Tsinghua University

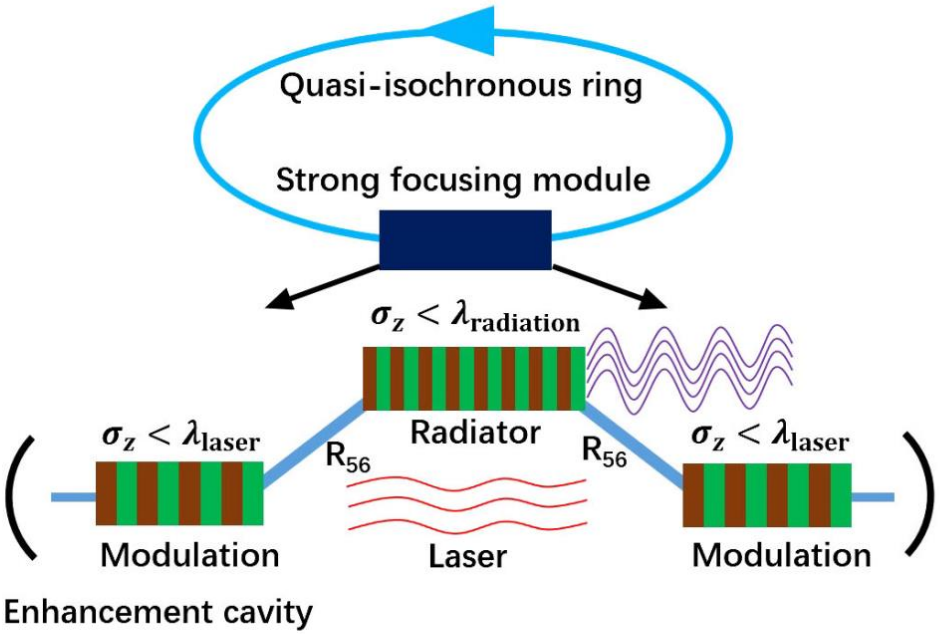
Thermal Instabilities in High-average-power Optical Enhancement Cavity

Huan Wang

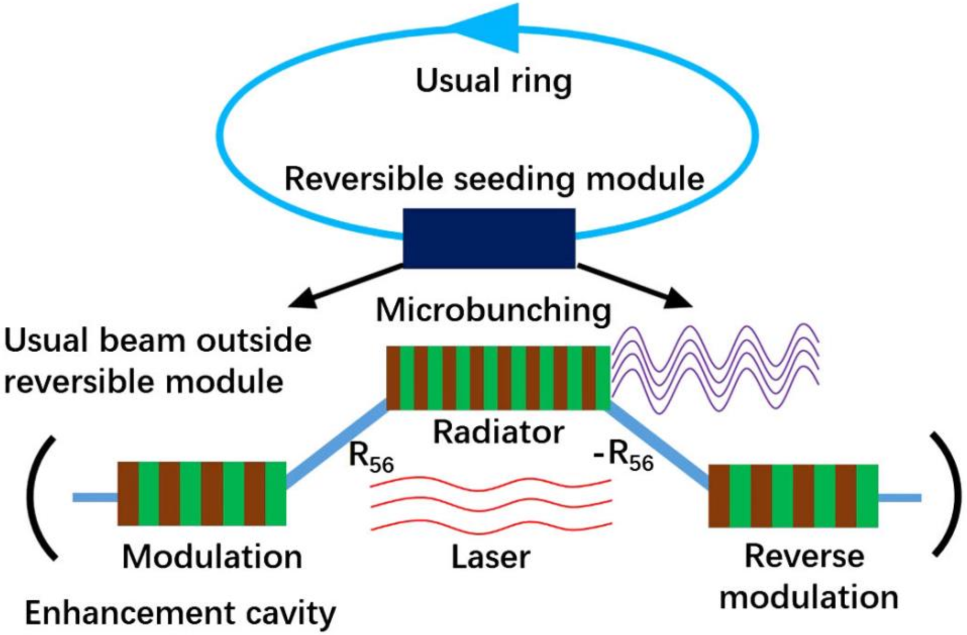
SSMB online workshop, 2020 Dec 7-9

OEC for SSMB light sources

- **Optical enhancement cavity (OEC)** provides high intensity, high stability modulation field for electron beam inside modulator



Physical Review Accelerators and Beams, 23, 044002 (2020)



OEC for SSMB light sources

demands:

1. high power,
2. high stability (amplitude, frequency/phase)

goal		status
ultimate	continuous wave (CW) laser power 1 MW, linewidth < 10 kHz	designed
intermediate	pulsed wave (PW) peak power ~100 MW (corresponding to ~200 kW average power, 20 ps pulse length with 100 MHz repetition rate)	preparing
preliminary	lock OEC with laser	realized

Brief review of state of the art of OEC development

OEC for Thomson scattering light sources

Information	λ (nm)	Injection laser type	Cavity working mode (CW/PW)	Cavity FSR (MHz)	P_c (kW)	P_p (MW)	τ_L (ps)	Gain	Linewidth (kHz)	Status
CLS, Lyncean, USA [1]	1064	Yb:fiber	PW	65	300	185	25	10000	2	Commercial Product
ThomX, IJCLab, France [2]	1030	Yb:fiber	PW	35.68	700	1900	10	7000	1.6	Under construction
ThomX prototype cavity [3]	1030	Yb:fiber	PW	133.33	200	6	250	5000	8	In operation
NESTOR, KIPT, Ukraine [4]	1064	Nd:YAG	PW	19.46	/	/	/	/	/	Under construction
LUCX, KEK, Japan [5]	1064	Nd:VAN	PW	357	2.45	1	7	/	/	In operation
cERL, KEK, Japan [6]	1064	Nd	PW	162.5	10	6	10	430	120	In operation
BriXS, INFN, Italy [7]	1030	/	PW	100	750	3750	2	/	/	Designed

OEC for gravitational wave detection interferometers

Information	λ (nm)	Injection laser type	Cavity working mode (CW/PW)	Cavity FSR (MHz)	P_c (kW)	P_p (MW)	τ_L (ps)	Gain	Linewidth (kHz)	Status
Advanced LIGO [8]	1064	Nd:YAG	CW	0.075	750	/	/	144	0.17	Under construction
Advanced VIRGO [9]	1064	Nd:YAG	CW	0.1	700	/	/	141	0.23	Under construction

[1] Advances in Laboratorybased X-Ray Sources, Optics, and Applications VII: volume 11110. International Society for Optics and Photonics, 2019: 1111003.
[2] Thomx technical design report. 2014.
[3] Applied Optics 59.1 (2020): 116-121.
[4] Proc. 4th Int. Particle Accelerator Conf. (IPAC'13), Shanghai, China, May 2013. 22532255.
[5] Proc. 7th Int. Particle Accelerator Conf. (IPAC'16), Busan, Korea, May 2016. 18671869.
[6] Physical Review Accelerators and Beams, 2016, 19(11): 114701.
[7] Advances in Laboratorybased XRay Sources, Optics, and Applications VII: volume 11110. International Society for Optics and Photonics, 2019: 1111005.
[8] Classical and Quantum Gravity, 2015, 32(7):074001.
[9] Classical and Quantum Gravity, 2014, 32(2): 024001.

OEC for high-order harmonic generation

Information	λ (nm)	Injection laser type	Cavity working mode (CW/PW)	Cavity FSR (MHz)	P_c (kW)	P_p (MW)	τ_L (ps)	Gain	Linewidth (kHz)	Status
MPQ [10]	1030	Yb:fiber	PW	18.4	2.8	3800	0.04	35	167	Experiment
JILA [11]	1070	Yb:fiber	PW	154	8	430	0.12	270	182	Experiment
Stonybrook [12]	1035	Yb:fiber	PW	88	11	800	0.155	270	104	Experiment
Canada [13]	1050	Yb:fiber	PW	60	10	1390	0.12	400	48	Experiment
Japan [14]	1040	Yb:fiber	PW	10	1	500	0.2	100	32	Experiment

[10] Nature communications, 2019, 10(1): 110.
[11] Nature, 2012, 482(7383): 6871.
[12] Structural Dynamics, 2018, 5(5): 054301.
[13] Review of Scientific Instruments, 2019, 90(8): 083001.
[14] Optics express, 2015, 23 (12): 1510715118.

OEC for fusion energy experiment

Information	λ (nm)	Injection laser type	Cavity working mode (CW/PW)	Cavity FSR (MHz)	P_c (kW)	P_p (MW)	τ_L (ps)	Linewidth (kHz)	Status
DEMO [15]	1064	Nd:YAG	CW	/	3000	/	/	/	Designed

[15] New Journal of Physics 18.12 (2016): 125005.

OEC for other applications

Information	λ (nm)	Injection laser type	Cavity working mode (CW/PW)	Cavity FSR (MHz)	P_c (kW)	P_p (MW)	τ_L (ps)	Gain	Linewidth (kHz)	Status
MPQ [16]	1040	Yb:fiber	PW	250	670/ 400	268/ 6400	10/ 0.25	2130/ 1270	37/ 63	Experiment
JILA [17]	800	Ti:Sapphire	CW	76	3000	/	/	30	806	Designed
Waseda Univ. [18]	10 μm	CO_2	PW	/	2.3	/	/	200	/	Experiment
Jefferson Lab [19]	532	SHG from Yb:fiber laser	CW	176	3.7	/	/	3800	15	Experiment for Compton polarimeter
Oak Ridge [20]	355 & 1064	Nd:YAG	Burstmode 10 Hz	201	/	50	50	50	1500	Experiment

[16] Optics letters 39.9 (2014): 2595-2598.
[17] Optics letters 28.19 (2003): 1835-1837.
[18] High-Power, High-Energy, and High-Intensity Laser Technology II. Vol. 9513. International Society for Optics and Photonics, 2015.
[19] Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 822 (2016): 82-96.
[20] Optics Letters 40.23 (2015): 5562-5565.

OEC for SSMB light sources

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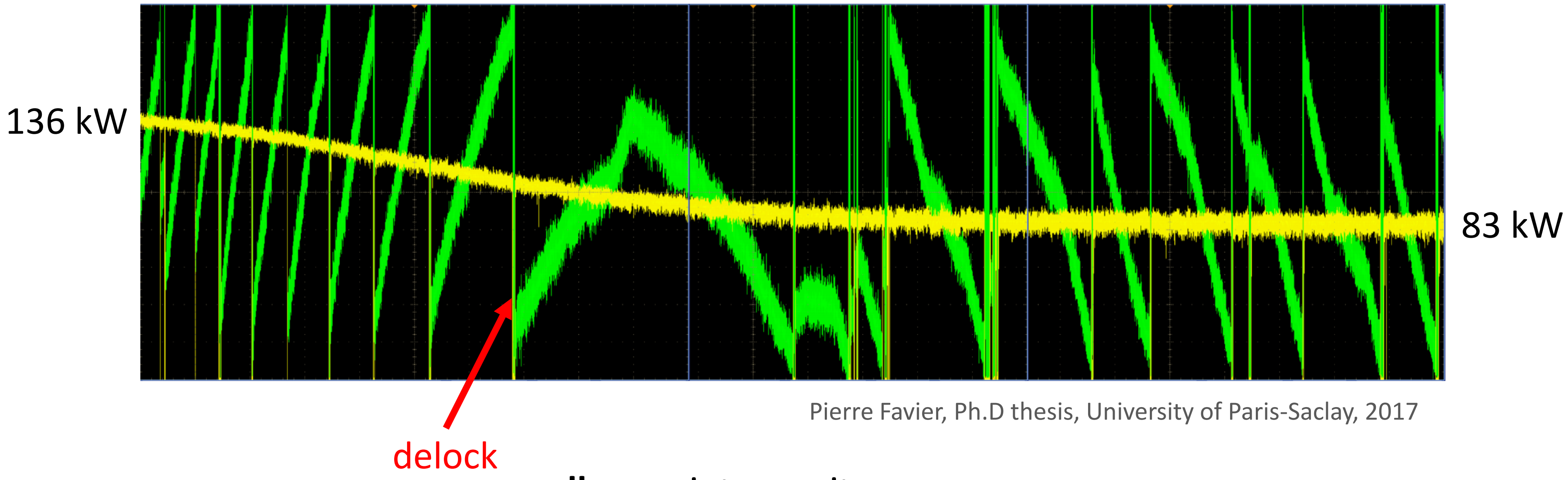
OEC R&D at IJCLab

- for OEC R&D, Tsinghua SSMB group collaborate with Fabian Zomer’s group at IJCLab, University of Paris-Saclay
- 2000, start R&D of OEC targeted for **Compton Polarimeter**
- 2015, start **high power** R&D of OEC for ThomX
- 2017, obtained **400 kW** intra-cavity average power for **few second**

intra-cavity average power measured for 40 minutes with many delocks



Pierre Favier, Ph.D thesis, University of Paris-Saclay, 2017

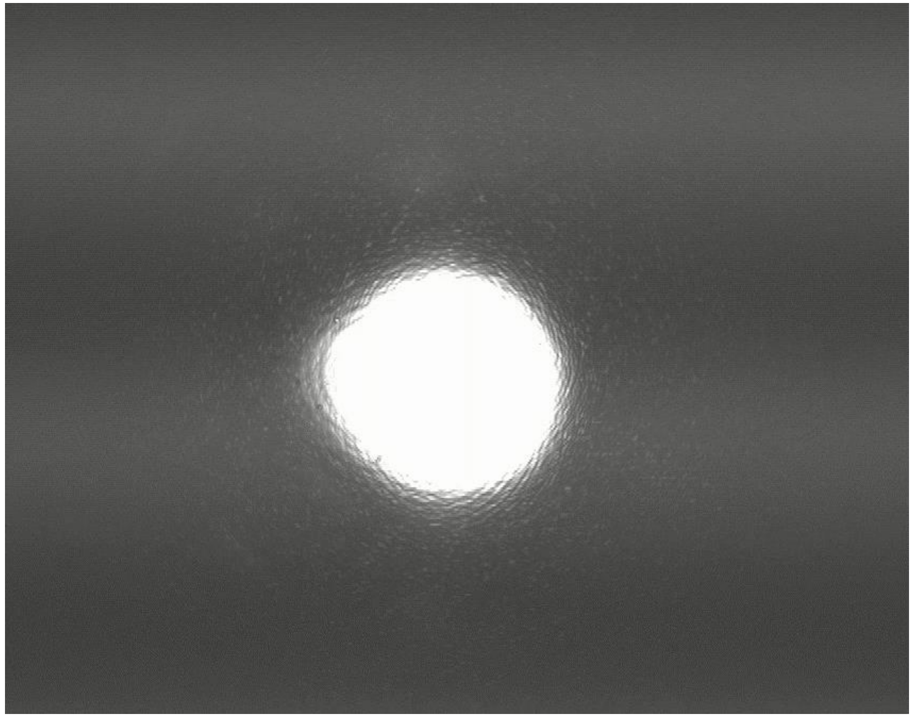
yellow : intra-cavity average power

green : laser piezo control signal

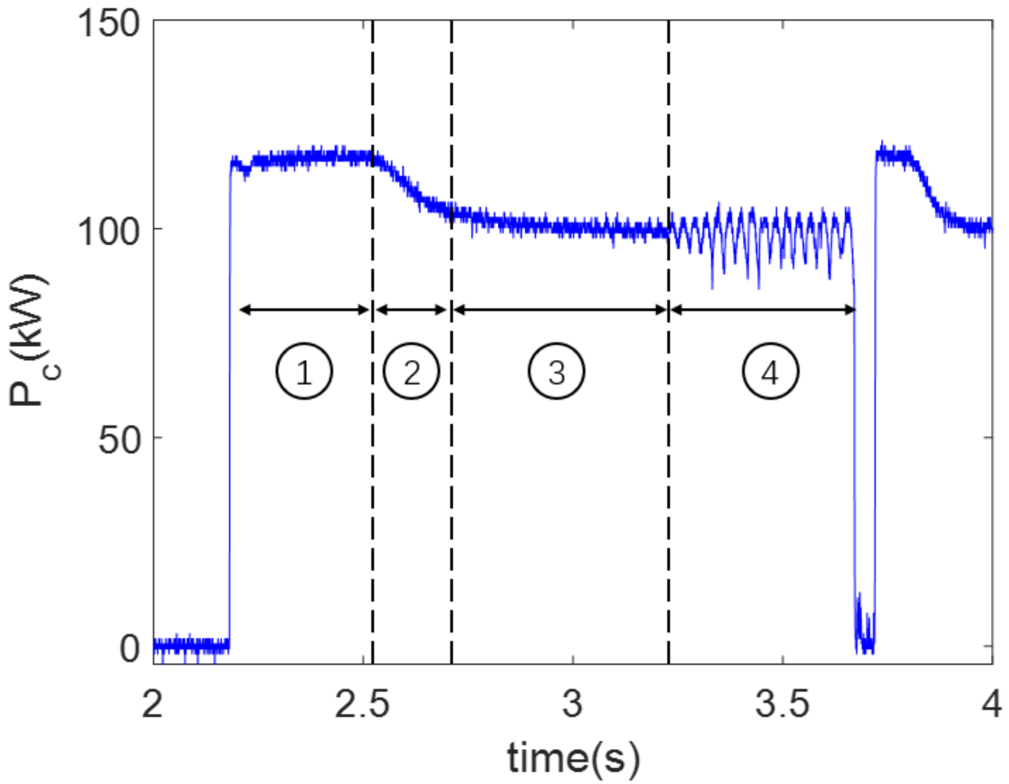
Suppression of modal instabilities

Applied Optics 59.1 (2020): 116-121.
Huan Wang, Ph.D thesis, Tsinghua University&University of Paris-Saclay, 2020

■ observation of modal instability



- **transmission of M2** when intra-cavity power at ~100 kW, TEM00 degenerated with high order mode



- **intra-cavity power change with modal instability**

① cavity locked to a single TEM00 mode
② cavity switched to a degenerated mode
③ cavity reached a steady state of degenerated mode
④ cavity entered an oscillation state finally lose of lock

Suppression of modal instabilities

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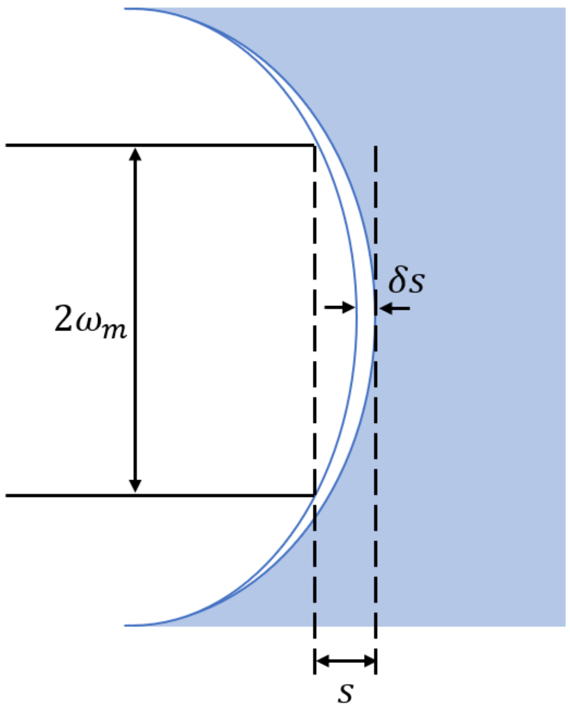
- modeling of modal instability
- mode degeneracy induced by thermoelastic deformation
- thermoelastic deformation- **Winkler model**

$$\delta s = \frac{\alpha A P_c}{4\pi k}$$

$\boldsymbol{\alpha}$: thermal expansion coefficient
A : laser power to thermal power conversion and absorption coefficient
$\boldsymbol{P_c}$: average power inside cavity
k : thermal conductivity



Physical Review A 44.11 (1991): 7022.

- change of mirror surface **radius of curvature** $\frac{1}{R'} = \frac{1}{R} - \frac{2\alpha A P_c}{4\pi k \omega_m^2}$
- **resonance condition for mode**
  TEMmn $(m+n+1)\zeta(L) + 2\pi\frac{L}{\lambda} = p \cdot 2\pi$
  where Gouy phase $\zeta(z) = \arctan(z/z_R)$
- order of degenerated mode can be calculated with **ABCD matrix**

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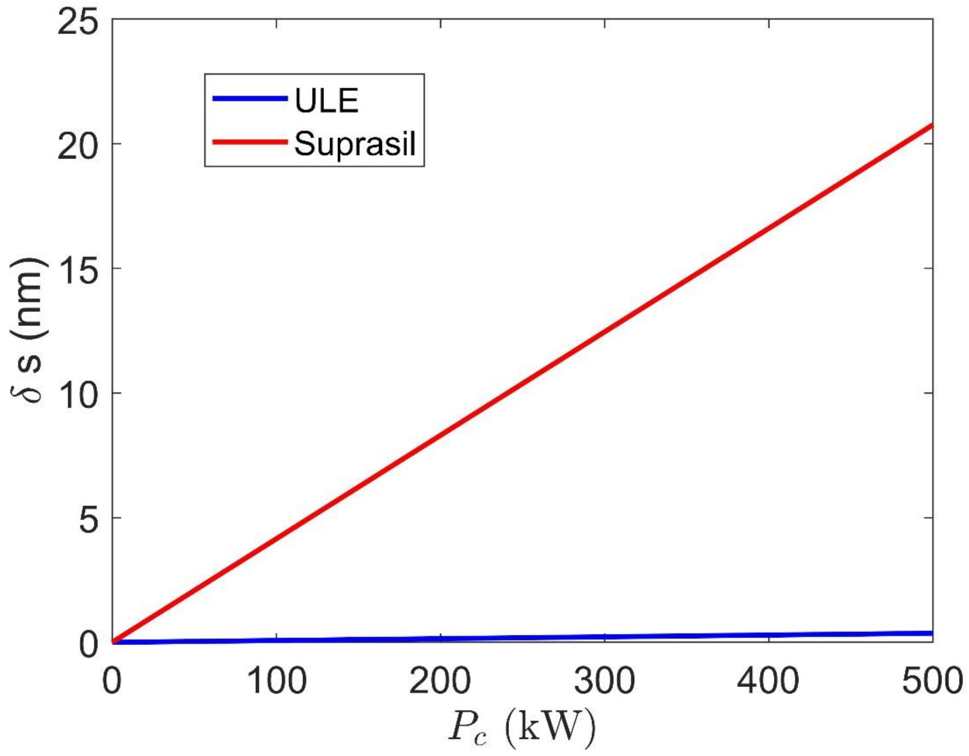
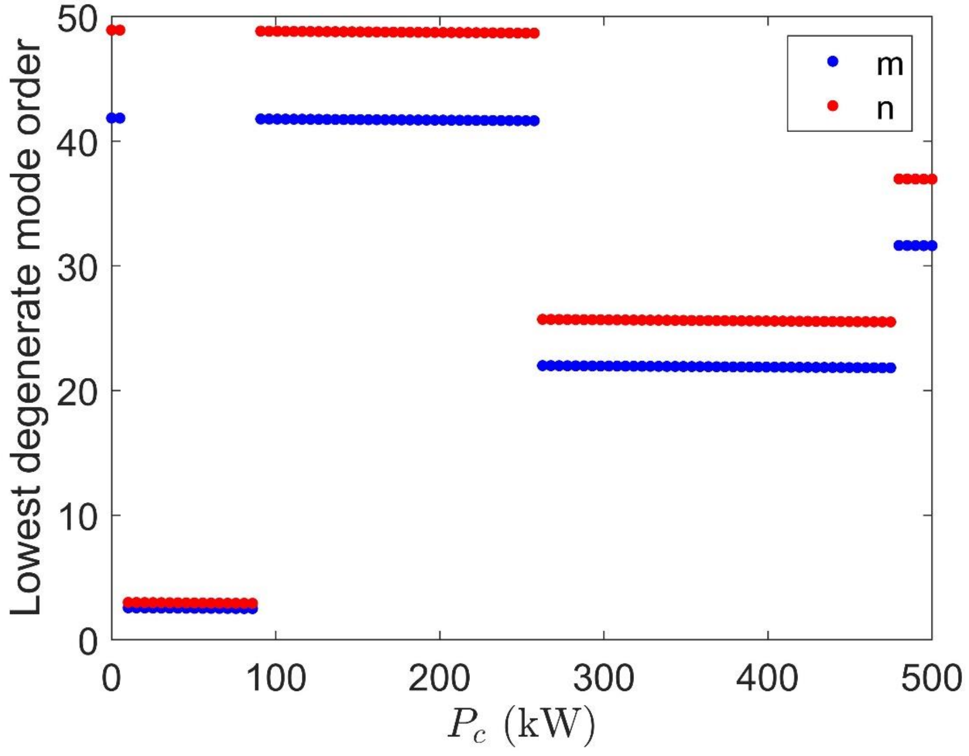
■ modeling of modal instability - **Winkler model**





- deformation of ULE and Suprasil

- lowest order of high order mode degenerated with TEM00 with longitudianal mode range [p00-10,p00+10]
- p00 is the longitudinal mode of TEM00
- **order of degenerated mode are pretty high** as $\boldsymbol{\omega_{mn} \propto \sqrt{n}\omega_{00}}$

Suppression of modal instabilities

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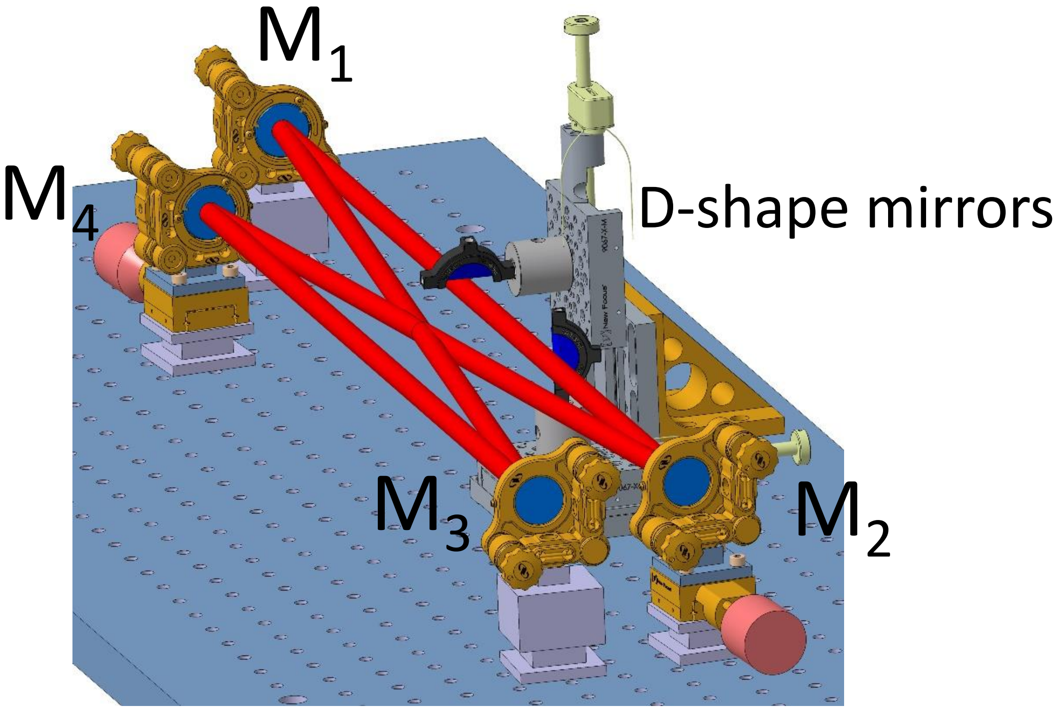
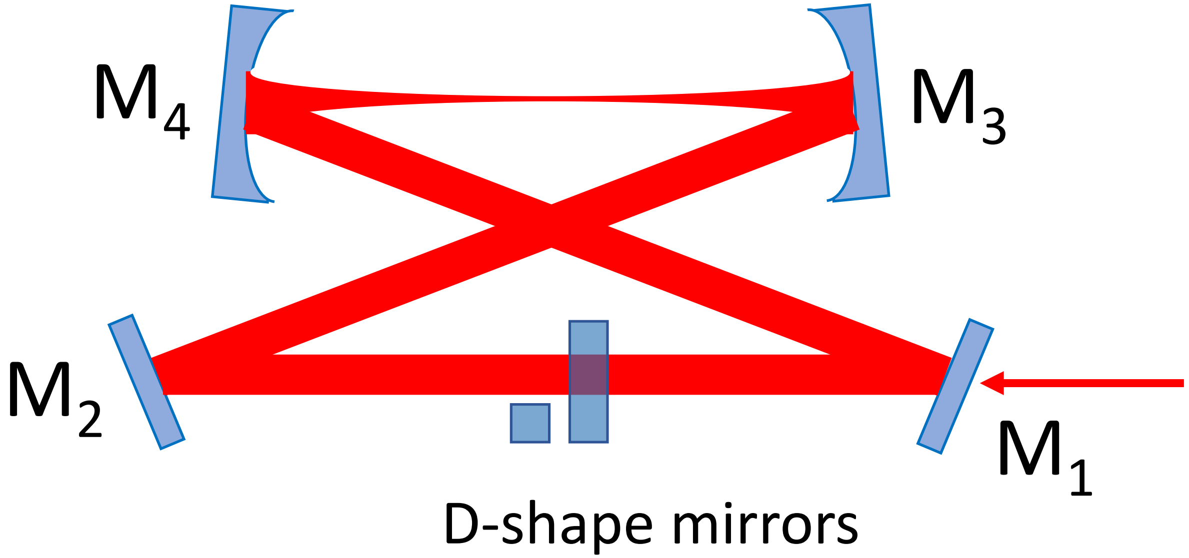
- **implement D-shape mirrors** in between M1 and M2
- dump degerated high order mode





Suppression of modal instabilities

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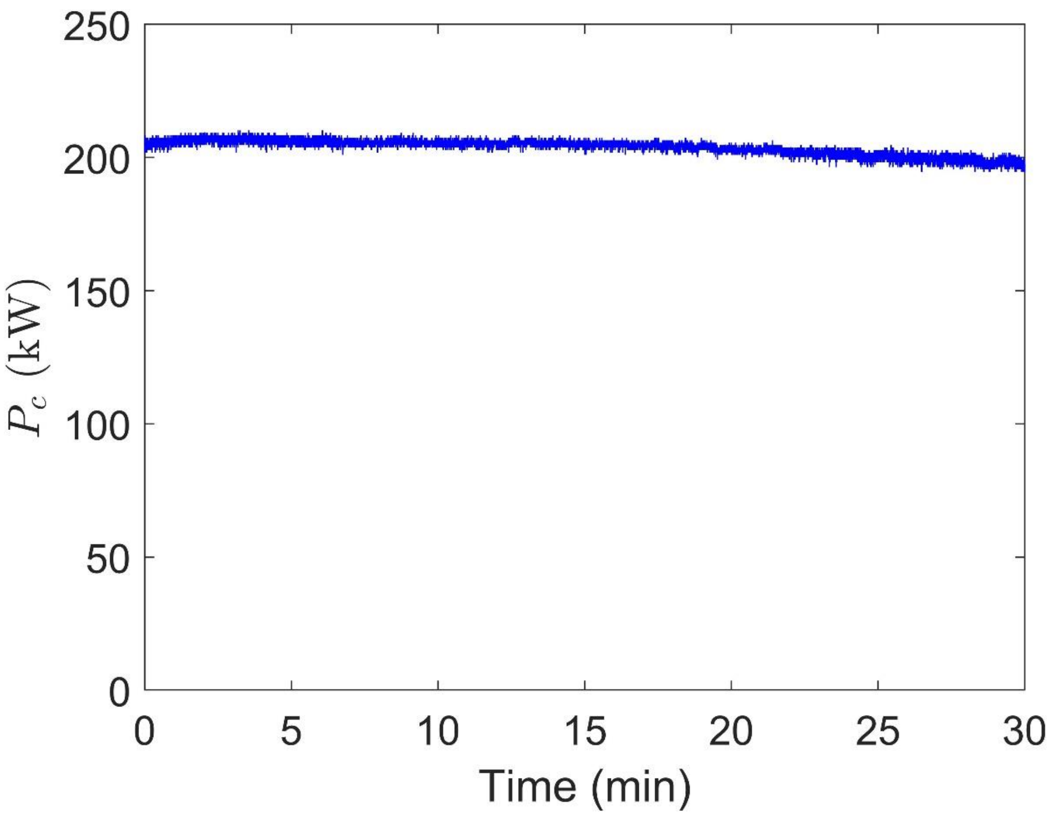
■ **experiment with implementation of D-shape mirrors in 2018**

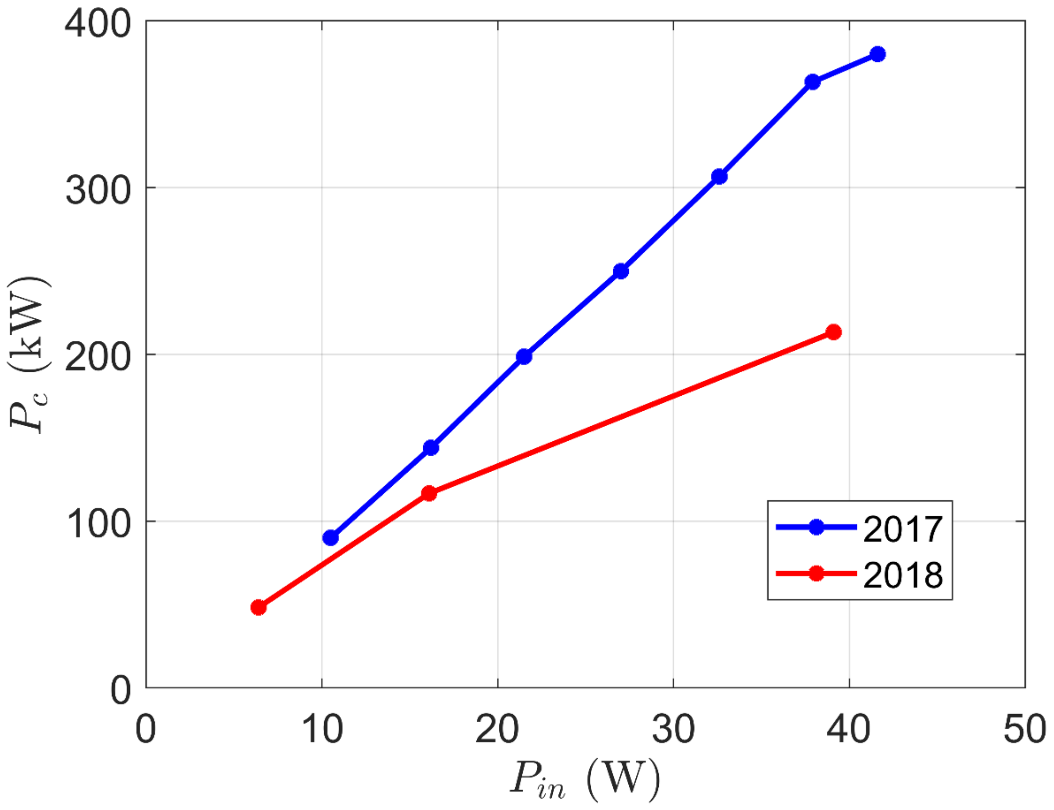


- stable **200kW** intra-cavity power recorded for 30 min
- during which no alignment and feedback correction

Suppression of modal instabilities

Huan Wang, Ph.D thesis, Tsinghua University&University of Paris-Saclay, 2020

- **issue of gain dropped needs to be solved**



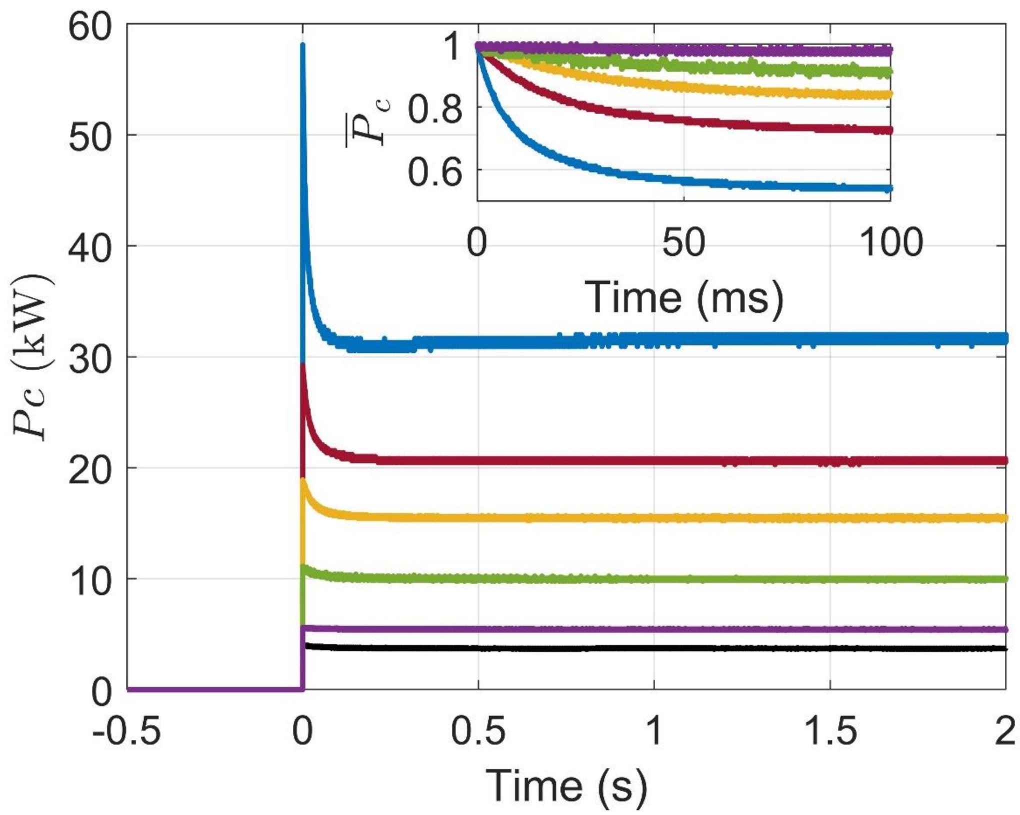
issue of cavity gain drop also has been reported before but not understood

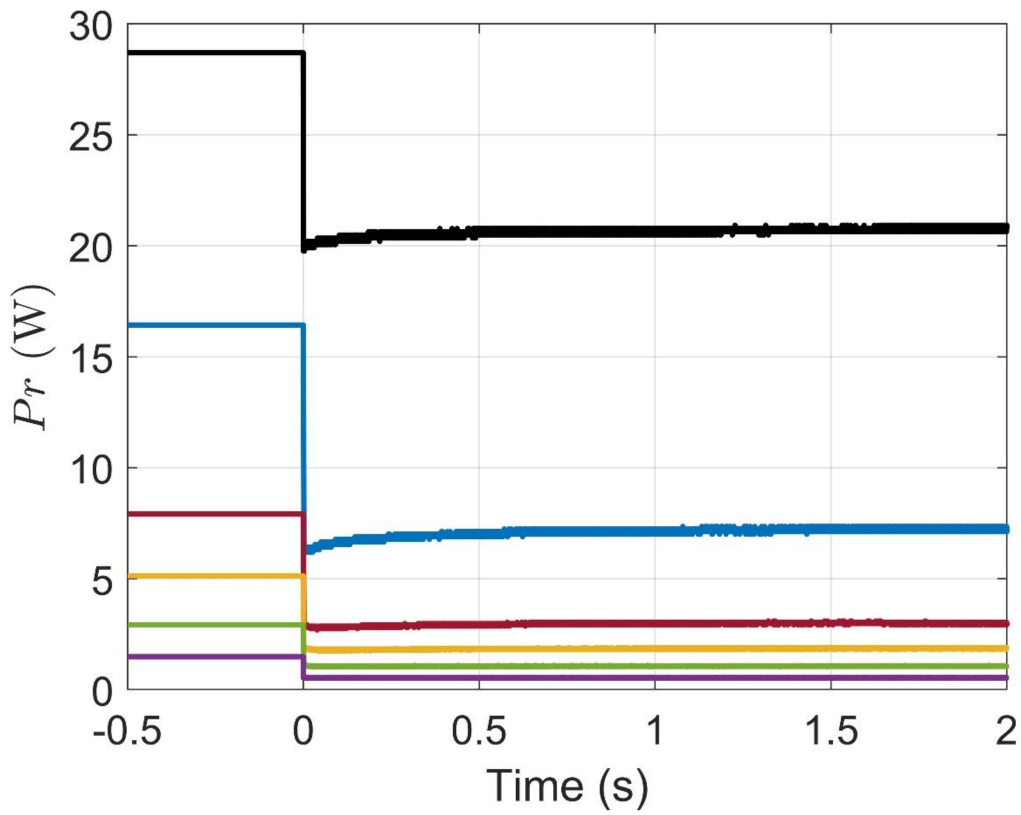
Optics Letters 35, 2052–2054 (2010).
Optics Letters, 28, 1835–1837 (2003).
Optics Letters, 28, 1835–1837 (2003).

Prior-damage dynamics

Applied Optics 59.35 (2020): 10995-11002.
Huan Wang, Ph.D thesis, Tsinghua University&University of Paris-Saclay, 2020

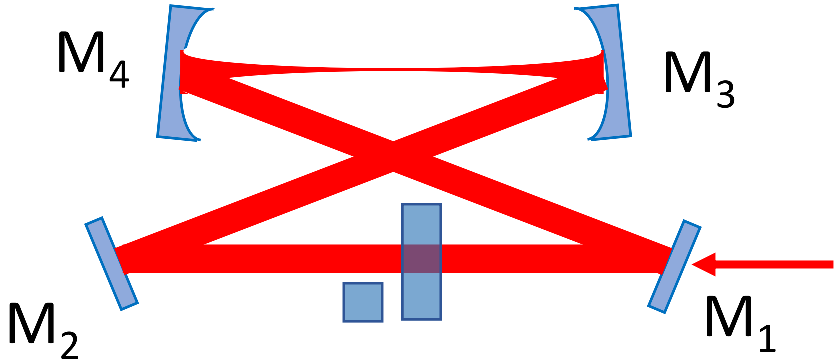
- **observation of fast power drop phenomenon in 2019**
  - **repeated** in two experiments
  - intra-cavity power drop amplitude **tens percent** of the maximum
  - time scale **tens of millisecond**



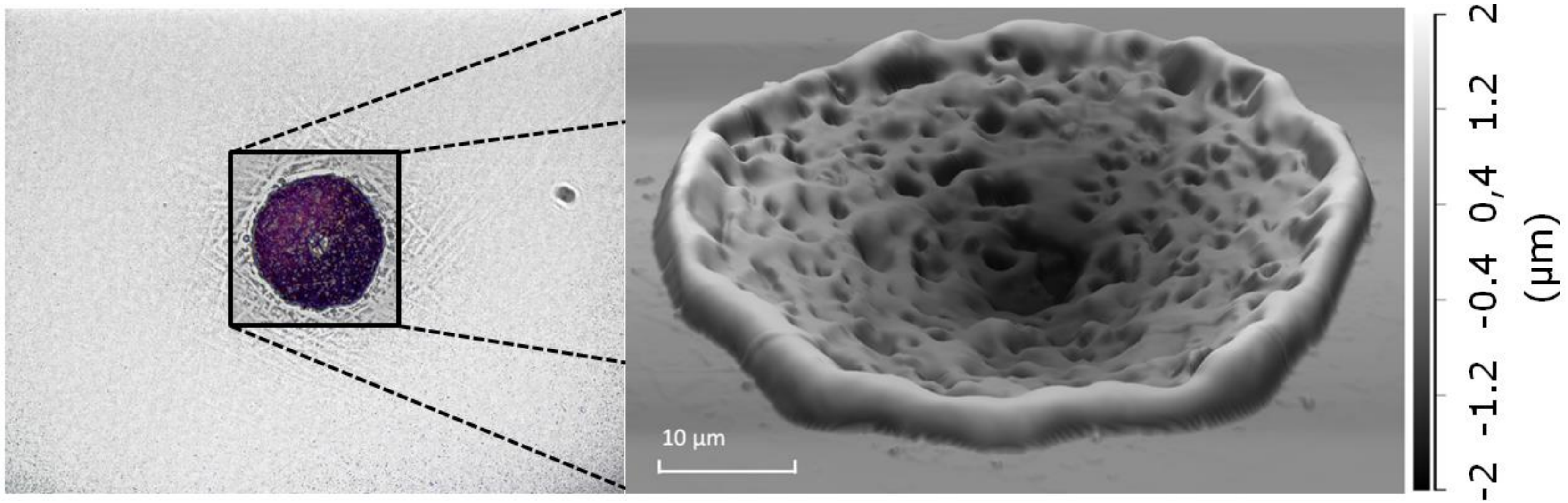


- **phenomenon needs to be understood**

Prior-damage dynamics



■ **analysis of fast power drop phenomenon**



- after experiments, microscope and atomic force microscope image of **M_1 surface**
- **damage area** with radius $\sim 25\ \mu m$ at center of M1 surface
- **crack zone** extends to area with radius **~100 μm**
- last dataset with damage occurred, eliminated from the analysis

Applied Optics 59.35 (2020): 10995-11002.
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Prior-damage dynamics

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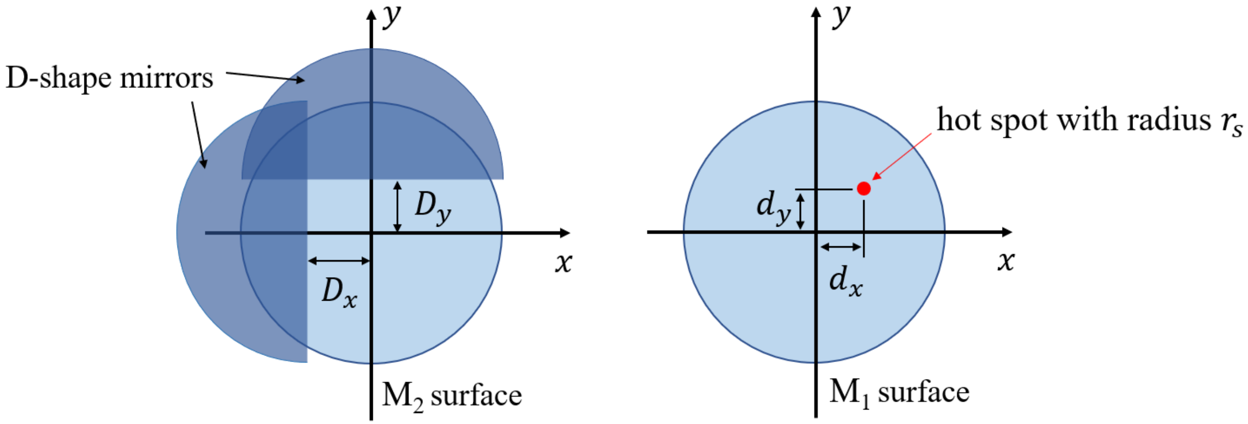
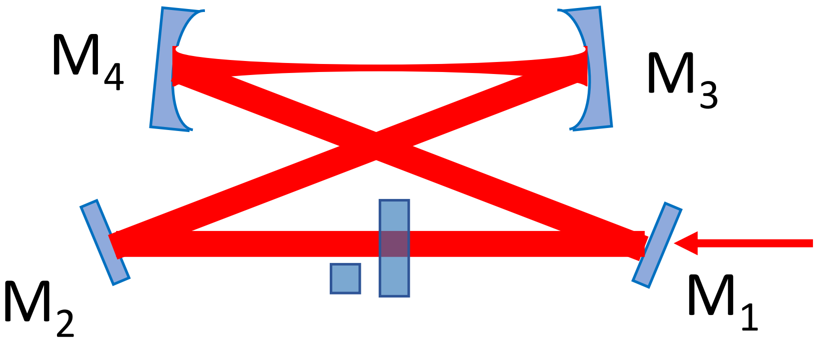
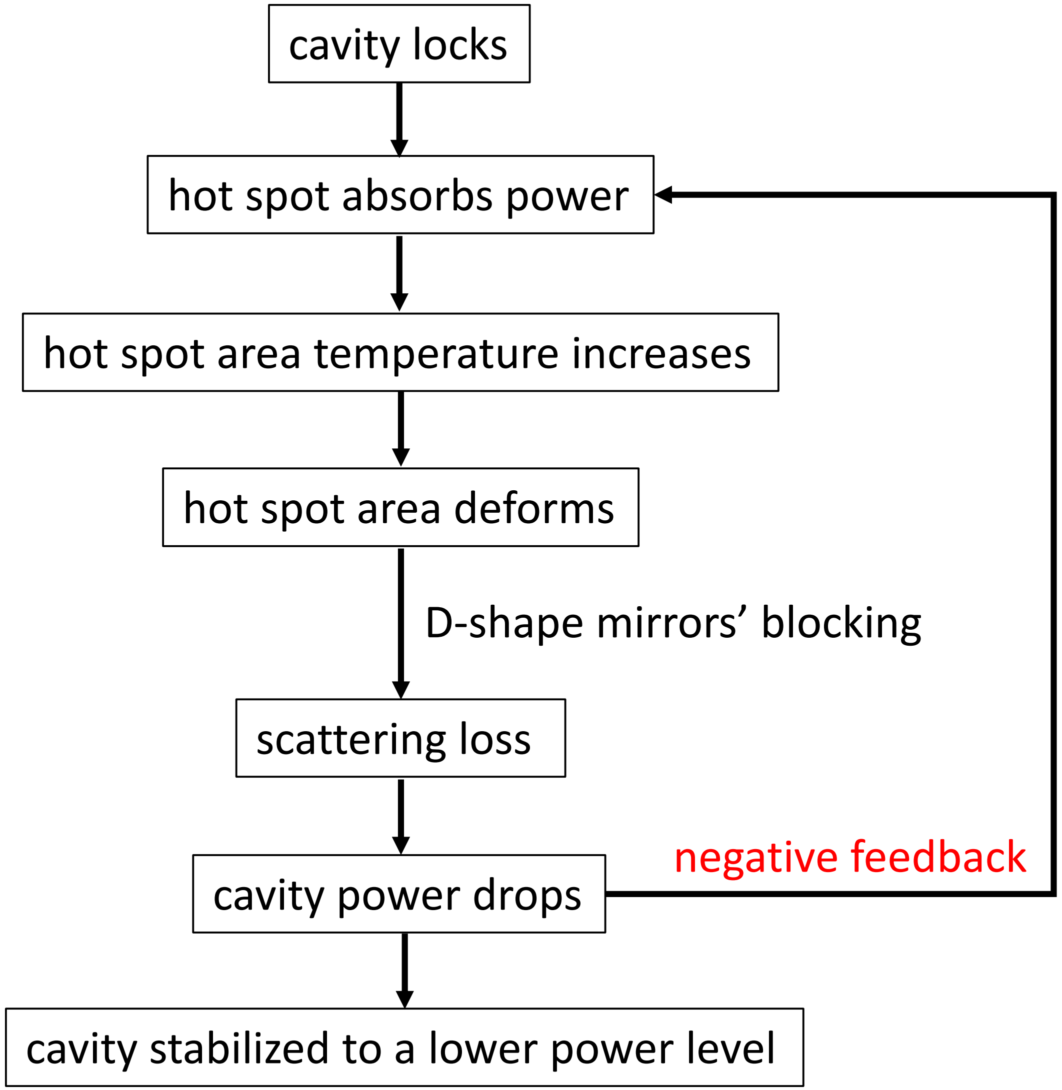
■ modeling with hot spot

- hot spot with radius r_s positioned at $[d_x, d_y]$ on M_1
- $\text{A} = \dfrac{\text{absorbed thermal power}}{\text{intra−cavity average laser power}}$
- edge of D-shape mirror positioned at $[D_x, D_y]$







Prior-damage dynamics

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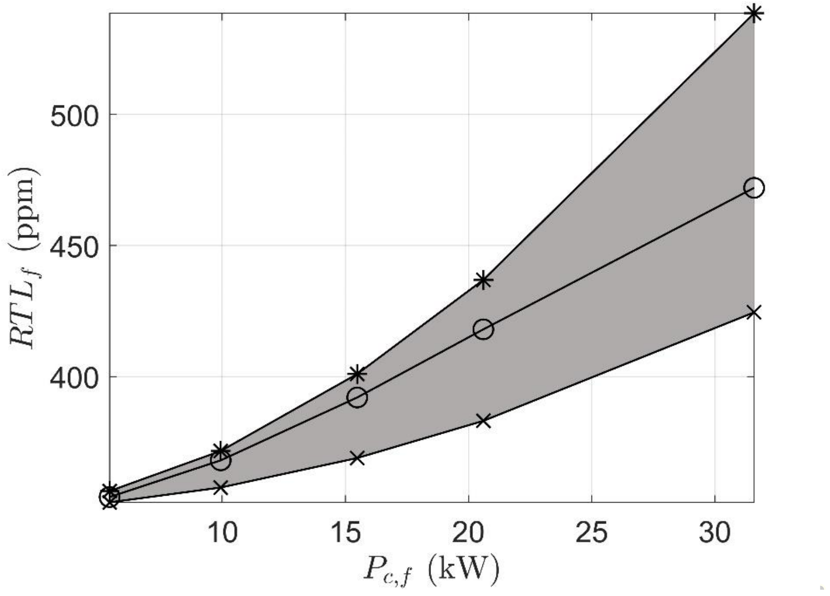
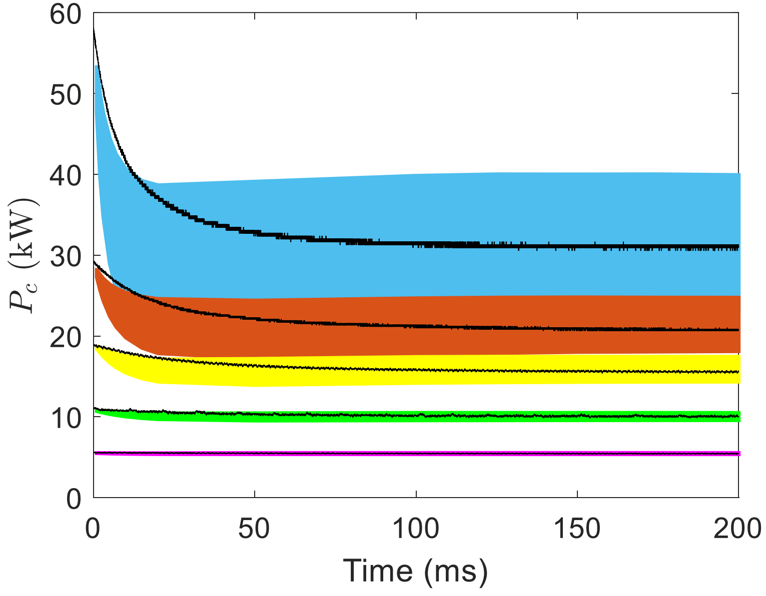
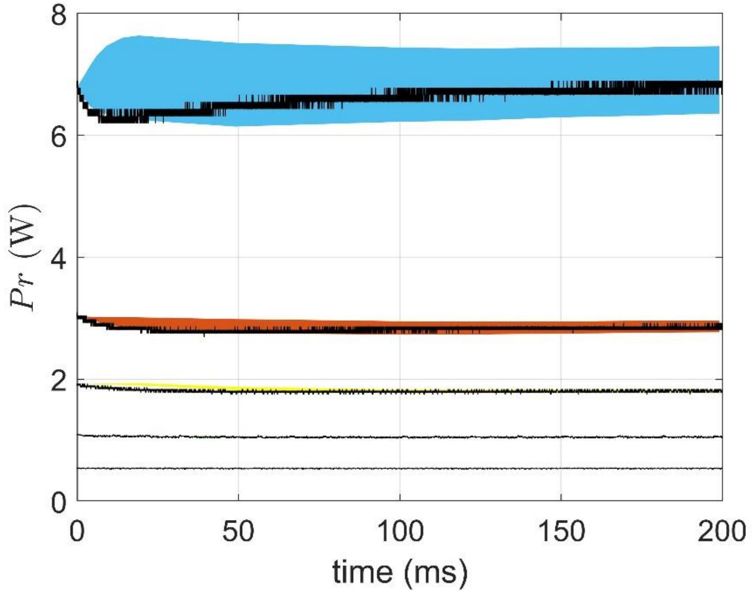
Huan Wang, Ph.D thesis, Tsinghua University&University of Paris-Saclay, 2020

- **compare simulation with experiment**

$r_s = 25\ \mu m, dx = dy = 0, Dx = Dy = 2.5\ mm$







o : experimental data

x : simulation results with $A_- = 1.5\ ppm$

* : simulation results with $A_+ = 2.5\ ppm$

black lines : experimental data

patches : area bounded by simulated $P_c/P_r - time$ with A_- and A_+

- **lesson learned: environmental cleanness very important !!**

Issue of cavity gain drop

- what is the reason of **cavity gain drop** vs. intra-cavity power increase?
- what happens on mirror surface ?

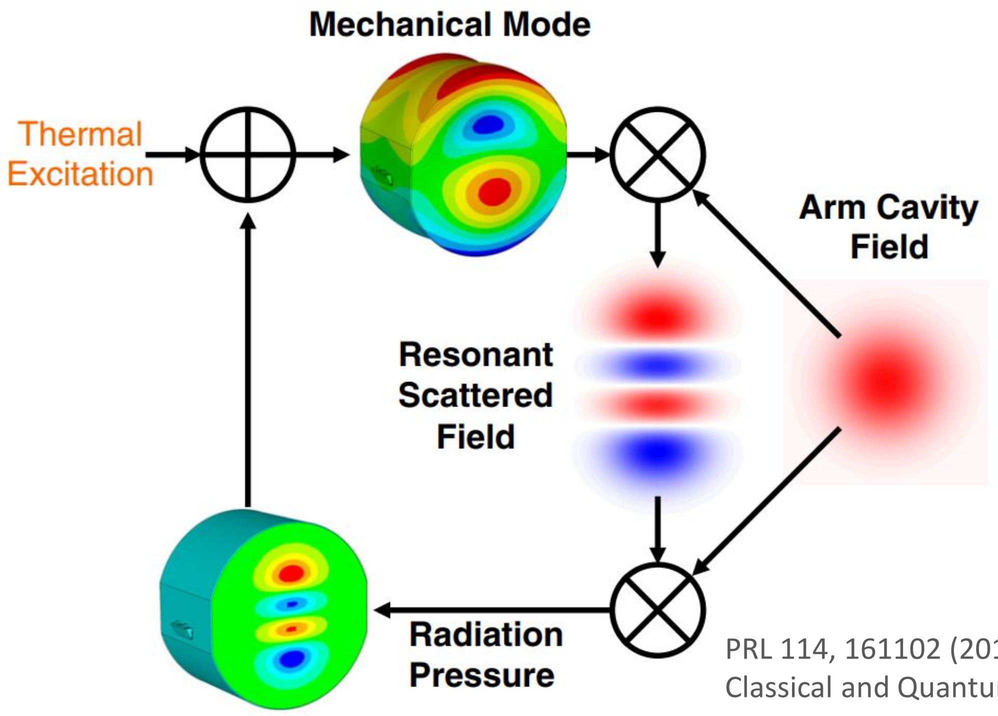
mirror coating material

- kept as being solid, nonlinear optics change?
- plasma generated?
- photochemical?
- ...

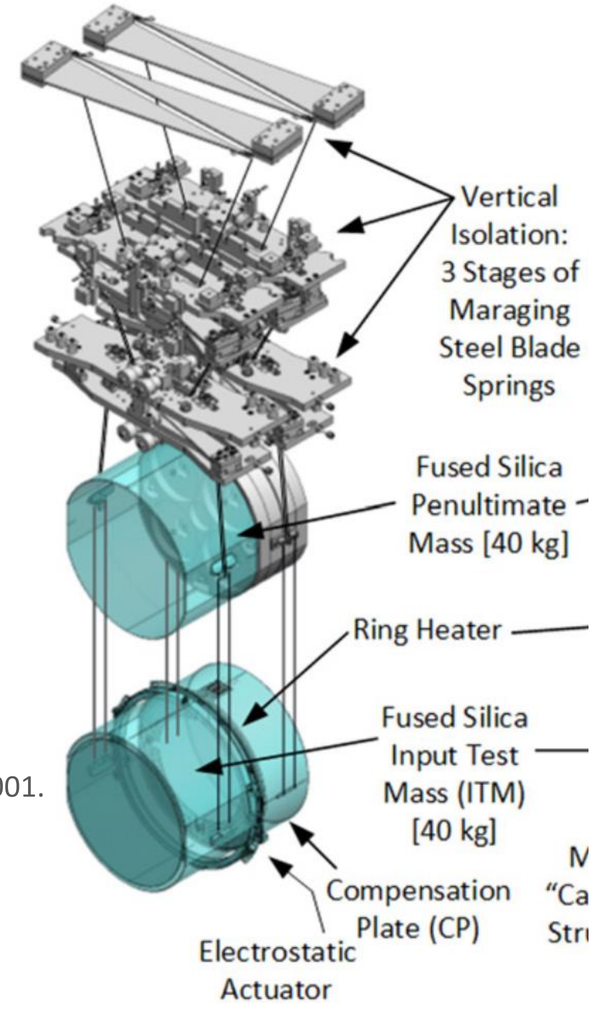
Optica 2.9 (2015): 803-811.
Journal of Applied Physics 124, 083102 (2018)

Issue of parametric instabilities

- laser radiation pressure induces vibrational modes of mirror
- vibrational modes induce optical high order mode



PRL 114, 161102 (2015)
Classical and Quantum Gravity, 2015,32(7):074001.



- much studied in LIGO & VIRGO CW high power regime
- studies need to be carried out with mounted mirrors

Summary

- Issues need to be studied for realizing MW OEC for SSMB

issue	**status**
modal instabilities	solved
fast power drop	understood
gain drop	to be understood
parametric instabilities	to be studied

- Tsinghua SSMB group has started experimental studies of OEC, and now preparing for high power OEC experiments

Thank you