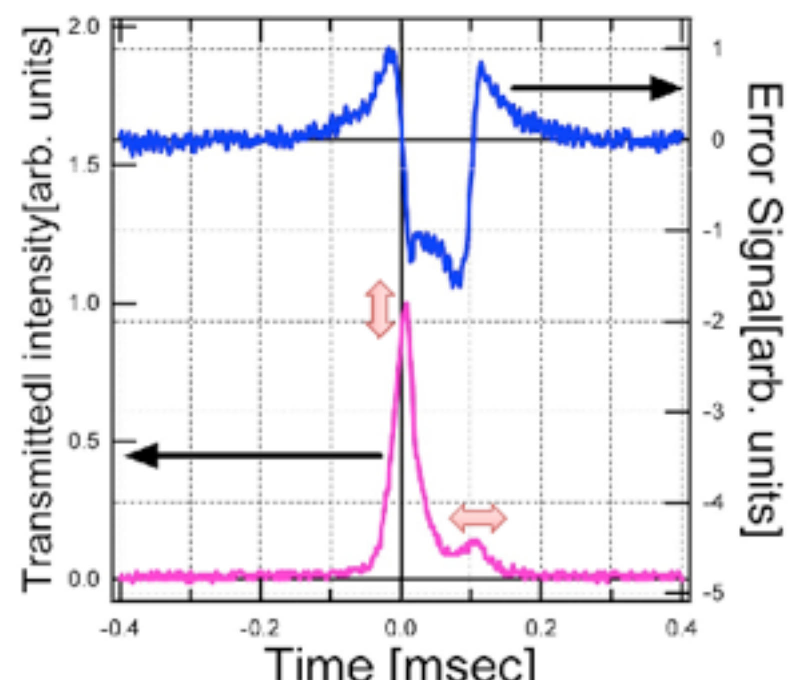


Cavity control

- An unique scheme to produce a feedback signal.
  - Utilizing a polarization property of a multi-layer mirror used in a finite incident angle.
  - LAL group has published a paper recently.
  - This scheme is used in KEK's system also.



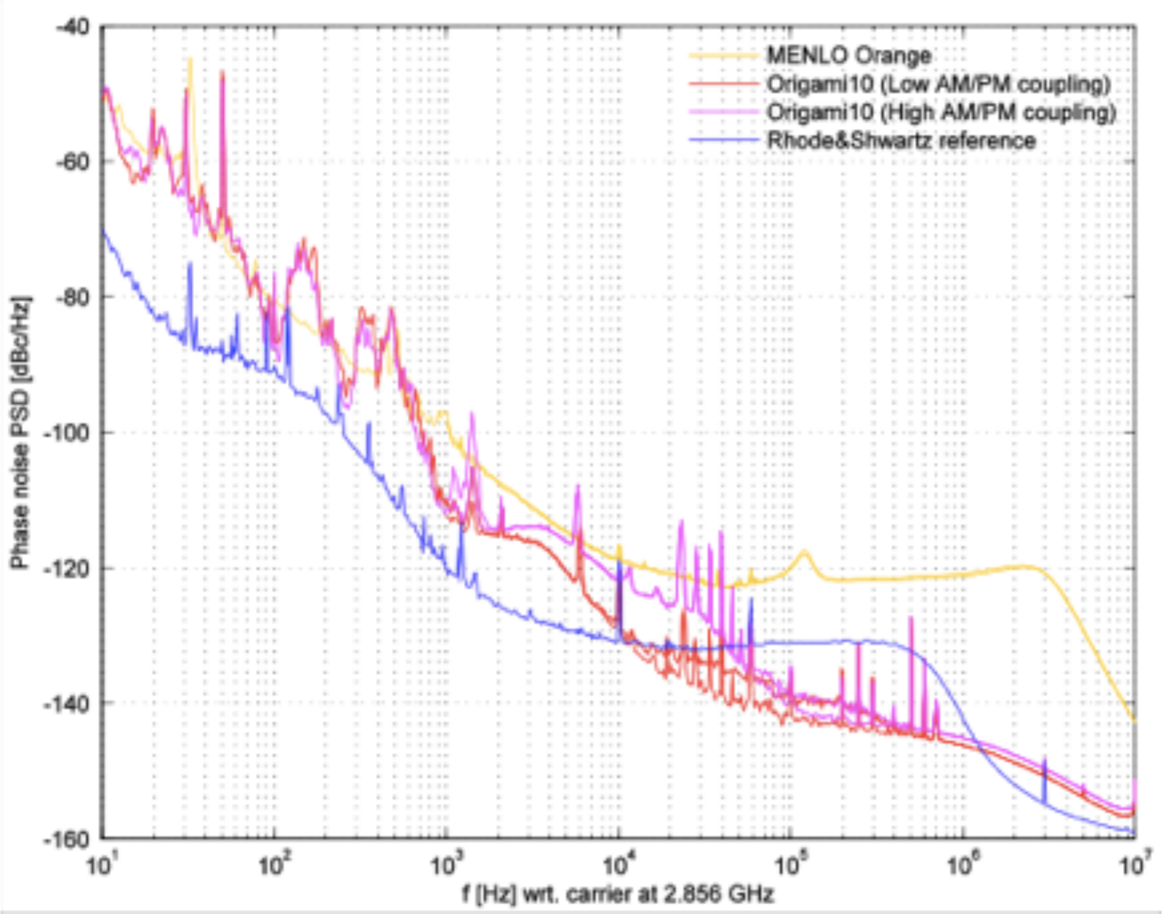




Laser frequency stabilization using folded cavity and mirror reflectivity tuning:
X.Liu et al., Optics Communications 369 (2016) 84-88

Cavity resonance control

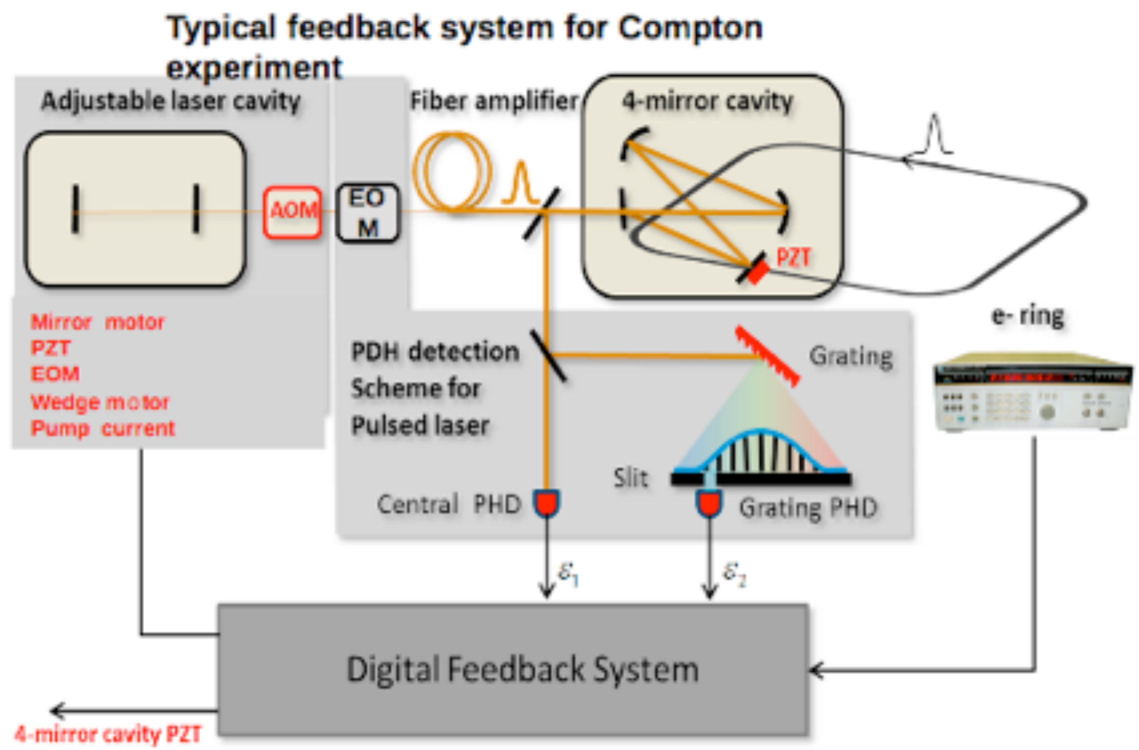
- Phase noise in the laser oscillator can be a problem when resonating a high finesse cavity.
- Characteristics of phase noise is difficult to know from information in laser's specifications.
- Exchanging information helps for both group.
  - Tested results of some commercial product
  - Experiences about modifications needed to a commercial product.



Phase noise measurements

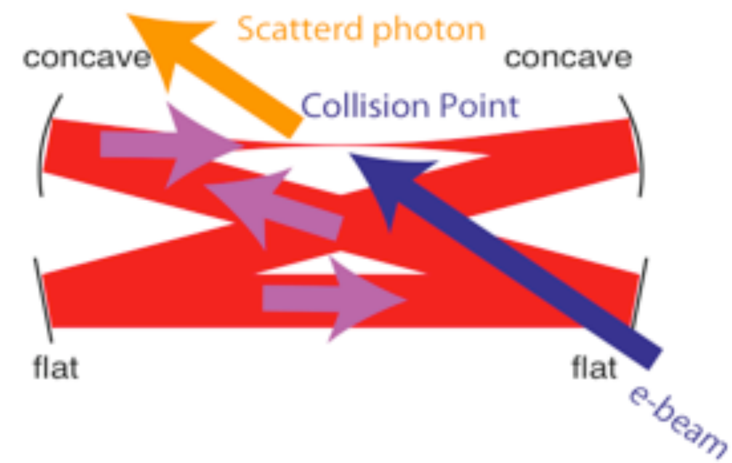
Cavity resonance control

- Fast and complicated feedback system is needed, for cavity lock and for beam synchronization.
- There are commercial FPGA boards, but not perfectly match our application and expensive.
- A dedicated digital feedback board has been developed in LAL.

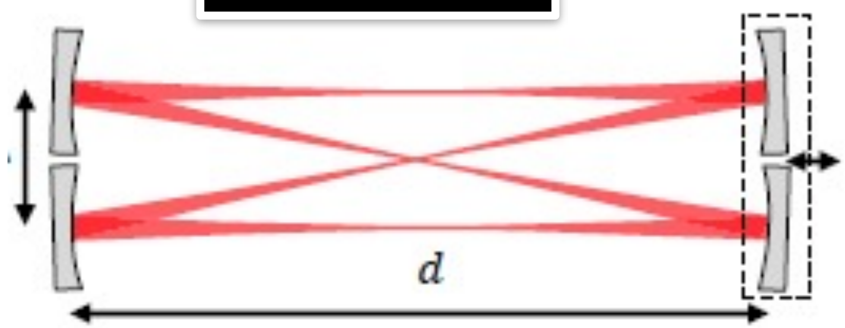


Cavity geometry

- Eigen mode depends on cavity geometry
- New ideas for realizing
    - small and round spot size
    - less sensitive to alignment errors and mirror deformations.

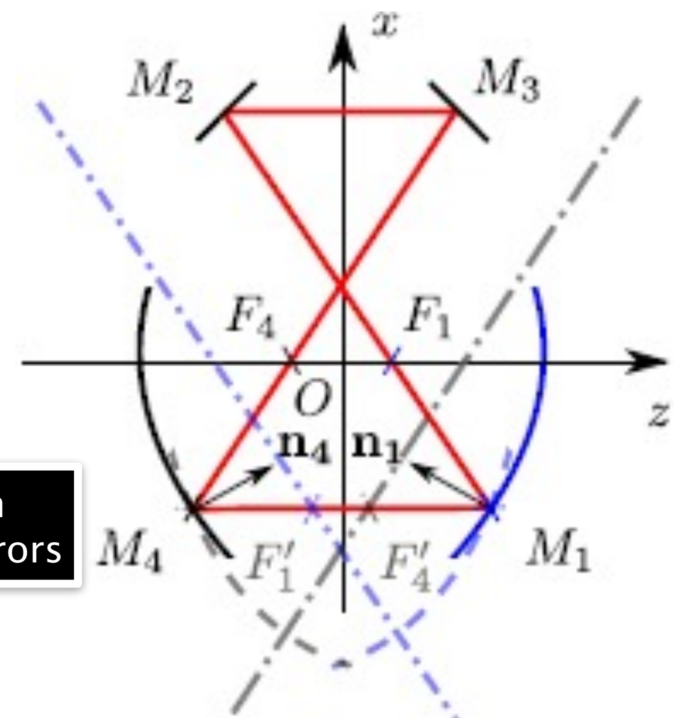


Cavity with
4 concave mirrors



(b) All-curved-mirror (ACM) cavity

Carstens et al. Opt Expr 21(2013)11606

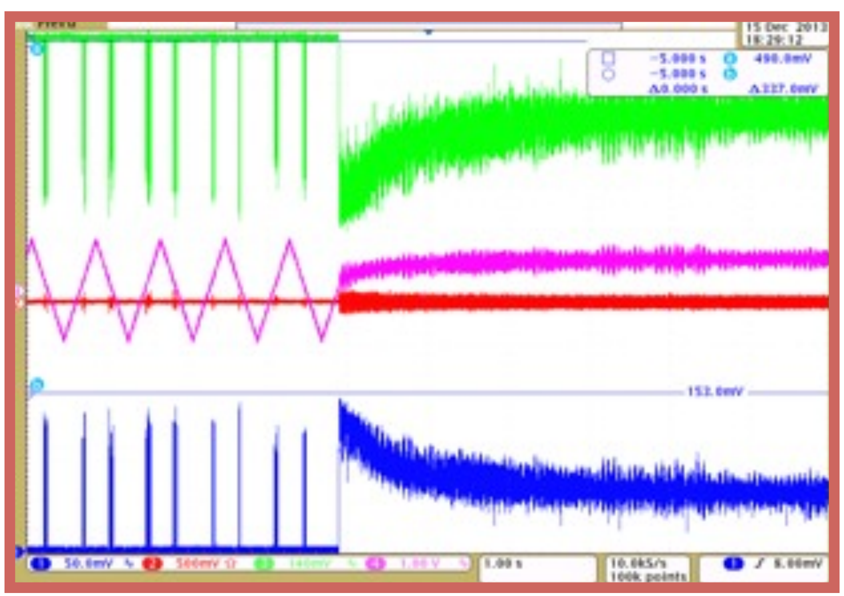


Cavity with
parabolic mirrors

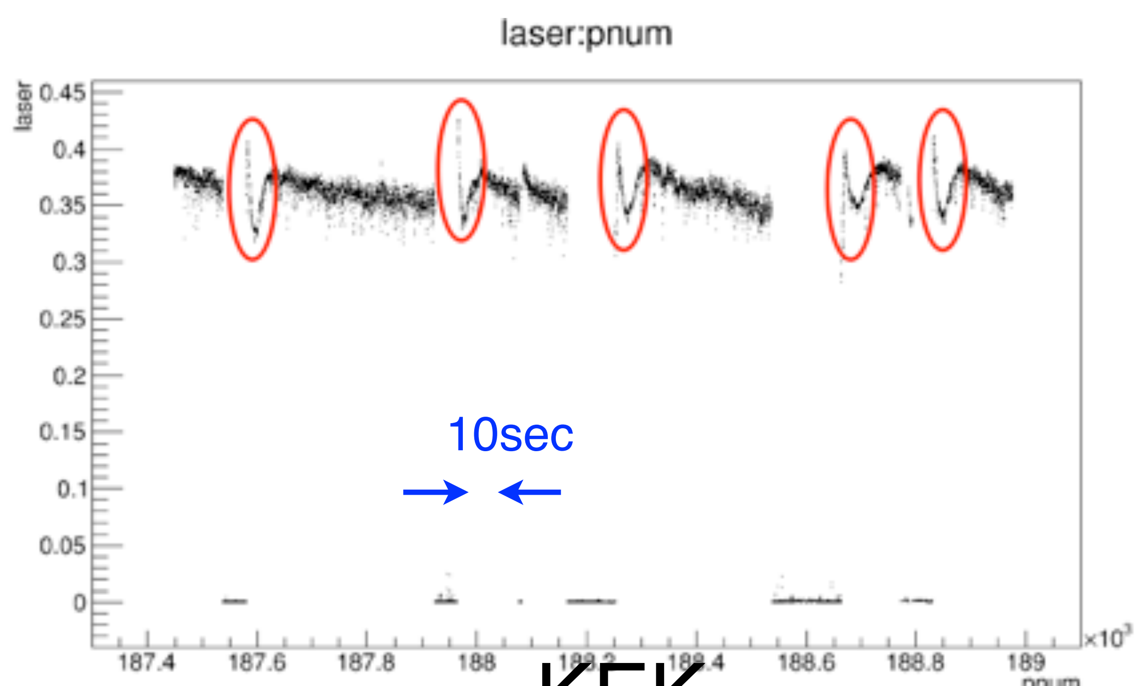
Recent simulations on this topic with parabolic mirrors:
Dupraz et al., Optics Communications 353 (2015) 178–183

Mirror deformation

- High stored power deforms the cavity mirror
  - Change eigen mode of the cavity
  - Change matching condition of the injected beam.
  - Stored power variation in ~sub-sec time scale.
- Experienced in both groups
- Idea to solve the problem
  - Lower the absorption loss
  - Use mirrors with low-expansion substrate
  - Active control of mirror shape or injection beam



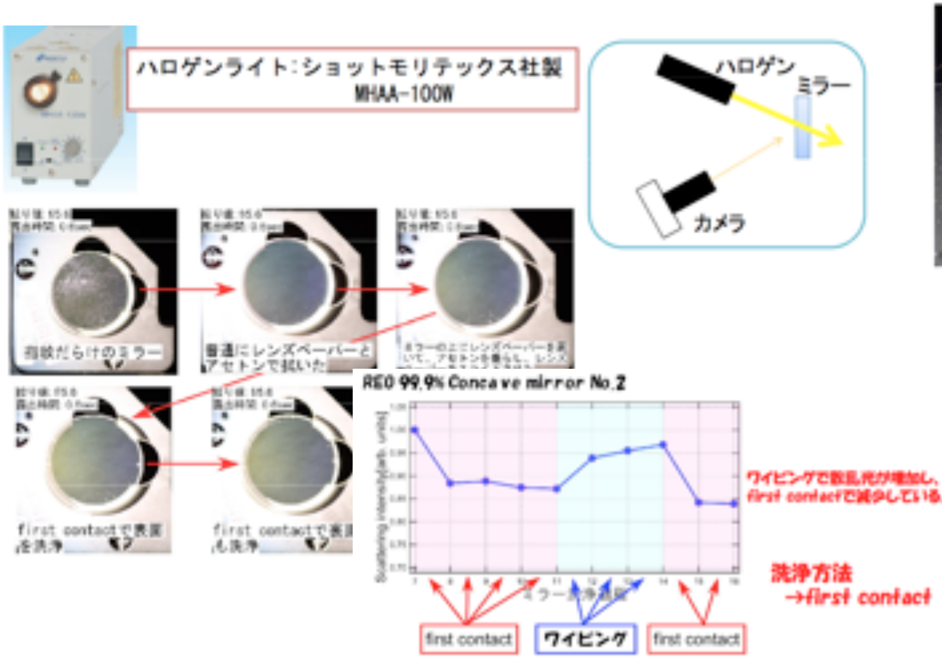
LAL

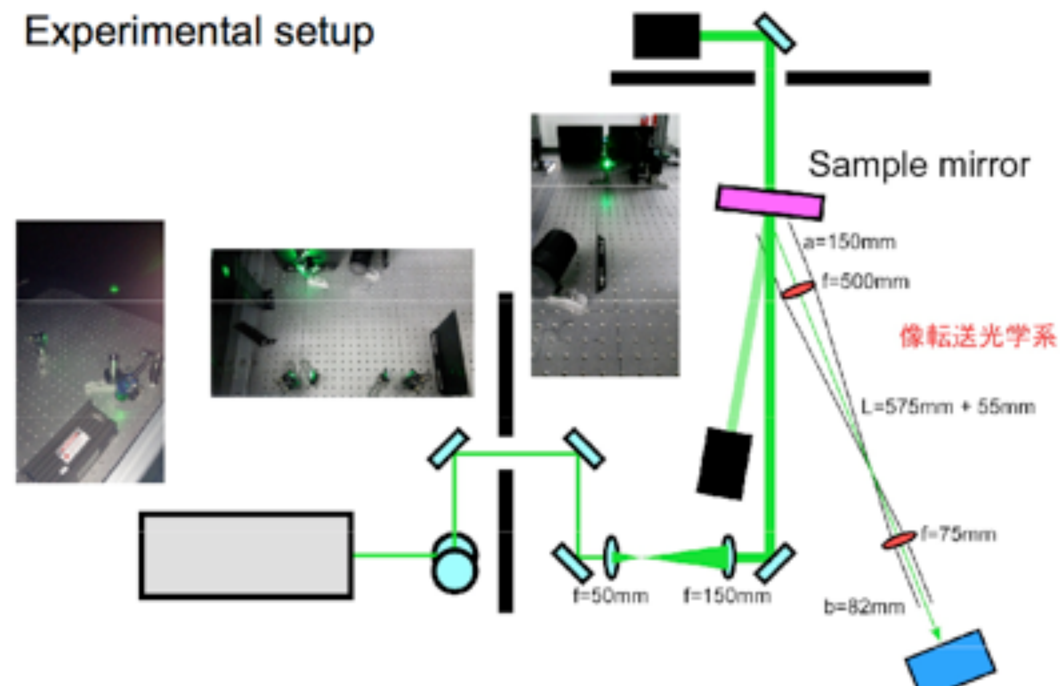


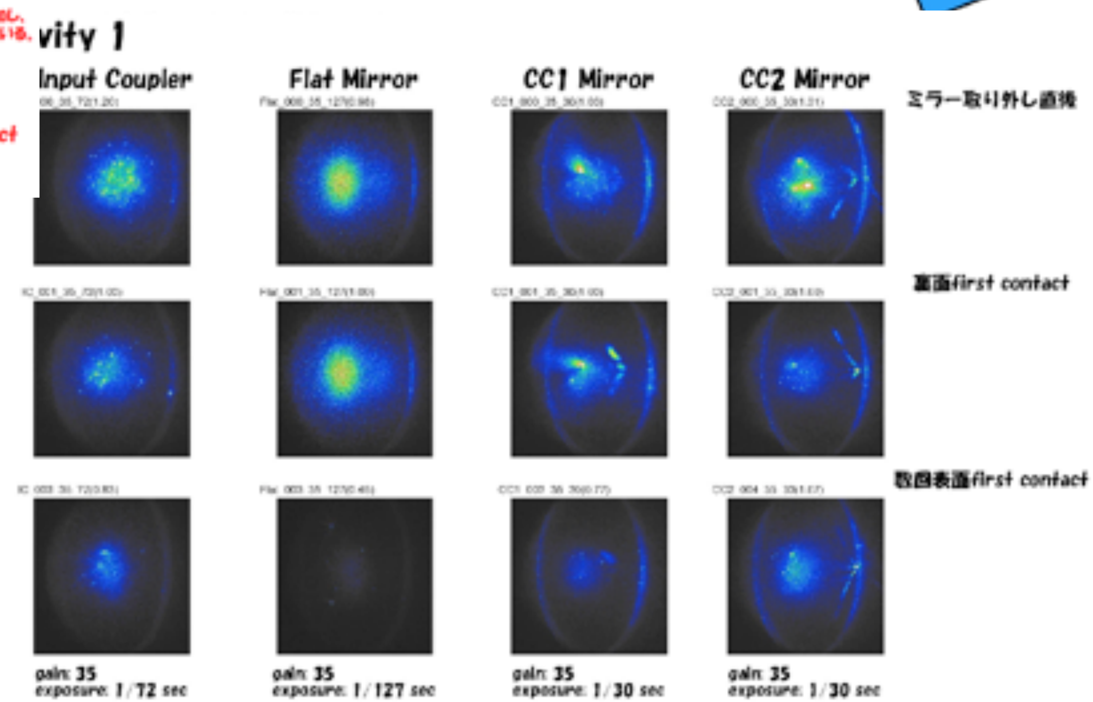
KEK

Mirror cleaning

- KEK
    - Mirror inspection system
    - Mirror cleaning procedure



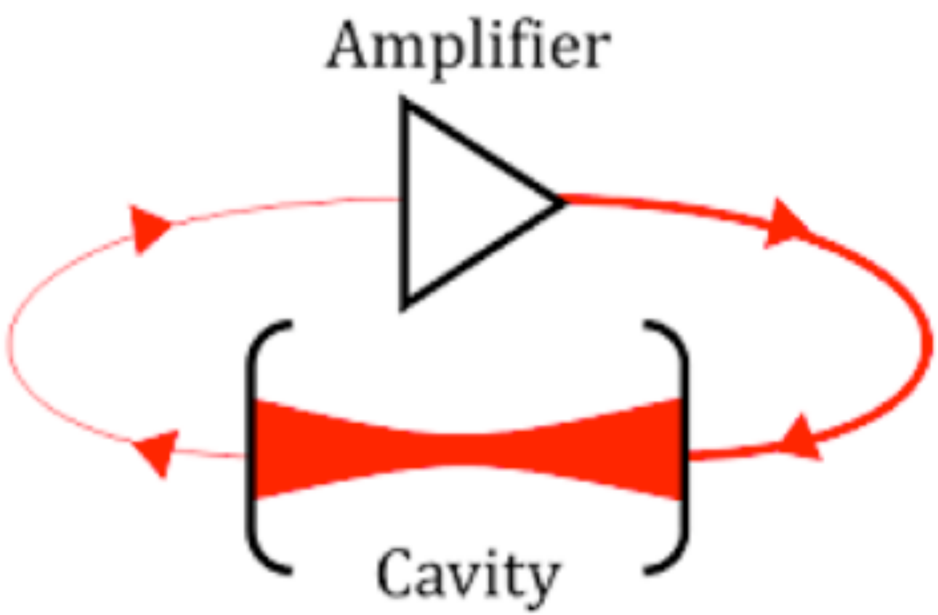


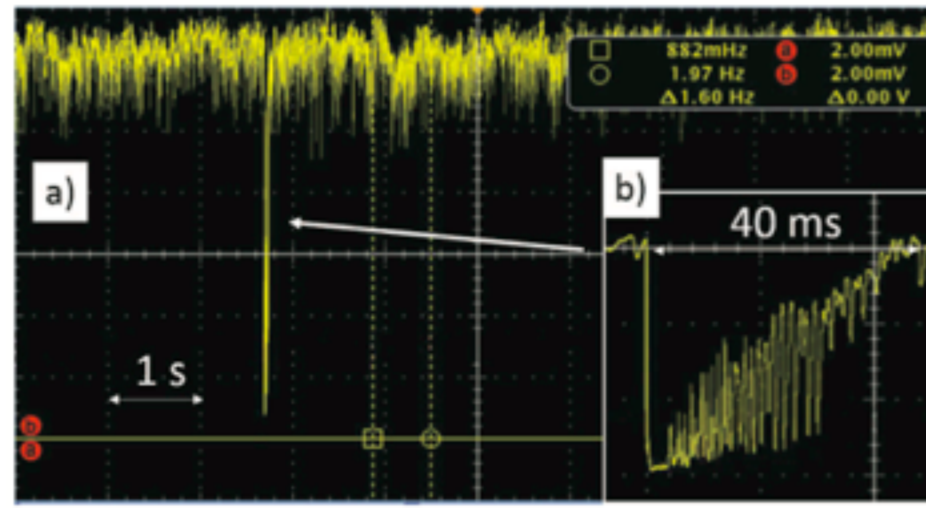


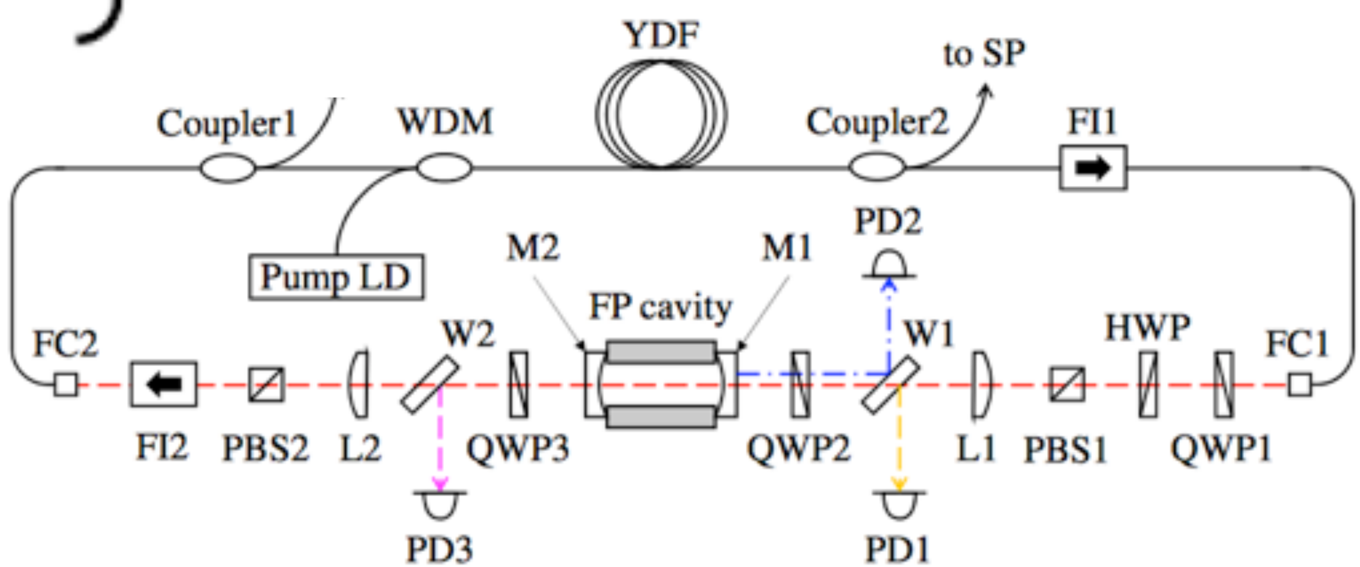
- Similar system has been set up in LAL

Self resonance system

- High enhancement cavity is difficult to handle
- KEK has invented a new scheme, feedback-free system
    - We can easily resonate Finesse=650,000 cavity
- This is useful to test high power load on mirror.



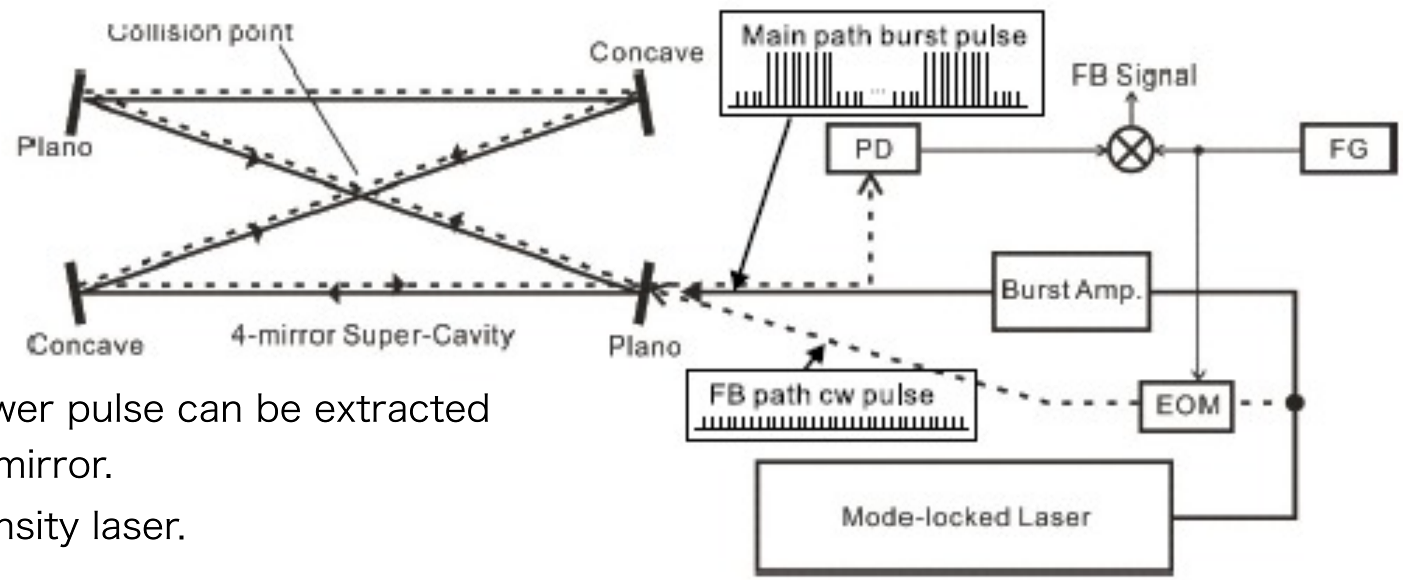




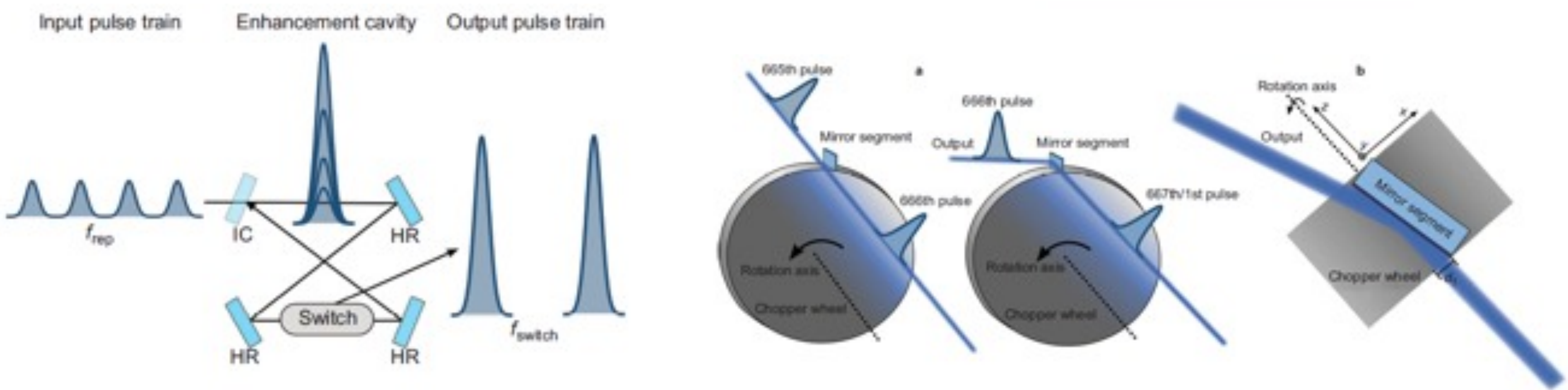
Uesugi et al. APL Photonics (2016)

Application of the optical cavity

- KEK has been developing a Burst mode cavity
    - Amplify the input laser in a pulsed mode
    - High peak, but low averaged power.



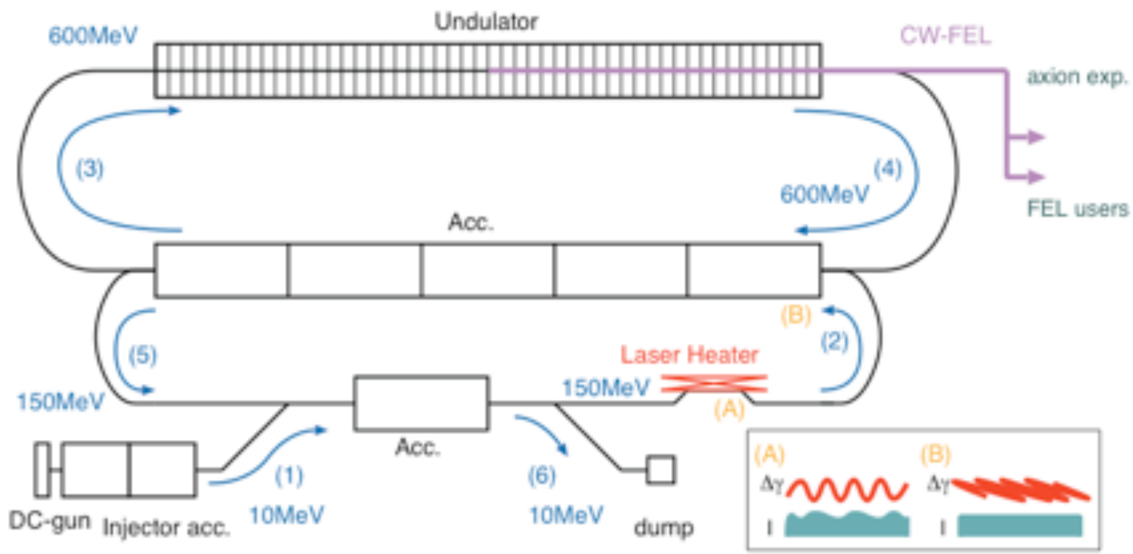
- The stored high peak power pulse can be extracted with a special extraction mirror.
- New scheme of high intensity laser.

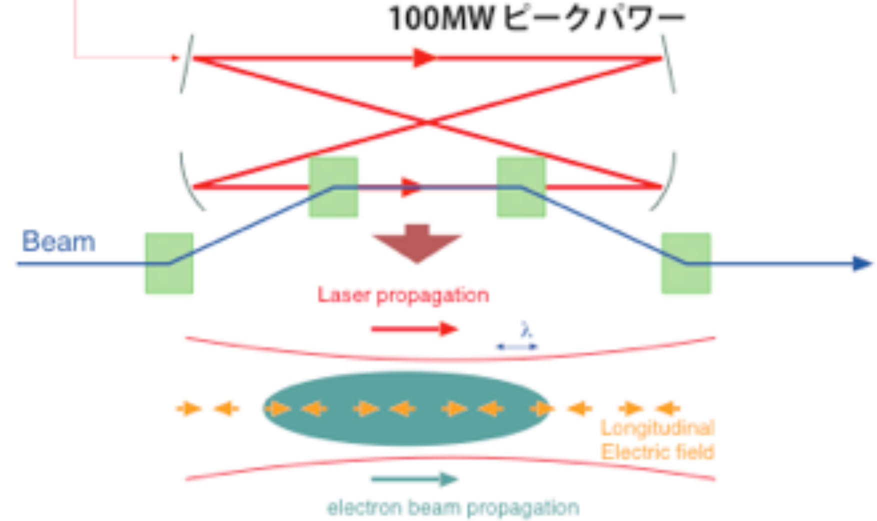


Potential extraction scheme of burst mode cavity for a high energy gamma gamma collider:
Breitkopf et al., Light: Science and applications (2014) 3

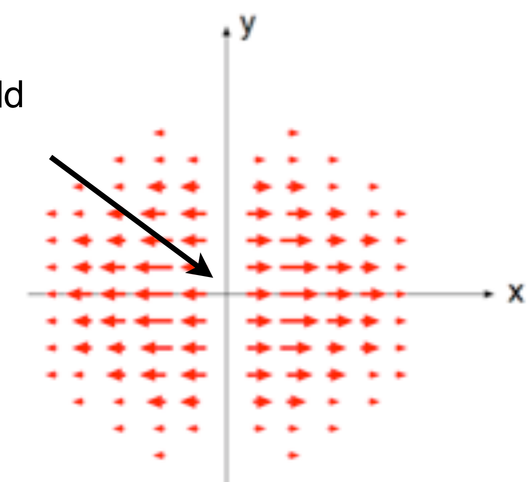
Application in FEL

- Optical cavity enables us to realize high repetition rate, high intensity laser pulse.
- High repetition rate FEL (ex. ERL-FEL) needs such laser
  - Laser seeding for time coherent radiation
  - Laser heater for controlling instability

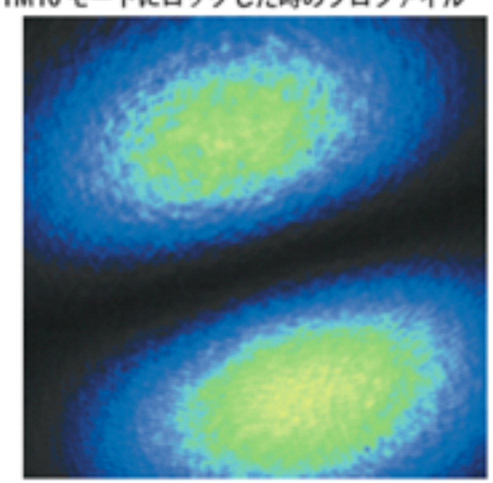




accelerating/decelerating field
in here



TM10 モードにロックした時のプロファイル



Summary

- LAL and KEK have similar project of laser-Compton X-ray source.
- Development of an optical cavity is the key.
  - High power load on the cavity mirrors
  - Precise resonance control
- Communication between groups helps the R&D
  - New ideas; cavity design, feedback scheme, ...
  - Test setup and experiences; mirror handling, noise survey,...
- Optical cavity has other applications
  - High intensity pulse extraction
  - Advanced FEL

- Plan of 2016
  - We plan to have a collaboration meeting in KEK
  - Request support of travel budget for LAL members to visit KEK
  - (no request for sending KEK member to LAL this year)