The 2nd International Advisory Committee for the RIKEN-RAL Muon Facility
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High Intensity Laser for Ultraslow Muon Production

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One of the key technology breakthroughs needed to the precise measurement of 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

\[ >100 \, \mu \text{J pulse energy at } 122 \, \text{nm} \]

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-\(\alpha\) generation based on laser technology developed in RIKEN.

VUV : vacuum ultraviolet (wavelength less than 200 nm)
Objectives

Proposal for high-intensity Lyman-\(\alpha\) 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 \(\mu\)J/pulse (<1\(\mu\)J/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.*
A new laser crystal: Nd:GdVO$_4$

- Nd:GdVO$_4$ shows good optical and thermal characteristics for 1$\mu$m 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

Practical Laser fabrication system with ultrashort-pulse Yb laser

Japan Laser Focus World 2008.6

Fiber laser technology
Breakthrough of VUV Laser

Laser material science

Integration

Laser engineering

FZ method, new laser crystals
Nonlinear crystal

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

\[ \omega_{\text{Ly-}\alpha} = 2 \omega_1 - \omega_2 \]

- \[ 2\pi c/\omega_1 = 212.55 \text{ nm} \]
- \[ 2\pi c/\omega_2 = 815 \sim 850 \text{ nm} \]
- \[ 2\pi c/\omega_{\text{Ly-}\alpha} = 122.21 \sim 121.46 \text{ nm} \]

Efficiency in small-signal region: \( \eta \)

\[ \eta \propto \chi_3 P_1^2 P_2 \cdot e(-\Delta k) \]
- \( P_1 \): Power @ \( \omega_1 \)
- \( P_2 \): Power @ \( \omega_2 \)

Estimated pump energy based on the previous laser system.

Pump energy: \( P_1 = 100 \mu\text{J}, \quad P_2 = 100 \mu\text{J} \)

Key points: increase of pump energy and satisfaction of phase matching condition.
**Pump laser 1:** 2-photon resonance at 212.55 nm

- DFB-LD
- LD pump Nd:GdVO₄
- Multiamp
- 5 HG
- Fiber amp system
- @1062.55 nm
- @212.55 nm
- 0.1 mJ
- 1 J
- 100 mJ

**Pump laser 2:** tunable from 815-850 nm

- DFB-LD
- LD pump Cr:LiSAF
- Multistage-amp. system
- 100 mJ

**Kr**

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

- Kr 4p⁵5p
- LD pump Nd:GdVO₄
- Multiamp
- 5 HG
- Fiber amp system
- 0.1 mJ
- 1 J
- 100 mJ

- Kr 4p⁶
- LD pump Cr:LiSAF
- Multistage-amp. system
- 100 mJ
- @122 nm

$$\omega_1 \approx 212.55 \text{ nm}$$

$$\omega_2 \approx 850 \text{ nm}$$

$$\omega_{\text{Ly-}\alpha} \approx 122.2 \text{ nm}$$
Pump Laser 1

DFB Diode Laser
- Voltage Ramp
- Current Driver 1062.75 nm

Fiber Laser MOPA System
- DFB Diode Laser
- Seed Pulse
- 0.1 mJ

All-Solid-State MultiAmplifier
- Nd:GdVO₄ Amplifier 10 mJ
- Yb:YAG Amplifier

Telescope
- λ/2

Nonlinear Frequency Conversion
- Beam Splitter
- CLBO
- 212.55 nm (5ω)
- 100 mJ
- 1J

Lens
Pump Laser 2

DFB Laser System
- Voltage Ramp
- Current Driver
- DFB Diode Laser
- Trigger Pulse
- Pockels Cell
- λ/4

Cr:LiSAF Regenerative Amplifier
- DFB Laser System
- Cr:LiSAF (Cr:LiSrAlF₆)
- λ/2
- Thin Film Polarizer (TFP)
- Faraday Isolator
- TFP

Additional
Cr:LiSAF MultiAmplifier
- Single-pass
- Double-pass
- Regenerative amplifier

Examination

100 mJ
@815-850 nm
**Improve of efficiency**

**LD pump solid-state amp.**

Electric power → LD → Nd:GdVO₄ → 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%
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

<table>
<thead>
<tr>
<th>Year</th>
<th>Laser 1</th>
<th>Harmonic generation</th>
<th>Laser 2</th>
<th>VUV generation in Kr cell</th>
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<tbody>
<tr>
<td>2008</td>
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<td>2009</td>
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<td>2010</td>
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Ship to RAL
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

DFB半導体レーザー → ファイバーMOPAシステム → LD励起Ndバナデートレーザー → マルチアンプシステム → 第5高調波発生 → 100 mJ@212.55 nm

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

DFB半導体レーザー

LD励起Cr:LiSAF MOPAシステム

100 mJ@815-850 nm

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

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>Research Group</td>
<td>Univ. of Maryland Bonin et al.</td>
<td>Imperial College Marangos et al.</td>
<td>SRI International Faris et al.</td>
<td>RIKEN</td>
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<tr>
<td>Method</td>
<td>Two-photon resonant four-wave mixing</td>
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<tr>
<td>Pump Laser 1</td>
<td>Nd:YAG laser + Freq. conversion</td>
<td>XeCl Excimer laser + Dye laser</td>
<td>ArF Excimer laser</td>
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<tr>
<td>Input Wavelength</td>
<td>216.67 nm</td>
<td>212.55 nm</td>
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<td>Input Energy</td>
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<td>0.18 mJ</td>
<td>~ 20 mJ</td>
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<tr>
<td>Input Wavelength</td>
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<td>355 nm</td>
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<tr>
<td>Input Energy</td>
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<td>0.72 mJ</td>
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<tr>
<td>VUV Wavelength</td>
<td>127.4 nm</td>
<td>121-123 nm</td>
<td>121.6 nm</td>
<td>121.5-122.2 nm</td>
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<td>VUV Energy</td>
<td>$110 \pm 60 \text{ nJ}$</td>
<td>$7 \mu \text{J}$</td>
<td>?</td>
<td>$1 \mu \text{J}$</td>
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<tr>
<td>Conversion</td>
<td>$10^{-5}$</td>
<td>$5 \times 10^{-4}$</td>
<td>?</td>
<td>$\approx 10^{-4}$</td>
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<td>Efficiency</td>
<td>(determined by SFG)</td>
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