Development of On-line Instrumentation and Techniques to Detect and Measure Particulates

Quarterly Technical Progress Report

From Oct 1, 2004 to December 31, 2004
Principle authors: Sheng Wu, Steve Palm, Yongchun Tang, William A. Goddard III
Date Report was issued: February 18, 2005
DOE Award number: DE-FC26-02NT41581

Name and Address of Submitting Organization:
California Institute of Technology
1200 East California Blvd.,
Pasadena, CA91125

Disclaimer

Abstract

In this quarter, we have started the data collection process of the first field deployable multi-wavelength PM measurement system. This system is now operating in real world on PM emissions from a turbine power generator *v. s.* known PM standard for the system that we designed and tested in the lab. We proved that we could repeatedly collect same scattering signal under same engine load conditions. We further improved the signal to noise ratio of the system, by shortening the exposure time below 1,500nanosecond and increasing the peak power. Here, we give detailed description on our investigation of the mechanisms in improving precision of pulsed laser timing.

Table of Content

Executive Summary

During the 9th quarter of this project, we continued to make several major upgrades to the laser drivers and detection system. In this report, we detail all the efforts and changes we have made. We also collected some field test data using the previous system, and compare it with past results.

1. The improvements in detection and laser probing subsystems
    - Our laser probing subsystem is being upgraded with the fast sequential laser pulsing capability, with all laser drivers now replaced by our "PQS" driver, we could now drive the laser with pulses of only 1.2µsec. This helps us reduce background noise and exposure in the detection subsystem. We also have proven that we could reduce the timing jitter for our diode pumped passively Q-switched laser, and we gave the detailed reasons behind such improvements.
    - Our new laser probing and detection subsystem share the same USB2.0 controller platform, and has the unique features such as short gating for linear array camera and fast 500 lines per second acquisition.
    - The integrated system could synchronize the firing of probing lasers and the exposure of the detector system
2. On-going field test
    - We collected the multi-color laser scatter data and found that we could repeatedly collect the same signal for same engine conditions. But, there is inconsistency in the field test data and our simulation results.
3. Improvements in data logging
    - We still need to automate the logging the generator's conditions along with the particulate emission data process for faster and reliable data collection.

Experimental

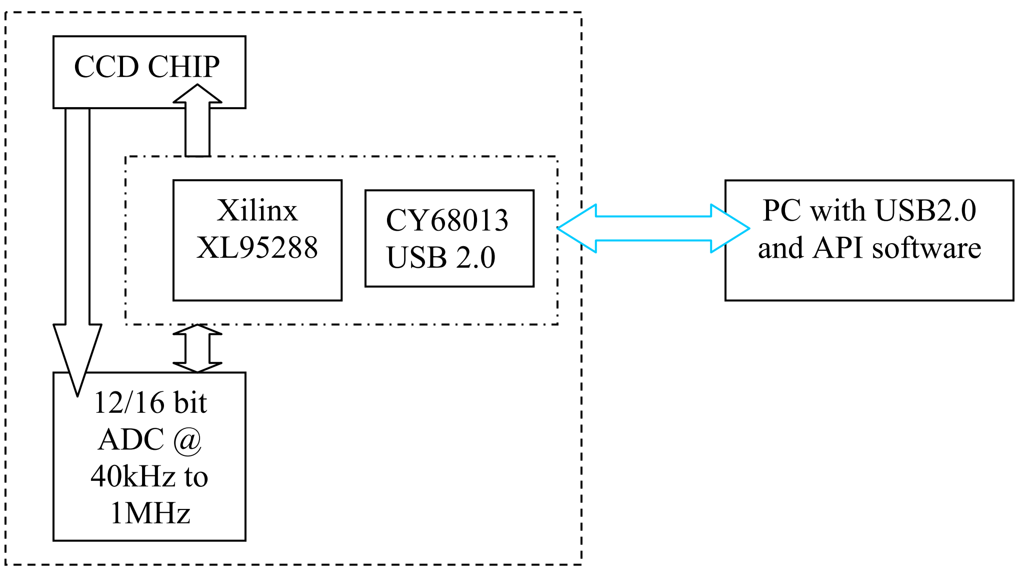
1. On the precise timing of the lasers and linear array camera

a. Linear Array Camera

In the last report (Q8), we started upgrading our USB linear array camera from USB1.1 to USB2.0, which gives us the capability to transfer 1000 Lines Per Second (LPS) and more importantly, giving us the capability to digitally adjust the integration time and make the controller suitable for different linear array cameras and ADC conversion modules.

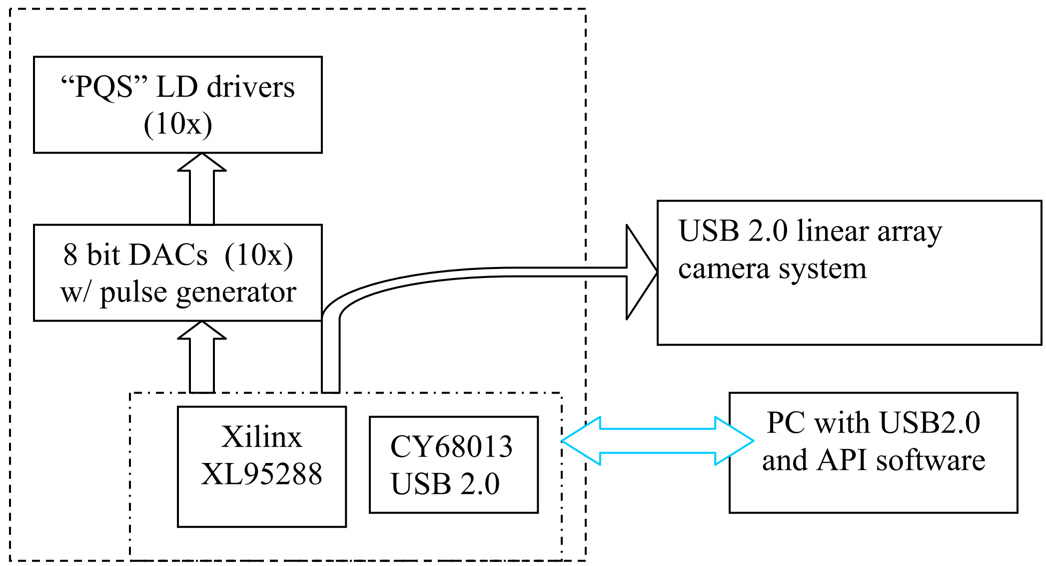
We found that it is necessary to upgrade to USB2.0 because we are collecting the different color light scattering signals sequentially, and for 10 different wavelengths, it takes 10 scans to finish a complete data collection cycle. For USB1.1, we could only acquire 8 scans per second, and this severely limits our collection speed. We found that we need to average data for about some 100 cycles to get reasonable consistently repeatable data, and need to acquire 100 cycles in ~120seconds means we are averaging over a quite long period of time, and this means this system's response time (2 minutes) is slow and time resolution is poor. With USB2.0, we hope to acquire 500 scans per second, and this gives us the ability to improve the response time to 1 second!

Below is the block diagram of our current design, we are still perfecting the hardware and electronic design right now, and current data is being taken with the old USB 1.1 linear array camera.



Block diagram for USB 2.0 Linear Array Camera for data collection in light scattering system.

b. Direct driven laser diode



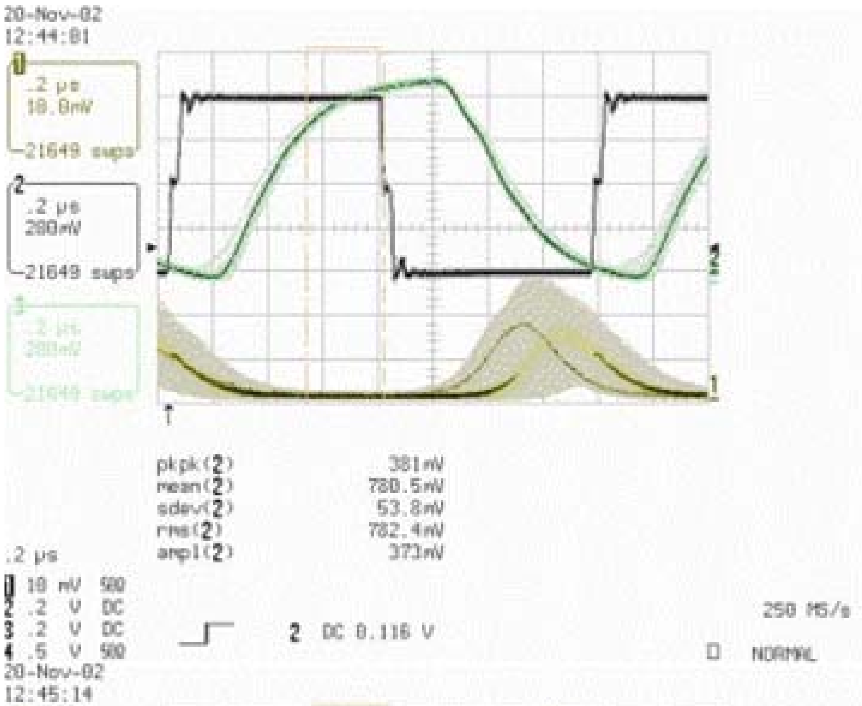
Block diagram for USB 2.0 Multi-ADC pulse generator for the controlled firing of 10 laser diodes

In our new diode laser pulse generator, we also used the controller module with USB2.0 controller and Xilinx CPLD, i.e. XC95288, along with 10 units of 8 bit DACs modules, for generating the current controlling pulses to the laser diodes. The XC95288 has 117 user I/O pins, and 27 pins are used for USB controllers, and the rest 80 pins are used for 10x8 bit DAC controls, and the last remaining 10 pins are used for controlling the pulsing of the laser diode. The pulses from the 10 pins are sent to a fast switching circuitry, and the voltage of the pulse is given by the DACs. The pulses from the 10 pins are also used to trigger the USB2.0 linear array camera system to collect scattered signal in a short flash.

The block diagram above shows the pulse generator and laser diode drivers.

In the probing laser beams, we use 10 different lasers listed below.
Table 1. The assembly uses 10 lasers at different wavelengths.

Wavelength	635nm	650nm	660nm	780nm	810nm	830nm	980nm	*355nm*	532nm	1064nm
Power (mW)	30	40	30	80	200	30	30	*14*	30	200
Package	TO	Cir. TO	Cir. To	Bare	C-mnt	TO	FC	*DP/PQS*	DP/CW	DP/CW



The diode lasers at 635nm, 650nm, 660nm, 780nm, 810nm, 830nm, 980nm are directly driven by external diode driver, and the precision of timing is only limited by the external driver. For our driver (code name PQS) using Wavelength Electronics' WLD3393 driver chip, the current from the driver (Green trace in the left figure) could respond to an external fast rising TTL (Black trace in the left figure) pulse with a rise time of 540ns, and a falling timing of 600ns. The timing jitter of the pulse is much smaller, only measured to be ±15ns (Green trace's rising/falling edge). This timing capability let us generate a full amplitude pulse with a pulse width of about 1,200ns and a timing jitter less than ±30ns. This PQS driver was designed for the high power passive Q-switched diode pump lasers, and has a capability to drive current at 5Amps, and it is actually faster than the laser driver that we used before for these laser diodes from Thorlabs.

Table below compares some of the features of our PQS driver with some of the popular ones from Thorlabs and Wavelength Electronics.

	"PQS" w/ WLD3393	LD1255	LD2000	ITC102	LD1100	IP500/250	MPL series
Modulation Bandwidth	***1.8MHz for 5A and 2MHz for 2.5A***	1.2kHz	30kHz	200kHz	No mod. Input, constant power	50kHz	1.4kHz
Maximum Current	***5A***	250mA	100mA	200mA	250mA	Up to 500mA	Up to 5A
Price/Cost	*BOM Cost $187*	$89	$158	$650	$72	$350	From $309

c. Detailed description on improving precise triggering of the diode pumped passively Q-switched laser

Compared to the other gain medium at 1064nm, Nd:YVO4, Nd:YAG has features that makes Passive Q-switching much easier to realize in a small package, but at the cost of requiring precise control of pump laser diode, and also stringent requirements on focusing the pump beam.

Table below compares some of the basic properties of Nd:YAG v.s. Nd:YVO4.

	Absorption FWHM	Fluorescence Lifetime	Lasing bandwidth	Absorption Coeff.	dn_o / dT $x10^{-6}$/K	Thermal Conduct.
Nd:YAG	<3nm	230 µs @ 1.0 wt %	0.8nm@ 1064nm	$8cm^{-1}$	9.0	0.13 W / (cm · °C)
Nd:YVO4	10nm	100 µs @ 0.87 wt %	0.6nm@ 1064nm	$30cm^{-1}$@ 1.1 wt %	8.5 ± 0.9, 2.9	0.05 W / (cm · °C)

We could see that the Nd:YAG has a Fluorescence lifetime of 230µsec, much longer than Nd:YVO4's 100µsec. This makes the passive Q-switching much easier for Nd:YAG when the passive Q-switch material is Cr:YAG. But, the absorption bandwidth at 808nm is only less than 3nm for Nd:YAG, whereas 10nm for Nd:YVO4. This means that the absorption efficiency of the pump laser beam does not change much even if the pump laser diode has temperature fluctuations if Nd:YVO4 is the gain medium. But, for Nd:YAG, the temperature fluctuation of 10ºC could easily create a wavelength shift of 3nm on the laser diode (with a shift ~0.3nm/ºC), and therefore change the absorption coefficient, therefore bringing fluctuations to the laser.

Also, Nd:YAG has the absorption coefficient per cm of material much smaller than Nd:YVO4, and with even better thermal conductivity and similar refractive index change, Nd:YAG has a much smaller thermal lensing effect than Nd:YVO4. Therefore, Nd:YVO4 could be pumped by a laser diode with poor focusing optics (usually a simple grin lens or ball lens after the edge emitter pump laser diode is sufficient), and thermal lensing will automatically tighten the focusing. Whereas for Nd:YAG, focusing optics that perfectly compensate for the asymmetric property of the pump laser diode and then nicely focus the beam are required to achieve tight focusing into the Nd:YAG medium.

The narrow absorption bandwidth for Nd:YAG makes it quite tough for controlling the pump laser diode. Evidences have be reported by other groups and verified again in this project that if pulsed pumping of laser diode is used, then there is significant broadening of laser diode bandwidth, along with shift of center wavelength is the duty cycle of the pump pulse is changed significantly.

Shown in the 2 figures below, the first figure shows that for different pump laser pulse width, the wavelength center shifts and also the bandwidth gets longer. This is happens because during laser pulse operation, the temperature of the diode increases, and therefore the center wavelength changes, and also the bandwidth now reflects the average effect over a longer pulse width, and therefore much wider. This makes the absorption efficiency for pump laser much lower and also fluctuating over the time, and particularly when the duty cycle and pulse width changes. These effects in the two figures below are also observed in our development of passively Q-switched Nd:YAG lasers. We believe that using simple pulsed pumping scheme will create a jitter over 2µsec between the TTL pulse's rising edge and the laser pulse, and the major reason behind this jitter is the thermal fluctuation caused by the pump laser diode. Note that such pump laser bandwidth shift and broadening could not be effectively alleviated by using better heat sink and thermal control for the pump diode, because the simple pump pulse is just creating the thermal fluctuation too fast for dissipation.

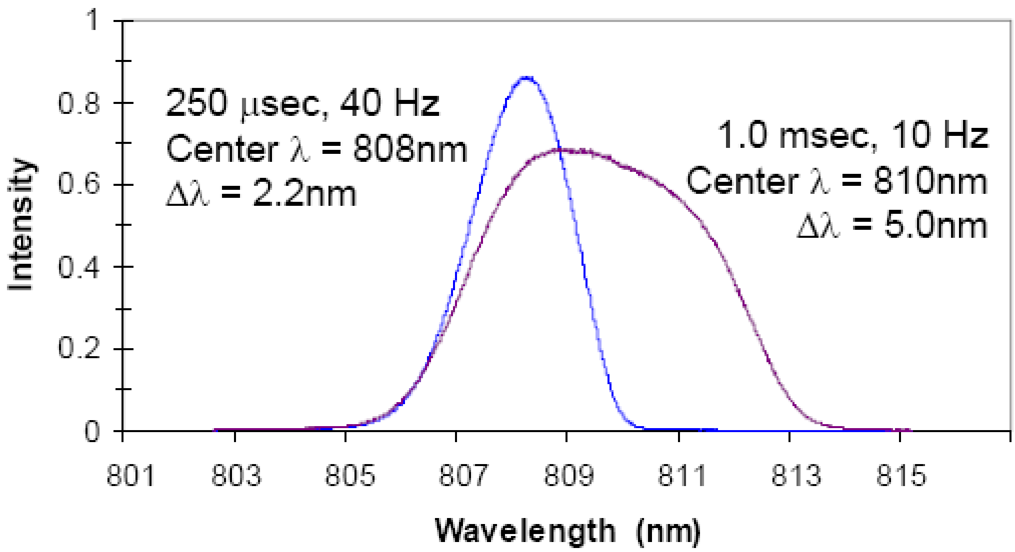


Figure 3. The center wavelength of the pump laser diode changes and broadens as the pulse width gets longer.

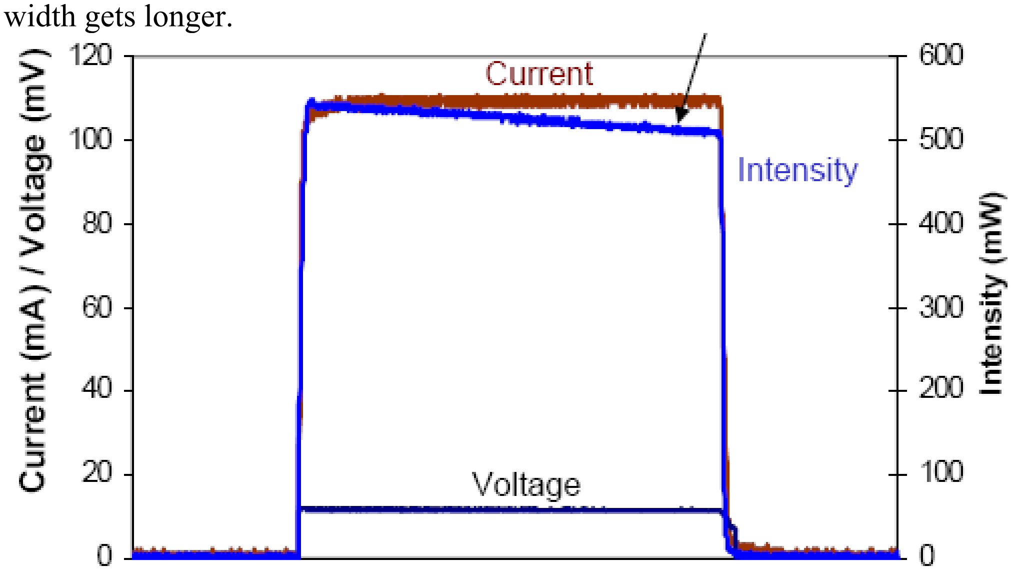


Figure 4. Laser Pump current pulse width change will also create lowered average power --- a result of elevated temperature, and therefore create noise in PQS laser operation.

We then found out that when we continuously pump the PQS laser, the pulse to pulse jitter is reduced significantly to about ±90ns. But, the repetition rate of continuously pumped PQS laser is only dependent on the pump laser power and can not be externally triggered or controlled.

This prompts us to explore the possibility of pre-pumping the PQS laser at a level just below threshold, and then when the TTL trigger comes in a higher current modulation pulse is sent to the PQS laser, triggering the Q-switched laser pulse. We then found out that we could improve the triggering precision significantly if we use this method. In this way, the delay between the TTL pulse and the laser pulse is reduced from 4msec to only 50µsec, and the jitter is reduced from ±2,000nsec to only ±30ns. This pre-pumping technique[1] could improve the performance of PQS in several ways ---

- first, it reduces the jitter significantly;
- second, it reduces the peak power needed for generating a laser pulse, which relief the diode laser driver's peak current specification;
- third, it should save laser diode life time when the peak current is reduced.

Reference 1 only attributes such effect to the changing thermal lensing conditions inside Nd:YAG material, we now have evidences to show that such changes are also result of temperature changes within the pump laser diode for simple pulsed operation, and such changes could be reduced through prepumping of the pump diode too. By reducing the pulsed amplitude and pulse width, we reduce the change of relative duty cycle ratio and this reduces the temperature fluctuations inside the pump laser, which then reduces the wavelength broadening and shift, and then reduces absorption efficiency fluctuations due to change of wavelength of the pump laser.

We also expect that we could apply such technique to other diode pumped PQS laser variants. We noticed that mode-locked PQS lasers consists of Nd:YVO4 and Cr:YAG[2] has similar problem of accurate triggering, and this technique could be used to further improve the precision in triggering.

A paper has been authored on this innovation, and has been presented at Photonics West 2005 and being submitted to "Optics Communications".

2. The field test platform and the field test setup

a. Turbine power generator

In the last quarter, our field test setup was set up at Alturdyne, Inc., our industrial collaborator, in El Cajon, San Diego, CA. Alturdyne set up a test engine, a 150hp T62-T32 gas turbine engine, in a container where we carry out our test.

We have collected some light scattering signals under different load conditions of the turbine. The signal seems to be able to repeat themselves under the same load conditionsm, indicating our instrument could repeat the results. But the angular distribution is different from what our theoretical calculation predicts. We guess that we have to modify our theoretical model to include water droplet's absorption due to carbon black inside.

In this quarter, we also moved the water jet generator to the container, where we will repeat the calibration test that we did at our lab.

Results and Discussion

1. Setting up platform for field test

We have set up the test platform at Alturdyne's test site, and preliminary results have shown our instrument could repeatedly detect changes during engines's normal load, overload, and fuel/air mixing ratio changes. But we have inconsistency between the data we collect and the simulation data. We will move our standard mono-sized water droplet generator into the field, and test it along with our instrument. We will then compare the differences between the two, and modify our simulation model, possibly to include the absorption effect of carbon black inside the water droplets from the turbine's emission.

We are collecting more data, and then also adding automatic data logging capability for the load conditions, fuel/air ratios, and the particulate emissions. This will help us systematically log the data and analyze it over long period of time.

2. Fast laser switching capability

In this quarter, we have upgraded our diode pumped PQS laser by improving its precise triggering capability. Now, we are able to reduce the jitter between the TTL pulse and the actual laser pulse to less than 20ns, and this value is already good enough for many applications previously only possible with EO Q-switched laser (jitter 1ns).

We also upgraded the drivers which directly drive other diode lasers to our home designed "PQS" driver. This upgrade allow us to reduce the window of integration down to 1.2μsec ~1.5μsec. The timing of all the lasers are controlled by computer through USB2.0 ports.

3. Digitally controlled fast scanning and ultra-short integration linear CCD detection

In this 9^{th} quarter, we have finished design and are finishing the upgrade for the fast scanning linear CCD camera. The upgraded CCD detection system will have all digitally controlled timing circuitry with gating as short as 21 ns, and as long as 6 seconds with minimal increment of 21 ns.

Work plan for the rest 3 quarters of the project

We see our work is following our schedule as outlined in the Statement of Work (SOW) at the start of this project.

Currently, we are finishing the following tasks:

- We will collect more scattering data from the engine, and modify our simulation model to include absorption effect of carbon black inside the droplet.
- We are adding extra I/O ports on the current system to enable us to simultaneously log the engine conditions such as load, fuel/air ratio, along with the PM emission data. Right

now, our data collection has to be done all manually and this takes long time and generate human errors.

- Finish upgrading the detection system using USB2.0 which gives us 500 scans/sec or 50 scans/sec for 10 lasers;
- Finish the upgrading on the electronics for the data acquisition so that we could control and instrument with notebook computers and therefore use it in the field.

Appendix:

Planed schedule from the statement of work

Task	Technical Milestone	Schedule
1. Assembly of the multiwavelength light source	Ready diode & DP chip lasers, drivers	Month 1-6
	Ready beam combination system	Month 1-6
2. Construction of the PM synthesizer	Verify that monosize PM are generated	Month 1-6
3. Simulation of Ralyeigh and Mie Scattering	Literature review	Month 1-3
	reviewComputer program that could generate simulated scattering spectrum	Month 1-6
4. Laboratory demonstration of instrument	Experimental scattering spectrum database for different PM sizes	Month 7-18
	Compare with theory and conventional PM monitoring data	
5.Application of the PM analyzer to a combustion environment: engine intake area	Correlation of our instrument data with conventional PM monitoring data	Month 13-24
6.Application of the PM analyzer to a combustion environment: engine exhaust	Correlation of our instrument data with total PM mass emission, new data (PM size and chemical composition) about in-situ PM monitoring	Month 13-24
7. Applicability assessment for PM emissions from coal fired power plants	Design/modify our PM instrument for smoke stack PM monitoring	Month 24-30
8. Instrument design optimization	Optimize the instrument during different experiments	Month 13-36

References

1. Z. Hong, H.Z., J. Chen, J. Ge, *Laser-diode-pumped Cr4+, Nd3+:YAG self-Q-switched laser with high repetition rate and high stability.* Applied Physics B., 2001. **73**: p. 205-207.