A study of Optical Enhancement Cavity with short laser pulses for laser-electron beam Interaction

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Contents

Motivation: X-rays applications and sources

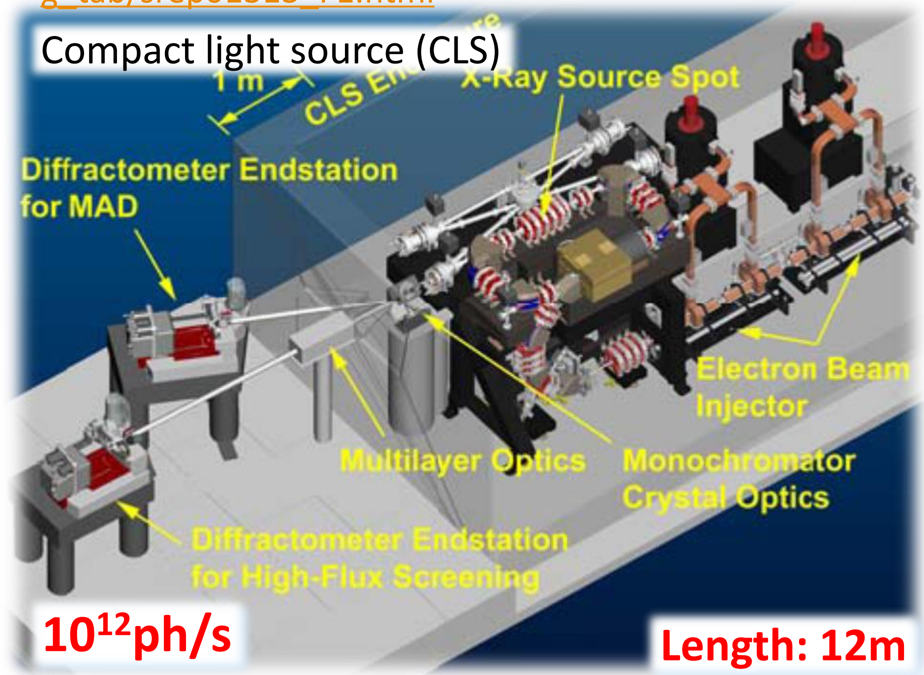
X-ray applications requires high quality source

- **Life science** : X-ray Tomographic Microscopy, X-ray crystallography of biological structure & function at the molecular level, …
- **Material science** : X-ray crystallography of ceramics, powders, agglomerates, …
- **Medical diagnosis** : Imagery, therapy, …

X-ray source examples

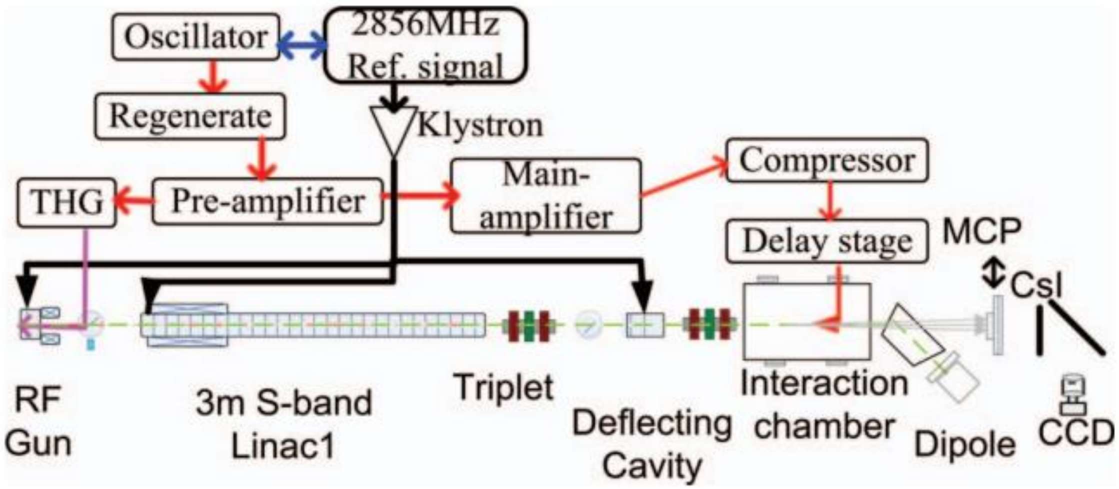
Facilities	Properties
Synchrotron Radiation	High brightness, high energy electron storage ring GeV, large device, high cost
Free Electron Laser	Far exceed brightness, intensity , but high energy electron Linac, large device, high cost,
Thomson scattering	**Compact, relative low cost**

http://www.nature.com/srep/2013/130221/srep01313/fig_tab/srep01313_F1.html



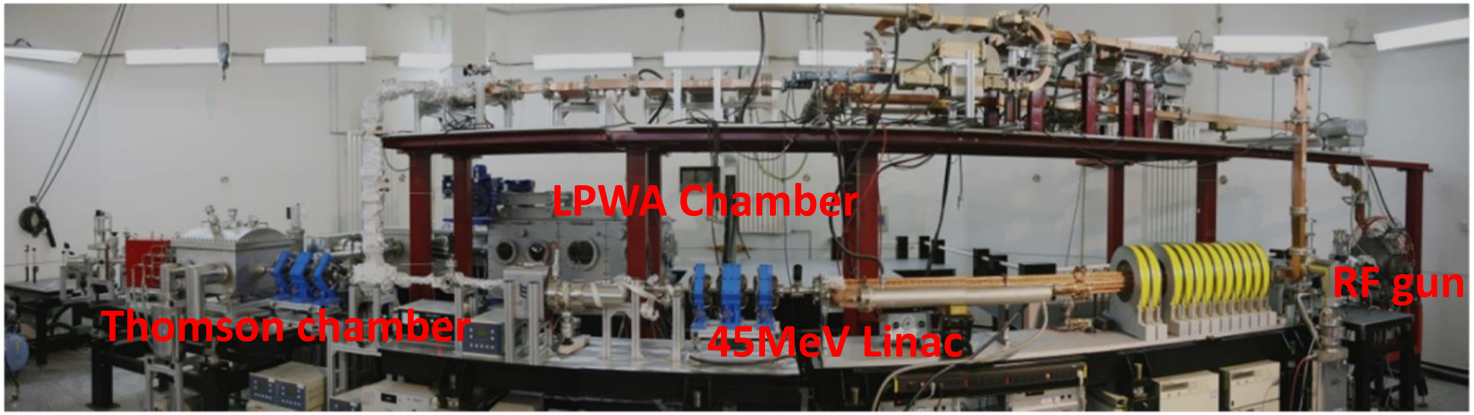
Tsinghua Thomson Scattering platform

- **Existing** setup: 10TW laser system and 45MeV LINAC



Electron beam		Laser beam	
Energy	45MeV	**Wavelength**	800nm
Bunch length	1~4ps	**Pulse duration**	~50fs
Charge	~0.7nC	**Pulse energy**	~500mJ
Beam size	30(H)x25(V)um	**Beam size**	~30um

Main features:
High peak power : TW-PW
Low average power : several W
Short pulse duration : tens of fs
Huge pulse energy : hundreds of mJ
Low repetition rate : tens of Hz



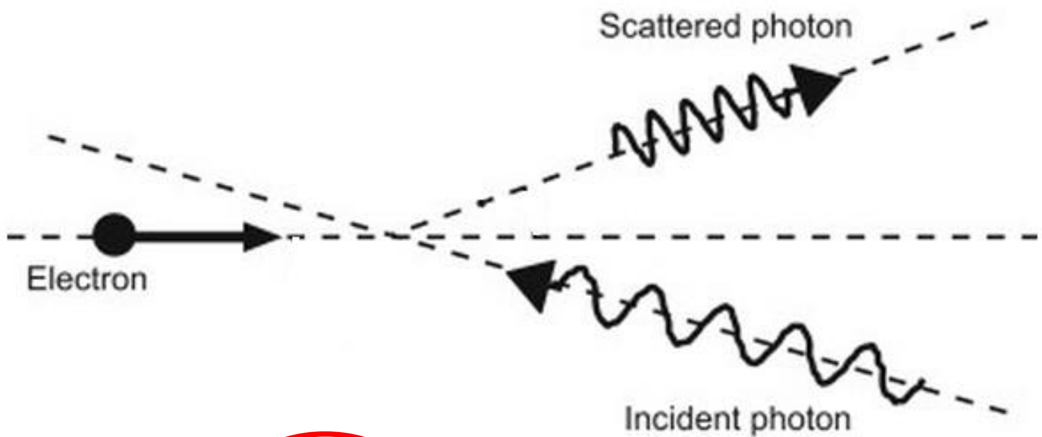
Thomson scattering: achieved X-ray photon Flux $3.4\text{x}10^7$ph/s

Laser plasma wakefield accelerator: obtained 10~40MeV high quality monoenergetic electron beams

Paper: Generation of first hard X-ray pulse at Tsinghua Thomson Scattering X-ray Source

Paper:Generating 10~40MeV high quality monoenergetic electron beams using a 5TW 60fs laser at Tsinghua University

Laser-Electron Thomson Scattering principle



$$N_\gamma \propto \frac{N_e\ N_l\ \sigma_T\ \mathrm{Frep}}{\sqrt{\sigma_{electron}{}^2 + \sigma_{laser}{}^2}}$$

Tens of Hz → Tens of MHz

N_e: electron number
N_l: laser photon number
σ_T: Thomson scattering cross-section
F_{rep}: colliding repetition rate

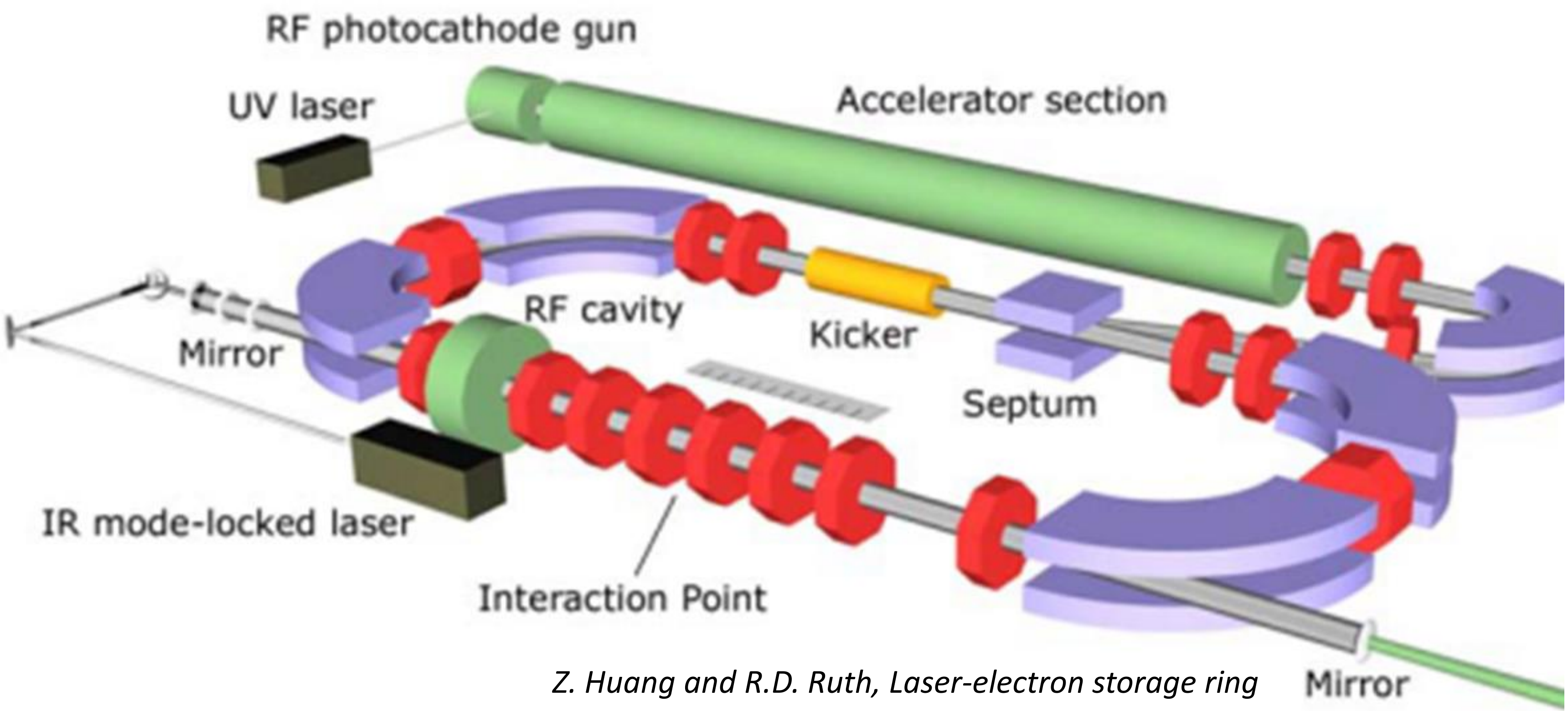
$\sigma_{electron}$: electron beam size r.m.s
σ_{laser}: laser beam size r.m.s

- The **cross-section** for this process is **very low** :

$\sigma_T = 6.65 \times 10^{-33}\ cm^2$

OEC based X-ray machine

First OEC based X-ray machine concept drawing



Z. Huang and R.D. Ruth, Laser-electron storage ring

R. J. Loewen, thesis

- **OEC**
  - → **recycle** laser
  - → accumulate the laser power
- **Enhancement factors** on the laser power: $10^3 \sim 10^4$

Main features:

High average laser power: kW-MW

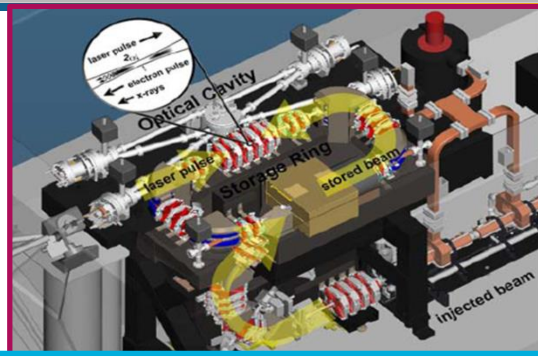
High colliding rate: ~ tens of MHz

High X-rays flux : 10^{11}-10^{13} ph/s

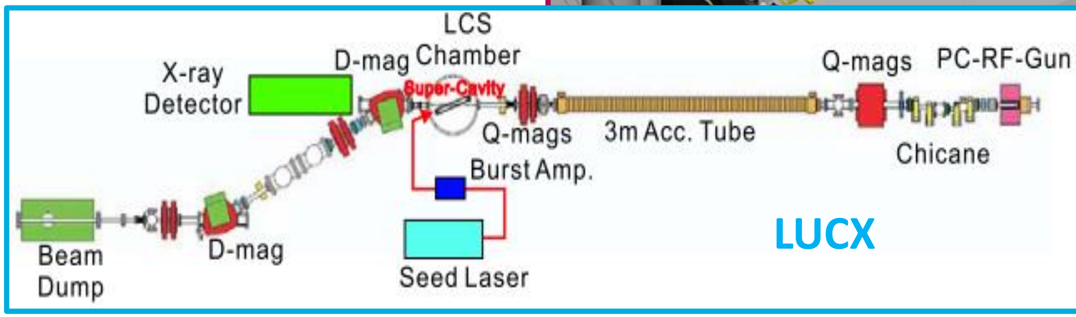
OEC based X-ray machine status

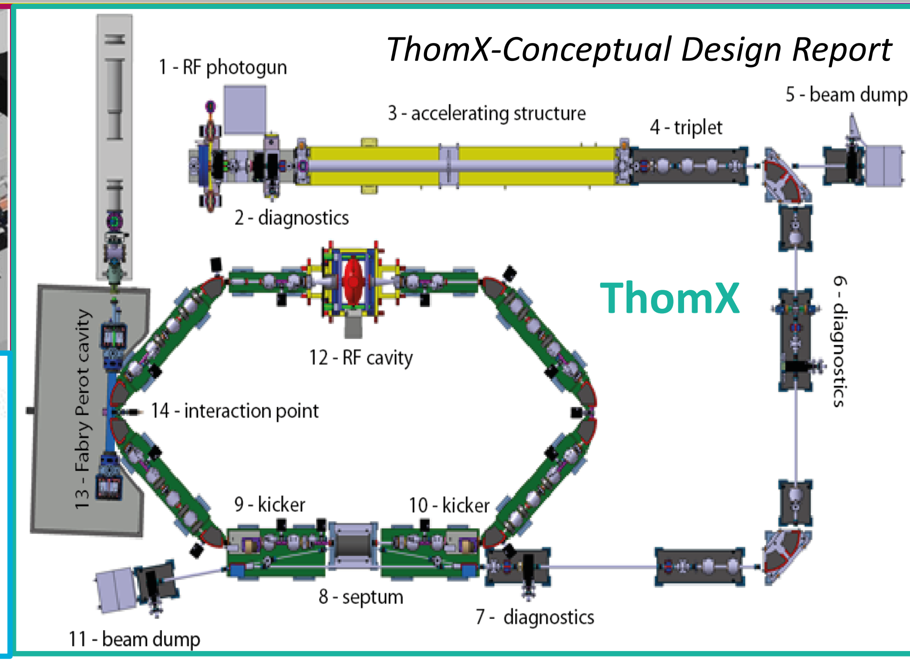
J. Abendroth et al. J Struct Funct Genomics 11:91-100(2010)

Lyncean Tech



K. Sakaue et al. Proceedings of EPAC 2006, THPCH154





Facility	Lyncean Tech/SLAC In operation	KEK:LUCX In operation	LAL: ThomX Under construction	Ukraine: KIPT Proposal
Electron energy [MeV]	20–45	30	50	40-225
X-ray Energy [keV]	Expected :7-35 Present: 10-20	Present :10	50-90	6-900
Flux [ph/s]	Expected :10^{13} Present: 10^{12}	Present :10^{5}	10^{11}-10^{13}	10^{13}
Size	12 m length	~10m LINAC	10m x7m total size	

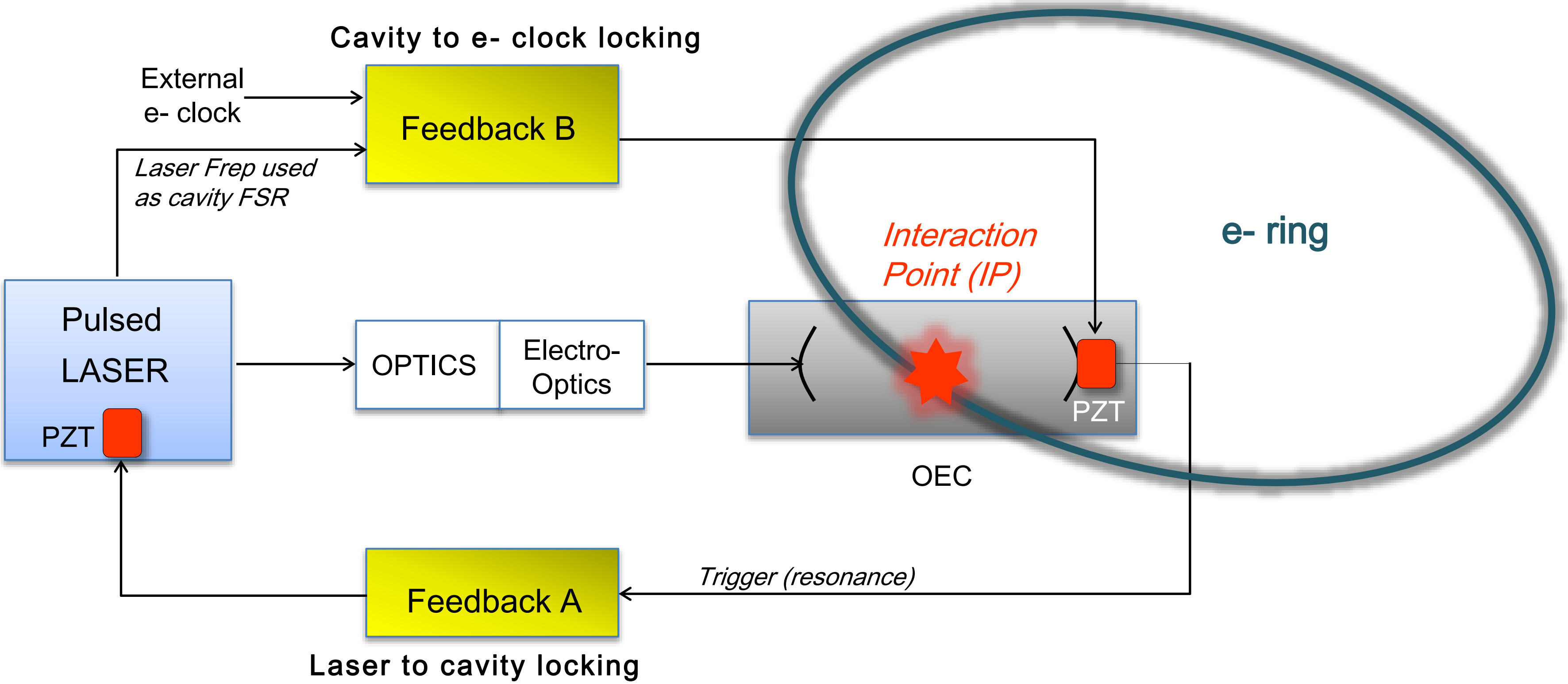
Other applications of pulsed laser injected OEC

Application	Detail	Institute
Thomson scattering	γ-rays source	KEK, LAL, SLAC, KIPT
Laser wire	Low emittance electron beam size monitor	KEK
Polarimeter	electron beam polarity diagnostic	DESY
HHG	soft X-ray source, XUV light	JILA, MPI
Frequency stabilization	Carrier-Envelope Phase Control of Femtosecond Mode-Locked Lasers	JILA

OEC system overview

The OEC system can be divided into **7 sub-systems** :

Laser, **OEC**, Optical setup, Electro-optical setup, Locking(**Feedback)** , Mechanics, Diagnostic tools.



Block diagram of the OEC sub-systems

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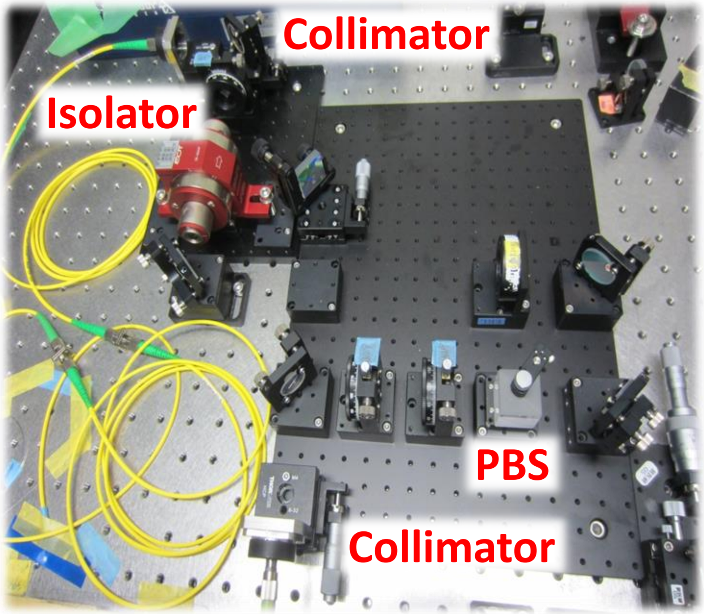
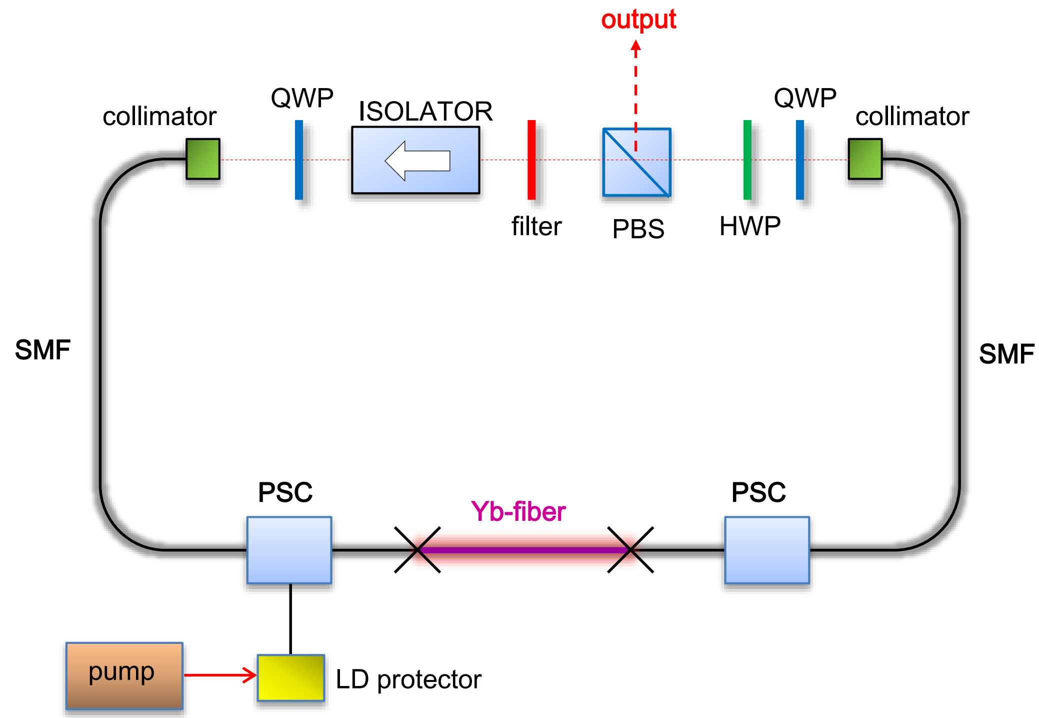
Mode-locked fiber laser construction

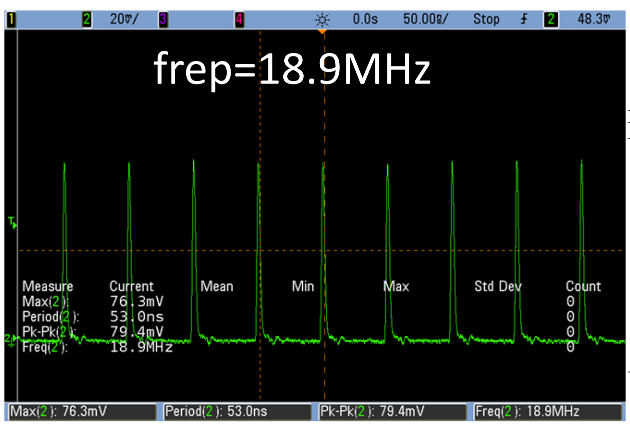


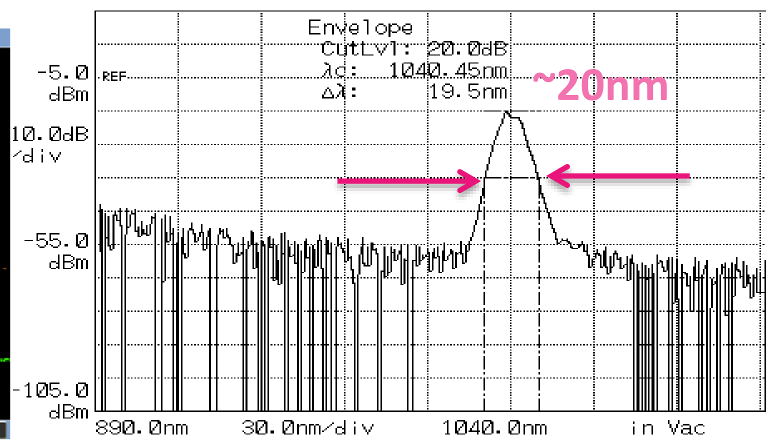
Picture of the laser



Setup layout of the mode-locked Yb-doped fiber laser based on Nonlinear polarization rotation

- Self-starting mode-locking





- Pulse duration ~300fs
- Output pulse power 65mW to 170mW

Y. You et al, IPAC13

Mode-locked fiber laser design

Laser type @ hundreds of MHz: solid-state -10W; Yb-doped fiber laser-420W, **high power**
Fiber laser **low cost** compared to the solid-state laser
-> best candidate for laser source of OEC

H. Carstens, et al, Optics Letters.,39, 2595-2598 (2014)

Mode-locking method

- Nonlinear polarization rotation(NLPR)

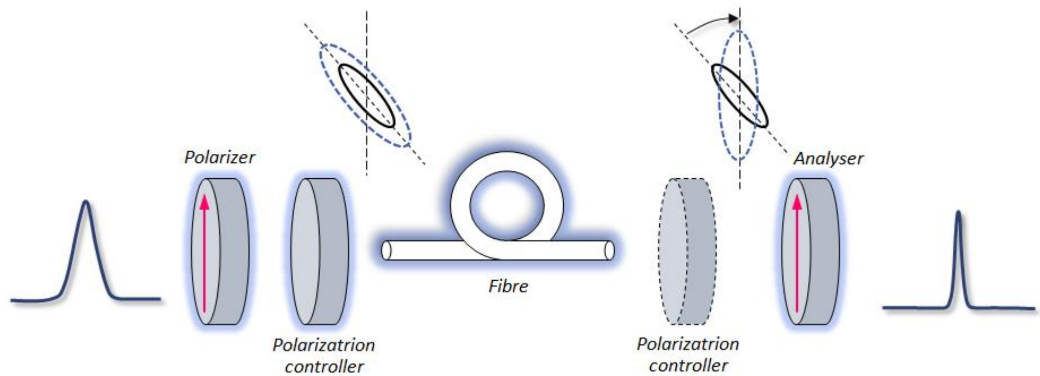
A power-dependent polarization change is converted into a power-dependent transmission through a polarizing optical element.

Advantages:

Easy to implement, no need saturable absorbers, applicable to high power output

Disadvantages:

optimum polarization settings can drift with temperature and fiber bends, suffers from polarization changes



A. Hideur, et al. Appl. Phys. Lett. 79, 3389 (2001)

Cavity configuration:

A. Chong et al, Opt.Express 14, 10095 (2006)

- All-normal dispersion setup

- Simple setup, only consists of elements with normal GVD, no need to have dispersion compensation elements
- Wave breaking free pulse, pulse energy up to about 50 nJ, output power several hundreds mW

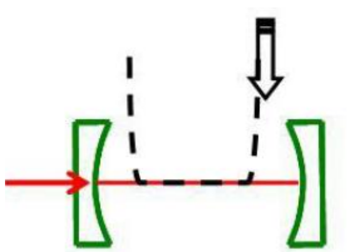
Contents

Cavity geometry

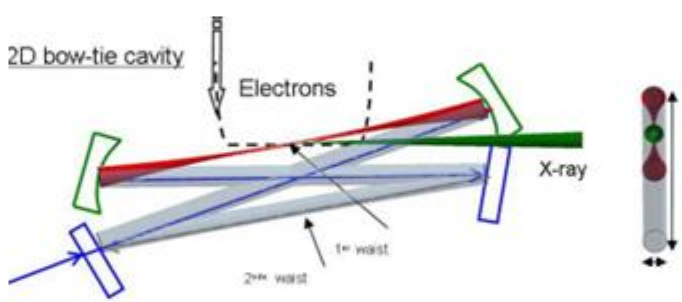
Criteria : **stable geometry + small waist size + easy to install and control**

	2-mirror	4-mirror	6-mirror , 8-mirror
2D	simpler design but concentric geometry is **mechanically unstable** when small laser waists are foreseen	compared to 2M, mechanically **more stable and** provides better flexibilities to adjust the cavity round trip frequency and the cavity waist size. 2D compared to 3D, **more compact** and more easy to install **2D crossed cavity** needs **less space** for integration to electron storage ring than the **2D bow-tie cavity**	compared to 4M cavity, **more unstable elements** and **more variable parameters** : control more difficult to achieve.
3D	*Not applicable*	compared to 2D, same mechanical stability, more difficult to install.	

2M

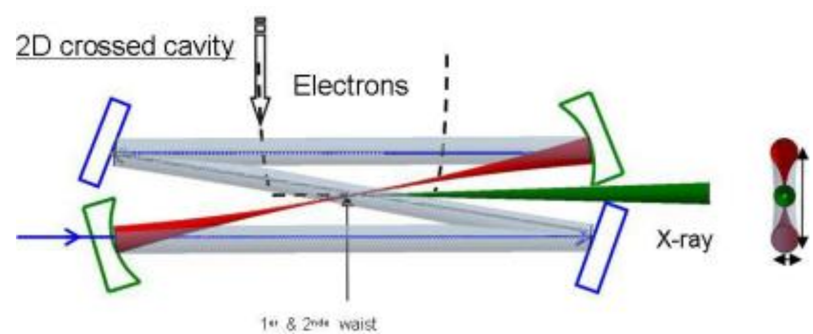


4M –2D bow-tie



4M – 2D crossed cavity

best geometry for **stable, small waist, easy to install and control**



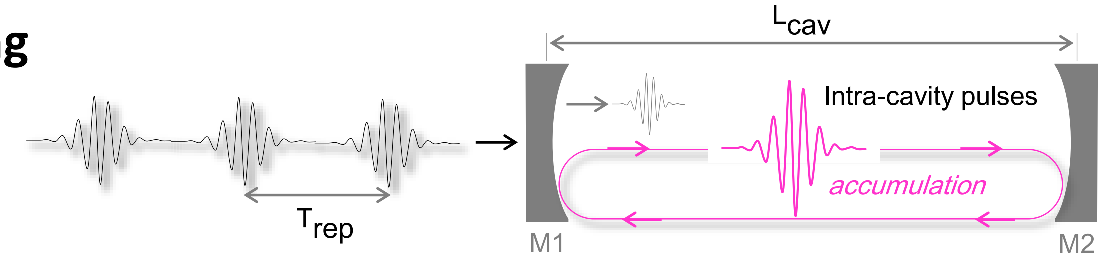
Pusled laser-OEC stacking

Enhancement : the cavity enhances the laser power by stacking each pulse.
The enhancement factor, G, is determined by cavity finesse $\mathcal{F}$: $G=\mathcal{F}/\pi$

$$\mathcal{F} = \frac{\pi\sqrt{R_{eff}}}{1-R_{eff}}$$

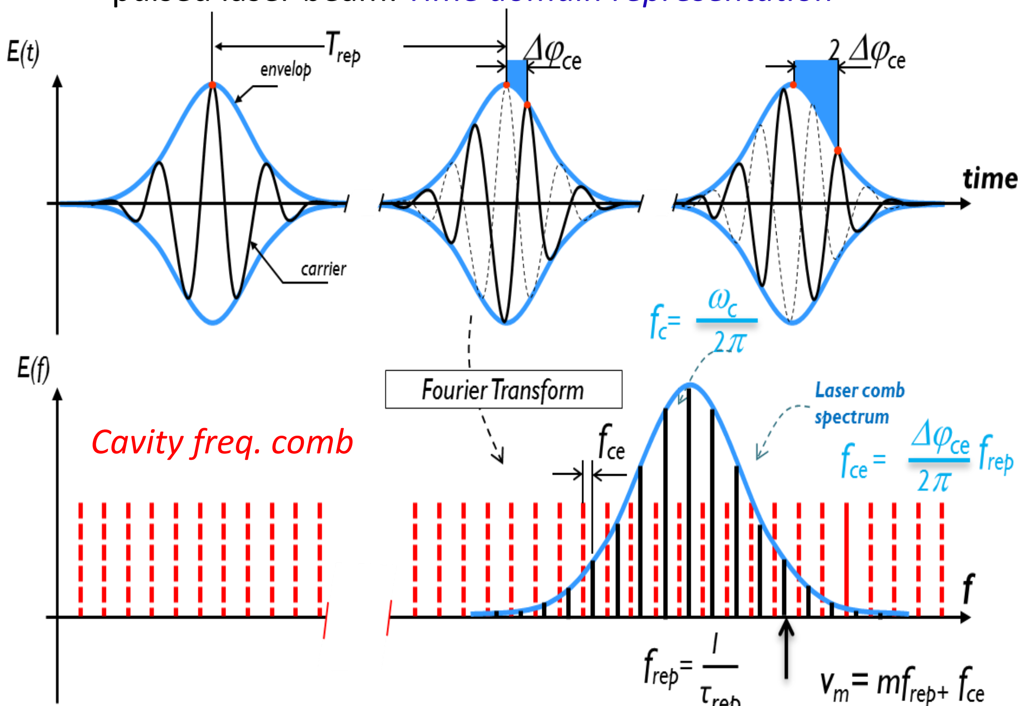
Laser pulse stacking

$$f_{rep} = \frac{1}{T_{rep}}$$



$$FSR = \frac{c}{2\,L_{cav}}$$

pulsed laser beam: *Time domain representation*



pulsed laser beam: *Frequency domain representation*

- The laser beam **repetition rate** f_{rep} must match the Free Spectral Range (FSR) of the cavity.

Comb <u>spacing</u> matching $\underbrace{f_{rep}}_{laser} = \underbrace{FSR}_{cavity}$

- The laser beam pulses are injected with a **pulse-to-pulse phase** $\boldsymbol{\Delta\varphi_{ce}}$ (laser-design dependent)

- The intra-cavity beam pulses acquire a **phase** $\boldsymbol{\Delta\varphi_0}$ in one cavity round-trip (*mirror dispersion*)

Comb <u>position</u> matching $\underbrace{\Delta\varphi_{ce}}_{laser} = \underbrace{\Delta\varphi_0}_{cavity}$

R. J. Jones et al. Opt. Commun., 175:409-418 (2000)

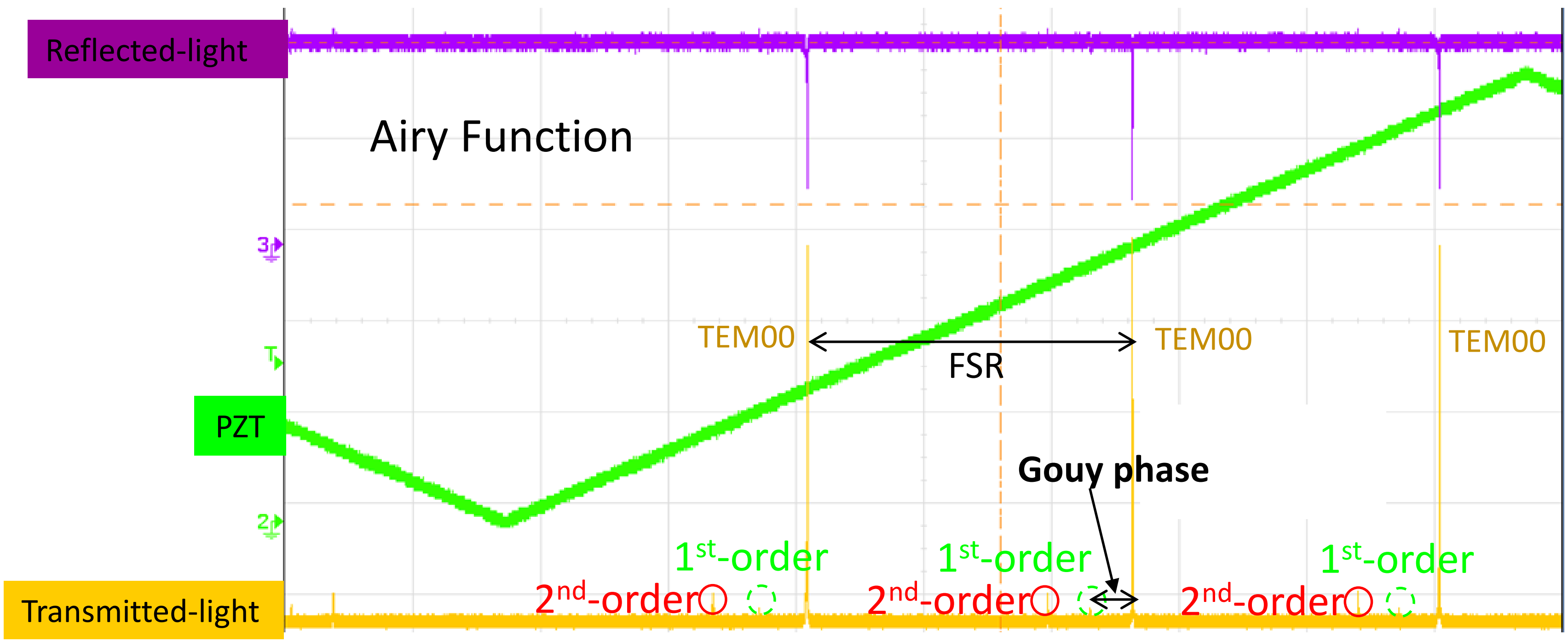
Cavity waist size measurement based on Gouy phase

Traditional method

Pinhole PD	CCD
Scan the cavity transmitted beam	Catch the beam profile of the cavity transmitted light
Use linear fitting of the transmitted light beam size to evaluate the cavity waist size, accuracy is correlated with the fitting	
Scan the beam, time consuming	Precision is affected by the CCD trigger time

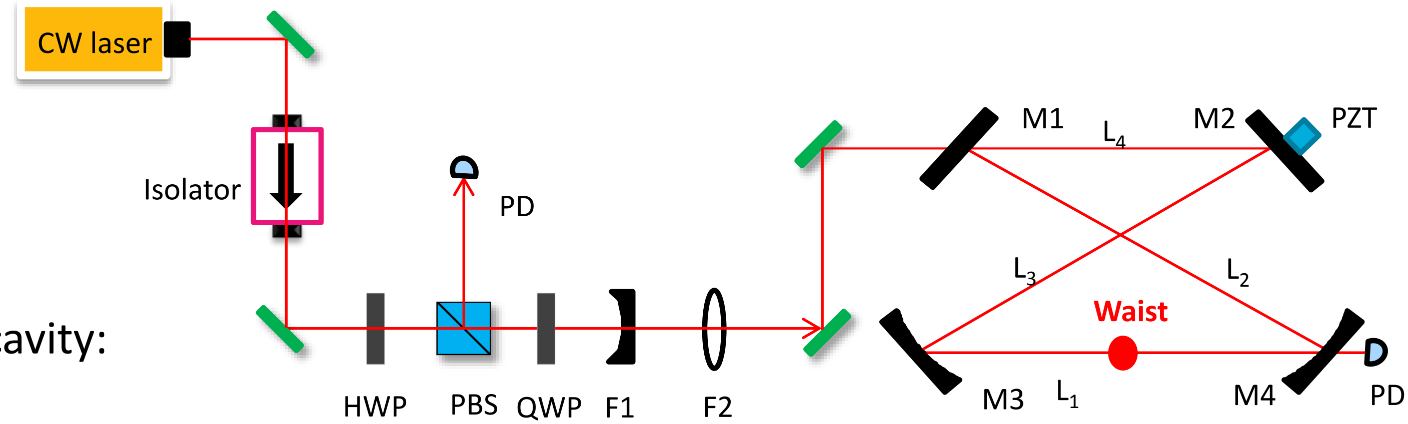
New method

Based on Gouy phase
Cavity waist size is derived directly from the Gouy phase
Simple, accurate
Gouy phase can be directly and precisely measured through the Airy function



Cavity waist size measurement based on Gouy phase

Demonstrated the effectiveness of this new method, based on the gouy phase measurement for planar n-mirror cavity



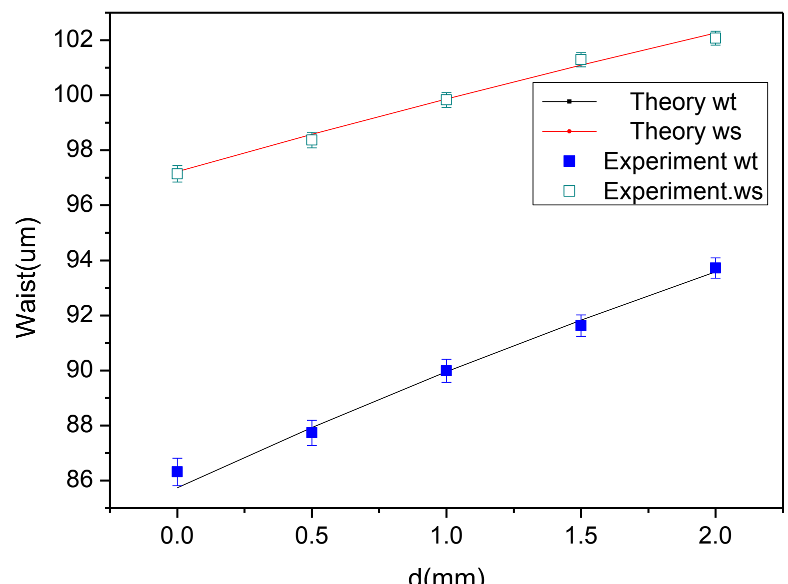
Experimental setup of 4M CW laser

Beam waist size for 4M cavity:

$$\begin{cases} w_{0s} = \sqrt{\dfrac{\lambda(-k_s + \cos(\varphi_s))}{\pi \sin(\varphi_s)}} \\ w_{0t} = \sqrt{\dfrac{\lambda(-k_t + \cos(\varphi_t))}{\pi \sin(\varphi_t)}} \end{cases}$$

w_{0s}: waist size in sagittal plane,
w_{0t}: waist size in tangential plane

φ_s: Gouy phase in sagittal plane,
φ_t: Gouy phase in tangential plane



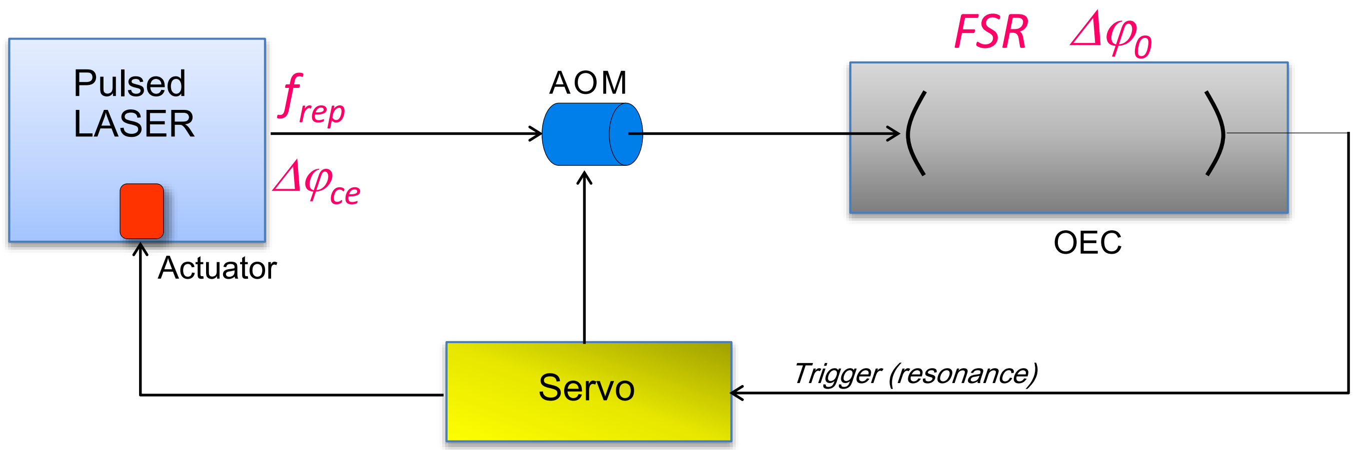
Theoretical and experimental results of 4M CW laser

Y. YOU et al.Nuclear Instruments and Methods in Physics Study A, 694, 6-10 (2012)

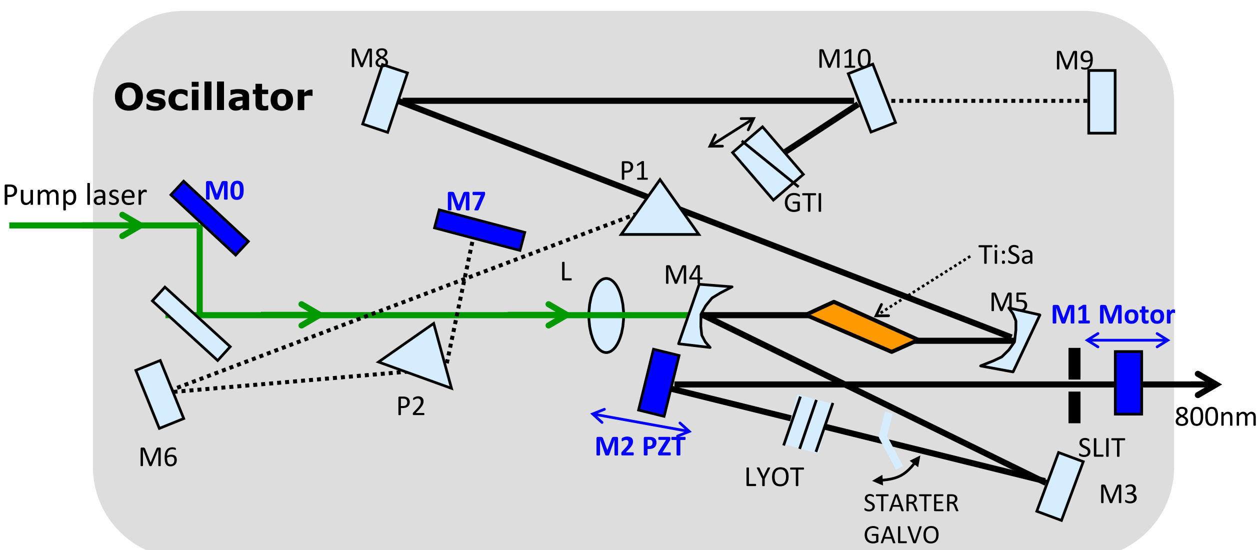
Contents

Locking

What is locking?



Laser to cavity locking



Example of mode-locked oscillator (MIRA, Coherent)

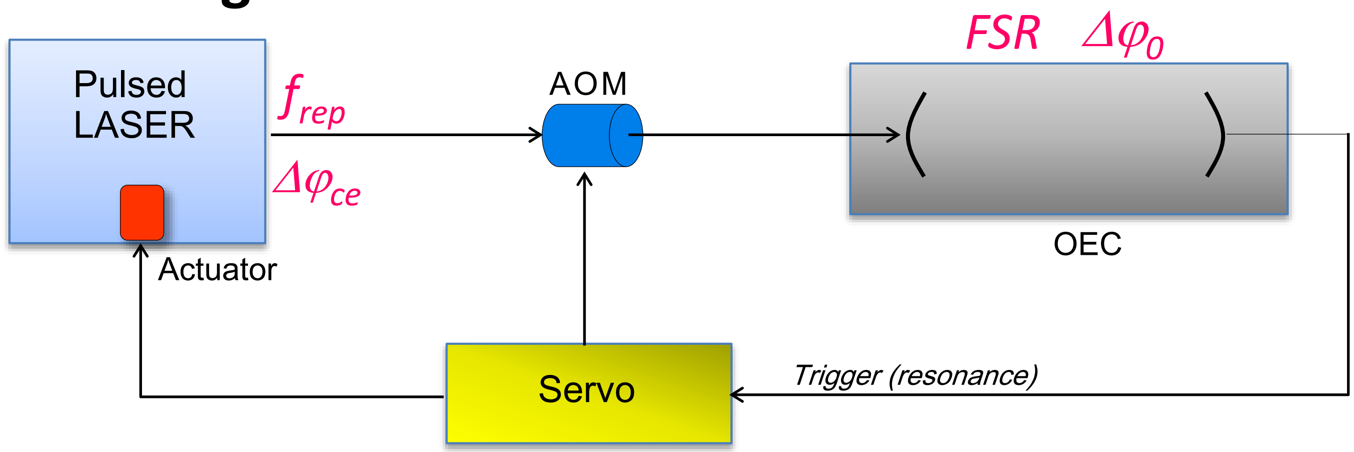
Why do we need a locking?

- laser noise sources: pump light, mirror position, beam axis fluctuations
- The free running mode-locked laser cavity fluctuates by several nano-meters
- The stacking conditions can not be maintained without locking:

$f_{rep}=FSR$ $\Delta\varphi_{ce}=\Delta\varphi_0$

Locking

How to achieve locking?



Laser to cavity locking

- Feedback is scheme to achieve locking.
- By feeding back the laser frep/fce using its PZT/ AOM, the stacking conditions: frep = FSR, and $\Delta\varphi_{ce}$ = $\Delta\varphi_0$ are maintained, thus the cavity is kept on resonance.

Locking stabilization precision: $\frac{\Delta f_{rep}}{frep} = 10^{-13}$ cavity finesse 30 k, relative length control 0.1 pm for a 1 m cavity

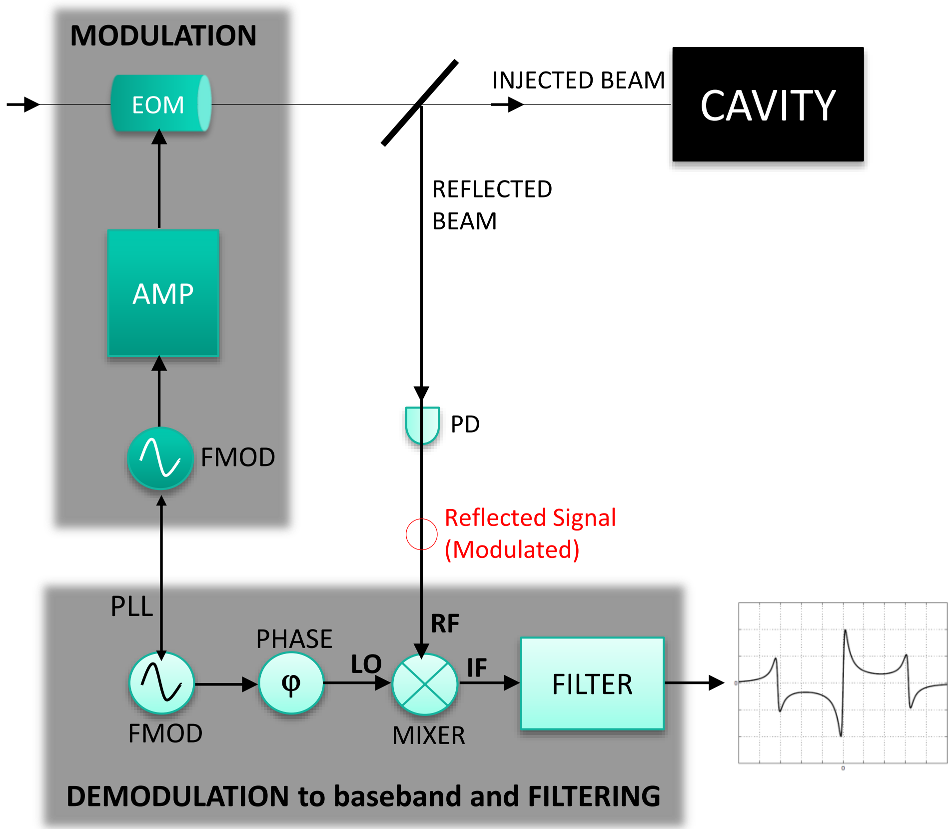
Feedback system consists:

Sensor (PD)
Error signal technique
Analog/Digital Regulator (PI, PI^2)
Actuators (PZT/AOM/EOM/Pump Current)

PDH and TL introduction

PDH technique

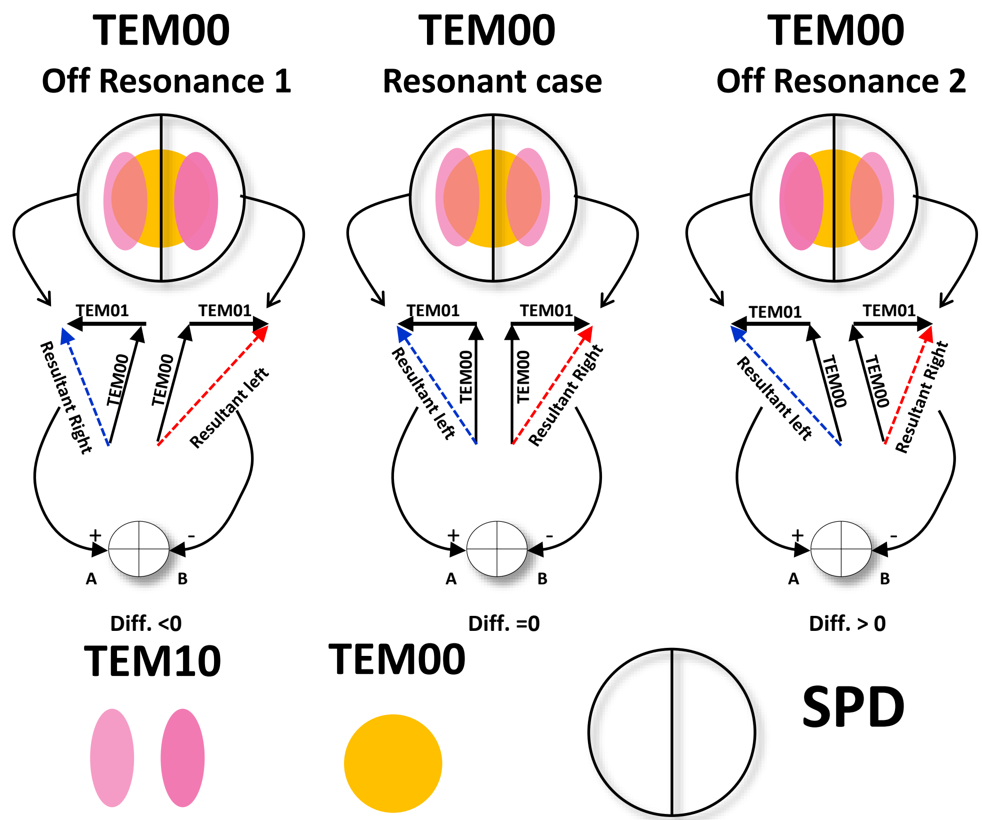
- Commonly used, mature technique
- Complex setup: error signal is got by electronic modulation the injected beam and demodulation of reflected beam



R. W. P. Drever et al. Applied Physics B. 31,97-105(1983)

Tilt Locking (TL) technique

- First used to stabilize the **CW** laser interferometer for gravitational wave detection
- Simple setup: error signal is the interference difference of TEM00 mode and TEM10 mode on the two halves of a Split-Photodiode (SPD)
- Propose to use TL for pulsed laser injected optical cavity locking

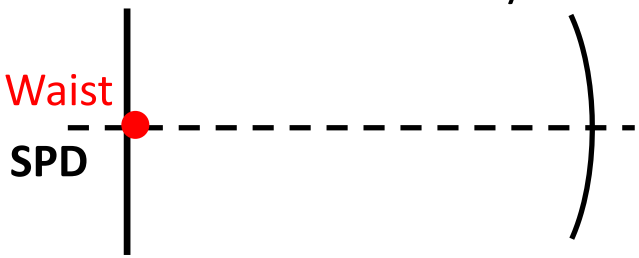


D. A. Shaddock et al. J. Opt. A: Pure Appl. Opt. 2, 400 (2000)

TL error signal derivation

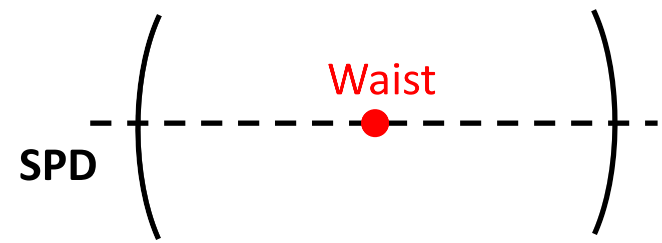
SPD @ near waist of interferometer

Plane-concave cavity

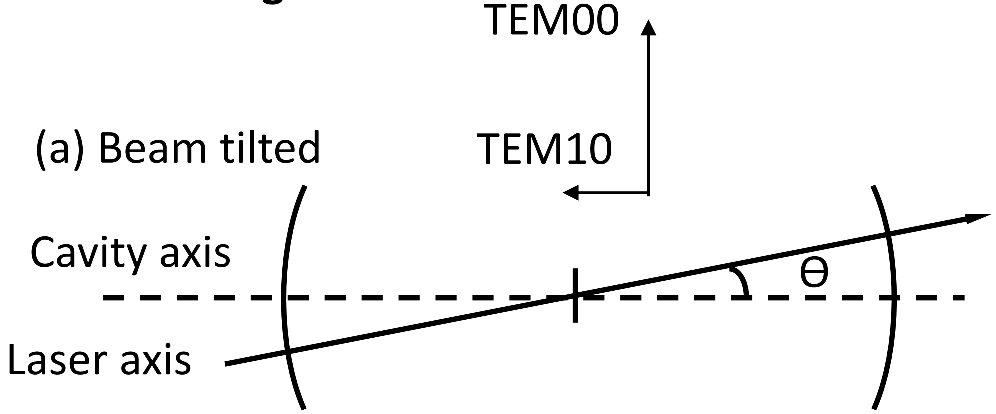


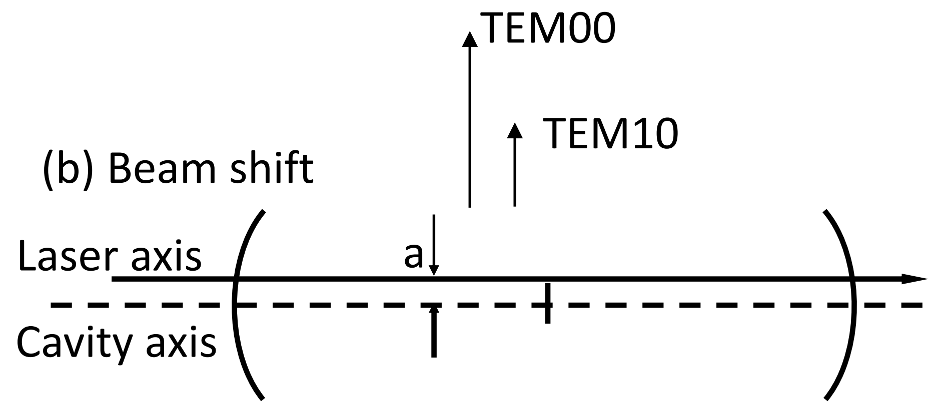
SPD @far away from waist

Concave-concave cavity



TEM10 mode generation





D.Z. Anderson, Appl. Opt. 23, 2944-2949 (1984)

Perfect aligned

SPD transverse offset

General form of error signal formula

$$\varepsilon = \varepsilon\left(z,\ \theta,\ \mathrm{a},\ \Delta,\ w_s / w_z \right)$$

Y. You et al, Rev. Sci. Instrum. 85, 033102 (2014)

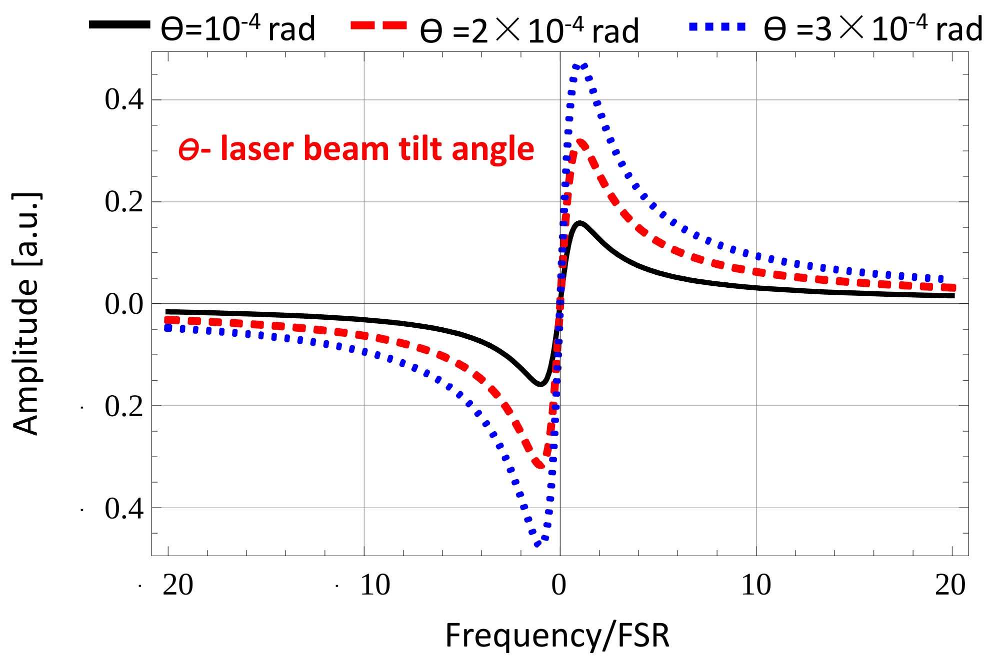
TL error signal simulation

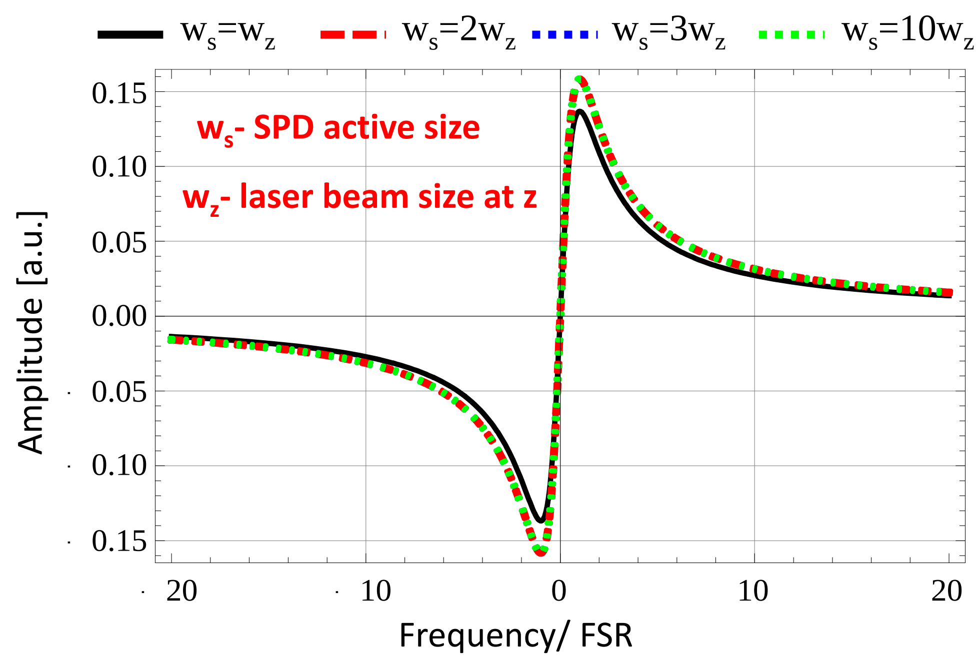
At the waist position, z=0

Symmetrical error signal :θ and SPD size

Tilt angle θ vs error signal

SPD size vs error signal

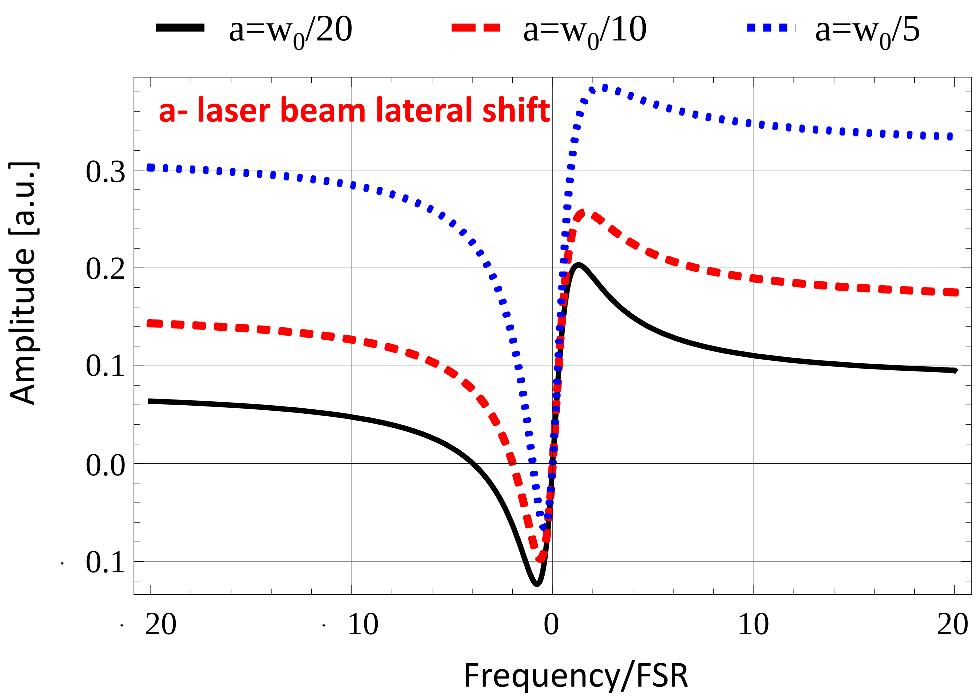


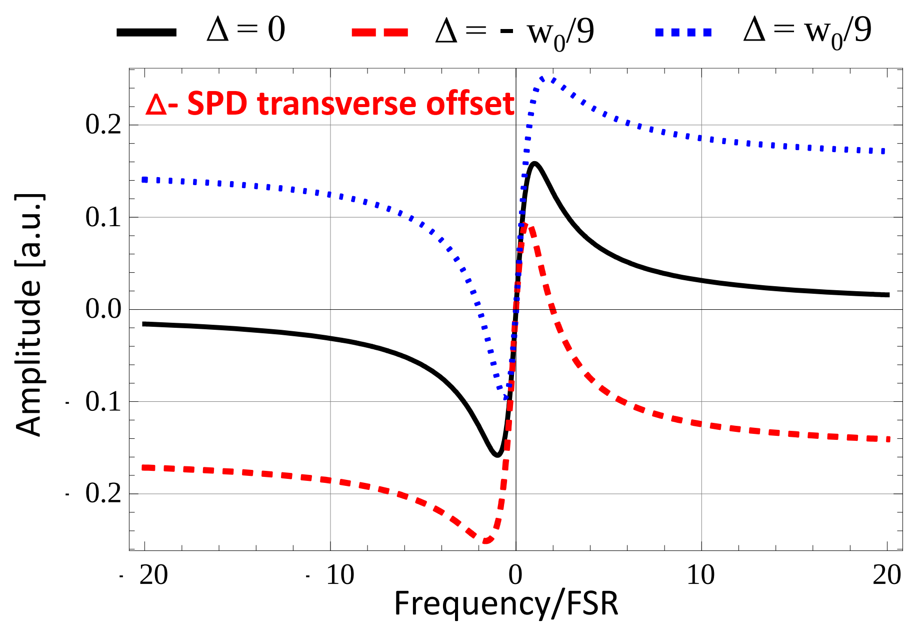


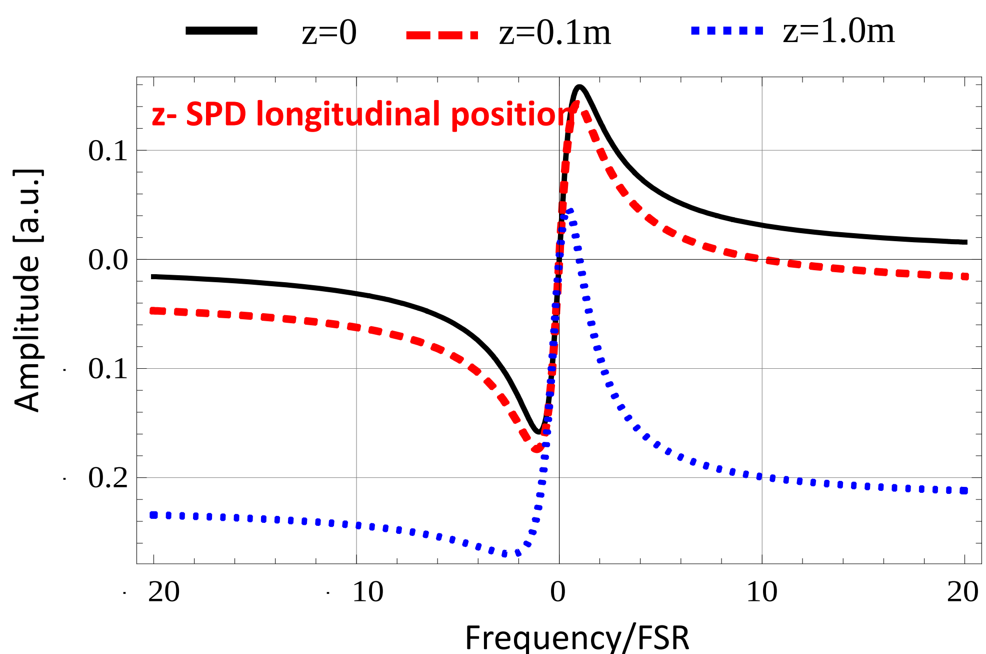
Tilt angle and SPD size only affect the amplitude of error signal, symmetrical error size at z=0

TL error signal simulation

Error signal deformation: z, a, Δ







TL Error signal deformation compensation

$$\varepsilon = \varepsilon\left(a,\quad \theta,\quad \Delta,\quad w_0,\quad z,\quad w_s / w_z\right)$$

a- laser beam lateral shift

θ- laser beam tilt angle

Δ- SPD transverse offset

z- SPD longitudinal position

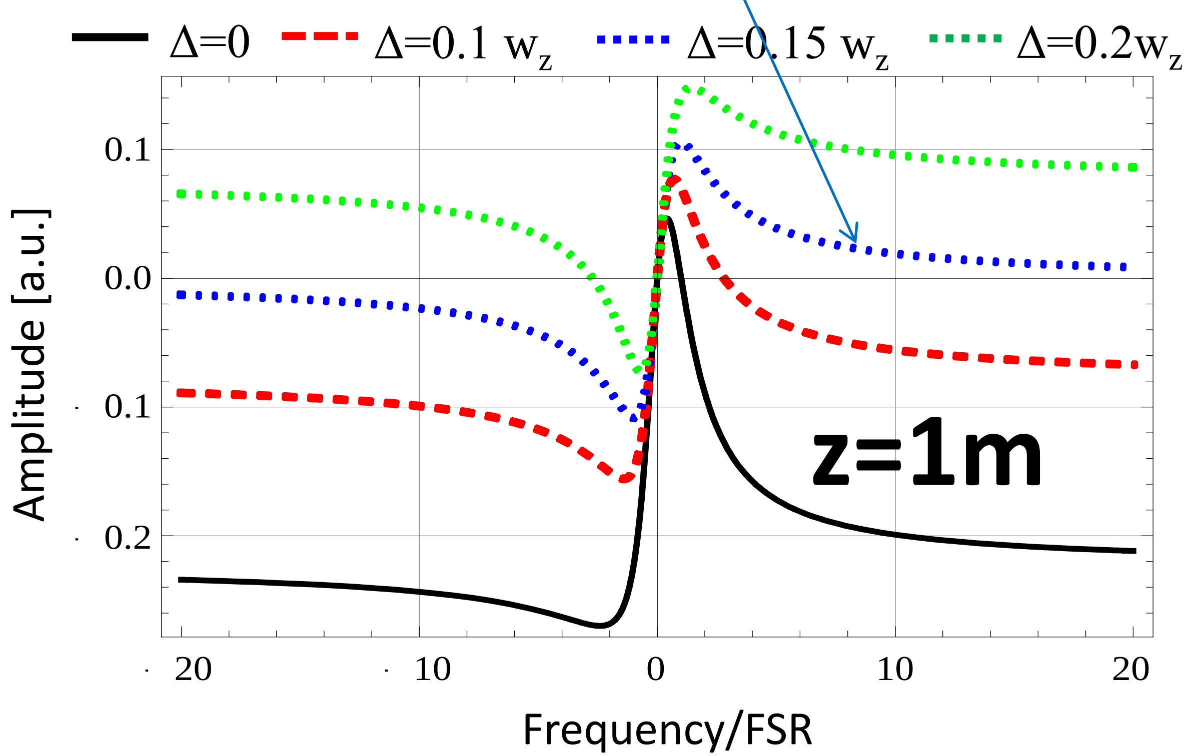
w_0- Cavity waist size

w_s- SPD active size

w_z- laser beam size at z

Deformed error signal

What we want is **Symmetrical error signal**

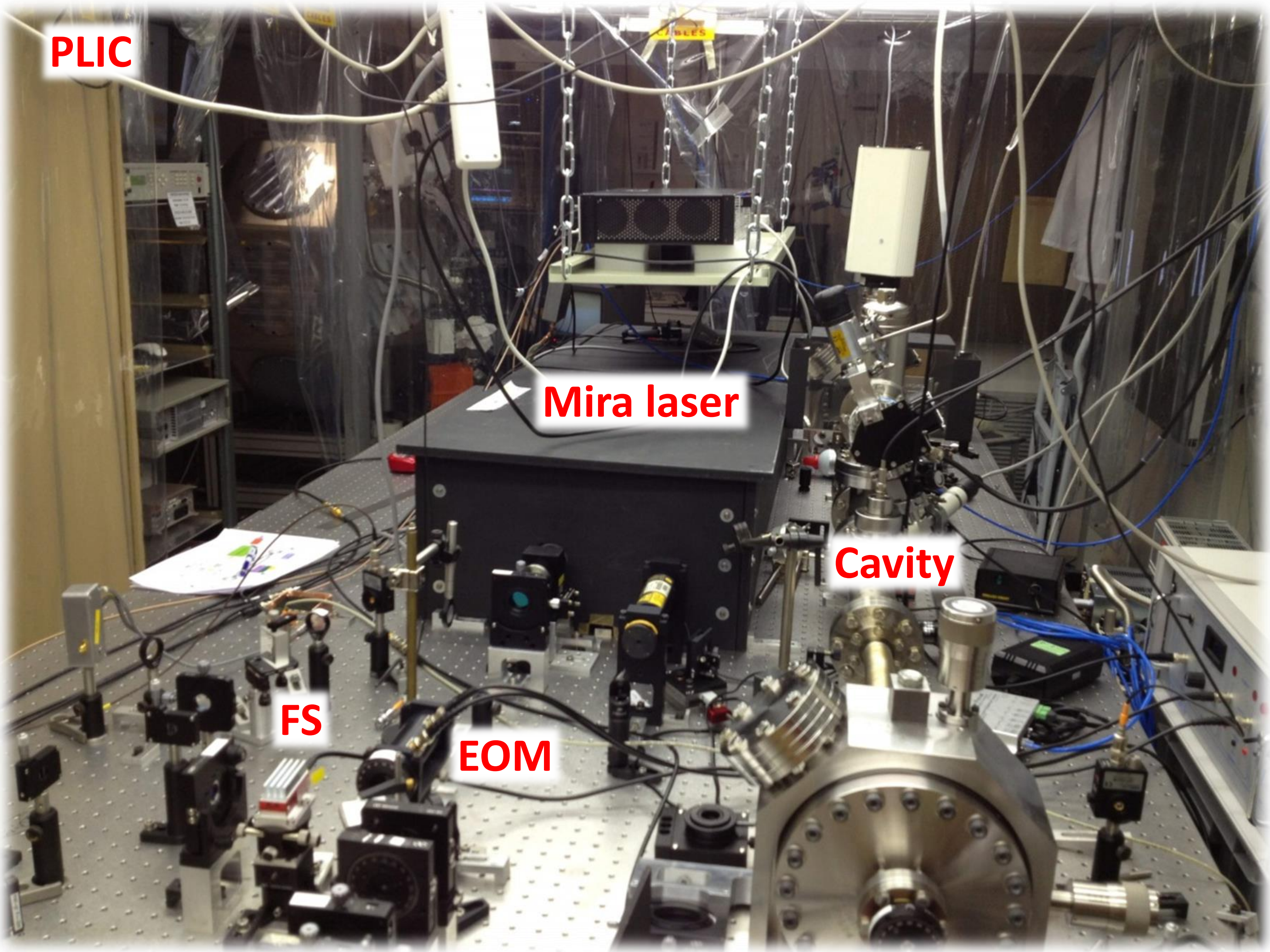


Θ =10^{-4}rad

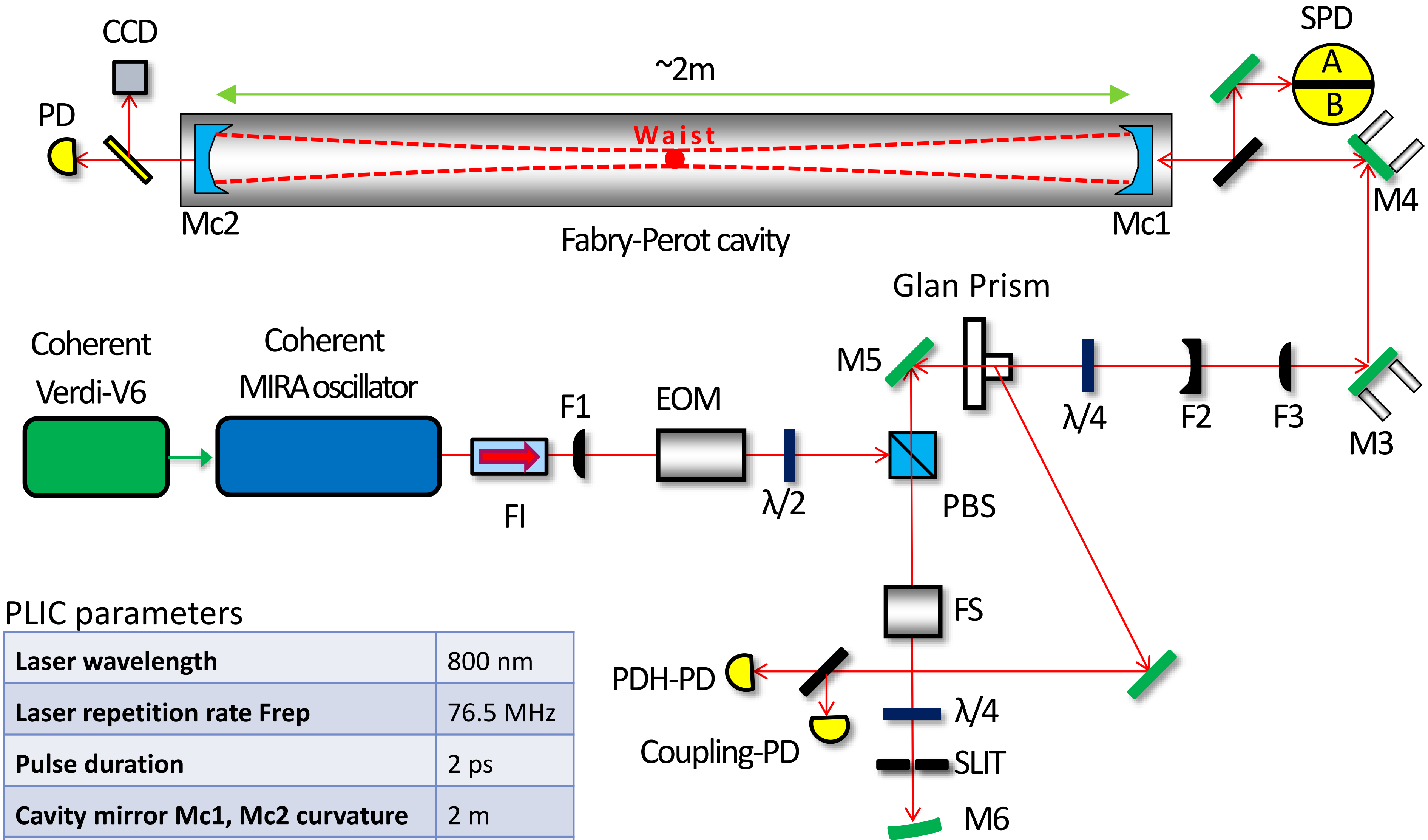
a=w0/10

w_s=w_z

Experimental setup @ LAL, France



Experimental setup @ LAL, Orsay



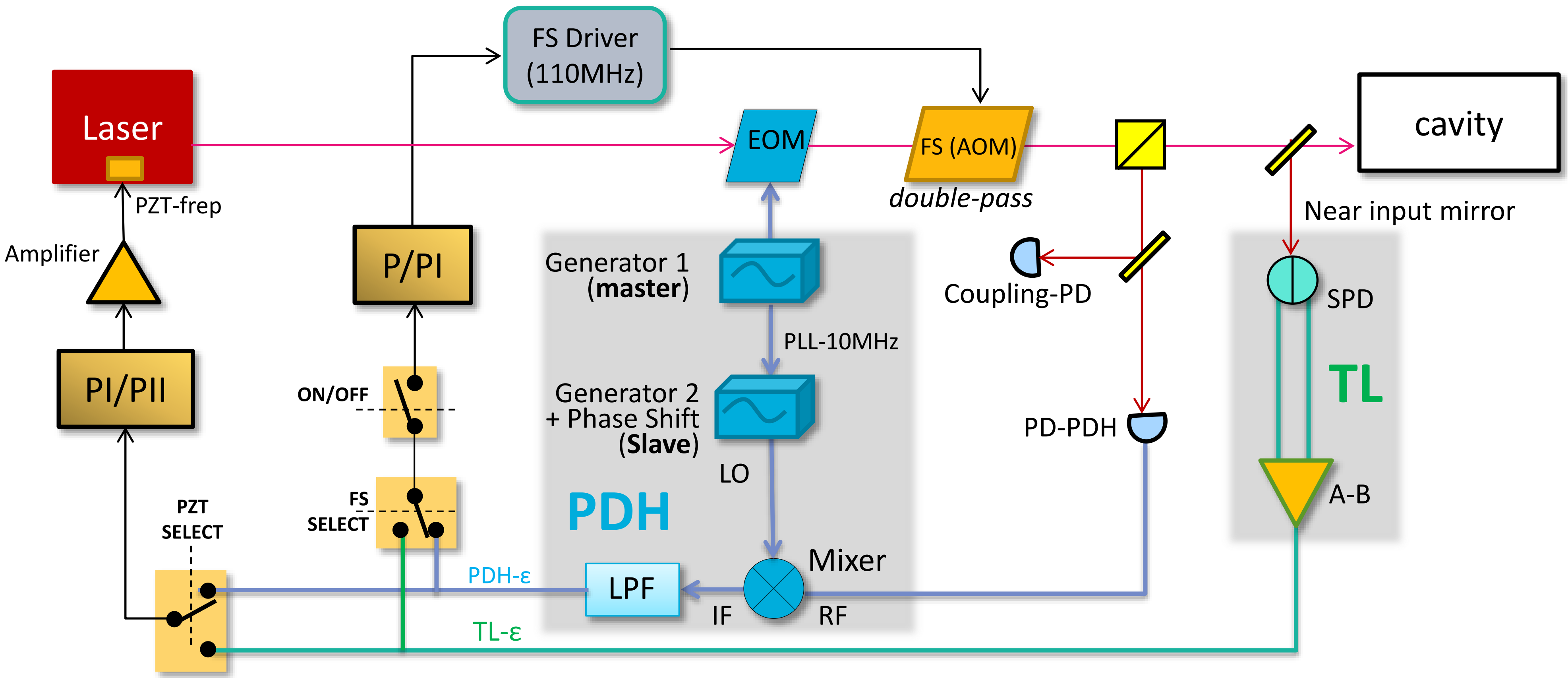
PLIC parameters

Laser wavelength	800 nm
Laser repetition rate Frep	76.5 MHz
Pulse duration	2 ps
Cavity mirror Mc1, Mc2 curvature	2 m
Cavity length Lcav	~2 m
Cavity finesse	28 000

Locking function diagram of PLIC

PDH and TL in one setup

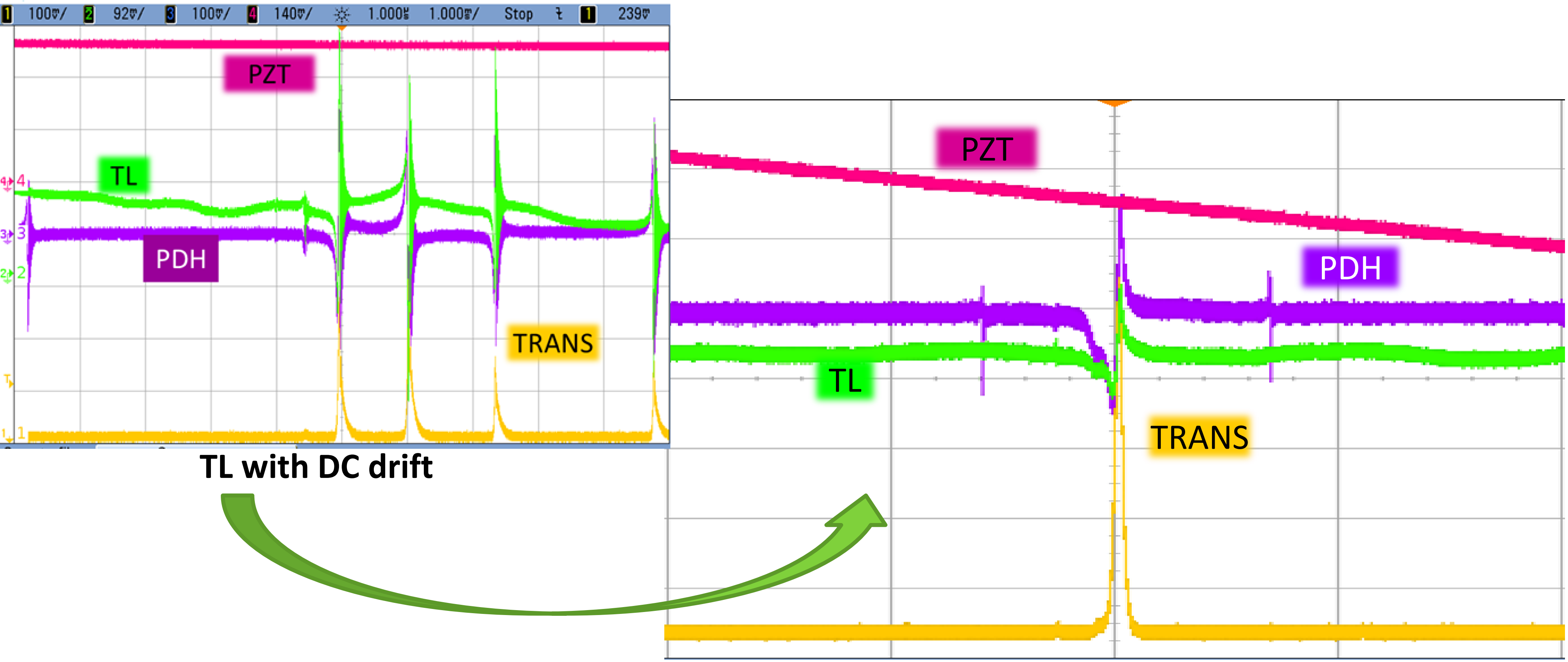
PZT for frep control, and FS for fce control



PZT and FS selections are independant

TL Experimental Results

TL and PDH error signal comparison



Housing & air-conditioner off

TL, PDH error signals and the transmitted signal.

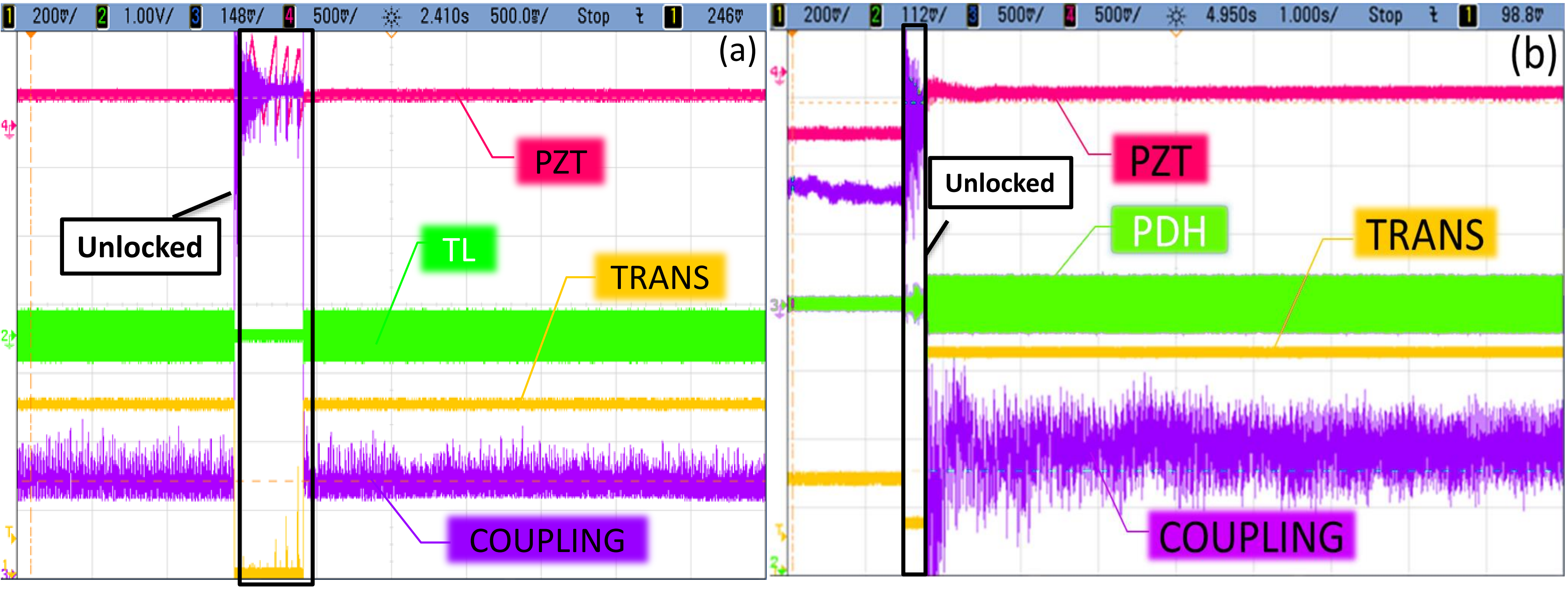
Y. You et al, Rev. Sci. Instrum. 85, 033102 (2014)

TL Experimental Results

TL and PDH locking comparison

Both TL and PDH: high sensitivity , stable locking the cavity more than 1h, and high coupling

- TL is sensitive to beam pointing, environment noises. Low noise environment is needed



Examples of (a) TL locking, average coupling ~80%; (b) PDH locking average coupling ~73%.

TL shows the same locking ability as PDH, high coupling rate, stable locking in a quiet environment.

- **Demonstrated that TL is applicable in the far field case**
- **TL can be used to lock a pulsed laser to a high finesse cavity**

Y. You et al, Rev. Sci. Instrum. 85, 033102 (2014)

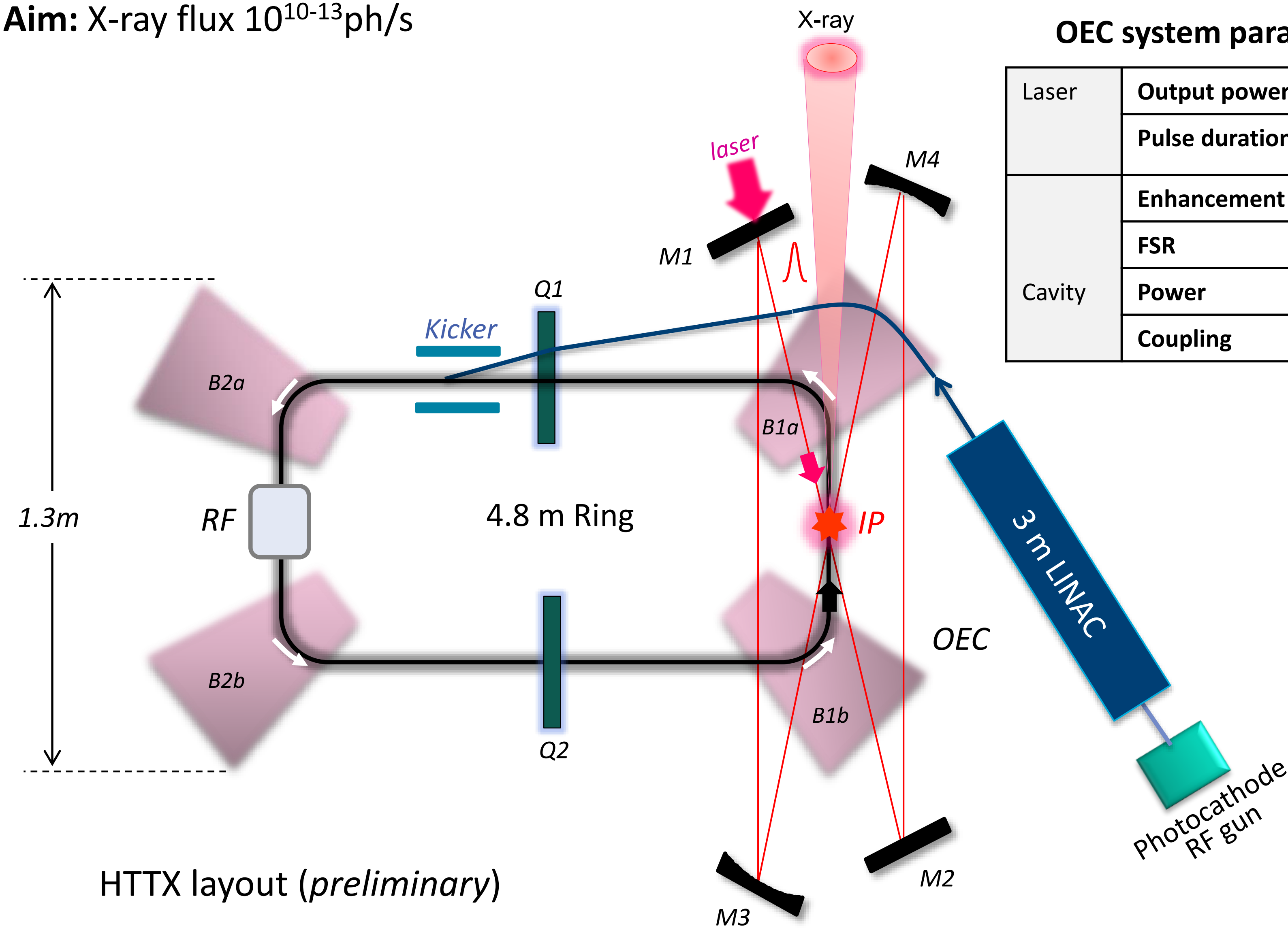
TL / PDH Comparison

	PDH	TL	Comments
Technique	Requires electro-modulation and demodulation.	Use the interference between TEM00 and TEM01 modes	TL has more simple setup
Components/Cost	EOM, EOM Driver, two waveform generator, Mixer, filter	One SPD, Diff. board	TL is cheaper
Stability	Very good.	Depend on error signal drift	Housing can be a solution
Error signal amplitude	Depends on EOM modulation depth.	Depends on the TEM01 mode amplitude.	
Locking	Very stable and long time, only depends on laser PZT dynamic.	Without drift, seems stable.	TL needs more systematic study
Coupling rate	~80%	~80%	Difficult to compare, it depends on feedback configuration
Sensitivity	high	high	The same order of sensitivity
Full spectrum locking	Easy, grating in reflected beam path.	Difficult to achieve right alignment, See my thesis Chapter 4	Thesis solution not convenient.

Contents

HTTX Machine

Aim: X-ray flux $10^{10\text{-}13}$ph/s



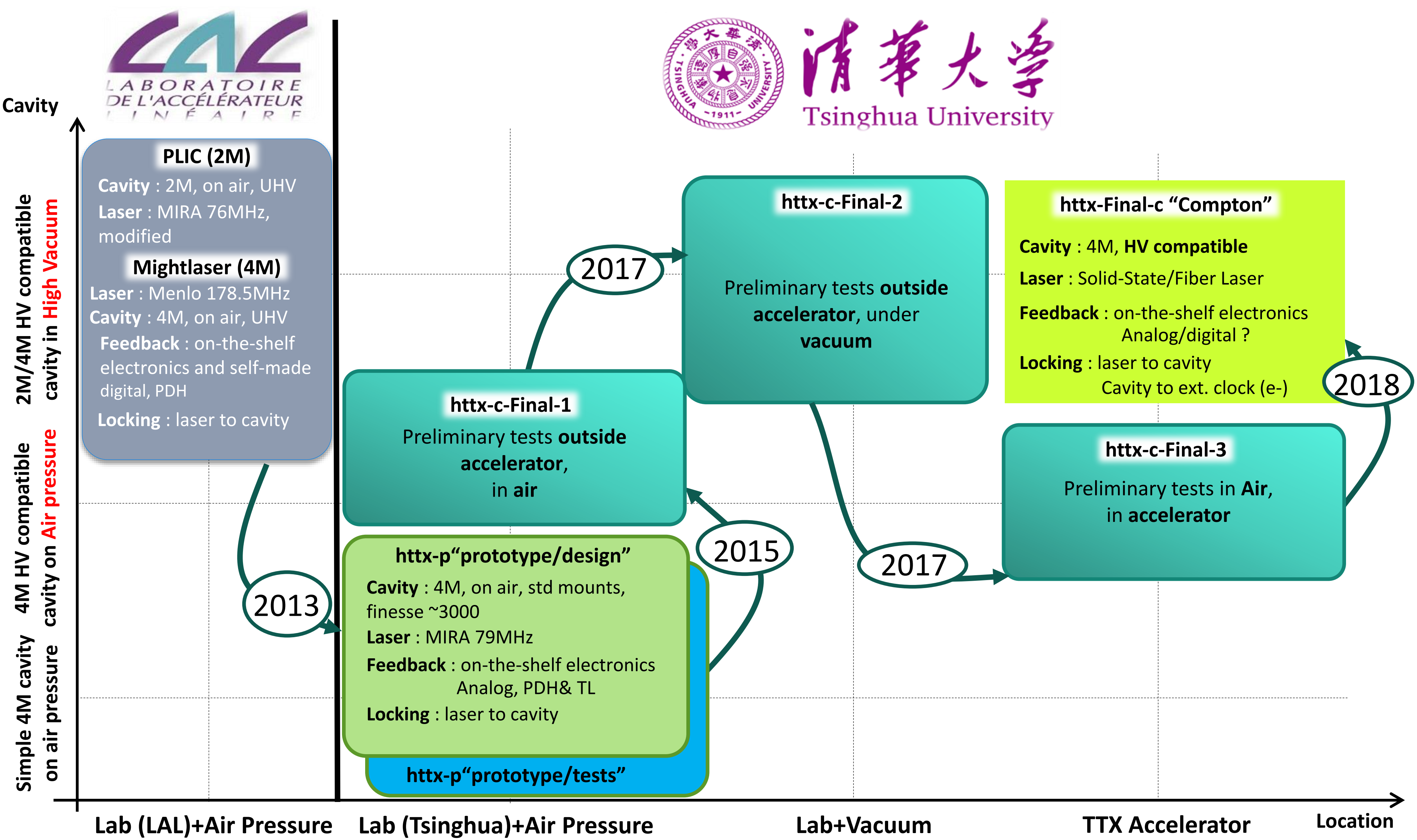
HTTX layout (*preliminary*)

OEC system parameters

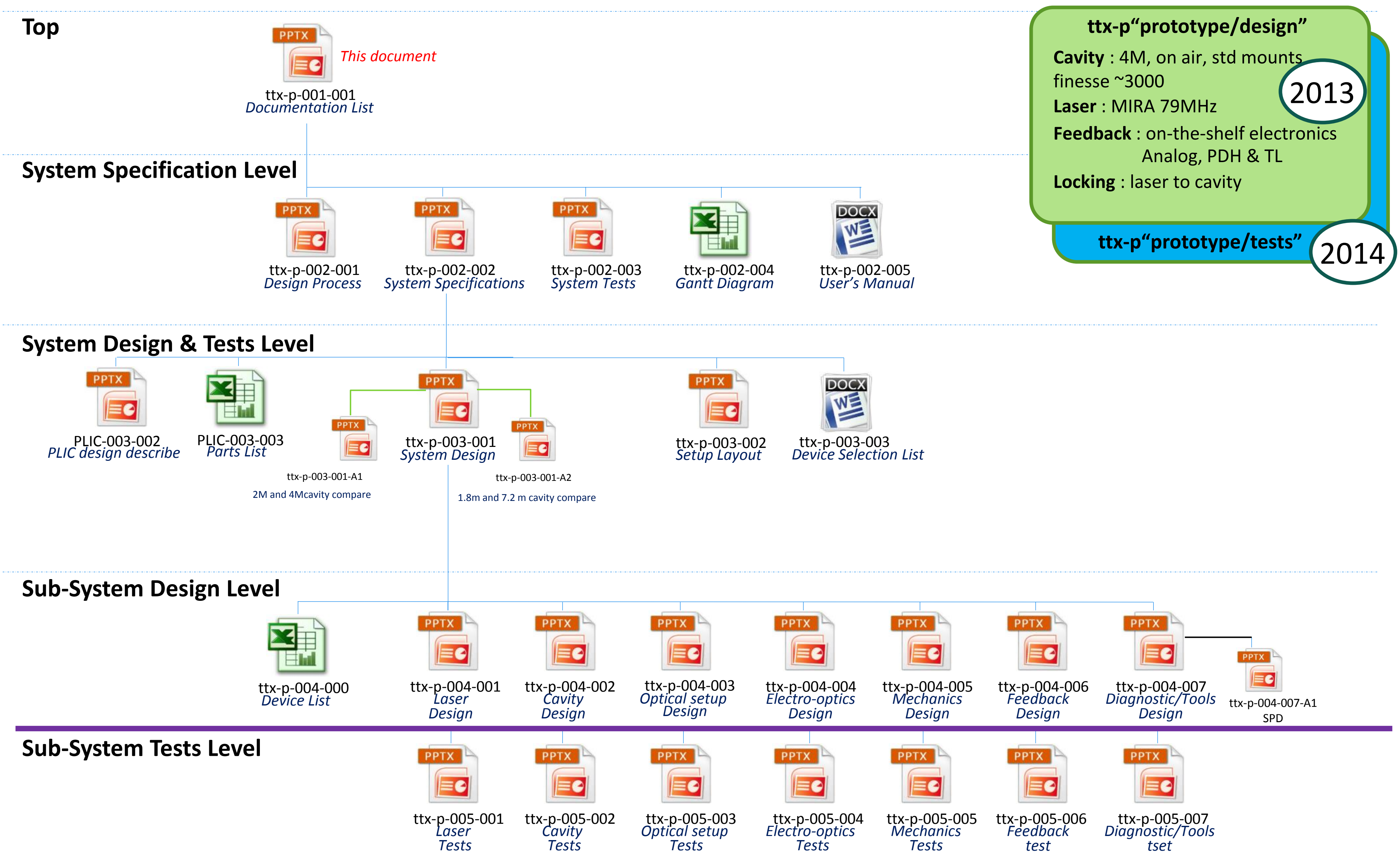
Laser	**Output power**	10W-100W
	Pulse duration	~ps
Cavity	**Enhancement factor**	10^4
	FSR	31.25 MHz (9.6m)
	Power	50kW- 500kW
	Coupling	>50%

H. Xu, Y. You et al, IPAC13

HTTX OEC System Design Flow



HTTX-OEC Prototype Literature



Summary

Studies optical enhancement cavity system:

laser source, cavity properties, and locking

designed and tested a operational mode-locked fiber laser

found a new method to measure beam waist size for planar n-mirror cavity

used the TL technique for a pulsed-laser optical cavity locking successfully

Thank you