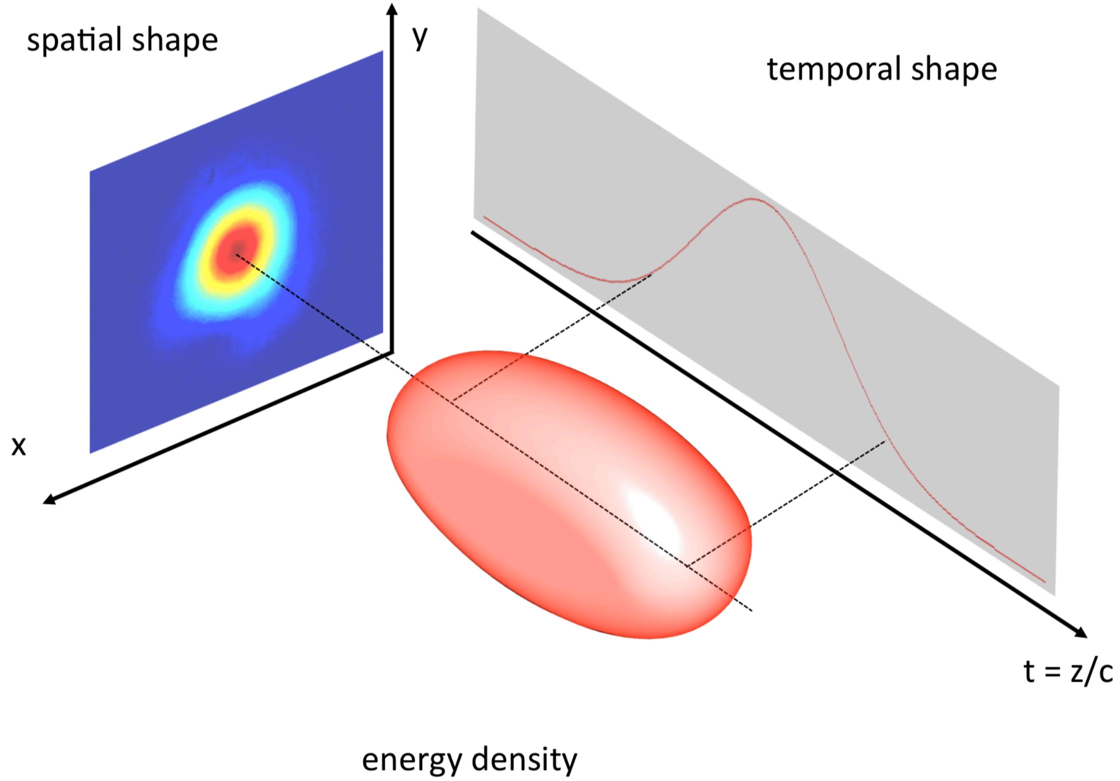
Pulse shaping of microchip laser under amplification in micro MOPA

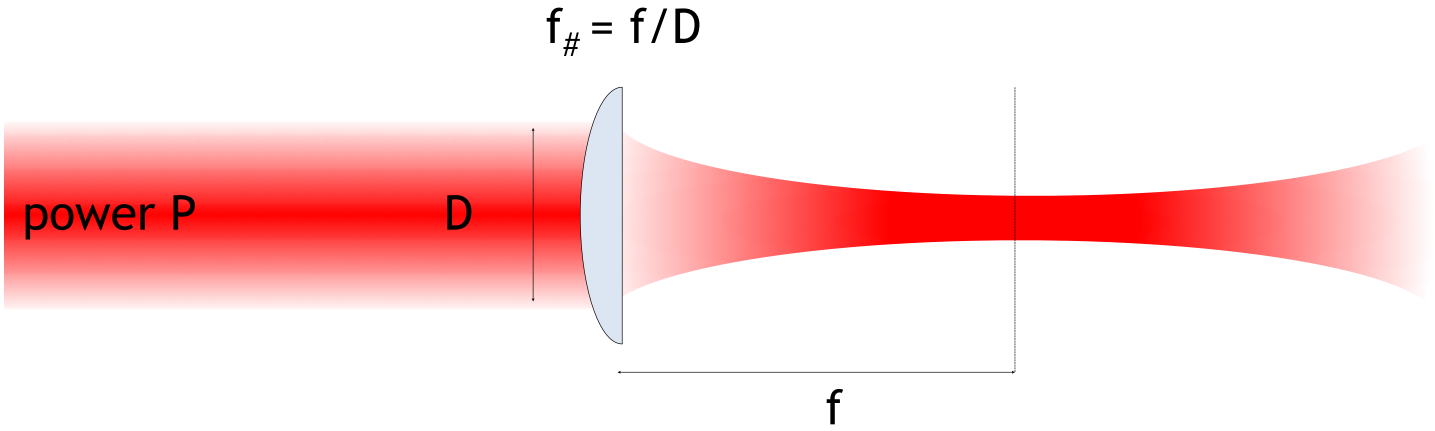
What do we mean by beam shape and beam shaping ?



- Beam shape is critical to maximize the energy density
- MOPA can increase energy but can it be used to shape the beam ?

1. Introduction – *1.2 Brightness*

How to caracterize the influence of beam shape ?



depends on temporal shape

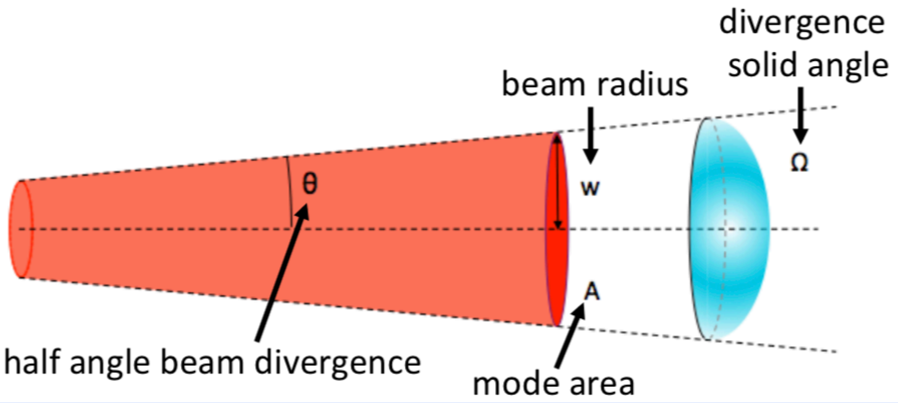
$$I = \frac{\pi}{2}\frac{P}{\lambda^2 f_\#^2}\frac{1}{\boxed{1+S_{HOM}}} \longrightarrow \propto \left(M^2\right)^2$$

depends on optics

contribution from higher order modes (spatial shape)

1. Introduction – *1.2 Brightness*

Radiometric definition of brightness



radiant power

$$B = \frac{P}{A\Omega}$$

emission area

emission solid angle

at waist *A* and Ω related by M^2

Practical equivalent definition for laser

$$\left.\begin{aligned} A &= \pi w_0^2 \\ \Omega &= \pi\theta^2 \\ M^2 &= \frac{\pi w_0 \theta}{\lambda} \end{aligned}\right\} \quad \boxed{B = \frac{P}{\left(\lambda M^2\right)^2}}$$

- ➢ independent of focusing optics
- ➢ I proportional to B
- ➢ M^2 is critical

1. Introduction – *1.3 MOPA and beam shape control*

Brightness is a key parameter

$$B = \frac{P}{\left(\lambda M^2\right)^2}$$

P : peak power
λ : wave length
M^2 : beam quality factor

Brightness value for a typical system

wavelength	λ = 1 µm
pulse energy	E = 100 mJ
pulse duration	τ = 500 ps
beam quality	M^2 = 1

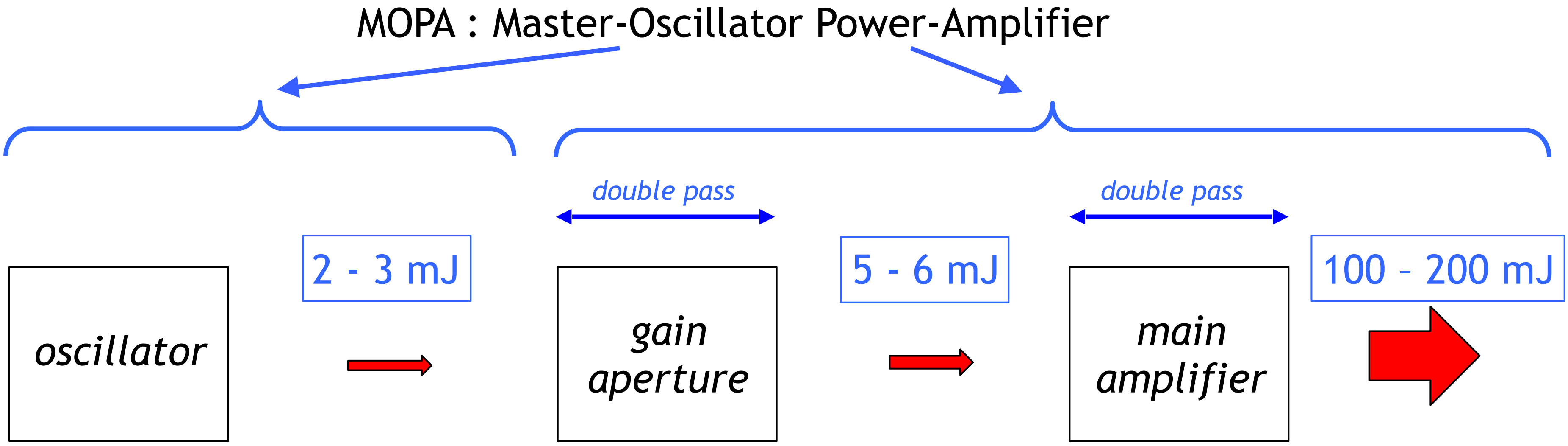
B = 20 PW/sr/cm²

if M^2 becomes 1.5
B = 9 PW/sr/cm²

- brightness scales as ~ P
- brightness scales as ~ $(1/M^2)^2$
- usually, beam quality degrades as power increases
- brightness might be poor even at high power

Not all oscillators have excellent beam quality hence brightness is reduced

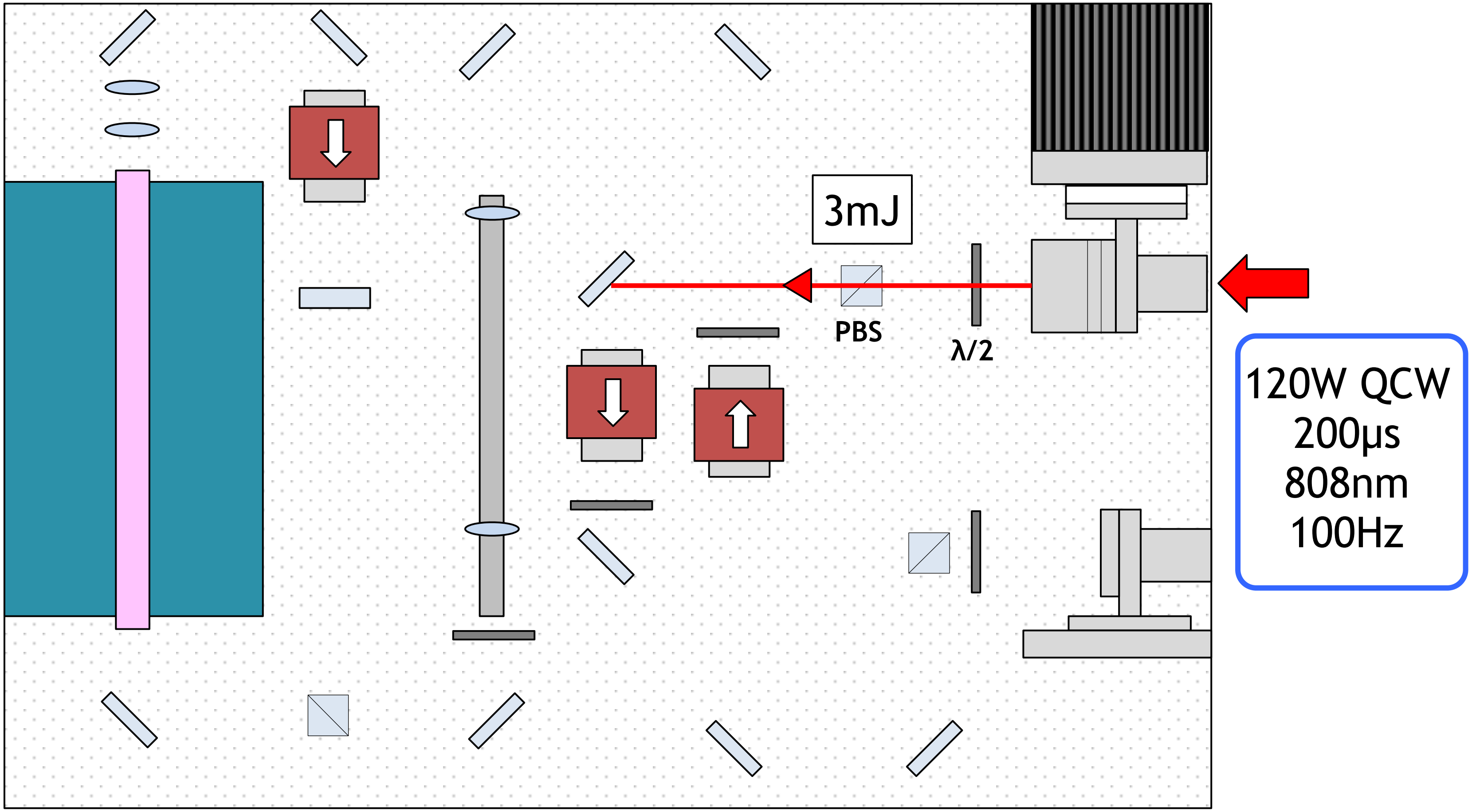
2. Presentation of MOPA system – *2.1 General architecture*



MOPA : Master-Oscillator Power-Amplifier

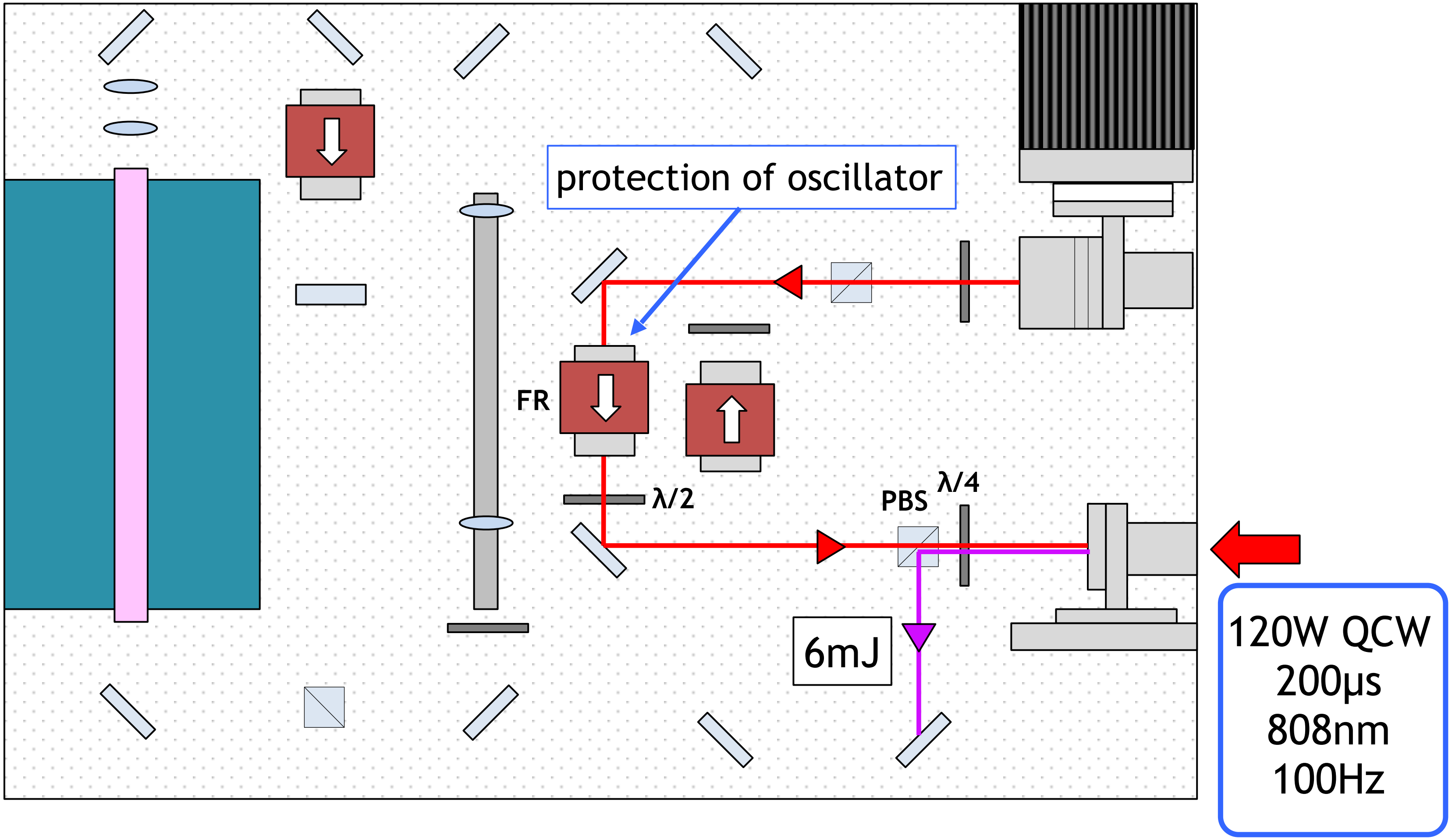
	Oscillator	***Gain aperture***	***Main amplifier***
Repetion rate Wavelength	10Hz/100Hz 1064nm	10Hz/100Hz 1064nm	10Hz/100Hz 1064nm
Energy	Input energy 3mJ	Pre-amplification 6mJ	Amplification 200mJ
Spatial shape	Mutimode	Beam cleaning near TEM00	Near TEM00
Temporal shape	Temporal shape	Beam stretching	Beam stretching Beam compression

– *2.2 Detailed setup*

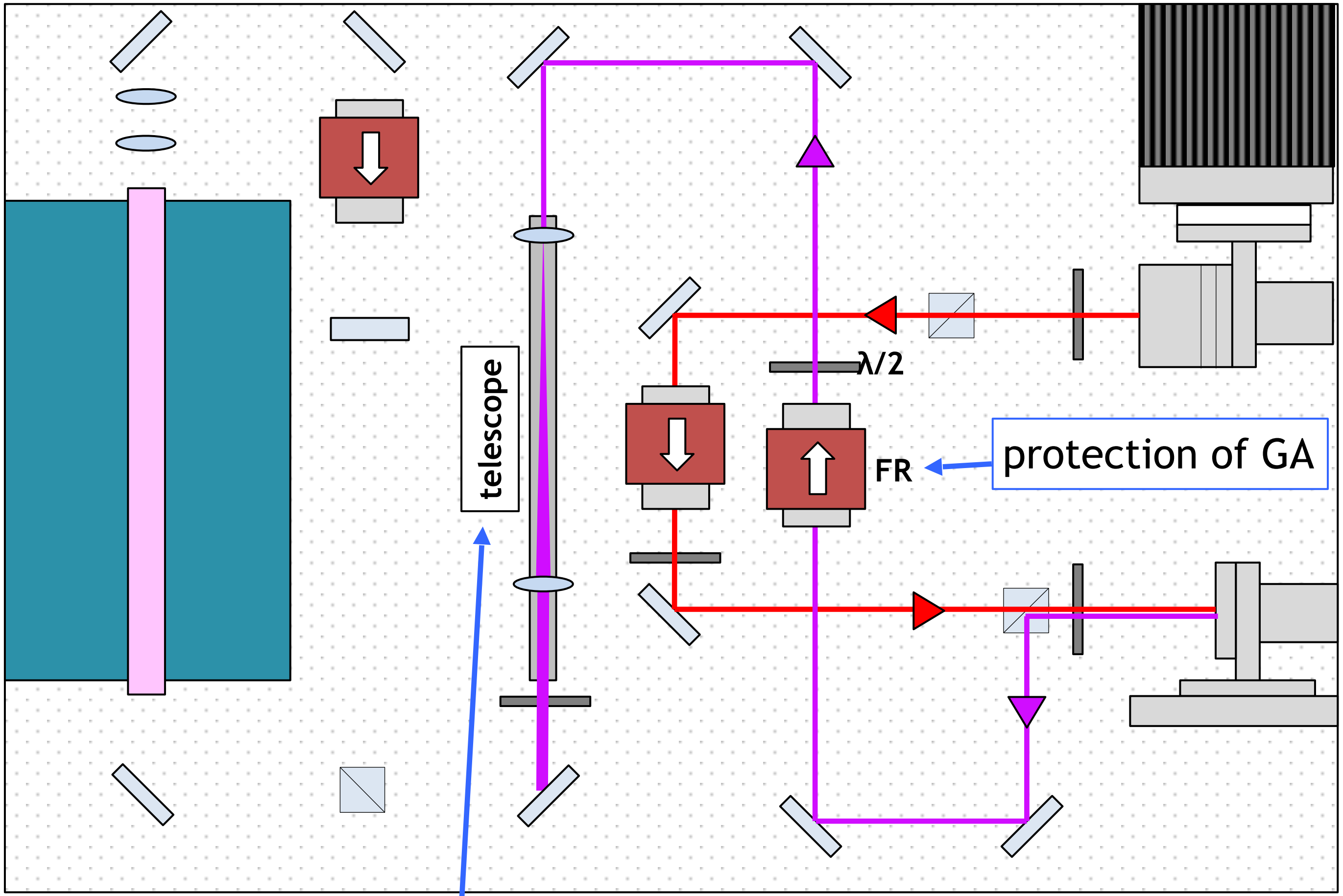


120W QCW
200µs
808nm
100Hz

2. Presentation of MOPA system – *2.2 Detailed setup*

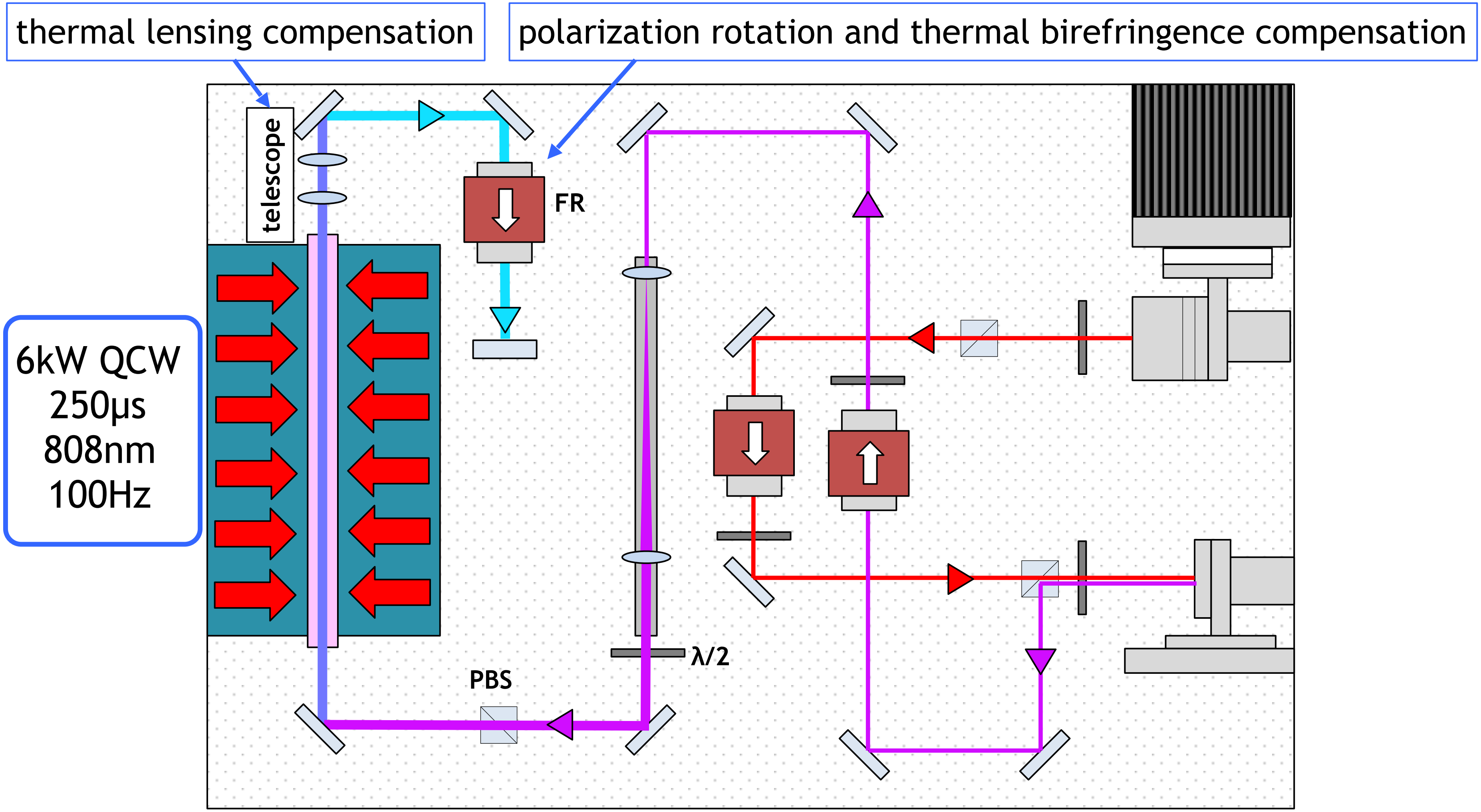


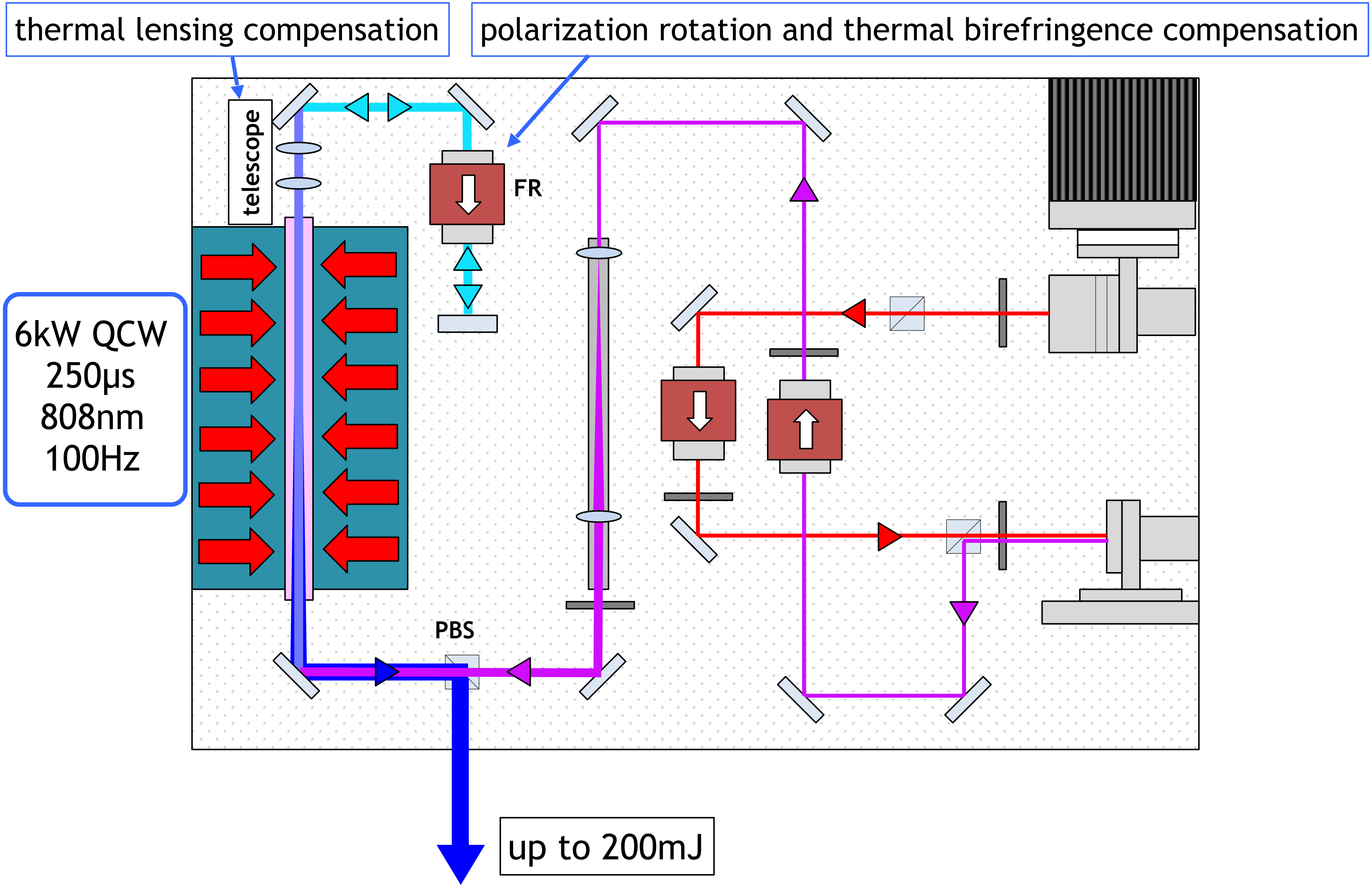
– *2.2 Detailed setup*



protection of GA

beam size matching
to main amp


thermal lensing compensation
polarization rotation and thermal birefringence compensation
telescope
FR
6kW QCW
250µs
808nm
100Hz
λ/2
PBS

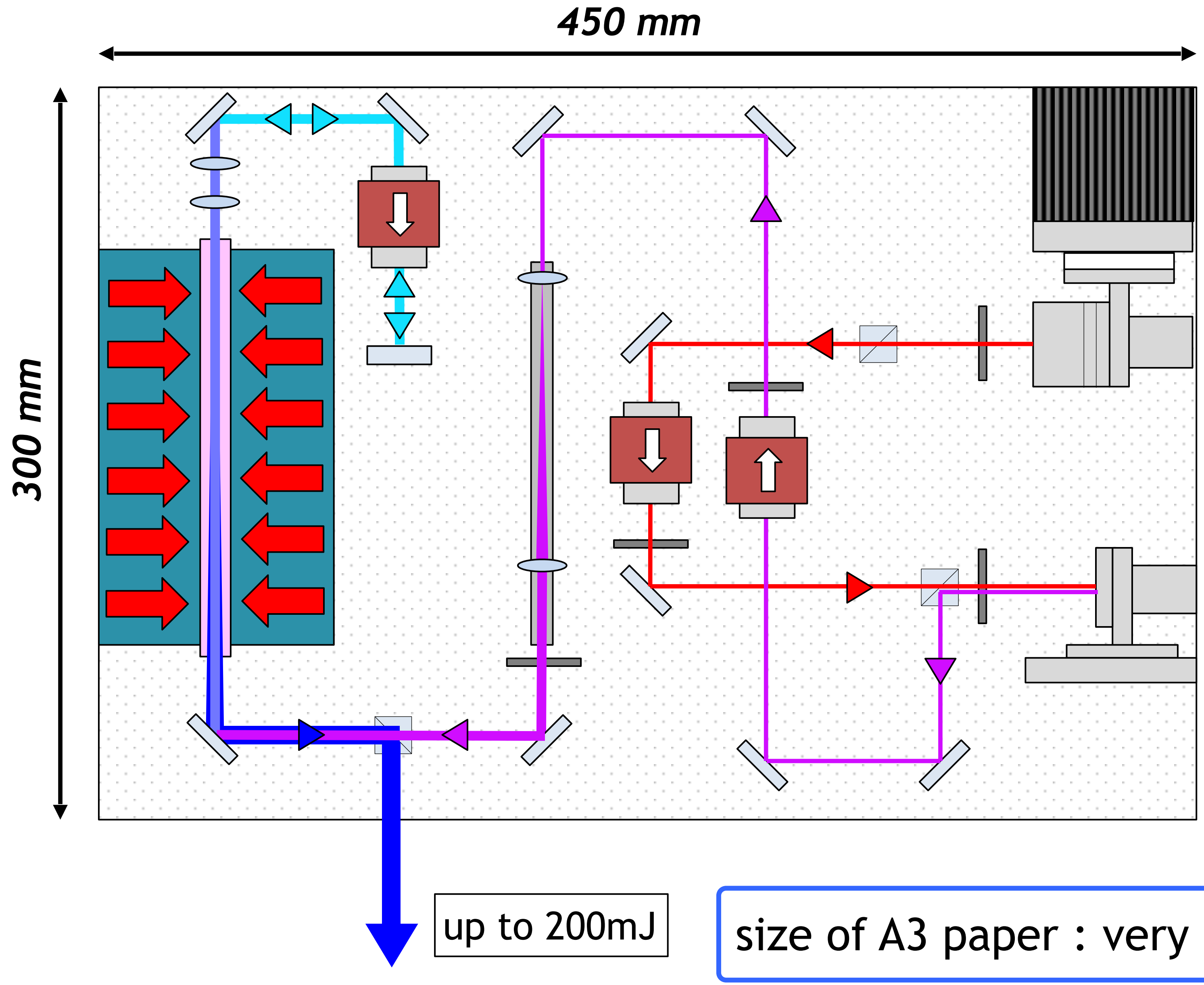


thermal lensing compensation

polarization rotation and thermal birefringence compensation

6kW QCW
250µs
808nm
100Hz

up to 200mJ

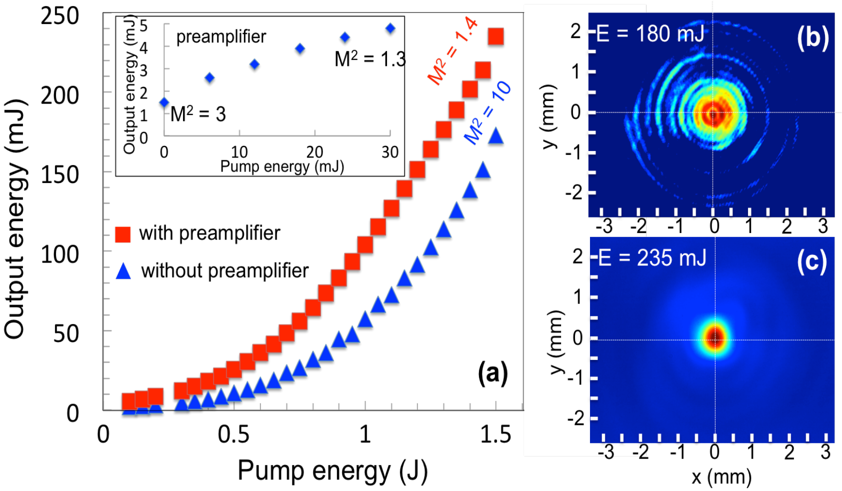


up to 200mJ

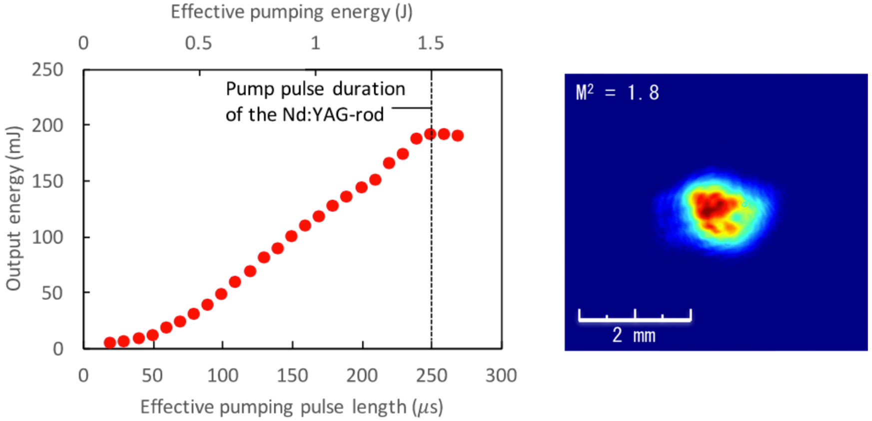
size of A3 paper : very compact

2. Presentation of MOPA system – *2.3 Experimental results and performance*

	E	*τ*	*M²*	*B*
10Hz	235mJ	600ps	**1.4**	18PW/sr/cm²
100Hz	190mJ	**470ps**	1.8	11PW/sr/cm²

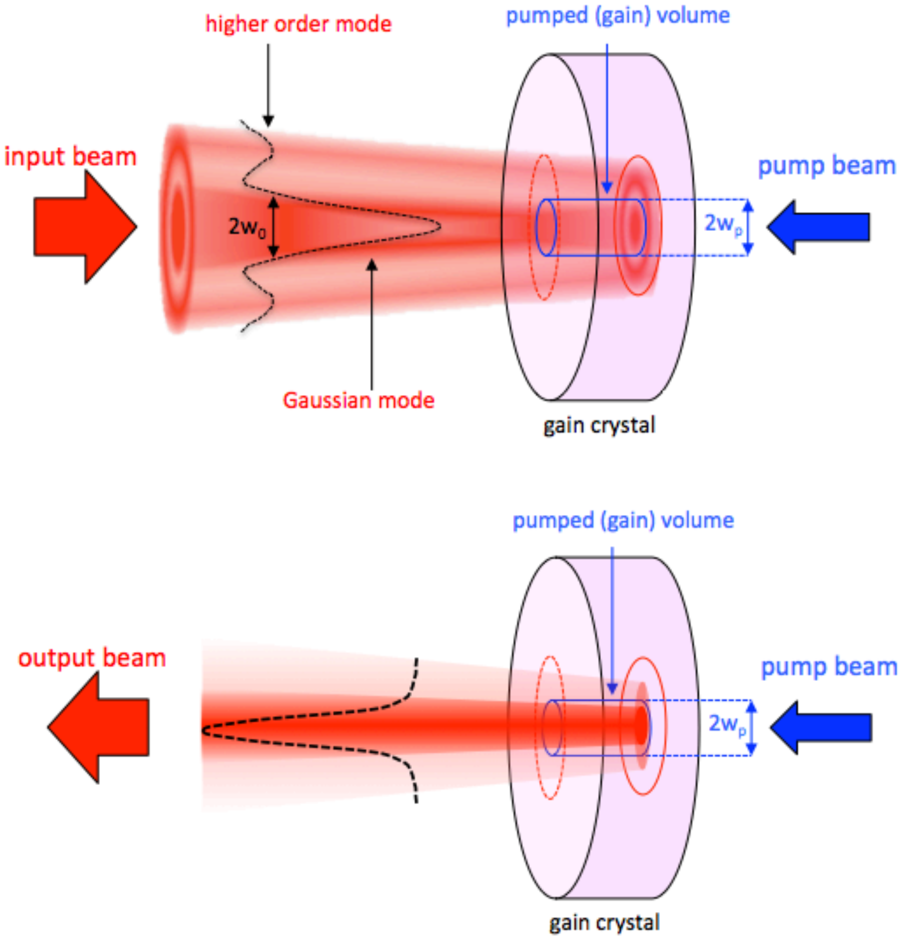


*V. Yahia and T. Taira, “High brightness energetic pulses delivered by compact microchip-MOPA system,” Opt. Express **26**(7), 8609-8618 (2018).*



*Taisuke Kawasaki, Vincent Yahia, and Takunori Taira, "100 Hz operation in 10 PW/sr·cm2 class Nd:YAG Micro-MOPA," Opt. Express **27**, 19555-19561 (2019).*

Gain aperture is a double-pass end-pumped amplifier



- ➢ end-pumping allows control of spatial gain distribution
- ➢ gain shape is matched to TEM_{00} mode size
- ➢ TEM_{00} is amplified and HOM are not
- ➢ output beam is cleaned

3. Spatial shape control – *3.2 Modeling beam shape control*

Radial pump distribution

$$\overline{I_p}(r)=\frac{P_p}{I_p^S}\frac{shape_p(r)}{2\pi\iint_{x,y} shape_p(r)\,r\,dr}$$

$$I_p^S=\frac{h\nu_p}{\sigma_{abs}\tau_f}$$

Radial input beam distribution

$$\overline{F_{in}}(r)=\frac{E_{in}}{F_S}\frac{shape_b(r)}{2\pi\int_0^{+\infty} shape_b(r)\,r\,dr}$$

$$F_S=\frac{h\nu_b}{\sigma_{em}}$$

Absorbed pump intensity (including saturation)

$$\overline{dI_{abs}}(r,z)=\alpha_0\frac{\overline{I}(r,z)}{1+\eta_q\overline{I}(r,z)}dz$$

Radial small-signal gain distribution

$$g_0(r)l=\eta_q\frac{\sigma_{em}}{\sigma_{abs}}\left[1-\exp\left(-\frac{\tau_p}{\tau_f}\right)\right]\int_0^l\frac{d\,\overline{I_{abs}(r,z)}}{dz}dz$$

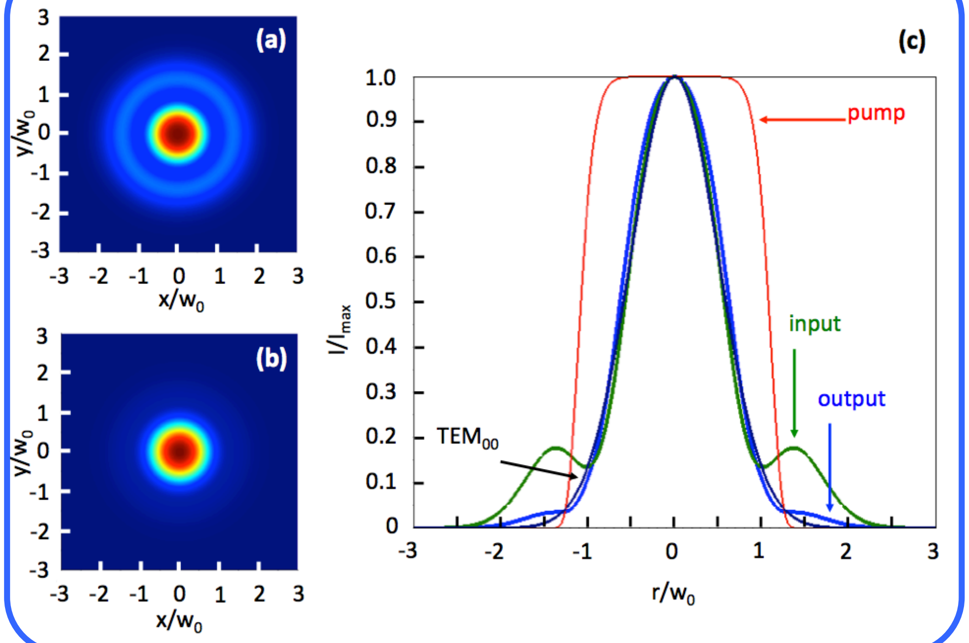
Radially dependent Frantz-Nodvik equations (double-pass)

$$\overline{F_{out}}(r)=\ln\left\{1+\frac{\left[\exp\left(\overline{F_{in}}(r)\right)-1\right]\exp\left(\overline{F_{in}}(r)\right)G_0(r)^2}{1+\left[\exp\left(\overline{F_{in}}(r)\right)-1\right]G_0(r)}\right\}$$

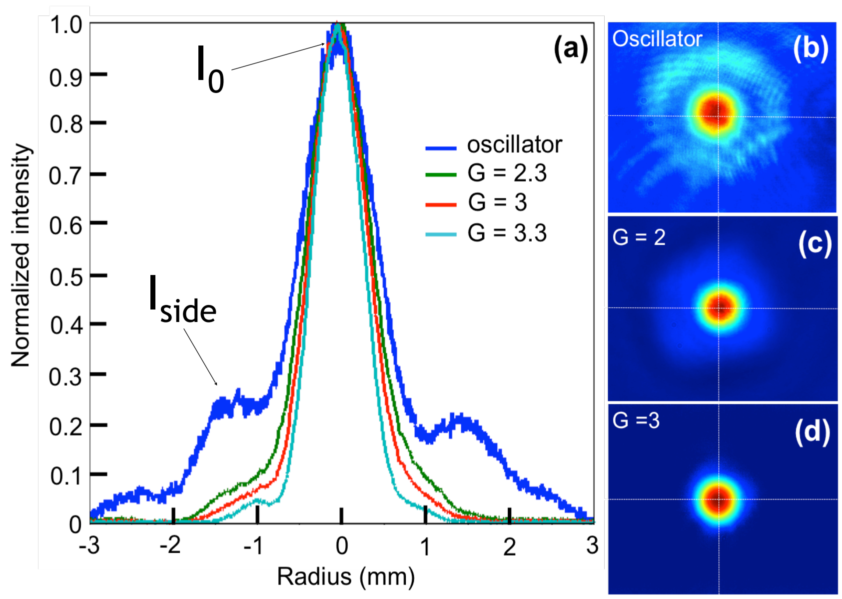
$$G_0(r)=\exp\left[g_0(r)l\right]$$

3. Spatial shape control – *3.3 Experimental results*

Calculation



Experiments



Effect of gain on beam profile

Increase of gain (pump energy) triggers pulse rectification.

- $I_{side}/I_0 \longrightarrow 0.01 - 0.03$
- energy increased up to 6 mJ

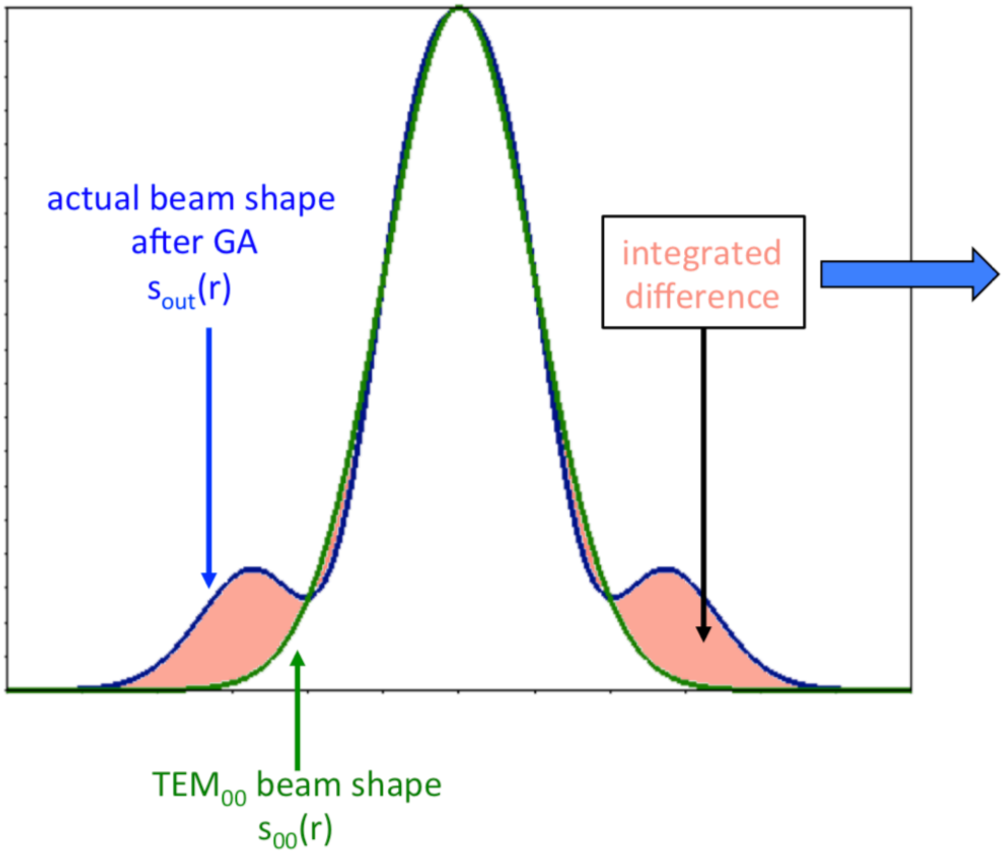
Characterization

Huge improvement on brightness
M^2 measurement on input and output beams

- $M^2 = 3 \longrightarrow M^2 = 1.3$
- $B = 66\ TW/sr/cm^2 \longrightarrow B = 512\ TW/sr/cm^2$

3. Spatial shape control – *3.4 Design criterion*

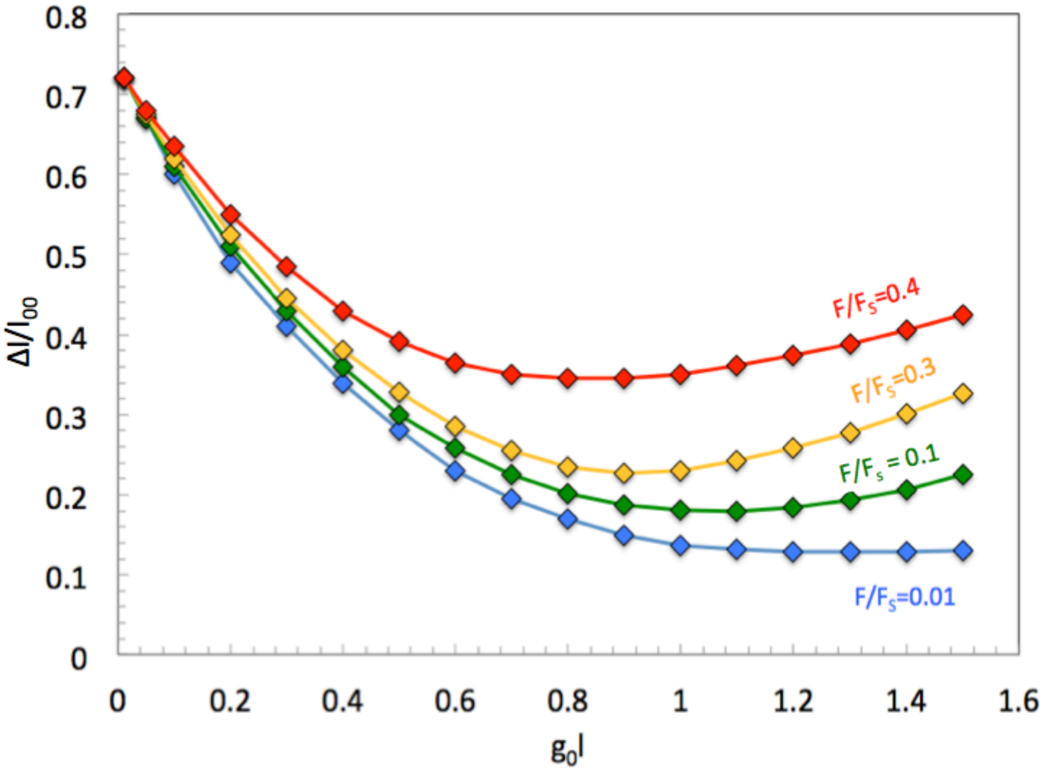
- this modeling does not allow M2 evaluation
- however, we can evaluate proximity of beam shape to Gaussian in far field



$$\frac{\Delta I}{I_{00}} \equiv \frac{\iint \left| s_{out}(r,\theta) - s_{00}(r,\theta) \right| r\,dr\,d\theta}{\iint \left| s_{00}(r,\theta) \right| r\,dr\,d\theta}$$

When $s_{out}(r) \longrightarrow s_{00}(r)$ we have $\boldsymbol{\Delta I / I_{00}} \longrightarrow \mathbf{0}$

Evolution of $\Delta I/I_{00}$ as a function of small signal gain g_0l (F_{in}/F_S is a parameter)

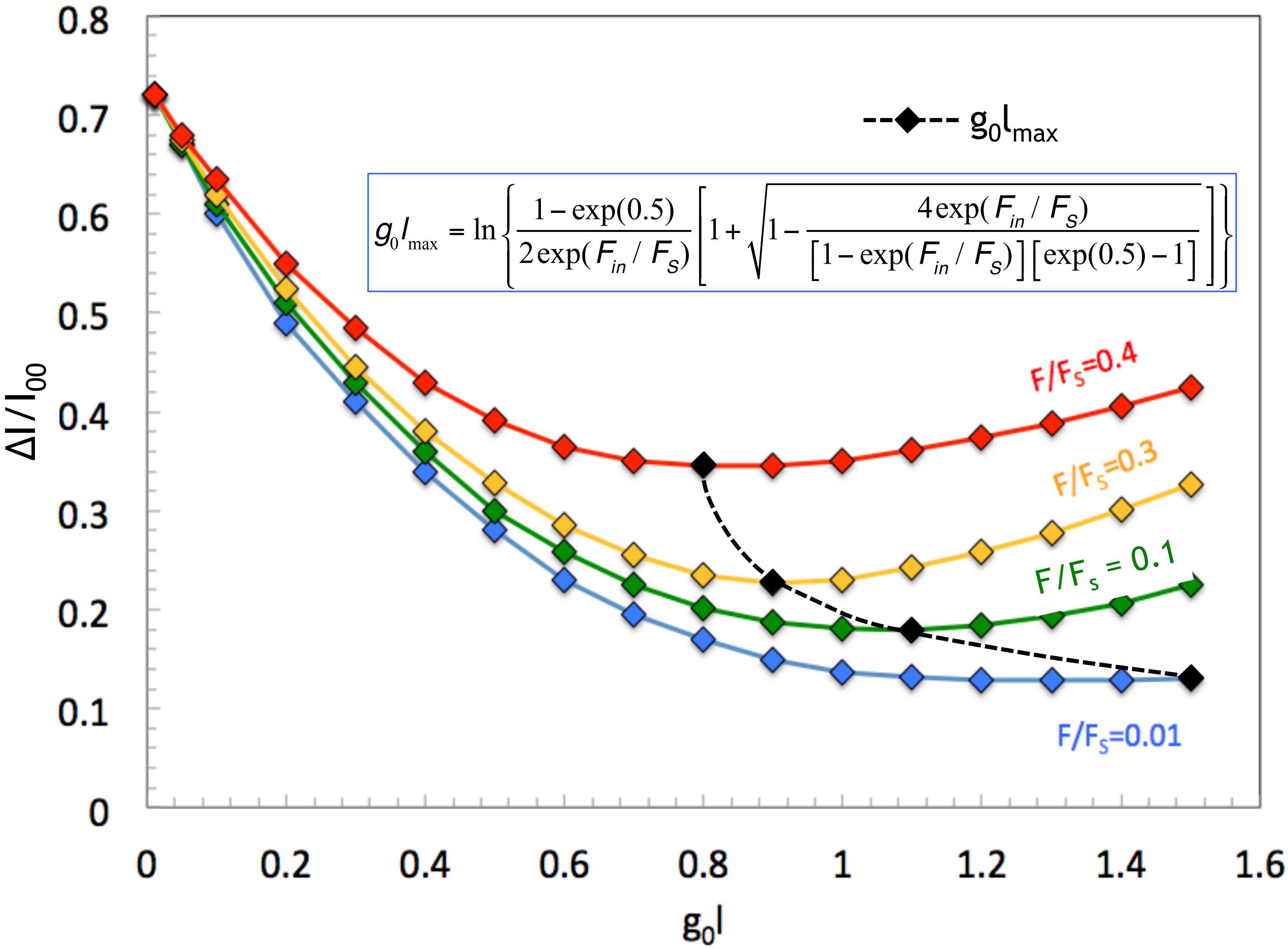


- ➢ general trend : $\Delta I/I_{00}$ becomes smaller when small signal gain increases
- ➢ however : $\Delta I/I_{00}$ tends to increase for high values of small signal gain
- ➢ this effect is smaller when the input fluence is small compared to saturation fluence

The increase of $\Delta I/I_{00}$ is due to gain saturation causing beam distortion.
This effect is significant when $F_{out}/F_S > 0.5$

$F_{out}/F_S < 0.5$ can be recast as a condition on small signal gain and F_{in}/F_s

3. Spatial shape control – *3.4 Design criterion*

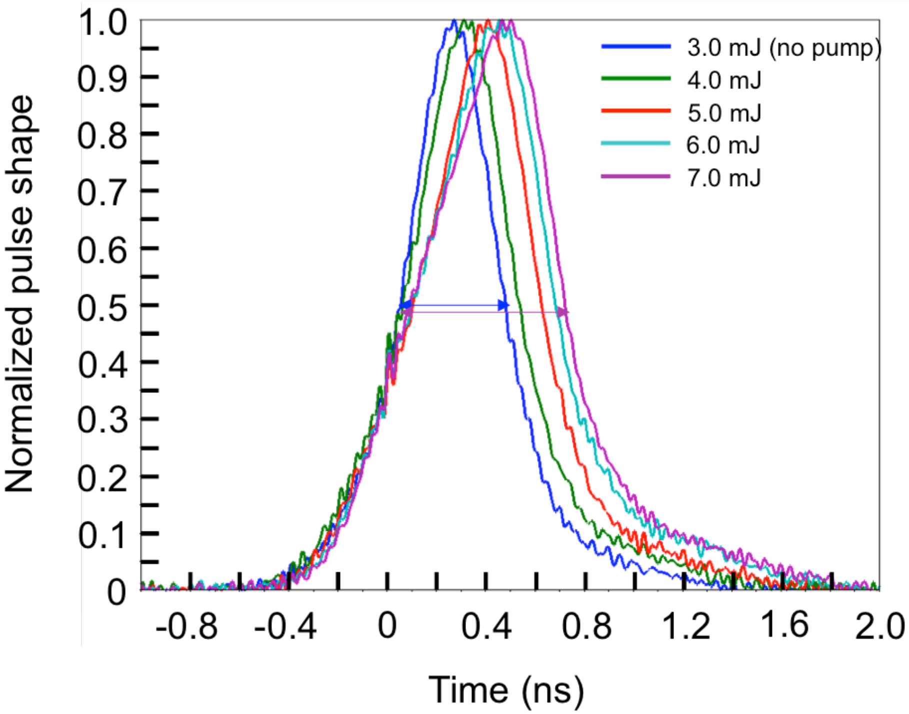


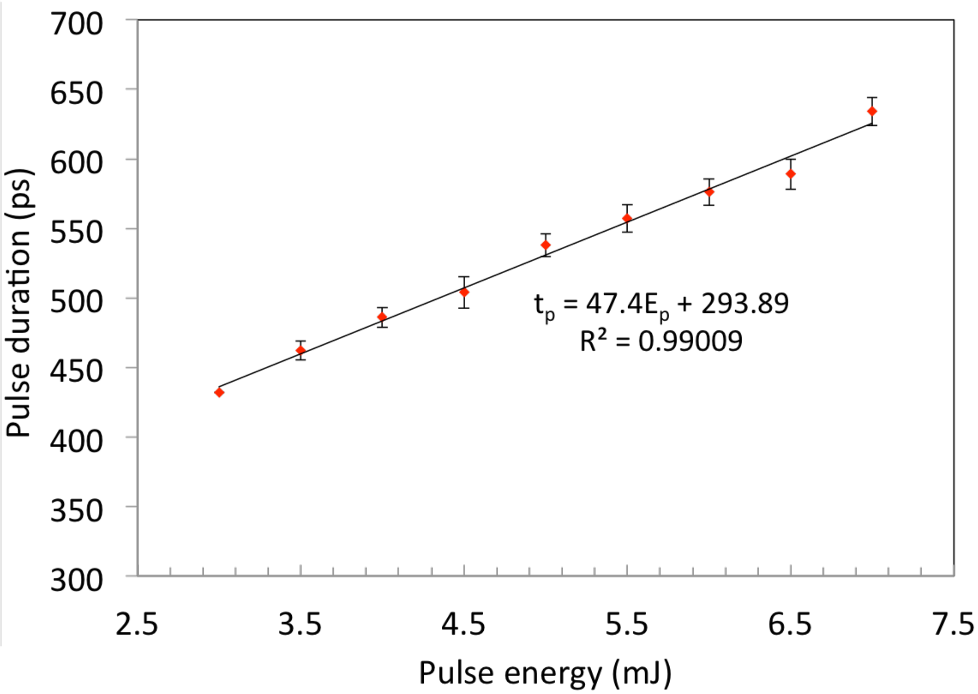
$$g_0 l_{\max} = \ln\left\{\frac{1-\exp(0.5)}{2\exp(F_{in}/F_S)}\left[1+\sqrt{1-\frac{4\exp(F_{in}/F_S)}{[1-\exp(F_{in}/F_S)][\exp(0.5)-1]}}\right]\right\}$$

- 10Hz and 100Hz system have different behaviors in terms of pulse duration

	10Hz	100Hz
Oscillator	430ps	400ps
Gain aperture	600ps	630ps
Main amplifier	700ps	470ps

- pulse duration depends on amplification stage : GA increases pulse duration





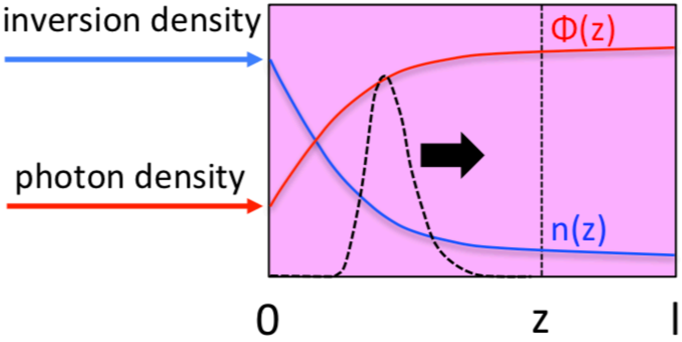
4. Temporal shape control – *4.2 Modeling of the effect*

To capture this effect, we must model the amplification dynamics

laser rate equations

$$\frac{\partial n}{\partial t} = -n\sigma_{em}c\phi$$

$$\frac{\partial \phi}{\partial t} = n\sigma_{em}c\phi - c\frac{\partial \phi}{\partial z}$$



numerical model equations (1D)

$$\frac{\Delta I}{I} = g\Delta z$$

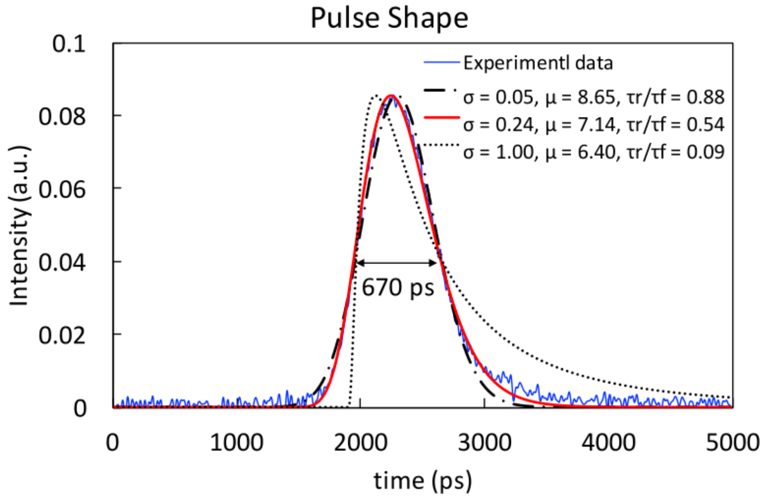
$$\Delta g = -Ig\Delta z$$

Experimental pulse shape is modeled by log-normal distribution

$$f(z) = \frac{1}{\sigma z\sqrt{2\pi}}\exp\left[-\frac{(\ln z - \mu)^2}{2\sigma^2}\right]$$

- ➢ *σ* and *μ* control the asymmetry (tail)
- ➢ experimentally : τ_r (rize time) and τ_f (fall time)

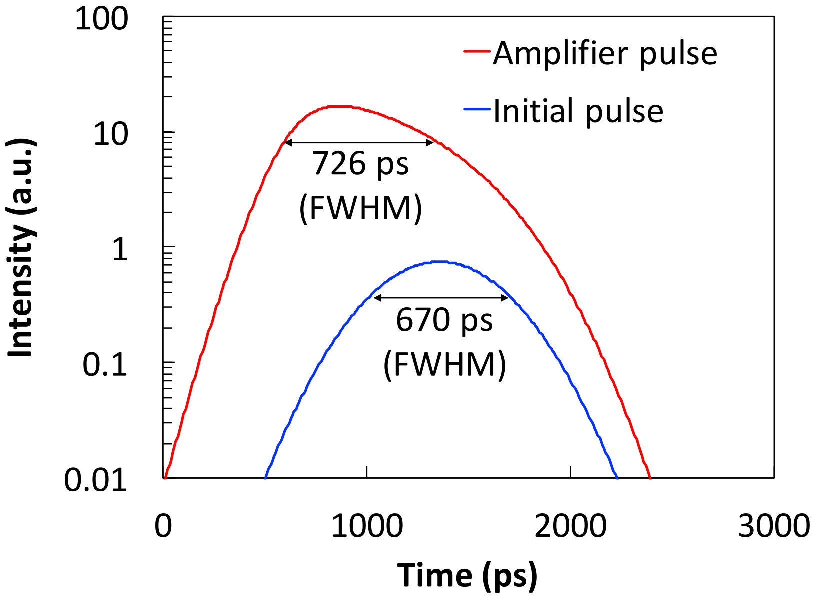
Saturation fluence of Nd:YAG	667 mJ/cm2	Pumping power	6 kW
Flourescent life time of Nd:YAG	230 us	Pumping pulse duration	250 us
		Pumping energy	1.5 J
Rod length	126 mm		
Rod diameter	5 mm	Stokes efficiency	0.76
Doping rate	1 at.%	Quantum efficiencty at 1 at.%	0.8
		Storage efficiency at 250 us pumping	0.66
Input beam energy	5 mJ		
Input beam diameter	2.4 mm		



4. Temporal shape control – *4.2 Modeling of the effect*

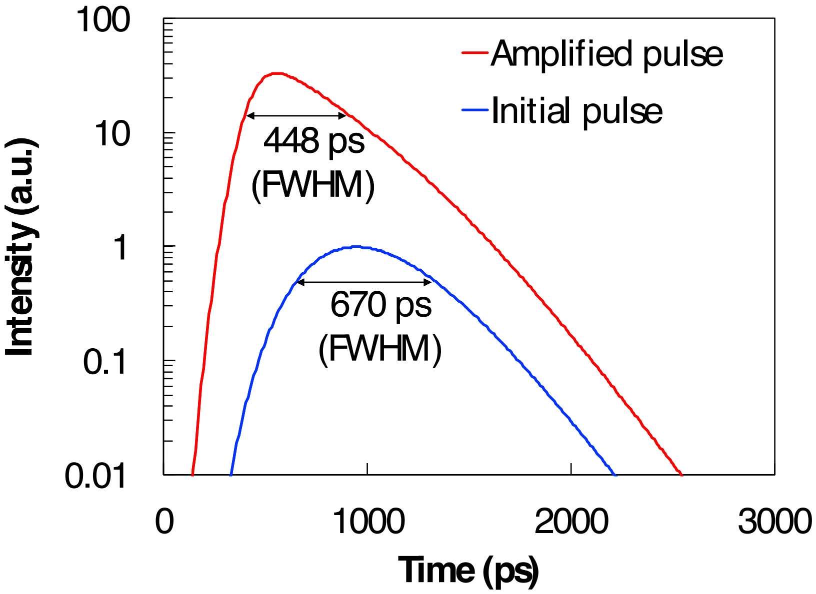
Calculation results show a strong effect of input beam temporal shape

Input $\tau_r/\tau_f = 0.98$



- ➢ τ_r/τ_f is close to 1
- ➢ leading edge of pulse grows slowly
- ➢ leading edge depletes the gain
- ➢ pulse is stretched

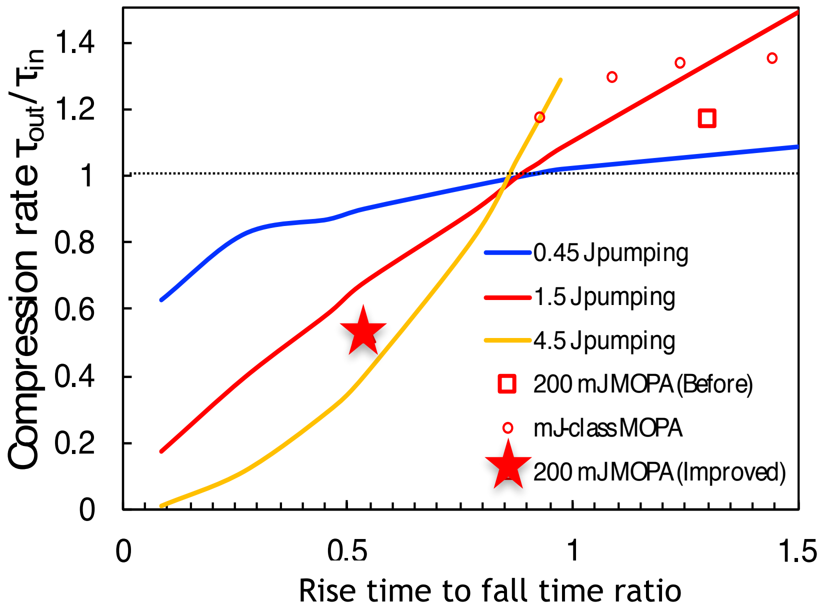
Input $\tau_r/\tau_f = 0.54$



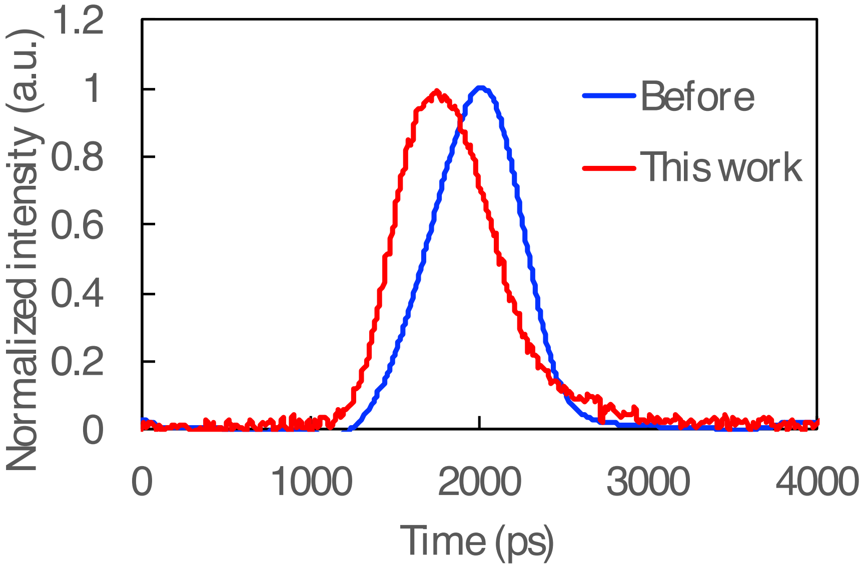
- ➢ τ_r/τ_f is < 1
- ➢ leading edge of pulse grows fast
- ➢ leading edge does not deplete the gain
- ➢ gain goes to peak of the pulse
- ➢ pulse is compressed

4. Temporal shape control – *4.3 Experimental results*

Experiments and calculation : results and discussion



- ➢ experiments and calculation show that compression rate depends on τ_r / τ_f
- ➢ it does not depends on initial pulse length
- ➢ compression is higher with higher pump energy



- ➢ pulse compression in 100Hz system is due to different oscillator pulse shape

	10Hz	**100Hz**
τ_r/τ_f oscillator	1.31	0.54
final pulse duration	470μs	700μs

5. Conclusion

Compact MOPA system with gain aperture can amplify and **shape the input beam**.

Spatial shaping

- Gain aperture device is efficient in supressing higher-order modes contributions.
- Higher gain results in stronger reduction as long as the gain is not saturated.

Temporal shaping

- Beam amplification can lead to both beam stretching and beam compression.
- Calculations and experiments show that beam leading edge slope is critical.

	Gain aperture	***Main amplifier***
Spatial shaping	- higher gain lower M^2 - if $F_{out}/F_S < 0.5$	- M^2 nearly stable at 10Hz - M^2 gets bigger at 100Hz
Temporal shaping	- only stretching observed - possibility of compression	- $\tau_r/\tau_f < 0.86$ —> compression - $\tau_r/\tau_f > 0.86$ —> stretching - effect is stronger if gain increases

Future work

- Preliminary calculation show that gain aperture can also produce compression.
- Combining gain aperture with volume Bragg Grating could allow further control on shaping .

Thank you for your attention