A High-Efficient Amplifier based on Room-Temperature Yb:YAG

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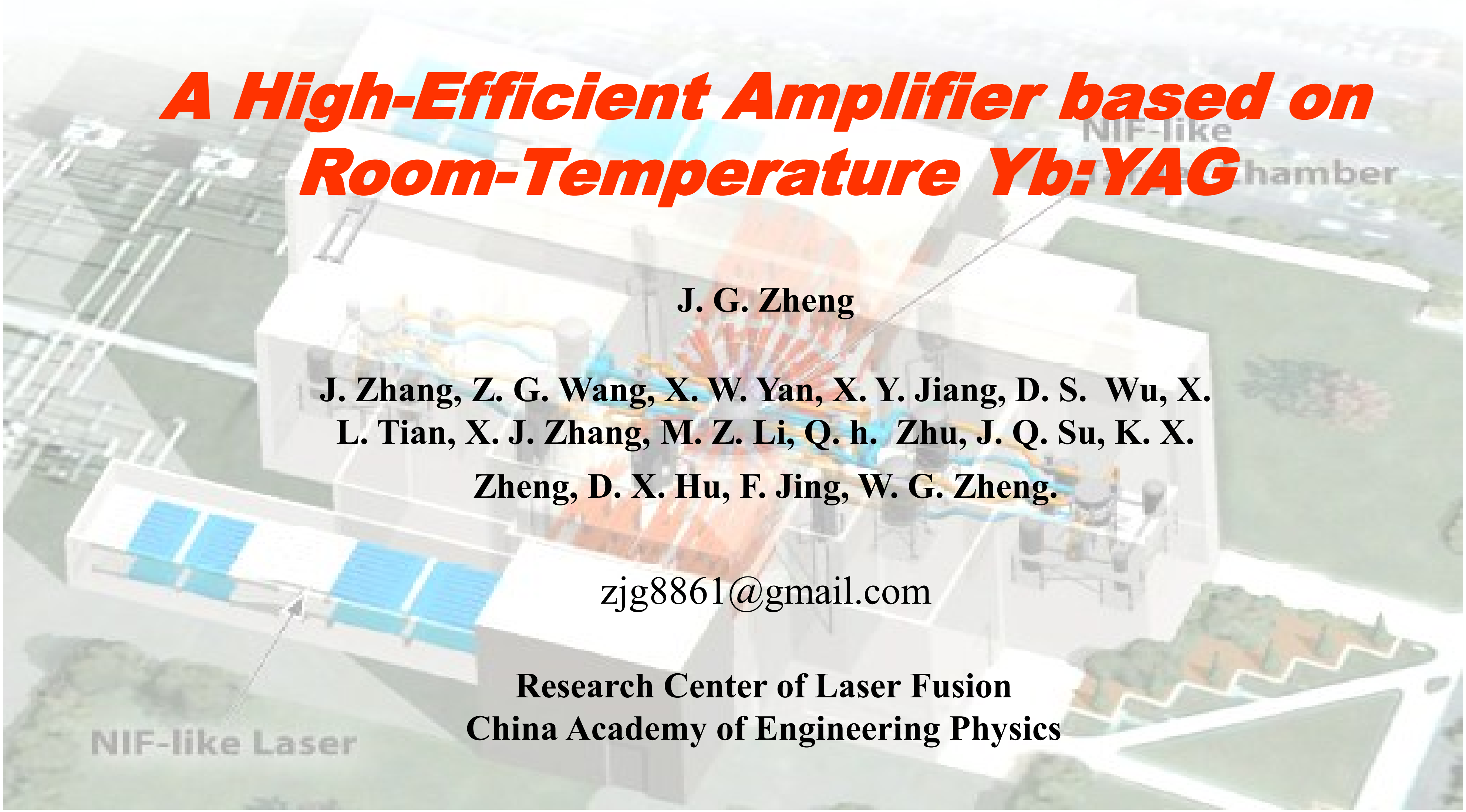


Outline

- **Background of the work**
  - **Motivation**
  - **Introduction**
- **The 10J laser system**
  - **Layout of the system.**
  - **The seed of system**
  - **The preamplifier**
  - **The booster**
  - **The main amplifer**
    - **–Pumping, The output of the main amplifer**
    - **Following Work**
- **High-Efficient Amp. for kJ-class Laser**
  - **Amplifier Requirement**
  - **Configuration of Amplifier**
  - **Energy storage**
  - **Extraction with double pulse**
- **Summary & prospect**

Motivation

Higher Efficiency, Large Energy and Repetition rate Laser can be used for

- **Inertial Fusion Energy**
  - **For example: LIFE, HiPER, KOYO-F……**
- **High energy density physics**
- **Strong field physics**
- **High energy and high brightness X-ray source**

  or High energy and high brightness particle beams et.al.

To realize higher efficiency, Large Energy and repetition rate, The materials, thermal management must be correctly selected.

Requirement of gain medium

To achieve the Higher Efficiency, Large energy and repetition rate, we must consider the following issues of gain medium……

- **Larger scale:** can provide larger energy in single beam
- **High thermal conductivity:**

  High efficient thermal management
- **Right Emission/Absorption section :**

  to get higher efficient energy conversion
- **Can be pumped by LD:**

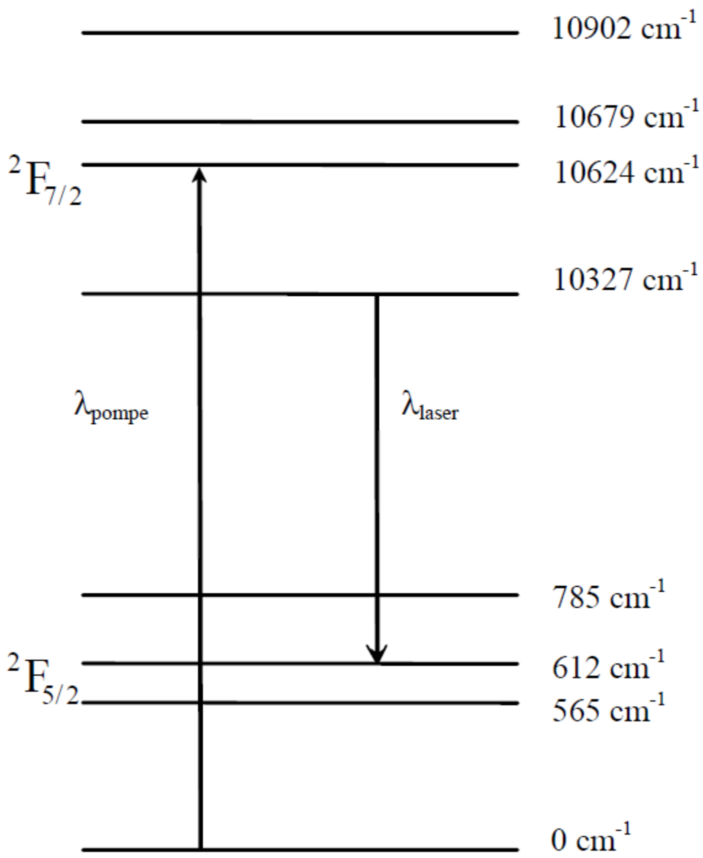
  reduce the thermal deposit and

  increase the energy conversion efficiency
- ……

Comparison of materials

Properties		$Yb:CaF_2$	Yb:S-FAP	Yb:YAG	Nd:glass
Energy storage and extraction	Lifetime of Upper level(ms)	2.4☺	1.1 ☺	0.95 ☺	0.35 ☹
	Saturated fluence (J/cm^2)	118 38.5 ☹	2.6 ☺	8.38 4.38 ☺	5.24 ☺
	Absorption bandwidth(nm)	>10☺	~4.2	>10 ☺	>10 ☺
	Emission section($10^{-20}cm^{-2}$)	0.16(RT) 0.49(LT) ☹	7.3 ☺	2.3(RT) 4.4(LT) ☺	3.3 ☺
	Suitable for LD pumping	Yes☺	Yes ☺	Yes ☺	Yes ☺
Achieved availability	Size	φ30cm☺	$4\times6cm^2$ ☹	No limits ☺	No limits ☺
	Configuration	Single☹	Single ☹	No limits ☺	Single ☹
Thermo-dynamic and thermal-optical properties	Thermal conductivity (W/m·K)	9.7☺	2 ☹	16.6 ☺	0.83 ☹
	Thermal expansion coefficient (10^{-7}/K)	190☹	100 ☹	48 ☺	99.6 ☹
	Fracture coefficient ($MPa/m^{0.5}$)	0.7☺	0.51 ☹	2 ☺	0.6 ☹
	Thermal shock coefficient (25-μm flaw size) (W/m·K)	242☺	63 ☹	3780 ☺	61 ☹

Why select Yb doped gain material ?



- **quasi-three-level system**
  Without concentration quench
- **lifetime ~ 1 ms**
  Reduce the pumping power
- **main pumping region around 941nm and emission at 1030 nm**
  high quantum efficiency
- **Can be high dopped**
  Increase the energy storage
- **Higher thermal conductivity**
  Can be easily managed

Introduction

The reason for selection of Yb:YAG is that the Yb:YAG ceramics would be available.

- Yb:YAG ceramics has the same optical property as the crystal, it can be more uniformly doped.
- Yb:YAG ceramics can be designed for some given function. Such as co-sintered Cr^{4+}/Yb^{3+}:YAG for suppression of parasitic oscillation, Gradient Doping for efficient thermal management.
- The large aperture Yb:YAG ceramics is available

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Layout of the system

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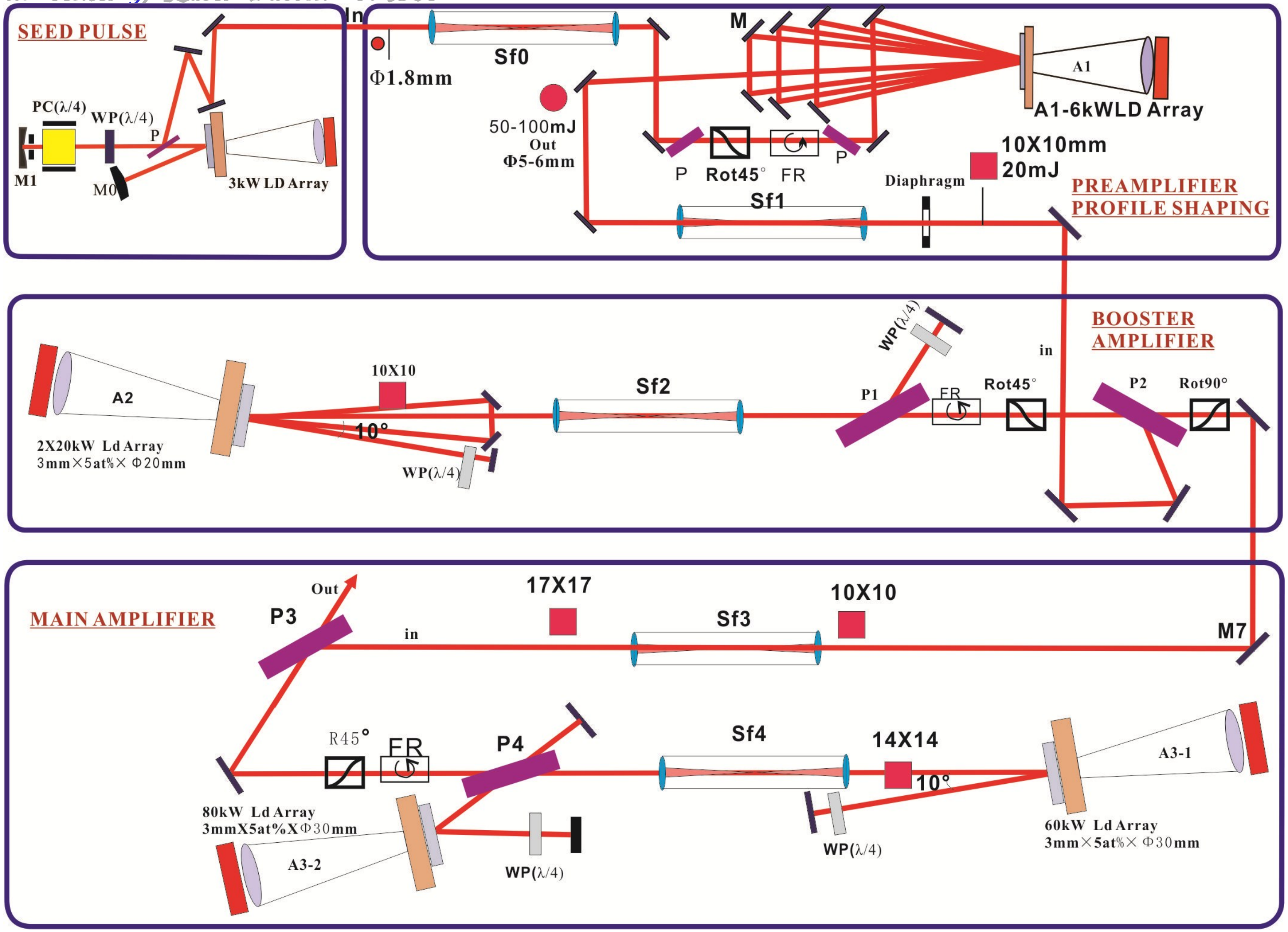
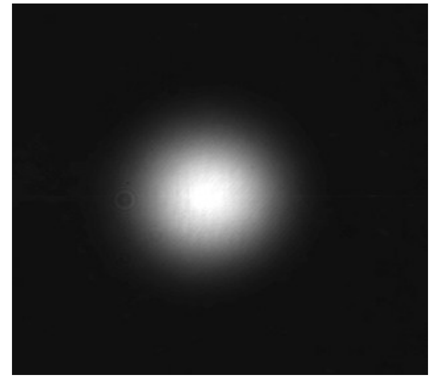
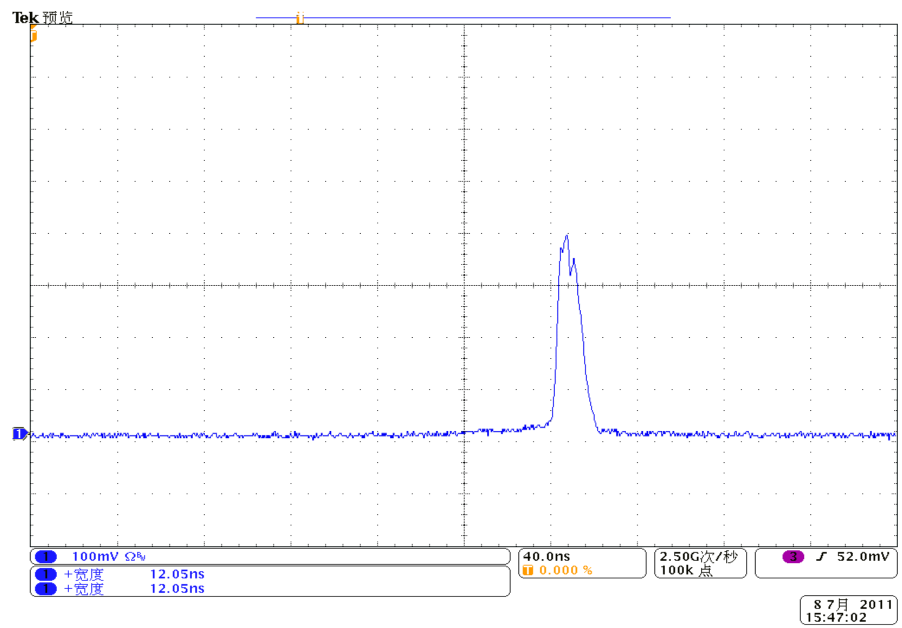


Seed of system

Energy： ＞10mJ
Duration： 10ns
Frequency： 1-10Hz
Beam profile： Guassian
Beam size： Φ1.5mm





Preamplifier

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- 5 passes preamplifier

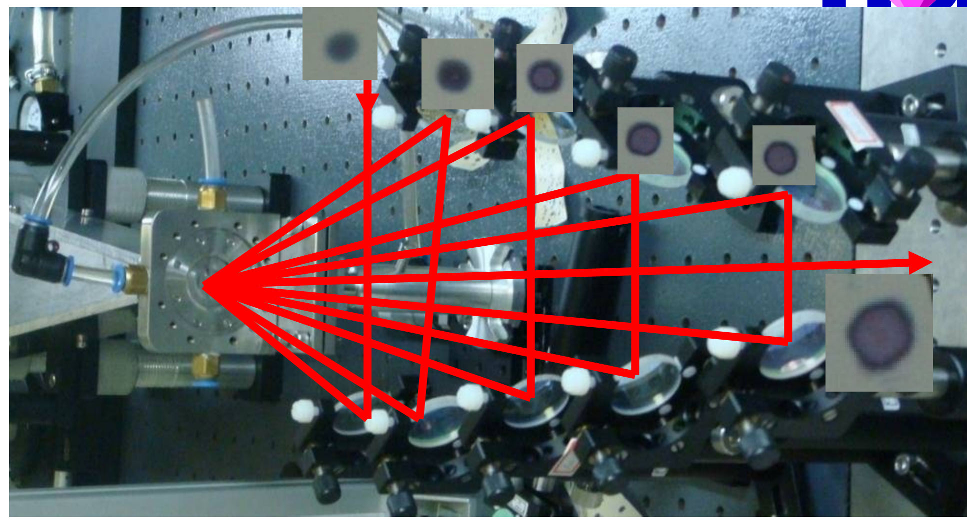
  Energy: ~100mJ

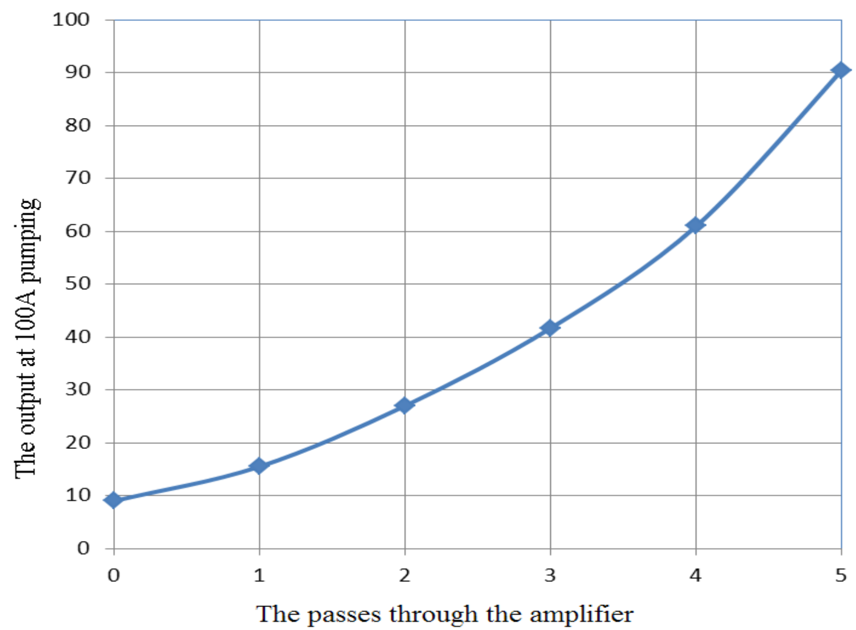
  Duration: 10ns

  Frequency: 1-10Hz

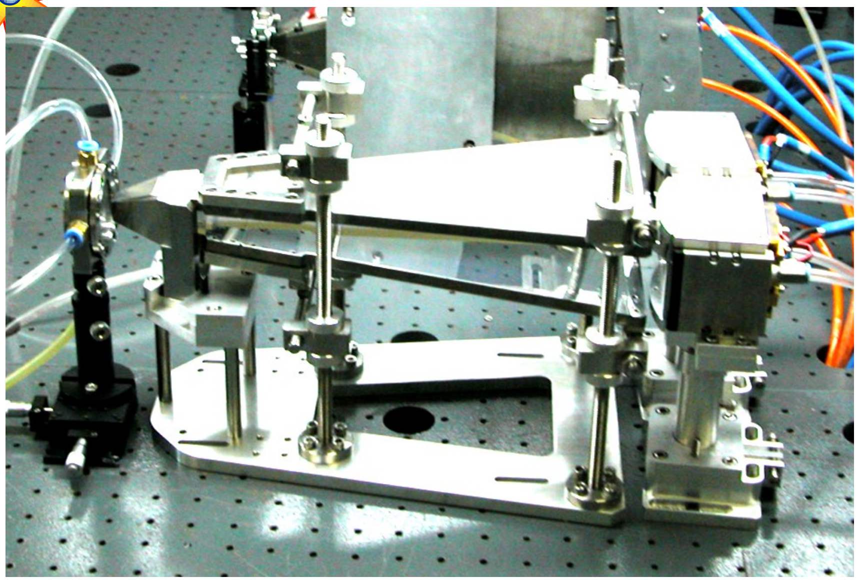
  Beam aperture: Φ5mm

- The beam keeps the Gaussian profile.
- The aperture became larger because of the thermal lens/mirror
- Some energy storage remains in the amplifier.





Booster



- **8 passes booster amplifier**

  Energy：~1.5J

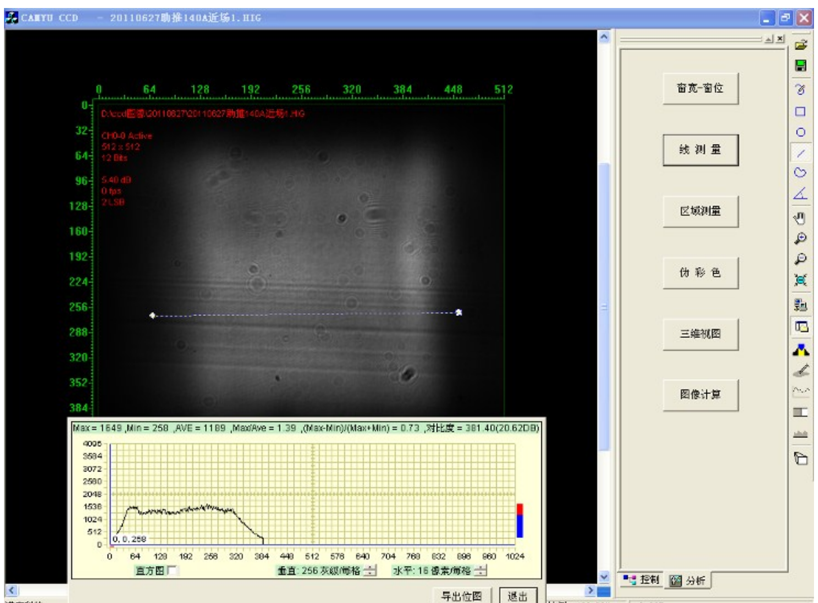
  Duration：10ns

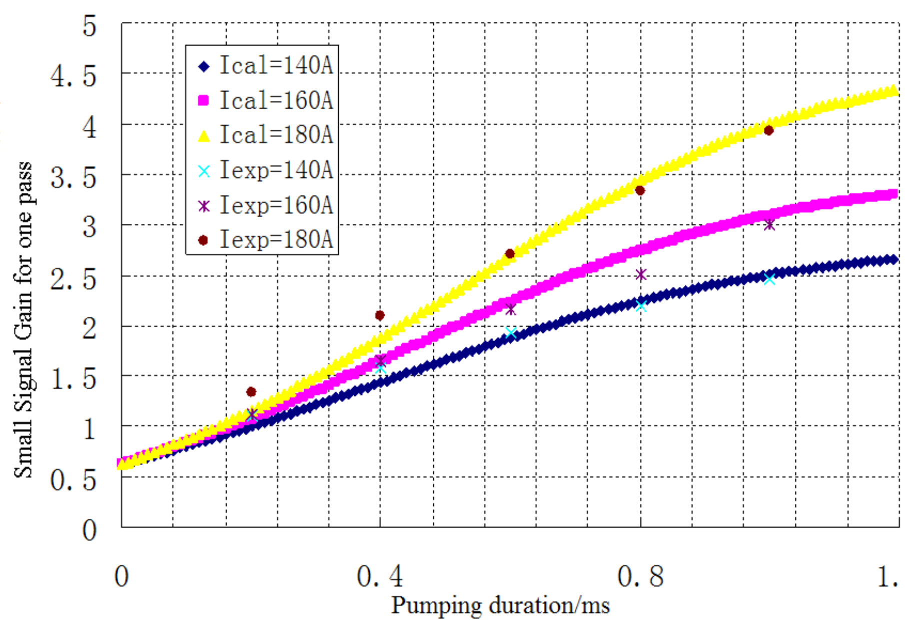
  Frequency：1Hz

  Beam aperture：8mmX9mm

  max./ave. for Near field: 1.36

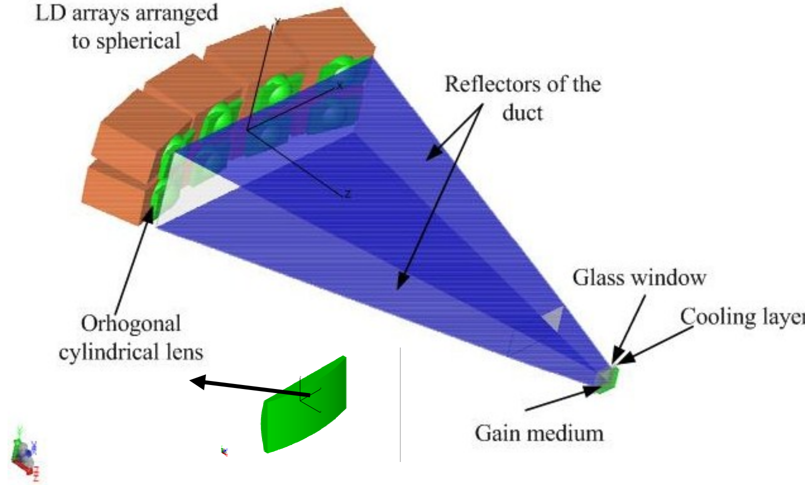
  Total gain: 150 times



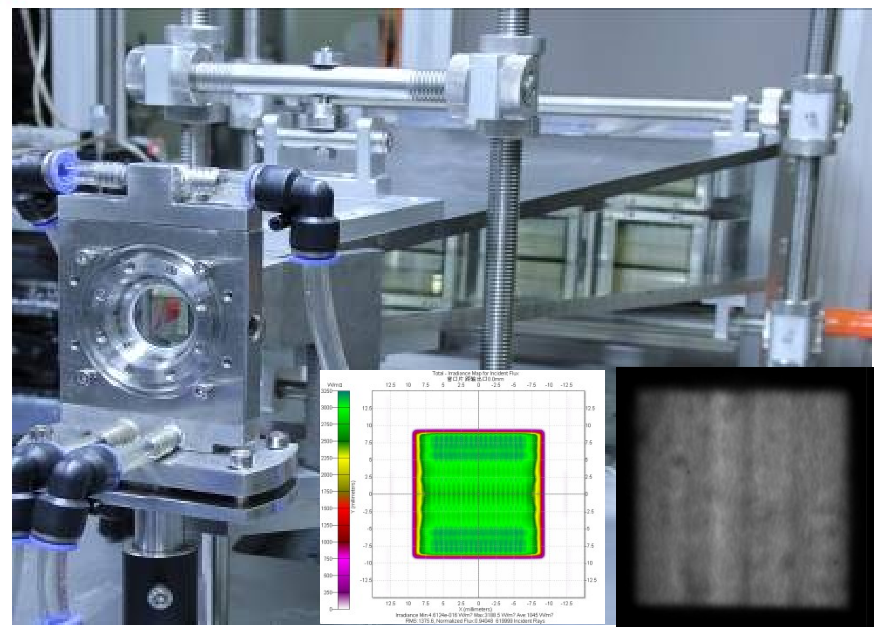


Main amplifier----Pumping

Power(kW)	2X3X10	2X4X10
Beam aperture(mm^2)	15X15	18X18
Power density((kW/cm^2)	22.9	21.3
Duration(ms)	1	
Frequency(Hz)	1-10	
Transmission eff.	86%	



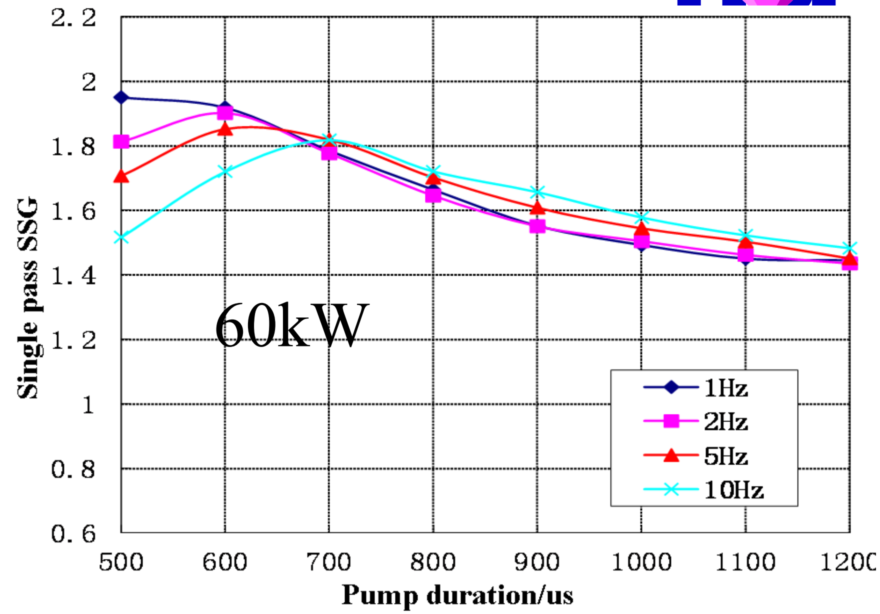
- LD stack ware assembled on the sphere, which center locates in the surface of the gain material.
- LD stack emitting light focused on the surface of gain material by lens.

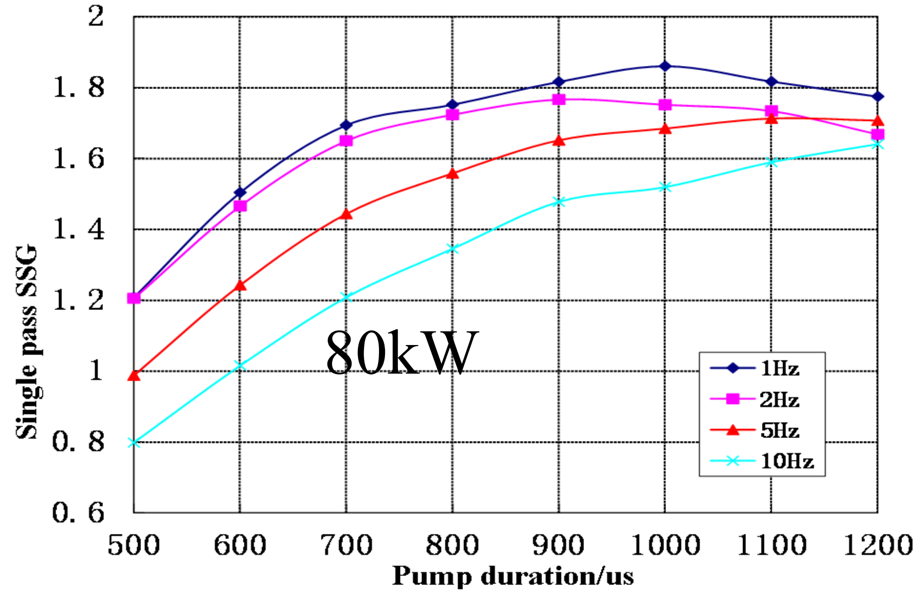


Main amplifer-SSG

Pumping power	60kW	80kW
Beam aperture(mm[2])	14mm×14mm	17mm×17mm
Maximum SSG(1Hz)	1.95	1.85
Pumping duration	0.5ms	1ms

- With the increasing of frequency, the SSG decreased.
- For 60kW pumped laser head, because of the higher pumping power density the SSG become smaller at the end of pumping duration. It means that there is more ASE.





Main amplifer-water-cooled laser head

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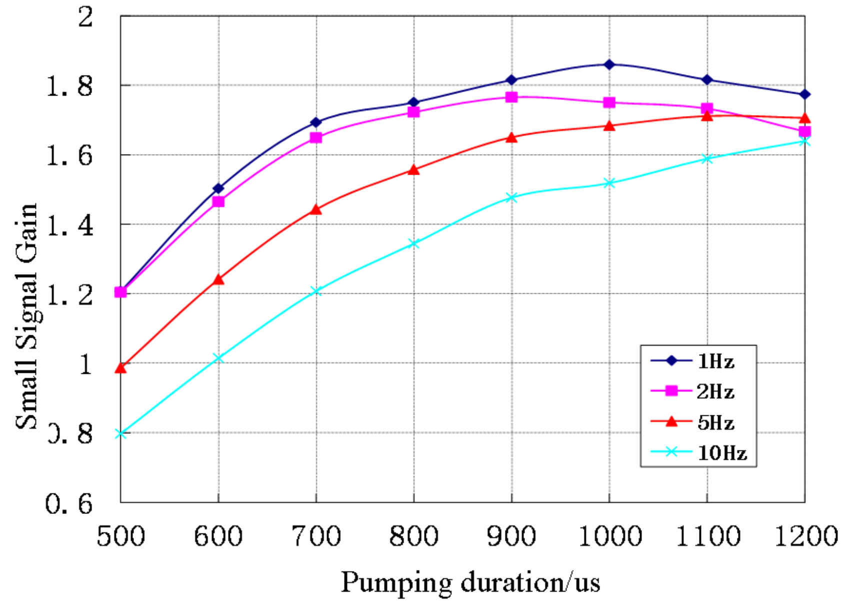
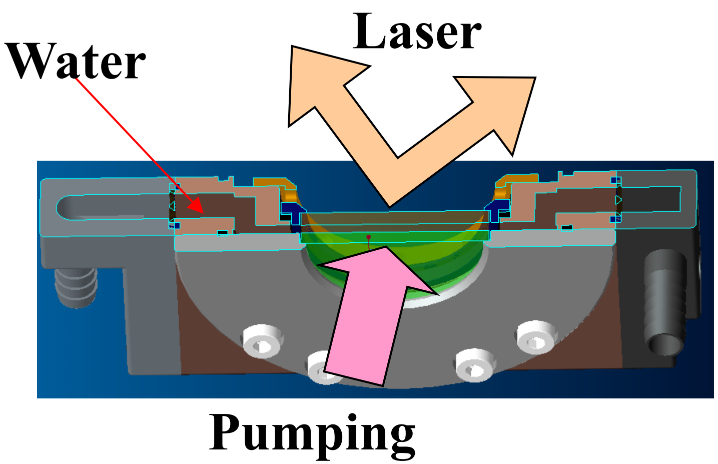
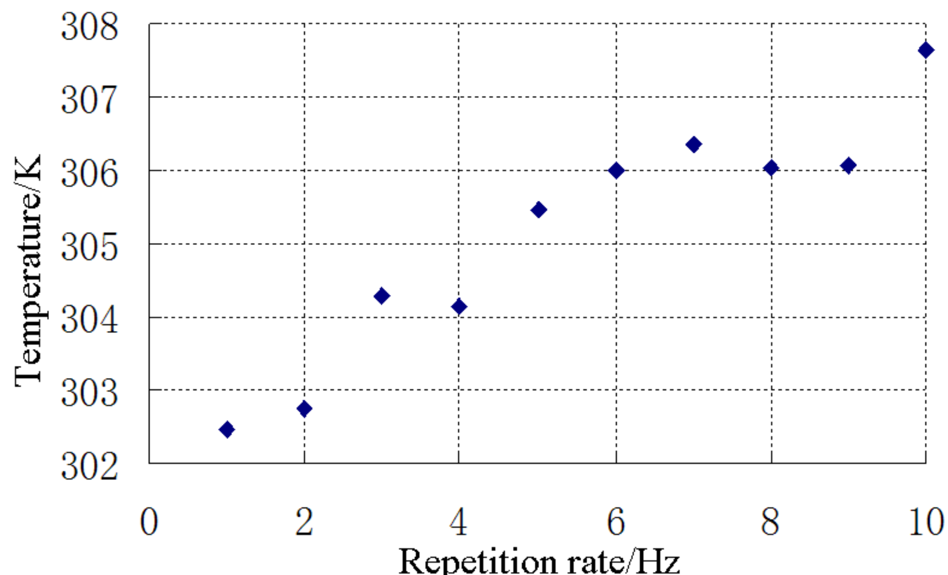
- In the condition of frequency increasing from 1Hz to 10Hz, the SSG decreased about 13%
- The surface temperature of gain material increased form 302.5K to 308K.







The laser system

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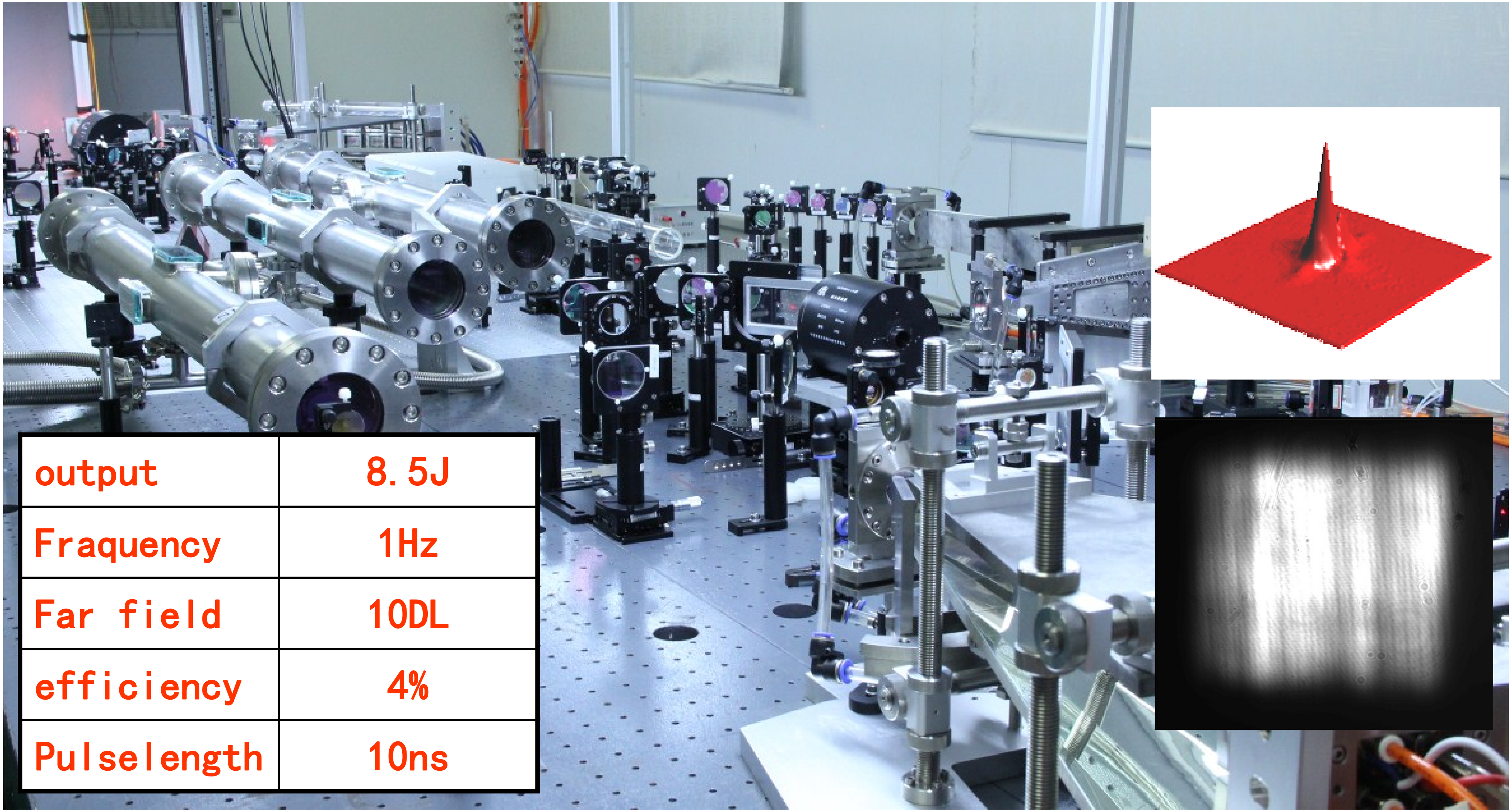
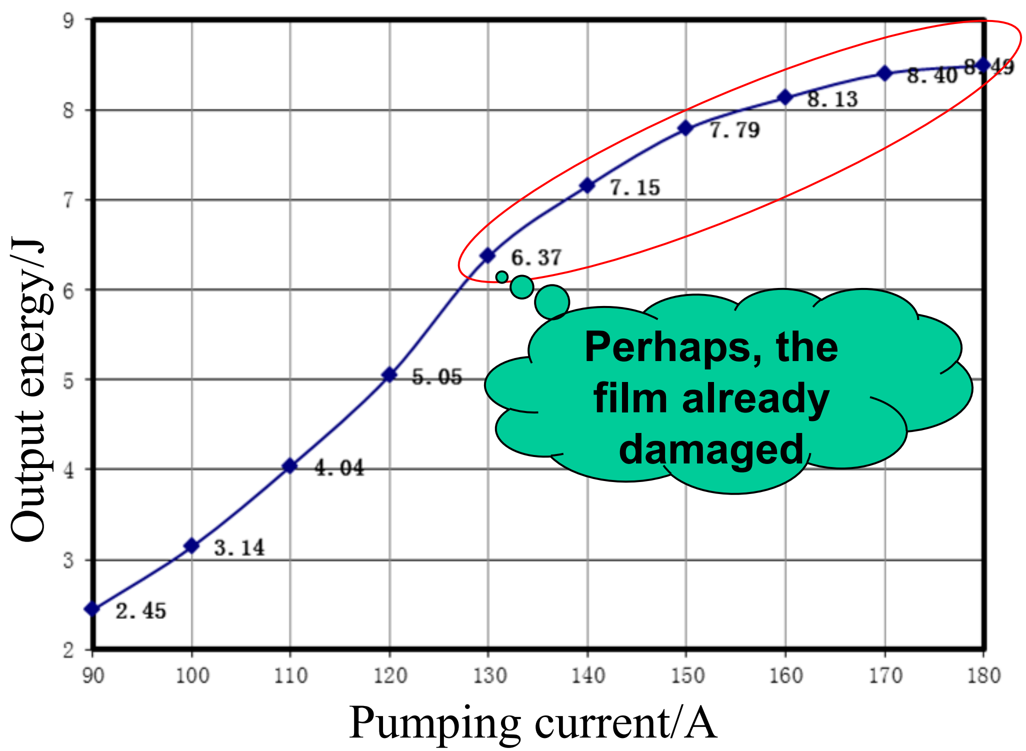


output	8.5J
Fraquency	1Hz
Far field	10DL
efficiency	4%
Pulselength	10ns

Damage Limit

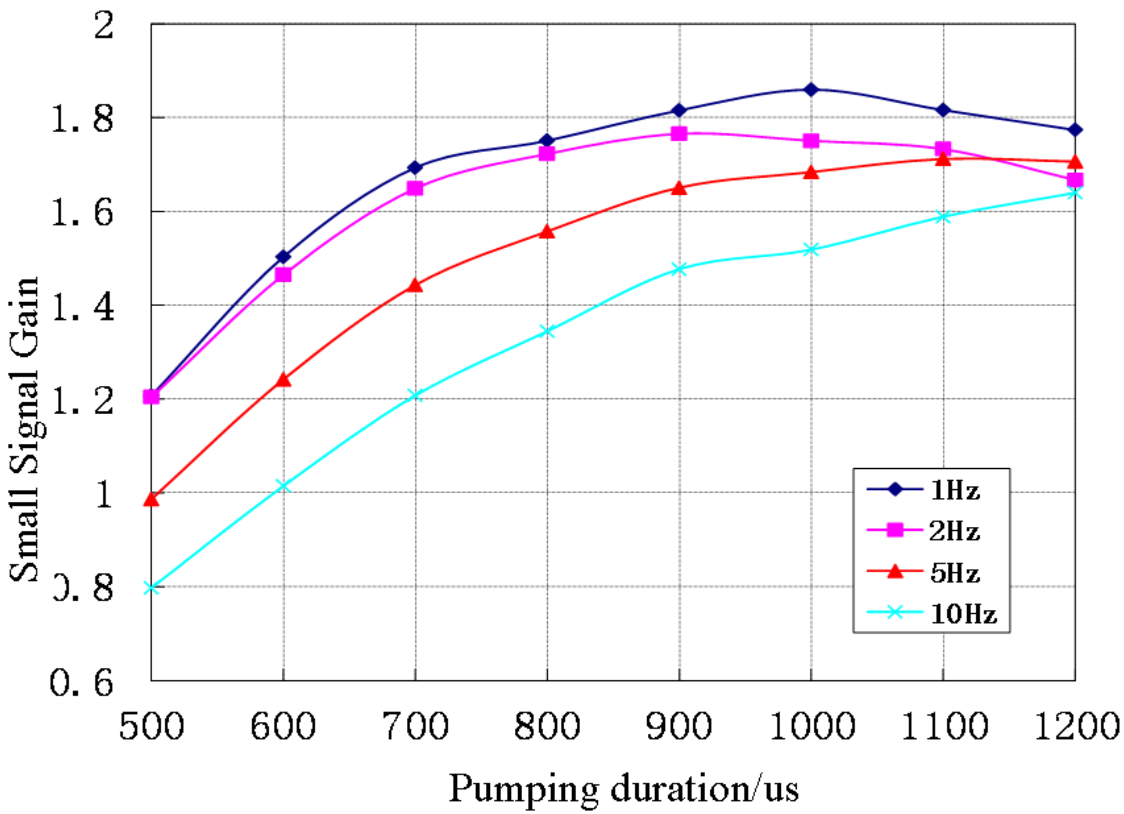
➢ **Damage: The surface of material was damaged.**

- **The overlying of front edge and the back edge of laser pulse doubled the intensity of laser at the surface of gain material.**



Limitted gain

- **Limitted gain: The gain too small.**
  - **The gain is about 1.85 times for a sigle V-shape pass. The reason is that the ASE too serious.**



Solution for limit

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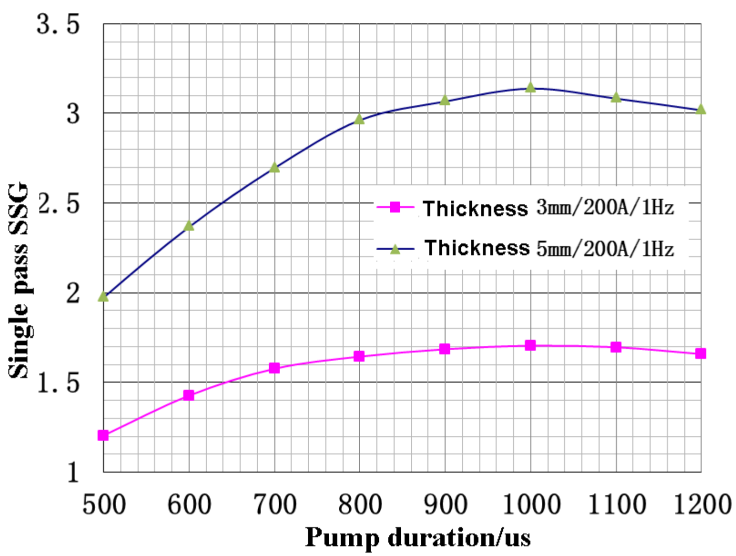
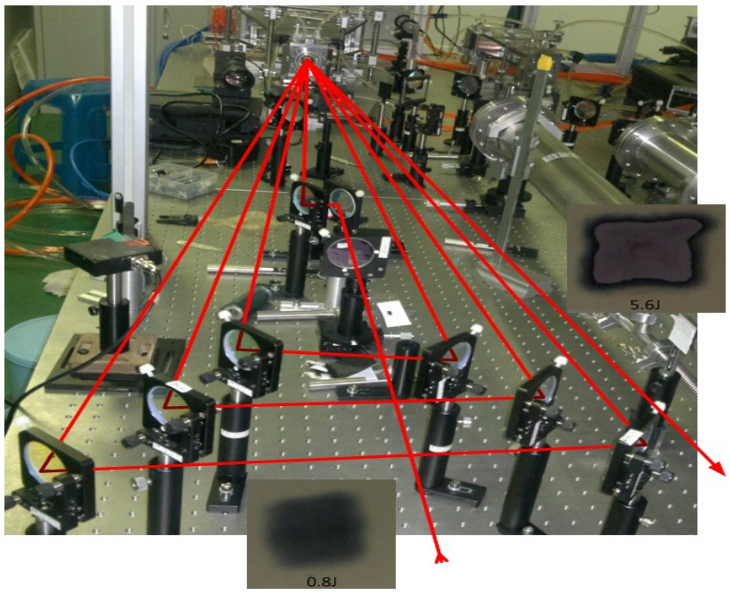
- For damage: lengthen the light path in the amplifier, so that the front and back edge would not be overlayed. Result: the energy flux increased from $3J/cm^2$ to $5.6J/cm^2$
- For limitted gain: enlarge the thickness of the gain material and keep the product of concentration and thickness to decrease the ASE in amplifier. Result: the single v-shape pass gain increased from 1.8 to 3.2 times.





Evaluation of the 10J laser system

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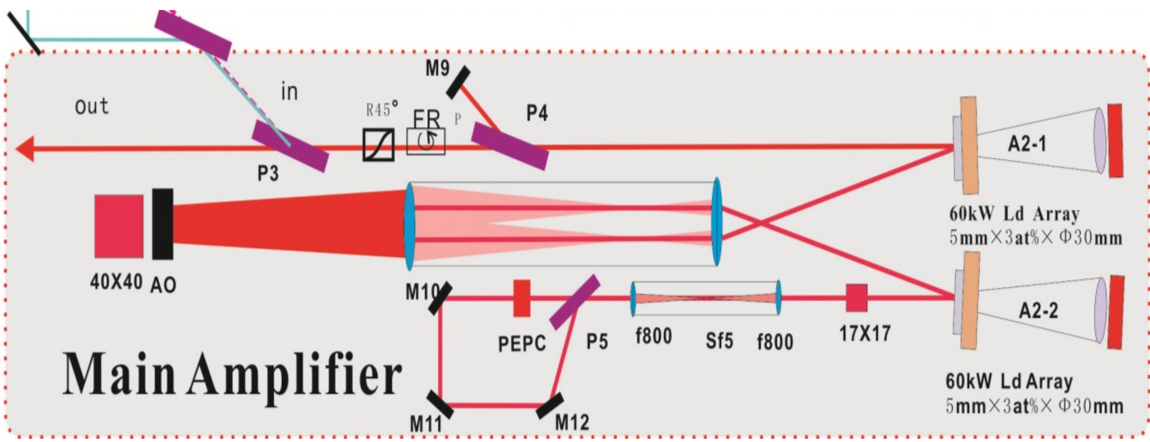
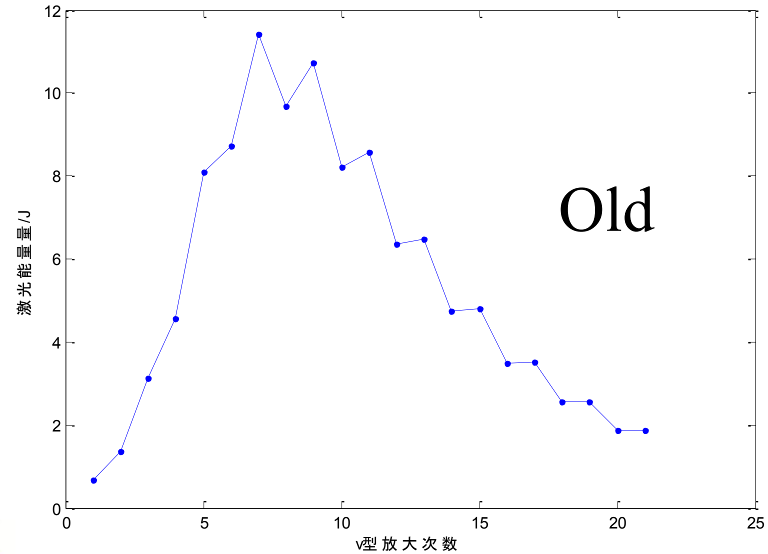
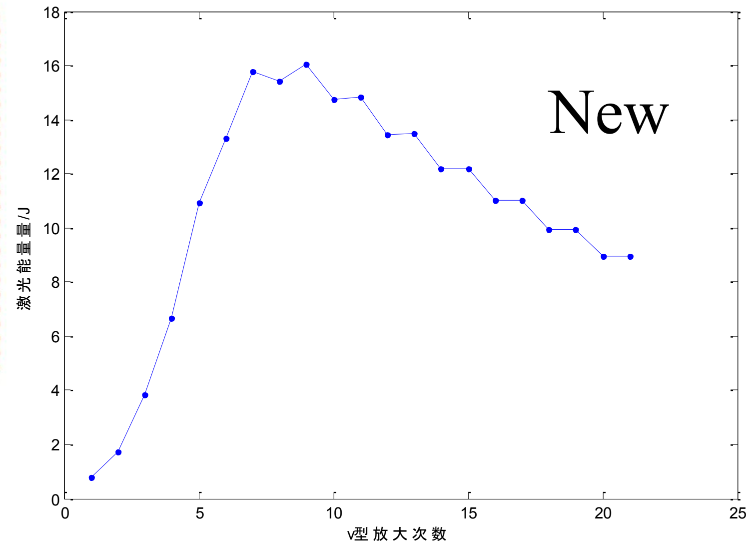
- Annular light path to avoid the damage
- 5mm thickness crystal(3at.%) to decrease the ASE and increase the gain of amplifier.
- Using Adaptive optics to correct the wavefront aberration







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Considered factors for kJ-class Amplifier

- **Energy for single beam:**

  About 10kJ to simplify the laser system

- **Total length of gain medium**

  Long to achieve high gain, But SHOT to avoid higher B-integration. So the length must be optimized.

- **Aperture of laser beam:**

  Large to achieve higher energy for single beam, so that the number of beams can be lessened. Like NIF,LMJ.SG-III etc., the aperture is more than 30cm*30cm.

Considered factors for kJ-class Amplifier

- **Energy fluence:**

  About 10J/cm^2, to avoid damage of components and ensure higher extraction efficiency.

- **Thermal management:**

  The heat must be well managed, so that the system can work repeatedly, especially for IFE driver， this is very important.

- ……

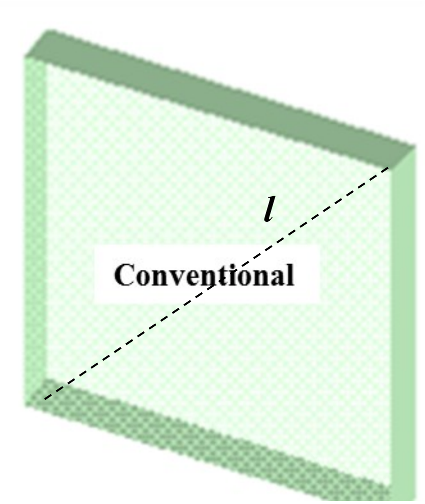
Influencing factors

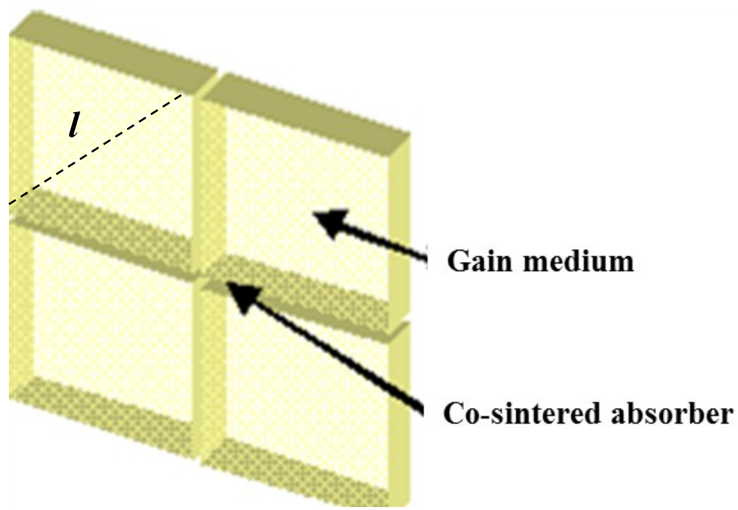
- **The main influencing factor on high energy, efficiency is the LOSS in amplifier, including:**
  - ASE: Large aperture and high energy in single beam unavoidably lead high ASE, and ASE will lessen the energy storage and its efficiency, affect on the distribution of energy storage.
  - Quantum efficiency: Higher Quantum efficiency means that more pumping power can be transformed into energy storage, at the same time, it also means less thermal deposit in amplifier.
- **The main influencing factors on repetition rate are the thermal management and gain material:**
  - The higher thermal conductivity means that the heat can be easily taken away from the gain medium.
  - The better thermal management means that the heat can be easily taken away from the laser system.

ASE Suppression

- **ASE loss arise from gain-coefficient (g_0)and transverse length(l) of the gain medium. It is proportion to the product of g_0 and l**

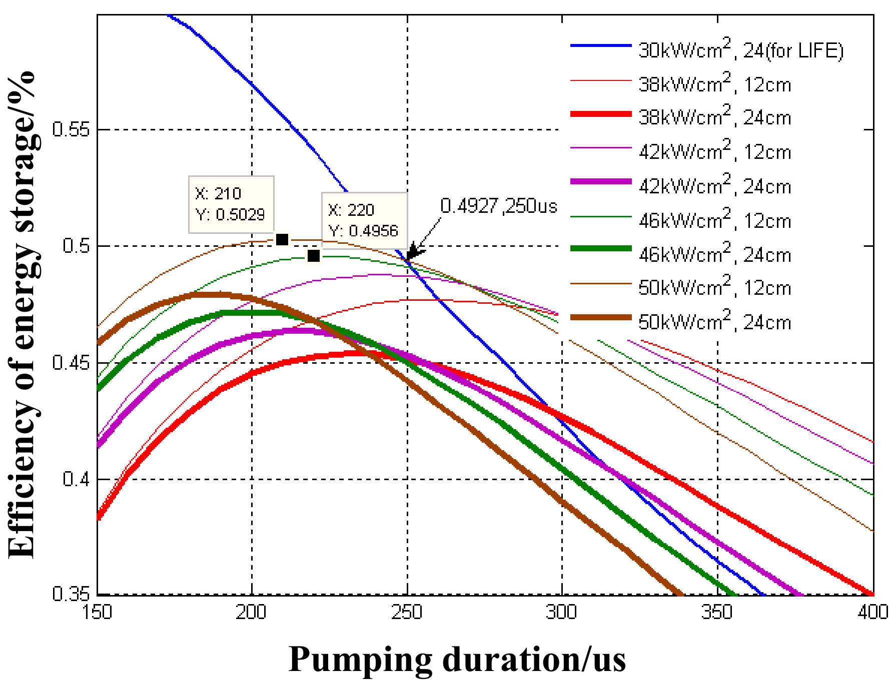
$$E_{ASE} \propto g_0 \times l$$

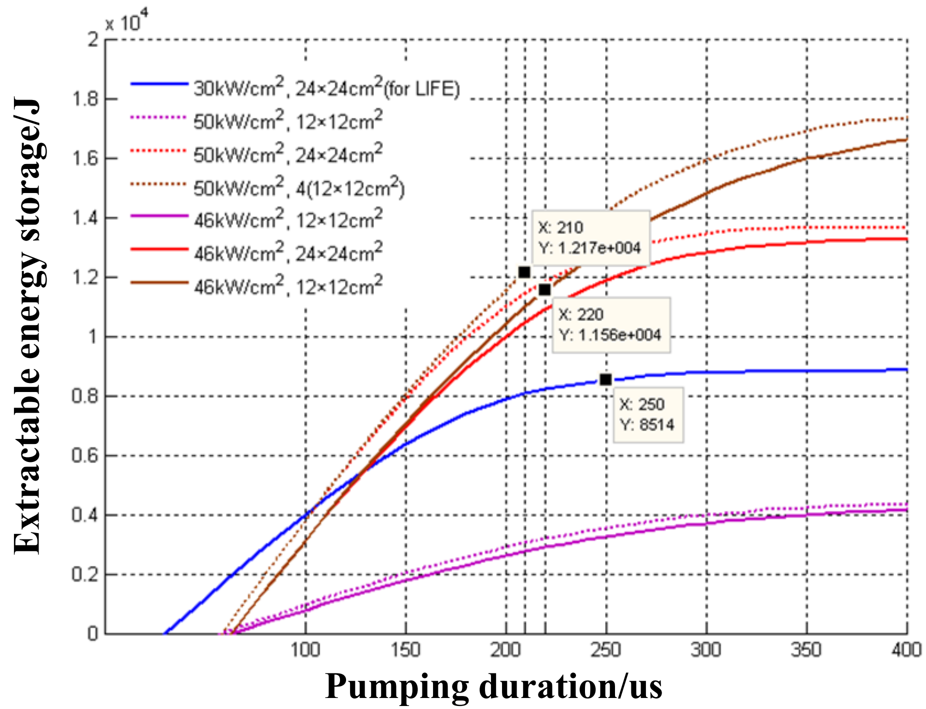




The selection of aperture and pumping power

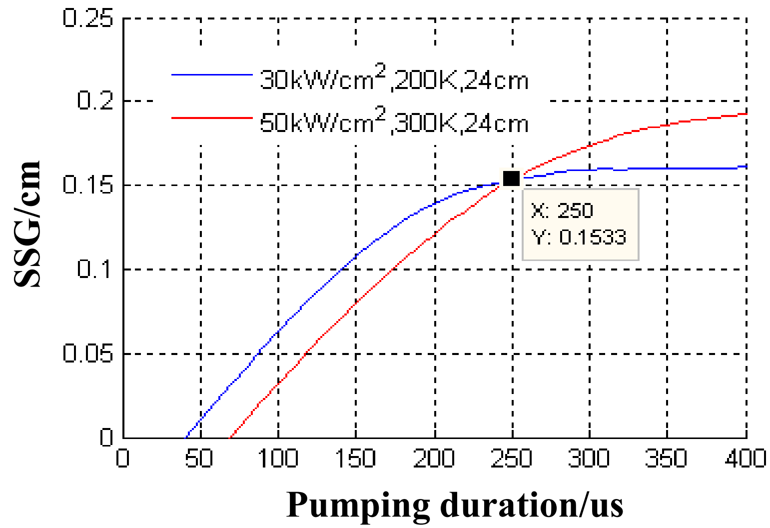
- With the increasing of aperture, the efficiency of energy storage decreased, and with the increasing of pumping power, the efficiency of energy storage increased.
- Pumping duration 250us, pumping power 50kW/cm², the eff. of energy storage is up to 50% for 12cm*12cm aperture at RT, and the Energy storage is up to 14kJ,

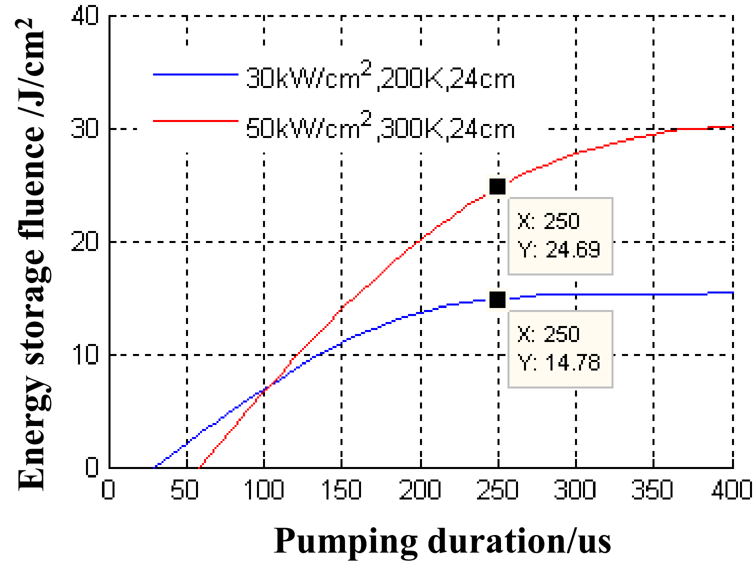




Evaluation of SSG

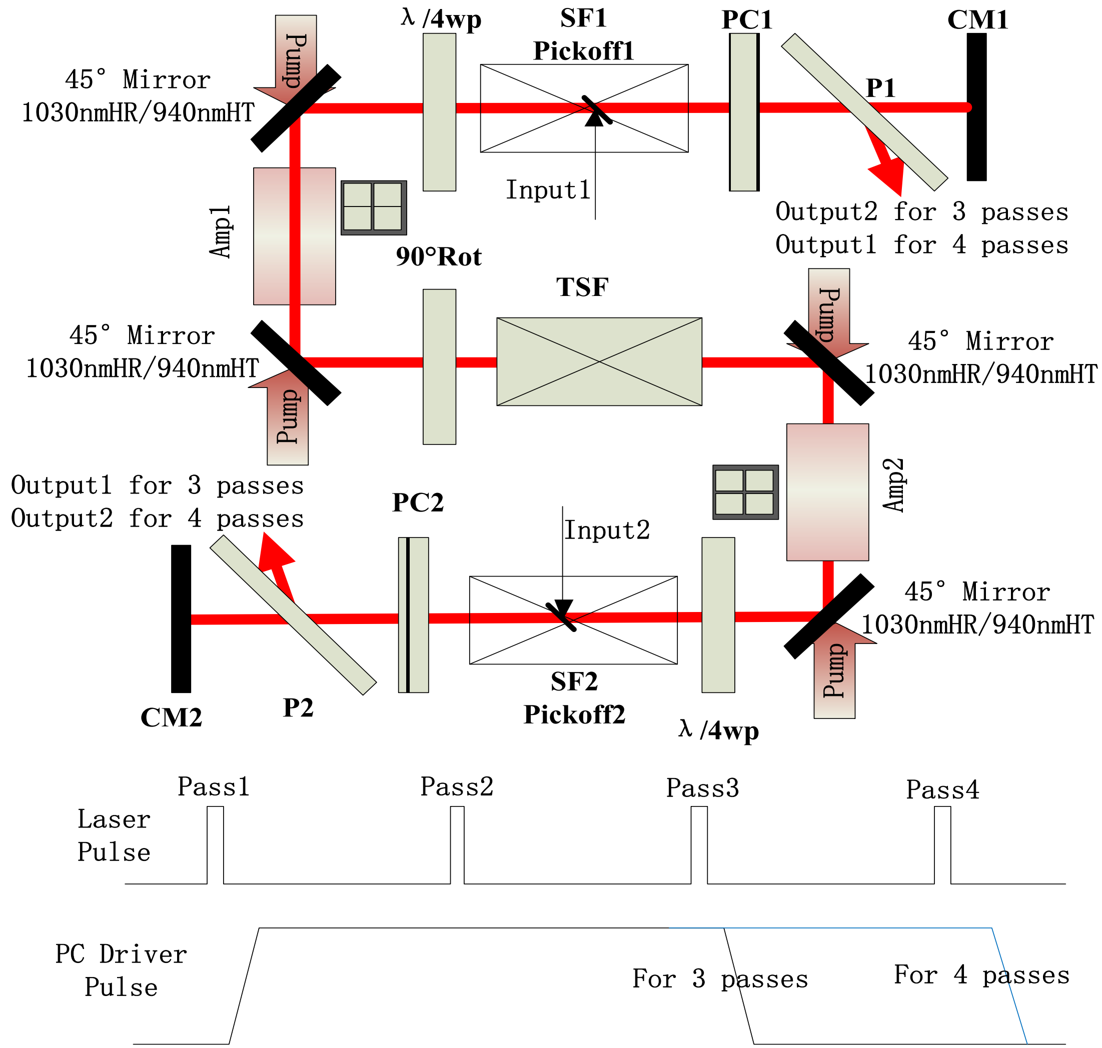
- Although the extratable energy storage is High, but the SSG are same. Energy storage will be higher at room-temperature because of the lower emission section.
- So to achieve large output beam energy, the energy fluence must be higher, this will lead a damage of components.
- For 50kW/cm^2 pumping on 2X2 gain medium, at RT, the maximum extractable energy fluence will be 24.69J/cm^2, it exceeds the damage threshold.
- How to solute the problem???





Configuration of main amplifier

- **Double pulse amplification**
  - Total energy fluence can be keeping in high (about 20J/cm^2), but for single pulse, it only about 10J/cm^2, it is far lower than the damage threshold.
  - The efficiency of energy conversion will be high (close to single pulse amplification)
  - The more energy can be achieved in one amplifier.
  - It is alterable, it can perform 3 passes or 4 passes amplification.

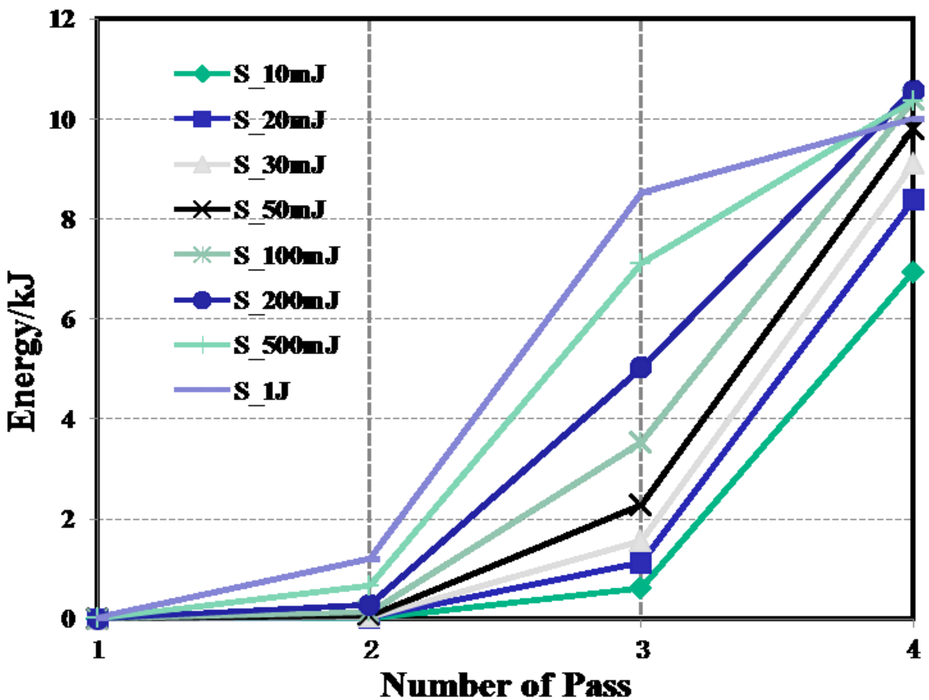


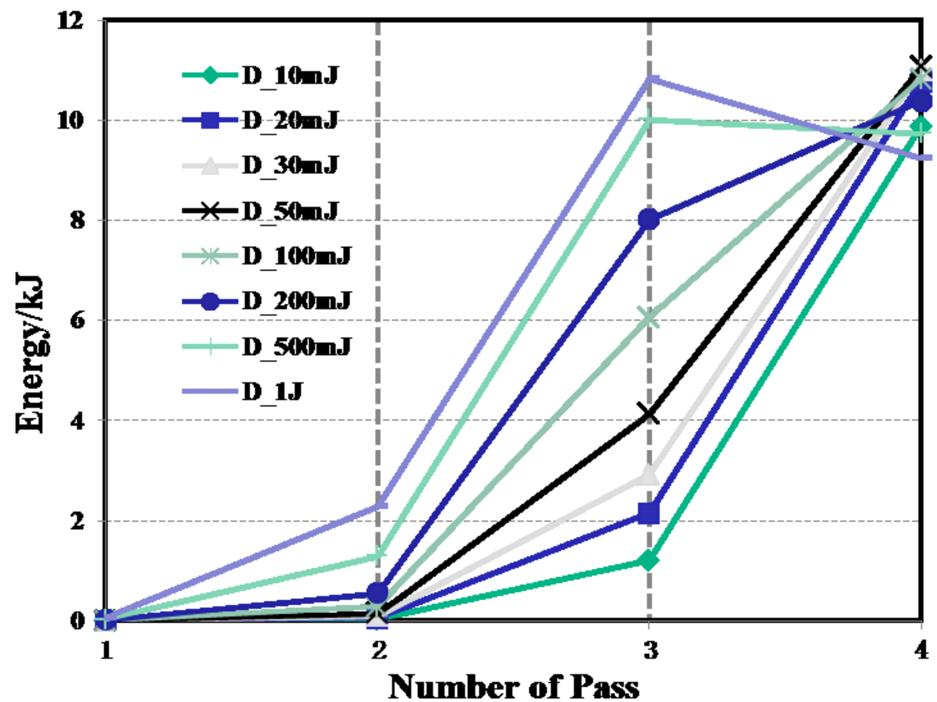
Evaluation of amplification

- **Condition of calculation**
  - **The loss was 0.3 for a single pass through whole amplifier.**
  - **The total energy storage was about 12kJ for the two laser head, SSG was about 0.15cm^{-1}**

Evaluation of amplification

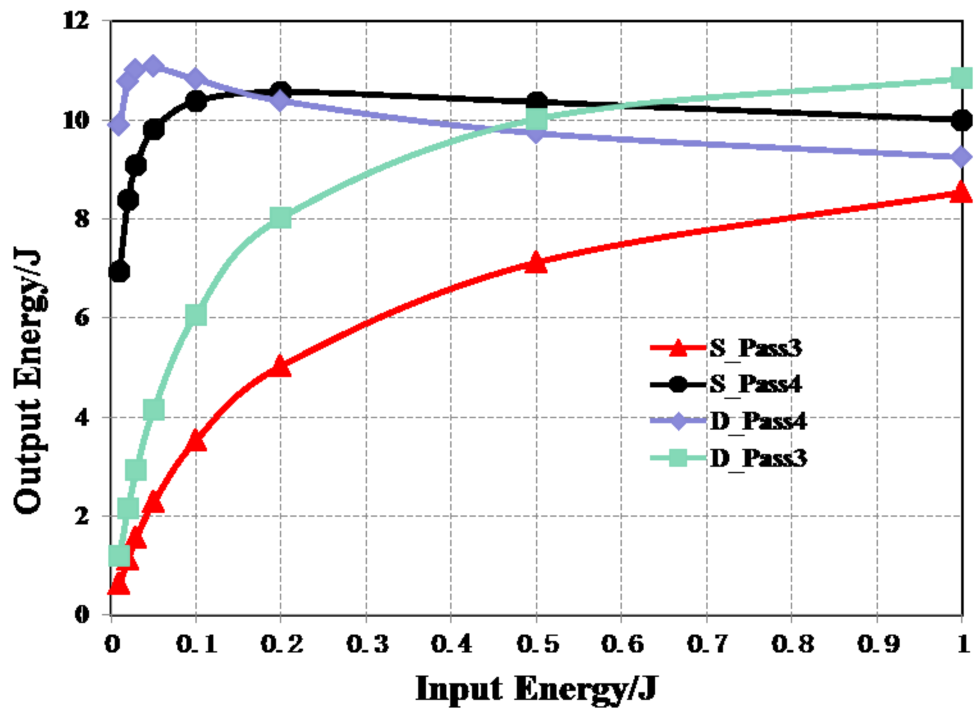
- **Extracted energy**
  - **For single pulse amplification the maximum output energy occurred at the last pass for the input from 10mJ to 1J. But for double pulse amplification it might occurred at the third pass, and more output energy can be achieved.**





Evaluation of amplification

- **Extracted energy**
  - For single pulse amplification the output will be increasing for the input from 10mJ to 1J. But for double pulse amplification the output energy has a maximum. Furthermore, the maximum is higher than the single pulse, the input is lower than the single pulse. It means that, we can achieve more energy from the amplifier, at the same time, the input is low, it will reduce the difficulties of the input laser pulse!!!



Summary & prospect

- Demonstrated the 10J water-cooled laser system, 8.5J/1Hz/10ns laser pulse was achieved. The beam quality 10DL , Energy efficiency more than 6%.
- The temperature increased from 302.5K to 308K with the increasing of frequency from 1Hz to 10Hz.
- The main reason for limitted output is that the pulse front edge and back edge overlaid and the concentration of ion was too high, leading serious ASE loss.
- Optimized the laser system, the output would be increased to 10J.
- Double pulse amplification in a single amplifier was evaluated, it shows a attractive advantage for the kJ-class high efficiency amplification.
- Next step
  - Annular light path to avoid the damage
  - 5mm thickness crystal(3at.%) to decrease the ASE and increase the gain of amplifier.
  - Use Adaptive Optics to correct the wavefront aberration.
  - Demonstrate the double pulse amplification in 100J laser system.


Thanks for your attention!