The 2nd International Advisory Committee
for the RIKEN-RAL Muon Facility

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Nishina Hall, RIKEN Nishina Center, Wako, JAPAN

High Intensity Laser for Ultraslow Muon Production

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Background

- One of the key technology breakthroughs needed to the precise measurement of the the anomalous magnetic moment of a muon is the substantial improvement of the Lyman alpha laser pulse energy (@122 nm) by at least two orders of magnitude.

  Since the presently available laser ionized muons at RIKEN-RAL has **1 μJ/pulse,** We require a new laser system with

  $\geq$100 μJ pulse energy at 122 nm

- VUV laser technology:
  There is no established method for generating high-power VUV light, because no suitable laser material or nonlinear crystal is available.
  However, the progress of laser technology has been remarkable. In this work, we challenge high-intensity coherent Lyman-α generation based on laser technology developed in RIKEN.

VUV :vacuum ultraviolet (wavelength less than 200 nm)

Objectives

Proposal for high-intensity Lyman-α coherent light (122 nm) generation for ultraslow muon production.

We newly introduce a hybrid laser system with a laser diode, solid-state laser and fiber laser.

The required specifications are as follows;

Wavelength:	122 nm	(122nm)
Pulse energy :	**100 μJ/pulse**	**(<1μJ/pulse)**
Spectral width:	80 GHz	(800GHz)
Repetition rate:	50 Hz	(25Hz)

Core technologies I

New laser crystal and crystal growth methods

Conventional technique

(Czochralski method)

Problems:

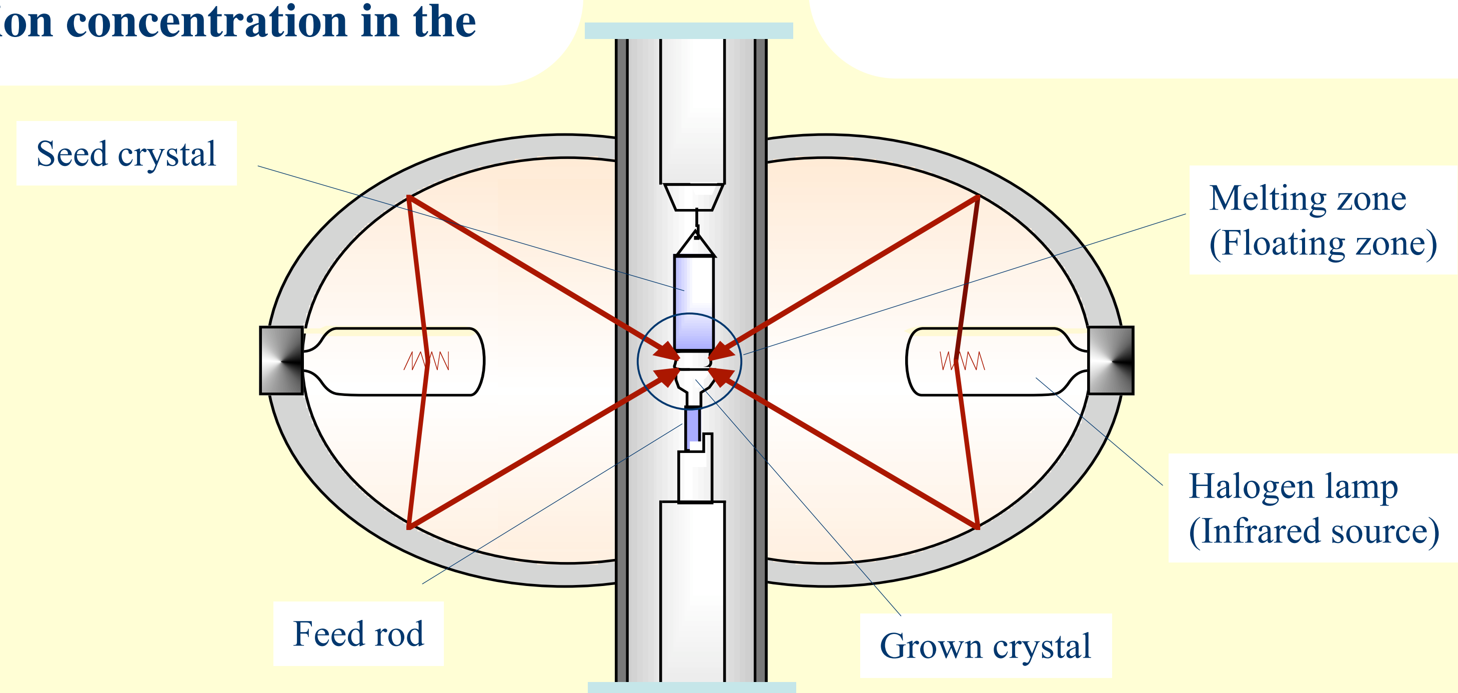
- Evaporation of materials
- Mixing of crucible materials

It causes poor uniformity of doping ion concentration in the crystal

Floating zone (FZ) method

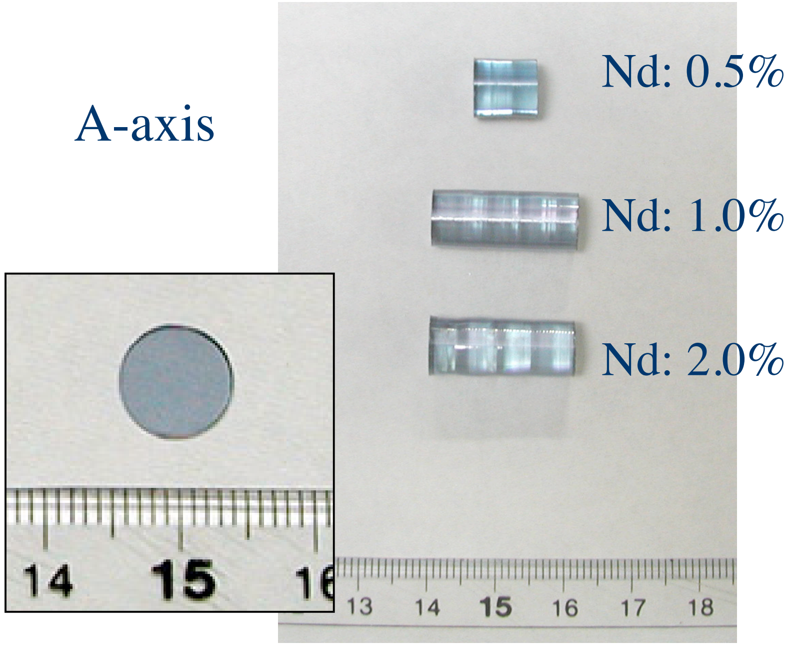
- No crucible is required.
- High O_2 pressure atmosphere is realized.

Homogeneous crystals are obtained.



< Image of furnace in the FZ method >

A new laser crystal: Nd:GdVO4

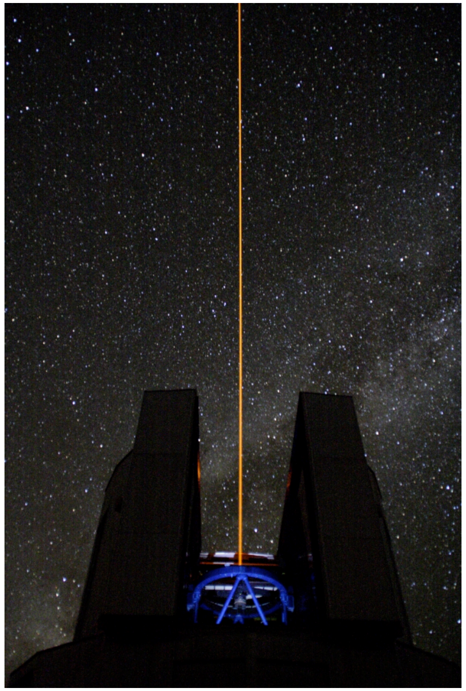


	Nd:YAG	Nd:YVO_4	Nd:$GdVO_4$
Thermal conductivity	◎	△	◎
Emission cross-section	○	a-axis ◎ c-axis ○	a-axis ◎ c-axis ○
Lifetime of upper state	◎	○	○
Crystal growth	◎	△	◎
Highly doping	×	△	◎
Wavelength	**1064**	**1064**	**1063**

- Nd:$GdVO_4$ shows good optical and thermal characteristics for 1μm laser.
- The fundamental radiation of 1062.75 nm can be efficiently amplified .
- The Fifth harmonics of 1062.75 nm is 212.55 nm.
- The wavelength matches to 2-photon resonance of Kr.gas.

Core technologies II

Solid-state Laser and Fiber Laser Engineering



Laser guide star at
Subaru telescope on
top of Mt. Mauna Kea
in Hawaii

Pratical Laser fabrication system
with ultrashort-pulse Yb laser

Japan Laser Focus World
2008.6

Fiber laser technology

Breakthrough of VUV Laser

Integration

Laser material science

FZ method, new laser crystals
Nonlinear crystal

Laser engineering

Solid-state lasers, fiber lasers
Nonlinear optics, hybrid lasers

High intensity Lyman-α laser

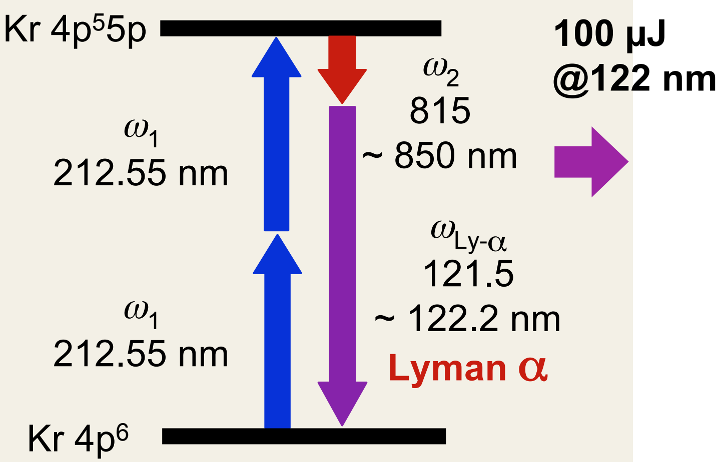
Breakthrough of muon science

Practical Design

2-photon resonance 4wave mixing in Kr gas

Kr $\omega_{Ly\text{-}\alpha} = 2\ \omega_1 - \omega_2$

■ Ly-α generation in Kr



■ $2\pi c/\omega_1$ = 212.55 nm,
$2\pi c/\omega_2$ = 815 ~ 850 nm
$2\pi c/\omega_{Ly\text{-}\alpha}$= 122.21 ~ 121.46 nm (Ly-α)

■ Efficiency in small-signal region: η

$\eta \propto \chi_3 P_1{}^2 P_2 \cdot e(-\Delta k)$

P_1: *Power @* ω_1

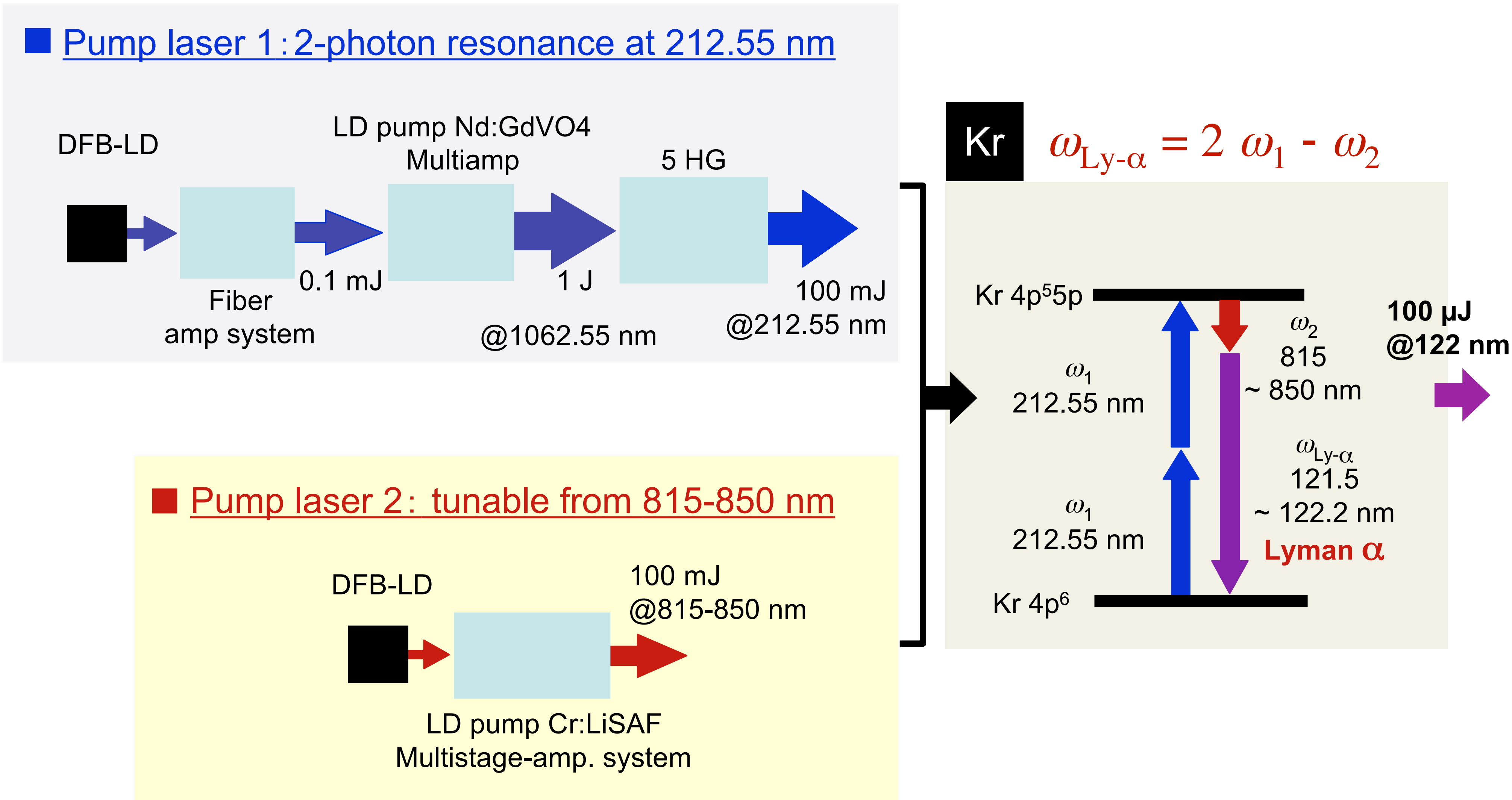
P_2: *Power @* ω_2

■ Estimated pump energy based on the previous laser system.

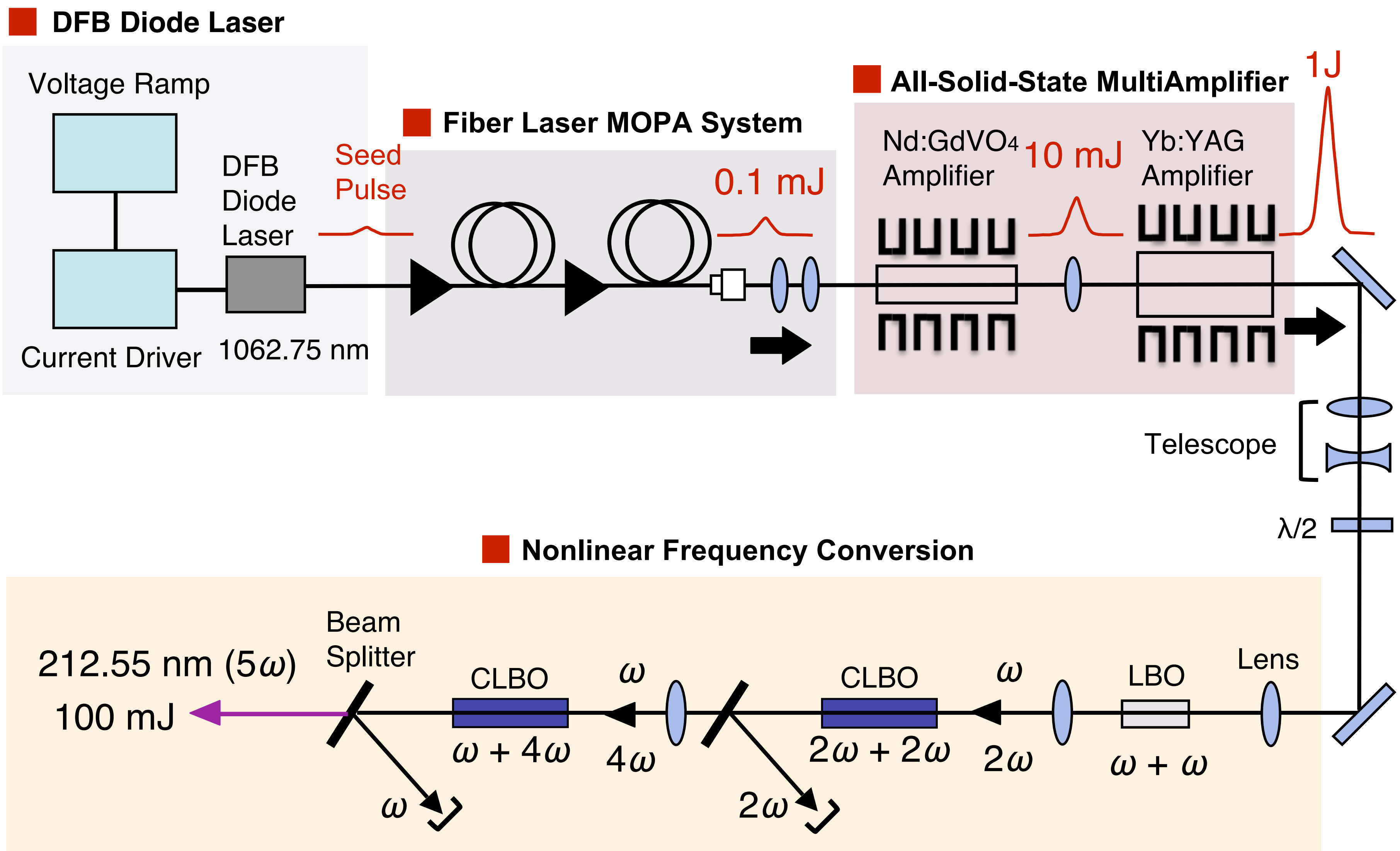
Pump energy: $P_1 = 100$mJ、 $P_2 = 100$mJ

■ Key points :increase of pump energy and satisfaction of phase matching condition.

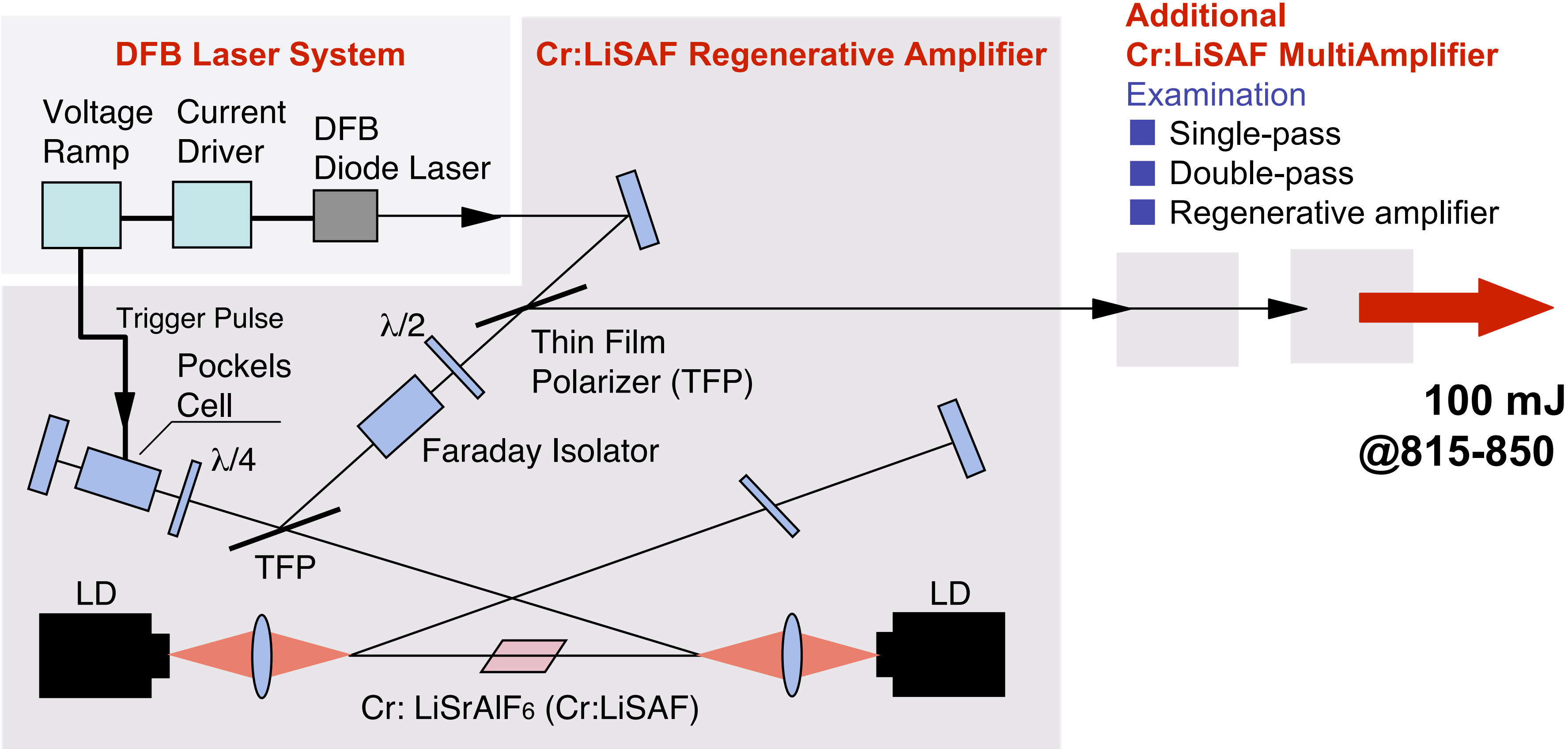
Schematic Diagram



Pump Laser 1


DFB Diode Laser
Voltage Ramp
DFB
Diode
Laser
Current Driver
1062.75 nm
Seed
Pulse
Fiber Laser MOPA System
0.1 mJ
All-Solid-State MultiAmplifier
1J
Nd:GdVO4
Amplifier
10 mJ
Yb:YAG
Amplifier
Telescope
λ/2
Nonlinear Frequency Conversion
Beam
Splitter
212.55 nm (5ω)
100 mJ
CLBO
ω + 4ω
ω
4ω
ω
CLBO
2ω + 2ω
ω
2ω
2ω
LBO
ω + ω
Lens

Pump Laser 2



Additional Cr:LiSAF MultiAmplifier

Examination

- Single-pass
- Double-pass
- Regenerative amplifier

100 mJ @815-850 nm

Improve of efficiency

LD pump solid-state amp.

Electric power → LD → $Nd:GdVO_4$ → 5HG → 212.55 nm

Typical eff. 50% 40% 10% 2.5%

212.55 nm generation at RIKEN-RAL

Electric power → Lamp → Nd:YAG → 2HG → 532 nm

Typical eff. 10% 20% 50% 1%

532 nm → OPO → 4HG → 212.55 nm

20% 5% 0.01%

Problems

Damage of optics

Damage of optics by high intensity UV pump laser and coherent VUV radiation.

↓

Improvement of optics or,
Introduction of gas jet without window

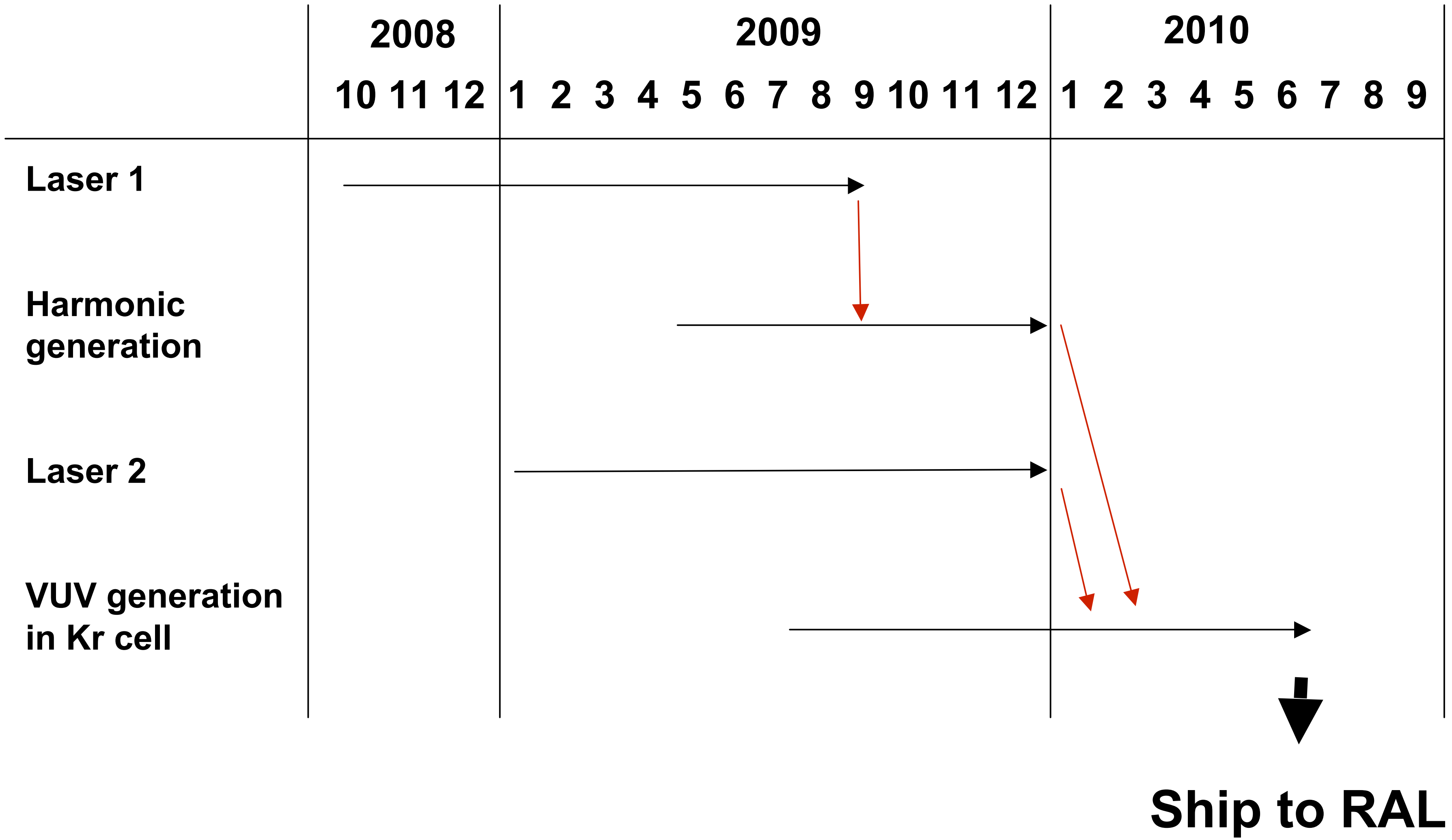
Satisfaction of phase matching condition in nonlinear process.

High Intensity pump laser brakes phase matching condition.
because of variation of index by changing population.

↓

Optimization of focusing geometry by simulation and experiment

Research schedule



Summary

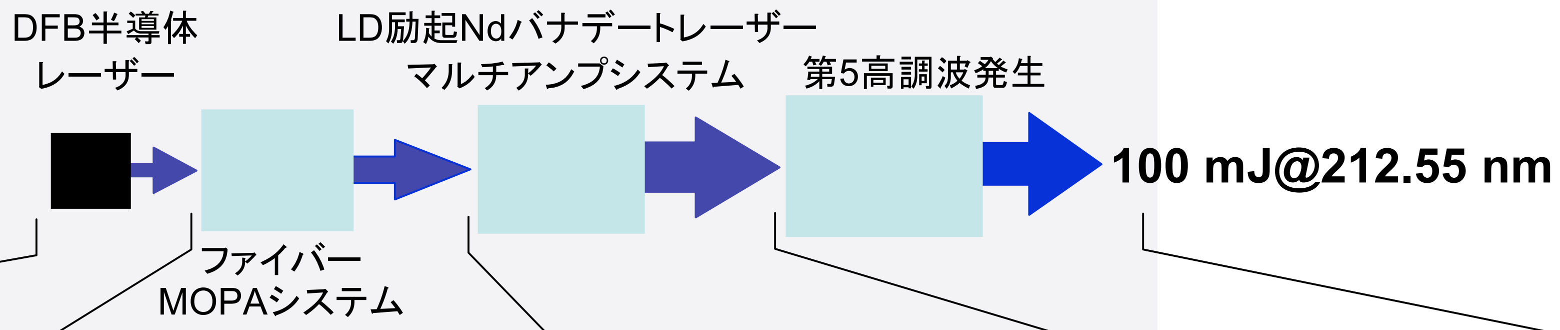
We propose a new Lyman-α laser with wavelength 122 nm based on a hybrid laser system.

Our goal is to realize substantial improvement of pulse energy at 122 nm by at least two orders of magnitude. Detailed specifications are as follows;

Pulse energy	**: >100 μJ**
Repetition rate	**: 50 Hz**
Line width	**: <80 GHz**
Wavelength	**: 122 nm**
Pulse width	**: 1-2 ns**

第1励起レーザー

■ 第1励起レーザー：2光子励起用212.55 nmレーザー



分布帰還型(DFB)レーザー

温度制御による波長選択

■ λ = 1062.75 nm (ω)

印加電流の調整によって
■ 繰り返し速度
■ パルス幅
の制御が可能

■ パルス幅: 1 ns
■ スペクトル幅: 2 GHz

ファイバー増幅器系

MOPA
(Master Oscillator
Power Amplifier)システム

■ 活性イオン:
■ 直線偏光
■ 自己位相変調の回避

■ 出力エネルギー
= 0.1 mJ まで増幅

全固体マルチアンプ系

Nd:GdVO4系+Yb:YAG系

前段
Nd:GdVO4アンプ系
■ 利得の中心: 1062.9 nm
■ 利得バンド幅: 2 nm
■ 出力エネルギー
= 10 mJ まで増幅

後段
Yb:YAGアンプ系
■ 出力エネルギー
= 1 J まで増幅

非線形周波数変換

第2高調波発生(SHG: 2 ω)
第4高調波発生(4th HG: 4 ω)
第5高調波発生(5th HG: 5 ω)

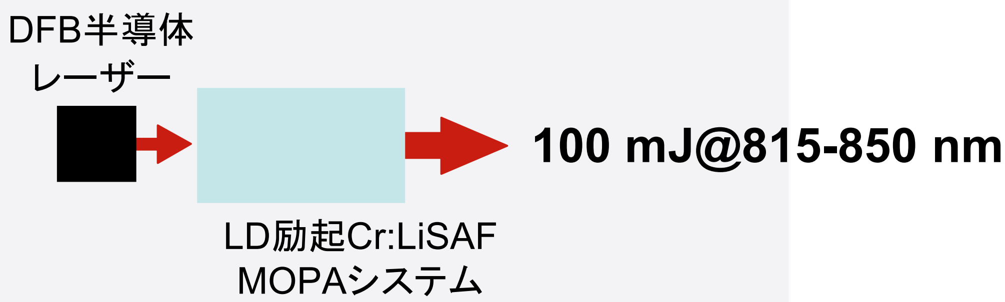
SHG 非線形光学結晶**LBO**
変換効率: 70%

4th HG 非線形光学結晶**CLBO**
変換効率: 20%

5th HG
非線形光学結晶: **CLBO**
変換効率: 10%
=100 mJ@212.55 nm

第2励起レーザー

■ 第2励起レーザー：815-850 nmレーザー



分布帰還型(DFB) レーザー

温度制御による波長同調

■ λ = 815-850 nm

印加電流の調整によって
■ 繰り返し速度
■ パルス幅
を制御可能

■ パルス幅: 1 ns
■ スペクトル幅: 2 GHz

Cr:LiSAF レーザー

LD励起全固体システム

■ 直線偏光
■ 波長同調域: 700-950 nm
■ 出力エネルギー
= 100 mJ レベル

VUV Generation in Krypton

Time	**1985**	**1990**	**2000**	**~ 2008**
Research Group	Univ. of Maryland Bonin *et al.*	Imperial College Marangos *et al.*	SRI International Faris *et al.*	RIKEN
Method		**Two-photon resonant four-wave mixing**		
Pump Laser 1	Nd:YAG laser + Freq. conversion	XeCl Excimer laser + Dye laser	ArF Excimer laser	?
Pump Laser 2	Dye laser (Tunable)	XeCl Excimer laser + Dye laser	Nd:YAG + Dye laser	?
Input Wavelength Input Energy	216.67 nm 1 mJ	212.55 nm 0.18 mJ	193 nm ~ 20 mJ	
Input Wavelength Input Energy	723.97 nm 0.5 mJ	843 nm 0.72 mJ	355 nm ?	
VUV Wavelength VUV Energy	127.4 nm	121-123 nm **110 ± 60 nJ**	121.6 nm **7 μJ**	121.5-122.2 nm **1 μJ**
Conversion Efficiency	**10^{-5}** (determined by SFG)	**5×10^{-4}**	?	**$\approx 10^{-4}$**
Reference	JOSA B **2**, 527 (1985).	JOSA B **7**, 1254 (1990).	JOSA B **17**, 1856 (2000).	