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DEVELOPMENT OF INNOVATIVE REPEATABLE POWER LASER FOR LASER FUSION

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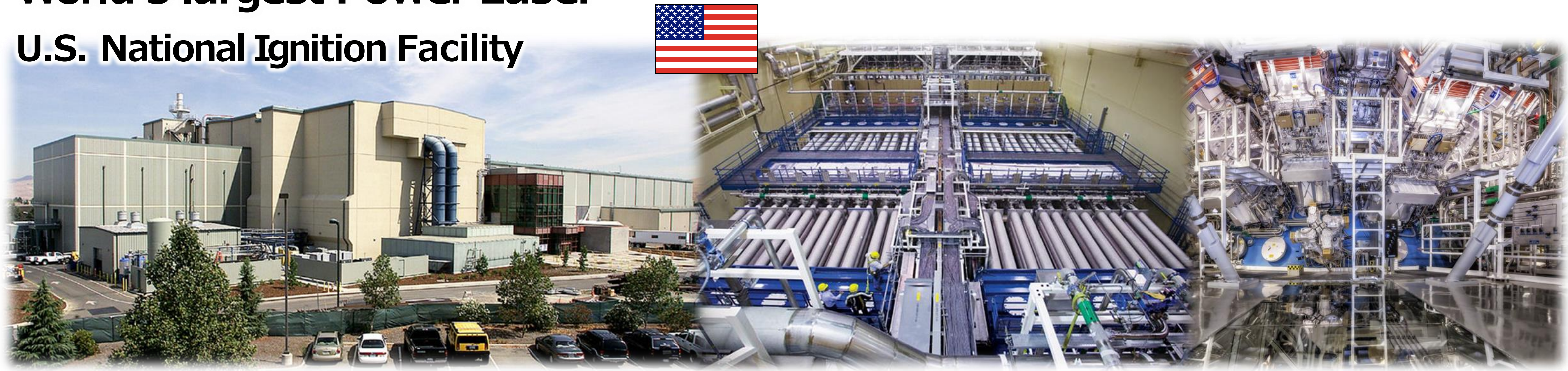
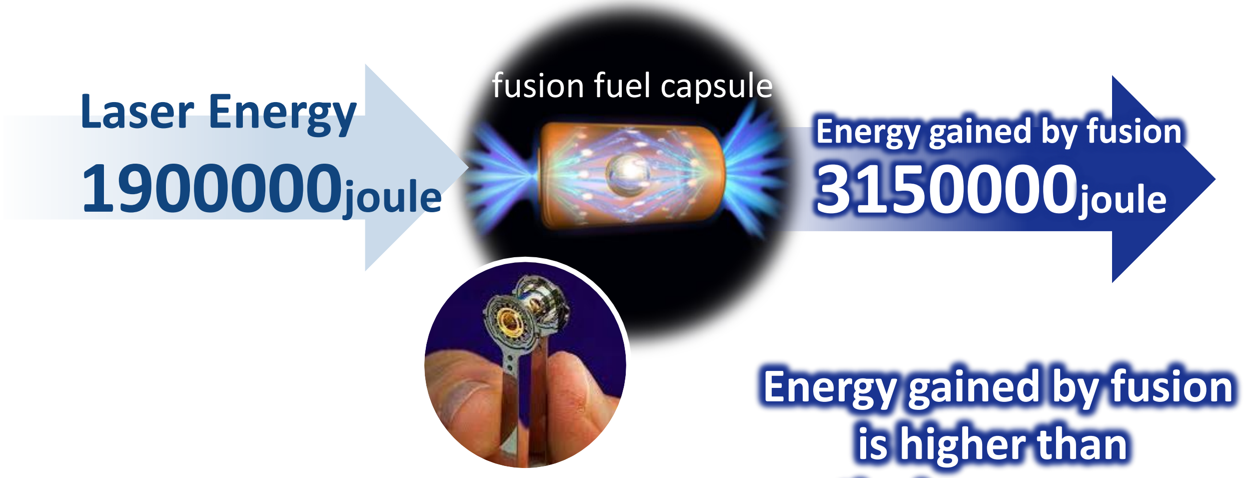
Motivation – Toward Practical Laser Fusion

World's largest Power Laser

U.S. National Ignition Facility





Energy gained by fusion is higher than the laser energy

Global Milestone

- In December 2022, the **National Ignition Facility (NIF)** at Lawrence Livermore National Laboratory achieved **fusion ignition, for the first time**
- This success marked a historic milestone for laser fusion research

Motivation – Toward Practical Laser Fusion

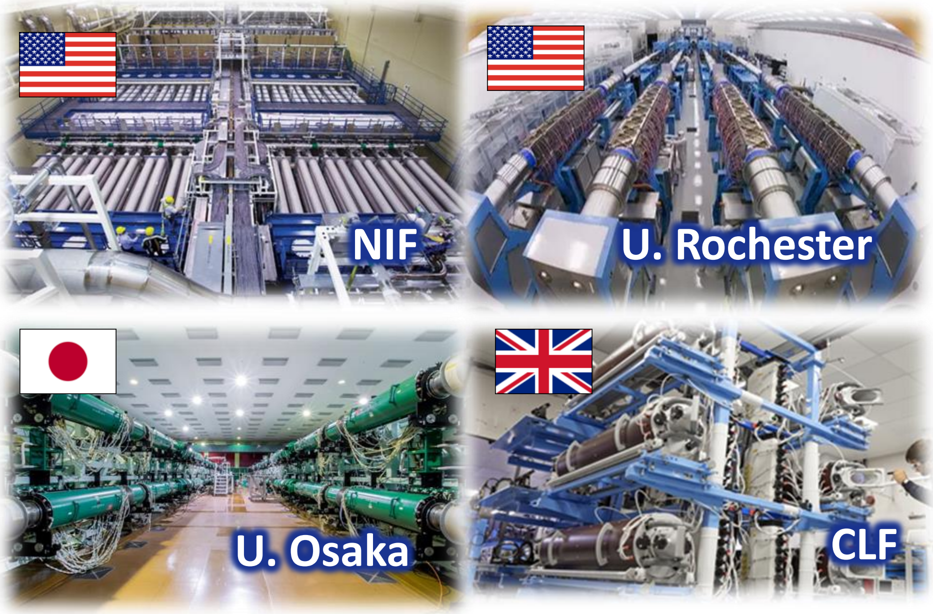
Contribution from ILE

- ILE also contributes to IFE research through facilities such as **GEKKO-XII** and **LFEX.**

Motivation – Toward Practical Laser Fusion

✓ **To realize sustainable fusion power and accelerate research**
There are the key challenges must be overcome in current laser systems.

Current high energy laser system
kJ - MJ



Key Challenges

- Operate at **single-shot mode.**
- **Low plug efficiency : <1%**

Need to improve **efficiency** and **repetition rate**
→ Essential for **sustainable fusion power**
→ Enables **AI-assisted control** and **real-time optimization**

Our Goal

- Develop a **next-generation laser system** that can be a **game-changer** in laser fusion research

From Flashlamp-Pumped Glass Lasers to Diode-Pumped solid-state laser

✓ **Why current high energy laser system low plug efficiency and reptation rate.**

Current laser system

Energy flow of the laser system:

Cooling 75%

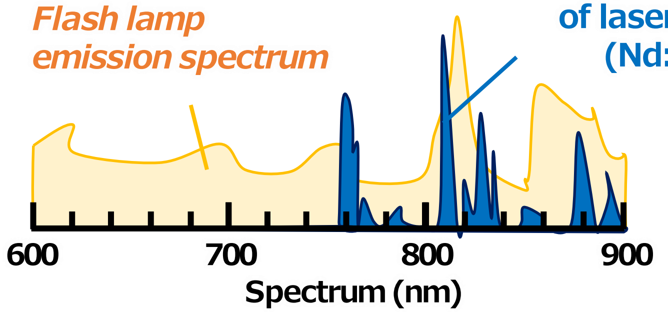
Source → 96% → Pump (Flash lamp) → 2% → Absorption → 92% → Extraction → 60% → Frequency conversion → 60% → Laser on target

Plug efficiency = 96%· 2% · 92%· 60%· 60%· 75% < 1%

National ignition facility user guide, LLNL last updated 09.08.2024

Critical issue : Low electro-optical efficiency

Pump source: Flash lamp



- **Flashlamp emits broad white light**: Only a small part of it overlaps with the absorption band of gain medium

From Flashlamp-Pumped Glass Lasers to Diode-Pumped solid-state laser

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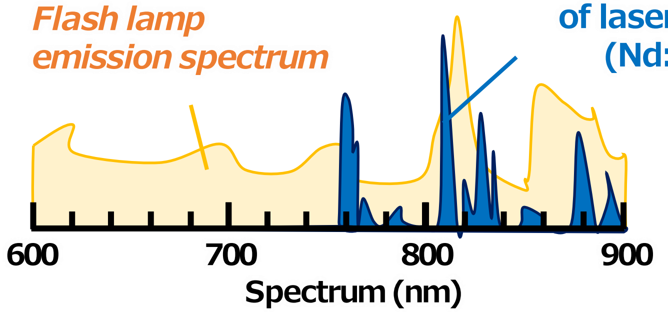


- **Flashlamp emits broad white light**: Only a small part of it overlaps with the absorption band of gain medium

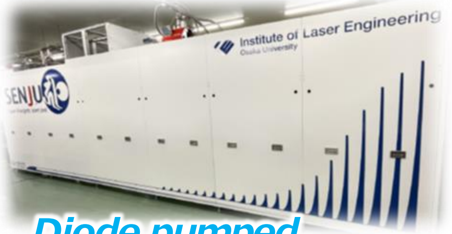
Critical issue : Low thermal conductivity

Laser medium :
Glass (Nd:glass)

- **Glass gain medium** has low thermal conductivity (1W/m·K): long time to remove the heat: **Few shots par day**

✓ To overcome the limitation, many groups are developing **DPSSL**

New laser system



Diode pumped solid-state laser: DPSSL

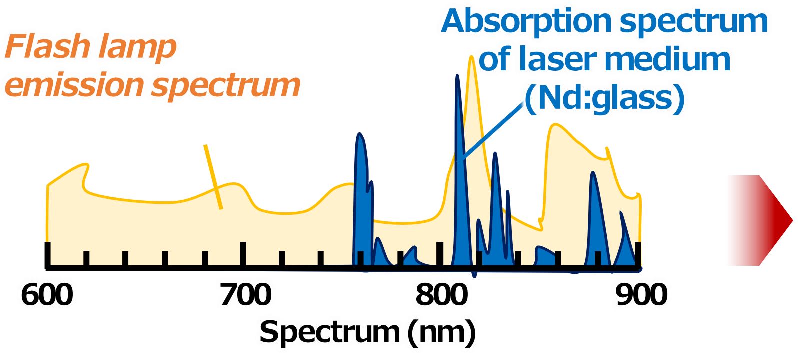
Energy flow of the laser system:

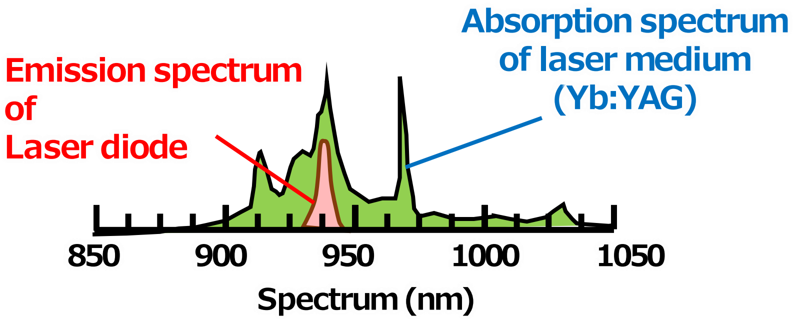
Source → 96% → Pump (Laser diode) → 60-70% → Absorption → 92% → Extraction (Cooling 75%) → 60% → Frequency conversion → 60% → Laser on target

Plug efficiency = 96%· 60-70%· 92%· 60%· 60%· 75% > 10%

Improvement: High electro-optical efficiency

Pump source: Flash lamp





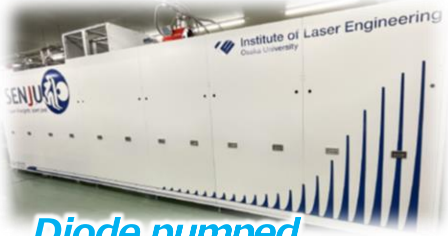
Pump source: Laser diode

- **The laser diode** has **high potential for electrical-to-optical efficiency**, theoretically reaching **60 to 70%**
- Emits **narrow-band light** that matches the absorption band of the laser medium: **High efficiency** compared flash lamp

From Flashlamp-Pumped Glass Lasers to Diode-Pumped solid-state laser

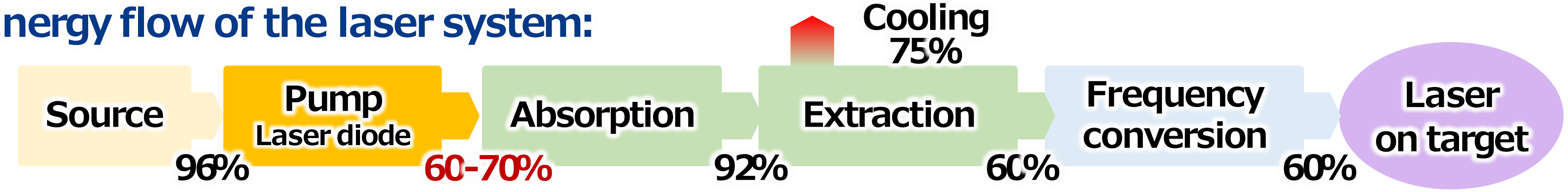
✓ To overcome the limitation, many groups are developing **DPSSL**

New laser system



Diode pumped solid-state laser: DPSSL

Energy flow of the laser system:



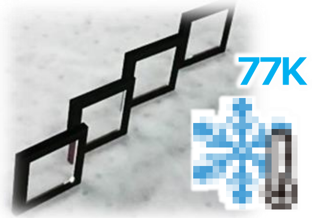
Plug efficiency = 96%· 60-70%· 92%· 60%· 60%· 75% > 10%

Improvement: High thermal conductivity

Laser medium :
Glass (Nd:glass)

- **Glass gain medium** has low thermal conductivity (1W/m·K): long time to remove the heat: **Few shots par day**

Laser medium :
Ceramics (Yb:YAG)

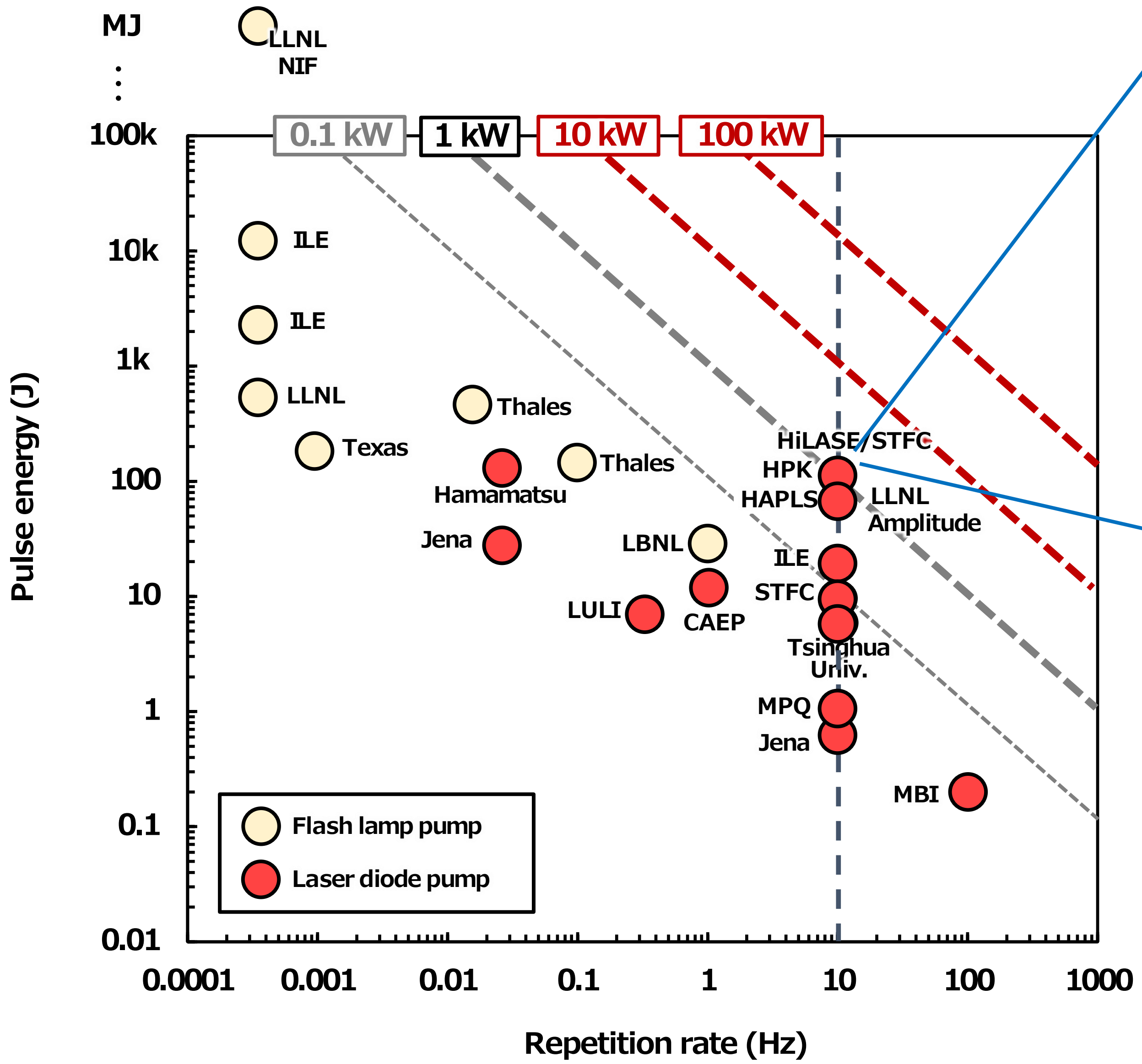


- **Ceramics** is **High thermal conductivity**
- **Cryogenic Yb:YAG ceramics: Fifty times higher thermal conductivity** than glass. (50 W/m·K @ 77 K)
- **Improved thermal and laser performance at cryogenic temperature**

Global Trends in POWER LASERs

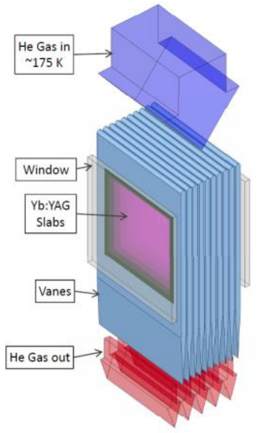
Institute of Laser Engineering
Osaka University

✓ Several systems are using cryogenic Yb:YAG ceramics

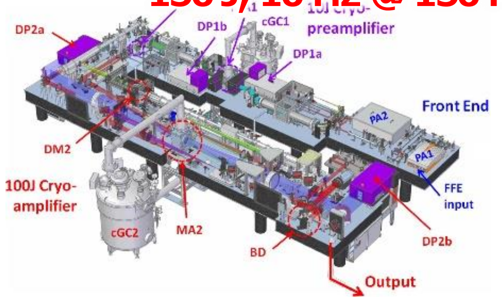


Current mainstream repetition rate: 10 Hz

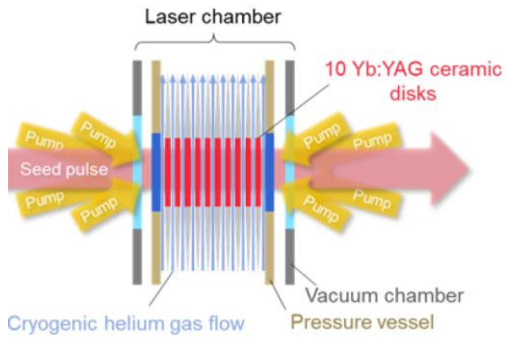
HiLASE/STFC (UK, Czechia)



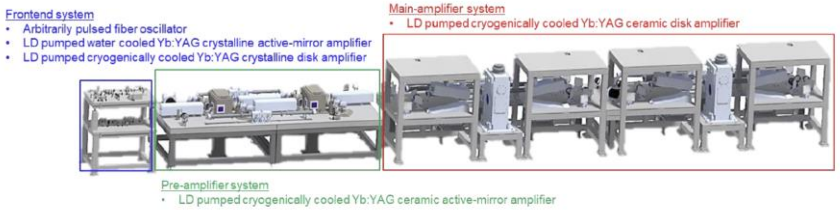
Gas-cooled Split-Disk
of Yb:YAG ceramic
150 J, 10 Hz @ 150 K



HAMAMATSU (Japan)



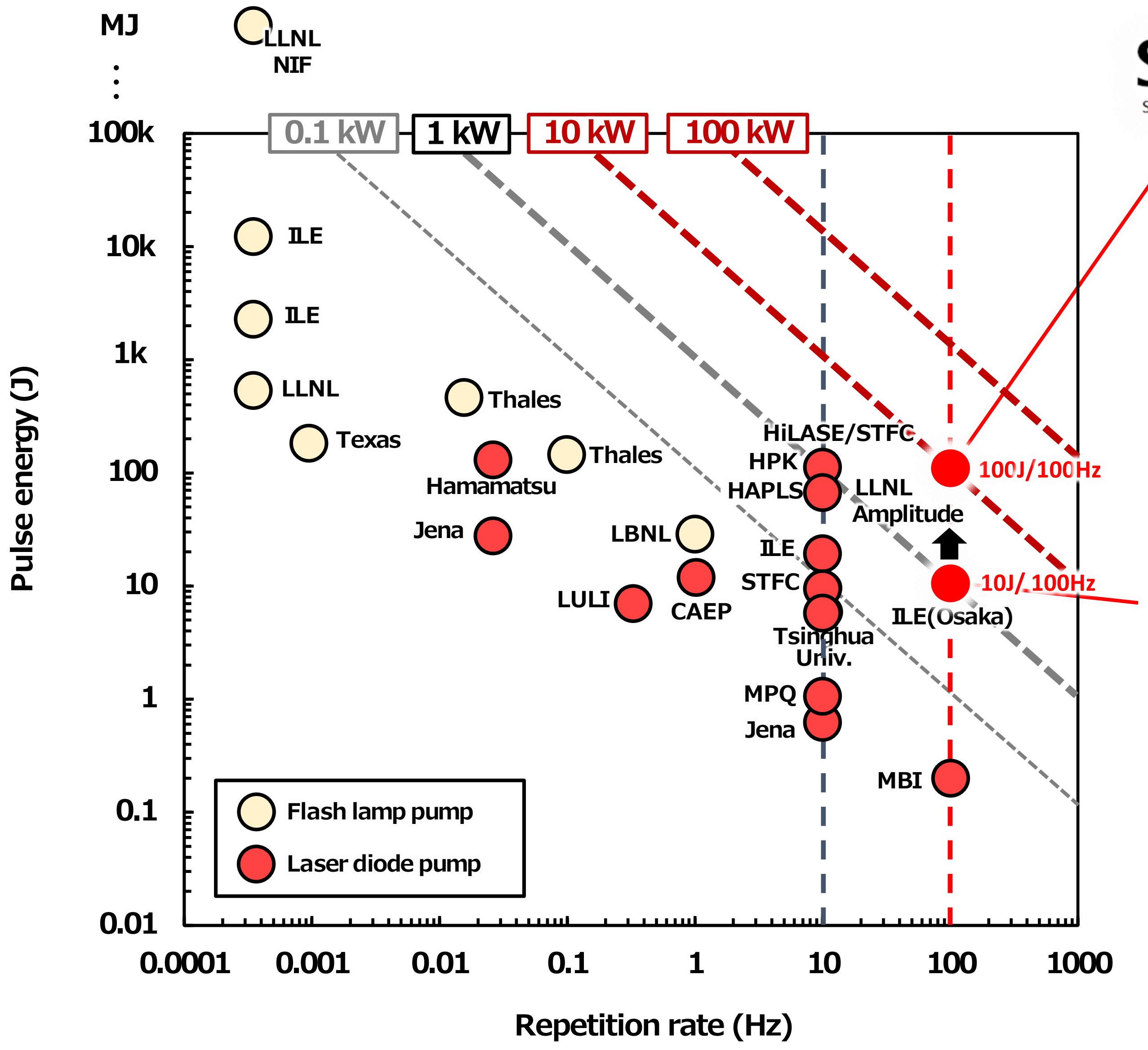
Gas-cooled Split-Disk
of Yb:YAG ceramic
200 J, 10 Hz @ 150 K



POWER LASER developments at ILE

Institute of Laser Engineering
Osaka University

✓ Our project aims for a ten-times higher repetition rate to realize a stable laser driver.

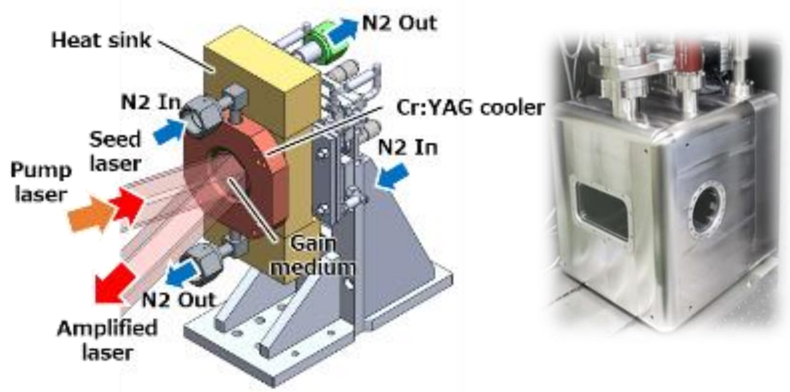


Cryogenically-cooled (77K)
Active-mirror of Yb:YAG ceramic
100 J, 100 Hz (10kW), 10 ns

Based on module concept to achieve even higher energy levels.

SENJU-Lite

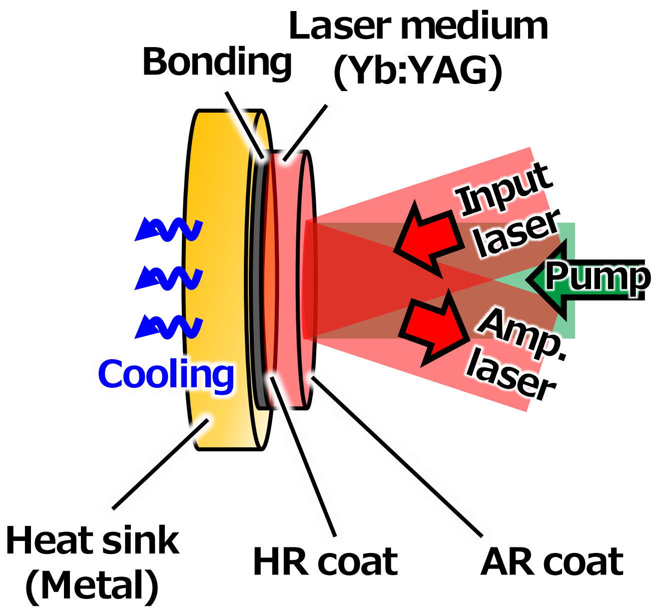
Cryogenically-cooled (77K)
Active-mirror of Yb:YAG ceramic
10 J, 100 Hz, 10 ns



For development elemental technology.

Amplification method: Conductive cooled active-mirror

Conductive cooled active-mirror

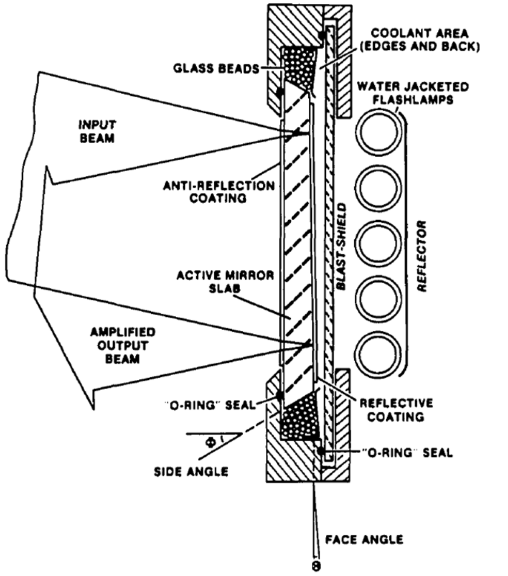


- **Simple structure**
  - Disk like laser medium with AR and HR coatings on each side
  - HR coating **works as a mirror**
    → amplification & reflection at the same time
- **High heat removal performance**
  - Gain medium **directly bonded** to metal heat sink
  - Cooling direction **along beam path**
    → minimize thermal distortion and lensing
- **Scalable design**
  - **Number of disks easy adjust** → easy power scaling

Amplification method: Conductive cooled active-mirror

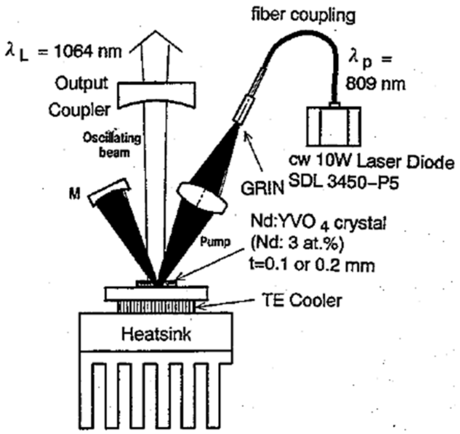
✓ **Active-mirror laser architecture is not a new concept.**

GE & Rochester
Φ15 cm, 245 J, 1 shot / 15 min



J. A. Abate et al., Appl. Opt. 20, 351 (1981).

University of Electro-Communications, (Tokyo, Japan)
Diode pumped, CW

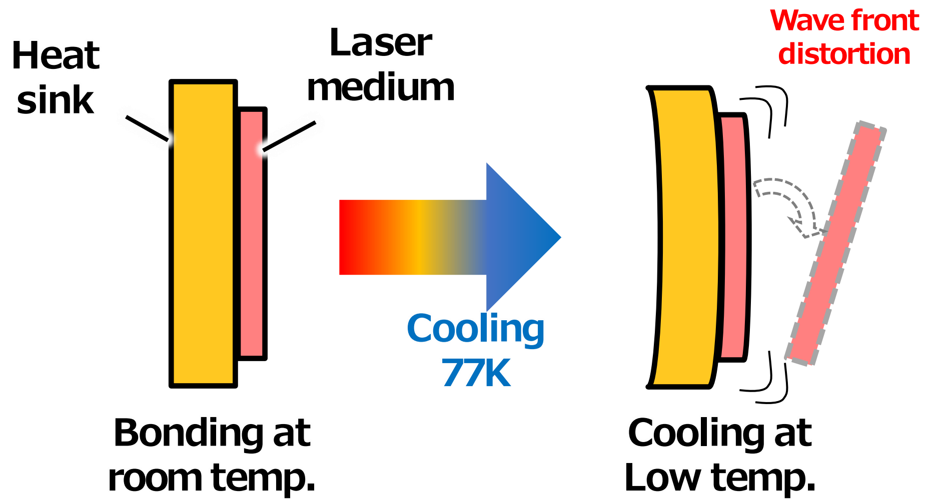


K. Ueda and N. Uehara, Proceedings of SPIE. 1837, 336 (1993).

- **Active-mirror laser concept has been studied since the 1980s.**
  – Basic principle was already demonstrated
  – However, scaling up to large aperture is difficult
- **To achieve >10 J output energy,**
  – Large-aperture (cm-class) laser medium is required
  – Large apertures present challenges.

Thermal Stress Challenges in Conductive-Cooled Active Mirror Lasers

✓ **The main challenge is thermal stress.**



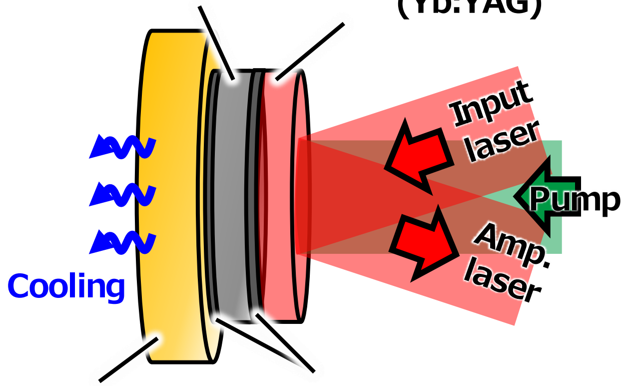
- **Thermal expansion mismatch** between heat sink and laser medium
  - High stress at the bonding interface during cooling
  - Causes **wavefront distortion** and reduced beam quality
- **Gap formation** at the interface
  - Increases **thermal resistance**, reduces cooling efficiency

Reliable bonding technology is critical for practical systems

Active-mirror laser : Bonding technology

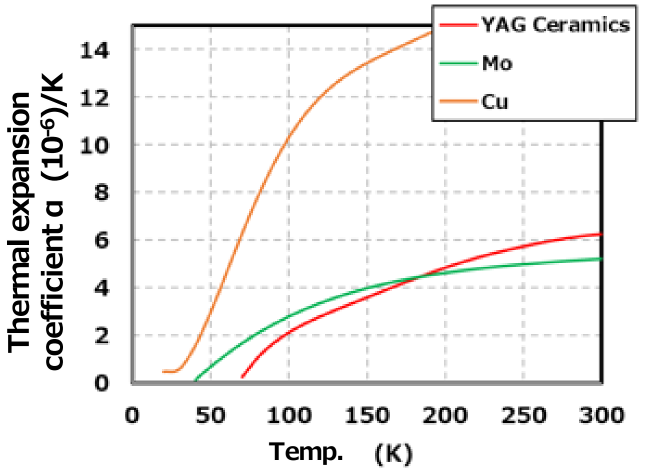
✓ **We solved the thermal stress challenge of active-mirror laser system.**

Conductive cooled active-mirror (Muti-layer bonding structure)



- **Matched thermal expansion**:
  – Use **molybdenum**, with thermal expansion close to laser medium
  – Inserting a molybdenum disk : **Greatly Reduces** stress

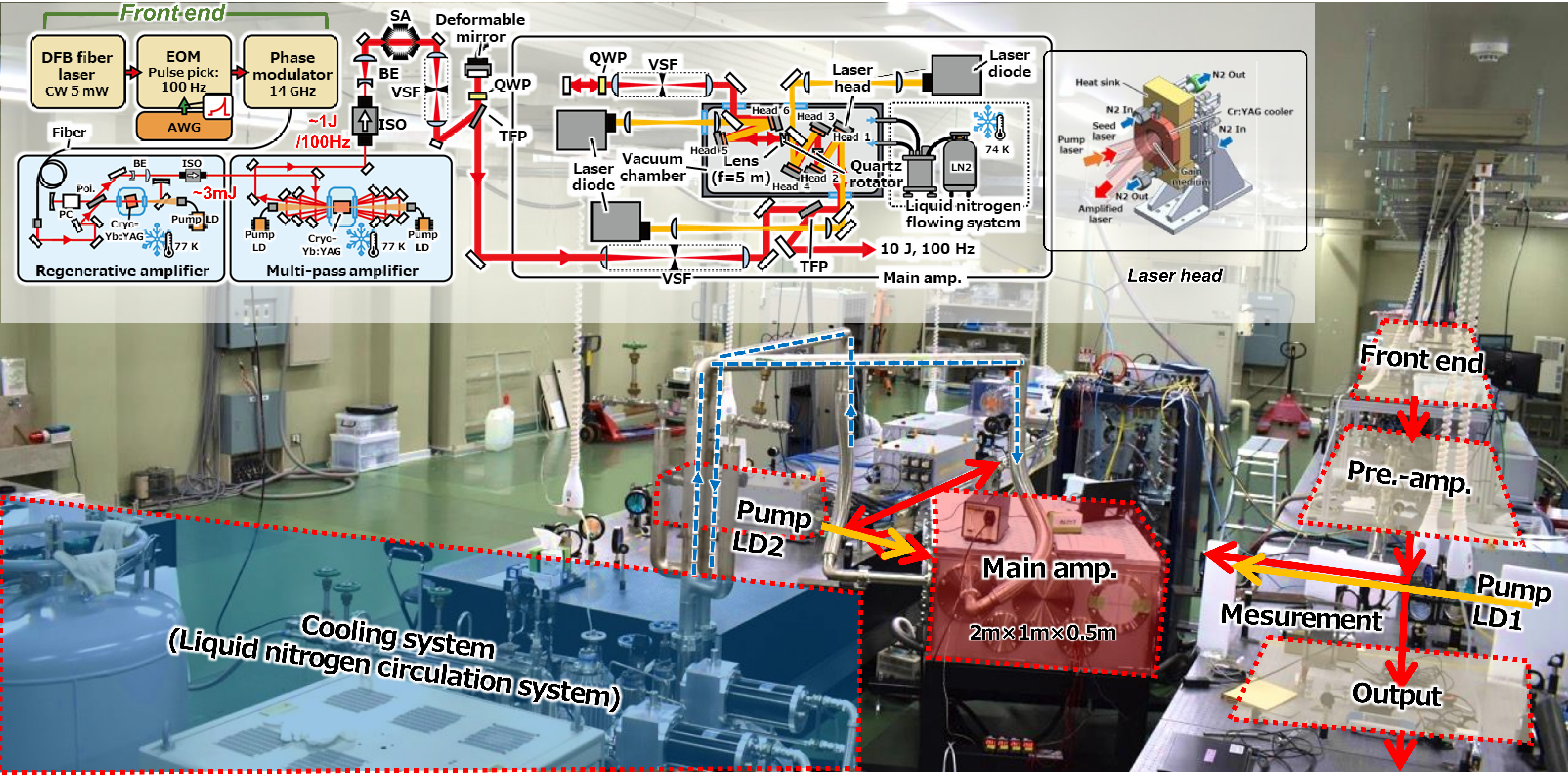
Temperature dependence of CTE



- **Reinforcing parts**:
  – Mo has high Young’s modulus
  – Prevents deformation transfer from the heat sink
- **Buffer layer**:
  – Bodied by a soft metal that reduces stress
  → improve thermal contact

Based on this bonding technology, achieved a **repeatable high-power laser system.**

SENJU-Lite 10 J, 100 Hz Conductive cooled active mirror laser system



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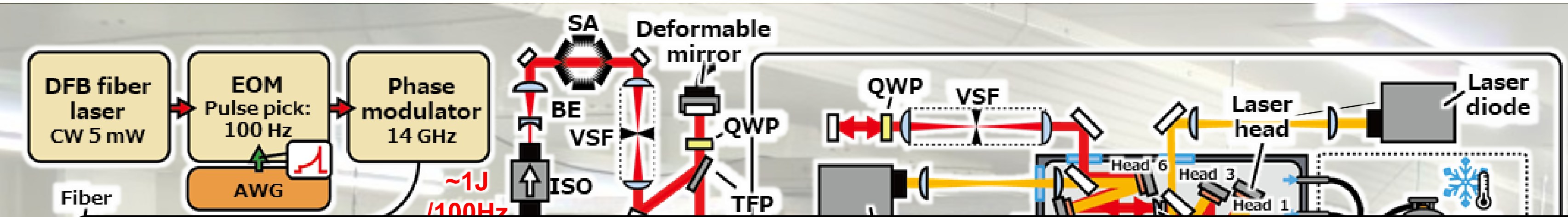
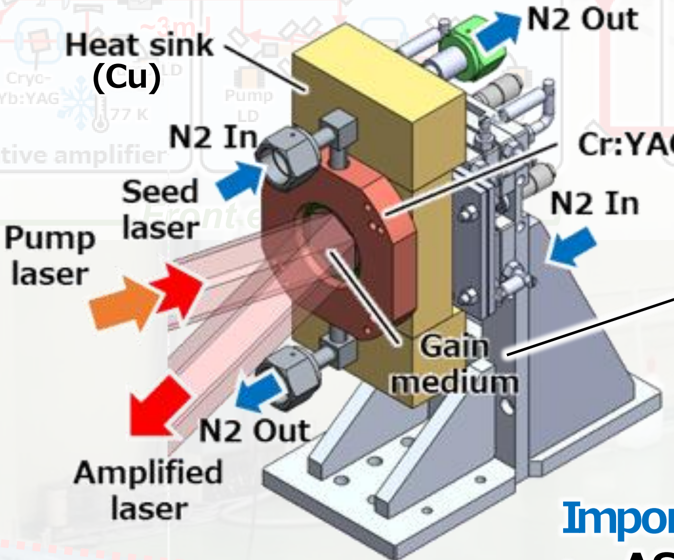
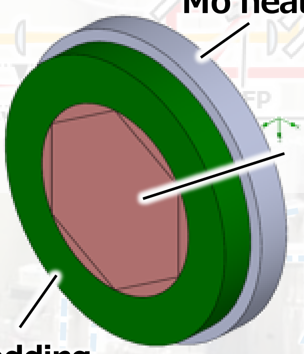
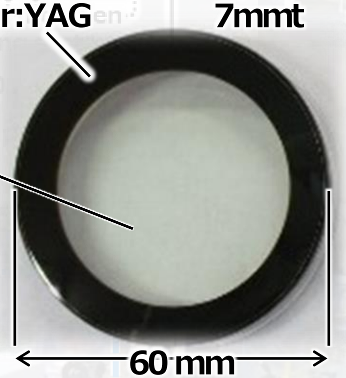








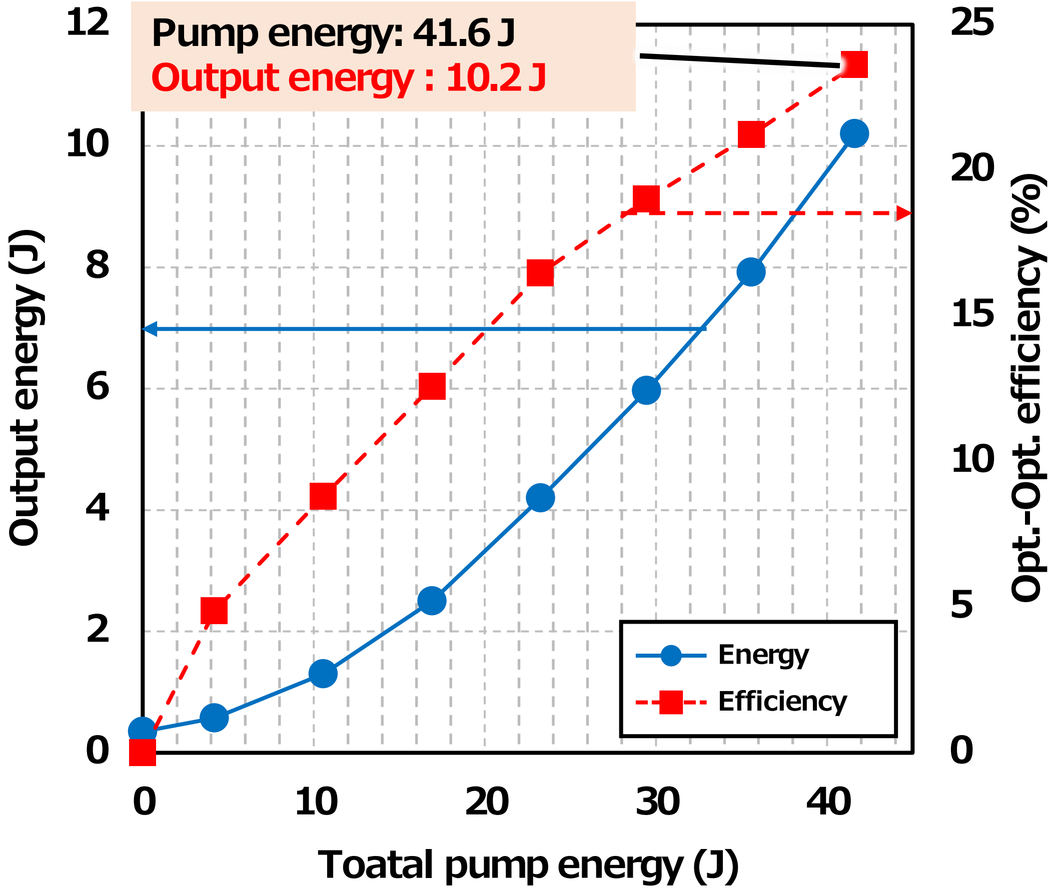
Important point: ASE control and edge-cladding cooling

- **ASE** (*Amplified Spontaneous Emission*) reduces laser gain.
- ASE circulates inside the gain medium: **Parasitic oscillation**
- **Cr:YAG edge cladding** absorbs ASE and prevents this oscillation.
- Edge cladding hot and transfers heat to gain medium.
- **Cooling jacket:** Connected to a LN_2 circulation system for locally cooling

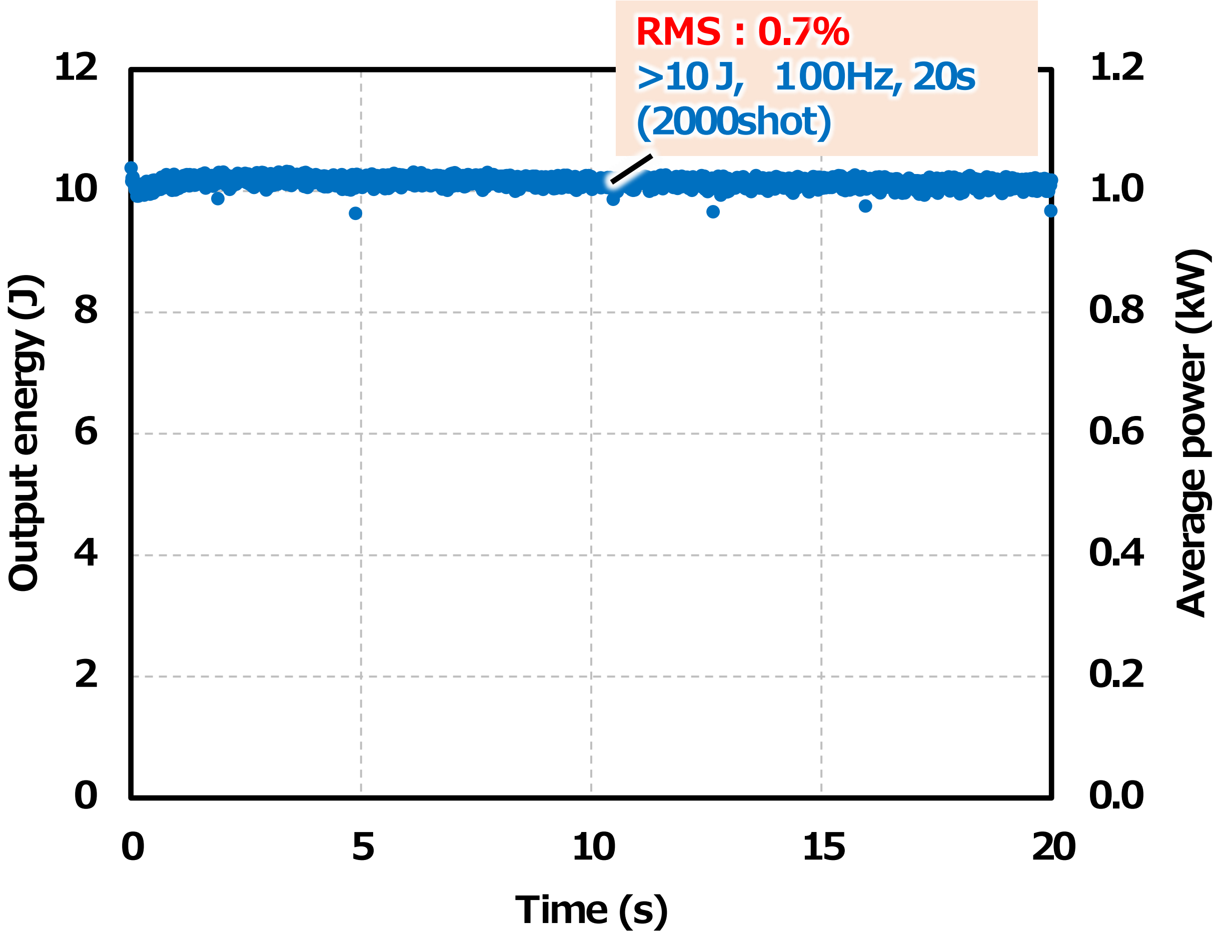
Stable ASE control and efficient edge cooling enable repeatable high-power operation.

Experiment result of 10 J, 100 Hz

Amplified energy and efficiency



Output stability

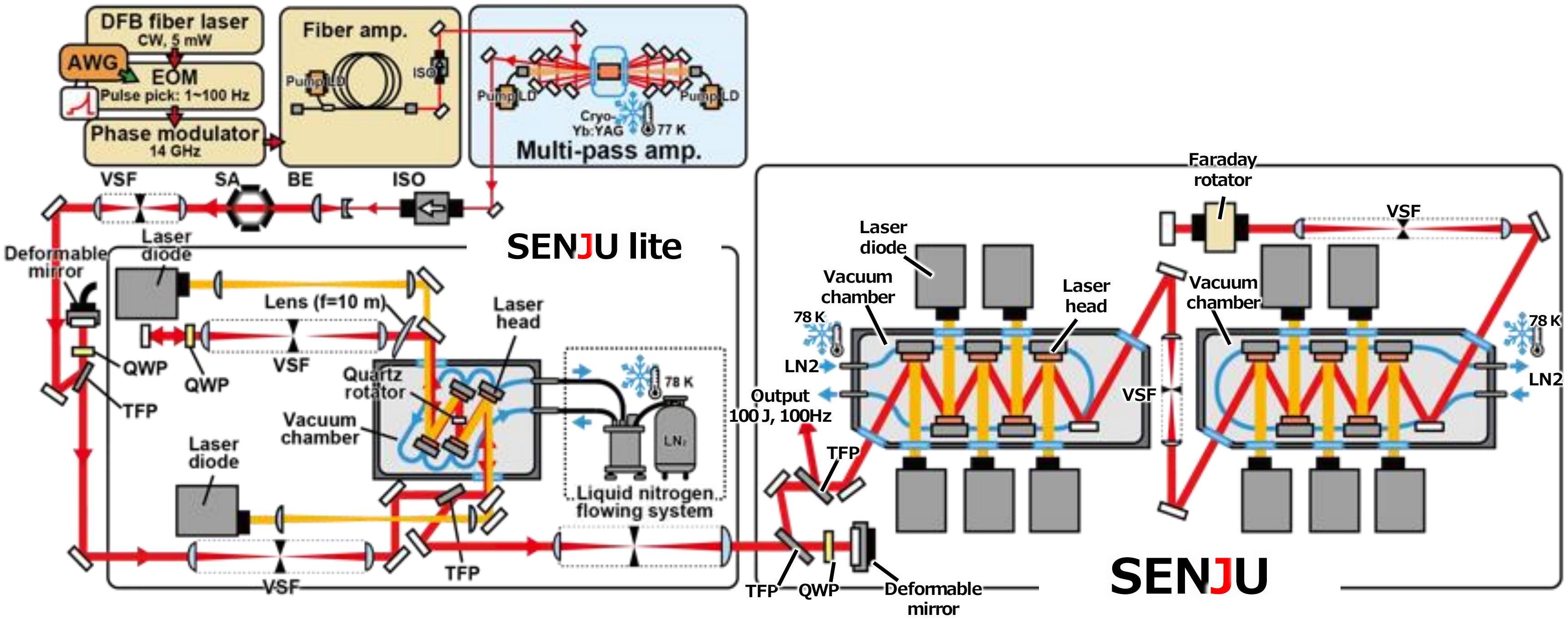


High plug efficiency

- Optical-to-optical efficiency: **23.6%**
- Pump LD electro-optical efficiency: **>50%**→ Indicates **high plug efficiency**

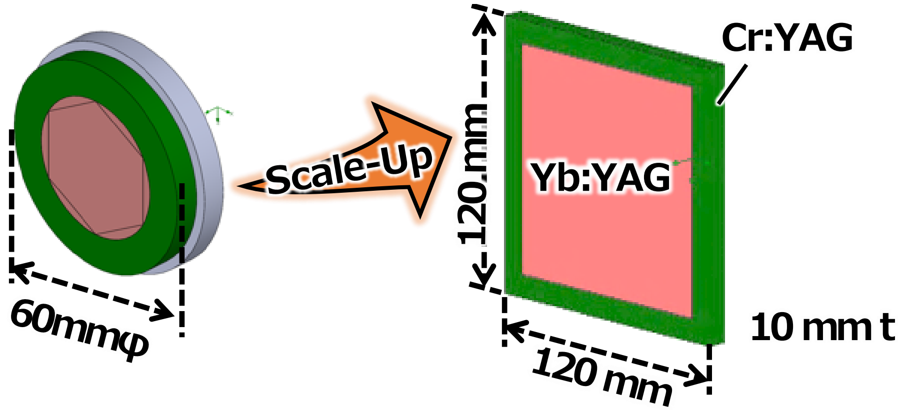
Demonstrated **e⇦cient** and **repeatable** laser technologies.

SENJU 100 J, 100 Hz active-mirror laser system



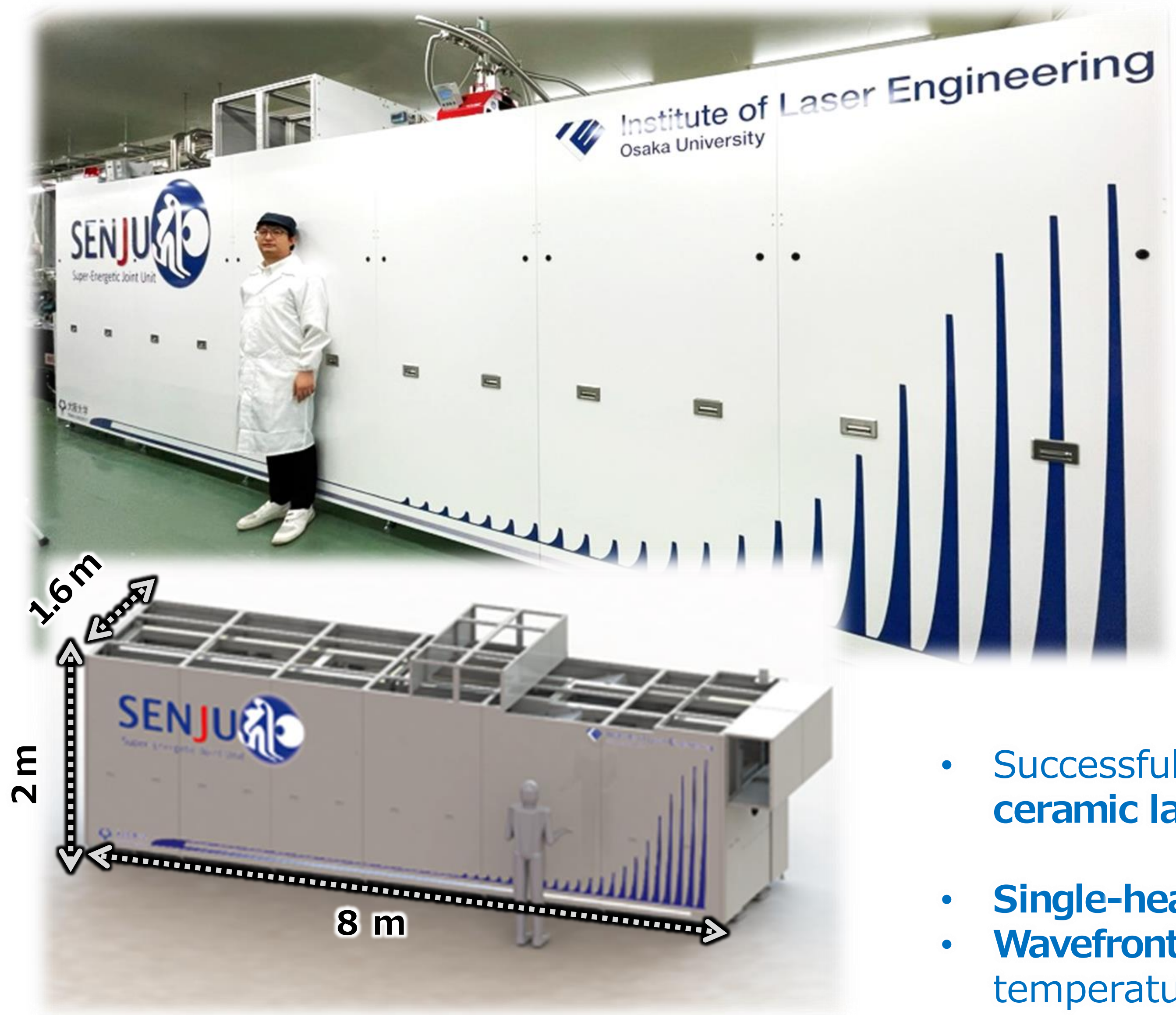
SENJU system design

- SENJU-lite output is used as the seed for SENJU.
- Laser medium size: **60 mm → 120 × 120 mm.**
- Number of amplifier heads: **6 → 10**.
- Each head: **conductively cooled active-mirror**.
- **100 J, 100 Hz** operation using the same cooling and control concept as SENJU-lite.

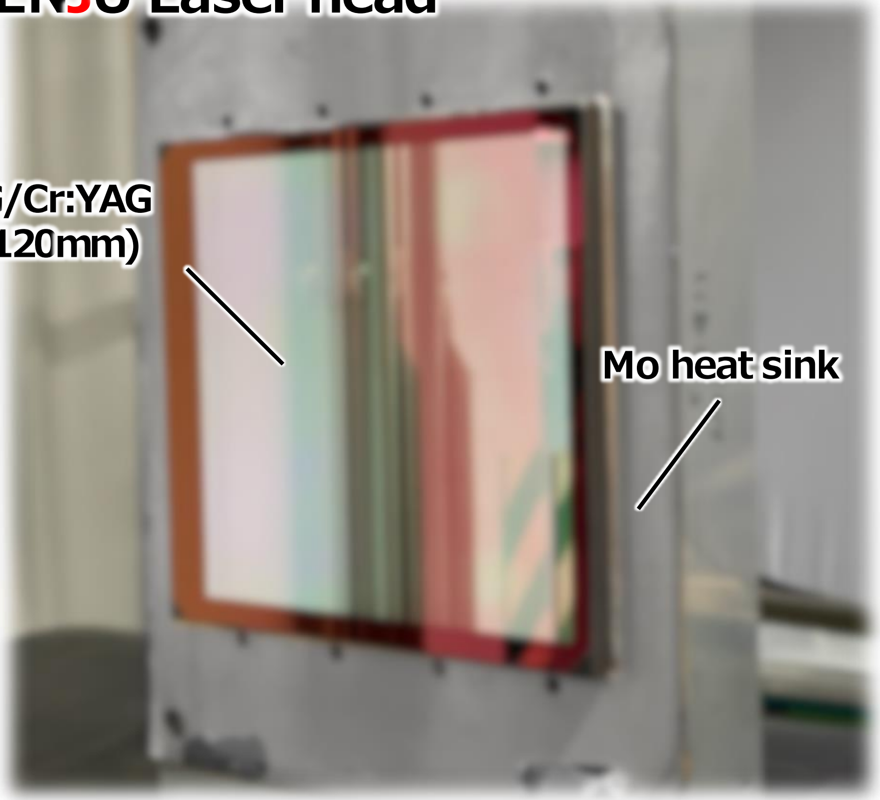


SENJU 100 J, 100 Hz active-mirror laser system

✓ **SENJU: Construction is now in progress.**



SENJU Laser head



- Successfully **bonded Large aperture (120 mm square) Yb:YAG ceramic laser head**.

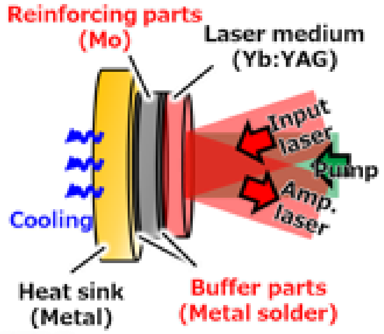
- **Single-head test** confirmed the **designed gain**.
- **Wavefront distortion** during cooling to liquid nitrogen temperature was **extremely small**.

DEVELOPMENT OF INNOVATIVE REPEATABLE POWER LASER FOR LASER FUSION

Validation and technological foundation

- Developed a **conduction-cooled cryogenic Yb:YAG active mirror laser**.
- **SENJU-Lite:** Achieved **10 J, 100 Hz**, **23.6 % efficiency (Plug eff.>10%)**.
- Solved key issues: **thermal stress, ASE-control, parasitic oscillations, thermal management.**
- **SENJU:** construction is now in progress.
- Established **efficient, repeatable, stable and scalable architecture.**

SENJU lite



SENJU

We believe that innovation in laser technology will open the path to laser fusion.

Acknowledgments

This work was supported by

2022-2026 For the Next 50 YEARS
大阪大学
レーザー科学研究所
Institute of Laser Engineering, Osaka University

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KONOSHIMA

EX-Fusion

IFE Laser driver requirement

Parameter	NIF [1]	Power plant*
Laser medium	Nd:glass	TBD
Wavelength	1053 / 351 nm	Green or UV
Pumping	Flash-lamp	Diode
Total energy	3.0 / 2.1 MJ	~1 MJ
Beam lines	192	< 1000
Energy / beam	~15 / 10 kJ	> 1 kJ
Plug efficiency	0.5%	> 10%
Bandwidth	λ_n (SSD) ~ 0.02%	~1% (10nm@1μm)
Temperature	RT @ 20°C	??

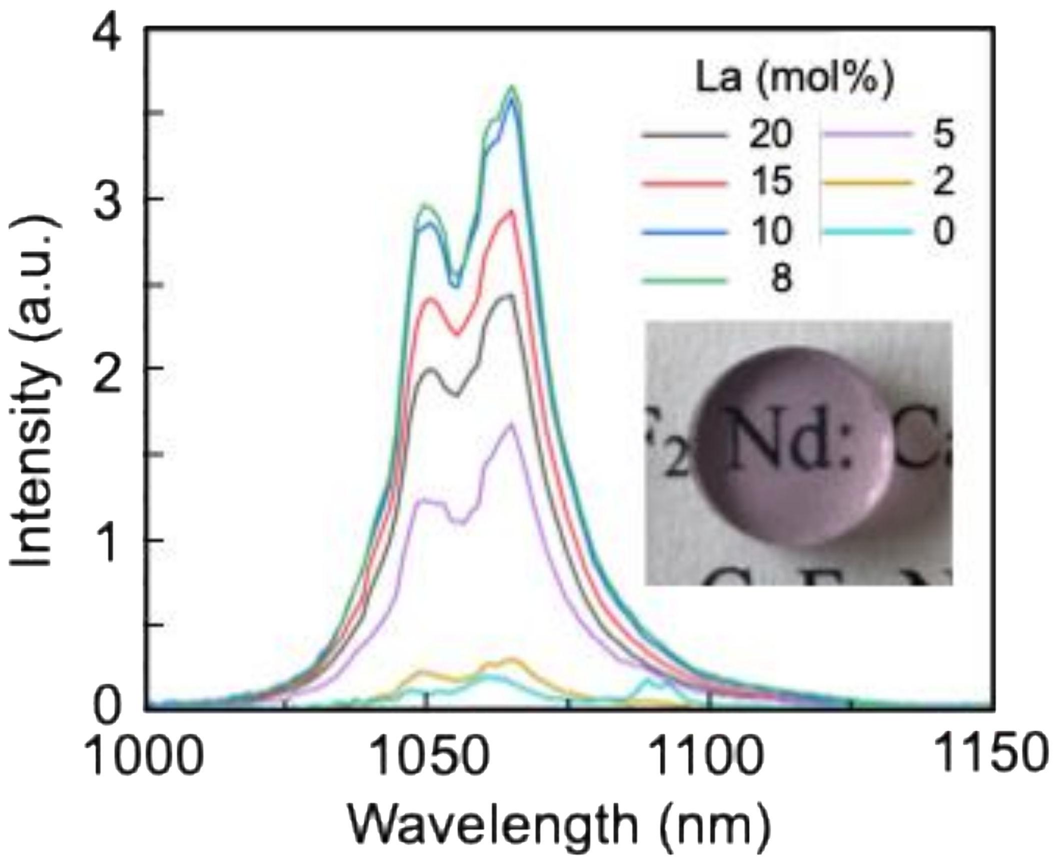
[1] National ignition facility user guide, LLNL last updated 09.08.2024
*** Assuming a direct drive implosion scheme**

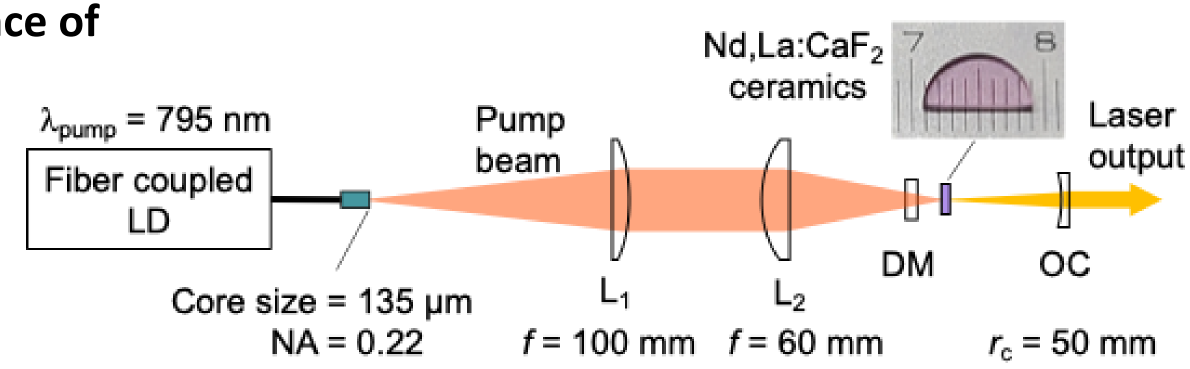
- There are two ignition schemes in IFE: **Indirect drive** and **Direct drive**.
- **Indirect drive:** uses X-rays generated in a hohlraum → requires *narrow bandwidth (~0.02%, ~0.2 nm @ 1 μm)*.
- **Direct drive:** lasers directly compress the fuel → needs *broad bandwidth (1–2%, 10–20 nm @ 1 μm)* for beam smoothing.
- **Cryogenic Yb:YAG lasers:** have narrow bandwidth (~0.1 nm) → suitable for indirect-drive or driver-technology development.
- Bandwidth broadening techniques are being studied (e.g., chirped or tailored gain media).
- The optimal laser medium for future power plants is **not yet defined**.
- Improving **efficiency and repetition rate** remains a top priority for all IFE drivers.

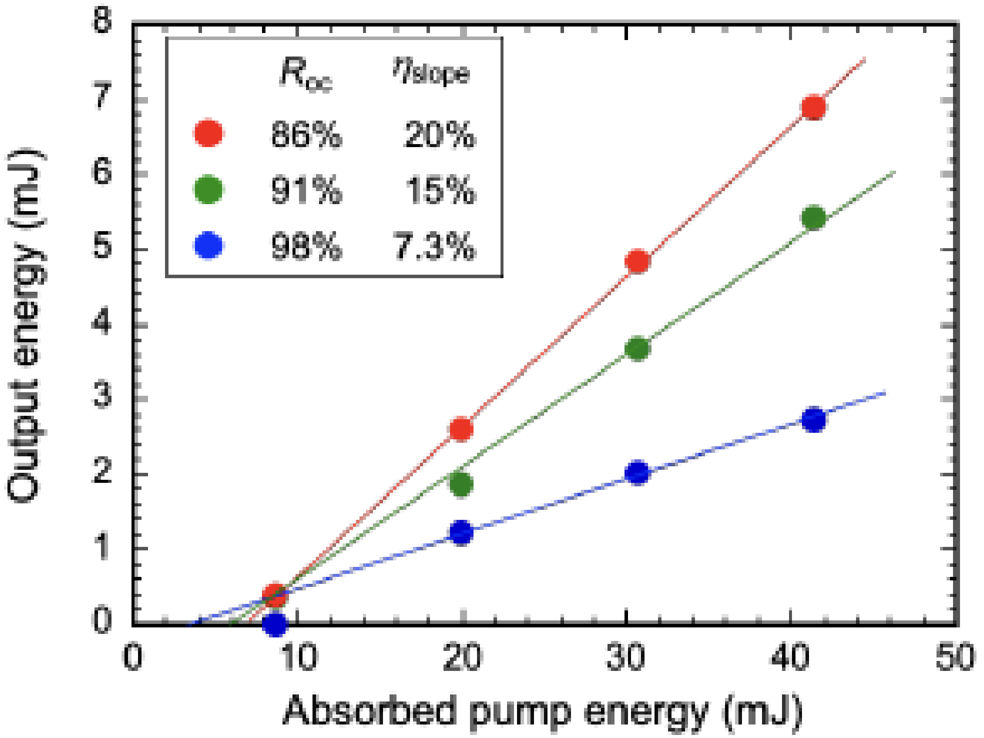
Optical Materials Express

Institute of Laser Engineering
Osaka University

Fabrication, spectroscopic characteristics, and lasing performance of Nd,La:CaF2 transparent ceramics





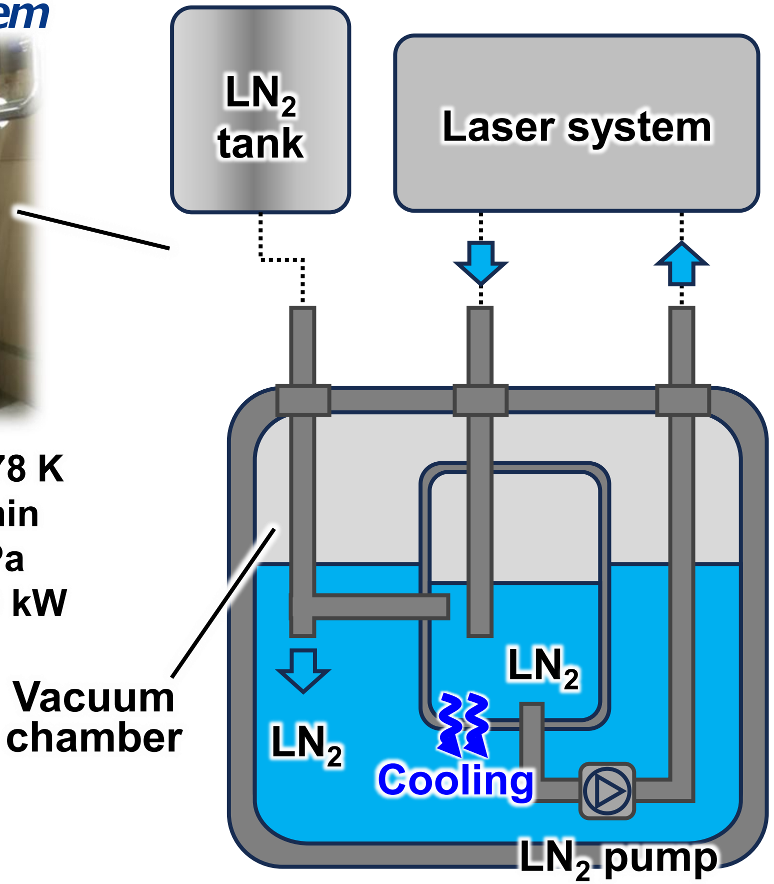


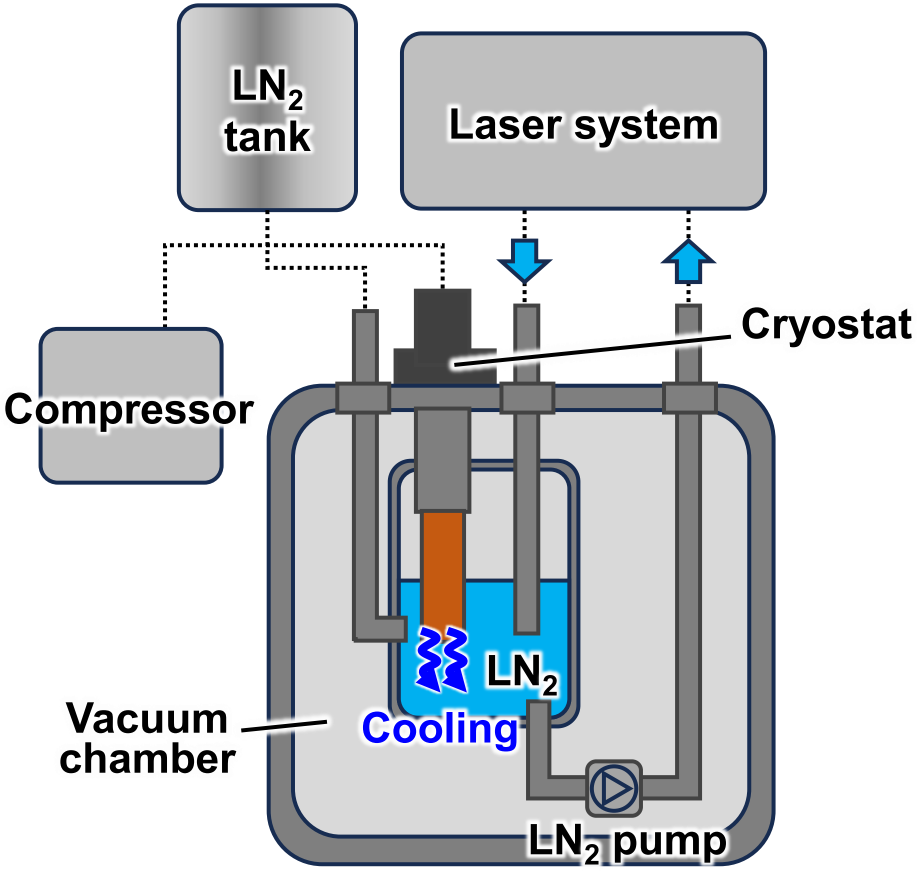
K. Fujioka, Y. Matsumoto, Y. Tamaru, *et al.*,
Opt. Mater. Express **15**(4), 890-902 (2025).

Low-Power LN_2 Cooling System vs. Conventional Cryostat Cooling

Liquid nitrogen flowing system

Cooling temp.: ~78 K
Flow rate: ~12 l/min
Pressure : 0.5 MPa
Cooling cap. : 4.0 kW





Liquid nitrogen flowing system
- LN_2 cooling

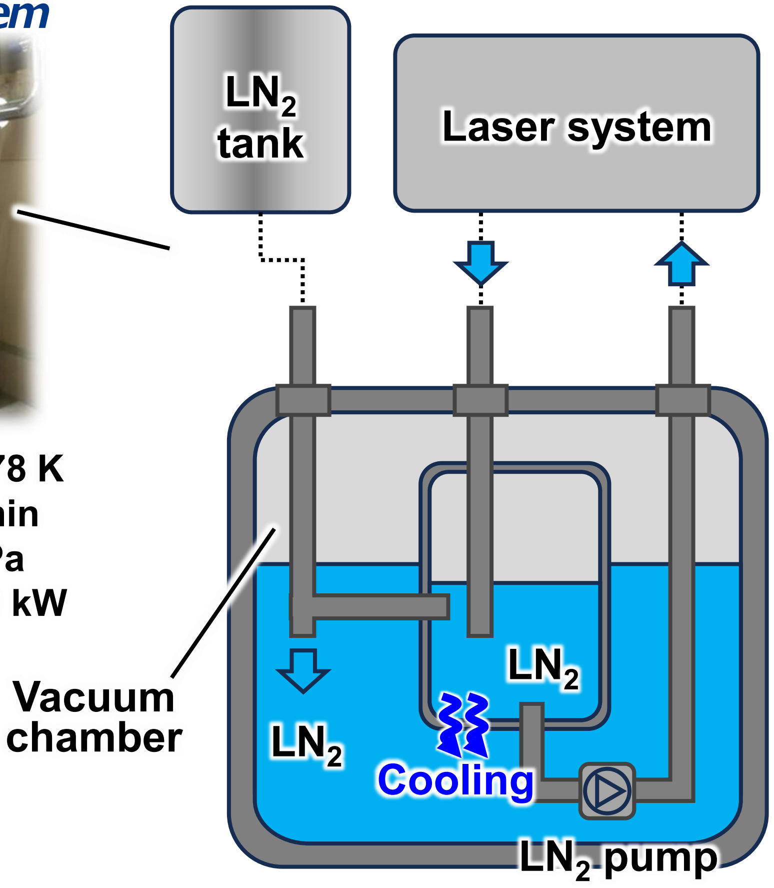
LN_2 cooled by liquid nitrogen itself
: Very low electrical power required

Liquid nitrogen flowing system
- Cryostat cooling

LN_2 cooled by cryostat using a compressor :
Requires large electrical power

Low-Power LN_2 Cooling System vs. Conventional Cryostat Cooling

Liquid nitrogen flowing system



Cooling temp.: ~78 K
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Liquid nitrogen flowing system
- LN_2 cooling

LN_2 cooled by liquid nitrogen itself
: Very low electrical power required

Liquid Nitrogen Cost and Production Background

- Accurate estimation of cooling efficiency is difficult due to the complex production and supply background of LN_2
- Most LN_2 is obtained as a **byproduct** of large-scale **air separation units (ASUs)**, producing oxygen and argon for industrial use
- It use for large industries such as **semiconductors**, **practical cost of LN_2 is extremely low**

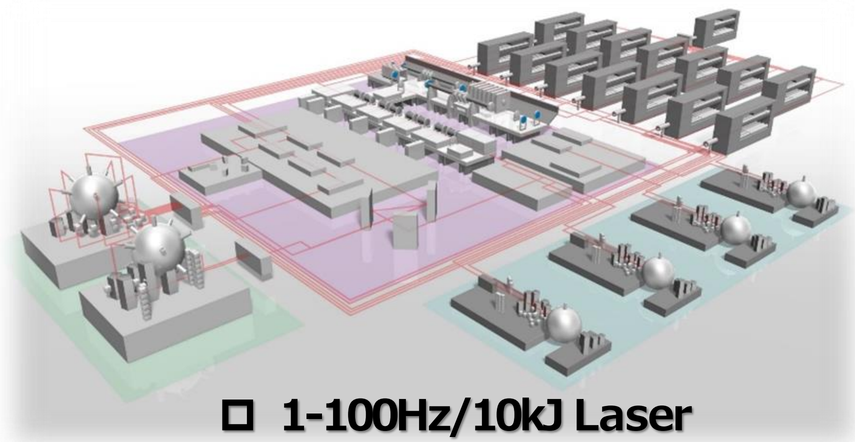
Future brought by high-average-power lasers in 2040

2025 | 2035

SENJU (module)

- 100Hz/100J Laser
- Test facility of the high repetition laser

J-EPoCH (Multi purpose)



- 1-100Hz/10kJ Laser
- Data-driven reseaech

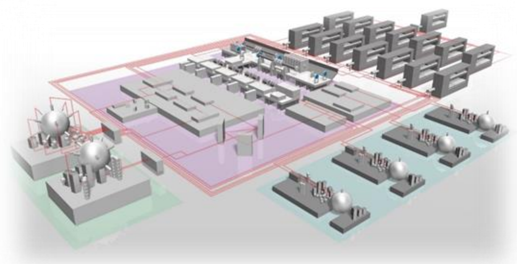
Deep learning requires 30,000 data sets at least

1 shot/2 hours = 4 shots/day

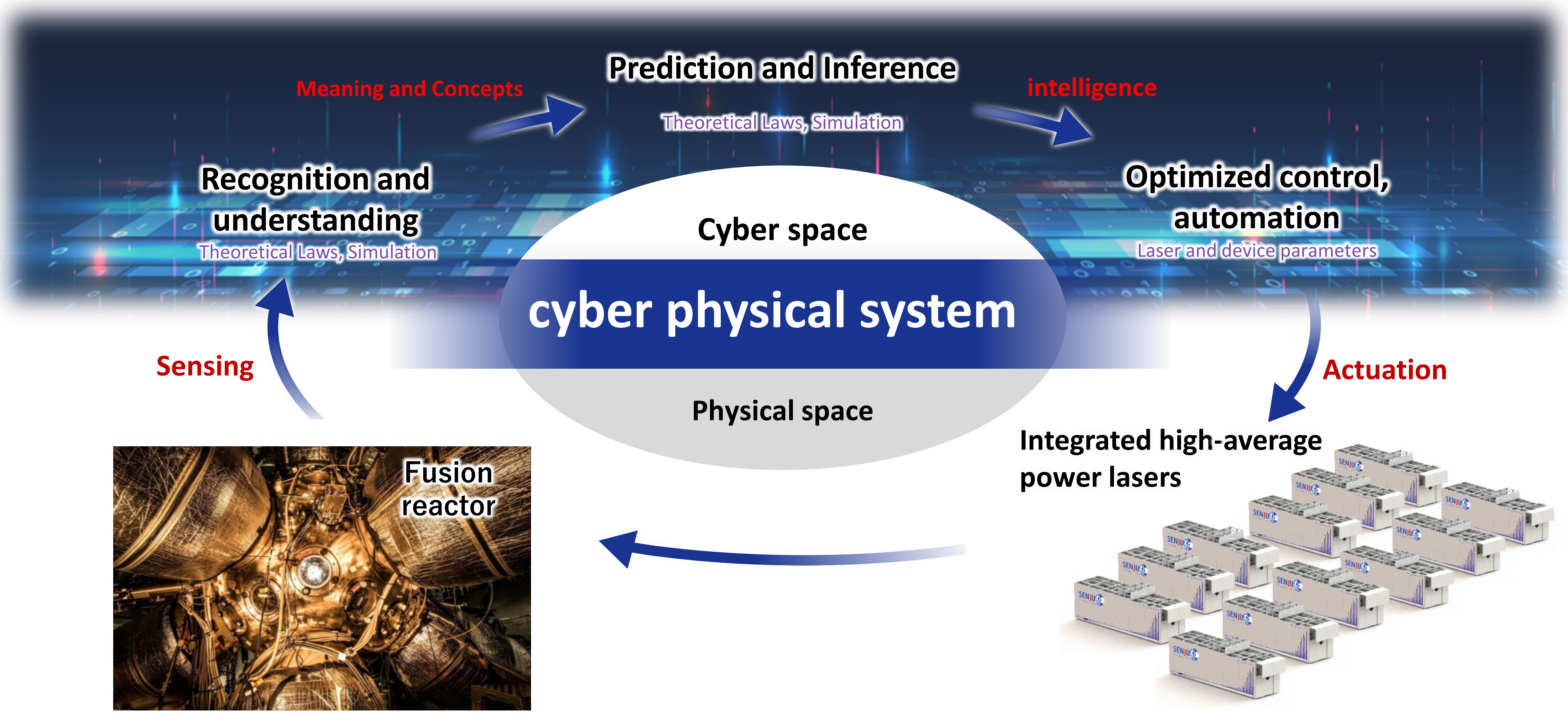
20 years…

10-100 Hz

5 – 50 min !

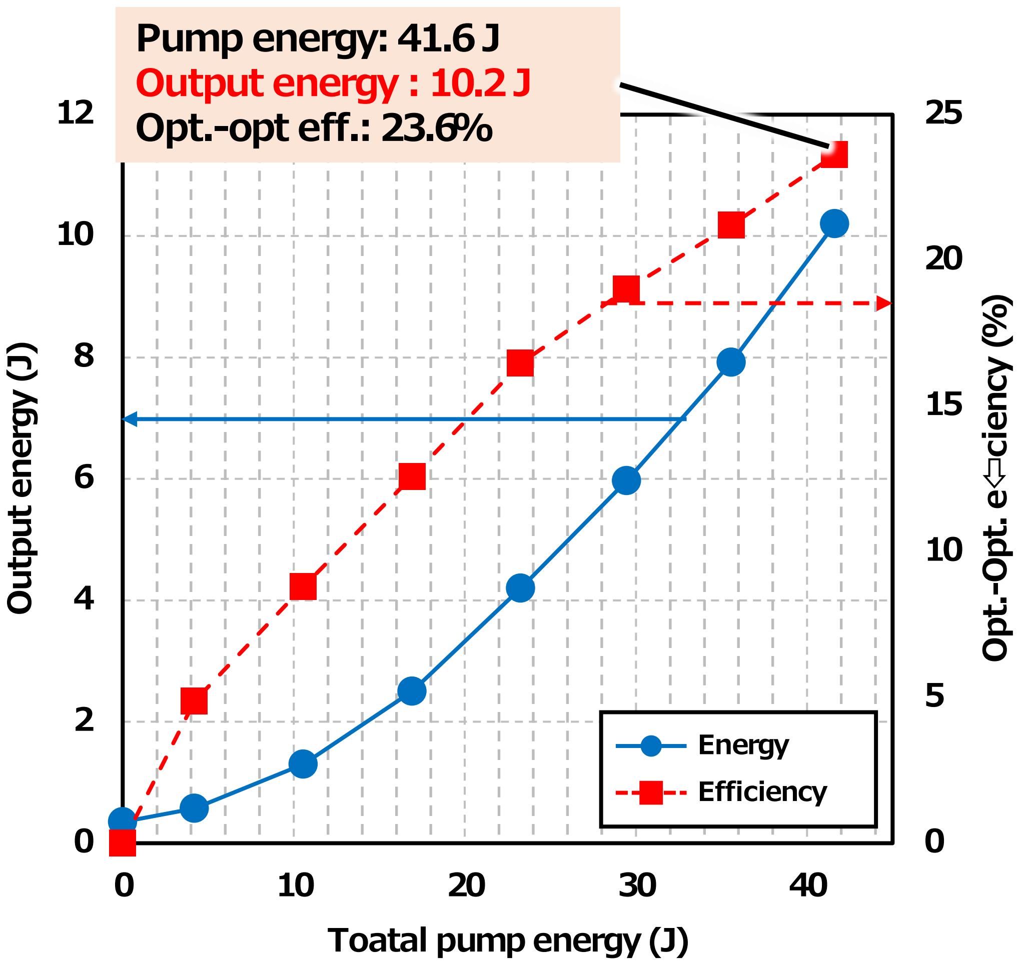


Future brought by high-average-power lasers in 2040

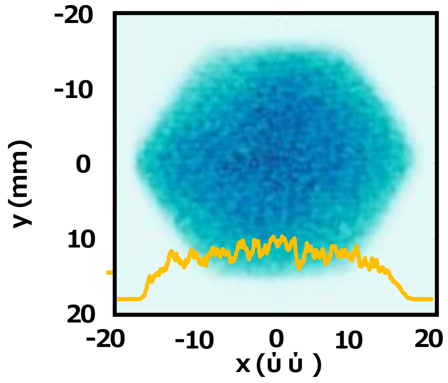


Experiment result of 10 J, 100 Hz

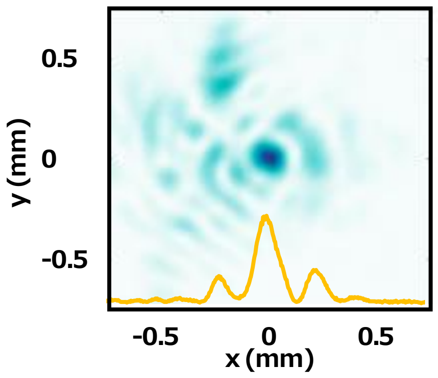
Amplified energy and efficiency



NFP

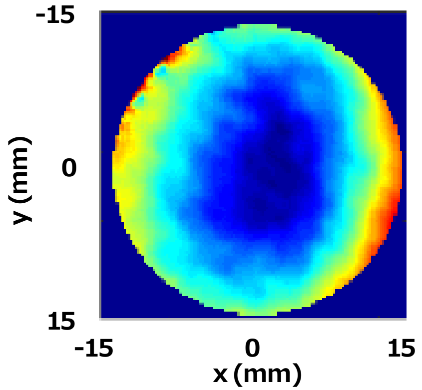


FFP



Flatness factor: 50.5 %
Calculated spot size : 235.6 μm (Airy disk)
Measurement spot size : 313 μm = 1.3 TDL

Wavefront change (Pumping)

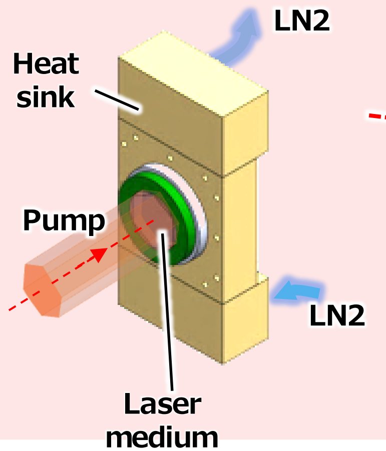


Total wavefront change : 1.2 λ

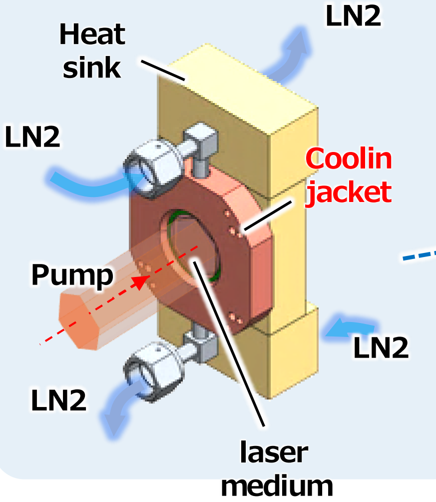
Estimate one head wavefront change : 0.1 λ

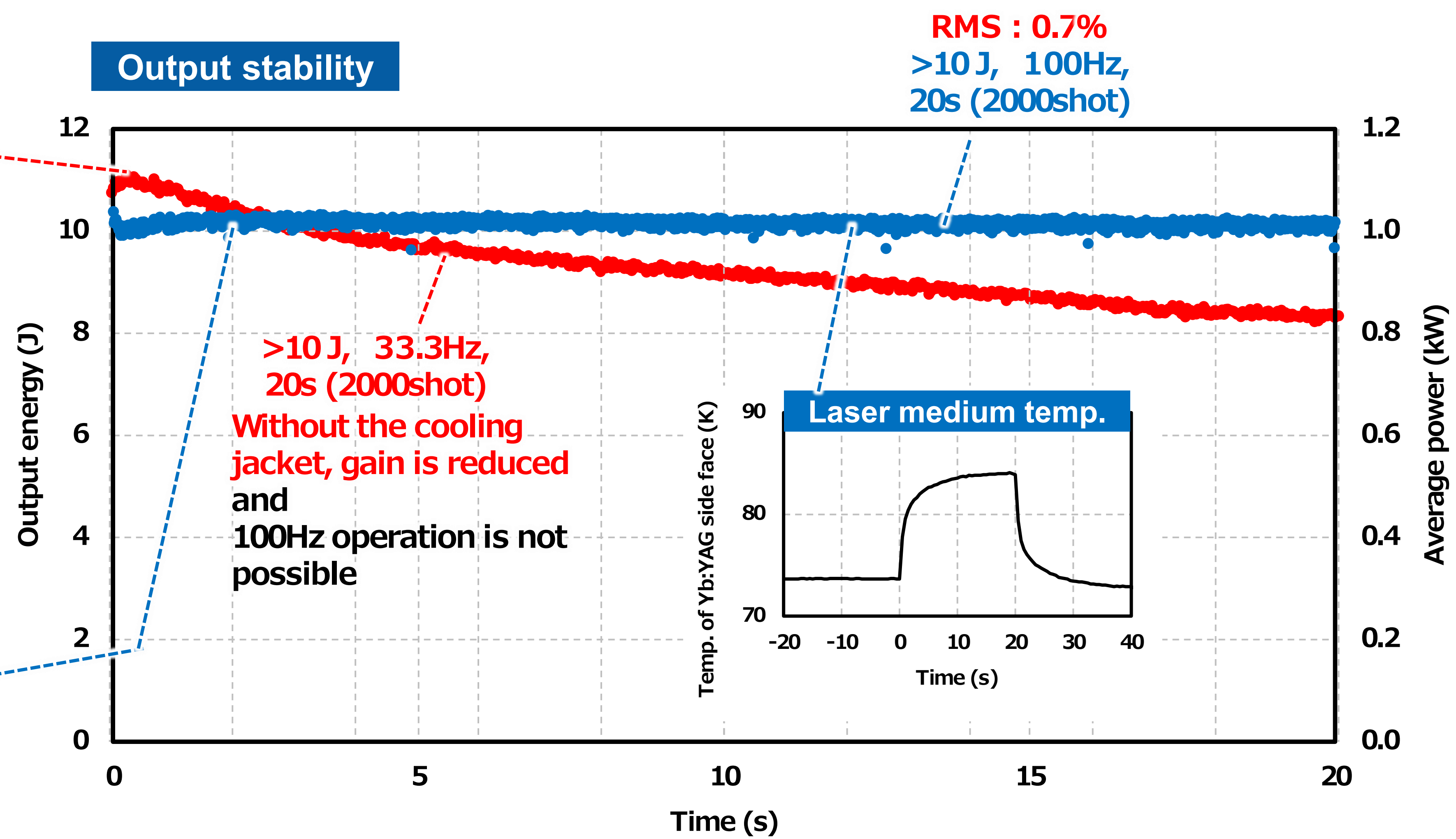
Experiment result : Output stability

Without cooling jacket



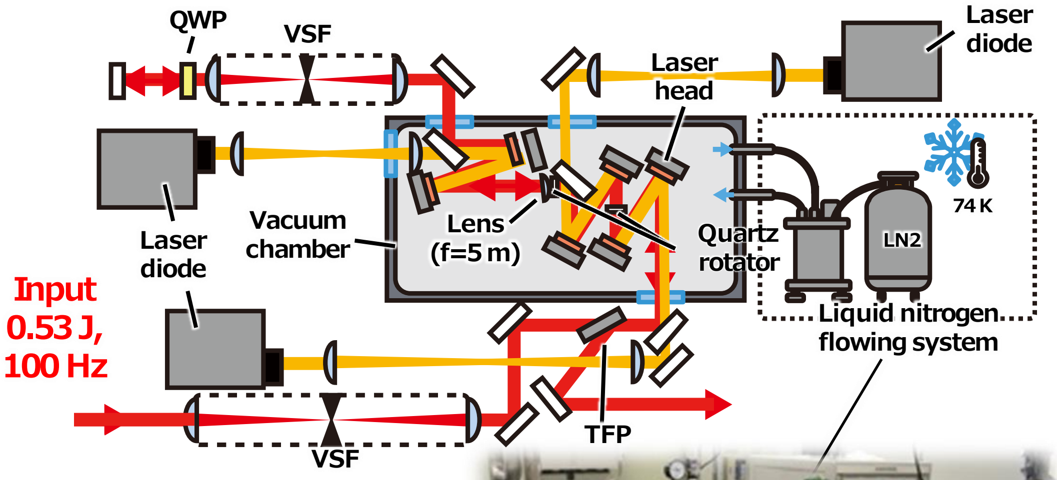
With cooling jacket





Stable output stability at 100Hz operation!

Steady-state operation at 10J, 100Hz



Heat generation

Yb:YAG : 64 W /head
Cr:YAG : 355 W/head
Num. head: 6
Total heat generation: 2.5 kW

Liquid nitrogen flowing system

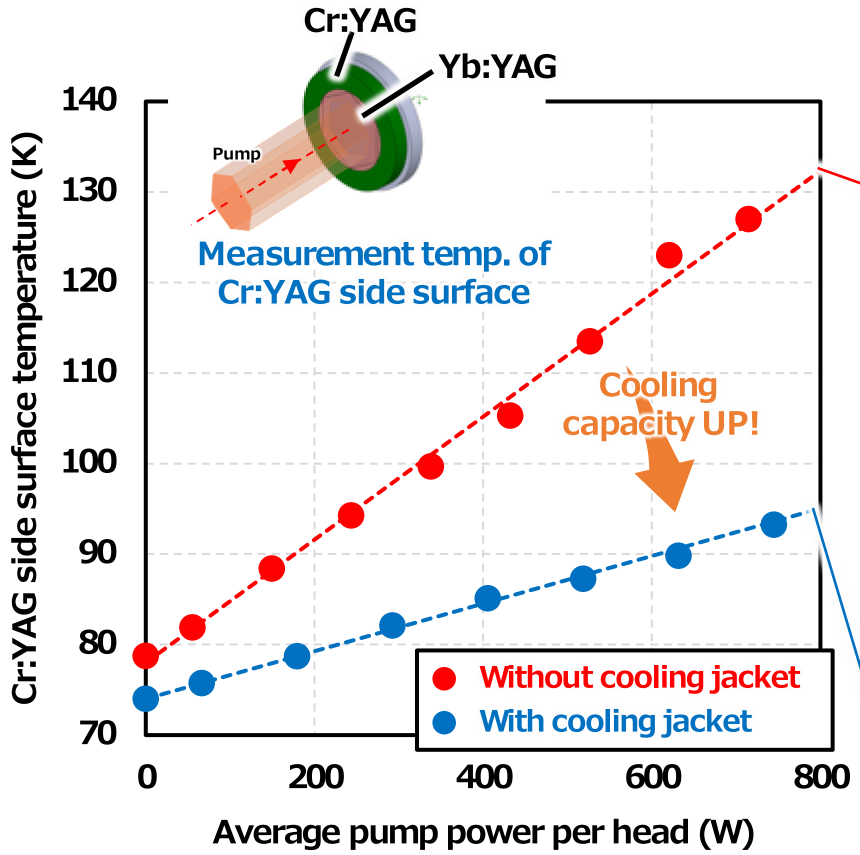
Cooling temperature: ~78 K
Flow rate: 6~9 l/min
Pressure : 0.1 Mpa
Cooling capability : 300 W

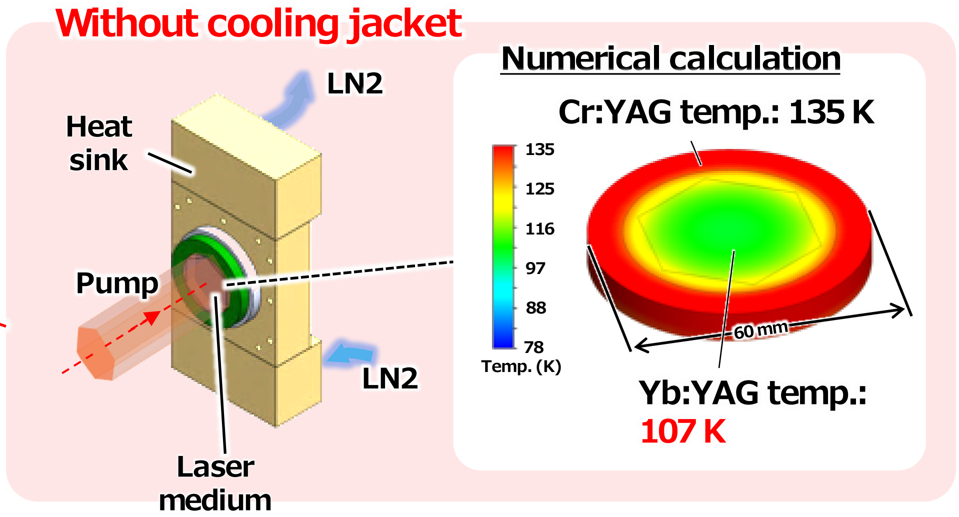
New Liquid nitrogen flowing system

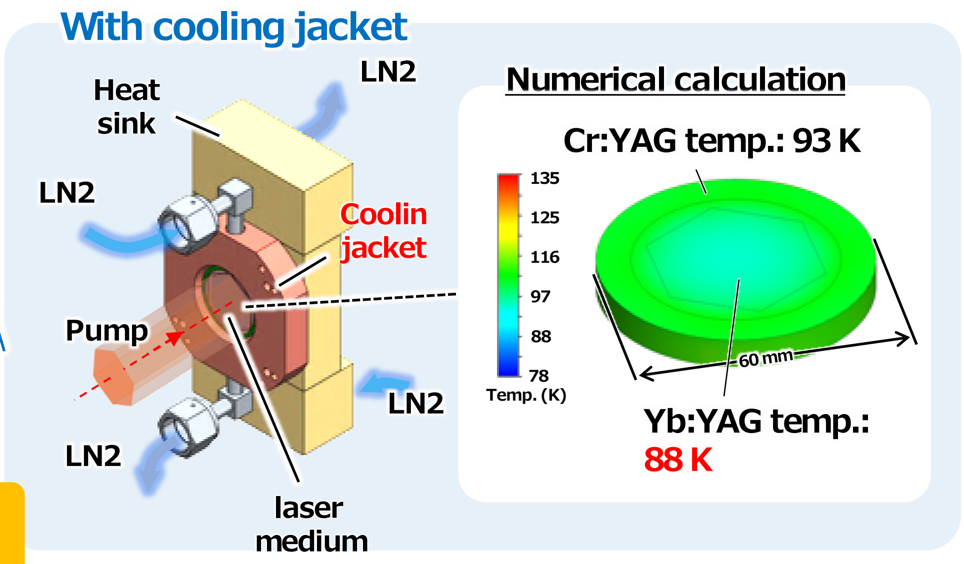
Cooling temperature: ~78 K
Flow rate: ~12 l/min
Pressure : 0.5 Mpa
Cooling capability : 4.0 kW

Improved cooling capacity with cooling jacket

- The temperature rise of the gain medium during pumping is measured and confirm the effect of the cooling jacket



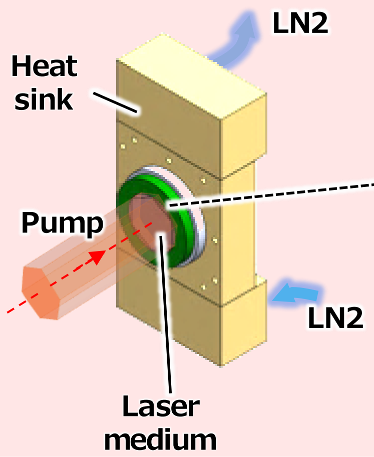




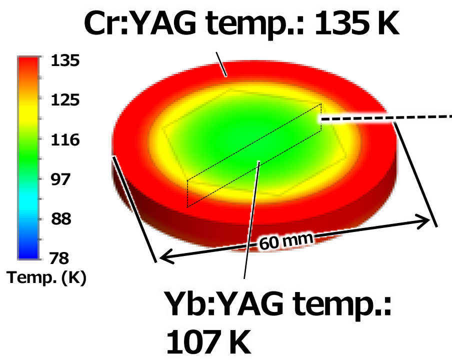
Cooling capacity is 3 times higher than that of the previous laser head.

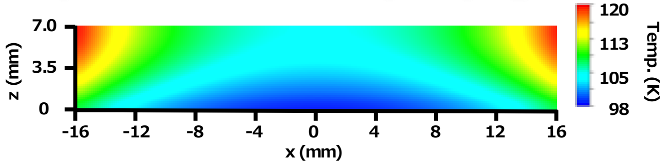
Cooling jacket improves temperature distribution

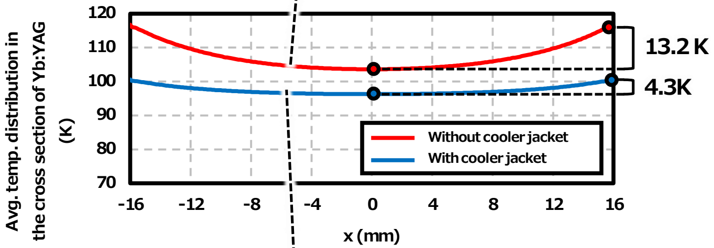
Without cooling jacket



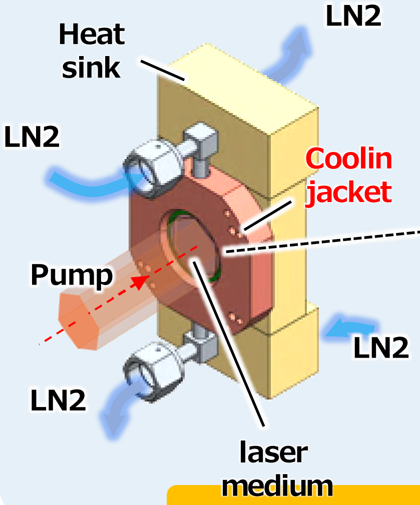
Numerical calculation



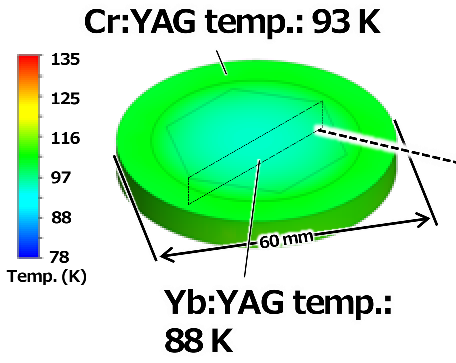


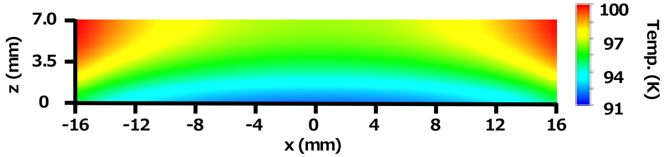


With cooling jacket



Numerical calculation

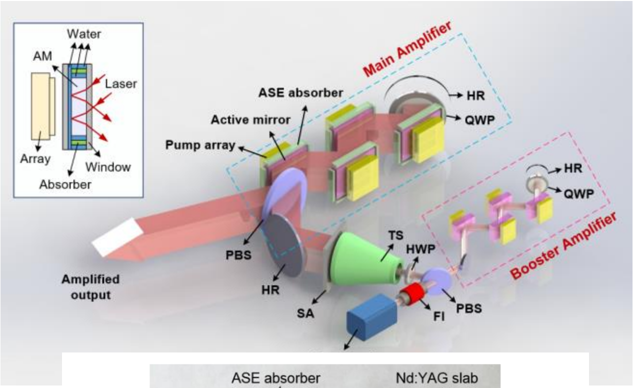


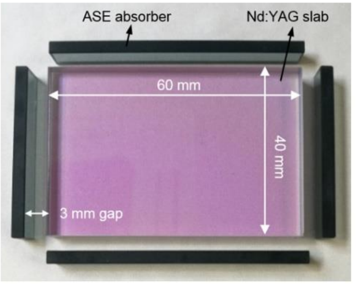


Cooling jacket improves temperature distribution

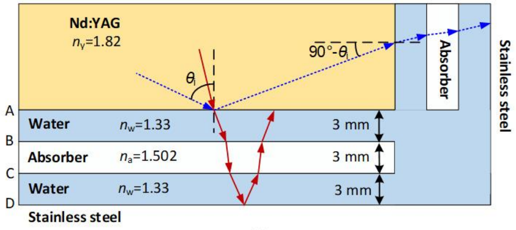
Parasitic oscillation control

T. Liu, Z. Sui, L. Chen, Z. Li, Q. Liu, M. Gong, and X. Fu, Opt Express 25, 21981-21992 (2017).





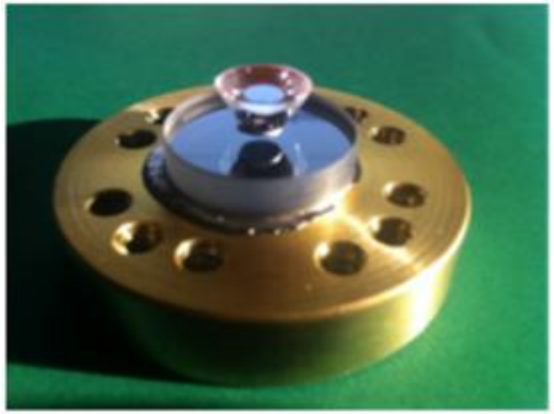
(a)

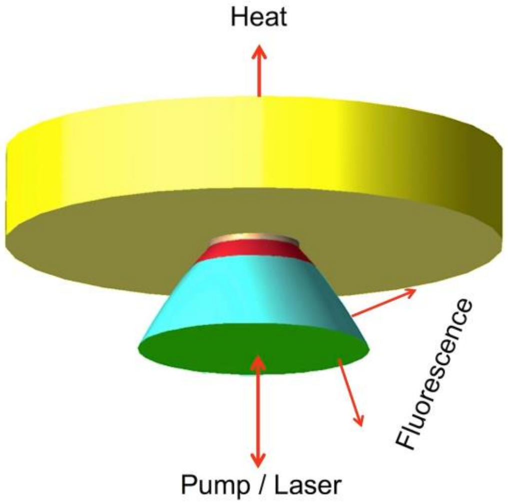


(b)

- Water flows between edge cladding and gain medium
- Heat generated from the edge cladding is not transferred to the gain medium

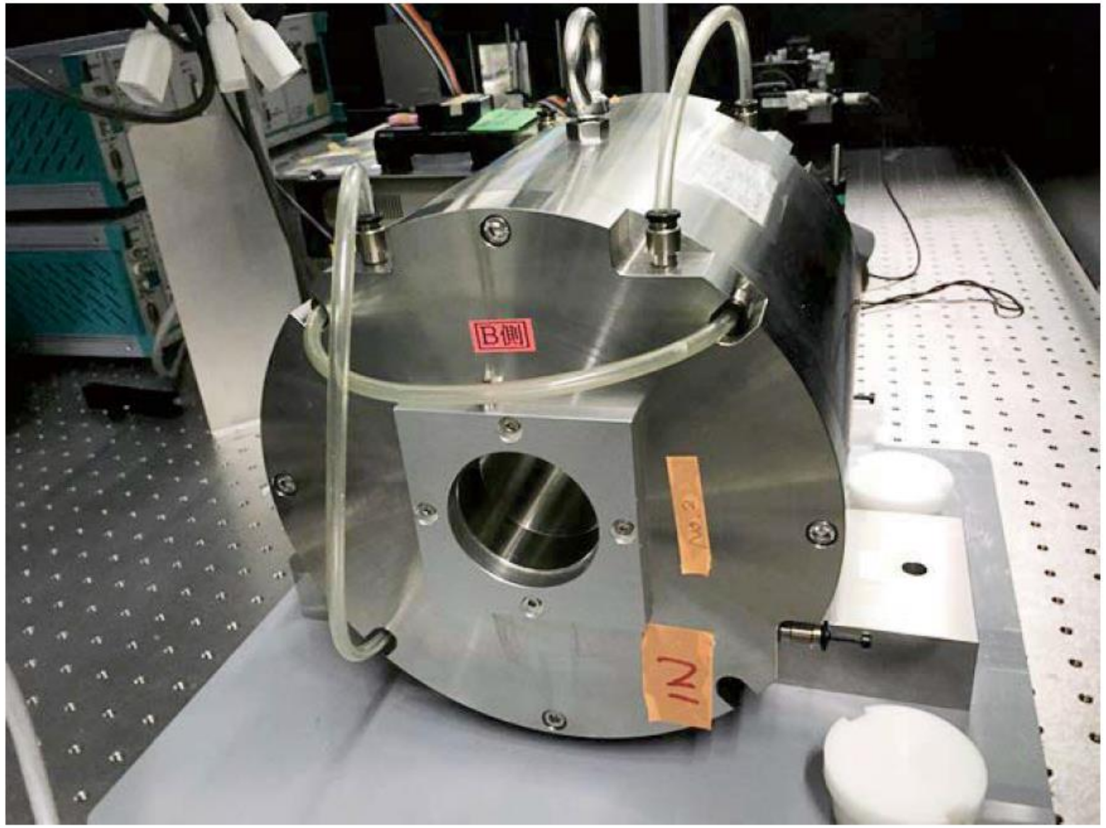
L. E. Zapata, H. Lin, A. Calendron et. al., Optics letters 40, 2610-2613 (2015)





- The gain medium shape is parabolic and structured to emit ASE.

Faraday rotator 55mmφ TGG



1.5 T, 55 mm-dia.
Permanent magnet

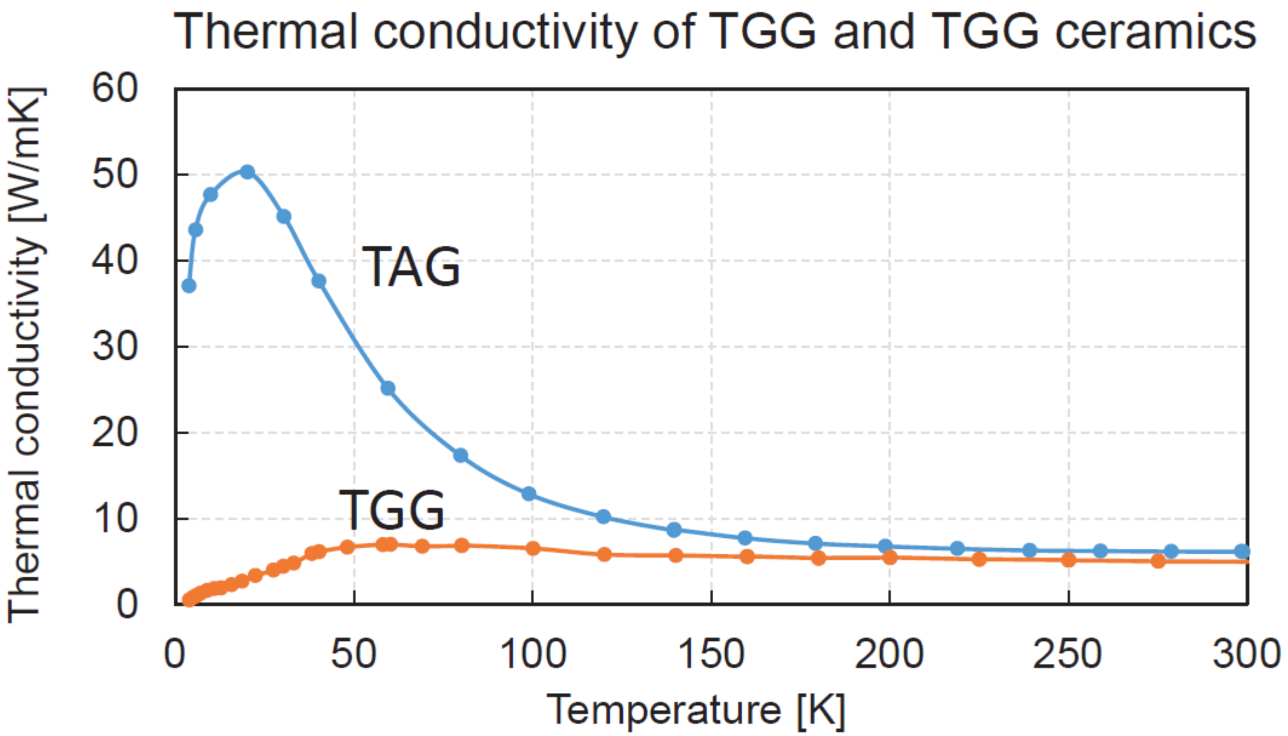
TGG-ceramic disks
Diameter: 53 mm
Clear aperture: 50 mm
Thickness: 5 mm
Number of disks: 3

Isolation: >20 dB
<u>Power capability: ~1 kW</u>

Faraday rotator for high power laser system

TAG ($Tb_3Al_5O_{12}$) ceramics
fabricated by Konoshima Chemical Co. Ltd.

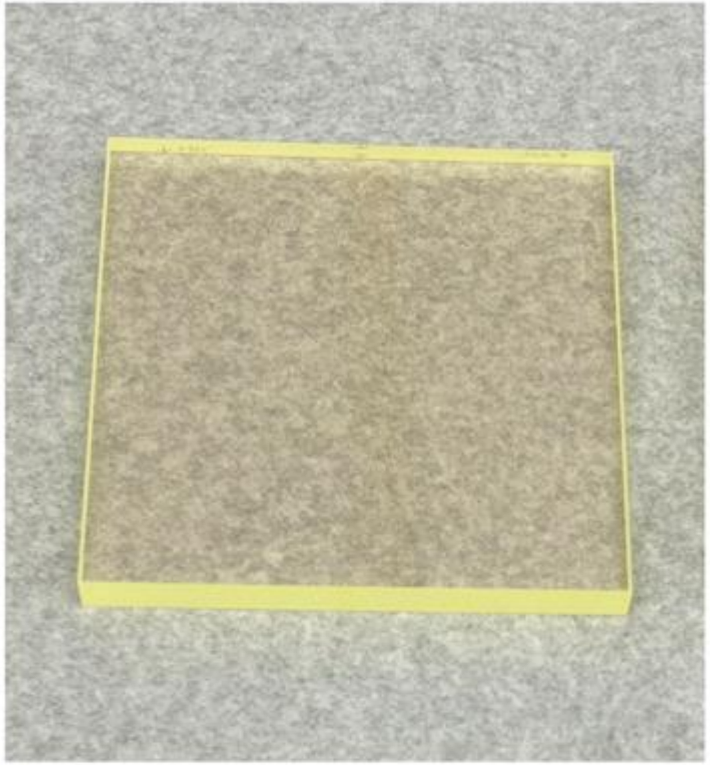
Sample size: 10 x 10 x 3 mm^3



12

Collaborative Research with Nippon Electric Glass on the Development of Large-Aperture Faraday Glass

QFM-003 glass



110 x 110 x 10mmt

Faraday Glass Evaluation (QFM-003)
110 × 110 × 10 mm QFM-003 Faraday glass

- Interferometric wavefront measurement using ZYGO
- No significant striae or birefringence observed after polishing
- Transmitted wavefront: 0.12 λ (excellent quality)
- Indicates clear progress in large-aperture glass production

→ For ~0.5 T operation, thickness ≥15 mm is required

Cryogenic Faraday Rotator Test
Faraday rotator with QFM-003 glass (15 mm thick) at ~116 K

- Irradiated with ~480 W laser for 1 hour
- Glass temperature increased from 116 K → 127 K
- Faraday rotation angle at 127 K: ~48°

→ Not saturated: indicates operation possible beyond 480 W

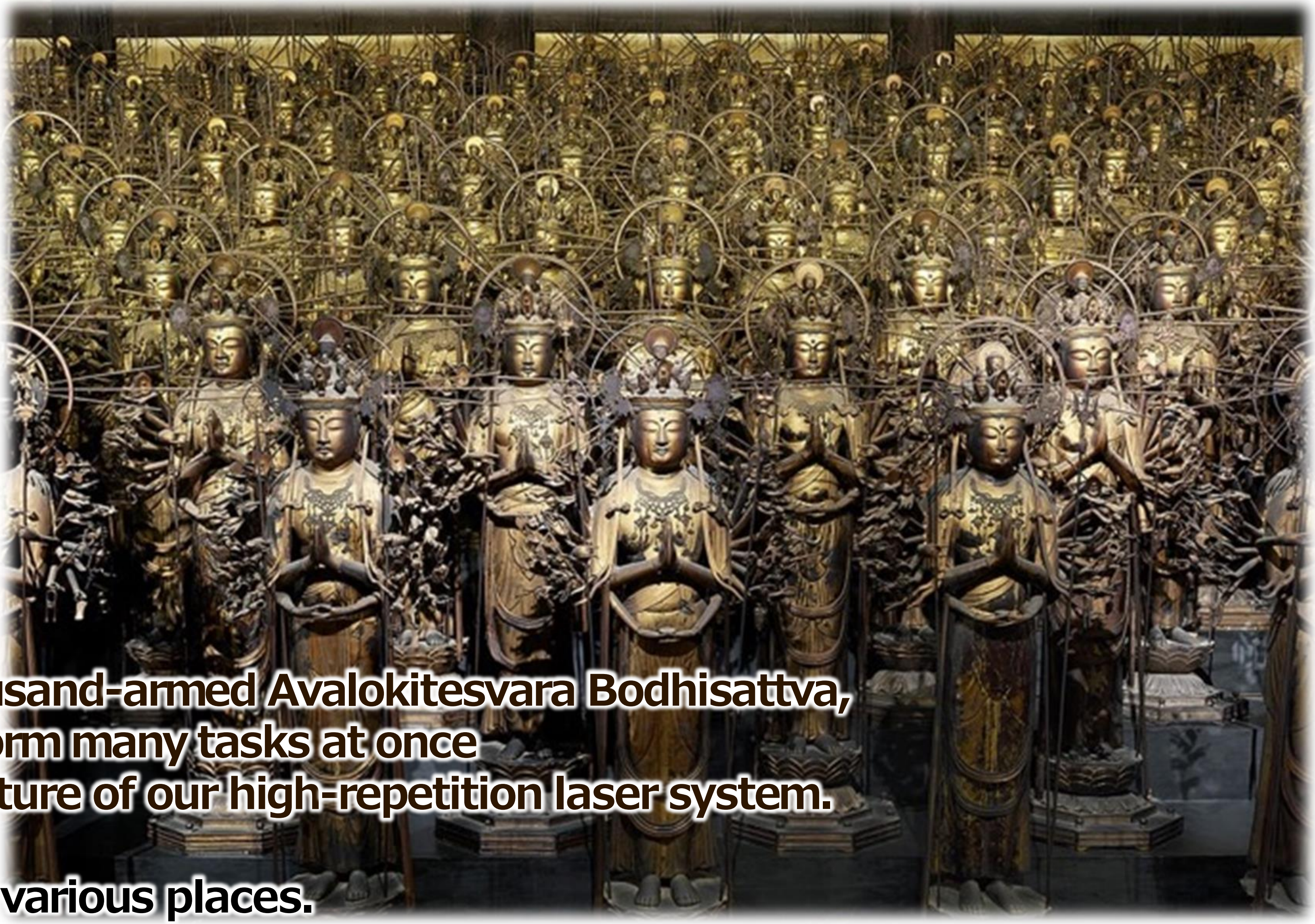
- Next step: Develop cryogenic Faraday rotator with better heat handling

What the SENJU ?

SENJU

Super Energetic Join Unit

10 kW (100 J/100 Hz) module



SENJU is named after the thousand-armed Avalokitesvara Bodhisattva, symbolizing the ability to perform many tasks at once — just like the modular structure of our high-repetition laser system.

We plan to deploy this laser in various places.