A high-energy and highly repetitive fs/ps short pulse laser production using OPCPA with ns Beam Combined Dream Laser pumping for fast/shock ignitions

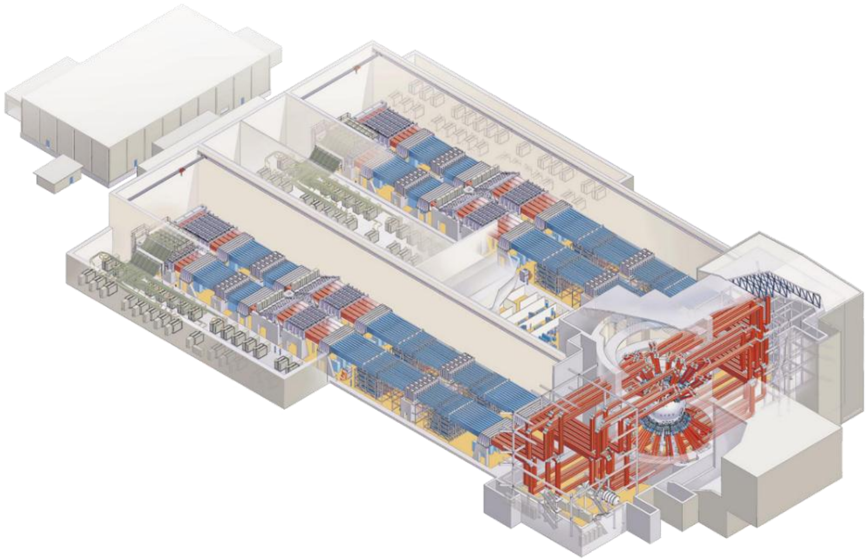
Hong Jin Kong[1], Sangwoo Park[1], Jungsuk Oh[1], Seongwoo Cha[1], Kilsung Churn[1], and Bong Ju Lee[2]

[1] *Department of Physics, KAIST, Republic of Korea*
[2] *Department of AGEE, HGU, Republic of Korea*

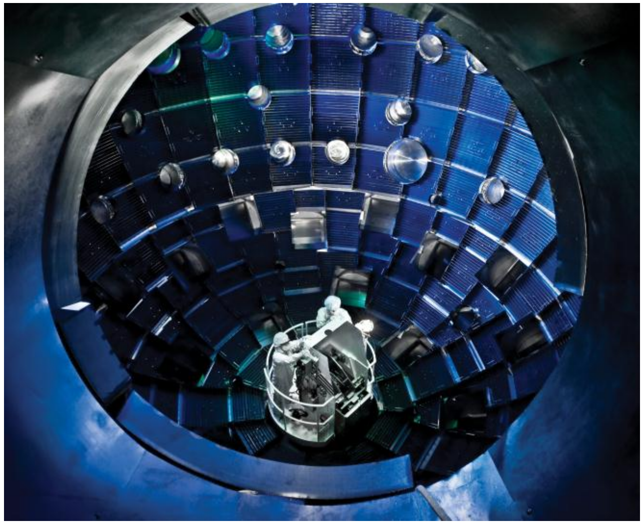
Motivation

- **To Achieve laser inertial fusion energy (LIFE), we need a laser driver :**
  - **10 Hz** repetition rate
  - Pulse energy per beam line **> 2.5 kJ**
  - Pulse width
    - **5~10ns for compression**
    - **1~15 ps for fast ignition**, **300~500 ps for shock ignition**
- **Solutions to increase the output pulse energy/power with high rep. rate :**
  - LD pumping
  - High thermal conductivity laser media (Ceramic laser materials)
  - **Cryogenically cooled ceramic lasers (Yb:YAG, …., many candidates are being developed)**
- **Cooling problem(thermal) and parasitic oscillation**
  - limit the size of the laser media > limit attainable output energy/power
  - Beam combination of available lasers ;
    - **extends the attainable energy/power → Energetic ns Beam Combined Dream Laser**
- **Solution to generate an igniting short pulse laser driver :**
  - **OPCPA** using a ns Beam Combined Dream Laser
  - **Beam combination** of short pulse lasers

Laser Inertial fusion facility: NIF



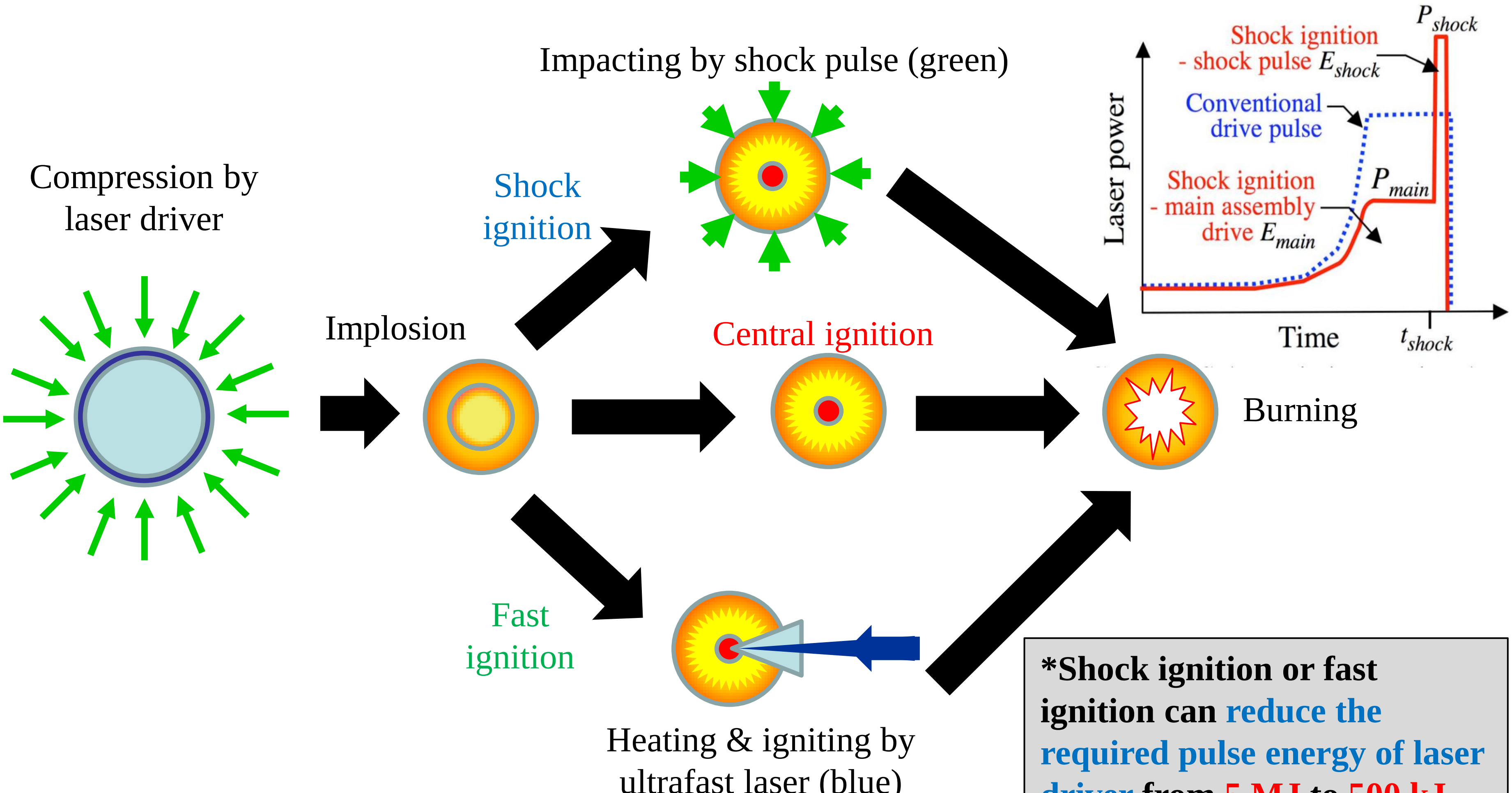
Schematic of entire system of NIF



Target bay of the NIF

- World's largest laser facility: 5.4 MJ @1.05 μm / 1.8 MJ @ 0.35 μm
  - At least, 25 kJ × 200 beam lines are required for IFE
- Low repetition rate : 1~2 shots/day
  - However, 10 Hz repetition rate is required for IFE plant

Several methods of the inertial fusion ignition



***Shock ignition or fast ignition can reduce the required pulse energy of laser driver from 5 MJ to 500 kJ.**

Comparison of ignition methods

types of ignition method	Estimation value of required pulse energy		note	Facilities
	ns laser	ps/fs laser		
Central ignition	5.4 MJ @ 1.05 μm	-	Most simple, but high pulse energy is required	NIF (USA) LMJ (France)
	1.8 MJ @ 0.35 μm			
Fast ignition	500 kJ @ 1.06 μm	100 kJ @ 0.53μm /1~10ps	special target(cone-inserted target) is required to deliver the igniting laser into the fuel	HiPER (EU) Gekko-XII &LFEX (Japan)
	180 kJ @ 0.35 μm			
Shock ignition	500 kJ @ 1.06 μm	100kJ @ 0.35μm /300~500ps	Single laser can be utilized for compression and ignition	HiPER (EU) NIF (USA)
	180 kJ @ 0.35 μm			

Stepano Atzeni, "Inertial confinement fusion with advanced ignition schemes: fast ignition and shock ignition" in *Laser-Plasma Interactions And Applications*, P. McKenna, D. Neely, R. Bingham, and D. Jaroszynski, Eds. (Springer, 2013) pp. 243-277

Most challenging issues in LFE

DT Laser ignition → DT Burn → Fusion Energy → Dream Energy

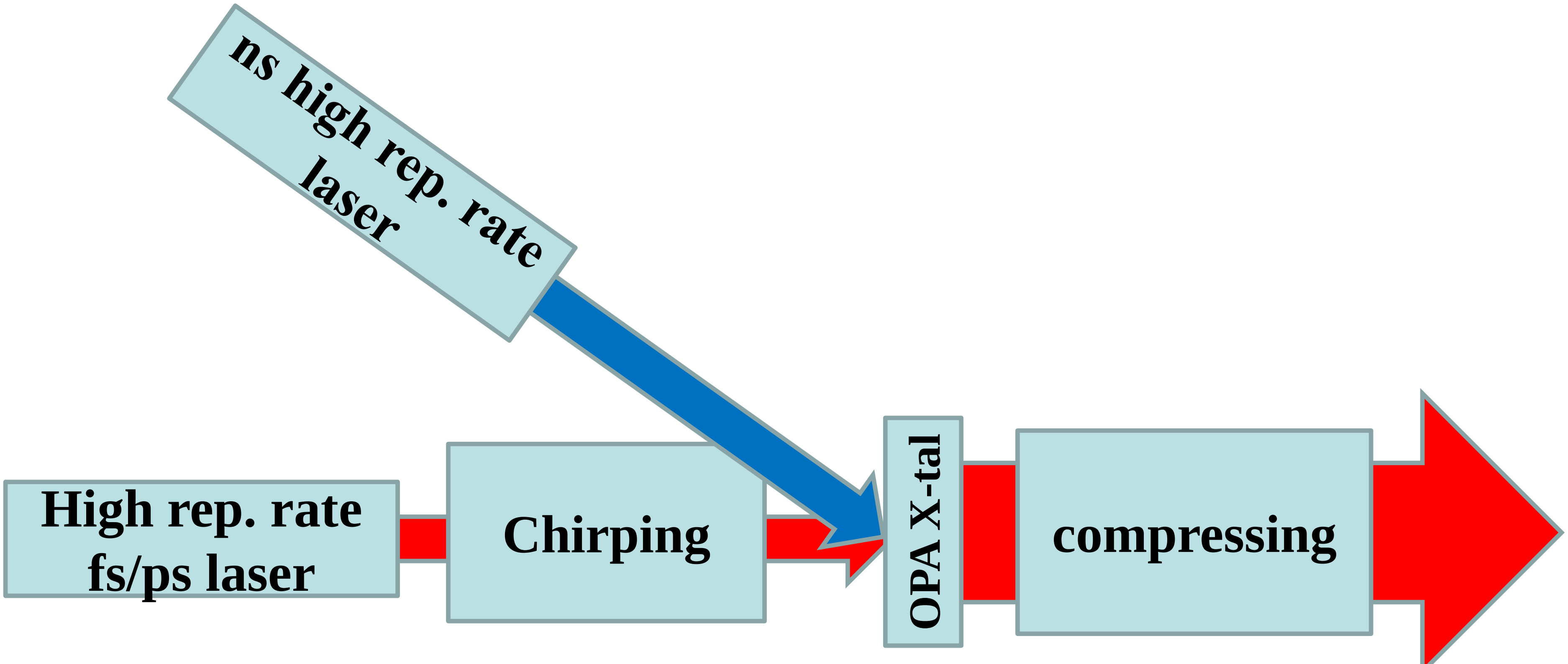
- High Rep. Rate Laser (2.5kJ@10Hz module)
- (option for Fast/shock ignition)
  High Rep. Rate ps/fs Laser (pulse width: 1~500 ps)
- Target injection (< 20μm@400m/s@5meters)
- Protection of windows from explosion debris

→ Resolved by
Coherent Beam Combination
by self-phase controlled SBS-PCM

Tactics to achieve IFE with the advanced ignition concepts

- 2.5 kJ @ 10 Hz, ~ns laser driver for compression
  - by coherent beam combining using SBS-PCMs
- 100kJ @ 10 Hz, fs/ps laser for fast ignition/shock ignition
  - through OPCPA pumped by ns Beam Combination dream Laser
- Target injection (<20 μm @ 400 m/s @ 5 m)
  - Self navigation technique using SBS-PCMs

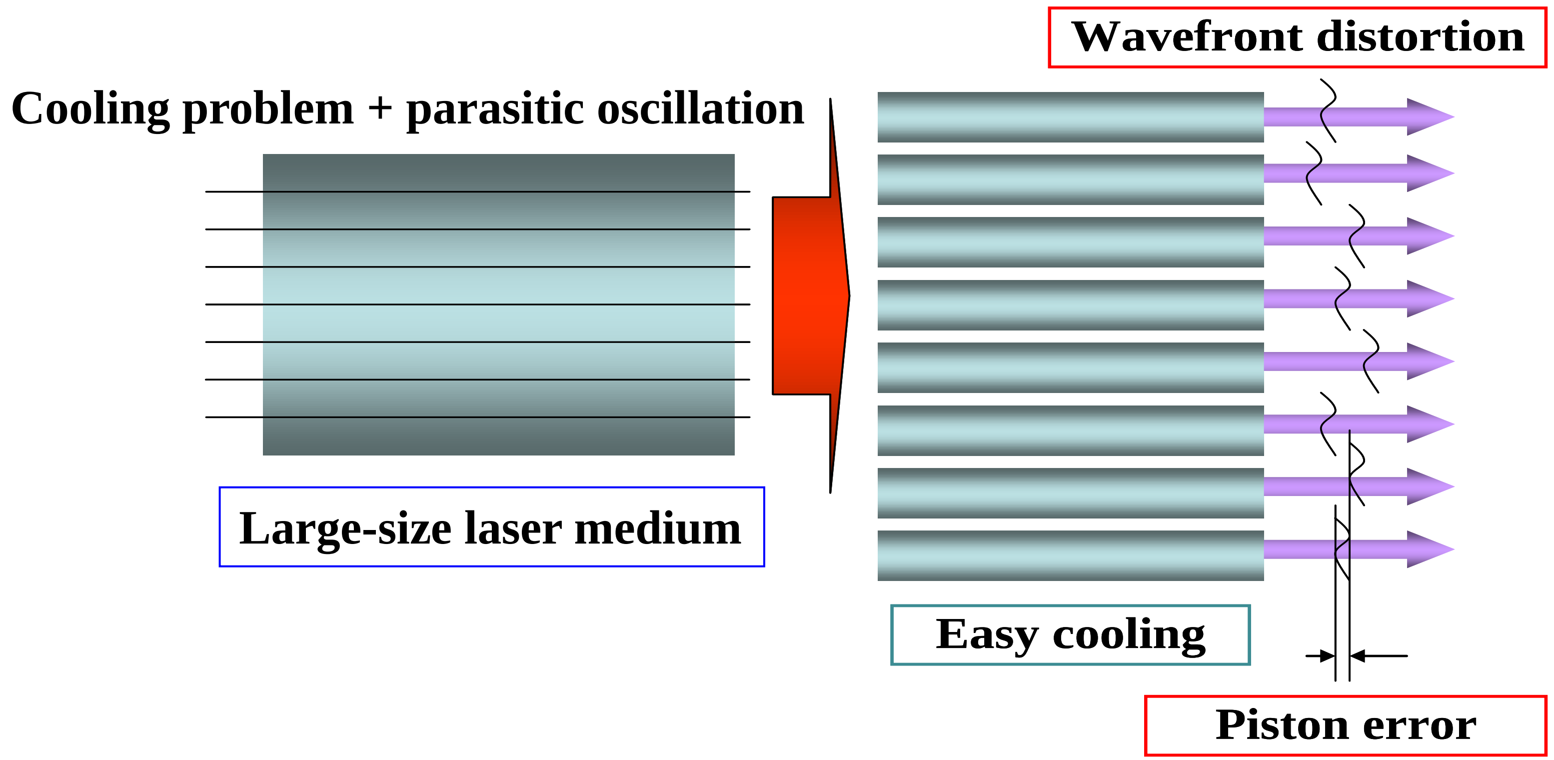
High rep. rate fs/ps laser can be produced by **OPCPA** using ns high rep. rate laser



Beam combination using self-controlled SBS-PCM: easy, proven, and scalable

- **Self-phase-controlled SBS-PCM:**
  - Most simple structure
  - only SBS medium cell and concave mirror
- **Experimentally proved:**
  - Coherent 4 beam combination system (~100mJ @ 10 Hz) is successfully demonstrated
- **Easily scalable**
  - By increasing additional gain medium, we can yield pulse energy we want

Beam combination and its problems



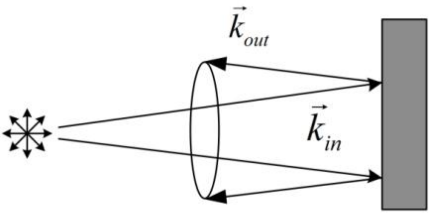
Ways of clean-up of wave-front distortion

	Spatial filtering	Adaptive Optics	Phase Conjugate	
			SBS	4Wave Mixing
Loss of Energy	Depends on the beam quality	small	**small**	small
system	Simple	Complicated	**Most simple**	Complicated
Input energy	No limit	No limit	**No limit**	Small
Piston error correction	OK	OK	**impossible before 2003***	OK

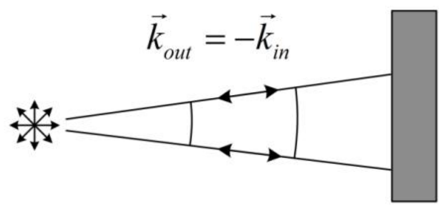
*** Random Piston Error of SBS-PCM**

- inherent problem of SBS,
- but it was resolved by H. J. Kong in 2003 by **the self-phase-control technique**

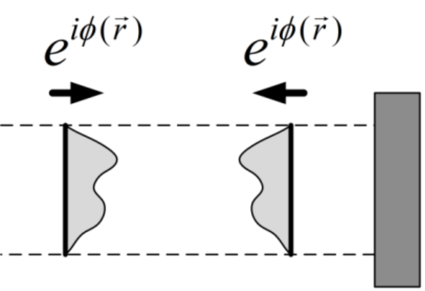
Phase conjugate mirror



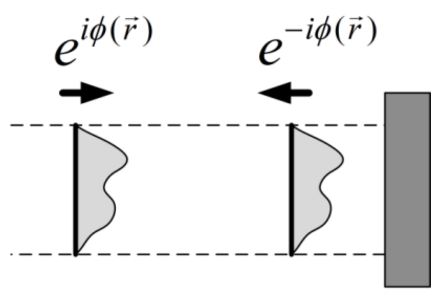
Conventional mirror



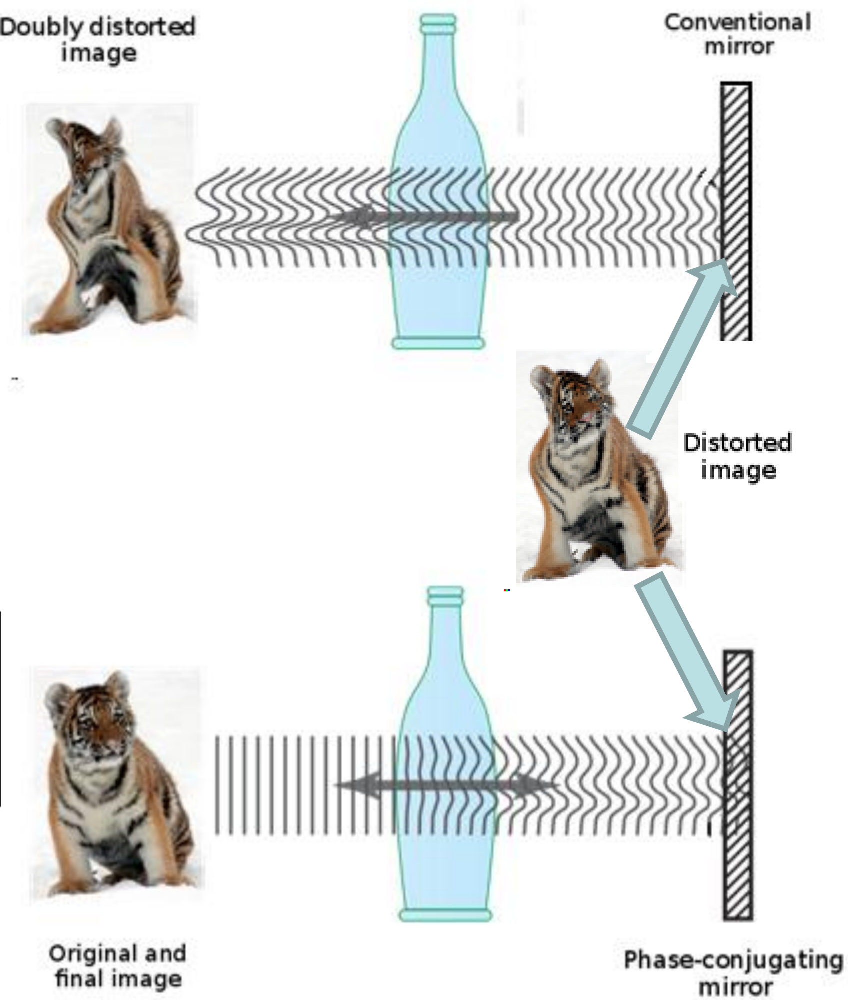
Phase conjugate mirror



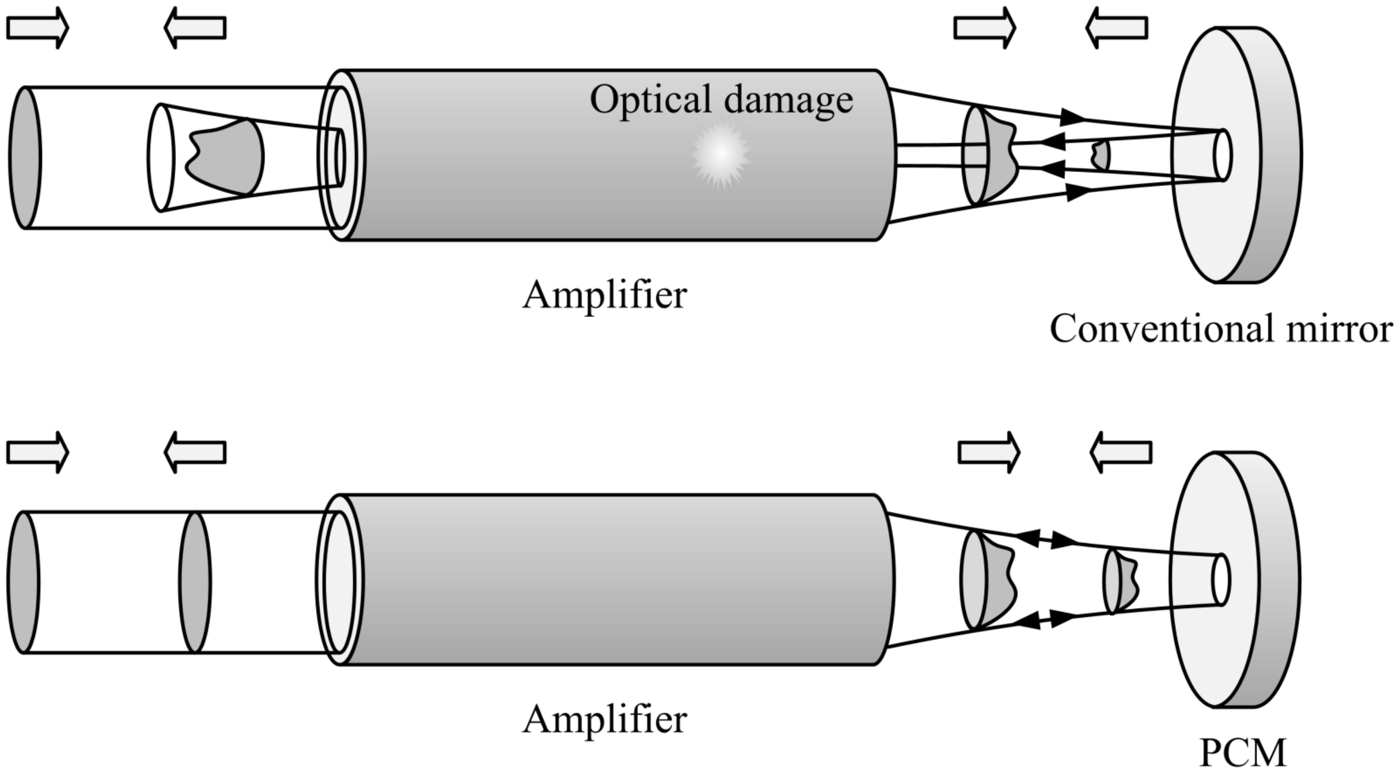
Conventional mirror



Phase conjugate mirror



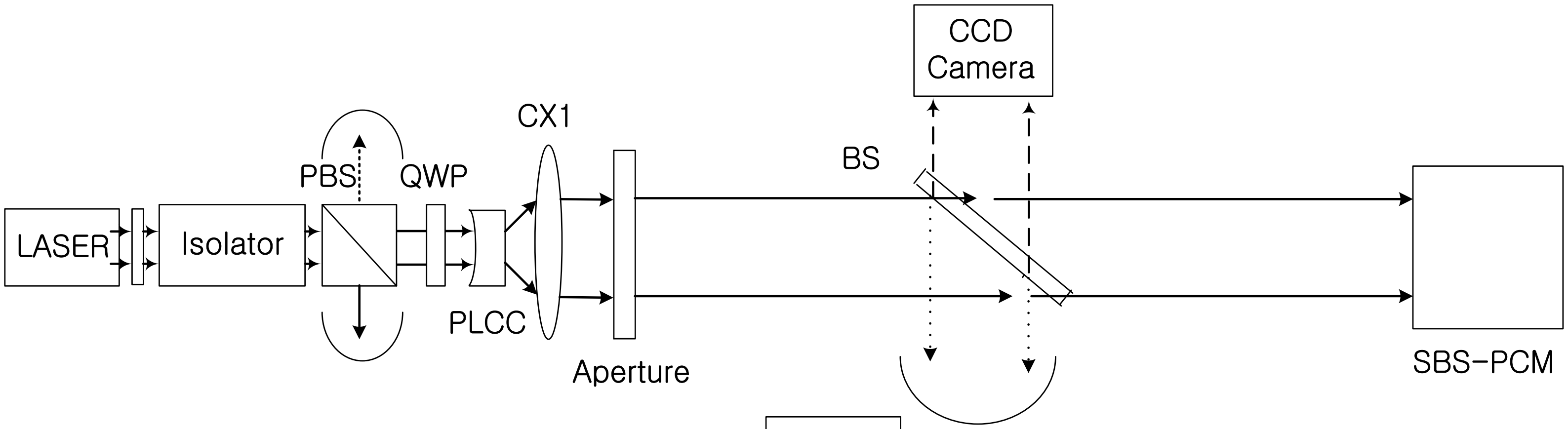
Practical Application of SBS-PCM



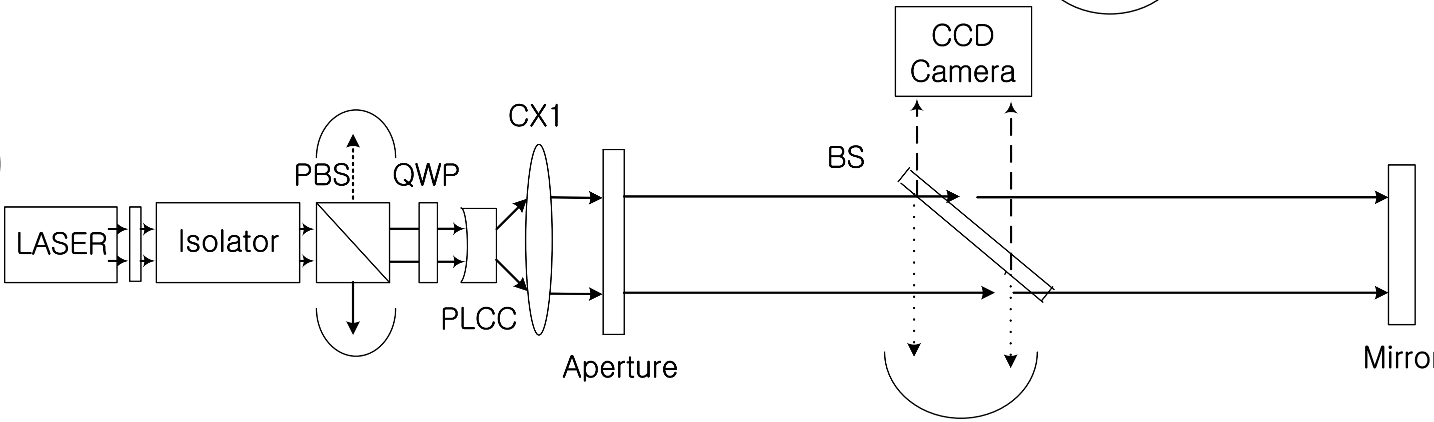
Master oscillator power amplification (MOPA) with phase conjugate mirror (PCM)

Image reconstruction by SBS-PCM

(a)



(b)

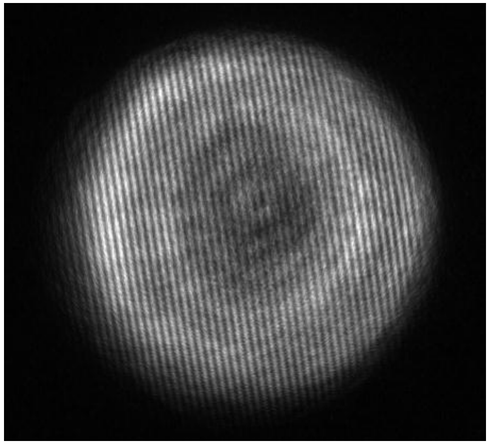


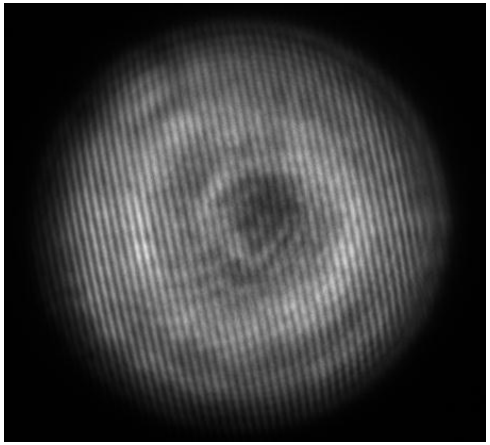
PBS : Polarizing beam splitter; BS : Beam splitter; QWP : Quarter wave plate; CX1, 2, PLCC : Lenses

Image reconstruction by SBS-PCM

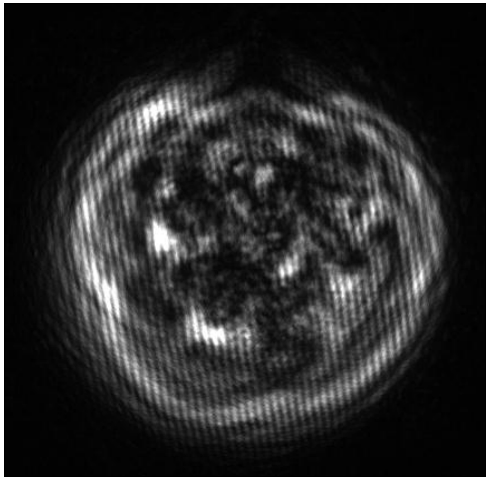
Conventional mirror | **SBS-PCM**

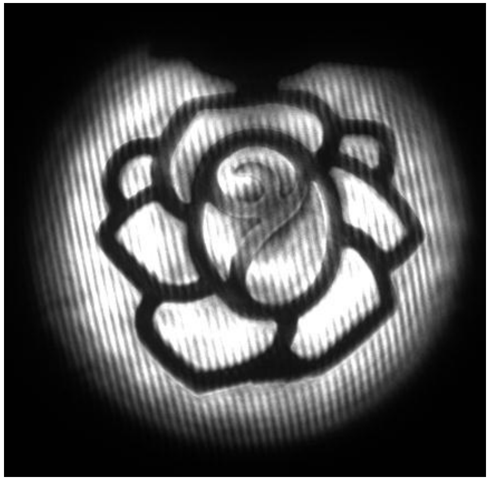
Without aperture





Rose shaped aperture





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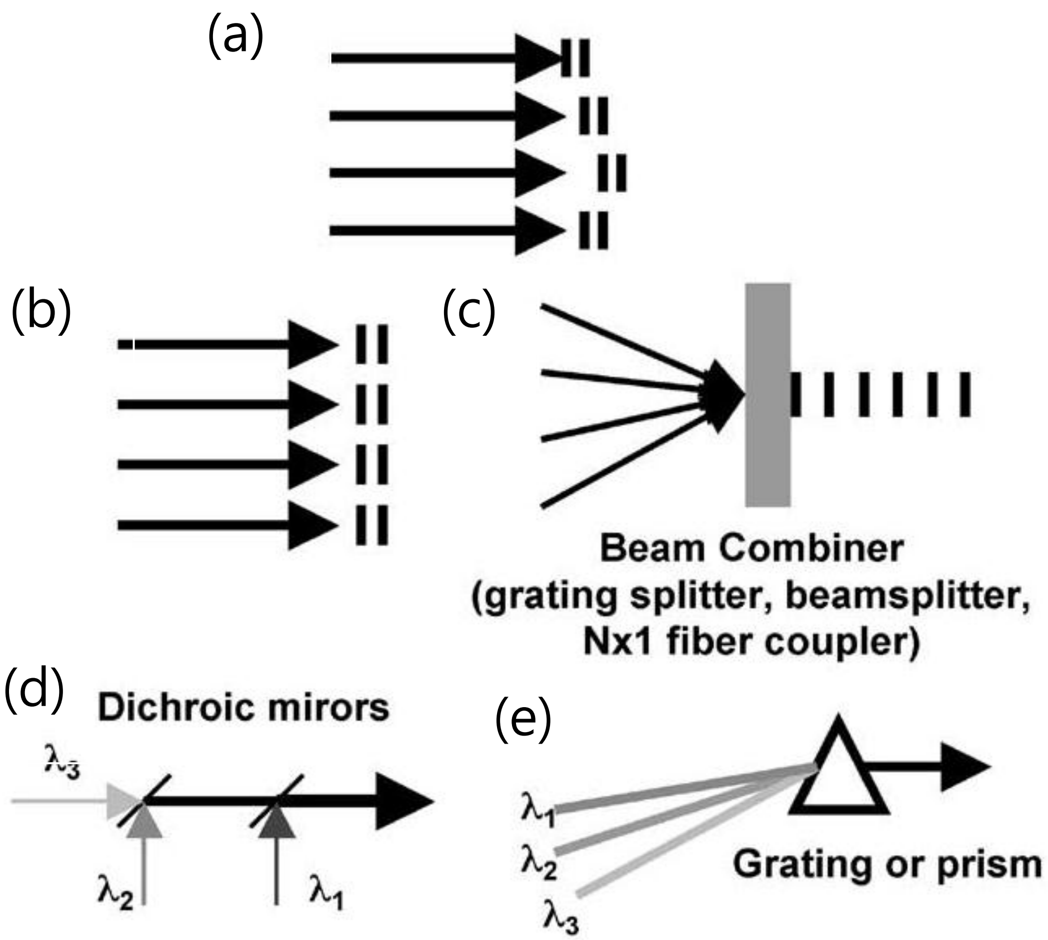
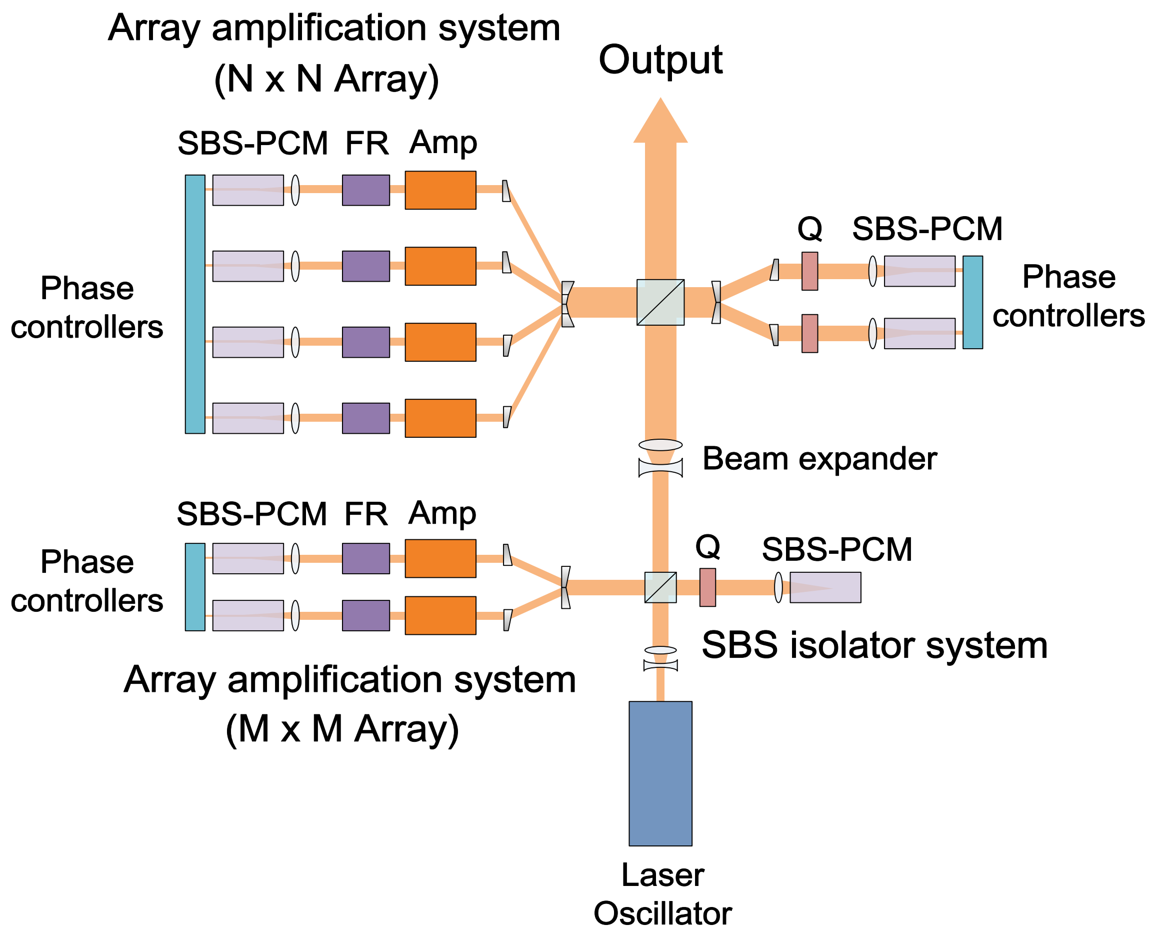
Beam combinations



- (a) Side-by-side beam combination
- (b) Tiled aperture coherent beam combination
- (c) Filled aperture coherent beam combination
- (d) serial wavelength beam combination
- (e) parallel wavelength beam combination

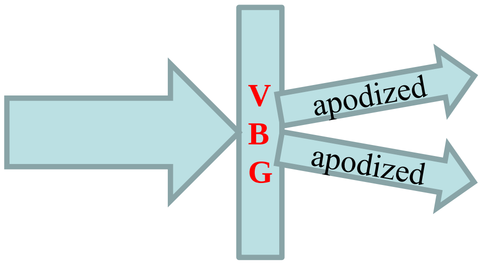
Beam combination laser system using SBS-PCMs

Wave-front dividing method

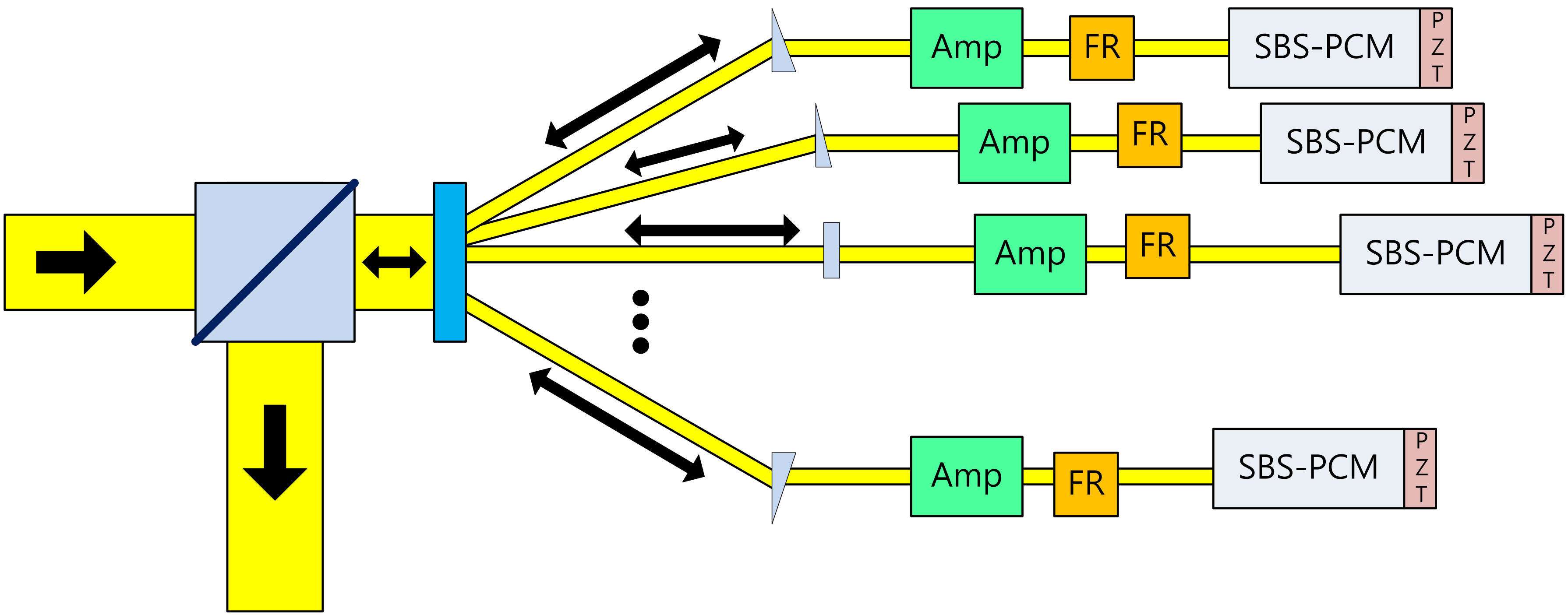


H. J. Kong, J. Y. Lee, Y. S. Shin, J. O. Byun, H. S. Park, and H. Kim, Opt. Rev. 4, 277 - 283, 1997.

WD M × M Amp array

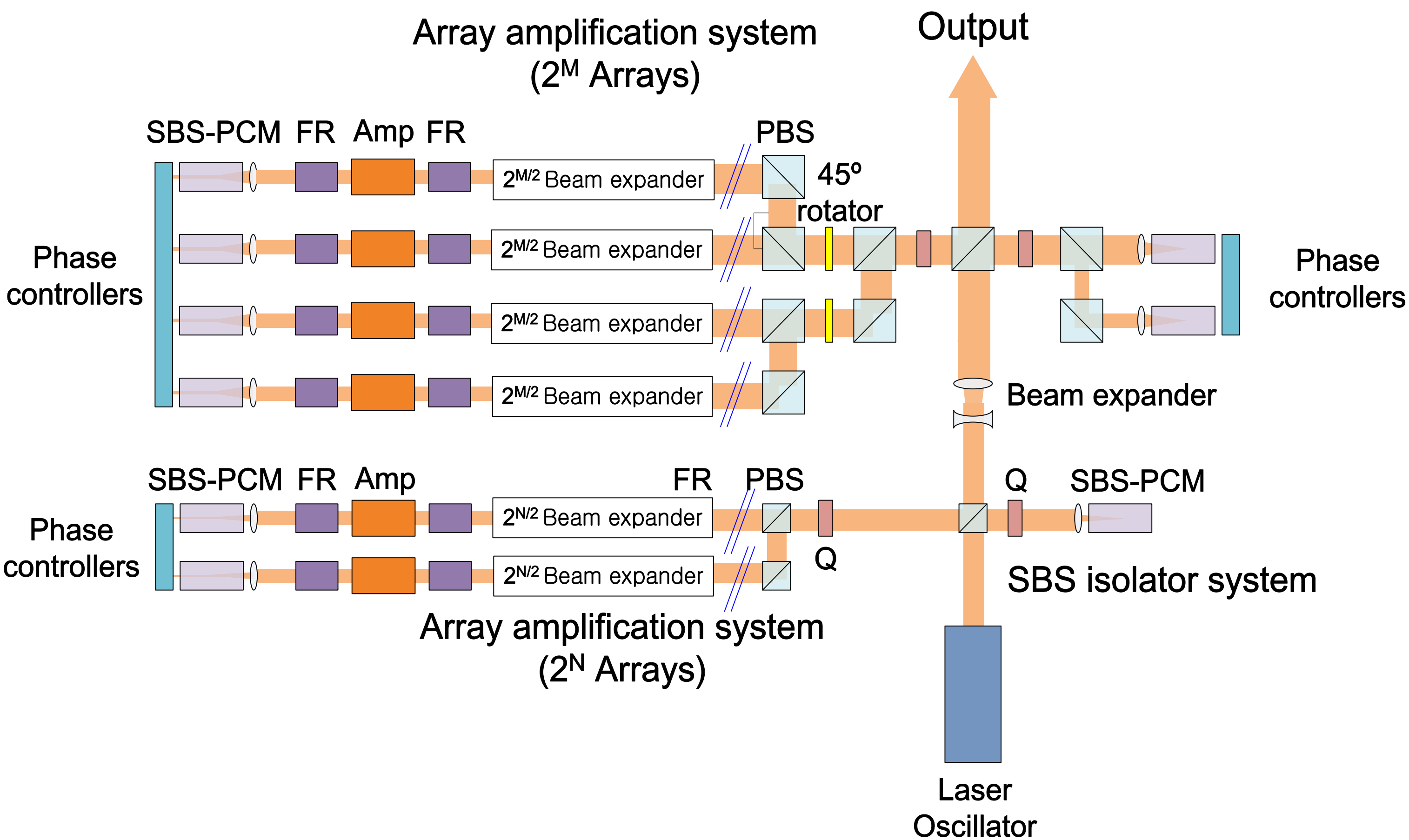


WD M X M Amp array



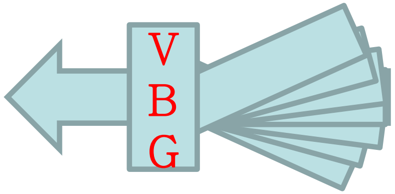
Beam combination laser system using SBS-PCMs

Amplitude dividing method

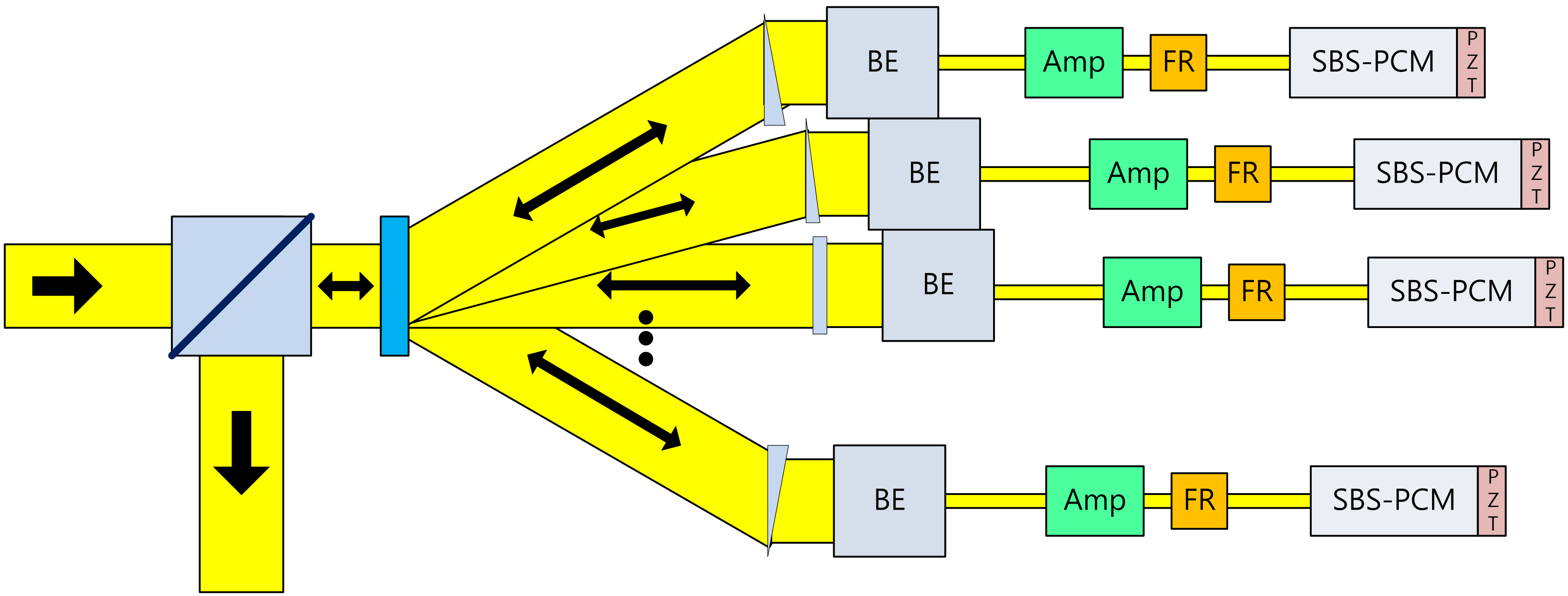


H. J. Kong, S. K. Lee, J. W. Yoon, and D. H. Beak, Opt. Rev. 13, 119, 2006.

AD M × M Amp array



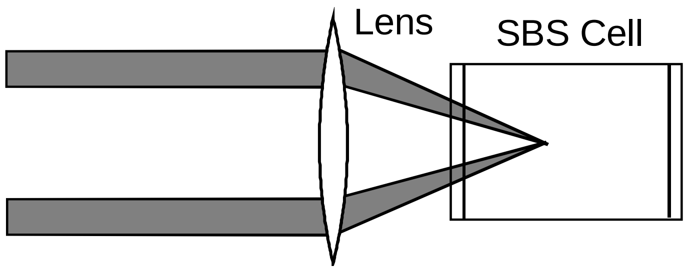
AD M X M Amp array



Previously developed phase control methods

1. **Overlapping the SBS focal points locks the phases of the beams.**

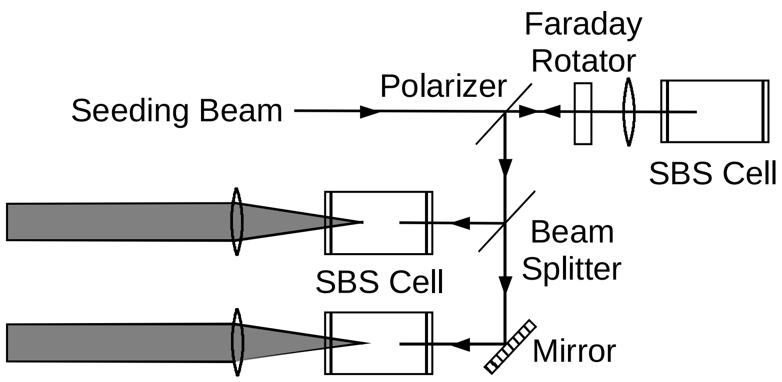
2. **Phase locking by back seeding the Stokes shifted beam, which locks the phase of the PC wave.**



a) Overlap of two focal points

D.A.Rockwell and C.R.Giuliano, Opt. Lett. 11, 147 (1986)

Impractical for many beams > 4



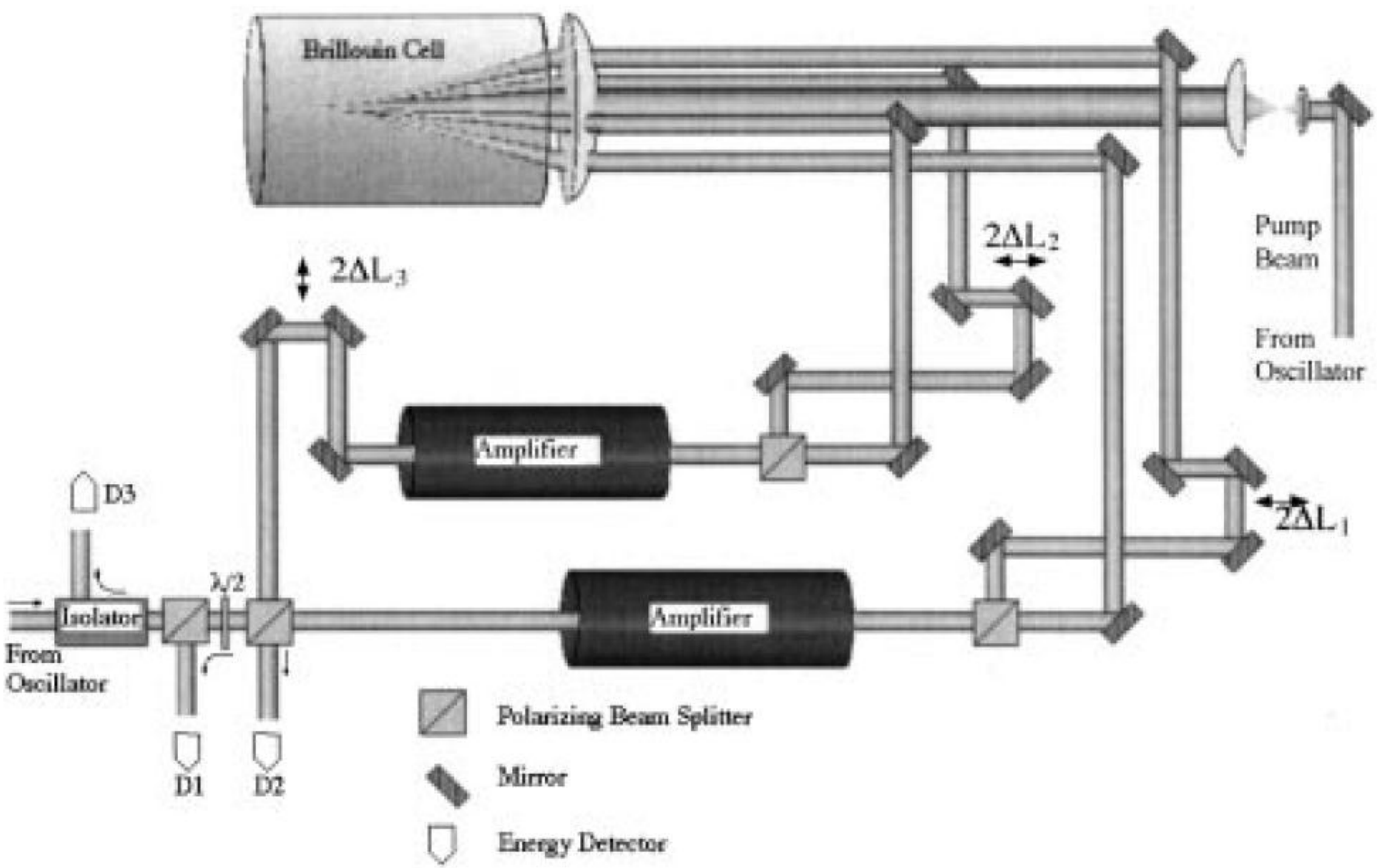
b) Back-seeding of Stokes wave

R.H.Moyer, et. al., J.Opt.Soc.Am.B, 5, 2473 (1988)

PC can be broken by back seeding beam
No PC anymore

Brilloun-enhanced four-wave mixing (BEFWM)

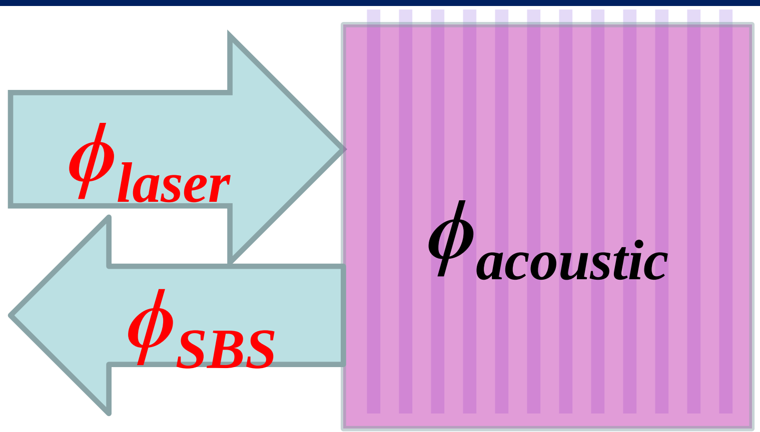
M.Bowers and R.Boyd, “Phase locking via Brillouin-enhanced four-wave mixing phase conjugation”, **IEEE QE-34**, 634(1998)



Good for controlling phase

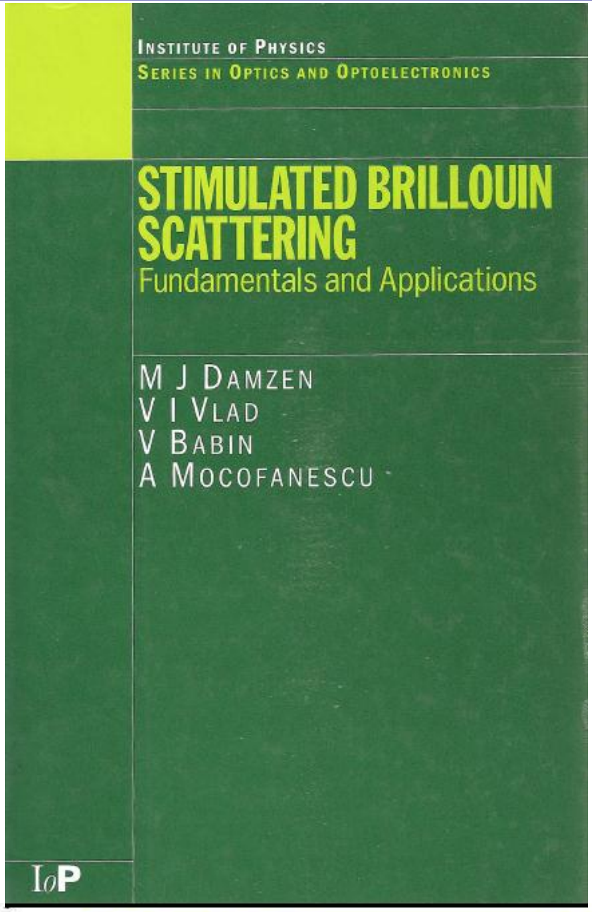
Too complicated optics

Phase of SBS wave



$$\phi_{SBS} = \phi_{laser} - \phi_{acoustic}$$

$\phi_{acoustic}$ is random for it is originated form noise.
If $\phi_{acoustic}$ is controlled, we can control ϕ_{SBS} .



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pulse duration to be long compared with the SBS onset time and intercell transit time. Similarly, for a coherent interaction it is necessary for the laser-coherence length to be at least twice the total length of the two-cell system. If the intercell transit time is long, then there will be a lengthy delay before the amplifier is seeded and power limiting becomes effective. For this reason it is desirable to use a relatively compact two-cell geometry.

A further feature demonstrated by the simulations but also observed experimentally at high powers is the ability to achieve greater than unity reflectivity on a transient basis. This overshoot by the Stokes radiation can be explained by storage of radiation in the two-cell system. The excess of Stokes power over the input pump will only be temporary since the severe depletion of the pump will reduce the seeding signal, resulting in an overshoot for a time of the order of twice the intercell transit time. The amount of overshoot is dependent on the gain of the amplifier and on the intercell losses. For low losses, the seeding level can be high, leading to a substantial overshoot.

The performance of the generator cell could be improved by the introduction of optical feedback, which has been shown to reduce the threshold and increase the phase conjugate fidelity of the SBS process [7.6], as described previously.

7.5 Laser beam combining using SBS

In the normal SBS configuration a single pump beam is incident upon the SBS medium, and the Stokes scattered output beam is generated by amplification of noise. This SBS scattered field will have a random overall phase since it starts from statistical noise and, in addition, this phase has been shown to fluctuate randomly in a time of the order of several times the phonon lifetime [7.14]. The SBS reflection, therefore, has no absolute temporal phase reference. As a consequence, if two beams are conjugated by SBS in separate interaction volumes the two Stokes beams will have a phase difference that is random and unrelated to the phase difference of the pump beams. Basov *et al* [7.15] first predicted this random phase difference and several groups demonstrated its existence [7.16–7.18]. If the random phase difference in the Stokes beams is to be avoided an absolute phase reference must be created. This can be accomplished by several methods.

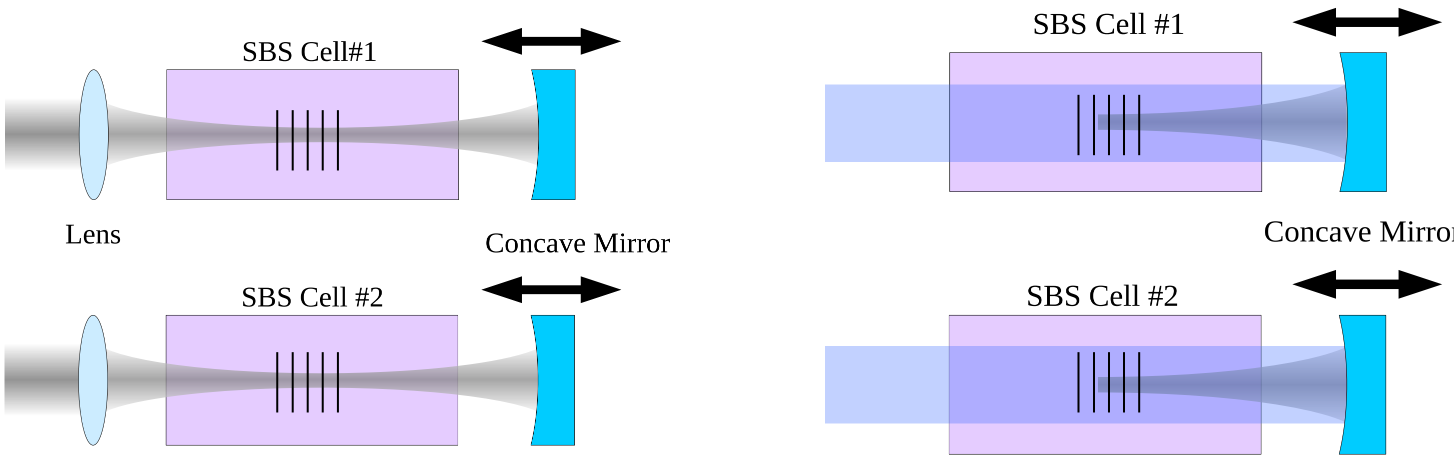
7.5.1 Laser beam combining using spatial overlap in SBS

Consider the case where two or more pump beams are overlapped in the same interaction volume. They appear to the SBS process as a single, but highly aberrated, beam with the relative phase between the beams appearing as an aberrated wave front. The standard mechanisms that phase conjugate a

cation of noise. This SBS scattered field will have a random overall phase since it starts from statistical noise and, in addition, this phase has been shown to fluctuate randomly in a time of the order of several times the phonon lifetime [7.14]. The SBS reflection, therefore, has no absolute

“Self-phase control” method

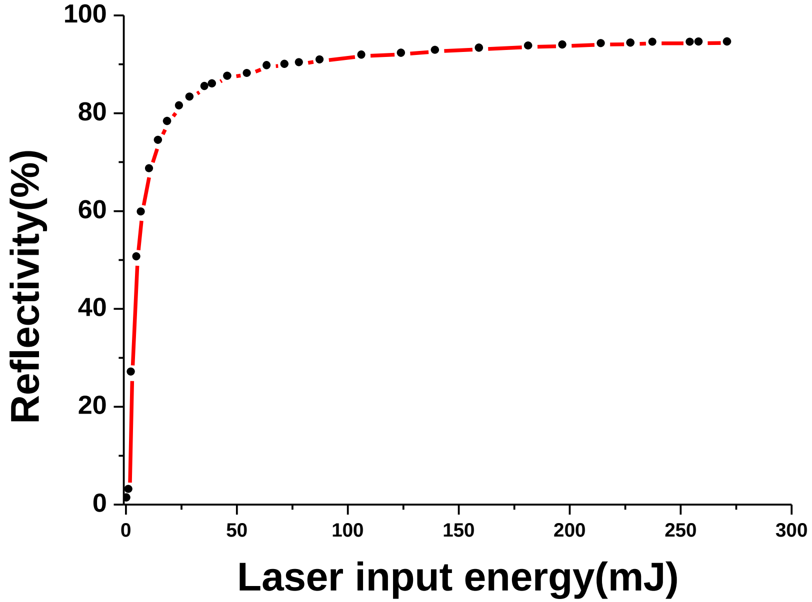
- Feed back mirror > Counter propagating beams > Standing wave > Density modulation
- Standing density modulation locks the ignition position of the moving Bragg grating.
- The Bragg grating locks the phase of the SBS wave.
- Phase controlling of SBS wave is possible by positioning the feed back mirror.



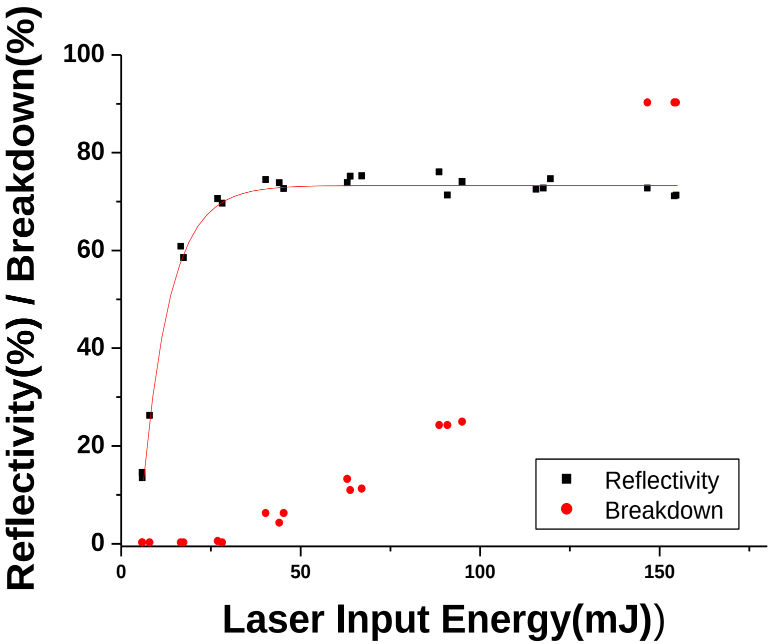
(a)Concentric type

(b) Confocal type

Reflectivity and breakdown probability depending on the laser mode of SBS-PCM with FC-75



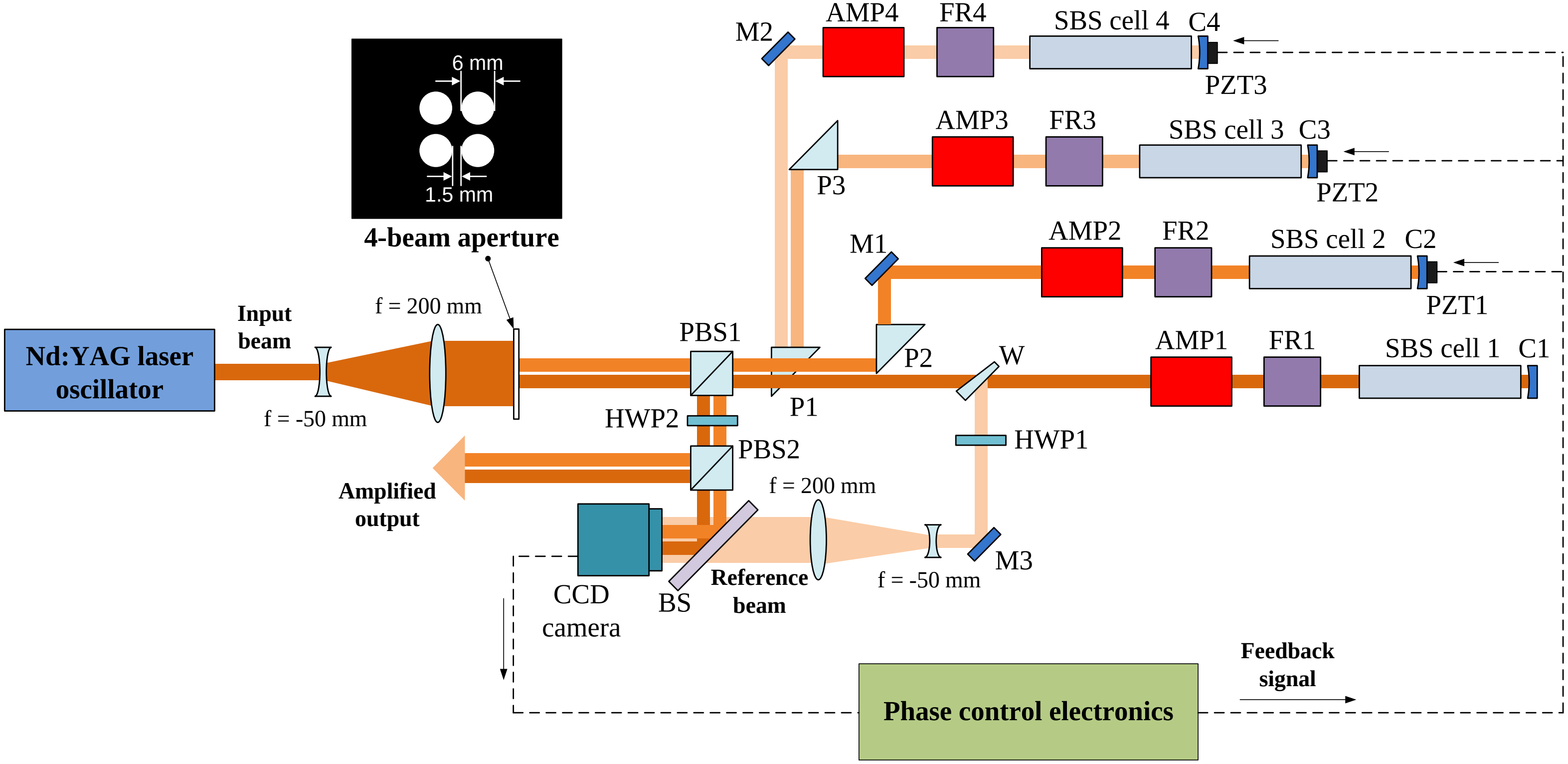
Single mode pumping
(Δν~120MHz, Γ=350MHz)
(No break down)



Multi mode pumping
(Δν~30GHz, Γ=350MHz)
(Break down occurs)

Seong Ku Lee, et. al, JKPS 46, pp.443~447, 2005.

Experimental setup for the wave-front dividing 4-beam combination



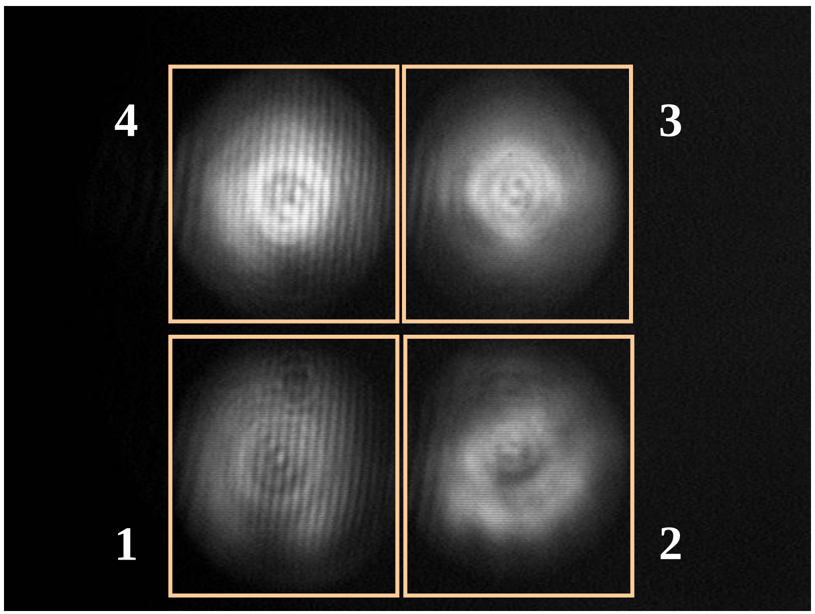
PB1&PBS2, polarizing beam splitters; HWP1&HWP2, half wave plate; P1, P2&P3, 45 degree prisms; BS, beam splitter; W, wedged window; FR1, FR2, FR3&FR4, Faraday rotators; C1, C2, C3&C4, concave mirrors; PZT1, PZT2&PZT3, piezoelectric translators.

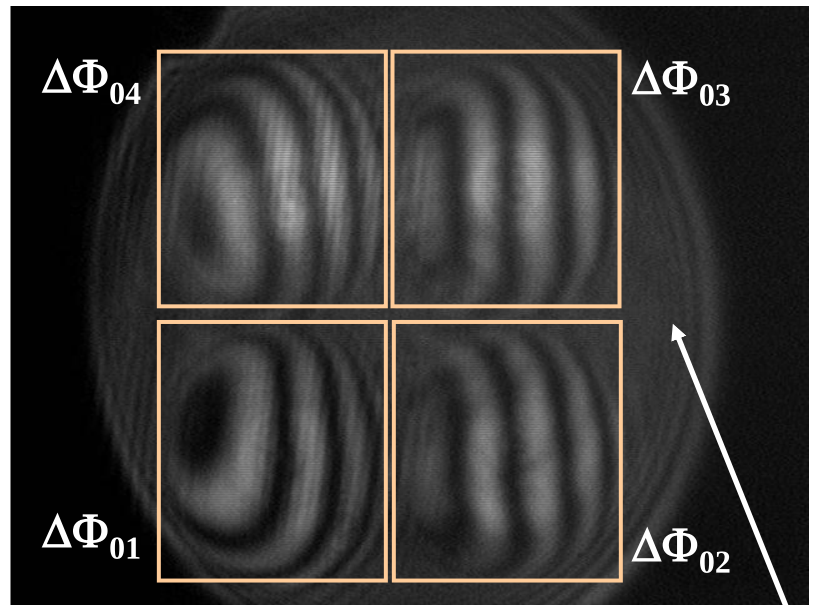
J. S. Shin, S. Park, H. J. Kong, and J. W. Yoon, Applied Physics Letters. 96.131116, 2010.

4-beam output profile & Interference patterns

4-beam combined output profile

Interference patterns at CCD camera





0: Reference beam

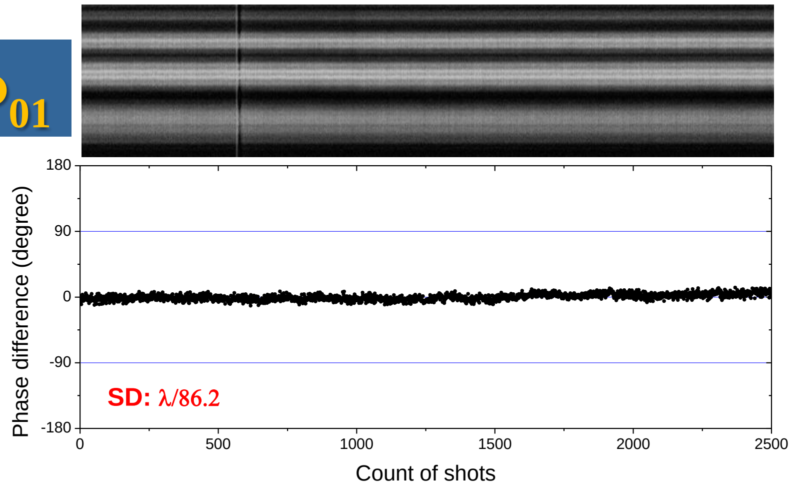
J. S. Shin, S. Park, H. J. Kong, and J. W. Yoon, Applied Physics Letters. 96.131116, 2010.

Beam Energy – AMP off case

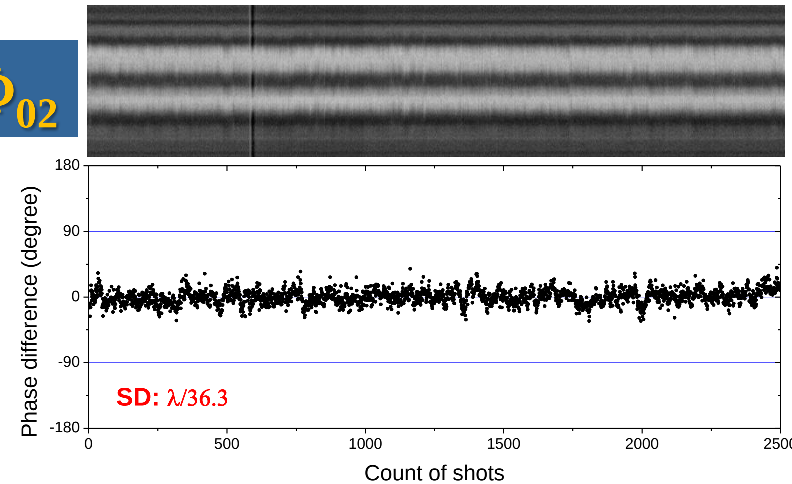
- **Input energy :** 32.2 ± 0.3 mJ
- **Output energy**
  - AMP off : 9.9 ± 0.5 mJ (reflected by SBS-PCMs)

Phase fluctuation without amplifier operation

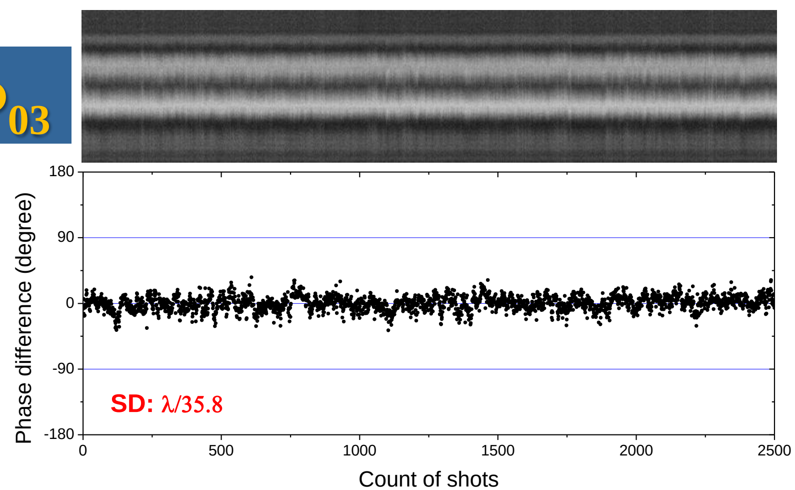
$\Delta\Phi_{01}$



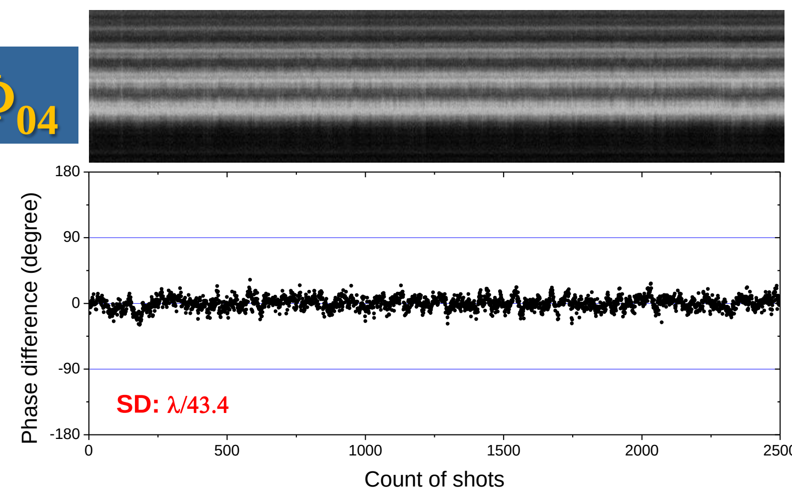
$\Delta\Phi_{02}$



$\Delta\Phi_{03}$



$\Delta\Phi_{04}$



J. S. Shin, S. Park, H. J. Kong, and J. W. Yoon, Applied Physics Letters. 96.131116, 2010.

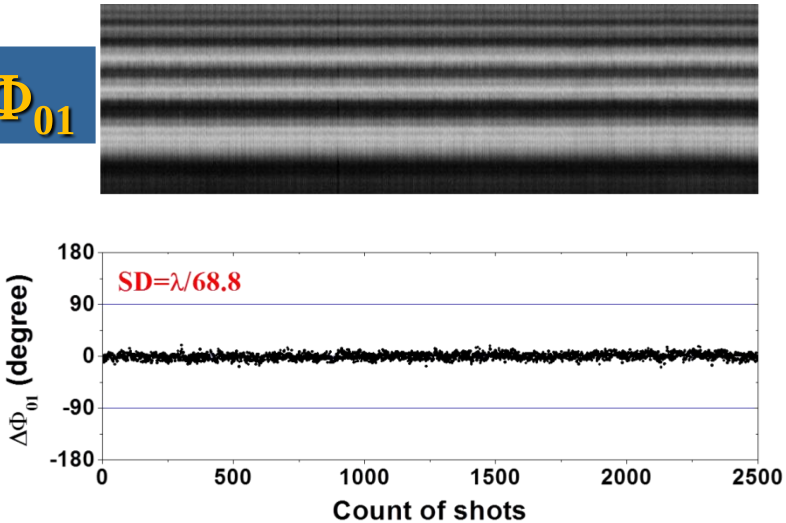
Beam Energy – AMP on case

- **Input energy :** 32.2 ± 0.3 mJ

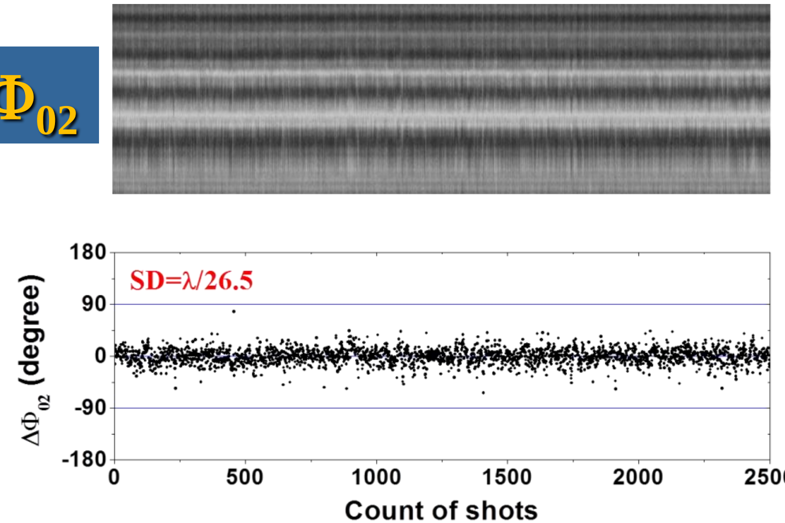
- **Output energy**
  - AMP off : 169 ± 6 mJ (gain : 5.3)

Phase fluctuation with amplifier operation

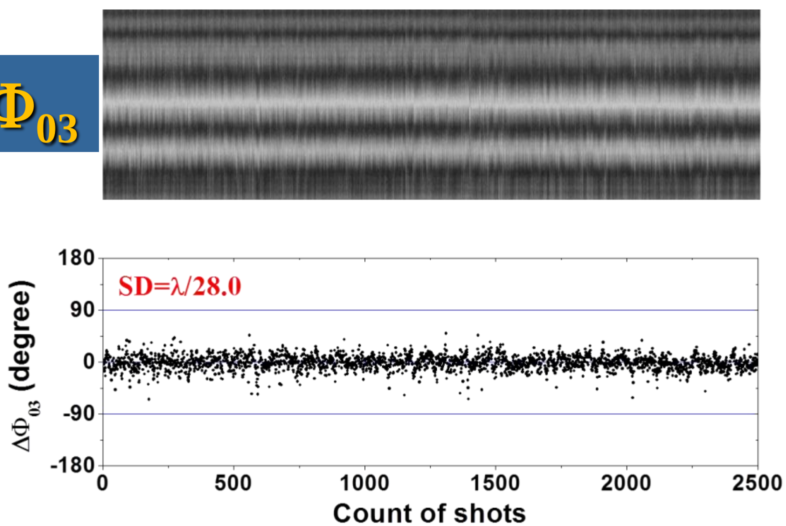
$\Delta\Phi_{01}$



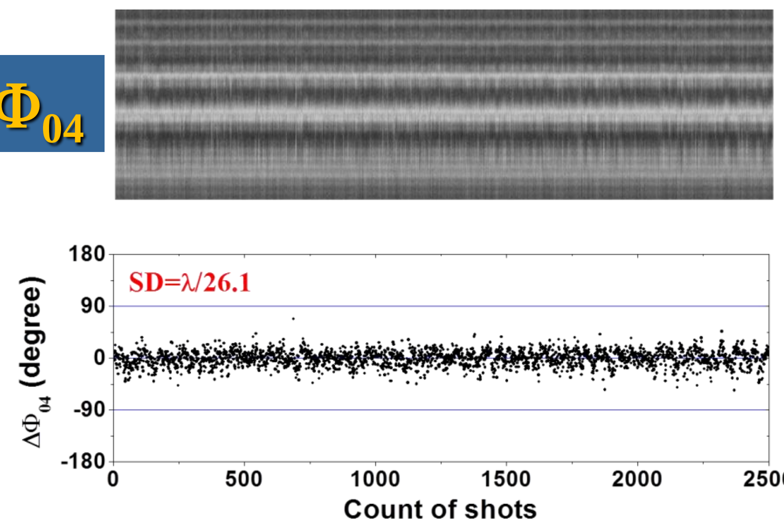
$\Delta\Phi_{02}$



$\Delta\Phi_{03}$



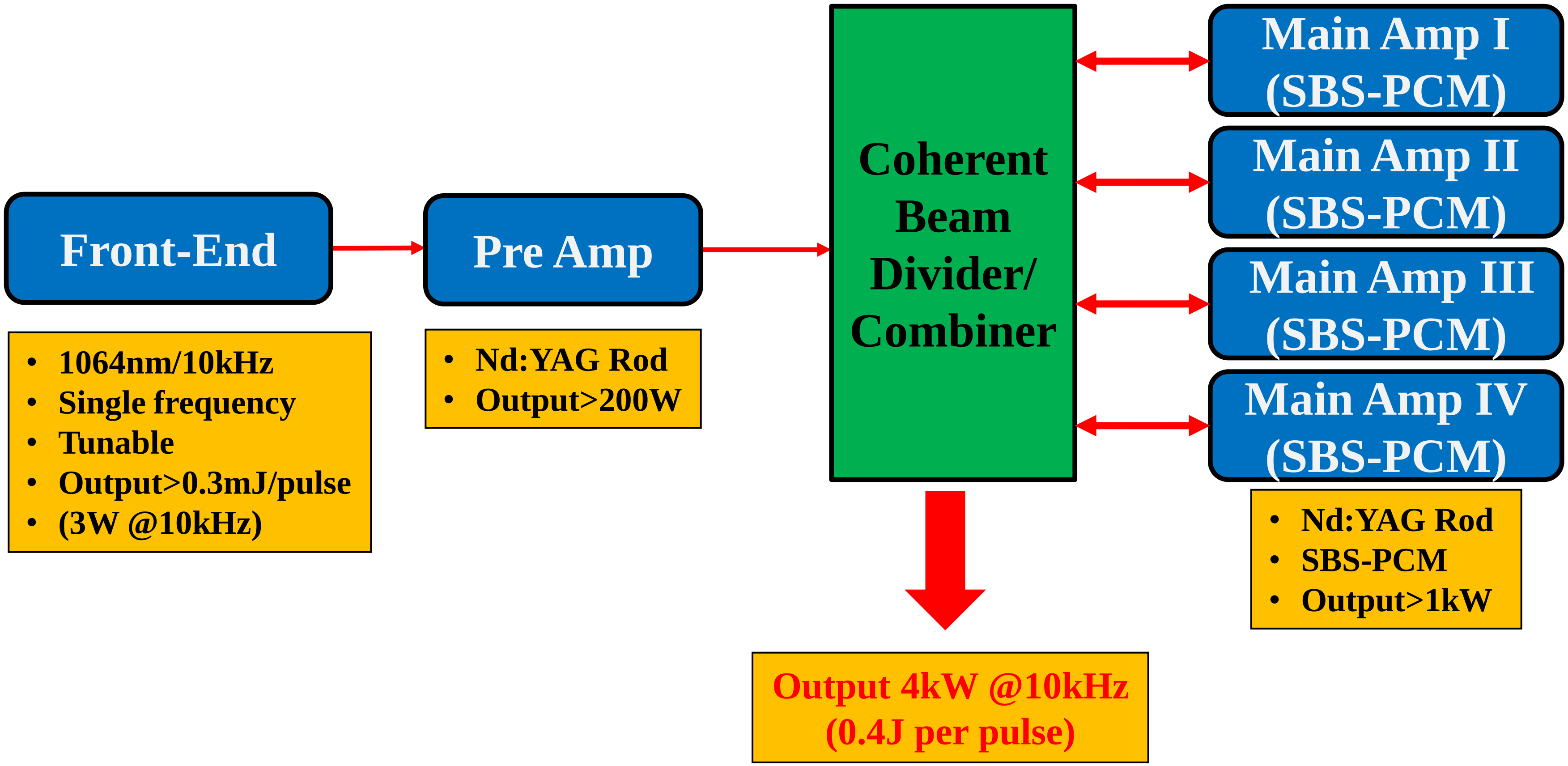
$\Delta\Phi_{04}$

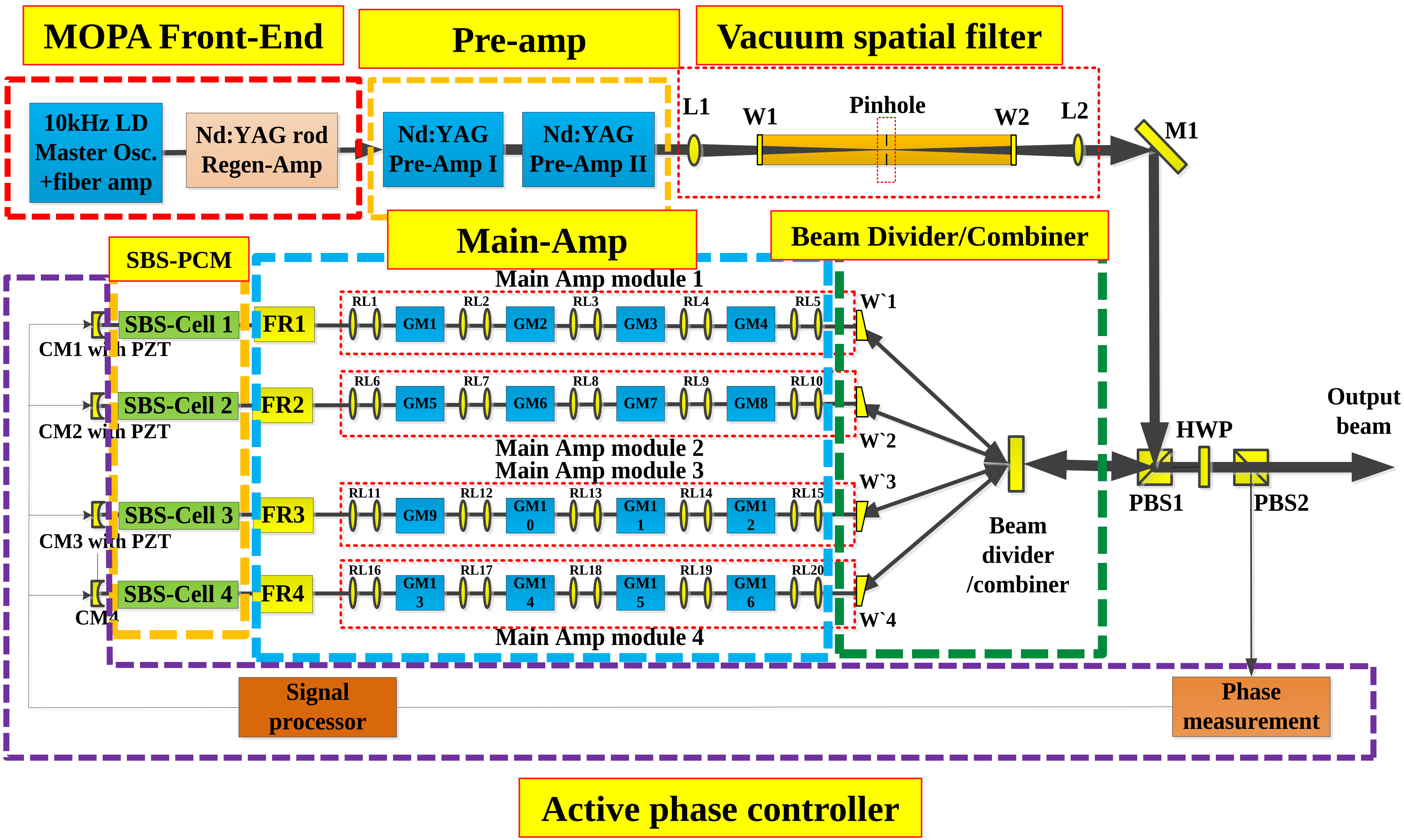


J. S. Shin, S. Park, H. J. Kong, and J. W. Yoon, Applied Physics Letters. 96.131116, 2010.

Kumgang (金鋼) laser: 0.1J@10ns@10kHz laser modules and beam combination for 4 kW using SBS-PCMs

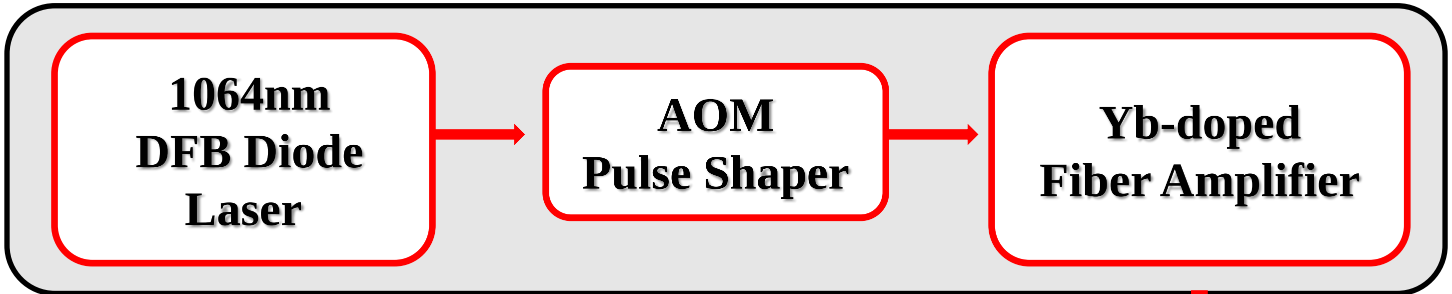
Laser System Configuration




MOPA Front-End
Pre-amp
Vacuum spatial filter
10kHz LD Master Osc. +fiber amp
Nd:YAG rod Regen-Amp
Nd:YAG Pre-Amp I
Nd:YAG Pre-Amp II
L1
W1
Pinhole
W2
L2
M1
Main-Amp
Beam Divider/Combiner
SBS-PCM
Main Amp module 1
RL1 GM1 RL2 GM2 RL3 GM3 RL4 GM4 RL5
W`1
SBS-Cell 1
FR1
CM1 with PZT
RL6 GM5 RL7 GM6 RL8 GM7 RL9 GM8 RL10
SBS-Cell 2
FR2
CM2 with PZT
W`2
Main Amp module 2
Main Amp module 3
RL11 GM9 RL12 GM10 RL13 GM11 RL14 GM12 RL15
SBS-Cell 3
FR3
CM3 with PZT
W`3
RL16 GM13 RL17 GM14 RL18 GM15 RL19 GM16 RL20
SBS-Cell 4
FR4
CM4
W`4
Main Amp module 4
HWP
Output beam
PBS1
PBS2
Beam divider /combiner
Signal processor
Phase measurement
Active phase controller

Front-End Laser System

Hybrid Front-End Laser System Design Requirement



10kHz Master Oscillator

DFB CW diode laser
- Tunable 1064-1065nm
- Single frequency linewidth

AOM Pulse shaper
- 10kHz-10ns Gaussian-like pulse
- High pulse contrast ratio

Yb-doped fiber amplifier
- Yb-doped PM gain fiber
- 976nm LD pump

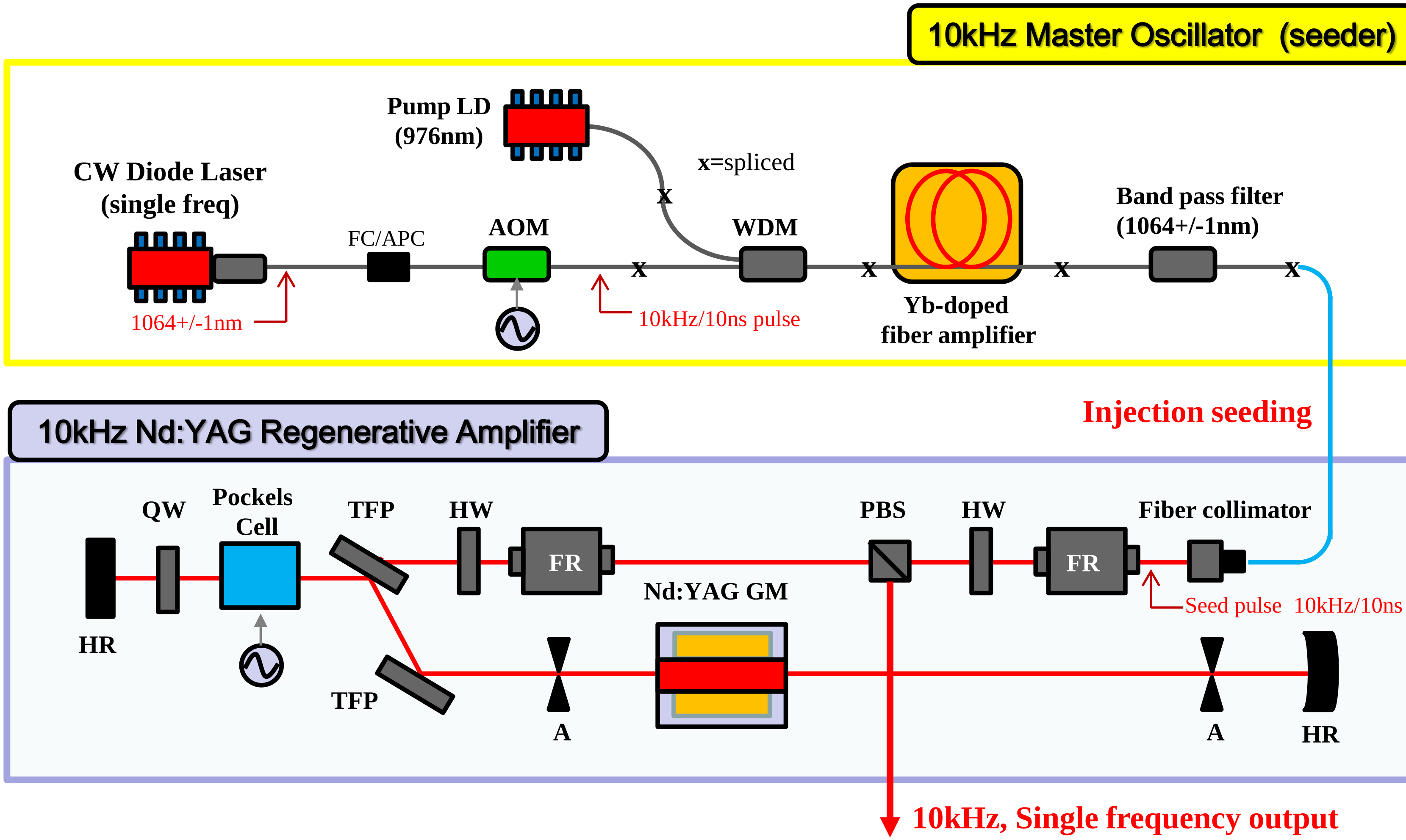
All PM fiber optic

Injection seed pulse
10nJ/10kHz/10ns

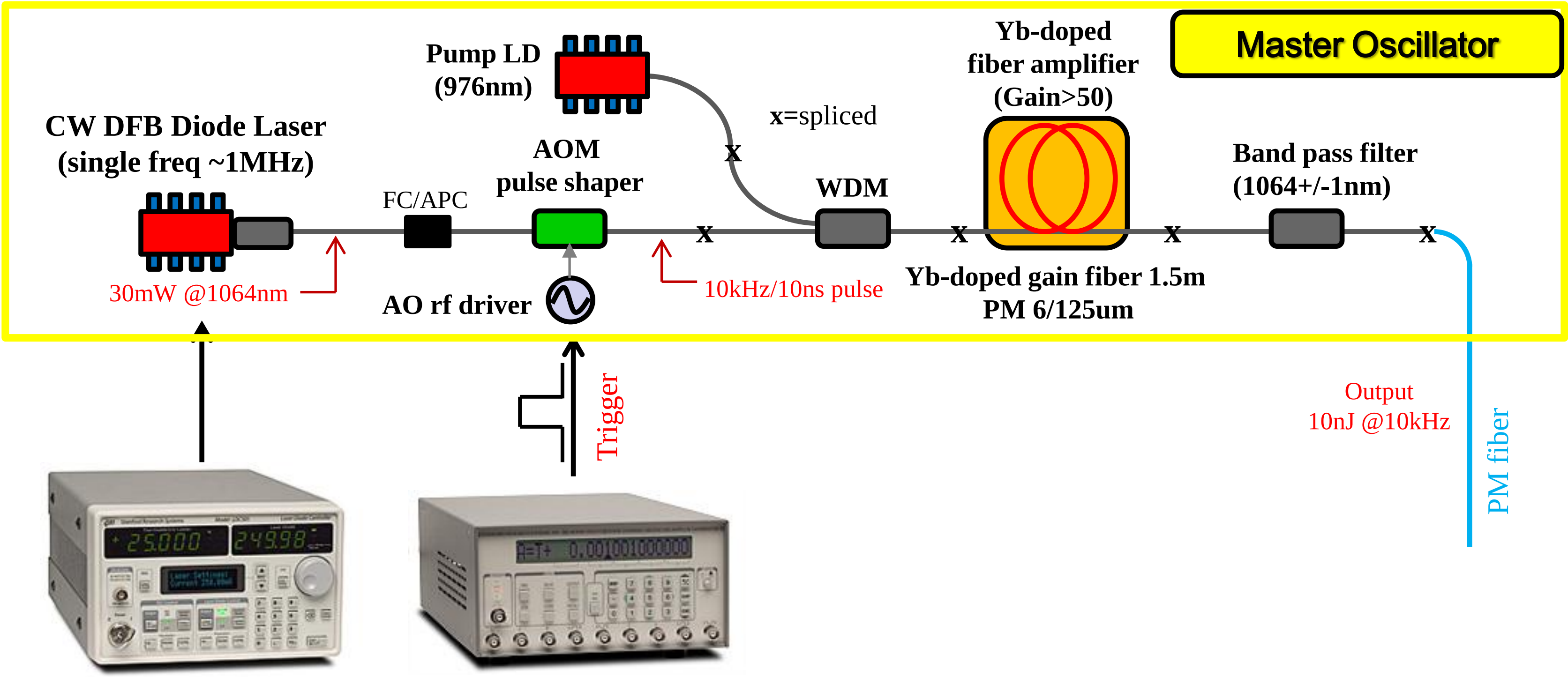
Diode-pumped
10kHz Nd:YAG
Regenerative Amplifier

Output>5W (0.5mJ)
Rep rate 10kHz
Pulsewidth ~10ns
Single frequency <100MHz

Hybrid Front-End Laser Layout



Master Oscillator Setup

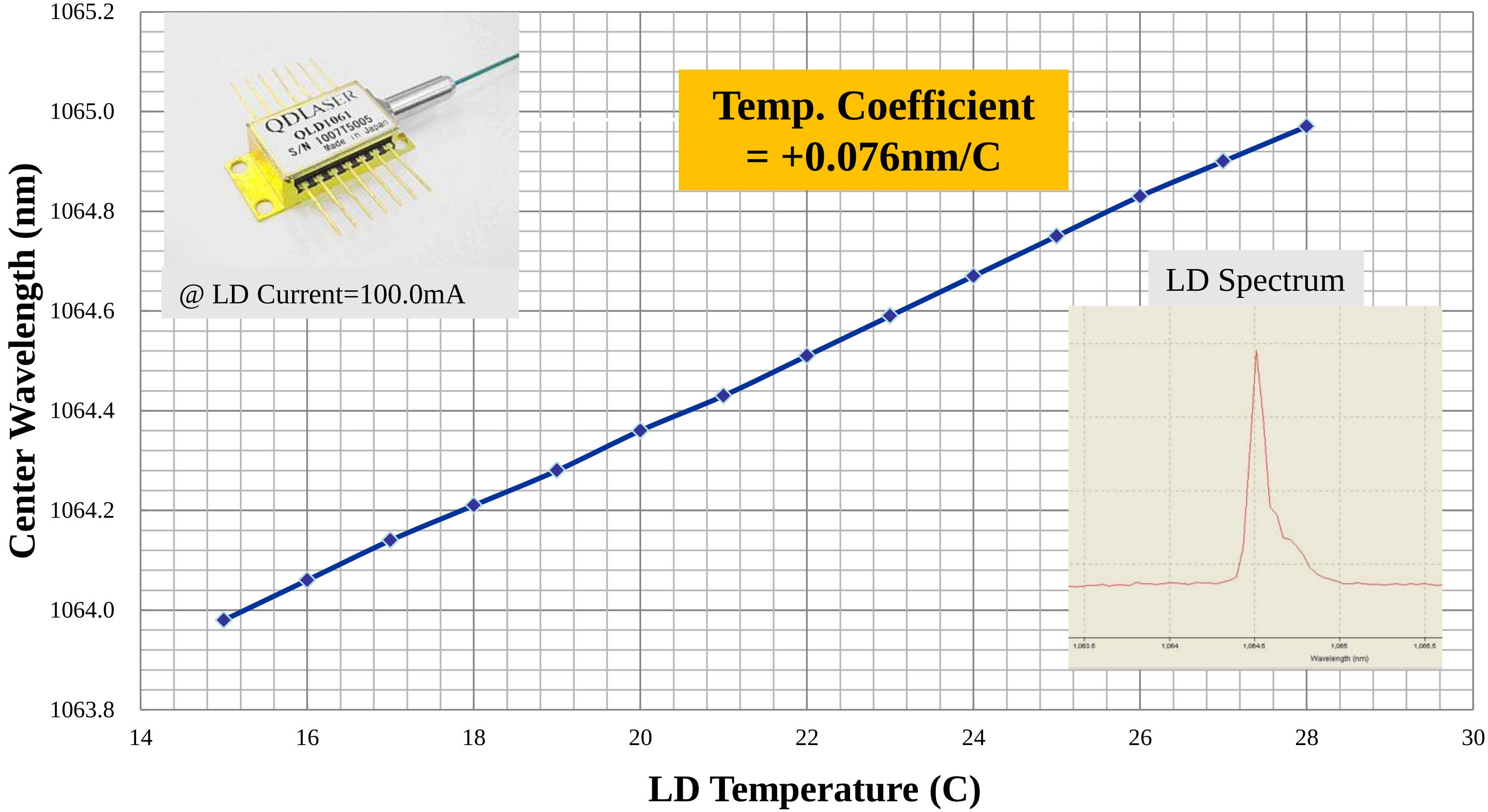


Laser diode controller (Current & TEC driver)

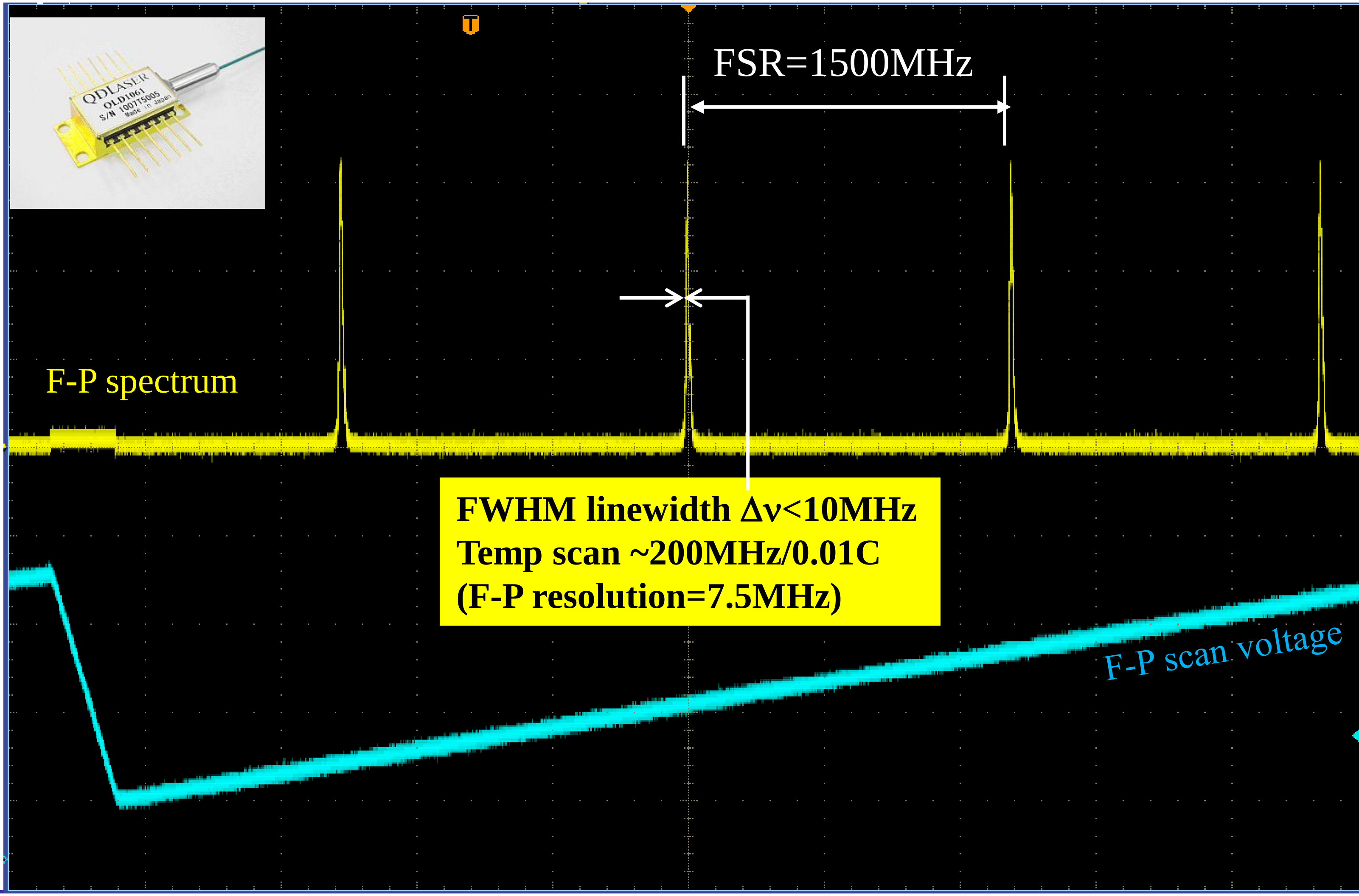
Digital pulse & delay generator

AOM: acousto-optic modulator
WDM:Wavelength division multiplexer

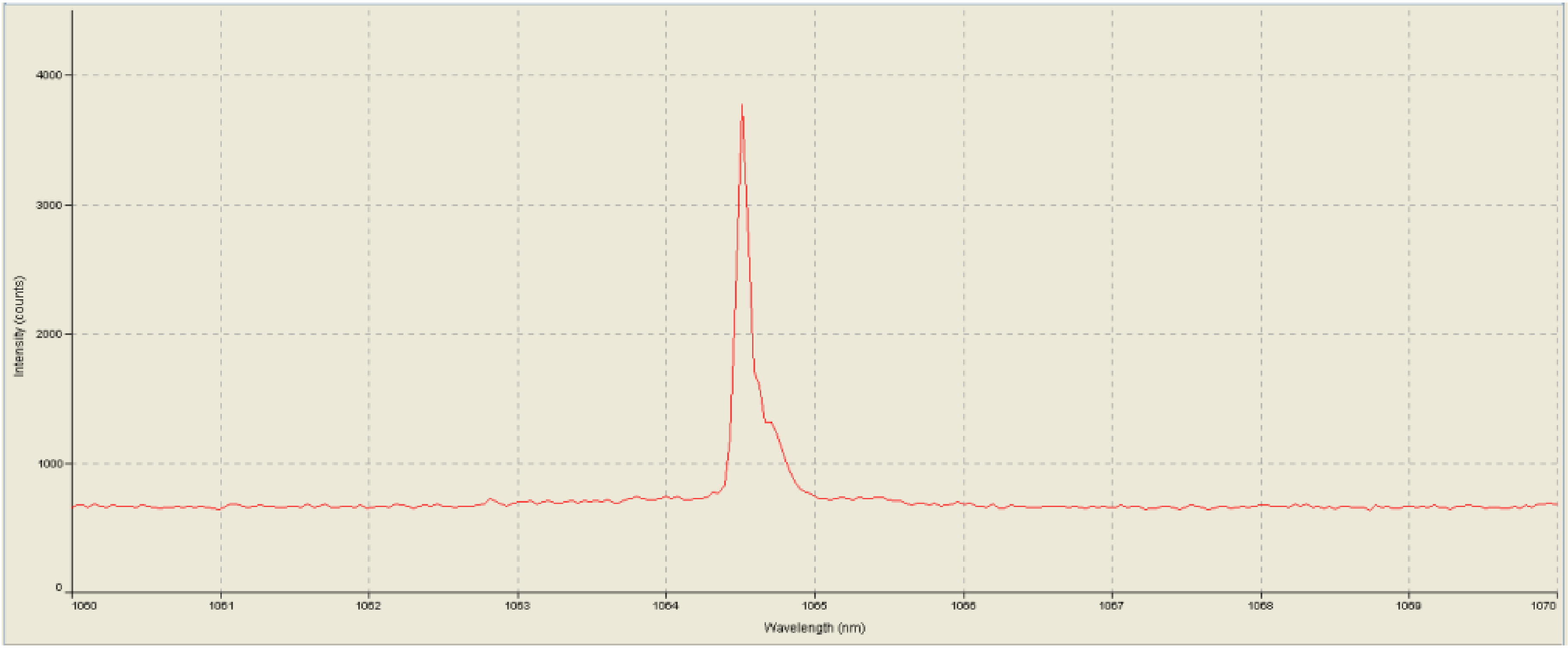
DFB Laser Diode Wavelength TEC Temperature Tuning



DFB Laser Diode Linewidth Measurement (Scanning Fabry-Perot Interferometer)

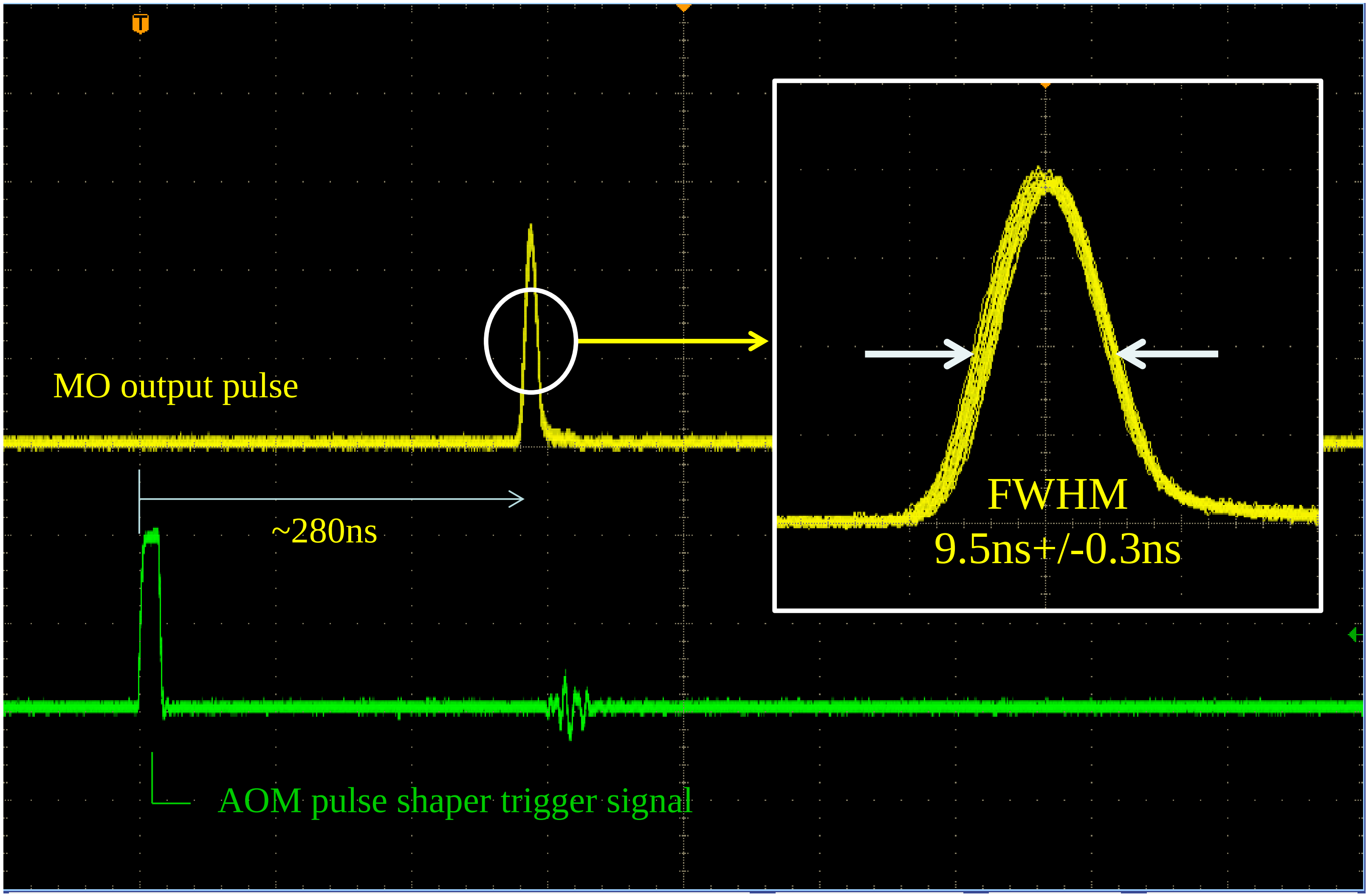


Master Oscillator Spectrum

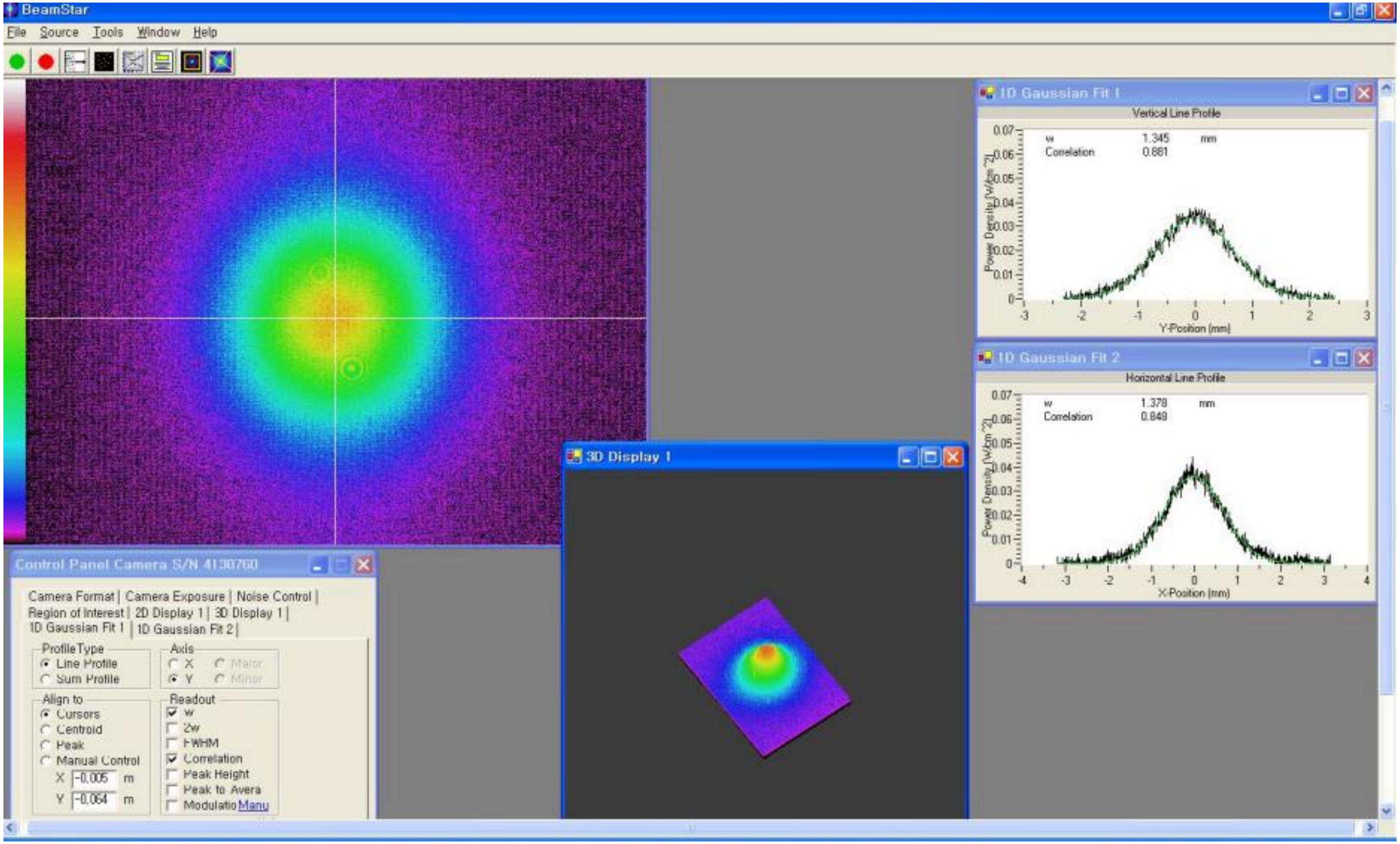


Central wavelength= 1064.5nm

Master Oscillator Output Pulse @ 10kHz

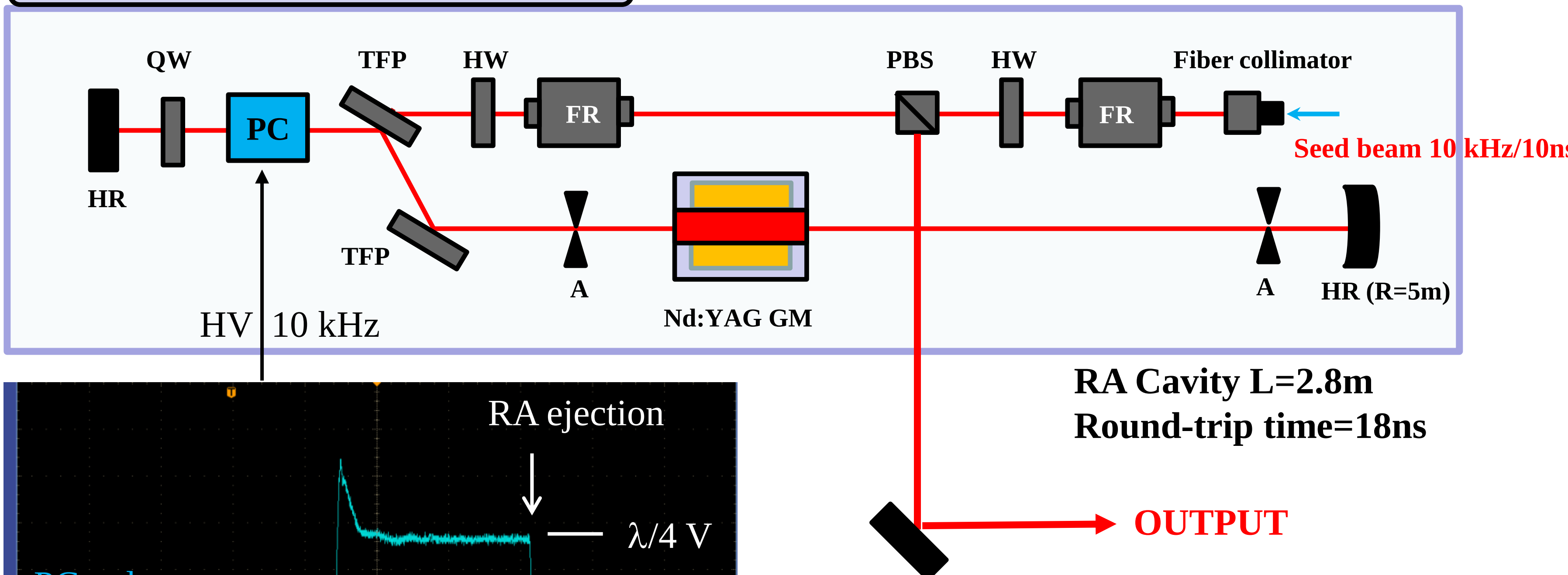


Master Oscillator Beam Profile

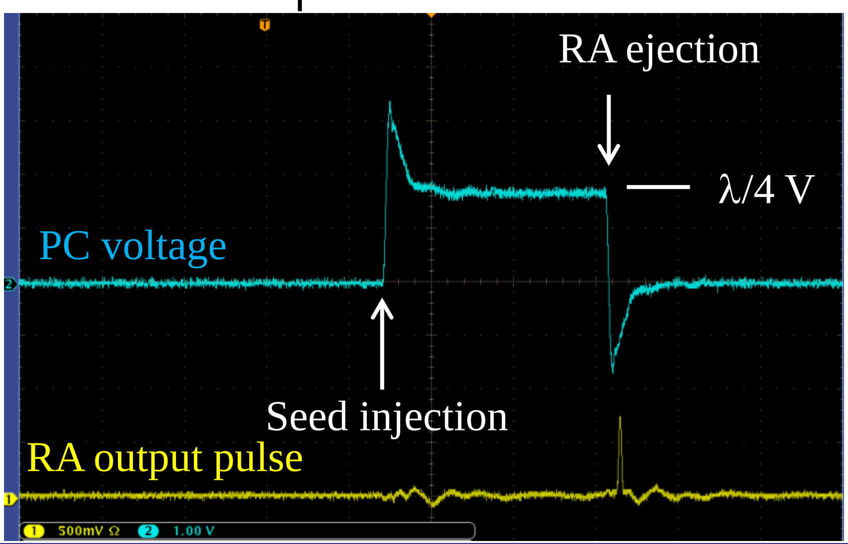


Nd:YAG Regenerative Amplifier(RA)

10kHz Nd:YAG Regenerative Amplifier

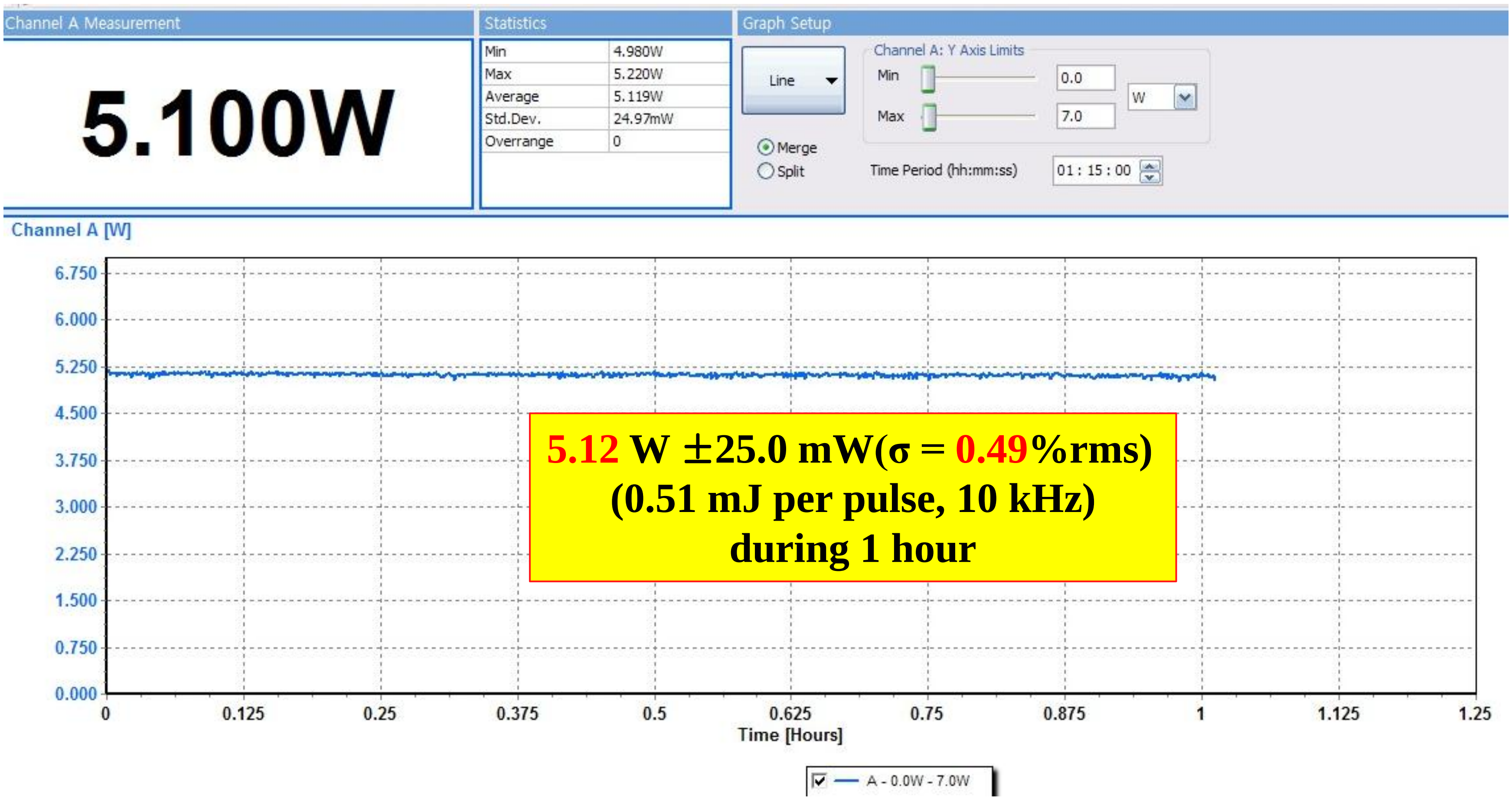


RA Cavity L=2.8m
Round-trip time=18ns

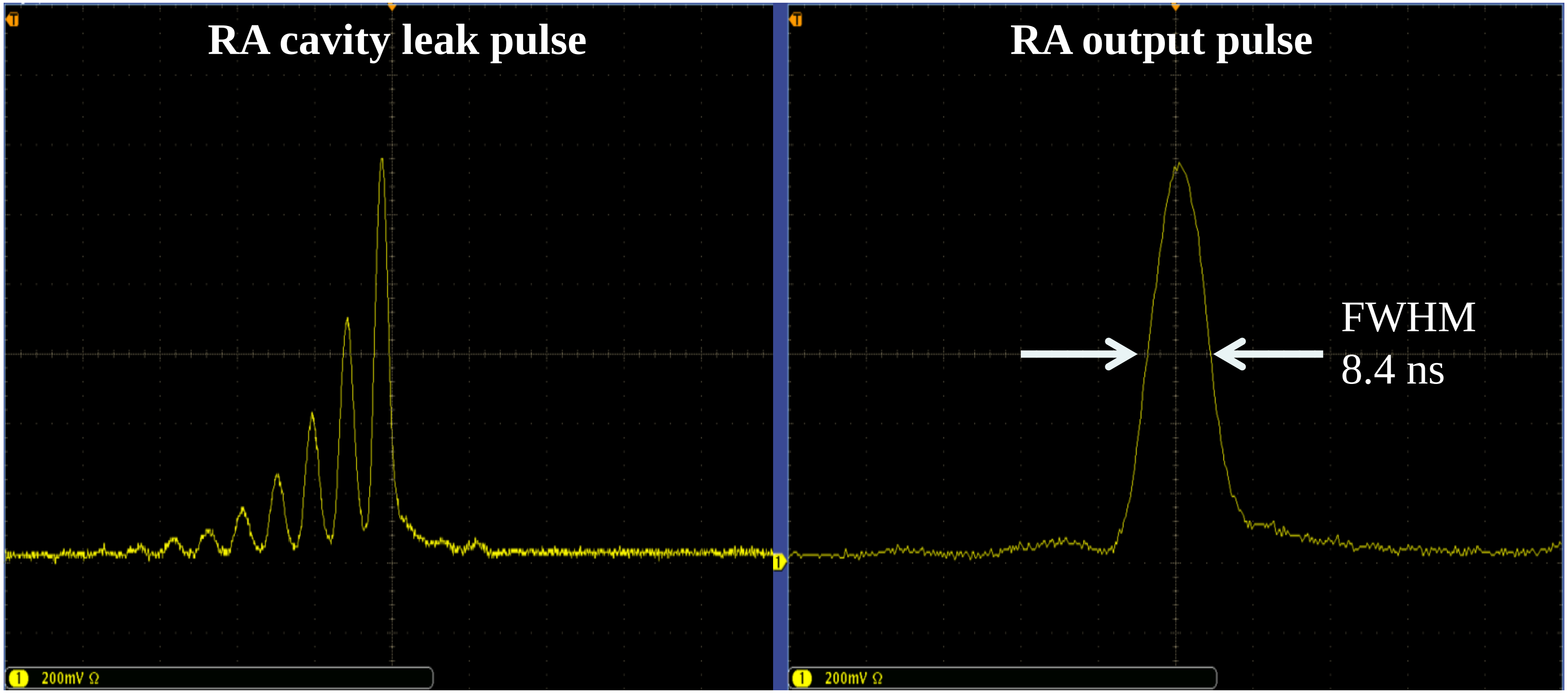


GM: Diode-pumped Nd:YAG gain module,
QW: Quarter waveplate, HW: Half waveplate
TFP: Thin film polarizer, P: Polarization beamsplitter, A: Aperture(for TEMoo mode),
FR: Faraday rotator

Nd:YAG RA Output Power & Stability

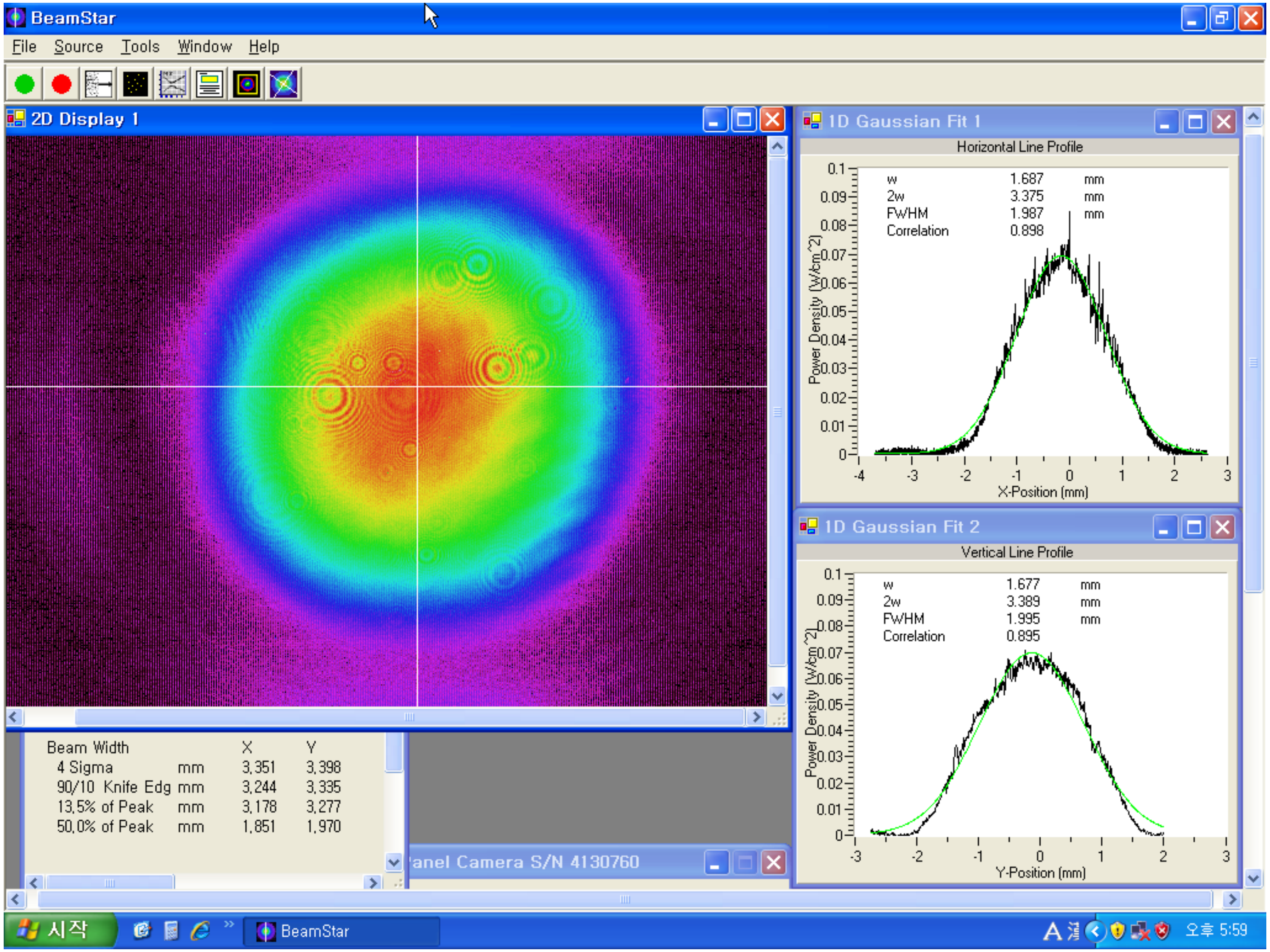


Nd:YAG RA Output Pulse

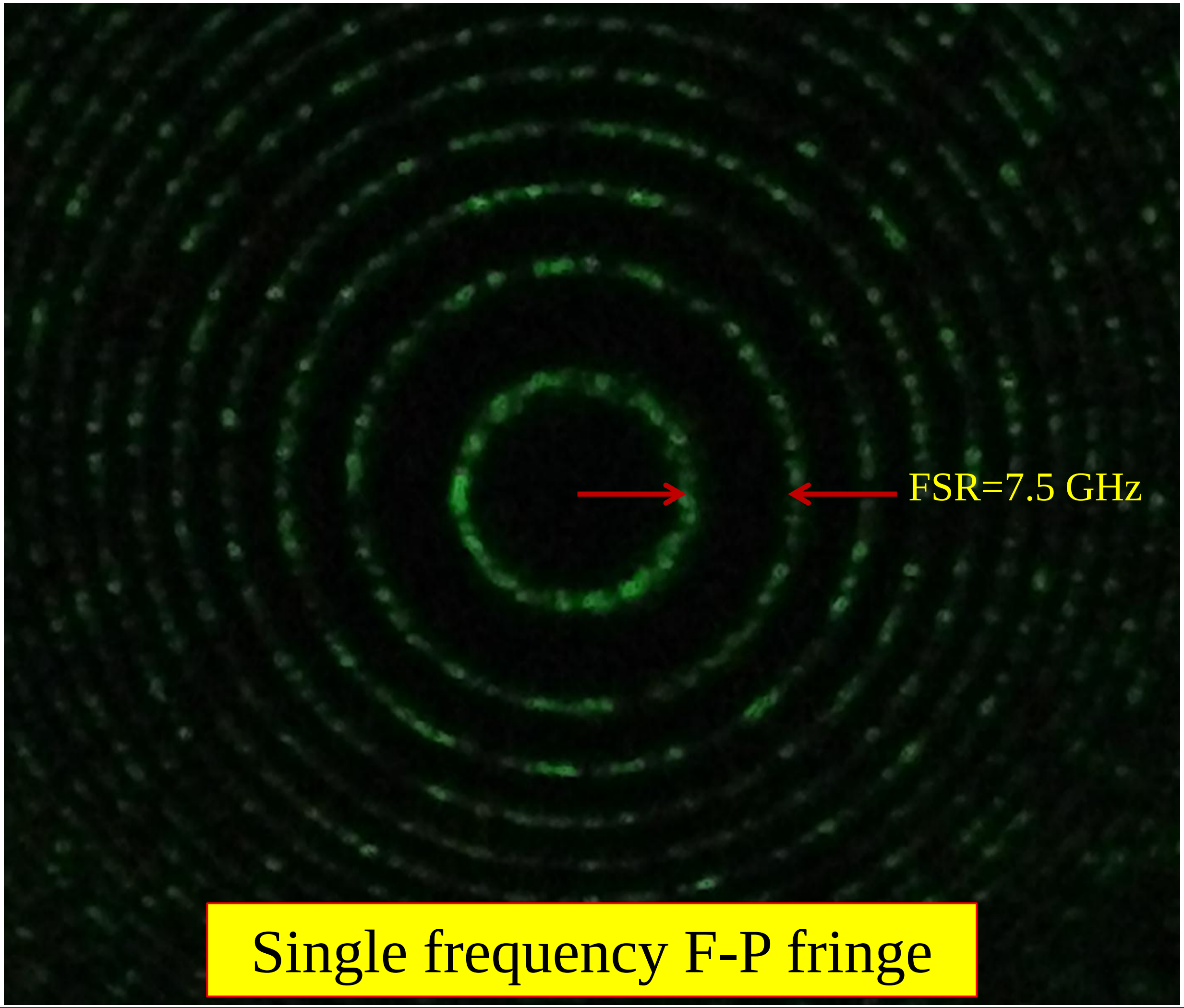


Output pulse ~35 round-trips in RA cavity
Variable pulsewidth 5-10 ns (typical~8.5 ns)
Pulse contrast ratio > 50:1

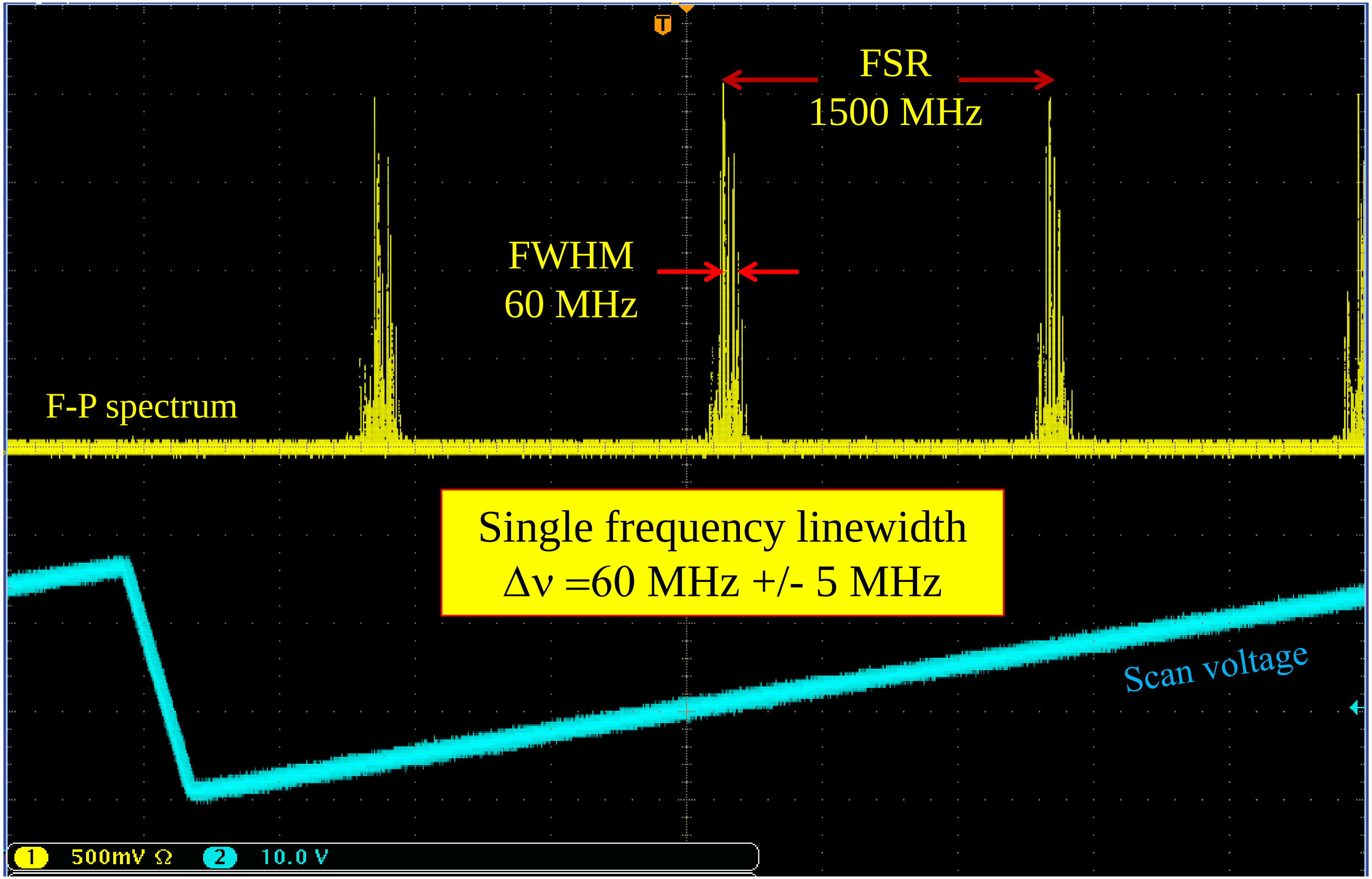
Nd:YAG RA Output beam profile



Nd:YAG RA Linewidth Measurement (Fabry-Perot Spectrum Analyzer)



Nd:YAG RA Linewidth Measurement (Scanning Fabry-Perot Interferometer)

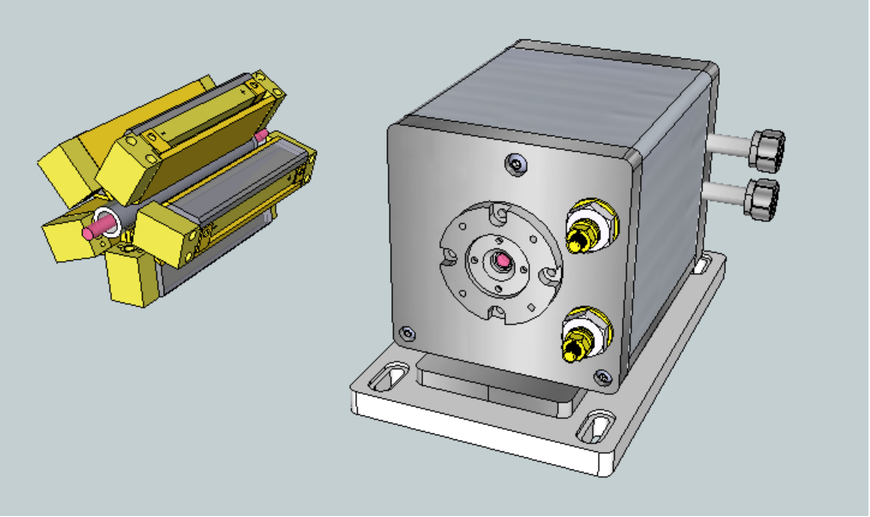


Nd:YAG rod Pre-Amplifier

Nd:YAG Gain Module Design for Pre-AMP

Nd:YAG rod Gain Module (GM) for Pre-AMP

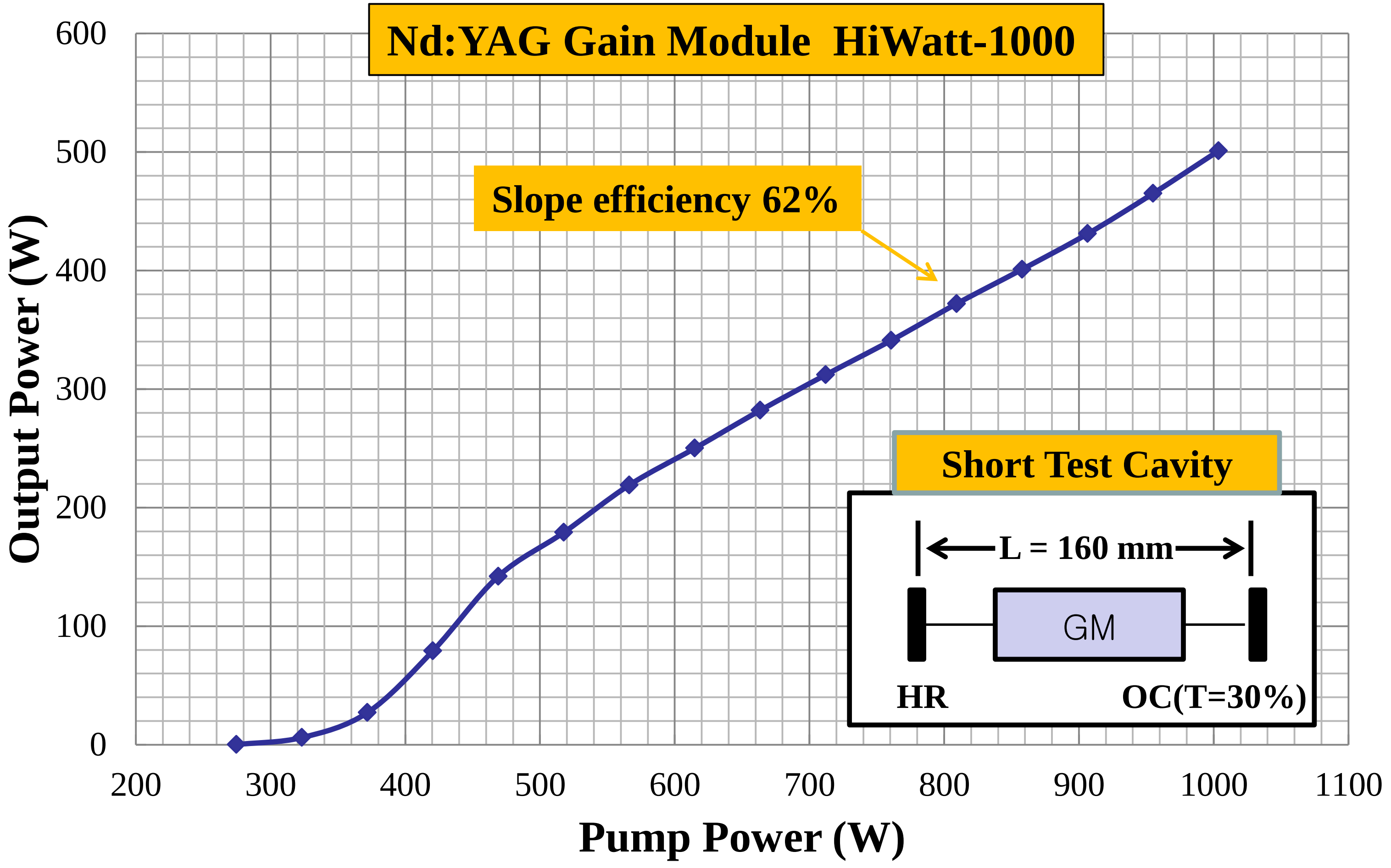
- Wavelength 1064 nm
- Nd:YAG rod- ϕ4.5 mm x 96 mm
- CW diode-stack side-pumped
- Pump power 1 kW max @808 nm
- CW output power 500 W max (Short test cavity, unpolarized)
- DI water-cooled



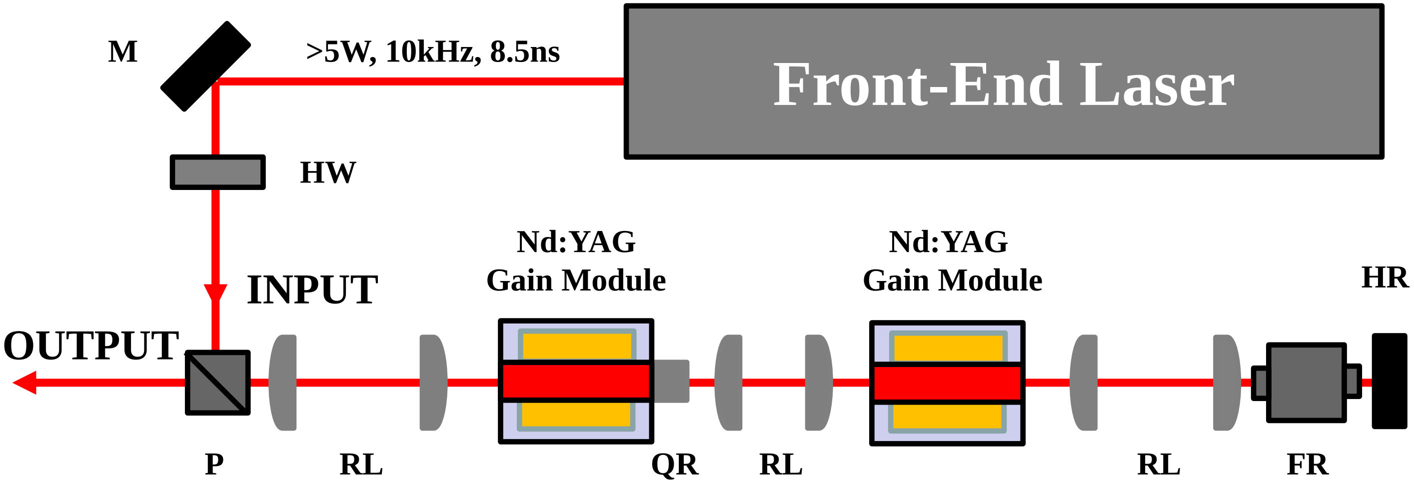
Gain Module*	Nd:YAG Rod	Pump LD (max Power)	CW Output*
HiWatt1000	4.5 mm dia, 0.6%	200 W x 5ea (1 kW)	> 400 W, MM

*Laser Spectronix

Nd:YAG Gain Module Short Test Cavity CW Output Power



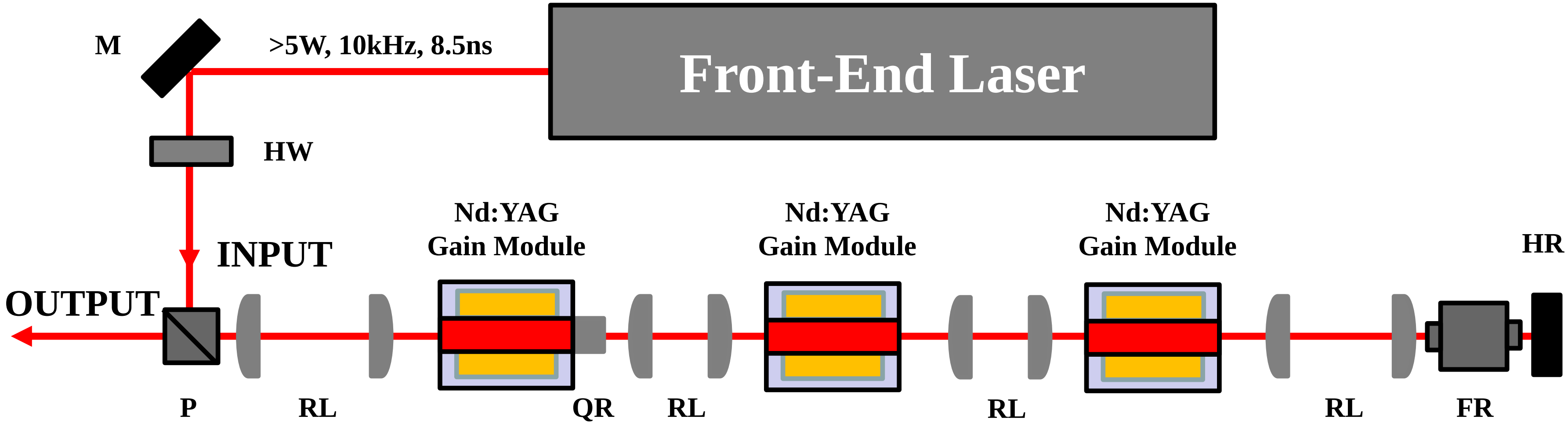
Pre-Amplifier Double-pass, 2 Gain Modules



PBS-polarizing beam splitter, RL-Image relay lens, QR-quartz rotator, FR-Faraday rotator, HW-Half waveplate (for input power adjustment)

- **Thermal lensing compensation → Image relay**
- **Thermal birefringence compensation → two rods arrangement & 90-degree polarization rotation by quartz rotator**

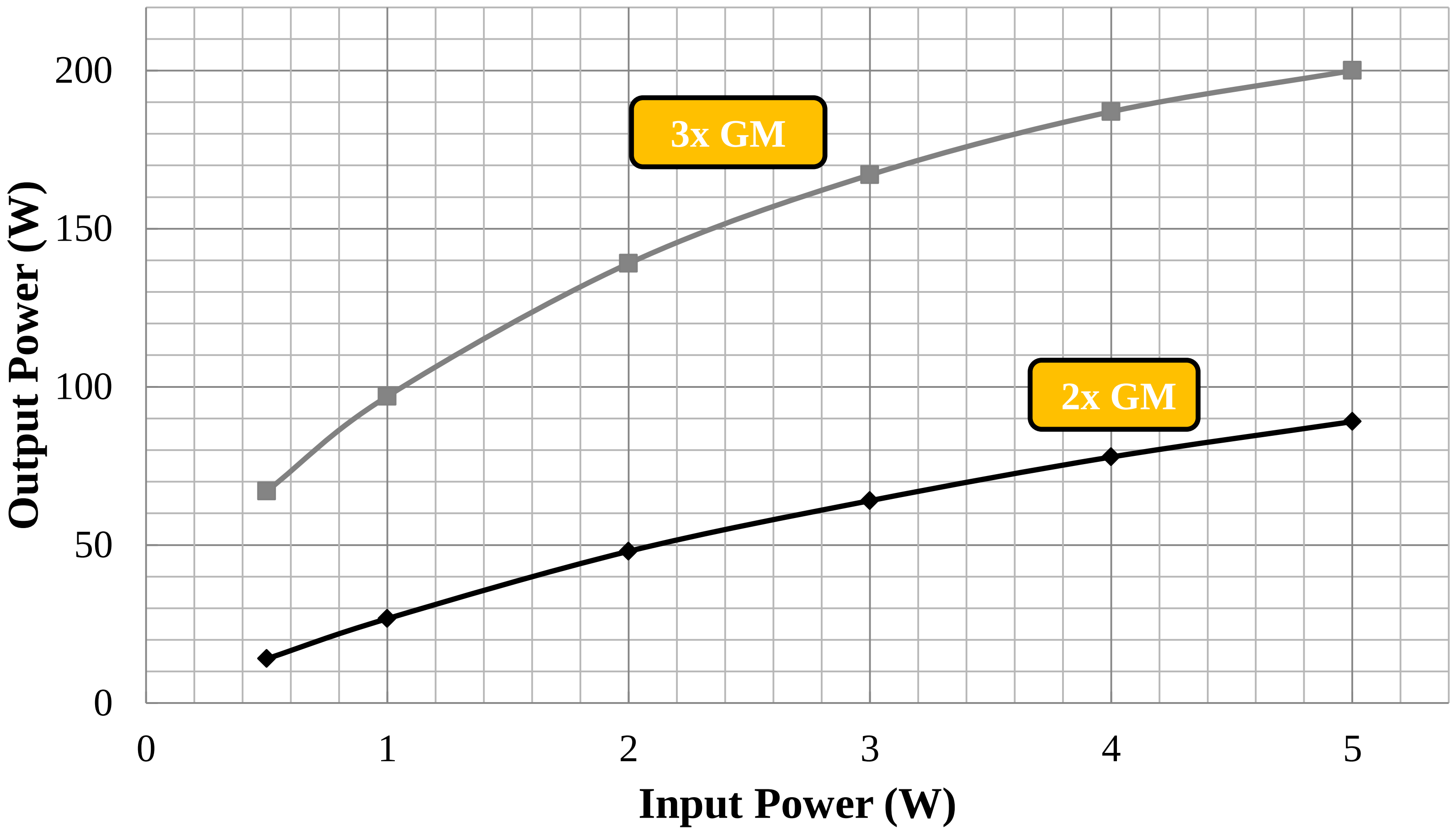
Pre-Amplifier
Double-pass, 3 Gain Modules



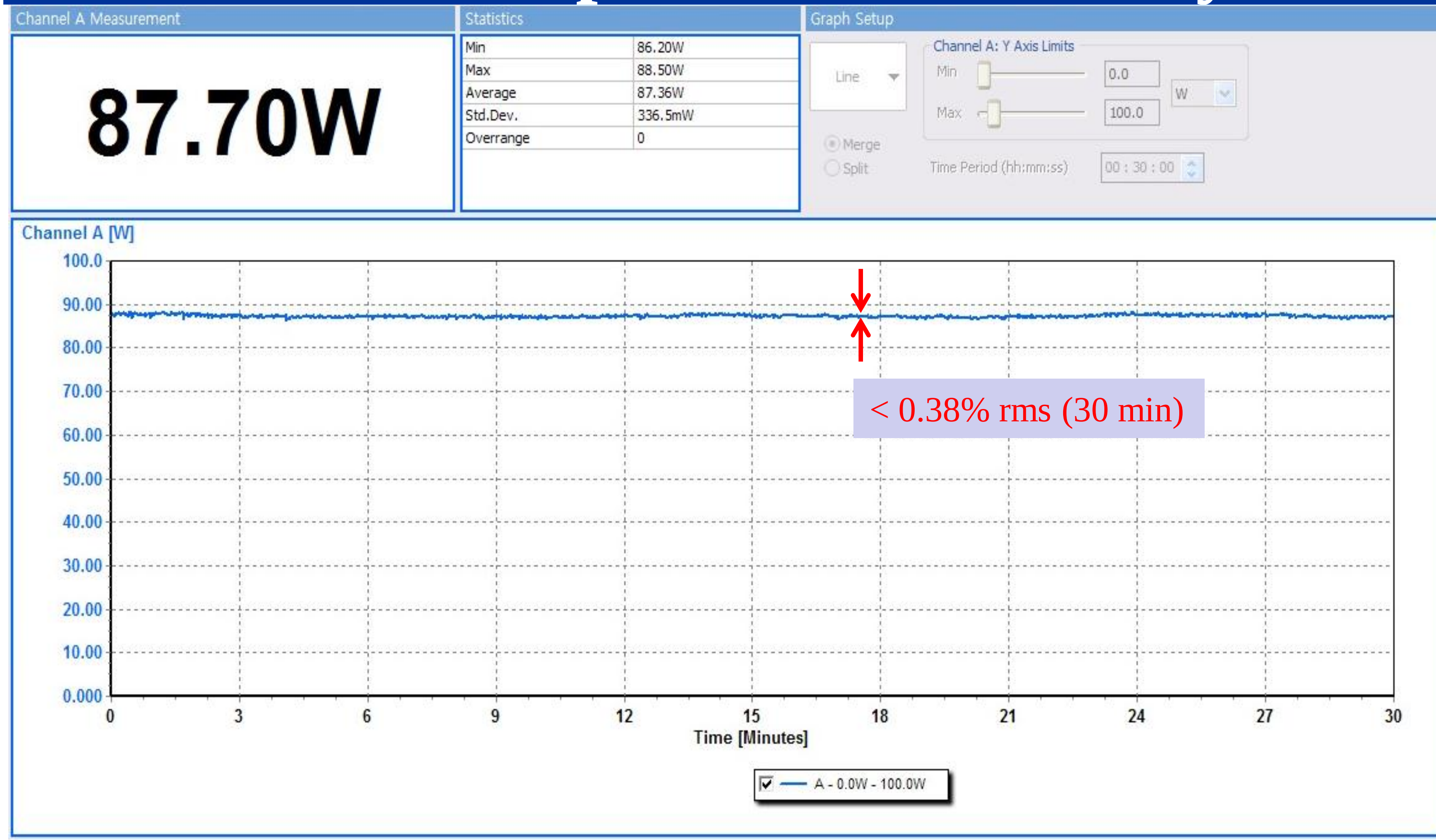
PBS-polarizing beam splitter, RL-Image relay lens, QR-quartz rotator, FR-Faraday rotator, HW-Half waveplate (for input power adjustment)

- **Thermal lensing compensation → Image relay**
- **Thermal birefringence compensation → two rods arrangement & 90-degree polarization rotation by quartz rotator**

Pre-Amplifier Performance
Double-pass Amplification

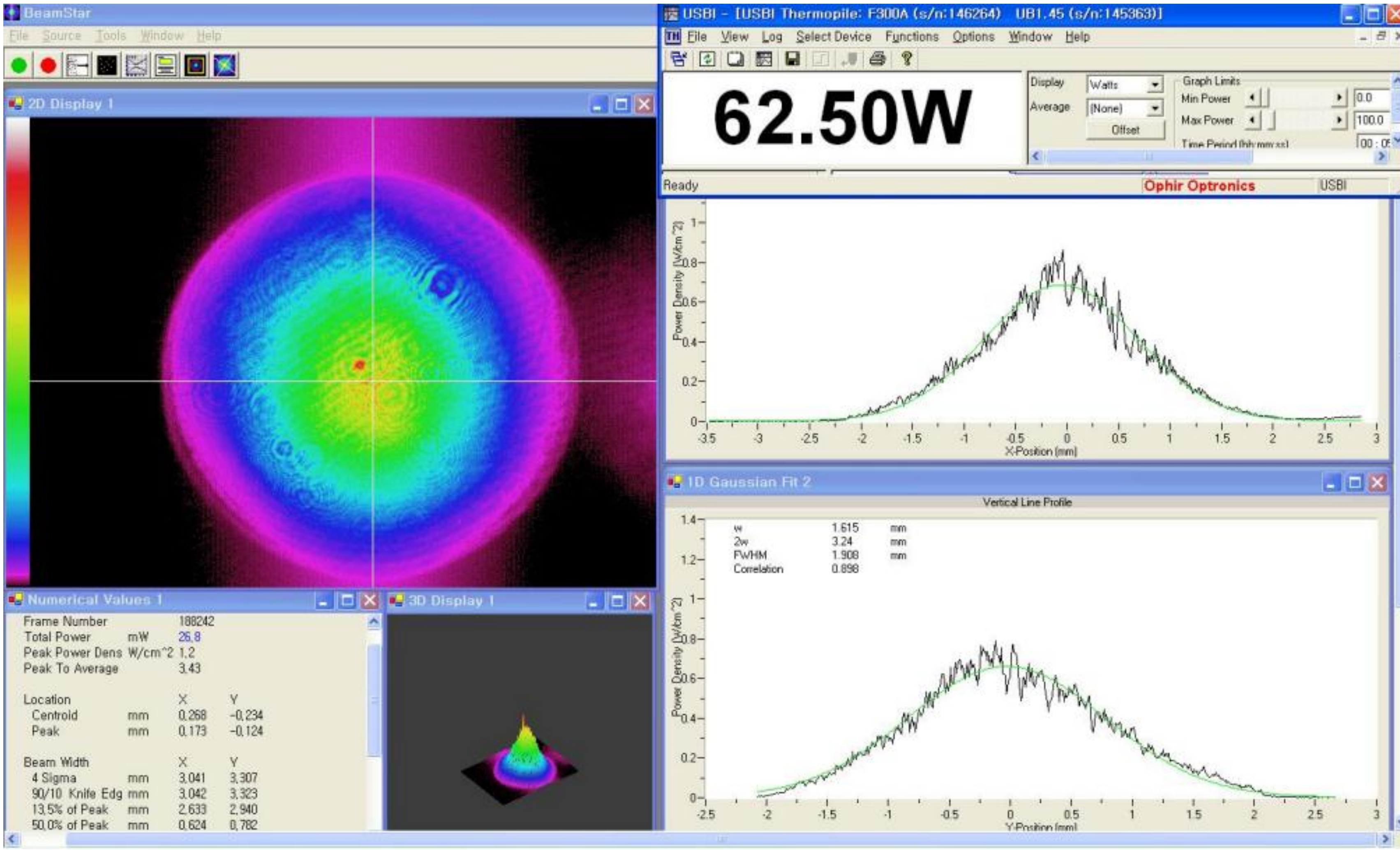


Pre-Amplifier Performance: 2-GM Output Power Stability



Pre-Amplifier Performance: 3-GM Output Power Stability

Pre-Amplifier Performance: Output Beam Profile

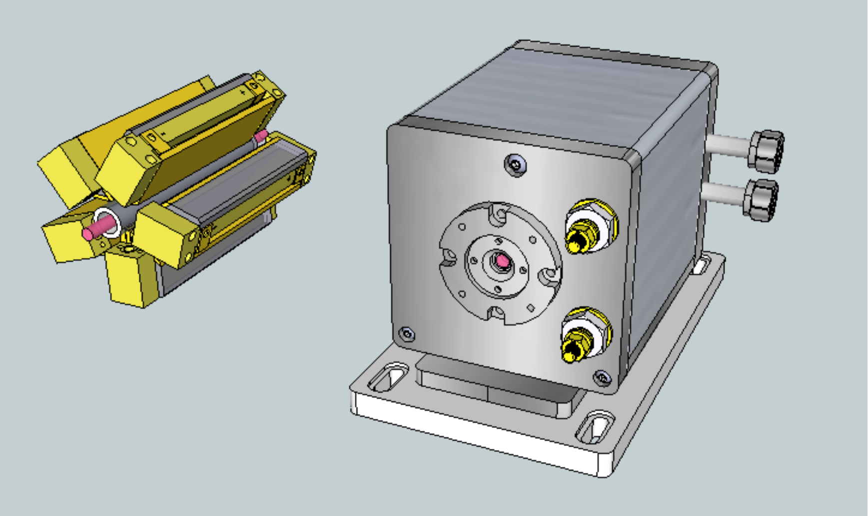


Nd:YAG rod Main Amplifier

Nd:YAG Gain Module Design for Main Amplifier

Nd:YAG rod Gain Module (GM) for Main Amplifier

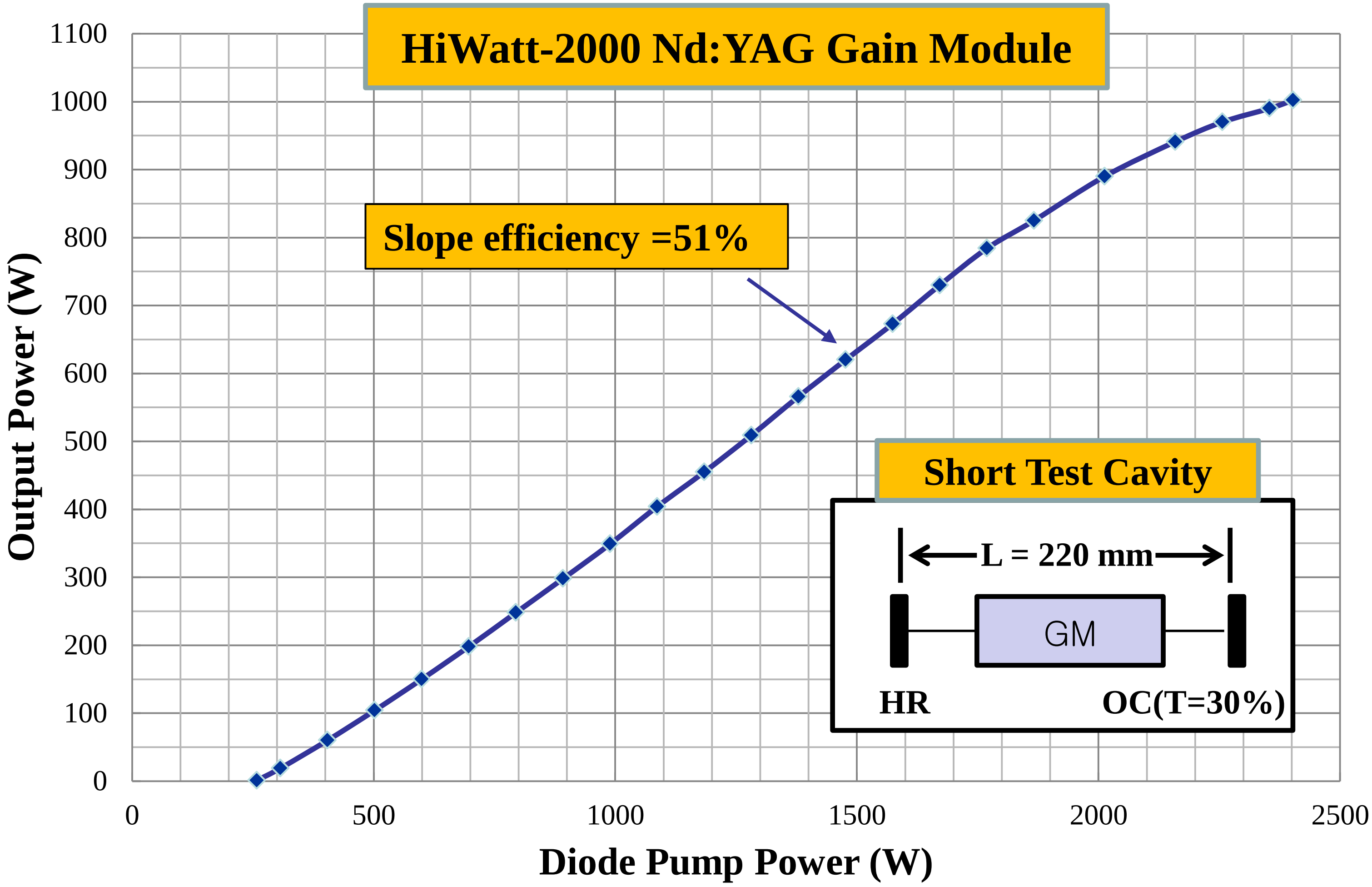
- Wavelength 1064 nm
- Nd:YAG rod- ϕ 6.35 mm x 148 mm
- LD pumping length- 96 mm
- CW diode-stack side-pumped
- Pump power 2 kW max @808 nm
- CW output power 1 kW max (short test cavity, unpolarized)
- DI water-cooled



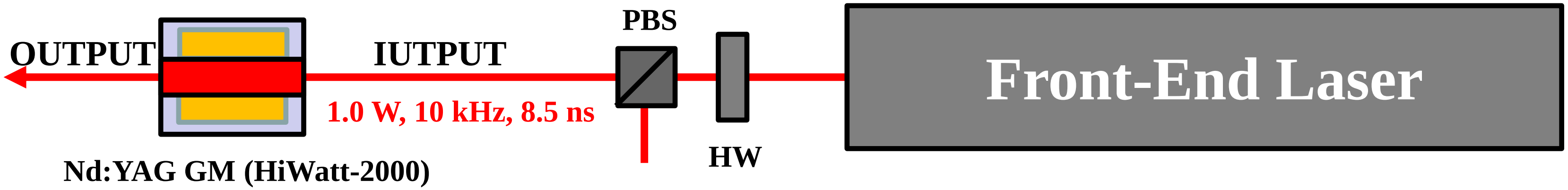
Gain module	Nd:YAG Rod	Pump LD (max Power)	CW Output
HiWatt 2000*	Φ 6.3 mm, 0.6%	400 W x 5ea (2 kW)	> 800 W, MM

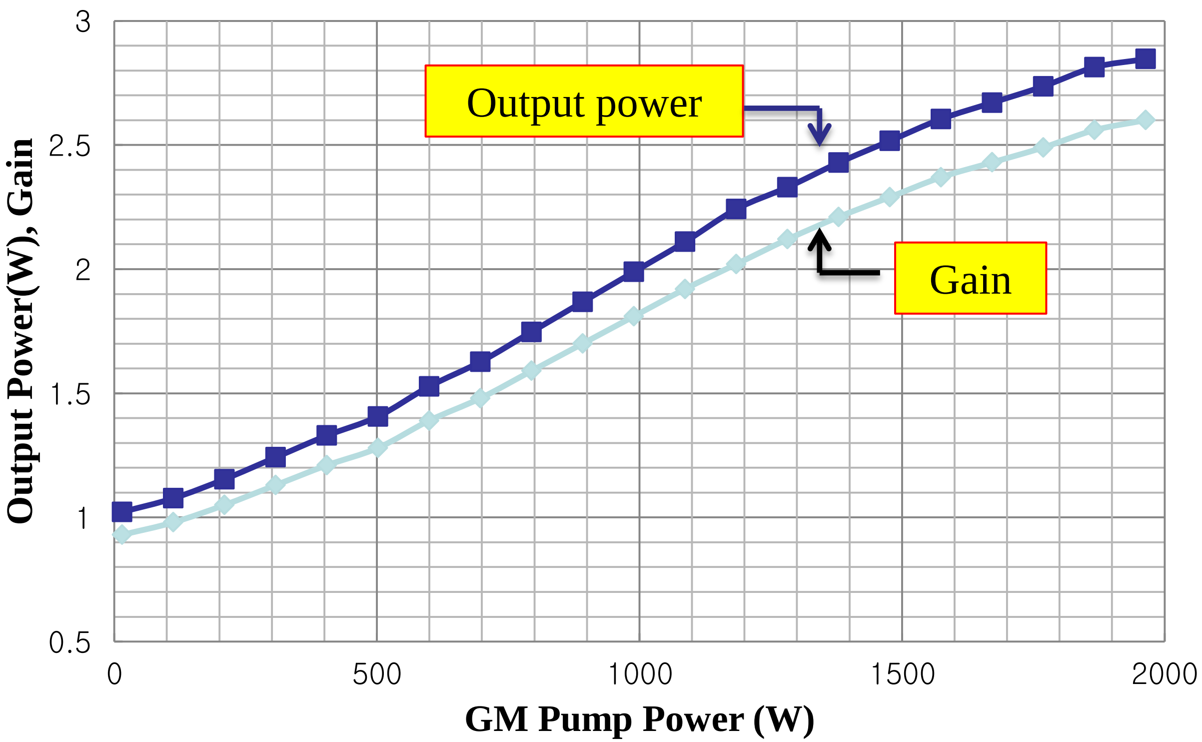
*Laser Spectronix

Nd:YAG Gain Module
Short Test Cavity CW Output Power

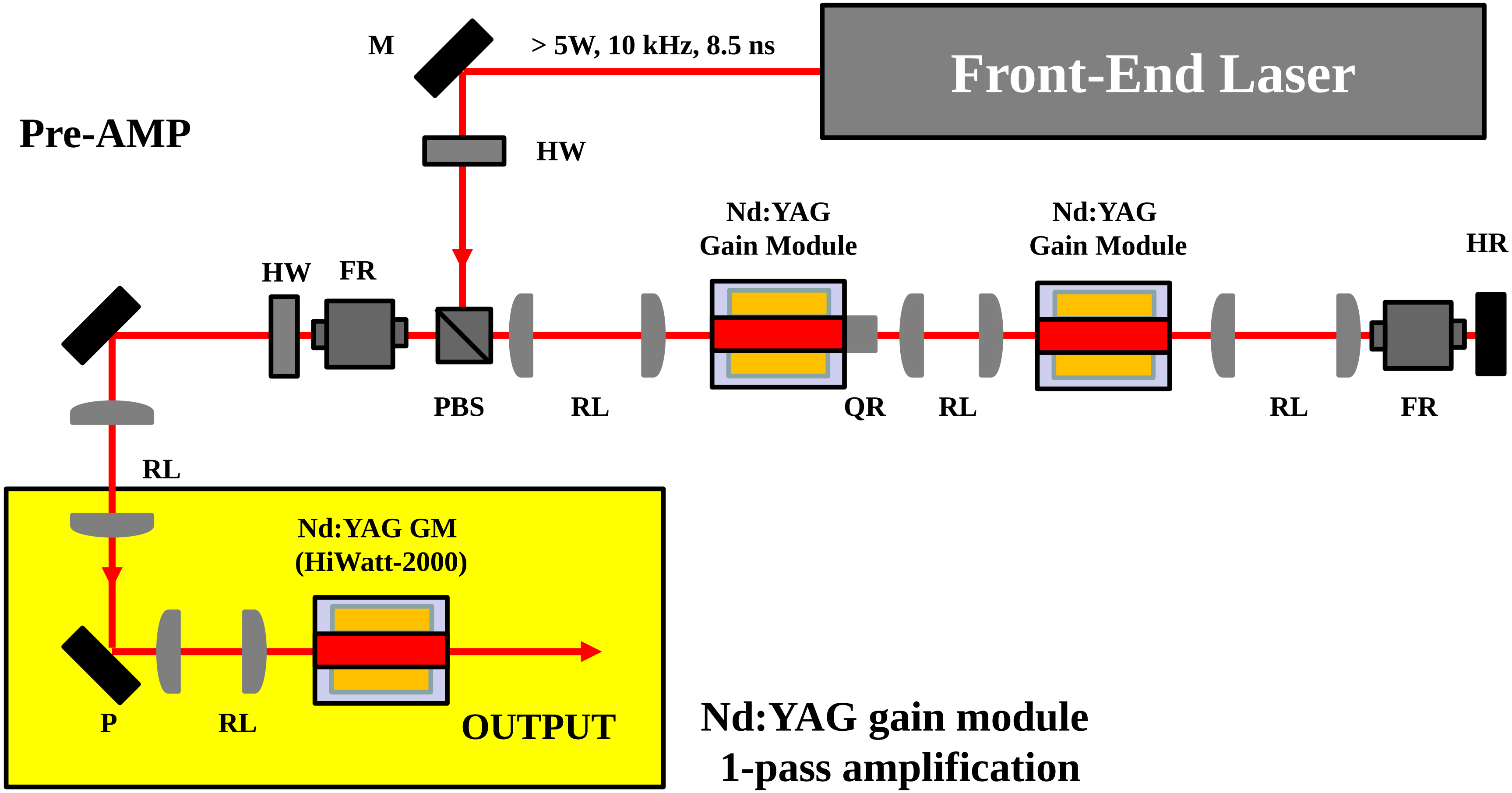


Nd:YAG 1XGain Module: Small Signal Gain Measurement



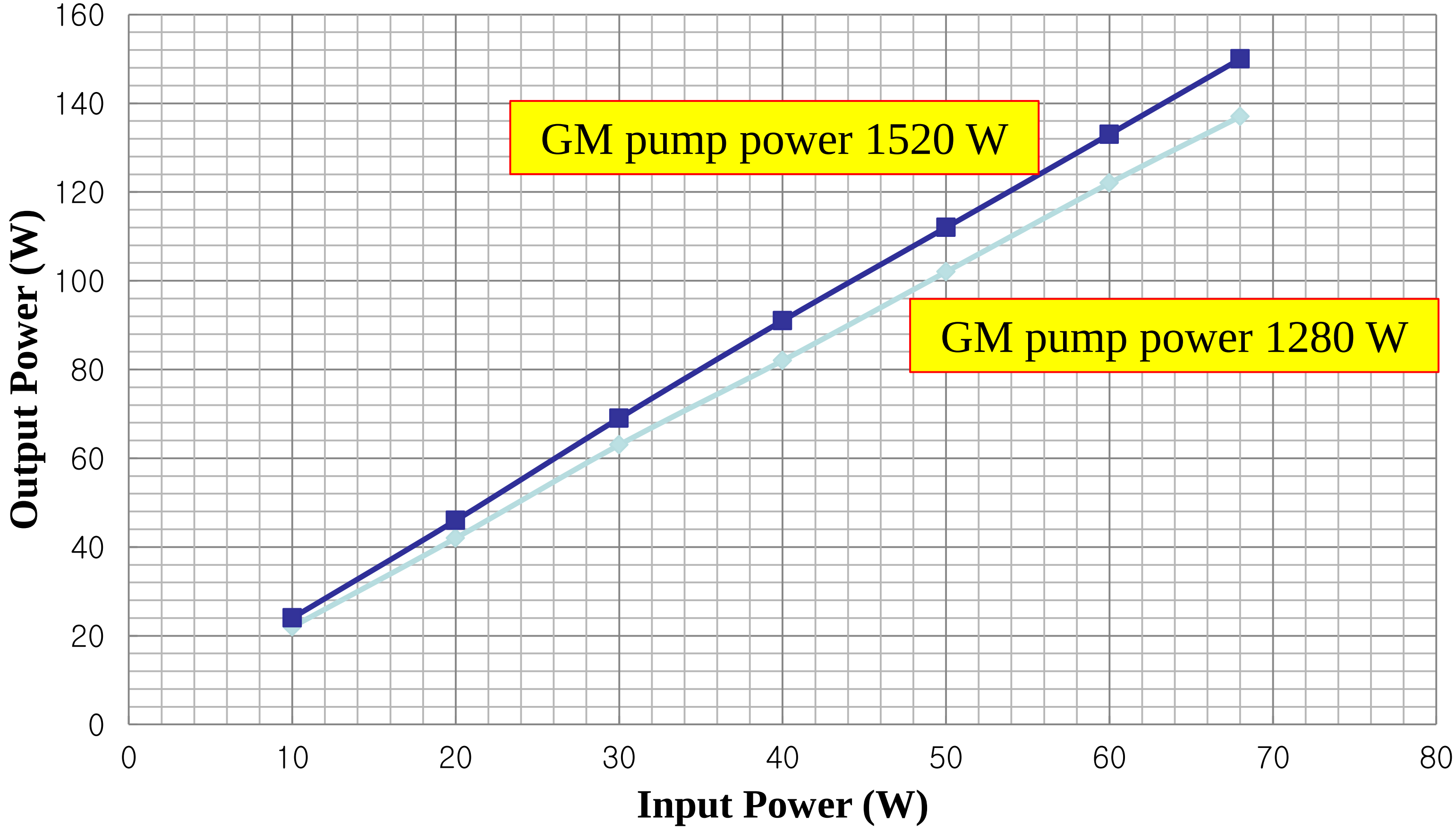


Nd:YAG 1XGain Module Single-pass(1P) Amplification

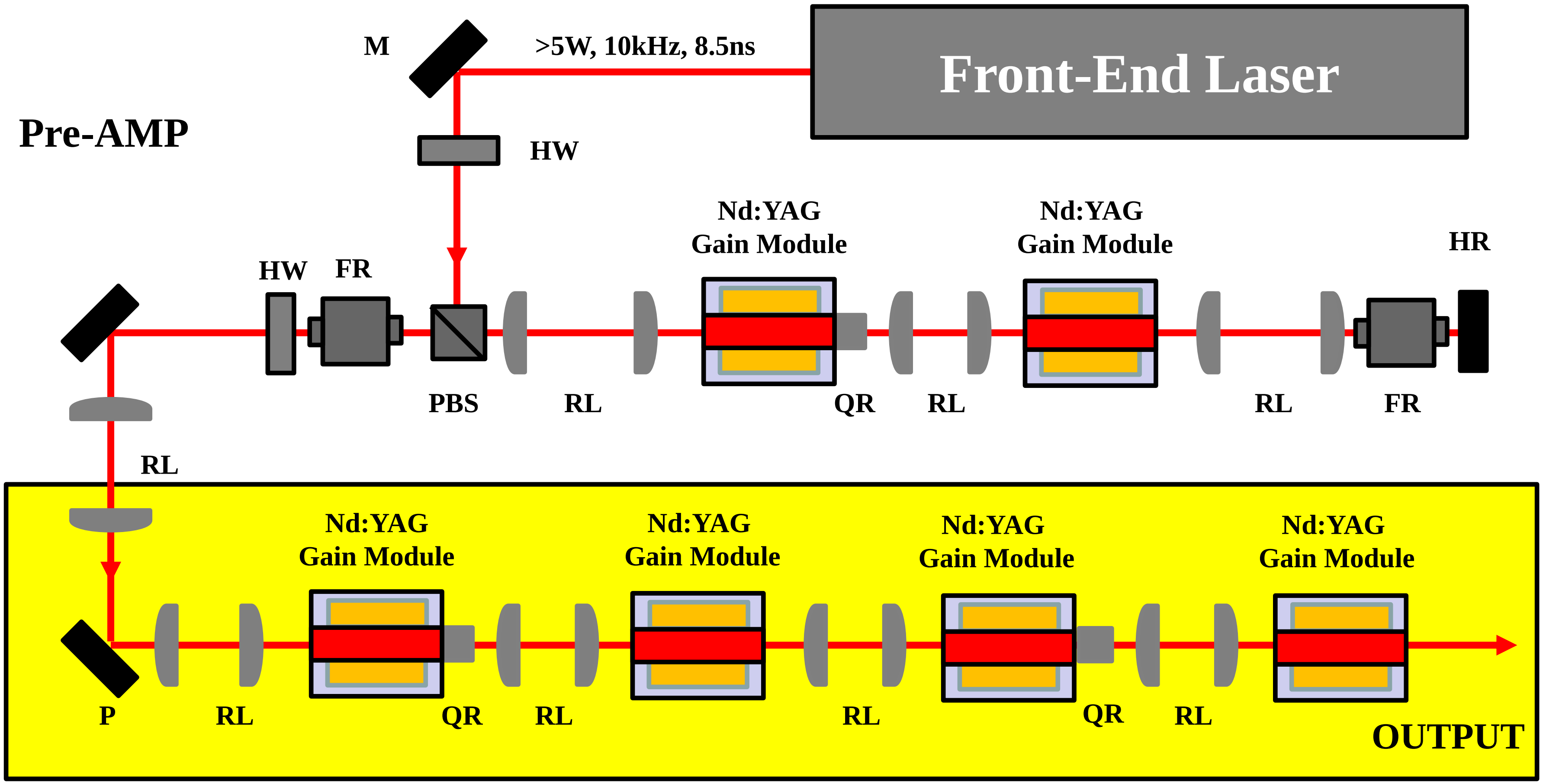


Nd:YAG gain module 1-pass amplification

Nd:YAG 1XGain Module: Single-pass(1P) Amplification

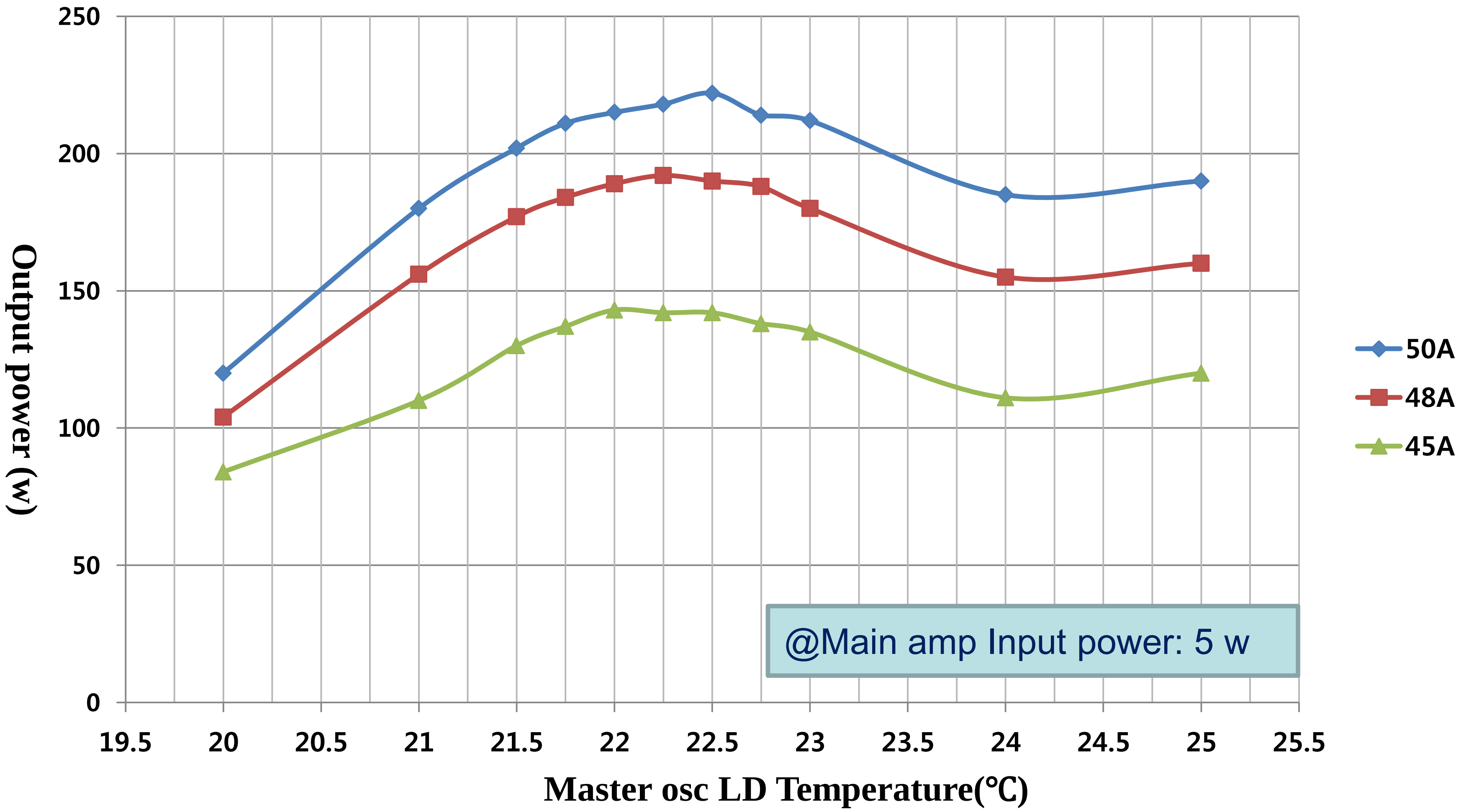


Main-Amp 4XGain Modules Single-pass (1P) Amplification

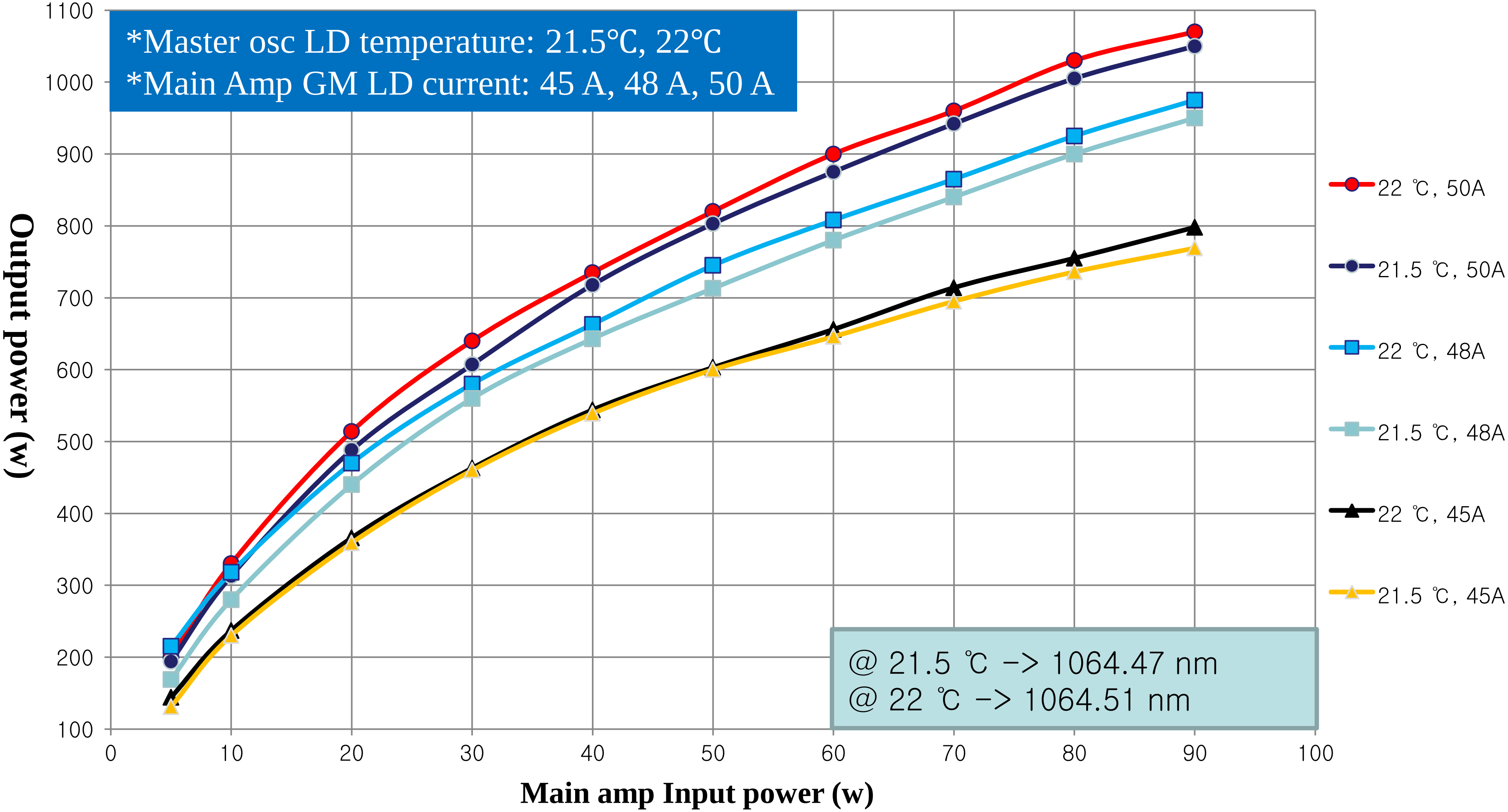


Main-AMP module

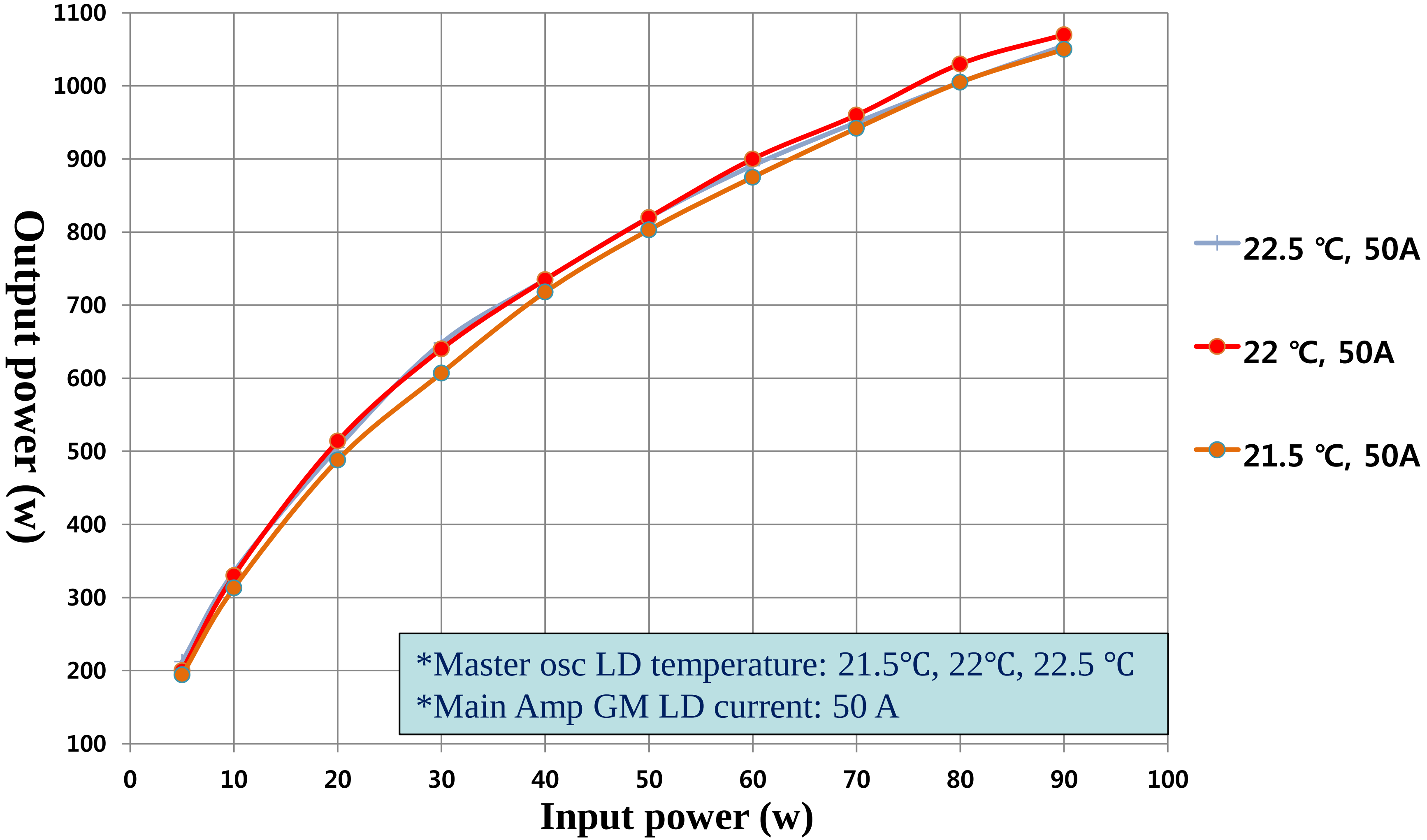
Master oscillator
LD Temperature VS. main amp 4XGM LD current



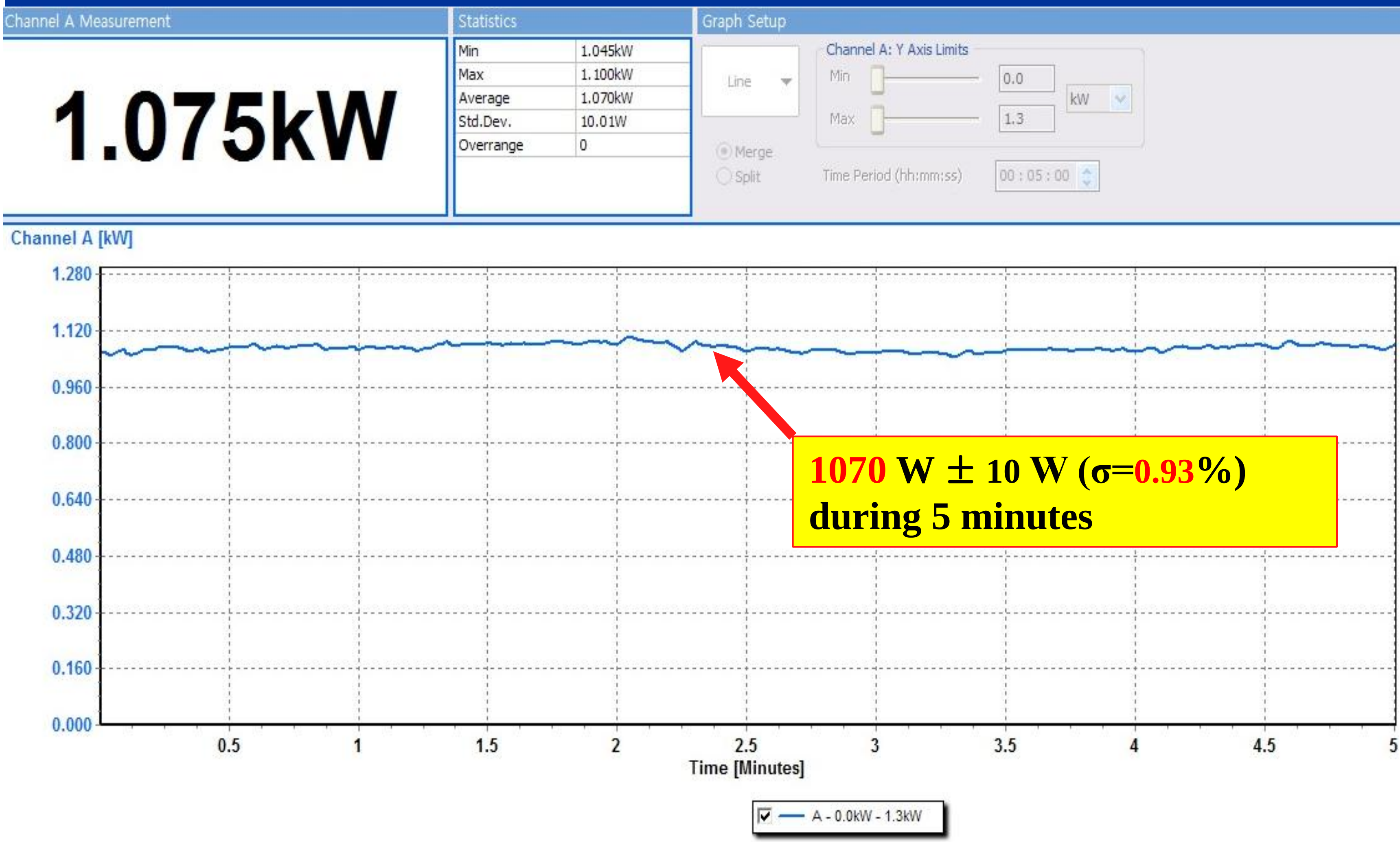
Main amp 4XGM 1P power test



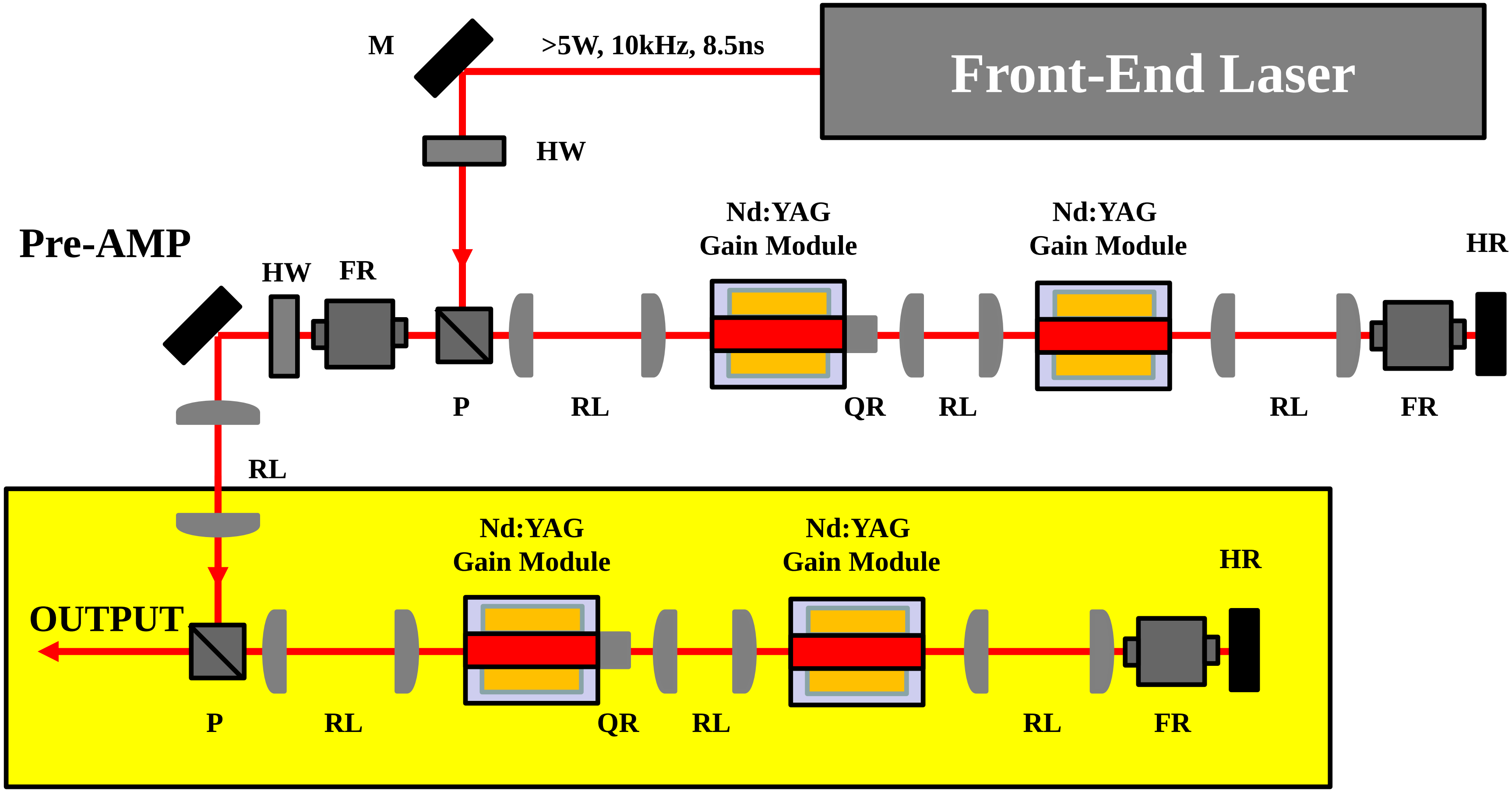
Main amp 4XGM 1P power test



Main-AMP 4XGain Modules: Single-pass(1P) Output Power & Stability

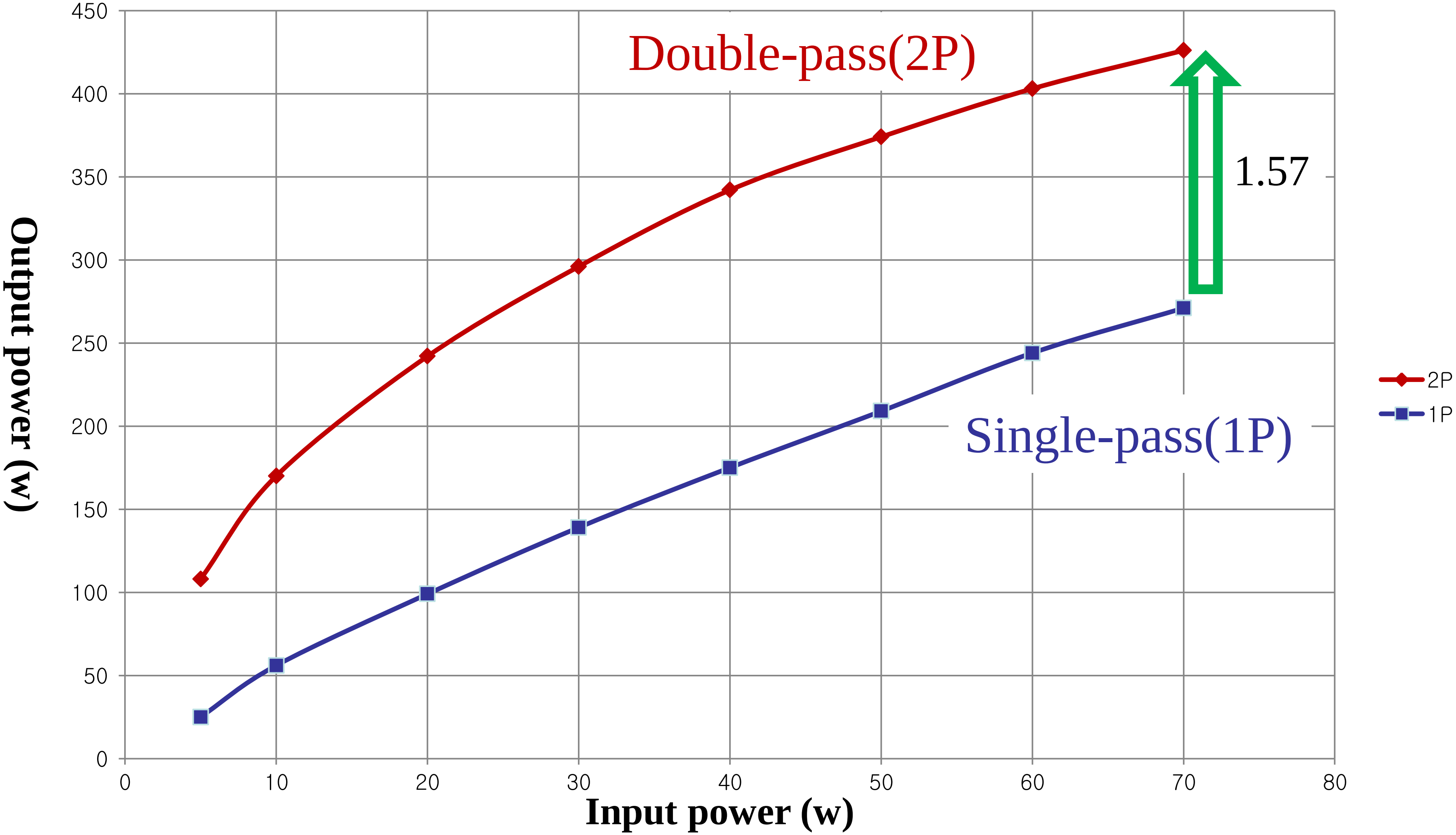


Main-Amp 2 Gain Modules Double-pass Amplification

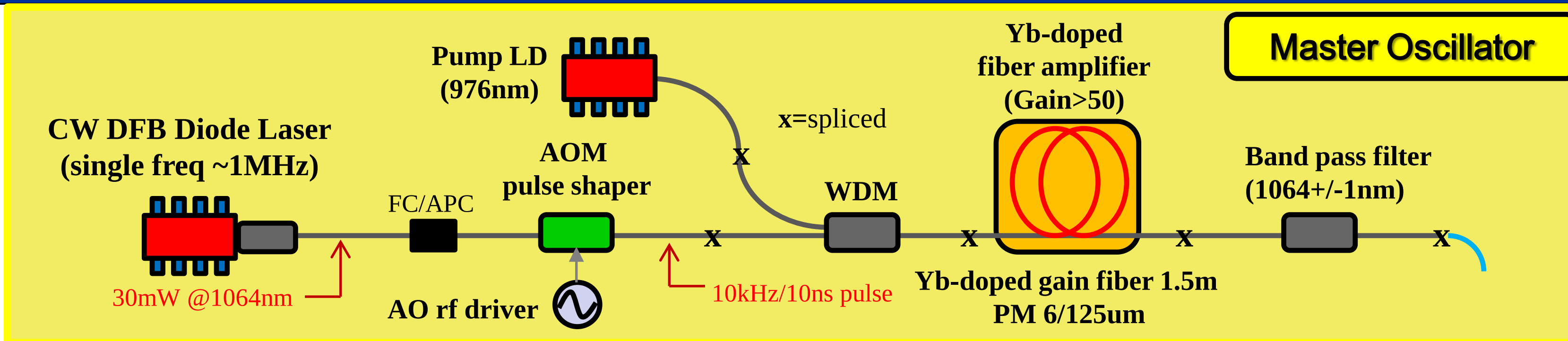


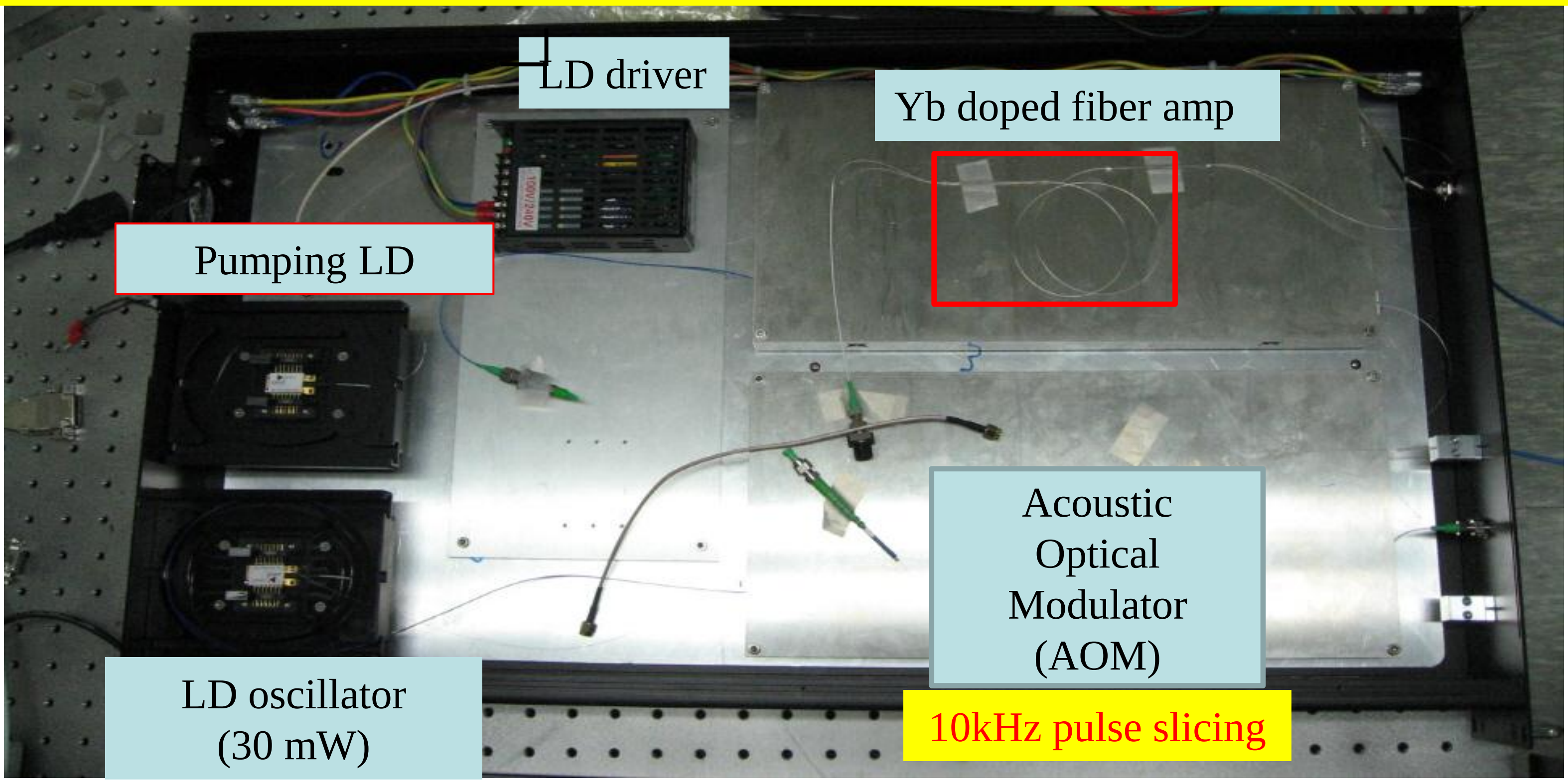
Main-AMP module

Main-Amp 2XGain Modules Single & Double-pass Amplification



LD laser oscillator module

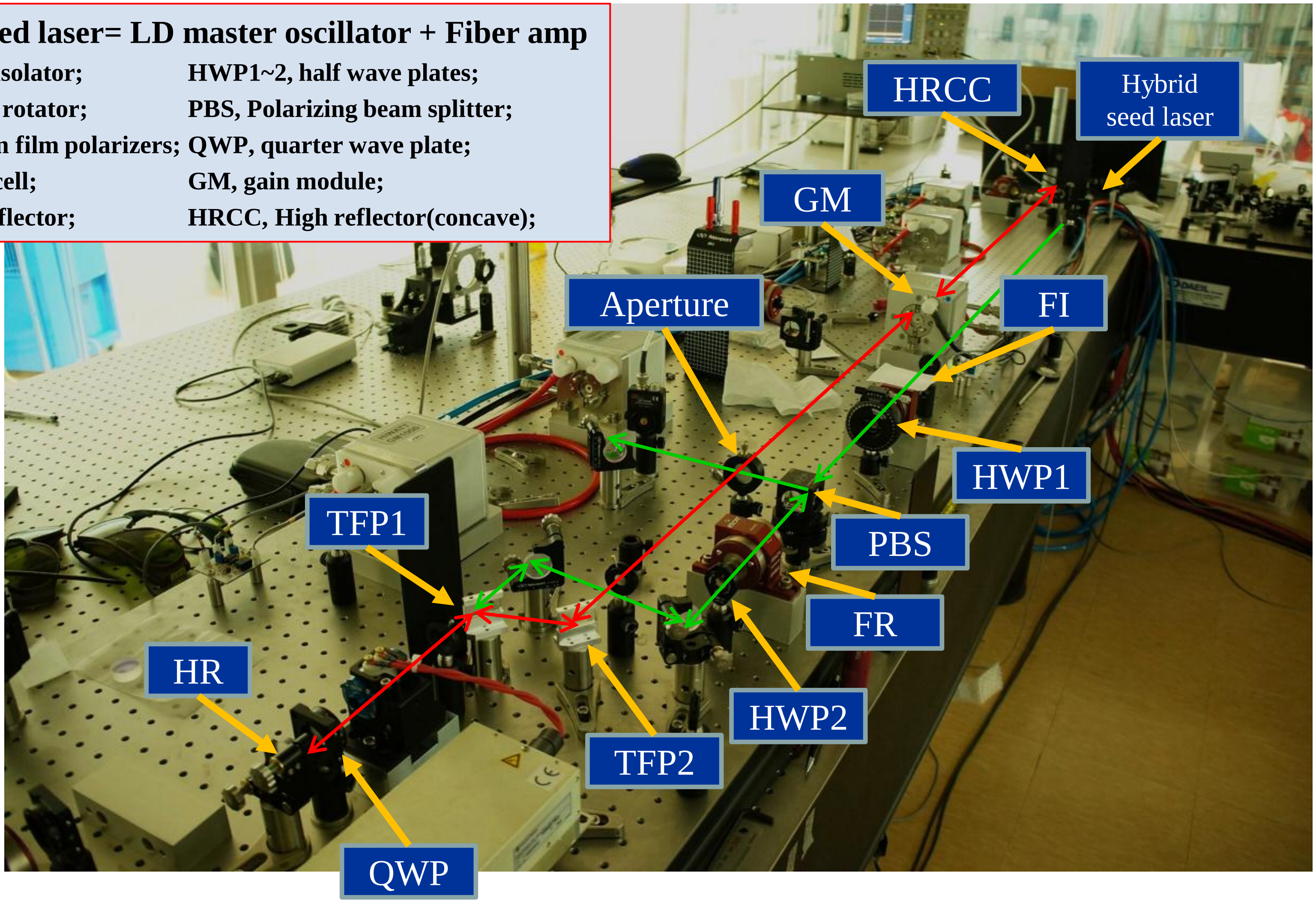




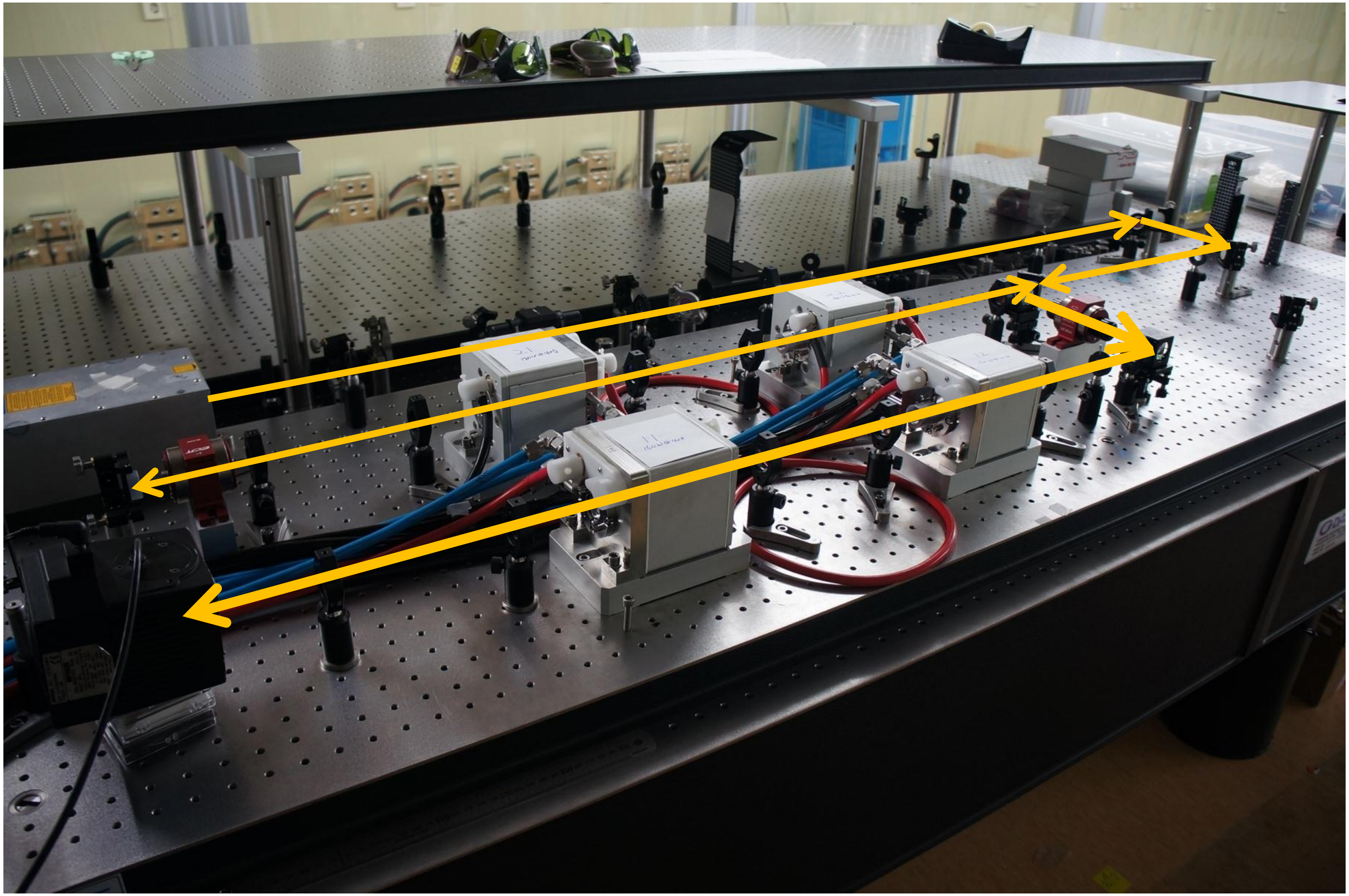
Regenerative Amplifier setup

Hybrid seed laser= LD master oscillator + Fiber amp

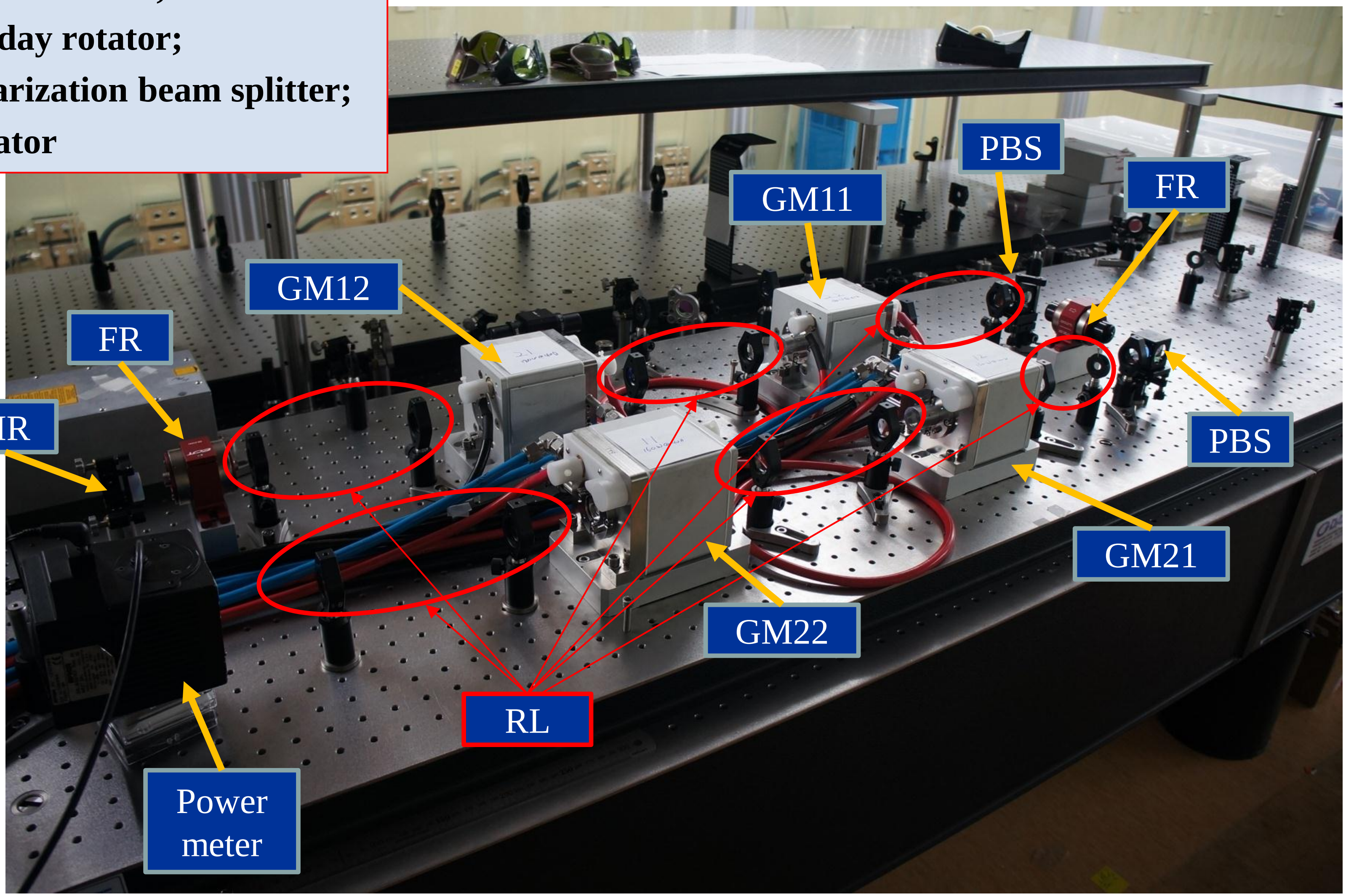
FI, Faraday isolator;
FR, Faraday rotator;
TFP1~2, Thin film polarizers;
PC, Pockels cell;
HR, High Reflector;
HWP1~2, half wave plates;
PBS, Polarizing beam splitter;
QWP, quarter wave plate;
GM, gain module;
HRCC, High reflector(concave);

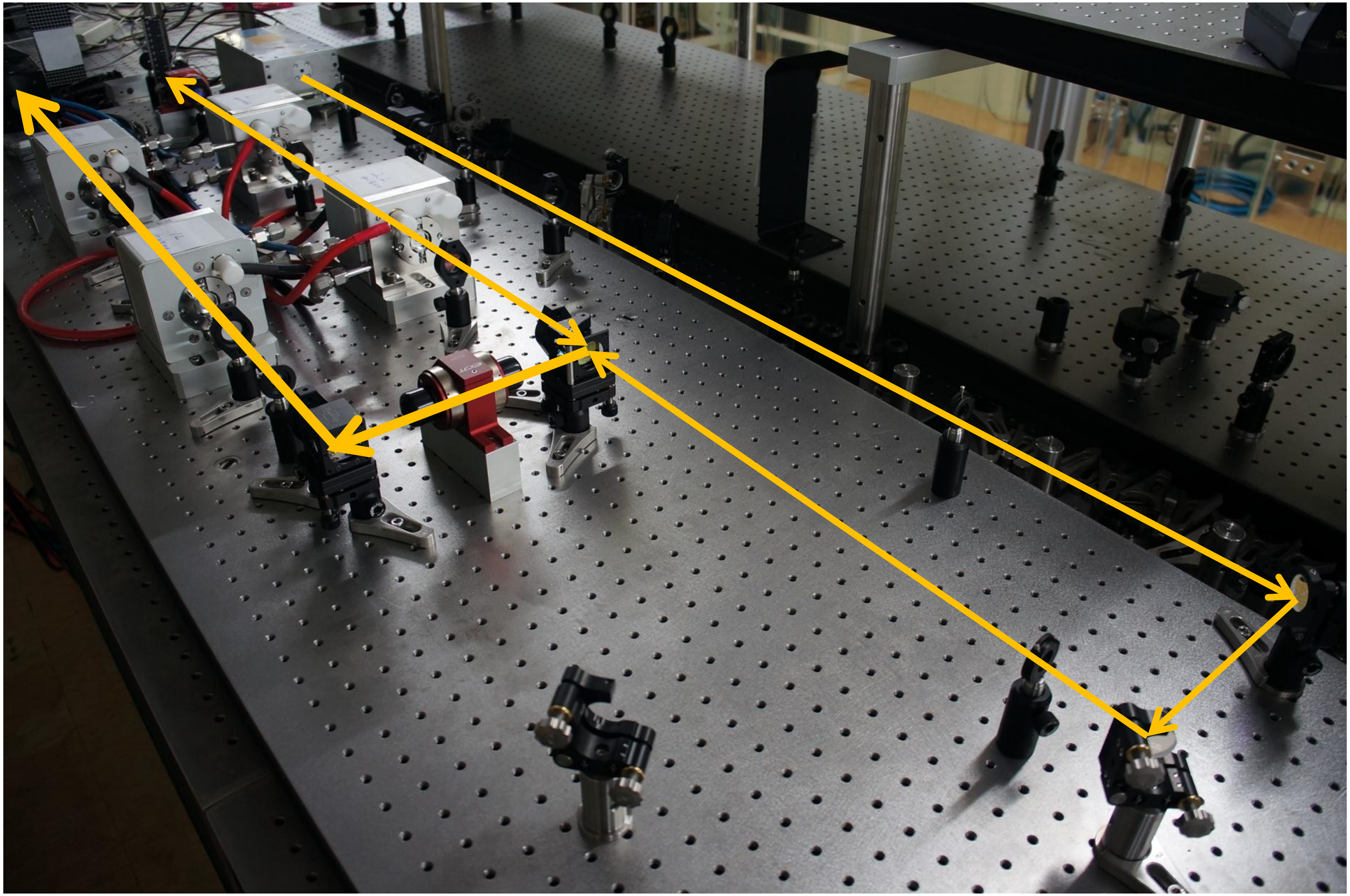


Pre-AMP setup

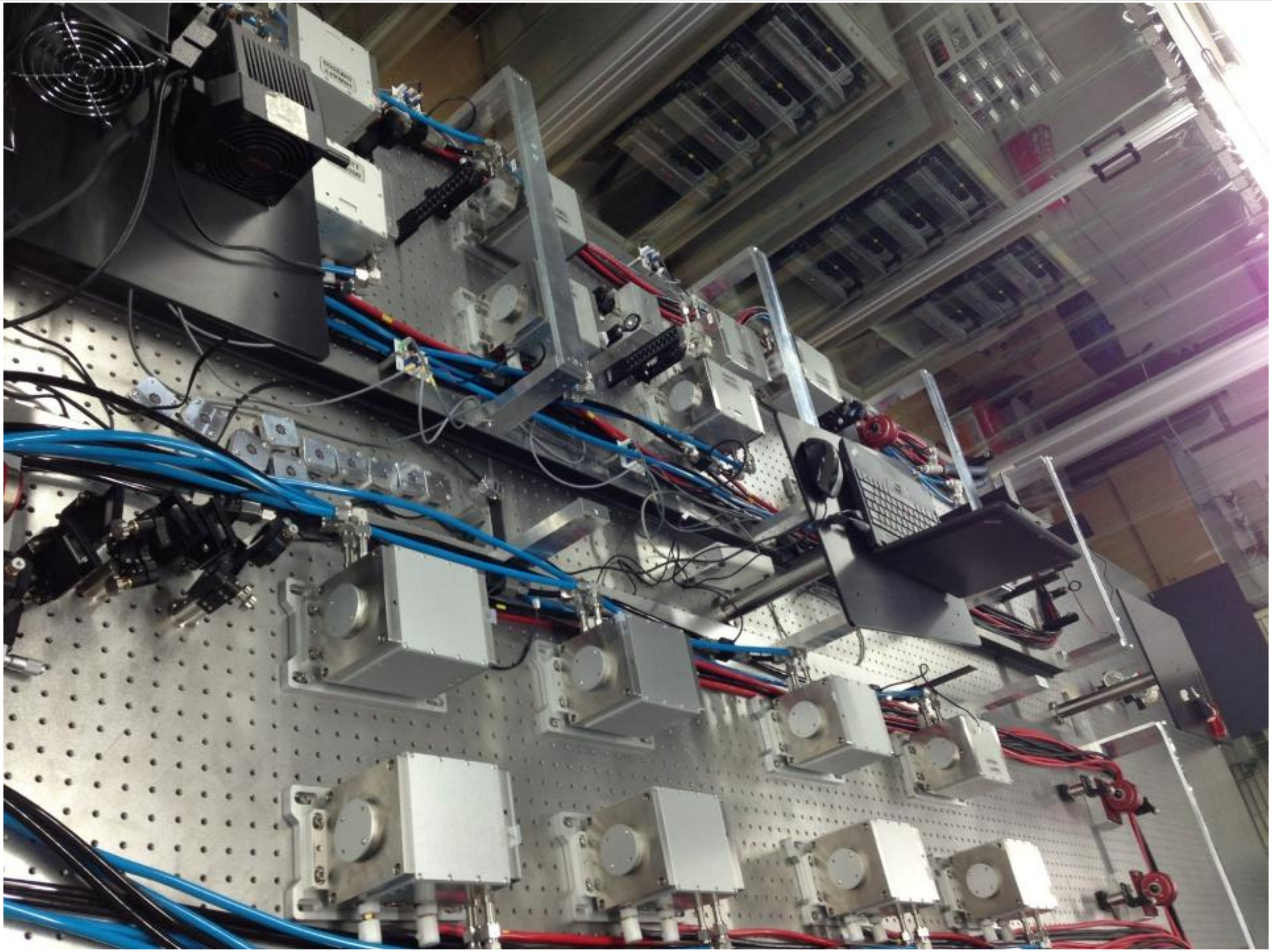


GM, Gain module;
RL, Relay image lens;
HR, High Reflector;
FR, Faraday rotator;
PBS, Polarization beam splitter;
ISO, Isolator





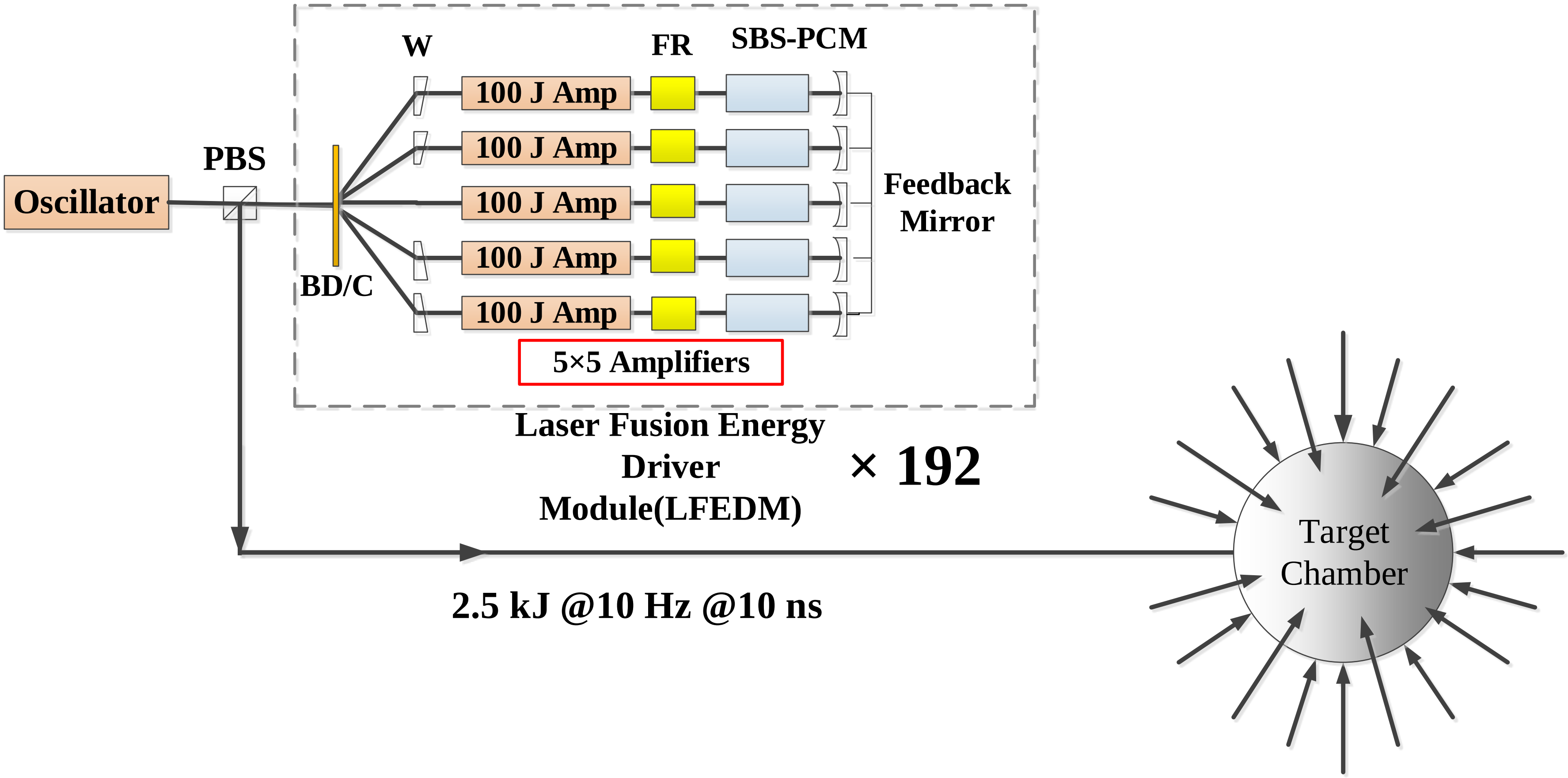
4 Main Amps



Critical power of SBS-PCMs

- If Kumgang laser is successfully demonstrated, we can apply the SBS-PCM to **100 J @ 10 Hz (1 kW)**, because the load to SBS-PCMs of Kumgang laser is same as **1 kW (0.1 J @ 1 kHz)**.
- Furthermore, We expect that SBS-PCMs can be utilized at the output power of **10 kW**.

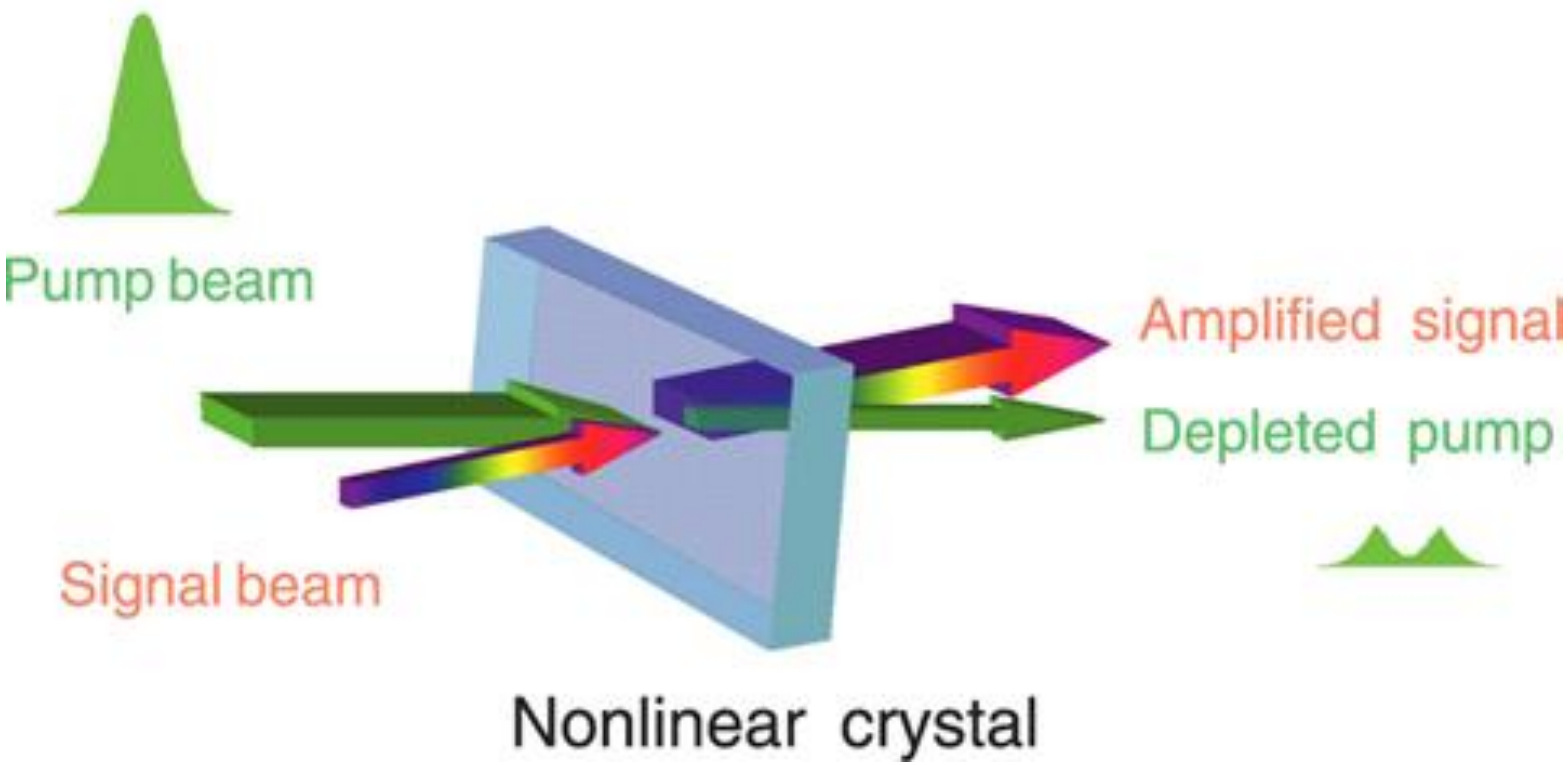
Schematic of proposed LFE driver (2.5 kJ @10 Hz module)



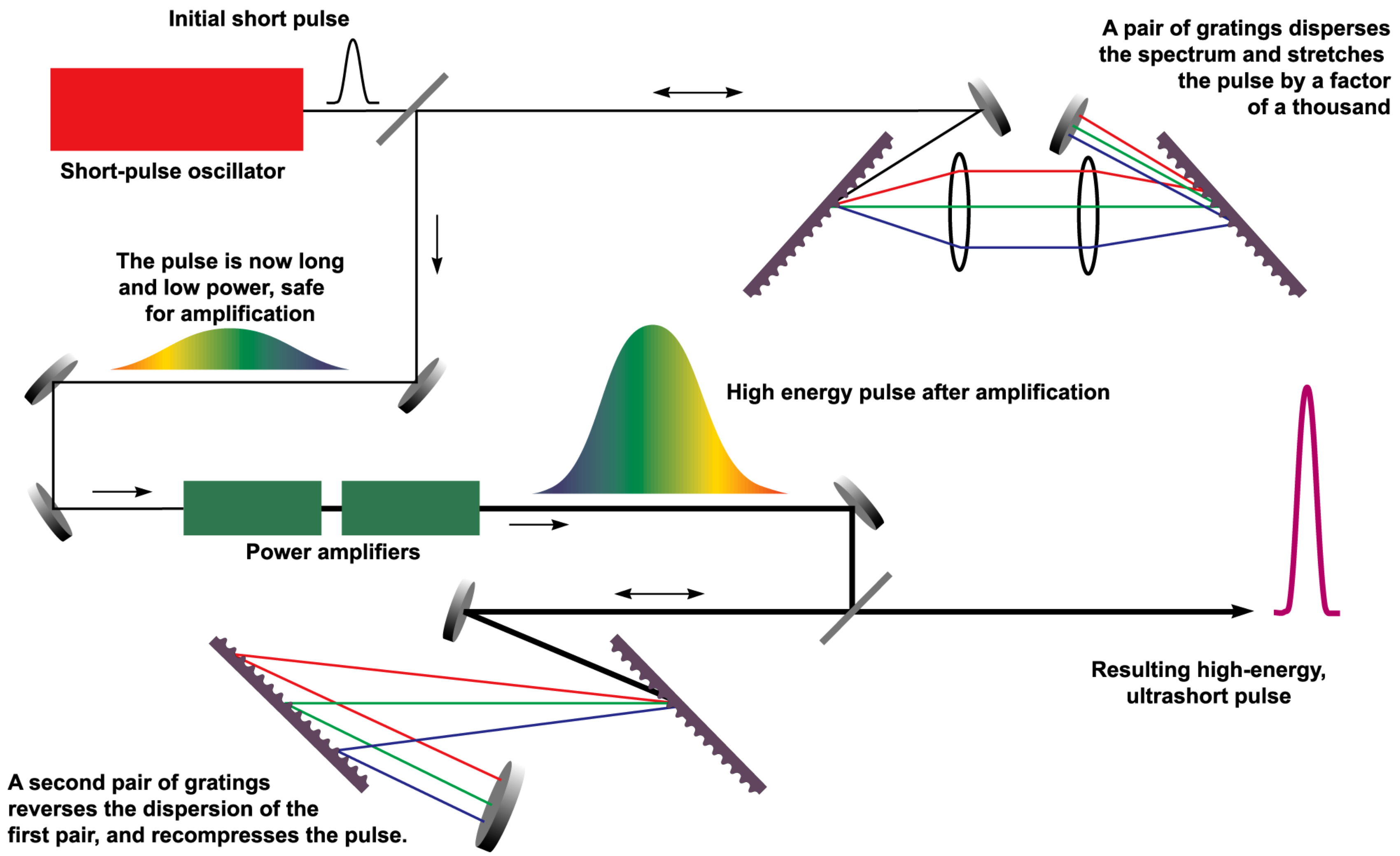
Plan for laser fusion driver configuration

- For 2.5 kJ @ 10 Hz,
  - 25 × 100 J
  - 3 × 1 kJ beam combinations are available
- For 25 kJ @ 10 Hz (NIF Class)
  - 250 × 100 J
  - or 25 × 1 kJ beam combinations are available

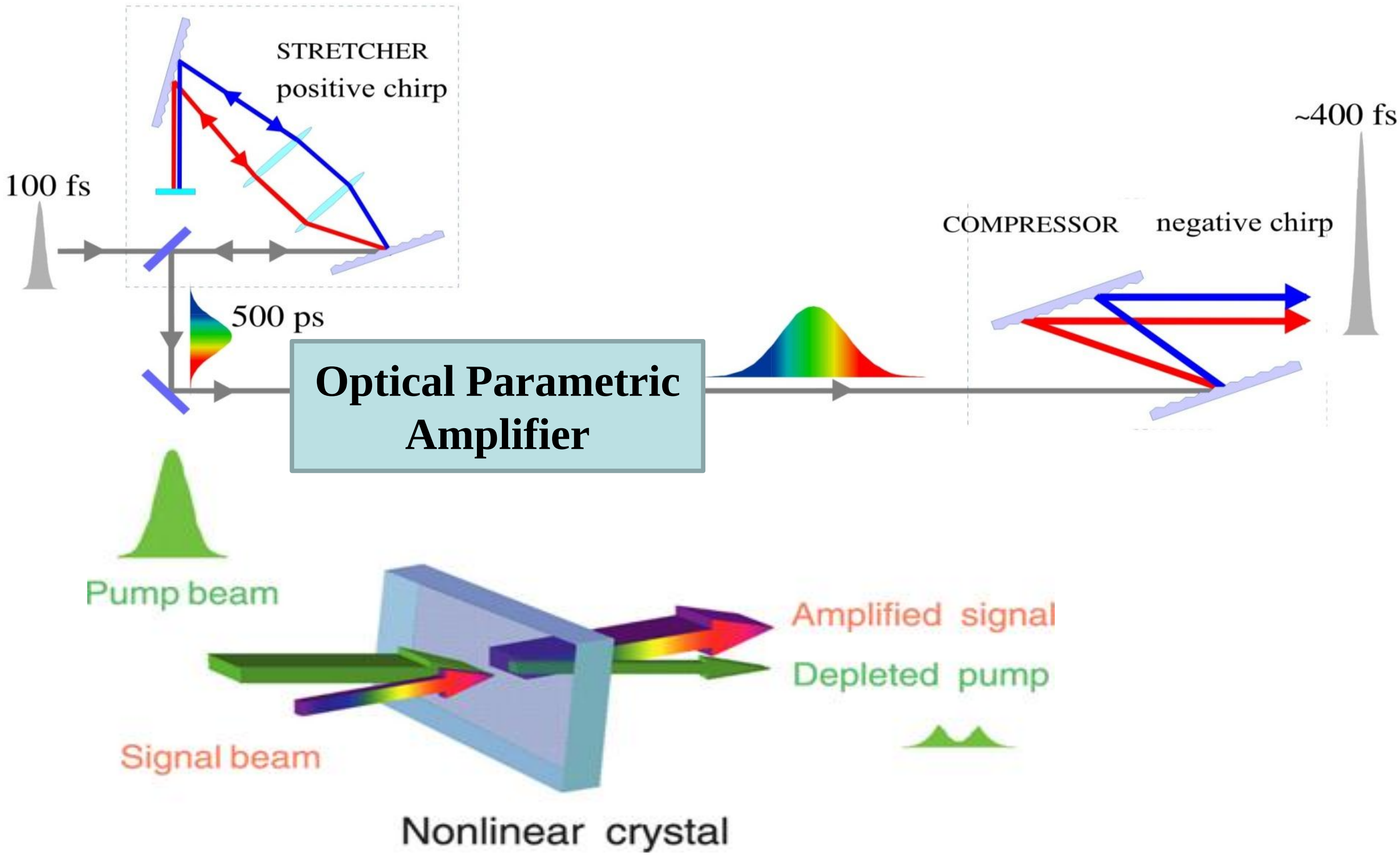
OPA: Optical Parametric Amplification



CPA: Chirped Pulse Amplication

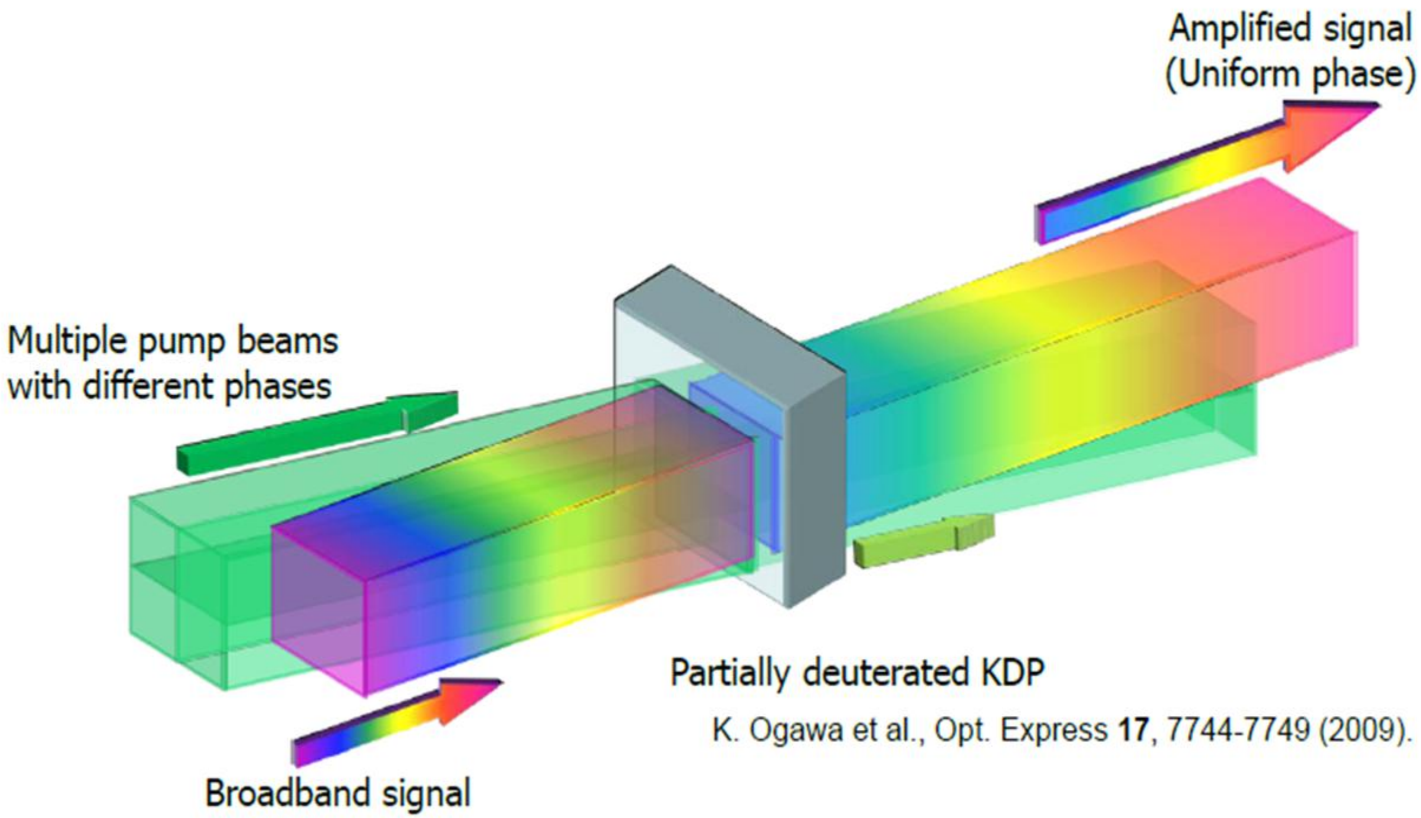


OPCPA = OPA + CPA

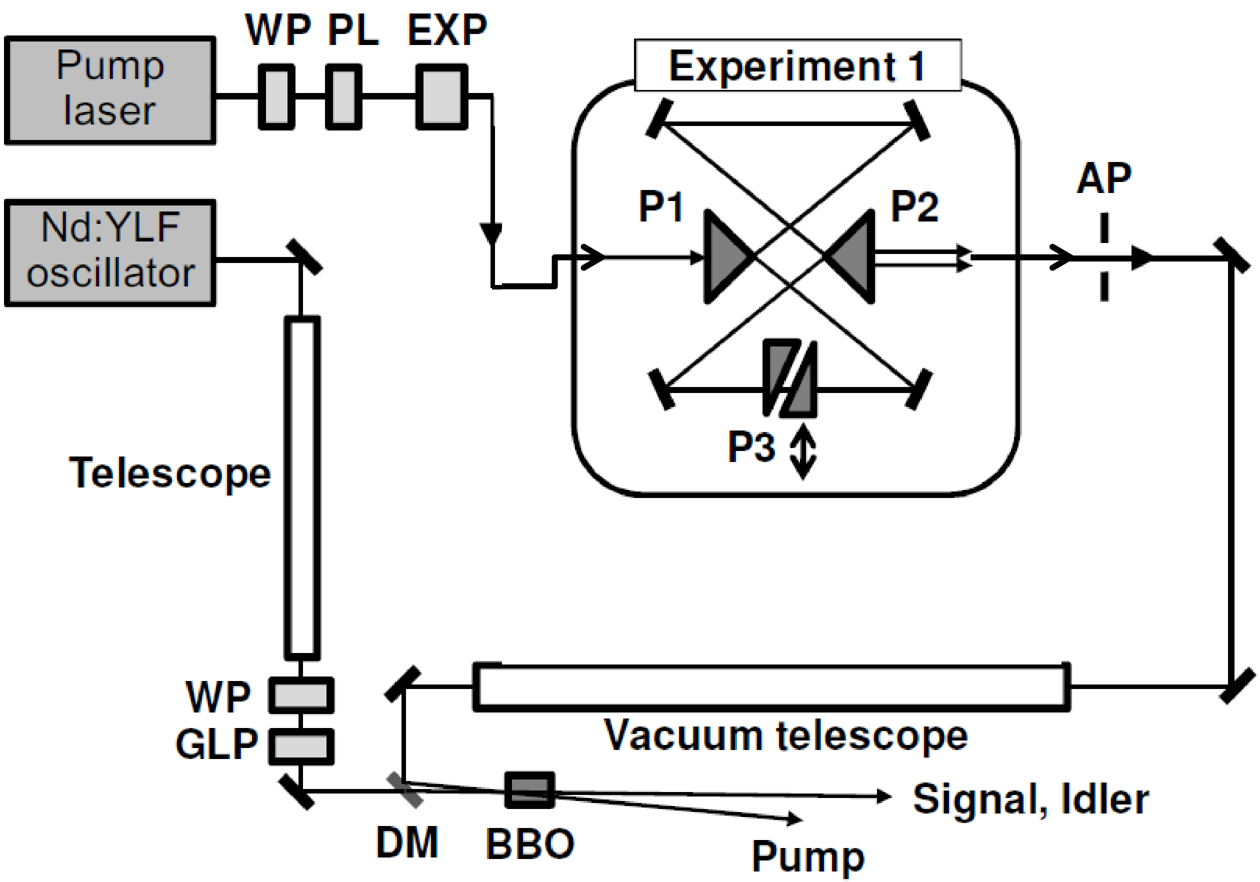


High rep rate high energy fs/ps laser by OPCPA

Exa-watt laser concept based on broadband OPA pumped by multiple beams



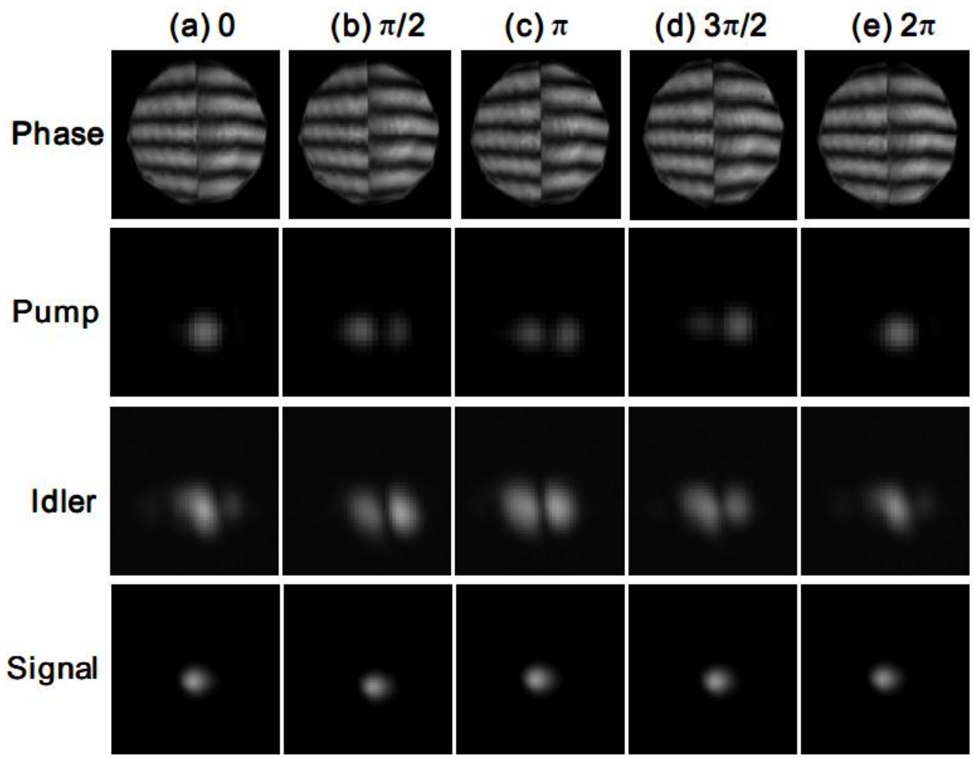
Experimental setup for the OPA pumped by 2x1 beams



WP: waveplate;
PL: polarizer;
EXP: beam expander;
P1 and P2: prisms that split the pump beam;
P3: prism for control of relative phase;
RPP: random phase plate;
AP: aperture;
DM: dichroic mirror;
GLP: Glan laser prism.

T. Kurita et al, OPTICS EXPRESS, Vol. 18, No. 14, pp. 521~526(2010)

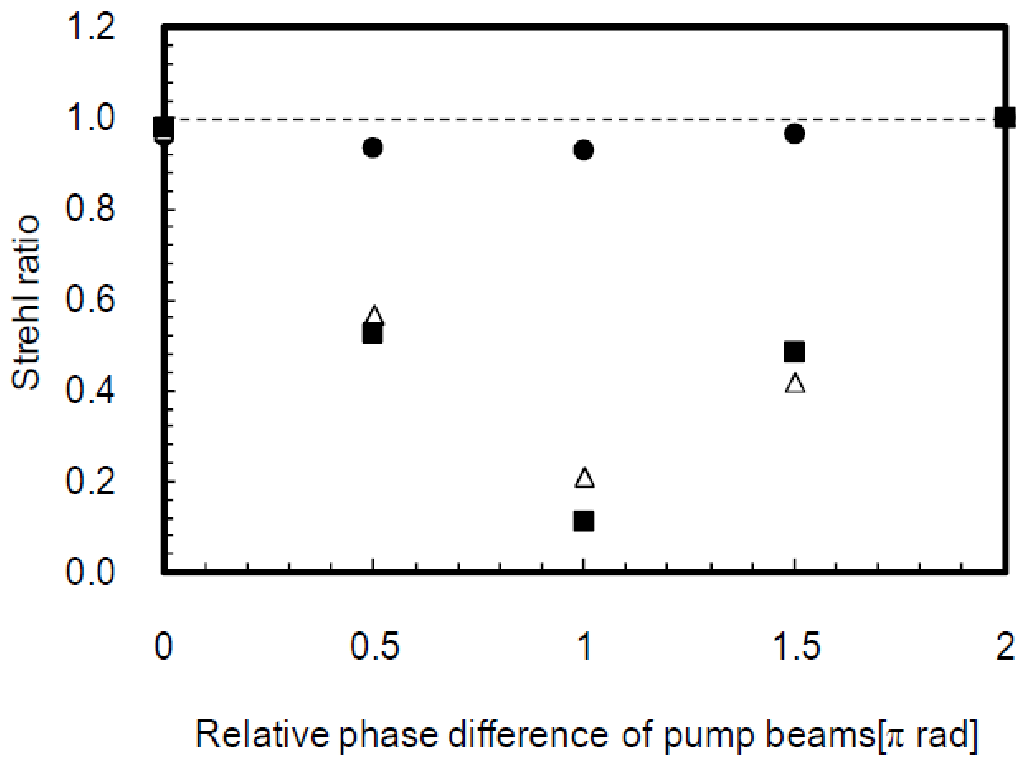
The OPA pumped by 2x1 beam



T. Kurita et al, OPTICS EXPRESS, Vol. 18, No. 14, pp. 521~526(2010)

Interferogram of the two pump beams obtained with a reference beam with uniform phase distribution and far-field pattern of the pump, the idler, and the amplified signal

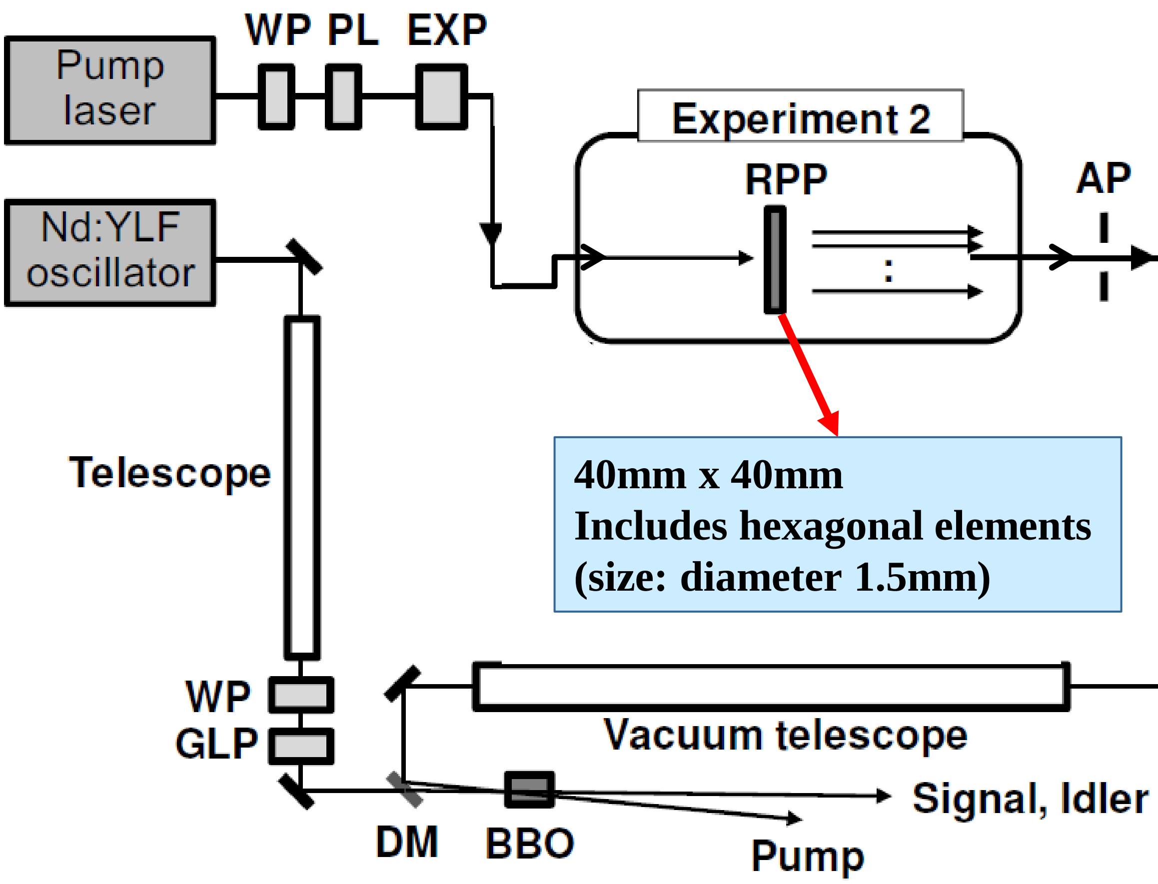
The OPA pumped by 2x1 beam



T. Kurita et al, OPTICS EXPRESS, Vol. 18, No. 14, pp. 521~526(2010)

Strehl ratio of far-field pattern of the pump (closed square), amplified signal (closed circle), and idler (open triangle).

Experimental setup for the OPA pumped by multi beams

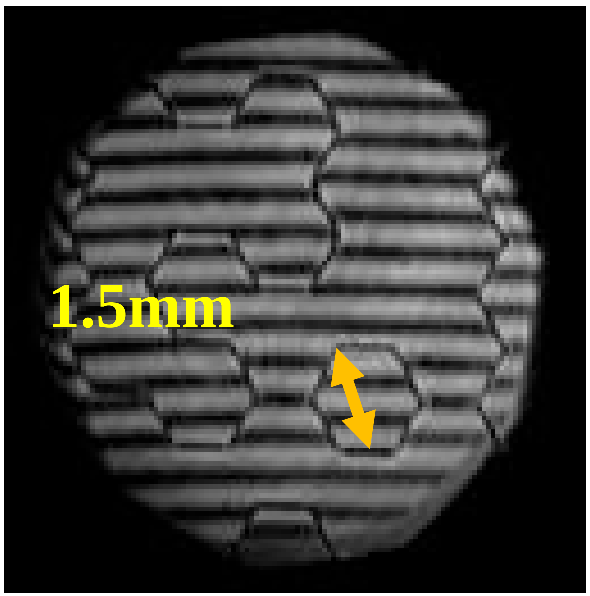


WP: waveplate;
PL: polarizer;
EXP: beam expander;
P1 and P2: prisms that split the pump beam;
P3: prism for control of relative phase;
RPP: random phase plate;
AP: aperture;
DM: dichroic mirror;
GLP: Glan laser prism.

T. Kurita et al, OPTICS EXPRESS, Vol. 18, No. 14, pp. 521~526(2010)

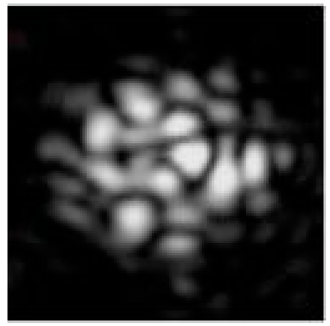
The OPA pumped by multi beams

Near field interferogram
with reference beam
(uniform phase)

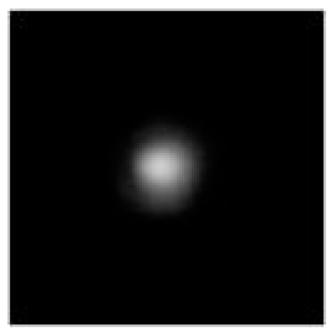


Random phase plate
(Size: 40mm x 40mm)

Far-field



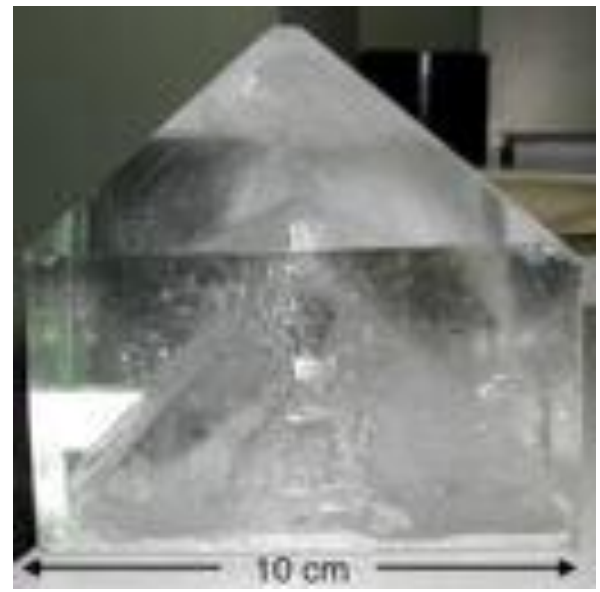
Pump beam



OPA output beam

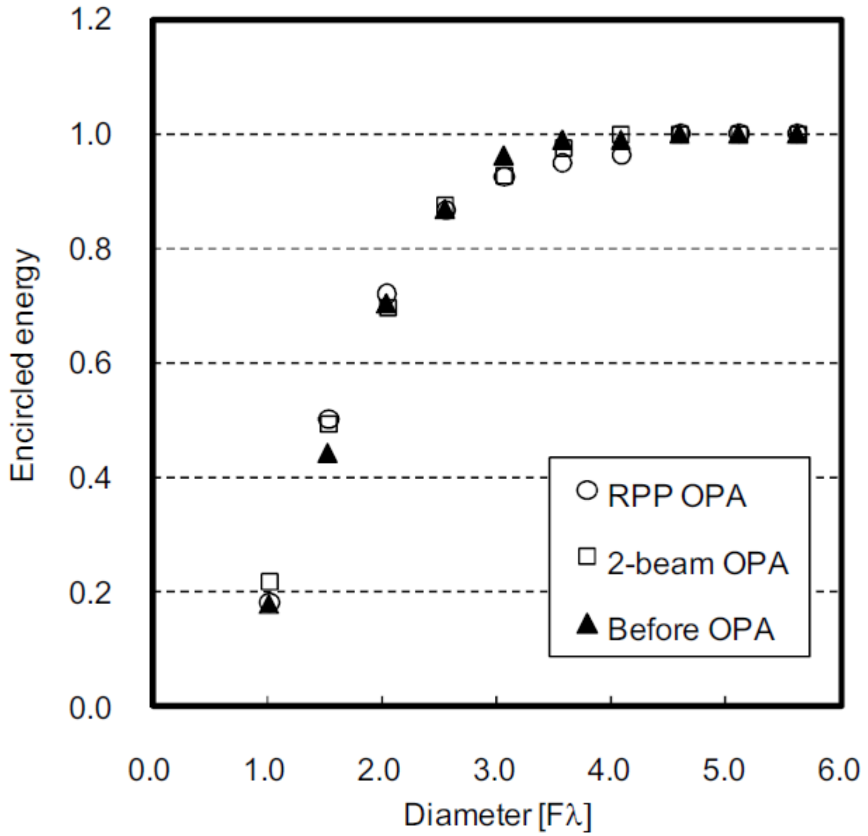
OPA material:

Wide band DKDP (13% D to H)



T. Kurita et al, OPTICS EXPRESS,
Vol. 18, No. 14, pp. 521~526(2010)

The OPA pumped by multi beams



T. Kurita et al, OPTICS EXPRESS, Vol. 18, No. 14, pp. 521~526(2010)

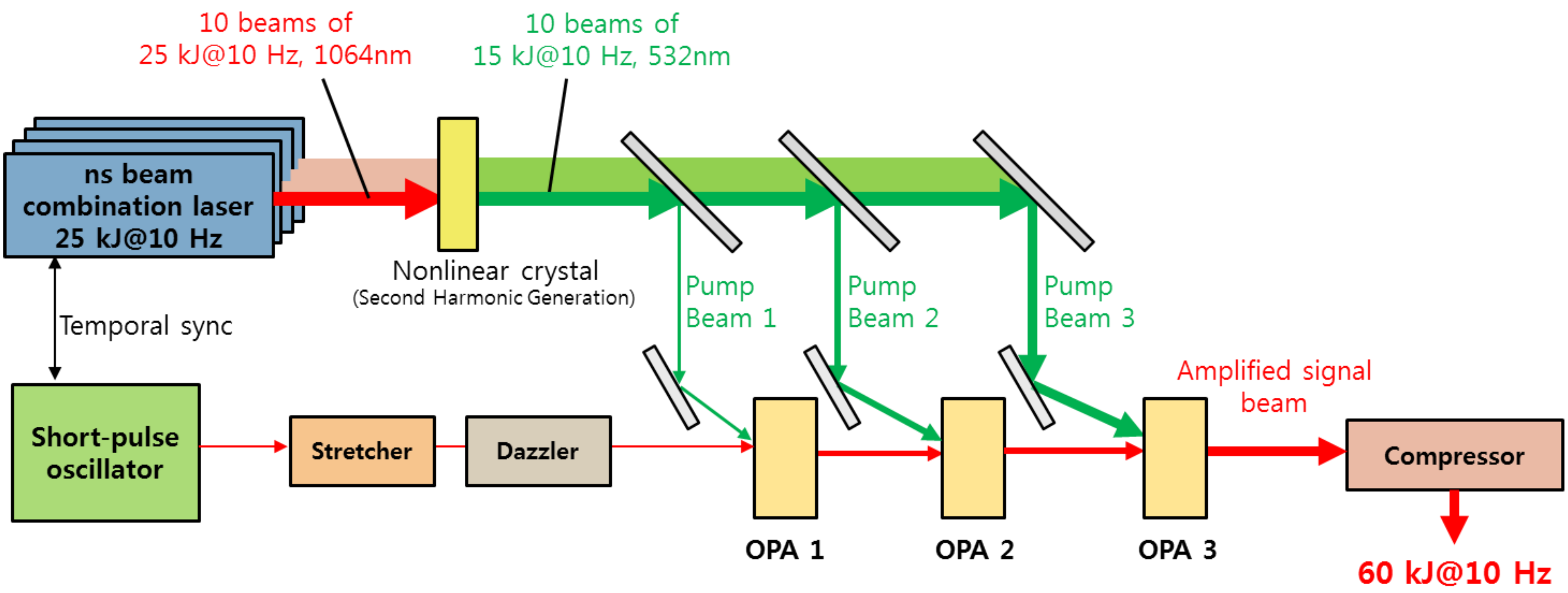
Encircled energy of the amplified signal with respect to the aperture diameter measured in a unit of Fλ (F: f number of the focusing optics, λ: wavelength)

Nonlinear crystals for OPCPA

Material	YCOB	DKDP	LBO	BBO
Mod (D_{eff})	0.952	0.225	0.828	2.2
Thermal conductivity (W/m*K)	2.68	1.045	1.4	1.2
Temperature acceptance (K*cm)	105	11.3	39.7	55
Angular acceptance (mrad*cm)	0.8	2.5	7	1.0
Damage threshold ($J*cm^{-2}$; $GW*Cm^{-2}$)	29.1 / 22.4	10.9 / 8.4	24.6 / 18.9	15.6/
Maximum aperture size (mm)	~80	~500	~50	~20

Jonathan Phillips, Klaus Ertel, Paul Mason, Saumyabrata Banerjee, Justin Greenhalgh, Jodie Smith, Tom Butcher, Mariastefania De Vido, Cristina Hernandez-Gomez, John Collier, "Frequency doubling at 7J of a High Energy, High Repetition Rate DPSSL System", **HEC-DPSSL March 2014**

OPCPA system for ignition lasers



Future Plans

1st step ($5M, 3.5years from Sept. of 2012)

- 0.1 J@10 kHz
- 4 Beam combination
- 0.4 J @ 10 kHz

2nd step (3 years)

- 10 X 10 Beam combination
- 10 J@ 10 kHz
  100 kW

✓ Laser machining by Hologram
✓ EUV source
✓ Etc.

2nd step (3~5 years)

- 100 J ~ 1 kJ @ 10 Hz
- 4 Beam combination
- 400 J ~ 4 kJ @ 10 Hz

- 10 X 10 Beam combination
- 10 kJ ~ 100 kJ @ 10 Hz
  > 100 kW

✓ Laser machining by Hologram
✓ Laser peening
✓ n/p generator
✓ **Laser Fusion**
✓ Etc.

Conclusion

- **To achieve the inertial fusion energy (IFE), Beam combination is one of the most promising techniques for the laser fusion driver**
  - **ns laser driver for compression : available with ns Coherently beam combined Dream Laser using SBS-PCMs**
  - **ps/fs laser for ignition:**
    - **available with**
      - **OPCPA using ns Beam Combined Dream Laser as a pumping source**
      - **or Beam combination of ps/fs lasers**
- **Real OPCPA Laser Fusion Driver system can be developed after Kumgang Laser is successfully demonstrated.**

Thank you for your attention.

Future Works

- With new amplifiers, the 4 beam combined output energy is expected to be around 2,000mJ (4×500mJ) at 10 Hz repetition rate.
    - ✓ For AD and WD
- For the WD beam combination
    - ✓ Beam-quality improvement by
        - ➢ image relays,
        - ➢ serrated apertures

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1. H. J. Kong, J. Y. Lee, Y. S. Shin, J. O. Byun, H. S. Park, and H. Kim, "Beam recombination characteristics in array laser amplification using stimulated Brillouin scattering phase conjugation," Optical Review **4**, 277-283, 1997.
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3. H. J. Kong, Y. S. Shin, and H. Kim, "Beam combination characteristics in an array laser using stimulated Brillouin scattering phase conjugation mirrors considering partial coherency between the beams," Fusion Engineering and Design **44**, 407-417, 1999.
4. H. J. Kong, S. K. Lee, J. J. Kim, Y. G. Kang, and H. Kim, "A cross type double pass laser amplifier with two symmetric phase conjugation mirrors using stimulated Brillouin scattering," Chinese Journal of Lasers **B10 Supplement**, I5-I9, 2001.
5. H. J. Kong, Y. J. Kwon, S. K. Lee, J. J. Kim, and Y. G. Kang, "The dependence of the reflectivity of a stimulated Brillouin scattering phase-conjugate mirror on the pumping laser mode", Chinese Journal of Lasers **B10 Supplement**, III20-III23, 2001.
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7. H. J. Kong, S. K. Lee, and D. W. Lee, "Beam combined laser fusion driver with high power and high repetition rate using stimulated Brillouin scattering phase conjugation mirrors and self-phase-locking," Laser and Particle Beams **23**, 55-59, 2005.
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12. H. J. Kong, J. W. Yoon, J. S. Shin, D. H. Beak, and B. J. Lee, "Long term stabilization of the beam combination laser with a phase controlled mirrors for the laser fusion driver," Laser and Particle Beams **24**, 519-523, 2006.

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13. H. J. Kong, J. W. Yoon, D. W. Lee, S. K. Lee, and M. Nakatsuka, "Beam combination using stimulated Brillouin scattering phase conjugate mirror for laser fusion driver," Journal of the Korean Physical Society **49**, S39-S42, 2006.
14. S. K. Lee, H. J. Kong, J. W. Yoon, M. Nakatsuka, D. K. Ko, and J. Lee, "Beam combined IFE driver using phase controlled stimulated Brillouin scattering phase conjugation mirrors", Journal De Physique IV France **133**, 621-625, 2006.
15. H. J. Kong, J. W. Yoon, D. H. Beak, J. S. Shin, S. K. Lee and D. W. Lee, "Laser fusion driver using stimulated Brillouin scattering phase conjugate mirrors by a self-density modulation," Laser and Particle Beams **25**, 225-238, 2007.
16. H. J. Kong, J. W. Yoon, J. S. Shin, and D. H. Beak, "Long-term stabilized two-beam combination laser amplifier with stimulated Brillouin scattering mirrors," Applied Physics Letters **92**, 021120, 2008.
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18. M. Ostermeyer, H.J. Kong, V.I. Kovalev, R.G. Harrison, A.A. Fotiadi, P. Mégret, M. Kalal, O. Slezak, J.W. Yoon, J.S. Shin, D.H. Beak, S.K. Lee, Z. Lü, S. Wang, D. Lin, J.C. Knight, N.E. Kotova, A. Sträßer, A. Scheikh-Obeid, T. Riesbeck, S. Meister, H.J. Eichler, Y. Wang, W. He, H. Yoshida, H. Fujita, M. Nakatsuka, T. Hatae, H. Park, C. Lim, T. Omatsu, K. Nawata, N. Shiba, O.L. Antipov, M.S. Kuznetsov and N.G. Zakharov, "Trends in stimulated Brillouin scattering and optical phase conjugation", Laser and Particle Beams **26**, 297-362, 2008.
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20. H. J. Kong, D. H. Beak, J. W. Yoon, and J. S. Shin, "Proposal of the practical laser fusion driver operating at high repetition rate over 10Hz by a beam combination technique using phase controlled stimulated Brillouin scattering mirrors," Journal of Physics: Conference Series **112**, 032034, 2008.
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23. H. J. Kong, J. S. Shin, J. W. Yoon, and D. H. Beak, "Phase stabilization of the amplitude dividing four-beam combined laser system using stimulated Brillouin scattering phase conjugate mirrors," Laser and Particle Beams **27**, 179-184, 2009.
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26. J. S. Shin, S. Park, H. J. Kong, "Compensation of the thermally induced depolarization in a double-pass Nd:YAG rod amplifier with a stimulated Brillouin scattering phase conjugate mirror," Optics Communications **283**, 2402-2405, 2010.
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28. M. Kalal, O. Slezak, M. Martinkova, H. J. Kong, and J. W. Yoon, "SBS PCM Technique Applied for Aiming at IFE Pellets: First Tests with Amplifiers and Harmonic Conversion," Journal of the Korean Physical Society **56**, 184-189, 2010.
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31. O. Slezak, M. Kalal, and H. J. Kong, "Phase control of SBS PCM seeding by optical interference pattern clarifed: Direct applicability for IFE laser driver", Journal of Physics: Conference Series, **244**, 032026, 2010
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33. J.S.Shin and H. J. Kong, "Phase fluctuation of self-phase-controlled stimulated Brillouin scattering waves via K8 glass", Optics Communications, **285(13-14)**, 2977-2979, 2012

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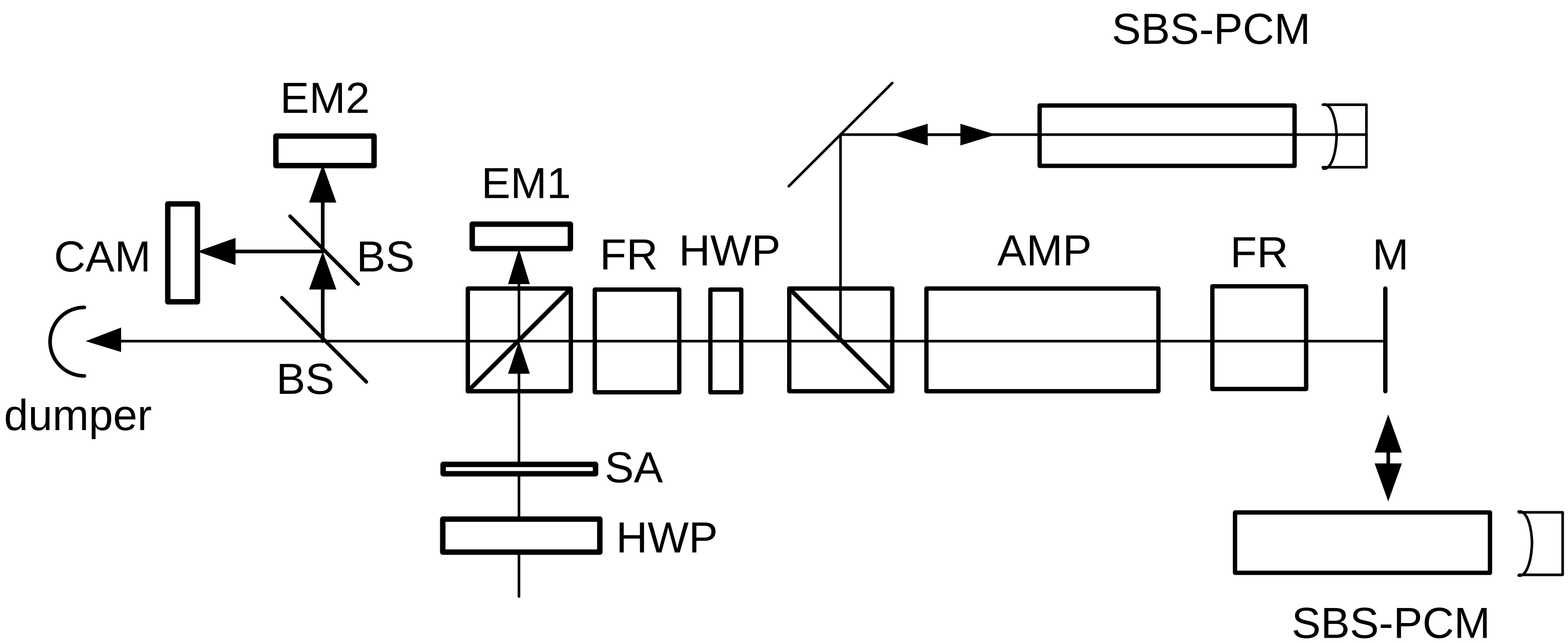
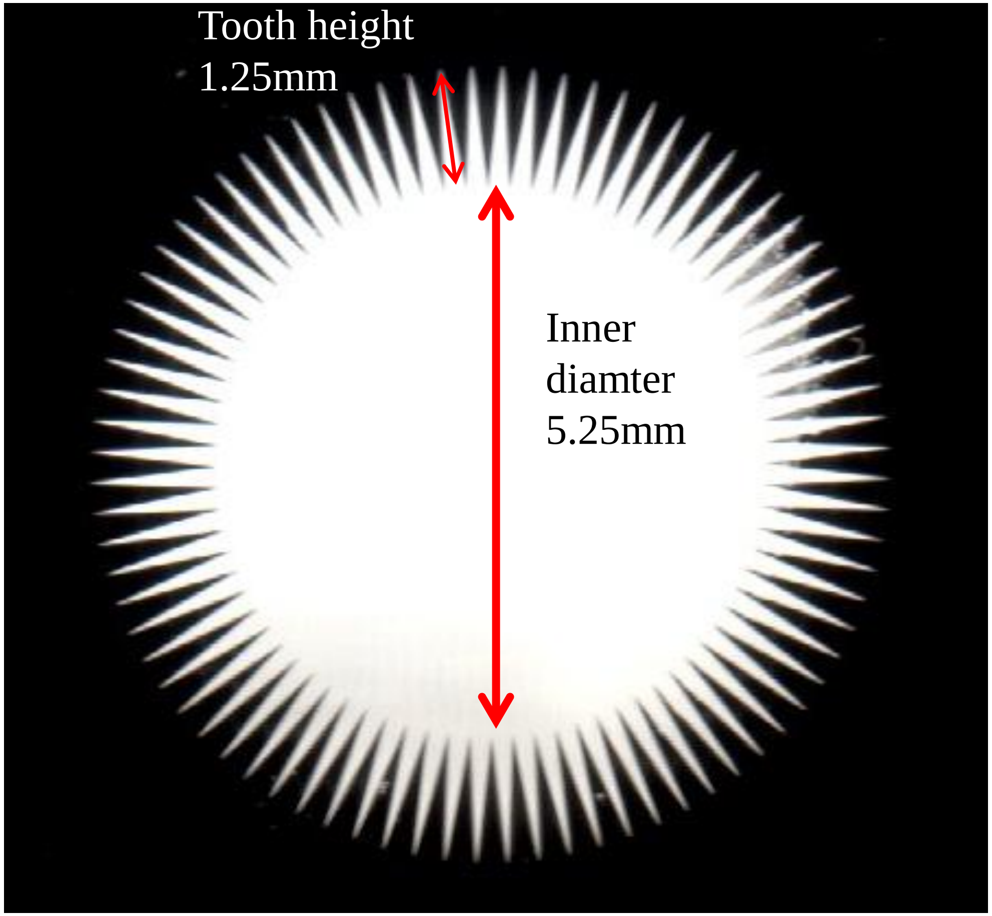
Experimental setup for 4-pass amplification



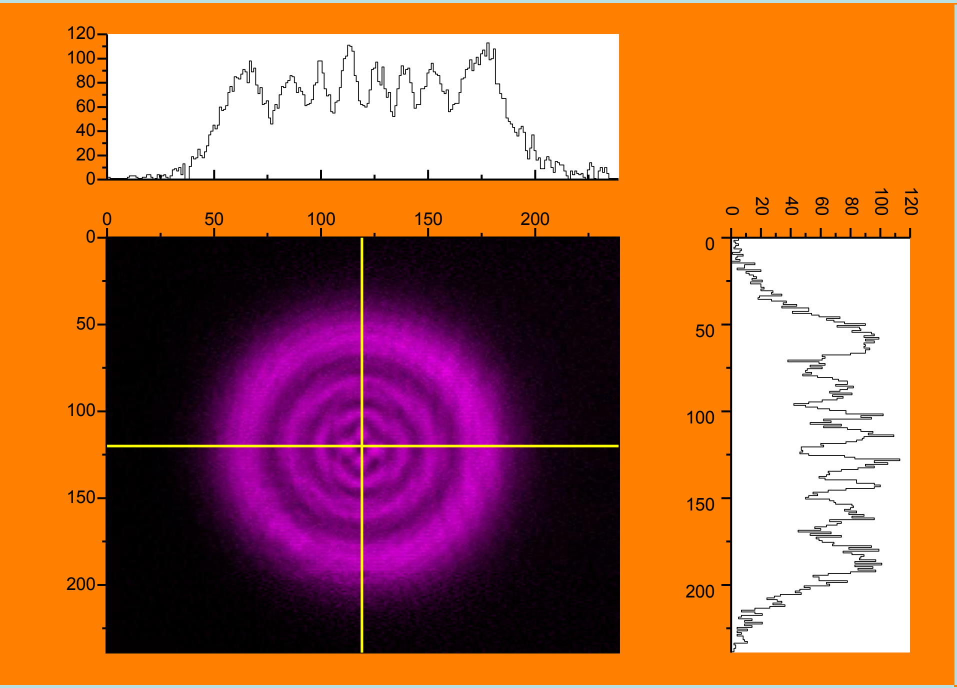
SA: serrated aperture
FR: Faraday rotators
AMP: amplifier
HWP: half-wave-plate
M: mirror
EM1,2: energy meters
BS: beam splitter
CAM: camera

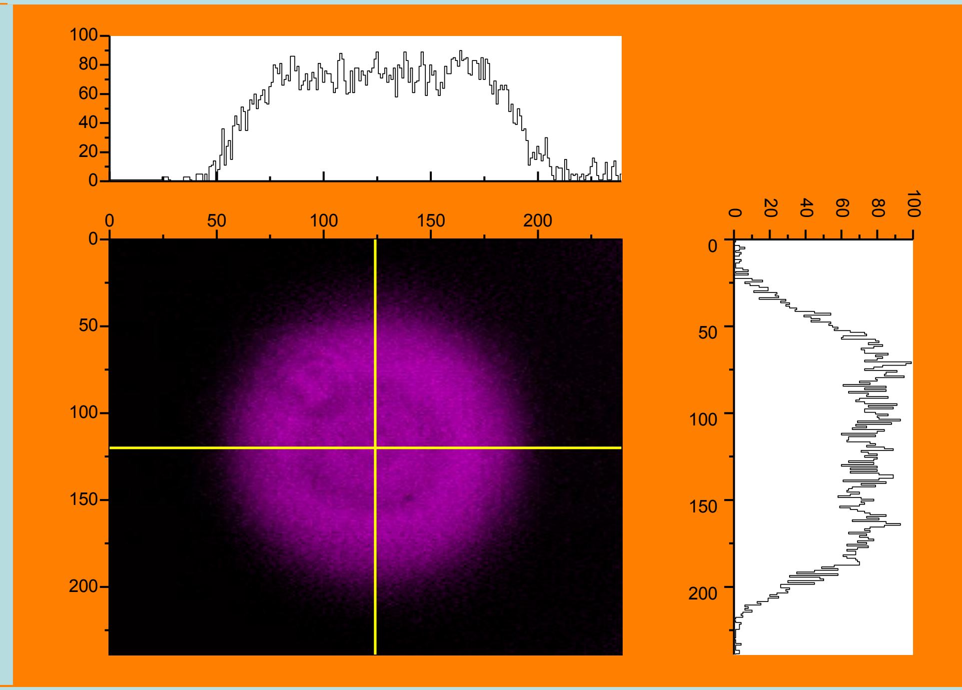
Serrated aperture



- Inner diameter of aperture =5.25mm
- Height of the tooth =1.25mm
- Number of teeth =80
- Base material: Sodalime glass
- Crom coating
- Thickness of crom coating: =100μm

Experimental results: Comparing between circular serrated aperture and circular hard aperture

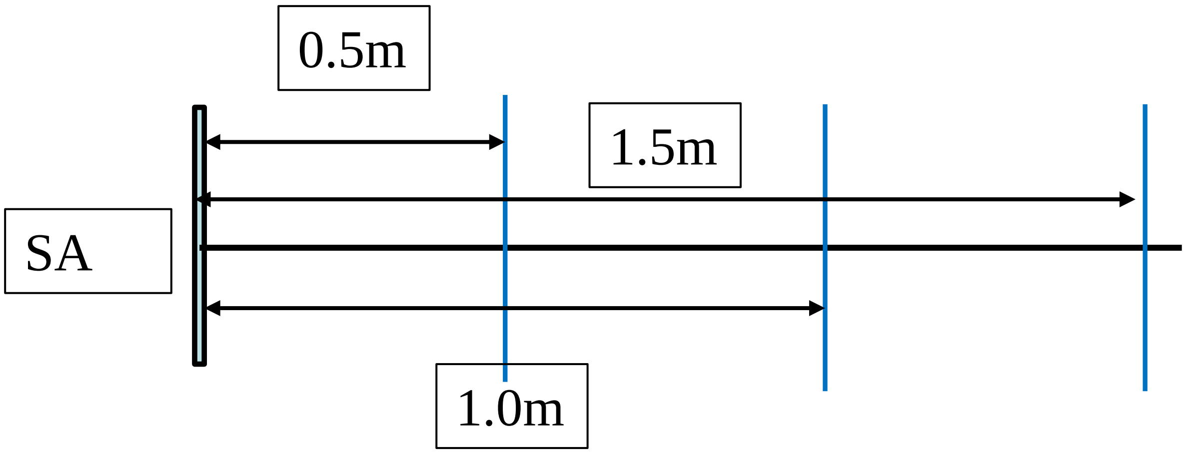




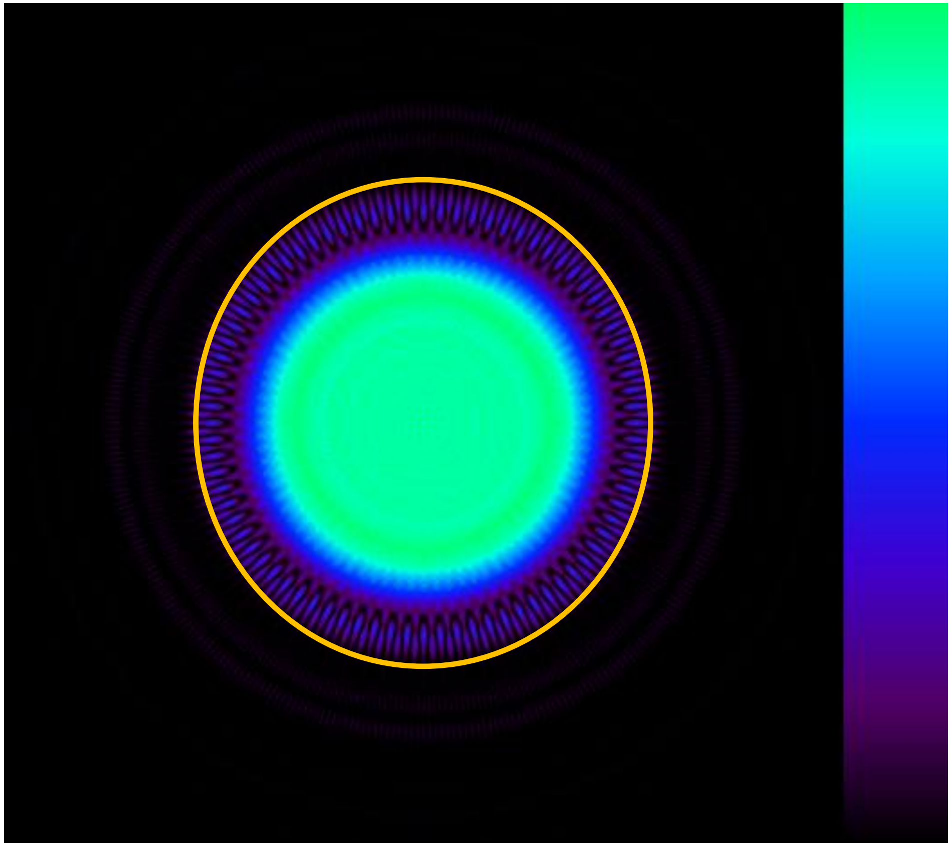
Circular hard aperture

Circular serrated aperture

Simulation condition

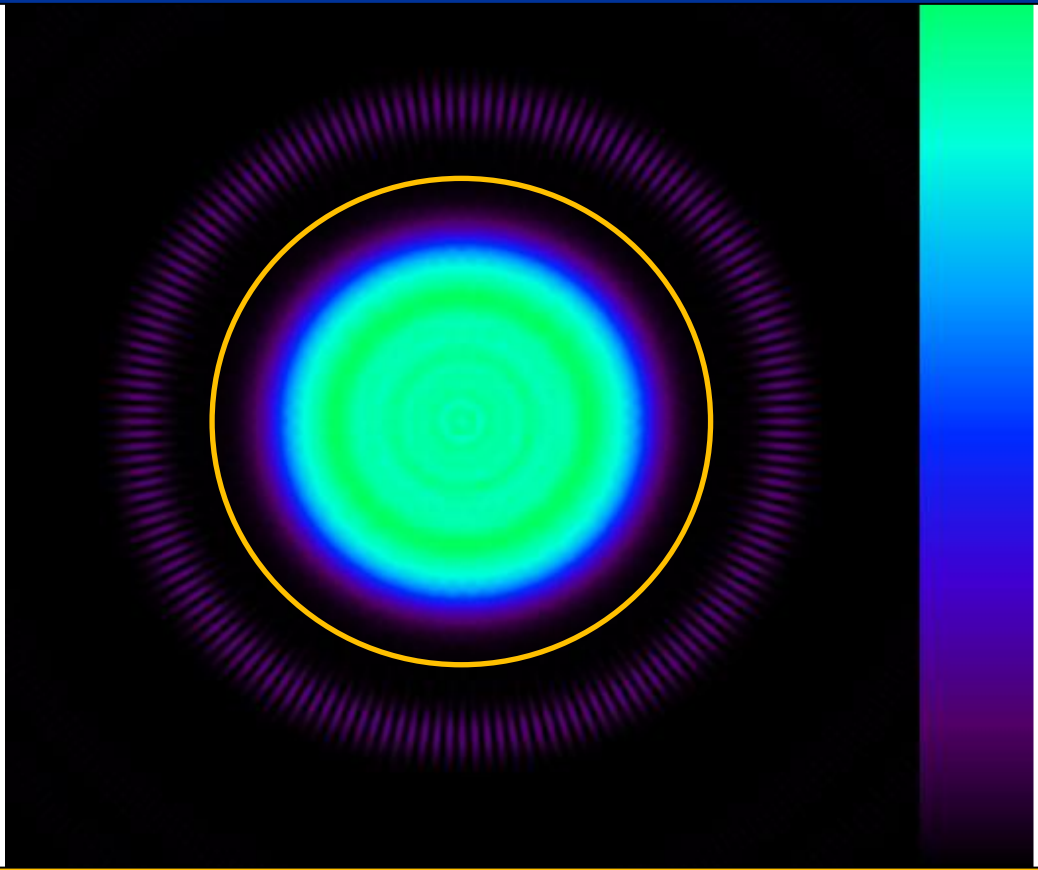


Simulation result



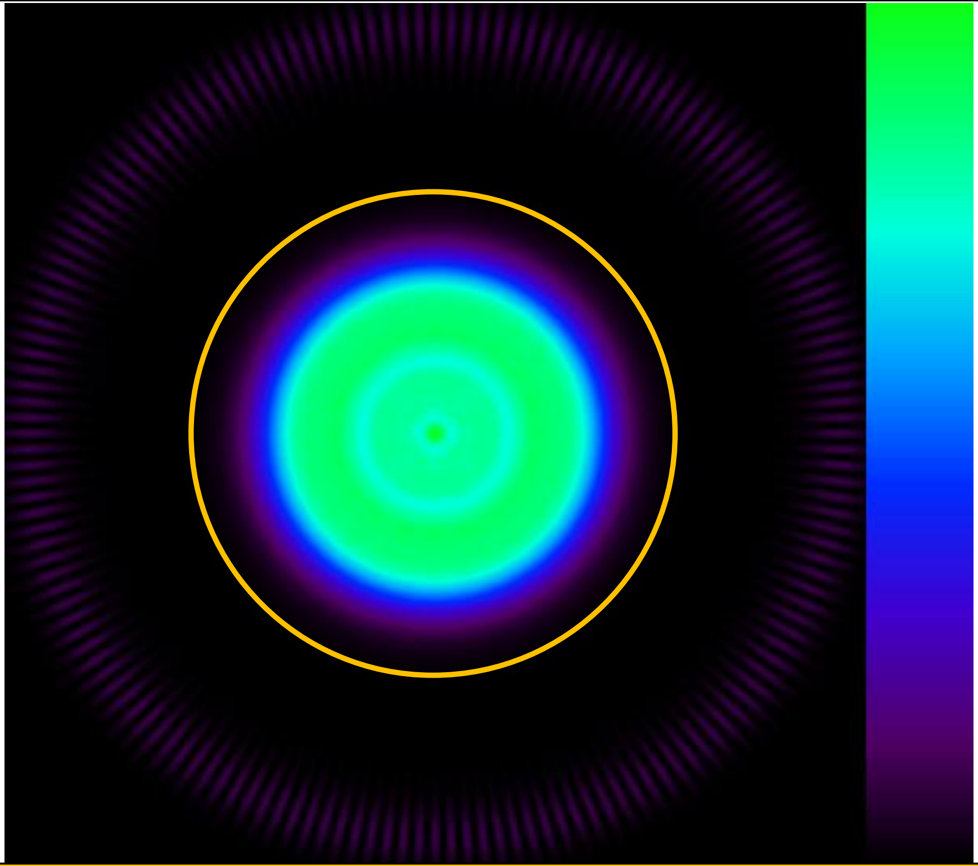
Bema patter at 0.5 m after Serrated aperture
Yellow circle : 8mm diameter

Simulation result



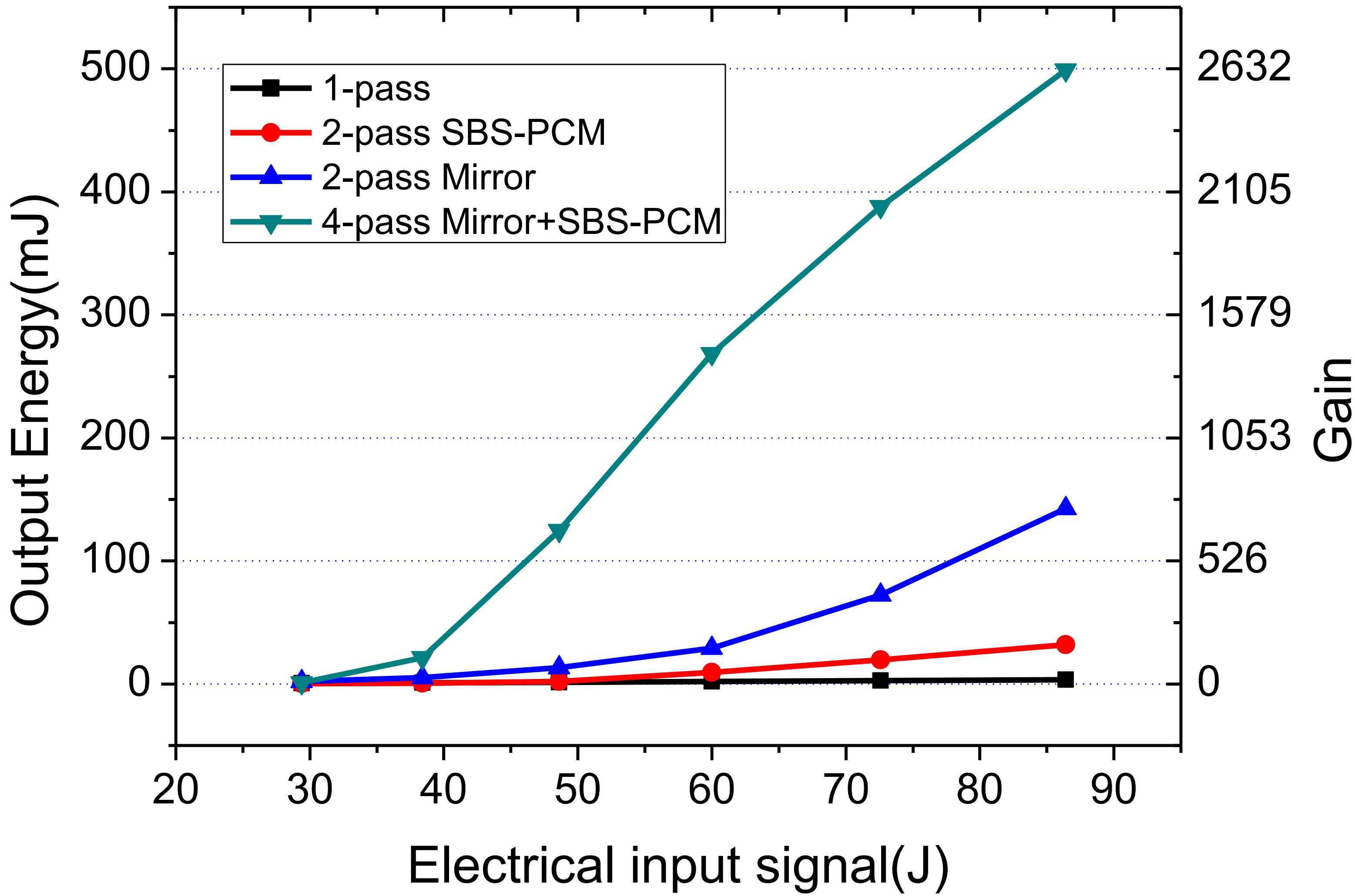
Bema patter at 1.0 m after Serrated aperture
Yellow circle : 8mm diameter

Simulation result

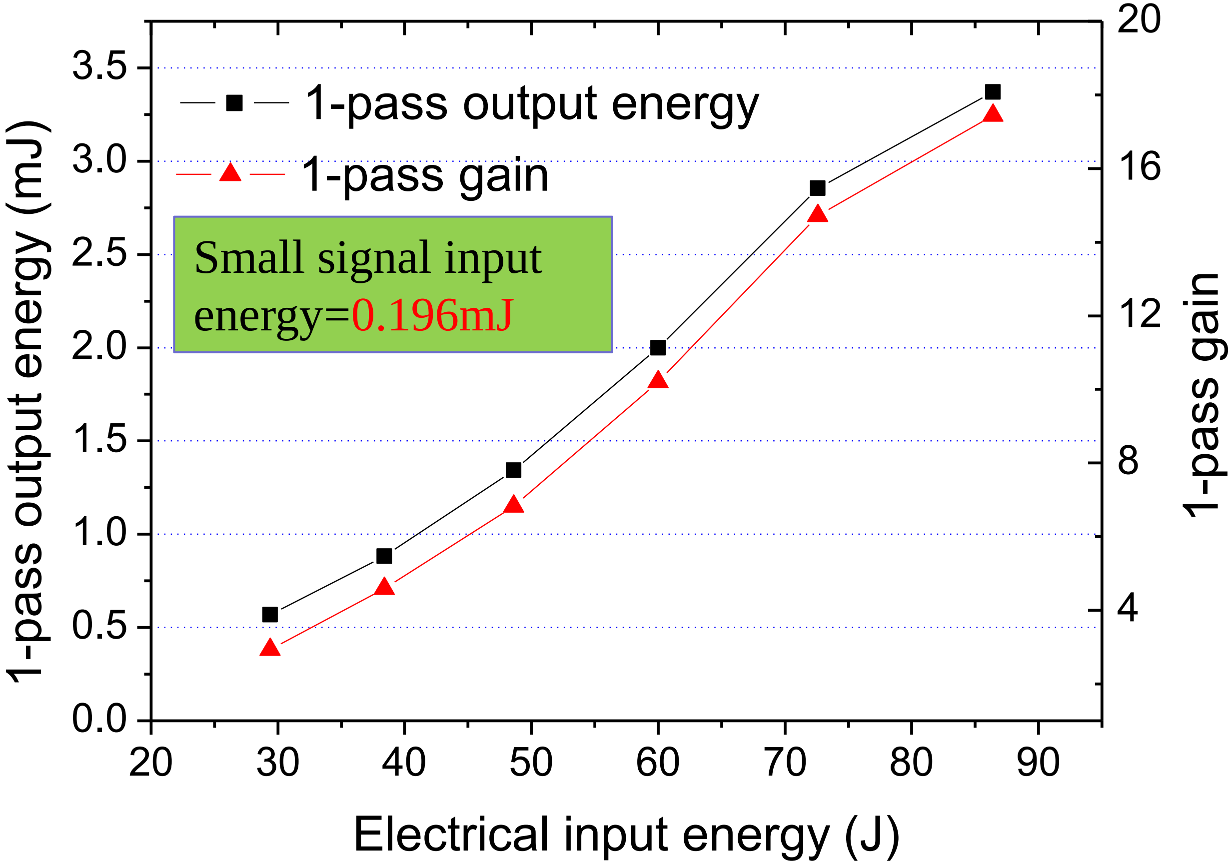


Bema patter at 1.5 m after Serrated aperture
Yellow circle : 8mm diameter

Gain of 1-pass, 2-pass, and 4-pass output

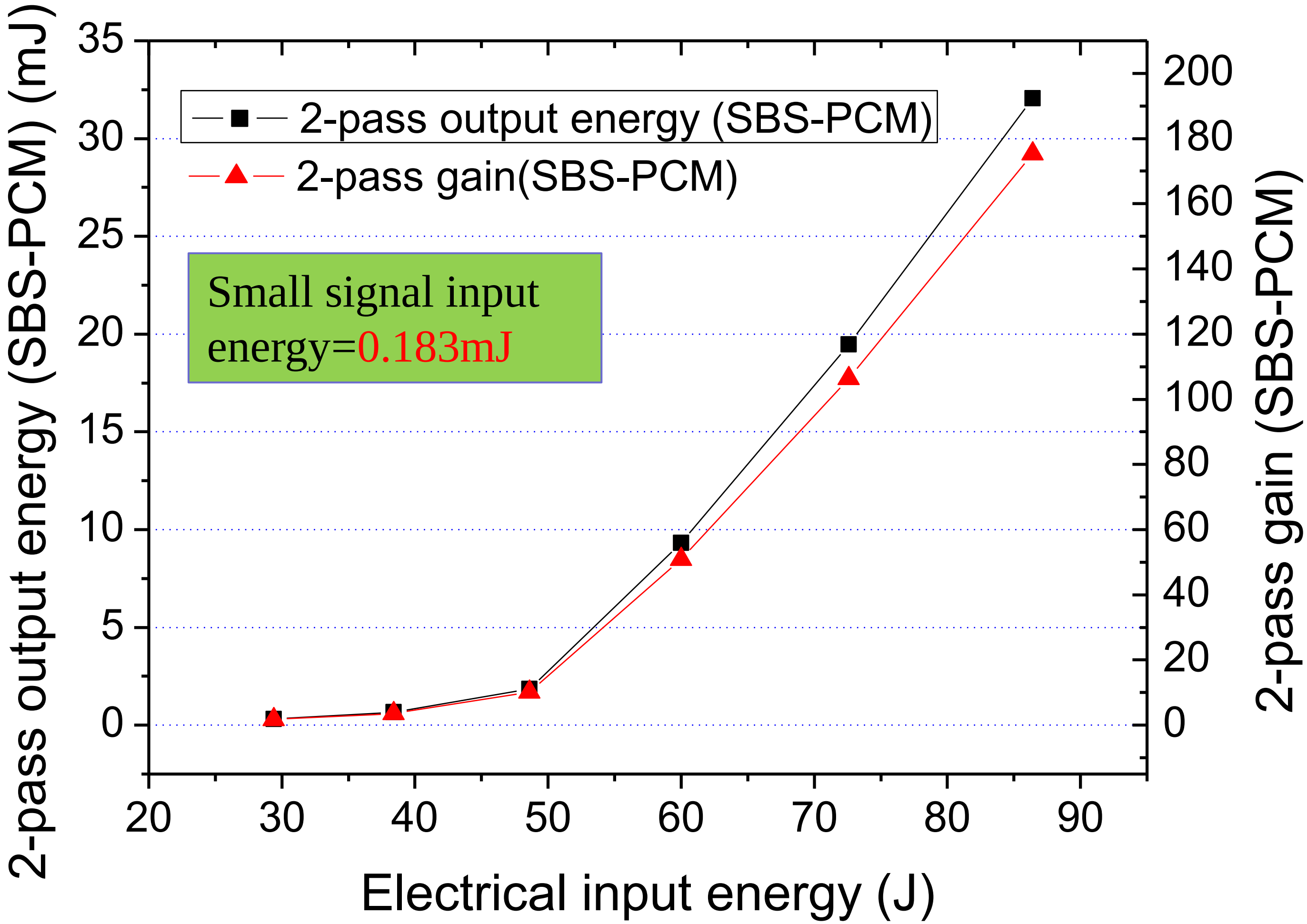


1-pass gain



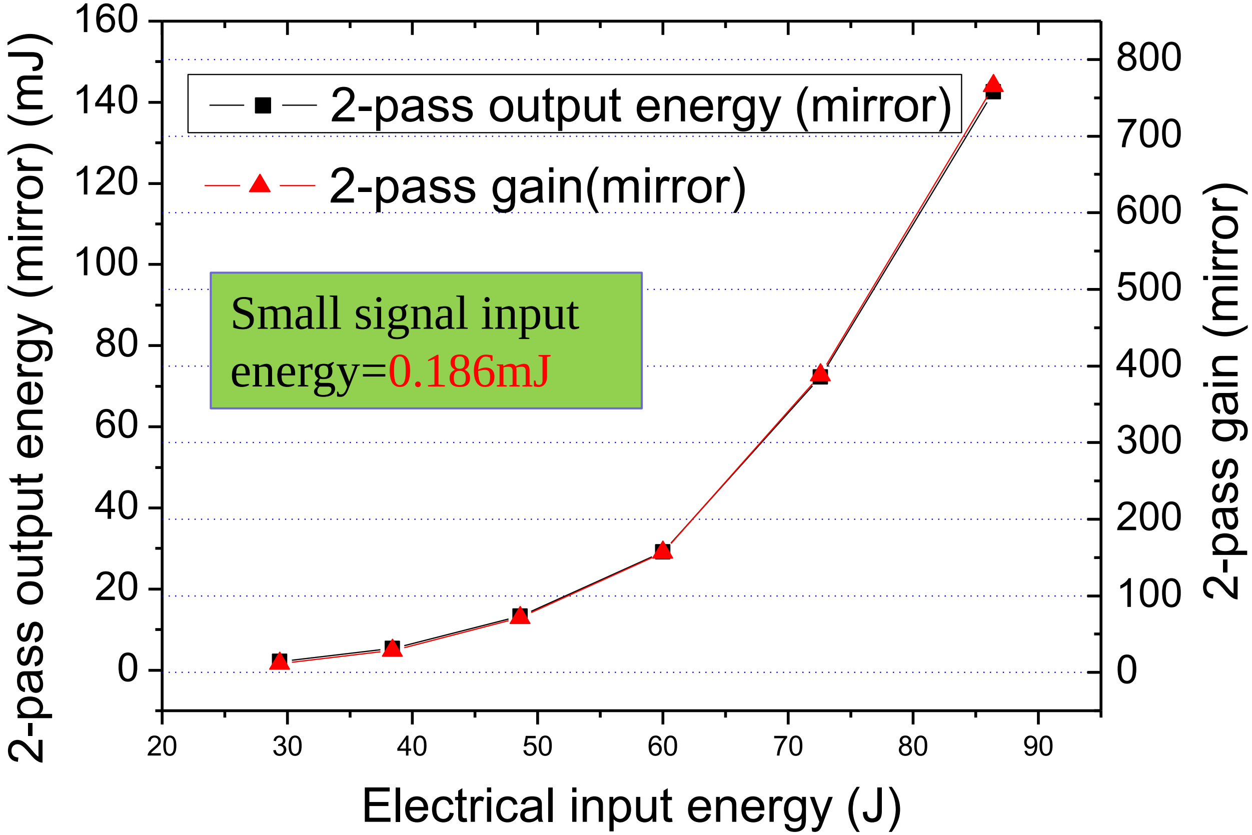
Flashlamp electrical input energy 86.4J
Small signal energy 0.196mJ, output energy 3.37mJ, gain =17.44

2-pass (SBS-PCM) gain



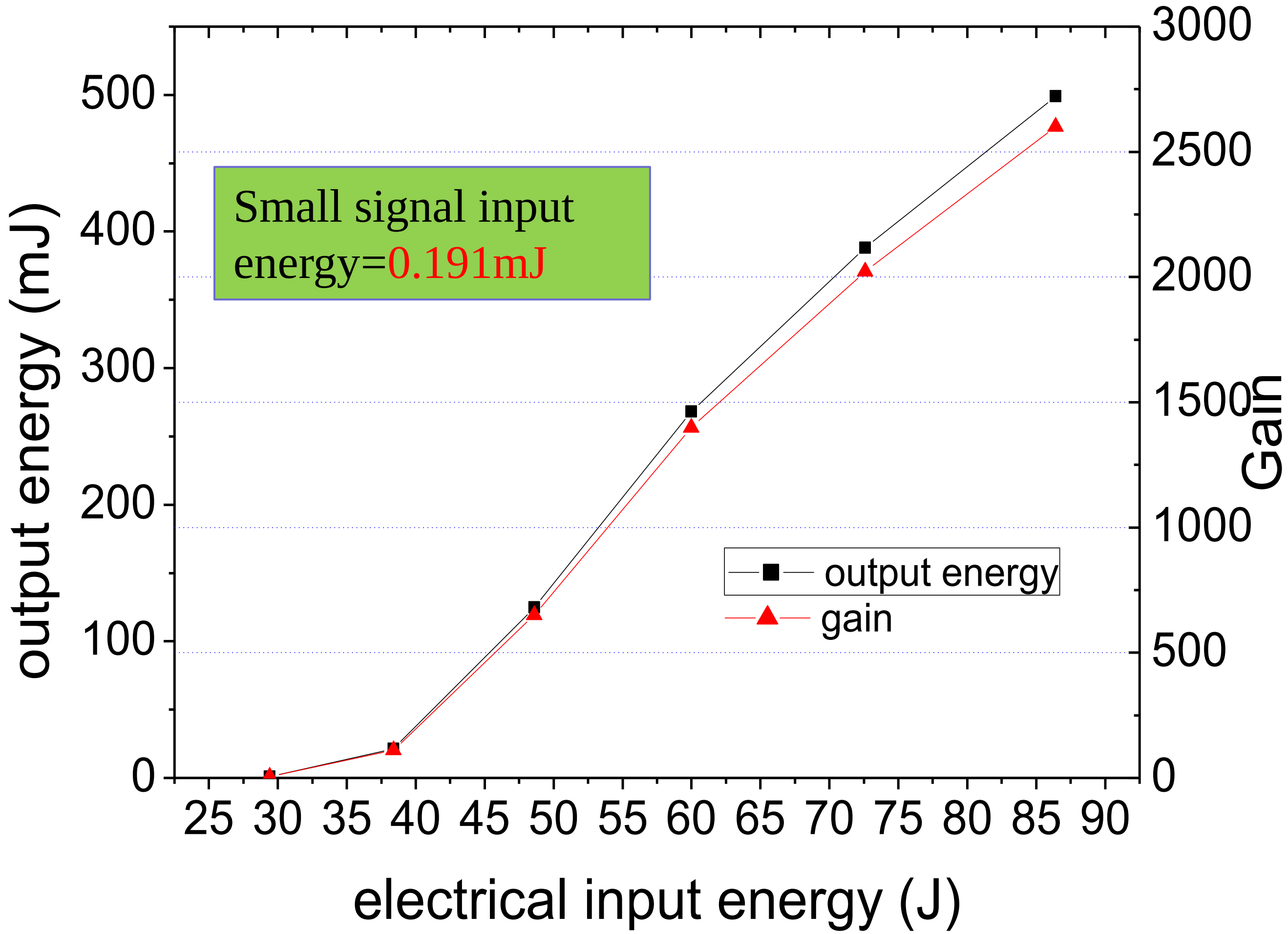
Flashlamp electrical input energy 86.4J
Small signal energy 0.183mJ, output energy 32.06mJ, gain =175.3

2-pass (mirror) gain



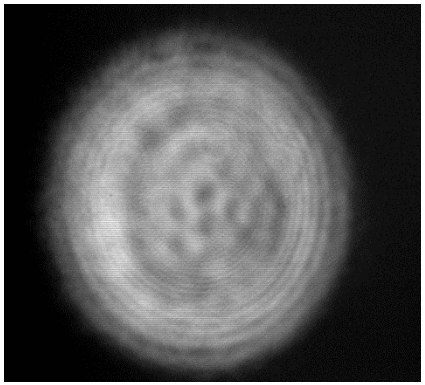
Flashlamp electrical input energy 86.4J
Small signal energy 0.186mJ, output energy 142.6mJ, gain =765.9

4-pass gain

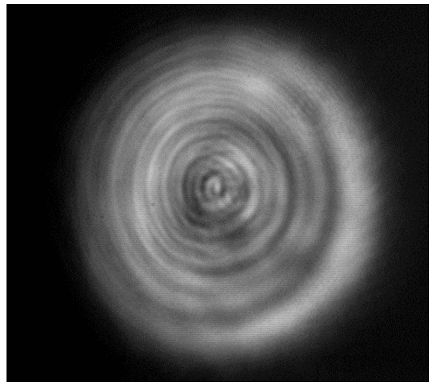


Flashlamp electrical input energy 86.4J
Small signal energy 0.191mJ, output energy 499.1mJ, gain =2600.9

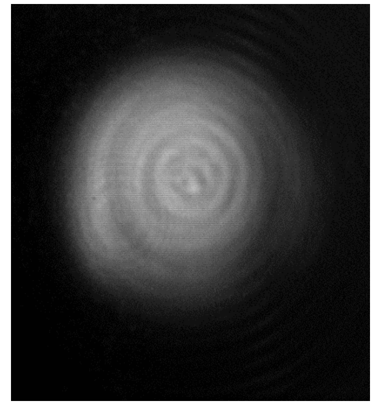
4-pass output beam patterns



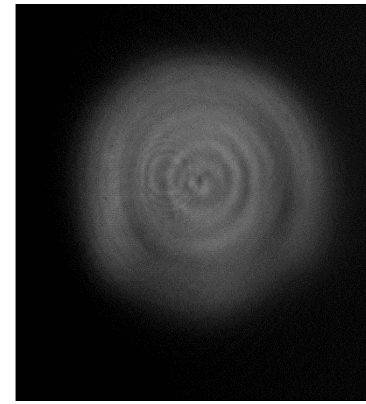
Before Amplifier



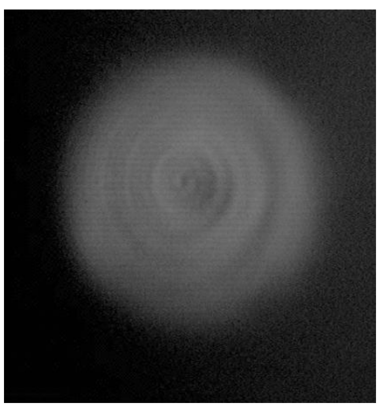
After 2-pass amp, before SBS-PCM



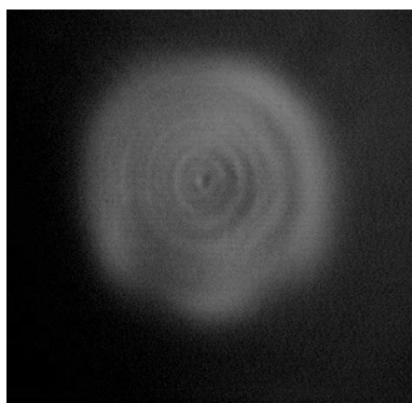
FL energy 29.4J



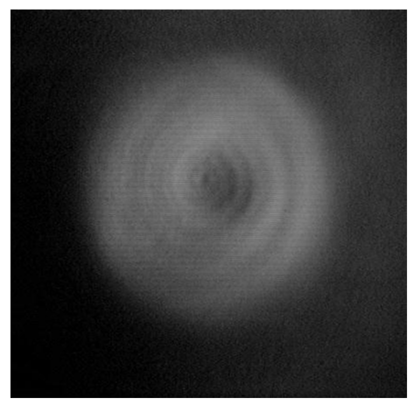
38.4J



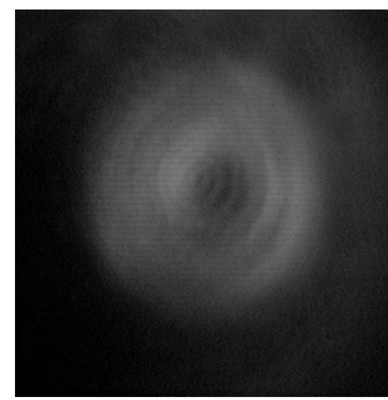
48.6J



60.0J



72.6J

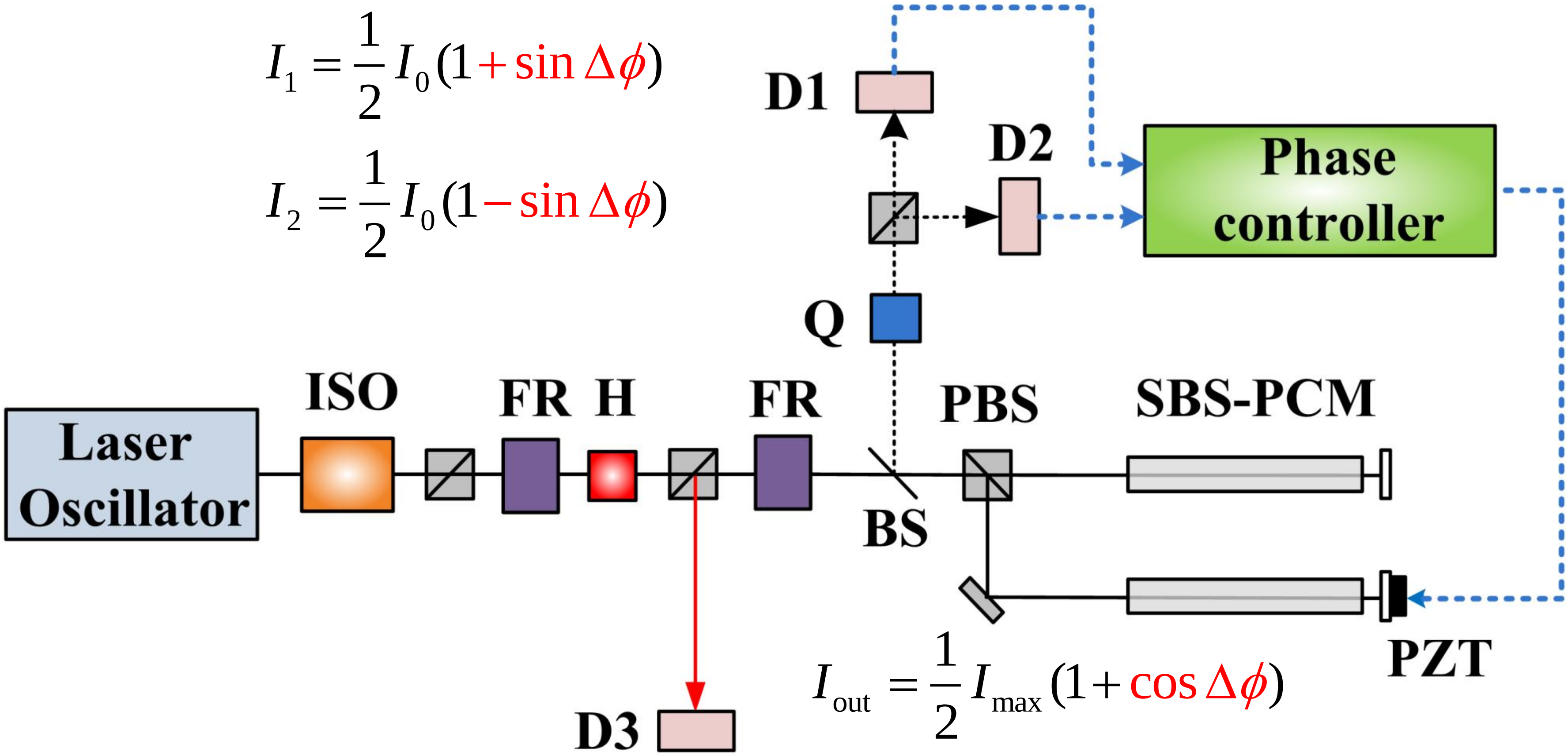


86.4J

Experimental setup for the long-term phase stabilization

$$I_1 = \frac{1}{2} I_0 (1 + \sin \Delta\phi)$$

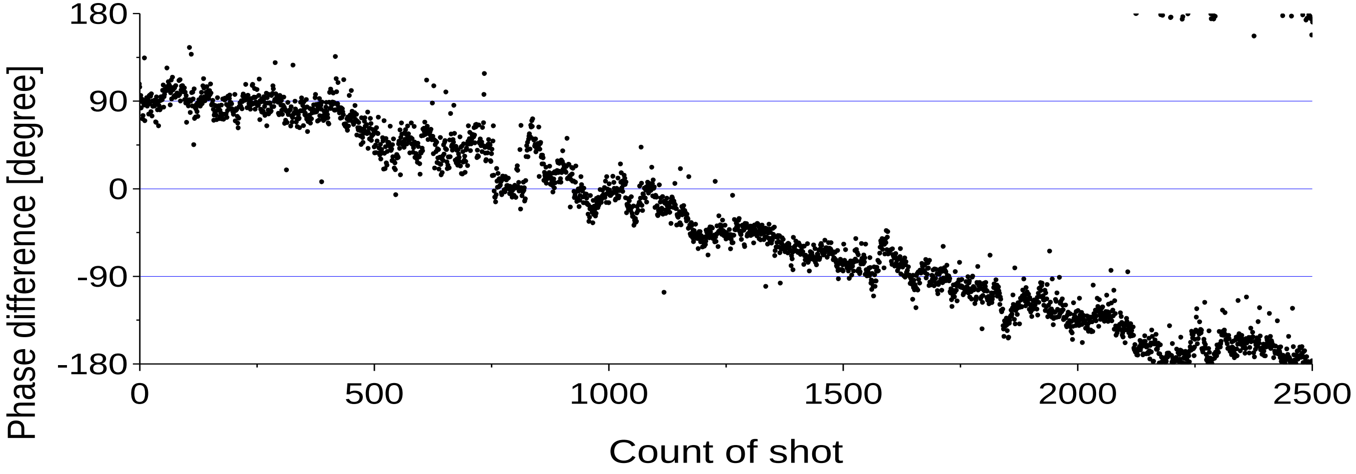
$$I_2 = \frac{1}{2} I_0 (1 - \sin \Delta\phi)$$

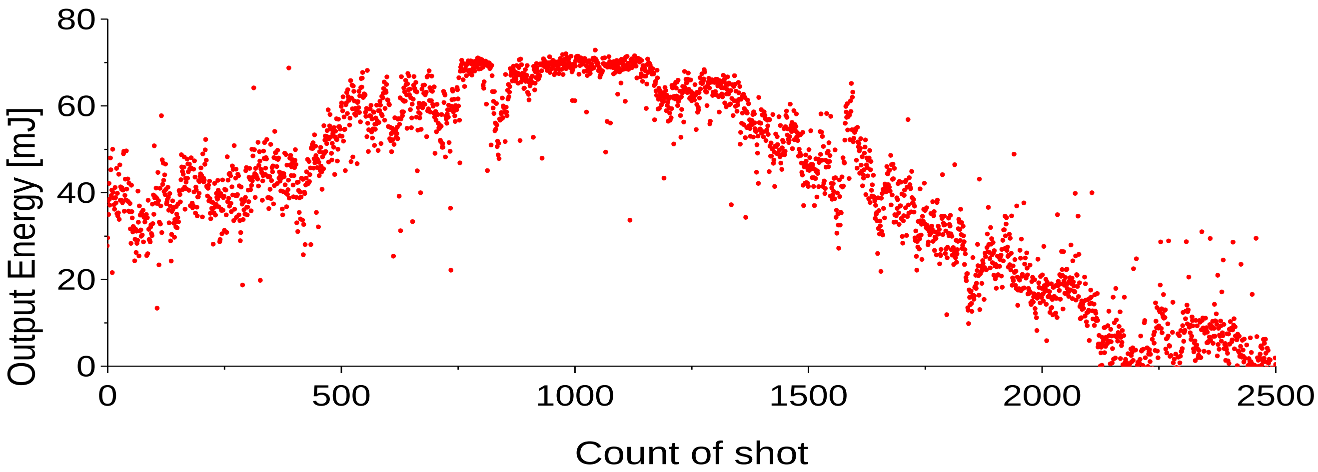


$$I_{out} = \frac{1}{2} I_{max} (1 + \cos \Delta\phi)$$

H. J. Kong, J. W. Yoon, J. S. Shin, and D. H. Beak, Applied Physics Letters 92, 021120, 2008.

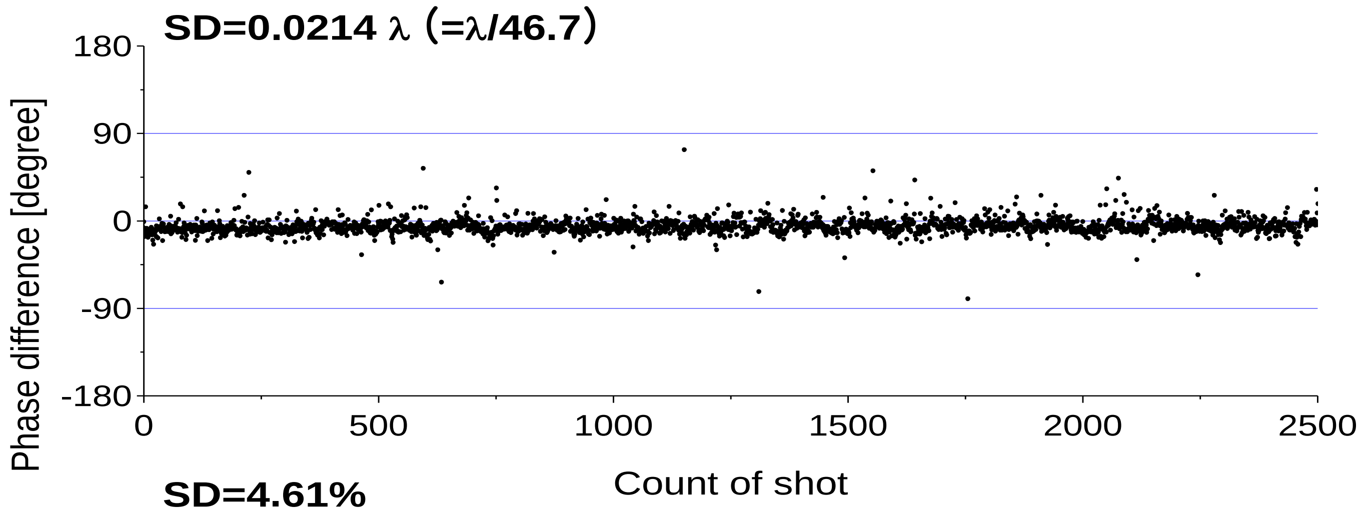
Long-term phase fluctuation – No PZT control case

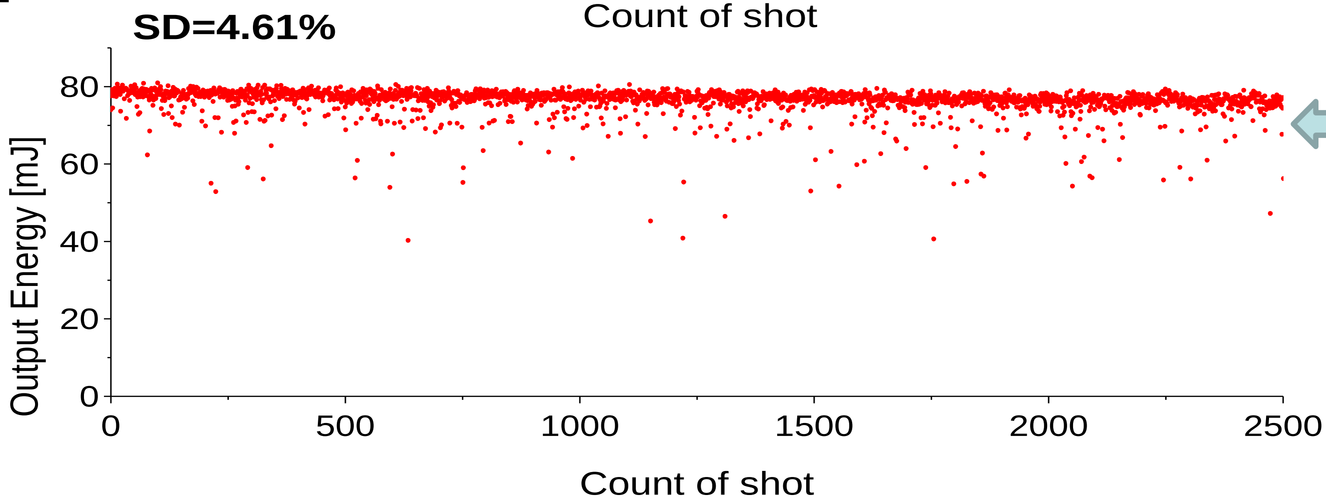




H. J. Kong, J. W. Yoon, J. S. Shin, and D. H. Beak, Applied Physics Letters 92, 021120, 2008.

Long-term stabilized result – PZT control case



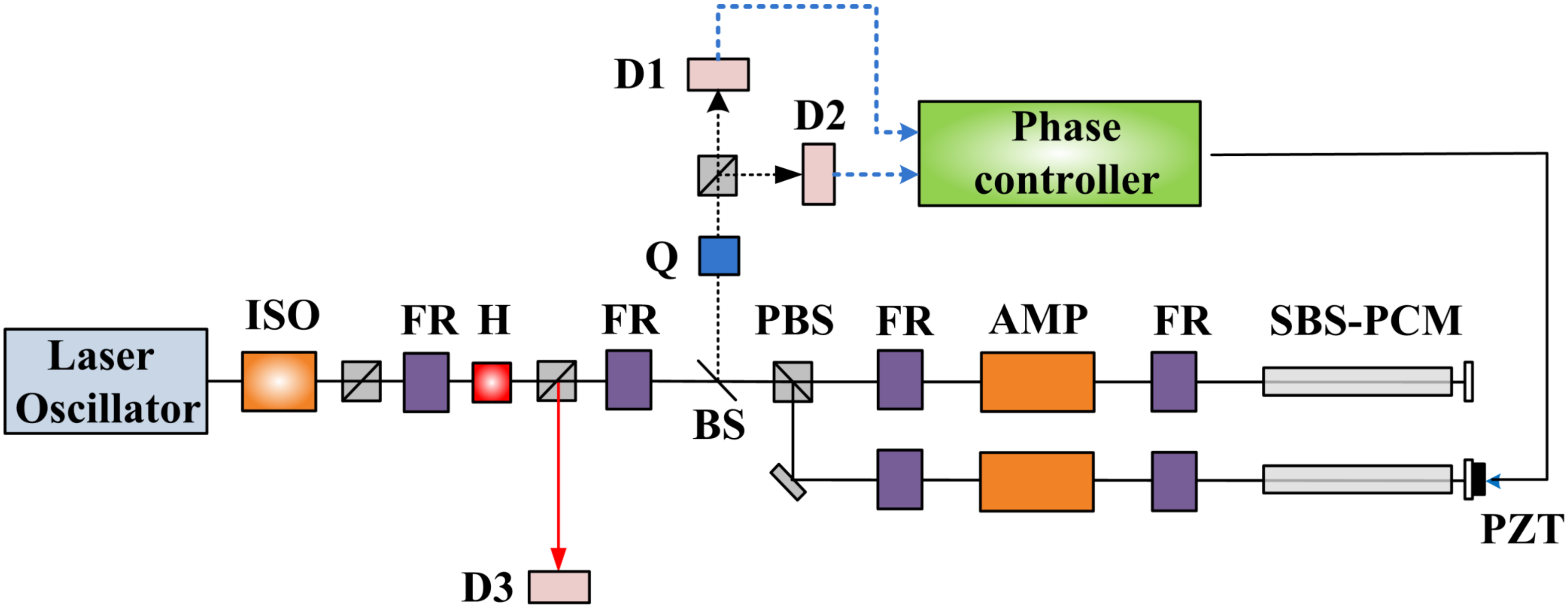


Max: 80.9mJ
Med: 77.1mJ
Mean:76.3mJ

(Reflectivity fluctuation: 1.34% & 1.42%)

H. J. Kong, J. W. Yoon, J. S. Shin, and D. H. Beak, Applied Physics Letters 92, 021120, 2008.

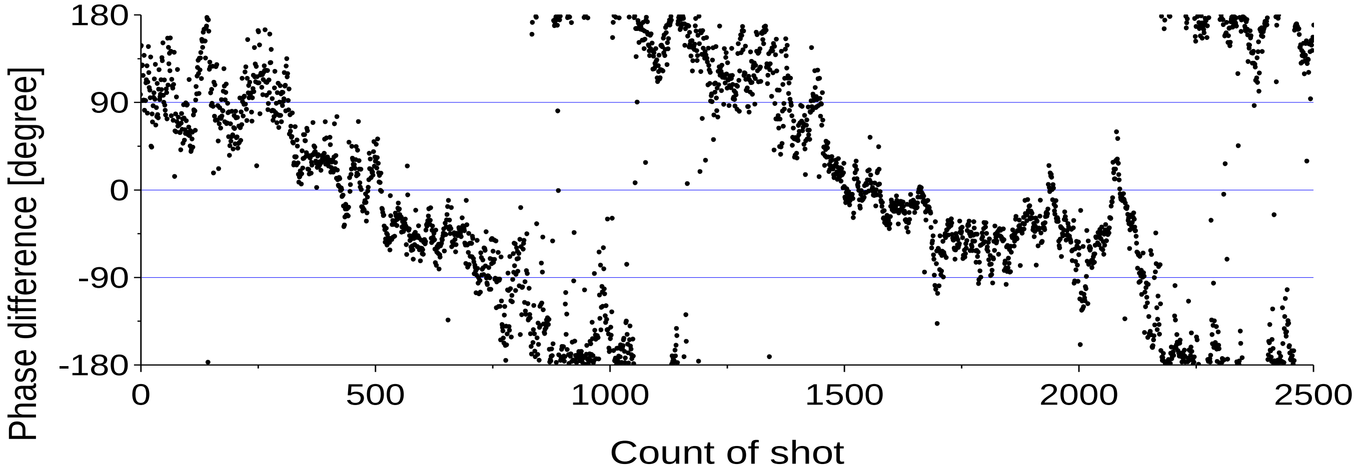
Experimental setup for the long-term phase stabilization with amplifiers

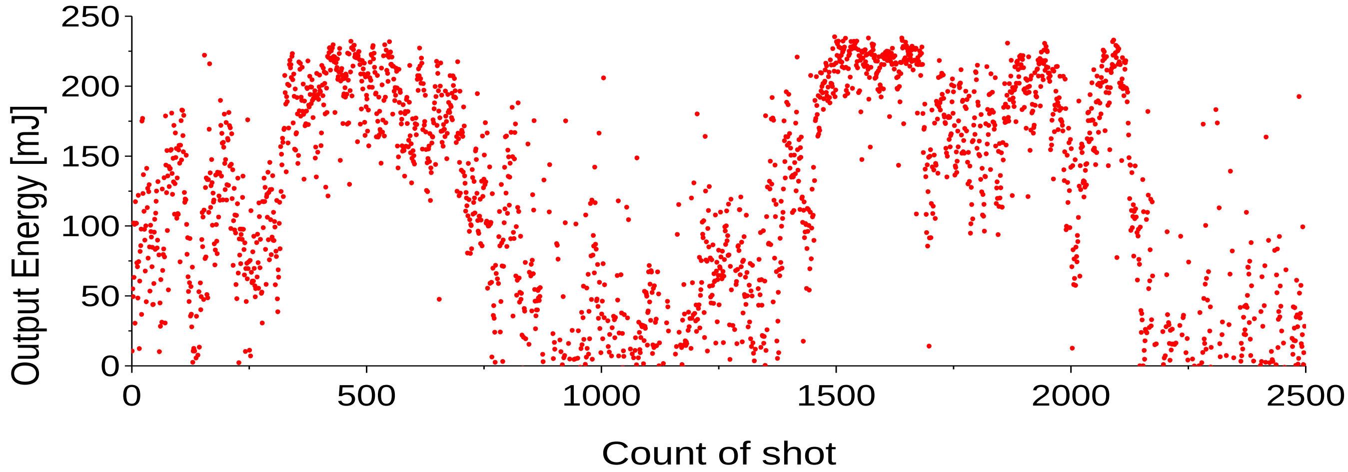


Experimental Setup for the Long Term Phase Stabilization (Amp operation case)

H. J. Kong, J. W. Yoon, J. S. Shin, and D. H. Beak, Applied Physics Letters 92, 021120, 2008.

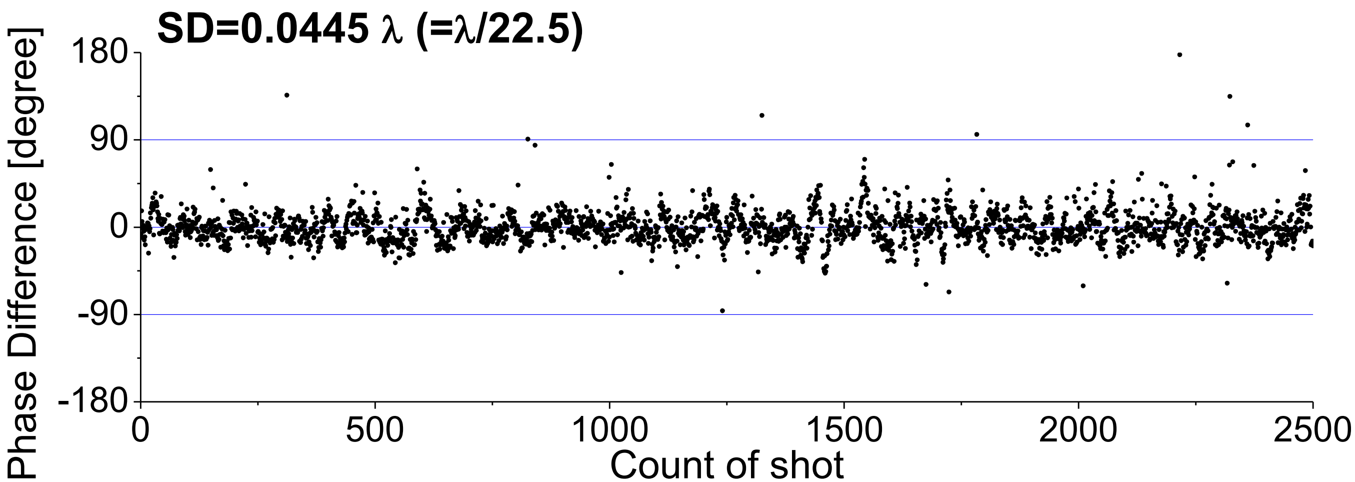
Long-term phase fluctuation – No PZT control case

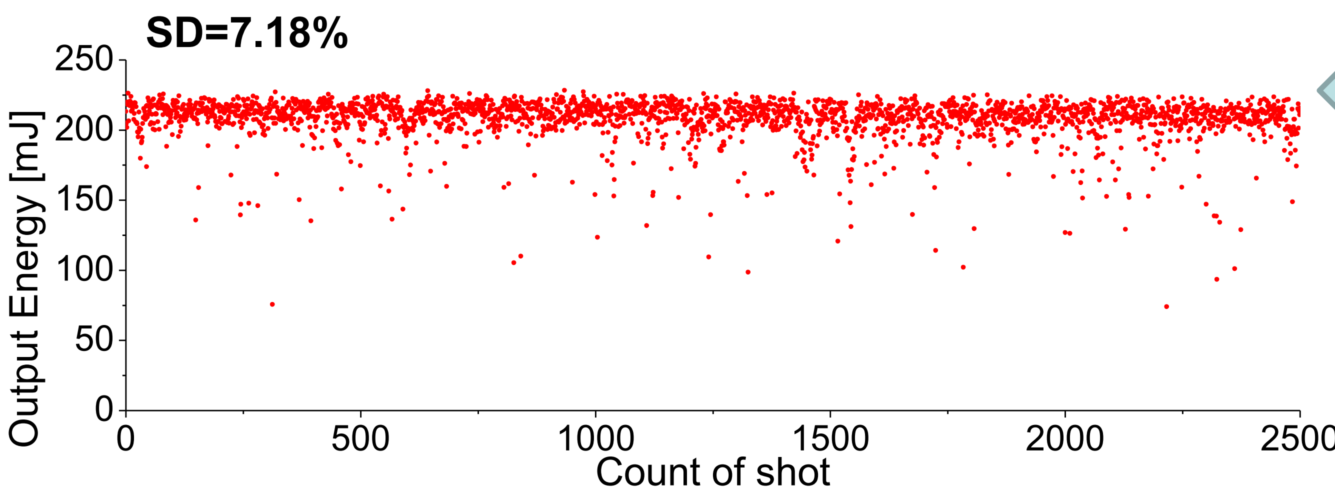




H. J. Kong, J. W. Yoon, J. S. Shin, and D. H. Beak, Applied Physics Letters 92, 021120, 2008.

Long-term stabilized result – PZT control case

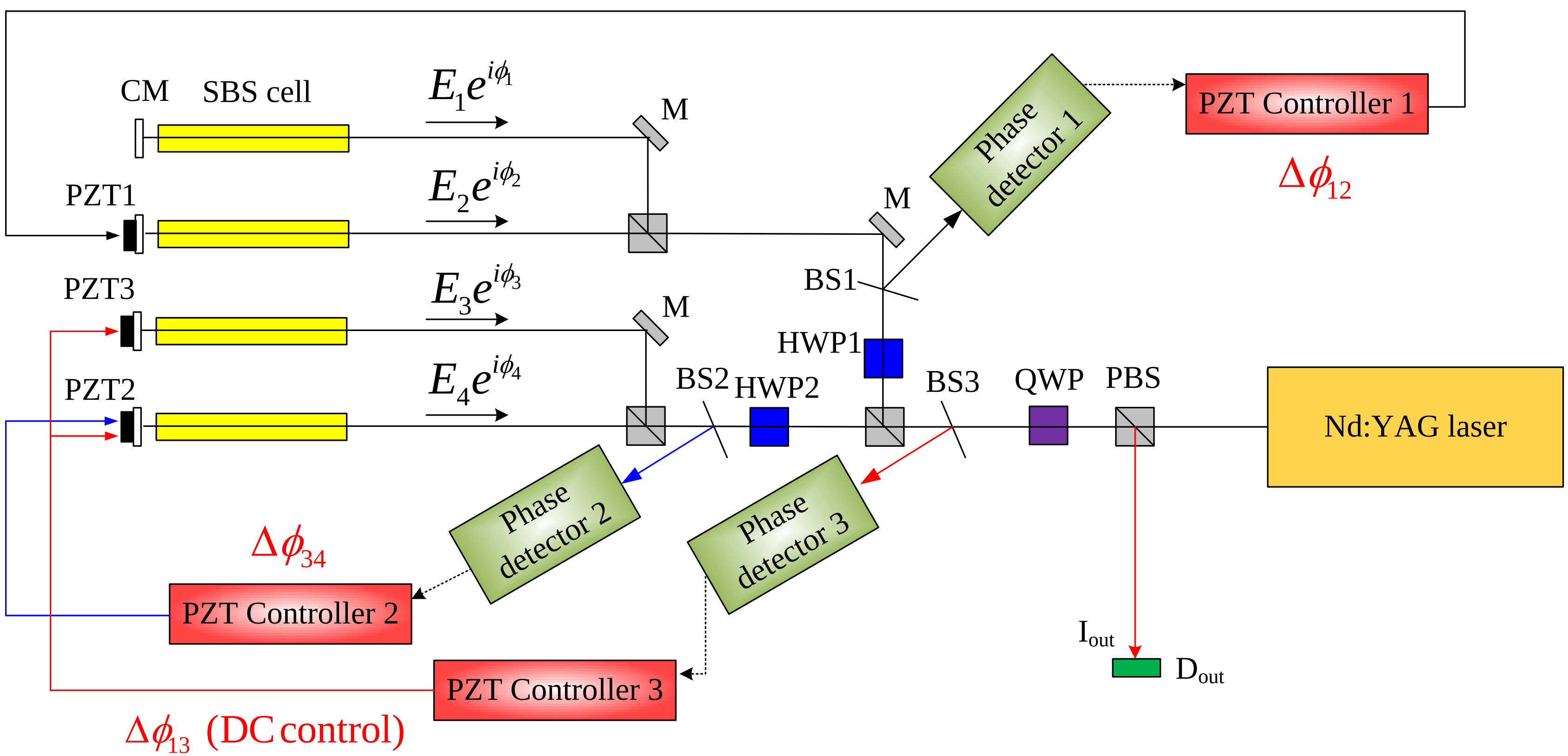




Max: 228 mJ
Med: 211 mJ
Mean: 208mJ

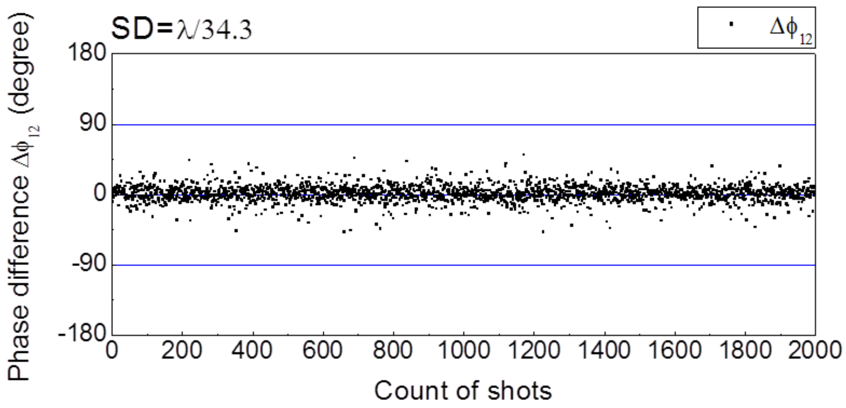
H. J. Kong, J. W. Yoon, J. S. Shin, and D. H. Beak, Applied Physics Letters 92, 021120, 2008.

Experimental setup for the amplitude dividing 4-beam combination

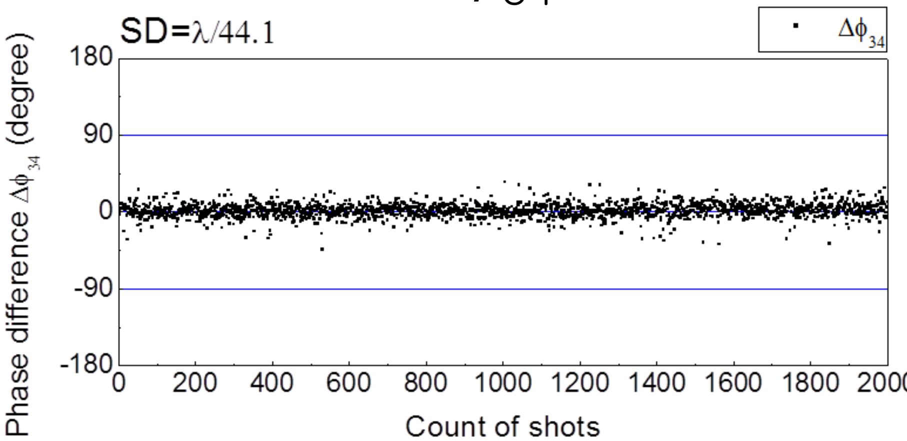


H. J. Kong, J. S. Shin, J. W. Yoon, and D. H. Beak, Laser and Particle Beams 27, 179-184, 2009.

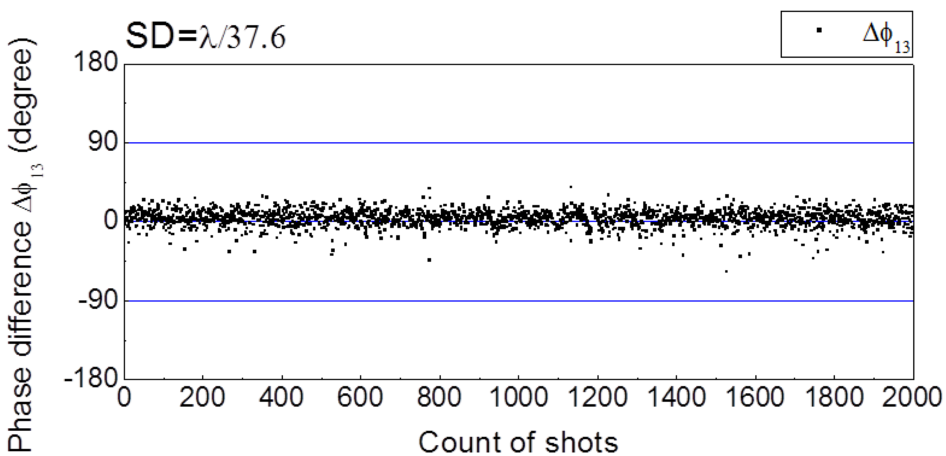
$\Delta\phi_{12}$



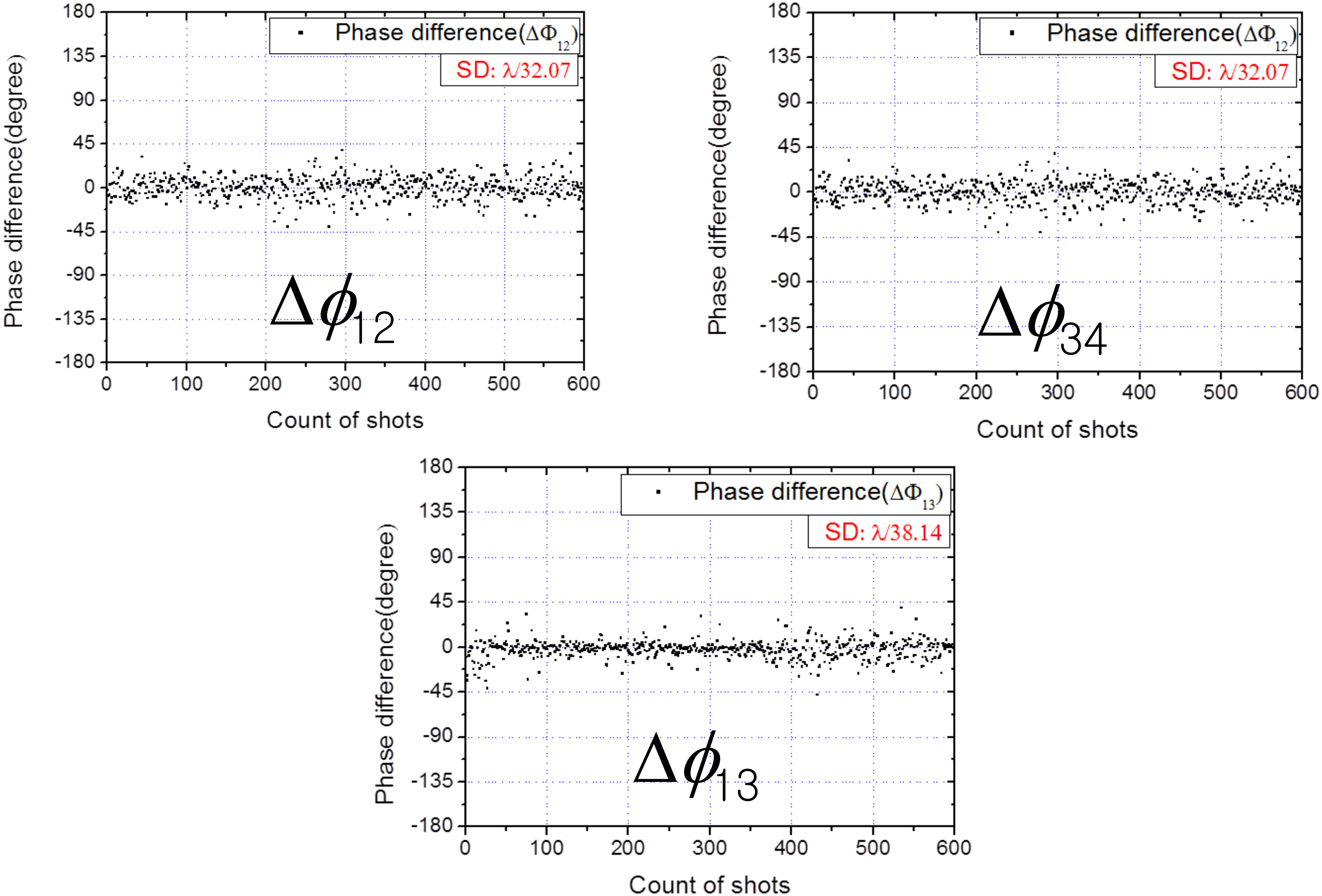
$\Delta\phi_{34}$



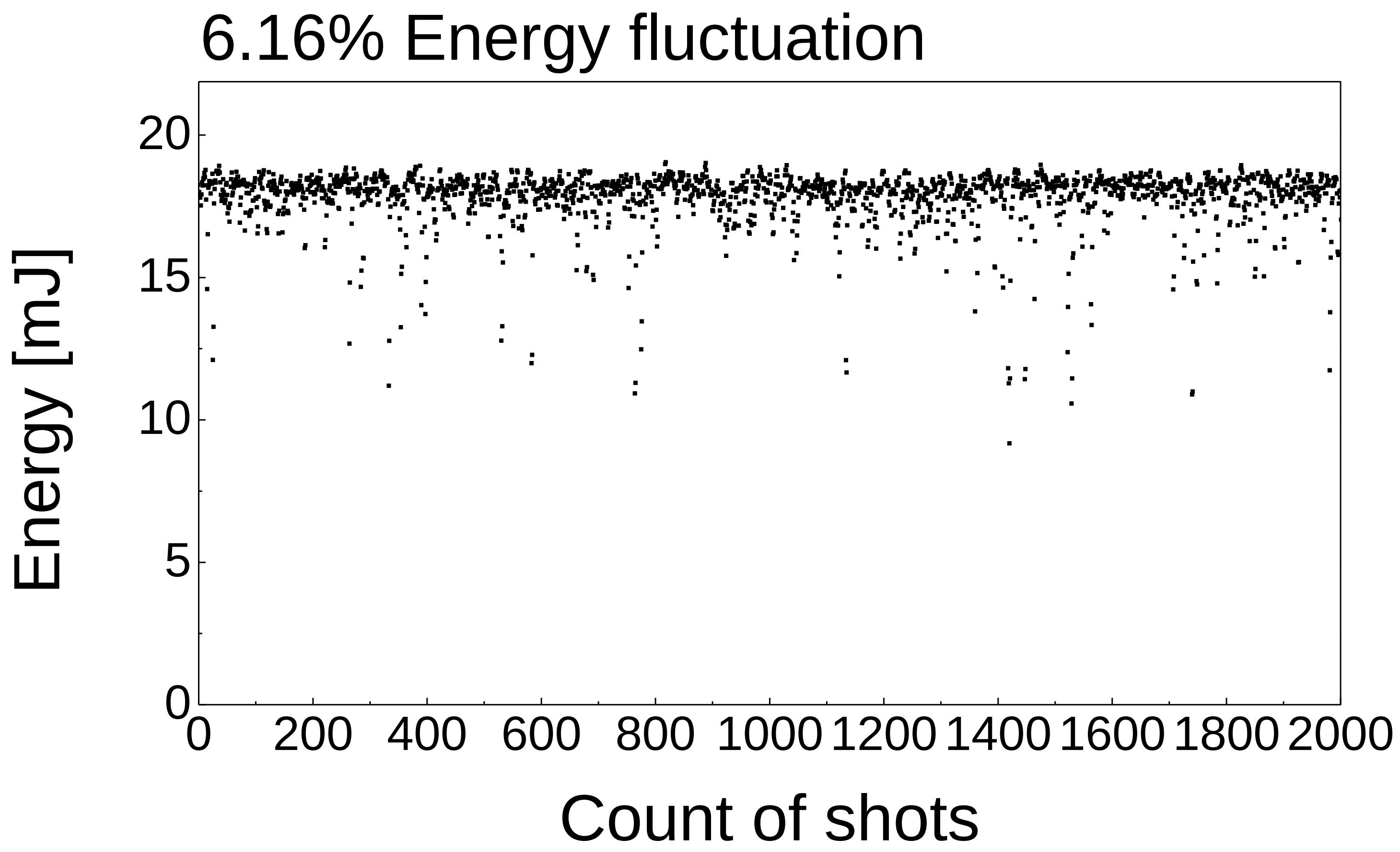
$\Delta\phi_{13}$



H. J. Kong, J. S. Shin, J. W. Yoon, and D. H. Beak, Laser and Particle Beams 27, 179-184, 2009.


Phase difference($\Delta\Phi_{12}$)
SD: λ/32.07
$\Delta\phi_{12}$
Phase difference(degree)
Count of shots
Phase difference($\Delta\Phi_{12}$)
SD: λ/32.07
$\Delta\phi_{34}$
Phase difference(degree)
Count of shots
Phase difference($\Delta\Phi_{13}$)
SD: λ/38.14
$\Delta\phi_{13}$
Phase difference(degree)
Count of shots

4-beam combined output energy



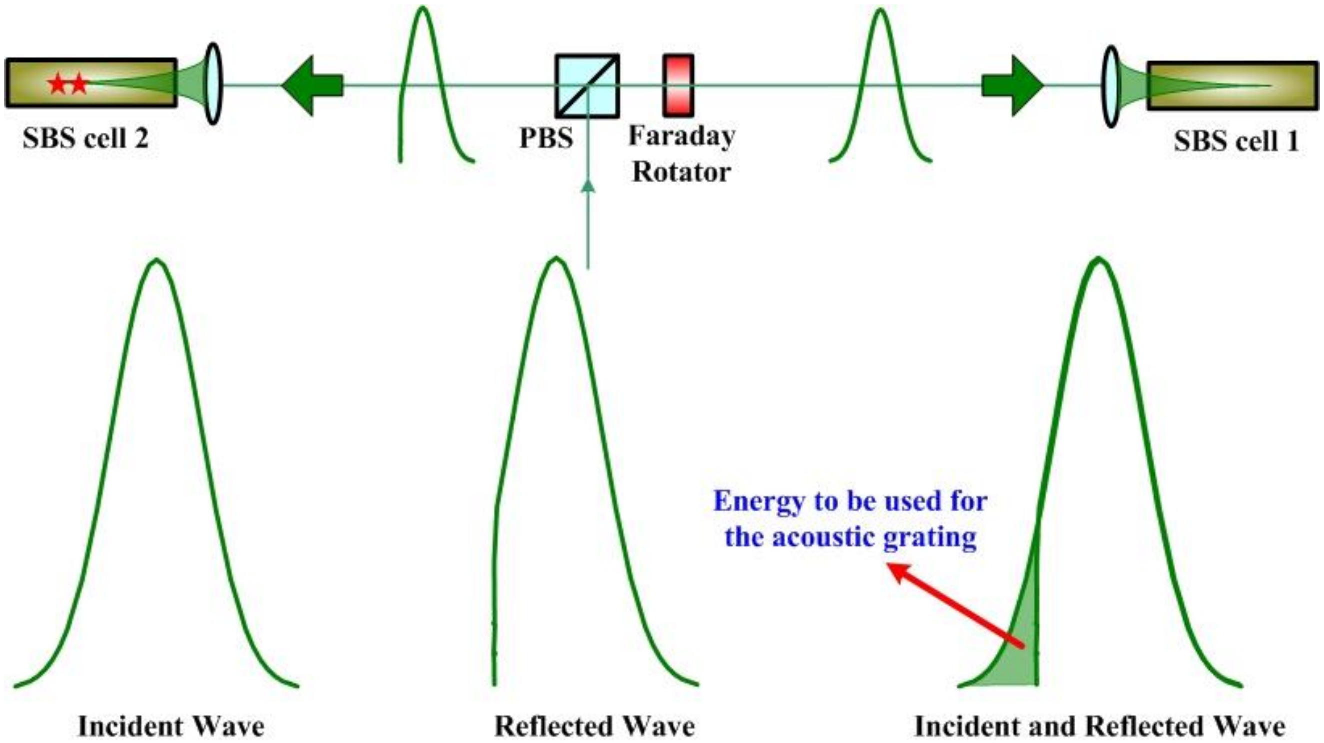
H. J. Kong, J. S. Shin, J. W. Yoon, and D. H. Beak, Laser and Particle Beams 27, 179-184, 2009.

Pre-pulse technique for waveform preservation of SBS waves

Pre-pulse technique

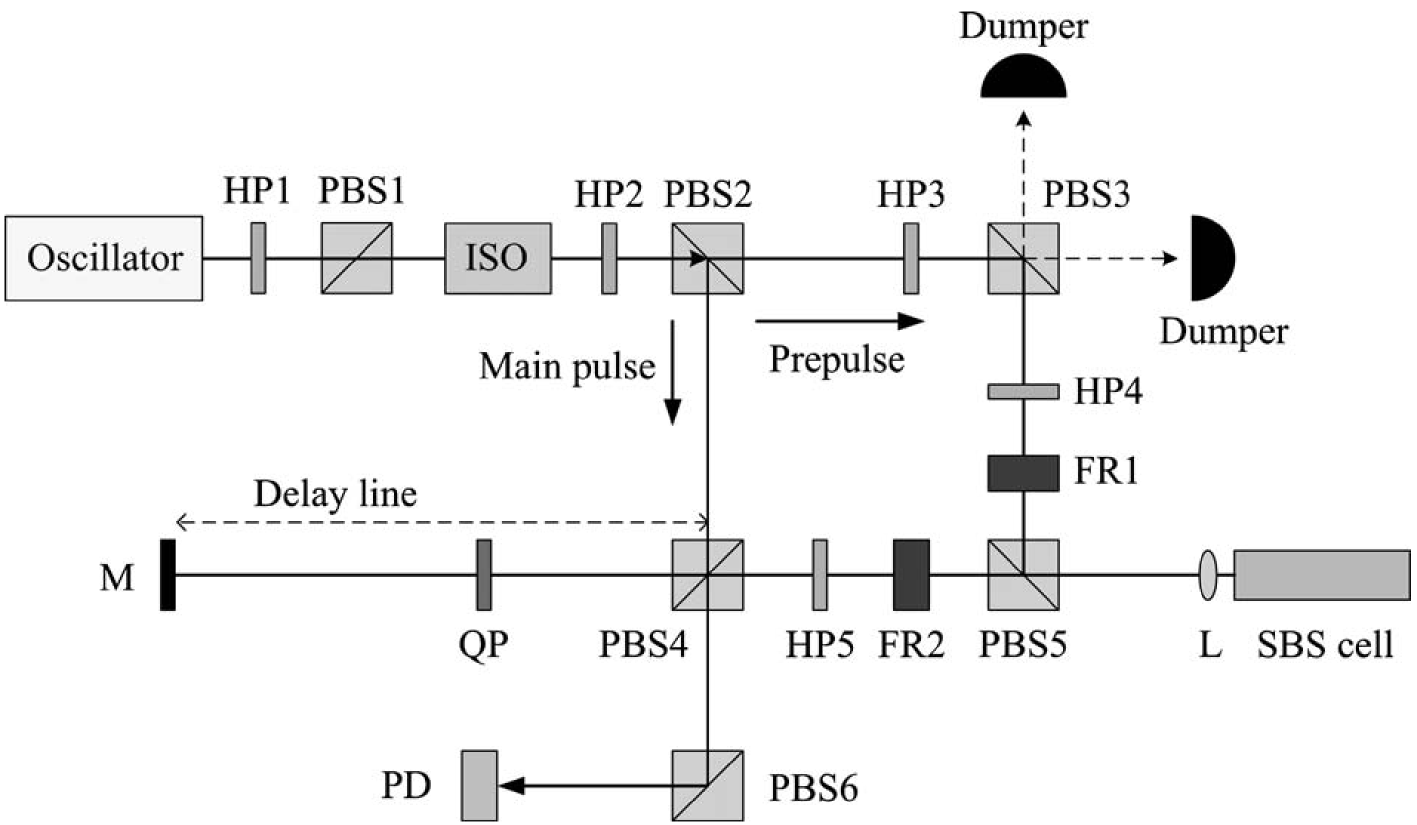
1. **To avoid the deformation of the waveform, the pre-pulse technique has been developed.**
2. **At first, the laser pulse is divided into two pulses with delay time. (main pulse + pre-pulse, $E_{main\ pulse} > E_{pre\text{-}pulse} \sim E_{threshold}$)**
3. **Pre-pulse which is incident on the SBS cell prior to the main pulse creates the acoustic grating.**
4. **Therefore, the main pulse does not lose its energy for the acoustic grating generation.**
5. **Waveform of the reflected main pulse can be preserved.**

Pulse shape deformation of the SBS wave



- The SBS wave has a steep rising edge because it consumes its front part energy to generate the acoustic grating.
- This steep rising edge causes the optical breakdown in the SBS cell 2.

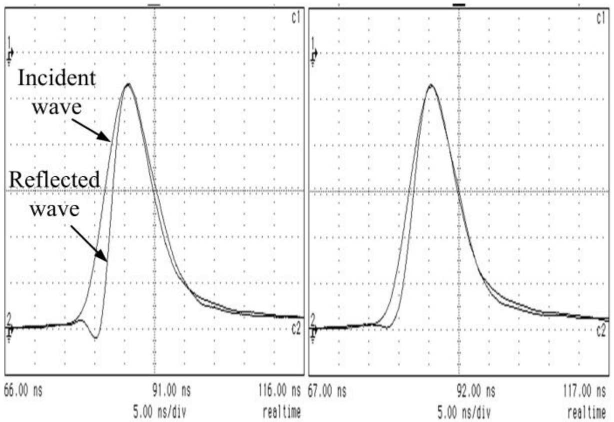
Pre-pulse technique



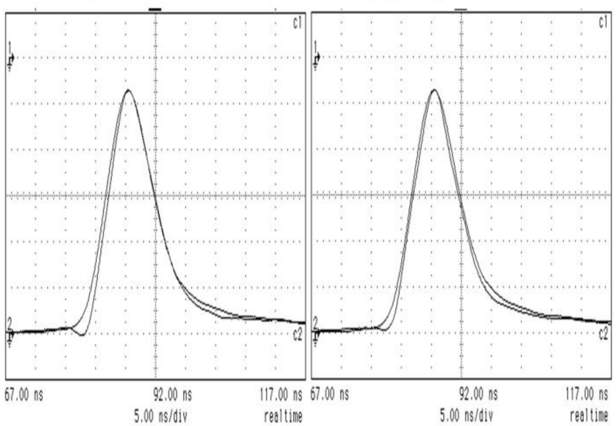
- HPs, half-wave plates; PBSs, polarizing beam splitters; ISO, optical isolator; FRs, Faraday rotators; QP, quarter-wave plate; M, mirror; L, focusing lens; PD, photodiode

Waveforms of the SBS wave according to the pre-pulse energy

Delay time: 3 ns

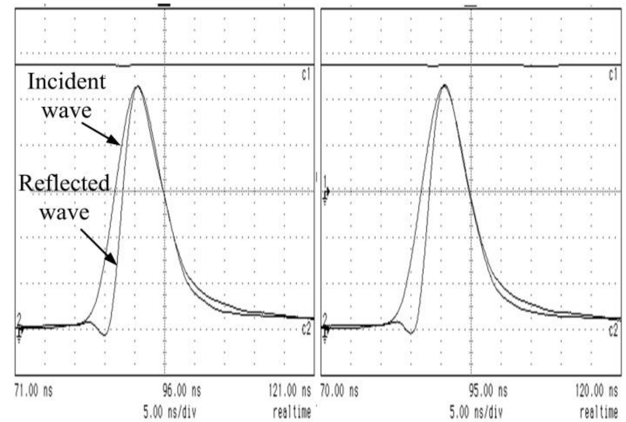


(a) E_{pre}=0 (b) E_{pre}=6mJ

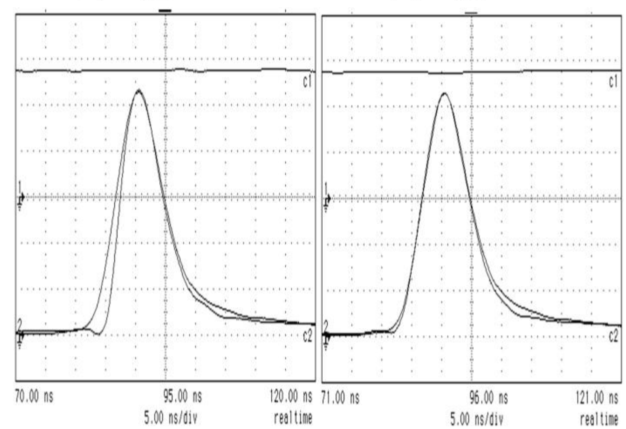


(c) E_{pre}=7mJ (d) $E_{pre} \geq$ 8mJ

Delay time: 8 ns



(a) E_{pre}=0mJ (b) E_{pre}=2mJ

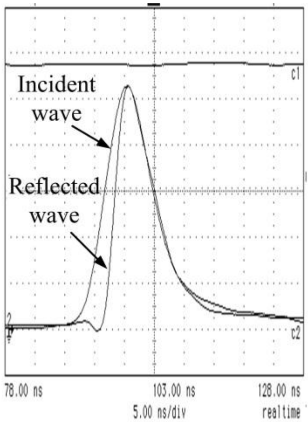


(c) E_{pre}=2.5mJ (d) $E_{pre} \geq$ 3mJ

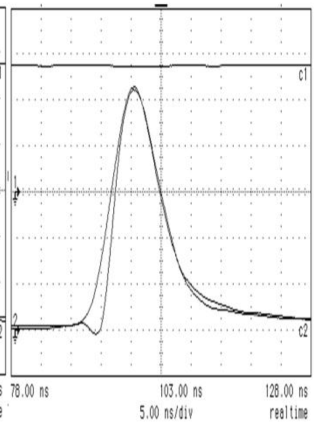
J. W. Yoon, J. S. Shin, H. J. Kong, and J. Lee, Journal of the Optical Society of America B 26, 2167–2170, 2009.

Waveforms of the SBS wave according to the pre-pulse energy

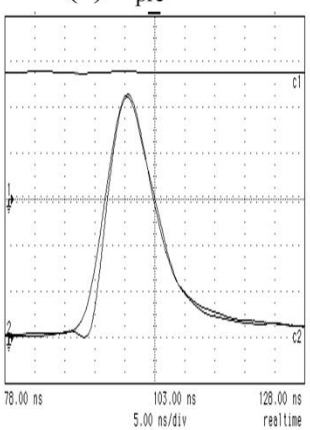
Delay time: 15 ns



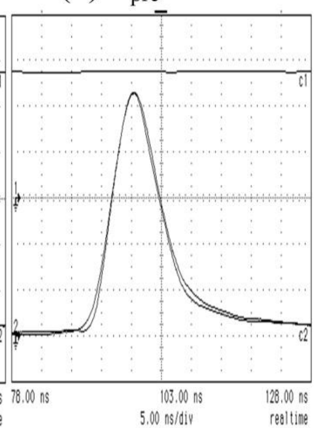
(a) E_{pre}=0mJ



(b) E_{pre}=1.5mJ

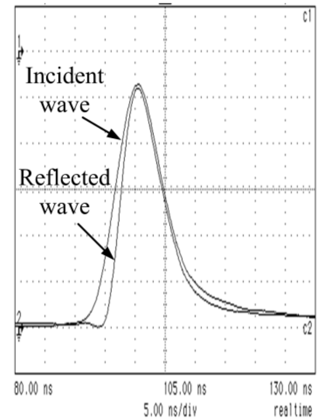


(c) E_{pre}=1.8mJ

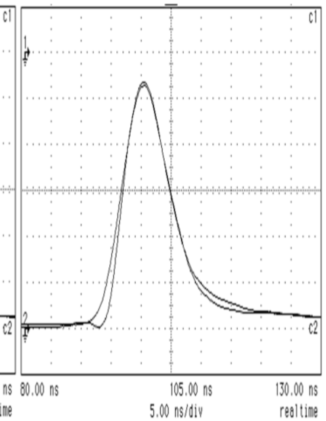


(d) $E_{pre} \geq$ 2mJ

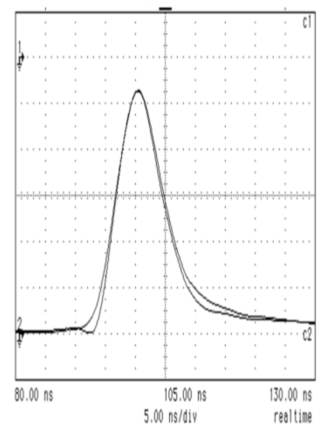
Delay time: 17 ns



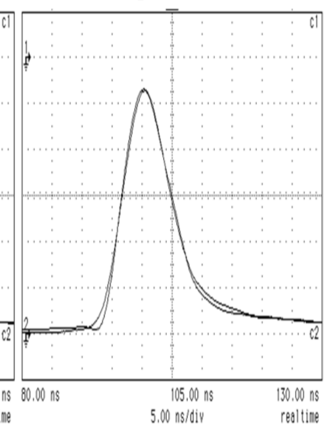
(a) E_{pre}=2mJ



(b) E_{pre}=2.5mJ



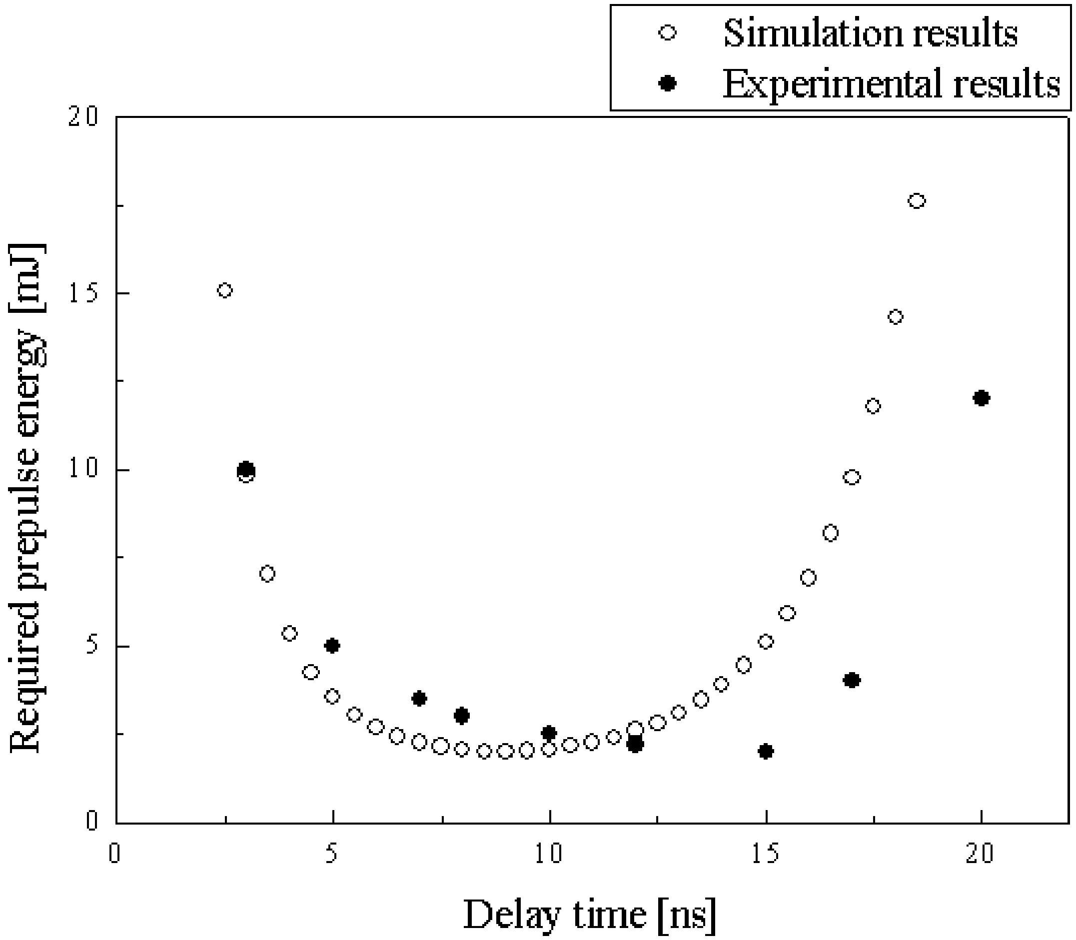
(c) E_{pre}=3mJ



(d) $E_{pre} \geq$ 4mJ

J. W. Yoon, J. S. Shin, H. J. Kong, and J. Lee, Journal of the Optical Society of America B 26, 2167–2170, 2009.

Required pre-pulse energy vs. the delay time



J. W. Yoon, J. S. Shin, H. J. Kong, and J. Lee, Journal of the Optical Society of America B 26, 2167–2170, 2009.